Advanced Accelerator Research & Development

2005

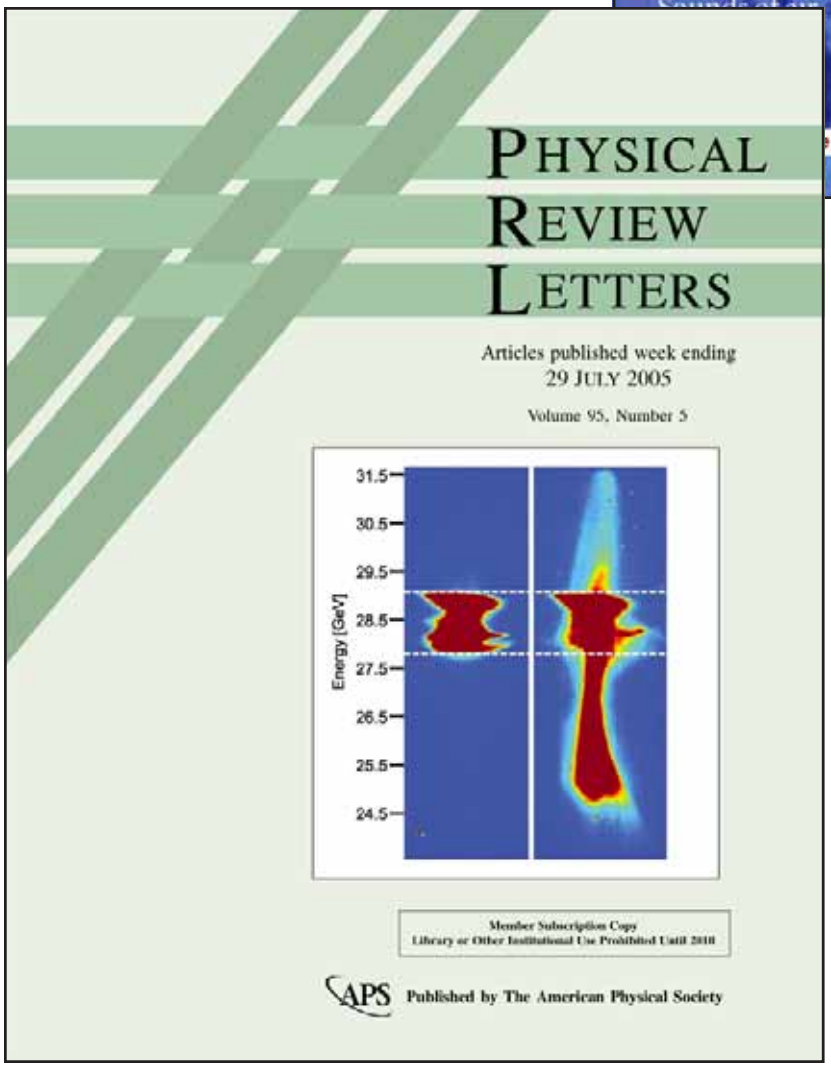

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TABLE OF CONTENTS

DOE-High Energy Physics, B. Strauss
Introduction……..……...……..…...…...i

UNIVERSITY PROGRAMS

Columbia University, T. C. Marshall
Experimental and Theoretical Research on Dielectric Wake Field Accelerators
and a Laser Cyclotron Auto-Resonance Accelerator….....1

Cornell University, H. Padamsee
Research in Superconducting Radiofrequency Systems…….....…..……....5

Florida A & M University, R. L. Williams
Electron Beam Transport in Advanced Plasma Wave Accelerators….....9

Florida State University, S.W. Van Sciver
Liquid Helium Fluid Dynamics Studies…….....….....13

Indiana University, S.Y. Lee
Physics of beam cooling, Space Charge Effects on Beams, and Beam
Manipulation Technologies in High Energy Accelerators……...…….....19

Massachusetts Institute of Technology, C. Chen
Periodically Focused Intense Charged-Particle Beams…….....……..…....….....23

Massachusetts Institute of Technology, R. Temkin
17 GHz High Gradient Accelerator Research…….....27

Michigan State University, M. Berz, K. Makino
Advanced Map Methods for the Description of Particle Beam Dynamics.....33

National Institute of Standards and Technology, L. Costrell
Instrumentation Standards.....39

National Institute of Standards and Technology, J. Ekin, N. Cheggour
Electromechanical Properties of Superconductors ……..…….....41

National Institute of Standards and Technology, L. Goodrich
Critical-Current Metrology for Nb_3Sn Conductor Development…….....47

Naval Research Laboratory, S. Gold
Dielectric-Loaded Accelerator and Active Pulse Compressor Development at 11.424 GHz.....53

Naval Research Laboratory, P. Sprangle
High Energy Laser-Driven Acceleration Based on the Laser Wakefield Accelerator…....59

Northern Illinois University, C. Bohn
Nonlinear Dynamics of High-Brightness Electron Beams and Beam-Plasma Interactions: Theories, Simulations, and Experiments.....65

Northwestern University, M. Velasco
Novel Instrumentation for future TeV e^+e^- Colliders…….....…….....…….....71

Ohio State University, E. Collings, M. Sumption
Materials Strands and Cables for Superconducting Accelerator Magnets……....……75

Princeton University, R. Davidson, H. Qin
Nonlinear Dynamics and Collective Processes in Intense Charged Particle Beams.....81

Linear Accelerator Center, R. Byer
Proposed Physics Experiments for Laser-Driven Linear Acceleration in a Dielectric-Loaded Vacuum…….....….....87

STI Optronics, Inc. W. Kimura
Staged Electron Laser Acceleration - Laser Wakefield (STELLA-LW) Experiment.....93

State University of New York, I. Ben-Zvi
Development Of Electro-Optical Detection For The Temporal Characterization Of Sub-Picosecond Electron Beam Bunch…….....99

Texas A&M University, P. McIntyre, A. McInturff
New Technology for Future Colliders…….....…….....105

University of California Berkeley, J. Wurtele
Advanced Accelerator Concepts…….....…….....111

University of California Los Angeles, D. Cline
Advanced Accelerator Physics Research at UCLA…….....…….....115

University of California Los Angeles, C. Joshi (PI) W. B. Mori, C. E. Clayton
Experimental, Theoretical and Computational Studies of Plasma-Based Concepts for Future High-Energy Accelerators.....….....121

University of California Los Angeles, J. Rosenzweig, C. Pellegrini
Theoretical and Experimental Studies in Accelerator Physics…….....…..127

University of Colorado, J.Cary
Chaotic Dynamics in Accelerator Physics…….....…….…...133

University of Kansas, J. Shi
Study of the Stability of Particle Motion in Storage Rings….....…….....137

University of Maryland, A. Dragt, R. Gluckstern
Dynamical Systems with Emphasis on Applications to Accelerator Physics…….....141

University of Maryland, M. Reiser
Studies of Microwave Sources for High Frequency Colliders ….....….....147

University of Maryland, H. Milchberg, T. Antonsen
Application of Plasma Waveguides to Advanced High Energy Accelerators….……..153

University of Maryland, P. O'Shea, M. Reiser, R. Kishek, and I. Haber
Study of Physics of Space Charge Dominated Beams for Advanced Accelerator Applications (Tasks A and C)…….....…….....159

University of New Mexico, J. Ellison
Investigations of Beam Dynamics Issues at Current and Future Accelerators.....167

University of Southern California, T. Katsouleas, P. Muggli
Program for Plasma-Based Concepts for Future High Energy Accelerator….....……....171

The University of Texas at Austin, M.Downer
Laser Wakefield Acceleration: Channeling, Seeding and Diagnostics.....177

The University of Texas at Austin, G. Shvets
Advanced Accelerator Studies…….…….....…....……....…….....181

University of Wisconsin-Madison, D. Larbalestier, P. Lee
High Field Superconductor Development and Understanding: Flux Pinning, High Field Current Density and Novel Fabrication Processes for Probing the Limits of Performance in High Field Superconductors…….....187

UNIVERSITY LINEAR COLLIDER PROGRAM

G. Dugan
Introduction to University-Based Linear Collider Research and Development.....…..193

Cornell University, G. Dugan
Investigation and Prototyping of Fast Kicker Options for the TESLA Damping Ring.....197

Illinois Institute of Technology, D. Kaplan
Neutrino Factory R&D at the Illinois Institute of Technology…….....201

Northwestern University, D. Seidman
Atom-Probe Tomography of Niobium for Superconducting RF Cavities.....207

Old Dominion University, L. Vušković
Investigation on Plasma Etching for Superconducting RF Cavities
Surface Preparation.....209

Princeton University, C. Lu
Undulator-Based Production of Polarized Positrons..…….....…….…....213

University of Tennessee, W.Bugg
Demonstration of Undulator Based Production of Polarized Positrons at
Final Focus Test Beam (FFTB) E166 at SLAC.....…….....227

University of California, Davis, M. Chertok & D. Pellett et al.
Radiation Damage Studies of Materials and Electronic Devices Using Hadrons.....231

University of Illinois at Urbana-Champaign, G. Gollin
ILC Damping Ring Kicker R&D at the University of Illinois….....…….....235

University of Wisconsin-Madison, R. Prepost
Development of Polarized Photocathodes for the Linear Collider.....239

NATIONAL LABORATORIES

Argonne National Laboratory, W. Gai , J. Power
Report on Advanced Accelerator R&D Activities at Argonne…….....243

Brookhaven National Laboratory, L. Cooley, A. Ghosh
Investigation of Advanced Superconductors for High-Energy Physics.....249

Brookhaven National Laboratory, M. Harrison
Brookhaven National Laboratory Superconducting Magnet R&D Program….....253

Brookhaven National Laboratory, V. Yakimenko
Accelerator Test Facility…….....…….…….....257

Fermi National Accelerator Laboratory, H. Edwards
Fermilab/NICADD Photoinjector Laboratory…….....…….....265

Fermi National Accelerator Laboratory, H. Piekarz
Superferric Magnet Development and Test…….....….....269

Fermi National Accelerator Laboratory, N. Solyak
Development of the 3.8Ghz Superconducting Cavities at Fermilab….....273

Fermi National Accelerator Laboratory, A. Zlobin
Advanced Accelerator Magnet and Superconductor R&D at Fermilab….....….....279

Lawrence Berkeley National Laboratory, J. Byrd
Beam Electrodynamics Studies at Berkeley Lab…….....…….....285

Lawrence Berkeley National Laboratory, M. Furman
Advanced Accelerator R&D…….....…….....291

Lawrence Berkeley National Laboratory, W. Leemans
Optical-Accelerator Experiments at Berkeley Lab…….....…….....295

Lawrence Berkeley National Laboratory, G.L. Sabbi
Superconducting Magnet Program…….....…….....303

***Stanford Linear Accelerator Center, R.H. Siemann*,**
SLAC Accelerator Research Department B…….....…….....309

Stanford Linear Accelerator Center, R. D. Ruth
Accelerator Research Department-A…….....…….....325

Stanford Linear Accelerator Center, J. Fox
Advanced Electronic Group…….....…….....337

Stanford Linear Accelerator Center, G. Stupakov
Collective Effects Group…….....……..…….....341

Stanford Linear Accelerator Center, S. Tantawi
High Power RF Group…….....…….....345

Stanford Linear Accelerator Center, J. Wang
RF Structures Group…….....…….....353

NATIONAL MUON/NEUTRINO COLLABORATION

Lawrence Berkeley National Laboratory, M. Zisman
Neutrino Factory and Muon Collider Collaboration R&D Program….....359

CONFERENCES, WORKSHOPS AND PARTICLE ACCELERATOR SCHOOL

W. Barletta
U.S. Particle Accelerator School Yearbook Report…….....….…….....365

T. Katsouleas
The Advanced Accelerator Concepts Workshop- Legacy of Progress….....….373

D.Larbalestier
The Low Temperature Superconductor Workshop.....377

APPENDICES

Current Graduate Students FY 2005.....381

Past Graduate (Ph.D.) Students and Placements FY 2005.....385

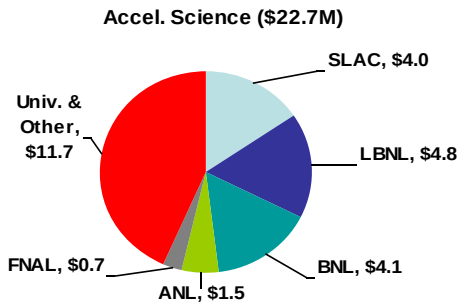
Acronyms.....397

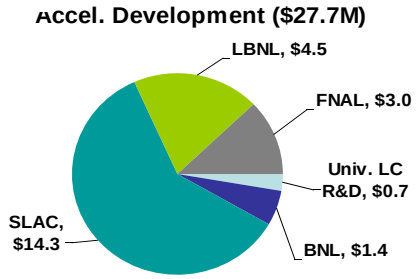
INTRODUCTION

Welcome to the third edition of the Advanced Accelerator R&D "Year Book" of summaries of the research work supported by the Department of Energy's (DOE) Office of High Energy Physics (HEP). The previous two editions of the Year Book, published in 2000 and 2003, found wide interest both in the physics community and in government.

Advanced Technology R&D is work that is not related to any specific project or potential project but rather addresses more fundamental accelerator physics and technology issues for the purpose of advancing frontiers in these areas and with a specific focus on topics that may be applicable to HEP.

This program continues to support a very broad range of accelerator technology and science ranging from advanced acceleration techniques such as laser and plasma acceleration to the materials optimization of state of the art superconductors. In FY'05 the funding for this effort was $50 million. Figures 1 and 2 illustrate the funding of this effort by institutions and topic.





Additional R&D and leveraging of the program in the technologies for HEP accelerators is supported under the SBIR/STTR program. In FY'05 the level of funding for these activities was $18 million covering 46 Phase I grants and 21 Phase II grants. The SBIR/STTR program is a set aside required by public law. A strong and largely successful effort has been made to integrate this work into the overall detector and accelerator R&D needs of the HEP program. Abstracts of grants funded may be found on the web at http://sbir.er.doe.gov/sbir/. At the hot link "Award Data" one can view abstracts of grants funded from FY'98 through FY'05.

In this edition of the year book we have added summaries of the U.S. Particle Accelerator School and lists of conferences where we support archival publication of the papers presented. While the U.S. Particle Accelerator School is not directly funded by the program, a description of its mission and activity is included. Also added are descriptions of two national research collaborations. The first in the Neutrino Factory and Muon Collider Collaboration and the second is the University Linear Collider Research Program. The second program is funded by both the National Science Foundation and DOE. Only those projects funded by DOE are included in this volume.

A measure of success in any R&D program is the successful education and graduation of professional scientists and engineers to support and continue the work. As before, two appendices of demographic data are included. Appendix A is a listing of current

graduate students that was compiled from the summaries submitted. Appendix B lists all of the Ph.D. students who obtained their degrees under the HEP accelerator science and technology program listed by institution and advisor. Because this list does not include grants supported by other elements of DOE or by the NSF it is only a subset, albeit a major one, of the degrees awarded in this field. It is our rough guess that the number of doctoral degrees in accelerator physics and technology approaches 480 since 1982. Additions and corrections to this list are solicited.

As in previous editions of the Year Book the individual research summaries were prepared by the principal investigator or the national laboratory manager for that research and therefore represent that individual's view of the work performed. These summaries are snapshots submitted in the summer of 2005. Included at the end of each summary are lists of recent publications and talks, current staff including graduate students working on projects funded by the grant, and contact information should additional information be required.

The work of Micah Gates, Michelle Sullivan and especially Valri Monroe in soliciting, editing and formatting the various submissions is most gratefully acknowledged. Melinda Menard of the University of Wisconsin-Madison who served as the executive editor of the first and second editions assisted us again with her technical consulting and expertise. Special thanks are due to the crew at the University of Wisconsin Applied Superconductivity Center under the leadership of Alex Squitieri who did final formatting and assembled all the submissions into the PDF CD-ROM. The work of the graphics and printing department of the Department of Energy for their help with graphics and final production has been invaluable.

While we have assembled this work, it is the reflection of all of the persons who have taken time to submit the summaries contained herein. We also thank all of those who have encouraged us to prepare this edition.

Bruce P. Strauss
Editor

Germantown, Maryland
October 2005

UNIVERSITY PROGRAMS

Experimental and Theoretical Research on Dielectric Wake Field Accelerators and a Laser Cyclotron Auto-Resonance Accelerator

Thomas C. Marshall
Columbia University

Summary

The project is a collaborative effort with Omega-P, Inc., located at Yale, and the Brookhaven National Laboratory (BNL) Accelerator Test Facility (ATF). At these locations, experimental work is progressing, testing certain principles of wakefield acceleration in dielectric wakefield accelerators (DWA), and the new LACARA (Laser Cyclotron Auto-Resonance Accelerator) which is under construction. Assistance to the project is provided by the participation of Dr. Jay Hirshfield of Yale and Omega-P and his co-workers, together with the staff of ATF.

Experimental work is financed by a grant to Columbia and by related projects at Omega-P funded by the SBIR program. At ATF 50 MeV bunches are provided by a linac equipped with an RF photocathode. One or more bunches cam pass through a linear structure, permitting measurements of bunch energy change and RF spectrum. The purpose of these experiments is to validate our understanding of multi-mode, multi-bunch wake fields set up in dielectrics, and to investigate the limits of wakefield superposition as a method to achieve high accelerating gradients from a train of "drive bunches" passing through a suitable dielectric structure. A new part of this project will be the study of the high power laser accelerator "LACARA," which will use a 0.8 TW CO_2 laser pulse and a 6T solenoidal field provided by a superconducting magnet to accelerate a bunch of charge obtained from the ATF linac from 50 to 85 MeV in about 1m. The magnet has been tested and installed at ATF, and the experimental components are being assembled. LACARA should function in 2006.

Recent Accomplishments

A major study of DWA physics has been completed in the past year. The experimental work was done at BNL-ATF on the second beam-line. The work was part of the PhD thesis of Dr. Sergey Shchelkunov, who worked with the ATF staff using their 50MeV RF linac and RF photocathode gun.

The first part of the study involved measurements of the spectrum of mm-wavelength radiation emitted by a single bunch which was passed through a 3 mm diameter channel in a 1.93 cm radius alumina cylinder, about 50 cm in length. The wide spectrum of closely-spaced TM modes radiated by the short bunch was measured using an mm detector and a set of filter meshes having bandwidth ~10 GHz and center frequencies spaced from 50 to 120 GHz. A novel method of forming ratios of power emitted for different charge and bunch length permitted the accurate measurement of both these quantities from the coherent radiation spectrum data. It turns out that it is the RMS bunch length which is significant and measurable, and that the distribution of charge within the bunch does not affect the result. Extension of the filter span to 300 GHz would permit the accurate measurement of bunch length as small as 200 fsec. *Figure 1* shows the experimental arrangement for the spectroscopy and *Figure 2* is a typical data set interpreted by fitting the data to the spectrum. A new, nondestructive, and easy-to-use bunch length diagnostic has been developed as a result of these investigations [7,8].

The second part of the study involved the superposition of wakefields from two bunches, separated by approximately one wakefield period. DWA's are generally attractive because injection from an external source of RF energy is not required, and accelerating fields are

generated from only the bunches themselves. It was possible to vary the spacing between the bunches accurately, so that, by measuring the energy loss of the two bunches, it was clearly revealed what the optimum separation of the bunches was and to determine the profile of the superposition resonance (see *Figure 3*). All data could be satisfactorily interpreted by theory, and thus there is now confidence in the possibility of building up very large wakefields by superposition of the fields from individual bunches. A train of bunches would be used since it might not be possible to obtain a single bunch having a large charge and satisfactory emittance to generate a substantial wakefield [9].

Our efforts are now concentrated on the construction of the LACARA experiment at ATF (*Figure 5*). In this project, a bunch of 50 MeV electrons is to be accelerated using a multi-TW CO_2 laser pulse which travels in the same direction as the bunch. The bunch moves along the axis of a solenoidal magnetic field ~6T, and undergoes a cyclotron auto-resonance enhancement of energy. The moving electron sees the optical wave Doppler-shifted to its cyclotron frequency in its rest frame. As the magnet is only a few gyro-periods in length (~1m), the resonance is very broad (*Figure 4*). LACARA, a vacuum accelerator of electron bunches, uses no structure other than that of the simple smooth bore magnet solenoid. LACARA is competitive with the Inverse Free Electron Laser (IFEL) in its ability to accelerate bunches of electrons, but unlike the IFEL, there is no longitudinal bunching occurring in the acceleration phase; rather, the entire bunch of electrons undergoes the same acceleration using *bunching in phase*. In the experiment to be done at ATF, it is expected that bunches of approximately 1 nC charge and 7 psec in length will be used. We are setting up to experimentally test the LACARA acceleration principle, which if validated, would be an important step forward in utilizing intense laser beams for advanced accelerators. Furthermore, the accelerated bunch of electrons at the LACARA output can be “chopped” into femtosecond bunches; these may then be injected into other laser accelerators.

The cryomagnet is now operative and installed at ATF. It is a “dry” magnet, meaning that the helium refrigerant is contained within the system refrigerator. The magnet is mounted onto a special highly-accurately-adjustable table which permits alignment of the bunch motion with the field. Various safety and operational hurdles have been dealt with. The experiment includes two major subsystems: a laser beam transport line (capable of handling a 10J pulse and focusing the radiation to a Gaussian waist ~1.5 mm inside the magnet bore); and a bunch transport system. The latter includes four sensor stations which assist in the alignment. These systems are being assembled and the experiment should begin operation in 2006.

Publications 2003-2005

1. C. Wang, J.L. Hirshfield, T.C. Marshall, "Stability of Electron Orbits in the Strong Wake Fields Generated by a Train of Fsec Bunches," Proceedings of the 2003 Particle Accelerator Conference, Portland OR; **3**, p. 1930
2. S.V. Shchelkunov, J-M. Fang, T.C. Marshall, "Experimental and Numerical Studies of Dielectric Wake Field Acceleration Devices," Proceedings of the 2003 Particle Accelerator Conference, Portland OR; **3**, p. 1924
3. J-M. Fang, T.C. Marshall, V.P. Tarakanov, J.L. Hirshfield, "Numerical Study of Interference between Transition Radiation and Cerenkov Wake Field Radiation in a Planar Dielectric Structure," proceedings of the 2003 Particle Accelerator Conference, Portland OR; **3**, p. 1882
4. C. Wang, J.L. Hirshfield, J-M. Fang, and T.C. Marshall, "Strong Wake Fields Generated by a Train of Femtosecond Bunches in a Planar Dielectric Microstructure," Physical Review Special Topics - Accelerators and Beams, **7**, 051301 (2004)
5. T.C. Marshall, Changbiao Wang, and J.L. Hirshfield; "GeV/m Wake Fields Set Up by a Train of pC, Fsec Bunches in a Planar Dielectric Microstructure," p. 949, Advanced Accelerator Concepts, Eleventh Workshop, Stony Brook NY, 21-26 June 2004; AIP Conference Proceedings **#737**, Melville NY 2004; Vitaly Yakimenko editor
6. "Wake Fields set up in a Semi-Infinite Rectangular Dielectric Waveguide by a Train of Electron Bunches," T.C. Marshall, N.I. Onishchenko, and G.V. Sotnikov; p. 698, Advanced Accelerator Concepts AIP Proceedings **#737** (as above)
7. S.V. Shchelkunov, T.C. Marshall, J.L. Hirshfield, and M.A. LaPointe, "A Nondestructive Method for Measuring the RMS Length of Charge Bunches Using the Wake Field Radiation Spectrum"; p.421, Advanced Accelerator Concepts, AIP Conference Proceedings **#737** (above)
8. S.V. Shchelkunov, T.C. Marshall, J.L. Hirshfield, and M.A. LaPointe, "Nondestructive Diagnostic for Electron Bunch Length in Accelerators Using the Wakefield Radiation Spectrum," Physical Review Science & Technology, Accelerators and Beams, **8**, 062801(2005)

Papers Submitted

S.V. Shchelkunov, T.C. Marshall, J.L. Hirshfield, M.A. Babzien, and M.A. LaPointe, "Experimental Observation of Constructive Superposition of Wake Fields Generated by Electron Bunches in a Dielectric-Lined Waveguide," Physical Review Science & Technology, Accelerators and Beams

To the May 2005 Particle Accelerator Conference (Proceedings to be published)

1. Changbiao Wang, et al., "Rectangular Dielectric-Lined Two-Beam Accelerator Structure,"
2. I.N. Onishchenko, et al., "Resonant Excitation of Selected Modes by a Train of Electron Bunches in a Rectangular Dielectric Wakefield Accelerator"
3. S.V. Shchelkunov, et al., "Observation of Superposition of Wakefields Generated by Electron Bunches in a Dielectric-Lined Waveguide"

Current Staff

T.C. Marshall, Professor of Applied Physics and principal investigator
Dr. S.V. Shchelkunov, Research Associate (located at the Yale Beam Physics Laboratory)

Doctoral Students Graduated

Dr. J-M. Fang (1997)
Dr. Iddo Wernick (1992)
Dr. Rodney Yoder (2000) [In collaboration with Prof. Jay Hirshfield]
Dr. Sergey Shchelkunov (03/05)

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Research in Superconducting Radiofrequency Systems

Hasan Padamsee
Cornell University

Summary

We are exploring improved cavity designs that lower the surface magnetic field, thereby raising the maximum possible accelerating field in superconducting cavities. Our first re-entrant shape cavity has a surface magnetic field 10% lower than the baseline shape for the International Linear Collider (ILC) cavity, developed by the TESLA collaboration. Cornell reached a world record accelerating field of 46 MV/m at a Q value of 10^{10}, and 47 MV/m in the pulsed mode, as suitable for a linear collider. One of our graduate students is pursuing research on understanding the Q-drop at high fields and why electropolishing and baking removes this Q-drop.

I. Improved Geometries, Fabrication and Preparation

The best single cell cavities at many laboratories now reach 40 – 42 MV/m at Q values exceeding $10^{10.}$ Above 40 MV/m the magnetic field at the surface of the resonator approaches the fundamental limit where superconductivity breaks down. One way to circumvent this limit is to modify the cavity shape to reduce the ratio of the peak magnetic field to accelerating field.

Our first re-entrant shape cavity (*Figure 1*) has a surface magnetic field 10% lower than the baseline shape for the ILC cavity, developed by the TESLA collaboration. The new re-entrant cavity has the same aperture (70 mm) as the baseline shape for the ILC. A second cavity design with a 60 mm aperture has 16% lower surface magnetic field. The down side of these new shapes is the higher accompanying surface electric fields which enhance “field emission” of electrons from the high electric field regions. But field emission does not present a brick wall limit because techniques such as high pressure rinsing with high purity water at pressures of about 100 bar eliminate microparticles contaminants which cause field emission. Another important aspect of cavity shape is beam aperture. Smaller apertures produce stronger wakefields. Studies are in progress to evaluate the trade-off between higher wake-fields and higher potential accelerating gradients.

We fabricated our first re-entrant cavity with a 70 mm aperture (*Figure 2*). Cornell reached a world record accelerating field of 46 MV/m at a Q value of 10^{10}, and 47 MV/m in the pulsed mode, as suitable for a linear collider. The corresponding surface magnetic field was 1755 Oe and the surface electric field was 100 MV/m. *Figure 3* shows the “Q versus Accelerating Field” of the cavity. To reach record performance levels, the cavity was made from high-purity, high thermal-conductivity niobium (residual resistivity ratio = 500) to avoid thermal breakdown of superconductivity. Electropolishing provided an ultra smooth surface. High pressure rinsing at 100 bar thoroughly scrubbed the surface free of field emission-causing microparticles. Final assembly took place in a Class 100 clean room environment. In addition, baking at 100 C for 50 hours promoted a needed redistribution of the oxygen in the rf layer which is known to avoid premature rf losses.

These are now standard techniques for the best superconducting cavity preparation. However, we altered some of the procedures with a view to exploring lower fabrication cost methods. For example, we used yttrium as the solid state gettering material at

1200 C to purify the niobium half-cells instead of the standard procedure of titanium at 1350 C. Purifying half-cells instead of complete structures, and lowering the temperature could eventually lead to reductions in fabrication costs. We also developed a new method of electropolishing the complete single cell cavity in a vertical orientation, which eliminated the need for rotating the cavity full of acids (*Figure 3*). This approach simplifies the complex rotary set up which could also lead to future cost reductions.

We have fabricated another single cell niobium cavity with a 60 mm aperture, and a geometry that has a 16% magnetic field reduction (*Figure 4*). We plan to test it in Fall 05.These results have been published in an oral paper at PAC 05.
Rong-Li Geng, Hasan Padamsee, Andrew Seaman and Valery Shemelin, "World Record Accelerating Gradient Achieved in a Superconducting Niobium RF Cavity," Paper ROAC009, PAC05 (2005).
See also: CERN Courier, June 05, "Records Fall at Cornell"

2. Basic Studies of high field Q-slope in Nb cavities

One of our graduate students is studying the physics of the high field Q-slope. Baking at 100 C for 48 hours is known to have a beneficial effect on the Q-slope of chemically etched cavities, but the extent of the improvement has a large variation from cavity to cavity for unknown reasons. Even the basic cause of the improvement due to baking is not well understood, although there are some theoretical models. One model relates to surface smoothness. *Figure 5* compares the surface roughness of a small grain and a large grain niobium sample obtained by stylus profilometry. Our corresponding niobium cavity experiments showed that the Q-slope improvement due to baking for the small grain (smoother) cavity is also much larger than for a large grain (rougher surface) cavity (*Figure 6 and b*). This result is consistent with the well-known behavior that the Q-slope of a very smooth electropolished cavity shows a large improvement with baking. Therefore, our studies strengthen the connection between surface roughness and the severity of the Q-slope, as well as to the amount of improvement due to baking.

Another model to explain the strong Q-slope invokes the existence of a pollution layer, i.e. an excess of interstitially dissolved oxygen just below the oxide. Presumably, the excess oxygen lowers the energy gap and the RF critical field. But the depth and concentration of this layer is not known. The model claims that baking reduces the Q-slope by diffusing the excess oxygen out over a larger region. In one study, we are using our Secondary Ion Mass Spectrometry (SIMS) microprobe to measure the oxygen presence below the oxide layer and to study the effect of baking on the excess oxygen. Preliminary studies show an excess presence of oxygen with a peak at about 25 nm below the surface. Baking gets rid of the peak. This result is consistent with the diffusion length of oxygen in niobium at 100 C for 48 hours. Students will continue these studies over the next year.

<u>Staff and Students</u>
Prof. Hasan Padamsee, PI
Dr. Rongli Geng, Research Associate
Valery Shemelin, Research Associate
Grigori Eremeev, Graduate Student, PhD Candidate
Gerry Shipman, Graduate Student, Masters Candidate
John Kaufman, Surface Analyst

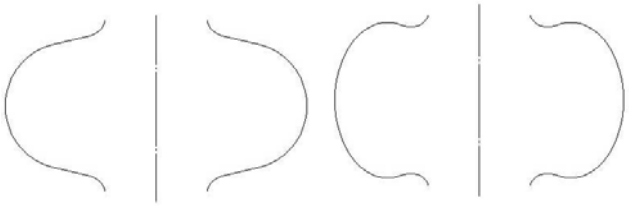

Figure 1 Comparison of the cell profiles of the standard TESLA shape cavity (left) with the re-entrant cavity (right). Both have the same aperture 70 mm

Figure 2 Comparison of the standard TESLA shape cavity (left) with the new re-entrant shape cavity. Both cavities have 70 mm aperture

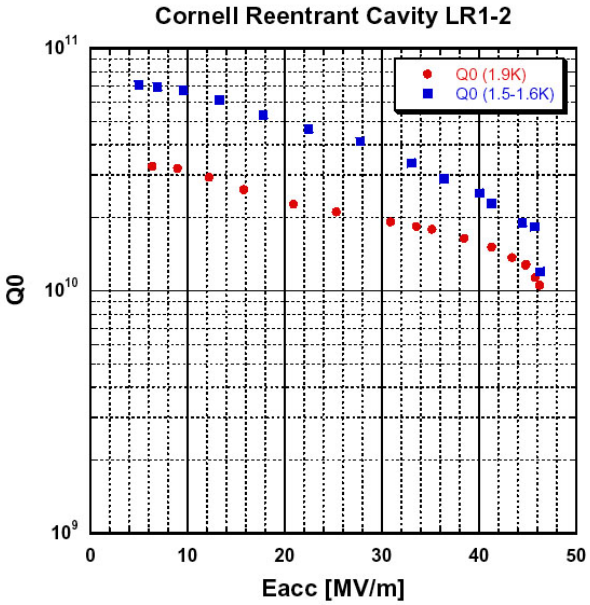

Figure 3 Record Q vs E curves for the first re-entrant shape cavity

Figure 4 Comparison of re-entrant (top) and standard TESLA shape (bottom) cavities. The re-entrant cavity has a 60 mm aperture

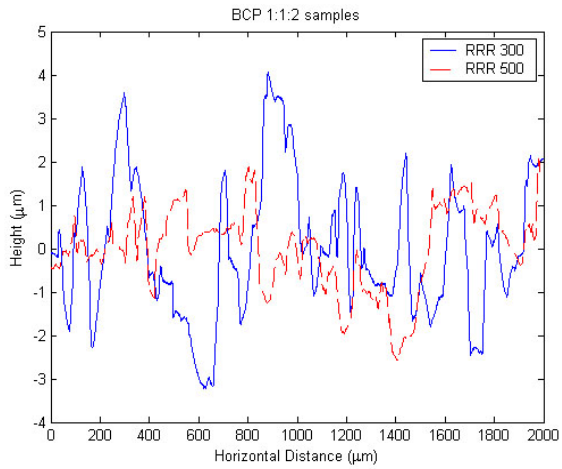

Figure 5 Stylus Profilometry results on niobium samples of two different grain sizes. Note that the larger grain sample is rougher judging from the larger step heights

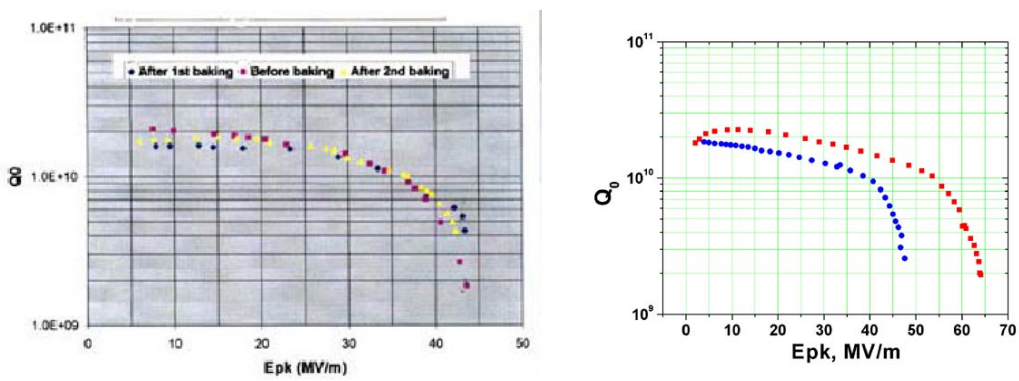

Figure 6 Q slope improvements for cavities made with niobium of (a) large grain ≈ 100 microns and (b) small grain ≈ 50 microns. Note that the Q-slope is stronger for the larger grain (rougher) cavity than for the smaller grain cavity, and that the improvement due to baking is also more for the smaller grain cavity

Electron Beam Transport in Advanced Plasma Wave Accelerators

R. L. Williams
Florida A. & M. University (FAMU)

Summary

Research activities are underway at the FAMU Laser Plasma Beam Physics Laboratory (FAMU LPBPL) which have the goal of contributing to the understanding of the physics of the interactions among lasers, particle beams and plasmas, in applications to advanced particle acceleration techniques. The general goals of this research area include discovering and developing ways to accelerate charged particles to very high energies over very short distances by using unconventional acceleration techniques. These unconventional techniques include the plasma wave accelerator in which the charged particles get trapped by and accelerated in the wave's relativistically-moving electrostatic potential. Acceleration gradients in excess of one gigavolt per meter have been attained in several laboratories. This means that accelerations that presently require machines several kilometers in length, could be accomplished in a plasma wave acceleration device that is just a few meters in length, theoretically. This research is expected to lead to future particle accelerators that are very compact, for many fields that rely on accelerators, such as industry, health and science. Our particular goals involve developing new ways to measure the very large accelerating electrostatic fields found in relativistic plasma waves, by probing the waves concurrently with cross-propagating laser beams and a low energy electron beam. In addition, we have developed some useful laboratory tools and techniques that support our main experiment.

The experimental layout in the LPBPL is shown schematically in *Figure 1*. The experiment is briefly described as follows: The CO2 and YAG laser beams are transmitted into an interaction chamber and focused to a tight spot by lenses located inside the chamber. The lasers ionize the gas at this spot creating a plasma. Presently, experiments are being conducted to produce plasma waves in this plasma. In past experiments, the interaction chamber was backfilled with gas, but recently an improvement was made by the installation of a pulsed gas jet plasma source. The laser-produced plasma will now be confined to a smaller volume at the tip of the gas jet nozzle, which is advantageous for producing more intense finite-sized plasmas. (*Figure 2* is a schematic of the apparatus used to test the gas jet plasma source prior to installation in the interaction chamber.) In the experiment, an initially cylindrical electron beam (5 to 50 keV) is injected transverse to the plasma wave, which then scatter the electrons to create a distorted electron beam cross section. A fluorescing screen, backed by cameras, is positioned downstream of the electron beam, and is used to display the distorted electron beam cross section. The distorted cross section gives information about the plasma wave through which the electron beam propagated. (Presently, experiments and computer simulations are being performed to study the emittance of the electron beam, as part of an effort to completely characterize the beam.) Computer simulations predict that the plasma waves' longitudinal electrostatic fields distort the electrons in the direction parallel to the waves's velocity; and the radial electrostatic fields distort the electrons in the directions perpendicular to the waves's velocity. Therefore, analysis of the plasma wave can be done by studying the images of the beam cross section displayed on the fluorescer. The computer simulations predict that by analyzing these images, we can obtain information on the plasma wave's amplitude, as well as information on the wave's wavelength and spatial extent. A YAG

laser will be used to analyze independently the plasma wave's amplitude by scattering light from the wave, and observing the resulting frequency and momentum shifts.

All major components of the experiment are now being operated together and are time sequenced using pulse/delay generators. These components include the lasers, electron gun, gas jet plasma source, and diagnostic devices. Improvements to the interaction chamber have been made so that focusing lenses can be placed internally, and additional diagnostic ports were added. The beam viewing system has been improved and now incorporates digital cameras and digital image processing. Some of the useful laboratory tools and techniques we have developed so far include the gas jet plasma source; plasma discharge tube apparatus used for calibrating optical diagnostics; a plasma shutter; interferometers, spectrometers, monochrometers and spectrum analyzers; and various photographic imaging devices. We are also continuing to use computer simulations to help design and analyze the experiments, as well as to study new topics in advanced accelerator concepts.

Presentations/Publications

1. R. L. Williams, Arnesto Bowman, Jorge A. Martinez, Jr., and Staci Brown, "Studies on Gas Jet Plasmas for Use in Electron Beam Diagnostic Experiments", presented at the 46th Annual Meeting of the Division of Plasma Physics, American Physical Society, November 15-19, 2004, Savannah, Georgia. Abstract published in: Bull. A.P.S., Vol. 49, No. 8, (2004) page 96.
2. Arnesto Bowman, Jorge Martinez, Jr., Staci Brown, and R. L. Williams," Model of an Imaging System that is Used for Diagnosing a Gas Jet Plasma Source",presented at the 46th Annual Meeting of the Division of Plasma Physics, American PhysicalSociety, November 15-19, 2004, Savannah, Georgia. Abstract published in: Bull. A.P.S.,Vol. 49, No. 8, (2004) page 96.
3. R. Williams and A. Bowman, "Electron Beam and Laser Beam Probes of Plasma Waves', presented at the 45th Annual Meeting of the Division of Plasma Physics, APS, Albuquerque, New Mexico, (October 27-31, 2003). Bull. A.P.S. Series II, Vol. 48, No. 7, p. 108 (2003).
4. Bowman and R. Williams, "Laser Beam Induced Plasma in a Gas Jet", presented at the 45th Annual Meeting of the Division of Plasma Physics, APS, Albuquerque, New Mexico, (October 27-31, 2003). Bull. A.P.S. Series II, Vol. 48, No. 7, p. 108 (2003).
5. M. Blunt, A. Bowman and R. Williams, "Construction of a Gas Jet Plasma Source", presented at the 45th Annual Meeting of the Division of Plasma Physics, APS, Albuquerque, New Mexico, (October 27-31, 2003). Bull. A.P.S. Series II, Vol. 48, No. 7, p. 142 (2003).
6. M. (S.) Brown, A. Bowman, R. Williams, "Construction of a Plasma Shutter for Shortening Laser Pulses", presented at the 45th Annual Meeting of the Division of Plasma Physics, APS, Albuquerque, New Mexico, (October 27-31, 2003). Bull. A.P.S. Series II, Vol. 48, No. 7, p. 142 (2003).
7. J. Martinez, A. Bowman, R. Williams, "Optical Measurements of Plasmas Using Schlieren", presented at the 45th Annual Meeting of the Division of Plasma Physics, APS, Albuquerque, New Mexico, (October 27-31, 2003). Bull. A.P.S. Series II, Vol. 48, No. 7, p. 144 (2003).

Current Staff

Prof. Ronald L. Williams	Principal Investigator
Arnesto Bowman	Graduate Student, pursuing Ph.D., physics
Staci Brown	Undergrad Student, pursuing B.S., physics

Additional students who contributed to this work but have graduated and are now at other schools

Kassatihun Gebre-Amlak	Graduate Student, Vanderbilt U., pursuing Ph.D.
Michael Gebrebrhan	Graduate Student, MIT, pursuing Ph.D.
Chris Lawyer	Graduate Student, U. of North Carolina, pursuing Ph.D.
Charlie Blackwell	Graduate Student, U. of Minnesota, pursuing Ph.D.
Jorge Martinez, Jr.	Graduate Student, U. of Central Florida, pursuing Ph.D.
Charles Hanretty	Graduate Student, Florida State U., pursuing Ph.D.
Chris Brown	Graduate Student, U. of Central Florida, pursuing Ph.D.
Johnny Williamson	Graduate Student, FAMU, pursuing Ph.D.
Kevin Johnson	Graduate Student, FAMU, pursuing Ph.D.
Michael Ghebrebrhan	Graduate Student, MIT, pursuing Ph.D.
Deveron Crawford	High School Physics Teacher, Orlando, FL.

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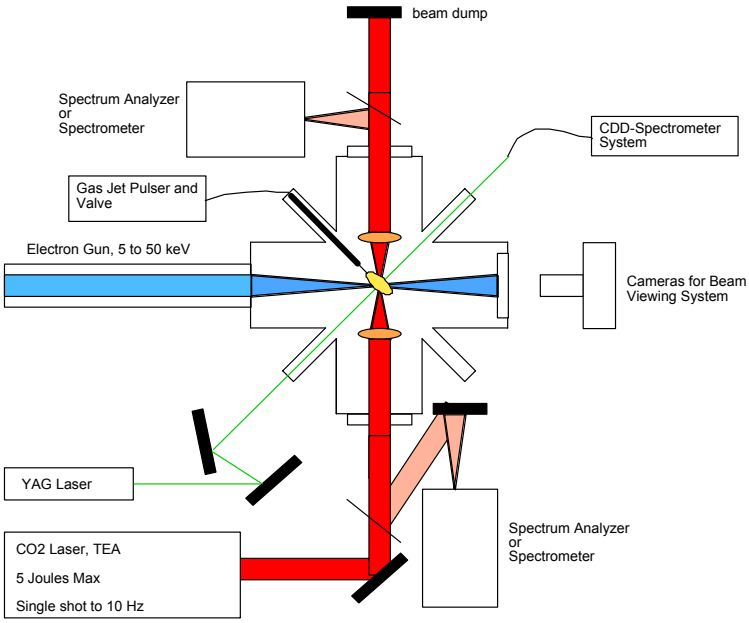

Figure 1. Schematic of the main experiment.

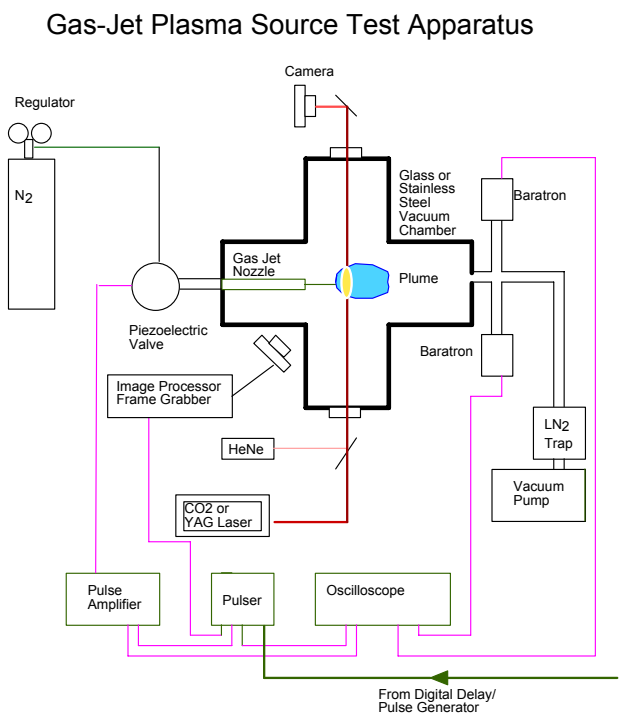

Figure 2. Schematic of gas jet plasma source test apparatus.

Liquid Helium Fluid Dynamics Studies

Steven Van Sciver
Florida State University

Summary

Liquid helium cryogenics is a critical enabling technology for particle accelerators. Virtually all accelerators under development or planned will use liquid helium as a coolant for the superconducting magnets, RF cavities and specialized vacuum applications. Further, many of the largest and most advanced accelerators will use He II (superfluid helium) cooling to achieve the best performance from their superconducting components. Hence, a thorough knowledge of helium fluid dynamics and heat transfer with emphasis on He II is valuable for advancing this technology.

Our work mainly involves experimental studies of liquid helium thermo-fluid dynamics with supporting numerical analysis. During the period 2003 to 2005, we have focused on three main activities all of which involve transport properties of He II:

1. Pressure drop and heat transport to forced flow He II at high Reynolds number
2. Transient heat transfer to static bulk He II and He II contained in porous media
3. Visualization of heat and mass transfer in He II

Here we summarize the progress within these main activities, research output based on publications and presentations and the contributions to education of future cryogenic engineers.

Research Accomplishments

Pressure drop and heat transport to forced flow He II at high Reynolds number

For several years we have been studying forced flow He II at high Reynolds number ($\mathrm{Re}_D = \rho v D / \mu_n$, where ρ is the total density, v the He II velocity, D the tube diameter, and μ_n the normal fluid viscosity of He II). The range of Reynolds number is up to $\mathrm{Re}_D \sim 3 \times 10^7$ which corresponds to a fluid velocity of about 20 m/s in the 10 mm ID tube test section. These experiments have been performed in the Florida State University (FSU) Cryogenic Helium Experimental Facility at the National High Magnetic Field Laboratory (NHMFL). To our knowledge, these are the highest Re_D He II experiments performed anywhere. The measurements include pressure drop, steady state, and transient heat transfer experiments along with numerical analysis. This work, which formed the basis for the PhD dissertation of Dr. Sylvie Fuzier, has produced several publications (Refs. 1 & 2 below) with others in preparation.

Typical results from this work are shown in *Figure 1* which compares the transient experimental temperature profile to our developed numerical analysis at the one He II velocity (v = 16 m/s). The shape of these pulses is close to the initial rectangular heat pulse because they transit the channel in too short a time for thermal diffusion to be significant. The numerical analysis that we performed is based on solution of the full time dependent He II energy equation. As can be seen in *Figure 1*, the numerical calculations are in very good agreement with the experimental results.

Transient heat transfer to static bulk He II and He II contained in porous media

Heat can be transported in static He II by two physically linked mechanisms: second sound shock (SSS) and thermal diffusion. For several years we have been investigating SSS to determine the limits to this process and its usefulness for stabilizing against local thermal disturbances. We have identified that there is a critical "breakpoint" energy flux of order 100 J/m^2 which can be carried by SSS and that energy fluxes above this value can only propagate by thermal diffusion. This previous work formed the basis for the PhD dissertation of David Hilton, who completed his work in the spring of 2003.

In recent experiments (Ref. 14), we have been investigating the effect of a steady background heat flux on SSS. The background heat flux generates turbulence in the He II which attenuates the SSS. Thus, the breakpoint energy decreases with the background turbulence. *Figure 2* shows the magnitude of this effect. For a steady heat flux of 60 mW/cm^2, one can see the breakpoint energy decreases by about an order of magnitude. This phenomenon may affect how well He II can stabilize a high current density magnet when the magnet experiences a steady heat load from, for example, nuclear heating.

We have also performed an experiment to study the propagation of SSS in forced flow He II. In these thermal shock experiments, we found that the energy propagation is significantly attenuated even at modest fluid velocities, $v > 0.2$ m/s. Thus, it appears that second sound is only effective for heat transport in He II if the fluid is static.

Visualization of heat and mass transfer in He II

We have begun a series of experiments using the Particle Image Velocimetry (PIV) technique to visualize heat and mass transfer in He II. PIV is one of the most advanced fluid dynamics techniques available to the research community. However, the technique has only recently been introduced to the study of liquid helium (Refs. 4-6).

PIV allows the full flow field of a fluid to be visualized by seeding the flow with neutral density particles and monitoring their motion with a laser/camera imaging system. The result is a velocity field which can be compared with total flow measurement by such techniques as conventional flow meters. In our previous work, we have confirmed that PIV can measure the flow of the normal fluid component in He II thermal counterflow (Ref. 5). More recently we have been studying thermal counterflow around a cylinder in order to better understand the heat transport mechanisms in configurations other than a one dimensional channel. This problem is technically important as it may help in the design of He II cooling systems for magnets and RF cavities where the heat flow is in complex geometries. *Figure 3* is a plot of the PIV measured velocity fields around a 6.35 mm OD cylinder at two different temperatures. The remarkable discovery in these results is the appearance of large turbulent structures both in front of and behind the cylinder. Similar structures occur behind the cylinder in classical fluid flow; however, the existence of turbulent structures in front of the cylinder has no classical analogue. Refs. 9 & 10 detail these results as will the Plenary talk at the 2005 CEC in Keystone, Colorado.

Collaborations/Service to the HEP community

- One of the engineering staff (C. Darve) at Fermi National Accelerator Laboratory is pursuing a PhD through the Mechanical Engineering Department at Northwestern University. The Principal Investigator (S. Van Sciver) is providing advice on this project and will sit on the PhD defense committee.

- S. Van Sciver co-taught a short course entitled: Principles of Cryogenic Engineering at the 2004 US Particle Accelerator School in Madison, WI. Next course offering is scheduled for January 2006.
- In 2002, S. Van Sciver was appointed a standing committee on the FNAL Superconducting Magnet Program Advisory Committee. Last meeting of the SMPAC was June 2003.

Publications (2003-2005)

1. "Pressure Drop in Forced Flow He II at High Reynolds Numbers," S. Fuzier, S. Maier and S. W. Van Sciver Proceedings ICEC 19, Grenoble, France July, 15, 2002, (2003) pp. 755-8
2. "Use of the bare chip Cernox^{TM} thermometer for the detection of second sound in superfluid helium," S. Fuzier and S.W. Van Sciver, Cryogenics Vol. 44, 211 (2004)
3. "Superconducting Magnets in High-Radiation Environment at Supercolliders," N. V. Mokhov, et al (S. W. Van Sciver), Proc. Workshop on Supermagnets for Supercolliders Erice, Sicily (2003)
4. "Measurements of He II Thermal Counterflow using PIV Technique," T. Zhang and S. W. Van Sciver, Advances in Cryogenic Engineering Vol. 49, 976 (2004)
5. "Use of the Particle Image Velocimetry (PIV) technique to study propagation of second sound shock in superfluid helium," Zhang and S. W. Van Sciver, Phys. of Fluids Vol 16, 99 (2004)
6. "Observing Thermal Counterflow in He II by the Particle Image Velocimetry Technique," S. W. Van Sciver, J. of the Korean Institute of Applied Supercond. and Cryog. Vol. 7, No. 2, 1 (2005)
7. "Direct Measurements of Quantum Turbulence Induced by Second Sound Shock Pulses in Helium II," D. K. Hilton and S. W. Van Sciver, J. Low Temp. Phys. (accepted)
8. "Large scale turbulent flow around a cylinder in counterflow superfluid helium (He II)," T. Zhang and S. W. Van Sciver, Nature Physics (submitted)
9. "Particle Image Velocimetry of He II Counterflow around a Cylinder," S. Fuzier, S. W. Van Sciver, and T. Zhang, 24th International Conference on Low Temperature Physics, Orlando, FL August 2005 (Physica B, submitted)
10. "Advances in Helium Cryogenics," S. W. Van Sciver, Special Anniversary Session of the 2005 CEC/ICMC, Keystone, CO, August 29, 2005 (to be published)
11. "Visualizing Heat Transport in Helium II," S. W. Van Sciver, Plenary talk and paper at the 2005 CEC/ICMC Keystone, CO, August 29, 2005
12. "H_2/D_2 Particle Seeding and injection system for PIV Measurement of He II," Ting Xu and S. W. Van Sciver, 2005 CEC/ICMC Keystone, CO, August 29, 2005
13. "Observation of He II Thermal Counterflow over a Flat Plate by the PIV Technique," S. Fuzier, T. Zhang, and S. W. Van Sciver, 2005 CEC/ICMC Keystone, CO, August 29, 2005
14. "Influence of the level of steady background turbulence on second sound shocks dynamics in He II," M. Dalban-Canassy, D.K. Hilton, S.W. Van Sciver, 2005 CEC/ICMC Keystone, CO, August 29, 2005

Thesis/Dissertations

"Heat Transfer and Pressure Drop in Forced Flow Helium II at High Reynolds Number," PhD Dissertation, Florida State University, Fall 2004

Current Staff

Dr. Sylvie Fuzier – Postdoc – former graduate student received PhD in Fall 2004
Matteau Dalban-Canassy – PhD graduate student, ME Department, FSU
Xu Ting – PhD graduate student, ME Department, FSU
Hyung Jin Kim – PhD graduate student, ME Department, FSU

Former and Present Graduate Students, Postdocs supported by DOE/HEP under grant DE-FG02-96ER40952

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Past Graduate Students at FSU

John S. Panek- PhD 1998- Dissertation Title: Heat Transfer in Horizontal Two Phase He II and Vapor – NASA Goddard Space Flight Center
David K. Hilton – PhD 2003 – Dissertation Title: Growth and Decay of Quantum Turbulence Induced by Second Sound Pulses in He II – Post doc, Florida State University
Silvie Fuzier (ME) - PhD 2004 – Dissertation Title: Forced Flow He II Heat and Mass Transfer – Postdoc, Florida State University

Current Graduate Students at FSU

Ting Xu (ME) – PhD expected 2006 – Dissertation Title: Two phase helium flow visualization
Matteau Dalban-Cannesy (ME) – PhD expected 2006 – Dissertation Title: Heat Transfer in He II contained in Porous Media
Hyung Jin Kim (ME) – PhD – expected 2008 – Dissertation topic: Forced flow He II

Past Post Doctoral Associates & visitors, dates (current position)

1. Xiaodong Huang 1994-6 (Investment banking)
2. Yuenian Huang 1994-6 (Engineer, Fermi National Accelerator Laboratory)
3. Bertrand Baudouy 1996-8 (Scientist, CEA Saclay, France)
4. Michael Smith 1995- 2000 (Engineer, KLA-Tencor, Portland, OR)
5. Xiang Yu 1997-9 part time (GSI, Darmstadt, Germany)
6. Natalya Filina 2001 (Moscow State University)

Current Post Doctoral Associates (PhD Institution)

Silvie Fuzier (Mechanical Engineering Department, FSU) (2005-present)

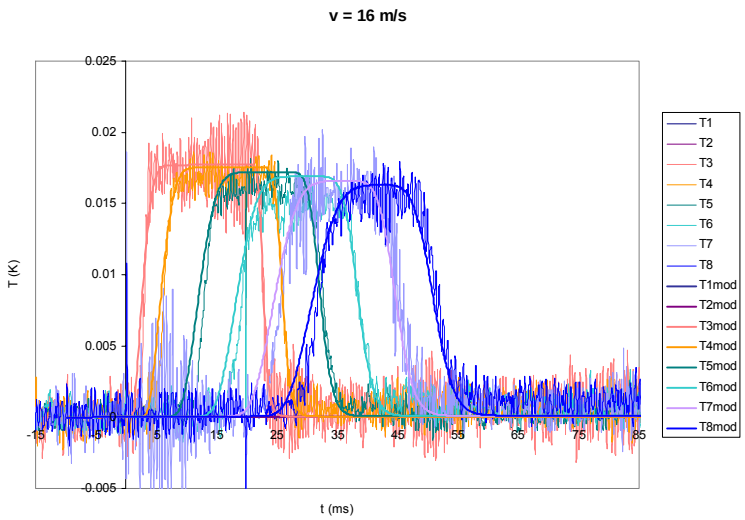

Figure 1 Experimental and numerically computed time evolution of the temperature at several locations along the test section. A rectangular heat pulse of power density 9.9 W/cm^2 has been generated between t = 0 and 20 ms at the heater. The forced flow velocity is 16 m/s and T_{bath} = 1.7 K.

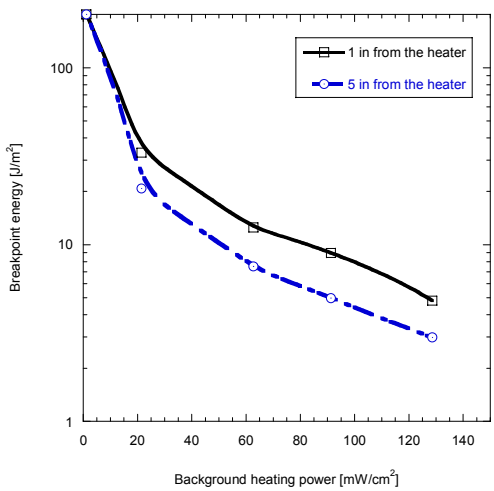

Figure 2 Variation of the breakpoint energy with steady background heat flux in a He II channel. The channel temperature is 1.7 K and the heat pulse power is 100 kW/m^2. Note that the breakpoint energy of > 100 J/m2 is reduced to less than 10 J/m2 for steady background fluxes of greater than 60 mW/m^2

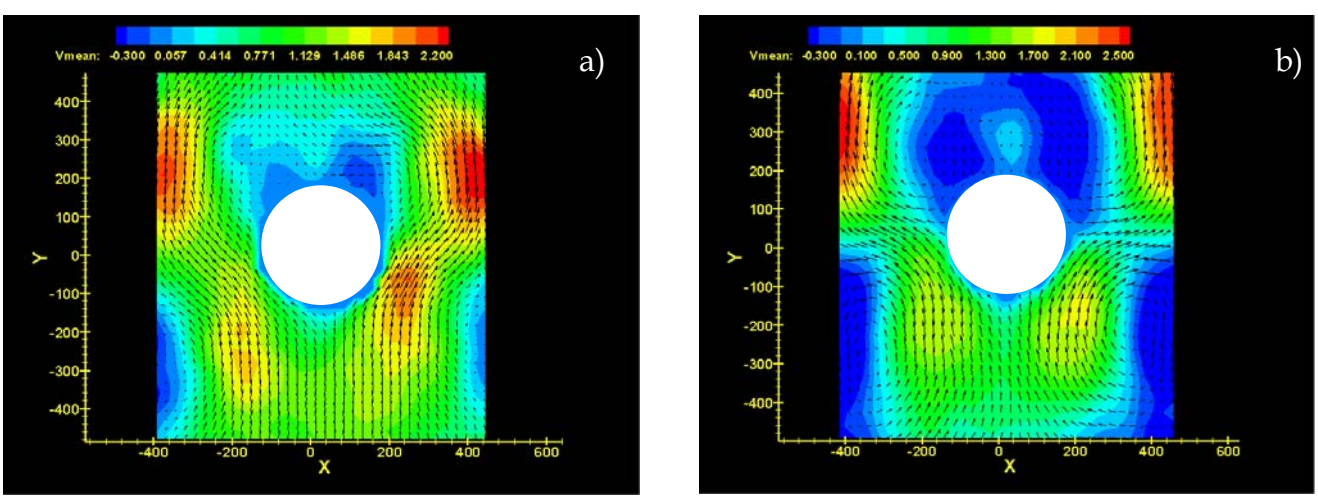

Figure 3 Measured particle velocity field around the 6.35 mm OD cylinder in He II. a) Heat flux is 4 kW/m^2 at T = 1.6 K corresponding to Re_D = 41000; b) Heat flux is 11.2 kW/m^2 at T = 2.03 K corresponding to Re_D = 21000. The velocity scale at the top is calibrated in pixels/ms (1 pixel/ms = 22 mm/s).

Physics of beam cooling, space charge effects on beams, and beam manipulation technologies in high energy accelerators

S.Y. Lee
Indiana University

Summary

The Indiana University Accelerator Physics devotes our efforts to investigate beam dynamics problems associated with high brightness beam including physics of space charge effects in high intensity beams, physics of beam cooling, and novel beam manipulation techniques in accelerators and storage rings.

We carry out theoretical and experimental studies on (1) measurements, modeling, space charge effects, and stop-band compensation at a high intensity synchrotron such as the Fermi National Accelerator Laboratory (Fermilab) Booster, (2) physics of beam manipulation techniques for attaining high brightness beams, (3) e-p instability simulations with ORBIT-code, and e-p instabilities feedback experiment at the Proton Storage Ring (PSR) at Los Alamos National Laboratory (LANL), (4) spin dynamics in Alternating Gradient Synchrotron (AGS) and Relativistic Heavy Ion Collider (RHIC), (5) physics of beam cooling dynamics such as the optical stochastic cooling (OSC), (6) scaling law of microwave instability growth during the transition energy crossing, and (7) nonlinear beam dynamics for high brightness electron storage rings.

In order to provide realistic space-charge stop-band compensation, we carry out the orbit response matrix method to model the Fermilab Booster, and introduce the independent component analysis (ICA) method to analyze the turn-by-turn beam-position data to measure Fermilab Booster lattice-parameters. We have also carried out turn-by-turn beam profile measurements to determine the emittance growth in the Fermilab Booster. These measurements will be used to provide basis for space-charge stopband compensation experiments to be carried out in the future. In 2005, we participated in the e-p instability-feedback experiments at PSR. Preliminary experimental results have shown that a broadband feedback system can suppress the e-p instability at PSR. We also participated in the development of e-p instability simulation-module in the ORBIT-code.

Since 1990, we have carried out research on nonlinear beam dynamics, collective beam instabilities, beam cooling, spin dynamics, high intensity beams, and advanced beam manipulation techniques. Some of our results have been employed to control and alleviate collective beam instabilities in high intensity storage rings, to understand phenomena such as chaos, strange and limiting cycle attractors, and bifurcation characteristics of attractors, to improve the Indiana University Cyclotron Facility (IUCF) Cooler beam quality, to provide design criterion for power supply ripple in high energy colliders, and to develop new methods for emittance preservation of high brightness beams. Future applications of high brightness beams include the e^+e^- linear collider, radioactive ion-beam accelerators, Spallation Neutron Sources (SNS), very high energy colliders, heavy ion fusion, biochemistry and bio-medical, material science, and defense research. We have also carried out an optimal design of a 300 MeV proton synchrotron, which is suitable for proton radiation therapy. Our accelerator physics group plays an important role in training accelerator physics graduate and undergraduate students.

Recent accomplishments and highlights

In 2003-2005, topics of accelerator physics research at Indiana University were physics of high intensity and high brightness beams, beam manipulation techniques. Some of our major findings can be summarized as follows:

- Accelerator modeling with the orbit response matrix method, and model independent measurements of beam parameters with the independent component analysis. The orbit response matrix method was successfully applied to verify and calibrate the lattice model and beam-position-monitor gains of a rapid cycling proton synchrotron - the Fermilab Booster. The resulting gradient errors were found to be consistent with closed orbit deviation in sextupoles.
- We introduced a new data analysis technique, called the ICA, to analyze turn-by-turn beam-position data taken around a synchrotron. Employing auto-correlation, beam-oscillation modes can be isolated from the turn-by-turn data. The ICA method has been used to derive characteristic properties of the machine, including normal mode beta-functions, betatron phase advances, dispersion functions, synchrotron tune, transverse impedance and chromaticities, etc. Our group is developing codes for both the orbit response matrix (ORM) and ICA methods.
- The horizontal and vertical beam emittances at the Fermilab Booster have also been measured by the turn-by-turn ionization profile monitor in a regular Booster ramping cycle as a function of beam intensity. Emittance growth due to various mechanisms has been carefully studied. The results have been used to improve the performance of the Fermilab Booster. We also study the source of emittance blow-up during the ramp. Correction of the half-integer stop-band can minimize the emittance dilution.
- We continue studying weak intrinsic and coupling spin resonances at the AGS, which can cause 35% depolarization, resulting in 50% polarization for RHIC. These weak intrinsic and coupling spin resonances can be overcome by spin-matching with trim quadrupoles for weak intrinsic spin resonances, and with skew quadrupoles for the coupling resonances. In carrying out the polarized beam experiments in RHIC, we would like to study dynamics of higher order snake resonances.
- Together with PSR and SNS, we participate in a series electron cloud feedback experiments at the PSR at the LANL. Experimental observations of the PSR beam have been successfully used to benchmark theoretical and computational models for the electron-cloud simulation module in the ORBIT-code.
- Although the basic principle of the optical stochastic cooling is well-known, it has not been fully studied. We have corrected some deficiencies in an earlier paper on the beam transport properties. We have derived a necessary condition for the transverse phase space damping, explored the damping rates, the amplification factor, cooling dynamics, and the required peak and average output power of the laser. We have also derived an optimal laser focusing condition for the charged particle beam and the laser beam interaction in an undulator. With the available optical amplifiers at the present, it is rather impractical to use the optical stochastic cooling method to cool proton and heavy ion beams at RHIC energies. However, we find that the cooling method may be beneficial to low energy electron beams, and hadron storage rings at around 1 TeV/u of beam energy using the existing Ti-Sapphire laser amplifiers. We are working with accelerator scientists at the BATES Linear Accelerator Center at the Massachusetts Institute of Technology for a possible OSC experiment at the SHR.

- There are several beam dynamics problems at the transition energy crossing. Recently, we obtained a scaling law of the emittance growth factor due to microwave instability for a beam during the transition energy crossing. The scaling law will be useful in the machine design, or estimating the impact on the beam properties in machine operation.

Current Staff

S.Y. Lee	Professor and Principle Investigator	
Mark Hess	Assistant Professor,	
S. Cousineau	PhD	awarded January 2003
W. Guo	PhD	awarded August 2003
Y. Zhang	PhD	awarded August 2003
C. Beltran	PhD	awarded November 2003
S. Wang	PhD	awarded October, 2004
Steven Daley	M.S.	awarded May 2005
X. Huang	PhD	to defend thesis in August 2005

Current Graduate Students

Y. Sato	PhD	(to defend thesis in December 2005)
D. Huang	PhD	
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F. Lin	PhD	
Y. Su	PhD	
F. Wang	PhD	
Q. Wu	PhD	
L. Yang	PhD	
L. Zhu	PhD	
C.S. Park	PhD	
J. Kowalski	PhD	

Publications 2003-2005

1. A. Shishlo et al, "Self-Consistent Electron-Cloud Simulation for Long Proton Bunches," Proceedings of the PAC05 (2005)
2. X. Huang et al., "Application of Independent Component Analysis for Beam Diagnosis," Proceedings of the PAC05 (2005)
3. X. Huang, et al. "Fitting the Fully Coupled ORM for the Fermilab Booster," Proceedings of the PAC05 (2005)
4. S. Breitzmann, S.Y. Lee and K.Y. Ng, "Impedance Calculation for Ferrite Inserts, Fermilab Technote:" Proceedings of PAC05 (2005) FERMILAB-TM-2289-AD; PSR technote 05-002 (2005)
5. H.P. Chang, S.Y. Lee, and Y. Yan, "Method for Symplectic Mapping in Systems with Three-Dimensional Magnetic Fields," Nucl. Instru. Meth. (2005)
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Periodically Focused Intense Charged-Particle Beams

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Summary

Under the auspices of this grant, we conduct vigorous theoretical and numerical investigations of periodically focused intense charged-particle beams in parameter regimes relevant to the development of advanced high-current, high-power accelerators for high energy and nuclear physics research and applications, as well as in parameter regimes relevant to the development of high-power microwave sources for the Linear Collider (LC).

The major breakthroughs in our research during 2003-2005

- Developed and verified, via computer simulation, a three-dimensional theory of high-brightness elliptic beam generation (Bhatt and Chen, 2005);
- Discovered an exact paraxial cold-fluid equilibrium of a high-intensity, space-charge-dominated, ellipse-shaped charged-particle beam, and developed the concept of ribbon-beam klystrons for the International Linear Collider (Zhou, Bhatt, and Chen, 2005);
- Investigated chaotic particle motion, halo formation and beam loss due to image charge effects in small-aperture systems (Zhou, Qian, and Chen, 2003; Zhou and Chen, 2005);
- Investigated dielectric photonic band gap structures for laser-driven particle acceleration (Samokhvalova, Chen, and Qian, 2005); and
- Determined the current limit of a finite-size bunched beam and applied it to successfully establish the operating condition for periodic permanent magnet focusing klystrons for the Next Linear Collider (Hess and Chen, 2004);

Awards

- First-Place Award for an Outstanding Technical Paper by Student (PAC05)
  R. Bhatt, T. Bemis, and C. Chen, "Three-Dimensional Theory and Simulation of Large-Aspect-Ratio Ellipse-Shaped Charged-Particle Beam Gun."
- Honorable Mention Award for an Outstanding Technical Paper by Student (PAC05)
  K. Samokhvalova, C. Chen, and B. L. Qian, "Analytical and Numerical Calculation of Two-Dimensional Dielectric Photonic Band Gap Structures and Cavities for Acceleration."

2003-2005 Publications in Referred Journals

1. "Exact Paraxial Cold-Fluid Equilibrium of a High-Intensity Periodically Twisted Ellipse-Shaped Charged-Particle Beam," J. Zhou, R. Bhatt, and C. Chen, Physical Review Letters, submitted for publication (2005)
2. "Analytical and Numerical Calculation of Dielectric Photonic Band Gap Structures," K. Samokhvalova, C. Chen, and B. L., Qian, Journal of Applied Physics, submitted for publication (2005)
3. "Parametric Studies of Image-Charge Effects on an Intense Beam in a Small-Aperture Alternating-Gradient Focusing System," J. Zhou and C. Chen, Nuclear Instruments and Methods in Physics Research **A544**, 493 (2005)

4. “Theory and Simulation of Non-Relativistic Elliptic Beam Formation with Child-Langmuir Flow Characteristics,” R. Bhatt and C. Chen, Physical Review Special Topics – Accelerators and Beams **8**, 014201 (2005)
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1. “Three-Dimensional Theory and Simulation of Large-Aspect-Ratio Ellipse-Shaped Charged-Particle Beam Gun,” R. Bhatt, T. Bemis, and C. Chen, Proceedings of 2005 Particle Accelerator Conference, in press (2005) – *First-Place Award for an Outstanding Technical Paper by Student.*
2. “Analytical and Numerical Calculation of Two-Dimensional Dielectric Photonic Band Gap Structures and Cavities for Laser Acceleration,” K. Samokhvalova, C. Chen, and B. L. Qian, Proceedings of 2005 Particle Accelerator Conference, in press (2005) - *Honorable Mention Award for an Outstanding Technical Paper by Student.*
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6. “Parametric Studies of Image-Charge Effects in Small-Aperture Alternating-Gradient Focusing Systems,” J. Zhou and C. Chen, Proceedings of 2005 Particle Accelerator Conference, in press (2005)

Selected Research Highlights

New Mechanism for Halo Formation
*From J. Zhou, C. Chen, and B. L. Qian, Phys. Plasmas 10, 4199 (2003); J. Zhou and C. Chen, Nucl. Instrum. Phys. Research **A544**, 493 (2005)*

Theory, Simulation and Application of High-Intensity Ellipse-Shaped Beams
*From R. Bhatt and C. Chen, PRST-AB **8**, 014201 (2005); R. Bhatt, T. Bemis and C. Chen, Proc. PAC (2005); J. Zhou, R. Bhatt, and C. Chen, Phys. Rev. Lett., submitted for publication (2005)*

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17 GHz High Gradient Accelerator Research

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Summary

The Massachusetts Institute of Technology (MIT) Plasma Science and Fusion Center (PSFC) conducts experimental and theoretical research on advanced accelerators, including high gradient accelerators, novel accelerator structures and novel electron beam diagnostics. The MIT PSFC currently operates both a 17.1 GHz, high gradient electron accelerator, built by Haimson Research Corp. (HRC), and, on a separate beam line, a 17 GHz RF photocathode gun. These experiments are powered independently by a 25 MW, 17.1 GHz klystron. The 17 GHz, 25 MeV, 0.5 m long accelerator is a unique facility. It operates routinely with 0.2 A average current; 80 A peak current; and bunch length of 180 fs. A beam line after the accelerator is used for testing novel structures, such as the Photonic Bandgap structure, and for testing novel diagnostics such as Terahertz Smith-Purcell radiation from femtosecond electron bunches. The RF photocathode gun, operating at gradients in excess of 200 MeV/m and driven by pulses from a Ti: sapphire laser, produces 1 ps electron bunches of up to 0.1 nC with energy in excess of 1 MeV and emittance of about 3 π mrad.

Recent Accomplishments (2003-2005)

- Demonstration of the first Phonic Bandgap (PBG) Accelerator structure in operation as an accelerator. The copper structure of six cells operated at 17.14 GHz and accelerated electrons with a gradient of 35 MV/m. This advance may permit the practical application of PBG structures to advanced accelerator applications.

- Demonstration of a non-destructive Smith-Purcell coherent Terahertz radiation diagnostic for femtosecond electron bunches. Smith-Purcell radiation is produced when an electron beam passes above a grating. For wavelengths that are longer than the bunch length, the radiation is coherent and is therefore enhanced by a large factor, namely the number of electrons in the bunch. There is also an enhancement due to the number of grating periods. Finally, if there is a train of bunches, the radiation is restricted to a set of harmonics of the accelerator frequency, further increasing the peak intensity. Careful experiments at MIT with a heterodyne receiver identified all of these enhancements.

- Routine operation of the Haimson Research Corp. 17 GHz RF accelerator with beam energy of over 17 MeV at 200 mA current, the highest frequency stand-alone accelerator in the world.

- Demonstration of electron bunches from a 17 GHz RF photocathode gun with charge of up to 0.1 nC, energy of 1 MeV, emittance of 3 π mmmrad and brightness of up to 50 10^{12} A/m^2, in excellent agreement with theory.

- Theoretical modeling of Smith-Purcell radiation, showing the exact effect of a finite number of grating periods on the intensity of the radiation. Experimental tests of the new theory.

- Measurement of coherent transition radiation at Terahertz frequencies from a train of femtosecond electron bunches, with good comparison to theory.

- Educational activities and thesis research for graduate and undergraduate students; former students active in accelerator physics; postdoctoral fellows.

Research Goals of this Program Include

- Measurement of the bunch length of the electron beam, estimated to be about 180 fs, using novel diagnostics.

- Measurement of the characteristics (beam energy, emittance, etc.) of the 25 MeV beam produced by the accelerator when using a DC thermionic gun as the injector.

- Operation of the 17 GHz accelerator with an RF Photocathode gun as injector, producing significantly improved beams with higher bunch charge and higher beam brightness.

- Design, build and test special cavities in order to measure breakdown, dark current and pulsed heating effects in room temperature structures.

- Investigate overmoded and quasi-optical structures suitable for use in high gradient accelerators at frequencies of 30 to 100 GHz.

- Train the next generation of graduate students and postdoctoral associates in accelerator physics.

In addition to the research funded at MIT, HRC has been separately and independently funded by the Small Business Innovation Research program of the Department of Energy's Office of High Energy Physics (DOE HEP) to develop microwave sources and 17 GHz accelerator components for use in the MIT research program. The progress made by HRC has been extremely valuable to the MIT research program.

We are also pursuing a number of other goals in advanced accelerator research. For example, we are interested in pursuing physics and engineering issues of accelerators operating at frequencies higher than 17 GHz, including operation at frequencies in the 30 to 100 GHz range where we have extensive operating experience and equipment. We are also interested in developing a basic understanding of rf breakdown and pulsed heating effects, which are the fundamental limits to advanced accelerator operation.

Research on accelerators driven by very high frequency microwaves is motivated by the possibility of operating such accelerators at higher gradients than present day or nearer term accelerators, such as the International Linear Collider. The main advantages of high frequency accelerators are operation at high accelerator gradients because dark current capture ("trapping") thresholds increase with frequency; operation at high accelerator gradients because pulsed heating on accelerator structures improves with frequency and operation at high accelerator gradients because breakdown thresholds may possibly increase with frequency. High frequency technology has an excellent industrial base and high frequency microwave technology should be competitive in cost, efficiency and longevity with lower frequency microwave technology. Even a factor of two improvements in accelerator gradient would make an enormous difference in the cost and complexity of future accelerators. It would also permit accelerators to be upgraded to higher energy. For these reasons, research on high frequency accelerators is crucial to the field of High Energy Physics.

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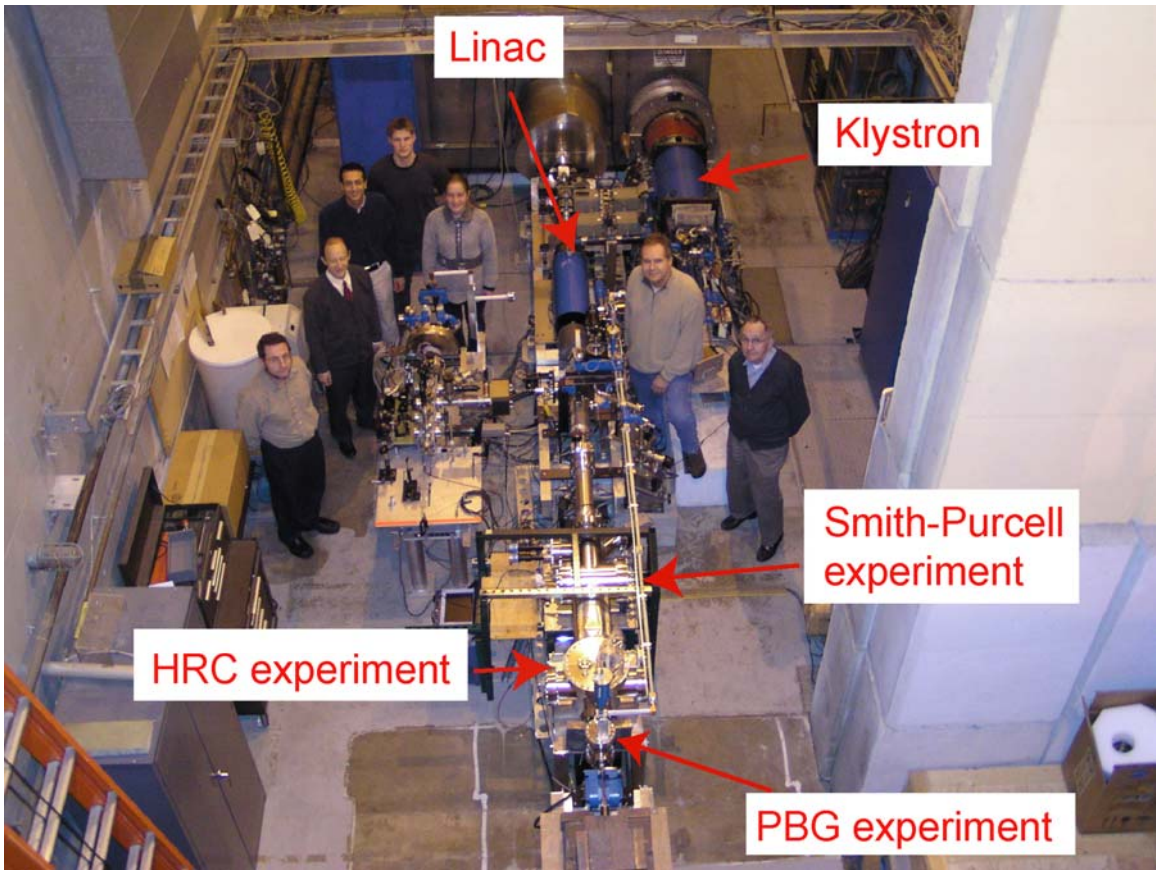

Figure 1: Haimson (HRC) / MIT 17 GHz Accelerator Laboratory, the highest frequency, stand-alone accelerator in the world and a world class facility for advanced accelerator research. The locations of the PBG test accelerator (see Fig. 2), the Smith-Purcell Terahertz radiation diagnostic, and the HRC electron beam deflection diagnostic are also shown.

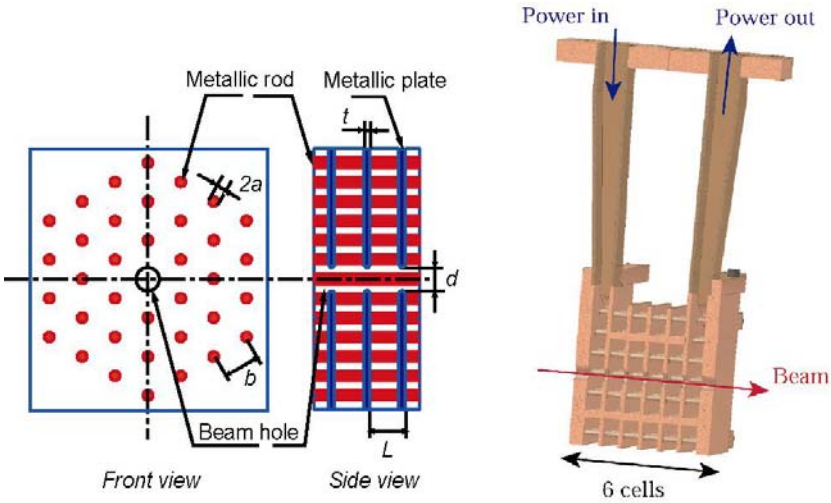

Figure 2: Schematic drawings of the six-cell, 17 GHz Photonic Bandgap (PBG) accelerator structure, which was built and tested at up to 35 MV/m at MIT.

Advanced Map Methods for the Description of Particle Beam Dynamics

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Summary

The work in the Beam Theory and Dynamical Systems Group in the Department of Physics and Astronomy at Michigan State University (MSU) contributes to the study of the nonlinear dynamics in particle beam dynamics. The work encompasses both the development of theoretical and computational tools for simulation and optimization, and direct involvement in various projects, including the Tevatron at Fermi National Accelerator Laboratory (FNAL), the Muon Collaboration, and recently the International Linear Collider (ILC) effort. Current work is also directed toward the further development of the code COSY INFINITY and support for its more than 1,000 users, as well as the VUBeam on-line degree and course program in Beam Physics.

Recent Accomplishments

As part of our activities for the muon collaboration, there is further development of our code COSY INFINITY, which is currently being used for muon simulation work at FNAL, CERN, Brookhaven National Laboratory (BNL), University of Illinois at Urbana-Champaign (UIUC), and MSU. Besides treating the full nonlinear Hamiltonian without the common approximation of expanding the square root, and within a fully symplectic framework, all nonlinearities of the 3D field representation are treated to the full order of the computation. This now allows the front-to-back simulation and optimization of bunchers and quad precooler merit factors. After the first stages of muon cooling systems consisting of bunchers followed by precoolers, one of the options currently being considered is a solenoidal matching section and a quadrupole channel for an initial cost effective reduction of the emittance by about a factor of two per dimension. Altogether, the system requires simulation of the action of cavities, quadrupoles, and solenoids, including all their nonlinear effects and possible field overlaps, as well as absorbers and both their deterministic and stochastic effects.

In cooperation with FNAL we have been involved in the simulation and correction of Tevatron beam dynamics for Run II. In particular, there are various problems connected to unexpected skew quadrupole effects related to physical displacements in the cold mass of the superconducting dipoles. The problems could be alleviated by proper shimming of part of the dipoles, but also required the development of various decoupling schemes and their testing. Further work on the Tevatron is connected to the correction of still remaining nonlinear effects. Another recent application is the use of rigorous global optimization in combination with normal form methods to determine the long-term stability of the Tevatron. It is expected that this method will become very favorable within the framework of the parallelization efforts for COSY discussed below, in particular since this approach allows us to replace inherently non-parallelizable tracking by inherently parallel global optimization.

The group has recently begun activities for the support of simulation work for the International Linear Collider effort. One project carried out in cooperation with the ILC group at Fermilab is the study and analysis of ILC final focus design scenarios. Particular emphasis is being given to correction of nonlinear terms by optimally placed octupole correctors, as well as design constraints imposed by the specific design of the final focus collimators. It is expected that the ILC simulation effort will increase in significance within the MSU group as specifics of the involve-

ment of the U.S. in general and FNAL in particular continue to emerge and become more focused.

Considering the large number of current users of the code COSY and the stream of new registrations, which over the recent past was about 100 per year and now exceeds a total of 1000, there is a great need for support of user questions to allow for the effective use of the various tools. This support requires advanced knowledge about the detailed workings of the code, and has continued to be one of the very time demanding aspects of the work of the group. To enhance the use of COSY for future work, efforts are being completed to provide standardized code-level parallelization based on Message Passing Interface (MPI). The resulting code has been installed on the Lawrence Berkeley National Laboratory (LBNL) National Energy Research Scientific Computing Center (NERSC) system, which has a set of approximately 6,000 parallel processors, as well as on smaller clusters at Argonne National Laboratory (ANL) and MSU. First applications of the parallelization tools for undulator simulations at LBNL and global optimization at ANL show almost linear speed gain up to nearly 1,000 processors. It is expected that the use of parallel techniques will continue to gain significance, in particular in connection with global optimization of large-scale high-energy accelerators.

The COSY code is also part of the backbone of the interactive homework system of VUBeam, MSU's Virtual University program in Beam Physics described below. Support is also being provided for various new features that are being implemented in the code, which include refinements to the methods for the verified integration of maps, the ability to treat detailed accelerating structures in connection with a collaboration with ANL, various enhanced fringe field methods, as well as tools for the study of universal generating functions.

One of the recent additions to the treatment of maps is the ability to rigorously estimate bounds of the remainders due to higher orders not explicitly retained. Current activities focus on the development of enhanced preconditioning techniques, which offer a significantly more favorable long-term behavior of the computational error, and various refinements thereof. Also, the development of more advanced preconditioners based on normal form methods is continuing. Combined with methods of validated global optimization, these methods have been able to study the long-term stability of the Tevatron without the need for tracking.

Besides the conventional training of graduate students within the group at MSU, we maintain the VUBeam program, the on-line education initiative in Beam Physics supported by MSU's Virtual University. Over the last several semesters, on average between 30 and 40 remote students were enrolled in courses each semester, which by this count has made Beam Physics the largest graduate specialization area in the MSU Physics Department. In addition, there are now around 20 external degree students admitted to the remote Master's and Ph.D. programs. In the last three years, seven of these students have completed Master's degrees, and various others are paired up with suitable mentors at U.S. National Laboratories and other locations to provide guidance and supervision for dissertation work.

Currently there are four on-line courses based on live lectures via internet videoconferencing and on downloadable Audio/Video files. In addition, we continue development of our interactive homework system in which students enter answers in a variety of formats over the web, which are then graded automatically. In the more advanced sections of the course, homework problems often consist of input decks for the program COSY that perform a typical aspect of accelerator design. Upon completion, they are submitted over the web, executed on the local web server, and then either graded automatically (for numerical results) or posted on the instructor's grading page (for more complex results including visual information).

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32. K. Makino and M. Berz, “High order flows around fixed points and verification of local dynamics with applications to particle accelerators,” Complexity, 2003, in print.
33. J. Hoefkens, M. Berz, and K. Makino, “Controlling the wrapping effect in the solution of ODEs of asteroids,” Reliable Computing, 9(1):21-41, 2003.
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35. B. Erdelyi, J. Hoefkens, and M. Berz, ”Rigorous lower bounds for the domains of definition of extended generating functions,” SIAM Journal on Applied Dynamical Systems, 2003, in print.
36. J. Hoefkens, M. Berz and K. Makino, “Computing Validated Solutions of Implicit Differential Equations,” Advances in Computational Mathematics 19, 231-253, 2003

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Kyoko Makino, Associate Professor

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Youn-Kyung Kim, pursuing PhD in Physics, MSU
Johannes Grote, pursuing dual PhD in Physics/Mathematics, MSU
Pavel Snopok, pursuing PhD in Physics, MSU
Alexey Poklonskiy, pursuing PhD in Physics, MSU
Stephen Weathersby, pursuing Ph.D. in Physics via VUBeam, SLAC
Lynn Bentson, pursuing MSc in Physics via VUBeam, SLAC
Gerald Schuman, pursuing MSc in Physics via VUBeam, Ford
Asish Satpathy, pursuing MSc in Physics via VUBeam, SLAC
Norman Robertson, pursuing PhD in Physics via VUBeam, Indiana
Farzad Nekoogar, pursuing PhD in Physics via VUBeam, LBL
Mahuya Sengupta, pursuing PhD in Physics via VUBeam, ANL

Not listed are approximately 15 other degree students in the MSU VUBeam program who are in the earlier stages of their degree work, and several dozen other VUBeam students participating in degree programs of Universities other than MSU.

Past Graduates from this contract in 2003-2005

Mandi Meidlinger, MSc 2003 (VUBeam program)
David Meidlinger, MSc 2003 (VUBeam program)
Reiko Taki, MSc 2003 (VUBeam program)
Mohamed Nasr, MSc 2003 (VUBeam program)
Pavel Snopok, MSc 2004 (VUBeam program)
Alexey Poklonskiy, MSc 2004 (VUBeam program)
Andrew Steere, MSc 2005 (VUBeam program)

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Instrumentation Standards

Louis Costrell
National Institute of Standards and Technology

Summary

This small project at the National Institute of Standards and Technology (NIST) is quite different from and is dwarfed by the much larger University and National Laboratory projects of the Department of Energy (DOE). Its function is that of standards development, processing and coordinating. Its first activity was the development of the Nuclear Instrumentation Methods (NIM) instrumentation system, through the DOE NIM Committee chaired by Louis Costrell of NIST, who initiated the development. The NIM system (DOE/ER-0457T) seems to age gracefully and, with some upgrades, is currently produced commercially by many manufacturers and used in numerous laboratories worldwide. An independent economics study several years ago concluded that the savings, as a consequence of the development and use of NIM, amounted to several billion U.S. dollars up to that time.

The FASTBUS and Computer Automated Measurements and Control (CAMAC) Institute of Electrical and Electronics Engineers, Inc. (IEEE) Standards are currently being balloted for reaffirmation. Such reaffirmation is expected to be approved by October. Additionally we are looking into whether standardization of some detector or detector systems for future high energy accelerator projects is feasible and what benefits standardization would provide. Standards for Homeland Security instrumentation, including those for portal monitoring, have been issued or are currently underway.

The NIM system was supplemented by the computer oriented CAMAC system (IEEE/ANSI 583) that was initiated by the late Harry Bisby of the Harwell Laboratory. Its development and implementation was a joint effort of the European Standards on Nuclear Electronics (ESONE) Committee of European Laboratories and the NIM Committee. Later, the high energy physics community asked the Committee to develop a high speed, high input capacity, and highly versatile electronics system to accommodate the detectors being developed for the new generation of high energy accelerators. The result was the FASTBUS system (IEEE/ANSI-960, IEC 935) that then served the needs of the high energy laboratories. The increasingly high speed, increased input/output (I/O), and other requirements for the detectors for accelerators currently under construction pose an even more severe challenge such that much of the early processing is to be done at the detector itself before the signals are routed to the rack electronics. When FASTBUS was first used, some installations utilized Versa Module Europa (VME) electronics though they suffered from incompatibilities, excessive level of crosstalk, limited I/O, and other shortcomings. NIM members (primarily Barsotti of Fermilab, Downing, formerly of the University of Illinois, and Costrell of NIST) together with Parkman of CERN, worked with the VME Standards Organization (VSO) that has upgraded VME to provide economical, high capability electronics system that overcomes many of the former limitations. Thus the current VME64extensions standard is suitable for many demanding applications, including those of the High Energy Physics community. Additionally NIM, in collaboration with CERN and KEK has produced a guide for VME for physics applications (DOE/SC-0013 - 27 September 1999, Designer & User Guide for ANSI/VITA 23-1998 -VME64 Extensions for Physics and Other Applications [VME64xP]).

As the VSO continues its work with VME, NIM continues involvement so as maximize VME's applicability for physics experiments. NIM also continues collaboration with European and Asian colleagues and will be discussing with them future physics instrumentation needs. The DOE/ NIST project continues to provide administrative maintenance of the NIM Committee and its standards.

Publications

1. E.J. Barsotti, R. W. Downing, Louis Costrell, and Christopher Parkman (Editors), DOE/SC-0013-27 September 1999, "Designer & User Guide for ANSI/VITA 23-1998 – VME64 Extensions for Physics and Other Applications," [VME64xP]

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Electromechanical Properties of Superconductors

Jack Ekin
Najib Cheggour
National Institute of Standards and Technology
Boulder, Colorado

Summary

This project specializes in state-of-the-art low-temperature measurements and is a world leader in the field of electromechanical measurements. It provides the mechanical-property research needed to develop low-T_c (Nb_3Sn, Nb_3Al) and high-T_c (BSCCO, YBCO, MgB_2) superconductors for high-field magnet and electric power applications. Since most of these conductors are made from brittle ceramic materials, they are susceptible to severe mechanical degradation during strand handling, and magnet winding and operation. Therefore, stress and strain management is one of the key technologies that need to be developed to study the mechanical tolerance of these conductors. This research program utilizes our unique measurement capabilities to study and develop parametric models for understanding the electromechanical properties of these conductors.

We work closely with the superconductor wire manufacturers in two areas: First is the need to develop a reliable measurement capability in the severe environment of superconductor applications: low temperature, high magnetic field, and high stress. The second area is to provide data and feedback to industry for the development of high performance superconductors. Among the measurement systems we developed are apparatus for measuring the effects of axial tensile stress, the effects of transverse compressive stress, the stress-strain characteristics, and, most recently, transverse tension. We have a unique system for determining the electromechanical properties of reinforced superconducting composite coils. Our electromechanical test capability for superconductors is one of the few of its kind in the world, and the only one providing specialized measurements for U.S. superconductor manufacturers. This measurements program is jointly funded by Department of Energy/High Energy Physics (DOE/HEP), Department of Energy/Office of Electric Transmission and Distribution (DOE/OETD), and National Institute of Standards and Technology (NIST), and benefits from cost sharing among these three funding sources.

Recent Accomplishments

- Carried out extensive measurements program on Nb_3Sn wires received from Oxford Superconductor Technology (OST), Supercon, and Outokumpu Advanced Superconductors.

- Determining the pre-compressive strain in a number of high-Nb density Nb_3Sn wires. These new conductors from OST were marginally stable and a new measurement method was developed in order to characterize them.

- Tested powder-in-tube (PIT) Nb_3Sn wires manufactured by Supercon.

- Accommodated an urgent request for measurements from Outokumpu to characterize their Nb_3Sn samples. The data we obtained will allow Outokumpu to decide what samples to use in a project with the National High Magnetic Field Laboratory.

- Developed scaling models to characterize the three-dimensional critical surface of advanced Nb_3Sn superconductors.

- Characterized a new generation of high-T_c YBCO coated conductors from American Superconductor and SuperPower Corp.

- Submitted the manuscript for textbook to Oxford University Press for publication in early 2006, entitled "*Experimental Techniques for Low Temperature Measurements – Cryostat Design, Materials, and Critical-Current Testing.*"

- Conducted our measurements program in close collaboration with superconductor manufacturing industries, national laboratories, and universities. Direct feedback was given to the wire manufacturers within each project and then disseminated to the general wire-development community.

Supplemental Information

New method developed for measuring the prestrain parameter of advanced high current-density Nb_3Sn wire - The next generation of particle accelerators for high energy physics will require the development of a new type of superconducting Nb_3Sn wire able to carry extremely high currents at high magnetic fields. One way to achieve high currents is to push the density of superconductor filaments in composite wires to new limits. OST has successfully demonstrated the feasibility of this concept. However, this could significantly reduce the beneficial "pre-compressive strain" in these conductors upon cooling, an important parameter for magnet design. Our electromechanical testing system utilizes stress-free cooling, which is essential for a direct measurement of pre-compressive strain. Unfortunately, the new Nb_3Sn wires, due to their relatively small amount of copper stabilizer, are only marginally stable, which makes electrical characterization extremely challenging. Hence, a new measurement procedure was required that did not compromise the stress-free cooling advantage of our electromechanical test apparatus.

We developed a new method that measures critical-current density (the maximum lossless current density that a superconductor can carry) versus axial strain for a number of copper-plated specimens of the same wire with different amounts of copper. We then deduced the strain properties of the virgin (non-copper-plated) wire by an extrapolation technique. Copper plating made the niobium-tin wires electrically stable enough to characterize, but the extra copper also influenced the value of the pre-compressive strain (ε_{max}); hence the need for extrapolation. We confirmed that ε_{max} indeed decreased linearly with increasing niobium fraction (*Figure 1*). However, we found that other parameters also influence ε_{max}, such as the matrix material and wire diameter.

We found that ε_{max} for the Nb_3Sn wire with the highest niobium fraction (28 % by volume) among those measured was only about 0.1 %, a very small strain window for magnet design (*Figure 1*). Fortunately, we also found that the use of copper alloys, instead of pure copper — along with small wire diameters — substantially mitigates the problem and provides reasonable strain operating margins in these high performance conductors.

Compressive Pre-Strain in PIT Nb_3Sn wires - Nb_3Sn wires fabricated using PIT technique are also candidates for the next generation of particle accelerators. Strain properties of PIT wires were not extensively studied in the past. We measured a PIT wire manufactured by Supercon. This conductor was stable and hence did not require additional Cu-plating. The compressive pre-strain for this wire was relatively low (0.1 %; see *Figure 2*). Note that this wire also had a high superconducting fraction (24.4 %), which would partially explain the low value of ε_{max}.

Textbook - This book presents a highly integrated, step-by-step approach to designing and constructing low-temperature test apparatus in general, and conducting superconductor critical-current measurements in particular. It is effectively two books in one: A textbook on cryostat design techniques and an appendix data handbook that provides materials-property data for carrying out that design.

The main text encompasses a wide range of information, written for specialists, without leaving beginning graduate students behind. After summarizing cooling methods, Part I provides core information in an accessible style on techniques for cryostat design and fabrication, including heat-transfer design, selection of materials, construction techniques, wiring, and thermometry, accompanied by many graphs, data, and clear examples. Part II gives a practical user's perspective of sample mounting methods and contact technology. Part III presents in-depth techniques for the measurement and analysis of critical current, including the latest performance data for high-T_c superconductors and recent developments in scaling theory.

The appendix is a ready reference handbook for cryostat design, encompassing seventy data tables compiled from contributions of experts and over fifty years of literature.

Recent Publications

1. Jack Ekin, *Experimental Techniques for Low-temperature Measurements—Cryostat Design, Materials, and Critical Testing.* Oxford University Press (2006)
2. J. W. Ekin, N. Cheggour, M. Abrecht, C. Clickner, M. Field, S. Hong, F. Parrell, and Y. Zhang, "Compressive pre-strain in high-niobium-fraction Nb_3Sn Superconductors," *IEEE Trans. Appl. Supercond.* **15**, 3560–3563 (2005)
3. N. Cheggour, J. W. Ekin, C. L. H. Thieme, D. T. Verebelyi, Y.-Y. Xie, V. Selvamanickam, and R. Feenstra. "Reversible axial-strain effect in Y-Ba-Cu-O coated conductors," Submitted to *Supercond. Sci. Techn*. (2005)
4. C.C. Clickner, J. W. Ekin, N. Cheggour, C. L. H. Thieme, Y. Qiao, Y.-Y. Xie, and A. Goyal. "Mechanical properties of Pure Ni and Ni-Alloy substrate materials for Y-Ba-Cu-O coated conductors," Submitted to *Cryogenics* (2005)
5. N. Cheggour, J. W. Ekin, Y.-Y. Xie, V. Selvamanickam, C. L. H. Thieme, and D. T. Verebelyi. "Enhancement of the irreversible axial-strain limit of Y-Ba-Cu-O coated conductors with the addition of a Cu stabilizer," Submitted to *Appl. Phys. Lett.* (2005)
6. Y.-Y. Xie, A. Knoll, Y. Chen, Y. Li, X. Xiong, Y. Qiao, P. Hou, J. Reeves, T. Salagaj, K. Lenseth, L. Civale, B. Maiorov, Y. Iwasa, V. Solovyov, M. Suenaga, N. Cheggour, C. Clickner, J. W. Ekin, C. Weber, and V. Selvamanickam. "Progress in scale-up of second-generation high-temperature superconductors at SuperPower," *Physica* in press (2005)

7. N. Cheggour, J. W. Ekin, and C. L. H. Thieme. "Magnetic-field dependence of the reversible axial-strain effect in Y-Ba-Cu-O coated conductors," *IEEE Trans. Appl. Supercond.* **15** (2005) 3577
8. J. W. Ekin. "Superconductors: An emerging power technology," *Gaseous Dielectrics X,* ed. L. G. Chrisophorou, J. K. Olthoff, P. Vassiliou, Springer (2004) p. 423
9. Y. Xu and J. W. Ekin. "Tunneling characteristics and low-frequency noise of high-T_c superconductor/noble-metal junctions," *Phys. Rev.* B **69** (2004) 104515
10. N. Cheggour, J. W. Ekin, C. C. Clickner, D. T. Verebelyi, C. L. H. Thieme, R. Feenstra, and A. Goyal. "Reversible axial-strain effect and extended strain limits in Y-Ba-Cu-O coatings on deformation-textured substrates*," Appl. Phys. Lett.* **83** (2003) 4223
11. N. Cheggour, J. W. Ekin, C. C. Clickner, D. T. Verebelyi, C. L. H. Thieme, R. Feenstra, A. Goyal, and M. Paranthaman. "Transverse compressive stress effect in Y-Ba-Cu-O coatings on biaxially textured Ni and Ni-W substrates*," IEEE Trans.Appl. Supercond.* **13** (2003) 3530
12. J. W. Ekin, "Superconductor Contacts," *Handbook of Superconducting Materials*, Institute of Physics, England, Chapter B5.1, pp. 857-887 (2003)
13. N. Cheggour, J. W. Ekin, C. C. Clickner, R. Feenstra, A. Goyal, M. Paranthaman, and N. Rutter, "Effect of transverse compressive stress on transport critical current density of Y-Ba-Cu-O coated Ni and Ni-W RABiTS tapes," *Ceramic Transactions* **140**, 157 (2003)
14. N. Cheggour, J. W. Ekin, C. C. Clickner, D. T. Verebelyi, C. L. H. Thieme, R. Feenstra, A. Goyal, and M. Paranthaman, "Transverse compressive stress effect in Y-Ba-Cu-O coatings on biaxially textured Ni and Ni-W substrates," *IEEE Trans. Appl. Supercond.* **13**, 3530 (2003)

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van der Laan, D.C	Postdoctoral Research Associate
Clickner, C. C.	Research Technician

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Postdoctoral Research Associates and Placements

Name	PhD From	Postdoc Advisor	Year	Present Placement
Daniel van der Laan	University of Twente	Ekin	2004 - present	NIST
Mike Abrecht	Swiss Technical U.	Ekin	2002 - 2005	U. Wisconsin
Najib Cheggour	University of Toulouse	Ekin	2000 - present	NIST
Yizi Xu	University of Shanghai	Ekin	1996 - 1999	NIST
Blaise Jeanneret	University of Neuchatel	Ekin	1990 - 1992	Swiss Inst. Of Standards
Steve Sanders	Iowa State Univ	Ekin	1988-1993	Storage Tech.
Steve Russek	Cornell University	Ekin	1987-1990	NIST
Alexano Roshko	Cornell University	Ekin	1986-1989	NIST
John Moreland	UC Santa Barbara	Ekin	1985-1988	NIST
Masters Student				
Robert McDonough	University of Colorado	Ekin	1986-1999	

Electro-mechanical Properties of Superconductors

National Institute of Standards and Technology, Boulder

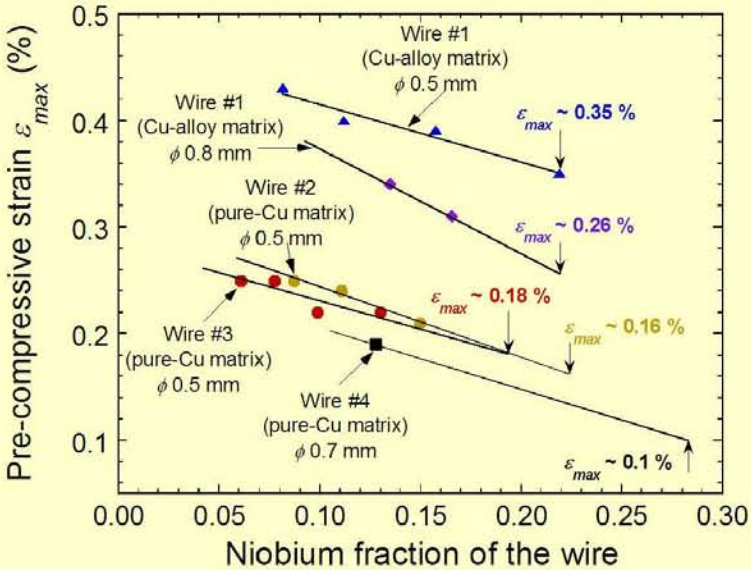


Figure 1. Compressive pre-strain e_{max} versus niobium fraction for several Nb_3Sn wires with high niobium density. Data were obtained using a new measurement method developed by NIST researchers for marginally stable superconductor wires.

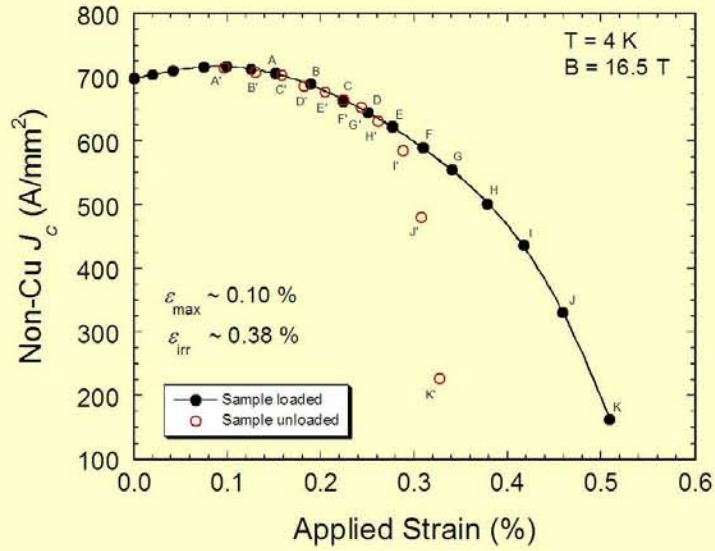
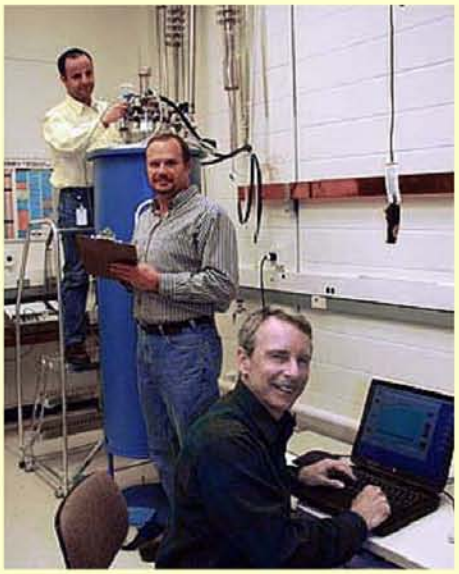


Figure 2. Critical-current density as a function of tensile strain for powder-in-tube Nb_3Sn wires with high niobium density. The compressive pre-strain and irreversible strain e_{irr} are relatively low.



Electro-mechanical test laboratory.

Experimental Techniques for Low Temperature Measurements:

Cryostat Design, Materials, and Critical-Current Testing

Jack Ekin

Oxford University Press (2006)

Part I Cryostat Design and Materials Selection

1. Introduction to Measurement Cryostats and Cooling Methods
2. Heat Transfer at Cryogenic Temperatures
3. Cryostat Construction
4. Wiring and Connections
5. Temperature Measurement and Control
6. Properties of Solids at Low Temperatures

Part II. Electrical Transport Measurements

7. Sample Holders
8. Sample Contacts

Part III. Critical-Current Measurements and Data Analysis

9. Critical-Current Measurements
10. Critical-Current Data Analysis

Appendixes: Data Handbook of Material Properties and Cryostat Design

Seventy tables

Table of contents for cryogenic-measurements textbook to be published by Oxford University Press in April 2006.

Critical-Current Metrology for Nb_3Sn Conductor Development

Loren Goodrich
National Institute of Standards and Technology - Boulder

Summary

This National Institute of Standards and Technology (NIST) project is a world leader in developing and creating measurement standards for superconductivity. It develops standard measurement techniques for critical current, residual resistivity ratio, and hysteresis loss, and provides quality assurance and reference data for commercial high-temperature and low-temperature superconductors. Project members assist in the creation and management of international standards through the International Electrotechincal Commission for superconductor characterization covering all commercial applications, including electronics. The project currently focuses on measurements of variable-temperature critical current, residual resistivity ratio, magnetic hysteresis loss, critical current of marginally stable superconductors, and the irreversible effects of changes in magnetic field and temperature on critical current. This project is jointly supported by Department of Energy/High Energy Physics (DOE/HEP) and DOE/Office of Fusion Energy Sciences, by purchase orders from U.S. companies and national laboratories, and internally by NIST.

For the HEP program, this research project provides critical current metrology for high-performance Nb_3Sn conductors. The requirements of the HEP high-field conductor development program call for conductors with higher-current densities, larger effective filament diameter, less stabilizer, and, in some cases, larger wire diameters than ever before. In addition, some of the conductor designs and heat treatments cause the residual resistivity ratio (*RRR*, ratio of room temperature resistivity to the resistivity at 20 K) of the stabilizer to be less than 20. These requirements create a series of challenges for routine, short-sample, critical-current (I_c) testing. Laboratories (including NIST) are now commonly observing early quenches that may result from damaged regions near the current contacts, conductor instability, conductor inhomogeneity, contact heating, or sample motion. We think that wires of 1 mm diameter and larger and/or wires that have less than 50 % stabilizer may require a new technique for measurement of I_c. The new technique may pay more attention to sample mounting details and additional measurements of contact resistance and voltages generated between the current contacts and the central voltage tap region. These wires will have critical currents from 800 to 2000 A at 12 T. The higher currents cause many minor problems to become significant engineering challenges. The focus of this work is to help develop a routine measurement technique for high-performance conductors and to provide feedback of conductor performance to the community.

Recent Accomplishments

- We participated in an interlaboratory comparison of critical-current (I_c) measurement on high-performance and more stable reference Nb_3Sn conductors.
- Started making voltage-field measurements to help determine the relative low-field (flux-jump) stability of conductors. The community is trying to find an easy measure of stability.
- Started measuring the effect of current ripple and spikes on critical current and the shape of the voltage-current curve (*n*-value), which may explain part of the interlaboratory differences.

- Provided hysteresis loss measurements of high-performance Nb_3Sn wires for the HEP community.
- Made variable-temperature, variable-angle, critical-current measurements on commercial Bi-2212 wires (0.81 mm diameter) with transport current up to 775 A.
- Made variable-temperature, variable-angle, critical-current measurements on commercial dip-coated and Ag-sheathed Bi-2212 tapes with transport current up to 845 A.
- We compared methods of measuring the residual resistivity ratio (RRR) of high-purity Nb using transport current. RRR indicates the purity and the low-temperature thermal conductivity of the Nb, and is often used as a material specification for superconducting radio-frequency cavities.

Supplemental Information

We participated in an interlaboratory comparison of critical-current measurement on high-performance and more stable reference Nb_3Sn conductors. This comparison was organized by personnel from Lawrence Berkeley National Laboratory. Both conductors had nominal wire diameters of 0.8 mm. This was the first comparison on these high-performance conductors that push the limits of stability, which we term marginally stable. The average critical current of the marginally stable sample was 759.5 A at 12 T and 4.2 K with a standard deviation of 27 A (3.6 %). The biggest difference was in n-values that varied from about 50 to 100 at 12 T. We measured the high-performance wire from 8 to 16 T with currents up to 1475 A and the stable reference wire from 2 to 14 T with currents up to 1200 A.

Recently, researchers have started to use measurements of voltage-field (*V-H*) curves at constant current (*I*) to investigate low-field instabilities (flux jumps) that have been observed in magnetization measurements and in some high-performance Nb_3Sn wire applications. *V-H* measurements may overcome some of the extrinsic conditions that limit the high-field *V-I* curve measurement. It also may give a more quantitative measure of the relative stability of conductors once we understand the best way to conduct these measurements. It is important to understand that some portion of the magnet windings will always (regardless of the central field) be at low field where the flux jumps occur and thus, can limit the performance of the magnet. We and the community have limited experience with *V-H* curve measurements, so these results are not very quantitative at this time. There is much uncertainty about the repeatability, reproducibility, and stability correlation of these measurements. However, going through this period before these aspects can be determined is informative and necessary. Our approach to the *V-H* curve measurement was to use the same equipment and specimen mounting conditions as used in *V-I* curve/I_c measurements. This meant trading off specialized high-speed acquisition for lower-speed, lower-noise acquisition.

We studied the systematic effect of current ripple or noise on the determination of *n*-value, the index of the shape of the voltage-current (*V-I*) curve. Commercial Nb_3Sn wires were measured with controlled amounts of a.c. ripple. A battery-powered current supply was used to provide the d.c. and ripple currents. The frequencies of the ripple current were 60, 120, and 360 Hz to represent common electrical power harmonics in high-current power supplies. A previous study focused on the effect on d.c. critical current (I_c). The current study focuses on how ripple changes the *n*-value. Recent high-performance Nb_3Sn wires have *n*-values as high as 80 at 12 T. These high *n*-values are more difficult to measure and this study shows that ripple has a larger effect on *n*-value than on I_c. We have examined models and measurements on superconductor simulator circuits to attempt to reproduce and explain the effects observed in

measurements on superconductors. We think that current ripple, noise, and spikes are one source of differences in *n*-values measured at different laboratories.

We have measured magnetic hysteresis loss on about 180 samples during this reporting period. Some of these measurements were done using a method that we developed to suppress the flux-jumps that occur in some high-performance conductors. This method improves the accuracy of the loss measurement under these conditions.

We made variable-temperature, variable-angle, critical-current measurements on commercial Ag-sheathed Bi-2212 wires (0.81 mm diameter) with transport current. Bi-2212 wires have been used in some of the highest-field superconducting magnets and may be used in specialty HEP magnets. Critical current depends on temperature, magnetic field, and, in many cases, the angle of the magnetic field with respect to the conductor cross section. The current-carrying properties of these round wires had never been systematically studied to determine how significant the angle dependence was until these measurements were made. NIST's results indicated that the angle dependence was insignificant and that applications could be operated at higher magnetic fields and temperatures than for other cross sections such as that of tape conductors. We made measurements in magnetic fields up to 8 T, at various magnetic-field angles, and temperatures from 4 to 30 K. NIST is the only laboratory in the U.S. that has such a multi-parameter and high-current variable-temperature measurement capability. The largest transport current applied to the wire samples was 775 A. No variable-temperature measurements at high current had been performed on these wires before. These data will be used to set the safe operating limits of the magnet system.

We made variable-temperature, variable-angle, critical-current (I_c) measurements on a commercial dip-coated and Ag-sheathed Bi-2212 tape, using a transport current. We measured at 4, 10, 15, 20, and 27 K. I_c at 1 μV/cm was 845 A in self field and 4 K. The tape specimens were straight and the angle with respect to the magnetic field was held and rotated with a worm gear drive. The field was always perpendicular to the tape axis and current. The highest I_c was measured when the field was parallel to the wide face of the tape, and this angle was defined as 90°. The lowest I_c was at 0°. I_c at 70° was less than the average of the lowest and highest I_c at all fields and temperatures measured, which indicates a strong angle dependence near the peak in I_c. The I_c hysteresis with field and angle sweep directions decreased with increasing temperature. These data allowed for optimization of magnetic field and operating temperature, as well as optimization of using or not using flux guides to control the angle of magnetic field in the application.

We compared methods of measuring the RRR of high-purity Nb using transport current. RRR indicates the purity and the low-temperature thermal conductivity of the Nb, and is often used as a material specification for superconducting radio-frequency cavities in HEP accelerators. Our experimental study is intended to answer some fundamental questions about the best measurement method for RRR and the biases that may exist among different measurement methods, model equations, and magnetic field orientations. Two common ways to obtain the extrapolated normal-state resistivity at 4.2 K are: (1) measure the normal-state resistivity as a function of field at 4.2 K and extrapolate to zero field and (2) measure the normal-state resistivity as a function of temperature in zero field and extrapolate to 4.2 K. Both approaches have their associated difficulties. We also compared data taken with the magnetic field both parallel and transverse to the specimen current, and we measured magnetoresistance at various temperatures from 4 to 16 K. We combined all of these data to estimate the RRR using an approach based on the Kohler empirical rule regarding magnetoresistance. The Kohler rule

imposes the shape of the magnetoresistance curve at higher temperatures to better predict the extrapolated normal-state values at lower temperatures.

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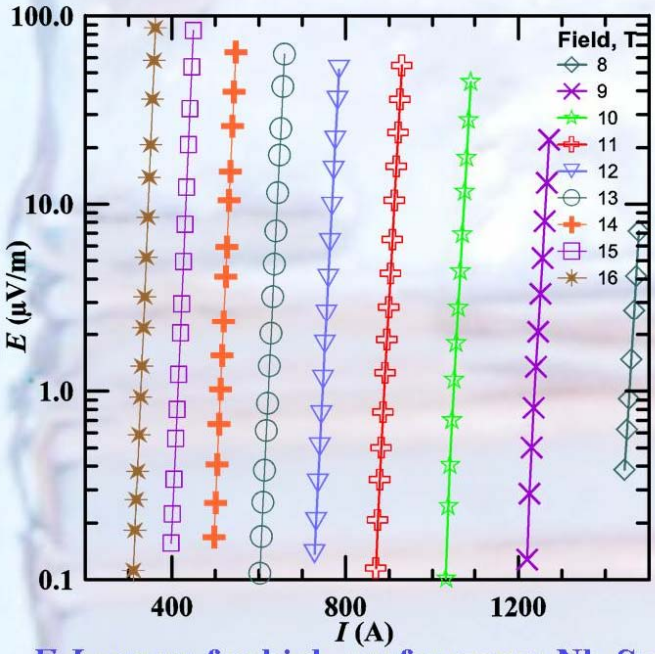
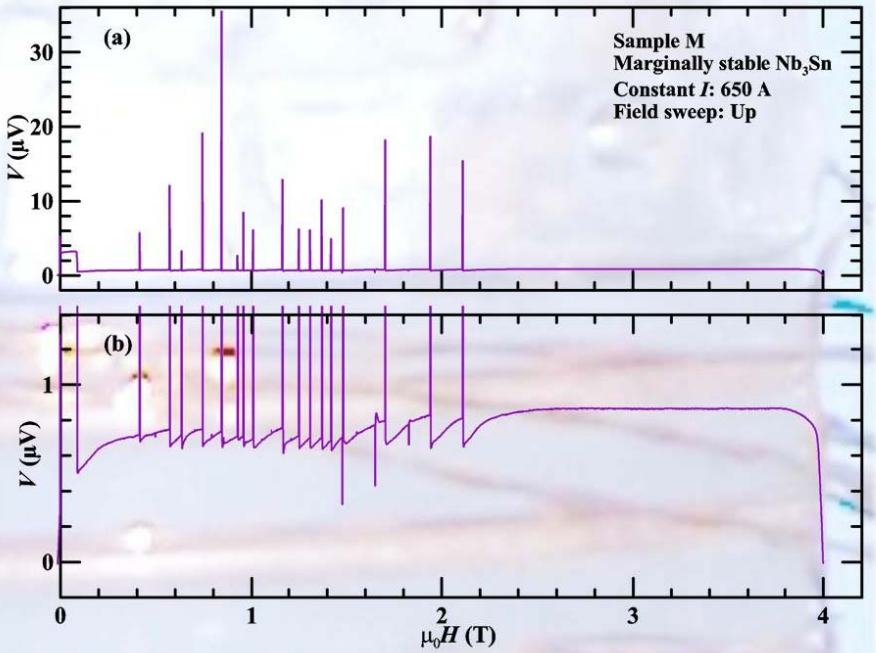
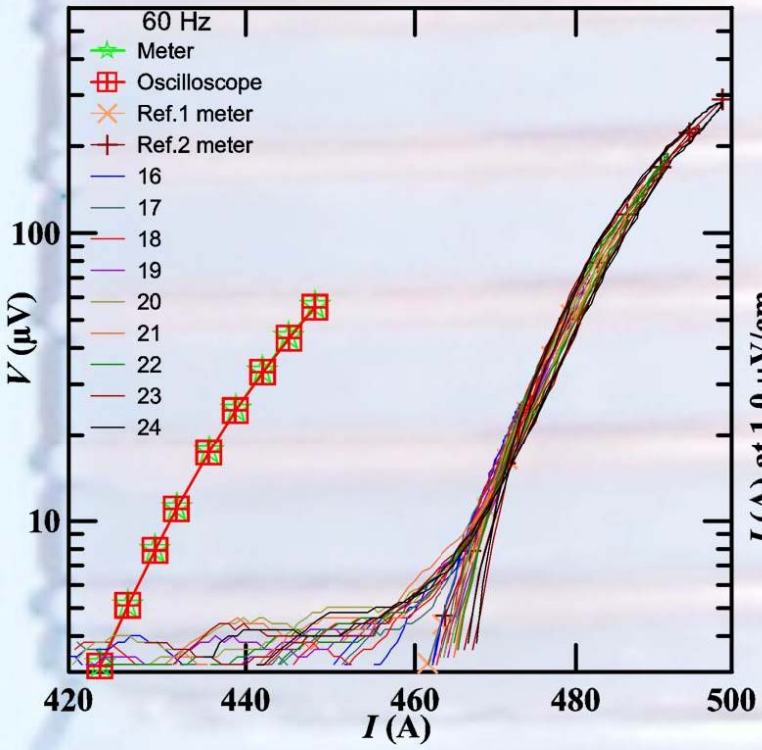
Critical-Current Metrology for Nb_3Sn Conductor Development at NIST



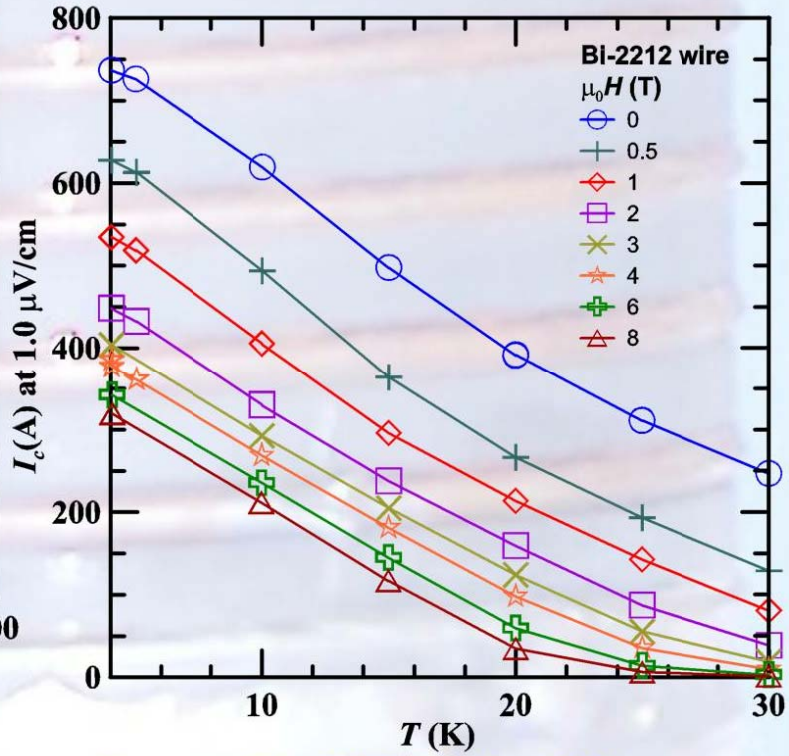
E-I curves for high-performance Nb_3Sn wire. Determines maximum current carrying capacity.



V-H curves for high-performance Nb_3Sn wire showing low-field flux jumps. Possible method to determine relative stability.



Full logarithmic *V-I* curves with and without a.c. ripple, showing average and instantaneous curves. Noise and spikes may be a source of differences in interlaboratory comparison.



I_c versus T for Bi-2212 wire (0.81 mm diameter). Determine the safe operating limits versus T and H.

Background is an image of coil test sample

Dielectric-Loaded Accelerator and Active Pulse Compressor Development at 11.424 GHz

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Summary

The goal of this program is to carry out studies of two new accelerator-related technologies using the high-power 11.424 GHz magnicon facility at the Naval Research Laboratory (NRL). The first technology is dielectric-loaded accelerating (DLA) structures, a potential alternative to conventional copper disk-loaded structures, for use in high-gradient rf linear accelerators. This technology is being developed in collaboration with Dr. Wei Gai and coworkers at the Argonne National Laboratory. The second technology is high-power active microwave pulse compressors using plasma switches. This technology is being developed in collaboration with Dr. Jay Hirshfield and coworkers at Omega-P, Inc. of New Haven, CT, and Dr. Anatoly Vikharev and coworkers at the Institute of Applied Physics of the Russian Academy of Science in Nizhny Novgorod, Russia, and is supported in part by several DoE SBIR grants to Omega-P, Inc. The heart of the NRL magnicon facility is an experimental magnicon amplifier tube that was developed under an earlier DoE program. The magnicon is a "scanning-beam," or deflection-modulated amplifier tube that offers the potential for high power and very high efficiency at frequencies ranging from 1 to 35 GHz. Unlike proposed fast-wave high-frequency alternatives to the klystron, the magnicon performance can equal or exceed that of high-power klystrons even at lower frequencies. Compared to klystrons, its potential advantages include: 1) higher efficiency, because of the use of a synchronous interaction that does not require beam bunching; 2) higher power, because of the potential for operating at higher perveance without loss of efficiency; 3) longer output pulse lengths (which would permit higher levels of microwave pulse compression to be employed), because of the lower fields in the output cavity and the lack of current interception on the rf circuit; and 4) insensitivity to mismatched loads. Experiments at the Budker Institute for Nuclear Physics, where the earliest magnicon research was carried out, have demonstrated 2.6 MW at 915 MHz with 73% efficiency in a 30-μs pulse, and 55 MW at 7 GHz with 56% efficiency in a 1.1-μs pulse. The goal of the NRL magnicon research, which has been carried out in collaboration with Omega-P, Inc., has been to develop a 60 MW, 11.424-GHz magnicon amplifier with a 1-μs output pulse, a 10-Hz repetition rate, >60-dB gain, and >60% efficiency. The magnicon presently provides up to 12 MW peak power in each of two output waveguides in 200-ns pulses, and up to 6 MW per waveguide in 1-μs pulses, and efforts are under way to increase the output power to the design level.

Recent Accomplishments

The performance of the magnicon amplifier has not as yet matched theoretical predictions as to peak power and efficiency, and efforts have been made to understand the reason for this discrepancy. In the process of those investigations, it was discovered that a strong oscillation was taking place in the magnicon collector at the magnicon drive frequency, i.e., at half the frequency of the output cavity. This oscillation appeared to limit the achievable output power and a new collector was designed to prevent this problem. In the old collector, a large trapped volume exists between the copper collector cone and the outer vacuum jacket. This volume is believed to be responsible for the oscillation. The new collector eliminates this trapped volume. The new collector has been fabricated and installed in the experiment and reconditioning of the magnicon is underway.

Dielectric-loaded accelerating (DLA) structures are a potential alternative to conventional copper disk-loaded structures for use in high-gradient rf linear accelerators. DLA structures are simple to fabricate (e.g., a smooth dielectric liner inside a cylindrical metal tube), can have comparable

shunt impedance to metal structures, offer straightforward methods to damp high-order modes, have no conduction band electrons, which should minimize dark current, and have none of the rf field enhancements associated with metal irises. The goal of this collaboration is to demonstrate high accelerating gradients in DLA structures, and to use this technology to develop a compact 20 MeV DLA test accelerator at NRL. High-power tests of several DLA structures have been carried out. Initial tests, reported previously, using an alumina dielectric liner showed a progressive increase in the attenuation through the DLA structure as a function of incident power, starting at approximately 100 kW and increasing to half the incident power at 5 MW. There was no corresponding increase in the reflected power, indicating that the missing power was being absorbed within the structure. This microwave absorption was accompanied by light emission from the dielectric surface. These two phenomena appeared to result from the formation of a microwave-absorbing electron cloud near the dielectric surface due to single-surface multipactor. This observation prompted a theoretical study of this regime, which includes strong normal and tangential electric fields, as the available models developed for normal window multipactor did not predict significant power absorption. A new model was developed with results in good agreement with observations. Recent experiments have explored a variety of means of reducing multipactor power loss by lowering the secondary emission coefficient of the dielectric surface to suppress electron multiplication, including 1) the use of a thin TiN layer on the inner surface of the alumina and 2) the use of an alternate ceramic liner material, magnesium calcium titanate (MCT). The TiN-coated alumina structure demonstrated reduced multipactor losses compared to uncoated alumina structures, while sustaining a gradient of 8 MV/m. However, multipactor power losses are still excessively high, and further tests with improved coatings are planned. Experiments using MCT structures achieved a gradient of 6 MV/m with significantly lower multipactor loading (~10%) than in the alumina structures, however, the maximum gradient was limited by rf breakdown at the liner joints. Efforts to eliminate joint breakdown are under way. Progress was also made in preparation towards commissioning the first DLA test accelerator. A 5-MeV electron injector for the program was constructed in China, and is undergoing final preparation at ANL; and a concrete bunker for the accelerator experiments has been installed in the magnicon facility.

The second technology being investigated is high-power active microwave pulse compressors using plasma switches. Such pulse compressors are of interest for a future linear collider because they offer the possibility of higher compression ratios and higher efficiencies than conventional passive pulse compressors such as SLED-II, as well as the possibility of lower capital costs than a delay line distribution system. The short-term goal is to demonstrate an active pulse compressor that can produce a 100 MW, ~50 ns compressed output pulse at a compression ratio of 10–12x, as a first step towards proving the utility of the plasma switch technology for Q switching microwave energy storage resonators for a future linear collider. In the active pulse compressor collaboration, where 50 MW of output power at ~10x power multiplication at 56% efficiency in a 43-ns pulse had already been achieved, we focused on testing alternative and improved configurations and on improving the robustness of the switch components. Two separate 6 week runs of new pulse compressor configurations were carried out. In the first experiment, the second test of a two-channel transmission pulse compressor demonstrated ~50 MW, 30-ns output pulses at 8x compression. However, the efficiency was limited to ~25% by breakdown in the switch during the switching process. The only solution to this problem is to reduce the fields in the switch tube during the switching process. This is difficult to do in a transmission experiment, since the flow of the extracted power is through the switch. Thus the second experiment explored a new dual-mode reflection pulse compressor configuration that was designed to reduce the rf electric fields in the switch during the switching process. This experiment demonstrated 16.5 MW, 54-ns pulses at 9x compression. The maximum power was limited by breakdown during the microwave energy storage. This

limitation is believed to be due to an rf field enhancement in the switching cavity in the vicinity of the high-voltage feed. This experiment also successfully tested a rugged new quartz switch tube design. The dual-mode configuration is believe to be capable of operating at 100 MW, once minor modifications are made to the geometry of the switch cavity, and once the magnicon is capable of supplying 10 MW in 1-μs output pulses to a single waveguide feed.

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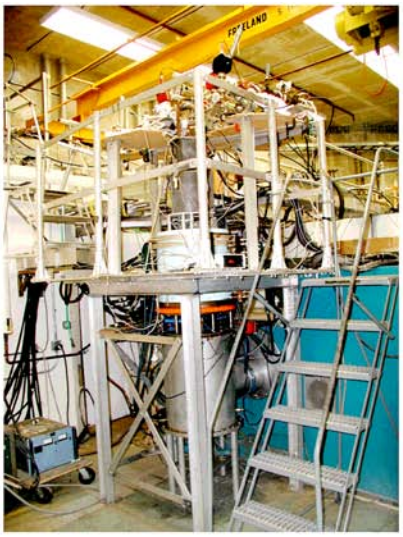
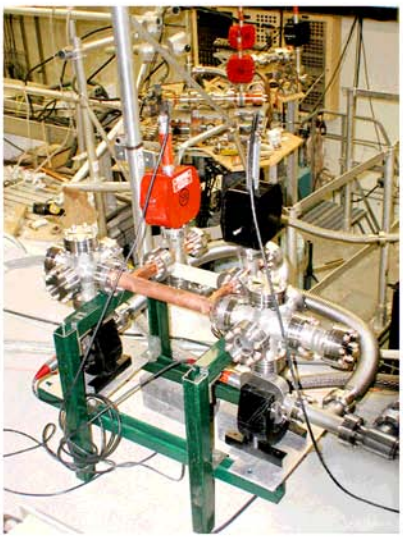
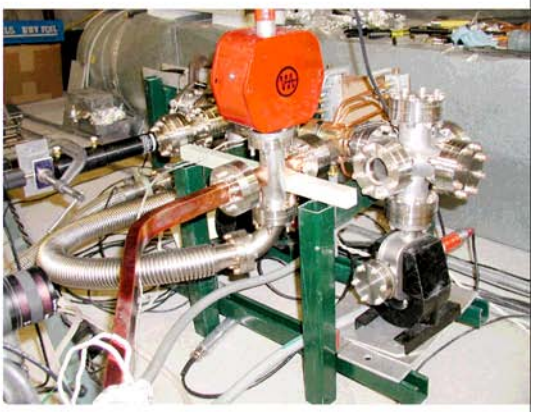
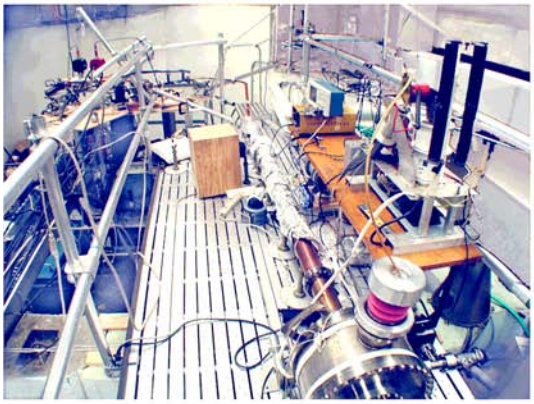
11.424-GHz Magnicon Amplifier (right) and output section (left)



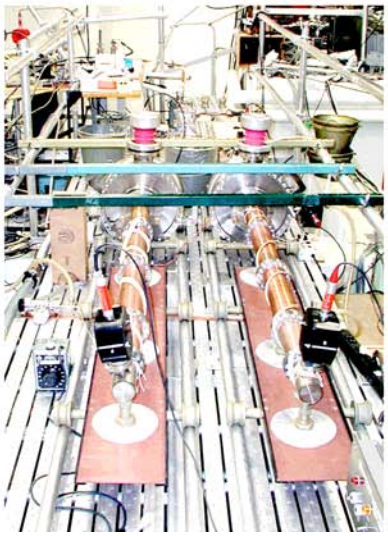


Dielectric-loaded accelerating structure test stand





One- and two-channel active microwave pulse compressors



High Energy Laser-Driven Acceleration Based on the Laser Wakefield Accelerator

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Summary

The Naval Research Laboratory (NRL) program addresses the key theoretical and experimental issues necessary for the development of a multi-GeV tabletop, laser wakefield accelerator. A laser wakefield accelerator (LWFA) uses a high power (>TW), short laser pulse to produce a large amplitude plasma wave that can accelerate electrons to high energies over extraordinarily short distances. Most LWFA experiments to date at NRL and elsewhere have operated in a long pulse, high plasma density regime where the laser is self-guided, and electrons are pulled directly from the laser-produced plasma. This "self-modulated" (SM) regime is relatively easy to achieve experimentally, but the laser pulse and the accelerated electron beam are highly unstable.

The general strategy for producing high quality stable electron beams in the future involves four basic components. First, laser and plasma parameters are chosen to be in the "standard" LWFA regime, where the laser pulse length $c\tau_p$ is less than the plasma wavelength $\lambda_p = 2\pi\chi/\omega_p$, and ω_p is the on-axis electron plasma frequency. In this regime, the laser produces a strong, well-defined wakefield while limiting the growth of dangerous instabilities. The second part of the strategy is to use a plasma channel to provide optical guiding and thus increase the acceleration length. The NRL program uses capillary discharges to provide the appropriate plasma channel conditions for guiding and acceleration. The third part of strategy is to use an external electron beam source that provides electrons with sufficient energy that they can be trapped and accelerated by the wakefield. Ideally, this source should produce precisely-timed, ultrashort bunches injected into the optimal phase of the wake. NRL is pursuing several optical injector concepts, including the Laser Ionization and Ponderomotive Acceleration (LIPA) concept, and low energy versions of the self-modulated LWFA. If the first three components of this strategy can be successfully implemented, the acceleration length and energy gain will eventually be limited by dephasing, that arises from the difference in speed between the beam electrons and the laser pulse, and laser energy depletion. The last component of the strategy involves increasing the dephasing limited energy gain through the use of tapered or discrete changes in the plasma channel density, and replenishing the laser energy through staging of acceleration sections.

All-optical injection and acceleration have recently been demonstrated simultaneously in a two-staged self-modulated- laser wakefield acceleration (SM-LWFA) acceleration experiment at NRL using the Tabletop Terawatt (T^3) laser, which produces 10 TW and 500 fsec pulses. Although phased optical injection has yet to be shown experimentally, simulations have indicated in channel-guided and other favorable conditions, non-ideal injection can still lead to high quality electron beam acceleration. The first integrated experimental demonstration of channel guiding, "standard" LWFA acceleration, and optical injection for high energy, high quality electron acceleration is now in progress using the NRL Ti:sapphire femtosecond laser (TFL) with 10 TW and 50 fsec pulses.

Recent Achievements (Experimental)

The NRL experimental program is focused on the investigation of all four aspects of high energy acceleration of electrons in a LWFA, namely, the injection, the injection/acceleration, the

extended acceleration distance for high final energies, and channel tapering and staging of accelerators. The injection scheme studied was the high density regime of the Laser Ionization and Ponderomotive Acceleration (HD-LIPA). A major finding of the experimental study of this special regime of the LIPA injector is that the space charge effect of the high density plasma substantially alters the properties of the injection electrons. The scheme behaves as a mix of the original LIPA and the familiar SM-LWFA where most of the energetic electrons are projected in a forward direction. This led to a simple design of an injector-accelerator experiment. Excellent experimental results have been obtained. We have demonstrated for the first time the successful optical injection of high energy electrons to be subsequently accelerated to even higher energies by the LWFA. To reach final high energies of near GeV, extended acceleration distances provided by guided propagation of the intense laser beam by a plasma channel is required. We have studied the propagation of TW laser beams in a laser triggered capillary discharge plasma channel which is being incorporated with the new injection-acceleration experiment presently in the setup phase.

The HD-LIPA injector was investigated through measurements and simulations for the generation of injection electrons into laser driven accelerators. Our measurements and their comparisons to simulations confirmed that the effect of space charge was to pitch a substantial amount of the high energy LIPA electrons in the forward propagating directions in violation of the LIPA angle-energy relationship. We measured the angular distribution of the ejected electrons and found the peak structure at 28 degrees indicates the presence of LIPA characteristics such as the non-forward ejection of electrons. We have also observed both experimentally and numerically that the energies of the HD-LIPA injection electrons are much higher than predicted when only the LIPA was considered. Electrons with energies as high as 7 MeV have been generated in the forward (0 degree) direction. Lower energy electrons at ~3 MeV were generated at the larger ejection angle of 30 degrees. This indicates that further acceleration of the injection electrons by mechanisms such as SM-LWFA may be present in the HD-LIPA environment. These high energy HD-LIPA electrons are most suitable for injection into a subsequent stage of laser driven accelerator such as a channel guided LWFA.

A laser driven accelerator has a very limited acceptance area that is comparable to the focal spot of the drive laser beam. In order to collect enough electrons from the optical injector the acceleration stage should be placed as close as possible to the injector. Following this requirement, most optical injectors are embedded inside the accelerator. However, it is difficult to understand and to study the various mechanisms involved in these injection/acceleration schemes because everything happens at the same location. In order to better understand injection/acceleration mechanisms and to avoid influence of the injector target on the acceleration laser beam, the accelerator stage is separated from the injector stage in the NRL experiment. Successful implementation of separate stages of injection and acceleration is also important to the design of future multi-stage laser-driven accelerators. We have therefore performed a proof-of-principal experiment on staged optical injection and laser wakefield acceleration using two different short laser pulses focused into two spatially separated gas jets. The first gas jet was used as an injector and the second one as the accelerator. Both the injector and the accelerator operated in the SM-LWFA regime, but in different trapping conditions. Relative amplitudes of the acceleration wakefields was measured by forward Raman scattering (FRS). Strong dependence of the electrons energy gain on the timing between the injection and acceleration laser beams, and the time difference between the occurrence of the maximum number of accelerated electrons and the peak FRS clearly identified the acceleration of injected electrons.

The upgraded NRL T-cubed laser system at a wavelength of 1054 nm was used for the experiment. The stretched beam from the chirped pulse amplification laser system was split before it reaches the final amplifier. The first beam containing most of the energy was sent through an adjustable delay line and then compressed in air. This laser beam (2 TW, 500 fs, 1 J) was focused into a nitrogen gas jet ($5x10^{18}$ cm^{-3} neutral density) using a 32 cm focal length (F#10 for this beam) off-axis parabola. The 2 TW laser beam and the nitrogen gas jet are being used as the injector. The second laser beam was sent through an additional amplifier, a spatial filter (1:1.7 beam expansion) and then compressed in vacuum, resulting in a 10 TW (5 J, 500 fs) output laser beam. After recombining collinearly with the first beam by using a thin-film polarizer and a half-wave plate, the second beam was focused by the same off-axis parabola (F#6 for this beam) into a helium gas jet that was separated by 0.5 mm downstream from the nitrogen jet. The maximum energy of the injected electrons was below 0.5 MeV. It was measured by firing the 2 TW beam and the Nitrogen gas jet only. When both gas jets and both laser beams were fired at the optimum time delay and 10 μm spatial alignment between the injection and acceleration laser beams, electrons well above 20 MeV were detected. By changing the time delay between the injection and acceleration laser beams, we observed that the high energy electrons (> 10 MeV) appear in a very narrow time window of 3 psec.

We have performed guiding of the TW T^3 laser beam in a new laser triggered (instead of the auxiliary-capillary triggered) capillary discharge plasma channel. The capillary used was a single capillary with laser ignition that allowed easy control of the plasma channel density and profile in order to get the best conditions for guiding. The length of the capillary was 1 cm with a bore diameter of 300 μm. Approximately 3–5 kV of high voltage was applied to the end electrodes. When an ignition laser was sent into the capillary, a high voltage breakdown was initiated in the capillary, which subsequently caused the capillary to discharge. The laser ignition capillary provided more stable discharges of the capillary and reduced the timing jitter of the discharges as was monitored by the current probe of the main discharge. The energy transfer efficiency with the discharge varied deeply with the timing between the discharge and the passage of the laser pulse through the capillary. The best energy transfer was obtained about 100 ns after the discharge current, which was monitored with a magnetic Pearson probe. The energy transfer efficiency at this point was between 70% and 80%. As a contrast, the energy transfer of an unguided beam (no plasma in the capillary) is negligible. The output beam size matches the size of the beam on the input.

Recent Achievements (Theoretical/Computational)

Work in this area has traditionally focused on simulation of possible future laser wakefield accelerators with single stage energy gain exceeding 1 GeV. There was also a particular emphasis on the use of tapered density plasma channels that have the potential to extend the channel length and energy gain beyond the usual dephasing limits for a resonant or standard LWFA. Typical LWFA parameters for these designs had pulse lengths of 100 fsec or less and plasma densities in the 10^{17}-10^{18} cm^{-3} range. Most of this work is now more closely coupled to the ongoing NRL experiments using the recently upgraded short pulse TFL laser at 10 TW and 50 fsec. Recent work has focused on nonideal injection studies and channel-guided, “standard” (CGS) LWFAs. Four different simulation models, LEM, WAKE, SIMLAC, and TurboWAVE, have been used at NRL to model these processes. The codes have been used to validate analytical scaling laws for LWFAs and to demonstrate the effectiveness of density channel tapering to increase the energy gain. With proper choice of laser and plasma parameters, stable channel-guided laser propagation and electron acceleration to energies well above 1 GeV can be obtained.

Major accomplishments during the last year include photon deceleration, pulse compression, hamiltonian modeling and simulations for trapping and acceleration in a channel-guided, standard (CGS)-LWFA, quasi-monoenergetic beams from unphased, monoenergetics injection and from warm beam injection, modeling of HD-LIPA and SM- LWFAs, trapping and acceleration in the vacuum-plasma transition at channel entrance, modeling of the second stage in the NRL double gas jet experiment, and implications of recent experimental and modeling advances for CGS-LWFA demonstration experiments.

At modest laser intensities, a CGS LWFA simulation with injection spot size properly matched to the strength of the channel exhibits little change in its pulse shape during propagation. However, a number of simulation studies have shown that significant pulse compression and other nonlinear effects can occur at higher laser intensities. The effects can be both damaging and beneficial to LWFA performance. The initial pulse compression can produce a moderate increase in the wakefield amplitude as the pulse propagates, which results in a noticeable increase in the final energy of accelerated electrons. However, in tapered or multi-stage plasma channels, in which the propagation distance can exceed the classical dephasing length, the pulse can be severely disrupted. In some simulation cases, this effect can be the dominant process that limits the eventual energy gain in a LWFA.

We had previously attributed the pulse compression effect to a simple frequency chirp produced by the modulation instability. In this case, the front of the pulse would be red-shifted (photon deceleration), and the back of the pulse would be blue-shifted (photon acceleration), so that the back propagates faster than the front. However, a more careful simulation analysis, reported in Physical Review Letters, reveals a much different and more complicated process. The density perturbation associated with the wakefield makes a strong nonlinear contribution to the refractive index that exceeds the usual self-phase modulation (SPM) contribution from the laser in the tail of the pulse and results in strong photon deceleration in the tail. The downward frequency shift can be a substantial fraction of the optical frequency. The simulations were carried out in one and two dimensions using turboWAVE.

Trapping and acceleration may be treated using a Hamiltonian model. This model captures major features seen in the simulations of unphased (long bunch), monoenergetic injection. Although the analysis is inherently 1-D, transverse effects can be partly accounted for by assuming that any particle that crosses into a region where the radial electric field is defocusing is instantaneously lost. In the ideal uniform plasma case, the focusing region of phase and the accelerating region are 90º out of phase. However, in a plasma channel, the focusing region of phase is both expanded and shifted relative to the acceleration region. Including this effect has important implications for LWFA requirements and performance. The wider range of focusing phases reduces the allowable injection energy and increases the final energy significantly from a longer than classical dephasing length. The particles are observed to be closely clustered in momentum, indicating a modest final energy or momentum spread.

Unphased, monoenergetic injection, where the bunch length is long compared with the plasma wavelength or wakefield period, can be studied more quantitatively using both Hamiltonian analysis and simulation. The Hamiltonian model can be extended to calculate the collection efficiency, dephasing length, final beam energy and spread, and final bunch location and bunch length as functions of the injection energy, normalized wake potential, group velocity, plasma to optical wavelength ratio and focusing phase range. The agreement between the simulation and Hamiltonian calculations is excellent except at high energies where the simulation energy spread is significantly lower than the Hamiltonian values. The models agree particularly well for energies near the minimum injection energy for trapping.

The case of warm beam injection into a CG-LWFA has also been investigated extensively using both turboWAVE and WAKE simulations. In these simulations, electrons are injected with a one-side Maxwellian velocity distribution over a limited range of phases. Although one might expect such a poor quality injection bunch to be unsuitable, those particles that are in a favorable region of phase space are trapped and accelerated to high energies, producing quasi-monoenergetic beams with modest energy spread.

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Nonlinear Dynamics of High-Brightness Electron Beams and Beam-Plasma Interactions: Theories, Simulations, and Experiments

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Summary

Funding for this project commenced on July 1, 2004, and it augments support that Northern Illinois University's Beam Physics and Astrophysics Group (founded in August 2002) have from other sponsors. According to the respective Statement of Work, the overarching objective is: "To enhance substantially the understanding of the fundamental dynamics of nonequilibrium high-brightness beams with space charge." Associated problems fall within two categories, (1) the physics of phase mixing, and (2) the physics of beam-halo formation. Both are related to the general phenomenon of rapid 'collisionless' relaxation in Coulomb systems, i.e., those in which the interparticle force respects an inverse-square dependence on the interparticle separation. In addition to charged-particle beams, self-gravitating stellar systems, e.g., galaxies, are another class of Coulomb systems, in which case rapid collisionless evolution is called "violent relaxation". Thus, a deeper understanding of the evolution of nonequilibrium beams has application to galactic dynamics, as well.

Related work involves probing the microscopic, i.e., orbital, dynamics in space-charge potentials. We seek to answer questions of nonlinear dynamics, such as the following: What conditions lead to a significant population of globally chaotic orbits in a space-charge potential? How does the presence of globally chaotic orbits influence the time scales that characterize the macroscopic evolution of the beam? To what extent does "noise", both white noise (granularity arising from discrete particles) and colored noise (such as will arise from machine imperfections and space-charge fluctuations), influence the population of chaotic orbits? More generally, under what conditions can the six-dimensional phase space of a single particle (the conventional Vlasov-Poisson formalism) adequately account for the dynamics associated with the full $6N$-dimensional phase space of the beam? If it cannot adequately do so, might augmenting the Vlasov-Poisson formalism with a judiciously constructed Fokker-Planck model make up the difference?

In keeping with recent findings that localized details generally do matter as concerns beam evolution, Northern Illinois University (NIU) is devising theoretical tools that center on multiresolution analysis, an example of which is the application of wavelet techniques to space-charge algorithms, with the ultimate goal of developing improved simulation codes. An auxiliary effort is underway to develop methods for efficiently quantifying orbital chaos. The overarching goal of the NIU work is a fundamentally correct and comprehensive understanding of the dynamics of nonequilibrium beams, especially as applies to high-brightness electron sources and accelerators.

Accomplishments (since July 2004)

We investigated the validity of the Vlasov-Poisson equations for calculating properties of systems of N charged particles governed by time-independent Hamiltonians. Through numerical experiments we verified that there is a smooth convergence toward a continuum limit as $N\rightarrow\infty$ and the particle charge $q\rightarrow 0$ such that the system charge $Q\rightarrow qN$ remains fixed. However, in real systems N and q are always finite, and the assumption of the continuum limit must be questioned. We demonstrated that Langevin simulations can be used to assess the importance of discreteness effects, i.e., granularity, in systems for which the physical particle

number N is too large to enable orbit integrations based on direct summation of interparticle forces. By applying Langevin techniques to a beam bunch in thermal equilibrium, we assessed the conditions under which the continuum limit can be safely assumed for this system. In the process we showed, especially for systems supporting a sizable population of chaotic orbits that roam globally through phase space, that for the continuum limit to be valid, N must sometimes be surprisingly large ($\sim 10^{10}$). Otherwise the influence of granularity on particle orbits cannot be ignored.

We investigated how collective space-charge modes and colored noise conspire to produce a beam halo with much larger amplitude than could be generated by either phenomenon separately. For the collective modes, we used the lowest-order radial eigenmodes calculated self-consistently for a configuration corresponding to a direct-current, cylindrically symmetric, warm-fluid Kapchinskij-Vladimirskij equilibrium. The ultimate source of colored noise is unavoidable machine errors that act on the beam and self-consistently perturb its internal space-charge force. We demonstrated that its presence quickly launches statistically rare particles to ever-growing amplitudes by continually kicking them back into phase with the collective-mode oscillations. The halo amplitude is essentially the same for purely radial orbits as for orbits that are initially purely azimuthal; orbital angular momentum has no statistically significant impact. Factors that do have an impact include the amplitudes of the collective modes and the strength and autocorrelation time of the colored noise. The underlying dynamics ensues because the noise breaks the Kolmogorov-Arnol'd-Moser tori that otherwise would confine the beam. These tori are fragile; even very weak noise will eventually break them, though the time scale for their disintegration depends on the noise strength. Both collective modes and noise are thus demonstrated to be centrally important to the dynamics of halo formation in real beams.

This phenomenology may have implications for beam loss in, for example, Fermi National Accelerator Laboratory's (Fermilab's) Booster synchrotron, and in fact our work attracted the attention of the Booster Group. We showed not only that colored noise acting for a short time on a beam with strong space charge, as in a proton linac for, e.g., driving an intense source of spallation neutrons, can cause serious emittance degradation and halo growth, but also this is true if the noise acts on a beam with weak space charge for a long time, as in a synchrotron or storage ring. Consequently, a University of Rochester Ph.D. student at Fermilab, Mr. Phil Yoon, has been modifying the code ORBIT to simulate the Booster with noise, this being done under the guidance of C. Bohn and W. Chou. His preliminary findings are that the presence of noise would indeed lead to continuous emittance growth and beam loss. The ultimate question is whether it is possible to identify sources of such noise in the Booster.

To pinpoint the essential dynamical ingredients inherent to time-dependent space-charge potentials, we constructed a family of 1D models corresponding to breathing spherically symmetric waterbags. They offer several attractive advantages: (1) the distribution function of particles in the phase space of a single particle, the charge-density profile, and the space-charge potential are all analytic; (2) the space-charge-depressed tune parameterizes the family of models, so one can readily explore the range from zero space charge to the space-charge limit; (3) the equilibrium configurations are all stable, and (4) whereas all of the equilibrium configurations are integrable in keeping with spherical symmetry, a range of models admits chaotic orbits once they are made to breathe. Hence, when it is present, this deterministic chaos is fully attributable to the time dependence alone. We have used these models for several purposes: (1) relating the population of globally chaotic orbits to the amplitude of the breathing mode and to the space-charge-depressed tune; (2) exploring how orbits mix through phase space in response to the time dependence, and to the presence of stochastic noise;

(3) determining to what extent halo formation in these models can be attributed to chaotic behavior; (4) discovering a fast indicator of orbital transitions between regular and chaotic dynamics, one that devolves from constructing an integral of motion in time-dependent potentials.

We also have been exploring another possible measure of chaos, one that involves pattern recognition in orbit segments. One cannot possibly use standard techniques like Lyapunov exponents (which are calculated from long-time-averaged orbital behavior) to decipher transient chaos. What people do instead is freeze the time-dependent potential at each time step and then compute, e.g., Lyapunov exponents in each frozen potential. But this is also completely unsatisfactory because it side-steps the essence of the problem: it ignores the actual dynamics of both the potential and the orbit(s). What really matters is how fast the frequencies that characterize the evolution of the orbit in the time-dependent potential change. This is why we turned to developing a new method. By applying the measure to orbits generated from different codes, but with statistically the same initial conditions, one has a precision method for *detailed* code verification. Differences originating from different computational algorithms *will* show up. This is our principal motivation for this work.

We successfully built and implemented an *N*-body, particle-in-cell (PIC) Poisson solver based on wavelet mathematics. Presently we are working on wavelet denoising of small-scale structure/granularity that has unphysical or minor consequences to the beam properties. Once finished, we should have a code that is not only more accurate than its predecessors, but also considerably faster. Once the wavelet code has been brought to maturity, we can then study complicated, but generic, nonequilibrium beams in which multiscale physics is important. A key advantage is 'compression': with wavelets one can represent a density profile or potential, even if complicated, by a small number of wavelet coefficients, where 'small' is with respect to the number of macroparticles or grid points in a *N*-body PIC simulation. This means one can store compactly the entire time-dependent density-potential pair computed in the course of a real machine simulation. This offers two immediate new applications. First, one can now populate the real time-dependent potential with a large number, say 10^6-10^7, of test particles. These particles feel the space-charge potential but contribute negligibly to it. This affords a means to compute accurately the formation and distribution of a diffuse halo. Actually, it may come to pass that the accuracy of such a computation would be limited primarily by uncertainties in the real boundary conditions (hardware irregularities) rather than in detailed space-charge dynamics. Second, one can accurately pursue computations that require the inclusion of retardation due to the finite speed of the electromagnetic field. This consideration is inherent to self-consistent interactions between wake fields and the beam, an important example being coherent synchrotron radiation (CSR). We envision eventually doing fully 3D simulations of bunch dynamics in magnetic bending systems, like bunch compressors, that include self-consistently generated CSR.

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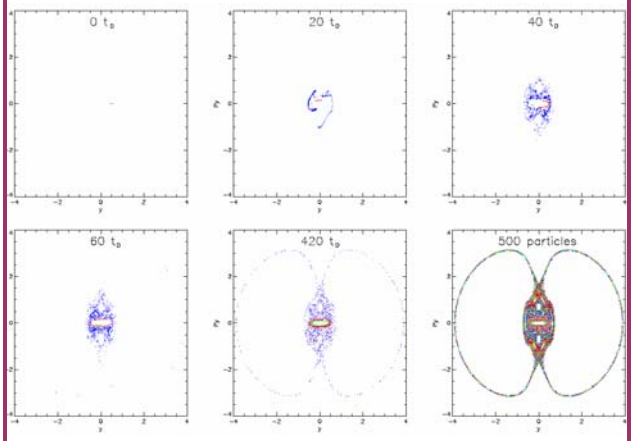
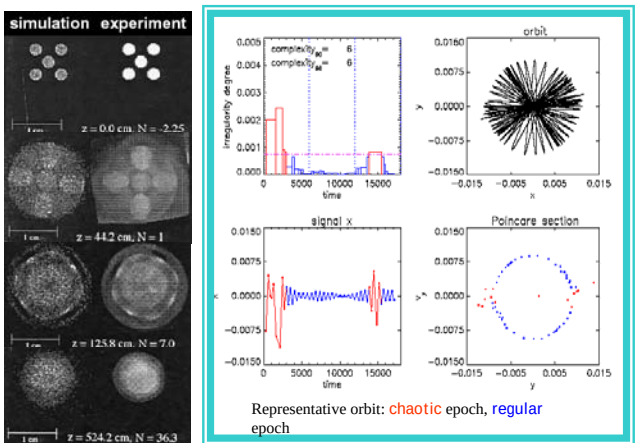
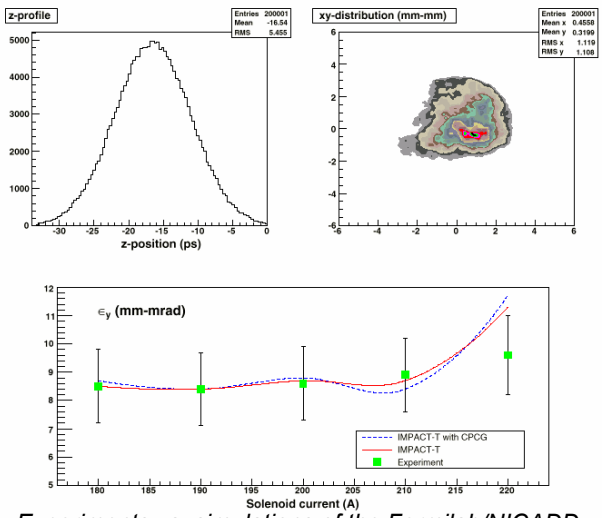


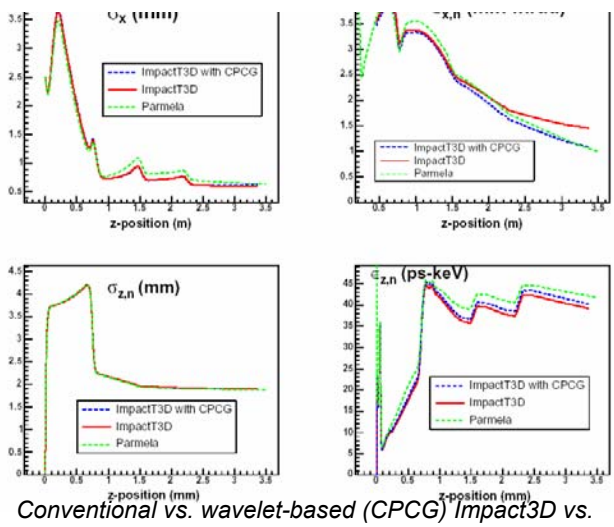
Stroboscopic snapshots of mixing in a breathing spherical waterbag. The first 5 plots illustrate evolution of 3 clumps of 1000 test particles initially tightly localized in phase space: (blue) wildly chaotic orbits, (green) regular orbits, (red) sticky chaotic orbits. The 6th plot shows the complete surface of section computed with 500 test particles initially distributed according to the waterbag density profile.



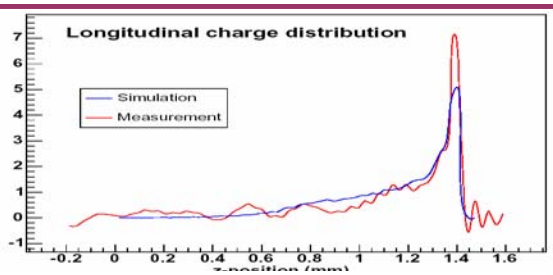
Measuring transient chaos in an orbit (right panel, top right) from an N-body simulation of the University of Maryland 5-beamlet experiment (left panel). Right panel: (top left) orbital irregularity vs. time; everything under the red line is more regular than chaotic; (bottom left) x-coordinate vs. time; (bottom right) surface of section. This figure symbolizes close collaboration between NIU and the Univ. of Maryland UMER Group.



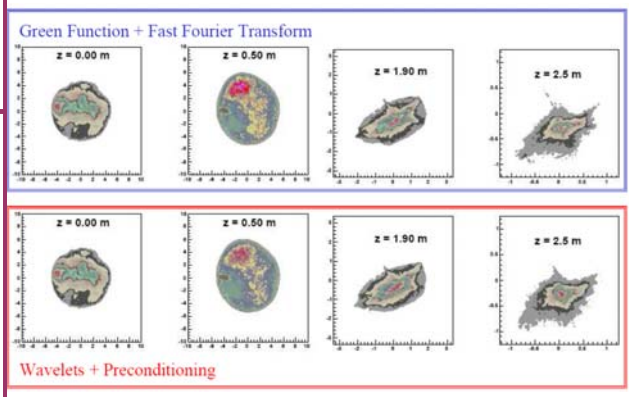
Experiments vs. simulations of the Fermilab/NICADD photoinjector: (top left) longitudinal bunch shape at cathode (simulation); (top right) transverse particle distribution at cathode (simulation, obtained by digitizing the laser spot on the photocathode); (bottom) normalized transverse emittance (simulation vs. experiment).



Conventional vs. wavelet-based (CPCG) Impact3D vs. Parmela in simulating a 133 pC bunch-charge (AES/JLab) photoinjector.



Measured longitudinal density profile of compressed 3 nC bunches in the Fermilab/NICADD photoinjector (red curve) vs. that resulting from a Parmela simulation using 20,000 macroparticles (blue curve).



Conventional (upper) vs. wavelet-based (CPCG) Impact3D (lower): transverse beam spots at different z-locations along a 133 pC bunch-charge (AES/JLab) photoinjector.

Novel Instrumentation for future TeV e^+e^- colliders

Mayda Velasco
Northwestern University

Summary

The goal of this work is to design, and construct novel beam diagnostic and control instrumentation for charged particle accelerators and beam transport lines required for the next generation of linear colliders. Our effort thus far has been focused on two main areas of experimental investigation: (1) beam loss monitoring; and (2) non-destructive bunch length measurement techniques. We have collaborated with Fermilab and Richardson Electronics LTD for the beam loss detector design since 1999 and with CLIC Test Facility 3 (CTF3), where these devices will be installed, since 2003. These devices can also be adapted for use in other machines, for example linear induction accelerator (ALINAC)s intended for Free Electron Lasers or high power proton beams for future neutrino factories.

1. Beam loss monitoring at CFT3

With its 4kW average beam power, the CFT3 [1] is a machine where the control of the beam losses is an important issue. Beam loss must be monitored along the length of the LINAC in order to keep the radiation level and the activation as low as possible. A quantitative beam loss measurement using a Beam Loss Monitor (BLM) system must be at a sensitivity of 0.1% of the nominal beam current. This is below the threshold of the current Beam Position Monitors (BPM) installed at CTF3. Thus, intensive simulation work has been carried out using Geant3.21 in order to estimate the secondary particles produced in the realistic accelerator environment should the electron beam become unfocused *(Figure 1)*. Current simulations model the CTF3 LINAC as composed of an accelerating module with a beam position monitor, followed by a set of three quadrupoles and two 3 GHz accelerating cavities *(Figure 2)*. Each module is 4m long, and there are a total of 9 consecutive modules along the LINAC. The electron beam energy ranges from 25-170 MeV along the LINAC, and beam loss flux levels were thus simulated to be of the order 10^{10}–10^{11} electrons/cm^2/s depending on the distance from the original point of beam loss. Low energy photons are also produced an order of magnitude higher in flux than the electrons in the range of 0-4 MeV.

From previous work to monitor high flux hadron beams at high power proton drivers and neutrino factories, we had already developed small radiation hard gas sealed ionization chambers (IC), and secondary emission monitors (SEM), which were installed as the initial BLM system. Thus in October 2004, a full installation of IC, SEM and Faraday Cups (to cross check the calibration online), and their respective readout electronics were mounted and tested along all girders in the LINAC on which there were accelerating structures. Beam loss measurements using the IC and SEM were successfully obtained at the required design level of 0.1% of the nominal beam current *(Figure 2).* A goal of the beam loss monitoring is not only to get the integrated loss per pulse, but also to study the loss within the beam pulse. To therefore distinguish beam losses from the transient or from the beam core, a 10-20 ns time response is required. Thus current work is ongoing to refine the setup, optimizing detector sensitivity and

[1] *G. Geschonke, "CTF3 Design Report," CTF3 note 047, (2002)*

electronics in order to get the best timing and signal resolution. Detectors based on Photomultiplier tubes (PMTs) sensitive to Cherenkov radiation in air are also being considered as beam loss monitoring devices. Online software is being developed to calculate the initial point and magnitude of the beam loss from the detected secondary shower, and feed back safety warning signals into the existing CTF3 control system.

2. Non-destructive bunch length monitors

The measurement of micro bunch lengths is one of the most challenging tasks for beam instrumentation in electron LINACs because typical R.M.S. for the bunch lengths are smaller than 1 mm, that is, they have a 3.3 ps time duration. This is far below the resolution of classical electronic instruments like oscilloscopes. The need for an accurate sub millimeter bunch length measurement in various new accelerator machines has driven the development of a variety of sophisticated measurement *(Figure 3)* devices in recent years. Many of them, although successful in demonstration experiments, can not be used in practice because the procedure is either too time consuming, and therefore not practical for tuning accelerators and/or they interfere with the beam.

A method which avoids both these problems has been developed and found to be very successful at the CTF2 facility; this is the so called RF-pickup [2]. This method is based on an on-line analysis of the spectra of electromagnetic pulses induced by the bunch in a waveguide connected to the vacuum pipe The shortest bunch length, σ_{min}, which can be measured with this method, can be estimated from:

$\sigma_{\min} = \frac{c_0\sqrt{-2Log(0.95)}}{2\pi\,\nu_{\max}}$, where ν_{max} the highest frequency accessible and c_0 the velocity of light. The set-up in CTF2 had ν_{max}=90 GHz and therefore σ_{min}=170 μm. The measurement time with this set-up was typically 5 min. This time was needed to scan the spectrum by stepping a frequency synthesizer, thus measuring one frequency on each machine pulse. This instrument was dismantled together the CTF2 end of 2002, when the construction of CTF3 started. We have begun to design and build a substantially enhanced version of this device for use in CTF3.

The main improvements in the enhanced device will be:

- Increase of ν_{max} to 170 GHz corresponding to a measurement limit of σ_{min}=90 μm
- Spectral analysis by single shot FFT analysis from a large bandwidth waveform digitizer
- Improved control software to facilitate measurements in regular operation.

The enhanced device is simulated using the GdfidL v1.8 Electromagnetic Field Simulator. The design is based on a single rectangular WR28 waveguide (cut-off frequency of 21.08 GHz) used as an RF-pickup, attached to the CTF3 beam pipe with a Gaussian beam of known σ. The design of the window in the waveguide to maintain vacuum in the beam pipe is currently based on an existing Al_2O_3 ceramic window used at CTF3, but other materials for optimal transmission and vacuum properties are also being investigated, and simulated. The RF signal is transported using a continuous WR28 waveguide for about 14m to the analysis station in the technical gallery. A local

[2] *C. Martinez, "Determination of Longitudinal Electron Bunch Lengths on Picosecond Time Scales" , Ph.D thesis, CLIC note 426 (1999)*

oscillator at 157 GHz with a down converter and D-band waveguide components and filters will provide the setup for the measurement up to a ν_{max} of 170 GHz.

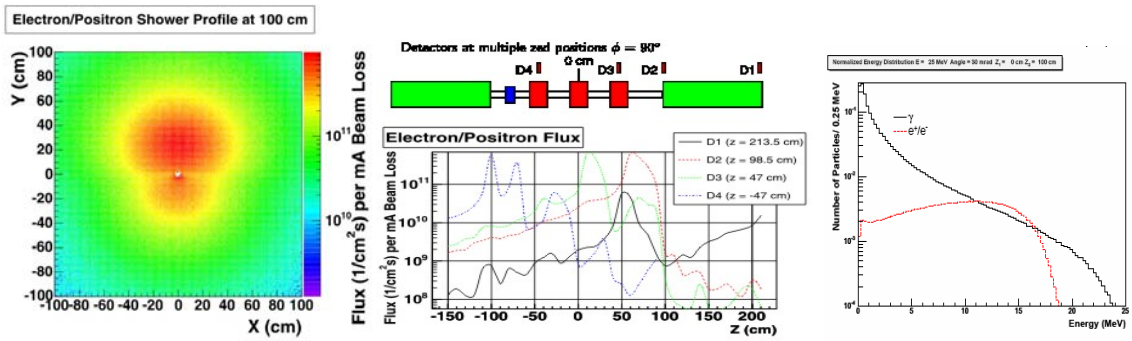


*Figure 1 Geant3.21 simulations -- **LEFT**: e^+/e^- flux distribution at 100cm from the point of the beam loss in the X/Y plane transverse to the beam line. **MIDDLE**: e^+/e^- flux versus the longitudinal position. Each curve corresponds to the output signal amplitude of each of the 4 detectors located at different z positions along a LINAC module. **RIGHT**: Energy distribution of photons and electrons produced by 0.1% loss of 25MeV electrons in the LINAC coming out at an angle of 30mrad.*

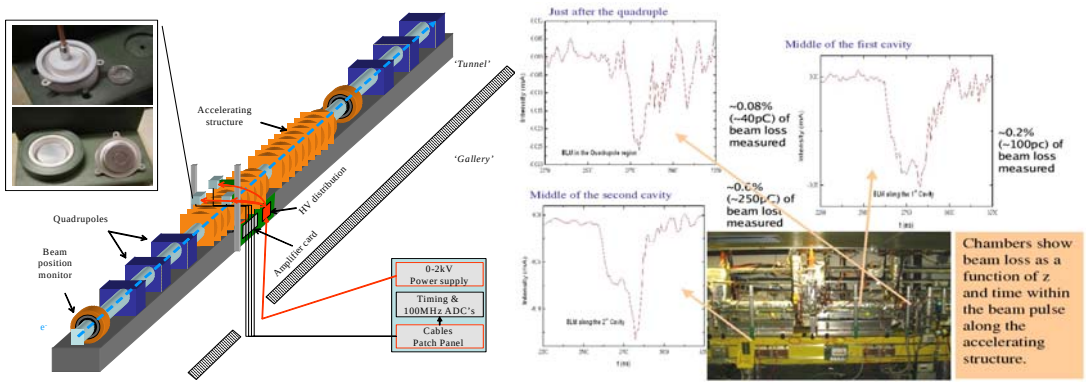


*Figure 2 **LEFT**: Layout of the beam loss system in a CTF3 LINAC module. The IC or SEM is photographed on the top left. **RIGHT:** Preliminary results from data taken at the CTF3-linac on October 2004. Signals can be detected even if the losses are below the per mille level.*

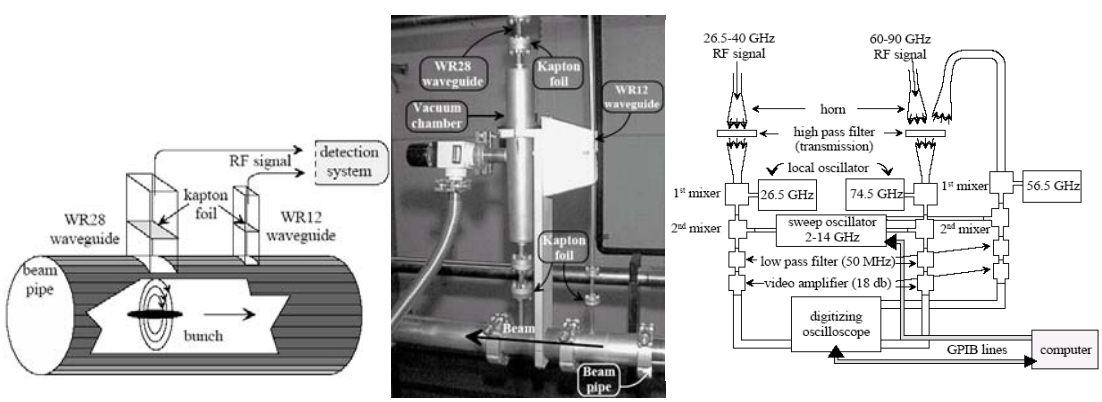


Figure 3 RF pick-up for bunch length monitoring in CTF2. Rectangular waveguide acts as RF pickup by being connects to the beam pipe. The signal is transported to technical

gallery where it is analysed using RF mixing technique. Two waveguides (and two detection systems) were needed in CTF2 to measure RF signals in the Ka (26.5-40 GHz) and E (80-90 GHz) frequency bands. The new design for CTF3 will use just one WR28 waveguide collecting all frequencies above cut-off of 21.08 GHz. The signals will be processed using an RF mixer in combination with a RF sweep oscillator, and Ka, E and D-band waveguide components.

Materials Strands and Cables for Superconducting Accelerator Magnets

Edward Collings
Michael Sumption
Ohio State University

Summary

Research in support of the goals of the Research and Development Branch of Department Of Energy (DOE)'s Division of High Energy Physics (HEP) is conducted at Ohio State University's Materials Science and Engineering Department (MSE) within the Laboratories for Applied Superconductivity and Magnetism (LASM), a research center dedicated to the study of superconducting materials, strands superconducting cables and the properties of magnets. The LASM group includes typically five graduate students whose choice of research topic reconciles the requirements of MSE's graduate committee with those of the DOE sponsor. Thus research programs being undertaken include: (1) solid-state diffusion and phase formation in Nb_3Sn and other advanced superconductors such as Nb_3Al, and MgB_2, (2) computer modeling using FEM methods of (i) coupling current paths in multifilamentary tapes and Rutherford cables, (ii) interelement bonding during hydrostatic- and conventional extrusion and wire drawing -- the latter representing an entry into the "processing" side of applied superconductivity, (3) magnetization and transport studies of MgB_2 and Nb_3Sn superconducting strands (critical current density measurements to 15 T, 1,700 A, and critical field measurements down to 2 K), (4) measurements of AC loss in strands (AC applied fields and AC and DC transport currents) and AC loss in Rutherford cables by calorimetric and magnetic techniques.

Research Accomplishments

During the present period (2003 - 2005) considerable progress has been made in all of the areas mentioned as evidenced by the resulting publications. For a time, LASM led a U.S. program to develop Nb_3Al strand for high field applications, continuous processing equipment was developed and good properties obtained. As the application Nb_3Al strand turned away from accelerator dipole towards the requirements of NMR magnets the program was discontinued and replaced by what is turning out to be a very successful MgB_2 materials-development program. Some of LASM's many research activities are summarized below.

Materials

Processing and superconducting properties of Nb-Ti-Ta alloys developed for enhanced 2K upper critical fields and critical current densities. Four ternary alloys compositions of Nb-Ti-Ta were selected as to lead (with proper thermomechanical processing) to β phase of high upper critical field at 2K and finely distributed α precipitates of volume fractions (~25%) needed for optimized J_c. Heavy strain was applied to the arc melted ingots by employing five passes of equal channel angle extrusion (ECAE) (total strain 5.75) to introduce the high dislocation density necessary to preclude the formation of a Widmannstatten type microstructure. Precipitation heat treatments at 550-600C were then applied between four stages of mechanical deformation by wire drawing (0.7 total strain per stage). Upper critical field measurements were performed on wire samples at 2.2 K and the results were discussed in conjunction with those of TEM-based microstructural analysis.

Characterization of Ti and Ta influences on grain shape and size, as well as transport properties of conductors fabricated by the internal-Sn process. The microstructures and super-conducting properties of three kinds of fully reacted internal-Sn conductors were studied. Three different

monofilamentary structures were investigated: (i) Cu-clad pure Nb filaments, (ii) Cu-clad Nb7.5% Ta filaments, and (iii) Cu-clad pure Nb filaments interspersed with Cu-clad Nb47wt%Ti filaments. After fully reaction, the Nb_3Sn filaments and their grain structures were observed using high resolution SEM, and STEM. Also EDS was used to obtain the composition profile across the filaments. Superconducting properties, with a focus on J_c, were measured. The purpose of the study is to determine the effects of Ta and Ti on the composition distribution and grain morphology, and the relationship of the local composition and morphology to the J_c value.

Strands

Ti diffusion in subelements and phase formation in internal-Sn Nb_3Sn strands. The Ti-moderated diffusion of Sn in "internal-Sn" Nb_3Sn precursor strands is the subject of considerable practical importance to investigate which a series of simple model billets were assembled in some of which the Ti was added in the form of Nb-replacing Nb47.5%Ti rods. After drawing to final size the strands were reacted according to typical schedules consisting of: (i) ramp at 10° C/h to 185 °C, hold 24 h, (ii) ramp at 25 °C/h to 340 °C, hold 48 h, (iii) ramp at 10° C/h to 650 °C, hold 150 h. The influence of the Ti, (which based on previous studies was expected to diffuse more-or-less evenly throughout the composite) on the Sn-diffusion rate and the Nb_3Sn layer growth rate were investigated as well as Sn concentration and Ti concentration as functions of radial position and time. On samples quenched from various stages during the heat treatment the formation of the various Nb-, Cu-, Sn-, and Ti-containing phases were studied by SEM and EDS and the results compared with predictions based on the Nb-Cu-Sn and Ti-Nb-Cu phase diagrams

Critical Current Density in NbCu-Alloy Sheathed MgB_2 Multifilament Superconducting Strands. Magnesium diboride (MgB_2) multifilamentary strands consisting of 7, 19, and 37 strands have been fabricated using Nb and 101 Cu as sheath material restacked in monel outer sheaths. These test strands were given single-step heat treatments at temperatures ranging from 700-800°C for times of 20–60 minutes. All of them turned out to have T_cs of around 36 K. Transport J_c measurements were performed on 2.5 cm and 1 m lengths of strand (in the latter case using the ITER protocol) using a four-point technique at 4.2 K and 20 K in fields of up to 15 T. Critical current densities at 5 T, 4.2 K of typically 10^5 A/cm^2 were compared with the 20 K values. The VSM-measured magnetic J_c of a 7-filament strand heat treated 20min/700°C was found to be $6x10^4$ A/cm^2 at 20 K and 1 T.

Investigation of Bonding Generation during the Drawing of Multifilamentary Wires. Experimental shear tests and FEM modeling have been used to study the generation of bonding during the multi-pass drawing of multifilamentary wire. The wires consisted of two kinds of geometries: (1) a simple cylindrical geometry of a mono wire: a Nb7.5%Ta core inside a Cu can (or sleeve), and (2) a 7 restack of the above mono wires. Two kinds of simulations were performed: (1) the initial state of the billet was assumed to be without bonding. The simulation was then performed, and from this the normal pressure, deformation, and temperature at the core/sleeve interface were calculated (2) a pressure welding model was used to estimate the bonding stress generated at the interface by the multi-pass drawing process.

Cables

AC loss and contact resistance in Nb_3Sn Rutherford cables, calorimetric and electric measurements. Calorimetric and magnetic techniques were used to measure AC loss in uncored Nb_3Sn Rutherford cables in the field-perpendicular and field-parallel orientations of the applied field. The five cables selected for study had widths of 8, 13, and 16 mm and strand

counts of 20, 30, and 36, respectively. Under various surface conditions describable as "as-cabled", "solvent-rinsed", or "HCl-rinsed," they were reaction heat treated (RHT) then vacuum impregnated with resin in preparation for measurement. The calorimetric measurements were made at 4.2 K in sinusoidal fields of amplitude 400 mT and frequencies of 5 to 90 mHz, and the magnetic measurements over the same frequency range using the pick-up coil method on cable samples already installed in the calorimeter. The total per-cycle loss so obtained was also expressed in terms of the interstrand contact resistances (ICR). On some of the cables ICR data were also obtained using the four-terminal transport method for comparison with the calorimetric and magnetic results. Attention is focused on the ICR of one particular 8-mm/20-strand cable measured under several pre-RHT/RHT conditions: (i) as-received plus mild RHT, (ii) as-received plus standard RHT, (iii) acetone-degreased plus standard RHT, and (iv) acetone-degreased then HCl-deoxidized plus standard RHT.

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Appendix A

Current Graduate Students

Last Name	First Name	Institute	Advisor
Wu	Xiaoxia	Ohio State University	M.D. Sumption
Bohnenstiehl	Scott	Ohio State University	M.D. Sumption
Bhatia	Mohit	Ohio State University	M.D. Sumption
Contractor	Anjun	Ohio State University	M.D. Sumption

Appendix B

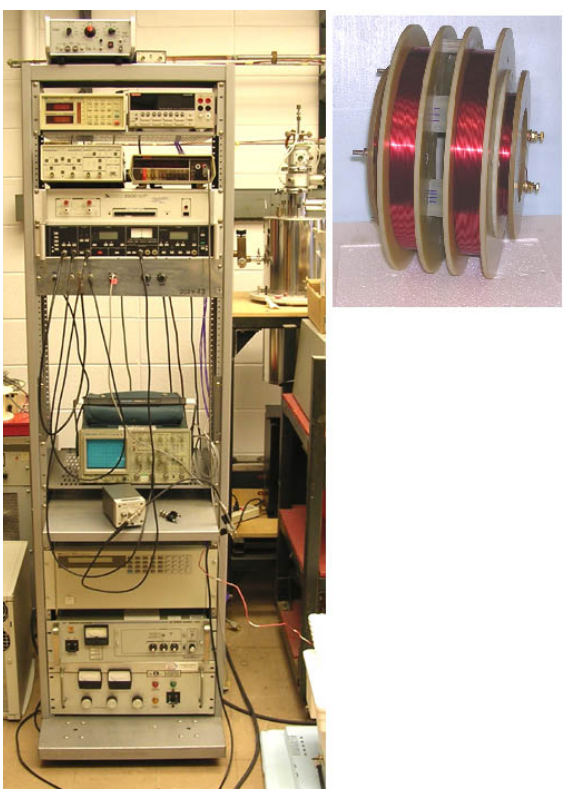
Past Graduate (PhD) Students

Last Name	First Name	Inst.	Advisor	Year	First Placement
Buta	Florin	OSU	M.D. Sumption	2000	Global R&D, Inc
Lee	Einguk	OSU	M.D. Sumption	2001	Korea
Peng	Xuan	OSU	M.D. Sumption	2005	HyperTech, Inc

Vibrating Sample Magnetometers: *(a)* 1.7-0-1.7 T, variable temp. (*b*) 9-0-9 T, 4.2 K

(*a*)

(*b*)



AC Loss Test Stand
Inset: "Double Helmholz" Field Coil

Critical Current Density: *variable temp., field to 15 T, current to 1,700 A*
Critical Fields: *temperatures to 2 K*

Nonlinear Dynamics and Collective Processes in Intense Charged Particle Beams

Ronald Davidson
Hong Qin
Princeton University

Summary

Present and next-generation accelerators and transport systems for high energy physics applications place stringent requirements on stable beam propagation at high beam intensities and luminosity. At the beam densities and currents of practical interest, it is increasingly important to develop a fundamental understanding of the influence of collective processes and self-field effects on beam stability and transport properties, with the aim of maintaining high beam quality and stable propagation over large distances. Under the auspice of the Department of Energy's Office of High Energy Physics, we have conducted detailed theoretical studies of critical problems related to the basic equilibrium, stability, and transport properties of intense charged particle beams for high energy physics applications (http://nonneutral.pppl.gov). The theoretical investigations are based on a first-principles model describing the collective processes and nonlinear beam dynamics – the nonlinear Vlasov-Maxwell equations, which describe self-consistently the evolution of the distribution function $f_b(\mathbf{x},\mathbf{p},t)$ in the six-dimensional phase space ($\mathbf{x},\mathbf{p}$) and the average electric magnetic field, $\mathbf{E}(\mathbf{x},t)$ and $\mathbf{B}(\mathbf{x},t)$, including both the self-generated fields and the applied focusing fields. The major research objectives include: (a) application of 3D multi-species nonlinear perturbative simulation techniques to investigate detailed nonlinear processes and collective interactions with particular emphasis on the electron cloud instability and the temperature anisotropy instability in high-energy hadron colliders, electron-positron colliders and storage rings; (b) development of theoretical models and analytical methods to study nonlinear beam dynamics and collective interactions, in particular, beam-beam interactions in next-generation colliders; and (c) identification of operating conditions for optimum performance (beam stability, luminosity, etc.) in which the detrimental influence of halo particles and collective instabilities are minimized. Advanced analytical methods, such as Hamiltonian average techniques and nonlinear stability and bond analyses are used, together with large-scale parallel computer simulations carried out at the National Energy Research Scientific Computing Center.

Recent illustrative research accomplishments in the beam dynamics area include

- Development of an improved g-factor model for the longitudinal kinetic description of long, coasting beams, including a self-consistent derivation of the Korteweg-deVries equation describing the evolution of weakly nonlinear excitations
- Analytical investigations of the electromagnetic Weibel instability in strongly anisotropic one-component charged particle beams, and analytical investigations of the multispecies Weibel instability (filamentation instability) for intense beam propagation through a background plasma
- Kinetic investigations of the wall-impedance-induced collective instability in intense charged particle beams
- Determination of the effects of electron collisions on the resistive hose instability for intense beam propagation through background plasma

- Calculation of ionization cross-sections for ion-atom collisions in high-energy ion beams
- Investigations of longitudinal drift compression for high intensity particle beams
- Development of Hamiltonian averaging techniques and application to periodic focusing systems and the coherent beam-beam interactions
- Nonlinear delta–f simulation studies of intense charged particle beams with large temperature anisotropy, including detailed investigations of the electrostatic Harris-type instability
- Nonlinear estimates of beam emittance growth due to the collective relaxation of space-charge nonuniformities
- Development of self-consistent model of nonlinear charge and current neutralization of an ion beam pulse in a pre-formed plasma
- Development of guiding-center Vlasov-Maxwell description of intense beam propagation through a periodic focusing field
- Analytical and numerical investigations of two-stream instabilities induced by a second charge component in high-intensity linacs and storage rings
- Development of self-consistent kinetic and macroscopic descriptions of periodically-focused nonneutral beam propagation in alternating-gradient field configurations
- Nonlinear simulation studies of intense nonneutral beam propagation in periodic-focusing transport systems using nonlinear delta-f perturbative techniques
- Investigation of collective mode excitations in high-intensity beams as a mechanism for the production of halo particles
- Development and application of a macroscopic warm-fluid model for the description of collective processes in intense charged particle beams
- Derivation and application of statistically-averaged rate equations for intense nonneutral beam propagation through a periodic focusing field based on the nonlinear Vlasov-Maxwell equations
- Development of a nonlinear kinetic stability theorem that identifies the class of stable beam distribution functions that can propagate quiescently over large distances at high beam intensity
- Development of a canonical transformation and Hamiltonian averaging technique based on the nonlinear Vlasov-Maxwell equations that describe intense nonneutral beam propagation in alternating-gradient field configurations
- Investigations of chaotic particle dynamics and nonlinear properties for an intense charged particle beam propagating through a periodic focusing field
- Analytical and numerical studies of the thermal equilibrium properties of intense charged particle beams
- Analytical and numerical studies of chaotic electron dynamics in free electron lasers, including self-field-induced chaoticity produced by the beam space charge and current, and chaoticity produced by transverse spatial inhomogeneities in the wiggler field

Princeton Davidson

Selected 2003-2005 Refereed Publications (see also http://nonneutral.pppl.gov for a complete list of refereed publications and electronic link to the papers)

1. "Delta-f Simulation Studies of the Ion-Electron Two-Stream Instability in Heavy Ion Fusion Beams," H. Qin, R. C. Davidson, E.A. Startsev and W.W. Lee, Laser and Particle Beams **21**, 21 (2003)
2. "Paul Trap Simulator Experiment," E. Gilson, R. C. Davidson, P. Efthimion, R. Majeski and H. Qin, Laser and Particle Beams **21**, 549 (2003)
3. "Nonlinear Perturbative Particle Simulation Studies of the Electron-Proton Two-Stream Instability in High-Intensity Proton Beams," H. Qin, E. A. Startsev and R. C. Davidson, Physical Review Special Topics on Accelerators and Beams **6**, 014401 (2003)
4. "Truncated Thermal Equilibrium Distribution for Intense Beam Propagation," R. C. Davidson, H. Qin and S. M. Lund, Physical Review Special Topics on Accelerators and Beams **6**, 024402 (2003)
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6. "Effects of Electron Collisions on the Resistive Hose Instability in Intense Charged Particle Beams Propagating Through Background Plasma," H. S. Uhm and R. C. Davidson, Physical Review Special Topics on Accelerators and Beams **6**, 034204 (2003)
7. "Kinetic Analysis of Intense Sheet Beam Stability Properties for Uniform Phase-Space Density," E. A. Startsev and R. C. Davidson, Physical Review Special Topics on Accelerators and Beams **6,** 044401 (2003)
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9. "Renormalization Group Reduction of the Henon Map and Application to the Transverse Betatron Motion in Cyclic Accelerators," S. I. Tzenov and R. C. Davidson, New Journal of Physics **5,** 67.1 (2003)
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27. “Three- Dimensional Simulation Studies of Temperature Anisotropy Instability in Intense Charged Particle Beams ,” E. A. Startsev, R.C. Davidson and H. Qin, Nuclear Instruments and Methods in Physics Research **A 544**, 125 (2005)
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33. “Chaotic Particle Trajectories in High-Intensity Finite-Length Charge Bunches,” S.R. Hudson, H. Qin and R.C. Davidson, Nuclear Instruments and Methods in Physics Research **A 544**, 458 (2005)
34. “The Electromagnetic Darwin Model for Intense Charged Particle Beams,” W.W. Lee, R.C. Davidson, E.A. Startsev and H. Qin, Nuclear Instruments and Methods in Physics Research **A 544**, 353 (2005)
35. “Simulations of Beam Emittance Growth from the Collective Relaxation of Space-Charge Nonuniformities,” S. M. Lund, D. P. Grote, E. P. Lee and R. C. Davidson, Nuclear Instruments and Methods in Physics Research **A 544**, 472 (2005)
36. “Kinetic Description of Neutralized Drift Compression and Transverse Focusing of Intense Ion Charge Bunches,” R. C. Davidson and H. Qin, Physical Review Special Topics on Accelerators and Beams **8**, 064201 (2005)
37. “Symmetries and Invariants of the Oscillator Equation and the Envelope Equation with Time- Dependent Frequency,” H. Qin and R. C. Davidson, submitted for publication (2005)
38. “An Exact Magnetic Moment Invariant of Charged Particle Gyromotion,” H. Qin and R. C. Davidson, submitted for publication (2005)

Invited Papers and Conference Proceedings

During 2003 –2005, members of the Princeton beam dynamics group have given nine invited papers on their research at major national and international conferences and professional society meetings; 20 papers describing this research have been published in the Proceedings of the 2003 and 2005 Particle Accelerator Conferences.

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Hong Qin	Co-Principal Investigator
Igor Kaganovich	Co-Investigators
Edward A. Startsev	Co-Investigators
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Proposed Physics Experiments for Laser-Driven Linear Acceleration in a Dielectric-Loaded Vacuum

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Summary

The Laser-Electron Accelerator Project (LEAP) is carried out jointly by the Applied Physics department at Stanford University and the Accelerator Research Department B (ARDB) group at Stanford Linear Accelerator Center (SLAC). The initial phase that included proof-of-principle experiment was carried out at the SCA-FEL facility at Stanford University and at present the experiment is being moved to the Next Linear Collider Test Accelerator (NLCTA) facility at SLAC.

In our very last run in November of 2004 at the SCA-FEL facility we have succeeded in linearly accelerating electrons in vacuum with the laser beam. Moreover, we were successful in observing the dependence of the energy modulation on the presence of a boundary, as predicted by the Lawson-Woodward Theorem, and have seen the expected dependence on the laser electric field strength and the laser polarization. These measurements constitute the proof-of-principle demonstration for laser-driven particle acceleration in vacuum completing our stated goal at the start of the program.

In addition, we were able to carry out an independent set of experiments with an Inverse Free Electron Laser (IFEL) working at visible wavelengths, which will be used as an optical buncher in upcoming staged accelerator experiments.

Furthermore we are nearing completion of the E163 experimental space at the NLCTA facility. The components of the LEAP experiment on campus have been brought to the new site and work to commission the UV laser photo-injector gun is presently under way. We expect to have electron beam by the end of 2005.

Significant progress has been made in accelerator structure design that covers a variety of photonic band gap architectures. Also, we are investigating nano-fabrication methods and materials for these structures. Finally, we have made progress in the laser phase-locking effort and are exploring laser architectures suitable for laser-driven particle acceleration.

Laser-driven particle acceleration in vacuum

The proof-of-principle demonstration was carried out with the simplest possible configuration that allows testing the key physics. We employed a single Gaussian laser beam terminated by a single downstream boundary, resembling a configuration originally proposed by Edinghofer and Pantell [1]. *Figure 1* illustrates the laser and electron beam configuration used in the proof-of-principle experiment.

As depicted in *Figure 1* the propagation axis z' of the laser is oriented at an angle α to the propagation axis *z* of the electron. The accelerating longitudinal electric field component $E_z(z)$ results from the component of the laser electric field parallel to the electron beam axis. An analytical expression for $E_z(z)$ resulting from a pair of crossed

Gaussian beams has been calculated by Esarey, Sparangle and Krall [2]. For the case of a single laser beam this $E_z(z)$ expression is reduced by a factor of ½. The energy gain of the electron corresponds to the integral of $E_z(z)$ over the interaction length of electron beam with the laser beam. However, in such a free space configuration the phase velocity of the laser beam is not matched to the velocity of the electrons, and in accordance to the Lawson-Woodward Theorem [3] the acceleration integrates to zero when the laser-electron interaction proceeds to infinity. The presence of a boundary limits the laser beam interaction with the electron beam and allows for non-zero energy exchange of the field with the electrons [4].

A high resolution 90° bending magnet located downstream of the laser-electron interaction region was employed to observe the energy spectrum of the electron beam. Since the electron beam was not optically bunched the electron beam was spread over all possible laser optical phases and hence the laser-driven particle acceleration effect manifested itself as an increase of the energy spread of the electron beam in the presence of the laser beam. *Figure 2* shows the observed electron bunch energy broadening at optimum overlap with the laser beam.

We present three measurements that confirmed the behavior expected from theory. We confirmed the validity of the Lawson-Woodward Theorem and verified the expected dependence of the modulation on the laser electric field strength and the laser polarization angle. The Lawson-Woodward Theorem was verified by taking two successive laser time scans, one with the boundary in place and the following with the tape moved out. As shown in *Figure 3* broadening of the energy spread was only observed when the boundary was present.

The Electric Field Strength dependence was verified by measuring the average modulation strength at different laser beam pulse energies. *Figure 4a* shows that energy modulation varies linearly with the incident laser electric field as expected from theory and shows no significant offset from the origin. The solid line is the linear fit of the experimental data and the dashed line is the average modulation from the model. The horizontal dashed line indicates the noise floor limit. The expected peak energy gain at the maximum laser pulse energy is 12 keV, corresponding to 24 keV peak energy modulation. As shown in *Figure 4a* the observed average modulation at maximum laser power is 14 keV, about ½ of the expected maximum modulation, confirming good agreement with the expected modulation strength. *Figure 4b* shows the observed average energy modulation as a function of laser polarization, which is found to be in good agreement with the expected dependence on polarization angle. The solid line is the cosine fit of the experimental data and the dashed line is the noise floor limit. The observed strong dependence on the laser polarization angle rules out plasma based acceleration mechanisms as significant contributors to the observed energy modulation.

IFEL experiments

The IFEL undulator was originally designed as part of an optical microbuncher for the E-163 laser acceleration experiments set to begin in fall of 2005. The HEPL-SCA linac operates at half the energy of the accelerator for E-163, so the IFEL interaction takes place at higher order. The undulator is also designed with an adjustable gap that allows further tuning of the interaction, as well as scanning over multiple resonances. The

undulator has three periods, 1.8 cm periodicity, and fields of ~0.3-0.9 Tesla depending on the gap height.

Preliminary results of the IFEL gap scan are shown in *Figure 5a*. Results come from 165 runs with scattered gap height values, placed in 0.2 mm bins and averaged with errors indicating the standard error of the mean for each bin. The peaks visible in *Figure 5b* can be identified as the 5th, 6th, and 7th orders of the IFEL interaction. Simulation also indicates that the 4th order is visible as a long spread out tail between 8 and 11 mm in gap height. As the gap height increases, the rate of change of the magnetic field is less since the electron beam is closer to one set of poles.

Accelerator structure development

Photonic crystal structures appear as having the potential to meet all the requirements for an optical accelerator structure. By introducing a linear defect into a photonic crystal lattice, an optical frequency within the band gap can be guided entirely in the defect, even with speed-of-light phase velocity. We have been exploring two types of photonic crystal structures that we intend to test at E163 in the future. One of them is the three-dimensional "woodpile"-based planar structure, shown in *Figure 6a*. Another type of structure under investigation is the photonic crystal fiber (PCF) shown in *Figure 6b*. For both these structures, development is underway of a method for coupling sufficient laser power into the structures to drive an experimental test. At the same time we are investigating the effects of fabrication error in order to determine the fabrication tolerance for an experimental structure.

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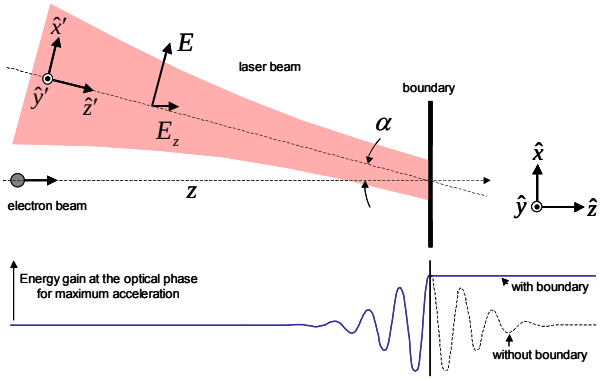

FIG 1: The laser beam, electron beam and boundary configuration

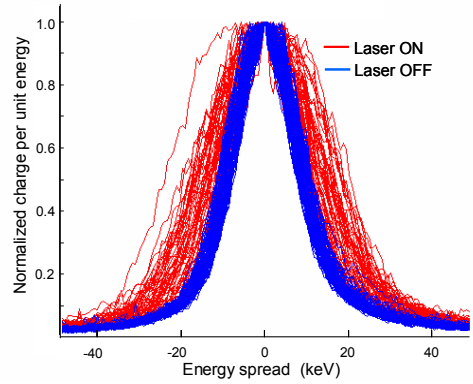

FIG 2: Oserved laser-driven energy modulation

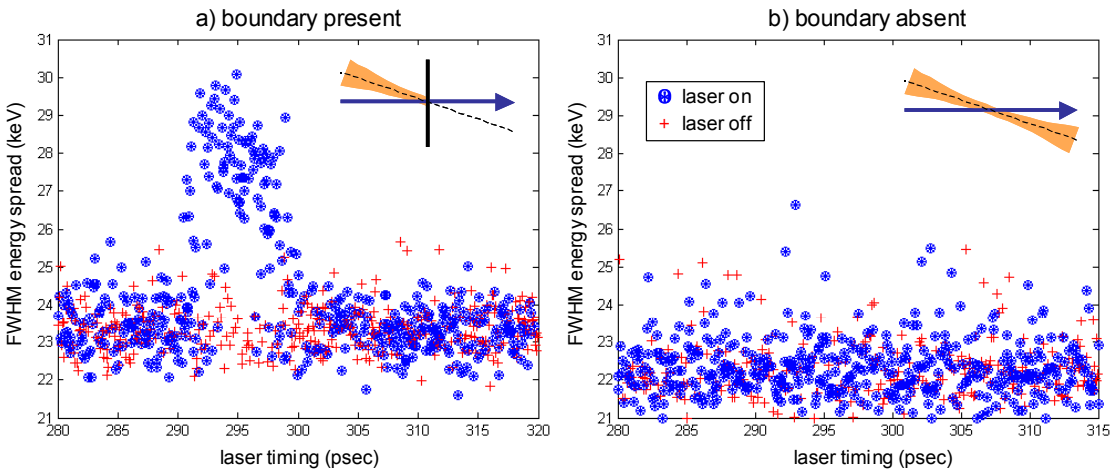

FIG 3: The experimental confirmation of the Lawson-Woodward Theorem

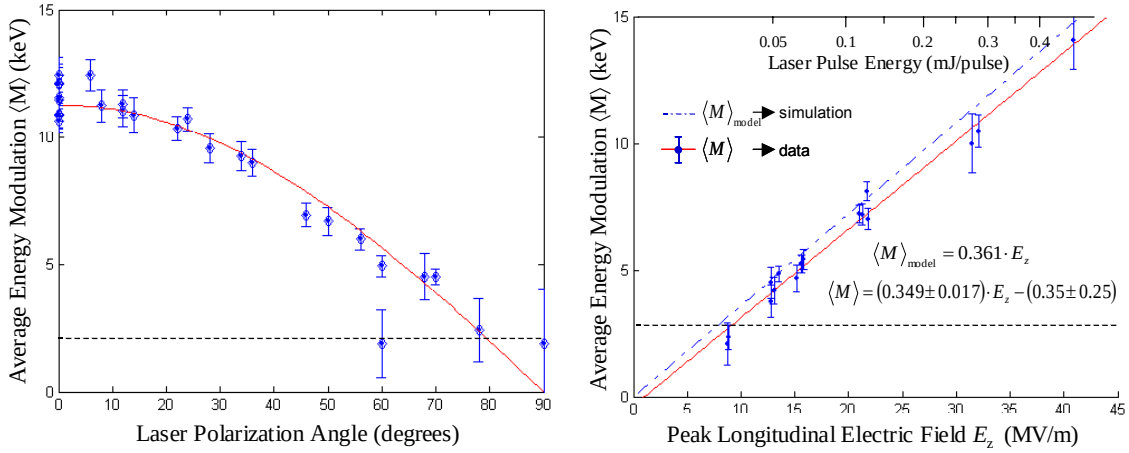

FIG 4: a) Dependence of $\langle M \rangle$ on E_z. b) Dependence of $\langle M \rangle$ on the polarization angle.

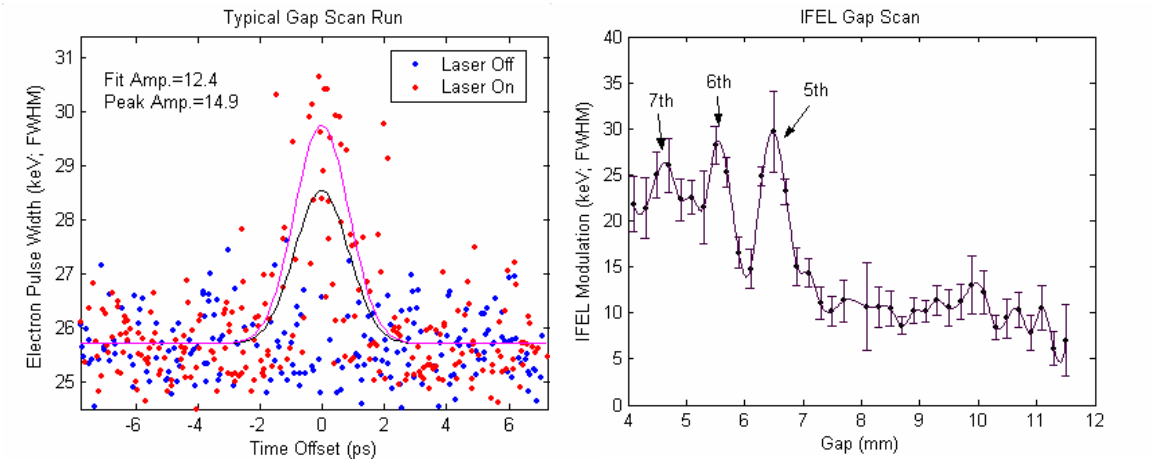

FIG 5: a) Example run from IFEL gap scan. b) Preliminary data for IFEL gap scan. Visible are 3 harmonics of the interaction: the 5th, 6th, and 7th.

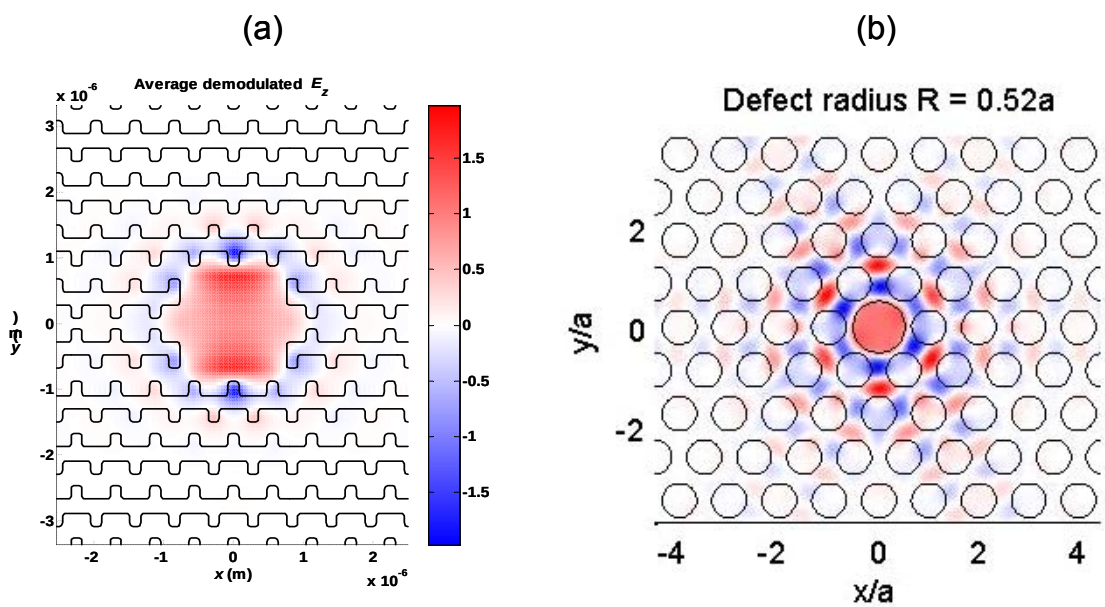

FIG 6: a) cross-section of a photonic band gap woodpile structure displaying the longitudinal component of the electric field. b) cross-section of a photonic bandgap fiber displaying the longitudinal component of the electric field in the hollow waveguide channel

Staged Electron Laser Acceleration - Laser Wakefield (STELLA-LW) Experiment

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Summary

The Staged Electron Laser Acceleration – Laser Wakefield (STELLA-LW) experiment is the progeny of the highly successful STELLA experiment. STELLA was the first experiment to demonstrate 1) staging between two laser-driven accelerators in which the electrons from the first device are rephased with the laser field in the second device, 2) high trapping efficiency (up to 80%) in which the electrons from the first device are efficiently grouped together for collective acceleration in the second device, and 3) monoenergetic acceleration in which the grouped electrons are all accelerated with nearly the same energy gain. These capabilities are vital for development of a practical laser-driven electron linear accelerator (laser linac). Such a laser linac has the potential to be much more compact than conventional microwave-driven accelerators. Much higher total electron energies are also feasible because of the extremely high acceleration gradients of laser accelerators (>1 GeV/m). Thus, a laser linac has possible applications in high-energy physics, industry, medicine, and academia.

STELLA used inverse free electron lasers (IFELs) for the laser-driven device. STELLA-LW will utilize laser wakefield acceleration (LWFA) for its mechanism. LWFA is capable of much higher acceleration gradients than IFELs and has more favorable scaling characteristics. Hence, the aim of the STELLA-LW program is to apply the same basic approaches developed during STELLA to LWFA. Moreover, this is the first time a CO_2 laser will be used to drive the LWFA process rather than a solid-state laser.

In LWFA, an intense laser pulse with an ultrashort pulse duration is sent into a plasma. The plasma density has been selected so that there is a resonant interaction with the laser pulse, thereby creating longitudinal wakefields trailing behind the pulse. These wakefields consist of electrons within the plasma grouping together to create plasma waves with wavelength λ_p. These waves can travel at nearly the speed of light. This means relativistic electrons can "ride" these waves and be accelerated to high energies.

In general, the pulse lengths from CO_2 lasers have not been short enough or, equivalently, the peak power has not been high enough to drive the LWFA process. The CO_2 laser at the Brookhaven National Laboratory Accelerator Test Facility (ATF), where the STELLA experiment was performed, is capable of generating close to a 1 TW peak power. It is being upgraded to eventually produce 2-3 TW. These are among the highest peak powers available in the world. Nevertheless, this is still not quite high enough to create longitudinal wakefields via the typical methods employed by solid-state lasers.

The STELLA-LW program has devised two new variations of the LWFA process to circumvent this limitation of the ATF CO_2 laser. The first is called seeded self-modulated laser wakefield acceleration (seeded SM-LWFA) and the second is called pseudo-resonant LWFA. Both of these new methods not only enable using the CO_2 laser, but they also may provide a means for permitting better control of the wakefield phase. Control of the phase is important for resynchronizing the accelerated electrons with the wakefields in multiple LWFA acceleration stages.

Figure 1 depicts the basic scheme for seeded SM-LWFA. Rather than have the laser pulse initiate the wakefield formation, an ultrashort electron beam (*e*-beam) pulse acts as a seed causing wakefields to trail behind it. These wakefields are amplified by the laser pulse, whose peak follows shortly after the seed *e*-beam pulse. This amplification process is a self-modulated one whereby the wakefields and laser field interact in a nonlinear fashion. As the wakefields grow in strength they cause a modulation of the laser field envelope; hence, this is referred to as self-modulated LWFA. A second *e*-beam pulse follows the seed pulse and provides witness or production electrons that can be accelerated by the amplified wakefields. Hence, this scheme requires dual *e*-beam pulses.

A sample model prediction for the process shown in *Figure 1* is given in *Figure 2*. Without the presence of the seed *e*-beam pulse, the laser field envelope is Gaussian in shape. With the seed pulse generating wakefields, the SM-LWFA process begins to build up leading to modulation of the laser field envelope as seen in *Figure 2*. *Figure 2* also shows an example of the witness *e*-beam pulse.

A noteworthy advantage of seeded SM-LWFA is that the wakefields start from the seed pulse and not from noise, which is the case for traditional SM-LWFA driven by an ultrashort laser pulse. This may permit better control of the wakefield phase while still providing the high acceleration gradients of traditional SM-LWFA.

As illustrated in *Figure 1*, the length of the witness pulse overlaps many wakefields. This means depending on where in the wakefield phase the witness electrons lie, they will experience differing amounts of either acceleration or deceleration. This results in a modulation of the energy of the witness electrons as shown in the model prediction given in *Figure 3*.

The second scheme, pseudo-resonant LWFA, avoids the need for dual *e*-beams. The arrangement is identical to *Figure 1,* but without the seed *e*-beam pulse. Instead it relies on nonlinear interaction of the laser pulse with the plasma causing pulse steepening of the tail end of the laser pulse. This is demonstrated in the model simulation for pseudo-resonant LWFA shown in *Figure 4*. Without the nonlinear interaction with the plasma, the laser pulse shape is Gaussian. With the interaction with the plasma, the pulse amplitude increases and the trailing edge drops faster. This steepening effectively makes the laser pulse have the characteristics of a shorter pulse. Thus, this portion of the laser pulse is able to resonantly interact with the plasma to generate the wakefields seen in *Figure 4.*

The plasma source for both schemes will be a capillary discharge. This technology has been well developed by other researchers. Capillary discharges are able to produce a parabolic plasma density profile (see *Figure 1*) that allows guiding the laser beam over distances longer than its Rayleigh length. This is important for maintaining high laser intensity over long plasma lengths.

One type of capillary discharge, which STELLA-LW intends to use, is where hydrogen gas is injected into the capillary to serve as the medium for the plasma. This gas-filled capillary has the advantages of permitting easier control of the plasma density by adjusting the amount of gas injected into the capillary and having more durable characteristics. *Figure 5* is a photograph of the gas-filled capillary fabricated for the STELLA-LW experiment. The capillary diameter is 0.5 mm and is <5 mm in length. Gas is injected in the middle of the capillary through a side port indicated at the top of the photograph.

Recent Accomplishments

The STELLA-LW program is in the process of preparing to perform its experiments. Hence, recent accomplishments are related to these preparations. These accomplishments include 1) development and modeling of two new schemes for LWFA – seeded SM-LWFA and pseudo-resonant LWFA, 2) demonstration of dual *e*-beam generation by the ATF linac, 3) demonstration of pulse compression of the seed *e*-beam pulse, 4) development of a capillary discharge model to assist in the design of the capillary, and 5) fabrication of a gas-filled capillary specifically designed for the STELLA-LW experiment.

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6. W. D. Kimura, *et al*., *Laser Wakefield Acceleration Driven by ATF CO_2 Laser (STELLA-LW)* in Advanced Accelerator Concepts, Jun. 21-26, 2004, Stony Brook, NY, AIP Conference Proceedings No. 737, V. Yakimenko, Ed., (American Institute of Physics, New York, 2004), p. 534-540
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Staged Electron Laser Acceleration - Laser Wakefield

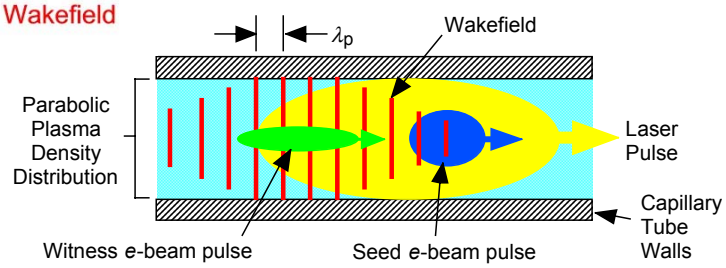

Fig. 1. Basic scheme for seeded SM-LWFA in a capillary discharge. Pseudo-resonant LWFA uses the same scheme, but without the seed *e*-beam pulse.

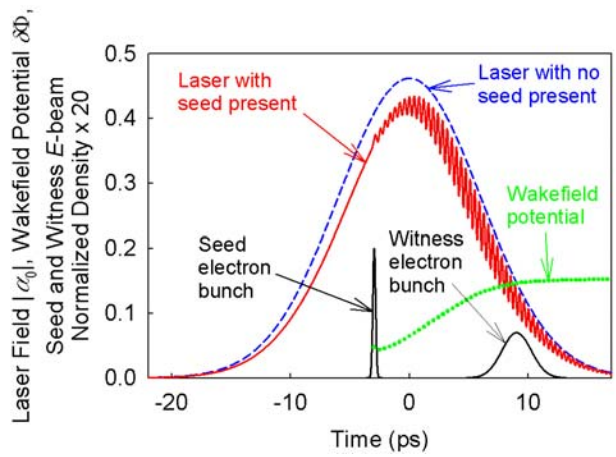

Fig. 2. Sample model prediction for seeded SM-LWFA. Plotted are the laser field parameter $a_0(r = 0)$, wakefield potential $\delta\Phi(r = 0)$, and an example of the witness *e*-beam pulse position.

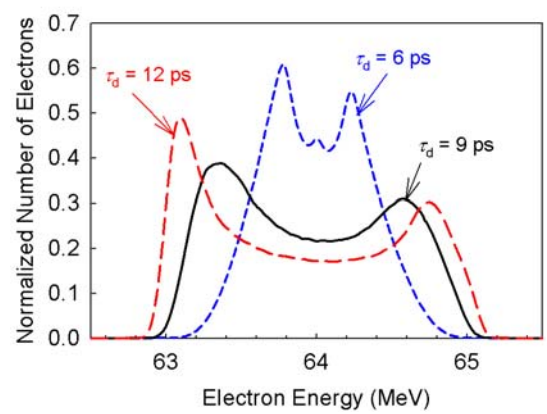

Fig. 3. Model prediction for electron energy spectrum of witness *e*-beam pulse shown in Fig. 2 as a function of time delay between the seed and witness *e*-beam pulses. The plasma acceleration length is 2 mm, mean energy of the seed *e*-beam is 64 MeV, and laser peak power is 0.5 TW.

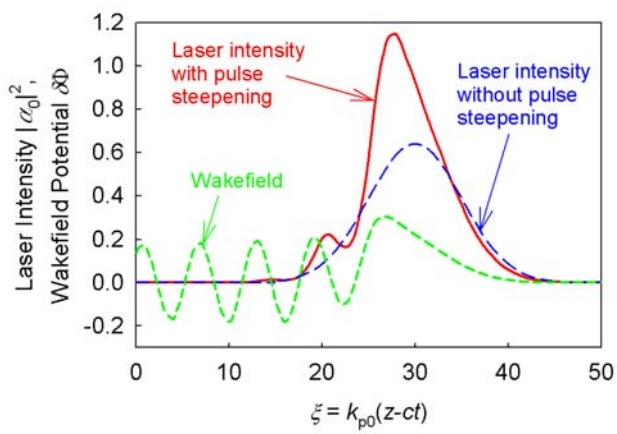

Fig. 4. Sample model prediction for pseudo-resonant LWFA. Plotted are the laser pulse intensity (with and without the pulse steepening effect) and change in wakefield potential $\delta\Phi$ on axis at propagation distance z = 5.5 cm into the plasma versus the dimensionless coordinate $\xi = k_{p0}(z - ct)$, where $k_{p0} = (4\pi e^2 n_e/m)^{1/2}/c$, e = electron charge, n_e = plasma density, m = electron mass, and c = speed of light.

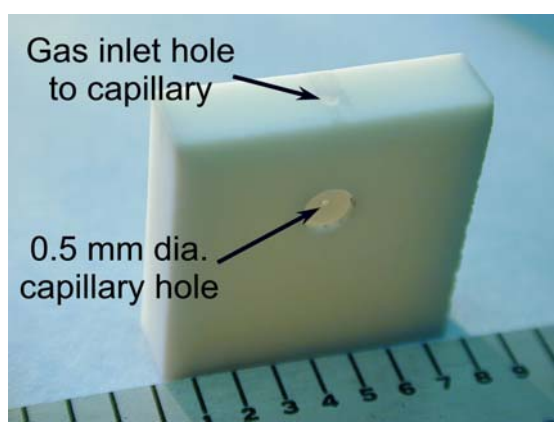

Fig. 5. Photograph of machinable ceramic block showing 0.5 mm entrance hole drilled for the gas-filled capillary discharge.

Development of electro-optical detection for the temporal characterization of sub-picosecond electron beam bunch

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Summary

During the past decade, various electron accelerators around the world have created relativistic electron beam bunches with unprecedented short duration into the subpicosecond regime. These accelerators included the Accelerator Test Facility (ATF) and the Source Development Laboratory at the Brookhaven National Laboratory. These and other electron injectors such as SLAC, DESY, and TESLA are essential for the future high-energy electron-positron colliders proposed as drivers for new femtosecond x-ray FELs. To optimize these electron injectors it is necessary to measure the single subpicosecond electron bunch length accurately in real time. Often nondestructive and noninvasive methods are preferred so that they introduce minimum interfere to the routine operation of the accelerator. In this program we develop a novel, single-shot, nondestructive method of determining the electron bunch longitudinal profile using an optical technique called electro-optical flash (EO-flash) detection. Our approach would convert the ultrashort density profile of the electron bunch in time to the spatial intensity distribution of an ultashort light pulse. The resolution of this optical technique is limited only by the inherent response of the EO crystal in tens of femtoseconds.

A relativistic electron beam produces an anisotropically directed, radially extended Coulomb field orthogonal to the electron beam direction shown in *Figure 1*. Thus the relativistic contracted Coulomb field provides an accurate representation of the longitudinal charge distribution in a beam bunch. When this ultrashort Coulomb beam field traverses a birefringent crystal, the refractive index ellipsoid is modulated and an optical phase shift is introduced. This time dependent changes in the birefringence at different spatial location can be probed by focusing a synchronized femtosecond light pulse to a line focus on the EO crystal. Using a pair of crossed polarizer, this induced optical phase shift is converted to an intensity variation along the line focus. Therefore the temporal shape of the electron bunch is transformed to a spatial intensity distribution on a linear CCD detector array, hence EO-flash technique, illustrated in *Figure 2*. The timing jitter between the laser pulse and the electron beam bunch can be observed as a shift of the spatial intensity distribution. When the width of the laser line focus is longer than the sum of the electron bunch length and the timing jitter, this single shot EO-flash technique can tolerate a large amount of timing jitter. The temporal resolution of the measurement system is limited by the laser pulse duration and the thickness of the EO crystal inasmuch they determine the extent of the electron bunch beam motion during the time that the laser light is passing through the crystal. The experiment is to be done at the Accelerator Test Facility (ATF) in Brookhaven National Laboratory. A 45 MeV electron beam in a bunch length of ~0.5 picosecond with a single bunch charge of up to 250 pC will be focused to a beam size of ~ 200 μm in diameter. The electron beam field is then analyzed by a thin 10x10x0.25 mm ZnTe <110> single crystal.

Recent Accomplishments

Laser source

At the ATF facility, the rf photoinjector light pulse is 6 ps long which is much longer than the anticipated 0.5 ps electron beam bunch to be measured using the EO technique. In order to characterize a sub-picosecond electron beam a sub-picosecond light pulse is required. We have identified a femtosecond Yb-glass laser oscillator at the ATF as the photon source in our EO detection scheme. The synchronization of the electron beam and the light pulse has been achieved by phase-locking the master rf clock at the ATF to the Yb-glass femtosecond laser.

This passively mode-locked laser emits at the center wavelength of 1.05 μm with an average optical power of 100 mW at the repetition rate 81 MHz in a pulse duration 210 fs FWHM. Therefore it has 1.2 nJ/pulse with a peak power of ~6 kW/pulse. Using a Pockels cell a single pulse was successfully sliced out of the phase-locked pulse train to be used for EO measurements, see *Figure 3*. Although this single light pulse alone has sufficient photons and was measured on a conventional line scan camera in a line focus condition, see *Figure 4*, after passing through crossed polarizer, the number of residual photons drops to <10 on each pixel element. Highly sensitive single photon detection, such as a gated intensified CCD array would be needed to recover the EO signal. Therefore, effort is being made and necessary equipment are constructed to amplify the light pulse from 1 nJ to ~10 μJ using one or two stages fiber amplifiers.

The ATF facility at the Brookhaven National Laboratory is presently considered upgrading the photoinjector system. We will be using a portion of the synchronized light output extracted from this system for the EO-flash detection experiment. The front end laser driver is a femtosecond Yb:YAG laser oscillator followed by 2 stages of fiber amplifier utilizing the large core fiber technology, see *Figure 5*. The output power after the first stage amplifier will be extracted for the EO-flash experiment. This 50 μJ IR light pulse in 200 picosecond duration will then be compressed to its original pulse width of 210 femtosecond, frequency doubled to the visible spectrum and sent to the EO measurement station. A gated, intensified, CCD camera and/or a conventional line scan camera will be used to collect the spatial intensity distribution. Image subtraction with and without the electron beam will be utilized to obtain the electron bunch length information.

Test of EO-flash scheme

In preparation for the EO-flash detection of sub-picosecond electron beam bunches, the validity of the optical design shown in Figure 2 was tested at the Instrumentation division at BNL. The light source was an amplified 250 femtosecond Ti:sapphire laser system running at the center wavelength of 800 nm. The light output was attenuated to 2-50 μJ/pulse for use in this experiment. The synchronized electron beam field was simulated by applying a 2-50 ns pulsed high voltage of up to 0.5 kV across a pair of parallel electrode plates. A <110> ZnTe crystal was placed between the plates so that a time dependent birefringence could be produced in the EO crystal. Because the temporal width of the simulated electron beam field is much larger than the light pulse, instead of a line focus the laser beam was unfocused on the EO crystal. After a pair of crossed polarizers, the extinguished beam was recorded on a conventional CCD camera. Single images with and without pulsed high voltage were captured on an 8-bit video frame grabber. After image subtraction, the beam field induced spatial image was clearly revealed, left images shown in Figure 6. The line graphs of the column sum of each images is plotted on the right side of Figure 6. An un-extinguished beam was observed propagating through the crossed polarizers due mostly to the residual birefringence of the EO crystal, while the non-Gaussian like spatial beam profile is a result of a mixture of the residual birefringence and the quality of the ZnTe EO crystal. These results clearly suggest that for pulse width measurements relying on the temporal to spatial transformation, not only the spatial quality of the light pulse is important, good optical quality of the EO crystal is also essential. Furthermore, the scheme required ~μJ/pulse of light intensity to achieve reliable signal after image subtraction, hence single light pulse emitting directly from a laser oscillator may not be adequate for temporal characterization. Also, because the temporal information depends on images subtraction an intensified CCD with >12-bit of dynamic range would significantly improve the SNR.

Optical technique based on EO modulation has the potential to greatly advance micro-bunch diagnostics in electron accelerators in a non-destructive manner. Using the well-known techniques in the characterization of femtosecond laser light pulse, femtosecond electron pulse can be completely characterized. One of our goals is to develop this EO-flash diagnostic

arrangement simple and compact enough so that we can transport it easily from one accelerator facility to another for various electron bunch length measurements.

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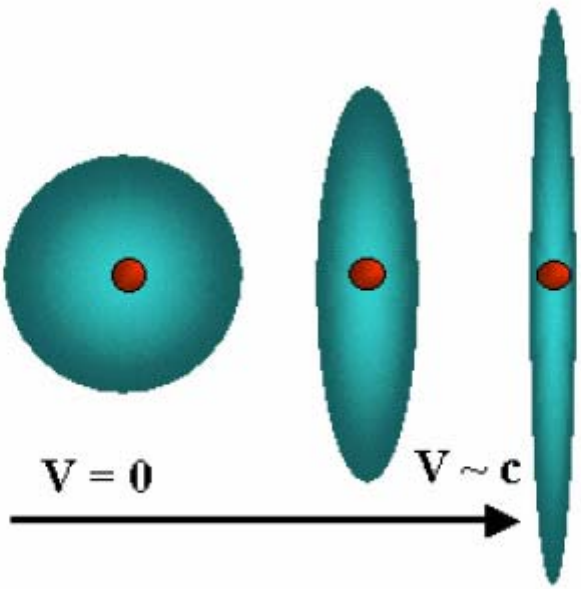

Fig. 1. E-field after Lorentz contraction

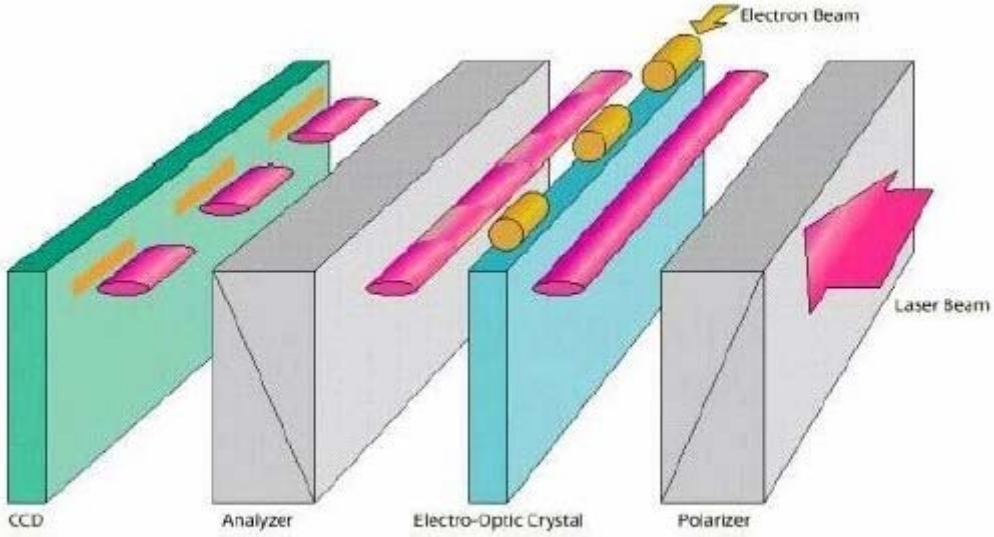

Fig. 2. Schematic of the EO-flash technique

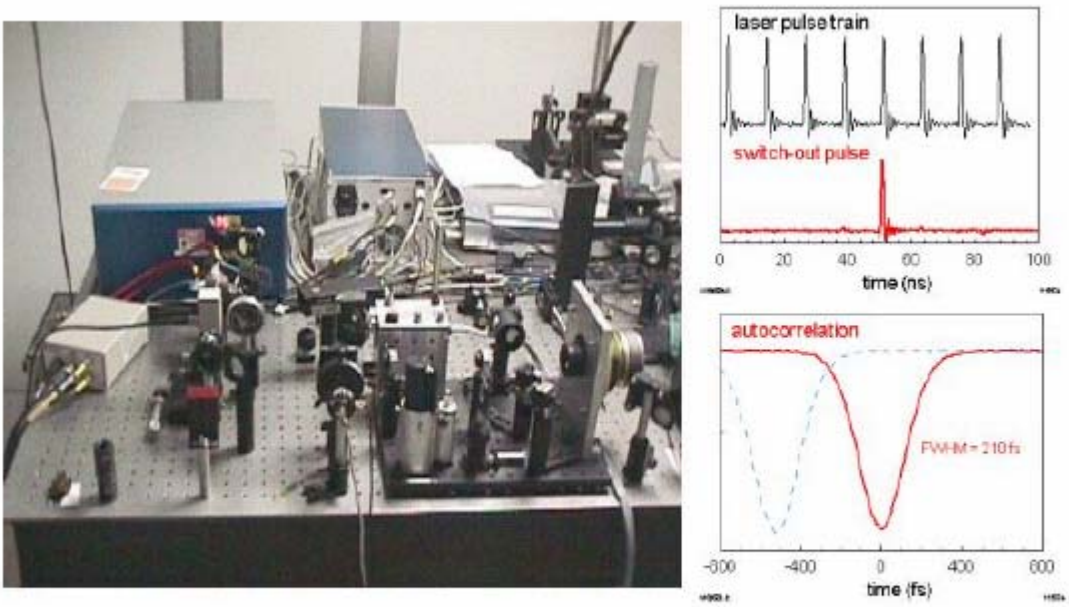

Fig. 3. Yb-YAG glass laser in ATF laser room

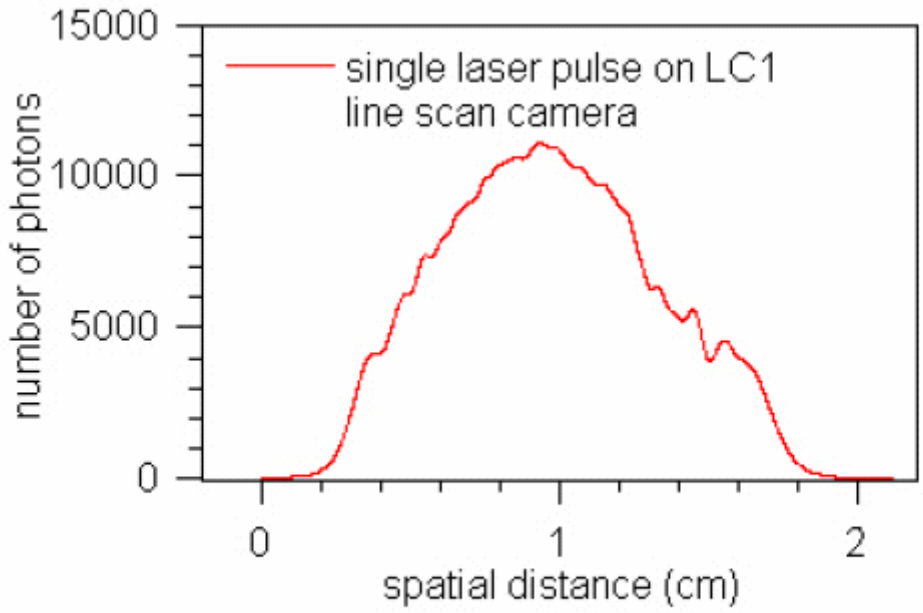

Fig. 4. Test of EO modulation using laser oscillator

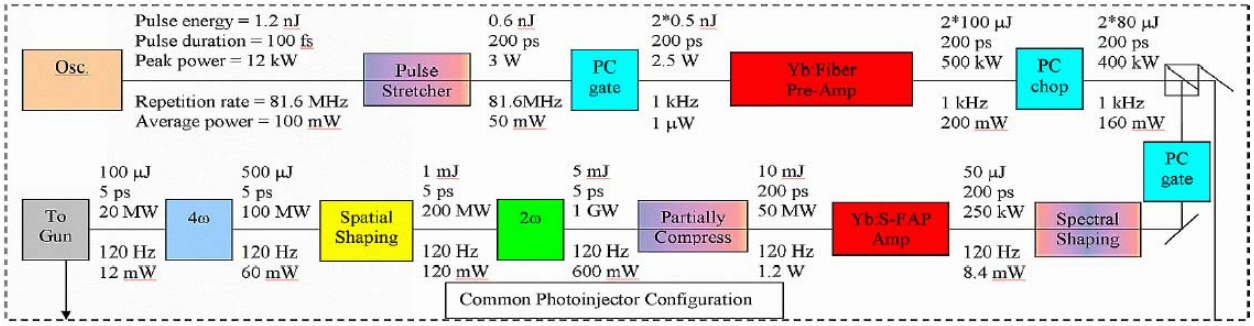

Fig. 5. Upgaded photoinjector configuration at ATF

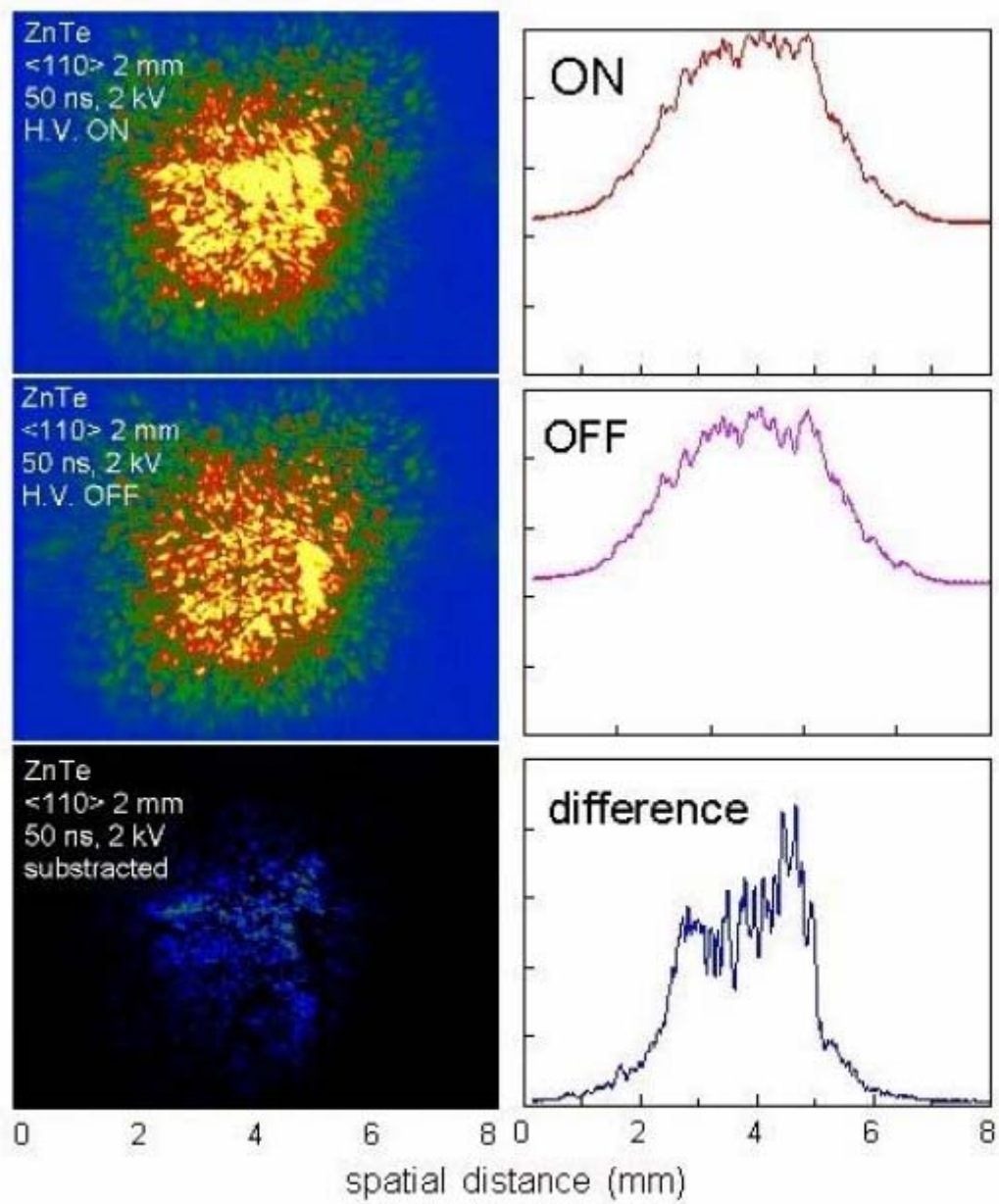

Fig. 6. Test of EO modulation using amplified Ti:sapphire laser

New Technology for Future Colliders

Peter McIntyre
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Summary

The colliders of the future will require major advances in technology if they are to provide the energy and luminosity at affordable cost to support a continuation of the present pace of discovery into the future. The Texas A&M University (TAMU) Accelerator Research Laboratory (http://accelerator.tamu.edu) is developing new technology for superconducting magnets, superconducting cavities, and accelerator device technology.

We are building and testing a sequence of model dipoles employing a new approach to high-field design: block-coil geometry, stress management, conductor optimization, bladder preload, and flux plate suppression of magnetization multipoles. Our development is conducted in a close cooperation with the Lawrence Berkeley National Laboratory (LBNL) Supercon program. We will soon test TAMU2, the latest model of our design. The ultimate objective of the base program is to develop and evaluate TAMU4, a 14 Tesla collider-capable model dipole, which would validate Nb_3Sn technology for the upgrades of Large Hadron Collider (LHC).

Recent Accomplishments

- We recently completed construction of TAMU2, a single-layer coil module to validate the construction details and stress management of the module that will form the building-block of TAMU4.
- We have applied a structured-cable technology, invented here, to a design for a 350 T/m quadrupole that should be capable of operating in the intense conditions of heat and radiation damage for an upgraded high-luminosity intersection region (IR) for LHC.
- Similarly we have devised a design for an 8 T levitated-pole dipole for use in combining and separating the proton beams in an upgraded high-luminosity IR for LHC.
- We are testing a prototype of a compact electrode assembly for installation in the LHC arc dipoles to kill the electron cloud effect, which otherwise could limit luminosity.
- We have developed a design for an extension of the TAMU4 technology to incorporate inner windings of Bi-2212 in a hybrid-coil dipole capable of 24 Tesla. This dipole could provide the basis for a future LHC Tripler in the same tunnel.
- We have designed a polyhedral cavity structure for the superconducting cavities needed for future linac colliders. The polyhedral structure eliminates welds, accommodates surface processing in the final shape, Q-spoils deflecting modes, eliminates Lorentz detuning, and eliminates the need for an immersion cryostat.

The above developments have major potential benefit for LHC and ILC, the two highest-priority endeavors in high-energy research. They also provide an ambitious road towards the dramatic improvements that will be needed if we are to be able to make a further generation of colliders thereafter.

Next steps in development

We are starting to build TAMU3, a two-module dipole with 13.5 Tesla short-sample field. All of the model magnets use the same flux return and outer structural elements. The expansion

bladder assembly technique enables us to remove and replace modules through the planned development sequence of ~4 TAMU3 models and several TAMU4 models. Each succeeding model dipole will be assembled to test a specific element of the overall design strategy – stress management, high-performance conductor, quench strategy, reduction of high-field maximum in coil ends, bending of ends to clear beam tube. This stepwise validation will enable us to learn coherently the best implementation of each element.

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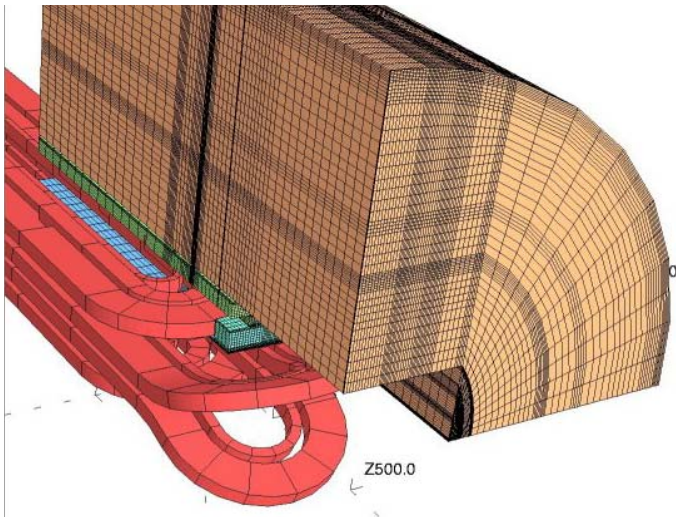
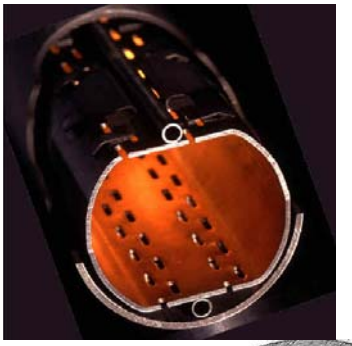
Preparing for lead splicing

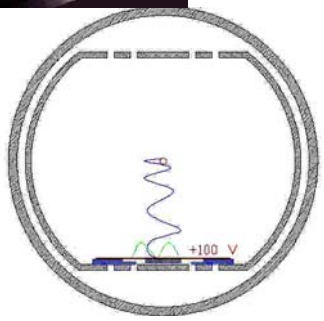
Reaction bake

Installing quench heaters and voltage taps

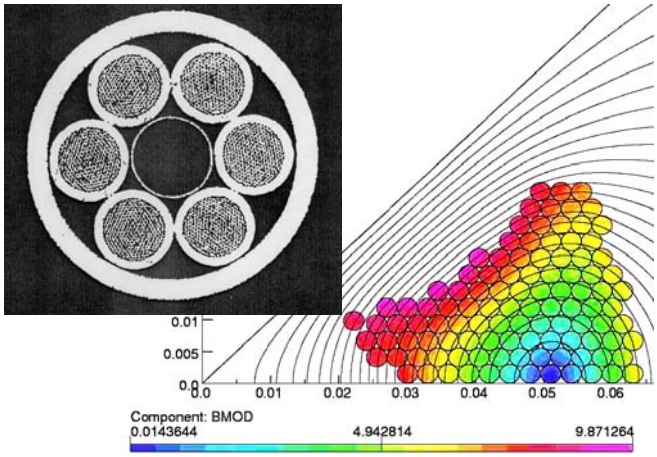


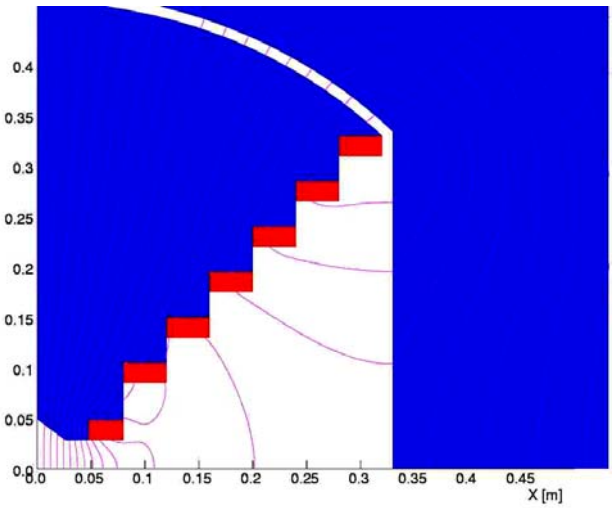


Killing the electron cloud effect in LHC arcs.

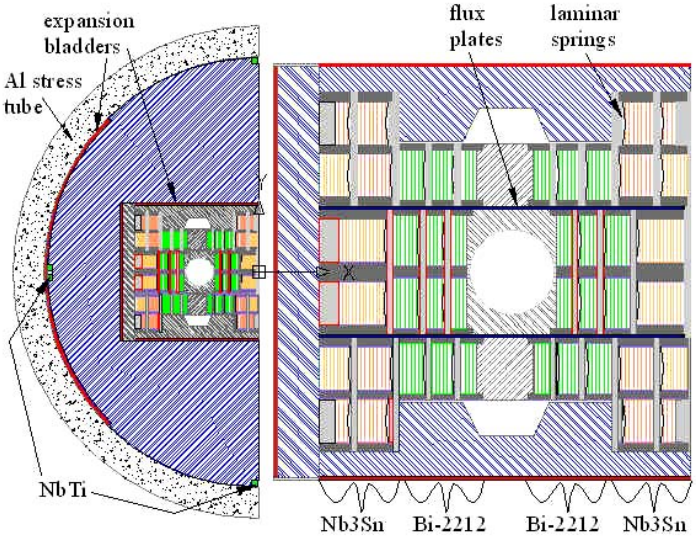


Structured-cable Nb_3Sn quadrupole, 350 T/m for LHC IR

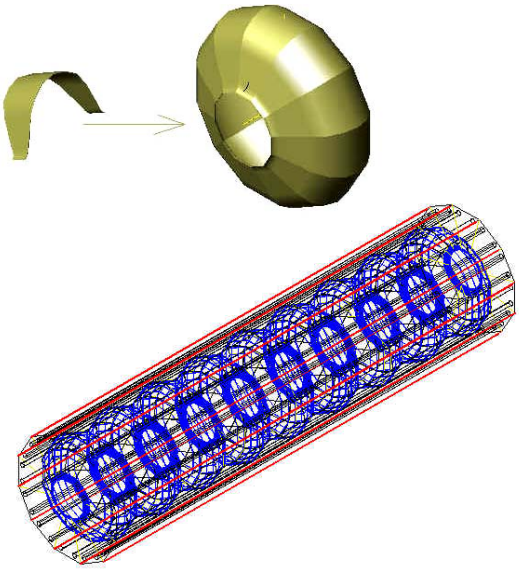


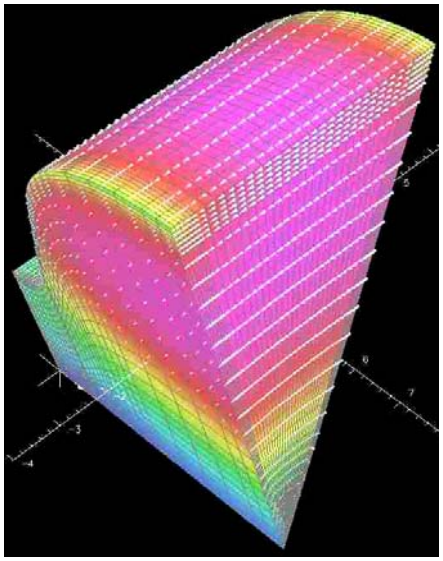


Levitated-pole dipole for beam separation in LHC IR.



24 Tesla hybrid dipole for LHC Tripler.





Polyhedral ellipsoidal superconducting cavity for ILC.

Advanced Accelerator Concepts

Jonathan Wurtele
University of California Berkeley

Summary

The development of a new generation of colliders beyond the Large Hadron Collider (LHC) is a central component of the future of high-energy physics. There is no new approved machine beyond the LHC and no consensus on the optimal path to extend high-energy physics experiments into the multi-TeV energy range, beyond the design-energy upgrade of the International Linear Collider (ILC). Indeed, prospects for high-energy physics may be limited by our ability to build new machines. Looking beyond the ILC, our group explores neutrino factories, muon colliders, plasma-based acceleration, and plasma lenses, waveguides, and other structures.

Our University of California Berkeley (UCB) program in advanced accelerator concepts has close connections with the Center for Beam Physics at Lawrence Berkeley National Laboratory (LBNL). The proximity to LBNL provides an ideal format for the training of graduate students and postdocs. This connection gives the theory graduate students the opportunity to interact with the Center's theory group and to participate in experimental programs. We collaborate closely with Prof. Fajans' experimental nonneutral plasma group at UCB and LBNL. The nonneutral plasma is an ideal medium for the study of a wide range of beam physics. Research on intense muon sources offers the students and postdoctoral researchers the opportunity to work with leading accelerator scientists throughout the world.

Undergraduate research is also an important component of the program. The activities of undergraduates include numerical investigation of the beam quality expected in laser-plasma accelerators with optical injection, Particle-in-Cell simulations of laser-plasma interactions, and pulse dynamics in free-electron lasers. Postdoctoral researchers have developed collaborations with accelerator physicists working on next generation Free Electron Laser light sources.

Our group is investigating concepts for the manipulation of six-dimensional beam phase space, in both non-conservative systems, such as ionization cooling of intense muon beams, and Hamiltonian systems such as beam conditioning for free-electron lasers. The muon beams are used in both neutrino factories and muon colliders. There are significant challenges in the production, cooling, acceleration (and, for the collider, collision) of the intense muon bunches. As part of this research, we developed a system of moment equations that capture the important physics of ionization cooling: energy loss, stochastic scattering and angular momentum generation in material, acceleration by radio frequency (RF) cavities, and focusing in solenoidal magnets. Application of this formalism greatly speeds up cooling channel design. We are investigating optical stochastic cooling for muons. Optical stochastic cooling, if it can be made to work, could yield muon beam emittances significantly smaller than can be achieved with ionization cooling. This, coupled with other innovations, could allow for increasing luminosity without increasing muon flux. Another avenue of research into phase-space manipulations concerns the autoresonant excitation of nonlinear BGK-like modes in non-neutral plasmas (or beams). By applying external drives of appropriate amplitude and chirped frequency, "holes,'' or charge-density perturbations, in particle phase space can be excited, which persist long after the drive is removed, while oscillating coherently in space. Theoretical analyses using a simplified kinetic model as well as experimental investigations using an electron Malmberg-Penning trap are ongoing.

A major thrust of our research is in plasma-based accelerating structures and lenses. We proposed a modified version of the Plasma Beat-Wave Accelerator scheme, based on autoresonant phase-locking of the nonlinear Langmuir wave to the slowly chirped beat frequency of the driving lasers via adiabatic passage through resonance. This new scheme is designed to overcome some of the well-known limitations of previous approaches, namely relativistic detuning and nonlinear modulation or other non-uniformity or non-stationarity in the driven Langmuir wave amplitude, and sensitivity to frequency mismatch due to measurement uncertainties, density fluctuations and inhomogeneities. As in previous schemes, modulational instabilities of the ionic background ultimately limit the useful interaction time, but nevertheless peak electric fields at or approaching the wave-breaking limit seem readily attainable. Compared to traditional approaches, the autoresonant scheme achieves larger accelerating electric fields for given laser intensity, or comparable fields for less laser power; the plasma wave excitation is much more robust to variations or uncertainties in plasma density; it is largely insensitive to the precise choice of chirp rate, provided only that chirping is sufficiently slow; and the quality and uniformity of the resulting plasma wave and its suitability for accelerator applications may be superior. In underdense plasmas, the total frequency shift required is only of the order of a few percent of the laser carrier frequency, and for possible experimental proofs-of-principle, the scheme might be implemented with relatively little additional modification to existing systems.

We have continuing studies on the generation of slow wakes in magnetized plasmas. These wakes, driven by high-frequency microwave sources, could be used to accelerate ions. The wakes are generated by electromagnetic induced transparency (EIT) in magnetized plasmas. In this concept, transparency of a resonant electromagnetic wave is created and controlled by application of a pump electromagnetic wave, detuned by the plasma frequency. The effect is clearly seen in the one-dimensional PIC simulations and analyzed theoretically; we further show the electromagnetic pump can be replaced by a static wiggler. The wiggler-based system can be used to excite accelerating fields with controllable phase velocity and a gradient >20 MeV/m. The analogy between atomic and plasma EIT has become clearer with the development in the group of a unified approach to analyzing both systems. Another novel idea that arises from the study of electromagnetic pulse propagation in magnetized plasmas is the concept of magnetic resonance waveguides. Here we envision guiding microwaves in homogeneous plasmas using spatially varying magnetic fields.

As part of fundamental radiation-electron beam studies, we derived a maximum-power variational principle applicable to classical spontaneous radiation from prescribed harmonic current sources. Results are first derived in the paraxial limit and generalized to non-paraxial situations. The techniques were developed within the context of undulator radiation from relativistic electron beams, but are more broadly applicable.

Recent Publications

1. R. R. Lindberg, A.E. Charman, J.S. Wurtele and L. Friedland, *Robust autoresonant excitation in plasma beat-wave accelerator,* Phys. Rev. Lett. 93:055001 (2004)
2. L. Friedland, F.Peinetti, W. Bertsche, J. Fajans, and J. Wurtlele, *Driven phase space holes and synchronized Bernstein, Greene, and Kruskal modes ,* Phys. Plasmas 11, 4305 (2004)
3. M.S. Hur, J.S. Wurtele, G. Shvets, *Simulation Of Electromagnetically And Magnetically Induced Transparency In A Magnetized Plasma*, Phys. Plasmas **10**, 3004 (2003)
4. R.R. Lindberg, A.E. Charman, J.S. Wurtele *Comparison Of The Laser Wakefield Accelerator And The Colliding Beam Accelerator*, in Proceedings of the 10'th Advanced

Accelerator Concepts Workshop (AAC 2002), Mandalay Beach, California, 23-28 Jun 2002. Published in AIP Conf. Proc. 647, 727-736 (2003)
5. G. Shvets, J.S. Wurtele, and M.S. Hur, *Applications Of Magnetized Plasma To Particle Acceleration*, in Proceedings of the 10th Advanced Accelerator Concepts Workshop (AAC 2002), Mandalay Beach, California, 23-28 Jun 2002. Published in AIP Conf. Proc. 647, 681-689 (2003)
6. G. Penn, P.H. Stoltz, J.R. Cary, and J. Wurtele, *Boris Push With Spatial Stepping*, J.Phys. G29, 1719-1722 (2003)
7. M.S. Hur, J.S. Wurtele, and G. Shvets. *Simulation of electromagnetically and magnetically induced transparency in a magnetized plasma*, Phys. of Plasmas 10, 3004-3011 (2003)
8. M.M. Alsharoa et al. (Muon Collider/Neutrino Factory Collaboration). *Recent progress in neutrino factory and muon collider research within the muon collaboration*. Phys. Rev. ST Accel. Beams 6, 081001 (2003)
9. Min Sup Hur, Gregory Penn, Jonathan S. Wurtele, and Ryan Lindberg, *Slowly varying envelope kinetic simulations of pulse amplification by Raman backscattering* . Phys. Plasmas 11, 5204 (2004)
10. W. Cheng, Y. Avitzour, Y. Ping, S. Suckewer, N. J. Fisch, M. S. Hur, and J. S. Wurtele, *Reaching the Nonlinear Regime of Raman Amplification of Ultrashort Laser Pulses*, Phys. Rev. Lett. 94, 045003 (2005)
11. Wolski, G. Penn, A. Sessler, and J. Wurtele, *Beam conditioning for free electron lasers: Consequences and methods,* Phys. Rev. ST Accel. Beams 7, 080701 (2004)
12. V. Gorgadze, T.A. Pasquini, J. Fajans, and J.S. Wurtele. *Injection into electron plasma traps. In Non-Neutral Plasma Physics* V, M. Schauer et al. (eds.). AIP Conf. Proc., no. 692, pp. 30-39 (2003)
13. R.R. Lindberg, A.E. Charman, and J.S. Wurtele*. Robust autoresonant excitation in the plasma beat-wave accelerator: a theoretical study.* physics/0403081
14. A.E. Charman, J.S. Wurtele, *A Hilbert-space formulation of and variational principle for spontaneous wiggler radiation* physics/0501018
15. J.S. Wurtele et al. (Committee on High Energy Density Plasma Physics, Plasma Science Committee, National Research Council*). Frontiers in High Energy Density Physics: The X-Games of Contemporary Science.* The National Academies Press, Washington, DC, 160 pp. (2003)

Recent Graduates

Cameron Geddes (Ph.D., Physics, UCB, Wim Leemans, research advisor) Currently a term scientist at LBNL.

Current Staff

Wurtele, J.S.	PI
Peinetti, F.	Visiting Scientist (Univ. of Turin)
Gomberoff, K.	Visiting Scientist (Rafael)
Charman, A.	Graduate Student (Ph.D., Physics, UCB)
Gogardze, V	Graduate Student (Ph.D., Physics, UCB)
Lindberg, R.	Graduate Student (Ph.D., Physics, UCB)
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Rebaum, J.	Undergraduate Researcher
Vinokurov, Y	Undergraduate Researcher

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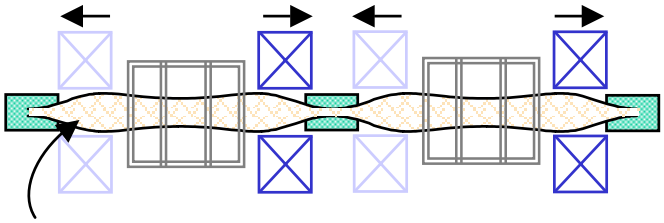
Autoresonant excitaion of beatwaves in CO2 and Ti-Sa systems. The excitation is robust to density errors as seen below the CO2 system has ~10GV/m fields with 20% density variation and the Ti-Sa system has ~200GV/m fields with 35% density variations. The primary limit is created by ion instabilities.

Controlling and utilizing correlations in beam phase space is important for radiation generation and muon cooling. A muon cooling channel (L) and FEL conditioning (R).



Advanced Accelerator Physics Research at UCLA

David Cline
University of California Los Angeles

Summary

The Advanced Accelerator Physics Research at the University of California Los Angeles (UCLA), under the direction of Professor David Cline, is mainly concerned with advances in accelerator physics for novel colliders and high gradient particle accelerators. The components of the research program include various experiments at the Brookhaven National Laboratory (BNL) Accelerator Test Facility (ATF), muon cooling and its possible uses in ring coolers, neutrino factories and a Higgs Factory Muon Collider, fast-timing (10 ps resolution) trigger systems for future muon cooling experiments, continuing participation in MUSCAT at TRIUMF leading to Muon Ionization Cooling Experiment (MICE), and studies at the Stanford Linear Accelerator Center (SLAC) Final Focus Test Beam (FFTB) involving optical diffraction radiation detectors for linear colliders. The program is carried out at the major U.S. particle beam facilities (BNL, Fermi National Accelerator Laboratory (Fermilab), and SLAC) and at TRIUMF in Canada. The advanced concepts investigated include beam monitors, beam focusing systems, novel accelerating systems, ring coolers, muon cooling, fast-timing trigger systems, and the design of a neutrino factory and a Higgs factory muon collider. The UCLA group has pioneered the concept of 6D ring coolers for the neutrino factory and muon collider. The research program is rich in providing training and hands-on experience to graduate students and postdoctoral trainees in accelerator physics.

Recent Accomplishments

- First demonstration of high-trapping efficiency and narrow energy spread in the staged electron laser acceleration at the Staged Electron Laser Acceleration (STELLA-II); and the results were published at Phys. Rev., Lett., and PRST-AB.
- Measurements at BNL of the wakefield effects from surface roughness of the beam tubes on the energy spread increase and energy loss of the electron beam. This has application to the International Linear Collider and X-ray Free Electron Laser efforts. Results are published in Phys. Rev. Lett., 89, No. 17 (2002).
- Successful running of the Compton Scattering Experiment at the BNL ATF. 1.7×10^8 photons/pulse were observed using a 14 GW laser and a 60 MeV electron beam.
- Significant progresses on the STELLA-LW: Seeded Self-Modulated Laser Wakefield Acceleration (Seeded SM-LWFA); and pseudo-resonant Laser Wakefield Acceleration (LWFA). UCLA is responsible for manipulations of ultra-short and ultra-small double e-beams within one RF bucket and plays a key role in the on-going integrated experiments.
- Successful feasibility study for the novel vacuum laser acceleration by using a tightly focused laser beam. The requirements to demonstrate the novel vacuum laser acceleration (VLA) proof-of-principle experiment at BNL-ATF are investigated. Modeling of the laser-electrons interaction using ATF practical parameters is conducted. The experiment layout and its diagnostics are proposed and designed.
- Successfully observed and characterized the second harmonic of Thomson x-ray scattering; submitted it to Phys. Rev. Lett., 2005.
- Successfully reconstructed transverse phase spaces of a beam at magnetic bunch compression at 60 MeV using tomography. First observation of transverse phase space bifurcation of a compressed beam at the energy; to be submitted to Phys. Rev. Lett., 2005.

- The invention of the quadrupole (UCLA) Ring Cooler (A. Garren and other members of the UCLA team). This will be a key device for muon colliders in the future.
- The Higgs Factory Study (D. Cline and G. Hansen).
- The development (with FNAL) of a Fast-Timing Trigger System (to 10 ps) for MuCool.
- Participation in the engineering run of the E875 experiment at TRIUMF to measure the scattering of muons off low Z targets. The UCLA group constructed a fast scintillator system for particle separation of the pions, muons and electrons in the beam.
- Formation of an International R&D Group to work on the Optical Diffraction Radiation beam size monitor for the Linear Collider which is proposed to do the beam test at the SLAC FFTB line; proposal of an experiment at the FFTB.

STELLA-II and STELLA-LW

UCLA is a major member of the STELLA-II program team, led by Wayne Kimura of STI Optronics. STELLA-II has successfully achieved its primary goal of demonstrating mono-energetic laser acceleration and high-trapping efficiency, as shown in *Figure 1*. In addition, UCLA led the beam dynamics analysis of fs microbunch produced at STELLA-II and defined the beam operating conditions; the result is published in Phys. Rev. Special Topics-AB, 2003.

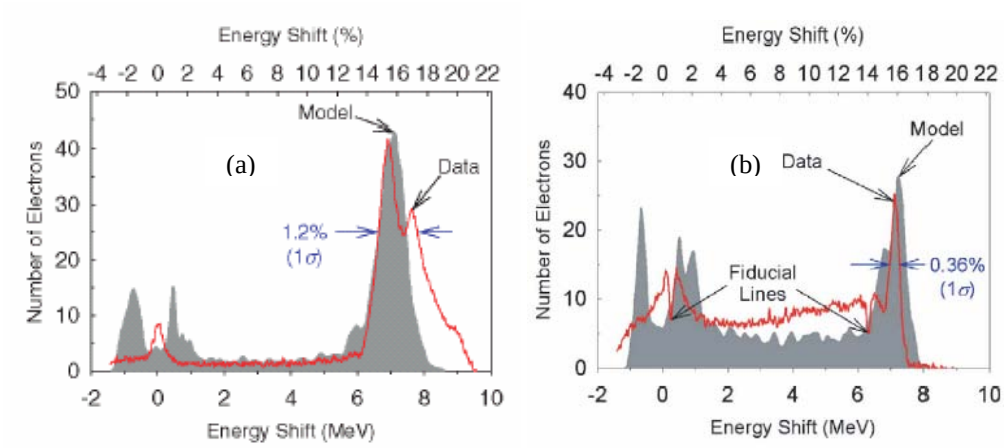


Figure 1: Experimental results at STELLA-II

The major goals of the continuing program, Staged Electron Laser Acceleration-Laser Wakefield (STELLA-LW), are to demonstrate both the seeded SM-LWFA and pseudo-resonant LWFA. Both experiments are investigating the issues of making controllable wakes, but using very different approaches. The seeded SM-LWFA experiment is to use sub-ps seed electron beam to generate weak wakefield in plasma, which is amplified with the following 10-ps CO_2 laser which is already available at the ATF, and then use the witness e-beam to probe the wakefield. The pseudo-resonant LWFA uses 2-ps CO_2 laser to excite significant wakefield in capillary discharge-created plasma. UCLA leads one of the challenging subjects for these programs: manipulate, characterize and transport the ultra-short and ultra-tiny double electron beams with <10 ps separation. UCLA also plays key role in the on-going integrated experiments.

Vacuum Laser Acceleration Experiment

UCLA leads the proof-of-principle experiment test of novel VLA, which was theoretically discovered by Fudan University in China. The VLA model revealed that the injection electrons with low energy (5-20 MeV) and small incident angle ($\tan(\theta)$~0.1) relative to the laser

propagation can be captured and significantly accelerated (CAS) in a strong laser beam ($a_0 \geq 4$), and also keep moving with laser wave for a long distance. The CAS predicts the energy gain can be up to a few GeV with laser intensity $a_0 \sim 100$. We used the BNL-ATF TW CO_2 laser and high-brightness electron beam to test it. The program is divided into two phases to simplify the experiment conditions: Phase I is to demonstrate Poneromotive potential acceleration using a tightly focused laser as a precursor of the CAS; Phase II is to demonstrate the real CAS slightly modifying the experimental setup at Phase I. Extensive simulations for PPM and CAS show ~5 MeV can be expected by interacting a tiny ATF TW-CO_2 laser beam ($a_0 \approx 5$) with electron beam. Requirements for the experiments are investigated extensively. Experiment setup and diagnostics are shown on the montage.

Neutrino Factory and Higgs Factory Muon Collider Project

a) E875: Study of Muon Scattering at TRIUMF

UCLA took part in the engineering run of the E875 experiment at TRIUMF in June and July of 2000 to measure the scattering of muons off low Z targets. UCLA contributed with the construction of a fast scintillator system for particle separation of the pions, muons, and electrons in the beam, with onsite preparation and shift taking at TRIUMF, and with post-experiment data analysis. In the ongoing post-experiment, analysis of a few 150 MeV/c momentum runs of the data so far has shown that the resolution was degraded by backgrounds. Most of the UCLA analysis effort has been focused on understanding the scattered events in the data of the Delayed Line Wire Chambers. The experiment has been restructured and a new run has been scheduled for April/May 2003.

b) Development of Ring Coolers for Neutrino Factories as Muon Colliders

The UCLA group has been a leader in the study of ring coolers for 6D coolers. Starting at the 2001 Snowmass, where Al Garren proposed a quad ring cooler to the present study of a Li lens and dipole ring cooler, we have shown that these rings can give a powerful 6D cooling. We are currently studying the use of such coolers for a muon collider. We believe this is a key step for general 6D cooling even for a broader system such as proton cooling.

c) Bunch Stacking and Final Cooler

A group from UCLA has worked on a new muon cooling scheme for the design of the Higgs Factory in which muon mini-bunches out of the front-end channel of the neutrino factory are stacked transversely into a single cooled muon bunch by using two additional storage rings which are placed between the initial acceleration section and the second acceleration section. A larger ring (150 meters circumference) contains all the muon mini-bunches which are transversely cooled through a Lithium lens in the ring. A smaller ring (30 meters circumference) is used to stack the muon mini-bunches transversely. Initial simulation studies on these two rings were done with the linear simulation code with a Lithium lens in a larger ring for the transverse phase space cooling. Work is in progress to simulate the muon bunch-stacking scheme with the exact ray tracing code.

d) Study of Neutrino Factory Storage Ring

The activities covered included neutrino factory Fixed Field Alternating Gradient accelerator and storage ring designs, and ways to use such a factory as the basis for a muon collider facility.

e) Fast Timing Work at FNAL

UCLA continued this past year to participate in the muon cooling project at Fermilab with a goal to develop a fast timing system with 10 picosecond accuracy. Two vacuum chambers (the detector enclosure) were designed and built and other parts of the fast timing detector

assembled. A test set-up was built to measure the transparency of the MgF_2 radiator, the attenuation of light by Cr film, and the efficiency of the CsI photo-cathode.

Select List of Published Papers: List of Published Papers (2003-2005)

1. H. Kirk et al, "A compact ring for the 6D cooling of a muon beam," Proceedings of the 2005 Particle Accelerator Conference, Knoxville, Tennessee, May 2005
2. F. Zhou, R. Agusstson, G. Andonian, I. Ben-Zvi, D. Cline, et al., "Experimental Characterizations of Transverse Phase Spaces of a Beam Through a Magnetic Bunch Compressor at a Medium Energy," to be submitted to Phys. Rev. Lett., 2005
3. F. Zhou, D. Cline, et al., "Manipulations of double electron beams within one rf period for seeded SM-LWFA," presented at PAC05, Knoxville, 2005
4. F. Zhou, R. Agusstson, G. Andonian, I. Ben-Zvi, D. Cline, et al., "Experimental characterizations of 4-d transverse phase-space of a compressed beam," presented at PAC05, Knoxville, 2005
5. L. Shao, D. Cline, and F. Zhou, "Novel vacuum laser acceleration by using a tightly focused laser beam," presented at PAC05, Knoxville, 2005
6. W. Kimura, N. Andreev, M. Babzien, I. Ben-Zvi, D. Cline, C. Dilley, S. Gottschalk, S. Hooker, K. Kusche, S. Kuznetsov, I. Pavlishin, I. Pogorelsky, A. Pogosova, L. Steinhauer, A. Ting, V. Yakimenko, A. Zigler, and F. Zhou, "Pseudo-resonant laser wakefield acceleration driven by 10.6 microns laser light," IEEE Transactions on Plasma Science, Feb. 2005
7. F. Zhou, D. Cline, L. Shao, "Proposal of experimental test for a novel VLA at the ATF," AAC04, 2004
8. W. Kimura, M.Babzien, I.Ben-Zvi, L.P.Campbell, D.B.Cline, C.E.Dilley, J.C.Gallardo, S.C. Gottschalk, K. Kusche, R.H. Pantell, I. Pogorelsky, D. Quimby, J. Skaritka, L. Steinhaur, V. Yakimenko and F.Zhou, "Demonstration of high-trapping efficiency and narrow energy spread in a laser-driven accelerator," PRL 92, 054801(2004)
9. W. D. Kimura, M.Babzien, I.Ben-Zvi, L.P.Campbell, D.B.Cline, et al., "Detailed experimental results for high-trapping efficiency and narrow energy spread in a laser-driven accelerator," PRST-AB, 2004
10. F. Zhou, D. Cline and W. Kimura, "Preservation of femtosecond microbunches produced by laser accelerators," Phys. Rev. ST-AB, 6, 054201(2003)
11. F. Zhou, et al., "Vacuum laser acceleration by using tightly focused laser," PAC03
12. W. Kimura, M.Babzien, I.Ben-Zvi, L.P.Campbell, D.B.Cline, C.E.Dilley, J.C. Gallardo, S.C. Gottschalk, K. Kusche, R.H. Pantell, I. Pogorelsky, D. Quimby, J. Skaritka, L. Steinhaur, V. Yakimenko and F. Zhou, "Demonstration of high-trapping efficiency and narrow energy spread in a laser-driven accelerator," PAC03, Portland, 2003
13. Y. Fukui et al, "A muon cooling ring with curved Lithium lenses," Proceedings of the 2005 Particle Accelerator Conference, Knoxville, Tennessee, May 2005
14. Y. Fukui et al, "Beam test proposal of an ODR beam size monitor at the SLAC FFTB," Proceedings of the 2005 Particle Accelerator Conference, Knoxville, Tennessee, May 2005

Current Staff

Prof. David B. Cline	PI Investigator	Dr. Kevin Lee	Postdoctoral Associate
Dr. Yasuo Fukui	Asst. Res. Physicist	Mr. Xiaofeng Yang	Elec. Dev. Engineer
Dr. Alper Garren	Res. Physicist	Dr. Feng Zhou	Asst. Res. Physicist

Current Graduate Students

Shao Lei Ph.D. Student

Past Graduate Students

Patrick Kwok	Masters of Science, March 1996, job unknown.
Vidia Kumar	Masters of Science, June 2000, job unknown.
Yabo Liu	Ph.D., Sept. 1997, Pharo Science & Applications, Inc. Current job: PWARE, Inc.
Ping He	Ph.D., June 2004 Current job: BNL Physicist

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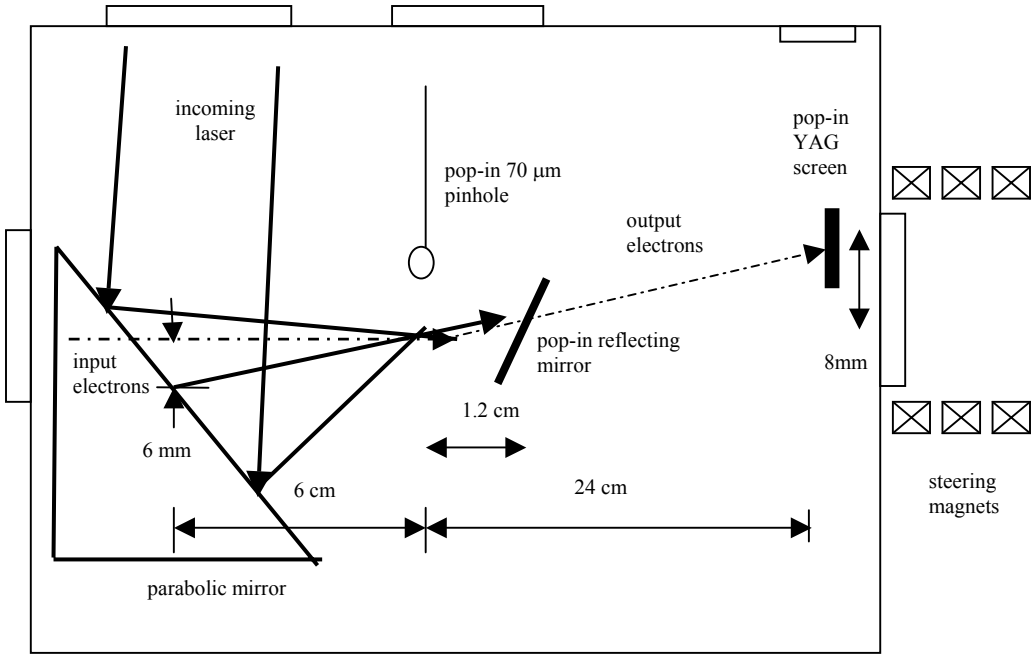
Schematic layout of the VLA experiment



Experimental, Theoretical and Computational Studies of Plasma-Based Concepts for Future High-Energy Accelerators

Chan Joshi, PI
Co-P.I.s: Professor W. B. Mori, C. E. Clayton
University of California Los Angeles

Summary

The University of California Los Angeles (UCLA) Plasma Accelerator Group has continued leading the effort on Advanced Accelerator Concepts in 2004. Notable successes include the first demonstration of Multi-GeV acceleration using the Stanford Linear Accelerator Center (SLAC) beam, a high gradient Inverse Free Electron Laser (IFEL) accelerator with the Rosenzweig/Pellegrini Group, and the successful implementation of several state-of-art computer modeling codes.

Recent Accomplishments

There have been many significant accomplishments on both the experimental front and on the theory/simulation front in the past years. The most notable among these are:

(a) The first demonstration of greater than 1 GeV energy gain in a plasma wakefield accelerator. The E164X experiment, carried out by groups from UCLA, University of Southern California (USC) and SLAC, demonstrated a maximum of 4.5 GeV energy gain in an ~ 15 cm long lithium plasma. This work culminated a five year research effort by this collaboration at SLAC, the goal of which was to demonstrate greater than 1 GeV energy gain in less than one meter using a plasma accelerating structure. These results are published in Physical Review Letters, Vol. 95, 054802 (2005).

(b) In the Neptune laboratory, the main accomplishment has been the demonstration of relatively high gradient acceleration of electrons using a TW class, CO_2 laser beam co-propagating through a strongly tapered undulator using the IFEL scheme. This work was carried out in collaboration with the Rosenzweig/Pellegrini group. These results were also published in Physical Review Letters, Vol. 94, 154801 (2005).

(c) On the theory/simulation side the main accomplishment has been the completion of several codes, OSIRIS, Turbowave and QuickPIC. QuickPIC in particular has been instrumental in our ability to be able to model in full 3D, the E164X and the upcoming E167 experiments at SLAC. It has also been used to model the E-cloud problem in circular machines. The code OSIRIS has been used to model and understand the laser wakefield acceleration experiments carried out at Rutherford, LOA and Lawrence Berkeley National Laboratory (LBNL). In particular, using OSIRIS to model the propagation of multi-TW class pulses through plasma channels, we were able to identify the mechanism that leads to self-trapping and eventual production of a quasi-monoenergetic accelerated electron beam. These results were published in Physical Review Letters, Vol. 93, 185002 (2004).

Current Work

Presently, this group is focusing most of its efforts on pushing the Plasma Wakefield Accelerator scheme as far forward as possible before the Final Focus Test Beam (FFTB) shuts down at SLAC in 2006. A new experiment, E167 designed to extend the energy gain of the SLAC beam to 10 GeV and to explore the electron beam hosing instability has been approved and it

currently underway. The SLAC shutdown during most of 2004 has had an unfortunate negative impact on this program but it is now scheduled and is in fact underway.

In Neptune present work is on a nonlinear Compton scattering experiment designed to detect the laser vector potential dependent frequency shift of the Compton scattering photons. The work is of interest to an eventual laser-based Compton scattering induced polarized positron source for a future collider.

Publications 2004-Present

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3. S. Ya. Tochitsky, R. Narang, C. V. Filip, P. Musumeci, C. E. Clayton, R. B. Yoder, K. A. Marsh, J. B. Rosenzweig, C. Pellegrini, and C. Joshi ," Experiments on Laser Driven Beatwave Acceleration in a Ponderomotively Formed Plasma Channel, "Physics of Plasmas, Vol. 11, (5), pp. 2875-2881, May (2004)
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Theoretical and Experimental Studies in Accelerator Physics

James Rosenzweig and Claudio Pellegrini
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Summary

The activities on this grant encompass the research interests of Profs. James Rosenzweig and Claudio Pellegrini. The on-campus work is based on the Neptune photoinjector/MARS high power CO_2 laser, which hosts basic beam physics (sub-ps beam manipulations and diagnostic) and plasma and laser acceleration programs. In addition to this on-campus program, which is a part of the larger Neptune collaboration with Prof. C. Joshi of UCLA Electrical Engineering (who directs the plasma beatwave experimentaa program), both PI's have off-campus experimental programs partially or fully supported by this grant at BNL, FNAL, LLNL, Frascati and SLAC.

Some of the highlights of the PBPL research from 2003 to 2005 include:

- The first phase I PBWA proposed experiments were completed, with over 40 MeV energy gain observed over a few cm of plasma, in a joint EE/Physics experiment published in *Physical Review Letters.* This work found strong 2D effects in the plasma beatwave, and also explored non-resonant excitation of the plasma by the EM beatwave.
- A new chicane commissioned at Neptune, and was used for experiments on pulse compression, including emittance growth in bends. These experiments uncovered a phase space bifurcation mechanism, published as the first *Physical Review Letter* from the Neptune lab.
- The a double-tapered inverse-free-electron laser (IFEL) experiment was built and performed at Neptune was studied, and an built. It has succeeded in accelerating electrons from 14.5 MeV to over 35 MeV, and shown unexpected physics results, such as the observation of higher harmonic undulator resonances. The results have been published in *Physical Review Letters*.
- A high demagnification underdense plasma lens experiment has been completed at FNAL A0 photoinjector, resulting in beam intensity enhancements of over 50. Asymmetric beam focusing measurements of high relevance to linear collider final focus systems have been performed. These results are now being submitted to *Physical Review Letters*.
- The concept of velocity bunching, in the form of ballistic bunching at Neptune and phase space rotation at LLNL, has been experimentally tested. This type of bunching has been proposed as an alternative to magnetic chicanes, as one may avoid beam quality-degrading effects. Velocity bunched beams were used at PLEIADES for ICS brightness enhancement. This work, along with velocity bunching simulation studies for the SLAC ORION Center, has been published in *PRST-AB.*
- The production of ultra-small spot sizes using a tunable (by precise change of longitudinal position) triplet based on very high-strength permanent magnet quadrupole (PMQ) was tested at LLNL. This final focus system was used in an inverse Compton scattering (ICS) experiment, PLEIADES. This innovative approach to small beam spot production is being extended for use in ramped beam pulse shaping, and related plasma wakefield experiments. This work has been published in *PRST-AB*.
- "Negative R_{56}" dogleg compression work on creating ramped beams/witness beams for use in wakefield acceleration experiments at Neptune has been developed. This work has led to the successful development of sextupole correction scheme for linearization of longitudinal

transformations, which was experimentally tested at Neptune. This scheme has been extended to the ATF, and is proposed for ORION. Results of the Neptune and off-campus work have been published *PRST-AB*. The use of a tunable PMQ final focus has been will be implemented in this beamline.

- The proposal of using a plasma density transition trapping process in plasma wakefields to produce ultra-high brightness, low energy spread beams was studied published in *PRST-AB*. This led to the development of an ambitious experiment for FNAL A0. A highly successful plasma source (alos used in the underdense plasma lens experiments) which has the sharp density transition needed for these experiments has been developed. The first run on this experiment has been completed.
- A new final focus for the Neptune PBWA phase II experiments using the same PMQs as will be used in the ramped beam final focus has been prototyped. This is a critical component of improvements in the next-generation PBWA experiments, as well as ultra-high field, circularly polarized ICS experiments at Neptune which are beginning in Aug. 2005.
- The INFN/UCLA collaboration on RF deflector development for 10-fs resolution beam measurements at Neptune, SPARC, and ORION has produced S-band and X-band prototypes. Computational studies for longitudinal phase space and slice emittance measurements have been completed. The full RF deflector system at Neptune is now being commissioned.
- The ORION photoinjector was completed at UCLA. Beam dynamics studies for the low energy hall (velocity bunching, dogleg compression) were completed. PBPL has formally joined the E163/LEAP collaboration, and has performed beam dynamics studies for the experiment. These include modeling of the planned observation of dynamically-produced “KV” ellipsoidal beams in the photoinjector.
- A new experiment to demonstrate multi-GV/m wakefields in dielectric structures has been built, with first runs (aiming to observe structure damage and coherent Cerenkov radiation) in Aug. 2005.
- More industrial collaborations have arisen at PBPL. A new type of photoinjector, the hybrid standing/traveling wave structure, has been studied with SBIR industrial partners and, subsequently, INFN researchers. Study of a new type of (old!) device, a fast-cycling fixed-field, alternating gradient betatron has also been recently funded in Phase II by the SBIR program with a partner firm started by ex-PBPL personnel, RadiaBeam Technologies. RadiaBeam, PBPL, and INFN-LNF/Univ. Roma, are now also collaborating on a traveling wave RF deflector for linear collider applications.
- A chicane compressor at BNL has been built and commissioned. Beams have been compressed to to 20 mm rms. First observation of the intensitiy, spectrum and polarization of FIR coherent edge radiation has been accomplished in initial runs. Both longitudinal and transverse phase space distortions due to collective effects have been measured.
- The VISA II experiment has produced results of extremely high FEL bandwidth, benchmarked to start-to-end simulations. Angular effects tied to details of the beam dynamics in the undulator have been explored with a unique double-differential spectrum diagnostic. This experiment serves as another test-bed of sextupole correction of dogleg compressors, and unique photon diagnostics that ultimately provide deep insight into the radiating electron beam phase space.
- Fundamental plasma wakefield theory concerning very high charge plasma response, and an accompanying computational study of scaling to afterburner conditions has been performed. These studies identified previously unexamined magnetic effects that produce a strong “snow-plow” effect. These works are accepted for publications in *PRST-AB*.

- A theoretical comparison between the FEL instability and newly discovered CSR instability, in which the CSR instability exponential gain regime was identified, has been published in *PRST-AB*.

Refereed publications 2003-2005:

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6. "The Effects of Ion Motion in Intense Beam-Driven Plasma Wakefield Accelerators" J. B. Rosenzweig, A. M. Cook, A. Scott, M. C. Thompson, and R. Yoder, submitted to *Phys. Rev. Letters.*
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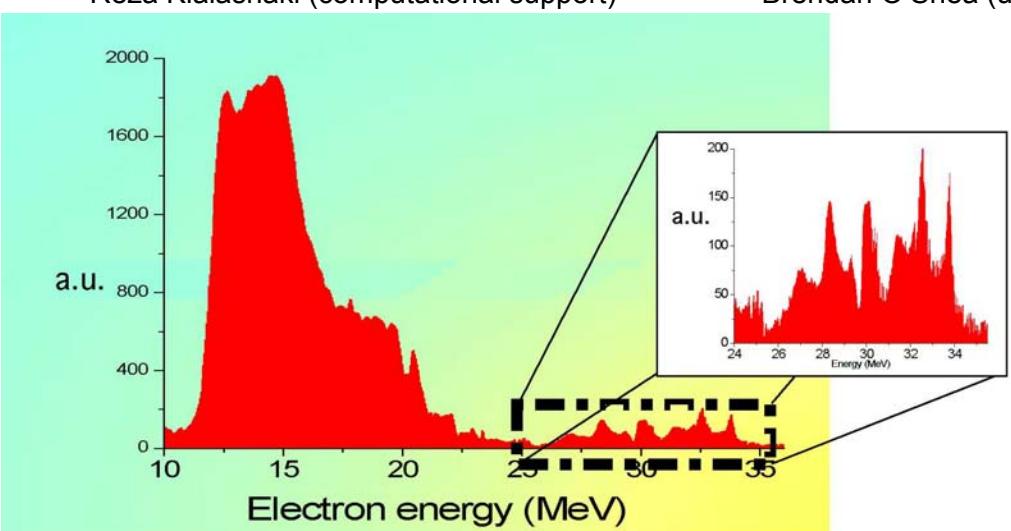
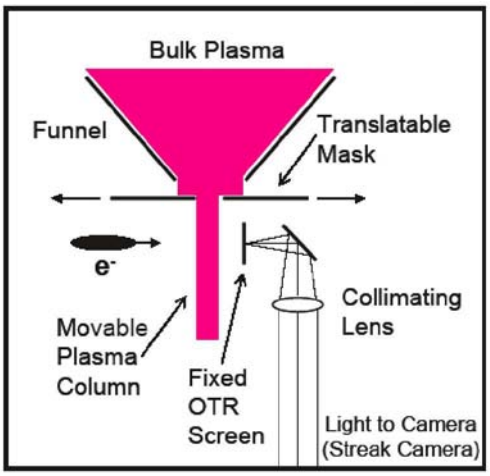
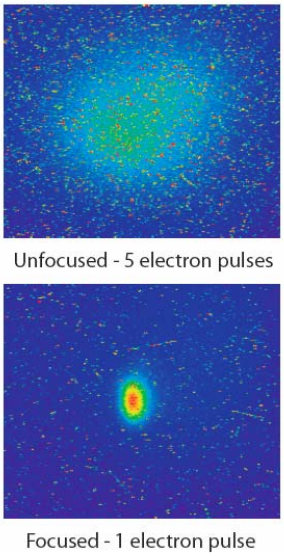
Aaron Cohen (undergraduate)
Brendan O'Shea (undergraduate)

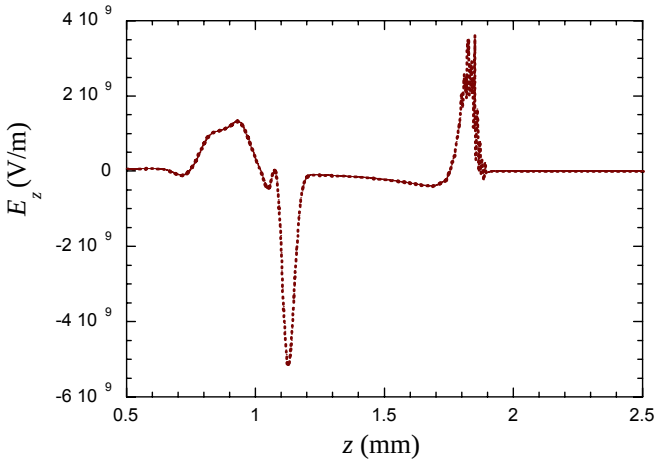


Momemtum spectrum in Neptune IFEL experiment, showing 20 MeV energy gain, and detailed structure due to higher harmonic interactions.

UCLA underdense ($n_b > n_p$) plasma lens experiment at FNAL A0: (left) schematic; (right) beam profiles with and without plasma focusing.

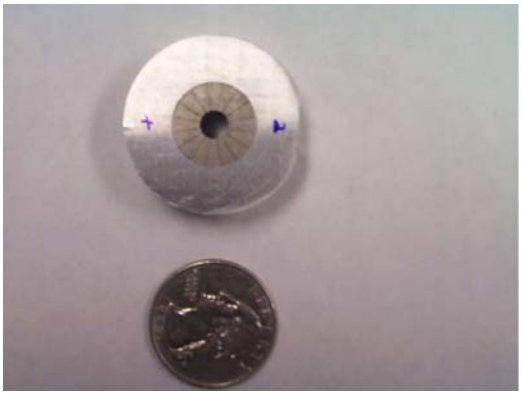






OOPIC simulation of longitudinal wakefield in UCLA/SLAC dielectric wake experiment at the SLAC FFTB.

Strongest quadrupole ever employed in beam optics, made of permanent magnet design at UCLA. These PMQs were employed in ultra-short focal length final focusing system to obtain <20 □m beams at the PLEIADES ICS experiment.



Census of PhD Graduates

Robin	David	UCLA	C. Pellegrini	1991	LBNL	LBNL
Hartman	Spencer	UCLA	C. Pellegrini	1993	SLAC	JT3 Corp.
Travish	Gilbert	UCLA	J. Rosenzweig	1996	UCLA/INFN	UCLA
Colby	Eric	UCLA	J. Rosenzweig	1997	FNAL	SLAC
Zhang	Renshan	UCLA	C. Pellegrini	1997	Hughes Corp.	
Barov	Nikolai	UCLA	J. Rosenzweig	1998	UCLA	Far-Tech
Hogan	Mark	UCLA	C. Pellegrini	1998	SLAC	SLAC
Terebilo	Andrei	UCLA	C. Pellegrini	1998	SLAC	SLAC
Tremaine	Aaron	UCLA	J. Rosenzweig	1999	UCLA	LLNL
Anderson	Scott	UCLA	J. Rosenzweig	2002	LLNL	LLNL
Murokh	Alex	UCLA	J. Rosenzweig	2002	UCLA	RadiaBeam Tech.
Musumeci	Pietro	UCLA	C. Pellegrini	2004	Univ. Roma	Univ. Roma
Thompson	Matthew	UCLA	J. Rosenzweig	2004	UCLA	LLNL
Bishofberger	Kip	UCLA	J. Rosenzweig	2005	LANL	LANL

Chaotic Dynamics in Accelerator Physics

John Cary
University of Colorado

Summary

Our research is currently concentrated in three areas: formation and acceleration of beams in Laser Wake Field Acceleration, mitigation of beam halo formation through use of nonlinear lattices, and development of medium-Q accelerator cavities through use of Photonic Band Gap (PBG) structures. In the recent past we also worked on beam (actually, non-neutral plasma) cooling through application of microwave fields, but that work has been completed and published. Our approach is both analytical and computational. Our computational work at present relies heavily on the VORPAL plasma simulation code, which has a number of unique characteristics, including the ability to select the dimensionality of the simulation at run time, to run in parallel or serial, and exceptional versatility, with the ability to use particles obeying various dynamics and with any number of internal degrees of freedom.

In laser-plasma acceleration, a laser pulse is injected into a plasma. The associated ponderomotive force creates a plasma wakefield that can have very high electric fields. These are subsequently used to accelerate particles. Our work in the area of Advanced Accelerator Concepts has concentrated on the injection and formation of quality beams – from injection into the wakes by optical means through the acceleration.

We have used our simulation capability carry out the first simulations of the colliding pulse injection scheme proposed by Esarey *et al* as well as others proposed later. In any of these schemes, particles are kicked up into the accelerating region of phase space through some physics (beat-wave, ponderomotive kick, wave breaking) associated with the collision of the pulses. Our work showed that the formation of multiple beams, which is undesired, is ubiquitous in these schemes. There can be spontaneous particle injection several accelerating buckets back from the pump pulse, apparently due to breaking of the interacting wakes. We characterized this process in some detail, ultimately showing that a third pulse is needed to eliminate the trailing beamlets. This work was selected for an invited talk at the 2004 Annual Meeting of the Division of Plasma Physics of the American Physical Society.

At the same time, our collaboration with the Leemans group of the Lawrence Berkeley National Laboratory was very successful in showing that one could get single, well-formed beams from the interaction of a single laser pulse with a plasma. This work appeared prominently last year in Nature. Indeed, a visualization of simulation data was on the cover of Nature for that issue, and this was declared one of the top 10 scientific discoveries of 2004.

Since then we have been carrying out extensive simulations of this process over a wide range of parameters in order to elucidate what is happening. We have so far shown that the hosing often seen in the simulations is not key to beam formation. We are now investigating the effects of collisions.

Our work in the area of beam halo generation has been to study the effects of nonlinear transport. Our first studies used the constant focusing model, where the focusing force is taken to be independent of angle and longitudinal displacement. With this model we have shown that nonlinear focusing can mitigate halo formation. The halo is produced by the large transverse

beam oscillations caused by a focusing mismatch. Nonlinear focusing causes the beam oscillations to damp away. Subsequently one can collimate the beam to remove halo particles, and they will not reappear, as the oscillations that produced them are no longer present. Because this is a nonlinear, self-consistent system, we have derived a set of self-consistent equations for a beam in the presence of a nonlinear force, following the work of Davidson et al for linear focusing systems. In the process we have found a new set of nonlinear transport lines with improved integrability, i.e., with significant nonlinear tune shift at the last confined phase-space surface.

Our new work in PBG's has found some cavity structures that do not have problems with higher-order modes. The appended figures show how slight shifts in the PBG structures can greatly reduced the field strength in the region of the dielectrics and so increase the Q of the cavity. It appears that we are able to obtain cavities with Q's much higher than typical for non-superconducting without needing to be at the very cold temperatures like superconducting. This work was presented at the 2005 Particle Accelerator Conference.

Our work is synergistic with other work being carried out in our group and in collaboration with others. In particular, our work on the development of a 3D hybrid (fluid and particle) simulation code, funded primarily by other grants, has proved invaluable to the work carried out under this grant. Without this synergy, we simply would not have 3D simulation capability. Moreover, we have made this capability publicly available to the accelerator community. Moreover, our code has been noted at the national, policy level. It is mentioned in the just released "Report to the President, Computational Science: Ensuring America's Competitiveness."

http://www.nitrd.gov/pitac/reports/20050609_computational/computational.pdf

We are proud of the fact that a large percentage of the students and postdocs educated in our group remain in the field of accelerator physics and science. Of the 9 postdocs and students that have been funded under this program, 8 (89%) are active scientists or mathematicians, while 2/3 remain in accelerator physics. Of those, two are at Department of Energy national labs.

Recent Accomplishments

- Development of the widely used Vorpal simulation code for modeling advanced accelerators and beam propagation in accelerating structures
- Discovery (in collaboration with LBL) of the formation of quality beams from the interaction of a single pulse with a plasma
- Discovery of the ubiquitous nature of beamlet train formation in laser wake fields
- Discovery of an optical injection method that produces a single, well-defined beam
- Discovery of a new, nonlinear lattice that has large dynamic aperture and significant nonlinear tune shift
- Discovery of a method for reducing beam halos

Publications 2003-2005

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2. C. G. R. Geddes, Cs. Tóth, J. van Tilborg, E. Esarey, C. B. Schroeder, D. Bruhwiler, C. Nieter, J. Cary, and W. P. Leemans, “Production of high-quality electron bunches by dephasing and beam loading in channeled and unchanneled laser plasma accelerators,” Phys. Plasmas 12 (5), 056709 (2005)
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9. C. G. R. Geddes, Cs. Toth, J. van Tilborg, E. Esarey, C. B. Schroeder, D. Bruhwiler, C. Nieter, J. Cary, and W. P. Leemans, “High-quality electron beams from a laser wakefield accelerator using plasma-channel guiding,” Nature 431, 538-541 (Sep. 2004)
10. K. Sonnad and J. R. Cary, "Finding a nonlinear lattice with improved integrability using Lie transform perturbation theory," Phys. Rev. E. 69, 056501 (2004)
11. C. Nieter and J. R. Cary, "VORPAL: a versatile plasma simulation code," J. Comp. Phys. 196, 448-472 (2004)
12. David L. Bruhwiler, D. A. Dimitrov, John R. Cary, Eric Esarey, Wim Leemans and Rodolfo E. Giacone, “Particle-in-cell simulations of tunneling ionization effects in plasma-based accelerators,” Phys. Plasmas 10 (2003), p. 2022

Current Staff Supported Under This Grant

Dr. Greg Werner (Research Associate)
Dr. Brent Goode (Research Associate)
Recruiting a Graduate Research Assistant pursuing Ph.D
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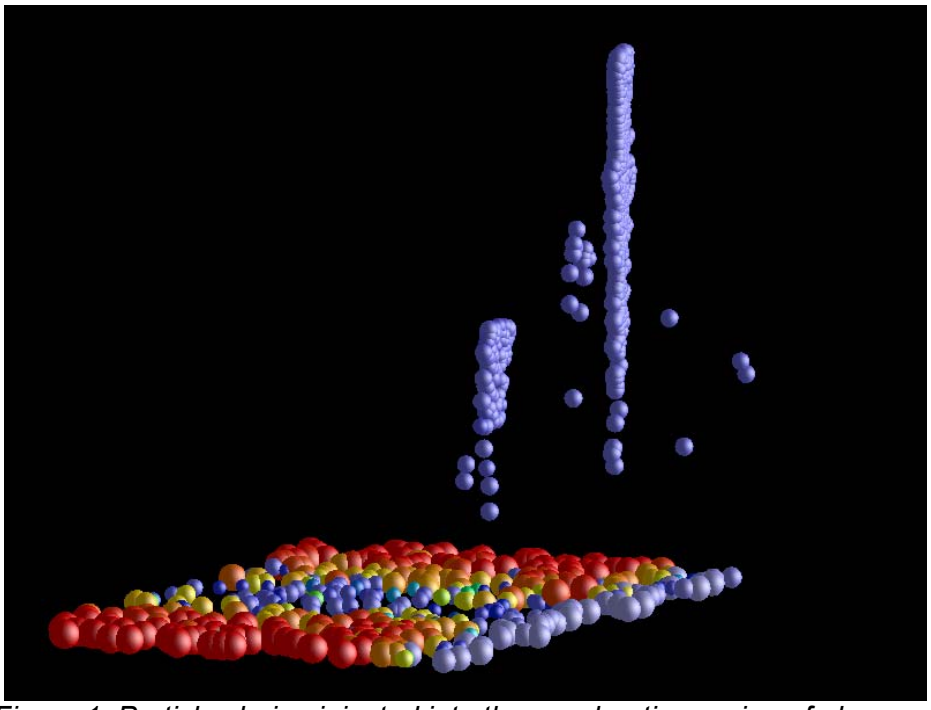

Figure 1 Particles being injected into the accelerating region of phase space. The formation of multiple beamlets is shown. The vertical axis is longitudinal momentum, while the horizontal axes are position.

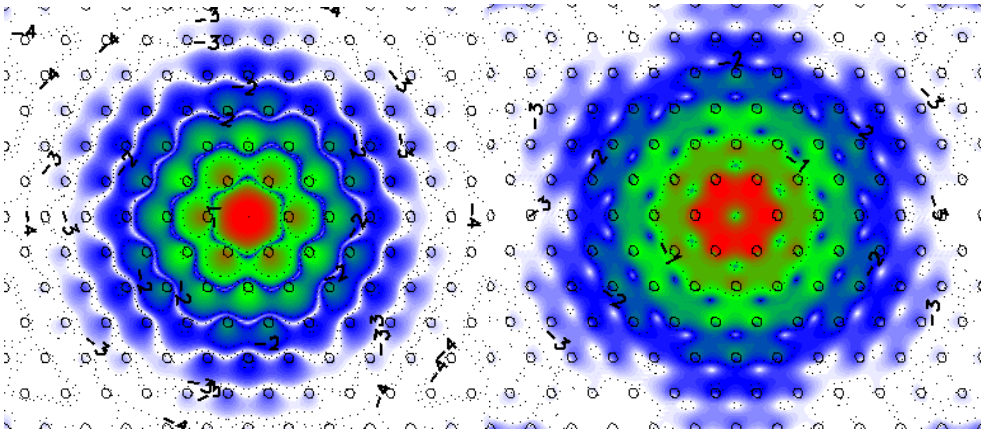

Figure 2 Magnitude of the electric (left) and magnetic (right) field strength times the square root of the distance from the defect in the trapped mode of a triangular lattice of r/a=0.25/sqrt{3} rods with one rod removed. Dotted contour lines are labeled with the number of powers of 10 below the maximum value; green is a factor of 10 below red; blue is a factor of 100 below red, and white is more than a factor of 1000 below the peak field (red)

Study of the Stability of Particle Motion in Storage Rings

Jack Shi
University of Kansas

Summary

The beam-dynamics group at the University of Kansas has been continuing the study of beam-beam effects in storage-ring colliders. Topics include the collective beam-beam instability of hadron and electron beams and its implication to bunch-current limit and global or local compensation of parasitic beam-beam interactions by using magnetic multipole correctors.

Recent Accomplishments

Study of the Coherent Beam-Beam Tune Shift of Unsymmetrical Beam-Beam Interactions

To study the coherent beam-beam effect, one important quantity that can be measured experimentally is the coherent beam-beam tune shift. Over decades, many studies have been conducted on the relationship between the coherent beam-beam tune shift and the beam-beam parameter. Two theoretical models, the linearized Vlasov equation and the rigid-beam model, have been studied extensively for the case of weak beam-beam perturbation in which the beam-beam parameter is relatively small. The situation of strong beam-beam perturbation is much more complicated and less understood. When the beam-beam parameter exceeds a threshold, the beam-beam interaction could induce chaotic coherent beam-beam instability. After the onset of the instability, the closed orbits could become unstable for beam centroids and two beams could develop a spontaneous unstable coherent oscillation. When the beam-beam parameter is below the beam-beam threshold, the coherent beam oscillation is stable. It is, however, not clear whether the linearized Vlasov equation or the rigid-beam model is still valid in the regime of strong beam-beam perturbation. As many efforts are being made to further increase the beam-beam parameter in upgrades of current and developments of future storage-ring colliders, an understanding of the coherent beam-beam tune shift in this regime not only is necessary for the interpretation of the tune measurement during operation of colliders with high-intensity beams but also could shed light on the onset of the chaotic coherent beam-beam stability.

To explore the beam-beam effect with a large beam-beam parameter, a beam experiment was performed on HERA. The beam-beam interaction in HERA is a typical case of unsymmetrical beam-beam interaction as the two beams have very different lattice tunes and beam-beam parameters. One important phenomenon observed in this experiment is that the measured coherent beam-beam tune shifts of the positron beam are much smaller than those calculated from the rigid-beam model, which indicates that the traditional models of the coherent beam-beam tune shift are no longer valid in the situation of strong beam-beam perturbations. It should be noted that in the HERA experiment, the single-particle motion is locally unstable at the closed orbit due to beam-beam interactions. The beam was, however, observed to have a very good lifetime and operation condition. This is the first direct experimental observation of the global stability of a beam coexisting with the local instability of beam particles due to beam-beam interactions. To have a better understanding of the experimental data, we reconstructed the HERA experiment with a self-consistent beam-beam simulation. Remarkable agreement between the experiment and the simulation was observed on emittance growth and luminosity reduction. More significantly, the computer simulation confirmed the experimental result of very small coherent beam-beam tune shifts in this case of a very large beam-beam parameter. It was found that the ratio of the coherent beam-beam tune shift and the total beam-beam

parameter of the weak positron beam decreases from 0.3 to 0.02 as the total beam-beam parameter increases from 0.01 to 0.54. On the contrary, in the symmetrical case of beam-beam interactions, this ratio maintains approximately a constant of 1.2 for a round beam or 1.3 for a flat beam in a large range of beam-beam parameter. The reason for this different characteristic of the coherent beam-beam tune shift is the intrinsic beam-size mismatch between two unsymmetrical colliding beams due to the difference in the equilibrium distributions of the two beams. This intrinsic mismatch in the beam distributions due to beam-beam interactions becomes more pronounced as the strength of beam-beam perturbations increases. The ratio of the coherent beam-beam tune shift and the beam-beam parameter, therefore, decreases with the increase of beam-beam parameters in the unsymmetrical case of beam-beam interactions. To examine the validity of the theoretical models for the coherent beam-beam tune shift, the linearized Vlasov equation and the rigid-beam model were solved for the HERA experiment. It was found that for the unsymmetrical beam-beam interaction with a large beam-beam parameter, the result of the rigid-beam model is inconsistent with the beam experiment and beam simulation. The coherent beam-beam tune shifts calculated from the linearized Vlasov equation with the single-mode approximation were also found to be significantly different from the result of the beam experiment and beam simulation no mater whether the beam-beam parameter is large or small. As the linearization of the Vlasov equation is expected to be valid for at least a small beam-beam parameter, this discrepancy suggests that the single-mode approximation used for solving the linearized Vlasov equation may not be valid in the case of unsymmetrical beam-beam interactions.

Study of Beam-Beam Effects in eRHIC

eRHIC is the proposed high-energy electron-ion collider in the Relativstic Heavy Ion Collider (RHIC) accelerator complex at Brookhaven National Laboratory, in which an electron ring will be constructed on the side of the RHIC rings that will provide collisions between a polarized electron beam and an ion beam from one of RHIC rings with high luminosity of ~10^{33} $cm^{-2}s^{-1}$ for electron-proton collision. In order to achieve such the luminosity, large bunch intensity and small beta-functions at the IP have to be employed. The beam-beam effect, especially the coherent beam-beam effect, is therefore one of important issues to the viability of eRHIC. Moreover, in order to have more flexibility and cost savings in the design, the circumference of the electron ring is chosen to be one third of that of the RHIC rings. During collision, each electron bunch will circulate three revolutions and collide with three different ion bunches during each revolution of the ion beam. Such a configuration of unequal circumferences could further enhance the coherent beam-beam effect. The beam-beam effect of eRHIC was therefore studied with a self-consistent simulation of the electron-proton collision by using the PIC method. Beam-beam limits of the two beams were examined as the thresholds of the onset of coherent beam-beam instability. With the proposed machine parameters, no beam-beam instability has been observed in the simulation and the beam-beam interaction results in a very limited (<15%) luminosity reduction. The study of the beam-beam limit of eRHIC, however, found that the proposed beam-beam parameter of the electron beam is uncomfortably too close to the threshold of the onset of coherent beam-beam instability. In consideration of the beam-beam effect, on the other hand, there is still a possibility to further increase the bunch intensity of the electron beam for the dedicated single IP mode since the proposed beam-beam parameter of the proton beam is relatively far away from its beam-beam threshold as compared with the electron beam. In order to have a comfortable margin to the beam-beam limit and to meet or exceed the proposed luminosity, we should consider to reduce the intensity of the proton beam slightly and to increase the intensity of the electron beam accordingly. A new phenomenon observed in this study is the high-order coherent beam-beam instability of PACMAN bunches. In the case that there are missing bunches in the ion beam, an electron

bunch could miss one or two head-on collisions at the IP during every three revolutions of the electron beam. Such a PACMAN bunch experiences a head-on beam-beam perturbation with an additional periodicity of three turns. It was found that this additional modulation in the beam-beam interaction can induce high-order coherent beam-beam instability with a spontaneous oscillation of transverse beam size and a chaotic oscillation of beam centroid of the PACMAN bunches. This high-order coherent beam-beam instability can result in a severe emittance blowup on both the beams. To avoid an increase of background due to large number of tail particles of the PACMAN bunches, in the case of missing proton bunches, the number of electron bunches has to be reduced accordingly in eRHIC.

It should be noted that the beam-beam interaction in eRHIC is traditionally considered as weak-strong or very unsymmetrical since the beam-beam parameter of the electron beam is more than 10 times larger than that of the ion beam and the two rings have a very different working point. For the weak-strong case of beam-beam interactions, a common misconception is that the coherent beam-beam effect is not important because of the existence of strong Landau damping. Recent simulation studies and beam-dynamics experiments, however, showed that the coherent beam-beam instability could also occur with weak-strong or very unsymmetrical beam-beam interactions. It was predicated in our numerical studies and later observed in beam-dynamics experiments on HERA that when the beam-beam parameter of the weak (lepton) beam exceeds a threshold, the onset of the coherent beam-beam instability could result in a significant emittance growth of the strong (proton) beam. The study of the beam-beam effect in eRHIC further confirmed that in the nonlinear regime of beam-beam interactions, the traditional boundary between the strong-strong and weak-strong beam-beam interactions is no longer valid and the beam-beam effect has to be studied self-consistently in both the situations.

Multipole Compensation of Long-Range Beam-Beam Interactions

In Tevatron, serious long-range beam-beam effects are due to many (72 for 36×36 bunches) parasitic collisions that are distributed around the ring. Because of the non-localized nature of the long-range beam-beam interactions, a compensation of the long-range beam-beam interactions in Tevatron requires a global compensation scheme. The multipole compensation of long-range beam-beam interactions based on a minimization of nonlinearities in one-turn or sectional maps is therefore under investigation. The principle of this multipole compensation scheme is based on the fact that the beam dynamics in a storage ring can usually be described by one-turn or sectional maps that contain global information of nonlinearities in the system. By minimizing nonlinear terms of the maps order-by-order with a few groups of multipole correctors, one could reduce the nonlinearity of the system globally. To include long-range beam-beam interactions into the maps, one should recognize that a large beam separation is typical at parasitic crossings. In Tevatron, for example, the beam separation at most parasitic crossings is between 7 and 14σ, where σ is the nominal beam size. In the phase-space region ($<4\sigma$) that is relevant to the beam, the long-range beam-beam interactions can thus be expanded into a Taylor series around the beam separation and be included into the maps for the global compensation. If there are a few parasitic crossings where the separation is small and the beam-beam interaction at those locations cannot be efficiently expanded with a reasonable truncation order, the beam-beam interactions at those “bad” locations could be separately compensated locally. In order to ensure a clean order-by-order expansion, the long-range beam-beam interactions have to be expanded in the direction of the beam separation. Since the direction of the separation rotates along the helix orbit in Tevatron, the transverse coordinate for the expansion has to be rotated accordingly. We have therefore developed a differential-algebra code that expands long-range beam-beam interactions in the rotating coordinate. The map obtained in this manner was found to converge very well. To examine the

effect of the compensation, emittance growth of both the beams during injection and collision were studied by beam trackings. During the collision, head-on beam-beam interactions at IPs were calculated self-consistently by using the PIC method. The study showed that the dominant long-range beam-beam effect in Tevatron is of the linear coupling due to the feed-down effect of the long-range beam-beam interactions and the coupled helix orbits. The multipole compensation especially a correction of the linear coupling due to the long-range beam-beam interactions and helix orbits can significantly reduces the emittance growth of the anti-proton beam.

Publications 2003-2005

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7. L. Jin and J. Shi, "Importance of Beam-Beam Tune Spread to Collective Beam-Beam Instability in Hadron Colliders," Phys. Rev. E**69**, 036503 (2004)
8. F. Wang, et al., "Progress of the eRHIC Electron Ring Design," *Proc. of the 9th European Particle Accelerator Conference*, Lucerne, July 2004
9. J. Shi, L. Jin, and G.H. Hoffstaetter, "Study of Beam-Beam Effects in HERA with Self-Consistent Beam-Beam Simulation," in *Proc. of the 2003 IEEE Particle Accelerator Conference*, Portland (2003)
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11. J. Shi, O. kheawpum, and L. Jin, "Multipole Compensation of Long-Range Beam-Beam Interactions," in *Beam Halo Dynamics, Diagnostics, and Collimation*, AIP Conf. Proc. 693, edited by J. Wei, W. Fischer, and P. Manning, (AIP, New York, 2003), p. 256

Current Staff

Jack Shi	Principal Investigator	
Lihui Jin	Ph.D. Graduate Student	Sep. 1999 - Jan. 2005, Graduated in Jan. 2005
	Post Doc	Jan. 2005 - April 2005
Ben Anhault	Ph.D. Graduate Student	Sep. 2002 - present

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Dynamical Systems and Accelerator Theory Group

Alex Dragt
Robert Gluckstern
University of Maryland

Summary

The University of Maryland Dynamical Systems and Accelerator Theory (DSAT) Research Group carries out long-term research in the general area of Dynamical Systems with a particular emphasis on applications to Accelerator Physics. Our work is devoted both to the development of new methods and to the application of these methods to problems of current interest in accelerator physics including the theoretical performance of present and proposed high-energy machines.

A major goal of the work of the DSAT Group is to describe, analyze, predict, and understand the linear and nonlinear behavior of single- and multi-particle systems. Considerable progress has been made in the single-particle case. Map methods employing Lie-algebraic and truncated-power-series-algebraic tools have been developed to compute and analyze both linear and high-order nonlinear behavior for machines with *idealized* beam-line elements. These methods are currently being extended to treat *real* beam-line elements including high-order multipole and fringe-field effects.

With regard to the multi-particle case including the Computation of Electromagnetic Fields and Beam-Cavity Interactions, work has been carried out on the understanding of halo formation and other resonant effects in high current beams with applications both to linacs and circular machines including the Spallation Neutron Source (SNS) rings, and on coupling impedances in beam pipes and their importance for understanding beam current limitations in circular accelerators. In addition, as described below, a hybrid Lie-PIC (Particle-in-Cell) code has been produced and is undergoing further development.

Finally, where appropriate and when opportune, research is carried out in other areas of the broad field of Dynamical Systems. Examples of such areas include light optics, electron microscopes, and operator methods applied to various problems in the rapidly developing field of Quantum Computing/Information.

These research efforts are described in more detail below and on the DSAT Web site. In addition, the DSAT Group is actively engaged in the education of students and post-doctoral research associates. To this end, it presents a regular graduate seminar course in accelerator physics, directs graduate students in M.S. and Ph.D. thesis research, and guides and fosters the research of Post-doctoral Research Associates and Visiting Scientists. There are currently 12 Ph.D. physicists working in the field of Accelerator Physics who were trained in our Group.

Computation of Charged Particle Beam Transport

Overview

New methods, employing Lie algebraic tools, have been developed for the computation of charged particle beam transport and accelerator design. These methods have been used for the design of the Stanford Linear Accelerator Center (SLAC) B factory and for final focus systems in the SLAC Test Beam Facility and in the preliminary design of the proposed International Linear Collider (ILC), for the design of the SNS, and are being used in the design

of the Large Hadron Collider (LHC) and in the design of high current accelerators for neutrino factories and muon colliders. They are also being used at Los Alamos National Laboratory (LANL) both for multimillion-macroparticle intense beam simulations and for proton radiography studies. This work is documented in the book "Lie Methods for Nonlinear Dynamics with Applications to Accelerator Physics" that is in draft form (currently 925 pages) and in the "MaryLie 3.0 User's Manual, A Program for Charged Particle Beam Transport Based on Lie Algebraic Methods" (900 pages). Copies of these documents are available upon request. Our goal is to provide a comprehensive treatment of the nonlinear (as well as fully coupled linear) behavior of charged particle orbits in both single pass and circulating machines.

Current Work

- Computation of Maps for real Magnets [work done with C. Mitchell; M. Venturini and A. Wolski (Lawrence Berkeley National Laboratory (LBNL)), and P. Walstrom (LANL)]. Work has been/is being carried out on the problem of computing accurate transfer maps for real (not idealized) beam-line elements using real field data. Applications include damping-ring wigglers for the ILC and other machines, permanent magnet elements in the Tevatron Recycler, low beta quads in the LHC, and dipoles in the Fermi National Accelerator Laboratory (Fermilab) electron cooling project. A method has been developed that uses field data on some surface surrounding the volume of interest to find interior data that both satisfies the Maxwell equations exactly and also has the expected analyticity in all spatial variables. This method is robust against both measurement and electromagnetic code errors since it automatically takes into account the smoothing properties of the Laplace Green function. So far it has been successfully applied using cylindrical surfaces in LHC, ILC, and TeV Energy Superconducting Linear Accelerator (TESLA) applications, and for RF cavities. The use of elliptical cylinders (designed for magnets with a small gap and wide pole faces) is under development and being applied to a prototype ILC wiggler magnet. See the first two figures of the accompanying montage. This work required an extensive knowledge of Mathieu functions, the development of robust numerical routines for their computation, as well as the development of spline routines, spline Fourier transform routines, and their fast Fourier transform analogs. The reward for this effort is that for the elliptical expansions the domain of convergence is larger and there is greater insensitivity to errors/noise in the surface data.

- Map methods have been developed for the treatment of misplacement, misalignment, and mispowering errors. These errors produce complicated feed-down effects (for example, a misplaced octupole produces sextupole, quadrupole, and dipole effects), as well as feed-up effects when calculations are carried out beyond third order. We have discovered that these analytic complications can be overcome by working with a higher dimensional phase space. We have found that the set of general maps for a $2n$-dimensional phase space can be imbedded in the larger set of origin preserving maps for a $(2n+2)$-dimensional phase space. Since a complete map calculus has already been developed for origin preserving maps in any dimension, this approach automatically provides complete results for general maps. These results are documented in Chapter 9 of the Lie Methods for Nonlinear Dynamics book, and are currently being used for the construction of the code MaryLie 7.1, a 7th order (16 pole) code that also treats all error effects.

- Construction of a Hybrid Lie-PIC Beam Transport Code including Space Charge Effects (work done with R. Ryne (LBNL) and other members of the Department of Energy Accelerator Physics SciDAC consortium, see Web site http://scidac.nersc.gov/accelerator/). Work is being carried out on the construction of a hybrid Lie-PIC code (MaryLie/Impact) that incorporates both the full linear and nonlinear beam-line element library of MaryLie through

7th order and standard Particle-in-Cell (PIC) routines frcts. The code also incuds acceleration so that it is fully applicable to linear accelerators and ramping synchrotrons and storage rings, as well as quiescent storage rings and static devices such as beam lines and spectrometers. A lower order version of MaryLie/Impact has already been written including a highly parallel version developed for use on the largest tera-scale computers at National Energy Research Scientific Computing Center (NERSC), and applications are being made to the SNS and the Fermilab booster.

- There is a great unity in science. It often happens that methods developed for one area of science have broad application to other areas of science. Such is the case for various Lie-algebraic methods originally developed for Accelerator Physics. These methods have now been applied to the problem of computing wave functions and their time evolution with application to the rapidly growing field of Quantum Computing. The last two figures in the montage illustrate the application of Lie-algebraic methods to computing the quantum behavior of a circuit consisting of two Josephson junctions coupled by an LC resonator. This circuit is a possible prototype element for a Quantum Computer. This work was carried out in conjunction with the experimental effort of the Maryland Superconducting Quantum Computing Research Group, and comprises part of the Ph.D. thesis work of Frederick Strauch (now at National Institute of Standards and Technology)) drected by Professor Dragt and supported by the National Security Agency (NSAatheNational Science Foundation (NSF).

Computation of Electromagnetic Fields and Beam-Cavity Interactions (work of Professor Gluckstern, now retired)

- Over the past 10 years, the University of Maryland group has made important contributions to the understanding of halo formation in high current linac beams. These same methods have also been applied (with A. Fedotov at Brookhaven National Laboratory (BNL)) to the understanding of possible halo formation and other resonant effects in circular accelerators, including the SNS rings designed at BNL.

- A second area of work (with S. Krinsky at BNL and F. Ruggiero and B. Zotter at CERN) has been the study of coupling impedances in beam pipes and their importance in understanding beam current limitations in circular accelerators. Results were obtained for the longitudinal impedance of a finite length resistive cylinder at high frequencies. The most recent activities include an attempt to obtain an analytical formulation for the calculation of the longitudinal and transverse coupling impedances for a beam bunch traveling along the axis of a narrow beam pipe with finite conductivity.

- A third area of recent activity (with R. Ryne and J. Qiang at LBNL) has been a study of the evolution of a mismatched spherically symmetric beam bunch in a focusing channel using the Vlasov equation supplemented by the Boltzmann equation to include intra-beam collisions. The purpose of the work was to understand a variety of mismatched collective modes as well as the details of the approach to thermal equilibrium. Various numerical methods to achieve fast and accurate time evolution of charged particle bunches in beam pipes were also studied.

Publications

1. M. Venturini, A. Wolski, and A. Dragt, *Wigglers and Single-Particle Dynamics in the NLC Damping Rings*, Proceedings of the 2003 International Particle Accelerator Conference (2003)
2. R. Ryne, A. Adelmann, P. Colella, J. Qiang, D. Serafini, R. Samulyak, S. Habib, T. Mottershead, F. Neri, P. Walstrom, V. Decyk, and A. Dragt, MaryLie/*IMPACT: A Parallel 5th Order Beam Optics Code with Space Charge*, Proceedings of the 2003 International Particle Accelerator Conference (2003)
3. A. Dragt, *The Symplectic Group and Classical Mechanics*, Annals of the New York Academy of Sciences (2005)
4. A. Dragt, Time *reversal Properties of Hamiltonians and their Transfer Maps*, 59 pp., University of Maryland Physics Department Preprint (2005)
5. F. Strauch, P. Johnson, A. Dragt, et al., *Quantum Logic Gates for Coupled Superconducting Phase Qubits*, Phys. Rev. Lett. 91 (2003)
6. F. Strauch, P. Johnson, H. Xu, A. Dragt, et al., *Spectroscopy of Multiparticle Entanglement in a Macroscopic Superconducting Circuit*, Phys. Rev. Lett. 94 (2005)
7. A. Fedotov, I. Hofmann, R. Gluckstern, and H. Okamoto, *Parametric Collective Resonances and Space Charge Limits in High Intensity Rings*, Phys. Rev. STAB 6 (2003)
8. J. Qiang and R. Gluckstern, *Three Dimensional Poisson Solver for a Charged Beam with Large Aspect Ratio in a Conducting Pipe*, Computer Physics Communications 160 (2004)
9. S. Krinsky, B. Podobedov, and R. Gluckstern, *Impedance of a Finite Length Resistive Cylinder,* Phys. Rev. STAB 7 (2004)

Current Staff

Dragt, A.J.	PI, Professor of Physics
Johnson, P.R.	Postdoctoral Research Associate
Mitchell, C.	Ph.D. Graduate Student
Zimmerman, M.	First-year Graduate Student and Department Fellow
Kurennoy, S.	First-year Graduate Student
Klakring, G.	Senior Mathematics Major

Past Ph.D. Students now in Accelerator Physics and their Current Employment:

David Douglas, Ph.D. 1982, Thomas Jefferson National Accelerator Laboratory.

Etienne Forest, Ph.D. 1984, KEK High Energy Physics Laboratory, Tsukuba, Japan and Associate Professor at the Graduate University for Advanced Studies, Kanagawa, Japan.

Robert Ryne, Ph.D. 1987, Lawrence Berkeley National Laboratory.

Govindan Rangarajan, Ph.D. 1990, Professor and Chair of the Mathematics Department, Indian Institute of Science, Bangalore, India.

Rui Li, Ph.D. 1990, Jefferson National Accelerator Laboratory.

Dan Abell, Ph.D. 1995, Tech-X Corporation.

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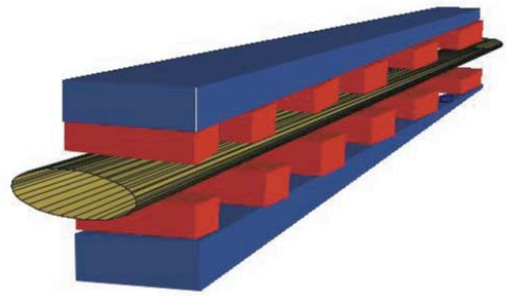
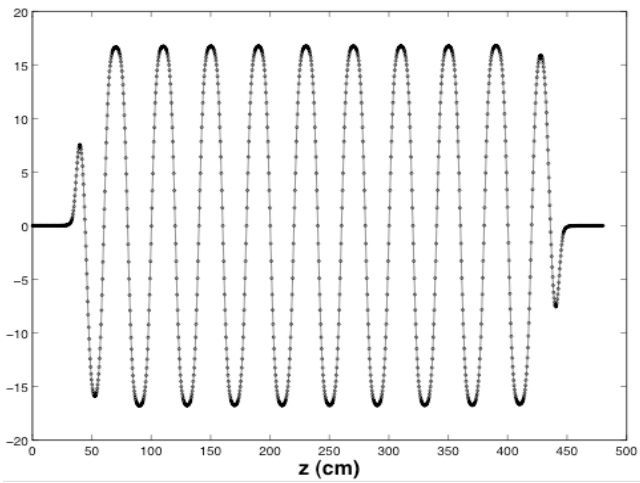
P

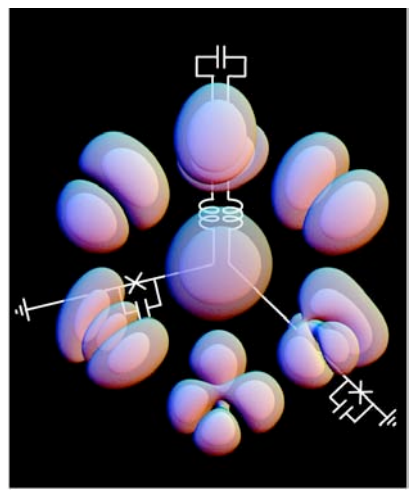
University of Maryland DSAT Group

Imaginary elliptical cylinder, within the magnet aperture, on which the normal component of the magnetic field is assumed to be known. All components of the interior field and its associated vector potential are to be computed from this surface data.

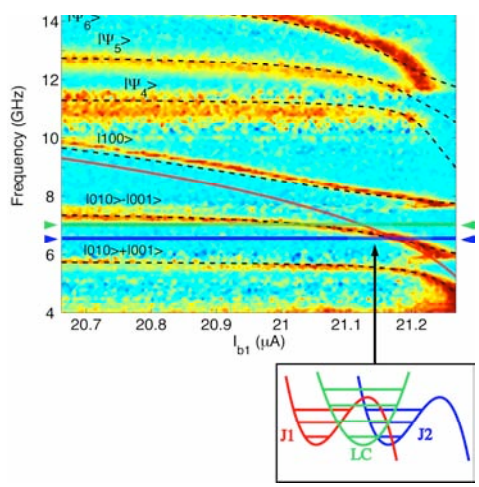




Off-axis vertical field (*kG*) at (*x,y*) = (.4, .2) *cm* for prototype ILC wiggler. Solid curve is predicted field based on surface data provided by a 3-d code. Points are interior data from the same code. Note the excellent agreement.



Wave functions for a prototype quantum computer element consisting of two Josephson junctions coupled by an LC resonator. This element has 3 degrees of freedom (2 junctions and 1 LC circuit), and all behave quantum mechanically. The wave functions and their energies, whose theoretical and experimental values are shown in the final figure, were computed using Lie-algebraic methods originally developed for Accelerator Physics. The arrow indicates a value for the bias current on junction 1 for which the first excited states of all 3 degrees of freedom (when uncoupled) are degenerate. The coupling produces an avoided crossing. One free parameter (the bias current on the second junction, which was not well measured but within experimental error) was used to fit all 6 curves.



Studies of Microwave Sources for High Frequency Colliders (Task B)

Martin Reiser
University of Maryland

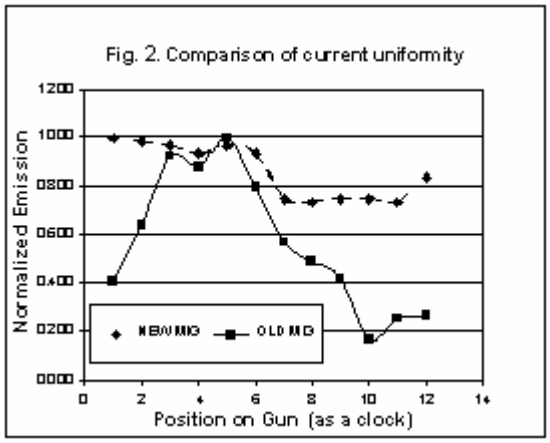
Summary

Electron-positron linear colliders are one option being considered for advancing High Energy Physics (HEP) research into the 3-4 TeV range effectively extending beyond the capabilities of Large Hadron Collider (LHC). At the University of Maryland we have been conducting research aimed at evaluating the capabilities of gyroklystron amplifiers as drivers for such advanced colliders. Below we present a description of recent work in gyroklystron experiments and in gyro-amplifier theory.

Gyroklystron Experiments

The Gyroklystron research program at the University of Maryland Institute for Research in Electronics and Applied Physics (IREAP) has as a preliminary goal the production of 80 MW peak power at 17.1 GHz frequency, using a 500 kV, 500 A electron beam, and then as a final goal the use of that microwave power to energize an accelerator structure developed by the Haimson Research Corporation (HRC) [1]. These goals had been hindered in previous years due to azimuthally non-uniform current emission from the beam source, a temperature-limited (TL) Magnetron Injection Gun (MIG). The variation was shown to be caused mainly by temperature variations on the emitter surface. The current variation restricted the maximum perpendicular beam energy via instabilities, which in turn kept our peak microwave output power to below 30 MW.

We have developed a three-prong approach to overcome this limitation and we have had success on all three research efforts. The first approach was to design a space-charge-limited (SCL) MIG, for which the emitter temperature variation would not result in an azimuthal current variation. We showed [4] that in fact one can design SCL MIGs that have beam qualities as good as TL MIGs, with only a slight cost in terms of increased cathode loadings and increased surface field levels. The design would involve only changing the cathode stalk assembly and could be constructed and installed if necessary. The second approach was to collaborate with industry, via Small Business Innovation Research (SBIR) funding and our own Department of Energy (DOE) support, to improve emitter technology and reduce temperature variations along the emitter surface. We worked with Semicon Associates, Inc., and Calabasas Creek Research, Inc. (CCR), who had an SBIR Phase-II program to build an improved TL MIG for our gyroklystron. The collaboration succeeded in reducing the temperature variation of 50°C on the old MIG emitter to less than 10°C on the new MIG emitter. The photo of a CCR cathode is shown in *Figure 1*. The resultant reduction in azimuthal current density variation is shown in *Figure 2*. Current density was inferred from X-ray measurements. The normalized X-ray density is shown at a comparable operating point for both MIGs as a function of angle from 12 o'clock facing up (0°), and 6 o'clock is facing down (180°)). The old MIG result is indicated by the solid line, and the minimum emission is less than 20% of the maximum emission. The dashed line gives the new MIG result, where the low emission



point is about 75% of the maximum emission point. After looking at data at a number of operating points, we concluded that we reduced the azimuthal current density spread from over 40% RMS in the old MIG to less than 12% in the new MIG. This new MIG has been installed in our test bed and will soon be in use.

Figure 1 Top view of a new CCR cathode

The third approach was to design a high gain tube that could produce at least 50 MW of peak power even if the perpendicular beam energy from the MIG remained at the reduced level of the previous system. This design was successfully completed and the results are detailed elsewhere [5, 6]. In summary, six cavities are needed (instead of the four cavities currently used) in order to meet the system design requirements, which, in addition to the peak power level, require the use of a 1.5 kW TWT driver in order to control the output phase of the power to the level required by the HRC accelerator.

With these three tasks completed, we are installing the four-cavity tube for hot testing. The six-cavity tube is under construction and will be tested if necessary. The HRC accelerator will be connected to the output of the gyroklystron before the end of the contract period and we will evaluate the ability of the gyroklystron to drive it.

1. J. Haimson and B. Mecklenburg, “A Linear Accelerating Power Amplification System for High Gradient Structure Research,” in Proc. AAC, AIP, vol. 472, 1003-1013, July 1998

Theoretical Studies

In 2004, we started to study effects caused by overlapping of cyclotron resonances in relativistic high-power gyro-amplifiers. It was shown that when the amplitude of the RF field is large enough, electrons in the process of interaction with a strong microwave field can change their energy so significantly, that corresponding changes in the electron cyclotron frequency can result in moving electrons from initial resonance with this field at a given cyclotron harmonic to resonances in neighboring harmonics. For instance, for present-day University of Maryland frequency-doubling gyroklystrons where the output cavity operates at the second cyclotron harmonic, this implies a possibility of additional resonance interaction at the first and third harmonics. In our first study, we analyzed electron motion in such gyro-amplifiers where interaction with a constant amplitude forward wave at three cyclotron harmonics simultaneously is possible. It was shown that taking the resonances at neighboring harmonics into consideration results (under certain conditions) in stochasticity of electron trajectories. These results were published in Ref. 7 and reported in invited paper [8] last year.

The final goal of that study was the analysis of the effect of such a stochastic electron motion on the radiation line width in relativistic gyro-amplifiers. This issue is especially important for amplifiers developed for driving linear accelerators, when the use of pulse compressors is anticipated. As known, practically all passive pulse compressors require an accurate phase shift of microwave radiation at a certain instant of time, so phase control of this radiation must be provided.

In the course of our work in the last year, we considered the interaction of relativistic electrons with an electromagnetic wave self-consistently, i.e. accounting for wave amplification by gyrating electrons. We considered the large-signal operation of the gyro-TWT and the gyro-twystron in the presence of additional cyclotron resonances.

The effect of these resonances on the gain is shown in *Figure 1* where the large-signal gain of the gyro-TWT is plotted as a function of the normalized axial distance. Parameter b characterizes the coupling of electrons to the wave at additional resonances; parameter μ is the ratio of initial cyclotron frequency to the wave frequency and $F(0)$ is the input field amplitude.

Electron trajectories in the presence of additional interaction at neighboring cyclotron harmonics are shown in *Figure* 2. A similar analysis of the effect of resonance overlapping was also carried out for the last stage of the gyro-twystron operating in the large-signal regime.

Presently, we are preparing a manuscript describing these results for publication in Phys. Rev. E. These results will be also reported at the joint 30th International Conference on Infrared and Millimeter Waves and Terahertz Electronics in Williamsburg, VA (Sept. 2005).

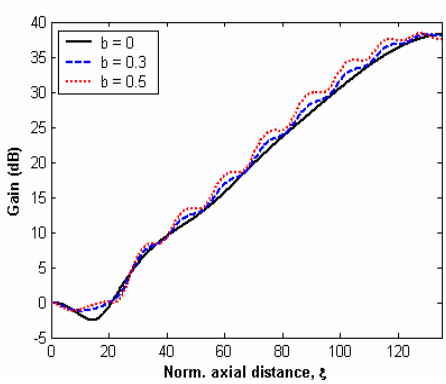


Figure 1 Gain curves for single harmonic interaction and for resonance overlap conditions when μ = 0.442, and F(0) = 0.001.

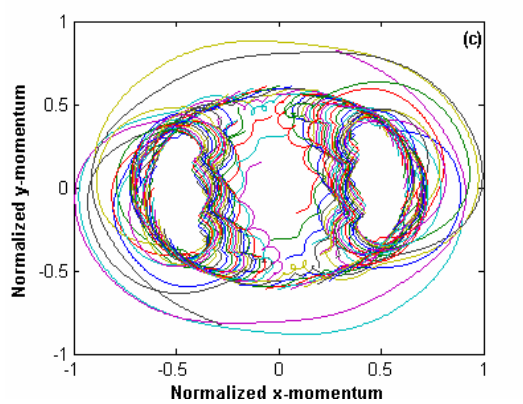


Figure 2 Plots of electron trajectories in gyro-TWT for b = 0.5, μ = 0.443, and F(0) = 0.01

Publications (2003-2005)

1. W. Lawson, H. Raghunathan, and M. Esteban, "Space-Charge Limited Magnetron Injection Guns for High-Power Gyrotrons," *IEEE Trans. Plasma Sci.,***32**, pp. 1236-1241 (2004)
2. W. Lawson, M. Esteban, H. Raghunathan, B. Hogan, and K. Bharathan, "Bandwidth Studies of TE_{0n} - $TE_{0(n+1)}$ Ripple-Wall Mode Converters in Circular Waveguide," *IEEE Trans. Microwave Theory Tech.* **53** (1), pp. 372-379 (2005)
3. W. Lawson, "The Design of a High-Power, High-Gain, Frequency-Doubling Gyroklystron," *IEEE Trans. Plasma Sci.,***33**, pp. 858-865 (2005)
4. H. Raghunathan and W. Lawson, "The Design of Space-Charge Limited Magnetron Injection Guns with Control Electrodes for Gyroklystron Applications," To be published in *IEEE Trans. Plasma Sci*., August 2005
5. K. Bharathan, W. Lawson, J. Anderson, E. S. Gouveia, B. Hogan, and I. Spassovsky, "Design and Cold-Testing of a Radial Extraction Output Cavity for a Frequency-Doubling Gyroklystron," accepted for publication in *IEEE Trans. Microwave Theory Tech, July 2005*
6. E. S. Gouveia, W. Lawson, B. Hogan, K. Bharathan, V.L. Granatstein, "Current Status of Gyroklystron Research at the University of Maryland," Presented at RF 2003, 6th Workshop on High Energy Density and High Power RF, Berkeley Springs, WV, June 22-26, 2003. Published in High Energy Density and High Power RF, AIP Conference Proceedings 691, New York: AIP Press, 2003, pp.79-88
1. G. S. Nusinovich, R. Ngogang, T. M. Antonsen, Jr., and V. L. Granatstein, "Overlapping of resonances and stochasticity of electron trajectories in cyclotron masers," Phys. Rev. Lett., 93, paper 055101 (2004)

Invited Presentations (2003-2005)

7. G. S. Nusinovich, "Stochastic phenomena in relativistic gyrodevices," Invited Keynote, 29 th Int. Conf. on Infrared and Millimeter Waves and THz radiation, Karlsruhe, Germany, Sept. 27 – Oct. 01, 2004
1. V. L. Granatstein, W. G. Lawson, G. S. Nusinovich, T. M. Antonsen, Jr., A. Singh and E. S. Gouveia, "Gyroklystrons for Driving Linear Accelerators," Invited paper at the 11th AAC Workshop, (Stony Brook, N. Y., 21-26 June 2004) given by V. L. Granatstein

Current Research Staff (Task B)

Granatstein, V. L.	Co-Principal Investigator, Professor, Department of Electrical & Computer Engineering
Lawson, W.	Co-Principal Investigator, Professor, Department of Electrical & Computer Engineering
O'Shea, P.G.	Principal Investigator, Professor and Chair, Electrical & Computer Engineering
Reiser, M.	Co-Principal Investigator, Professor Emeritus and Senior Research Scientist
Nusinovich, G.	Senior Research Scientist
Hogan, B. P.	Assistant Research Engineer
Krumrine, M.	Faculty Research Assistant

Graduate Students

Stamatiou, I.		Pursuing M.S.
Tiwari, S.		Pursuing M.S.
Purohit, P.		Pursuing M.S.
Gebeyah U, N.		Pursuing M.S.
Ngogang, R.		Pursuing M.S.
Raghunathan. H	M.S. Granted 12/03	Currently working at TI
Bharathan, K.	M.S. Granted 8/04	Currently working at Verizon
Gouviea	Ph.D. Granted 8/04	Currently employed by the Baltimore Government

Undergraduate Students (B.S.)

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Krumrine, M.	(2004)			
Wojnar, E.	(2004)			
Esteban, M.	(2005 – U. San Diego)			
Karlstadt, M.	(2005)			
Katz, D.	(2005)			
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Application of Plasma Waveguides to Advanced High Energy Accelerators

Howard Milchberg
Thomas Antonsen, Jr
University of Maryland

Summary

Our group has concentrated on the development of plasma waveguides and the study of the guiding of intense laser pulses for plasma based accelerators. Our approach is a combination of theory, experiment, and computation. Most notable are our invention of the hydrodynamic shock formed plasma channel, the development of efficient algorithms for the simulation of laser pulse propagation in plasmas and most recently, the discovery of self guiding of laser pulses in gases of atomic clusters.

Resonant heating of a cluster plasma by intense laser light

Gases of atomic clusters are interaction media for laser pulse propagation with properties useful for applications such as Extreme Ultra-Violet (EUV) and X-ray microscopy, harmonic generation, EUV lithography, and laser plasma acceleration. To understand cluster heating and expansion, a series of two and three dimensional electrostatic particle in cell simulations of the explosion of argon clusters of diameter in the range 20 nm - 53 nm have been preformed. The studies show that heating is dominated by a nonlinear, resonant absorption process that gives rise to a size-dependent intensity threshold for strong absorption and that controls the dielectric properties of the cluster. Electrons are first accelerated out from the cluster and then driven back into it by the combined effects of the laser field and the electrostatic field produced by the laser-driven charge separation. Above the intensity threshold for strong heating there is a dramatic increase in the production of energetic particles and harmonic radiation. The dielectric properties of a gas of clusters are determined by the ensemble average cluster polarizability. Individual electrons contribute to the polarizability differently depending on whether they are in the core of the cluster or in the outer edge. Consequently, there can be large fluctuations in polarizability during the heating of a cluster.

Effective coupling of ultra-intense laser pulse to funnel-mouthed plasma waveguides

The injection of laser pulses into hydrodynamically preformed plasma channels can be hindered by the conditions at the entrance of the channel. In particular, neutral gas and narrowing of the channel prevent efficient coupling of laser pulse entering into the channel. To solve this problem, a funnel shaped plasma lens can be grafted onto the channel using an auxiliary formation pulse. Simulations of channel formation show that such a funnel can be made in the density ramp of a gas jet. Simulations of laser pulse propagation show that such a funnel efficiently couples pulse energy into the channel. For a backfill target with a funnel, the coupling efficiency is lower and required funnel parameters are more restrictive than for the gas jet case
.

A highly efficient, fully parallelized, fully relativistic, three-dimensional particle-in-cell model for simulating plasma and laser wakefield acceleration has been developed in collaboration with personnel from the University of California, Los Angeles, and the University of Southern California. The model is based on the quasi-static or frozen field

approximation, which reduces a fully three-dimensional electromagnetic field solve and particle push to a two-dimensional field solve and particle push. This is done by calculating the plasma wake assuming that the drive beam and/or laser does not evolve during the time it takes for it to pass a plasma particle. The complete electromagnetic fields of the plasma wake and its associated index of refraction are then used to evolve the drive beam and/or laser using very large time steps. This algorithm reduces the computational time by 2 to 3 orders of magnitude from that of a fuu format Particle-in-Cell (PIC) simulation. Comparisons between the new algorithm and conventional fully explicit models (OSIRIS) have been made. The agreement is excellent for problems of interest.

Demonstration of ultra-intense pulse guiding in plasma waveguides generated in elongated cluster jets

Clustered gas jets were shown to be an extremely efficient means for plasma waveguide generation, for both femtosecond and picosecond generation pulses. These waveguides enable significantly lower on-axis plasma density (< 10^{18} cm-3) than in conventional hydrodynamic plasma waveguides generated in unclustered gases. Ten times less energy is needed for waveguide generation then in previous schemes using laser heating. Using femtosecond pump pulses, self-guided propagation and strong absorption (>80%) are used to produce long centimeter scale channels in an argon cluster jet, and a subsequent intense pulse is coupled into the guide with 50% efficiency and guided at $3x10^{17}$ W/cm^2 intensity over 40 Rayleigh lengths (PRL **94**, 205004 (2005)). This level of intensity is limited only by our laser energy. We also demonstrated efficient generation of waveguides using 100 ps axicon-generated Bessel beam pump pulses. Despite the expected sub-picosecond cluster disassembly time, we observe long pulse absorption efficiencies up to a maximum of 35%. Simulations show that in the far leading edge of the long laser pulse, the volume of heated clusters evolves to a locally uniform and cool plasma already near ionization saturation, which is then efficiently heated by the remainder of the pulse (Phys. Rev E, in press).

Current Staff

Howard M. Milchberg, Co-Principal Investigator
Thomas M. Antonsen Jr., Co-Principal Investigator
Vinod Kumarappan postdoc (experiment) - NSF funded
Hua Sheng Ph.D. Candidate (experiment)-NSF and Sematech funded
Andrew York Ph.D. Candidate (experiment)-NSF funded
Brian Layer Ph.D. Candidate (experiment)-NSF funded
Sanjay Varma Ph.D. Candidate (experiment)-DOE funded
Yu-Hsin Chen Ph.D. Candidate (experiment)-DOE funded
Ayush Gupta Ph.D. Candidate (theory)-NSF and DOE funded
Jianzhou Wu Ph.D. Candidate (theory)-NSF and DOE funded
John Palastro Ph.D. Candidate (theory)-NSF and DOE funded

Recent Graduates

James Cooley, Ph.D 2004, (currently at Los Alamos Lab),
Kiyong Kim, PhD 2004 (currently at Los Alamos)

Ilya Alexeev, PhD 2004 (currently at NRL)

Recent awards

Kiyong Kim won the 2004 APS Division of Plasma Physics Doctoral Dissertation Award based on his work on ultrafast plasma diagnostics
H. Milchberg won the 2005 APS Division of Plasma Physics Award for Excellence in Plasma Physics Research, for experimental and theoretical work in intense pulse optical guiding

Publications: 2003-2005

1. *Self-focusing of intense laser pulses in a clustered gas,* Alexeev I, Antonsen TM, Kim KY and HM Milchberg, Phys Rev. Lett 90 (10): Art. No. 103402 MAR 14 2003
2. *Laser pulse splitting and trapping in tenuous gases,* Wu JZ and Antonsen TM
3. Phys Plasmas **10** (6) 2254 (2003)
4. *Time-resolved explosion of intense laser-heated clusters,* K.Y. Kim, I. Alexeev, E. Parra, and H.M. Milchberg
5. Phys. Rev. Lett. 90, 023401 (2003)
6. *Hydrodynamic timescales for intense laser-heated clusters,* E. Parra, I. Alexeev, J. Fan, K. Y. Kim, S. J. McNaught, and H.M. Milchberg
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8. *Measurement of the average size and density of clusters in a gas jet*, K. Y. Kim, V. Kumarappan, and H. M. Milchberg, Appl. Phys. Lett. **83**, 3210 (2003)
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submitted to Phys. Rev. E

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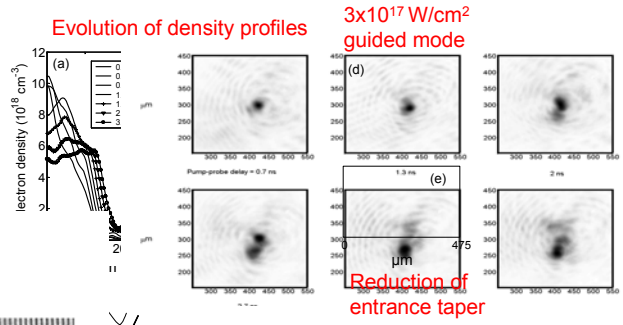
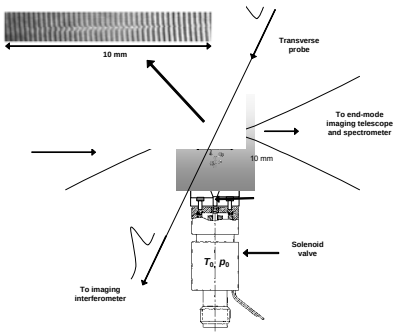
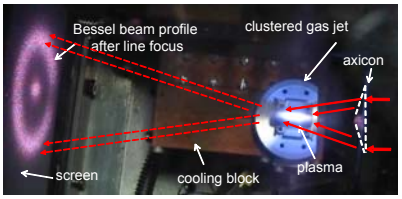
Plasma waveguides efficiently generated in elongated cluster jets



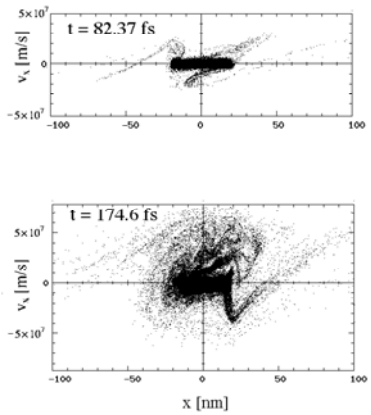


Femtosecond self-guided generation of plasma waveguides in a cluster jet



Long pulse Bessel beam generation of plasma waveguides in a cluster jet

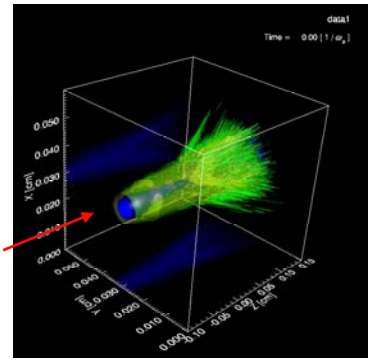
Simulations



Simulation of laser-cluster interaction: phase space (x,v_x) plot for electrons along the polarization axis of the cluster at 2 times during the laser pulse

3D Simulation of Ionization Scattering
Image of electron density after passage of laser pulse

Laser Pulse



Study of Physics of Space Charge Dominated Beams for Advanced Accelerator Applications (Tasks A and C)

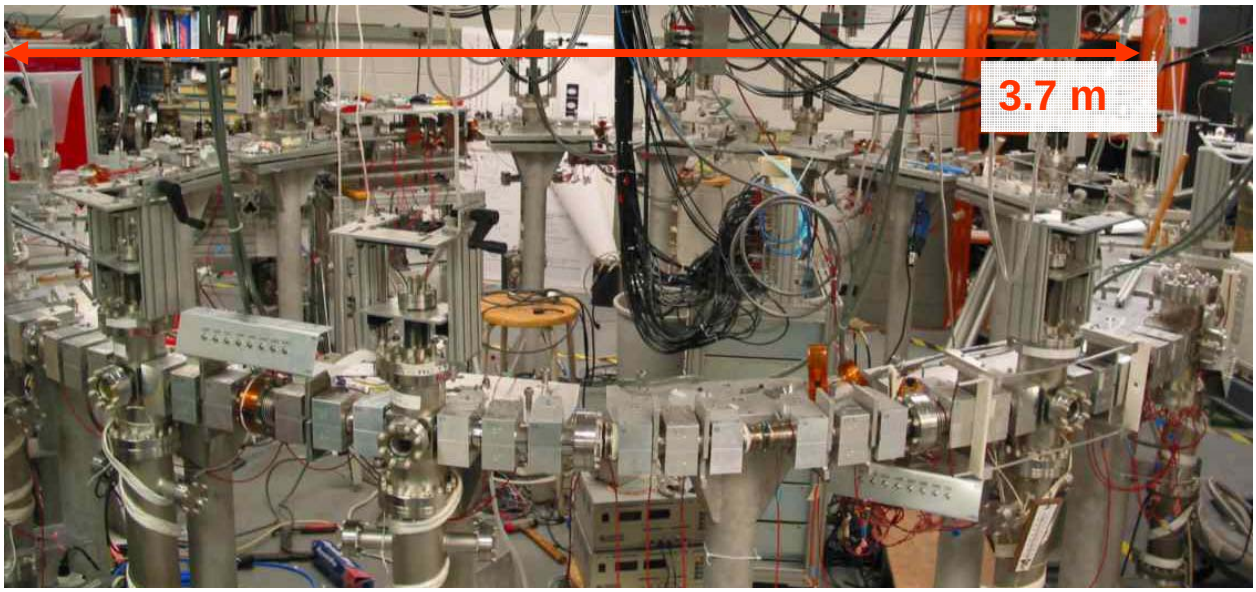
Pat O'Shea, Martin Reiser, Rami Kishek, and Irving Haber
Institute for Research in Electronics and Applied Physics
University of Maryland, College Park

Summary

Existing high energy accelerators are substantially constrained by space charge forces within the beam, which if not properly controlled, can lead to deleterious effects such as emittance growth, instabilities, and halo formation. These effects limit the number of particles that can be transported in a given phase space volume, ultimately impacting the luminosity of the machine. At the University of Maryland Electron Ring (UMER) Facility, we employ a number of low-energy electron experiments designed to deliberately enhance space charge effects, in order to shed light on these issues and learn how to better control and manage space charge effects in beams. The centerpiece of our laboratory is the Electron Ring, a small-scale (4-m diameter) recirculator transporting up to 100 mA of 10 keV electrons, or about 10 nC per a 100-ns pulse. When scaled to energies and parameters comparable to the International Linear Collider (ILC) or the Fermilab damping rings, for instance, the UMER beam correspondingly possesses orders of magnitude more space charge. This beam intensity and the density and quality of the UMER diagnostics and simulation support place our lab at the forefront of understanding space charge dynamics.

In addition to UMER we have a separate experiment, the Long Solenoid Experiment (LSE) for offline development of diagnostics, such as a high-resolution energy analyzer, and for exploring longitudinal dynamics in beams and energy spread evolution. This work is closely coupled with a program on free electron lasers and photocathode development. All these experiments are augmented by a superb computer simulation capability closely coupled with the experimental program. The main computational workhorse is the Particle-in-Cell (PIC) code WARP, developed at Lawrence Livermore National Laboratory/Navel Research Laboratory (LLNL/NRL) [Grote, *et al.*, Fus. Eng. Des **32-33**, 1996] and extensively benchmarked on our experiments.

Altogether, this valuable investment from the U.S. Department of Energy (DOE) enables a large number of students to carry out cutting-edge experiments of relevance not only to existing and future high-energy machines but also to many other emerging applications of high-brightness beams, such as spallation neutron sources and free-electron lasers.



University of Maryland Electron Ring

Recent Accomplishments [with references to the publications below]

- Closure of UMER in late 2004 and the beginning of multi-turn commissioning. With little attempt at multi-turn steering, four consecutive signals were detected in a beam position monitor (May, 2005), indicating at least part of the beam has propagated over three turns. The number of turns propagated is expected to increase significantly as UMER is fine-tuned for multi-turn operation. [Pubs. 18-19]
- Many experiments were conducted on the beam prior to complete closure of the ring, including emittance measurements around the ring and development of new centroid steering, envelope matching, and rotation correction algorithms, all of which proved successful in attaining their goals. [Pubs. 6,9,12,19]
- All the different control programs have been integrated into a single LabView interface, and have been extended to accept feedback from the beam position monitors in addition to the phosphor screen – an essential step for multi-turn operation. [Pubs. 18-20]
- The injection Y-section has been extensively tested using the beam and simultaneously simulated both using WARP and using simpler centroid codes. [Pubs. 7,18,22]
- A high-resolution energy analyzer was developed and tested in the LSE, and has achieved an energy resolution of 10^{-4} and a time resolution of a few ns. This will soon be deployed in UMER. [Pubs. 3,11,16].
- The same energy analyzer deployed on the LSE was used to measure the energy spread evolution, resulting in remarkable agreement with the theoretical scaling laws derived from existing Coulomb collision models. At high solenoidal focusing strength, an unexpected fast nonlinear rise (within ~3 plasma wavelengths) of the energy spread was observed, which far exceeds the expectation for Coulomb scattering. We believe that it represents a collective instability that requires further study in future experiments and theoretical work including simulation. [Pubs 1,8]
- A novel laser photoemission perturbation technique was developed and later extended to multiple pulses. Detailed measurements were taken using both set-ups along the first turn of UMER. The perturbations were observed to decompose into fast and slow waves, in

agreement with theory. The wave speed estimated from the measurements agrees well with the theoretical value for small perturbations. [Unpublished results and pubs. 2,5]

- Both the average beam energy and the intrinsic energy spread as functions of time have been measured for a perturbation deliberately initiated near the cathode on the LSE. The experimental measurements confirm the predictions of the WARP code and are in general agreement with theory. [Pub. 23]
- WARP simulations of the UMER gun have achieved a level of sophistication whereby they accurately reproduce much of the detailed appearance of the observed UMER beam, such as beam density profile, a hollow velocity distribution, an observed 4-fold symmetry, and the dependence of all those on the bias voltage of the cathode grid. This level of success depended strongly on the accurate representation of the cathode grid in the simulation model, relying on mesh refinement techniques only recently introduced into WARP. [Pubs. 4,13,17,21]
- In addition to confirming and explaining observations, the WARP simulations of the UMER gun have predicted the formation of a pair of interacting virtual cathodes in the cathode-grid and grid-anode regions. Their mutual interactions result in a strong oscillation in the beam current at a frequency of 2 GHz, with an amplitude that can be controlled by varying the grid voltage. These predictions have subsequently been verified experimentally using a spectrum analyzer and a pickup antenna. [Pub. 21]

In addition to the main source of funding provided by the DOE Office of High Energy Physics, this research also benefits from partial support by the DOE Office of Fusion Energy Science and by the Department of Defense Office of Naval Research.

Publications (2003-2005) (complete list at http://www.umer.umd.edu/)

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3. Y. Cui, Y. Zou, M. Reiser, R.A. Kishek, I. Haber, S. Bernal, and P.G. O'Shea, "Coherent error study in a retarding field energy analyzer," Nuclear Instruments and Methods A **544**, 527-532 (2005)
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12. S. Bernal, *et al.*, "Intense Beam Transport Experiments in a Multi-Bend System at the University of Maryland Electron Ring (UMER)," Nuclear Instruments and Methods A **519**, 380-387 (2004)
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19. S. Bernal, G. Bai, D. Feldman, R. Feldman, T.F. Godlove, I. Haber, J. Harris, M. Holloway, R.A. Kishek, J. Neumann, C. Papadopoulos, B. Quinn, M. Reiser, D. Stratakis, K. Tian, T.C.J. Tobin, M. Walter, M. Wilson, and P.G. O'Shea, "Commissioning of the University of Maryland Electron Ring (UMER)," Proc. PAC 2005
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23. K. Tian, Y. Zou, Y. Cui, M. Reiser, I. Haber, R.A. Kishek, and P.G. O'Shea, "Study of Longitudinal Space-Charge Wave Dynamics in Space-Charge Dominated Beams," PAC 2005

Current Research Staff (Tasks A and C)

O'Shea, P.G.	Principal Investigator, Professor and Chair, Electrical & Computer Engineering
Reiser, M.	Co-Principal Investigator, Professor Emeritus and Senior Research Scientist
Kishek, R.	Co-Principal Investigator, Associate Research Professor
Haber, I.	Co-Principal Investigator, Senior Research Scientist
Walter, M.	Assistant Research Scientist
Feldman, D.*	Senior Research Scientist
Bernal, S.	Assistant Research Scientist
Quinn, B.	Engineer
Godlove, T.	Visiting Scientist

Graduate Students

Tian, K.	(M.S. 2005)	Pursuing Ph.D.
Bai, G.		Pursuing Ph.D.
Tobin, C.		Pursuing Ph.D.
Papadopoulos, C.*		Pursuing Ph.D.
Stratakis, D.		Pursuing Ph.D.
Holloway, M. *		Pursuing Ph.D.
Li, H.	Ph.D. Granted 8/04	Currently employed at Microsoft
Cui, Y.	Ph.D. Granted 8/04	Currently employed at KLA-Tencor
Harris, J. *	Ph.D. Granted 7/05	Currently employed at LLNL
Huo, Y.	M.S. Granted 8/04	Currently at Stanford

* Funded from sources other than DOE-OHEP

Undergraduate Students (B.S.)

An Diep	(2003)	Wing Tze Lee	(2005)
Mike Quirius	(2003)	Christopher Jordan	
Maggie Snowel	(2003)	Chris Annabelle	
Brian Beaudoin	(2003)	Colin McFall	
Glanzer, M.	(2003)	Genna Davidson	
Allyson Gregory	(2004)	John Wyrus	
Mike Holloway	(2004, currently a graduate student in our group)	Kuanwen Hsieh	
Damon Lamb	(2004)		

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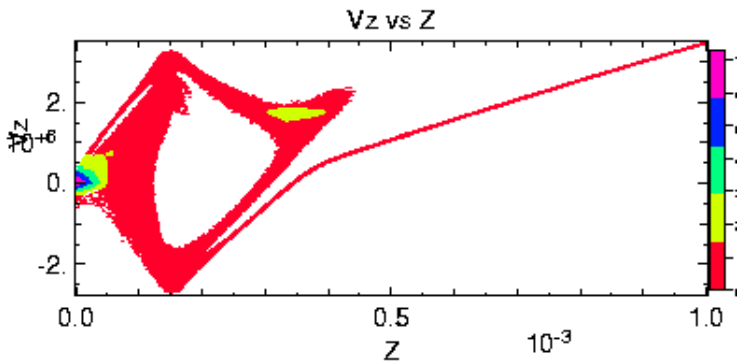
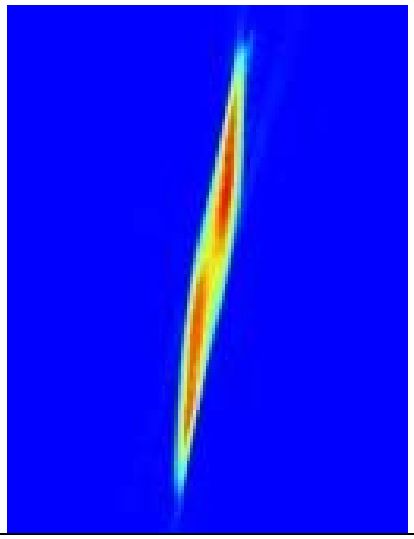
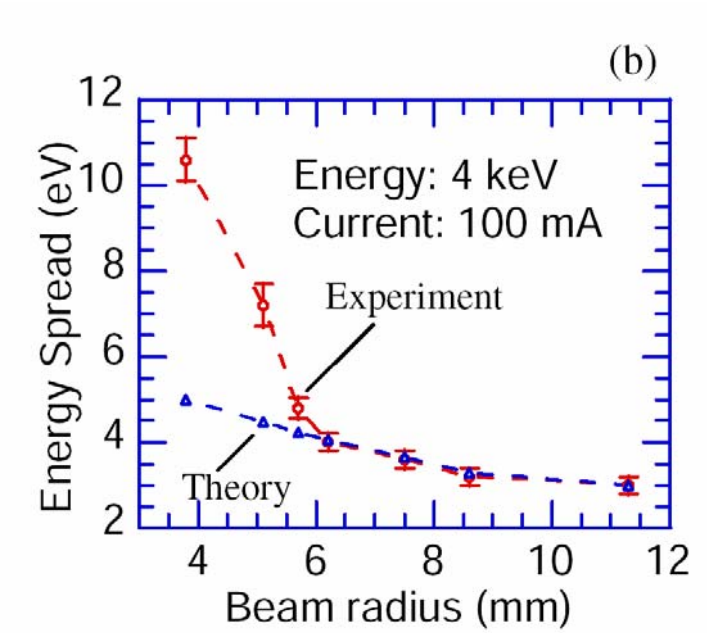


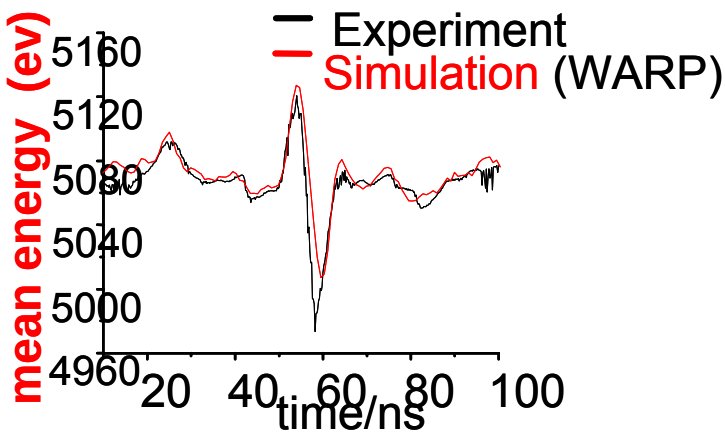
z-vz phase space from a WARP simulation showing the interplay between 2 virtual cathodes in the first 1/2 mm of the UMER gun.



Tomographically- reconstructed beam phase space



Anomalous growth of energy spread for smaller beams.



Energy Analyzer measurement of fast and slow space-charge waves compared to WARP simulation

Investigations of Beam Dynamics Issues at Current and Future Accelerator

James A. Ellison
University of New Mexico

Summary and Recent Accomplishments

There are many significant problems in beam dynamics that raise issues at the forefront of what is understood in dynamical systems, probability and scientific and high performance computing. This makes it an ideal area for interaction between academic applied mathematics and accelerator laboratories. The Advanced Technology R&D Program at Department of Energy (DOE) makes this possible. Collaborators are essential to our beam dynamics work and Warnock Stanford Linear Accelerator Center (SLAC) has played a central role in much of the work. In addition, specific projects would not be possible without the collaboration of P. Alsing, D. Barber, G. Bassi, V. Boocha, P. Colestock, H.S. Dumas, K. Heinemann, G. Hoffstaetter, M. Salas, T. Sen, A. Sobol, M. Venturini, I. Vlaicu, and M. Vogt.

Vlasov Equation

A major focus of our work is an analytical and numerical study of collective effects using the Vlasov equation which governs the evolution of the phase space density of the beam [1, 8, 12-17, 20, 22, 23]. With Warnock, we have developed a general numerical algorithm for its integration which is having wide application. This was first reported in the Proceedings of the 2nd International Committee for Future Accelerators (ICFA) Advanced Accelerator Workshop, University of California Los Angeles, 1999 (See also SLAC-Pub-8404), where the sawtooth instability was studied. The algorithm is based on a discretization of the Perron-Frobenius operator, which is equivalent to integrating along characteristics locally, and we refer to it as the PF method. Most of our numerical work has been done in one-degree freedom (1DOF) but we are beginning to apply the algorithm in 2DOF. In addition, we have developed an algorithm for the computation of moments of the Vlasov equation, in the collective beam-beam case, using an improved macro-particle tracking algorithm. The associated code, weighted macroparticle tracking (WMPT), was written by Vogt. We are pushing the boundaries of what can be calculated in reasonable time and therefore are using and investigating high performance computing techniques. Analytically we are investigating the existence of equilibria and linearized behavior about these equilibria. We are developing a weakly nonlinear theory and investigating fully nonlinear effects by studying perturbations with respect to an equilibrium and with respect to the collective force, both short and long time. The Vlasov work is applied in several contexts below.

Coherent Synchrotron Radiation (CSR)

We have studied CSR effects on the 1DOF longitudinal dynamics, for both the coasting and bunched beam cases, using an impedance formalism [12, 13]. We are presently studying [14] the SLAC damping rings and the Vacuum UltraViolet (VUV) ring at Brookhaven National Laboratory (BNL), incorporating both CSR and machine wake, using the work of [12, 13]. We have made significant progress on the very difficult and subtle problem of calculating CSR from arbitrary planar orbits in the fully self-consistent Vlasov-Maxwell 2DOF framework and are applying it in the bunch compressor case [9, 15-17, 22]. In a first attempt, the formula was implemented in a full Fourier domain. The idea was to apply the method of stationary phase to get an efficient evaluation of the fields. A summary of this attempt can be found in [9] where the conclusion is that the method is only partially effective. The current approach works in a 1D

Fourier domain. The efficient numerical evaluation of the new formula, which was quite a challenge, has been accomplished and has been checked against benchmark results [15, 16].

Collective Beam-Beam (CBB) Interaction

A major advance in understanding the existence of equilibrium phase space densities in the lepton [1] and hadron cases [20] has been made. This has been a combination of numerical work and analysis. We completed our numerical study of the PF and WMPT methods in one degree of freedom. A major advance is Vogt's two degree of freedom WMPT code which uses a hybrid fast multipole method for computing the beam-beam forces. A proposal for a partial parallelization of the code using a force decomposition method was positively evaluated [4, 10]. A parallel code that calculates the density evolution in the 2DOF case using the PF method is being developed by Sobol as part of his Ph.D. thesis, a very preliminary discussion can be found in [3]. Finally, we have developed a new model, an approximating Vlasov equation, for the CBB based on the classical method of averaging which has already had success in simplifying the usual study of σ and π modes [20].

Weak-Strong Beam-Beam (WSBB) Interaction

We have generalized the *Method of Averaging* to maps and have applied it to a class of beam dynamics problems in both 1 and 2DOF, including the WSBB [2, 5, 11]. We have constructed tune diagrams for the averaging normal forms, clarified the dynamics near the crossing of two resonance lines and are poised to study the WSBB with tune fluctuations and the so-called modulational diffusion. In addition, Boocha's thesis work made a contribution to a beam-beam simulation code that Sen is creating for the Tevatron [4].

Longitudinal Collective Effects Due to Machine Wakes and CSR

We have considerably deepened our understanding of longitudinal dynamics with machine wakes and CSR in both the coasting and bunched beam cases [8, 12, 14]. The PF code, which was developed to understand the sawtooth instability in the SLAC damping rings, has been refined and applied [12, 14]. Progress is being made on the understanding of microbunching due to CSR. Finally, a theory of weak turbulence including Schottky noise is nearly complete [23] and is the subject of Vlaicu's Ph.D. thesis.

Spin Dynamics

A definitive paper on quasiperiodic spin motion and spin tune for orbital flows has been published [6]. The invariant spin field is a central concept in the theory and we have made significant progress on determining sufficient conditions for its existence, a very difficult mathematical problem. For example, we have applied the Birkhoff ergodic theorem to stroboscopic averages of spin fields which leads to a periodic polarization field. This is a foundational issue for the current state of the art code, SPRINT, used for spin tracking and which is based on stroboscopic averaging. We note that SPRINT, developed by Vogt and Hoffstaetter, is slowly making inroads at Relativistic Heavy Ion Collider (RHIC). Finally, considerable progress on understanding the adiabatic invariance of the invariant spin field when parameters are slowly varied has been made [19, 21].

Most Significant Accomplishments

- The PF algorithm developed by Warnock and Ellison has become a major workhorse for solving the Vlasov equation in 1DOF. Its power has been demonstrated in studies of the sawtooth instability and microbunching due to CSR. This is illustrated by the attached figure where we show the phase space density at seventy synchrotron periods, after the sawtooth has developed. The structure is complicated and the fact our Vlasov algorithm can follow the density for long times illustrates its power.
- We have formulated an integral equation that must be satisfied if equilibrium is to exist for the CBB lepton case and shown that it has a solution. We have made a significant case for the existence of an approximate equilibrium in the proton case using formal perturbation theory and numerics.
- The development of Vogt's macro-particle code using Greengard's fast multipole method for the CBB in 2DOF is complete.
- We have developed the Method of Averaging for maps complete with error bounds in the single frequency case, extended the formalism to the two frequency case and investigated the 2DOF WSBB. This has clarified the dynamics near the crossing of two resonance lines.
- A deep understanding of quasiperidic spin motion for orbital flows and the application of the ergodic theorem to the question of existence of invariant spin fields.
- A new formula for calculating the CSR field from arbitrary planar orbits has been developed.

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Program for Plasma-Based Concepts for Future High Energy Accelerators

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Summary

The goals of the University of Southern California (USC) program are to explore and develop new schemes for particle acceleration and focusing, to adapt plasma physics techniques to enhance modeling and control of near term rf accelerators and to train advanced graduate students with a unique blend of accelerator, beam, plasma, laser and computational expertise needed for future advances in accelerators. We are actively pursuing these goals through experiments, advanced computational modeling and theory. Our vision is to address critical issues for realizing the promise of a plasma-based accelerator at the energy frontier in the next decade.

Recent Accomplishments

Highlights of accomplishments in this period include:

- Demonstration of energy gain above 1 GeV in the E-164X Plasma Wakefield Accelerator Experiment at the Stanford Linear Accelerator Center.
- Further development and modeling of the Plasma Afterburner concept for doubling the energy of a future linear collider.
- Development and application of advanced 3-D particle simulation tools (OSIRIS and QuickPIC) on high-performance platforms for modeling current plasma accelerator experiments with unscaled parameters and unprecedented fidelity, including self-consistent plasma ionization, beam and plasma imperfections, aperturing effects of the diagnostics, etc.
- Deployment of a novel circular accelerator simulation code exploiting the power of plasma wakefield algorithms to model the dynamics and stability of circulating beams in electron clouds.

The E-164 Plasma Wakefield Accelerator experiment was designed to demonstrate ultra-high-gradient electron acceleration at energies of relevance to high-energy colliders and over length scales of tens of centimeters. This experiment has produced a wealth of spectacular results and physics milestones. As described in the references that follow, the collaboration between USC, University of California Los Angeles (UCLA), and Stanford Linear Accelerator Center (SLAC) achieved a number of firsts: These include the acceleration of electrons in the tail of a 30 GeV SLAC bunch by up to 4 GeV over 10 cm of plasma. The experiment was also the first to operate in a self-ionized regime in which the electric field of a longitudinally compressed beam was sufficiently intense to tunnel-ionize a working Li gas. The viability of this simple approach greatly reduces the technological barrier to realizing the several meter long plasmas that will be needed for extending the energy frontier. The good agreement between these results and the expected scaling up of the gradient from our previous E-162 experiment (280 MeV gain over 1.4m) bodes well for the collaboration's ultimate goal of realizing a plasma afterburner. Our next experiment, E-167 will attempt to extend the interaction length and energy gain to the 10 GeV level.

If plasma accelerators are to have impact in future high energy physics colliders, they must address not only the need for high-gradients but also the need for high beam quality and the

need to accelerate positrons as well as electrons. E-164 accomplished this by designing the incoming beam optics to match the theoretical Twiss parameters associated with the plasma's strong transverse focusing fields, thereby preserving the beam emittance. The recently completed E-162 experiment also exploited the unique capability of the SLAC facility to deliver positron beams in order to perform the first plasma acceleration test of positrons *Figure 1*. The results confirmed that the physics of positron acceleration and focusing is significantly different from that of electrons in the nonlinear regime, but showed excellent agreement with detailed Particle-in-Cell (PIC) simulations. In the near future E-167 will explore novel approaches to forming a shaped witness beam that can demonstrate not only high energy gain but small energy spread in a plasma wakefield accelerator.

In experiments we are designing at the Accelerator Test Facility (ATF) facility in Brookhaven, we will soon explore the use of multiple drive bunches for increasing the energy gain (transformer ratio) of a plasma wakefield accelerator. Preparatory modeling and theory (Ref. 7) and preliminary experiments have been performed in this contract period.

On the theory front, graduating PhD student Suzhi Deng completed her thesis on advanced modeling of plasma wakefield physics in ionizing plasmas. For this work she implemented ionization algorithms into the PIC code OSIRIS and used these to study 3-D physics. New results include detailed comparisons to the E-164 experiments, identification of a new regime of hose-free beam propagation, and identification and quantification of a new instability associated with coupling of beam offsets to the offset ionization channels they produce.

The interaction between positively charged high current beams with the low-density electron clouds they create in circular accelerators has become a major concern in a number of accelerators world-wide *Figure 2*. The electron-cloud effect will be important to Large Hadron Collider (LHC), Spallation Neutron Source (SNS) and Fermilab upgrades, and is already important for Relativistic Heavy Ion Collider (RHIC), PEP-II, Brookhaven National Laboratory (BNL) booster, AGS, Los Alamos Neutron Scattering Science Center (LANSCE) PSR and KEK. The mechanisms of the e-cloud interaction are not well understood and predictive models are greatly needed. The challenge for computational modeling of e-clouds arises from the need to model beam propagation over hundreds of thousands of kilometers while resolving the self-consistent space charge fields of the cloud on cm scales. But just such a predictive model now appears possible feasible using high-performance parallel computing techniques and advanced algorithms developed for plasma wakefield studies.

A collaboration of the plasma wakefield accelerator groups at USC and UCLA has now adapted a code which they have been using for plasma based accelerators studies over the past decade, to the electron cloud problem (the electron cloud is after all a non neutral plasma problem). The code, QuickPIC, is based on Viktor Decyk's (UCLA) Framework for developing parallel PIC codes. This includes highly optimized components and parallelization. In order to properly model the e-cloud problem, the capability of QuickPIC to model the cloud interaction needed to be combined with algorithms from the circular accelerator community to track particles in the external magnets and RF fields. Particularly synchrotron and betatron motions are added to the code and the chromaticity is also included to take care of the changes in the betatron frequency due to momentum spread of the beam. Recent graduate Ali Ghalam, devoted his PhD thesis to this topic, and his accomplishments have been recognized by invited talks at the ECLOUD04, PAC05 and APS DPP 05 meetings. The code has now been used to model LHC for over a thousand turns, PEP-II and the International Linear Collider damping rings. We are currently collaborating with P. Spentzouris at Fermi National Accelerator Laboratory to model the Tevatron, and we are continuing to improve the fidelity and speed of

the model through advanced algorithms. The goal is to develop predictive capability to ensure the performance of major upcoming facilities such as the LHC and SNS.

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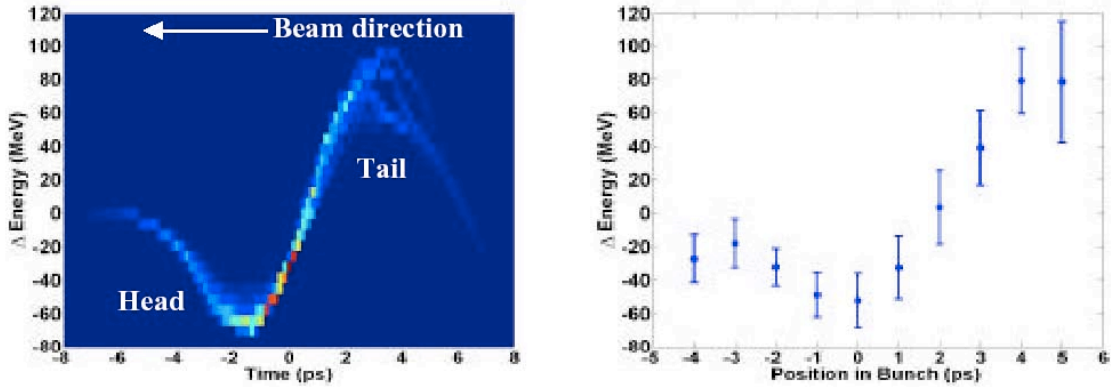

Figure 1 shows results of a 3-D OSIRIS simulation of the E-162 experiment (left) and the experimental data (right) for *positrons*. Plotted are the time-resolved energy loss and gain along the bunch. The tail was accelerated by 80 MeV in 1.4 meters.

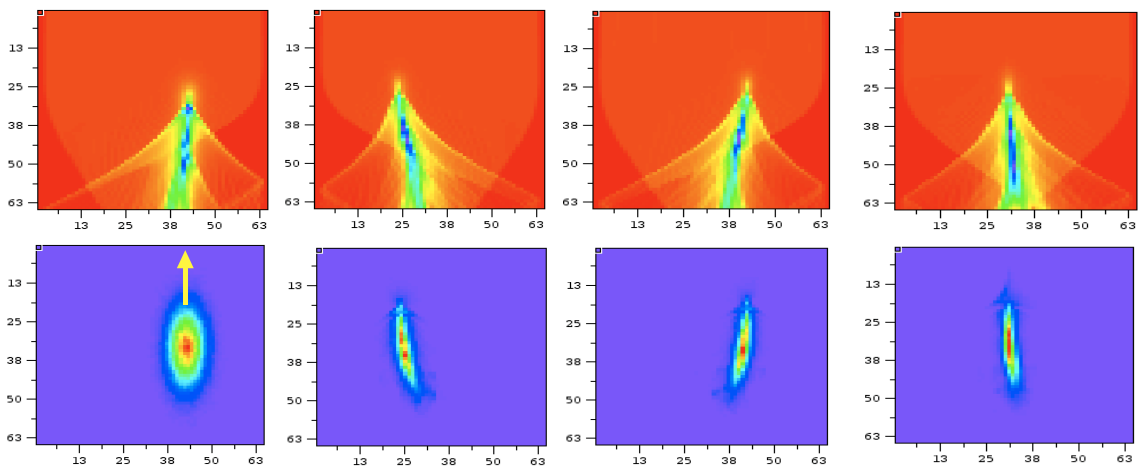

Figure 2 shows snapshots of off-centered (by 3σ_r) beam and electron cloud interaction over 1 turn (27Km) of SPS storage ring at CERN. The upper figures show cloud density and the lower ones show the corresponding beam density. The snapshots from (a) to (d) are taken at propagation distances of Z=0, 15.3, 20.4 and 27 km. The beam is oscillating over the center of the pipe due to the space charge of the cloud and the machine magnets. Small head-tail phase mixing due to the cloud compression behind the beam is observed. Beam and cloud are initialized with SPS storage ring parameters at CERN.

Laser Wakefield Acceleration: Channeling, Seeding and Diagnostics

Michael Downer
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Summary

The Texas program is developing methods of diagnosing and controlling laser-driven plasma accelerating structures in a tabletop terawatt laser laboratory setting. Our group developed spectral interferometry methods that we used to make the first femtosecond-time-resolved measurements of laser wakefield accelerator structures in both resonant and self-modulated regimes. We also demonstrated distortion-free propagation of terawatt laser pulses through cm-long, fully-ionized He and hydrogren plasma waveguides, thus laying the groundwork for laser wakefield acceleration (LWFA) up to GeV energies. Most recently we developed the theory and experimental system for a two-pulse, Raman-seeded LWFA configuration that enables relativistic electrons to be generated with less energetic, higher repetition rate laser pulses than is currently possible with single-pulse configurations, and thus to be potentially useful for medical radiation applications.

Recent Accomplishments

Pump-probe experiments in plasma channels. Pump-probe experiments with guided pump intensity $I_{guided} \approx 0.2 \times 10^{18}$ *W/cm*^{2} were performed in the plasma waveguide, a pre-requisite to diagnosis of channeled LWFAs. Fs interferometric diagnostic methods were applied in channels for the first time. Special issues that arise from applying them in channels (pump depolarization, cumulative ionization blueshifts of the probe pulse, group velocity walk-off of pump and probe pulses) were exhaustively measured and analyzed.

Raman-seeded LWFA. Raman-seeded (RS) LWFA, a two-pulse technique for improving the efficiency and coherently controlling the growth of a wakefield in the self-modulated regime was extensively investigated with 1D and 2D PIC simulations. The effect of a weak seed pulse ($a_{0seed} \sim 0.1a_{0main}$) on pulse modulation, wakefield excitation and particle trapping and acceleration was explored. The simulations show that main pulses of only 38 mJ can generate relativistic bunches of ~0.5 nC when Raman-seeded. RS-LWFA by pulses of *sub-critical* power ($0.5P_{crit}$, 19 mJ) was demonstrated by simulations in a plasma channel. Such low pump pulse energies enable LWFA at repetition rates approaching 1 kHz, which in turn enables dose rates > 4 Gy/min in radiation therapy. The feasibility of medical applications of RS-LWFA, including full dosimetric analysis of the simulated RS-LWFA output beam in light of accepted medical criteria, has been demonstrated in collaboration with colleagues at University Texas-Houston MD Anderson Cancer Research Center.

On the experimental side, we made progress toward experimental demonstration of Raman-seeded LWFA. Specifically we developed a ~3 mJ, 870 nm, 120 fs pulse source synchronized with the parent .25 J, 800 nm, 80 fs Ti:S pulses by shifting a portion of the latter, prior to compression, by stimulated Raman scattering in a $Ba(NO_3)_2$ crystal. In current experiments the 873 nm seed pulse and 800 nm main pulse co-propagate through a supersonic gas jet. An electron analysis system consisting of a magnetic spectrometer and an integrating current transformer has been implemented. The 873 nm Raman seed also provides a novel source of synchronized probe pulses at wavelengths other than the fundamental or its harmonics.

Single-shot frequency domain holography. We made progress toward applying single-shot frequency-domain holography to the characterization of resonant laser wakefields. This work

follows up on previous single-shot measurements of ionization fronts. Specifically, various sources of phase noise are now much better controlled, and a differentially-pumped cell providing highly uniform, controlled gas density profiles was designed, built, and tested.

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***** *winner of Farrington Daniels Award of the American Association of Physicists in Medicine for "one of the two best papers published in Medical Physics during 2004"*

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Gennady Shvets	faculty collaborator	theory and simulation of laser-plasma physics
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Franklin Grigsby	Ph. D. student	Raman-seeded LWFA experiments
Nicholas Matlis	Ph.D. student	laser wakefield diagnostic experiments
Bonggu Shim	Ph.D. student	cluster plasma experiments
Rafal Zgadzaj	Ph.D. student	plasma channel experiments
Sebastian Jung	M. S. student	laser wakefield diagnostic experiments
Philip J. Smith	M. S. student	laser pulse compression

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Alexander Debus	M. S. 2004	plasma channel experiments

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Advanced Accelerator Studies

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The University of Texas at Austin

Summary

Our theoretical/computational group has recently relocated from Illinois Institute of Technology (IIT) to The University of Texas at Austin, and is presently based in Physics Department and at the Institute for Fusion Studies (IFS). The focus of our work is on the development of plasma based and structure-based accelerating concepts, including laser-plasma accelerators, microwave-based plasma accelerators, and laser driven structure-based accelerators. While pursuing this applied research, we pay special attention to the fundamentals of high intensity laser-plasma interactions, such as parametric instabilities in plasma channels, parametric excitation of plasma waves using multiple laser beams, instabilities of laser beams in plasmas, and propagation of microwave beams in the magnetized plasma. Most important advances have been made in the following areas: (i) excitation of accelerating plasma waves in the plasma beatwave accelerator (PBWA) configuration using the discovered by us concept of Dynamical Bi-Stability; (ii) generation of ultra-short pulse trains using the discovered by us concept of the Electromagnetic Cascade in the plasma; (iii) generation of accelerating waves in magnetized plasma using Undulator Induced Transparency (UIT), (iv) design, fabrication, and testing of a laser-driven Surface Wave Accelerator Based on Silicon Carbide (SWABSiC). These advances are briefly described below.

Excitation of accelerating wakes using Dynamical Bi-Stability of relativistic plasma waves (Shvets, PRL **93,** 195004 (2004)).

Although plasma beatwave accelerator is the oldest plasma-based concept, our group has found a new important improvement of the concept. Accelerating waves are excited by an intense two-color laser beam, and the frequency detuning between the two colors is assumed to be slightly smaller that the plasma frequency. When the laser beam intensity exceeds a detuning-dependent threshold, the phenomenon of dynamical bi-stability occurs: a long beatwave leaves behind a relativistic wake. Remarkably, we have found that the wake is left behind for a very broad range of laser pulse durations. The amplitude of the final wake is close to cold-plasma wavebreaking limit, and is fairly insensitive to possible initial perturbation of the plasma.

Dynamical Bi-Stability can be explained in terms of a representative Hamiltonian particle describing the plasma wave. The representative particle undergoes a complicated nonlinear dynamics in the phase space that includes separatrix crossings and phase space bifurcations. Whether the wake is excited or not is determined by the pulse duration and the initial (if any) plasma wave amplitude and phase. We have also demonstrated the nonlinear “cleanup” by the trailing laser pulse of the undepleted plasma wake left behind the leading laser pulse. Particle-in-Cell (PIC) simulations have been used for first principles proof of the Dynamical Bi-Stability. In three dimensions we have demonstrated that the Dynamic Bi-Stability takes place when the laser intensity on axis exceeds the detuning-dependent threshold while the off-axis intensity is below the threshold. Extremely localized in the transverse dimension plasma wakes can thus be obtained. Those are of interest for future collider applications because the accelerated beam needs to be very narrow.

Generation of ultra-short pulse trains using the Electromagnetic Cascade in the plasma (Kalmykov & Shvets, PRL **94,** 235001 (2005); highlighted in Nature on July 14, 2005).

Periodic trains of ultra-short laser pulse has long been recognized as an efficient tool for driving strong plasma waves. Unfortunately, making such trains is not trivial. We have developed a new approach to producing trains of few-cycle laser pulses that we believe can be reduced to practice. A long laser pulse is time-compressed into a series of intense spikes in the plasma due to the generation of a coherent cascade of electromagnetic sidebands. This technique requires two co-propagating beams detuned by a near-resonant frequency $\Omega < \omega_p$. The ponderomotive force of the laser beat wave drives an electron plasma wave (EPW) which modifies the refractive index of plasma so as to produce a periodic phase modulation of the laser field with the beat period $\tau_b < 2\pi/\Omega$. A train of chirped laser beatnotes (each of duration τ_b) is thus created. The group velocity dispersion (GVD) of radiation in plasma can then compress each beatnote to a few-laser-cycle duration. As a result, a train of sharp electromagnetic spikes separated in time by τ_b is formed. Depending on the plasma and laser parameters, chirping and compression can be implemented either concurrently in the same plasma, or sequentially in different plasmas.

Generation of Accelerating Waves Using Undulator Induced Transparency (Shvets et. al., Phys. Plasmas **12,** 056701 (2005))

The quest to higher accelerating gradients (and, consequently, shorter and more practical accelerators) inevitably points to higher frequencies of the accelerating field. This is because, according to the dark current trapping criterion, the accelerating gradient scales linearly with frequency. In a conventional metallic accelerating structure higher frequencies also imply smaller feature size. Those are hard to fabricate, and can be easily damaged by single-pulse Ohmic heating and the resulting cyclic stress. It appears unlikely that future metallic accelerators will be operated at a shorter than 1 cm wavelength. At the other end of the frequency spectrum are the laser-driven plasma accelerators that require short-pulse high power laser pulses because the accelerating plasma wave is driven via the nonlinear ponderomotive force.

We have initiated theoretical and computational investigations of the previously overlooked regime of intermediate frequencies (hundreds of GHz) and plasma densities (of order 10^{14}-10^{15} cm^{-3}) where high power microwaves can be directly converted into plasma waves. The incident microwave pulse is compressed in the plasma and converted into a predominantly longitudinal wave. Therefore, plasma is both the power compressor and the accelerator. External magnetic field is necessary to enable coupling of the incident electromagnetic waves into the plasma. The configuration we are currently exploring requires two magnetic fields: axial (along the beam and wave propagation) and a transverse undulating field. This configuration is based on the recently discovered by us phenomenon of UIT of magnetized plasma at the cyclotron frequency. The essence of UIT is that the normally opaque at the cyclotron frequency plasma becomes transparent in the presence of an undulator when the electron plasma and cyclotron frequencies are equal. Our analysis and PIC simulations demonstrate that it should be possible to efficiently couple microwaves in without reflections, and use the predominantly longitudinal plasma wave for accelerating electrons or even ions. Our work demonstrates power compression by almost two orders of magnitude for realistic magnetic field and plasma density profiles.

Publications

Selected Refereed Journal Articles (listed chronologically):

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3. G. Shvets and M. Tushentsov, “Nonlinear propagation of electromagnetic waves in a plasma by means of electromagnetically induced transparency,” Journal of Modern Optics, **15**, 2583 (2003)
4. S. Yu, Kalmykov and G. Shvets, “Stimulated Raman Backscattering of Laser Radiation in Deep Plasma Channels,” Phys. Plasmas **11**, 4686 (2004)
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7. G. Shvets and Ya. A. Urzhumov, “Polariton-enhanced near field lithography and imaging with infrared light,” Mat. Res. Soc. Symp. Proc. **820**, R1.2.1 (2004)
8. G. Shvets and Ya. A. Urzhumov, "Engineering Electromagnetic Properties of Periodic Nanostructures Using Electrostatic Resonances,” Phys.Rev.Lett. **93,** 243902 (2004)
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10. M. Tushentsov, G. Shvets, A. Kryachko, and M. Tokman, "Undulator-Induced Transparency of Magnetized Plasma: New Approach to Electromagnetic Energy Compression,” IEEE Trans. Plasma Science **33,** 23 (2005)
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13. S. Kalmykov, O. Polomarov, D. Korobkin, J. Otwinowski, J. Power, and G. Shvets, “Novel techniques of laser acceleration: from structures to plasmas,” accepted for publication to the Philosophical Transactions of the Royal Society (2005)

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3. G. Shvets, “Applications of surface plasmon and phonon polaritons to developing left-handed materials and nano-lithography,” SPIE Conference Proceedings, v. 5221, 124 (2003), San Diego, CA., Aug. 3-8 (2003)
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9. S. Reiche, C. Joshi, C. Pellegrini, J.B. Rosenzweig, S. Ya. Tochitsky, G. Shvets, “Feasibility Study of a Beat-wave Seeded Thz FEL at the Neptune Laboratory,” Proceedings of Particle Accelerator Conference, May 16-20, 2005, Knoxville, TN
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Current and Past Staff

Gennady Shvets	Principal Investigator
Sergey Kalmykov	Postdoctoral Associate
Dmitriy Korobkin	Postdoctoral Associate
Michael Tushentsov	PhD Student, UT-Austin
Burton Neuner III	PhD Student, UT-Austin

Theoretical Investigations of Plasma-Based Accelerators
(PI: Gennady Shvets, The University of Texas at Austin)

- **Generation of Ultra-Short Pulse Trains Using Electromagnetic Cascade (highlighted in Nature on July 14, 2005)**

PLASMA PHYSICS

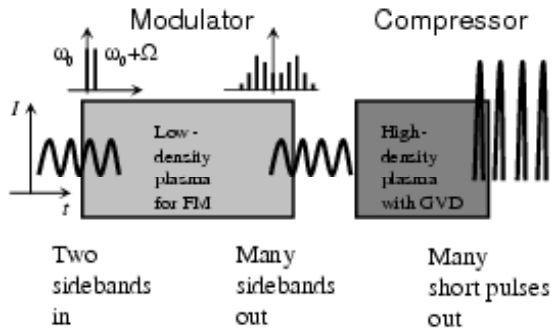
Bright sparks

Phys. Rev. Lett. **94,** 235001 (2005)

Two researchers from the University of Texas at Austin have identified a promising way to amplify laser power using a plasma of ions and electrons. If the technique holds up in experiments, it could be used to build desktop particle accelerators for medical applications and fundamental physics research.

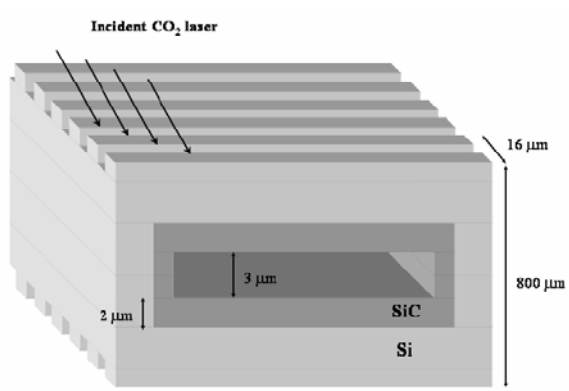
Serguei Kalmykov and Gennady Shvets calculate that a laser beam travelling through a dense plasma will create a wave that focuses the laser light into a train of sharp pulses — each about 10 to 100 times as intense as the initial beam. A similar technique has been tested with low-power lasers and standard gases, but the duo asserts that using a plasma could push the power of the laser pulses to a thousand trillion watts.

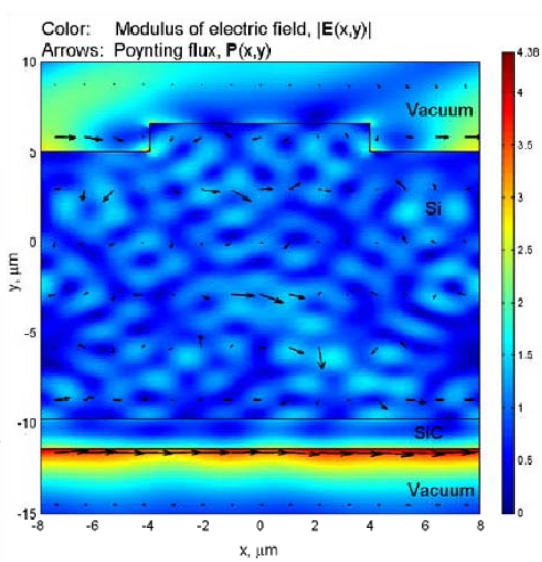
Schematic of a two-stage EM cascade compressor. Frequency modulation occurs in a rarefied plasma. Denser plasma is used for the pulse compression.
Kalmykov & Shvets, PRL 94, 235001 (2005)



- **Surface Wave Accelerator Based on Silicon Carbide (SWABSiC)**

Bottom: Schematic of a CO2 laser powered SWABSiC. Right: Electromagnetic simulation of field enhancement in SWABSiC





High Field Superconductor Development and Understanding: Flux Pinning, High Field Current Density and Novel Fabrication Processes for Probing the Limits of Performance in High Field Superconductors

David Larbalestier
Peter Lee
University of Wisconsin-Madison

Recent Accomplishments

We have shown that magneto optical (MO) imaging can be an immensely useful tool for positional evaluation of the superconducting behavior of accelerator strand, allowing us to add direct localized physical property measurements to our bulk quantitative-microstructure/physical property measurements that enable us to compare such properties as the Nb_3Sn layer J_c values (top left montage), and our Field Emission Scanning Electron Microscope-Energy Dispersive Spectroscopy (FESEM-EDS) and electron backscatter capabilities (top right) that enable us to measure macro-and micro-chemical variations. In the lower right of the montage we show how MO imaging can be used to demonstrate the effectiveness of the sub-element dividers needed to reduce hysteretic losses, in this case Ta+Nb-47Ti dividers in an OI-ST composite. With our new dual beam Focused Ion Beam (FIB) we are now using the MO imaging to determine areas of interest for thin foil preparation for subsequent high resolution-analysis. In the lower left we show how MO imaging can demonstrate sub-element to sub-element variability (in this case in collaboration with Emanuela Barzi at Fermi National Accelerator Laboratory (Fermilab).)

We have two PhD students, Matt Jewell (top right montage providing K12 teacher outreach) and Arno Godeke (graduated July 2005), who have been working on this program. In collaboration with Lance Cooley at Brookhaven National Laboratory we have clarified many important aspects of the optimization of conductors. It was clearly demonstrated in the last year that J_c and the irreversibility field H_k as determined by the commonly used Kramer function extrapolation are much more sensitive to the inevitable and generally ignored composition gradients than is H_{c2}. Lance Cooley developed a shell model in order to understand the effect of compositional gradients on the properties of the Nb_3Sn (Journal of Applied Physics 2004).

Arno Godeke investigated the complete field-temperature phase diagram for fields ranging from 0 to 30 T and for temperatures from 1.4 to 20 K on a substantial, diverse sample set of present commercial Nb_3Sn wires (J. of Appl Physics 2005), that conform many aspects of the modeling of Cooley et al. The results have attained considerable insights into: A) the field-temperature H_{c2}(T) boundary which was shown to be $\mu_0 H_{c2(0)} = 29.5 \pm 0.5$ T and $T_{c(0)} = 17.9 \pm 0.2$ K for all investigated wires, independent of manufacturing technique or composition and B) the property loss which occurs in present Nb_3Sn wires due to compositional gradients.

Matt Jewell has fabricated stoichiometric and off-stoichiometric 1 mm³, homogeneous, binary Nb_3Sn samples using hot isostatic pressing of powder-in-tube bulk samples. The effects of Sn concentration and of Sn gradients on critical temperature (T_c) and the measured upper critical field ($\mu_0 H_{c2}$) were examined using high sensitivity magnetometry. $\mu_0 H_{c2(0)}$ varied linearly from 10.9 Tesla (T) at 19.3 at.% Sn to >30 T at 24.6 at.% Sn. The surprisingly high value suggests that either (1) strain or (2) the Cu present in all practical Nb_3Sn conductors significantly suppresses H_{c2}. Additionally; we have demonstrated a very strong propensity for stoichiometric Nb_3Sn to form below 1800 °C, even when the nominal composition is decidedly off-stoichiometric. This shows the need for a fully volumetric measurement to accurately assess the effects of chemical inhomogeneity, and calls into question the Nb-Nb_3Sn boundary on the accepted phase diagram of Charlesworth. These issues matter in wires because it is clear from

Cooley and Godeke's work that managing the composition gradient is a crucial part of determining the properties.

Matt Jewell has performed high field property measurements on both Nb_3Sn and MgB_2 at NHMFL, showing exceptional high-field superconductivity in alloyed MgB_2 thin films (Physical review 2005).

Alex Gurevich has been working on the fundamental physical mechanisms, which limit the performance of superconducting cavities. The presentations of his work at the "Pushing the Limits of Superconducting Cavities" workshop at Argonne National Laboratory and at SRF'05 at Cornell University have been very well received by the SRFC community. It also provides crucial theoretical support to our SRFC collaboration with Fermilab.

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2. "The Microstructure and Micro-Chemistry of High Critical Current Nb_3Sn Strands Manufactured by the Bronze, Internal-Sn and PIT Techniques," P. J. Lee, C. M. Fischer, M. T. Naus, M. C. Jewell, A. A Squitieri, D. C. Larbalestier. IEEE Trans. Applied Superconductivity 13(2): pp. 3422-3425, 2003.

3. "The Influence of Nb_3Sn Strand Geometry on Filament Breakage under Bend Strain as Revealed by Metallography," Matthew C. Jewell, Peter J. Lee and David C. Larbalestier, presented at the 2nd Workshop on Mechano-Electromagnetic Property of Composite Superconductors, Supercond. Sci. Technol. 16 (2003) 1005–1011.

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10. “Progress On The Use Of Internal Fins As Barriers To Reduce Magnetization On High Current Density Mono Element Internal Tin Conductors (MEIT),” B. A. Zeitlin, E. Gregory, T. Pyon, R. M. Scanlan, A. A. Polyanskii, and P. J. Lee, Adv. Cryo. Eng., 50B, pp. 417-424, 2004

11. “Attempts To Reduce A.C. Losses In High Current Density Internal-Tin Nb_3Sn,” E. Gregory, B. A. Zeitlin, M. Tomsic, T. Pyon, M. D. Sumption, E. W. Collings, E. Barzi, D. R. Dietderich, R. M. Scanlan, A. A. Polyanskii, and P. J. Lee, Adv. Cryo. Eng., 50B, pp. 789-796, 2004

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16. “High-field superconductivity in alloyed MgB_2 thin films,” V. Braccini, A. Gurevich, J.E.Giencke, M.C. Jewell, C.B. Eom, D.C. Larbalestier et al, Phys. Rev. B 71, 012504 (2005)

17. “The upper critical field of filamentary Nb_3Sn conductors,” A. Godeke, M. C. Jewell, C. M. Fischer, A. A. Squitieri, P. J. Lee and D. C. Larbalestier, J. Appl. Phys. 97-9, 093909 May, 2005

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20. “Microstructure, Microchemistry and the Development of Very High Nb_3Sn Layer Critical Current Density,” P. J. Lee and D. C. Larbalestier, IEEE Trans. Applied Superconductivity, 15(2), pp: 3474-77, 2005

Theses

Arno Godeke, "Performance Boundaries of Nb_3Sn Superconductors," Ph.D. thesis, University of Twente, Enschede, The Netherlands, 2005 (the major experimental part of this work was performed at the University of Wisconsin).

Current Staff

Principal Investigator:	Prof. David Larbalestier
Co-Principal Investigator:	Dr. Peter Lee (Senior Scientist)

Staff

Dr. Alexander Gurevich (Senior Scientist)	Theory of flux pinning and the phenomenology of superconductors
Alex Squitieri	Magnet facility development and supervision.
Bill Starch	Fabrication laboratory supervision and strand fabrication and characterization.
Kate Liu	Workshop organization

Graduate Student

Matt Jewell

Undergraduate Students

Tyler Gerczak, Mike Fulton, Seth Haynes, Scott Olig, Brian Orf

Graduates from ASC from this contract in 2003-5

Arno Godeke:	PhD. University of Twente

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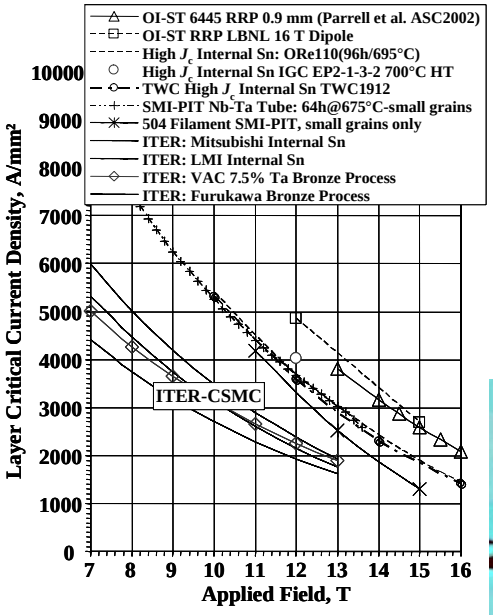
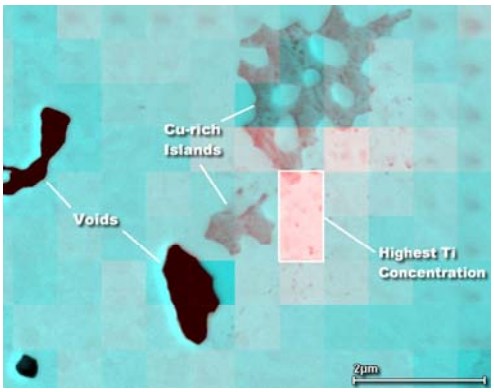
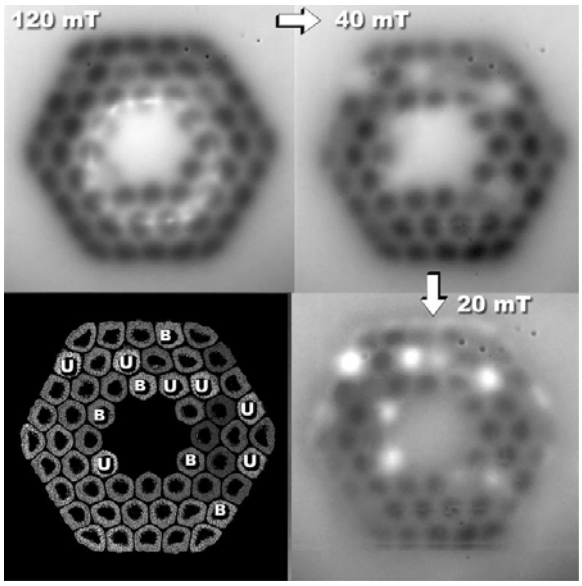


Comparison of layer critical current densities of engineering quality Nb_3Sn strands including the strand used for the record breaking LBNL 16 T dipole.

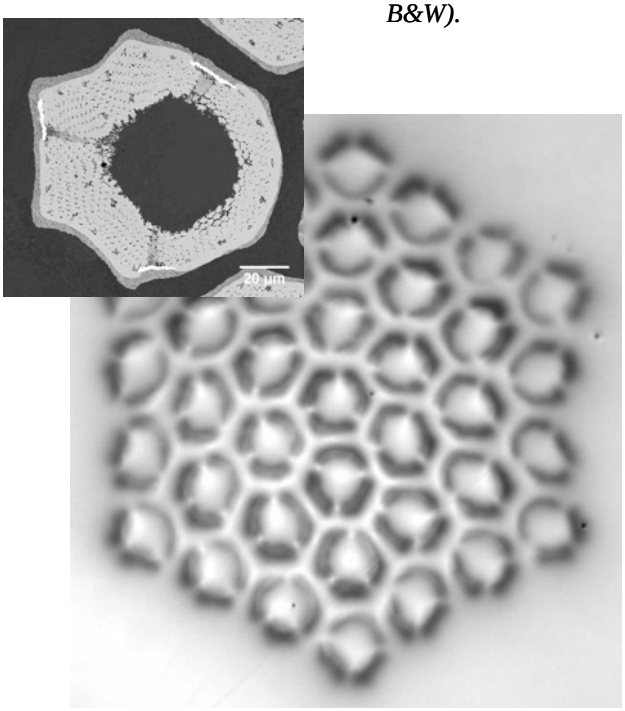
Graduate Student Matt Jewell demonstrates "Project Superconductivity" kits to school teachers at the ASC'04 Teacher Scientist Workshop



OI-ST distributed Nb-47Ti rod process internal Sn Nb_3Sn after heat treatment: Spectral image for Ti combined with atomic number sensitive FESEM-BEI image such that the higher Ti concentrations are shown in red (lighter shade if viewed in B&W).



Magneto-optical Image progression from 120 mT to 40 mT to 20 mT showing flux jumping from (bright) sub-elements in an OI-ST strand heat treated at FNAL. In the bottom left hand corner we compare these images with sub-elements shaded according to their measured Nb_3Sn area, with brightest sub-elements having the smallest areas. We also label the sub-elements "B" if the Nb Barrier has not been reacted through and "U" if there are Unreacted cores to the filaments. All the flux-jump sub-elements are either "B" or "U".



OST B7981 Nb-47Ti rods and Ta sheets combined to sub-divide sub-elements. Magneto Optical image (Zero Field Cooled, T=12 K H=80 mT) shows that the sub-elements have been divided flux has penetrated into the cores. Inset FESEM-BEI detail of sub-element showing Ta strips (white) and 3 adjacent dividers.

UNIVERSITY LINEAR COLLIDER PROGRAM

University-Based Accelerator R&D in Support of the International Linear Collider

Gerald Dugan
Cornell University

Introduction

In 1999, the International Committee for Future Accelerators recognized the world-wide consensus that the next large facility for particle physics should be an international high energy electron-positron collider. The strong recommendation in 2002 from the U.S. High Energy Physics Advisory Panel (HEPAP) [2] that a high energy, high-luminosity, electron-positron linear collider be the highest priority of the U.S. program was paralleled in Europe and Asia. Each region recognized the central importance of the physics to be studied, the maturity of the accelerator designs being advanced at laboratories in the U.S., Germany, and Japan, and the necessity for international cooperation.

Since then, progress on the International Linear Collider (ILC) has been swift. Regional steering committees, charged with organizing and coordinating ILC activities in Asia, Europe, and the Americas, have been formed, as has their global counterpart, the International Linear Collider Steering Committee (ILCSC). In 2003, the International Linear Collider Technical Review Committee (ILC-TRC) convened by the ILCSC, reviewed two designs based on differing accelerator technologies and concluded that both were feasible [1]. Then, in 2004, an international panel recommended that the ILC be based on the superconducting technology. The world's major laboratories have accepted that decision, and in November 2004, accelerator physicists gathered at Japan's KEK to identify the research required in order to complete the design. Currently, the ILCSC is forming the Global Design Effort, which will manage this research. At the national level, the U.S. Department of Energy (DOE) announced inclusion of the ILC in its 20-year plan for new facilities, according it the highest priority among the mid-term projects under consideration. At the HEPAP meeting in February 2005, Ray Orbach, director of DOE's Office of Science, said that the ILC is "our highest priority for a future major facility... we're going to work our hardest to bring the [I]LC to these shores."

The response from the U.S. High Energy Physics community has been equally swift. In early 2002, physicists from U.S. universities and laboratories organized a series of workshops at Chicago, Fermi National Accelerator Laboratory, Cornell University, Stanford Linear Accelerator Center, and the University of California, Santa Cruz, aimed at identifying important directions for research and collaboration toward the ILC. These groups organized themselves into the University Consortium for Linear Collider R&D (UCLC) [3] in the context of National Science Foundation support, and the Linear Collider Research and Development Working Group (LCRD) [4] in the context of DOE support. This year, with the development of a joint process for the review and funding of ILC R&D at universities, UCLC, and LCRD have effectively merged, and they now comprise groups from 49 U.S. universities, 7 national and industrial research laboratories and 23 foreign institutions. All concerned are working together to coordinate their activities to the single task of building the linear collider.

Physics Goals of the International Linear Collider

The physics goals of the ILC are ambitious and compelling. Over the past decade, a wide variety of experiments has shown that elementary particle interactions at the TeV scale are

dictated by an SU(3)xSU(2)xU(1) gauge symmetry. The non-zero masses of the W and Z particles imply, however, that the electroweak SU(2)xU(1) symmetry is broken spontaneously. We do not know how the symmetry is broken, and we will not know until the agents of electroweak symmetry are produced directly in the laboratory and, also, are studied in precise detail. But we have every reason to believe that whatever is responsible for electroweak symmetry breaking will be accessible at the ILC.

Although we do not know the mechanism of electroweak symmetry breaking, we have some good hypotheses. In the so-called Standard Model, one doublet of scalar fields breaks the symmetry. This model has one physical Higgs particle, which is the window to electroweak symmetry breaking. The global consistency of precision electroweak measurements gives this model credence, and suggests that the Higgs boson is relatively light, μH ~ 200 GeV. However, we know this model works poorly beyond TeV energies. A theoretically preferable scenario is based on supersymmetry (SUSY) at the expense of a whole new spectrum of fundamental particles and at least five Higgs states. But the lightest of these states looks much like the Standard Model Higgs, with nearly standard model couplings and a mass less than 200 GeV or so. Nature may break electroweak symmetry through some other mechanism, of course, but most realistic mechanisms we have imagined result in a Higgs boson or some related phenomena accessible to the ILC.

The TeV scale is the natural place to look for the agents of electroweak symmetry breaking. Thus, the ongoing Run 2 at Fermi National Acclerator Laboratory's Tevatron has a chance of getting the first glimpses of these phenomena. Starting later in the decade, CERN's Large Hadron Collider (LHC), with seven times the energy, will almost certainly observe the Higgs boson, and has a very good chance of discovering something else. Most high-energy physicists believe, however, that the LHC will not unravel the mysteries of symmetry breaking on its own.

Experimentation at a linear e+e- collider provides information that cannot be obtained by other means. Let us just cite two examples. First, a series of cross section and branching ratio measurements will trace out a detailed profile of the Higgs boson, in a model-independent way, and incisively test whether its couplings are proportional to mass. Second, if SUSY is at play, the ILC can determine the lightest superpartners' masses with exquisite precision. The ILC measurements would be key to determining, for example, whether supersymmetric particles are the "dark matter" in the universe. In both these cases, the ILC adds critical information to what will be learned at the LHC. The ILC is the right next step for experimental high energy physics, and now is the time to take it in order to maximize the interplay of its results with those of the LHC.

The full scientific case for the ILC can be found in the Resource Book [5] prepared for Snowmass 2001 or the physics chapter of the TESLA Technical Design Report [6]. We believe the essential elements of the physics case have been made persuasively, and we are responding by banding together to meet the technical challenges that remain, so that the instrument can be built in a timely and cost-effective fashion.

The Need for Accelerator R&D for the International Linear Collider

The physics goals of the ILC require [7] a starting center-of-mass energy of 500 GeV, upgradeable to approximately 1 TeV or more, and a luminosity of approximately 2 x 1034 cm-2s-1, an ambitious four orders of magnitude larger than the luminosity achieved by the first linear collider, the SLC. Achieving the high energy and ultra-low emittance of the ILC requires significant advances in accelerator physics and technology: end-to-end simulation of the entire

accelerator complex; mastery of the consequences of strong wakes; ultra-fast beam manipulation; nanometer stability of the beams at the crossing point; extreme stability in beam energy, luminosity and polarization; handling unprecedented beam power; and the development of instrumentation to monitor the beam on a bunch-by-bunch basis. A construction start in 2010 requires that the basic R&D required for a full technical design be complete by 2006. Much R&D remains to be done, and is urgently needed. The ILC-TRC [1] concluded its 2003 report with a list of high priority R&D items in the areas of: accelerator simulation and design; accelerator experiments; the development and test of radio-frequency (RF) systems, instrumentation, and other hardware; and operational issues.

Many of the R&D tasks identified by the laboratories and the ILC-TRC are ideally matched to the experience and talents of both elementary particle physicists and accelerator physicists at U.S. universities. These physicists have invaluable expertise in: large-scale computer simulations; data acquisition and control system architecture; innovative instrumentation; accelerator theory, design, and experiments; and accelerator RF systems. The U.S. university community, through the UCLC and LCRD consortia, is taking up the challenge of completing the necessary R&D in collaboration with the laboratories and affiliated institutions worldwide that are developing the Linear Collider designs.

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Investigation and Prototyping of Fast Kicker Options for the TESLA Damping Ring

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Summary

The large number of bunches (2,820) and the relatively large inter-bunch spacing (337 ns) in the TESLA linear collider design give a bunch train which is more than 200 km long. A damping ring of this size would be very costly, so the bunch train is damped in a compressed form, with a bunch spacing of 20 ns, leading to a damping ring with a circumference of 17 km.

In the TESLA baseline, the rise and fall time of the damping ring injection and extraction kickers determine the circumference of the ring. There is considerable leverage in developing faster kickers, as this translates directly into a smaller circumference ring. The baseline system for 500 GeV (cm) parameters has a 20 ns specification for the kicker pulse width; this becomes about 12 ns for the 800 GeV (cm) parameters. Designs and prototype results exist [1] for conventional kickers with widths of 7 ns, and design have been developed for more novel ultrafast schemes [2] using electron beams.

We propose to further explore the feasibility of the kicker designs described in the references cited above, particularly the very fast stripline kicker [1]. We have chosen a ring circumference of 3 km (similar to the PEP-II ring) as the smallest feasible circumference, and focused on the development of a kicker, with its associated pulser, appropriate for this ring. We assume the TESLA parameter of 2820 bunches. In a 3 km ring, these bunches, equally spaced, will have a 3.5 ns bunch spacing, so to allow the injection and extraction of individual bunches, the overall time-dependent kick seen by the beam must have a duration of less than 7 ns.

Recent Accomplishments

Design specification for kicker and pulser

Bunch-by-bunch manipulation in a 3 km ring can be accomplished using a system of stripline kickers (for an example of an early design, see [1]), driven by synchronized very fast pulsers, capable of delivering pulses in the multi-kV regime. The rise time and fall time of the pulser can be about 0.5 ns, with a pulse width of about 4 ns. Individual bunches must be injected or extracted from the ring approximately once every 337 ns, forming a train of 2820 bunches, with an overall train duration of about 1 ms. The train is injected into a linac for subsequent acceleration. This process is repeated at a cycle rate of 5 Hz.

As the basic module of the kicker, we consider a 0.36 m long stripline kicker, similar to that described in [1]. The kicker can be represented essentially as a vacuum parallel-plate transmission line, with an impedance of $50\ \Omega$. It will be terminated in its characteristic impedance, to suppress any reflections. Two synchronized pulses, of opposite polarity, injected onto the stripline plates at one end of this line, traveling opposite to the beam, will deliver a transverse kick to the beam. For a specific example applicable to the ILC damping ring, a 5 kV pulse applied to each plate of a 0.36 m long kicker with a half-gap of 35 mm, and a plate half-width of 50 mm, will deliver a kick of 20 μrad to a 5 GeV beam.

In *Figure 1*, an idealized pulse waveform is given, together with the resulting time variation of the kick. The pulse rise time and fall time (10% to 90%) is 0.64 ns, and the pulse flat top (90% to

90%) is 2.96 ns. The time-dependent kick, shown in *Figure 2*, has rise and fall time (10% to 90%) of 1.97 ns, and the kick flat top (90% to 90%) is 1.63 ns. This time-dependent kick at ±3.5 ns is 0.09% of the peak value, so it satisfies the requirement of being less than 7 ns in duration. The pulses must be delivered to the stripline kicker with a separation of 337 ns, and occur in a train of 2820 successive pulses, with a total duration of 0.950 ms. The burst pulse rate during this train is 2.97 MHz. These trains are separated by a gap of 200 ms; i.e., the train rate is 5 Hz. The average pulse rate is 2820x5 Hz=14.1 kHz. In a given pulse train, the relative pulse-to-pulse repeatability requirement on the total kick angle given to a beam bunch is 7x10-4. In addition, in order to not disturb the neighboring bunches, the amplitude of the time-dependent kick at the time of the neighboring bunches must be less than 0.3% of the peak kick amplitude.

The length of a single kicker module is constrained due to the requirement for a rapid rise time for the time-dependent kick. Consequently, a number of kickers will be required in series. For example, 30 stripline kickers of the design described above, excited by pulses of voltage ±5 kV, are required to deliver the total 600 μrad kick needed in the TESLA damping ring.

Implementation of the fast pulser

To implement the fast pulser, we need a very fast rise and fall time device, capable of delivering voltage pulses in the kilovolt range, with a burst pulse repetition frequency of 3 MHz, capable of 1 ms bursts at 5 Hz, and extremely high pulse-to-pulse reproducibility. Meeting these demanding requirements is very challenging. Compared to gas-filled amplifiers, solid-state devices can potentially have very good reliability and reproducibility, but have difficulty meeting the high-power-pulse rise and fall time requirements.

We have begun to investigate a relatively new high-power ultra-fast-switch technology, based on a 4-element npnp structure called a fast ionization dynistor [3, 4, 5, 6, 7, 8, 9, 10, 11]. Ultra-fast high voltage pulse generators based on this technology are now commercially available [12, 13]. We have contacted a commercial firm, FID Technology, GMBH, which makes these pulse generators, and made them aware of the pulser requirements described above.

Discussions with this vendor have led to the development of the pulser FPG2-3000-MC2, whose specifications have been tuned to this application. The specifications are shown in *Figure 3*. The pulse is asymmetric, with the fall time being somewhat longer than the rise time. Nevertheless, the resulting time-dependent kick should be acceptable.

In early 2005, we ordered a ±1 kV pulser (FPG2-3000-MC2) from FID Technology, using a combination of funding from this proposal and from other sources. The pulser has been completed, and in *Figures 4 and 5*, we show photographs [14] of the pulses as measured by the vendor into a dummy load. From *Figure 4*, the rise time (10% to 90%) is 0.87 ns, the flat top (90% to 90%) is 1.75 ns, and the fall time (90% to 10%) is 1.2 ns. These numbers are all satisfactory, but there is a 7% undershoot after the pulse which will be a problem if left uncorrected. This undershoot is believed to be due to an imperfect impedance match between the pulser and the load, and once the pulser arrives at Cornell, we will work to reduce this undershoot with careful load matching. Delivery of the pulser is estimated for August 2005.

Future plans

Once the prototype pulser described above arrives, we will test it with a 50 W dummy load, and check that the performance specifications are met. In particular, we will measure the amplitude stability, and the pre- and after-pulse levels, as well as the detailed shape of the current pulse.

Subsequently, we are currently planning to test the pulser on a 100 W stripline kicker which has been built by Fermi National Accelerator Laboratory (Fermilab) and the University of Illinois. This stripline kicker will be installed in the 16 MeV electron beam at the Fermilab A0 photoinjector facility. Measurements of the kick delivered by the pulser to the beam will allow the time-dependence of the kick to be studied in detail.

Provided that the FID pulser performs according to requirements, we will continue development of the fast kicker system as planned in the original proposal. We will build a 50 W kicker, suitable for the ILC damping ring, along the lines of the design described above. We will procure a higher voltage FID pulser, probably in the ±5 kV range. We may test this kicker-pulser combination, which will be a true prototype for the ILC damping ring system, using the electron beam from the Cornell linac.

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Neutrino Factory R&D at the Illinois Institute of Technology

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Summary

One of the options for future high-energy-physics accelerator facilities is a high-power proton source producing a Neutrino Superbeam, upgradeable to a muon storage ring-based Neutrino Factory and possibly a high-energy muon collider. The 128-member international Neutrino and Muon Collaboration explores the technological challenges of such facilities [7,12,13]. At Illinois Institute of Technology, Sr. Research Associate Y. Torun is supported by the Department of Energy, and this report summarizes his work, which has focused on resolving critical experimental questions in Neutrino Factory R&D.

MuCool: Muon Ionization Cooling

MuCool (FNAL-E904) is an R&D program on components of a Neutrino Factory muon ionization-cooling channel [Ref. 1], including rf cavities with unique features. The high-gradient (16 MV/m at 201 MHz) copper cavities are within superconducting solenoid magnets providing large magnetic fields (2–4T). There is no previous experience with such an arrangement - one normally avoids putting cavities in strong magnetic fields since the field lines can form multipacting channels. Also, to improve power efficiency, the cavities have thin Be windows (or grids of aluminum tubes) covering the beam aperture to create a pillbox-like geometry (a technique applicable only to muon acceleration). The windows must be thin to minimize muon scattering and are vulnerable to spark damage given the high stored energy. A key technology challenge for MuCool is thus to demonstrate that such cavities can be built, conditioned and reliably operated in high magnetic fields. A critical aspect of commissioning and operating an accelerator is diagnostics, which for the cooling channel requires robust instrumentation that can operate near high-gradient rf cavities and in strong magnetic fields. We have been investigating behavior of cavities in strong magnetic fields, radiation from the cavities, and instrumentation techniques.

Field Emission in rf Cavities

Field emission at surfaces limits accelerating gradients in many rf structures. The current density j due to barrier penetration at a metal surface (work function $f\phi$) is given by $j(E) = fbfb(A/\phi\beta E)^2 \exp[-B\phi^{3/2}/(\beta E)]$, with E the nominal dc electric field at the surface, $b\beta$ the local field enhancement factor due to sharp features on the surface, and A and B constants [Ref. 6]. For an rf field, j is reduced by a duty factor of order 0.1. For a small range of E, one can approximate this by a power-law dependence, $j \sim E^n$, with $n = E/j\ dj/dE \sim 2 + 67.4\ bb$GV/m/$(\beta E)$, giving n~10 for βE = 8 GV/m and illustrating the instrumentation challenge: no single detector technology can cover the entire dynamic range (about 14 orders of magnitude) encountered during cavity operation. The dark current is dominated by the worst emitter sites, and the measured current depends on cavity geometry. The electric field is highest at irises and windows, and the emitter distribution is determined by surface treatment and conditioning history of the cavity. The mechanisms that cause dark currents are also involved in sparking and destructive breakdown, which could prevent reliable operation. Electrons stripped from the surface and accelerated by the electric field generate x-rays when they hit metal surfaces. Those reaching the windows can heat them and deposit energy in the liquid-hydrogen

absorbers, causing extra cryogenic heat load and also generating additional x-rays. If not kept in check, the resulting flux of x-rays may flood any tracking detectors placed downstream.

Lab G Test Facility

The 201MHz cavities needed for the cooling channel are large, expensive and difficult to handle. While a 201MHz prototype closely resembling the final design was in preparation, we have addressed issues of cavity operation and diagnostics at Laboratory G of Fermi National Accelerator Laboratory (Fermilab) which was set up [Ref. 8] for MuCool rf tests with a 12MW, 805MHz klystron. A superconducting magnet was built, with coils that can be powered with the same polarity for up to 5T solenoidal field or in opposition for a field gradient exceeding 30T/m. We have tested two 805MHz cavities using a variety of detectors. Radiation monitors tracked radiation levels and overall progress in conditioning. A smaller, more accurate radiation meter recorded integrated radiation output close to the cavity exit window. Current transformers measured total electron dark current emerging from the cavity. Glass and photographic film [Ref. 4] were used to record and image dark-current spatial distributions at the cavity window. Scintillation counters provided rate measurements and fast diagnostics. Two cryogenic Ge-diode spectrometers measured the x-ray spectrum, and range telescopes of plastic, graphite and aluminum with current transformers or scintillators measured approximate electron spectra. This work was done in close collaboration with MuCool Collaboration members from Argonne National Laboratory (ANL), Fermilab, Lawrence Berkeley National Laboratory (LBNL), the University of Illinois, and Muon Ionization Cooling Experiment (MICE) Collaboration members from CERN and Imperial College, London. The klystron used in Lab G had been borrowed from the Fermilab Linac and was reclaimed as a spare for operations at the end of 2003. This ended the rf program at Lab G.

MuCool Test Area

A dedicated experimental facility [Ref. 18] has been built at Fermilab for testing muon cooling components under conditions similar to those in a high-performance Neutrino Factory. The planned infrastructure for the new MuCool Test Area (MTA) includes 805 and 201MHz rf power for cavity testing, cryogenic systems to support a superconducting magnet and liquid-hydrogen-absorber test setup, and a beamline to bring the 400MeV proton beam from the Linac for high-power testing of absorbers. With the civil construction completed, we have been working on installation of cooling hardware and diagnostic equipment at the MTA and Linac along with Fermilab, ANL, and LBNL collaborators. The superconducting magnet has been moved from Lab G to its new location in the MTA experimental hall as shown in *Figure g*, and waveguides for rf power have been installed. Cabling and controls are now in place for the magnet, rf cavities, liquid-hydrogen system, and detectors. The 805MHz rf test program is expected to resume shortly and the 201MHz program should be running by fall 2005.

Recent Accomplishments

The first cavity installed in Lab G was a six-cell open-iris prototype [Ref. 6] built by Fermilab with a field on the cavity irises about 2.6 times the on-axis field. During high-power conditioning with no magnetic field (B = 0), we initially measured large dark currents, but the cavity was able to operate at accelerating gradients exceeding 20MV/m (52MV/m surface field). With B = 2.5T, cavity conditioning was more difficult, and dark current focused by the magnetic field punched holes through the titanium window, twice causing vacuum failure. Inspection of the window and cavity interior revealed heavy pitting on the irises, splashes of molten copper and a layer of deposited copper on the interior surface of the window.

Next, an 8cm-long pillbox cavity built by LBNL [Refs. 2,3] was installed, with copper windows. Since in this geometry the surface field was approximately equal to the accelerating field, conditioning at B = 0 up to the design gradient of 30MV/m proved straightforward. With the thick windows initially provided, the dark current was not measurable and radiation levels were low. However, at B = 2.5T, stable operation was only possible up to about 16MV/m [Refs. 15,17]. Above this gradient, sparking caused loss of cavity conditioning. Subsequent inspection showed minor pitting on the windows and no damage inside the cavity. The pillbox cavity was then fitted with TiN-coated Be windows, and the ensuing conditioning progress was similar to that in the copper-window case. Inspection showed no window pitting but Cu deposits on window surfaces and corresponding pits on the Cu irises around them. These results suggest that coating the highest-field areas of the cavity body in addition to the windows may cure most of the problems encountered in operation. This will be tested in the next phase of the program.

A 201MHz prototype cavity was built by LBNL and is currently under surface processing at Thomas Jefferson National Accelerator Facility. In addition to mechanical polishing, electropolishing of the interior is being used to achieve a smooth surface and limit field emission. The cavity will then be shipped to Fermilab for installation at the MTA.

Some results are shown in the figures page. The field emission photos *(Figure a)* were taken using a few dozen rf pulses with the 805MHz pillbox cavity *(Figure d)* using photographic paper [Ref. 4] placed against the cavity window. An individual emitter is seen to be active at low gradient (*top*), blowing up at high gradient (*middle*), and extinguished (*bottom*) showing the conditioning process. The gradient reliably achieved in the same cavity is plotted as a function of magnetic field *(Figure b)* showing the onset of reduced performance at low field, presumably due to focusing of dark current. A typical experimental setup for measuring radiation from the cavity installed in the magnet is shown in *Figure c*.

While the main rf functions are integrated into Fermilab's standard control systems, a significant portion of the instrumentation we have used in rf cavity diagnostics is borrowed, with various remote-control interfaces. We have designed a supplemental data-acquisition system so that the data for each rf pulse (rf controls as well as output data from detectors) can be read and saved onto a single computer for analysis. The system was used for some measurements in Lab G and has been reconfigured for use at the MTA.

MICE: The International Muon Ionization Cooling Experiment

An experimental demonstration of ionization cooling is widely considered to be essential if a future high-energy muon storage-ring facility is to be built. A cooling experiment (MICE) [Ref. 5] using MuCool-developed components in a section of the "Study-II" channel [Ref. 7] has been approved for running at the ISIS facility of Rutherford Appleton Laboratory and is under active development [Refs. 11,19]. The tracks of single muons through the apparatus will be measured using standard particle-physics techniques, since bunched-beam diagnostics lack the needed precision. The layout of MICE is shown in *Figure h* with cooling channel components in the middle surrounded by tracking detectors [Ref. 14] to measure beam emittance at the entrance and exit and particle-ID detectors to reject particles other than muons. In this setup, tracking detectors must be placed close to the rf cavities and are therefore sensitive to backgrounds caused by dark-current electrons and their associated x-rays. A good estimate of such backgrounds is essential to the successful planning and execution of the experiment.

We have contributed to the conceptual development of MICE as well as the Monte Carlo simulations. We performed the first GEANT simulations of the experiment, set up the software infrastructure, organized a series of workshops [Ref. 20] and led the software project. A GEANT4-based architecture was built to combine, for the first time, the beamline elements, cooling hardware and particle detectors within the same framework, and a full end-to-end simulation including geometry, materials, readout electronics, reconstruction and emittance analysis was accomplished [Ref. 21]. We also performed measurements in Lab G with 805MHz cavities to estimate backgrounds and noise [Refs. 9,10] for the tracking detectors proposed for MICE, and we are preparing for similar measurements with the 201MHz prototype cavity at the MTA.

MICE has over 140 collaborators from 42 institutions (14 from the U.S) in nine countries around the world. Efficient communication is essential for such a diverse group to function. We have set up and maintain the website [Ref. 22], mailing lists, notes publication system and video- and phone-conferencing for the collaboration and have served on the collaboration technical and executive boards.

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Websites

http://mice.iit.edu/sm/
http://mice.iit.edu/software/release/ReleaseNotes-1-0.html
http://mice.iit.edu/

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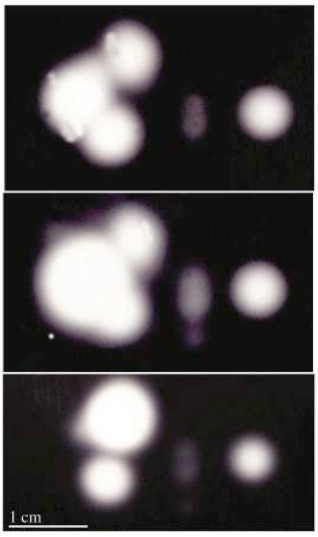
Muon Cooling - IIT



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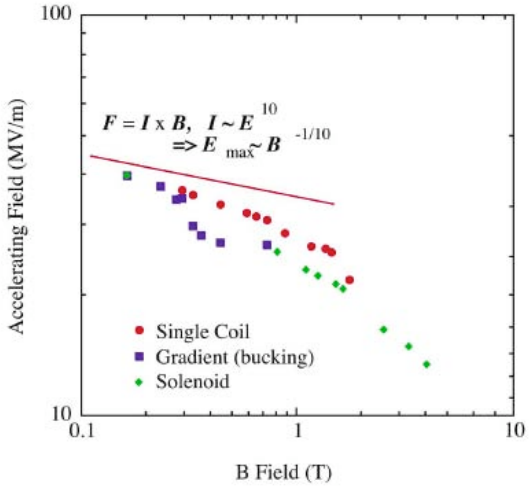

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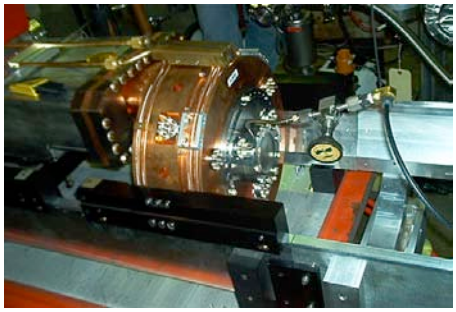

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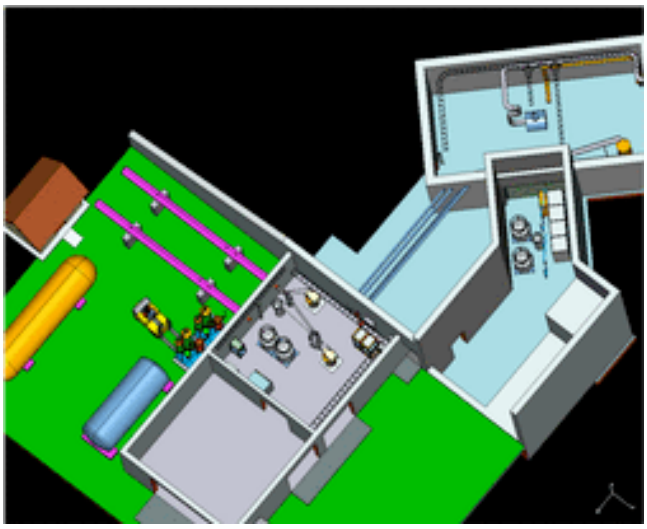

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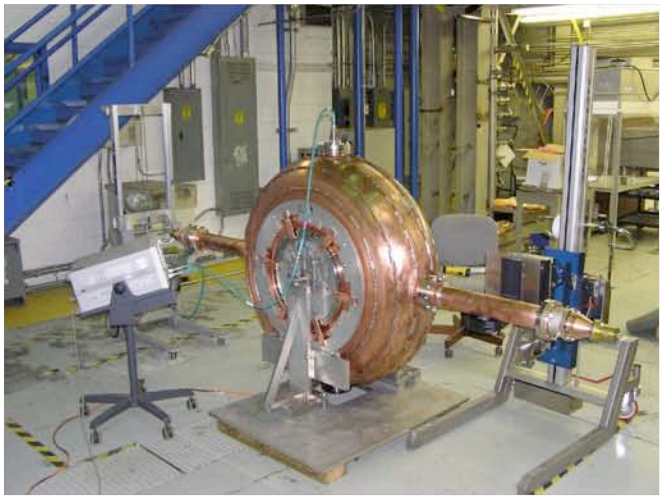

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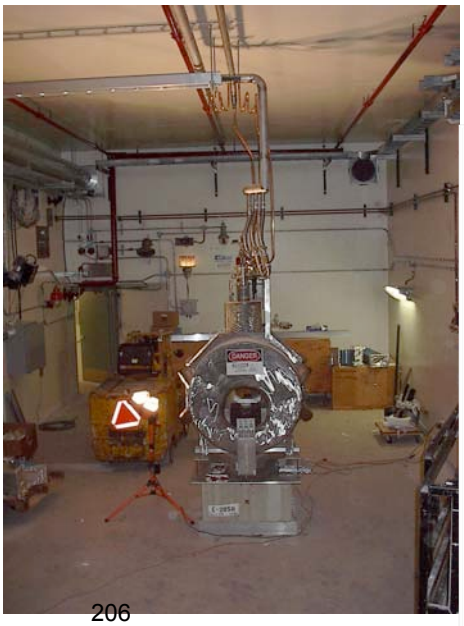

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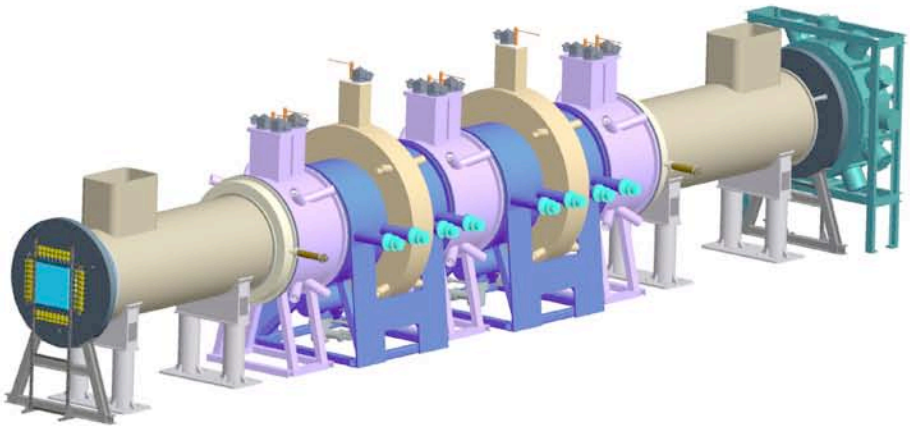

Atom-Probe Tomography Of Niobium For Superconducting Rf Cavities

Professor David N. Seidman
Northwestern University

The Northwestern University Center for Atom-Probe Tomography (NUCAPT), Evanston, Illinois, is investigating the properties of the high purity niobium used in the RF cavity fabrication for the future International Linear Collider (ILC), in collaboration with Fermilab and Argonne. The NUCAPT is among the world leaders in the field of three-dimensional atom-probe tomography, particularly as result of the recent installation of a local-electrode atom-probe (LEAP) tomograph, manufactured by Imago Scientific Instruments. First atom-probe tomographic (APT) measurements of niobium for superconducting RF (SRF) cavity material were conducted. APT involves the atom-by-atom dissection of sharp niobium tips, along with their niobium oxide coatings, via the application of a high-pulsed electric field and the measurement of each ion's mass-to-charge state ratio with time-of-flight mass spectrometry *(Figure 1).* The resulting atomic reconstructions, typically containing at least 10^5 atoms and with typical dimensions of 10^5 nm^3 (or less), show the detailed, nano-scale chemistry of the niobium oxide coatings, and of the underlying high-purity niobium metal. *Figure 2* shows an example of our initial results, which show a nano-chemically smooth transition through the oxide layer from near-stoichiometric Nb_2O_5 at the surface to near-stoichiometric Nb_2O as the underlying metal is approached (after ~10 nm of surface oxide). The underlying metal, in the near-oxide region, contains a significant amount of interstitially dissolved oxygen (~5-10 at.%), as well as a considerable amount of dissolved hydrogen. The experiments also show surface adsorbates such as fluorine *(Figure 2)*. These investigations aim:

- To improve the understanding of the chemical composition of the surface of state of the art high purity niobium for SRF cavities;
- To improve the understanding of the chemical composition of the grain boundaries in state-of-the-art high purity niobium for SRF cavities;
- To correlate surface and grain-boundary chemical composition with the various macro-treatment steps used to prepare cavities for RF performance of SRF cavities, such as for instance the low temperature, in situ bake-out, which was recently shown to significantly increase cavity performance by removing Q-drop; and
- Understanding the interactions between high electric fields and materials (electron field emission, field evaporation of ions, surface stability, field induced stresses, fracture, etc.).

Strong material scientific tools such as APT are needed to generate the intellectual understanding of phenomena such as, for instance, Q-drop in order to achieve reproducibly an electric field of 35 MV/m, in SRF cavities, for the ILC.

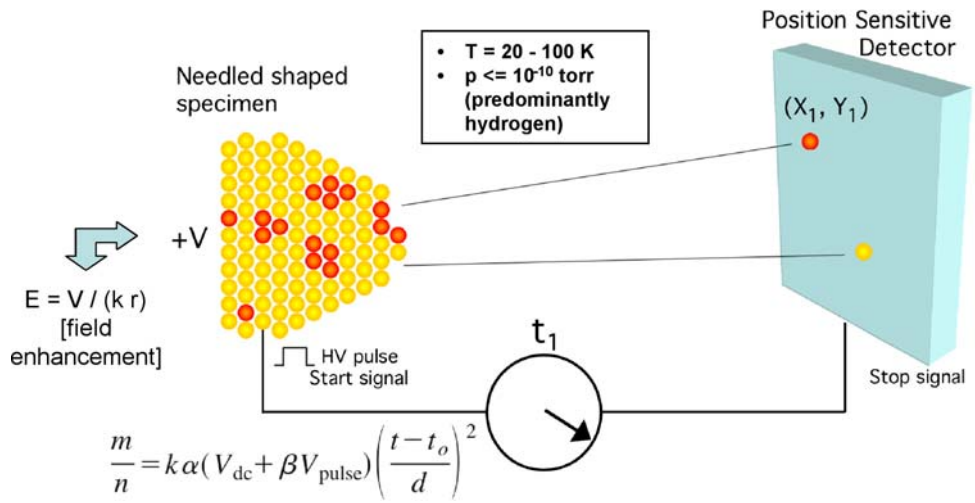

Figure 1 Schematic diagram showing the principle of atom-probe tomography (APT). The equation relating an ion's mass-to-charge state ratio (m/n) to its time-of-flight (t) is included in the lower left of the figure; t_o is the delay time in the electronics.

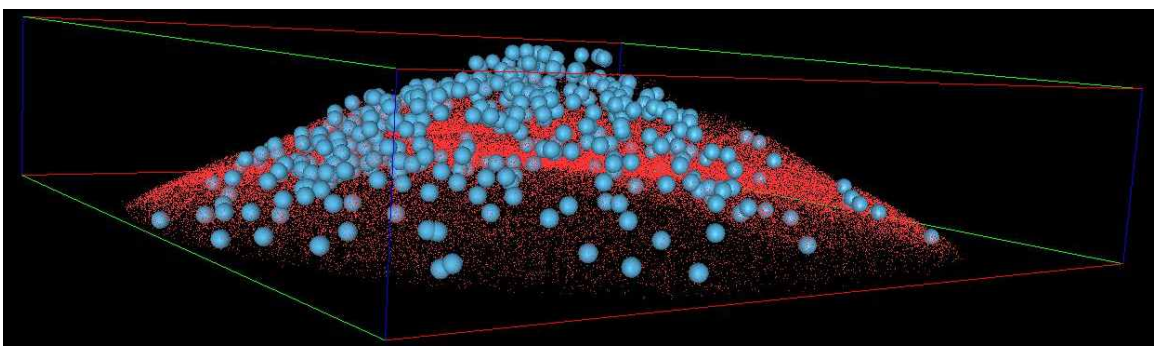

Figure 2 Three-dimensional atomic reconstruction of the oxide layer on the surface of a niobium RF cavity material sharp tip. The overall reconstruction dimensions are 23 nm x 21 nm x 11 nm (5313 nm^3); the volume contains ~112,000 atoms. Approximately 200 fluorine atoms, residues from the chemical processing, are adsorbed at the surface (shown in blue and artificially enhanced).

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Investigation on Plasma Etching for Superconducting RF Cavities Surface Preparation

Leposava Vušković
Old Dominion University

Summary

Niobium is a suitable material for fabrication of superconducting RF (SRF) cavities and Josephson tunnel junctions. It has highest transition temperature, T_c=9.2K, of all elemental superconducting materials. Niobium is a refractory metal and forms a refractory dielectric pentoxide, Nb_2O_5, that gives a mechanical ruggedness, long-time stability and stability in repeated thermal cycling between room and liquid He temperature of 4.2K. Despite the favorable properties of Nb, a small, but finite dissipation of RF currents exists in application. The current heating contributes to RF performance degradation or "Q-drop" in SRF cavities that is observed when oxidation procedures are applied to Nb, but not for coated clean Nb. This implies that composition and structure of oxide layers on the surface of bulk Nb plays a crucial role in RF performance degradation. Different surface preparation and oxidation methods yield various types of deterioration of superconductivity. No recipe presently used to prepare SRF cavity surfaces provides repeatable performance reasonably close to fundamental limits, and no one is fully understood at the microscopic level in terms of their effects on variability of RF performance.

The objective of the present research is to minimize presence of Nb-oxides and subsequent RF properties degradation by employing various techniques of SRF cavity surface modification involving electric discharge plasmas. For instance, discharge plasma etching provides a unique opportunity to explore Nb oxide-free surfaces by directly testing a cavity surface after processing without exposure to air. This technique also allows control of the final oxidation phase that cannot be avoided with SRF cavities.

Niobium and Nb-oxides etching in reactive discharge plasmas have been sparsely described in literature. In the case of Nb etching, rates of the order of 0.2-0.3 m/min were obtained, while for Nb-oxides significant structural changes were obtained. This limited empirical experience has been used as a starting point for present study of the inner surface modification of superconductive cavities using low-pressure discharge plasmas. The proposed experiment is devoted to the use of metal-to-discharge interfaces to generate an adequate environment for transformation of Nb oxides from the surface of SRF cavity into removable volatile compounds. To define proper combination of reactive gases mixture, chemical properties of Nb compounds relevant for plasma etching process are investigated. All Nb oxides are stable solid compounds with relatively high melting point. A possible chemical way of removing them from the surface of bulk Nb would be transformation of oxides in volatile halogenides. Melting points for halogenides are in a temperature range easily obtained in discharge plasmas. Some of the listed reactive gases are toxic and/or corrosive, but concentrations used in plasma etching processes are much smaller than concentration of acids used in BCP or EP. When developed, the oxide removal process could serve as a complementary surface modification method to those currently used in preparing the SRF cavities for operation.

Two types of high frequency, low pressure gas discharges will be applied on plasma etching of Nb surfaces: RF parallel plate reactor with dielectric barrier and microwave discharge (barrel reactor). MW discharge has a more efficient transfer of energy from MW electric field to gas that has as a consequence higher electron densities and higher radical densities in plasma. This plasma conditions are more favorable for pure chemical etching than for sputtering processes. Also higher gas temperature in plasma contributes a higher rate of chemical

reactions and vaporization of products of chemical reaction. Biasing the sample can increase the small value of the sheet potential. RF discharge on the other hand has much bigger sheet potential and higher kinetic energy of radical species. These two favor sputtering over pure plasma etching process. Combination of plasma diagnostic and of surface analysis is probably the best strategy to develop an understanding of the plasma-surface interaction, in particular, when the surface can be analyzed in situ and, possibly, in real-time, or using vacuum transfer in such a way that it does not suffer any dramatic chemical or structural modifications.

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Linear Collider Accelerator Physics R&D Progress Report 2.37a
April 14, 2005

Undulator-Based Production of Polarized Positrons
(SLAC Experiment E-166)

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Joseph Henry Laboratory, Princeton University, Princeton, NJ 08544

Summary

Princeton University is participating in SLAC experiment E-166 [1], an international accelerator-physics project involving 15 institutions to demonstrate undulator-based production of polarized positrons for a linear collider. This effort, and that of U. Tennessee, forms LCRD 2.37 of the Linear Collider Accelerator Physics R&D Program [2]

The full exploitation of the physics potential of future linear colliders such as the JLC, NLC, and TESLA will require the development of polarized positron beams. In the scheme under study in experiment E-166, a helical undulator is employed to generate photons of several MeV with circular polarization which are then converted in a relatively thin target to generate longitudinally polarized positrons.

To characterize the success of this technique, the experiment includes diagnostics of the polarization of both the MeV-scale photons and positrons, based on the polarization dependence of the rate of transmission of photons through magnetized iron. Princeton University has responsibility for construction of a magnetic spectrometer for the positrons, and also for construction of a pair of siilica aerogel counters for use in the polarimeter to diagnose the undulator photons.

All of the hardware construction for experiment E-166 is now complete. In addition, Princeton has purchased tungsten shielding for the positron spectrometer, a waveform generator to control the reversal of magnetic field of the photon polarimeters, a 4-channel digital oscilloscope for use with the 3 Faraday cup diagnostics of the positron spectromter, and two PC's for use in the E-166 data acquisition system.

The LCRD budget award for Princeton was $30k in FY05, with the anticipation of a renewal of $40k in FY06. Because the experiment is to run in FY05, it has been necessary to spend about $60k to date, with another $10k needed to cover travel expenses for the coming run of the experiment.

Experiment E-166 had taken two days of beam at SLAC in October 2004, before the lab was shut down due to an electrical accident. As of today, we believe the experiment can run again from May 15-June 4, 2005, and for an additonal 3 weeks around Sept. 1, 2005.

Section 1 presents some relevant extracts from the E-166 proposal [1]. Section 2 reviews the Princeton effort on E-166.

1 Introduction

The full exploitation of the physics potential of future linear colliders such as the JLC, NLC, and TESLA will require the development of polarized positron beams.

In the proposed scheme of Balakin and Mikhailichenko [3] a helical undulator is employed to generate photons of several MeV with circular polarization which are then converted in a relatively thin target to generate longitudinally polarized positrons.

To advance progress in this field, a new experiment, SLAC E-166 [1, 4] (approved June 30, 2003), will test this scheme to determine whether such a technique can produce polarized positron beams of sufficient quality for use in future Linear Colliders. The experiment will install a 1-meter-long, short-period ($\lambda_u = 2.4$ mm, $K = 0.17$), pulsed helical undulator in the Final Focus Test Beam (FFTB) at SLAC. A low-emittance 50-GeV electron beam passing through this undulator will generate circularly polarized photons with energies up to a cutoff energy of about 10 MeV. These polarized photons are then converted to polarized positrons via pair production in thin targets.

1.1 Undulator Based Production of Polarized Positrons

A polarized positron source for a Linear Collider was first proposed by Balakin and Mikhailichenko in 1979 in the framework of the VLEPP project [3]. The concept, schematically sketched in Fig. 1, sends the high energy ($\geq$ 150 GeV) electron beam of a Linear Collider through a ($\sim$ 200 m-long) helical undulator to produce circularly polarized photons with energies of about 11 MeV. While the electrons are further accelerated and brought into collision after passing through the undulator, the photons are converted in a thin target into electron-positron pairs. Here the polarization state of the photons is transferred to the positrons and electrons. Only the on-axis photons of the helical undulator radiation are completely circularly polarized; the degree of polarization is decreasing with increasing emission angle. Hence, the polarization of the photons and of the generated positrons can be increased at the expense of the total number of positrons by collimation. The positrons are captured behind the target similarly to the case of a conventional positron source [5, 6], and fed into a linac.

This undulator-based positron source concept offers the additional advantage that the heat load on the target is less than that of a conventional source, and so the former is very well suited for the production of high intensity positron beams [7]. An undulator-based polarized positron source can in principle be realized independently of the linac technology, *i.e.*, independently of the details of the required pulse structure, because the number of produced positrons scales with the number of the electrons in the drive linac, and the pulse structure of the electrons is directly copied to that of the positrons. In this sense it is an option for all Linear Collider projects.

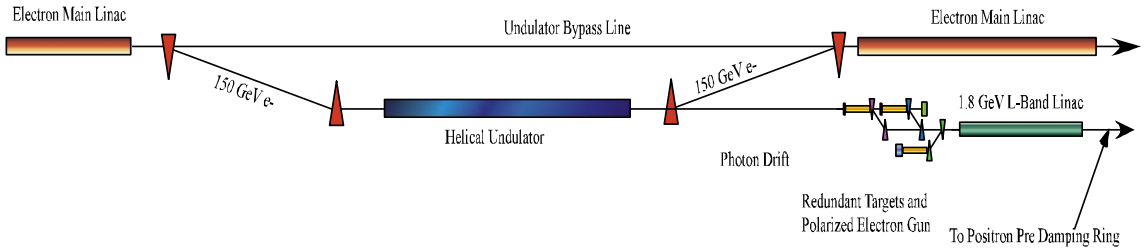

Figure 1: Conceptual scheme for undulator-based production of polarized positrons.

1.2 Physics Opportunities at a Linear Collider with Polarized Electrons and Polarized Positrons

Polarized electrons have been a part of each of the different Linear Collider proposals for a long time. Recently much scrutiny has been given to the case for polarized positrons in addition to polarized electrons. A consensus has emerged that polarized positrons are a highly desirable option for a Linear Collider.

The importance of beam polarization in general was demonstrated e.g., at the SLAC Linear Collider (SLC). Because of the high degree of electron polarization (during its last run in 1997/98, an average longitudinal beam polarization $P_{e^-} = 74\%$ was reached [8]) one of the world's most precise measurements of the weak mixing angle at Z-pole energies was performed.

Having both beams polarized offers a number of advantages:

- Higher effective polarization.
- Increased signal to background in studies of Standard Model Physics.
- Enhancement of the effective luminosity.
- Precise analysis of many kinds of non-standard couplings.
- The option to use transversely polarized beams.
- Improved accuracy in measuring the polarization.

1.3 The Need for a Demonstration Experiment

The aim of the proposed experiment E-166 is to test the fundamental process of polarization transfer in an electromagnetic cascade. For this, a simplified version of the scheme shown in Fig. 1 will be used, in which a 50-GeV electron beam passes through a 1-m-long undulator as shown in Fig. 2. The resulting photon beam of MeV energy is converted to positrons (and electrons) in a thin target, after which the polarization of the positrons (and photons) is analyzed.

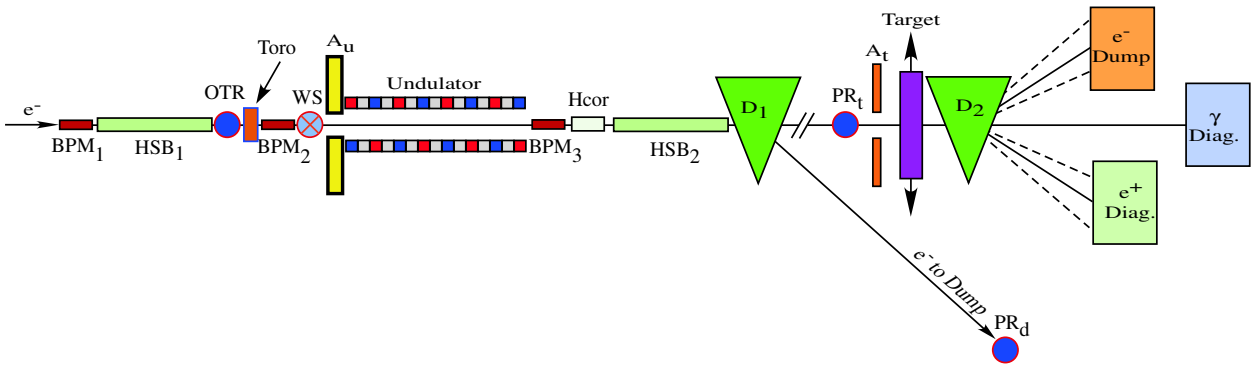

Figure 2: Conceptual layout (not to scale) of the experiment to demonstrate the production of polarized positrons in the SLAC FFTB. 50-GeV electrons enter from the left and pass through an undulator to produce a beam of circularly polarized photons of MeV energy. The electrons are deflected away from the photons by the D_1 magnet. The photons are converted to electrons and positrons in a thin target. The polarization of the positrons, and of the photons, are measured in polarimeters based on Compton scattering of electrons in magnetized iron. BPM_i = beam-position monitor; HSB_i =“hard” soft bend; OTR = optical-transition-radiation beam-profile monitor; Toro = beam-current toroid; WS = wire scanner; A_i = aperture limiting collimators; Hcor = horizontal steering magnet; D_1 = FFTB primary beam dump bend-magnet string; PR_d = dumpline beam-profile monitor; PR_t = e^+ target beam-profile monitor; D_2 = analyzing magnet.

While the basic cross sections for the QED processes relevant to polarization transfer were derived in the late 1950's, experimental verification of the polarization development in an electromagnetic cascade is still missing. From this point of view, the proposed experiment has some general scientific aspects in addition to its importance for Linear Colliders.

Each approximation in the modeling of electromagnetic cascades seems to be well justified in itself, but the complexity of polarization transfer in cascades makes the comparison with an experiment desirable, so that the decision whether a Linear Collider should be built with or without a polarized positron source can be based on solid grounds. The achievable precision of the proposed transmission polarimetry of 5-10% is sufficient for this purpose. This experiment, however, will not address detailed systems issues related to polarized positron production for a Collider, such as capture efficiency, target thermal hydrodynamics, radiation damage in the target, or an undulator prototype suitable for use at a Linear Collider; such issues are well within the scope of R&D by a Linear Collider project that chooses to implement a polarized positron source based on a helical undulator.

1.4 Overview of Experiment E-166

The goal of the experiment is

- To measure the yield and polarization of the photons produced by passing an electron

beam through a helical undulator.

- To measure the yield and polarization of the positrons produced by conversion of undulator photons in a thin target.
- To compare the results to simulations.

A schematic layout of the experiment is shown in Fig. 2 with emphasis on the particle beams, while Fig. 3 shows the layout of the detectors to measure the flux and polarization of the photons and positrons.

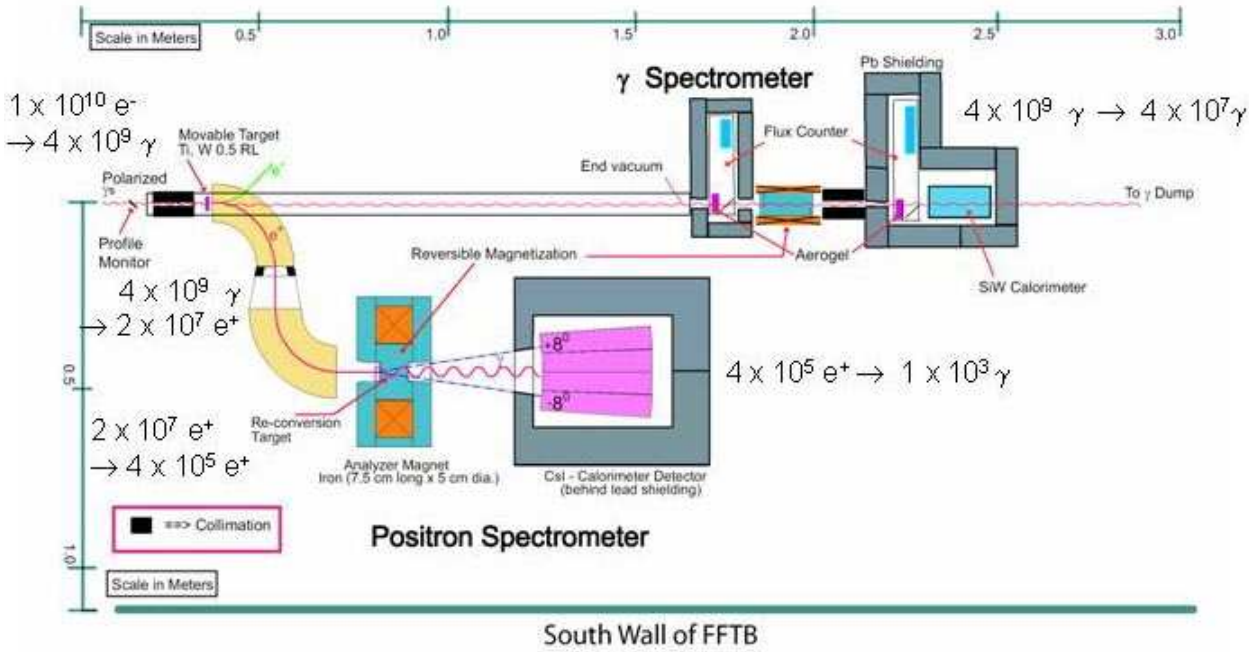

Figure 3: Conceptual layout of the E–166 positron generation and photon and positron diagnostic systems. Representative rates of photons and positrons, per electron pulse, are shown in various regions of the apparatus.

The experiment uses a low-emittance, 50-GeV electron beam in the SLAC Final Focus Test Beam (FFTB) plus a 1-meter-long, short-period ($\lambda_u = 2.4$-mm, K=0.17), pulsed helical undulator, to produce circularly polarized photons of energies up to 10 MeV. These polarized photons are then converted to polarized positrons through pair production in a Ti target which has a nominal thickness of 0.5 rad. len. The polarizations of the photons and positrons are measured by the Compton transmission method using a magnetized iron absorber [9].

This experiment is a demonstration of undulator-based production of polarized positrons for Linear Colliders at a scale of 1% in length and intensity:

- Photons are produced in the same energy range and polarization as in a Linear Collider;
- The same target thickness and material are used as in the Linear Collider;

- The polarization of the produced positrons is expected to be in the same range as in a Linear Collider.
- The simulation tools being used to model the experiment are the same as those being used to design the polarized positron system for a Linear Collider: EGS4 [10] and GEANT3, both modified to include spin effects for polarized e^+ production, and BEAMPATH [11] for collection and transport.

1.5 The Photon Polarimeter

Measurements of the circular polarization of energetic photons are most commonly based on the spin dependence of Compton scattering off atomic electrons [12, 13]. One can either observe the scattered electrons and/or photons emerging from a thin, magnetized iron foil [14], or measure the transmission of unscattered photons through a thick, magnetized iron absorber [9, 15, 16]. Experiment E-166 uses the latter technique, which is sketched in Fig. 4. The basic components are a magnetized iron absorber and a detector that measures the photons that penetrate through the absorber.

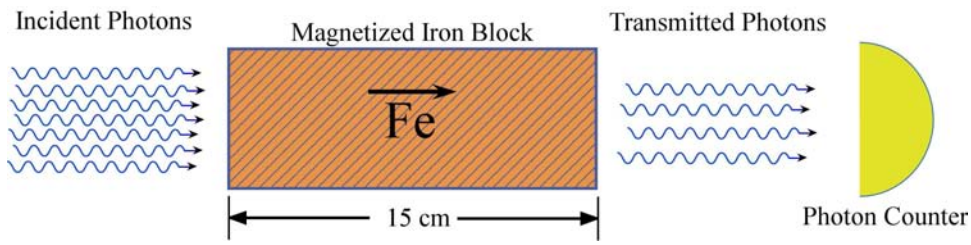

Figure 4: The concept of transmission polarimetry, in which the survival rate is measured for photons that pass through a magnetized iron absorber.

On reversing the sign of the magnetization of the absorber, an asymmetry $\delta = P_\gamma P_{e^-} A_\gamma$ is measured in the rate of transmitted photons, where P_γ is the photon polarization, P_{e^-} is the polarization of the electrons in the iron, and A_γ is the so-called analyzing power which is proportional to the spin-dependent part of the Compton scattering cross section [1].

The implementation of the photon polarimeter for E-166 is sketched in Fig. 3. The photon polarimeter will include two types of photon detectors, a total absorption calorimeter and a Čerenkov detector.

1.5.1 Silicon-Tungsten Calorimeter

The total absorption calorimeter for the transmitted photons is a silicon-tungsten sampling calorimeter, similar to that employed in SLAC experiment E-144 [18]. As shown in Fig. 5, this device consists of 20 plates of tungsten, each 1 rad. len. thick, separated by silicon detectors in the form of a 4×4 array of pads, each 1.6×1.6 cm^2 in area. The pads are read out in longitudinal groups of 5, for a total of 64 readout channels. The resulting transverse

and longitudinal segmentation of the calorimeter will permit confirmation that the energy deposited in the calorimeter has the profile expected from the signal of undulator photons, rather than that of possible backgrounds of scattered electrons and photons.

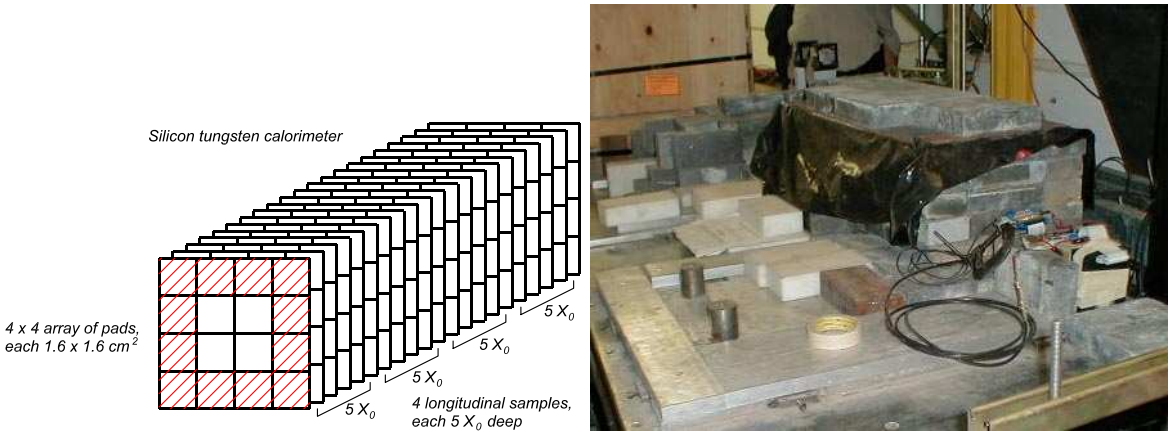

Figure 5: a) The silicon tungsten calorimeter consists of 20 longitudinal samples of 1 X_0 each, grouped into 4 segments of 5 X_0 each. The transverse sampling is via a 4×4 array of pads, each 1.6×1.6 cm^2 each. b) View of E-166/T-467 test apparatus in the FFTB: the silicon tungsten calorimeter is the small object (with cabling)at the right; a CsI counter is under the lead brick shield in the center; the aerogel flux counters are at the top center.

The resolution of a similar sampling calorimeter has been measured to be [18]

$$\sigma_{\mathcal{E}}^2 = (0.19)^2 \mathcal{E} + (0.4)^2, \tag{1}$$

where $\mathcal{E}$ is the electron energy in GeV. For a pulse of 10^{10} electrons, some 4×10^7 photons of average energy 5 MeV reach the calorimeter, depositing about 200 TeV. Hence, the relative error on that energy of only 0.06 %.

1.5.2 Aerogel Flux Counters

A complementary measurement of the transmitted photon flux will be made with a pair of aerogel Čerenkov counters with index of refraction $n = 1.009$ [19]. This extremely low-index material is available from the BELLE experiment. The two flux counters are deployed before and after the magnetized iron absorber, as shown in Fig. 3.

The signal in the aerogel flux counter is generated by conversion of undulator photons in the aerogel, after which electrons and positrons of energy greater than 4.3 MeV will emit Čerenkov light. This light is observed in a photomultiplier that views the aerogel through an air light pipe, as shown in Fig. 6.

Because of their threshold energy of 4.3 MeV, the aerogel flux counters are insensitive to synchrotron radiation in the beam. Hence, a pair of aerogel flux counters that are placed upstream and downstream of the magnetized iron absorber, as shown in Fig. 3, can confirm

Figure 6: a) Sketch of the photon flux counter, consisting of a 2-cm-thick block of aerogel of index $n = 1.009$, viewed by a photomultiplier tube at the end of an air light pipe. b) Photograph of the two aerogel flux counters. c) A block of aerogel mounted in a Michelson interferometer in order to measure its index of refraction [19].

the attenuation of this absorber on photons of energy above 5 MeV, independent of possible backgrounds of lower-energy photons.

The conversion probability of an undulator photon in the 1-mm-thick Al cover plate of the detector will yield about 1 electron or positron per 300 photons, but only 1/3 of these will have energy above Čerenkov threshold. The number of photons of energy that penetrate the iron absorber is about 4×10^7 per pulse of 10^{10} electrons, so the number of useful conversions is about 4×10^4. There will be about 50 $\theta_C^2 \approx 5$ ŏptical Cerenkov photons per conversion, leading to about 1/2 photoelectron per conversion in a photomultiplier whose photon collection efficiency times quantum efficiency is 10%. Hence, the expected signal in the Čerenkov counter downstream of the magnetized iron absorber is about 2×10^4 photoelectron per electron beam pulse.

1.6 The Positron Polarimeter

The measurement of positron polarization is to be made by first transferring the polarization to photons, and then using a photon-transmission polarimeter [17]. Measurements of the asymmetry $\delta = P_{e^+} P_{e^-} A_{e^+}$ in the rate of transmitted photons can be related to the positron polarization P_{e^+} and the polarization P_{e^-} of the electrons in the magnetized iron absorber via a calculable analyzing power A_{e^+} [1].

The layout of the positron polarimeter has been shown in Fig. 3, and is shown again in Fig. 7. A double 90°-bend magnet transports a ±20% momentum bite of the positron spectrum to the reconversion target (0.5 rad. len. of tungsten). The photons that emerge from the target are then incident on an 7.5-cm-long magnetized iron absorber. The photons that are transmitted through the absorber ($\approx 10^3$ per pulse) are detected in a CsI array. The latter device was chosen, rather than a Si-W calorimeter, because the typical energy of

photons reaching the detector in the positron polarimeter is only about 1 MeV; the energy resolution of a CsI calorimeter for such energies is about 2.5%, compared to 20% for a Si-W device.

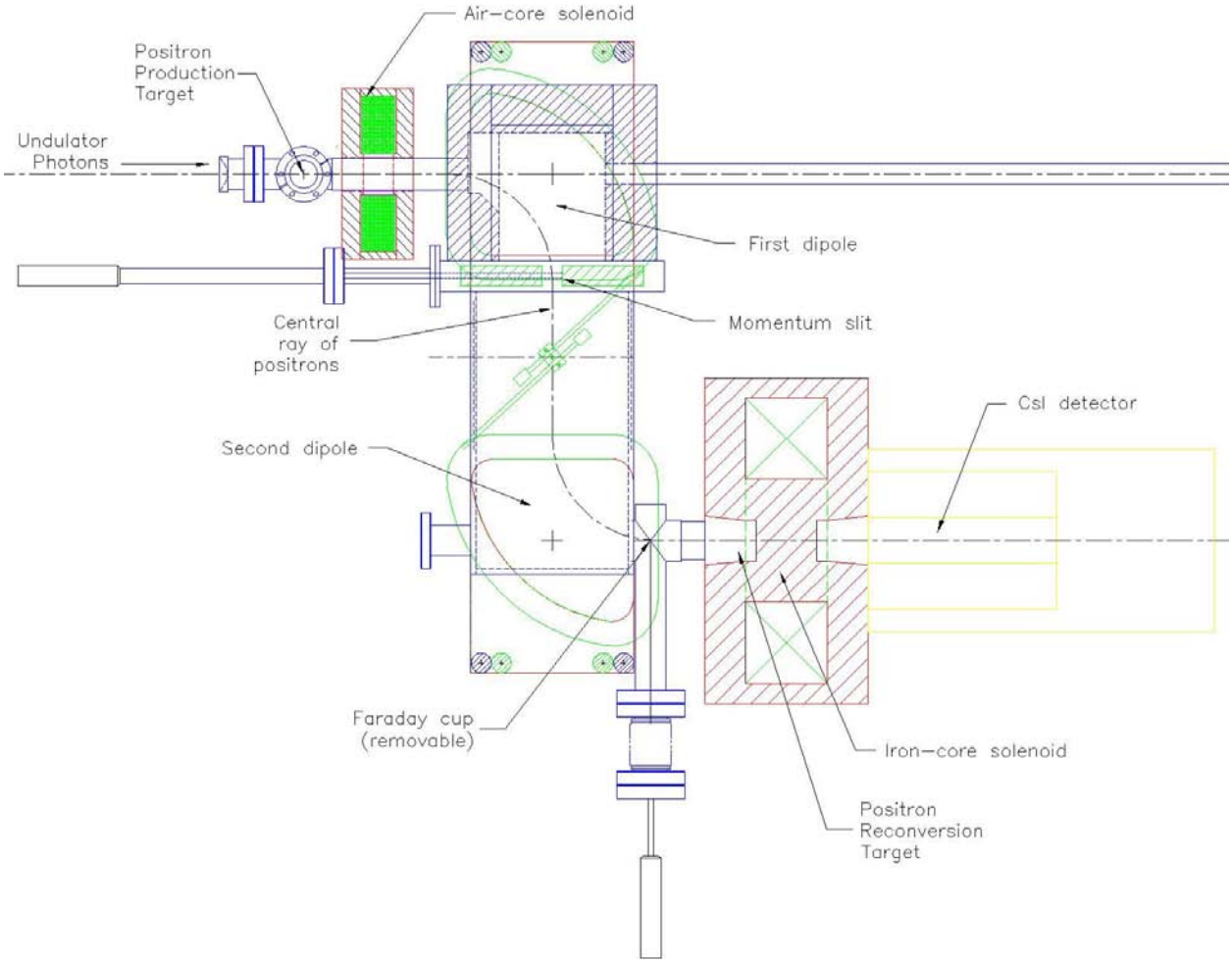

Figure 7: Layout of the positron polarimeter.

2 Princeton Activities on E-166

1. K. McDonald is Co-Spokesperson of E-166 (along with J. Sheppard of SLAC).

2. The solenoid and dipole pair for the positron spectrometer were fabricated at Princeton, and are now installed in the FFTB tunnel (Fig. 8).

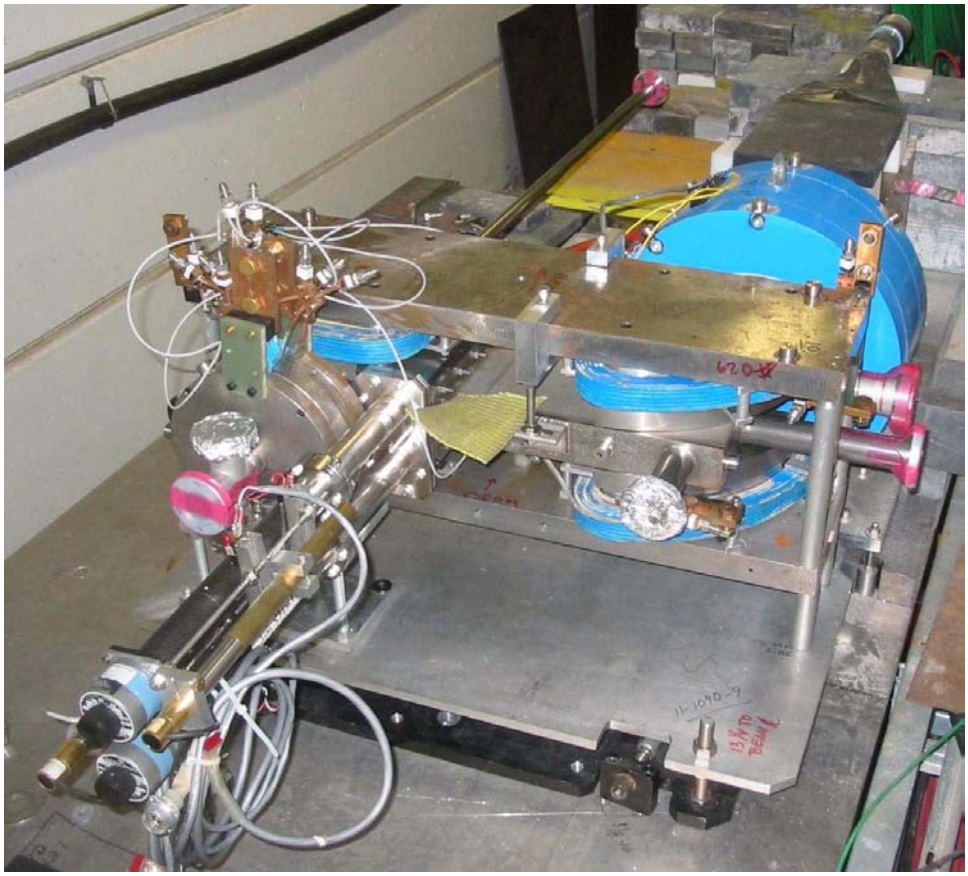

Figure 8: The positron spectrometer in the FFTB tunnel.

3. Princeton participated in the mechancial design of the vacuum chamber for the positron spectrometer (Fig. 9).

4. Princeton participated in the mechancial design of the Faraday "cup" at the end of the positron spectrometer (Fig. 10).

5. Princeton participated in the design and fabrication of the temporary articulated bellows system that permits use of two parallel beam pipes at the location of the unulator (Fig. 11).

6. Princeton fabricated a pair of silica aerogel detectors (index of refraction $n = 1.09$) for use with the undulator photon polarimeter (Fig. 12).

Figure 9: The half of the vacuum chamber that fits inside the first dipole of the positron spectrometer. The tungsten jaws of the momentum slit are visible.

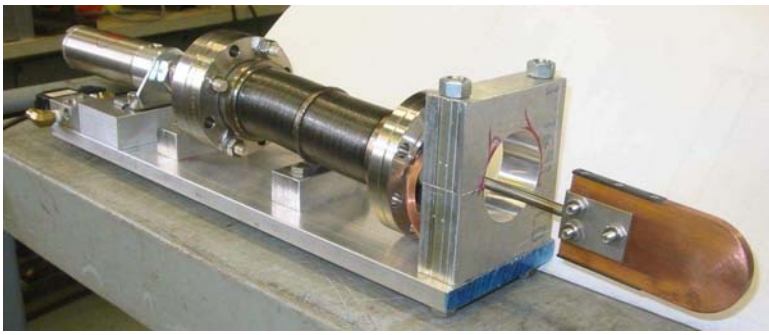

Figure 10: The Faraday cup and associated motion control, to be placed at the downbeam end of the positron spectrometer.

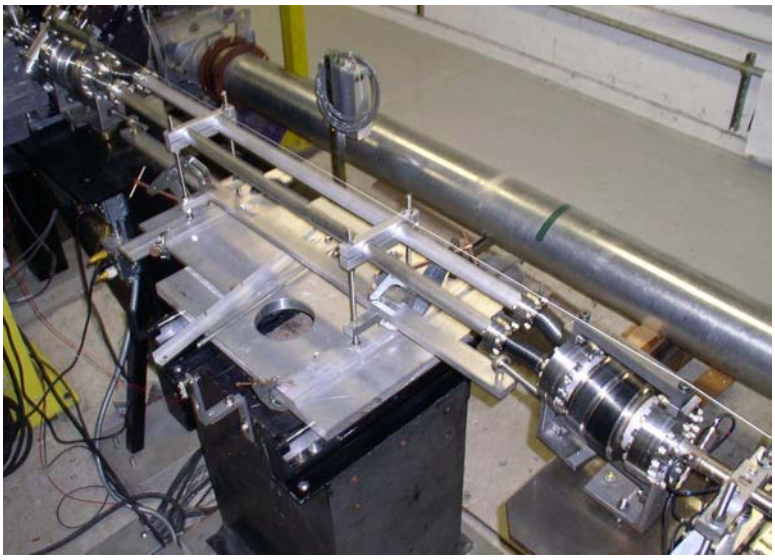

Figure 11: The temporaty articulated bellows system at the eventual location of the undulator in the FFTB tunnel.

Figure 12: The aerogel detectors in the FFTB tunnel, surrounding the undulator-photon polarimeter solenoid.

7. Princeton purchased 3 sets of tungsten (heavimet) shielding of various geomtries for use in and around the positron spectrometer.

8. Princeton purchased an Agilent 33220A arbitrary function generator to control the ramping of the iron-core solenoids, when their field directions are reversed during the polarimetry measurements.

9. Princeton purchased a Tektronix TDS5504N 4-channel digitial oscilloscope for use with the 3 Faraday cup diagnostics of the positron spectrometer.

10. Princeton purchased to PC's for use in the E-166 data acquisition system.

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Demonstration of Undulator Based Production of Polarized Positrons at Final Focus Test Beam (FFTB) E166 at SLAC

William Bugg
University of Tennessee

Summary

The full exploitation of the capabilities of the International Linear Collider (ILC) depends on the ability to generate polarized beams of positrons as well as electrons, without appreciable loss of luminosity. See, e.g. CERN-PH-TH/2005-036. E166 is a collaboration of 15 Universities and National Laboratories with major contributions coming from Cornell, Deutsches Elecktronen Synchrotron, Princeton, Stanford Linear Accelerator Center (SLAC) and the University of Tennessee. The aim of E166 experiment is to test the fundamental process of generating circularly polarized photons in a helical undulator and the production of polarized positrons in a thin target by these photons, a technique originally suggested in 1979 by Balakin and Mikhailichenko at VEPP. The parameters of the undulator and electron beam energy and emittance were chosen to render E166 a scaled down version of a polarized ILC positron source with identical photon energy spectrum. Photon polarization is measured in E166 by measurement of transmission asymmetry through a magnetized iron target and positron polarization in a similar fashion by reconversion of positrons to polarized photons followed by measurement of the conversion photon transmission asymmetry. Details of the experiment can be found at http://www.slac.stanford.edu/exp/e166/

Originally scheduled to run in October, 2004, and delayed due to a SLAC shutdown for several months, E166 finally began setup for its initial run June1, 2005, with installation of undulator and its support table, target assembly, positron transport assembly, analyzing magnets for polarization measurements. Silicon-W and Aerogel Cherenkov photon counters, Si-W and CsI calorimeters for energy measurements and found in a wide variety of detectors to measure backgrounds. The helical undulator, a critical component, was constructed at Cornell University by Mikhailichenko. While the experiment has just completed its initial run on June 29, 2005, it has been remarkably successful to date.

1) The undulator worked immediately when turned on June 17 and delivered the predicted number of photons/incident electron.

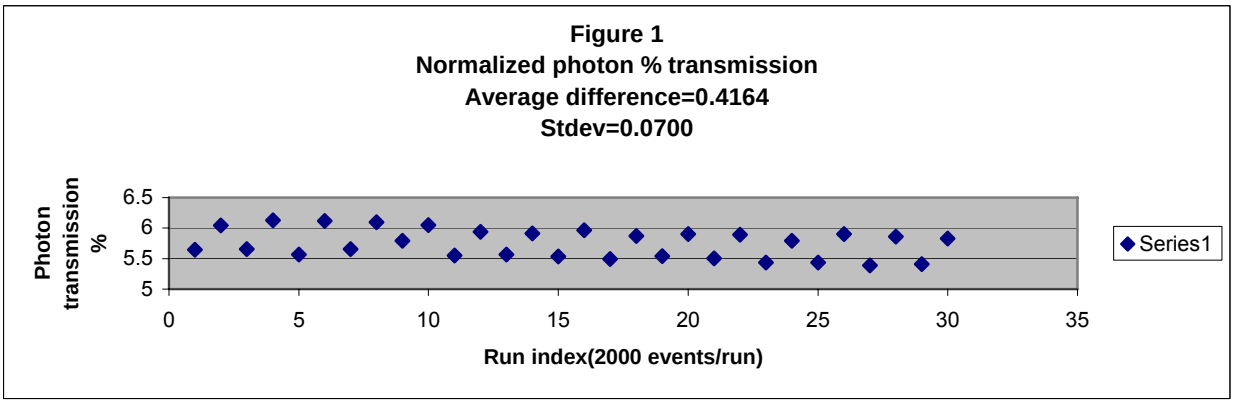
2) The polarization of these photons was established with an uncertainty of about 17% by transmission measurements.

3) Positrons were produced and successfully transported by spectrometer system to reconversion target.

4) Positron polarization asymmetry established but not well measured at present due to backgrounds and limited statistics

Figure 1 is a preliminary result showing the change of photon transmission in a series a series of runs with alternating magnetization in analyzing magnet.

Figure 2 shows the E166 undulator and its designer Alexander Michailichenko. It is one meter long, has an aperture 800 microns, strength K=0.17 with period 2.4mm and was designed to create 0.37 photons/incident electron. A one-month run is scheduled in September 2005 to complete the experiment with improved statistics and backgrounds.



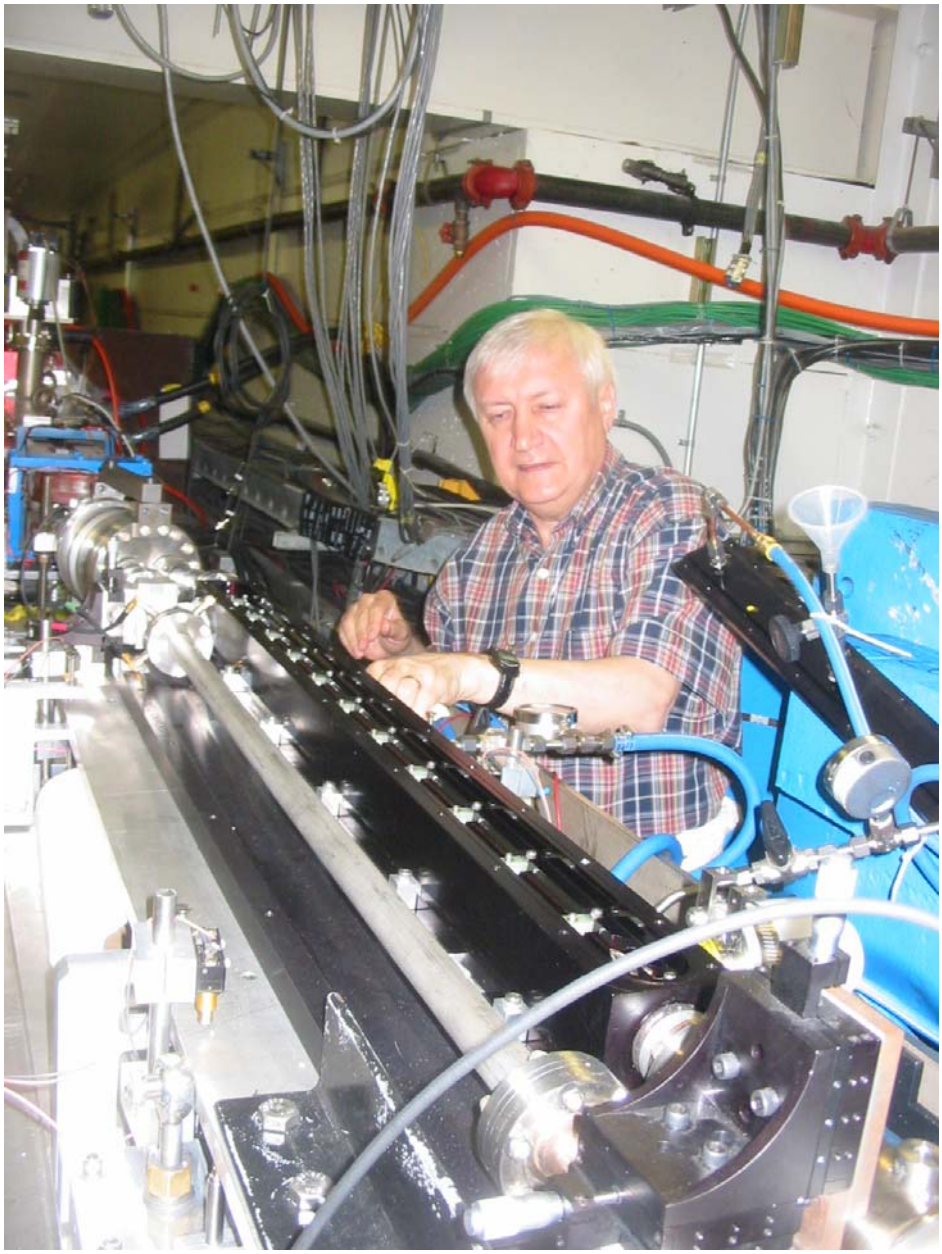


Figure 2

Staff

William Bugg- Professor
Yuri Efremenko – Professor
Steve Berridge - Engineer

Radiation Damage Studies of Materials and Electronic Devices Using Hadrons

Maxwell Chertok & David E. Pellett – Physics Department, University of California, Davis
James E. Spencer and Zachary R. Wolf – Stanford Linear Accelerator Center
James T. Volk – Fermi National Accelerator Laboratory

Summary

This project is part of the Department of Energy (DOE) university-based advanced technology program in generic accelerator R&D relevant to a future linear collider. It is described more fully in the 2004 LCRD Accelerator Proposal, Sec. 2.9. Many components of the accelerator and detectors will be subjected to large fluences of hadrons as well as electrons and gammas during the lifetime of the accelerator. For example, NdFeB permanent magnets have many potential uses in the damping rings, injection and extraction lines and final focus, even though the linacs will be superconducting. This material is advantageous for its relatively low cost and its high energy product $(BH)_{\max}$, but due to its relatively low Curie temperature T_C, one needs to better understand and characterize the degradation of its magnetic properties due to radiation damage. Other possible candidates for testing in this program are electronic and electro-optical devices which will be utilized in the detector readout, possible gamma channels and accelerator control systems and charged coupled devices which will be required for the vertex detector.

Neutrons from photonuclear reactions are expected to be an important source of radiation damage to most materials in the beam tunnels and damping ring enclosures. Electron beam losses create showers of secondary particles dominated by electrons, positrons, photons and neutrons. The neutron energy spectrum is broad but expected to be peaked near 1 MeV. This irradiation can reduce the remanence of NdFeB permanent magnets significantly. Among other factors, the rate of reduction with fluence depends on the type of magnet, its operating point during irradiation, the intrinsic coercivity (and remanence) of the material and the manufacturer of the material. Thus, we chose a range of materials with the basic goal of giving a predictive procedure that obviates the need to characterize the damage of every candidate material and application.

University of California, Davis has two major facilities that can be used to provide needed information on hadron radiation damage, the McClellan Nuclear Reactor Center (MNRC), located in Sacramento (approximately 50 mi. round trip from the Davis campus), and the UC Davis Crocker Nuclear Laboratory (CNL) cyclotron (on campus). Our initial study concerns radiation damage from fast neutrons in samples of NdFeB permanent magnet materials from different vendors using the MNRC facilities. Our measurements appear to be unique in their ranges of loading or operating points and they are complementary to existing measurements using protons.

Recent Accomplishments

Small magnet test structures with NdFeB sample blocks (nickel plated to prevent oxidation) and thin iron flux returns have been fabricated to fit into the MNRC reactor irradiation chambers. They provide a broad variation in effective operating points over the different constituent blocks. A schematic diagram is shown in *Figure 1* giving the relative placements of three specific Sumitomo blocks used here (Blocks 3, 5 and 7). The basic configuration is an asymmetric quadrupole magnet with simple two-pole geometry with a gap that can be varied through the choice of the flux return pieces. Typical block dimensions are in the range 6-9 mm so gaps were made in the range of 2-7 mm. In *Figure 1*, the load-line of Block 5 is in the first $B-H$

quadrant (from the field of Block 3 and the rest of the magnetic circuit) and is nearly uniform throughout the block. Its matching partner at the top (Block 7) has material that is clearly in the second quadrant, as is also the case with Block 3. As the gap is decreased, the load-line difference between Blocks 7 and 5 increases, making the upper one more susceptible to damage. The magnet structure is shown in *Figure 2* undergoing a field scan using a Hall probe. The Hall probe fixture has since been automated using stepping motor micropositioners controlled by a laptop computer running LabVIEW. Accurate measurements of the effective vector magnetizations of individual blocks are made using the Standford Linear Accelerator Center (SLAC) Magnetic Measurements Group Helmholtz coil facility shown in *Figure 3.* Easy axis field component measurements are repeatable within small errors even for the small blocks. The Hall probe scans are being done to ascertain changes in the field distributions resulting from radiation damage. Such measurements are especially relevant for damping ring wigglers where nonlinear dynamics can limit beam lifetime and damping efficiency.

An initial irradiation of the magnet test structure containing Blocks 3, 5 and 7 was performed directly downstream of a hydrogen target in the A-Line at SLAC, achieving a dose of 10 kGy of gammas and 1 kGy of 1 MeV equivalent neutrons (stated as tissue equivalent dose to simplify comparisons). This was followed by a continuing series of irradiations using 1 MeV-equivalent neutrons at the MNRC reactor. Magnet structures using blocks manufactured by Sumitomo and isolated (open circuit) blocks from Shin-Etsu (N50M and N34Z) and Hitachi (HS36E and HS46A) were also irradiated to provide a wide variation in magnetization characteristics, as illustrated in *Figure 4* for the Shin-Etsu materials. The irradiation takes place at a location outside the core but within the reactor vessel (indicated by the arrow in *Figure 5*) inside the NIF facility, a suspended shielded container which absorbs thermal neutrons and significantly attenuates the γ flux. The container is shown opened in the *Figure 5* insert. Magnets are attached to a hexagonal structure inside the container which is rotated during irradiation to insure uniform neutron doses. The irradiations have been relatively short (46 minutes) to allow safe handling of the irradiation vessel by reactor personnel and to avoid long delays for the induced radioactivity to decay prior to shipping to SLAC for measurement. Gamma ray spectroscopy was performed on samples after irradiation to characterize the radiation dose and induced radioactivity as well as to evaluate the effects of doping the material (by the manufacturer) with other rare earth substitutions.

Figure 6 shows the magnetization loss of Blocks 3, 5 and 7 vs. run number after the irradiation in End Station A (Run 1) and three runs at MNRC (Run 0 corresponds to the initial magnetization measurements prior to irradiation). The associated fluences for the runs at MNRC were 9.7×10^{12} n/cm^2 for Run 2 and 1.9×10^{13} n/cm^2 each for Runs 3 and 4. The total 1 MeV-Si equivalent neutron dose delivered at MNRC in this series was 35 Gy. The results are consistent with fast neutron damage being proportional to dose, but depending as well on the disposition of the effective load lines relative to the nonlinear part of the hysteresis curve. The two larger blocks bracket the smaller one (Block 4) and the variation of the damage with dose is roughly twice as great for Block 7 as for Block 5.

Results on the demagnetization rate due to radiation dose $-\delta M_{xy}/\delta D$ (in G/Gy) are given in Table 1 after three additional doses at MNRC. In this table, $\langle M_y \rangle$ is the average over all runs of one component of **M** (with x defined as the easy axis direction) and M^i_{xy} is the initial measurement, before irradiation, of the easy axis projection in the xy plane. The Shin-Etsu blocks received 6 doses totaling 77.8 Gy (Si). New magnet blocks using materials from Hitachi (HS36, HS48) received 2 doses totaling 28 Gy (Si). The damage appears to be linear with dose over these ranges. Stepped doses are continuing for these and additional 3-block test structures.

We have also investigated the effects on magnet radiation resistance and induced radioactivity due to the presence of additional rare-earth components such as Tb as revealed by the gamma

spectra. Essentially all of the observed lines have been identified. The sources of most lines are clear e.g. n-capture on Fe^{58}, Nd^{146} or the substitution element Tb^{159}. Neutron knockout (n,2n) on Nd^{148} also has a cross section comparable to capture leading to Nd^{147} while (n,p)-exchange reactions on Fe^{54}, Ni^{60} or trace contaminants esp. from the rare earths are also seen. Pm^{151} results from $Nd^{150}(n,\gamma)Nd^{151}$ followed by β^- decay. The results indicate that N50Z has about 55% as much Tb as N34Z. Based on known capture cross sections for Fe^{58} and Tb^{159} and relative abundances one infers a large substitution in N34Z that greatly improves its radiation resistance. Further information on the gamma spectra, material doping and the relation to radiation hardness is given in the listed publications.

Further runs in the series will continue on our enlarged sample set and also include certain electrical and fiber optic materials such Suprasil 300 based on previous studies with gammas.

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3. S. Anderson, J. Spencer, Z. Wolf, A. Baldwin, D. Pellett, M. Boussoufi and J. Volk, “Fast Neutron Damage Studies on NdFeB Materials,” PAC'05, Knoxville, May 2005.

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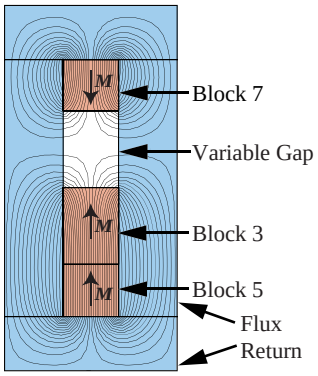


Figure 1: Diagram of three block magnet test structure showing sample locations (not to scale).

Figure 2: Three block magnet test structure (in foreground) being measured with Hall probe.

Figure 3: Helmholtz coil magnet measurement facility.

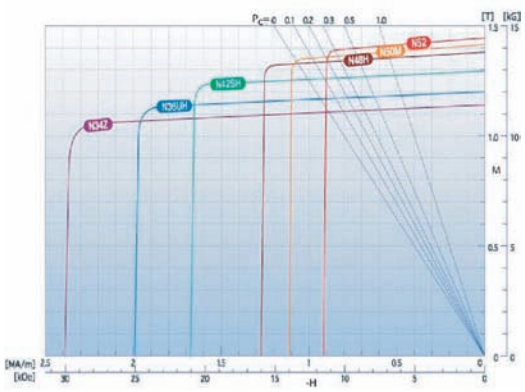


Figure 4: Demagnetization curves for Shin-Etsu N50M (yellow) and N34Z (violet) NdFeB materials showing range of characteristics.

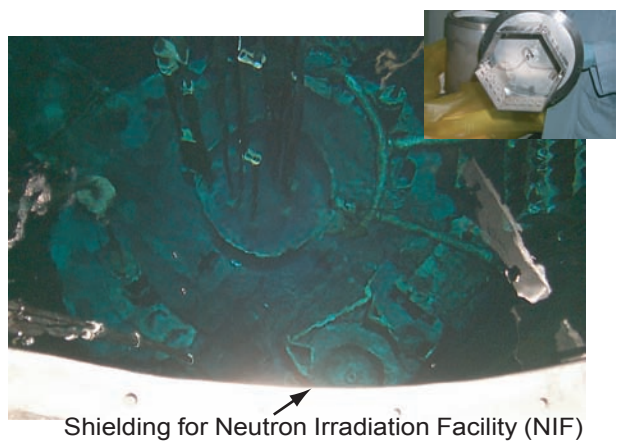


Figure 5: View looking down into MNRC "swimming pool" reactor. Inset: hexagonal attachment structure of NIF vessel.

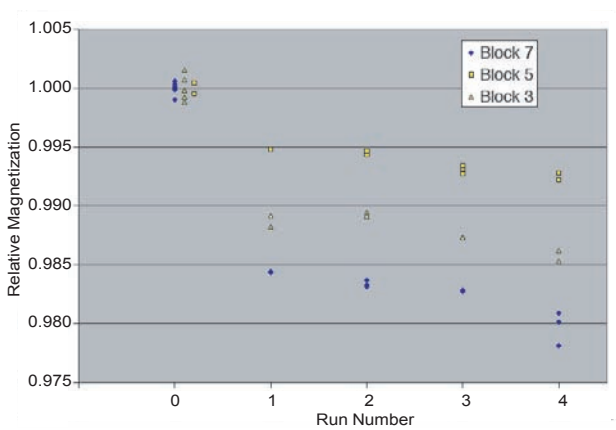


Figure 6: Relative magnetization loss vs. irradiation run number for NdFeB blocks in magnet test structure. Run 0 is the initial measurement prior to irradiation.

Table 1: Demagnetization results for irradiated NdFeB magnet blocks using Hitachi, Shin-Etsu and Sumitomo materials.

Block	$\langle M_y \rangle$ [G]	M^i_{xy} [T]±[G]	$-dM_{xy}/dD$ [G/Gy]
HS36EH	-62 ± 29	1.1595 ± 0.8	0.00 ± 0.03
HS46AH	-154 ± 18	1.3298 ± 2.0	3.84 ± 0.07
N34Z1	-301 ± 35	1.1106 ± 1.8	0.49 ± 0.02
N50M1	-50 ± 38.	1.3706 ± 1.1	1.81 ± 0.02
Block 3	-350 ± 57	1.0748 ± 6.7	0.78 ± 0.08
Block 5	93 ± 177	1.0622 ± 2.2	0.64 ± 0.03
Block 7	466 ± 183	1.0714 ± 0.9	1.04 ± 0.03

ILC Damping Ring Kicker R&D at the University of Illinois

George Gollin
University of Illinois at Urbana-Champaign

Summary

The Illinois group participates in two distinct accelerator R&D projects as well as playing a leadership role in the U.S. linear collider community. One of our efforts concerns design studies of International Linear Collider (ILC) damping ring kickers, while the other has focused on the use of acoustic techniques to diagnose high voltage breakdowns in RF power couplers for the ILC main linac. Gollin is a proposal coordinator for UCLC/LCRD, the U.S. university-based program of linear collider research and development, and the editor of the annual proposal document *A University Program of Accelerator and Detector Research for the International Linear Collider.*

The work is well suited to student participation. The Illinois contingent includes the participation of one professor (Gollin), two engineers (Haney and Simaitis), one postdoctoral research associate (Williams), one graduate student (Ely), and four undergraduates (Calvey, Chang, Davidsaver, and Phillips). Keri Dixon, now a graduate student at SUNY Stony Brook, wrote her senior thesis a year ago on the kicker project.

Investigation of Novel Schemes for Injection/Extraction Kickers

The 2,820 bunches of an ILC pulse would require an unacceptably large damping ring if the 337 ns linac bunch spacing were used in the damping ring. As a result, the preliminary 500 GeV design[1] called for 20 ns bunch separation in a 17 km circumference damping ring; a fast kicker would deflect individual bunches on injection or extraction, leaving the orbits of adjacent bunches in the damping ring undisturbed.

One of the kicker designs under consideration involves the creation of short electromagnetic field pulses in stripline modules. The demands of short rise/fall times and pulse-to-pulse stability are challenging, though a system capable of generating shorter pulses would allow the construction of a smaller damping ring.

It is also interesting to consider a different design in which the pulsed kicker is replaced by a low-*Q* RF device filled with a broadband signal whose amplitudes, frequencies, and phases correspond to the Fourier components of a periodic, narrow pulse. Instead of energizing the system only when a bunch was about to be injected (or extracted) to the damping ring, the device would run continuously. This might allow the frequencies, phases, and relative amplitudes of the impulse to be determined with great precision. Our "Fourier series pulse compression kicker" design would entirely avoid the challenges of fast HV switching and near-perfect stripline termination by running constantly.

With a properly chosen set of parameters, either system would kick every M^{th} bunch in a train, leaving undisturbed the train's other (M - 1) bunches. At the present time we are studying kickers intended to function with M = 60, admitting the construction of a 6 km circumference damping ring. We are pursuing studies of both a conventional stripline kicker and a Fourier series kicker; both are done in collaboration with Fermi National Accelerator Laboratory (Fermilab).

Design and construction of a stripline kicker module for installation in the AØ Photoinjector's 16 MeV electron beam was completed in April 2005. The device has

[1] *TESLA Technical Design Report*, http://tesla.desy.de/new_pages/TDR_CD/start.html (March, 2001).

been installed in the AØ beam and we are currently (June 2005) configuring the data acquisition and beamline instrumentation systems to begin our tests. Initial measurements will be performed using a high voltage pulser copied from an existing Fermilab linac chopper pulser. Its ±800 V pulses have ~10 ns rise times, too slow for an ILC kicker, but adequate for commissioning the device in the AØ line. Gerry Dugan (Cornell) has ordered a FID ("Fast Ionization Dynistor") HV pulser that we will use with our kicker after the summer. Both pulsers are expected to deflect the beam by approximately 10 mrad.

We have two primary goals at this time. The first is to use this simple kicker to understand the fine points associated with using the AØ beam to characterize damping ring kickers. How do the beam's position, intensity profile, and timing characteristics influence (and limit) our ability to use the beam to study the stability of a more complicated kicker? The second goal is to determine how well our kicker (with increased aperture) might actually perform as a damping ring kicker.

Figure 1 shows a diagram of the downstream end of the AØ beamline beginning at the kicker. *Figure 2* shows a photograph of the kicker after installation.

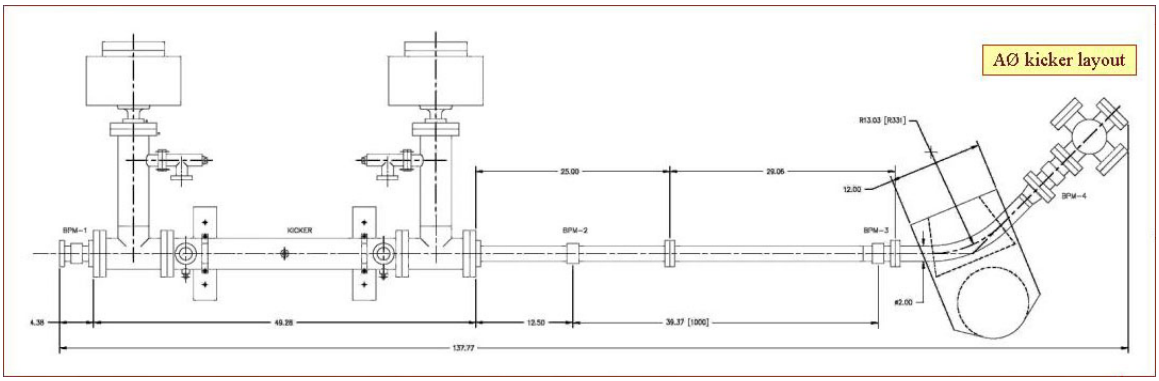


Figure 1 AØ beamline with UIUC/FNAL stripline kicker installed

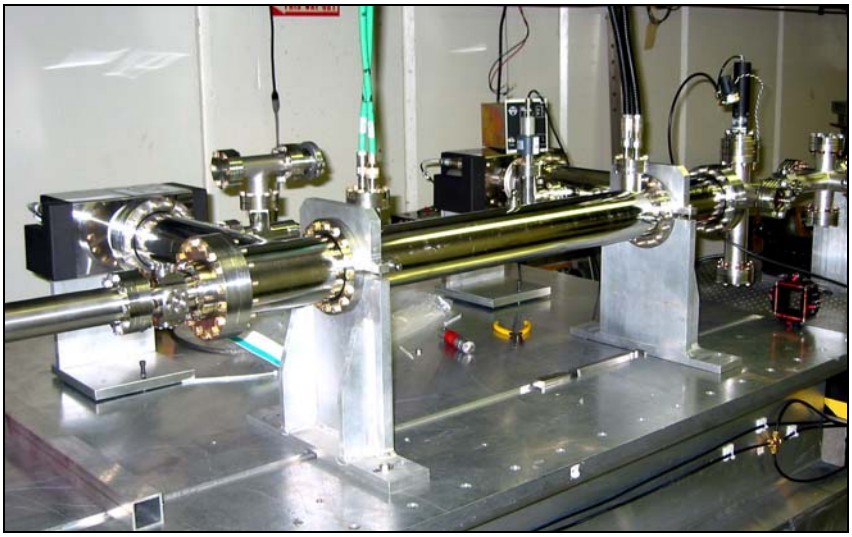


Figure 2 UIUC/FNAL stripline kicker in place in the AØ beamline

We hope to have initial results in time for presentation at Snowmass later this summer.

A detailed discussion of a Fourier-series kicker system can be found on the web.[2] We are concentrating on a particular implementation in which an RF amplifier will send a broadband signal down a waveguide to a $Q \approx 25$ RF structure. Dispersion in the waveguide shifts the relative phases of the Fourier components of the signal so that it is compressed: power arrives at the RF structure in short, periodic bursts, filling it in order to eject the target bunch without disturbing adjacent bunches. The RF structure is able to store energy, so its maximum field strength is approximately 20 times greater than the maximum field strength in the downstream end of the waveguide. A schematic representation of the kicker is shown in *Figure 3*.

We have been studying an impulse function of the following form:

$$A(t) = \frac{1}{N^2}\frac{\sin^2\left(\frac{1}{2}\omega_{DR}t\right)}{\sin^2\left(\frac{1}{2}\omega_L t\right)}\cos\left(\omega_{RF}t\right) = \frac{1}{N^2}\frac{\sin^2\left(\frac{1}{2}N\omega_L t\right)}{\sin^2\left(\frac{1}{2}\omega_L t\right)}\cos\left(\Gamma N\omega_L t\right). \qquad (1)$$

Here, ω_L is the main linac bunch frequency (~3 MHz) and ω_{DR} is the damping ring bunch frequency (~180 MHz). The modulation frequency $\Gamma N\omega_L t$ corresponds to approximately 1.8 GHz. The impulse function during an interval ±25 ns around the kicking peak at $t = 0$ is shown in *Figure 4*. For the time interval shown in the figure, unkicked bunches pass through the device at $t \sim \pm 6$ ns, ±12 ns, ±18 ns, and ±24 ns.

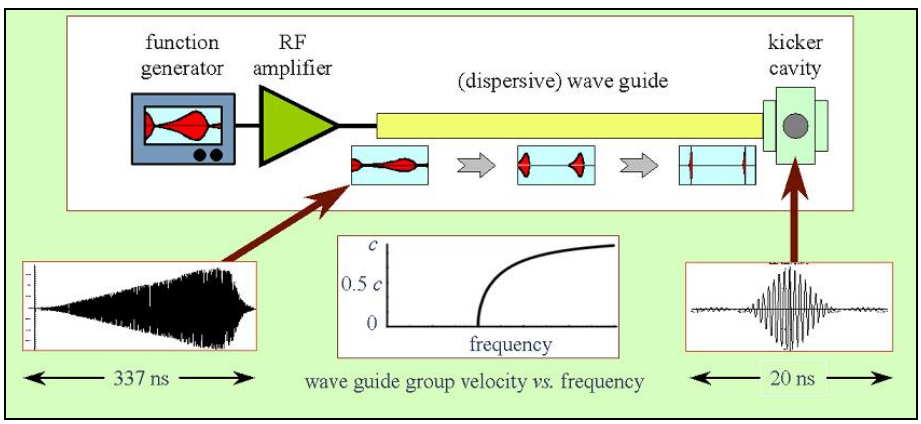


Figure 3 Schematic representation of a Fourier series pulse compression kicker

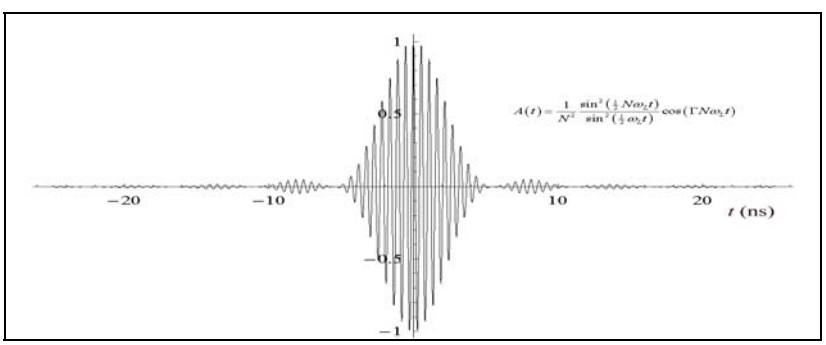


Figure 4 Kicker field integral A(t) in an interval ±25 ns around the kicking peak

[2] G.D. Gollin *et al.*, *Performance Modeling of a Fourier Series Pulse Compression Kicker for the International Linear Collider Damping Rings*, available on the web at http://www.hep.uiuc.edu/home/g-gollin/talks/fourier_series_kicker_technical_memo_draft.doc (2005).

Our simulations of the Fourier series pulse compression kicker include imperfections in geometry and cavity parameters, as well as noise, amplifier harmonic distortion, and intermodulation distortion. Results are promising; our principal concern at this time is the level of third-order intermodulation distortion associated with noise down-mixing with second order distortion amplitudes to interfere with the genuine signal.

Because the parameter space describing the couplings of noise and nonlinear effects is so large, it is appropriate to begin studying real RF systems in the laboratory. We have begun to do this, thanks to the loan of space (and equipment) in an advanced undergraduate RF engineering laboratory at UIUC. Amusingly, an inexpensive source of L-band waveguide has proved to be a building supply store in Champaign: aluminum downspouts used in conventional home construction work nicely, with a sharp cutoff frequency at approximately 1.4 GHz and efficient transfer of power from the signal "launcher" into the receiving antenna at the far end. Until we need greater uniformity and precision we will continue to work with the RF hardware shown in *Figure 5*.

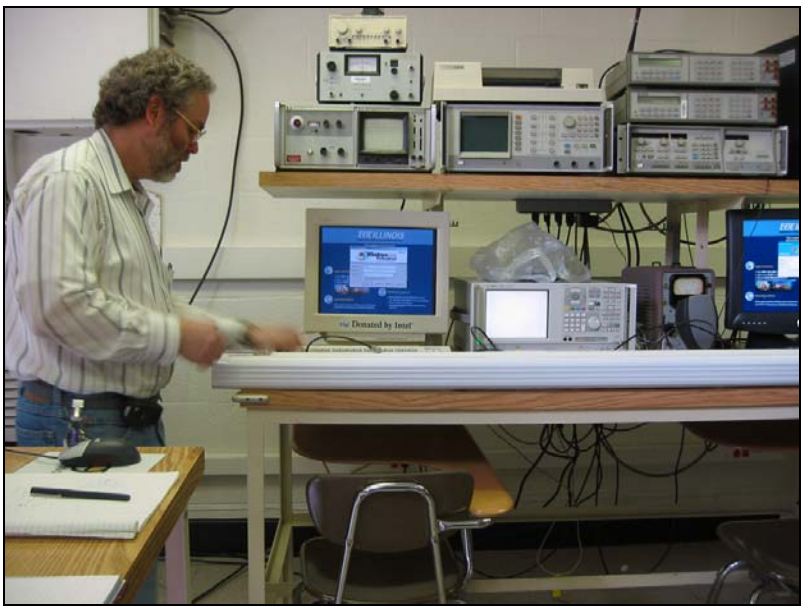


Figure 5 RF studies using aluminum downspout as L-band waveguide at UIUC

We hope to demonstrate pulse compression of a simple "chirp" in time for presentation at Snowmass later this summer. As the sophistication of our efforts increases we will collaborate more and more closely with the Fermilab RF engineering group on this project.

Development of Polarized Photocathodes for the Linear Collider

R. Prepost
University of Wisconsin-Madison

Summary

The development of high current polarized photocathodes is very important for the International Linear Collider (ILC) project. Physics requirements call for highly polarized electron beams with a goal of at least 90% polarization.

A Wisconsin - Standford Linear Accelerator Center (SLAC) collaboration has been developing and studying polarized photocathodes which have been used for the SLAC Stanford Large Detector (SLD) and fixed target programs. A more recent goal is the development of photocathodes with a polarization in excess of 90% which meet the ILC charge requirements. This work started as a SLAC -Wisconsin collaboration (E. Garwin, T. Maruyama of SLAC and R. Prepost of Wisconsin) and has evolved into a formal SLAC collaboration called the Polarized Photocathode Research Collaboration (PPRC).

Early research efforts focused on the development of strained photocathodes since electron spin polarization higher than 50%, approaching 100%, is theoretically possible using cathode structures which have less crystal symmetry than unstrained GaAs. Excellent performance was achieved with strained GaAs epitaxial layers grown on a GaAsP buffer layer. The 1994-1998 Stanford Linear Collider (SLC) operation with the SLD detector and subsequent fixed target experiments E-142, E-143, E-154, E-155, and E-155X used strained gallium arsenide cathodes which produced at least 80% polarization at the source. More recently, a newly developed high current polarized photocathode used for SLAC experiment E-158 achieved a polarization of about 90% with a charge approaching that required for the ILC.

We have continued R&D efforts on cathode structures to address certain issues, specifically 1) fundamental properties of materials, 2) higher polarization, and 3) higher charge limit. One limitation of singly strained heterostructures is that the thickness of the active layer is limited to about 0.1 μmLarger thickness of the active layer results in serious degradation of the strain. Superlattice structures can in principle overcome the inherent thickness limitation of single heterostructures.

We will study a superlattice stucture proposed by the Russian St. Petersburg group of Y. Mamaev. The Mamaev group has had California Desert Research Funds (CDRF) funds in partnership with SLAC to study and grow certain superlattice structures. The two year CDRF grant ended November 2004 and resulted in an interesting structure which requires additional study. The structure is an InAlGaAs/GaAs superlattice of about 18 periods. This particular stucture has a lattice matched buffer layer which should result in higher quality with less dislocations and a smaller conduction band offset which should result in greater electron transport. The previous GaAsP/GaAs superlattice structures we have studied do not have these particular beneficial characteristics. The structure has several parameters which require systematic study.

Recent Accomplishments

We have placed an order for several of the InAlGaAs/GaAs stuctures with SVT Associates in Minneapolis. This company has grown other structures for us and we are pleased with the quality of their work. Another structure we plan to study is a superlattice based on GaAs and InGaP. A GaAs/InGaP superlattice structure differs from the previously studied GaAs/GaAsP

superlattice in that GaAsP superlattice barrier layers are replaced by InGaP. The GaAs strained wells remain the same. The new strained superlattice is expected to increase the polarization because the spin relaxation rate in InGaP is less than in GaAsP. Since the band-gap energy of InGaP is larger than that of GaAsP, an enhancement of the Quantum Efficiency is also expected.

Publications 2001-2004

1. T. Maruyama et al., "Systematic Study of Polarized Electron Emission from Strained GaAs/GaAsP Superlattice Structures", Appl. Phys. Lett. **85,** 2640 (2004).

2. T. Maruyama et al., "Atomic Hydrogen Cleaning of Polarized GaAs Photocathodes", Appl. Phys. Lett. **82**, 4184 (2003).

3. T. Maruyama et al., "A Very High Charge, High Polarization Gradient Doped Strained GaAs
4. Photocathode", Nucl. Instrum. Meth A **492**, 199 (2002).

5. G. Mulhollan et al., "Photovoltage Effects in Photoemission from Thin GaAs Layers'", Phys. Lett. A **282**, 309 (2001).

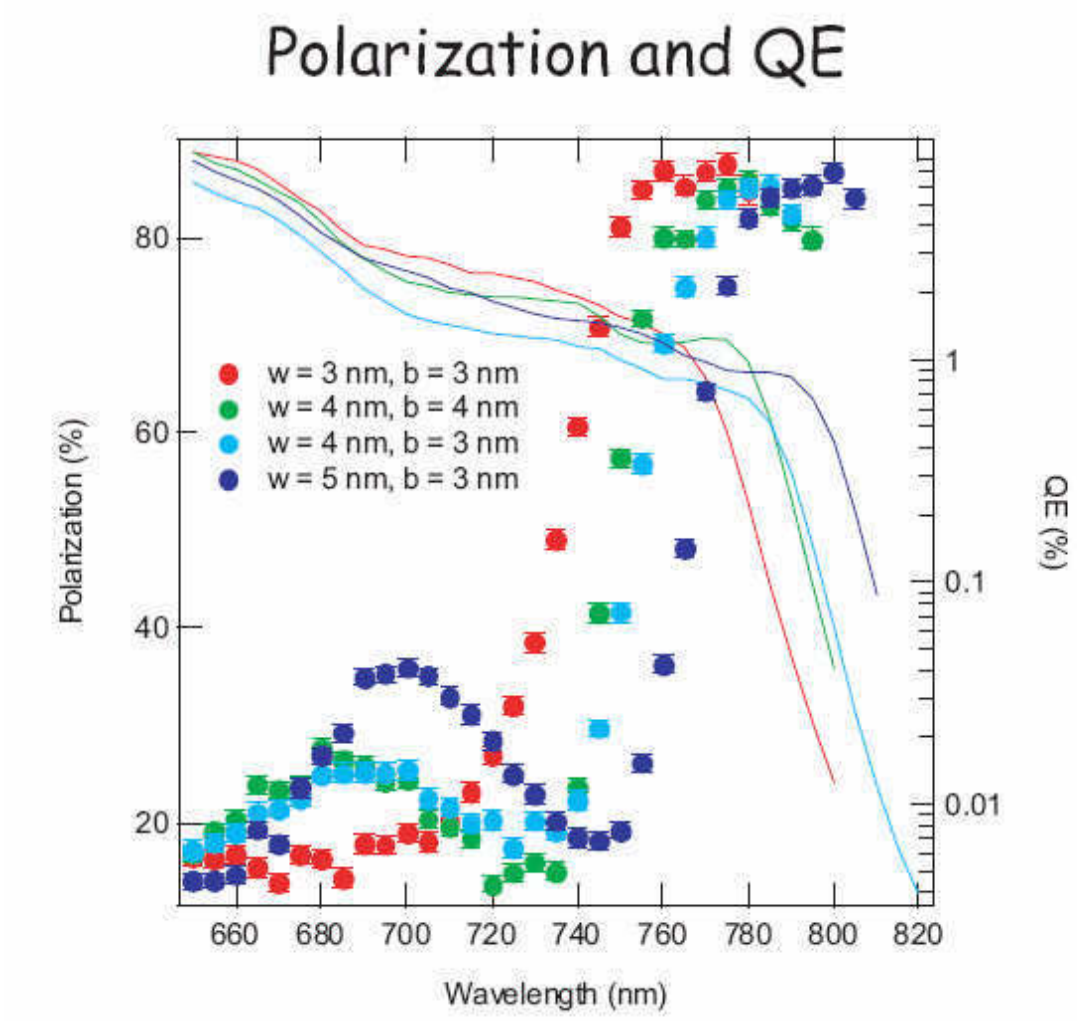
Current Staff: (Current grant does not support any personnel)

- Prof. R. Prepost Principal Investigator: University of Wisconsin - Madison
- Dr. J. Clendenin SLAC
- Prof. E. Garwin SLAC
- Dr. R. Kirby SLAC
- Dr. T. Maruyama SLAC

Polarization and QE Results from a GaAsP/GaAs Superlattice

w = GaAs well width; b = GaAsP barrier width APL **85** 2640 (2004)

Peak Polarization ~86% QE (at peak) ~ 0.1%



NATIONAL LABORATORY PROGRAMS

Report on Advanced Accelerator R&D Activities at Argonne

Wei Gai and John Power
Argonne National Laboratory

Summary

The advanced accelerator program at Argonne focuses on advancing the physics and technology of beams, particularly new approaches to electron beam acceleration and instrumentation important to the world High Energy Physics (HEP) program. Our past major accomplishments include: the first ever demonstration of collinear wakefield acceleration in dielectric devices, plasmas, and disk-loaded structures; the first ever direct measurement of transverse wakefields in linac structures, including the Next Linear Collider prototype design; generation of ultrahigh current electron beams, unique among RF photocathode based linacs; production and measurement of high accelerating gradients in both plasmas and dielectric structures; origination and demonstration of the principle of the wakefield step-up transformer (two beam acceleration) using dielectrics; first ever high-power testing of dielectric accelerating structures that lead to the discovery of a new multipactoring phenomena; and first ever observation of Schottky-enabled photoelectron emission in an RF photocathode gun with possible application for high brightness electron beam generation. The program has also served as a training ground for many undergraduate, masters, and Ph.D. thesis students. We currently have three Ph.D. students and two undergraduate students working in the group.

Our group operates the Argonne Wakefield Accelerator (AWA) facility and performs research on beam-structure interaction, such as beam- and rf- driven acceleration concepts. One of the acceleration schemes that we are currently developing – dielectric-based, two-beam acceleration – uses a train of low-energy, high-current electron bunches (the drive bunch train) to accelerate a second electron bunch (the witness beam) to higher energy through the use of a dielectric-loaded structure. If successful, the technique developed at the AWA could have impact on future HEP machines. We are also working on experiments related to the collinear wakefield acceleration schemes in dielectric and metal structures. In order to develop these wakefield-based, beam-driven acceleration techniques, the group is necessarily involved in the design and operation of novel high-current electron sources. Based on our prior experience with high-current RF photoinjectors, we recently developed a third-generation, photocathode-based electron source capable of producing, for the same 100 nC-scale intensities, drive beams that are a factor of three shorter in duration and ten times smaller in emittance than our previous second-generation gun. This improvement in beam quality translates to a significant increase in the expected level of performance of our wakefield accelerator devices, making them comparable to, or exceeding, those of conventional high-frequency structures.

Another major activity of this program is the series of high-power RF tests carried out on externally RF-driven, dielectric-based, X-band structures in collaboration with S. Gold at the Naval Research Laboratory and R. Ruth's Department at Stanford Linear Accelerator Center. This collaboration has yielded many important physics results. We plan to establish a facility to provide both an X-band RF source (> 50 MW) and an electron beam source (> 5 MeV) for the purposes of high-power RF testing of dielectric and other advanced accelerating structures. Our goal is to eventually establish a 20 MeV compact X-band accelerator module based on dielectric technology.

Recent Activities

The AWA Facility Status. The AWA Facility uses a high charge (10-100 nC), short pulse (3-5 psec) drive bunch to excite high-gradient accelerating fields in various slow-wave structures. To

generate this bunch, a new 1 -1/2 cell RF photocathode gun has been in operation in the AWA facility for the last two years and has significantly improved the drive beam performance. Currently the gun produces beams with energy of ~ 8 MeV and single bunch charges up to 100 nC with the Mg cathode installed. Overall, upgrades to a Ti:Sapphire photocathode laser system, a PC-based control and DAQ system, the installation of a standing-wave linac after the gun, and vastly improved diagnostics have enabled us to generate the beam parameters needed for the planned dielectric-based, two-beam acceleration experiments; along with the many other high current beam physics experiments that we have planned. In order to create the high charge drive train needed for our planned high total energy gain experiments, the upgrade to a Cs2Te photocathode is underway. An ultra-high vacuum chamber and thermal vapor deposition system to fabricate Cs_2Te photocathode is being assembled.

Beam-driven Wakefield Experiments at the AWA. Several dielectric-based structure experiments are underway at the AWA beamline. Most recently, a 15 GHz dielectric loaded wakefield structure was used to extract energy from a 13 MeV electron beam. Short electron bunches (13 ps FWHM) of up to 60 nC traversed the structure, generating an accelerating field of ~30 MV/m. The structure consists of a cylindrical ceramic tube (cordierite) with a dielectric constant of 5, inner and outer radii of 5 mm and 7.49 mm, respectively. The 102 mm long dielectric cylinder is inserted into a cylindrical copper waveguide. Short metallic cylinders, with the same inner and outer radii as the ceramic, are inserted on both ends of the copper waveguide, making it a standing wave structure. A field probe present near the outer edge of the dielectric samples the RF field generated by the electron bunches. The measurements were also made with two bunches separated by 1.5 ns. As a next step in these experiments, another structure, with an output coupler, will be used for high power extraction. This structure has been designed and is presently being fabricated. In another experiment, working with Dr. Schoessow and Dr. Kanareykin of Euclid Concepts, we will use a triangular envelope bunch train to achieve a high transformer ratio in a collinear wakefield experiment. We will also emphasize other high-current electron beam driven methods, and further explore the possibility of high-efficiency linac designs for two-beam acceleration. We have also explored several exotic accelerator physics applications including Photonic Band Gap (PBG) materials and Left-Handed Metamaterials. For example, during the last year, we have investigated (1) The Multilayer Dielectric-Loaded Accelerator (DLA): a 1-D PBG structure that is similar to our standard single-layer DLA, but with vastly improved power attenuation; and (2) The Reverse Cherenkov Radiator: a beam diagnostic where cherenkov radiation propagates in the direction opposite to the electron beam. We have simulated this device using Microwave Studio ® and have now begun to make cold test measurements with an HP Network Analyzer.

Beam Physics at the AWA. Wide varieties of beam dynamics issues and diagnostics are studied at the AWA facility. For the high charge beam, we have measured bunch lengths of 10 ps FWHM for charges up to 70 nC using a quartz cherenkov radiator and a streak camera. A ~ 60 nC beam passed through a small dielectric tube with minimum losses. In addition, we developed a modified 3-screen emittance measurement method that uses a beam envelope model that includes both space-charge and emittance effects for the measurements of a 1 nC, 8 MeV beam in the drift region directly following the rf drive gun. In a related experiment, measurements of the transverse beam envelope were made in the drift region directly after the photocathode plane, and were found to be in reasonably good agreement with the PARMELA predictions. We have also initiated a first-ever study of Schottky-enabled photoemission, where the incident photon energy is approximately equal to the photocathode work function, so that the emitted electrons have very little kinetic energy. Since the intrinsic emittance is thought to be the limiting value of the emittance, this technique opens up the possibility of reaching even lower emittance values. We are currently developing a novel OTR-ODR interferometry experiment (in collaboration with R. Fiorito of the University of

Maryland) that, in addition to measuring the usual rms emittance, should also be capable of measuring the energy spread. This technique is essential when measuring the emittance directly from a photoinjector due to the non-negligible energy spread.

Externally RF-driven Structures at NRL. Over the last two years, high-power tests have been carried out on three Dielectric-Loaded Accelerating (DLA) structures using two dielectric materials: Alumina (ε=9.4) and MgxCa1-xTiO3 (ε=20) or MCT20. Problems arising in each of these experiments have been investigated, understood and are now being solved. In order to suppress multipactor in the alumina based DLA structure (discovered in the previous experiment) we coated the inner surface of alumina tube with 75 nm layer of TiN. We have observed improved performance with the coated structure. Further tests are scheduled for the TiN coated structures. Other experiments using the MgxCa1-xTiO3 (MCT) based DLA structures were performed during this period. We discovered that dielectric breakdown occurs in the joint between the tapered matching section and the straight accelerating section where strong local field enhancement (20 times greater than the field in the dielectric) can creates fields of more than 100 MV/m. To further test the dielectric joint breakdown, we filled the gap at the joint with a high-Q epoxy (ε=5.2) and a dielectric strength of 23.6 MV/m. Based on this dielectric constant, we expect that the local field enhancement factor should be reduced from 20 to 3.8 thus allowing higher gradient operation. Experiment verified the above assumption that the field breakdown near the gap has increased as we expected. Further testing will be performed to study a new structure that is designed to have no gaps in the high field region in the near future.

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2. J.G. Power, H. Wang, M.E. Conde, W. Gai, R. Konecny, W. Liu, and Z. Yusof, “Transverse beam envelope measurements and the limitations of the 3-screen emittance method for space-charge dominated beams”, *Nucl. Instr. Meth. in Phy. Res. A* 546 (2005) 345–355
3. J.G. Power, W. Gai, S. H. Gold, A. K. Kinkead, R. Konecny, C. Jing, W. Liu, and Z. Yusof, “Observation of Multipactor in an Alumina-Based Dielectric-Loaded Accelerating Structure”, *Phy. Rev. Lett.* 92.16 , 2004, pp. 164801
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5. C. Jing, R. Konecny, W. Gai, S. H. Gold, J. G. Power, A. K. Kinkead, and W. Liu, “High Power rf Test on X-band MgxCa1-xTiO3 Based Dielectric-Loaded Accelerating Structure” *Proceedings of 11th Advanced Accelerator Concepts Workshop,* Stony Brook, New York, June 2004, edited by Vitaly Yakimenko, pp.258-264.
6. J. G. Power, W. Gai, S. H. Gold, A. K. Kinkead, R. Konecny, C. Jing, and W. Liu, “Experimental Study of Multipactor Suppression in a Dielectric-Loaded Accelerating Structure”, *Proceedings of 11th Advanced Accelerator Concepts Workshop,* Stony Brook, New York, June 2004, edited by Vitaly Yakimenko, pp.265-271.
7. Kanareykin, W. Gai, J. G. Power and P. Schoessow, “Transformer Ratio Enhancement for Structure-Based Wakefield Acceleration”, *Proceedings of 11th Advanced Accelerator Concepts Workshop,* Stony Brook, New York, June 2004, edited by Vitaly Yakimenko, pp.272-280.
8. M. Conde, S. Antipov, W. Gai, C. Jing, R. Konecny, W. Liu, J. Power, H. Wang, and Z.Yusof, “The Argonne Wakefield Accelerator Facility: Capabilities and Experiments”, *Proceedings of 11th Advanced Accelerator Concepts Workshop,* Stony Brook, New York,

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12. W. Gai, C. Jing, R. Konecny, W. Liu, and J.G. Power, "New RF Design for 11.4GHz Dielectric Loaded Accelerator", *Proceedings of the 2003 Particle Accelerator Conference,* Portland, Oregon, edited by Joe Chew, Peter Lucas, and Sara Webber, May 2003, pp.1810-1813.
13. J. G. Power, "Slit Scattering Effects in a Well Aligned Pepper Pot", *Proceedings of the 2003 Particle Accelerator Conference,* Portland, Oregon, edited by Joe Chew, Peter Lucas, and Sara Webber, May 2003,, pp.2432-2434.

Current Staff

- Gai, W Principal Investigator
- Conde, ME Staff Scientist
- Franchini, F Technician
- Konecny, RS Staff Engineer
- Power, JG Staff Scientist
- Yusof, Z Staff Scientist
- Liu, WM Visiting Staff Scientist

Current Ph.D. Candidates

- Antipov, Sergey. Physics Department, Illinois Institute of Technologies
- Gao, Feng. EE Department, Illinois Institute of Technologies
- Wang, Haitow. EE Department, Illinois Institute of Technologies

Current Undergraduate Students

- J. Walsh, Physics, University of Chicago
- J. Hsieh, Physics, University of Chicago

Recently Graduated Ph.D. Students

- Zou, P (2002) Ph.D., Currently Senior Staff Engineer, Intel Corp.
- Jing, C (2005) Ph.D., Currently Physicist, Euclid Techlabs, LLC

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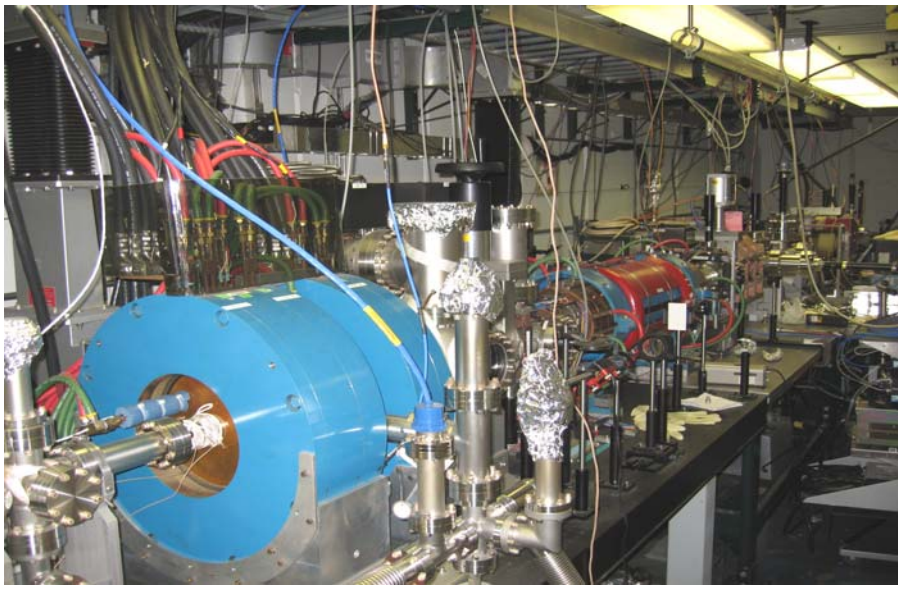
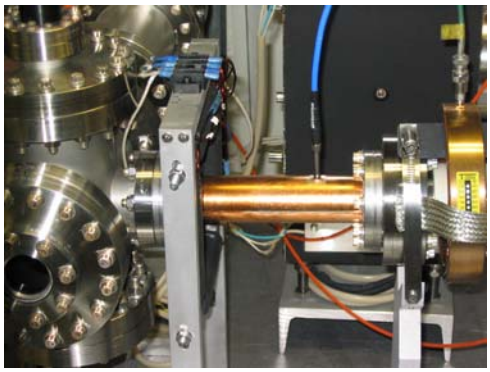
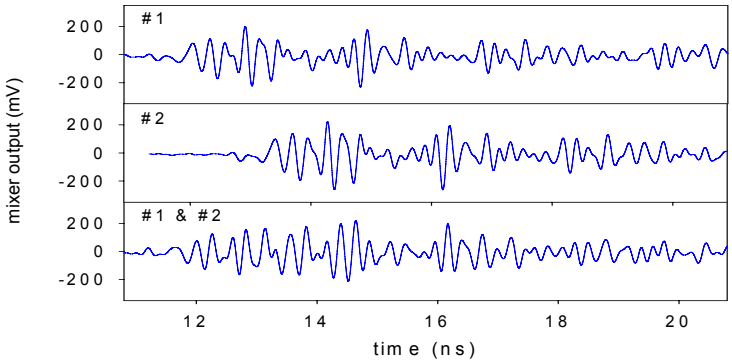
Advanced Accelerator R&D at ANL



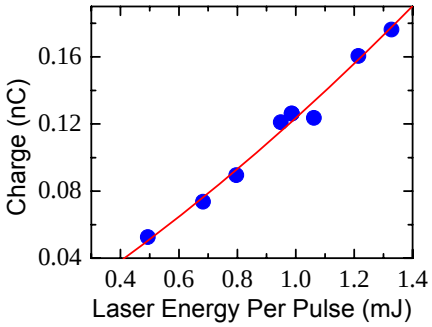
The newly upgraded AWA beamline. A research facility produces high charge and short bunch electron beam for wakefield acceleration experiments.





Recently measured wakefield in a dielectric structure. A ~ 50 nC beam passed through a small dielectric structure (above left) generated ~ 30 MV/m gradient. The figure shows wakefield data for two bunches pass through the structure: bunch #1 alone; bunch #2 alone; bunches #1 and #2 separated by 1.5 ns (two RF periods of the klystron frequency).

A CsTe cathode preparation chamber under assembly



Measured Schottky enabled photoelectron emissions from Mg cathode with photon energy of 3.3 eV. A new way to generate high brightness beam.

Investigation of Advanced Superconductors for High-Energy Physics

Lance Cooley – Materials Science Department
Arup Ghosh – Superconducting Magnet Division
Brookhaven National Laboratory

Summary

At Brookhaven National Laboratory (BNL), synergistic programs in the Materials Science Department and the Superconducting Magnet Division are studying superconducting materials, strands, and cables important to High Energy Physics (HEP) magnet programs. The scope of work ranges from studies of basic properties to the materials science of composite strands and testing of Rutherford cables. The vertical nature of this coordinated effort is unique among Advanced Technology R&D programs. This has provided understanding of key issues for accelerator magnets at many levels, and that understanding is more detailed than that which would be obtained by the individual programs working separately.

Basic properties receiving most attention are the upper critical field H_{c2} and the mechanisms of flux pinning. Experiments seek to understand whether it is possible to exceed flux-shear limits and reach the single-vortex pinning limit in Nb_3Sn and emerging MgB_2 superconductors by making nanostructured materials and adding nanoscale pinning centers. In addition, work continues to address the effects of the compositional homogeneity of Nb_3Sn and alloyed MgB_2 on the superconducting properties. MgB_2 now receives significant attention because it has a simple formation reaction, can already be made in long-length multifilamentary wires, and has potentially low cost, qualities that are important for accelerator magnet strands. Alloying MgB_2 with carbon is essential to reach H_{c2} values of interest to HEP, and accordingly significant work emphasizes the materials science of carbon alloying.

The main effort is devoted to the materials science of Nb_3Sn strands being developed by industry. Optimization of reaction heat treatments, metallography, electron microscopy, and property measurements are central activities. Coordination with programs at Fermi National Accelerator Laboratory (FNAL) and Lawrence Berkeley National Laboratory (LBNL) has contributed to the overall understanding of the state of the art. Feedback to industry has improved strand designs with regard to the HEP conductor performance goals. For example, through close interaction with Oxford Superconducting Technology a reaction sequence shorter than the standard one by almost a factor of two was found, strands with smaller effective filament diameter were designed, and the relative effectiveness of tantalum or titanium alloying on upper critical fields is being understood. During the last three years, approximately 120 different strand reactions and critical current density J_c tests have been completed. A smaller number of Nb_3Sn cable J_c tests have also been completed. In some cases, a single strand has been explored at all levels, from probes of its basic superconducting properties, to short-sample J_c measurements, to J_c tests of cables wound from the strand, to performance in 10-turn coils, and finally to tests of strands extracted from the cable. All of this knowledge is being applied to the Large Hadron Collider (LHC) Accelerator Research Program.

A new collaboration has been established with the National Synchrotron Light Source (NSLS) to develop superconducting undulator magnets. In addition to wire-wound designs being considered at BNL and elsewhere, an innovative approach explores thick films that are patterned like printed circuits and should be compatible with ultra-high vacuum. This would allow both the removal of the beam tube (and its associated image current problems) and the ability to open the undulator magnet at the mid-plane, strategies that are crucial for management of cryogenic heat loads. Main support for this work will come from the NSLS-II

project, but the close similarity of planned work to areas in HEP provides opportunities for cross-fertilization of ideas and synergistic collaboration.

Recent Accomplishments

(1) *Dynamic stability threshold in Nb_3Sn strands:*

At the beginning of FY 2004, U.S. accelerator magnet programs at LBNL, FNAL, and BNL encountered a common problem, in that many R&D magnets quenched (uncontrollable loss of superconductivity) below designed fields. Experiments done at BNL and FNAL suggested that spontaneous avalanches of the flux gradient (flux jumps) could be the primary problem. During FY 2004 and continuing into FY 2005, a set of experiments at BNL showed definitively that over-reaction of the Nb_3Sn strand led to a loss of thermal conductivity in the copper stabilizer, thereby preventing the recovery from heat being generated by flux jumps (Fig. 1). When magnet load lines cross a threshold current density, flux jumps in the low-field regions will quench the magnet. On the other hand, safe operation of magnets is possible when the stability threshold is higher than the critical current at the design field. These observations correlated with the experience of magnet designers at LBNL, FNAL, and BNL.

Our approach combined measurements of the voltage vs. current sweep, as routinely performed by the other labs, with measurements of the voltage as a function of field sweep (Fig. 2). The latter technique, while being over 30 years old, was applied to modern strands for the first time. Some of these measurements required the use of the cable test facility (Fig. 3). Using this combination, we were able to rule out mechanical sources of the instabilities. Then, by analyzing the instability development with final reaction time and the residual resistivity ratio of the copper stabilizer, we were able to determine that a lack of dynamic stability was the key problem.

A surprise in this study was the finding that a rather short reaction could produce J_c almost as high as that of the fully reacted, but unstable, strands. Evidently, the new generation of HEP strands contains so much tin that the primary reaction occurs very quickly, which is good news for magnet programs. That is, the dynamic stability problem can be circumvented without significantly affecting the target performance of magnets. Ongoing studies now focus on mapping the stability threshold as a function of parameters such as sub-element number, final reaction temperature and time, and wire diameter.

(2) *Costs of high-field superconducting magnet strands*

Together with R. Scanlan (LBNL), a comprehensive review of the costs of superconducting magnet strands over the past 30+ years was completed. This review covered projects from FNAL up through the LHC, and included R&D scale projects and emerging conductors. Sets of indices were derived that place conductor costs in various forms used by magnet procurements (e.g. $/kA-m) and industry (e.g. $/kg). A central conclusion of the study is that the superconductor cost of a large project based on Nb_3Sn strands could drop by as much as two-thirds by simply increasing the mass of conductor fabricated in a single restacking stage. This study also showed that the cost per meter of MgB_2 strand could be competitive with that of Nb-Ti strand and less than that of strands where niobium or silver make up a significant fraction of the wire cross-section.

(3) *Reduction of the effective Nb_3Sn filament diameter*

During FY 2004 we worked with our collaborators at Oxford Instruments – Superconducting Technology to explore the effects of subdividing the sub-element. The goal of these experiments was to reduce the transverse dimension of the Nb_3Sn formed after reaction below the threshold for the onset of flux-jump instability (believed to be about 30 μm). Magnetization measurements done in collaboration with Dr. Arnold Moodenbaugh in the Materials Science Department probed currents that either traversed the entire sub-element or were effectively broken by the dividers. At 4.2 K, the dividers were found to be of limited effectiveness because they were made of Ta and subsequently form a superconducting Ta_3Sn phase that provides a link for magnetization currents. Above about 6 K, the Ta_3Sn phase was no longer superconducting and the link was broken as intended. This showed that the principle of dividers could work as long as the material used does not form a superconducting phase at 4.2 K. New divider materials are now being researched as a result of this work.

(4) *Composition gradients in alloyed magnesium diboride*

High-field forms of MgB_2 must be alloyed with carbon to achieve upper critical fields of interest to HEP applications. In this sense, alloyed magnesium diboride is similar to Nb_3Sn and unlike pure MgB_2, in that a diffusion reaction provides the final material and therefore determines the homogeneity of the superconducting properties. By using detailed x-ray diffraction analyses, the homogeneity of Al substitution for Mg and C substitution for B was investigated on small pellets made from pure elements or B_4C. These analyses showed that alloyed samples reacted at 700-900 °C, the range where pure MgB_2 can be made with good quality, contained significant variations of the crystal lattice parameter, which was attributed to gradients in the Al or C distribution. Reactions at 1200 °C for long times, by contrast, removed these gradients. Since the gradients produce variations of superconducting properties across the samples (much like they do in Nb_3Sn wires), different properties are obtained depending on the degree of homogeneity. However, annealing at 1200 °C is not possible for magnets, so the elements must be mixed on the atomic scale prior to a reaction. There are several strategies that can be explored; one that we are excited about is the production of boron carbides by plasma spray synthesis (Fig. 4), and we are working with the nearby Center for Thermal Spray Research at State University of New York – Stony Brook and with Specialty Materials, Inc.

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Staff and Students

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Support

"Understanding Flux-Pinning Limits, React-and-Wind Strand Optimization, and Critical Current Measurements of High-Energy Physics Superconductors", Cooley, B&R code KA1501020, $150,000.

"Superconductior R&D and Testing," Ghosh and Cooley, B&R code KA1502010, $770,000.

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Brookhaven National Laboratory Superconducting Magnet R&D Program

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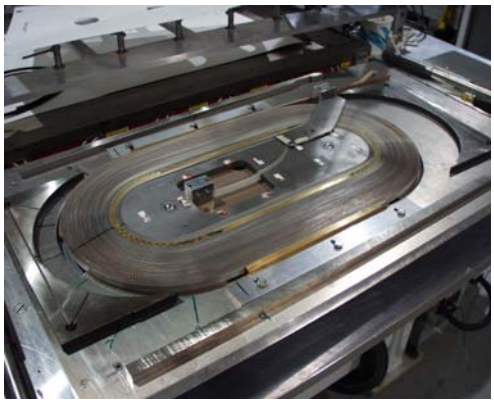
Summary

The Superconducting Magnet Division at Brookhaven National Laboratory (BNL) is developing several different technologies for a variety of future applications primarily in the area of next generation accelerators such as the International Linear Collider (ILC) and a Large Hadron Collider (LHC) upgrade. The R&D activities are based around high-field racetrack coil magnets using Rutherford cables that operate at high currents and direct-wind magnets capable of highly specialized applications at lower fields. The direct wind technique where a computer controlled winding machine places wires and small cables directly onto a support tubes in essentially arbitrary patterns is a technology unique to BNL. We are also actively using high temperature superconductors (HTS) materials in R&D for a possible application for the Rare Isotope Accelerator (RIA).

HTS and Nb_3Sn superconductors hold the key to attaining high fields in future magnets. However, these conductors are brittle in nature. The conventional cosine theta designs with Rutherford cable put a significant restriction on how these conductors can be used in a magnet. Therefore, alternate conductor-friendly racetrack coil designs, such as the “common coil” design, with large bend radius, have been developed at BNL to overcome the limitations posed by the brittle nature of these conductors. These designs and construction techniques are expected to be scaleable for large, economic production of the magnets. In addition, these designs allow the use of “React & Wind” technology where a brittle pre-reacted cable is used in winding coils. This puts many fewer restrictions on the materials that can be used in making coils. Moreover, the required temperature regulation for reacting HTS materials means that the “React & Wind” technology must be used in making magnets of this type.

Recent Accomplishments

High Field Magnets



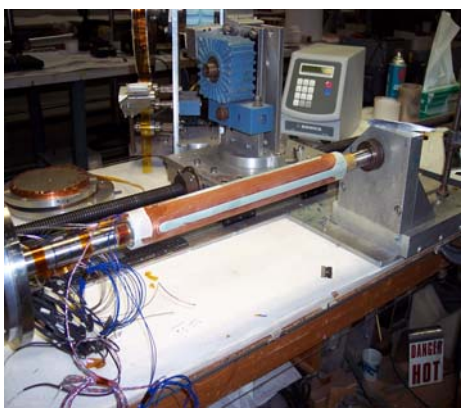
The Nb_3Sn high field cable magnet R&D at BNL is based on the results of the past few years with a 10 turn coil program which has already demonstrated that a react-and-wind coil can achieve at least 90% of the calculated short sample performance in a low field environment. Extending this performance to high fields (and thus higher Lorentz forces) is the next step. The current goal of the program is to design and build a ~12T dipole for subsequent use in the superconductor test facility to enhance the capability to characterize the operating parameters of the recent much higher performing Nb_3Sn superconductor. The ~12T dipole has an aperture of 45 mm, sufficient to house a cable testing fixture, an uses 4 racetrack coils of 45 turns each in a ‘common-coil’ structure. One of these 45 turn coils is shown in fig 1. This magnet when operating towards the end of CY 2005 would be the first magnet of this kind operating at these elevated fields.

LHC Upgrade

BNL is a member of a U.S. collaboration (with Fermi National Accelerator Laboratory and Lawrence Berkeley National Laboratory) whose goal is to develop a high gradient Nb_3Sn quadrupole suitable for use in a luminosity upgrade of the LHC. While the exact details of any upgrade are not known at this point, many scenarios require large aperture (~120 mm i.d.) high gradient (~250 T/m) final focus quadrupole elements. The U.S. LHC Accelerator Upgrade Program has adopted these parameters and a medium-term goal of demonstrating them with a proof of principle device by 2009. To date, BNL had been investigating the implications of a dipole first IR design. This style of IR design would be preferred in the LHC luminosity is limited by the long range beam-beam interaction. A dipole first design provides a rapid beam separation geometry but is forced to survive in a very high energy deposition environment. BNL successfully developed the concept of a split plane high field magnet that was resilient against particle losses emanating from the IP. With the projected resources over the next few years, developing both quadrupoles and dipoles was deemed impractical so BNL joined the other members of the collaboration in the quadrupole program. BNL will seek to demonstrate long (4m) race track coils based on the wind-and-react technique during FY 2006.

Final Focus Magnets for the International Linear Collider

For the ILC, BNL is developing a final focus magnet that is sufficiently compact so that the outgoing, disrupted beam may pass outside the cryostat, despite a crossing angle of only 20 mrad and less than 4 m from the IP to the first element. The design concept for this quadrupole magnet features a 6-layer compact coil using the direct wind form of fabrication. The coils are wound on and bonded to a coil support tube using an 11-axis ultrasonic wiring machine. Because of the small, 20 mm, beam pipe i.d., one of the challenges is to wind small diameter coils with resultant tight bends in the conductor. BNL has performed several winding tests with successful results. The first test coil consisted of a single layer dipole wound on a .075 inch diameter support tube. This is by far the smallest magnet attempted to date using this technology. Subsequently, after the first ILC workshop at KEK, the conceptual magnet design stabilized and a short proof of principle coil of the final cross section was constructed. This coil is shown during winding in Fig 2 (*left*). The field quality has been measured warm and is well within the rather generous specifications of 10^{-3}. This proof of principle device was then tested cold in a background solenoidal field of 3T to simulate the operating environment of the detector spectrometer magnet. The performance was encouraging at 4.2K with the coil reaching the calculated short sample limit of 185 T/m with a 3T background field. Further tests are planned at superfluid temperatures and higher fields.

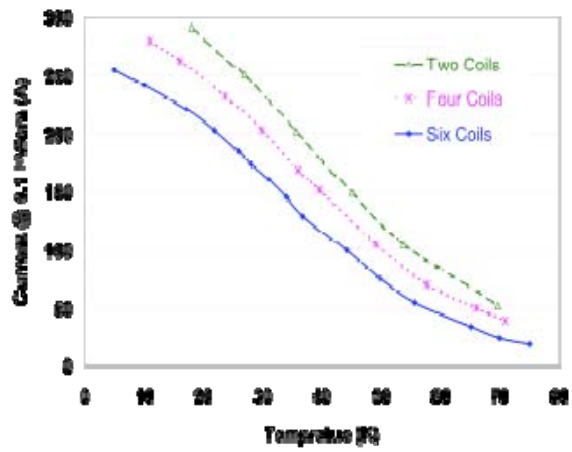


Another challenge in the development of a final focus ILC quadrupole is stabilization of the magnetic center of the element. The very small beam sizes at the ILC IP result in sensitivity to beam motion of all kinds including that caused by motion of the IP magnets. Cold mass motion relative to the cryostat, including that caused by ground motion and cryogenic system vibration, must be reduced to the 10's of nanometer level. BNL is performing vibration measurements in

an effort to incorporate vibration minimization, including both active and passive damping systems, into future designs. The potential accuracy of direct field measurements is also under investigation. To date no data exists on the stability of cryogenic magnets at the nanometer scale.

HTS Magnets for the Rare Isotope Accelerator

BNL, in collaboration with the National Superconducting Cyclotron Laboratory, is developing radiation-resistant HTS quadrupole magnets for the proposed Rare Isotope Accelerator. These magnets are one of the more challenging elements in the RIA proposal. Immediately downstream of the production target, these magnets are subjected to several orders of magnitude more radiation and energy deposition than typical beam line and accelerator magnets receive during their entire lifetime. To optimize the particle flux a large aperture strongly focusing doublet is located close to the target. Magnets based on low temperature superconductors can not handle the energy deposition from the target spray, conventional copper and iron magnets do not achieve sufficient field gradient. A super-ferric warm iron design has been developed that significantly reduces the energy deposited in the cold structure (15 kW to ~130 W in the first quadrupole alone) while providing twice the gradient of a conventional magnet. The coils are made from commercially available BSCCO tape. An operating temperature ~30K offers a factor of ~10 decrease in the cooling requirements compared to 4K operation. This large thermodynamic savings in the operating cost for removing the above-mentioned heat is an additional motivation for using HTS magnets in RIA. Stainless steel tape is used as a radiation-resistant insulation between the turns. To test key critical issues prior to proceeding with a full-length magnet, a magnetic mirror model consisting of six HTS coils has been designed, built and tested. The magnet is shown in *Fig.3*. The magnet was cooled to 4K and then allowed to slowly warm up. At ~5K intervals, the current carrying capacity of the three pairs of coils was measured. The full magnet performance is achieved with all three coil pairs powered in series. The results of this test are given in *Fig.4*. The coil performance was quite uniform and very stable. The current decreases with the increasing number of coils due to the higher magnetic fields. The design goals of 125A operating current at 30K were exceeded. The next step in this program will be the demonstration of the cold coils/warm iron concept.



Accelerator Test Facility

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Summary

The Accelerator Test Facility (ATF) at Brookhaven National Laboratory (BNL) has been in operation since 1992. The ATF is a dedicated proposal-driven, program-committee-reviewed user facility available for experimental research in plasma and laser acceleration of particles, beam-plasma physics, ultra-short pulse electron and radiation sources, advanced diagnostics and high-brightness electron beams. The ATF provides high-brightness electron beams (e.g. normalized rms emittance of 0.8 μm at a charge of 1.0 nC) at up to 75 MeV energy to four well instrumented beam-lines. High-power laser beams synchronized to the electron beam are available at most of the beam lines. The bunch length is variable from 2 to 8 ps from the photoinjector. It can be further compressed with a new a bunch compressor down to 100 fs.

ATF users come from universities, small businesses, and national laboratories mostly from the United States. The users of the ATF enjoy extensive support infrastructure, with a few tens of million dollars investment and embedded in a large and highly-capable national laboratory. The ATF staff provides its users with close, hand-holding support and expertise in electron beam dynamics, lasers and optics, advanced diagnostics, energy spectrometers and computer control. ATF support is free of charge, while other BNL resources as well as the experiment's dedicated equipment are under the responsibility of the users.

The number of ATF users is kept relatively steady by its Program Advisory Committee. As *Figure 1* shows, this number hovers at about a dozen experiments from 1992 to the present. The publication rate is shown in *Figure 2*. The ATF averages about three Physical Reviews (either PRL, PRE, or PR-ST-AB) per year.

ATF experiments are serving all Department of Energy (DOE) divisions – High Energy, Nuclear Physics, and Basic Energy Science. The experiments cover various subjects, such as structure based laser acceleration (including inverse free electron lasers (IFEL) and vacuum acceleration), dielectric wake and plasma wake field (beam driven) experiments and soon laser wakefield experiments, instrumentation and advanced diagnostics, free-electron lasers, generation of picosecond (soon sub ps) hard X-rays, development of laser-photocathode RF guns and much more.

The ATF is an excellent training ground for graduate students in accelerator physics and the physics of beam research. The number of graduations of students as a function of time is shown in *Figure 3*. While a large number of students come from nearby Stony Brook University, the majority of the students come from a large sample of universities across the country and the world. The ATF staff is proud of its contribution to graduate education in accelerator and beam physics, and it educates and supports the students.

The BNL ATF receives steady support from the DOE. Thanks to this climate of steady support the facility evolved not only in terms of hardware and expertise of its staff, but also in terms of stability and superb performance of the electron and laser beams. This environment is particularly beneficial to the rather difficult, cutting-edge experiments in advanced accelerator and coherent source physics carried out by its users.

The ATF staff continuously improves the performance of the facility. Among the equipment that was recently made available for user experiments as of June 2005 are a new RF photoinjector, the chicane bunch-compressor and bunch length diagnostics, a new computer control system and the picosecond-terawatt CO2 laser. Future plans include an energy upgrade to 120 MeV, sub picosecond 1 micron laser and consequently sub picosecond CO2 pulse.

Internal R&D includes work on high-brightness electron beams, such as R&D on laser photocathode RF guns, high-power CO2 lasers, advanced diagnostics and computer control systems. A few examples of this line of R&D follow.

The ATF pioneered metallic photocathodes for robust, good quantum efficiency operation such as copper, magnesium and, most recently, niobium. These photocathodes are found everywhere in the world and are also produced industrially. The same holds true for the celebrated BNL one-and-a-half cell S-band series of RF guns. Examples of advanced diagnostics include the first slice-emittance measurement, the first pulse-length measurement using shot noise driven fluctuation in incoherent radiation, high-resolution phase-space tomography and more. The ATF is developing high-performance plasma capillary channels that channel the CO2 laser beam and provide a convenient source of plasma for a variety of experiments. Most recently R&D is carried out on optical stochastic cooling of hadron beams.

By far the most important aspect of the ATF is research carried out by its users. Milestone ATF user experiments in laser acceleration include the Cherenkov acceleration experiment and the IFEL experiment, the STELLA experiment that demonstrated for the first time staging of two laser accelerators and the steady production of 3 fs electron beam bunches, and the STELLA II experiment that demonstrated monoenergetic laser acceleration for the first time.

Experiments in laser-photocathode RF gun development include the “Next Generation Photoinjector” or Gun III in the ATF series (which now stands at Gun IV, while a new superconducting CW RF gun is being developed).

Experiments in the generation of unique radiation sources include the pioneering high-gain harmonic-generation FEL that set a new trend towards coherent, ultrashort pulse X-ray FEL, the VISA experiment which served as a proof-of-principle experiment for the LCLS, reached saturation in the visible and demonstrated the generation of harmonics, their growth and saturation properties and the relationship to Microbunching. The Compton scattering experiment produces a record of about 10^8 hard X-ray photons per pulse of a few ps duration. Angular distribution of the nonlinear component of the Compton scattering experiment were recorded.

The plasma wake-field experiment demonstrated the phase relationship between the accelerating and focusing component of the plasma wake, showing that they have a 90 degrees phase difference, thus allowing plasma wake accelerators to accelerate and focus the beam at the same phase.

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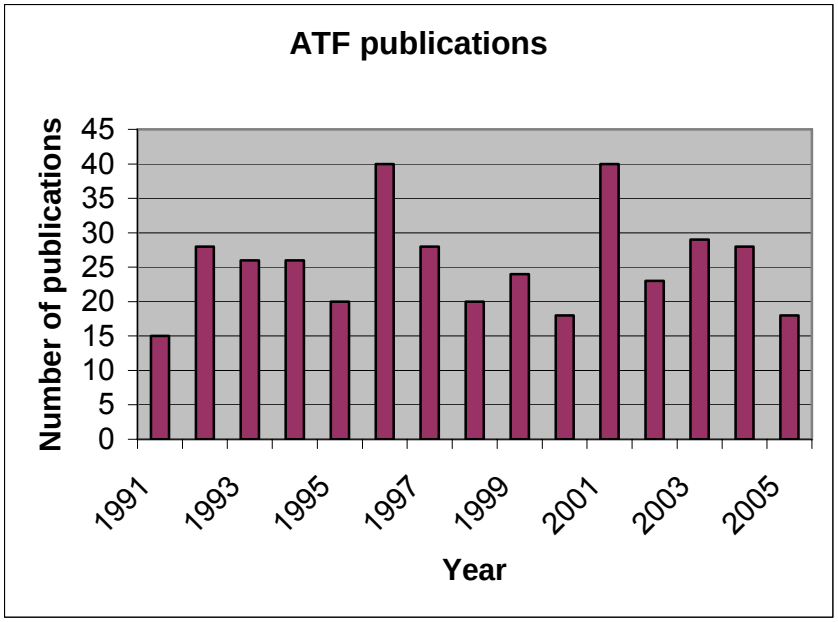

Figure 1 The number of ATF experiments as a function of time

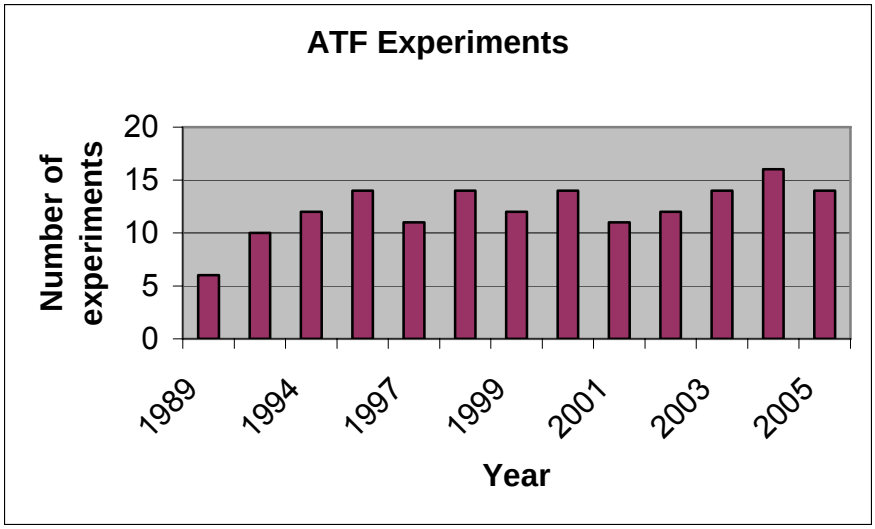

Figure 2 ATF publications as a function of year, from 1990 to 2002

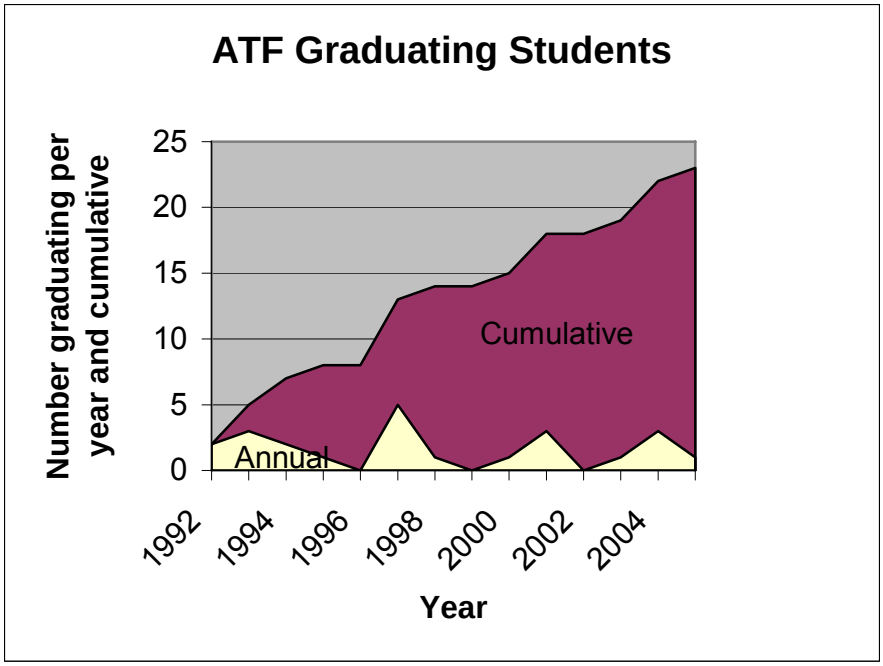

Figure 3 Graduate students by year of graduation (yellow) and cumulative total (red)

Figure 4 Poster Session at 2004 Advanced Accelerator Concept Workshop hosted by ATF in Stony Brook

Fermilab/NICADD Photoinjector Laboratory

Helen Edwards
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Summary

The Fermilab/NICADD Photoinjector Laboratory (FNPL) at Fermi National Accelerator Laboratory (Fermilab) is a joint collaboration between Fermilab and Northern Illinois University. There has been and continues to be strong participation by the University of Rochester, University of California Los Angeles (UCLA), Deutsches Elektronen Synchrotron (DESY), National Institute of Nuclear Physics (INFN), and Lawrence Berkeley National Laboratory over the years.

The front end of the apparatus consists of a 1+1/2 cell L-band radio frequency (RF) gun equipped with a high quantum efficiency CsTe photocathode allowing the photoemission of electron bunches with charges up to 15 nC. These bunches are further accelerated to 16 MeV by a downstream TeV Energy Superconducting Linear Accelerator (TESLA) superconducting accelerating cavity with a nominal gradient of 12 MV/m. Downstream of the TESLA cavity is a skew quadrupole channel allowing for the production of flat beam using an angular momentum dominated beam created in the gun. This is followed by a bunch compressor chicane capable of enhancing the bunch peak current to approximately 2.5 kA, and a quadrupole channel for transport. The end of the beamline consists of a dispersive section to measure the beam energy distribution. The beam can be also directed into a user experimental area for outside users. Diagnostics include electromagnetic beam position monitors, optical transition radiation screens to measure the transverse profile, and a steak camera for measuring bunch length. A Martin-Puplett interferometer can be used to measure the bunch length using coherent transition radiation. The infrastructure includes a laser, two RF modulator systems, dewar feed 2K helium system and miscellaneous magnets, diagnostics, and controls.

The user experimental area currently includes of a fast kicker experiment that is aimed at producing a fast kicker necessary for the International Linear Collider (ILC) damping rings. An optical transition interferometer has also been installed to develop this method of beam energy measurement.

Other activities include research on a cryogenically cooled RF gun to host a strained GaAs photocathode necessary for polarized electron beam production. Laser development toward providing an ILC electron bunch train without polarization is being pursued.

Two types of 3.9GHz superconducting cavities are under development. These will be used in the future upgrade of the injector for energy linearization of the electron bunch prior to bunch compression and for bunch slice diagnostics.

Recent Accomplishments

Major improvements have been made to the photocathode drive laser. These included replacing the oscillator with a commercially available one, optimization of the amplification scheme, and increasing the frequency quadrupling efficiency. This allowed

for more stable and reproducible laser operation. A single shot autocorrelator was developed to allow pulse by pulse measurement of the temporal laser profile. These improvements led to the first measurements of the impact of laser transverse profile on the electron beam. The ability of the laser to function in an upgraded facility with ILC bunch structure has been investigated and seems feasible with minimal optimization.

The first phase of the flat beam experiment has been completed. Further work is planned after the energy upgrade of the injector. This experiment was able to produce a beam with a transverse emittance ratio of 100 ± 5 with normalized emittance of 41 and 0.41 m in the two planes. Simulations predict that space charge forces in the RF gun limit the final emittance ratio to 350. The measured emittance ratio is limited by spurious dispersion and measurement resolution. This initial experiment culminated in the Ph.D. thesis of Yin-E Sun.

Measurements of the transverse beam emittance vs. the laser pulse time structure have been performed. These measurements show that at 1 nC charge a 15% decrease in the emittance that was expected from simulations can be achieved when using a temporally flat laser pulse of 19 ps full width at half maximum (FWHM) duration as compared with a Gaussian of 5.4 ps FWHM. The effect of the laser pulse length vs. charge was investigated and compared with ASTRA simulation including space charge. These measurements, combined with measurements of the magnetic compression (R_{56}) with the bunch compressor, will culminate in the Ph.D. thesis of Rodion Tikhoplav. Tikhoplav also implemented a redesign of the laser pulse stacker, and a laser operating in the TM_{01} mode (doughnut shape transverse mode).

A team from UCLA concluded an experiment studying the transverse focusing of a plasma in the under-dense regime. The experiment concluded that a plasma was able to focus the tail of an 8 nC electron bunch with an equivalent magnetic field gradient of 180 T/m. This experiment is part of the Ph.D. thesis of Matt Thompson at UCLA.

Work continues with development and analysis of bunch length diagnostics using a Martin-Puplett interferometer and transition radiation. The issue here is consistent application of the light transmission bandwidth correction.

A team headed by George Gollin from University of Illinois at Urbana-Champaign has installed a stripline kicker to test the feasibility of making a fast kicker for the ILC damping rings. Initial measurements to understand the action of the stripline driven by a high voltage pulser were performed and are being analyzed. Future plans include installing an RF source and dispersive waveguide to produce the fast rise time needed.

In the same beamline an experiment to measure the beam energy using optical transition radiation (OTR) interference was installed. By interfering the OTR from two closely spaced mica sheets, it should be possible to measure beam energy. Initial measurements were performed to show the suppression of background from Cherenkov radiation and OTR from the light extraction mirror, and measure the OTR from the mica sheets.

Work continues on RF gun research directed toward the ultimate goal of a gun that can realize a polarized and flat electron beam. The gun must support a strained GaAs photocathode necessary to make polarized electron beams and a longitudinal magnetic field on the cathode. The major difficulty in this task is to provide a high quality vacuum

with RF applied to the gun and to determine the necessary vacuum requirement. Initial work proceeded with cooling a gun to 92K using liquid nitrogen to use the gun walls for cryopumping. The results show that probably sufficient vacuum was not achieved. However the critical test of cathode survival must be carried out to verify the actual vacuum required in the RF gun environment. A cathode preparation chamber has been received from Advanced Energy Systems as part of a Phase I Small Business Innovation Research. Plans include outfitting the cathode preparation chamber to gain expertise in producing GaAs photocathodes that will ultimately be tested in the RF gun.

Upgrade of the injector is planned. This includes increasing the energy to 40 MeV, the addition of the two types of 3.9 GHz cavities, improvements in the gun, modulator and laser systems. The upgrade will take place in phases over a few years. A second TESLA superconducting cavity has arrived in the summer from DESY. This cavity is able to operate with a gradient of 25 MV/m and when added to the present injector will increase the electron beam energy to ~40MeV, provide a more relativistic beam and freeze the space charge forces for better emittance preservation down the beam line. It is presently planned to use the upgraded injector for the ILC Module Test Facility under development at Fermilab, as well as for accelerator R&D and student training.

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Li, J. Postdoctoral Research Associate
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Current Students

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Tikhoplav, R. Ph.D. candidate, University of Rochester

Recently Graduated Students

Sun. Y.-E (2005) Ph.D. University of Chicago
Thompson, M. (2005) Ph.D. UCLA

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Superferric Magnet Development and Test

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Summary

A superferric, warm-iron magnet with operational magnetic field of 2 Tesla was designed, developed, and successfully tested at Fermi National Accelerator Laboratory. This report pertains to work carried out during the period of 2003 - 2005 under the support of the U.S. Department of Energy's Office of High Energy Physics. The purpose of this R&D program was to develop a magnet system for the Injector Accelerator of a Very Large Hadron Collider (VLHC) of about 240 km in circumference. The Injector Accelerator also referred to as a Stage-1 VLHC, would produce the proton beams of 20 TeV (40 TeV cms in the beam colliding mode). A binding condition of the design and test was to achieve the required accelerator quality magnetic field in the 2 Tesla range with the magnet pole gap of 2 cm while minimizing the magnet overall dimensions in order to save space in the underground accelerator tunnel, and lower the magnet fabrication costs. In addition to the magnet itself, this R&D program included the design, development, and tests of: (1) the 100 kA transmission line superconductors, (2) the 100 kA dc current supply, and (3) the 100 kA current leads transporting the current from the room temperature power supply to the magnet conductors operating at liquid helium temperature. A cryogenic system was also designed and assembled to support the operations of the transmission line superconductor as well as the current leads. The magnetic fields were measured using a tangential coil and a 102-element hall probe. All final subsystems used in the magnet test are of original designs. The magnet test system with a 1.5 m long magnet operated successfully multiple times reaching currents of up to 104 kA, thus significantly exceeding the nominal operational design current of 87.5 kA.

Recent Accomplishments

Magnetic Design

The conceptual design of the accelerator main arc magnet is shown in *Figure 1*. The magnet features two pole gaps between its half-cores with the magnetic field induced by a dc current in a single conductor line located in the center of the half-cores assembly. The magnetic fields in the pole gaps are in the opposite directions, so same-charge particle beams circulate in the opposite directions as well, a requirement for the accelerator with colliding beams. The magnetic field in the pole gaps is shaped by the laminations and does not depend strongly on the conductor position. The accelerator arc main magnet is a combine function gradient dipole, thus allowing for both bending and focusing (or defocusing) of the circulating beams. The focusing and the defocusing type magnets will be placed interchangeably in the accelerator ring. The challenging problem in the warm iron magnetic design is a potential distortion of the field caused by the saturation effects in the (1.7 – 2) Tesla range. In the test magnet design a set of four holes in each magnet pole was used to control the saturation effects. The measured field gradient across the 20 mm wide pole gap in the 1.5 m long test magnet is shown in *Figure 2*. The gradient value is as expected at +/- 4%, and remains unchanged from 0.37 T (blue line) through 1.23 T (green line) to 1.83 T (red line). These are raw data, uncorrected for the residual hall probe currents from the preceding excitations; hence

small fluctuations. As typical expected beam size is of σ = 0.2 mm the measured magnetic field quality makes this magnet a good candidate for the accelerator use.

Magnet Assembly Technique

In order to achieve the required accelerator vacuum level in a small beam pipe of the VLHC magnet an antechamber must be attached to the beam pipe (as shown in *Figure 1*) along its entire length. This arrangement prevents using of the outer walls of the half-cores for welded fixtures holding the magnet assembly together. Consequently, the half-cores are welded into a magnet assembly with help of 4 mm thick connecting plates placed inside the magnet pole gaps between the conductor cryostat wall and the pole gap spacer bar. The magnet welding arrangement is shown in *Figure 3*. The magnet assembly procedure is as follows: (1) the half-connecting plates are laser welded to the half-cores, (2) the top and bottom half-cores are assembled with the conductor line between them, and (3) the magnet assembly is placed inside a 5 Ton/m press and the half-connecting plates are laser welded together through the staggered slots in the spacer bars. As welding causes shrinkage of the connecting plates the actual tension on the spacer bars was measured to be 15 Ton/m. Such a tension is sufficiently high to minimize the effect of ~3 Ton/m force on the magnet poles resulting from energizing the magnet with a 100 kA current. A close-up of the test magnet is shown in *Figure 4*. The tangential coil is placed in the front magnet beam gap, and the 102 element Hall array is placed in the rear magnet beam gap.

Transmission Line Superconductor

The transmission line superconductor was designed to minimize its cross-section, and thus to minimize the size of the laminations which constitute the largest component of the magnet cost. The design also aimed at providing satisfactory control of the cable shrinkage during the cool-down process, and at simplifying its assembly work. Several designs of the super-conducting cables including the Rutherford types and the braided ones were tested. All samples performed well but the braided cable shown in *Figure 5* was selected due to its simple and cost-effective design. This cable consists of 288 NbTi strands arranged in 48 crossing bundles. The additional copper balance for the superconductor comes from the copper wire braid placed under the conductor braid. Both braids are supported from a perforated invar pipe serving also as a liquid helium channel. The outer invar pipe is designed to withhold 40 bar pressure during the conductor quench. Using the invar pipes and invar bellows minimizes the shrinkage of the transmission line conductor in the cool-down process and simplifies fabrication of conductor anchors and cryo-brakes. The injection molded ULTEM rings support the conductor cable inside the cryostat vacuum jacket. As the ULTEM pegs shrink about 0.1 mm during the cool-down process a pre-stress of ~200 kG/m at room temperature is necessary to prevent their movement in a cold state. Careful calculations followed by precision fabrication of the conductor cryostat and ULTEM supports generate the necessary tension on the pegs during magnet assembly welding process. The test system conductor line is about 12 m long. This conductor quenched at ~104 kA current at the liquid helium temperature of ~5 K.

Power Supply
A 1.5 V, 100,000 A DC switcher power supply was developed for testing the super-conducting transmission line magnet. This supply consists of a bulk power source filtered and regulated at 400 V and 240 kW, and 10 switcher cells. The high current part of the supply consists of ten 1.5 V and 10,000 A forward converter cells connected in parallel at the input to the current leads. As only one magnet of total load resistance of 0.7 micro-ohms was used in the test this supply was used as both ramping and holding supply.

Current Leads

A pair of conventional current leads has been developed to pass the 100 kA dc current from the room temperature power supply poles to the magnet transmission line conductor at the liquid helium temperature. The conceptual design of the leads is shown in *Figure 6*. Each lead consists of 202 pieces of copper rods with diameter of 6.35 mm arranged horizontally. The effective length of the leads is 1,650 mm. The copper rods are soft-soldered at both warm and cold ends. The liquid helium gas flow is guided by multiple baffles along the lead length thus allowing for a relatively high heat transfer coefficient between helium and the copper rods. As a result these leads operated successfully with the ramping currents above 100 kA. The required stand-by liquid helium flow is ~3 G/s, and it is ~6 G/s for the currents in the 100 kA range.

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Development of the 3.9 GHz Superconducting cavities at Fermilab

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Summary

Superconducting radio frequency (SRF) has emerged over the past several decades as a key technology for particle accelerators. Amazing progress achieved in SRF technology in the last decade led to considerable improvements in cavity performance: accelerating gradient and quality factor. Many new large-scale accelerator projects (ILC, XFEL, RIA, ERL, Proton Driver, etc.) are based on SRF technology. Fermilab, having the largest superconducting accelerator in the world – the Tevatron, has a strong superconducting (SC) accelerator magnet R&D program and recently started working on superconducting RF R&D. The goal of SRF program is to develop the technology base for building reliably cavities with a high accelerating gradient, ~35 MV/m, for the International Linear Collider (ILC), Proton Driver and other applications.

Part of this R&D program is the development of two types of 3.9 GHz cavities for special applications. One of them is, the so-called 3rd harmonic cavity. This cavity will be used in the next generation of photoinjectors (TTF/DESY, XFEL, NICADD/FNAL) to linearize the energy distribution in the long bunch before pulse compression to produce short high intensity bunches needed for laser generation (see *Figure1*). The second type is the 3.9 GHz transverse deflecting cavity developed for beam diagnostics and as a prototype of the crab-crossing cavity for the future linear collider. Series of copper and niobium prototypes of these 3.9 GHz cavities were built and tested. The short 3-cell 3rd harmonic cavity prototype achieved a gradient of ~19MV/m, the deflecting cavity a transverse gradient of 7.5 MV/m. In both cases the gradient was limited by thermal breakdown, with no field emission problem encountered after appropriate cavity treatment and high pressure water rinsing.

Strong and reproducible cavity performance can be only achieved by controlling all steps of cavity production, cleaning and handling. This state-of-the-art technology requires adequate infrastructure, which now exists at Fermilab. We have clean rooms, a BCP facility, a cryostat for vertical tests, clean furnaces, RF and mechanical control equipment, RF power, a SCRF materials lab, etc. Some additional key components of the technology (electro-polishing, coupler test-stands, vertical and horizontal cryovessels for cavity tests) are under development.

The SCRF program at Fermilab also includes the collaboration with labs and universities in the U.S.A. and abroad (JLAB, ANL, Michigan State University, Cornell University, DESY, KEK). In addition to that collaborations were established with several local university partners with the objective of boosting the material science component of this program. The Applied Superconductivity Center at the University of Wisconsin is analyzing material samples with the magneto-optics technique, transport measurements and high-resolution microscopy. The Northwestern University Center for Atom Probe Tomography (NUCAPT), Evanston/Illinois, investigates the nano-chemistry of the material with three-dimensional atom-probe tomography (APT). Strong material scientific tools such as APT and magneto-optics are needed to generate the intellectual understanding of phenomena such as Q-drop in order to achieve reproducibly accelerating gradients of ~35 MV/m in SRF cavities.

Recent Accomplishments

- The design of nine-cell 3rd harmonic cavity is shown in *Figure 2*. Two HOM couplers from both cavity ends should provide good damping of all dangerous monopole and dipole modes with

Q_loaded < 10^5. To measure cavity properties in the fundamental mode and HOM, two copper models with HOM couplers and main couplers were built and tested. The goal was to measure and study properties of the higher order modes (Q_loaded, field distribution, spectrum, etc.) in each individual cavity and in a string of two cavities. Measurements demonstrated good agreement with RF simulations.

- The study cavity performances at high field, a short 3-cell niobium cavity was built and tested. The cavity is made out of 2.8 mm thick, fine grain niobium sheets by the deep drawing technique. After production and field flatness tuning, the cavity was first etched and heat-treated at JLAB. In first tests strong field emission (FE) at 12 MV/m was encountered, but after high pressure rinsing with ultra-pure water the FE problem was resolved and a accelerating gradient ~19MV/m (~105mT peak surface field) was achieved with a very small residual resistance of ~6 nOhm (*Figure 3*). This cavity was tested several times after etching in different facilities, high-pressure water rinsing in different regimes and in-situ baking at low temperature (120°C /48hrs). In all cases the cavity repeatedly quenched at same field level. Two other modes in the 3-cell cavity, characterized by the peak-field location being either the middle-cell or the end-cells, also showed the same quench limit. This level was also found to be temperature independent in range of T=1.45-2°K. This can be explained by the non-linear BSC resistance model proposed by A.Gurevich [10]. The achieved accelerating gradient is well above specification: Eacc=14 MV/m.

- In the frame of a collaboration with DESY Fermilab is required to deliver one cryomodule with four 3.9 GHz cavities at the end of 2006. As an initial step of production, the major components of the module were built and tested, including helium vessel and frequency tuner. The first nine-cell cavity was finished, but unfortunately with a faulty equator weld. It will be repaired and tested soon. Another six cavities are in production in collaboration with JLAB and will be completed by the end of 2005. Coupler and cryomodule designs are completed and ready for bidding. All necessary infrastructure items for cavity / coupler treatment and testing as well as tooling for module assembly are being procured.

- The deflecting cavity was proposed to separate kaons from protons and pions for the CKM experiment at Fermilab. The original design is that of a 13-cell niobium cavity with deflecting transverse kick of ~5 MV/m (*Figure 2*). Eight prototypes with a different number of cells (1-cell, 3-cell, 5-cell, 9-cell, 13-cell) made of 1.6 mm and 2.2 mm thick niobium were built and tested. The best result, which was achieved in a 3-cell cavity, made of 2.2 mm thick niobium, is ~7.5 MV/m. As expected, field was limited by thermal breakdown (peak surface magnetic field ~120 mT). Helium vessel, frequency tuner and cryomodule for two deflecting cavities were built and tested. New applications for deflecting cavities for beam diagnostics in the photoinjector and as a crab-crossing cavity for ILC require good damping of the HOM. Design of a new HOM and LOM (low order mode) couplers for deflecting cavity are completed.

- An essential component of the Fermilab SRF program is the materials R&D. The primary goal of the SRF materials R&D is to support the Fermilab SCRF cavity and accelerator projects with material testing and material science. The following activities are currently unfolding at Fermilab: -1- eddy current scanning of the Nb blanks before cavity production for detection of sub-surface defects, cracks and foreign inclusions; -2- characterization of the surfaces as obtained after processing (e.g. chemical polishing, electro-polishing, etc.) with Scanning Electron Microscopy and surface roughness measurements; -3- RRR tests to verify the purity of the as received material as well as after processing, including the welds; -4- chemistry studies to develop the optimal electro-polishing parameters, testing of different chemical solutions for the chemical polishing. As an example of the Fermilab efforts in eddy current scanning for SRF materials QA, the result of a recent scan of a Nb sheet for the 3.9 GHz cavity program is shown in *Figure 4*.

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1. N. Solyak et al., PAC 05, FNAL Memo Conf-05-121-AD.
2. C. Boffo et al., "Eddy Current Scanning at Fermilab," paper TuP048 at the 2005 RF superconductivity workshop, Ithaca, USA, July 2005
3. C. Boffo et al. "EP on Small Samples at Fermilab," ThP01 paper at the 2005 RF superconductivity workshop, Ithaca, USA, July 2005
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5. P. Bauer et al., "Recent RRR Measurements on Niobium for Superconducting RF Cavities at Fermilab," 2005 RF superconductivity workshop, Ithaca, USA, July 2005
6. T. Khabiboulline et al,"SRF Cavity and Materials R&D at Fermilab," Linac2004, Lubeck,p213
7. N. Solyak et al., "Test Results of the 3.9 GHz Cavity at Fermilab," Linac 2004, Germany, p.797
8. N. Solyak et al., "Development of the Third Harmonic Cavity at Fermilab," PAC2003, p.1213
9. N.A. Solyak, First Results of Testing 3.9 GHz TM010 Superconducting Cavity," ASC04, Jacksonville, 2004
10. P.Bauer et al., "A Comparison of Q-Slope Models and Data in Bulk Nb SRF Cavities," RF superconductivity workshop, Ithaca, USA, July 2005
11. C.Boffo et al., Control system for the BCP processing facility at FNAL," SRF 2003, Lubeck, 2003
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13. C. Boffo et al., "Facility for Chemical Polishing of Superconducting Niobium RF Cavities" , ASC04, Jacksonville, 2004
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16. A. Polyanskii et al., "A Magneto Optical Study of Grain Boundary Flux Penetration in Niobium Sheet Sampled Across Simulated Cavity Production Route," RF superconductivity workshop, Ithaca, USA, July 2005
17. P.J. Lee et al., "Grain Boundary Flux Penetration and Resistivity in Large Grain Niobium Sheet," RF superconductivity workshop, Ithaca, USA, July 2005
18. K. Yoon et al., "Atom-Probe Tomography Analyses of Niobium Superconducting RF Cavity Materials," RF superconductivity workshop, Ithaca, USA, July 2005

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Picture gallery

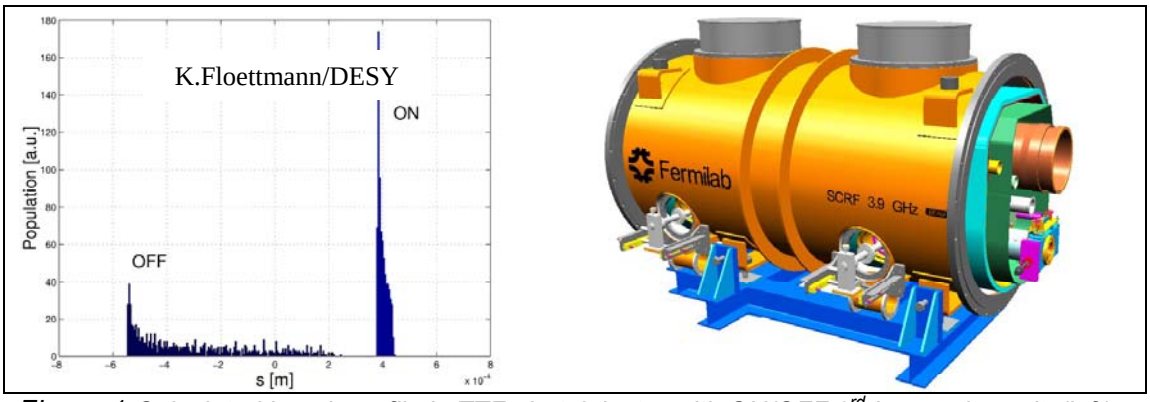

Figure 1 Calculated bunch profile in TTF photoinjector with ON/OFF 3rd harmonic cavity(left) Cryomodule developing by Fermilab for TTF/DESY with four 3.9 GHz cavities inside.

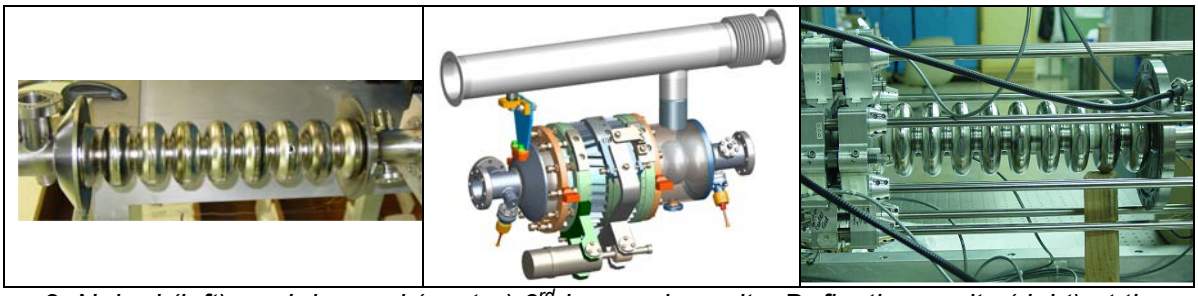

Figure 2 Naked (left) and dressed (center) 3rd harmonic cavity. Deflecting cavity (right) at the tuning stand

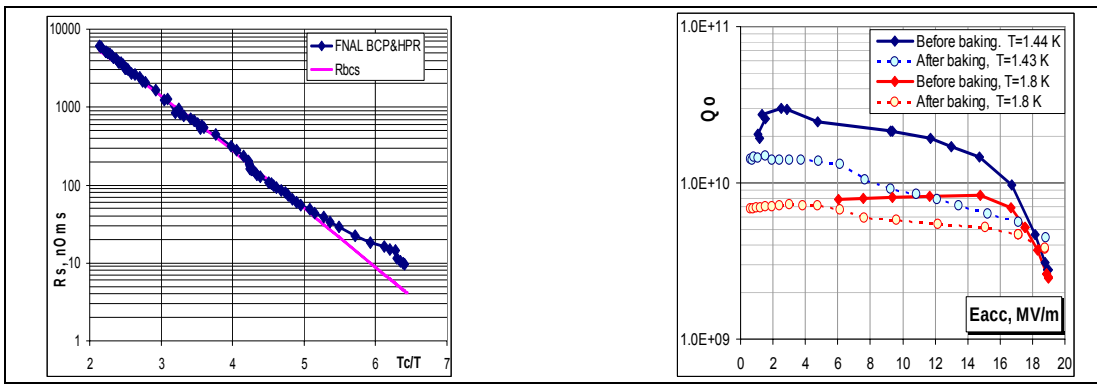

Figure 3 Test results of the 3ra harmonic cavity. Q vs. Tc/T (left) and Q vs. Eacc (right)

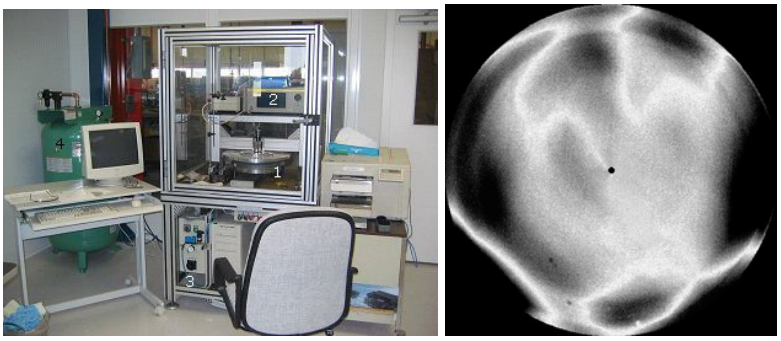

Figure 4 Left: eddy current scanner at Fermilab. Right: example of eddy current scan of niobium sheet for 3.9 GHz cavity

Advanced Accelerator Magnet and Superconductor R&D at Fermilab

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Summary:

Fermilab is developing a new generation of superconducting accelerator magnets with high operation fields and large operation margins based on Nb_3Sn superconductor for LHC luminosity and energy upgrades, and for future accelerators such as ILC, VLHC, etc.. Fermilab has developed a unique fabrication and test infrastructure to perform both short and long magnet R&D programs as well as extensive superconductors and structural materials R&D. We continue improving our infrastructure to fulfill growing program needs. A long oven for coil heat treatment up to 6-m long is being procured and will be in operation by March of 2006. Recently we added a second Teslatron with a 77 mm aperture 16 T solenoid to our Short Sample Test Facility. A compact 28-strand cabling machine has been automated and upgraded to 42-strand capability.

High Field Magnet (HFM) R&D program started at Fermilab in 1998 with the investigation of small-aperture 10-12 T dipoles for VLHC, based on shell-type and block-type racetrack coils, and two technologies – Wind-and-React (W&R) and React-and-Wind (R&W). Good progress was made in these directions [19]. Since 2003, due to limited resources, the program focused on the W&R technology and single-bore magnets with magnetic fields up to 15 T, as well as material development in support of magnet R&D.

Fermilab participates in the U.S. LHC Accelerator Research Program (LARP). Our contributions to LARP Magnet R&D include conceptual design studies of various magnets, participation in short and long model magnet R&D, material development and characterization. Fermilab will also lead the design, fabrication and tests of full-scale Nb_3Sn prototypes of LHC IR quadrupole. We provide a strong connection between our core HFM program and the LARP magnet R&D.

Recent accomplishments:

After testing a series of Nb_3Sn MJR magnets with limited quench performance, a model to calculate the current carrying capability of modern Nb_3Sn strands with flux jumps was developed at Fermilab in 2003. The analysis based on this model revealed significant reduction of strand current carrying capability at low fields. It was found that the transport current at low fields can be significantly smaller than the transport current at high fields for strands with large d_{eff} and high J_c. This result was consistent with the observed quench performance of our first Nb_3Sn models.

The results of this analysis were verified and confirmed experimentally in Nb_3Sn strand and cable measurements. The dependence of critical current vs. field was measured at high and low fields using the V-I method at constant external magnetic field and the V-H method at constant transport current in the sample. Both methods showed low current quenches at low fields in high-J_c Nb_3Sn strands with large d_{eff} as predicted by the stability analysis. Since then, low field measurements have become standard in Nb_3Sn strand characterization for high-field accelerator magnets. Our study of round strands and strands extracted from cables revealed also the effect of filament size increase due to strand deformation on cable stability.

We also studied instabilities in cable short samples. Cable samples made of different Nb_3Sn strands were tested at Fermilab in self-field ~2 T at 2-4.2 K using a 28-kA SC transformer, at BNL in external magnetic fields up to 7T at 4.2 K, and at CERN in external magnetic fields up to 10 T at 1.8-4.2 K. A good correlation of experimental data for similar samples tested at the three

Labs was observed. The results are also consistent with the stability calculations and magnet quench performance. The high efficiency of tests performed using the SC transformer developed at Fermilab allowed efficient studies of cables made of different strands, impregnated and non-impregnated with epoxy, and with various values of RRR. A special technique to measure inter-strand contact resistance (ICR) important for cable stability inside magnet coils was also developed at Fermilab and systematic studies of ICR have been started in 2004.

Relatively long Nb_3Sn cable samples were tested using racetrack coils. A 2-layer coil wound from a single cable piece into a common coil configuration, supported by a simple mechanical structure, was used. Two racetracks made of different cables were fabricated and tested in 2004. Racetrack SR01, made of PIT strand, reached its high-field short sample limit at 4.5K. SR02, made of MJR strand used in the first dipole models, was limited by quenches in the low-field regions near coil lead splices. Both results were expected based on the strand and cable stability analysis and measurements. This method will be used also to test cables based on RRP strands.

Stability studies allowed improving quench performance of Fermilab's Nb_3Sn magnets. One mirror and two dipole models based cosθ coils and 28-strand Nb_3Sn cable made of stable PIT strand were fabricated and tested in 2004-2005. All three magnets reached their short sample limits and the field of 10 T at 4.5 K. The maximum quench current, its ramp rate and temperature dependences for both dipoles were practically identical. The analysis of field quality in Nb_3Sn accelerator magnets was performed based on measurements of five nearly identical dipole models. The field quality was also reproducible and well understood. This is the first time that the reproducibility of Nb_3Sn accelerator magnet technology was practically demonstrated.

To advance the field to 11-12 T, three new half-coils based on 39-strand Nb_3Sn cable made of high-J_c RRP strand were fabricated and two of them were tested in magnetic mirror configurations in 2005. The magnet low-field and high-field short sample limits estimated based on strand and cable tests were on the level of 12-13 kA for both coils. However, the maximum current of both magnets at 2.2-4.5 K was limited to only 5-7 kA. The magnet and witness sample test data indicated that the observed quench performance of both RRP coils was limited by electromagnetic instabilities in the cable. In this case it was due to local breakage of sub-element barrier and sub-element fusing. The work on stability improvement of round RRP strand and its preservation in Rutherford-type cable will continue in collaboration with OST.

Successful testing of magnets based on stable PIT strand allows moving towards the Nb_3Sn technology scale up. The first step starts in 2006 with fabricating and testing 2-m and 4-m PIT coils in mirror configuration. Then the work will be continued using the RRP strand. The results will be applied to LARP long IR quadrupoles.

Studies of 13-16 T dipole magnets with 40-45 mm aperture based on shell-type and block-type coils and Nb_3Sn or Nb_3Al superconductor were performed in 2005. Several high-field magnet designs based on 3-layer and 4-layer coils were analyzed. The design of a 15 T dipole model based on 4-layer graded shell-type coil has been started.

In 2005 we developed for LARP a Nb_3Sn technological quadrupole model (TQC) based on two-layer shell-type coil and collar-yoke-skin mechanical structure as used in present NbTi LHC IR quadrupole (MQXB). The work on the first 1-m long model is in progress in collaboration with BNL and LBNL. Three short TQC models will be produced and tested at Fermilab in 2006-2007.

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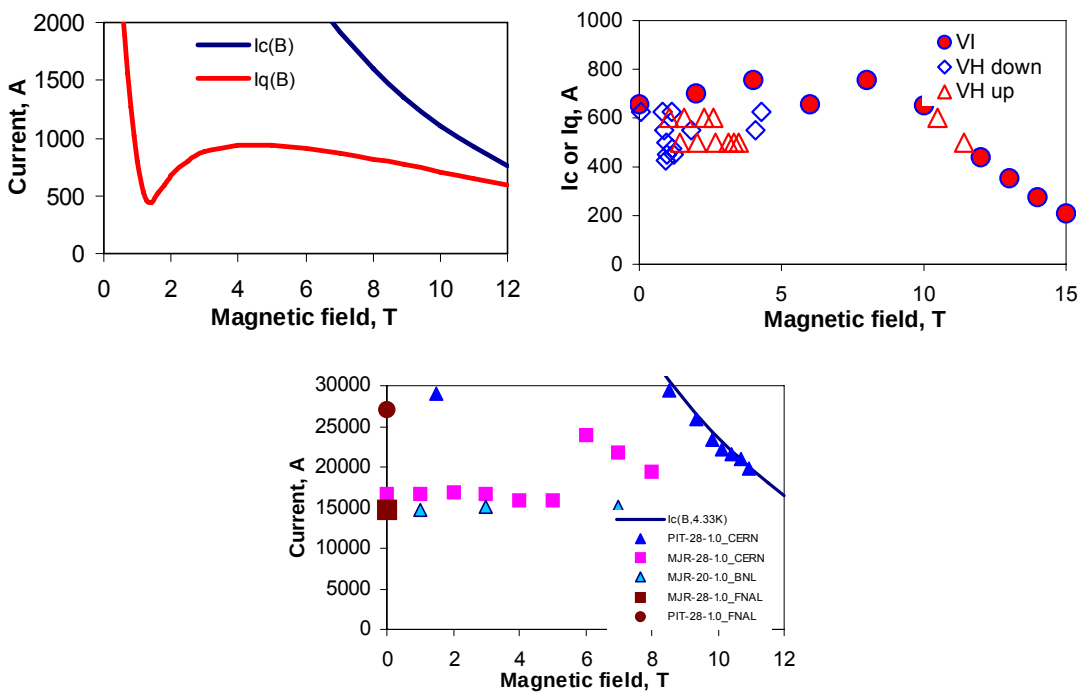

Figure 1. Examples of strand stability calculation (top-left) and measurement (top-right) and cable short sample tests (bottom).

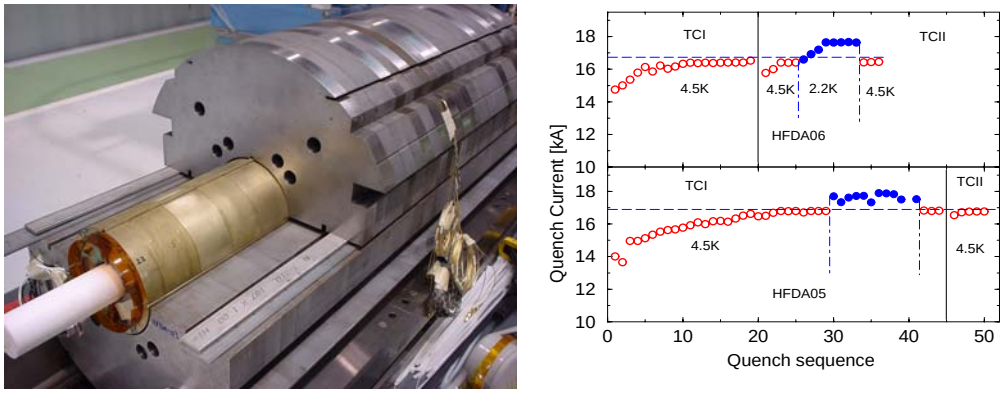

Figure 2. HFDA05 and HFDA06: magnet assembly (left) and training curves (right).

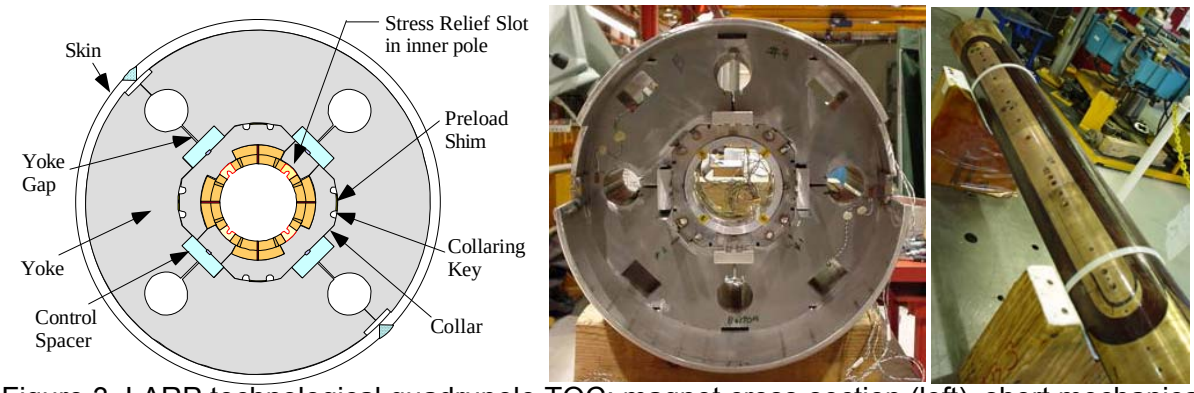

Figure 3. LARP technological quadrupole TQC: magnet cross-section (left), short mechanical model with Al “dummy coil” (center) and reacted and epoxy-impregnated coil (right).

Beam Electrodynamics Studies at Berkeley Lab

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Lawrence Berkeley National Laboratory

Summary

The increasing sophistication of the present and future generations of particle accelerators requires exquisite control of the manipulation of charged particle beams and extreme sensitivity in their measurement. Because the primary means of controlling and measuring the beam is electromagnetic in origin, there is an acute need for specialists in electromagnetic interactions, components, and systems for the production, acceleration, control, and diagnosis of charged particle beams. The Beam Electrodynamics Group (BEG) provides core expertise and facilities for these areas.

Accelerator physics and technology issues related to intense, short, well-focused charged particle bunches form the primary theme of the group's R&D. Interaction of these beams with accelerator components and diagnostic devices is typically electromagnetic in origin, and so measurement and control will involve both low-level and high-power microwave, radiofrequency (rf), and millimeter wave technology. Ultra-short (picosecond scale) bunches will have broad frequency spectra reaching up to hundreds of gigahertz. Thus, high-frequency microwave detection techniques using specialized pickups, novel signal processing and electronics schemes, and high-frequency rf beam manipulation must all be mastered in order to use these beams effectively. Production of beams with high charge and small emittance, analysis of effects leading to emittance growth, and means of providing control of the multitude of deleterious processes are vital in providing high brightness for synchrotron radiation sources and high luminosity in future high-energy colliders. Development of techniques for acceleration of particles using highly efficient structures but with minimal parasitic interaction with beams is critical in providing high-energy and high-current beams with good beam lifetime, and with minimal contribution to collective effects causing emittance growth. The BEG has considerable experience and expertise in the design and fabrication of such higher-order-mode (HOM) damped cavities.

The BEG maintains the Lambertson Beam Electrodynamics Laboratory, named for retired former group leader and mentor Glen Lambertson, and provides experimental facilities in two primary areas: low-power test and measurement of rf and microwave devices and systems and laser facilities for development of fiber-based master oscillator distribution which will allow sub-picosecond synchronization of accelerator systems over long distances. For low power microwave characterization of accelerator components, network analyzers, spectrum analyzers, time-domain reflectometers, bead-pull apparatus, and beam impedance measurement apparatus are available. For optical fiber development, long coherence length and mode-locked lasers are available as well as a variety of optical instrumentation and components.

The BEG also maintains a workstation dedicated to running electromagnetic analysis and design software, including the fully three-dimensional code MAFIA, and Microwave Studio. A small workshop supports the fabrication of test and measurement supports and fixtures. The BEG program combines theoretical work with strong experimental and engineering hardware development skills. We provide a world-class resource in the design of rf and microwave devices and systems for acceleration and control of charged particle beams, impedance analysis and measurement, and analysis of collective

effects. In addition to analytical and test-laboratory experimental work, the group has significant experimental, commissioning, and operating experience with large-scale accelerators.

The BEG draws upon extensive expertise in electromagnetic fields and waves, microwave and rf technologies, and laser systems, to design accelerator systems and components and to combat deleterious effects arising from beam-environment interactions.

Recent Accomplishments

Recent accomplishments include the following. The rf and mechanical design of coupling coil accelerating structures for ionization cooling of muon beams, including construction of a prototype 201 MHz cell for high power test has been completed. A novel optical sampling technique using nonlinear crystals with synchrotron radiation for longitudinal density measurement of high energy multibunch beams such as the International Linear Collider (ILC) damping rings and Large Hadron Collider has been successfully demonstrated. A model for understanding the collective effects of coherent synchrotron radiation (CSR) in a storage ring such as the ILC damping rings has been developed. This includes the first experimental characterization of the CSR microbunching.

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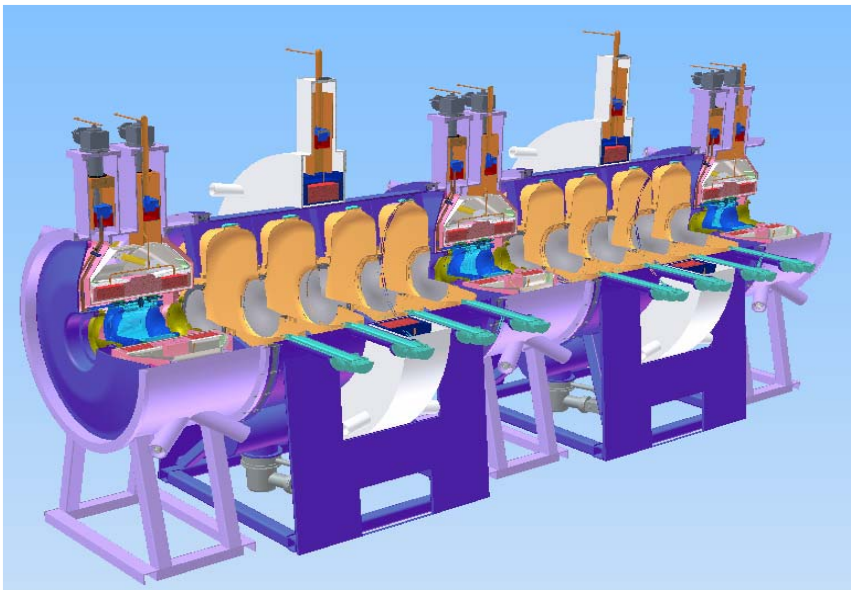
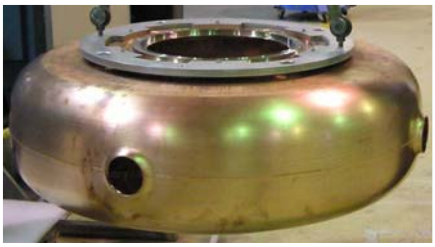
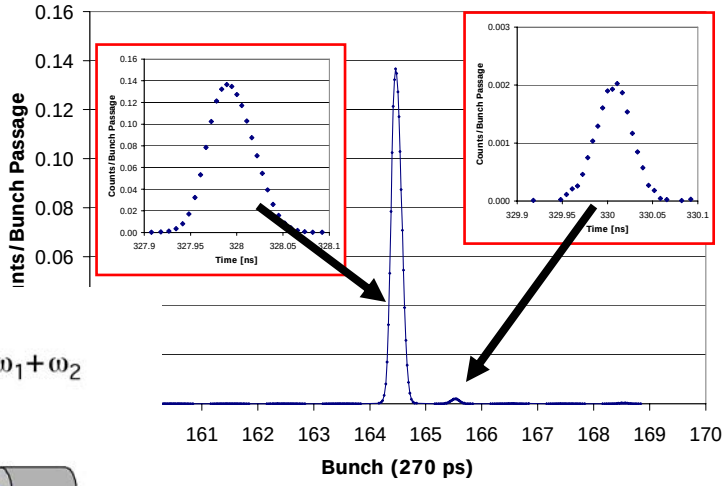
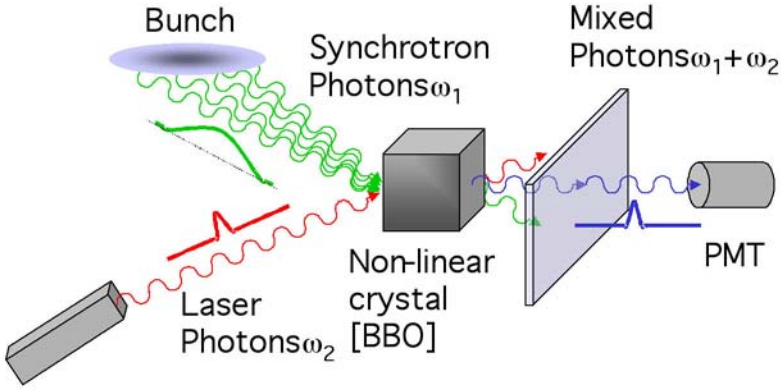




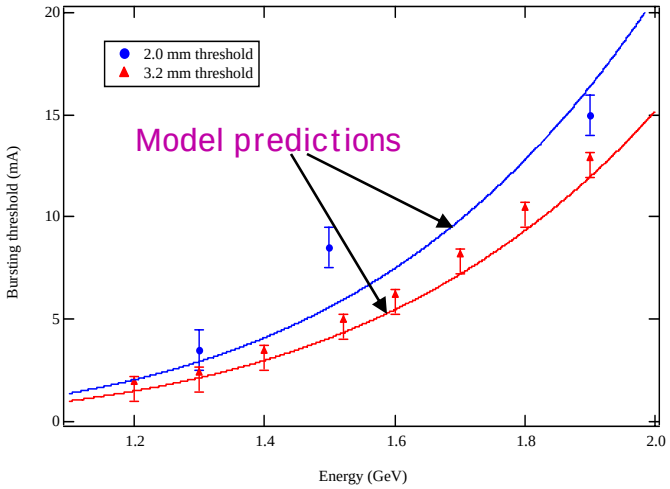
MICE coupling coils and 201 MHz cavity construction

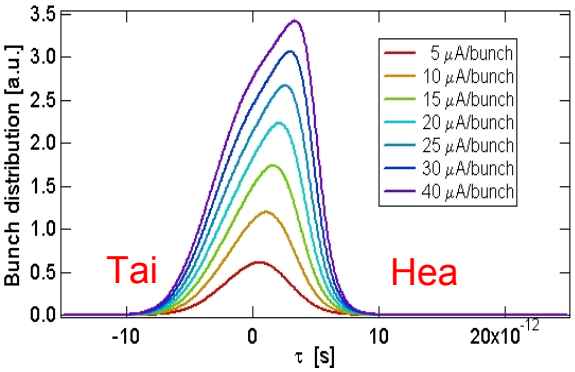
Optical sampling scope: synchrotron light diagnostics





Model and observations of CSR collective effects in a storage ring





Advanced Accelerator R&D

Miguel Furman
Center for Beam Physics Theory Group
Lawrence Berkeley National Laboratory

Summary

The mission of the Center for Beam Physics Theory Group is to carry out original research at the forefront of beam dynamics, specifically: the electron-cloud effect, beam-beam interaction, optical stochastic cooling, lattice design issues for damping rings, new acceleration mechanisms, and laser-pulse amplification.

Recent Accomplishments

- We have calibrated our electron-cloud simulation code POSINST against measurements at the APS and the PSR; agreement is within ~50% or better, depending on which quantity is studied. We have applied POSINST to simulate the Super Proton Synchrotron, and compared results against other codes and measurements. An ongoing effort is the use of POSINST to simulate the Large Hadron Collider (LHC) heat deposition from the electron cloud; we find good qualitative agreement with CERN simulations.
- In collaboration with the Heavy Ion Fusion group (Lawrence Berkeley National Laboratory (LBNL)), we have begun to develop a new self-consistent 3D electron-cloud simulation code by merging WARP and POSINST. As an initial test, we have simulated a full LHC arc FODO cell. This tool is arguably the state of the art in the field. A similar code is being developed in collaboration with PSI whose ultimate capabilities will be similar to the previous one, but there are essential differences in the field solver and visualization techniques. Experience will decide which code is better for any given application.
- We have transferred to Tech-X Corporation several of our secondary-emission computer modules. Funded by a Small Business Innovative Research grant, Tech-X has adapted and repackaged them for general-purpose use and distribution.
- In collaboration with the Accelerator Modeling and Advanced Computing group (LBNL), we have developed a 3D PIC code for strong-strong beam-beam simulations. The code is fully parallel, allows for crossing angles collisions, bunch length effects, and parasitic collisions. The code has been tested against measurements at Relativistic Heavy Ion Collider (RHIC) with good agreement, and has been applied to simulate TEVATRON and LHC operations.
- Developed a new approach to optical stochastic cooling by considering an optical parametric amplifier that operates at 12 μm instead of the former 1-μm system based on Ti:Sapphire laser amplifier. This new approach allows extending optical cooling of particles to lower energies.
- Applied the new scheme to cool the gold ion beam in RHIC; this work is presently pursued in collaboration with the particle-cooling group at Brookhaven National Laboratory.
- Developed various design possibilities for the lattice and optics of the International Linear Collider (ILC) damping rings, and assessed their dynamic aperture and potential for collective effects. This work entailed the development of new techniques to construct maps for combined-function magnets, and the application of frequency map techniques to assess dynamical effects.

- Developed a new concept for producing an ultra bright beam of electrons - 3 to 4 orders of magnitude brighter (in 6D phase space) than existing sources. Such a source has the potential to enable significant advances in high-temperature superconductivity, photocathodes, alignment and calibration of electric and magnetic fields in detectors and accelerator optics, accelerator instrumentation, etc.
- Developed the concept for, and collaborated in the construction of a prototype of, a device to measure the longitudinal particle distribution of a beam.

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Optical-Accelerator Experiments at Berkeley Lab

Wim Leemans
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Summary

The Lasers, Optical Accelerator Systems Integrated Studies (LOASIS) Program of the Accelerator and Fusion Research Division at Lawrence Berkeley National Laboratory (LBNL) is focused on developing the physics and technology of advanced laser-driven and plasma-based ultra-high gradient accelerators, to fit the needs of the Department of Energy's High Energy Physics program. These devices offer the ability of producing gradients well over 100GV/m and can accelerate both electrons and ions. The proposed research program presents a comprehensive approach to studying both electron and ion accelerators, through experiments, theory, and simulation. The main focus of the program is on the development of a compact channel guided laser wakefield accelerator module with a 1 GeV energy output. Experiments are conducted at the LOASIS laboratory, which has a multi-beam, femtosecond, multi-terawatt laser system and radiation shielded experimental areas. We are studying electron acceleration using standard and self-modulated laser wakefields, laser guiding in plasma channels, laser triggered injection, plasma tailoring to control trapping and acceleration, and femtosecond time resolved beam diagnostics. Ion acceleration experiments are in their early stage of development and will aim at producing high quality ion beams for future application as a hadron injector. The physics behind these accelerators and diagnostic is being studied using analytical theory and a variety of computational tools ranging from multi-dimensional fluid models, fast envelope codes, test particle simulations and full scale particle-in-cell simulations. The LOASIS Ti-sapphire laser system (operating at 10 Hz) currently provides multiple beams (up to four) at the 1-10 TW level to one target area and a 100 TW-class beam (40-50 TW at present) to a new target area.

The theory and computational efforts of the Group are focused on new concepts and analysis of ongoing experiments at the LOASIS Laboratory and significant progress has been made in developing analytic and computational tools (e.g. fluid codes) for prediction and analysis. To further extend our capabilities, a collaborative effort (part of a SciDAC program, between CBP researchers, the University of Colorado, Tech-X Corporation, and our group) has continued on the use of particle-in-cell codes for self-consistent modeling of the laser-plasma interactions, including particle trapping and acceleration.

Recent Accomplishments

We succeeded in 2004 in the first experimental demonstration of laser guiding in preformed plasma channels at relativistic intensities and production of high quality electron beams from such a channel guided laser wakefield accelerator. The experiments employed an ignitor and heater beam and used the 10 TW laser beam as drive beam for the excitation of the plasma wake, We demonstrated that (1) relativistic intensities as high as 10^{19} W/cm^2 can be guided in preformed plasma channels and (2) that through control of the plasma channel and laser parameters electron beams with percent level energy spread at 100 MeV can be produced with a few 100 pC of charge and a normalized emittance of 1-2 p mm-mrad. These results made the cover of the September 30, 2004 issue of *Nature* (C.G.R. Geddes et al., Nature **431**, 538-541 (2004)) and were part of Cameron Geddes' dissertation. In addition, this work showed that 10's GV/m dark-current free plasma structures can be excited which allows us to perform a "clean" experiment on laser triggered injection. Such an experiment was first attempted in 2002 when electron yield enhancement was observed by using a second laser pulse intersecting the driving

laser pulse at an angle of 170 . However, to minimize electron self-trapping the drive pulse had to be lowered significantly which negatively affected the overall performance. Experiments will be conducted during FY06 on laser triggering in the dark-current free operating regime of the channel. We have also continued experiments on coherent radiation emission via the transition radiation mechanism of laser accelerated electron bunches at a plasma-vacuum boundary [W.P. Leemans et al., Phys. Rev. Lett. **91**, 074802/1-4 (2003)]. By temporally resolving the electric field of the radiation, we have now been able to measure for the first time the bunch shape of the femtosecond electron bunches from a laser wakefield accelerator(J. van Tilborg et al., submitted to Phys. Rev. Lett. 2005). We have also begun experiments with the new 100 TW-class, 10 Hz laser system on guiding intense laser beams using capillary discharges. To date, intensities on the order of $5x10^{17}W/cm^2$ (laser power of 13 TW) have been guided over a distance of 33 mm in a hydrogen filled low current capillary dicharge. This work is done in collaboration with researchers from Oxford University and Strathclyde, UK. Experiments are underway that aim at producing GeV electron beams from this structure.

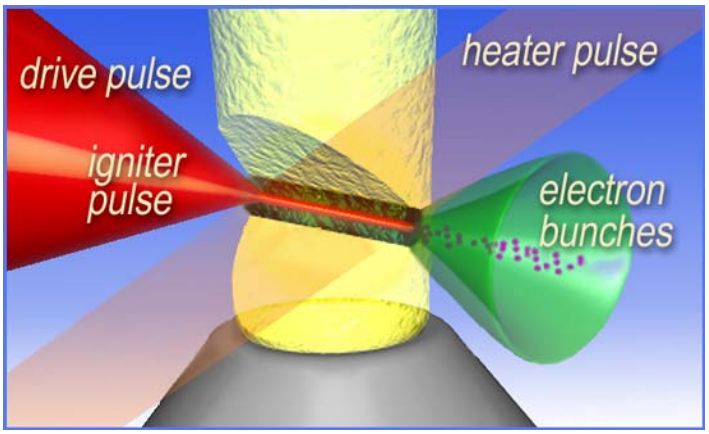

Figure 1 Schematic of the channel guided laser wakefield accelerator. A first laser pulse (the igniter pulse) is used to ionize hydrogen gas and form a few mm-long thin (10-20 micron diameter) rod of plasma. A second laser pulse (heater pulse), arriving right after the igniter pulse, is focused on this plasma rod and rapidly heats it. The hot plasma then expands and hollows out in the center via the hydrodynamic expansion. This density depression is suitable for guiding the third laser pulse (drive pulse) over distances that are long compared to its depth of focus. Under the appropriate conditions, this configuration has been shown to produce mono-energetic beams (few % energy spread) at the 100 MeV level over a distance of 1.5-2 mm.

Figure 2 Nature magazine cover of the September 30th issue, 2004 showing a two dimensional plot of the accelerated electron density profile. The laser beam is located at the top of the figure. The accelerated electron beam can be seen as a brightly colored dot riding on the electric field associated with the laser excited plasma density wake. Simulations performed with the code VORPAL (developed by John Cary and Chet Nieter of the University of Colorado, Boulder and Tech-X Corporation, Boulder).

Current Scientific Staff

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- C. Toth Staff Scientist
- C.B. Schroeder Staff Scientist
- C.G.R. Geddes Scientist
- B.A. Shadwick Scientist, half time
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- C. Filip Postdoc, UNR

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- J. van Tilborg, Ph.D., Technische Universiteit Eindhoven, the Netherlands, in progress.
- K. Nakamura, Ph.D., University of Tokyo, Japan, in progress.
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Publications 2003-2005

Refereed Journals

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Superconducting Magnet Program

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Summary

Performance requirements of modern accelerators continue to press the limits of magnet technology. Ever-higher beam energy is a constant goal in high-energy physics, requiring both stronger and more cost-effective magnets. The LBNL superconducting magnet program is directed towards advancing all aspects of the technological infrastructure for high field magnet development relevant to possible future accelerators.

Our role—as not only a leading R&D group but also the administrators of the multi-institutional DOE/HEP National Conductor Development Program—is to develop both evolutionary improvements and paradigm shifts in the application of accelerator magnets, providing innovative technology that enables new science. Achievement of these goals requires development and application of new materials, new magnet designs, and new techniques for magnet construction. In recent years, we have achieved a number of key milestones culminating with the successful test of the HD-1 dipole, which exceeded 16 Tesla. Magnet R&D is, and will continue to be, an important component of the DOE R&D portfolio. Despite the success of the Berkeley program, there remains a vast amount of unexplored phase space that will yield new applications across the DOE programs.

In the near term, these innovations can find application in final-focus dipoles and quadrupole magnets, required for the high-luminosity collision points. The Large Hadron Collider (LHC), presently under construction at CERN, will be the world's most powerful accelerator. A timely upgrade of the LHC machine luminosity was identified by the High-Energy Physics Advisory Panel (HEPAP) as an absolutely central goal. Our program is a key contributor to the US LHC Accelerator Research Program (LARP), developing powerful Nb_3Sn quadrupoles for this upgrade.

Much of our magnet R&D work involves close collaborations with industry, in particular on the development of advanced superconductors and improved manufacturing methods. This area of R&D includes superconducting materials with high critical current density at high field, and very fine filaments (to improve stability and reduce losses). New cable manufacturing methods and insulation materials are also required. These collaborations are carried out through the DOE/HEP National Conductor Development Program as well as the Small Business Innovation Research (SBIR) program. Each year we contribute to the SBIR program by providing technical support to the companies and advice on the DOE programmatic goals.

Achieving 16 T in a dipole configuration was a major step, establishing the feasibility of Nb_3Sn for accelerator applications. But it is only the beginning of a complex, synergistic group of processes that will lead to the ultimate goal of an industrialized, multi-meter-long magnet with large aperture and accelerator-grade field quality. Getting there will require an intensive, long-term effort by both LARP and our base program to address several issues.

The medium-term goals (5 – 7 years) include increasing the field to the maximum practical limit for Nb_3Sn, which is approximately 17 T; increasing the bore size; and improving the field quality. Length issues are particularly important to understand, so within the next several years, a 3-4 m long quadrupole should be produced, followed a few years later with the demonstration of a practical quadrupole that meets the requirements for an LHC interaction region upgrade.

A very-high-field, accelerator-quality collider dipole that operates above 15 Tesla under high synchrotron-radiation heat loads will take significantly longer to develop. With a vigorous, adequately funded program, a demonstration of this technology can be achieved by 2015

Recent Accomplishments

Following the successful test of the RD3b prototype up to 14.5 Tesla, a new common coil dipole (RD3c) was fabricated and tested. RD3c was conceived as an economical test to address, for the first time, basic accelerator quality issues for the common coil configuration. The magnet achieved a magnetic field above 10 Tesla in a 35 mm clear bore, with field harmonics at the 10^{-4} level at the nominal operating current. Based on these results, a roadmap toward fully operational, high-field common coil dipoles for future colliders was established.

In parallel, the conceptual design of an alternative block-type layout (HD series) was completed. The first prototype of the new series, HD1, featured a conductor-free mid-plane and stress levels above 150 MPa (an important issue for magnets based on Nb_3Sn). The magnet reached its design field of 16 Tesla, surpassing by more than one Tesla the dipole field record established by RD3b. HD1 pushes the limits of accelerator magnet technology to unprecedented levels in terms of magnetic field and mechanical stress, opening the way to a new generation of hadron colliders. This result demonstrates that block-coil dipoles are well suited to high-field applications using brittle conductors.

It is becoming increasingly apparent that sophisticated analysis is the key to building successful magnets, so we have placed more and more emphasis on this area, making significant progress. Our design team has combined a number of engineering tasks into a single streamlined process. Integrating mechanical, magnetic, structural, thermal and electrical design has now become routine. This level of integration of multiple disciplines is used to investigate new and more complex magnet designs. It will also help us unravel subtle mechanics-related performance issues, such as the near universally observed but still incompletely understood “training” process by which a magnet reaches its full potential in a series of ramps to successively higher fields, interspersed with quenches.

In order to probe the ultimate performance limits of materials and magnets, full scale prototypes are required. However, many technology development issues can be more effectively addressed using small models. During the last several years, we have fabricated about 20 sub-scale coils for applications such as the test of support structures, advanced cable R&D, quench-protection studies, and development of new fabrication techniques. The most recent success of this program has been the fabrication and test of a large aperture quadrupole for LARP. In the future, the sub-scale series will also be used to evaluate new High Temperature Superconductor (HTS) materials such as MgB_2 or Bi-2212, as they become available in sufficient quantity and with properties and cost suitable for practical magnet R&D.

Superconducting Magnet Program Publications

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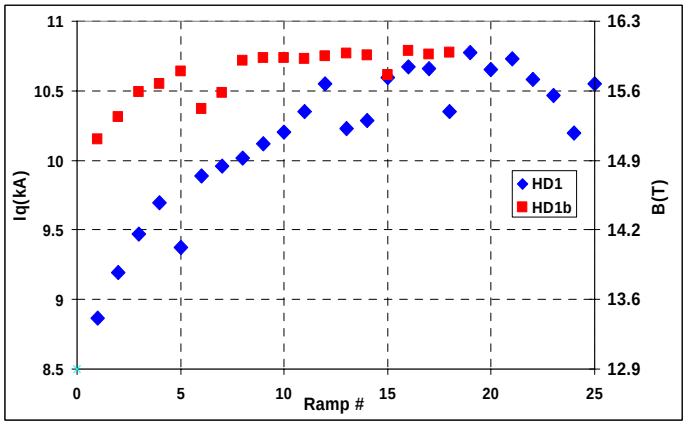
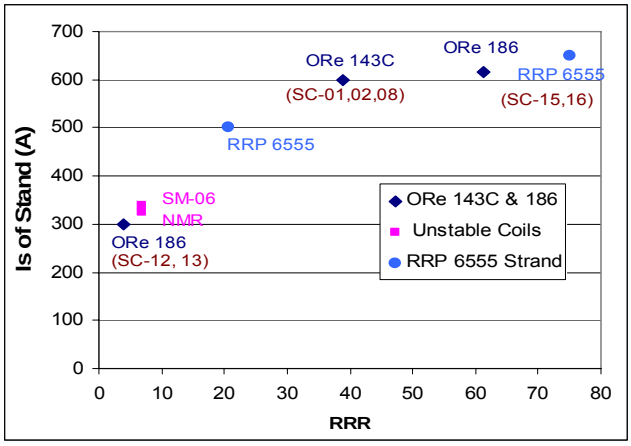
http://supercon.lbl.gov





SLAC Accelerator Research Department B

Robert H. Siemann
Stanford Linear Accelerator Center

Overview

Stanford Linear Accelerator Center (SLAC) Accelerator Research Department B (ARDB) performs experimental research in high gradient acceleration. Laser driven structures and plasma based accelerators are explored. Much of the ARDB work is performed at SLAC facilities in collaboration with other principal investigators, including: Profs C. Joshi, W. Mori and J. Rosenzweig of UCLA, T. Katsouleas of USC, and R. Byer of Stanford.

Highlights of Laser Acceleration Research
Leap and E-163

It has long been appreciated that lasers are capable of producing extraordinarily high electric fields. The accelerator challenge has been and remains developing a way to accelerate particles with these fields. The most significant impediment to doing that is that laser light is transversely rather than longitudinally polarized. This has led to research in laser driven accelerators such as laser driven plasma waves where particles are accelerated by the plasma wave rather directly by the laser light, and the Inverse Free Electron Laser (IFEL) where the particles are wiggled in synchronism with the laser light. This research takes a different tack, one that is inspired by the technological revolution in lasers and photonics.

This revolution is being driven by commercial applications such as telecommunications and laser machining. *Figure 1* is one of many ways to illustrate this. It shows the exponential growth in fiber laser power and the exceptionally high efficiency for conversion efficiency for converting pump power to laser light.*

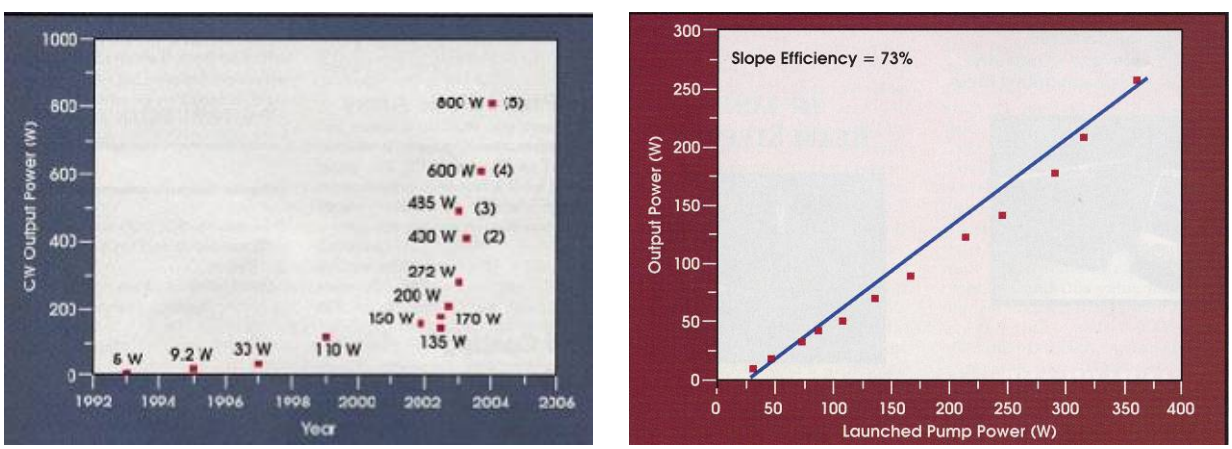


Figure 1 The CW output power of fiber lasers has grown from a few Watts to almost a kW in a decade and the efficiency of conversion of pump to laser power is almost 75%. These figures are from an article by J. Limpert et al, "Scaling Single-Mode Photonic Crystal Fiber Lasers to Kilowatts" in the May 2004, issue of Photonics Spectra, a laser and photonics trade journal

* *Efficiencies of over 50% are achieved in conversion of wall-plug power to pump power making the overall conversion efficiency of wall-plug to laser power of about 40%.*

These developments have made it natural to think about laser driven accelerators similar to those that we routinely use at much longer radio frequency wavelengths. All the basic ingredients are there: high power, high efficiency lasers, dielectric structures that can sustain high fields without damage, and, very importantly, the demonstrated ability to lock lasers together in phase to make them coherent with each other.**

There is enormous promise for accelerating particles. Very high accelerating gradients, compact laser driven accelerators, particle and photon beams with attosecond time scales could all be in the future. The potential is limited only by imagination since this is the transition from accelerators driven by vacuum tubes to ones driven by solid-state devices.

This research is a Stanford/UCLA/SLAC collaboration. The current participants are:

R. L. Byer, T. Plettner, S. Wong (Stanford University)
J. Rosenzweig (University of California, Los Angeles)
E. R. Colby, B. M. Cowan, M. Lincoln, R. J. Noble, C. Sears,
R. H. Siemann, J. E. Spencer, S. Tantawi, D. R. Walz, Z. Zhang (SLAC)

Laser-Acceleration of Relativistic Electrons in a Semi-Infinite Vacuum

T. Plettner et al, accepted for publication in Physical Review Letters

The Laser-Electron Accelerator Project (LEAP) is a proof-of-principle experiment for laser-driven particle acceleration of electrons in a structure loaded vacuum. The experiment, shown in *Figure 2*, was conceptually simple. A single laser beam was incident on a thin, gold coated kapton tape that truncated the interaction. By continuously moving the tape we could apply laser power above the material damage threshold at to maximize the interaction strength.

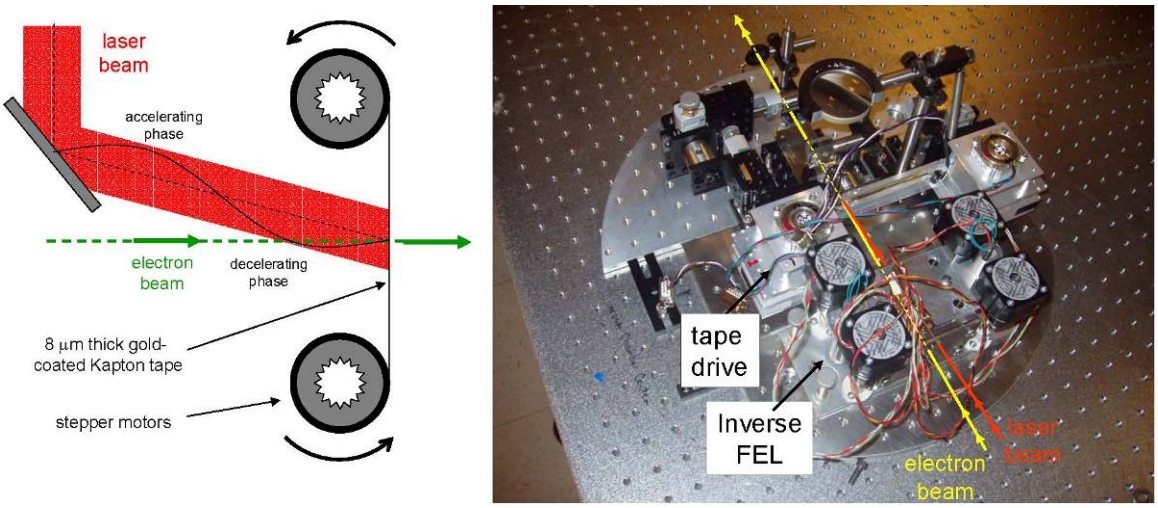


Figure 2 Schematic and realization of the experiment showing the tape drive with the terminating boundary and an Inverse Free Electron Laser preceding it in the beam path.

The goals of the experiment were verification of several general results expected from theory, including polarization dependence (*Figure 3*, left), linear dependence on the field strength

*** See for example Diddams et al, "Direct Link between Microwave and Optical Frequencies with a 300 THz Femtosecond Laser Comb", Phys. Rev. Lett., 84, p.5102, (2000).*

(*Figure 3* right), and to provide conclusive evidence that plasma interaction, inverse Cerenkov acceleration, or other acceleration mechanisms were not the cause. In addition, the Lawson-Woodward theorem was demonstrated by removing the tape boundary and observing that the interaction went to zero.

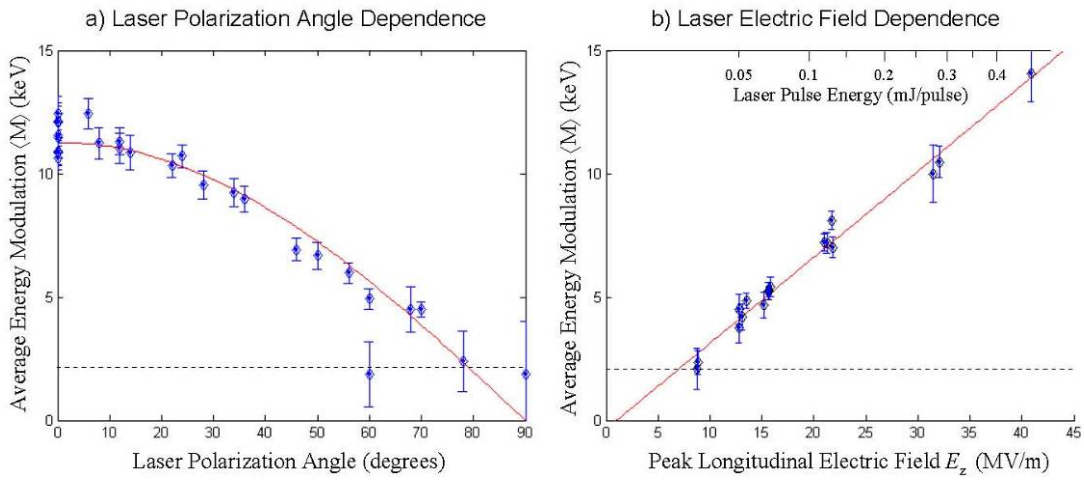


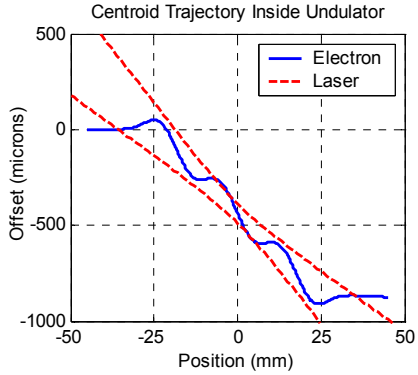
Figure 3 Experimental results and comparison with theory for polarization and electric field strength dependences.

High Harmonic IFEL Interaction at 800 nm

C.M.S. Sears et. al., submitted to Physical Review Letters.

Current injectors for laser acceleration research produce electron pulses of a few picoseconds length. By comparison the optical period of the laser is just a few femtoseconds. In order to obtain net acceleration and increase capture efficiency the electron pulse must first be micro-bunched at the optical wavelength. This is best done with an IFEL interaction that first modulates the beam followed by a magnetic chicane to convert the energy modulation into a longitudinal density modulation.

As a first step to microbunching a beam we have tested the IFEL modulation and scanned the harmonics of the interaction. The harmonic scan confirmed some interesting physics of the IFEL interaction. Most undulators are designed such that the electrons undergo a symmetric figure eight motion in the electron beam frame of reference. This symmetry means that the electrons will only couple to odd harmonics of the radiation field. However, if the undulator is adjusted such that the electrons have an asymmetric trajectory, as was done for this experiment (*Figure 4a*), the electrons can then couple to even harmonics as well. This is confirmed from the gap scan data shown in *Figure 4b*. The data consists of 164 separate runs each with ~400 laser-electron interactions. Between runs the gap of the undulator is changed, thus changing the field seen by the electrons. The data is compared to simulation done with a particle tracking code. While the overall amplitude is off by ~33% in the gap scan, a discrepancy believed due to the uncertainty in the beam position w.r.t. to the wiggler pole face, other runs taken during the experiment showed very good agreement of the amplitude as well.



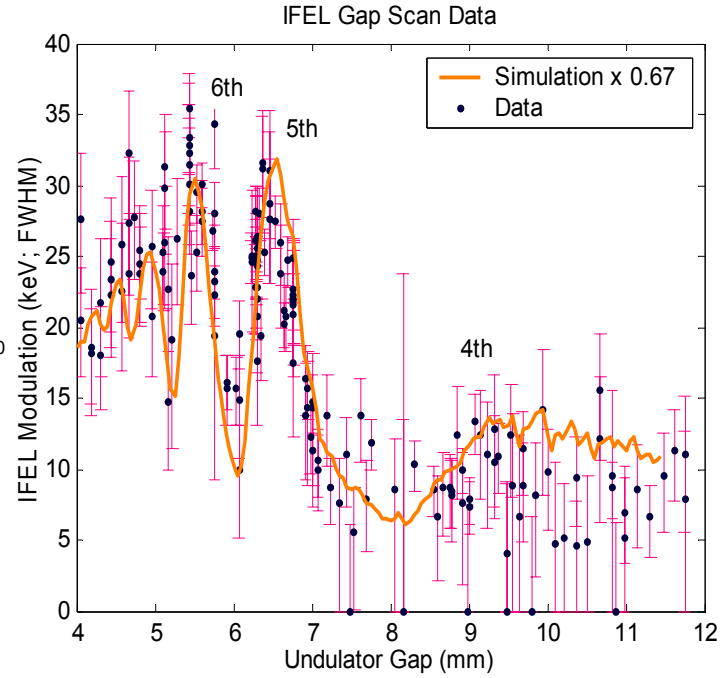


Figure 4a Above, laser & electron trajectories inside undulator for a gap of 5.4 mm. 4b Left, gap scan data with simulation The data shows clear peaks matching the simulation. Scan is composed of 164 separate runs with a fixed gap position for each run.

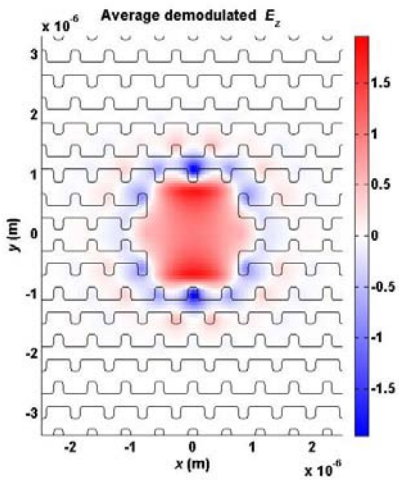
Photonic Crystal Laser Acceleration

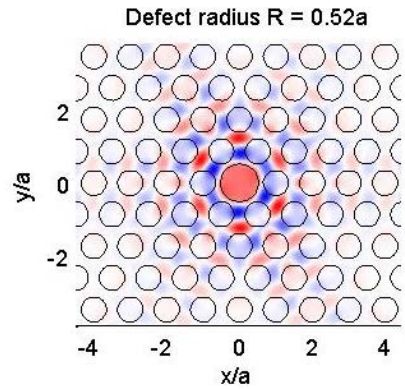
X. E. Lin, *Phys. Rev. Special Topics-AB* **4**, 051301
B. M. Cowan, *Phys. Rev. Special Topics-AB* **6**, 101301

Photonic crystal structures have the potential for high-efficiency, high-gradient laser-driven acceleration. Laser-driven acceleration in vacuum requires a waveguide that can confine a mode with a longitudinal field and speed-of-light phase velocity. Additionally, such a waveguide must be built entirely out of dielectric materials, since metals exhibit low breakdown thresholds at optical frequencies.

A photonic crystal is a structure with permittivity periodic in one or more of its dimensions. Optical modes in a photonic crystal form bands, just as electronic states do in a crystalline solid. Similarly, a photonic crystal can also exhibit one or more photonic band gaps, with frequencies in the gap unable to propagate in the crystal. Confined modes can be obtained by introducing a defect into a photonic crystal lattice. Since frequencies in the bandgap are forbidden to propagate in the crystal, they are confined to the defect. A linear defect thus functions as a waveguide. Such waveguides have the benefit that only frequencies within a bandgap are confined. In general, higher order modes excited by the electron beam simply escape through the lattice.

Several years ago an accelerating mode was found in a photonic band gap fiber structure. Since then, we have continued to study fiber structures, and developed new structures in a planar geometries amenable to lithographic fabrication. Several examples of structures are shown in *Figure 5*. Synchronous waveguide modes have been studied in a two-dimensional planar structure, and we have also computed an accelerating mode in a three-dimensional planar photonic crystal and studied the particle beam dynamics in that structure.





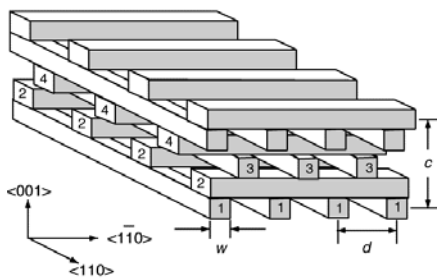


*Figure 5 Top left: An accelerating mode in a "woodpile" structure; bottom left: Schematic of the woodpile lattice (from S. Y. Lin et. al., Nature **394**, 251 (1998)); above: mode in a photonic crystal fiber structure. In both mode diagrams the e-beam comes out of the page.*

Construction and Commissioning of E-163

With the successful completion of the LEAP experiment in November 2004, the experiment was disassembled and removed from its installation at the Hansen Experimental Physics Laboratory and moved to SLAC, where a new facility for advanced accelerator R&D is being constructed. The Next Linear Collider Test Accelerator (NLCTA) has been expanded to include a new shielded experimental area, a state-of-the-art laser facility, a new building for experiment preparation and a dedicated experiment control room. In addition, the electron source for the NLCTA has been upgraded from a long-pulse thermionic source to a single-bunch high brightness rf photoinjector.

As of this writing, the rf and laser systems are completed, the new injector is installed and will be commissioned in September 2005. Installation of the extraction beamline and experiment in the new shielding enclosure is slated to take place this fall, with first laser acceleration experiments taking place in early winter 2006.

Once commissioned, the facilities will provide users with a well-diagnosed 60 MeV electron beam with ~1 ps duration, up to 1 nC charge, tightly synchronized with a high power Ti:Sapphire laser system, and a facility for performing high-resolution spectrometry on accelerated beams. An experimental preparation area and a user control room will be available for the users.

Highlights of the Plasma Wakefield Acceleration Experiments
E-157, E-162, E-164 and E-164X

In the past five years plasma wakefield accelerators have emerged as a leading advanced accelerator scheme due to progress on a number of fronts. The SLAC/UCLA/USC E-162/164 collaboration has been arguably the lead group pioneering this research. Accomplishments include the first demonstration that controlled beam propagation and high-gradient acceleration could be extended from the mm scale to meter scales (E-157 and E-162), the first acceleration of positrons (E-162) in a plasma and most recently the first acceleration of electrons by more than one GeV (E-164X). These experiments have yielded a number of rich new beam and plasma physics results, demonstrated the promise of beam-driven plasma accelerators and developed a sophisticated laboratory infrastructure for beam and plasma experiments in the Final Focus Test Beam (FFTB).

Unlike in vacuum, electromagnetic waves in a plasma have a longitudinal component. The idea to use this to accelerate particles was proposed by Dawson. Recent work has shown that laser-driven plasma accelerators can reach accelerating fields over 100GV/m. However, it has not been demonstrated that such a large field can be sustained over a distance above 1cm. The Raleigh length of the laser limits the interaction region.

Experiment E-157, proposed in 1997, used the high-energy electron beam itself to generate the plasma wake in a 1.4m long laser-ionized lithium plasma. It explored the transverse dynamics of the electron beam propagating in a plasma reaching a few 10^{14} plasma electrons/cm^{-3}. The plasma density was controlled via the laser intensity and the temporal evolution of the bunch was measured with a streak camera.

The follow-up experiment E-162, proposed in November 2000, consisted of three experimental runs. The first, starting in March 2001, repeated the E-157 experiment with a positron beam. Electrons were chosen for the second run and the experimental apparatus was relocated to the focal point (IP-0) of the FFTB. The new location allowed the construction of an energy spectrometer to separate the energy gain measurement from transverse beam dynamics in the plasma.

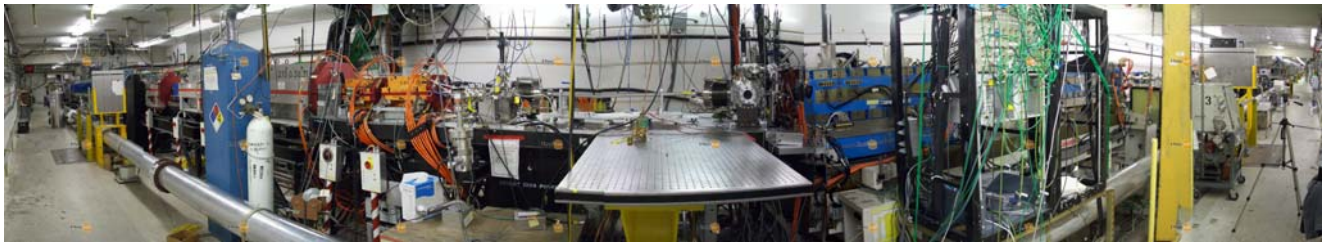


Figure 6 a panoramic view of the FFTB beamline. The plasma oven will be installed on the table in the middle of the picture.

This allowed an unambiguous measurement of the accelerating field in the plasma. Peak longitudinal fields of 250MV/m were sustained over a plasma length of more than 1m. The final E-162 run quantified the energy gain for a positron beam in the same setup.
In the summer of 2002, a chicane was added to the SLAC linac, to reduce the length of the electron bunch from 650µm down to 12µm rms in the FFTB. Experiments E-164 and E-164X made use of the higher accelerating fields generated by the compressed bunches.

An added benefit is that the reduction of the bunch length increases the transverse electric field of the bunch, which ionizes the lithium vapor to Li+. With sufficiently short bunches, the ionization is accomplished by the leading particles of the bunch, such that the majority of the bunch encounters a fully ionized plasma. Thus, it is no longer necessary to pre-ionize the gas with a laser. This mitigates the issues of timing and alignment of the laser with the electron beam. In the summer of 2004, energy gains of more than 3GeV in 10cm plasma were consistently observed
.
In the following, the highlights of the plasma wakefield acceleration experiments E-157, E-162, E-164 and E-164X are presented. The experiments are carried out by a collaboration between SLAC, UCLA and USC.

Current members of the collaboration are:

Christopher Barnes, Caolionn O'Connell, Franz-Josef Decker, Paul Emma, Mark J. Hogan, Rasmus Ischebeck, Rick H. Iverson, Patrick Krejcik, Robert H. Siemann and Dieter Walz (SLAC)

Chris E. Clayton, Chengkun Huang, Devon K. Johnson, Chan Joshi, Wei Lu, Ken A. Marsh, Warren B. Mori and Miaomiao Zhou (University of California, Los Angeles)

Suzhi Deng, Bing Feng, Tom Katsouleas, Patric Muggli and Erdem Oz (University of Southern California)

E-162: Electron Beam Acceleration Using a Matched Beam in a Plasma

P. Muggli et al., Physical Review Letters, Vol. 93, 014802 (2004).

The key to controlling the transverse effects of a plasma is to propagate a matched beam. In a matched beam the emittance force of the beam balances the focusing force by the plasma and the beam propagates without spreading, i.e., it exits the plasma as it entered it, which makes it easy to image the beam. *Figure 7* shows conclusive evidence for matched-beam propagation. At lower densities, the emittance force of the beam exceeds the focusing force. As the focusing force is increased (by increasing the density), the beam spot size oscillations damp down. Eventually the beam is matched to the plasma.

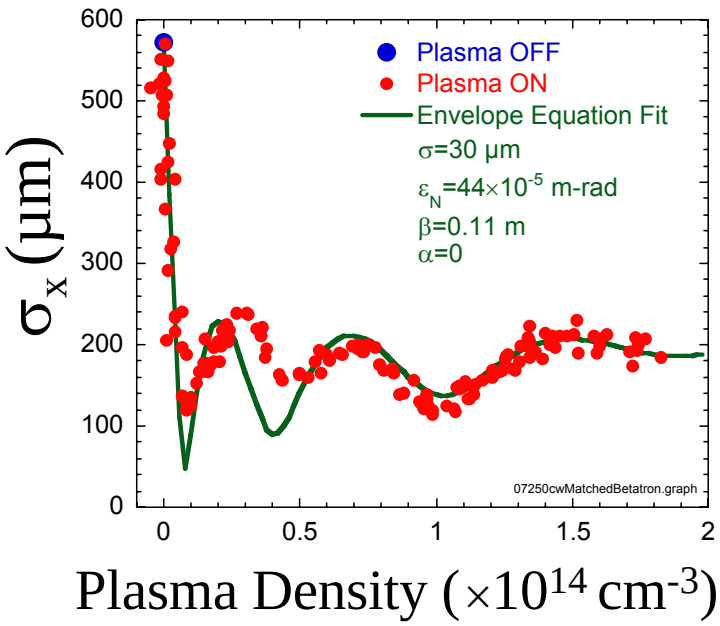


Figure 7 Variation of the transverse spot size of the beam vs plasma density. Initially the beam emittance force is larger than the plasma focusing force. As the two forces become equal the beam spot oscillations damp out and the beam is said to be "matched."

A breakthrough, which qualitatively changed the information available from spectrometry, was the conversion of the dispersion (dipole) magnet into a proper imaging spectrometer. This together with a streak camera to time resolve the dispersed images of the beam lead to clear evidence for energy loss of the bulk of the beam followed by energy gain of the latter slices of the beam.

Figure 8 shows the change in energy of the picosecond wide slices of the beam. The peak energy loss and gain were about 160 MeV for a density of 1.8×10^{14} cm^{-3}. However, this number is for the centroid of the slice. The maximum energy gain was ~ 275 MeV in good agreement with 3D PIC code simulations of our experiment.

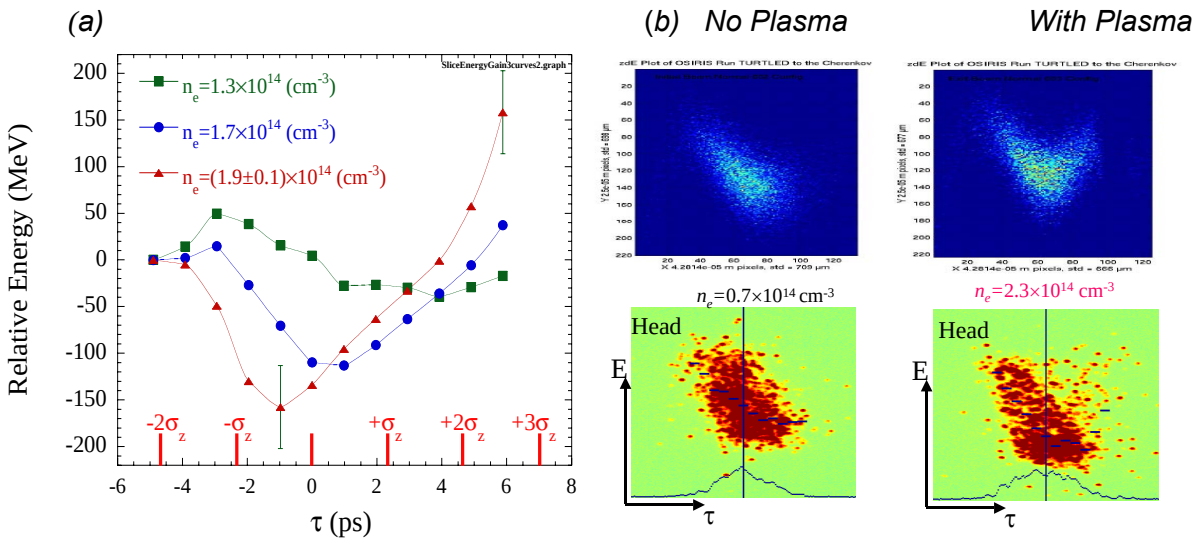


Figure 8 (a) Relative change in energy of 1 ps wide slices of the beam at three different densities. At the highest density, energy loss of most of the beam slices and energy gain by the last two beam slices can clearly be seen. (b) PIC code simulations and corresponding streak camera data of energy dispersed slices of the beam without and with the plasma (E-162 experiment).

E-162: Halo Formation Around Positron Beam Core

P. Muggli et al., to be submitted for publication

The understanding of how intense, ultra-relativistic electron and positron beams propagate through meter-scale, dense plasmas is critical to the development of a beam-driven, plasma wakefield accelerator. In particular, any physical effect that can degrade the transverse emittance of the beam as it traverses the plasma is deleterious to the final luminosity that can be achieved in this scheme. For instance, the extremely nonlinear transverse wakefields induced in the plasma by a positron beam can increase the slice emittance of the beam. This manifests itself by forming a halo around the core of the positron beam. Although much work has been done on understanding how beam halos are formed in space-charge dominated electron and ion beams, there is not work done on halo formation around an ultra-relativistic positron beam. In this case, it is the nonlinear focusing forces and not the space charge that is responsible for the loss of beam particles from the core to the halo.

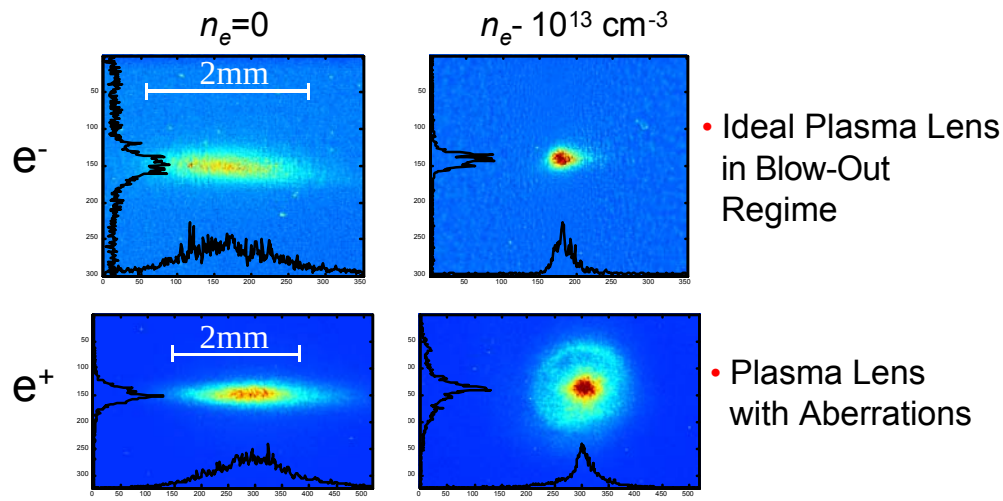


Figure 9 The difference between focusing of grossly asymmetric ultra-relativistic electron and positron beams by an underdense plasma lens. The electron beam shows a clear tightly focused spot while the positron beam displays a focused core surrounded by a halo indicative of an aberrated lens.

As part of E-162 we carried out the first experimental and numerical study of halo formation in a high charge (3 nC), ultra-relativistic (28.5 GeV) positron beam after propagating through a 1.4 m long, dense ($n_e \leq 5 \cdot 10^{14}$ cm^{-3}) plasma column. This is done by analyzing the images of the beam before and after the plasma. The beam entering the plasma has an emittance ratio ($\varepsilon_x/\varepsilon_y$) of 5. As the plasma density is increased, the core of the beam exiting the plasma is seen to be nearly symmetric with more and more particles contributing to the halo that surrounds this core. Simulations of the experiment using a particle-in-cell code give a good agreement on both the beam spot-size and the fraction of particles in the core with the experimental measurements. Simulations indicate that the slice emittance of the beam increases along the bunch and that an incoming beam with grossly unequal emittances, exits the plasma with approximately equal emittances in both transverse planes. This is clearly seen in *Figure 9*. This self-matching of the beam to the plasma through emittance growth is a characteristic particular to positron beams.

E-164: Plasma Formation by field Induced Ionization by the Electron Beam

C. O'Connell et al., to be submitted for publication

The original idea of E-164 was to increase the average gradient of the PWFA from 100 MeV/m (seen in E-162) to 5 GeV/m by reducing the pulse length from 700μm to 100 μm. It was pointed out by Dr. Bruhwiler at the Advanced Accelerator Conference 2002 that as the beam became shorter the transverse electric field of the beam itself would eventually field-ionize the atoms and produce a plasma. Furthermore, the transverse size of the plasma can be larger than the beam.

In Run 1 of E-164, this field ionization became apparent for the first time. At a charge of $N = 1.2 \cdot 10^{10}$, $\square_z$ = 100 μm and $\square_r$ = 20 μm, the beam modified the plasma density via field-ionization (also called tunnel-ionization) at the peak of the beam (see *Figure 10*). However, because we were at the threshold for field-ionization, the plasma formation was not very reproducible and in any case there were not too many beam particles left in the back of the

beam to “see” the accelerating phase of the wake. It was decided therefore to go to even shorter bunches in E-164 Run II to increase the electric field associated with the beam.

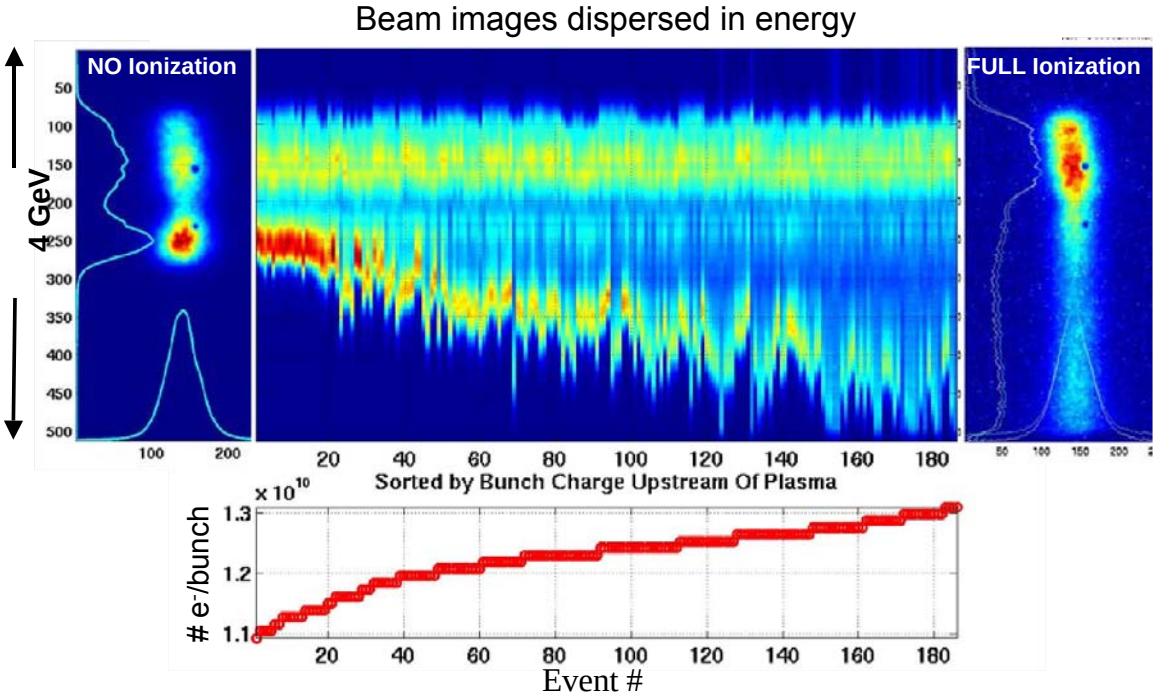


Figure 10 The change in beam energy as a function of beam charge in the E-164 Run I. Up to 1.2 x 10^{10} electrons the beam energy spectrum shows only a slight change. For a charge greater than 1.2 x 10^{10} the electric field of the beam ionizes the Li and produces a fully ionized plasma. A wake response leads to the beam suddenly losing more than 1 GeV energy.

We have taken an extensive amount of data on field ionization of H_2, He, NO and Li by varying the beam charge, beam spot size, and the pulse width. The diagnostic of the onset of the plasma formation is the sudden onset of energy loss experienced by the main body of the beam whereas the diagnostic of formation of a fully ionized plasma is the eventual saturation of this energy loss at some maximum value.

E164X: Conclusive Observation of Greater Than 4 GeV Energy Gain

M. J. Hogan, et al, Phys. Rev. Lett. 95, 054802 (2005)

E-164X has demonstrated energy gain of more than 1 GeV in a 10 cm long plasma. This is both the largest energy gain ever achieved by a plasma accelerator and the largest accelerating gradient ever achieved by a beam driven plasma wakefield accelerator. The results were made possible by the combination of short electron bunches (~30 μm or 100 fs) and field ionized plasmas in the $3 \cdot 10^{17}$ cm^{-3} density range.

In previous experiments where the bunches were > 1ps the energy changes imparted by the plasma wakefield were of the same order or smaller than the incoming energy spread. To directly measure the effects of the plasma wakefield we used a streak camera to time resolve the energy spectrum and compare plasma on and off events.

With the 100 fs bunches in E-164X it is no longer possible to time resolve the energy spectrum and the energy changes imparted by the plasma must be larger than the 1.2 GeV (full width)

energy spread of the incoming bunch. Longitudinal wakefields in the main linac impose an additional challenge by giving the particles in the back of the bunch (which we accelerate) the lowest incoming energy. Thus, particles in the back of the bunch must be accelerated by more than 1.2 GeV before energy gain can be observed. *Figure 11* shows the energy spectrum for two similar bunches with and without the 10 cm long $2.7 \cdot 10^{17}$ cm^{-3} plasma.

Typically about 7% of the incoming $2 \cdot 10^{10}$ electrons are accelerated to energies greater than the maximum incoming energy, with some particles gaining more than 3 GeV. We have observed many such events and the acceleration signal is consistent and reproducible.

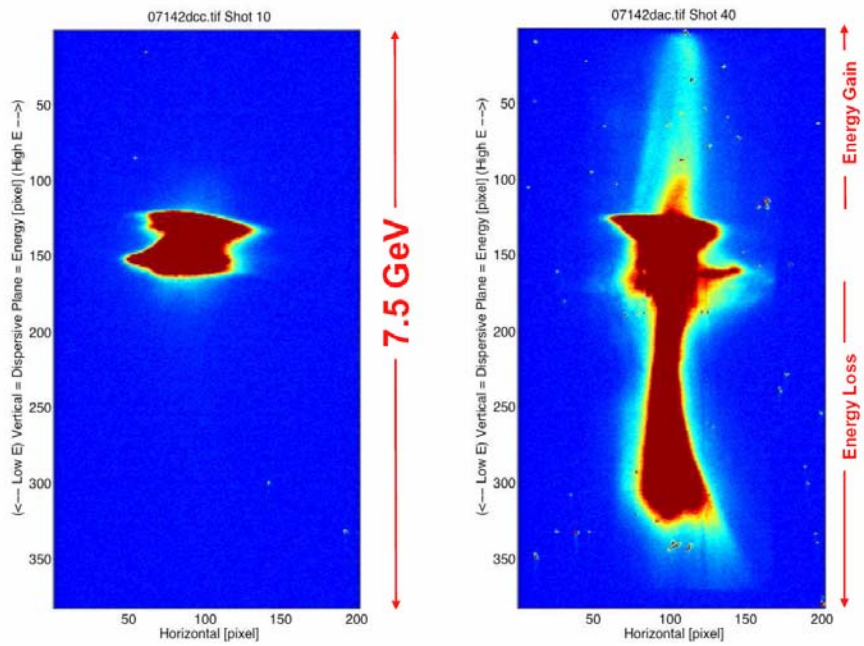


Figure 11 The energy spectrum of the nominally 35μm long electron beam without the plasma and after it traverses the ~ 15cm long plasma. The beam has an approximately 1.5GeV head-to-tail energy spread. With the plasma on, one can clearly see energy loss of the bulk of the beam and energy gain of the tail particles in the beam.

Current ARDB Scientific Staff

Robert H. Siemann	Professor, SLAC and Stanford Applied Physics
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Mark Hogan	SLAC Staff
Robert Noble	SLAC Staff
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Refereed Publications Since May 2004

1. P. Muggli, B. E. Blue, C. E. Clayton, S. Deng, F.-J. Decker, M. J. Hogan, C. Huang, R. Iverson, C. Joshi, T. C. Katsouleas, S. Lee, W. Lu, K. A. Marsh, W. B. Mori, C. L. O'Connell, P. Raimondi, R. H. Siemann, and D. Walz, "A Meter-Scale Plasma Wakefield Accelerator Driven by a Matched Electron Beam," Physical Review Letters 93, 014802 (2004)
2. R. H. Siemann, "Energy Efficiency of Laser Driven Structure Based Accelerators" Physical Review Special Topics – Accelerators and Beams, 7, 061303 (2004)
3. Y. C. Neil Na, R. H. Siemann, and R. L. Byer, "Energy Efficiency of an Intracavity Coupled, Laser-Driven Linear Accelerator Pumped by an External Laser," Physical Review Special Topics – Accelerators and Beams, 8, 031301 (2005)
4. R. H. Siemann, T. Plettner, and R. L. Byer, "The Impact of Einstein's Theory of Special Relativity on Particle Accelerators," Journal of Physics B: Atomic, Molecular and Optical Physics, 38, S741 (2005)
5. C. M. S. Sears, E. Colby, B. Cowan, R. H. Siemann, J. E. Spencer, R. L. Byer, and T. Plettner, "High Harmonic Inverse Free Electron Laser Interaction at 800 nm," submitted to Physical Review Letters
6. T. Plettner, R. L. Byer, E. Colby, B. Cowan, C. M. S. Sears, R. H. Siemann, and J. E. Spencer, "Visible-laser acceleration of relativistic electrons in a semi-infinite vacuum," to be published in Physical Review Letters
7. M. J. Hogan, C. D. Barnes, C. E. Clayton, F.-J. Decker, S. Deng, P. Emma, C. Huang, R. H. Iverson, D. K. Johnson, C. Joshi, T. Katsouleas, P. Krejcik, W. Lu, K.A. Marsh, W. B. Mori, P. Muggli, C. O'Connell, E. Oz, R. H. Siemann, and D. Walz, "Multi-GeV Energy Gain in a Plasma Wakefield Accelerator" submitted to Physical Review Letters
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Graduate Theses since May 2004

1. Wei Lu, M.S., UCLA, “Some Results on Linear and Nonlinear Plasma Wake Excitation: Theory and Simulation Verification.”
2. Chenkun Huang, M.S., UCLA, “Development of a Novel PIC Code for Studying Beam-Plasma Interactions.”
3. Caolionn O’Connell, Ph.D., Stanford, “Field Ionization of Neutral Lithium Vapor Using a 28.5 GeV Electron Beam,” June 2005.

Accelerator Research Department-A

Prof. Ronald D. Ruth
Stanford Linear Accelerator Center

Overview

Accelerator Research Department A performs research to address the near, mid and far term aspects of particle beam physics and accelerator technology. Our scientists push the capabilities of operating facilities, we develop the beam physics and accelerator technology for the upcoming next generation of accelerator facilities, and we pursue selected topics in Advanced Accelerator Research. In all these efforts we focus on fundamental research which not only can impact present facilities, but which lays a foundation for future research and development.

The department is presently composed of six groups

1. The **Lattice Dynamics** group pushes the state of the art of the design of magnetic focusing lattices for particle accelerators. This design work includes geometrical layout, linear optics, chromatic compensation, particle stability, magnet tolerance, correction of imperfections, luminosity simulation/optimization and nonlinear beam dynamics in the accelerators.
2. The **Collective Effects** Group investigates coherent interaction of electromagnetic fields and particle beams in both linear and circular accelerators. This includes research on instabilities in accelerators as well as devices for creating coherent radiation such as free electron lasers (FELs).
3. The **Advanced Electronics** group combines accelerator dynamics and instability control with technology development in high-speed signal processing. The group designs and develops instability control hardware, develops theoretical models of stability and control techniques, and develops special accelerator instrumentation for experiments.
4. The **RF Structures** group designs, engineers, and tests new types of accelerator structurwith high RF efficiency, good higher order mode suppression and high gradient performance.
5. The **High Power RF** Group conducts research on the generation and control of ultra-high-power rf, including passive rf components, active rf switches, novel rf sources and high-power, overmoded rf pulse compression/distribution systems for linear accelerators.
6. The **Advanced Beam Concepts** group has moved towards topics in astrophysics which make use of the group's background and expertise in beam physics. This research includes topics such as higher-order microlensing for the detection of dark matter and experiments at Standford Linear Accelerator Center (SLAC) to address the calibration of air shower detectors for ultra high energy cosmic rays (FLASH experiment). The Advanced beam concepts group will be moving to the Kavli Institute for Particle Astrophysics and Cosmology (KIPAC) institute and so will not be covered in this report.

In the follow sections we present the research of each of the groups separately. We conclude with the overall summary statistics.

Lattice Dynamics Group

Group leader: Yunhia Cai

Summary

The primary expertise of the group is the design of magnetic focusing lattices for particle accelerators. This design work includes geometrical layout, linear optics, chromatic compensation, particle stability, magnet tolerance, correction of imperfections, luminosity simulation/optimization and nonlinear beam dynamics in the accelerators. We also participate in the commissioning and operation of the accelerators such as PEP-II and develop advanced methods to analyze the measured orbits for improving the machine optics. . Moreover, we develop state-of-art computer programs to simulate multi-particle beam dynamics such as the beam-beam interaction and electron cloud effects to understand the limitation of the colliders and to improve their luminosity.

In the past year, we continued the work of improving the machine optics for PEP-II as its luminosity has surpassed $9x10^{33}cm^{-2}s^{-1}$, three times of its design luminosity. In addition, we studied the beam-beam effects in e^+e^- colliders and made significant progress in realistic simulations using a parallel supercomputer. The code has been carefully calibrated against the controlled experiments. As a result of this work, the simulation has become a reliable tool to compute the luminosity and is widely accepted for designing and optimizing storage ring colliders. An invited talk was given on this subject at PAC05.

Beam-beam simulation

We introduced a new and symplectic method to handle a large and finite crossing angle in the beam-beam interaction. This method is implemented in a parallel computer program to simulate three-dimensional effects in the beam-beam interaction utilizing the technique of particle-in-cell. Over the past year, the code has been speeded up by a factor of twenty after the implementation of interpolation between the longitudinal slicing. Now each simulation takes only eight hours to complete on a parallel supercomputer. To model the recent bunch pattern in the PEP-II operation, we also added the parasitic collisions into the beam-beam simulation. The simulation has shown a 7% degradation of luminosity compared with 5% observed in the machine.

Precision modeling of accelerator optics

We have developed a Model-Independent Analysis method for high-precision measurement of linear optics including coupling in circular accelerator. From two resonantly excited transverse orbits (horizontal and vertical), we extract 2 pairs of conjugate orbits that yield a total of 4 independent orbits at the resonant frequencies. These four orthogonal orbits are sufficient to determine the linear optics. Using these precision orbits, we then fit to the orbit-derived quantities: the Greens functions, the phase advances, the eigen-mode coupling ellipses by varying the quadrupole strengths, sextupole offset, and Beam Position Monitors (BPM) gains and cross couplings. The final product of the fitting is an accurate model of the measured circular accelerator. The model is used to correct optical errors in the machine or to fine tune of the optics.

In the past year, we have continued to improve Model-Independent Analysis (MIA) for PEP-II optics measurements, and MIA has now become a routine off-line measurement tool for characterizing optics. It has also become a routine tool to fix the High Energy Ring (HER) and Low Energy Ring (LER) beta beats and the linear couplings to help PEP-II achieve a steady luminosity increase.

ILC accelerator design

Damping rings
The current designs of damping rings for International Linear Collider (ILC) do not have adequate acceptance for the injected position beam when the nonlinear wigglers are properly taken into account in the calculation of dynamic aperture. Over the past year, we have designed two damping rings (3 km and 17 km) based on a different types of cells. The dynamic aperture has been significantly improved because of the pairing of the sextupoles for the cancellation of their nonlinearity. Currently, we are coordinating an international effort to evaluate seven possible designs of the ILC damping ring to select a baseline design by the end of this year.

Extraction lines
We have designed the conceptual optics for the ILC extraction line for 20-mrad and 2-mrad crossing angles at the interaction point (IP), and studied the possibility of head-on collisions. The main challenge of the extraction design is to achieve a very large momentum acceptance for the disrupted spent beam with large energy spread of 60% to 80%. A satisfactory optics for the 20-mrad extraction line has been designed which provides transport for both the electron and beamstrahlung photons to one common dump. It has a sufficient acceptance for acceptable beam loss and includes the dedicated optics for post-IP energy and polarization diagnostics. The preliminary design of the 2-mrad optics has been developed; however, the design needs to be optimized to satisfy all the requirements.
.
Solenoid compensation
A new method of detector solenoid compensation in a linear collider using weak anti-solenoids has been investigated and found to be better compared to a skew quadrupole correction. The study was performed for a realistic detector solenoid field overlapped with the final focus quadrupoles and for a beam crossing the solenoid at an angle. The main conclusion of this study is that most of the correction is produced by that part of the compensating anti-solenoid field which overlaps the final focus quadrupoles. Therefore, relatively weak and short anti-solenoids can be used for the correction of the full detector solenoid.

SPEAR3 upgrades

A realistic version of the SPEAR-3 lattice with double waist low beta optics has been designed for the proposed machine upgrade. The modification of the long straight section includes an asymmetric chicane and a quadrupole triplet to provide low beta locations for two Insertion Devices (ID). In addition, four low beta locations have been created in the matching cells for the small gap IDs. Although the modified lattice has a stronger focusing than in the nominal design, it still provides reasonable size of dynamic aperture. This lattice design was evaluated at the SPEAR-3 external review and is scheduled to be implemented in the machine in this year.

PEP-II upgrades

The PEP-II upgrade for a higher luminosity requires a lattice upgrade to reduce the $\beta*$ functions at the interaction point and decrease momentum compaction factor for a smaller bunch length. Several options of the LER and HER lattices have been designed to satisfy these parameters, and their effect on dynamic aperture was evaluated in particle tracking simulations.

Among many studies of possible lattices, a lattice that has stronger focusing in the arcs by increasing the phase advance per cell from 60^0 to 90^0 for the HER is chosen to be implemented in the machine in the next year. This modification reduces the momentum compaction factor by 30% and bunch length by 16% which would allow the proportional reduction of vertical $\beta*$ without luminosity loss due to the hourglass effect. We expect a luminosity increase of 16% as a result of the upgrade. The simulation also showed an adequate dynamic aperture (more than 10 □) in the designed lattice.

Coming activities

ILC design
We will continue to coordinate the international effort of improving the design of damping ring for ILC. It is going to be a challenge to make a sound choice of a baseline configuration by the end of this year. After the selection, we need to develop a more detailed design so that a complete design report can be written. We will continue to design and optimize the ILC damping ring and extraction lines.

PEP-II operation
We will continue the beam-beam simulation for optimizing the PEP-II luminosity and predicting its future performance. Evaluating the luminosity sensitivities to many realistic errors such as the dispersion and coupling at the IP, and then use the information to tune the collider. We plan to extend MIA to include dispersion and reduce the vertical dispersion so that the beam height can be reduced for further increases in the luminosity of PEP-II.

LHC collimation
As a part of U.S. Large Hadron Collider (LHC) Accelerator Research Program and in collaboration with the ILC department, we will simulate the collimation system for LHC and try to find a solution to reduce the impedance of the collimators and make the system more efficient. Otherwise, the beam currents in LHC are most likely to be limited at half of their design value.

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4. Yunhai Cai, *Dynamic Apeerture In Damping Rings With Realistic Wigglers*, Slac-Pub-11084, Apr 2005. 23pp. Presented At Wiggle 2005 Mini-Workshop On Wiggler Optimization For Emittance , Control, Frascati, Italy, 21-22 Feb 2005
5. Y. Cai, A.C. Kabel , *A Multi-Bunch, Three-Dimensional, Strong-Strong Beam-Beam Simulation Code For Parallel Computers*, Slac-Pub-11188, Jul 2004. Epac 2004 Proceedings, Lucerne, Switzerland, 5-9 Jul 2004
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7. K. Ohmi, M. Tawada, Y. Cai, S. Kamada, K. Oide, J. Qiang, *Luminosity Limit Due To The Beam-Beam Interactions With Or Without Crossing Angle*, Phys. Rev. St Accel. Beams 7:104401, 2004.
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9. Y.T. Yan And Y. Cai, *Precision Pep-Ii Optics Measurement With An Svd-Enhanced Least-Square Fitting,* Slac-Pub-10719, Sep 2004. 7pp.
10. Yunhai Cai ,Symplectic *Treatment Of A Finite Crossing Angle In The Beam-Beam Collision,* Slac-Pub-10674, Aug 2004. 11pp. Icfa Beam Dyn.Newslett.34:11-19, 2004**.**
11. Y.T. Yan, Y. Cai, *Precision Measurement Of Coupling Ellipses Parameters In A Storage Ring,* Slac-Pub-10371, Aug 2004. 13pp.
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13. J. Seeman Et Al. *Design For A 10**36 Super-B-Factory At Pep-Ii,* Slac-Pub-10548, Epac 2004 Proceedings, Lucerne, Switzerland, 5-9 Jul 2004.
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15. Yunhai Cai, *Single Particle Linear And Nonlinear Dynamics.* Epac-2004-Weylh02, Slac-Pub-10511, Invited Talk At 9th European Particle Accelerator Conference (Epac 2004), Lucerne, Switzerland, 5-9 Jul 2004.
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19. P. Chang, S.Y. Lee, And Y.T. Yan , *A Differential Algebraic Integration Algorithm For Symplectic Mappings In Systems With Three-Dimensional Magnetic Field*, Slac-Pub-10720, Sep 2004. 6pp.
20. Yuri Nosochkov, Andrei Seryi, *Compensation Of Detector Solenoid Effect On The Beam Size In Linear Collider,* Slac-Pub-10592, Phys. Rev. St Accel. Beams 8:021001, 2005.

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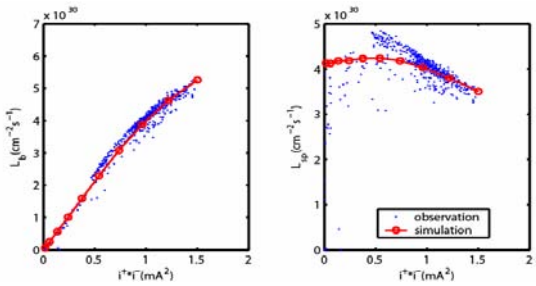
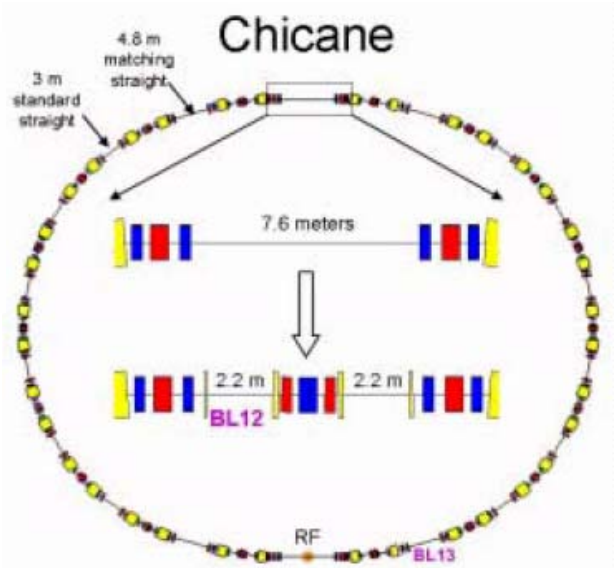
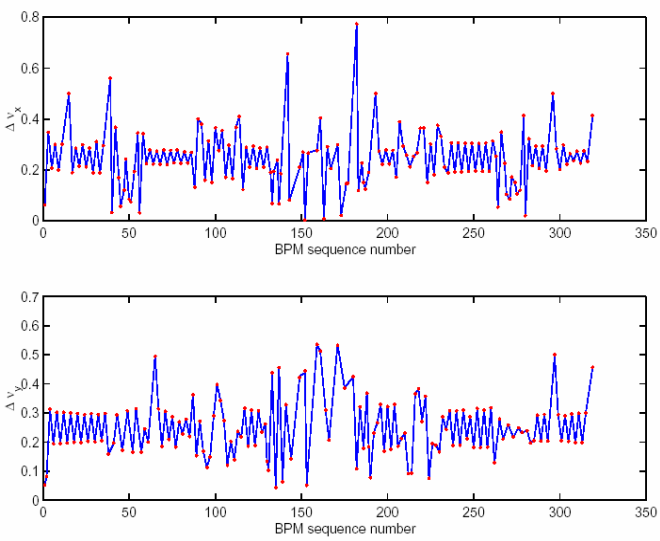
24. K. Moffeit, M. Woods, Y. Nosochkov, And W. Oliver, *Polarization Setup And Polarimetry For 2 Irs, And Status Of Downstream Polarimeter Designs*, Slac-Pub-11322, 2005.
25. Y. Nosochkov, K. Moffeit, A. Seryi, R. Amold, W. Oliver, B. Parker, E. Torrence, *Desgin Of Ilc Extraction Line For 20 Mrad Crossing Angle,* Slac-Pub-11205, Pac05 Proceedings, Knoxville, Tennessee, 16-20 May 2005.



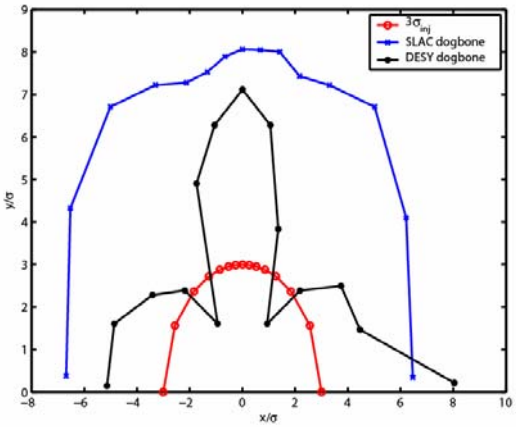
Comparison of luminosity and specific luminosity between The measurement and simulation (Cai [2, 10])



SPEAR3 upgrades: to add two long undulators in a long straight section (Nosochkov[22])



Precision phase advance measurement at PEP-II using MIA (Yan and Cai [9,11])



Dynamic aperture improvement of the dogbone damping rings for ILC (Cai [4])

Collaborators and SBIRs

ARD-A collaborates closely with other departments and groups at SLAC, as well as research groups worldwide.

ARD-A also actively contributes to SBIRs. A selected list of SBIRs supported by ARD-A, past and present, is given below:

ITEM	PROJECT TITLE	DATE	SLAC P.M.	COMPANY	
1	Intelligent graphics user interface for the SLEGO program	1995 Aug 22	Irwin	G.H. Gillespie	Completed
2	Automated component calibration and error diagnostics for model-based accelerator control	1997 Sep 25	Lee, MJ	Vista	Completed
3	Development of high power windows and waveguide components for the Next Linear Collider	1998 Mar 06	Tantawi	Calabazas Creek	completed
4	Automated tuning systems based on hybrid neural networks	1998 Mar 16	Lee, MJ	POC	Completed
5	An automated beam-based system for analyzing accelerator misalignment problems	1998 Dec 01	Lee, MJ	SandiaView Software	Completed
6	Pulse-to-pulse emittance measurement system	1999 Mar 09	Nantista	FARTECH	Completed
7	RF pulse compression using a diamond switch	1999 Sep 10	Tantawi	Alameda Applied Sciences	Completed
8	Adaptive, nonlinear model predictive control for accelerator feedback systems	1999 Nov 12	Lee MJ	Pavilion	Completed
9	Robust Optimatal Adaptive, System Identification and Nonlinear Model Predictive Control Strategy for Accelerator Feedback Control System	2001 Feb 01	Lee MJ	Pavilion	Completed
10	High-Power Plasma Switch for 11.4 GHZ Microwave Pulse Compressor	2003 Feb 24	Tantawi	Omega-P, Inc.	Working proj
11	Self-Validating Knowledge Guided On-Line Optics and Orbit Correction in an Electron Storage Ring Neural Network and First-Principle Model	2003 Oct 10	Lee MJ	Pavilion	Working proj
12	High Precision Integrated Beam-Position and Emittance Monitor	2004 Apr 02	Nantista	FARTECH	Working proj

Current Staff of Accelerator Research Department-A, SLAC

Department Head
Ronald Ruth

Administration
Margie Bangali
Joan Valine

Lattice Dynamics
Yunhai Cai Group Leader
Thomas Knight
Jerry Wong
Yuri Nosochkov
Yiton Yan

Collective Effects
Gennady Stupakov Group Leader
Karl Bane
Alexander Chao
Zhirong Huang
Samuel Heifets
Boaz Nash – SRA
Bob Warnock

Advance Beam Concepts (not coverd here, will move to KIPAC 10/1/2005)
Pisin Che Group Leader
John Irwin
Johnny Ng
Kevin Reil-Research Associate
Marina Shmakova-Research Associate
Kathleen Thompson
Aleksander Yashin-SRA

Advanced Electronics
John Fox Group Leader
Themistoklis Mastorides-SRA
Claudio Rivetta
Dmitry Teytelman
Daniel Van Winkle

RF Structures
Juwen Wang Group Leader
Gordon Bowden
Roger Jones
James Lewandowski
Roger Miller

High Power RF
Sami Tantawi Group Leader
Deji Akinwande-SRA
Valery Dolgashev
David Farkas
Jiquan Guo-SRA
Yasser Hussein-Research Associate
Christopher Nantista
Perry Wilson
Anahid Yeremian
Zhiyu Zhang-Research Associate

SRA = Student Research Assistant (Stanford University Students)
Research Associate = Post Doctoral Research Associate

Graduate Students and Postdocs

Past Students	Advisor	Present affiliation	
Bill Gabella	Ron Ruth	Vanderbilt	
J. Scott Berg	Ron Ruth	Brookhaven	
Tor Raubenheimer	Paterson/Ruth	SLAC	DPB thesis prize 1991
Zhirong Huang	Ron Ruth	SLAC	DPB thesis prize 1999
Rod Loewen	Ron Ruth	Lyncean Tech.	
Eric Nelson	Roger Miller	Los Alamos	
Pablo Saez	Roger Miller	finance	
Dennis Palmer	Roger Miller	industry	
Lenny Rifkin	Helmut Wiedemann	PSI	
Mary James	Roger Miller	Reed College	
Waldi Hosseini	John Fox	Applied Sig. Tech.	
Leonid Sapozhnikov	John Fox	SLAC	
Haitham Hindi	John Fox	Xerox PARC	
Shyam Prabhakar	John Fox	LBL	DPB thesis prize 2001
Dmitry Teytelman	John Fox	SLAC	DPB thesis prize 2004
Liane Beckman	John Fox	Lockheed-Martin	
Bo Chen	Alex Chao	Netscape	
Ghislain Roy	John Irwin		
Chunxi Wang	John Irwin	Argonne	
S. Rajagopalan	Pisin Chen		
Patrick Kwak	Pisin Chen		
Shinichi Masuda	Pisin Chen		
Anatoly Spitkovsky	Pisin Chen	Summer	
Ken Shen	Pisin Chen	Summer	
Karl Bane	Perry Wilson	SLAC	
Chris Nantista	Sami Tantawi	SLAC	

Selected past postdocs

Tor Raubenheimer	SLAC
Frank Zimmerman	CERN
Marco Venturini	LBNL
Nicoleta Baboi	DESY
Ina Reichel	LBNL
Andreas Kabel	SLAC
Norbert Holtkamp	Oak Ridge
Ricky Campisi	Jefferson Lab

Current Postdocs

Kevin Reil	Pisin Chen
Marina Shmakova	Pisin Chen
Zhiyu Zhang	Sami Tantawi
Yasher Hussein	Sami Tantawi
Yantao Ding	Ron Ruth

Current Students

Deji Akinwande	Sami Tantawi	High Power RF
Jiquan Guo	Sami Tantawi	High Power RF
Navid Hassanpour	John Fox	Adv. Electronics
Shahzad Khalid	John Fox	Adv. Electronics
Themis Mastorides	John Fox	Adv. Electronics
Boaz Nash	Alex Chao	Collective Effects

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Advanced Electronic Group

John Fox
Stanford Linear Accelerator Center

Overview

The ARDA Advanced electronics group combines interests in accelerator dynamics and instability control with technology expertise in high-speed signal processing. The group does machine physics, designs and develops of instability control hardware, develops theoretical models of stability and control techniques, and serves to develop special accelerator instrumentation for experiments.

The group's interests span the physics of dynamic systems and beam interactions with RF systems. The efforts include experimental measurements and development of simulation models and simulation tools. The group has a very strong technology base, and designs and develops new instruments and control systems using a mix of wideband RF/microwave and fast digital electronic technologies. Close coupling with the campus strengths in control theory have brought many optimal control techniques and capabilities to the SLAC for application to accelerator needs.

The group comprises SLAC staff and Stanford Ph.D. students in EE/Applied Physics. The group is involved in graduate education, supervising Stanford Ph.D. research assistants, teaching graduate courses in Applied Physics and courses for the US Particle Accelerator school. Two APS Dissertation Prizes in Beam Physics have been awarded to group members.

Recent Activities and Accomplishments

Efforts in 2005 center on high-current stability in PEP-II via modelling, machine measurements and the expansion of non-linear simulation models of interacting beam-RF systems. In 2004-2005 specialized hardware for control of low-mode instabilities (the low group delay woofer) was developed and commissioned in PEP-II. Technology development has centered on next-generation 1.5 GSample.sec. feedback channels in conjunction with LNF and KEK.

We maintain an active collaboration on technology development and measurements with KEK, LNF-INFN and LBL on many accelerator projects. John Fox teaches courses in electronic techniques and lab measurements for the Stanford Applied Physics department (these lab courses are required for the Applied Physics Ph.D. degree). An undergraduate seminar course in Energy Options for the 21st Century was co-developed with Ted Geballe and has been offered for three years. The "RF Engineering and Signal Processing" USPAS course was offered at William and Mary (2004) and Cornell (2005).

PEP-II Instability Control and LLRF systems

We continue to make measurements and are involved with PEP-II operations, particularly on high-current configurations and issues involving interaction of the RF systems and the feedback systems. We regularly do machine development, as well as respond to immediate PEP-II operational needs. We continue to measure transverse and longitudinal modal growth rates in PEP-II using our time-domain transient techniques. These studies, and their implications for upgrades to the machine, have been summarized and reported at various workshops and Machine Advisory Committee

meetings. The development of new RF operating configurations uses the model based parameter fitting technique developed by our group.

Our efforts include expanding our beam dynamics and RF simulation codes, so that a realistic appraisal can be made of practical limits of the existing RF architecture. This work also evaluates possible new control methods, in conjunction with a technology effort to explore all-digital direct loop implementations.

We developed and prototyped a Klystron Linearizer, which uses a feedback technique to equalize the small-signal and large signal gain of the high power klystron. This is a new idea to improve the effectiveness of the impedance control loops in the PEP-II LLRF systems. We completed full- power tests on the test stand and are just beginning tests with the beams. Yubo Zhou has made this effort his Engineer's degree thesis.

A production low-mode longitudinal control processor (the Low Group Delay Woofer) was developed and commissioned this past year (this technique immediately allowed an increase in stable operating current from 1350 mA to over 1600 mA)- the production LGDW was built by Dan Van Winkle and Dmitry Teytelman, building on the design and success of the initial prototype.

We commissioned the new overdamped-cavity longitudinal kickers for the PEP-II LER in anticipation of increased LER beam currents.

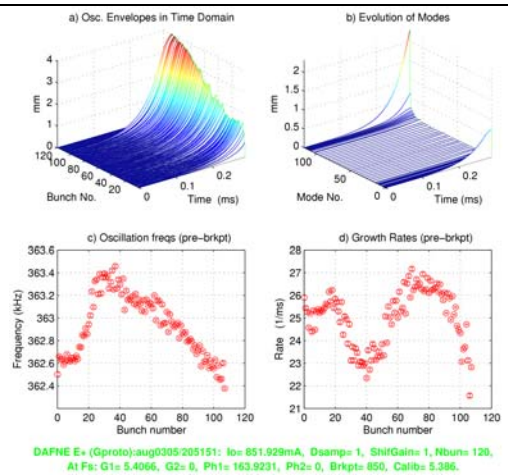
GBoard next-generation processing channel

Our group, in conjunction with Makoto Tobiyama (KEK) and Alessandro Drago (LNF-INFN) has been developing a new signal processing architecture for our next-generation 1.5 GSample/sec. processing channel (what we have been calling the GBoard). In the past year we have prototyped several key signal paths at the full speed, and made substantial progress on finalizing the design. A prototype signal processor using this approach has been recently tested at the Frascati DAFNE collider with excellent results. We have been awarded the third year of our multi-year US-Japan collaboration grant from KEK (roughly another $110,000), and have been using these funds to purchase components and evaluate sub-circuits for the full-speed design. We are planning on using the third year funds to do a layout of the prototype VME64X module needed for beam testing.

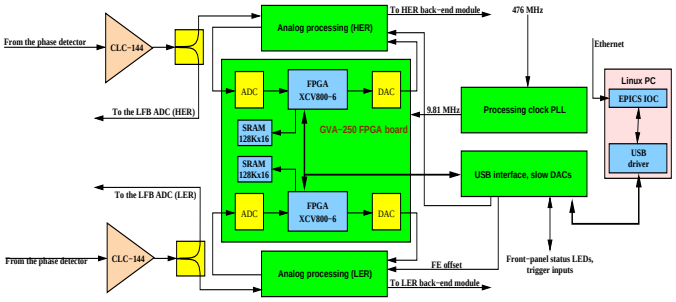
Recent Publications and Talks

1. D. Teytelman, *Beam loading compensation for Super B-factories*, Invited paper at the 2005 Particle Accelerator Conference (PAC 2005) Knoxville, Tn, May 2005
2. J. Fox, S. Gallo, T. Mastorides, D. Teytelman, D. Van Winkle and Y. B. Zhou, *Klystron Linearizer for use with 1.2 MW 476 MHz Klystrons in PEP-II RF Systems*, Presented at the 2005 Particle Accelerator Conference (PAC 2005) Knoxville, Tn, May 2005
3. Daniel Van Winkle, John Fox, Dmitry Teytelman, *In Depth Diagnostics for RF System Operation in the PEP-II B Factory*, Presented at the 2005 Particle Accelerator Conference (PAC 2005) Knoxville, Tn, May 2005

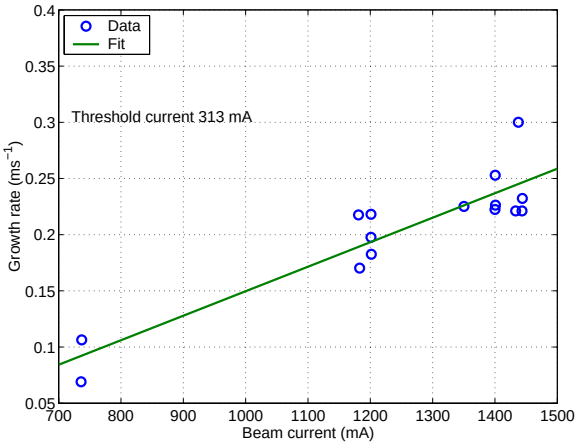
4. D. Teytelman, *A Non-invasive Technique for Configuring Low Level RF Feedback Loops in PEP-II*, Presented at the 2005 Particle Accelerator Conference (PAC 2005) Knoxville, Tn, May 2005
5. D. Teytelman, *Operating performance of the low group delay woofer channel in PEP-II,* Presented at the 2005 Particle Accelerator Conference (PAC 2005) Knoxville, Tn, May 2005
6. D. Alesini Et Al., *Proposal Of A Bunch Length Modulation Experiment In Dafne*, Slac-Pub-11077, Lnf-05-04-Ir, Feb. 2005
7. S. Heifets, D. Teytelman, *Study of the Beam-Ion Instability at BESSY-II*, SLAC-PUB-10892, Dec. 2004. (Submitted to PRST-AB)
8. D. Teytelman, *Longitudinal Beam Dynamics and Feedback*, Talk for the PEP-II MAC, December 2004
9. D. Teytelman, *2007 Goals and Feedback Systems*, Talk for the PEP-II MAC, December 2004
10. D. Teytelman, PEP-*II Longitudinal Feedback and the Low Group Delay Woofer*, Talk for the PEP-II Accelerator Physicists and Operations Group
11. J. Browne, J.E. Dusatko, J.D. Fox, P.A. Mcintosh, W.C. Ross, D. Teytelman, D. Van Winkle, *Pep-Ii Rf System Operation And Performance*, Presented At The 2004 European Particle Accelerator Conference (Epac 2004) Lucerne, Switzerland, July 2004
12. D. Teytelman, R. Akre, J. Fox, S. Heifets, A. Krasnykh, D. Van Winkle, and U. Wienands, *Measurements of Transverse Coupled-Bunch Instabilities in PEP-II,* Presented at the 2004 European Particle Accelerator Conference (EPAC 2004) Lucerne, Switzerland, July 2004
13. D. Teytelman, L. Beckman, D. Van Winkle, J. Fox, and A. Young, *Development and Testing of a Low Group-delay Woofer Channel for PEP-II,* Presented at the 2004 European Particle Accelerator Conference (EPAC 2004) Lucerne, Switzerland, July 2004
14. D. Teytelman, *PEP-II RF aborts and coupled-bunch stability*, talk presented at PEP-II machine Advisory Committee, April 2004
15. D. Teytelman, *RF and longitudinal stability in Super-PEPII*, talk presented at Super B Factory Workshop, January 2004



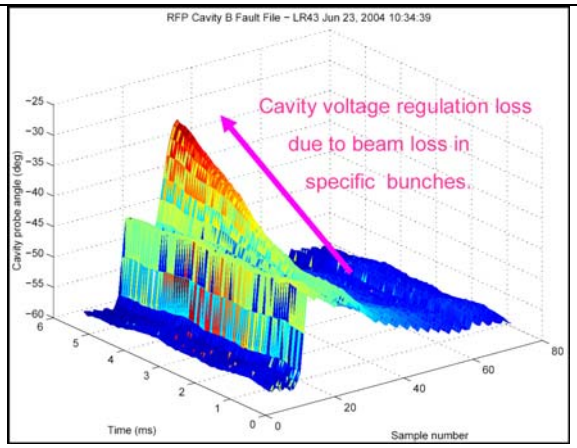
Recent Transverse Instability Measuremens from DAFNE showing tune and growth rate variaions along the bunch train



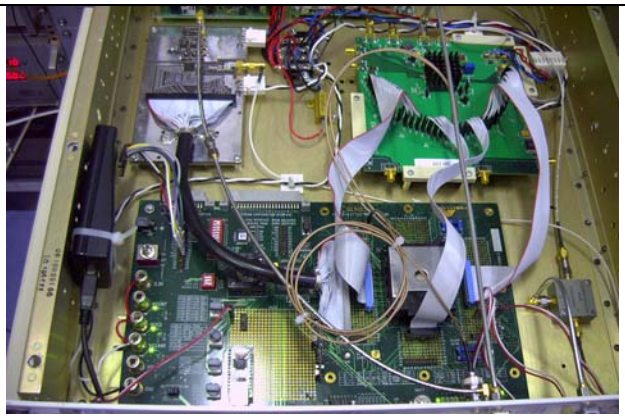
Block Diagram of the Low Group Delay Woofer – a reconfigurable low-mode instability control channel developed for PEP-II



Measurement of HOM growth rates vs. current in the PEP-II HER



Fault analysis of beam loss in PEP-II involving RF system transient, initiated by partial beam loss in fill



Technology Efforts from Advanced Electronics – the Klystron Linearizer (Left) and Gproto processing channel (right)

Collective Effects Group

Gennady Stupakov
Stanford Linear Accelerator Center

Overview

The primary expertise of the Collective Effects Group is the investigation of coherent effects in both linear and circular accelerators. The group continued studies of beam physics in the Linac Coherent Light Source (LCLS) including methods to shorten x-ray pulse duration. We have also studied the problem of next linear collider (NLC) single bunch instability and the effect of dark currents in NLC accelerating structures on the beam emittance.

Summary of current activities

Short X-ray pulses in LCLS
A scheme for producing femtosecond and sub-femtosecond x-ray pulses in the LCLS was proposed in 2003 which involves a slotted-spoiler foil in a bunch compressor chicane. The work was published in Physical Review Letters (PRL, **92**, 074801, (2004)). The latest development of this idea showed a possibility of pushing this scheme into the sub-femtosecond range (P. Emma et al., FEL'04, Trieste, Italy, 2004). The result of computer simulations demonstrated a possibility to generate 380 attosecond pulses of x-rays.

Enhanced SASE in LCLS.
Following the original proposal by A. Zholents, significant enhancement of the electron peak current entering a Self-Amplified Spontaneous Emission (SASE) undulator was studied which utilizes an energy modulation in an upstream wiggler magnet via resonant interaction with an optical laser, followed by microbunching of the energy-modulated electrons at the accelerator exit (A. Zholents et al., FEL'04, Trieste, Italy, 2004). The x-ray output consists of a series of uniformly spaced spikes, each spike being temporally coherent. Detailed "start-to-end" simulations showed that the output SASE x-ray pulse will be dominated by spikes of a few hundred attosecond or less duration.

Space-charge instability in LCLS
An intensive study of microbunching instability in the LCLS including longitudinal space charge, coherent synchrotron radiation (CSR) and linac wakefield was carried out. As the result of this study, it was decided to scrap the super-conducting wiggler in the LCLS design and include a laser-heater system at low energy. This study, and the specific design for such a laser-heater, has been published (Phys. Rev. ST Accel. Beams 7, 074401 (2004)).

Resistive wall wakefield in the LCLS undulator.
The largest contributor to energy change in the undulator region of the LCLS is the (longitudinal) resistive wall wakefield of the copper coated beam pipe. The relative energy variation (over the bunch) induced within the undulator region must be kept to a few times the Pierce parameter, otherwise a part of the beam will not reach saturation. Previously, for resistive wall wake calculations in the LCLS, a formula that includes only the dc conductivity of the metal has been used. Recently, more accurate calculations of the wake, ones including also the effect of the ac conductivity in the beam pipe wall were carried out (K. Bane and G. Stupakov, SLAC-PUB-10707, 2004). It was shown that the

present LCLS undulator design, with its round copper beam pipe, will result in a relatively large energy variation induced within the bunch over the length of the undulator (0.8%). Calculations also show that if, instead, one uses an aluminum chamber, the energy variation can be reduced to within acceptable limits (< 0.2 %). It was also shown that the effect of the anomalous skin effect in the beam pipe wall is small, and can be ignored.

Laser acceleration in vacuum
A new method was developed which allows calculating laser acceleration in vacuum based on the energy exchange arising from the interference of the laser field with the radiation field of the particle. The method was applied to a simple accelerating structure consisting of a conducting screen with a round hole. Limitations due to material damage threshold and energy scaling of this acceleration method were studied. A paper has been published in PRSTAB (vol. 7, 011302, (2004)).

Numerical study of single bunch instability
A numerical code was developed that solves single bunch stability problem using linearized Vlasov equations (R. Warnock et al., SLAC-PUB-10648). It avoids problems associated with the singularity of the integral equations, and improves the Oide's method currently used for the numerical stability analysis. The linearized Vlasov equation for a bunched beam subject to an arbitrary wake function is rephrased so that it becomes non-singular in the sense of operator theory, and has only regular solutions for coherent modes. The code finds thresholds of instability by detecting zeros of the determinant of the system as they enter the upper-half frequency plane, upon increase of current. Results were compared with a time-domain integration of the nonlinear Vlasov equation with a realistic wake function for the Stanford Linear Collider (SLC) damping rings and showed a close agreement between the two calculations.

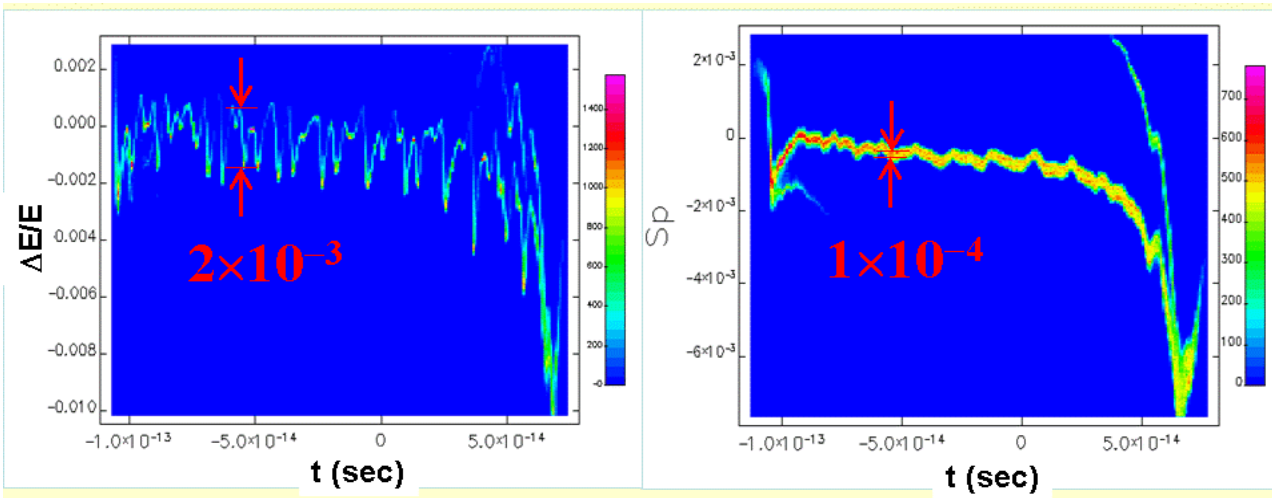
Dark current simulations for NLC structures
The metal surface of accelerating structures emits electron currents when operating at rf electric fields higher than 100 MV/m. These “dark currents” may have various deleterious effects, one of which is an interaction with the primary electron (or positron) bunch. Kicks to the beam centroid caused by the field of the dark current may dilute the beam emittance. The transverse kicks induced on the primary beam by a single emitter of dark current (see Figure 3) in an X-band traveling wave accelerating structure were calculated (V. Dolgashev et al., SLAC-PUB-10666). Those kicks were found to have maximum amplitude of about 4 V per 1 mA of emitted current. A rough estimate of the emittance dilution for an on-axis beam was calculated which gave a small number compared to the typical NLC-beam wake field deflection.

Synchrobetatron stop bands due to a single crab cavity

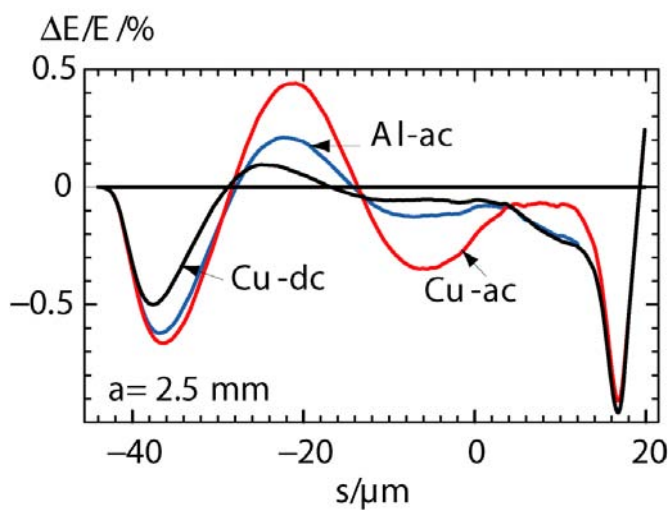
The stop band due to crab cavities for horizontal tunes that are either close to integers or close to half integers was analyzed (G. Hoffstaetter and A. Chao, PRSTAB, 7, 071002 (2004)). The latter case is relevant for today's electron/positron colliders. This stop band was compared to that created by dispersion in an accelerating cavity and shown that a single typical crab cavity creates larger stop bands than a typical dispersion at an accelerating cavity. It was also found that stop bands can be avoided when the horizontal tune is located at a favorable side of the integer or the half integer. It was shown that the stop bands can be weakened, although not eliminated, significantly when two crab cavities per ring are chosen suitably.

Major publications

1) P. Emma Et Al. *Femtosecond And Subfemtosecond X-Ray Pulses From Sase Based Free Electron Laser*. Phys. Rev. Lett. 92:074801, 2004.
2) Z. Huang Et Al. *Free Electron Lasers With Slowly-Varying Beam And Undulator Parameters. Phys*. Rev. St Accel. Beams 8:040702, 2005
3) T. Shaftan Et Al. *Experimental Characterization Of A Space Charge Induced Modulation In High-Brightness Electron Beam*. Phys. Rev. St Accel. Beams 7:080702, 2004
4) Z. Huang Et Al. *Suppression Of Microbunching Instability In The Linac Coherent Light Source. Phys.* Rev. St Accel. Beams 7:074401, 2004
5) Z. Huang Et Al. *Femtosecond X-Ray Pulses From A Frequency Chirped Sase Fel. Nucl. Instrum. Meth*. A528:28-33, 2004
6) P. Emma Et Al. *Femtosecond X-Ray Pulses From A Spatially Chirped Electron Bunch In A Sase Fel. Nucl. Instrum. Meth*. A528:458-462, 2004
7) G. Stupakov Et Al. *Microbunch Instability Theory And Simulations. In Icfa Beam Dyn. Newslett*. 35:39-57, 2004
8) G. Stupakov. *Resistive Wall Impedance Of An Insert. Phys. Rev. St Accel. Beams* 8:044401, 2005
9) M. Venturini Et Al. *Coherent Synchrotron Radiation And Bunch Stability In A Compact Storage Ring. Phys.* Rev. St Accel. Beams 8:014202, 2005
10) R. Warnock Et Al. *Impedance Description Of Coherent Synchrotron Radiation With Account Of Bunch Deformation*. Phys. Rev. St Accel. Beams 8:014402, 2005
11) F. Sannibale Et Al. *A Model Describing Stable Coherent Synchrotron Radiation In Storage Rings.* Phys. Rev. Lett. 93:094801, 2004
12) G. H. Hoffstaetter Et Al. *Synchro-Betatron Stop-Bands Due To A Single Crab Cavity. Phys.* Rev. St Accel. Beams 7:071002, 2004
13) K.L.F. Bane Et Al. *Dark Currents And Their Effect On The Primary Beam In An X-Band Linac.* Phys. Rev. St Accel. Beams 8:064401, 2005
14) K. Bane Et Al. *Resistive Wall Wakefield In The Lcls Undulator Beam Pipe.* Slac-Pub-10707, Lcls-Tn-04-11, Sep 2004. 18pp.
15) L.D. Bentson Et Al. *Inverse Free Electron Laser Heater For The Lcls*. Presented At The 9th European Particle Accelerator Conference (Epac 2004), Lucerne, Switzerland, 5-9 Jul 2004.
16) A.A. Zholents Et Al. *Current-Enhanced Sase Using An Optical Laser And Its Application To The Lcls*. Presented At 26th International Free Electron Laser
17) G. Stupakov Et Al. *Suppression Of The Effective Secondary Emission Yield For A Grooved Metal Surface*. Slac-Tn-04-045, Lcc-0145, Jun 2004. 4pp.
18) P. Emma Et Al. *Issues And Challenges For Short Pulse Radiation Production*. Invited Talk At 9th European Particle Accelerator Conference (Epac 2004), Lucerne, Switzerland, 5-9 Jul 2004.
19) P. Emma Et Al. *An Optimized Low-Charge Configuration Of The Linac Coherent Light Source.* Slac-Pub-11243, May 2005. 3pp.
20) K. Bane Et Al. *Resistive Wall Wakefield In The Lcls Undulator*. Contributed To Particle Accelerator Conference (Pac 05), Knoxville, Tennessee, 16-20 May 2005.
21) Juhao Wu Et Al. *Luminosity Loss Due To Beam Distortion And The Beam-Beam Instability.* Contributed To Particle Accelerator Conference (Pac 05), Knoxville, Tennessee, 16-20 May 2005.



The increased energy spread of the beam due to the microbunch instability in the LCLS caused by the combined effect of the coherent synchrotron radiation and space charge effects (left). Theoretical study of this effect in the Collective Effects Group resulted in the proposal of a laser heater that would suppress the instability and result in the tolerable level of the energy spread (right picture).



The induced energy deviation due to the wake within the 70 micron long beam inside the LCLS undulator for aluminum (red line) and copper (blue line) vacuum chambers. The black curve shows the previous calculations which did not take into account the effect of ac conductivity.

High Power RF Group

Sami Tantawi
Stanford Linear Accelerator Center

Mission Statement:

We conduct research on the generation and control of ultra-high-power rf. This involves designing passive rf components, active rf switches, and novel rf sources. A focus of our work is the design and development of high-power, overmoded rf pulse compression/distribution systems for linear accelerators. We also write computer codes to facilitate this work, participate in accelerator structure R&D, study rf breakdown, and design accelerator beam lines. We develop novel and advanced accelerator structures including optical accelerators. Recently we turned our attention to the application of ultra-high power RF available to us to the realization of RF undulators for FEL.

Major Accomplishments

- Our group was responsible for the realization of *world record in coherent RF generation*; we produced flat top 400 ns rf pulses at x-band/ku-Band with power level approaching 600 MW.
- We have invented a new methodology in the design of RF components: the *multimode structures*. This is set of components that can manipulate two or more modes at the same time.
- We developed *planer* overmoded rf structures and transitions to circular waveguide.
- We developed a new type of *fundamental mode RF couplers* for accelerator structure. This had an enormous impact of structure performance and is gradually becoming the standard world wide.
- We *analyzed the breakdown process in waveguides* and produced a credible simulation that agreed with experimental results. This was a breakthrough in understanding the physics of RF breakdown. We measured, for the first time, the spectrum of light emitted during an RF breakdown process. This gave us an insight into the physics of the process.
- We have developed the *theoretical foundations for active pulse compression* and how to combine active pulse compression with passive compression.
- We demonstrated the *first optically controlled active pulse compression system*.
- We designed and developed the *X-band high power RF system at the NLCTA*
- Our contributions to Mode converter development and RF windows *solved the problem of klystron windows* and became the standard for such a device.
- We developed an all metal load, which became *the standard for Ultra-high power loads around the world.*
- Some of the codes we developed was instrumental in the design of stainless-steel-loaded cavities fro klystron development and solved the early problem associated with instabilities.
- We developed *a new concept of spatially combined devices* to produce ultra-high power semiconductor switches and modulators
- We have developed a *new geometry for overmoded nonreciprocal devices*.

Activities for the Past Year

- During 2004 we built the distribution system that takes the power from our multimode rf pulse compression system and divides it to feed 4 different accelerator structures. The system ran continuously without faults for more than 1500 hours. Every part of this RF system performed near perfectly.
- The feedback system that we added to the low-level RF circuits that drives the klystrons was also used to shape the compressed pulse with an initial ramp. This would provide an appropriate pulse for beam loading compensation. The system ran while feeding accelerator structures for more that 3 month at 60 Hz 24 hours a day.
- We designed a Bragg optical waveguide consisting of multiple dielectric layers with alternating index of refraction, which is an excellent option to form electron accelerating structures powered by high power laser sources. We studied a side coupling scheme using Bragg-grating-assisted input coupler to inject the laser field into the waveguide.
- Our efforts in high power solid-state switches for pulse compression systems continued. We have built and demonstrated a new type of fast switches based on an array of PIN diodes on a single wafer.
- For active pulse compression systems, we created a practical design for nonreciprocal switches based on our theoretical developments.

Current and Future Activities

- *RF Undulators*-The idea of using high-power microwaves in a waveguide as an undulator is old. However, recent advances in high power rf pulse compression systems and RF sources at x-band make these types of undulators a competitor to static magnetic undulators. These types of rf undulators have several properties that makes them very attractive alternative to magnetic undulators. The polarization of the RF and hence the polarization of light can be controlled at will using the rf source. We plan to study this type of undulator. We will also propose to do an experiment at the NLCTA enclosure using the exciting infrastructure for e-beam and rf sources.
- *Optical Accelerators*-We will build our planar optical accelerator structures and coupling gratings. These are fabricated using well developed micro-processing technology. It will be test at the Orion test facility.
- *Active Pulse Compression* -For active pulse compression systems, we are going to test two types of switches at high power; our semiconductor PIN/NIP diode array and a plasma switch in collaboration with Omega-p, inc. and the Institute of Applied Physics in Russia. The PIN/PIN diode array was build on an Silicon on Insulator (SOI) wafer. This holds the promise of a fast and low loss device. If successful it will open the door for further development in ultra-high-power semiconductor devices

- *High Gradient Research* - Fundamental understanding of high gradient limits in room temperature rf accelerator structure is the most important topic for future accelerators and colliders such as CLIC. Understanding the frequency scaling of the RF breakdown limit is fundamental for CLIC and for advancing the art of high gradient accelerators. To this end, we have started the design of a series of experiments aimed on studying the basic physics of the problem. We introduced the concept of single cell traveling wave structure; a cell that has the boundary conditions of an infinite periodic structure. We built in collaboration with KEK several single cell test pieces made out of copper and molybdenum and some pieces that combined the two elements. We plan to test them as soon as operation conditions are restored in the test lab
- *Advanced Concepts for the ILC* -The present design for ILC main linac fundamental mode coupler is very complicated and expensive. We could contribute to the modification of these devices to increase their reliability and decrease their cost. We would like to change the design of these couplers in a fundamental way. Instead of using a coaxial waveguide to transmit the power we would use an over moded dielectric coaxial waveguide operating at the TE_{01} mode. This may prove advantageous to isolate different section that has different temperatures and different vacuum enclosures. We have developed the first mode launcher for this mode. The dielectric material of choice is alumina.
- *Fundamental Research in Superconducting Materials* - Superconducting materials for use in at DC applications have developed considerably. However, the same revolution did not happen for RF superconducting materials for accelerator structure. To date, the only widely explored material is niobium. Building accelerating cells from other materials and studying their properties is expensive and the study is complicated due the complicated physics in an accelerator cell. In collaborations with scientist from SNS and LANL, and JLAB we are studying different material on a test setup that is rather simple and promises a fast turn around time. This system capitalizes on our advances in mode converters and cavity designs.

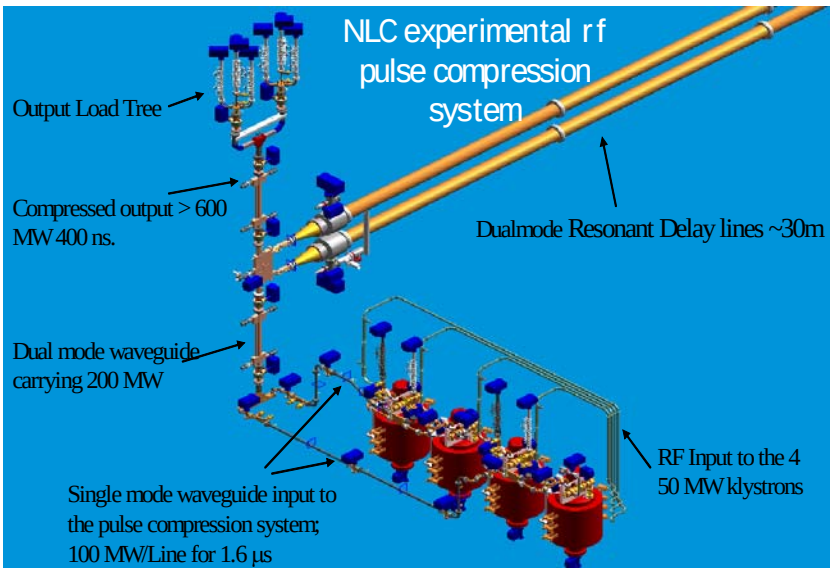
Recent Publications

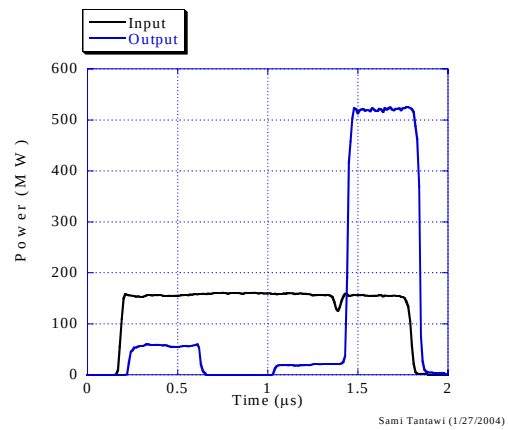
1. *Distributed Bragg Coupler For Optical All-Dielectric Electron Accelerator,* by Zhiyu Zhang, Sami G. Tantawi, Ronald Ruth, Presented At 2005 Particle Accelerator Conference, Pac05, Knoxville, Tennessee, Usa, May 16-20, 2005.
2. *Distributed Grating-Assisted Coupler For Optical All-Dielectric Electron Accelerator,* by Zhiyu Zhang, Sami G. Tantawi, Ronald Ruth , Physical Review Special Topics-Accelerators And Beams; July 2005; V.8, P.071302.
3. *High-Power Multimode X-Band Rf Pulse Compression System For Future Linear Colliders, by* Sami G. Tantawi *Et Al.* (Slac), Phys. Rev. St Accel. Beams, Vol. 8, Issue 4, 042002 (2005), April 2005, 19 Pp.
4. *A Novel Circular Te_{01}-Mode Bend For Ultra-High-Power Applications,* by Sami G. Tantawi (Slac), Journal Of Electromagnetic Waves And Applications, Jemwa, Vol. 18, No. 12, Pp. 1679-1687, 2004.
5. *Low-Field Accelerator Structure Couplers And Design Techniques*, by C. Nantista, S. Tantawi, And V. Dolgashev (Slac), Physical Review Special Topics-Accelerators And Beams; Jul 2004; V.7, No.7, P.072001, 7 Pp.; Slac-Pub-10575.

6. *Multimoded Reflective Delay Lines And Their Application To Resonant Delay Line Rf Pulse Compression Systems*, by Sami G. Tantawi (Slac), Physical Review Special Topics-Accelerators And Beams; Mar 2004; V.7, No.3, P.032001.
7. *Status Of High-Power Tests Of The Dual Mode Sled-Ii System For An X-Band Linear Collider*, by Sami G. Tantawi (Slac), Xxii International Linear Accelerator Conference, Lubeck, Germany, August 16-20, 2004.
8. *A Half Gigawatt Dual-Moded X-Band Transmission And Rf Pulse Compression System,* by Tantawi, S.G., *Et Al.* (Slac), International Microwave Symposium Digest, 2004 Ieee Mtt-S , Volume: 2 , June 6-11, 2004, Pp. 1021–1024.
9. *An Ultra-High Power Amplifier And Switch Arrays On Single Wafer*, by Jiquan Guo And Tantawi, S.G. (Slac), International Microwave Symposium Digest, 2004 Ieee Mtt-S , Volume: 2 , June 6-11, 2004, Pp. 1011–1014.
10. *Experimental Demonstration Of An Rf System For The X-Band Linear Collider,* by S. Tantawi *Et Al.* (Slac), Third Asian Particle Accelerator Conference (Apac 2004), March 22-26, 2004, Gyeongju, Korea; Slac-Pub-10550.
11. *Development Of A 300 Kw Cw L-Band Industrial Heating Magnetron,* by Wynn, Ap; Blank, De; Campbell, Ps; Lentz, Rr; Main, Wt; Tantawi, Sg; Kato, Kg; Beutel, Hk; Brown, Kw; Crouch, Dd, Fifth Ieee International Vacuum Electronics Conference, 27-29 April 2004, Monterey, Ca, Usa; Pp. 164-5.
12. *Rf Breakdown In Normal Conducting Single-Cell Structures,* by Valery Dolgashev *Et Al.* (Slac), Invited Talk At The 2005 Particle Accelerator Conference, Knoxville, Tennessee, May 16-20, 2005.
13. *High-Precision Resonant Cavity Integrated Beam Moment Monitors*, by N. Barov, J.S. Kim, A.W. Weidemann (Far-Tech, Inc.), R.H. Miller, C.D. Nantista (Slac), Presented At The 2005 Particle Accelerator Conference, Knoxville, Tennessee, May 16-20, 2005.
14. *Development Of A 20-Mev Dielectric-Loaded Accelerator Test Facility,* by S.H. Gold, *Et Al.*, Presented At The 2005 Particle Accelerator Conference, Knoxville, Tennessee, May 16-20, 2005.
15. *Test Bed For Superconducting Materials,* by C. Nantista, *Et Al.*, Presented At The 2005 Particle Accelerator Conference, Knoxville, Tennessee, May 16-20, 2005; Slac-Pub-11246.
16. *Progress Toward Nlc/Glc Prototype Accelerator Structures,* by J.W. Wang *Et Al.*, Presented At The Xxii International Linear Accelerator Conference (Linac 04), Lubeck, Germany, August 16-20, 2004; Slac-Pub-10711.
17. *Travelling Wave And Standing Wave Single Cell High Gradient Tests,* by V.A. Dolgashev, S.G. Tanttawi, C.D. Nantista (Slac), Y. Higashi, And T. Higo (Kek), Presented At The Xxii International Linear Accelerator Conference (Linac 04), Lubeck, Germany, August 16-20, 2004; Slac-Pub-10667.
18. High-*Power Rf Distribution System For The 8-Pack Project,* by Christopher Nantista *Et Al.*, Presented At The Xxii International Linear Accelerator Conference (Linac 04), Lubeck, Germany, August 16-20, 2004; Slac-Pub-10665.
19. *Multimoded Rf Systems For Future Linear Colliders,* by S.G. Tantawi *Et Al.*, Presented At The 9th European Particle Accelerator Conference (Epac 04), Lucerne, Switzerland, July 5-9, 2004.
20. *Status Of A Linac Rf Unit Demonstration For The Nlc/Glc X-Band Linear Collider*, by David Schultz, *Et Al.*, Presented At The 9th European Particle Accelerator Conference (Epac 04), Lucerne, Switzerland, July 5-9, 2004; Slac-Pub-10517.
21. *Development Of A 20 Mev Dielectric-Loaded Accelerator Test Facility,* by Steven H. Gold *Et Al.*, Presented At The 11th Advanced Accelerator Concepts Workshop (Aac 04), Stony Brook, New York, June 21-26, 2004.

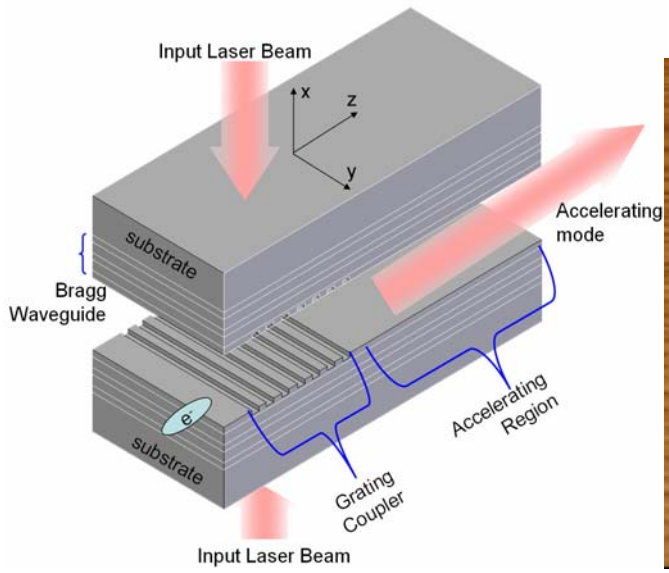
22. *Design Of A Standing-Wave Multi-Cavity Beam-Monitor For Simultaneous Beam Position And Emittance Measurements,* by Jin-Soo Kim (Far-Tech, Inc.), Roger Miller, And Christopher Nantista (Slac), Presented At The 11th Advanced Accelerator Concepts Workshop (Aac 04), Stony Brook, New York, June 21-26, 2004.
23. *Simulation Of Rf Breakdown Effects On Nlc Beam,* by V. A. Dolgashev And T. Raubenheimer, Presented At The 22nd International Linear Accelerator Conference (Linac 2004), Lubeck, Germany, 16-20 Aug 2004.
24. *Effect Of Dark Currents On The Accelerated Beam In An X-Band Linac,* by V.A. Dolgashev, K.L.F. Bane, J. Wu, G.V. Stupakov And T. Raubenheimer (Slac), Presented At The 9th European Particle Accelerator Conference (Epac 2004), Lucerne, Switzerland, July 5-9 2004; Slac-Pub-10666.
25. *Wire Measurement Of Impedance Of An X-Band Accelerating Structure*, by N. Baboi *Et Al.*, Presented At 22nd International Linear Accelerator Conference (Linac 2004), Lubeck, Germany, 16-20 Aug 2004; Slac-Pub-10685.
26. *A Study Of Coupler-Trapped Modes In X-Band Linacs For The Glc/Nlc,* by R.M. Jones, V.A. Dolgashev, Z. Li And J.W. Wang (Slac), Presented At 22nd International Linear Accelerator Conference (Linac 2004), Lubeck, Germany, 16-20 Aug 2004.
27. *Beam Loading And Higher-Band Longitudinal Wakes In High Phase Advance Traveling Wave Accelerator Structures For The Glc / Nlc*, by R.M. Jones, V.A. Dolgashev, Z. Li And T.O. Raubenheimer (Slac), Epac-2004-Moplt133, Presented At 9th European Particle Accelerator Conference (Epac 2004), Lucerne, Switzerland, 5-9 Jul 2004.
28. *Simulation Of Dark Currents In X-Band Accelerator Structures,* by K.L.F. Bane, V.A. Dolgashev, G.V. Stupakov (Slac),. Epac-2004-Tupkf059, Slac-Pub-10486, Jun 2004. 4pp. Presented At 9th European Particle Accelerator Conference (Epac 2004), Lucerne, Switzerland, 5-9 Jul 2004.
29. *High Gradient Performance Of Prototype Nlc/Glc X-Band Accelerator Structures*, by Steffen Doebert *Et Al.*, Presented At 2005 Particle Accelerator Conference, Pac05, Knoxville, Tennessee, Usa, May 16-20, 2005.
30. *Studies Of Room Temperature Accelerator Structures For The Ilc Positron Source,* by Juwen W. Wang *Et Al.*, Presented At 2005 Particle Accelerator Conference, Pac05, Knoxville, Tennessee, Usa, May 16-20, 2005.
31. *Rf Breakdown In Normal Conducting Single-Cell Structures,* by Valery Dolgashev *Et Al.*, Invited Talk At 2005 Particle Accelerator Conference, Pac05, Knoxville,Tennessee, Usa, May 16-20, 2005.
32. *Design Of A Standing-Wave Multi-Cell Rf Cavity Beam Monitor For Simultaneous Position And Emittance Measurement,* by Jin-Soo Kim (Far-Tech, Inc.), Roger Miller, And Christopher Nantista (Slac), Rev. Sci. Instr. Accepted For Publication.
33. Yasser A. Hussein *Et Al*, *Measurements And Simulations Of Electronically-Excited Thz Structures For Astronomy And Medical Applications*, *IEEE Transactions On Microwave Theory And Techniques*, To Be Submitted August 2005.
34. Yasser A. Hussein *Et Al. Radiative Characteristics Of On-Chip Terahertz Thz Structures,* In *IEEE Ap-S Int. Antennas And Propagation Symp. Dig.*, 2005.
35. Yasser A. Hussein *Et Al. Efficient Modeling Of Pin Diode Switches Employing Time-Domain Electromagnetic-Physics-Based Simulators*, In *IEEE Mtt-S Int. Microwave Symp. Dig.*, 2005.
36. Yasser A. Hussein *Et Al.*, *Calculations For Terahertz Thz Radiation Sources*, In *The Particle Accelerator Conference Dig.*, 2005.

37. Yasser A. Hussein *Et Al.*, *Hybrid Fdtd Analysis For On-Chip Thz Structures*, In *IEEE Computational Electromagnetics Dig.*, 2005.
38. Yasser A. Hussein *Et Al.*, *Modeling And Optimization Of Microwave Devices And Circuits Using Genetic Algorithms*, *IEEE Transactions On Microwave Theory And Techniques*, Vol. 52, Pp. 329-336, Jan.2004.
39. Yasser A. Hussein *Et Al.*, *Novel Possibilities For Coherent Radiation Sources*, In *IEEE Mtt-S Int. Microwave Symp. Dig.*, 2004, Pp. 365-368.
40. Yasser A. Hussein *Et Al.*, *Time-Domain Electromagnetic-Physics-Based Modeling Of Complex Microwave Structures,* In *IEEE Mtt-S Int. Microwave Symp. Dig.*, 2004, Pp. 1791-1794.
41. Yasser A. Hussein *Et Al.*, *Numerical Modeling And Analysis Of Optical Response Of Electro-Optic Modulators,* In *IEEE Mtt-S Int. Microwave Symp. Dig.*, 2004, Pp. 777-780.
42. Yasser A. Hussein *Et Al.*, On The Design And Optimization Of Waveguides Using Evolutionary Approaches, In *IEEE Ap-S Int. Antennas And Propagation Symp. Dig.*, 2004, Pp. 1110-1113.





The Ultra-High Power Multimoded Pulse Compression System. The system achieved world record in coherent RF generation; we produced flat top 400 ns rf pulses at x-band/ku-Band with power level approaching 600 MW. The output waveform shown demonstrate the flat top pulse which is suitable for multi-bunch acceleration



Optical Dielectric Accelerator. Accelerating mode is guided by the Bragg waveguide. Grating coupler couples laser light from the side and converts it to accelerating mode Waveguide and coupler are fabricated with micro-processing technology

Spatially Combined Semiconductor Devices Fabricated on one 4 inch floatzone silicon wafer. Hundreds of PIN diodes integrated. Silicon on Insulator (SOI) structure is preferred. The device works at the TE_{01} mode in circular waveguide

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RF Structures Group

Juwen Wang

Mission

The mission of RF Structures group is to design, engineer, and test variety of accelerator structures with superior properties in high RF efficiency, good Higher Order Mode suppression and high gradient performance.

Our activities span design theory and practice, simulation, structure related beam dynamics studies, fabrication technology, microwave measurements, structure characterization and high power experiments. We have been closely collaborating with the Accelerator Research Department A (ARDA) high power RF group, ACD Department, Klystron Department, KEK, LLNL and FNAL.

We support accelerator R&D programs at SLAC including the ILC, LCLS and others.

Major activities in the past years

- We played a leading role in the NLC main linac structure R&D.
- We designed, fabricated and tested 50 X-Band accelerator structure sections. (Among them, 8 were completed with KEK collaboration and 12 were fabricated by FNAL).
- Contributions to accelerator technology include:
- Theoretical analysis for full understanding of HOM suppression in RF accelerator structures.
- Simulation of interaction between beam and structure, structure wakefield calculation, emittance growth calculation and analysis of structure alignment and dimension tolerances.
- Optimization of accelerator parameters including modes, group velocities, length, attenuation factor for highest RF efficiency and structure dimension determination with sub-micron precision.
- Design principles for Damped and Detuned Structures which can be applied to any low emittance, high beam loading accelerator, for example, the CLIC linac structure.
- Development of manifold damping which provides structure position monitoring with micron transverse sensitivity and frequency multiplexed longitudinal resolution on the order of several cells.
- Advanced fabrication technology for normal conducting accelerator structures including precision machining, diffusion bonding and long structure alignment.
- Experimental technologies including higher order modes (HOM) measurements for beam diagnostics, and wire impedance measurement for wakefield analysis.

- We supported SLAC high gradient study program. The requirement of extremely low breakdown rate at 65 MV/m for NLC/GLC was met by all recent accelerator sections.
- We have configured and made a detailed plan for the final prototype of RF accelerator structure for the NLC main linac.
- The Micro Linac is a small, SW linac intended as a low-cost radiography source with dosage larger than 100 Ci to be a viable replacement for radioactive

sources, which can potentially be used for “dirty bombs”. We have contributed both the electrical and mechanical design for these accelerator structures.

Activities After ITRP Decision

After the International Technology Recommendation Panel (ITRP) announced its decision to select superconducting technology for a future linear collider, we quickly adjusted our R&D program to embrace the ILC opportunity with enthusiasm and to support SLAC photon science projects.

- We made feasibility studies of recirculating traveling wave linacs for the ILC main linac.
- We have proposed an improved alternative design for L-Band normal conducting accelerating system for ILC positron source including both standing wave and traveling wave sections. We have made theoretical feasibility analysis of RF and beam acceleration stabilities under different cooling conditions. The design work for a short test L-Band standing wave accelerator section is in progress. The design of traveling wave sections will be further optimized.
- We are participating in positron beam dynamics studies aimed at increasing the yield of positrons for both conventional and modulator-based positron sources. Phasing the positron capture section so that it initially decelerates and bunches the positrons can shorten the bunch and produce a positron bunch with significantly smaller longitudinal emittance. We have completed the conceptual design layout of the ILC positron pre-accelerator system for both conventional and undulator-based positron source with acceleration and initial deceleration scheme.
- The wakefield in the superconducting ILC L-band structures is being carefully investigated. The effect of splitting the frequency degeneracy on the coupling of horizontal beam motion to the vertical motion and degradation of vertical emittance will be investigated under various realistic ILC configurations.
- We are actively participating in the S-Band structure related work for the LCLS project including design discussions for the microwave gun, modification of the accelerator sections and preparation for structure measurements. We have designed and fabricated a horizontal bead pulling setup. The two 9.5 ft sections and six 10 ft sections have been evaluated. We have provided some important suggestions for the LCLS injector engineering.
- We have given engineering support to several other SLAC projects such as the ILC superconducting quadruples, and remote positioning cam support system for LCLS undulator measurement.

Projected Activities for the Coming Year

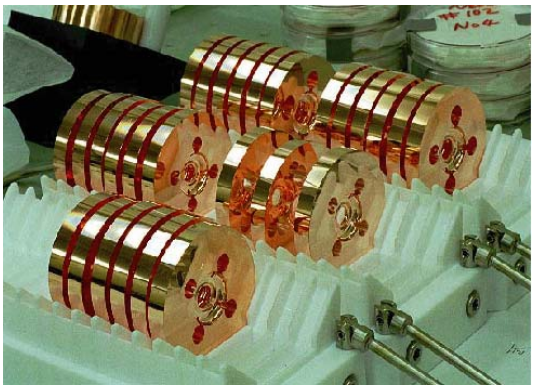
- The R&D on the L-Band normal conducting accelerating system for ILC positron source will continue. A 5-cell L-Band normal conducting standing wave accelerator section with all necessary features for positron capture section will be completely designed, fabricated, tuned and high power tested to full gradient of 15 MV/m with pulse length of 1 ms. Some traveling wave structures will be optimized, and test structures will be fabricated for high power tests. The whole pre-accelerating system will be simulated and beam line components will be studied in detail.

- The positron beam dynamics studies for increased the positron yield and finalized RF structure layout for both conventional and undulator-based positron source with acceleration and initial deceleration scheme will contribute to the Center for Design Research (CDR) of the ILC positron source.
- We will continue to support the accelerator structure related work for the LCLS project:
- Finish to measure and evaluate all needed S-Band accelerator sections. Tune and characterize two 10 ft booster sections after with new double input waveguides.
- Measure and characterize two RF deflectors.
- We will perform complete microwave measurement and tuning of the 1st microwave gun. The analysis of test results will contribute to the future upgraded gun design.
- We will continue to work on the simulation and analysis of wakefield and beam structure interaction in the ILC linac.
- We will continue to give engineering support to various SLAC projects.
- We intend to work on wire measurements to determine the dipole mode impedance for standing wave structures with discrete dipole modes such as the superconducting structures for ILC.
- We will participate in the collaboration on CLIC structures and may collaborate on an ASSET test of the CLIC heavily damped structure to measure the dipole wake.

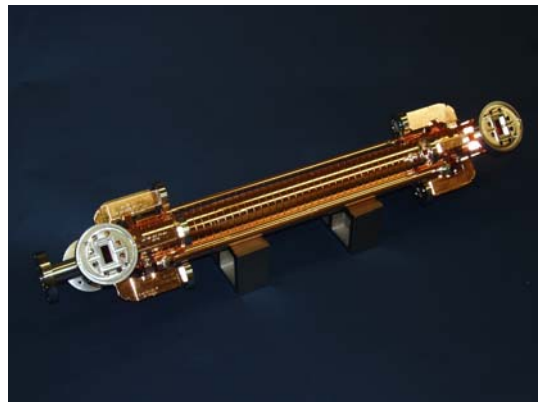
Recent Publications

1. *Studies Of Room Temperature Accelerator Structures For The Ilc Positron Source*, J. Wang, et al., Proceedings Of Pac 2005, May 2005.
2. *Design Issues For The Ilc Positron Source*, V. Bharaadwaj, et al., Proceedings Of Pac 2005, May 2005.
3. *Emittance Dilution Due To Many-Band Long-Range Dipole Wakefields In The International Linear Collider Main Linacs*, R. Jones, et al., Proceedings Of Pac 2005, May 2005.
4. *Emittance Dilution Due To Dipole Mode Rotation And Coupling In The Main Linacs Of The Ilc,* R. Jones, et al., Proceedings Of Pac 2005, May 2005.
5. *Beam Position Resolution And Centering Accuracy Achieved Using Hom Signals From Damped And Detuned X-Band Accelerator Structures*, S. Döbert, Proceedings Of Pac 2005, May 2005.
6. *Wakefield Measurements Of A Pair Of Dipole Frequency Interleaved, High Gradient, X-Band Accelerator Structures*, C. Adolphsen, et al., Proceedings Of Pac 2005, May 2005.
7. *Cavity Alignment Using Beam Induced Higher Order Modes Signals In The Ttf Linac*, M. Ross, et al., Proceedings Of Pac 2005, May 2005.
8. *High Gradient Performance Of Prototype Nlc/Glc X-Band Accelerator Structures*, C. Adolphsen, et al., Proceedings Of Pac 2005, May 2005.
9. *Heat Deposition In Positron Source For Ilc*, V. Bharaadwaj, et al., Proceedings Of Pac 2005, May 2005.
10. *Progress Toward Nlc / Glc Prototype Accelerator Structures*. J. Wang, Et Al., Linac2004, Slac-Pub-10711, Sep 2004.
11. *Accelerator Structure Bead Pull Measurement At Slac*, J. Lewandowski, Et Al., Proceedings Of Linac2004, Sep 2004

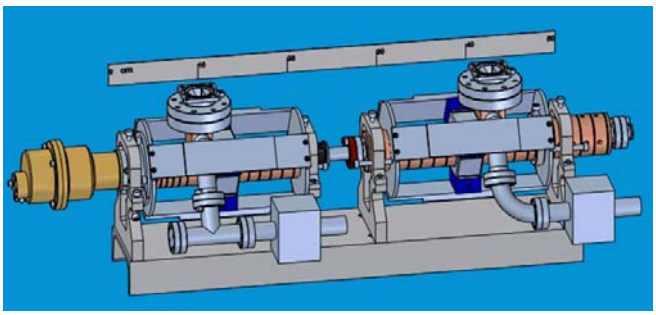
12. *Wire Measurement Of Impedance Of An X-Band Accelerating Structure*, N. Baboi, et al., Linac2004, Slac-Pub-10685, Sep 2004.
13. *A Study Of Coupler-Trapped Modes In X-Band Linacs For The Glc/Nlc*, R. Jones, et al., Linac2004, Slac-Pub-10681, Sep 2004.
14. *A Study Of Higher-Band Dipole Wakefields In X-Band Accelerating Structures For The G/Nlc,* R. Jones, et al., Proceedings Of Linac 2004, Slac-Pub-10682.
15. *Linac Alignment And Frequency Tolerances From The Perspective Of Contained Emittances For The Glc/*Nlc, R. Jones, et al., Proceedings Of Linac 2004, Slac-Pub-10683.
16. *Emittance-Imposed Alignment And Frequency Tolerances For The Tesla Linear Collider,* R. Jones, et al., Proceedings Of Linac 2004, Slac-Pub-10684.
17. *Beam Loading And Higher-Band Longitudinal Wakes In The High Phase Advance Traveling Wave Accelerator Structures For The Glc/Nlc*, R. Jones, Et Al., Proceedings Of Epac 2004, Slac-Pub-10557, July 2004.
18. *Emittance Dilution Simulations For Normal Conducting And Superconducting Linear Colliders,* R. Jones, et al., Proceedings Of Epac 2004, Slac-Pub-10556, July 2004.
19. *Accelerator Structure Development For Nlc / Glc*, J. Wang, et al., Icfa Beam Dynamics Newsletter No. 32, Slac-Pub-10370.
20. *Proving High-Field Operation Of X-Band Structure For Linear Colliders,* Y. Chin, et al. Proceedings Of Apac2004.
21. *Energy Dispersion Compensation And Beam Loading In X Band Linacs For The Jlc / Nlc*, Proceedings Of Pac2003, Slac-Pub-9870.
22. *Status Of X Band Standing Wave Structure Studies At Slac*, V. Dolgashev, et al., Proceedings Of Pac2003, Slac-Pub-10124.
23. *Simulating Accelerator Structure Operation At High Power,* V, Ivanov, et al., Proceedings Of Pac2003.
24. *Optimization Of The X-Band Structure For The Jlc/Nlc,* Z. Li, et al., Proceedings Of Pac2003.
25. *Transverse Impedance Bench Measurements In Nlc/Jlc Accelerating Structures*, N. Baboi, et al., Proceedings Of Pac2003.
26. *A Circuit And Scattering Matrix Analysis Of The Wire Measurement Method Of Beam Impedance In Acclerator Structures*. R. Jones, et al., Proceedings Of Pac2003, Slac-Pub-9871.
27. *Optimized Wakefield Suppression & Emittance Dilution-Imposed Alignment Tolerances In X-Band Accelerating Structuress For The Jlc/Nlc,* R. Jones, et al., Proceedings Of Pac2003, Slac-Pub-9868.



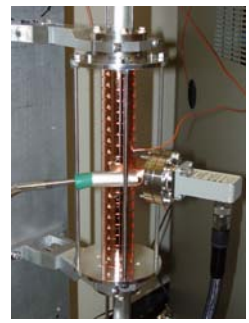
Accelerator discs with super precision for Damped Detuned Structures.



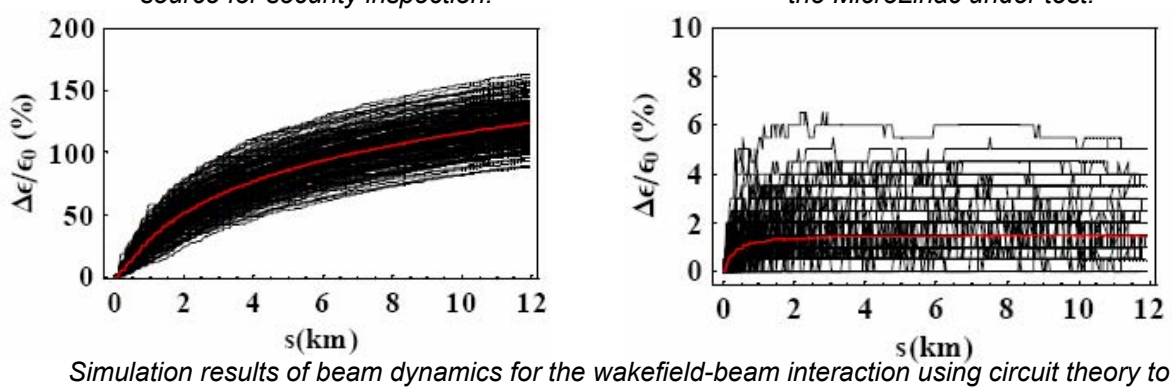
Prototype accelerator structure for the NLC main linac.



MicroLinac as low cost radiography source for security inspection.

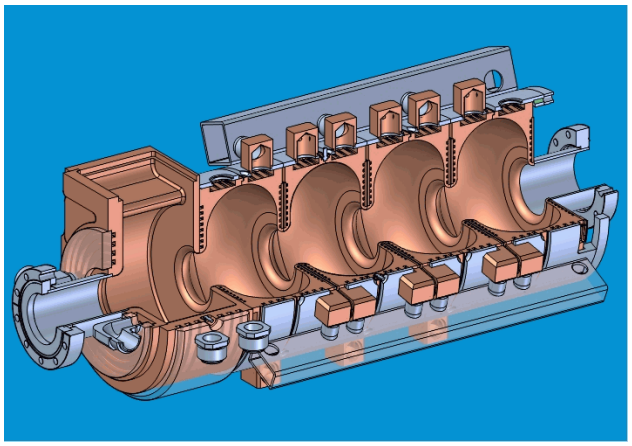


An accelerator section of the MicroLinac under test.



Simulation results of beam dynamics for the wakefield-beam interaction using circuit theory to ILC superconducting accelerator show the emittance dilution without (left) and with (right) randomizing the azimuthal position of the Higher Order Mode (HOM) couplers.

L-Band normal conducting SW test accelerator structure for the ILC positron source.



NATIONAL MUON/NEUTRINO COLLABORATION

Neutrino Factory and Muon Collider Collaboration R&D Program

Michael S. Zisman
Lawrence Berkeley National Laboratory

Summary

The Neutrino Factory and Muon Collider Collaboration (NFMCC) began as an informal group of about 100 scientists and engineers investigating the feasibility of building a Muon Collider. It became a formal entity in May 1997 and obtained its first significant funding in spring 1998. It now has some 135 members from 6 U.S. national labs, 17 U.S. universities, and 14 foreign institutions. The collaboration has a defined oversight and review structure that was negotiated with the Department of Energy (DOE) and the directors of the sponsoring Labs: Brookhaven National Laboratory (BNL), Fermi National Accelerator Laboratory (FNAL), and Lawrence Berkeley National Laboratory (LBNL). Since 1999, motivated by the exciting discovery that neutrinos oscillate, the NFMCC has focused mainly - but not exclusively - on Neutrino Factory design; this is viewed as a technically simpler option that addresses an area of high scientific interest and priority. There have now been two Neutrino Factory Feasibility Studies, the first sponsored by FNAL and the second co-sponsored by BNL and the NFMCC, along with a significant update of the second study in connection with the recent American Physical Society (APS) Neutrino Physics Study. The Collaboration also supports a strong research and development (R&D) program having three main components: target studies, cooling studies, and simulations. The first two topics emphasize component R&D, including tests of a mercury-jet target system and development of liquid-hydrogen absorbers and high-gradient normal conducting radio frequency (RF) cavities. Universities participate strongly in the R&D program, especially in the absorber R&D effort. In addition to its own R&D program, the NFMCC has helped launch two international experiments; the Muon Ionization Cooling Experiment (MICE), and a target experiment at CERN (nTOF11), and is playing a key role in the International (Neutrino Factory) Scoping Study (ISS). NFMCC members serve as Spokespersons for the nTOF11 experiment, as Deputy Spokesperson and Chair of the Collaboration Board for MICE, and as Leader of the Machine Working Group of the ISS.

Goals and Organization

The Neutrino Factory and Muon Collider Collaboration is governed by a formal charter that defines its goals and organization. The goals include:

- Developing theoretical tools unique to the design of Neutrino Factories and Muon Colliders
- Developing simulation tools unique to the design of Neutrino Factories and Muon Colliders
- Carrying out R&D on the hardware that is unique to the design of Neutrino Factories and Muon Colliders
- Carrying out an extensive experimental program to verify the theoretical and simulation predictions and to gather the necessary data for a future facility

The organization is illustrated in *Figure 1*. The NFMCC is run by elected Co-spokespersons, currently Steve Geer (FNAL) and Bob Palmer (BNL), who appoint an Executive Board to deal with policy matters and a Technical Board to deal with R&D planning, priorities, and budgets.

Oversight of the Collaboration's performance is provided by the Muon Collaboration Oversight Group (MCOG), with members (S. Aronson, BNL, S. Holmes, FNAL, and J. Siegrist, LBNL) designated by the directors of the three sponsoring labs. MCOG appoints a Technical Advisory Committee (MUTAC), currently chaired by Helen Edwards of FNAL, to review the technical accomplishments of the Collaboration annually, and has appointed a Project Manager to be responsible for execution and monitoring of the NFMCC's national R&D program.

Each year, the R&D groups propose a budget to the Technical Board, based on guidance from DOE on the available NFMCC funding. The Project Manager prepares a budget based on this input that is then approved by the Technical Board, the Executive Board, and the Spokespersons. The budget is dictated by the R&D program needs, not by institutional commitments. After the budget is finalized, the Project Manager negotiates milestones— specifying deliverables and dates— with each institution based on the current R&D plan. At the end of the year, a spending summary along with an evaluation of progress toward the R&D milestones are presented to MUTAC, MCOG, and DOE.

The NFMCC interacts closely with corresponding organizations in Europe and Japan to minimize duplication of effort and maximize the effectiveness of the global R&D effort. Although this coordination is done informally, at the grass-roots level, it has been very effective, and has led to three fully international activities; the MICE and nTOF11 experiments mentioned earlier and the recently launched ISS.

Recent Accomplishments

In the last several years, the NFMCC has carried out two feasibility studies of a Neutrino Factory, participated strongly in the APS Multi-divisional Neutrino Physics Study, developed and validated a simulation tool, ionization cooling (ICOOL), specifically designed for muon beam line design, and helped launch the ISS. We have also led the worldwide development of the so-called "non-scaling" fixed field, alternating gradient (FFAG) ring concept, which has potential applications as a high-intensity proton driver and/or a rapid acceleration system for muons.

In the target area, we have carried out proton bombardment experiments at the AGS, using a specially constructed beam line funded by us, with candidate target materials including carbon rods and a mercury jet (see *Figure 2*), and done irradiation studies on various target materials to look for changes in mechanical and physical properties. We are currently fabricating a 15-T test magnet to be used in the nTOF11 experiment at CERN (see *Figure 3*). A closed-loop mercury-jet system for the nTOF11 experiment is also being designed and built by us.

For cooling R&D we have fabricated and tested two different styles (open-cell and pillbox) of 805-MHz normal conducting RF cavities, and have almost completed fabrication of a 201-MHz cavity (see *Figure 4*) that will be tested in the newly constructed MUCOOL Test Area (MTA) at Fermilab, a facility constructed with NFMCC funds. The 201-MHz cavity will serve as a prototype for the cavities planned for use in MICE. We have also designed a liquid-hydrogen absorber in collaboration with colleagues at KEK, and have successfully test-filled it with liquid hydrogen in the MTA. In collaboration with colleagues at University of Oxford, we have developed very thin (125 μm) aluminum windows (see *Figure 5*) suitable for containing the liquid hydrogen, and have verified finite-element analysis estimates of their strength.

Selected Publications

1. N. Holtkamp and D. Finley, eds., "A Feasibility Study of a Neutrino Source Based on a Muon Storage Ring," Fermilab-Pub-00/108-E (2000),
2. http://www.fnal.gov/projects/muon collider/nu-factory/nu-factory.html

3. S. Ozaki, R. Palmer, M. Zisman, and J. Gallardo, eds., "Feasibility Study-II of a Muon-Based Neutrino Source," BNL-52623 (2001), http://www.cap.bnl.gov/mumu/studyii/FS2-report.html

4. J. Gallardo, S. Geer, and M. Zisman, eds., "Report on Neutrino Factory and Beta Beam Experiments and Development," LBNL-55478 (2005),
5. http://www.aps.org/neutrino/loader.cfm?url=/commonspot/security/getfile.cfm&PageID=58766

6. M. Alsharo'a, et al., "Recent Progress in Neutrino Factory and Muon Collider Research within the Muon Collaboration," Phys. Rev. ST Accel. Beams, 6, 081001 (2003).
7. http://prstab.aps.org/abstract/PRSTAB/v6/i8/e081001?qid=5c54379a8cd1be3b&qseq=2&show=10

8. MC notes listing: http://www-mucool.fnal.gov/notes/notes.html

9. MICE notes listing: http://mice.iit.edu/notes/notes.html

Current Staff

Co-Spokespersons: Stephen Geer (FNAL); Robert Palmer (BNL)
Project Manager: Michael Zisman (LBNL)

Complete membership list: http://www.cap.bnl.gov/mumu/cgi-bin/membership.cgi

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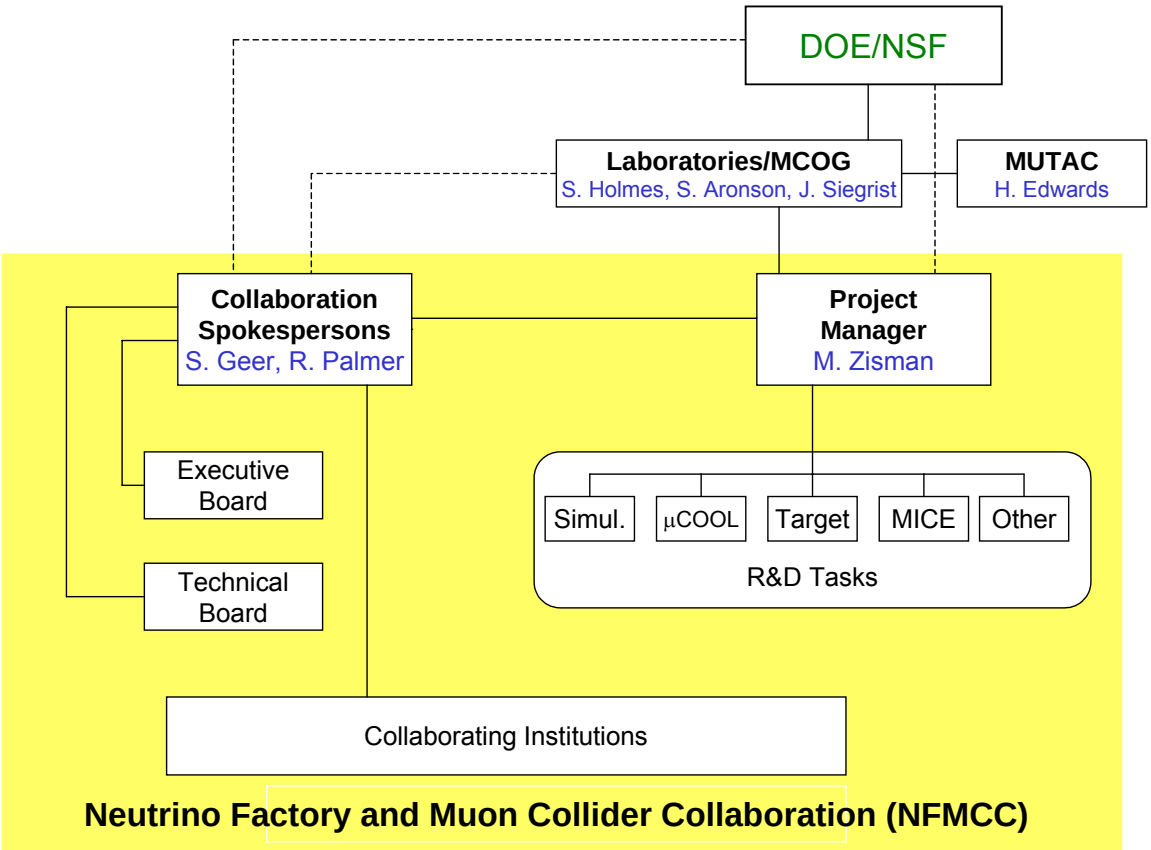


Figure 1 Organization chart for NFMCC

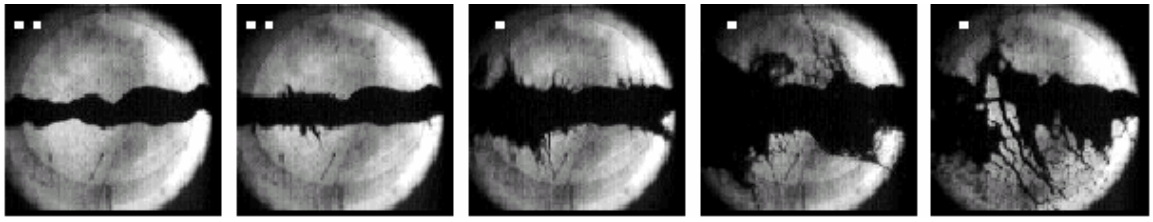


Figure 2 (top) Mercury-jet apparatus under test at Princeton; (bottom) jet response to interaction with proton beam at AGS at t = 0, 0.75, 2, 7, and 18 ms

Figure 3 (left) Solenoid coils that will be nested to produce a 15 T field for the nTOF11 experiment; (right) cryostat into which the coils will be placed. The magnet operates at liquid-nitrogen temperature to reduce demands on the power supply

Figure 4 Prototype 201-MHz RF cavity during low-power testing at Jlab

Figure 5 Thin aluminum window for liquid-hydrogen absorber, fabricated at University of Mississippi. Both front view (left) and back view (right) are shown

CONFERENCES, WORKSHOPS AND PARTICLE ACCELERATOR SCHOOL

U.S. Particle Accelerator School Yearbook Report
September 2005

Introduction

The U.S. Particle Accelerator School (USPAS, or School) is a Virtual National Graduate School that provides educational programs in the field of beams and their associated accelerator technologies not otherwise available to the community of science and technology. It also promotes the development and publication of advanced technology textbooks.

We see the role and responsibility of the USPAS growing over the next decade. For example, the next four years will see the operation of challenging machines such as the Spallation Neutron Source, Large Hadron Collider (LHC), X-ray Free Electron Lasers (FELs), and laser-driven accelerators. The next decade is likely to see the design and construction of an LHC upgrade, a Linear Collider, and possibly an accelerator-driven neutrino source. Therefore, it is imperative that U.S. accelerator-based science have access to sufficient scientific and engineering talent with a broad array of requisite skills. To meet this challenge, the USPAS has been training more early-career scientists & engineers than ever. In developing its cadre of instructors, the USPAS also provides an opportunity to mentor and counsel the upcoming intellectual leaders of the U.S. accelerator community.

Because its continuing, rigorous program of academic courses is unmatched by programs in other parts of the world, the USPAS has become a growing contributor to the education of accelerator scientists and technologists internationally. As a survey of the accelerator staff at Department of Energy (DOE) laboratories will readily demonstrate, our international outreach directly benefits DOE laboratories.

Structure

The USPAS is governed and funded by an 11-member consortium comprised of seven DOE Office of Science national laboratories, two DOE National Nuclear Security Agency national laboratories, and two National Science Foundation (NSF) university laboratories. Member laboratories each contribute $25K annually to support USPAS operations. Each member laboratory is entitled to one representative on the USPAS Board of Governors, which elects a Chair and appoints the USPAS Director. The administrative office of the USPAS, which performs and coordinates all functions and activities of the School, is funded by the Office of High Energy Physics and is located at Fermi National Accelerator Laboratory (Fermilab), which provides fiduciary oversight of the School activities.

Established in 1981, the USPAS originally offered a seminar format that seemed adequate to expose senior members of the accelerator research community to the many facets of accelerator physics and technology. After a few years it became clear that to provide sufficiently substantive staff development and to educate scientists and engineers entering the field, a more rigorous classroom regimen would be required. In 1987 the USPAS initiated its credit course program.

The USPAS curriculum is designed not only to train scientists and engineers to perform the tasks necessary to complete projects and run facilities but also to cultivate education in the many areas of technology that will arise in the coming decade at the national laboratories and in the industrial, medical, and university laboratories across the country.

Enrollment

The USPAS has attracted more than 2,600 students in its 32 university-credit sessions since the first such program at the University of Chicago in 1987. Originally serving as a continuing education program for scientists and engineers already at our sponsoring institutions, the USPAS now boasts a student population consisting of more than 50% graduate and post-graduate students from around the world. Approximately 120 -150 students attend each program, with about 2/3 of them enrolling for university credit. Some students are currently matriculating in a university degree program while others work at laboratories or in private industry. Approximately 20% travel from outside the United States to attend USPAS/university-sponsored programs. *Figure 1* shows this attendance record at our host universities since the winter session, 1997.

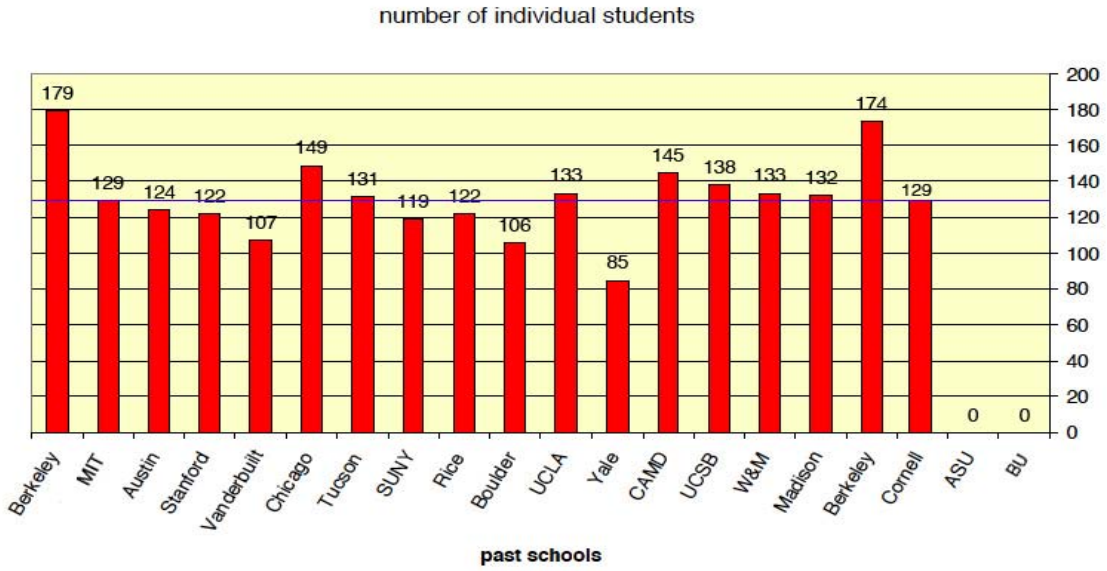


Figure 1 Student attendance at the past 18 sessions of the U.S. Particle Accelerator School. The sessions at Arizona State and Boston University will be held in the winter and summer of 2006 respectively.

The USPAS continues to provide an unparalleled source of continuing education for accelerator scientists and technologists for our national laboratories. Attendees from the national laboratories remain a core constituency of USPAS. The breakdown of attendees from our sponsoring institutions is shown in *Figure 2*.

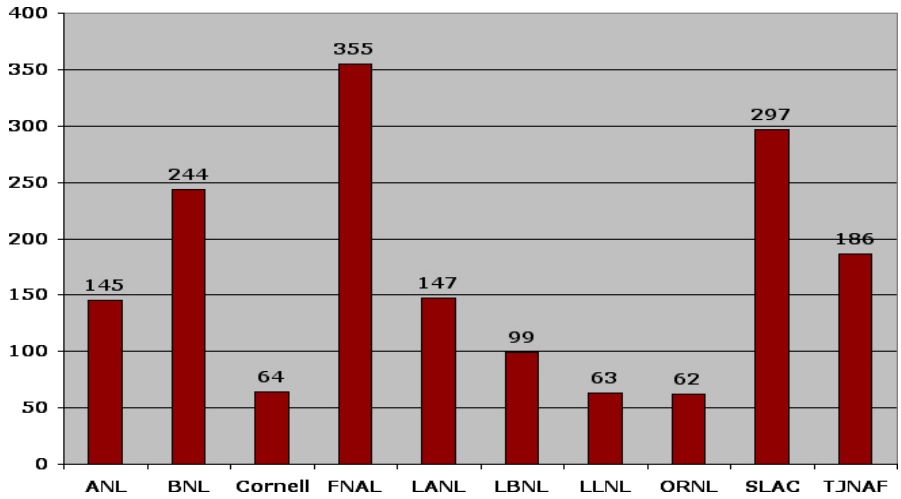


Figure 2 Attendance at USPAS sessions from sponsoring laboratories. Statistics compiled before Michigan State University joined the consortium.

Our University Partners

An essential component of the school is the nation-wide pool of leading U.S. research universities, from which the school selects hosts for its semi-annual sessions of graduate-level courses. Universities that have sponsored past USPAS programs include the University of California at Berkeley, the University of California at Los Angeles, the University of California at Santa Barbara, the University of California at San Diego, the University of Chicago, the University of Colorado at Boulder, Cornell University, Duke University, Florida State University, Harvard University, the University of Illinois – Urbana Champaign, Indiana University, Massachusetts Institute of Technology, Rice University, Stanford University, State University of New York at Stony Brook, the University of Texas-Austin, Vanderbilt University, the University of Washington at Seattle, the University of Wisconsin - Madison, the College of William and Mary, and Yale University. Each host university provides: a) university credit for courses, b) approval of all course offerings and faculty, c) assignment of course numbers, and d) a liaison at the university to help with administrative issues. Occasionally, the university assigns nine classrooms plus a PC center and one office for the USPAS staff, all of which will be used during the two weeks of the program. More commonly, however, USPAS uses a local hotel for its classroom and office facilities to maximize the total number of contact plus study hours for the students. In this case, the hotel provides meeting rooms at no charge based on the number of sleeping rooms.

The USPAS office headquartered at Fermilab provides all planning, organization, and on-site management for the School. The USPAS Office handles advertising, collection of student applications and acceptance notification, faculty arrangements, distribution of course materials, and all other local arrangements.

- The USPAS traditionally pays $80 per credit hour per enrolled student to the university in lieu of tuition.
- The School invites students from the host university to attend at no cost.

The USPAS Curriculum

USPAS course sessions are held in January and June, and run 10 days in duration. Students may register for one full course (at least 45 contact hours) or they may choose two half-courses (at least 23 contact hours each) where each half-course is one-week in duration. By successfully completing the course requirements that include lectures, daily problem-solving and examinations, students can earn university credit. A full-course earns the equivalent of three semester hours of host university credit; each half-course earns the equivalent of 1.5 semester hours of credit. All courses run in parallel so students can take one full course, or two half-courses, or they may opt for only one half-course during either week of the program. The prerequisites are minimally classical mechanics and electromagnetism at the junior or senior undergraduate level. However, specific prerequisites are listed in each course description.

The highly varied USPAS Courses are developed for the school with the advice of a Program Advisory Committee composed of representatives from our consortium laboratories in addition to representation from universities with accelerator science programs\graduate-level courses are being offered in many subjects both general and specific. They include:

- General principles of accelerator physics, strong focusing rings, linacs, intense beam accelerators, beam design, magnetic optics, light optics, high current and high brightness beams, spin dynamics;
- Experimental techniques, microwave measurement and beam instrumentation labs, accelerator vacuum labs, beam manipulation techniques;
- Synchrotron radiation sources, free electron lasers, high gain FEL, strong field radiation;
- Beam Theory, modern dynamics, numerical methods, beam instabilities;
- RF systems, magnetic systems, superconducting magnets, superconducting RF, superconducting materials;
- Computational methods in beam dynamics, beam optics, and electromagnetism;
- Radiation physics and accelerator safety, radiation effects; and
- Accelerator applications, in medicine, industry.

Due to great interest in and attendance at radiation control and effects courses, we hold these courses on a regular basis (every one and a half years). The American Academy of Health Physics (AAHP) awards 32 continuing education credits for the USPAS radiation course for certified Health physicists (64 needed per two years). Similarly the USPAS Accelerator System Safety Course carries continuing education credit from the AAHP, the Health Physics Society, and the American Board of Industrial Hygienists. The instructors are also given permission by the Board of Certified Safety Professional to administer the Certified Functional Safety Expert and Certified Functional Safety Technician exams at the end of their USPAS course.

Where possible, an instrumentation course where students are introduced to the working and use of more sophisticated instrumentation like network analyzers, etc., is offered. Agilent Technologies, Inc., has been instrumental in loaning equipment for this type of Course at no cost. As displayed in *Figure 3*, attendance at USPAS courses reflect an enthusiastic student response to a curriculum that addresses the broad needs for

accelerator scientists and engineers across the programs of the entire DOE Office of Science. The largest number of USPAS students opt for courses that cover the fundamental aspects of accelerator science and technology. This response reaffirms the Board's decision in the late 1980's to offer an academically focused curriculum.

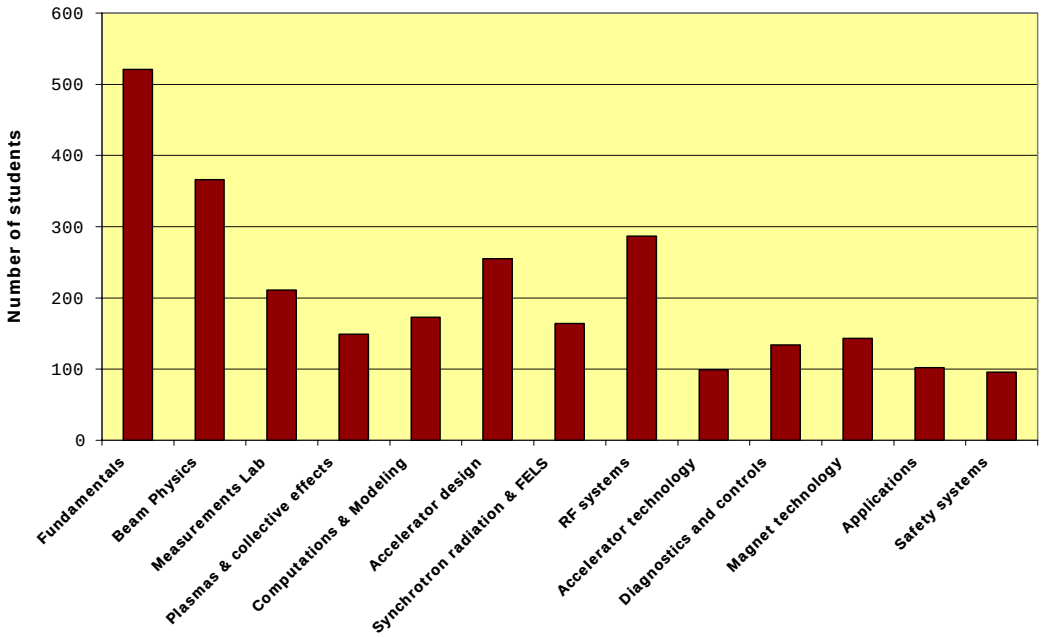


Figure 3 Attendance at USPAS courses 1997 – 2005.

Graduate students in university degree programs generally qualify for financial assistance from the USPAS at its semi-annual programs. This assistance includes the registration fee (~$700), shared housing and two meals per day during the program dates.

USPAS faculty

Highly-qualified instructors are selected by the USPAS Director. Their CVs are submitted to the host university for approval and for adjunct teaching appointments as appropriate. The USPAS selects its instructors from university faculty members and senior researchers from national laboratories and industry (*see Figure 4*) drawing on their practical experience in specific technical fields. The result is a large pool (Appendix D) of prospective instructors with a rich variety of forefront knowledge and methods. A list of books by USPAS faculty is given in Appendix E. Consequently, our curriculum can cover the broad, multi-disciplinary spectrum of material that represents the field of beam physics and accelerator technology.

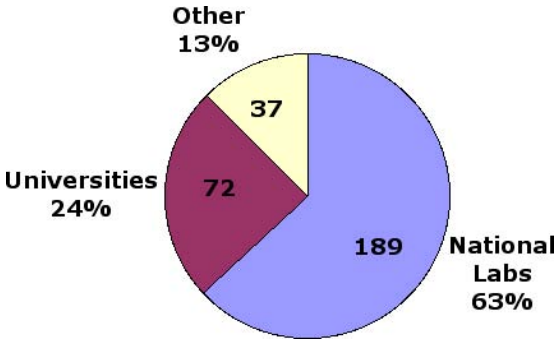


Figure 4 Distribution of USPAS lecturers by home institution

A look at the distribution of lecturers by source of support at their home institution, (see *Figure 5*) shows that the perspectives of the several program offices of DOE's Office of Science, of the NSF, of industry (IND) and of other government agencies both in the U.S. and abroad (category EUR) are equally broadly represented in our instructor pool.

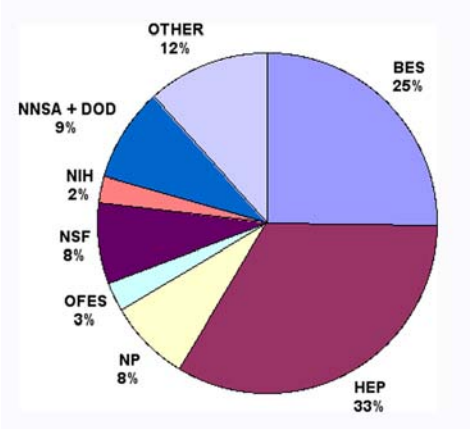


Figure 5 Distribution of USPAS lecturers by home institution source of support.

The USPAS degree program

The U.S. Particle Accelerator School together with Indiana University (IU) offers an opportunity to earn a Master of Science Degree in Beam Physics and Technology. Students may earn credit toward the Indiana University diploma at USPAS/university-sponsored courses. Participants would select their USPAS course for Indiana University credit instead of the host university credit. For each program, USPAS instructors are given visiting professor appointments and USPAS courses are added to the Indiana University curriculum. Award of a Master of Science Degree requires 30 hours of credit with a grade point average of B or above; a maximum of eight credit hours may be transferred; some credits earned at previous USPAS courses may be eligible for transfer. There is a strict five-year limit to obtain the Master of Science degree. The student can meet the IU requirement for both the Classical Mechanics and the Electromagnetism courses by taking one two-week USPAS course titled "Classical Mechanics and Electromagnetism in Beams."

Generally, students may complete the Master's degree program within three years. The maximum completion time is five years. At this time, we are unable to accept international students into the IU/USPAS Master's Degree Program. To date IU/USPAS Master's Degrees have been awarded to four students.

The Advanced Accelerator Concepts Workshop: Legacy of Progress

Tom Katsouleas
University of Southern California

The Advanced Accelerator Concepts Workshop sponsored by the Department of Energy (DOE) Office of High Energy Physics began in 1982 at Santa Fe, New Mexico, under the title "Laser Acceleration of Particles" and has continued roughly every two years until the most recent meeting in Brookhaven, New York, in 2004. The name was changed to "Advanced Accelerator Concepts" at the 1986 meeting in Madison, Wisconsin, reflecting interest in non-laser schemes such as two beam accelerators as well as the expansion of topics to include not just acceleration schemes but advanced research in related areas such as beam focusing and manipulation, novel injectors, ultra-fast diagnostics etc.

Over the past 23 years, the meeting has grown to become the world's premier forum for the exchange of ideas between a diverse community of scientists and engineers that make up the field of advanced accelerator research. It derives intellectual richness from this diversity of backgrounds, and it nurtures scientific advancement through its carefully preserved workshop structure and focus. As such it has served an important role, complementing large meetings such as the Institute of Electrical and Electronics Engineers, Inc. (IEEE) and American Physical Society (APS) sponsored Particle Accelerator Conferences (PACs) by enabling greater interactivity of a smaller group in a quiet setting, providing time for working sessions and spurring advances with specific charges that energized the community and directed it toward important goals.

Year	Location	Chair	Attendees
1982	Santa Fe, NM	Andrew Sessler	67
1985	Malibu, CA	Lee Teng	120
1986	Madison, WI	Robert Siemann	104
1989	Lake Arrowhead, CA	Chan Joshi	87
1992	Port Jefferson, NY	John Nation	145
1994	Lake Geneva, WI	Andrew Sessler	128
1996	Lake Tahoe, CA	Swapan Chattopadhyay	165
1998	Baltimore, MD	Victor Granatstein	160
2000	Santa Fe, NM	Michael Fazio	155
2002	Mandalay Beach, CA	Chan Joshi	163
2004	Stony Brook, NY	Ilan Ben-Zvi	190
2006	Lake Geneva, WI	Wei Gai	

Table 1 History of the Advanced Accelerator Concepts Workshop. The first two were named Laser Acceleration of Particles Workshop

Over the years the size, structure and goals of the workshop have evolved as the field experienced significant advances. In the early meetings, the focus was on exploring laser concepts capable of high accelerating gradients. The first workshop divided into three working groups: near field, far field and media (both dielectric and plasma). Two notable participants who were at that first meeting have participated in every meeting since: David Sutter of DOE and Chan Joshi of University of Los Angeles (UCLA). The

second workshop in January of 1985 in Malibu, California, was nearly double in size and duration (nine days). It saw the first experimental results, highlighted by Chan Joshi's group reporting the first measurement of a plasma beat wave with an accelerating field above 1 GeV/m. Some of us recall that Burt Richter, who opened the meeting, challenged the field by setting a bar at 1 GeV energy gain as a meaningful figure of merit for an advanced concept. By the time of the third workshop in Madison in 1986, the field was turning toward addressing other important figures of merit as well such as number of particles that could be accelerated, and simulations (now mostly 2-D) were taking on an increasingly important role. In 1989 at Lake Arrowhead, CA experimental progress was reported on Inverse Cherenkov Acceleration (ICA) by Wayne Kimura and his group from Spectra Physics and Stanford; and Jamie Rosenzweig and a group at Argonne National Laboratory reported energy gain in a two beam plasma wakefield accelerator. The 1992 Workshop in Port Jefferson, New York, saw a dramatic increase in the number and diversity of publications in the proceedings. The idea of a photonic band gap structure accelerator was proposed. Conceptual work was being augmented with new experiments and new facilities. The UCLA group reported the first ultra-high-gradient acceleration of electrons in their plasma beat wave experiment. And the idea of a Muon Collider that germinated at the 1986 Workshop blossomed here and would later grow and develop to the point of having its own workshop. By 1994 on Lake Geneva, Wisconsin, the workshop had expanded to six working groups (beam handling and conditioning, near and far field, plasma concepts, exotic colliders, novel electron sources and novel rf. Experimental results were presented from around the world including labs in Osaka and KEK in Japan and France's Ecole Polytechnique. Don Umstadter introduced a laser injector scheme that used an inexpensive beam splitter to cross lasers in a plasma and inject electrons into a wakefield (for which he received a $200 check and an order at the banquet!)

The Lake Tahoe Workshop in 1996 was sparked by new results from the Rutherford Appleton Laboratory (RAL)-UCLA-Imperial College group and others at University of Memphis/University of Tennessee, Naval Research Laboratory, Lawrence Livermore National Laboratory, and Japan, demonstrating self-modulated laser wakefield acceleration up to 100 MeV in mm long gas jets. J. Marques' group in France and Michael Downer in Texas also showed advanced optical diagnostic images of stable and long-lived plasma wave structures. Innovations were made in novel structures such as slab-symmetry, in high frequency microwave sources and in sub-ps beam monitoring and control.

At the 1998 Baltimore Workshop, the important educational role of the meeting was clear from the presence of 40 students among the 160 total attendees. David Sutter inspired the working groups by challenging each to design a 100 MeV – 1 GeV demonstration experiment that achieved at the same time a gradient of 1 GeV/m and greater than 10^8 particles in a bunch of low emittance and energy spread. This was also the first of the workshops to have a working group on physics of high energy density beams, a topic that led to novel cooling, focusing and radiation concepts. In 2000 the Workshop returned to its original locale of Santa Fe. The overall theme of the meeting was the celebration of John Dawson's 70th birthday. Several groups were making progress on laser guiding in plasma channels originally demonstrated by Howard Milchberg from University of Maryland. A highlight of the meeting was the results of the STELLA collaboration at Brookhaven National Laboratory's Accelerator Test Facility which showed that electrons could be phased and injected into an Inverse Free Electron Laser operating at 10 micron wavelength, resulting in mono-energetic acceleration. The 2002

Workshop took place at Mandalay Beach in Oxnard, CA. 3-D simulation capability at full-scale to experimental parameters had emerged on scene, and this was the first meeting in the series to feature a working group on advanced modeling techniques. Numerous experimental advances were reported including high-power dielectric-loaded accelerator and focusing and wakefield acceleration experiments on the Stanford Linear Accelerator Center 30 GeV beam line.

The year 2004 in Brookhaven, NY saw two major breakthroughs: the generation of mono-energetic beams in laser wakefield accelerators by three groups at Stanford Linear Accelerator Center, Lawrence Berkeley National Laboratory, LOA (France) and RAL (UK); and the acceleration of electrons beyond 1 GeV by the UCLA/University of Southern California/SLAC collaboration on plasma wakefield accelerators. The editors of Nature trumpeted this year as the "Dawn of the Age of Compact Accelerators." It is an exciting time for the field, and that excitement is sure to be captured at the next Advanced Accelerator Concepts Workshop in Lake Geneva, WI in 2006.

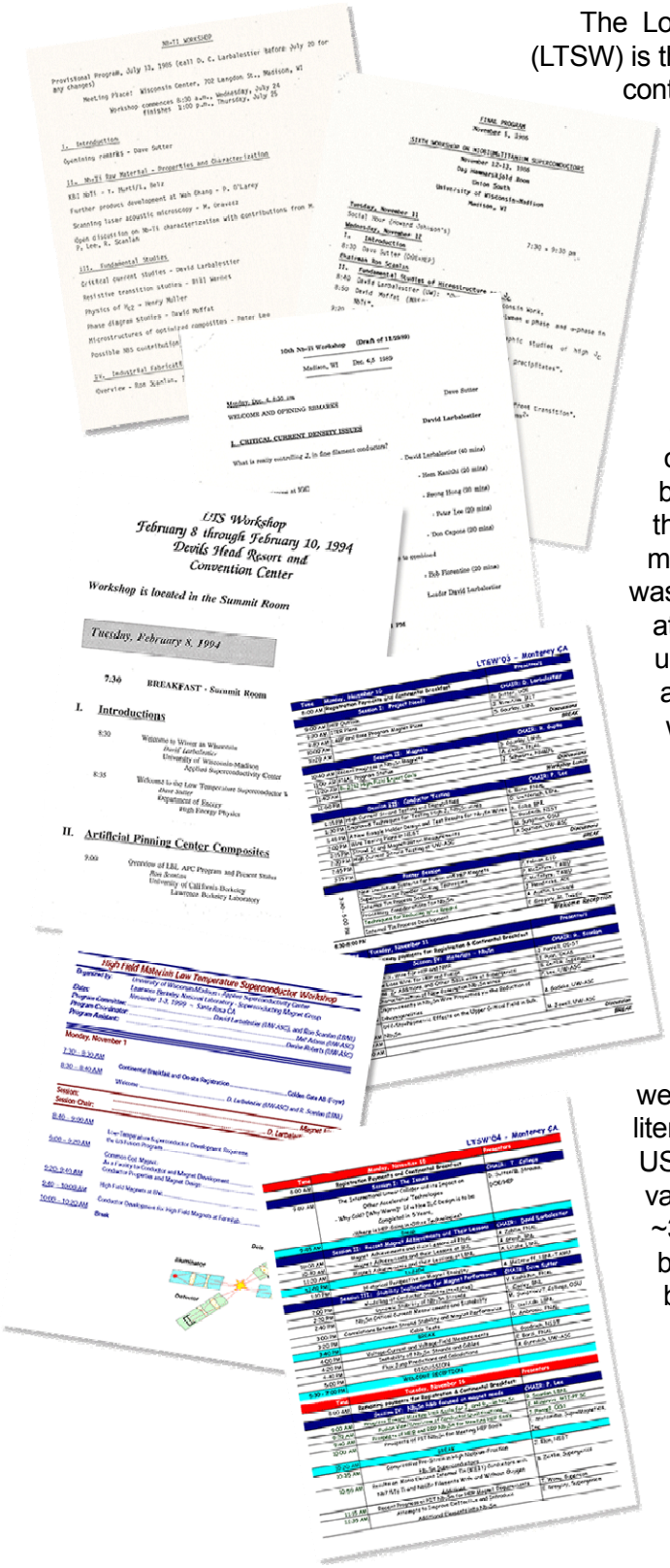
AIP Series No.	Date	Editors
91	1982	P. J. Channell
130	1985	C. Joshi, T. Katsouleas
156	1986	F. E. Mills
193	1989	C. Joshi
279	1992	J. S. Wurtele
335	1994	P. Schoessow
398	1996	S. Chattopadhyay, J. McCullough, P. Dahl
472	1998	W. Lawson, C. Bellamy, D. Brosius
569	2000	P. L. Colestock, S. Kelley
647	2002	C. E. Clayton, P. Muggli
737	2004	V. Yakimenko

Table 2 Workshop Proceedings: All are AIP Conference Proceedings, American Institute of Physics, NY

Acknowledgment

This summary is dedicated to Dr. David Sutter, whose steadfast and thoughtful guidance and support have made it into the successful tradition it has become.

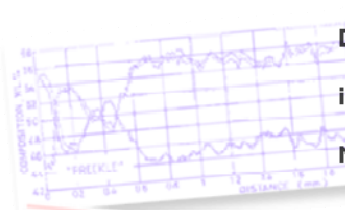
The Low Temperature Superconductor Workshop (LTSW)



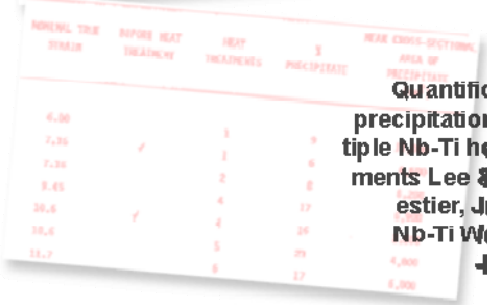
The Low Temperature Superconductor Workshop (LTSW) is the name given to a series of workshops held continuously in every year since 1983 that started out as the Niobium-Titanium workshop. The first of these was held in Madison, WI, in July 1983, sponsored by the US Department of Energy, Division of High Energy Physics. It was designed to serve both as a program review of the grant made to the University of Wisconsin group studying the mechanism of developing high current density in Nb-Ti and as a means of passing on the benefits of this research to the US accelerator builders and to US manufacturing industry. In the first workshop formal presentations were made by UW researchers only; however, it was clear from strong discussion by the attendees that such a researcher-application user-industrial supplier forum was highly appreciated. And indeed, using the workshop-discussion format, that there would be a strong contribution from the entire community in future workshops. An important focus of the first workshop was on the fact that US Nb-Ti wire was not competitive with the best R&D wires elsewhere and that systematic experiments with US industrial Nb-Ti generally did not produce systematic responses, and that studies of the precipitate structures seen in modern wires were not similar to those reported in the literature. The prospect of doubling the regular US wire production critical current density, J_c, values from ~1600-1800 A/mm² at 5 T to the ~3500 A/mm², 5 T, 4.2 K, 10^{-14} Ω·m reported by European and Chinese groups attracted both strong applications and industrial interest.

There were 26 non-UW attendees to the 1984 Nb-Ti workshop and presentations were made by several of these participants. The UW was able to report J_c values exceeding 3000 A/mm² in

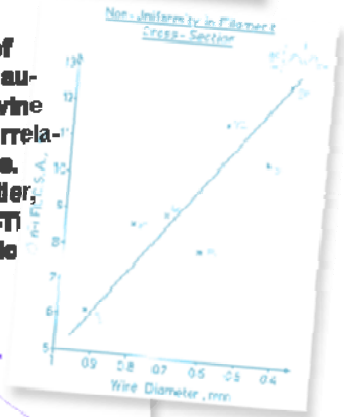
LTSW



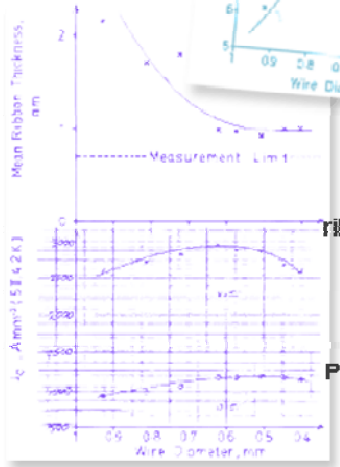
Detailed electron microprobe characterization of Nb-Ti alloy Lee & Larbalestier, Nb-Ti workshop-Jan 1985, Berkeley CA.



Quantification of precipitation in multiple Nb-Ti heat treatments Lee & Larbalestier, July 1985 Nb-Ti Workshop -Madison



Quantification of Nb-Ti filament sausaging during wire drawing and correlation with n-value. Lee & Larbalestier, March 1986 Nb-Ti Workshop-Menlo Park, CA and



Relationship between alpha-Ti ribbon thickness and high Jc Lee & Larbalestier March 1986 Nb-Ti Workshop, Menlo Park, CA and ASC'86

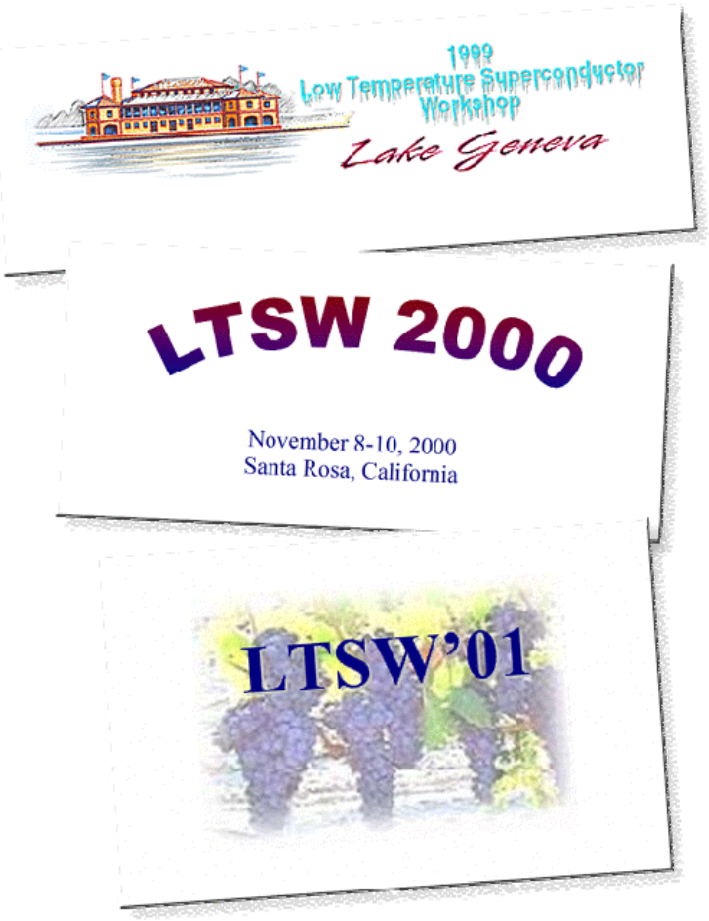
Determination of Nb-Ti prestrain-composition–precipitate morphology relationship - Lee, McKinnell, Larbalestier, and Remsbottom. Nb-Ti Workshop, March 1988 Asilomar, CA.

a > 60 filament multifilamentary conductor (361 filaments) for the first time. In January 1985, the Nb-Ti workshop took place at Lawrence Berkeley Laboratory, reflecting the importance of the meeting to magnet builders. With the increasing urgency necessitated by the design schedule of the Superconducting Supercollider the next workshop was held in July of the same year in Madison. US manufacturers were able to report high (~3000 A/mm^2, 5 T, 4.2 K) critical current densities in fine (~ 5 µm diameter) filament conductors but with a trade-off in piece lengths. The UW was now achieving over 3200 - A/mm² (5 T, 4.2 K) with only three heat treatments by raising the temperature of the precipitation heat treatments (the UW would raise this to over 3500 A/mm² by the end of the year).

By the 6th Workshop on Nb-Ti Superconductors all the US wire manufacturers were able to report critical current densities exceeding 3000 A/mm² (5 T, 4.2 K) in large filament trial billets. By the 8th Nb-Ti workshop, held at Asilomar, CA, in March 1988, the technology for obtaining SSC current requirements and beyond had been developed in both 6 and 9 µm diameter filamentary conductor.

There was considerable pressure over the years from overseas strand manufacturers to open up the Nb-Ti workshop to non-US participants. With SSCL strand procurement under way it was decided that the 11th Nb-Ti workshop would be the last. SSCL wanted to take over some of the technical direction of the purely Nb-Ti and manufacturing aspects of the program. The workshops were of such value, however, that the format was retained for the broader long-term needs of the High Energy Physics and Fusion program. Thus Chevrel phase and Nb_3Sn and Nb_3Al studies started to enter the presentations and discussions, considerably broadening the workshop yet again. In order to distinguish the workshop from the much more numerous high temperature superconductor workshops that were taking place, the workshop name was changed to the Low Temperature Superconductor Workshop (LTSW). Following the cancellation of the SSCL, the workshop again

regrouped to focus on longer term accelerator applications of the HEP community, as well as needs for improved Nb_3Sn of the fusion program, particularly some of the ITER model coil magnets. The annual meeting has continued without a break since that time. The next meeting will take place in November 2005 in Napa CA under the same joint sponsorship of LBNL and the Applied Superconductivity Center of the University of Wisconsin. As in the prior era where the workshop focused on understanding the underlying factors controlling the current density of Nb-Ti and on greatly improving it, a major focus of the last 5 years has been on doing exactly the same for Nb_3Sn. Using a similar combination of national lab-industry-university collaborations the properties of Nb_3Sn have been approximately doubled from a J_c of ~1500 A/mm² at 12 T to 3000 A/mm². The workshop is also nurturing conductor development of Bi-2212 ($Bi_2Sr_2CaCu_2O_x$) and of MgB_2 wires of high performance.



In summary, the LTSW has nurtured a highly productive collaboration of superconducting wire user, superconducting wire manufacturer and superconducting wire researcher over more than 20 years. Low temperature superconductors continue as the "workhorse" conductors for HEP, Fusion, NMR, and MRI; thus, the LTSW continues to be a vital forum for discussing the needs and opportunities for improvements for these applications. The workshop has also been an introduction for many undergraduate and graduate students into the way that lab-industry-research collaborations can spark continuous technical innovation in a very stimulating atmosphere, as well as leading to many employment opportunities. The impact of the workshop is unequalled in the field – the best Nb-Ti and Nb_3Sn wires are made in the United States and the forefront development lead remains in the US still. This collaboration benefits not only the forefront DOE uses for science but the whole US manufacturing industry for superconductor applications.

APPENDICES

Current Graduate (Ph.D.) Students Data FY 2005			
Last Name	**First Name (MI)**	**Institute**	**Advisor**
Vass	Ileana	University of Florida	C. Bohn
Bollinger	Dan	FNAL	C. Bohn
Betzel	Gregory	Northern Illinois University	C. Bohn
Rihaoui	Marwan	Northern Illinois University	C. Bohn
Antipov	Sergey	Illinois Institute of Technology	W. Gai, J. Power
Gao	Feng	Illinois Institute of Technology	W. Gai, J. Power
Wang	Haitow	Illinois Institute of Technology	W. Gai, J. Power
Eremeev	Grigori	Cornell University	H. Padamsee
Shipman	Gerry	Cornell University	H. Padamsee
Grigsby	Franklin	University of Texas at Austin	M. Downer
Matlis	Nicholas	University of Texas at Austin	M. Downer
Shim	Bonggu	University of Texas at Austin	M. Downer
Zgadzaj	Rafal	University of Texas at Austin	M. Downer
Jung	Sebastian	University of Texas at Austin	M. Downer
Smith	Philip	University of Texas at Austin	M. Downer
Tushentsov	Michael	University of Texas at Austin	G. Shvets
Neuner III	Burton	University of Texas at Austin	G. Shvets
Charman	A.	University of California Berkeley	J. Wurtele
Gogardze	V.	University of California Berkeley	J. Wurtele
Lindberg	R.	University of California Berkeley	J. Wurtele
Lei	Shao	University of California Los Angeles	D. Cline
Tzoufras	Michail	University of California Los Angeles	C. Joshi
Sung	Jay	University of California Los Angeles	C. Joshi
Johnson	Devon	University of California Los Angeles	C. Joshi
Zhou	Miaomiao	University of California Los Angeles	C. Joshi
Ralph	Joe	University of California Los Angeles	C. Joshi
Lu	Wei	University of California Los Angeles	C. Joshi
England	Joel	University of California Los Angeles	Rosenzweig/Pellegrini
Lim	Jay	University of California Los Angeles	Rosenzweig/Pellegrini
Andonian	Gerard	University of California Los Angeles	Rosenzweig/Pellegrini
Dunning	Mike	University of California Los Angeles	Rosenzweig/Pellegrini
Cook	Allen	University of California Los Angeles	Rosenzweig/Pellegrini
Osoba	Efunwande	University of California Los Angeles	Rosenzweig/Pellegrini
Hemsing	Erik	University of California Los Angeles	Rosenzweig/Pellegrini
Mitchell	C.	University of Maryland	A. Dragt
Zimmerman	M.	University of Maryland	A. Dragt
Kurennoy	S.	University of Maryland	A. Dragt
Sheng	Hua	University of Maryland	H. Milchberg
York	Andrew	University of Maryland	H. Milchberg
Layer	Brian	University of Maryland	H. Milchberg
Varma	Sanjay	University of Maryland	H. Milchberg
Chen	Yu-Hsin	University of Maryland	H. Milchberg
Gupta	Ayush	University of Maryland	H. Milchberg
Wu	Jianzhou	University of Maryland	H. Milchberg
Palastro	John	University of Maryland	H. Milchberg

Last Name	First Name (MI)	Institute	Advisor
Tian	K.	University of Maryland	P. O'Shea, R. Kishek
Bai	G.	University of Maryland	P. O'Shea, R. Kishek
Tobin	C.	University of Maryland	P. O'Shea, R. Kishek
Papadopoulos	C.	University of Maryland	P. O'Shea, R. Kishek
Stratakis	D.	University of Maryland	P. O'Shea, R. Kishek
Holloway	M.	University of Maryland	P. O'Shea, R. Kishek
Stamatiou	I.	University of Maryland	M. Reiser
Tiwari	S.	University of Maryland	M. Reiser
Purohit	P.	University of Maryland	M. Reiser
Gebeyahu	N.	University of Maryland	M. Reiser
Ngogang	R.	University of Maryland	M. Reiser
Oz	Erdem	University of Southern California	T. Katsouleas
Kallos	Thomas	University of Southern California	T. Katsouleas
Feng	Bing	University of Southern California	T. Katsouleas
Wang	Xiaodong	University of Southern California	T. Katsouleas
Jewell	Matt	University of Wisconsin-Madison	D. Larbalestier P. Lee
Bowman	Arnesto	Florida A. & M. University	R. Williams
Dalban-Canassy	Matteau	Florida State University	S. Van Sciver
Ting	Xu	Florida State University	S. Van Sciver
Kim	Hyung Jin	Florida State University	S. Van Sciver
Anhault	Ben	University of Kansas	J. Shi
Shiaru	Ji	Lawrence Berkeley National Laboratory	J. Byrd
Mattafirri	Sara	University of California Berkeley	G. Sabbi
Bhatt	Ronak	Massachusetts Institute of Technology	C. Chen
Henestroza	Enrique	Massachusetts Institute of Technology	C. Chen
Samokhvalova	Ksenia	Massachusetts Institute of Technology	C. Chen
Zhou	Jing	Massachusetts Institute of Technology	C. Chen
Korbly	Stephen	Massachusetts Institute of Technology	R. Temkin
Smirnova	Evgenya	Massachusetts Institute of Technology	R. Temkin
Marsh	Roark	Massachusetts Institute of Technology	R. Temkin
Manikonda	Shashikant	Michigan State University	M. Berz
Kim	Youn-Kyung	Michigan State University	M. Berz
Grote	Johannes	Michigan State University	M. Berz
Snopok	Pavel	Michigan State University	M. Berz
Poklonskiy	Alexey	Michigan State University	M. Berz
Weathersby	Stephen	Michigan State University	M. Berz
Bentson	Lynn	Michigan State University	M. Berz
Schuman	Gerald	Michigan State University	M. Berz
Satpathy	Asish	Michigan State University	M. Berz
Robertson	Norman	Michigan State University	M. Berz
Vlaicu	Irina	University of New Mexico	J. Ellison
Sobol	Andrey	University of New Mexico	J. Ellison
Salas	Marc	University of New Mexico	J. Ellison
Betzel	Gregory	Northern Illinois University	C. Bohn
Rihaoui	Marwan	Northern Illinois University	C. Bohn
Vass	Ileana	Northern Illinois University	C. Bohn

Last Name	First Name (MI)	Institute	Advisor
Rašković	Marija	Old Dominion University	L. Vušković
Wu	Xiaoxia	Ohio State University	M. Sumption
Bohnenstiehl	Scott	Ohio State University	M. Sumption
Bhatia	Mohit	Ohio State University	M. Sumption
Contracter	Anjun	Ohio State University	M. Sumption
Barnes	Christopher	Stanford University	R. Siemann
Blumenfeld	Ian	Stanford University	R. Siemann
Cowan	Benjamin	Stanford University	R. Siemann
Kirby	Neil	Stanford University	R. Siemann
Lincoln	Melissa	Stanford University	R. Siemann
Johnson	Devon	University of California Los Angeles	R. Siemann
Sears	Christopher	Stanford University	R. Siemann
Akinwande	Deji	Stanford University	R. Ruth
Guo	Jiquan	Stanford University	R. Ruth
Hassanpour	Navid	Stanford University	R. Ruth
Khalid	Shahzad	Stanford University	R. Ruth
Mastorides	Themis	Stanford University	R. Ruth
Nash	Boaz	Stanford University	R. Ruth
Cowen	B.	Stanford University	R. Byer
Sears	C.	Stanford University	R. Byer
Lincoln	M.	Stanford University	R. Byer
Koeth	T.	Rutgers University	H. Edwards
Tikhoplay	R.	University of Rochester	H. Edwards
Li	Jianjian	Illinois Institute of Technology	N. Solyak
Zhou	Weihua	Princeton University	R. Davidson
Sato	Y.	Indiana University	S.Y.Lee
Huang	D.	Indiana University	S.Y.Lee
Breitzman	S.	Indiana University	S.Y.Lee
Hao	Y.	Indiana University	S.Y.Lee
Lin	F.	Indiana University	S.Y.Lee
Su	Y.	Indiana University	S.Y.Lee
Wang	F.	Indiana University	S.Y.Lee
Wu	Q.	Indiana University	S.Y.Lee
Yang	L.	Indiana University	S.Y.Lee
Zhu	L.	Indiana University	S.Y.Lee
Park	C.S.	Indiana University	S.Y.Lee
Kowalski	J.	Indiana University	S.Y.Lee

Past Graduate (Ph.D.) Students and Placements FY 2005						
Last Name	**First Name**	**Institute**	**Advisor**	**Year of Ph.D.**	**First Placement**	**Present Placement**
Zou	P.	ANL	Wei Gai	2002		Intel Corp.
Biedron	Sandra	BNL	Ilan Ben-Zvi	2001		ANL
Murokh	Alex	BNL	Ilan Ben-Zvi	2001		UCLA
Smedley	John	BNL	Ilan Ben-Zvi	2001		BNL
Meng	Wuzeng	Boston University	Krienan	1991	BNL	BNL
Zwart	G. Townsend	Boston University	Krienan	1997	Bates	Bates
Zhang	Ge	Clark Univ./MIT	J. Davies J. Wurtele	1993		Lorel Corporation
Mahmoud	Gamal	Clarkson	T. Bountis	1988		
Papageorgiou	Vassilis	Clarkson	T. Bountis	1988		Crete
Bier	Martin	Clarkson	T. Bountis	1990		Carolina-Greenville
Wernick	I.	Columbia	T.C. Marshall	1992	Rockefeller University	Columbia (Earth Sciences Inst.)
Lin	L-Y	Columbia	T.C. Marshall	1993	FOM Jutphass (Neth. FEL)	North Holland Publishing
Fang	J-M	Columbia	T.C. Marshall	1997	Columbia	Columbia
Fang	J-M	Columbia	T.C. Marshall	1997	Yale Beam Physics Laboratory	
Yoder	Rodney	Columbia	T.C. Marshall J. Hirshfield	2000		
Shchelkunov	Sergey	Columbia	T.C. Marshall	2005	Yale Beam Physics Laboratory	Yale Beam Physics Laboratory
Adler	Richard	Cornell University	J. Nation	1980	AFWL	North Star Research, Inc.
Fenstermacher	Daniel	Cornell University	J. Nation	1985	Harvard	
Providakes	George	Cornell University	J. Nation	1985	Mitre Corp	
Anselmo	Antonio	Cornell University	J. Nation	1987	Varian	
Sheffer	Donald	Cornell University	J. Nation	1991	Duke University	

Last Name	First Name	Institute	Advisor	Year of Ph.D.	First Placement	Present Placement
Koury	Daniel	Cornell University	J. Nation	1992	Texas Instruments	
Davis	Timothy	Cornell University	J. Nation	1993	Kionix, Inc.	Kionix, Inc.
Kuang	Erjia	Cornell University	J. Nation	1994	Motorola, Far East	
Naqvi	Shahid	Cornell University	J. Nation	1996	U. Chicago Radiaology Stu	
Fletchner	Donald	Cornell University	J. Nation	1999	Diamond Microelectronics	Diamond Microelectronics
Koyama	Taka	Cornell University	J. Nation	1999		Intel Corp.
Kashikhin	V.V.	Fermilab	A.V.Zlobin	2002	St. Petersburg Technical University	Fermilab
Imbasciati	Linda	Fermilab	A.V.Zlobin	2003	Vienna Technical University	
Panek	John. S	Florida State University	S. VanSciver	1998	Jet Propulsion Lab/Cal Tech	Goddard Space Flight Center
Hilton	David	Florida State University	S. VanSciver	2003	Florida State University	
Kurki	Taina	Harc/UT-Austin	R. Huson	1989	UC-Berkeley	
Tompkins	Perry	Harc/UT-Austin	R. Huson	1990	Vanderbilt	
Kazima	Reza	Harc/UT-Austin	R. Huson	1992	JLAB	JLAB
Li	Xiaohu	Illinois Institute of Technology	G. Shvets	2001		Lehman Brothers
Goodwin	J.E.	Indiana University	R. Pollock/Lee	1989	Fermilab	Software Industry
Ellison	T.	Indiana University	S.Y. Lee	1990	IUCF	Energy Storage Industry
Minty	Michiko G.	Indiana University	S.Y. Lee A. Krisch	1991	SLAC	DESY
Pei	A.	Indiana University	R. Pollock/Lee	1992	BNL	Lucent
Ellison	M.	Indiana University	S.Y. Lee	1995	University of Colorado	Industry
Huang	Haixin	Indiana University	S.Y. Lee	1995	BNL	BNL
Li	Derun	Indiana University	S.Y. Lee	1995	UC San Diego	LBNL

Last Name	First Name	Institute	Advisor	Year of Ph.D.	First Placement	Present Placement
Nagaitsev	Sergei	Indiana University	P. Schwandt/Lee	1995	Fermilab	Fermilab
Kang	X.	Indiana University	S.Y. Lee	1998	University of Washington	UC-Davis
Riabko	A.	Indiana University	S.Y. Lee	1998	Software Industry	Software Industry
Bai	Mei	Indiana University	S.Y. Lee	1999	BNL	BNL
Ranjbar	V.	Indiana University	S.Y. Lee	2002	Indiana University	
Cousineau	S.	Indiana University	S.Y. Lee	2003	Indiana University	
Van Oort	Johannes	LBNL	S. Gourlay	2000		General Electric Company
Reitsma	A.	LBNL	W. Leemans	2002		Technische Universiteit Eindhoven
Hoffstaetter	George	Michigan State	Martin Berz	1994	University of Darmstadt	DESY
Wan	Weishi	Michigan State	Martin Berz	1995	University of Colorado	ORNL
Makino	Khoko	Michigan State	Martin Berz	1997	Michigan State	Michigan State
Shamseddine	Khodr	Michigan State	Martin Berz	1999	Michigan State	Michigan State
Erdelyi	Bela	Michigan State	Martin Berz	2001	FNAL	
Hoefkins	Jens	Michigan State	Martin Berz	2001	Gene Data	
Ige	O.O.	MIT	Y. Iwasa	1989		
Conde	Manoel	MIT	G. Bekefi	1992	ANL	ANL
Chu	Yiu	MIT	J. Wurtele	1993	VCR Plus	TRW Corporation
Menninger	William	MIt	R. Temkin B. Danly	1994	Hughes Electron Devices	Hughes Electron Devices
Stoner	Richard	MIT	G. Bekefi	1994		
Yu	Xiao Tong	MIT	J. Wurtele	1994	Long Term Capital Management	
Lin	Chia-Lian	MIT	S. Chen A. Danly J. Wurtele	1995	Torrey Communications	Phillips Corporation
Shvets	Gennady	MIT	J. Wurtele	1995	PPPL	PPPL

Last Name	First Name	Institute	Advisor	Year of Ph.D.	First Placement	Present Placement
Huang	Wen	MIT	G. Bekefi R. Temkin	1997	Goldmand Sachs	Goldman Sachs
Trotz	Seth	MIT	R. Temkin B. Danly	1997	Dartmouth	MIT Lincoln Laboratory
Catravas	Palmyra	MIT	H. Haus J. Wurtele	1998	LBNL	LBNL
Volfbehn	Pavel	MIT	W. Leemans J. Wurtele	1998	LBNL	Harmonic, Inc.
Fink	Yoel	MIT	C. Chen J. Joannopoulos E. Thomas	2000	Mitre Corp	MIT, Faculty
Hess	Mark	MIT	C. Chen	2002	Visiting Prof. Clark University	MIT
Brown	Withrop	MIT	R. Temkin	2001		LLNL
Gonichon	Jerome	MIT/University of Paris	C. Travier S. Chen B. Danly R. Temkin	1995	GE Medical Systems, France	GE Medical Systems, France
Baine	Michael	NRL/UCSD	S. Ride A. Ting P. Sprangle	2000	Advanced Propulsion Lab, NASA Johnson Space Center	NASA Johnson Space Center
Sumption	M.D.	Ohio State University	E. Collings	1992	OSU	OSU
Buta	Flori	Ohio State University	E. Collings	2002		Hyper Tech Research
Russell	D. Patrick	Princeton University	K. McDonald	1992	U. Wisconsin Med Phys	
Strasburg	Sean	Princeton University	Ronald Davidson	2001		NRL
Kinglsey	Lawrence	Rochester University	A. Melissinos	1990	University of Toronto	Army Lab - New Jersey
Bamber	Charles	Rochester University	A. Melissinos	2002	University of Rochester	
Plettner	Thomas	Stanford University	R.L. Byer	2002		Stanford University
Soika	Riainer	Texas A&M University	P. McIntyre	1990	BNL	
Bruhwiler	David	University of Colorado	J.R. Cary	1991	Grumman	Tech-X Corporation

Last Name	First Name	Institute	Advisor	Year of Ph.D.	First Placement	Present Placement
Gabella	William	University of Colorado	J.R. Cary	1996	UCLA	Vanderbilt FEL
Hendrickson	Scott	University of Colorado	J.R. Cary	1996	Kaiser Technologies	Tech-X Corporation
Stoltz	Peter H.	University of Colorado	J.R. Cary	1990	PPPL	Tech-X Corporation
Li	Minyang	University of Houston	S. Ohnuma	1990	SSCL	
Machida	Shinji	University of Houston	S. Ohnuma	1990	KEK	KEK
Raparia	Deepak	University of Houston	S. Ohnuma	1991	SSCL	
Zhang	Peiei	University of Houston	S. Ohnuma	1981	SSCL	
Grossman	John	University of Maryland	C. Striffler	1982	NRL	NRL
Douglas	David	University of Maryland	A. Dragt	1983	LBNL	TJNAF (CEBAF)
Floyd	Linton E.	University of Maryland	M. Reiser W. Destler	1983	NRL	Industry
Cremer	T.	University of Maryland	W. Destler	1984	Industry	
Forest	Etienne	University of Maryland	A. Dragt	1984	LBNL	KEK HEP Lab
Forest	Etienne	University of Maryland	A. Dragt	1984	LBNL	KEK High Energy Physics Laboratory
Loschialpo	Peter F.	University of Maryland	M Reiser	1984	NRL	NRL
Milutinovic	Janko	University of Maryland	A. Dragt	1984	BNL	Wall Street
Lawson	Wesley	University of Maryland	W. Destler C. Striffler	1985	University of Maryland	University of Maryland, Faculty
O'Shea	Patrick G.	University of Maryland	W. Destler M. Reiser	1985	LANL	University of Maryland, Faculty
Schneider	Ralph F.	University of Maryland	M.J. Rhee	1985	Defense Threat Reduction Agency	Industry
Healy	Liam	University of Maryland	A. Dragt	1986	CERN	NRL, Celestial Mechanics Group

Last Name	First Name	Institute	Advisor	Year of Ph.D.	First Placement	Present Placement
Chojnacki	Eric P.	University of Maryland	W. Destler	1987	ANL	Cornell University
Kehs	R.A.	University of Maryland	V. Granatstein	1987	LLNL	LLNL
Ryne	Robert	University of Maryland	A. Dragt	1987	LANL	LBNL
Aghamir	Farzin	University of Maryland	W. Destler	1988	UCLA	UCLA
Chang	Chu Rui	University of Maryland	M. Reiser	1989	SSCL	Industry
Park	Gun-Sik	University of Maryland	V. Granatstein	1989	Seoul National University, S. Korea	Seoul National University, S. Korea
Bleum	Hans	University of Maryland	V. Granatstein	1990	Industry	Industry
Li	Rui	University of Maryland	R. Gluckstern	1990	TJNAF (CEBAF)	TJNAF (CEBAF)
Rangarajan	Govindan	University of Maryland	A. Dragt	1990	LBNL	Indian Institute of Science
Zhang	Xiaohao	University of Maryland	C. Striffler	1990		
Calame	Jeffrey	University of Maryland	V. Granatstein W. Lawson	1991	NRL	NRL
Lou	Wei Ran	University of Maryland	V. Granatstein Y. Carmel	1991	Lucent Technologies	Lucent Technologies
Abe	David K.	University of Maryland	W. Drestler	1992	NRL	NRL
Kehne	David	University of Maryland	M. Reiser	1992	TJNAF (CEBAF)	FM Technologies
Tantawi	Sami G.	University of Maryland	V. Granatstein	1992	SLAC	SLAC
Fischer	Richard P.	University of Maryland	V. Granatstein	1993	NRL	NRL
Wang	Dunxiong	University of Maryland	M. Reiser	1993	TJNAF (CEBAF)	TJNAF (CEBAF)
Zhang	Zexiang	University of Maryland	V. Granatstein	1993	Lucent Technologies	Lucent Technologies
Meyers	T.	University of Maryland	W. Destler	1994		
Rappaport	Harold	University of Maryland	C. Striffler	1994	University of Texas	University of Texas

Last Name	First Name	Institute	Advisor	Year of Ph.D.	First Placement	Present Placement
Abell	Daniel	University of Maryland	A. Dragt	1995	BNL	Tech-X Corporation
Brown	Nathan	University of Maryland	M. Reiser	1995	Gillespie Associates	Industry
Cheng	Wen-Hao	University of Maryland	R. Gluckstern	1995	LBNL	Intel Corp.
Allen	Chris	University of Maryland	M. Reiser	1996	Industry	LANL
Jiang	Shicheng	University of Maryland	A. Dragt	1996	Cable and Wireless, Inc.	Cable and Wireless, Inc.
Suk	Hyyong	University of Maryland	M. Reiser	1996	UCLA	UCLA
Fedotov	Alexei	University of Maryland	R. Gluckstern	1997	BNL	BNL
Cheng	J.P.	University of Maryland	W. Lawson	1998		
Clark	Thomas	University of Maryland	T. Antonsen	1998	NRL	NRL
Nikitin	Sergei	University of Maryland	T. Antonsen	1998	Quantronix Corporation	Quantronix Corporation
Venturini	Marco	University of Maryland	A. Dragt	1998	SLAC	LBNL
Bernal	Santiago	University of Maryland	M. Reiser	1999	University of Maryland	University of Maryland
Zou	Yun	University of Maryland	M. Reiser	2000	Industry	Industry
Castle	M.	University of Maryland	W. Lawson	2001		John Hopkins APL
Alexeev	I.	University of Maryland	H. Milchberg	2003	NRL	
Bian	Zhigang	University of Maryland	H. Milchberg	2003	Lucent Technologies	
Parra	E.	University of Maryland	H. Milchberg	2003	National Institute of Health	
Fan	J.	University of Maryland	H. Milchberg	2002	NEC Labs	
Schuett	Petra	University of Maryland/ Hamburg	A. Dragt T. Wailand	1988	TU, Darmstadt	GSI, Darmstadt
Goodwin	J.E.	University of Michigan	Krisch	1990	FNAL	
Anferov	V.A.	University of Michigan	Krisch	1992	IHEP	

Last Name	First Name	Institute	Advisor	Year of Ph.D.	First Placement	Present Placement
Shoumkin	D.S.	University of Michigan	Krisch	1993	IHEP	
Chu	C.M.	University of Michigan	Krisch	1994	IUCF	
Koulsha	A.V.	University of Michigan	Krisch	1994	Industry/Russia	
Van Guilder	B.	University of Michigan	Krisch	1994	Montclair State College	
Blinov	Boris	University of Michigan	Krisch	1995	University of Michigan	University of Michigan
Alexeva	L.V.	University of Michigan	Krisch	1996	IHEP	
Crandall	D.A.	University of Michigan	Krisch	1996	Industry	
Varzar	S.M.	University of Michigan	Krisch	1996	IHEP	
Abedi-Khafri	M.	University of Oregon	Csonka	1985		
Watanobe	Hiroshi	University of Oregon	Csonka	1985	Colgate University	
Chen	Li	University of Oregon	Csonka	1992		
Fisher	David L.	University of Texas	T.Tajima	1995	UTA Applied Physics Lab	UTA Applied Physics Lab
Ottinger	Michael	University of Texas	T.Tajima	1997	Turman State University	Turman State University
Chen	X.M. Jerry	University of Texas	T.Tajima	1999	Dupont Photmaks	
Hawksworth	David G.	University of Wisconsin, Madison	D. Larbalestier	1981	Oxford Magnet Technologies	Oxford Magnet Technologies
Smathers	David	University of Wisconsin, Madison	D. Larbalestier	1983	Teledyne Wah Chang	TOSHOH SMD
Moffat	David	University of Wisconsin, Madison	D. Larbalestier	1985	Was in the field	Madison Software Company
Larson	Delbert	University of Wisconsin, Madison	D. Cline F. Mills	1986	University of Wisconsin	SAIC

Last Name	First Name	Institute	Advisor	Year of Ph.D.	First Placement	Present Placement
Marken	Kenneth R.	University of Wisconsin, Madison	D. Larbalestier	1986	NIM Japan	Batelle-Columbus
Warnes	William H.	University of Wisconsin, Madison	D. Larbalestier	1986	Oregon State University, Faculty	Oregon State University, Faculty
Rosenzweig	James	University of Wisconsin, Madison	D. Cline J. Simpson	1988	ANL	UCLA
Holmes	D. Scott	University of Wisconsin, Madison	S. VanSciver	1989	Lake Shore Cryotronics	Consulting
Meingast	Christopher	University of Wisconsin, Madison	D. Larbalestier	1989	ITP, Forschungszentrum Karlsruhe, Germany	ITP, Forschungszentrum Karlsruhe, Germany
Muller	Henry	University of Wisconsin, Madison	D. Larbalestier	1989		Midwest Superconductors
Weisdand, II	John G.	University of Wisconsin, Madison	S. VanSciver	1989	SSC Laboratory	Cryogenics at SLAC
Daumling	Manfred	University of Wisconsin, Madison	D. Larbalestier	1990		NKT Research Center
McKinnell	Jim	University of Wisconsin, Madison	D. Larbalestier	1990	Oxford Superconducting Technology	HP
Seuntjens	Jeffrey	University of Wisconsin, Madison	D. Larbalestier	1990	Oxford Superconducting Technology	Singapore Fine Wire
Buckett	Mary	University of Wisconsin, Madison	D. Larbalestier	1991	3M	
Daugherty	Mark A.	University of Wisconsin, Madison	S. VanSciver	1991	LANL	Private Practice
Hampshire	Damian	University of Wisconsin, Madison	D. Larbalestier	1991		POHANG

Last Name	First Name	Institute	Advisor	Year of Ph.D.	First Placement	Present Placement
Maddocks	James	University of Wisconsin, Madison	S. VanSciver	1991		
Palkovik	John	University of Wisconsin, Madison	D. Cline F. Mills	1991	SSCL	
Stejic	George	University of Wisconsin, Madison	D. Larbalestier	1993	Eaton Corporation	Tesla Laboratories
Bonney	Laura	University of Wisconsin, Madison	D. Larbalestier	1994	FSU - NHMFL	Johns Hopkins University
Cooley	Lance	University of Wisconsin, Madison	D. Larbalestier	1994	NRC Fellow - NIST	BNL
Huang	Yuenian	University of Wisconsin, Madison	S. VanSciver	1994	FNAL	FNAL
Huang	Ziaodong	University of Wisconsin, Madison	S. VanSciver	1994	NHMFL	Position in finance
Jablonski	Paul	University of Wisconsin, Madison	D. Larbalestier	1994	Teledyne Wah Chang	Precision Castparts Airfoils
Heussner	Robert	University of Wisconsin, Madison	D. Larbalestier	1997	HP	
Kadyrov	Earnest (Eric)	University of Wisconsin, Madison	D. Larbalestier	1997	Hewlett-Packard	Hewlett-Packard
Parrell	Jeff	University of Wisconsin, Madison	D. Larbalestier	1997	Oxford Superconducting Technology	
Cole	Benjamin	University of Wisconsin, Madison/North Texas State	D. Cline F. Mills	1992 1993	SSCL	
Govil	Richa	UC-Berkeley	J. Wurtele W. Leemans	1999	Consulting	
Schoeder	Carl	UC-Berkeley	J. Wurtele	1999	UCLA	UCLA
Backhaus	Ekaterina	UC-Berkeley	J. Wurtele	2001	High School Science Teacher	
Wu	Boris	UC-Berkeley	J. Wurtele A.	2002	Semi-Conductor Industry	

Last Name	First Name	Institute	Advisor	Year of Ph.D.	First Placement	Present Placement
Kawamura	Emi	UC-Berkeley	J. Wurtele C. Birdsall	2003		
Golden	Fletcher	UC-Berkeley	Fisher Rostoker	1985	EG&G	
Irans	Ardeshir	UC-Berkeley	Fisher Rostoker	1985	BNL	
Darrow	Chris	UC-Irvine	C. Joshi	1986	LLNL	LLNL
Figueroa	humberto	UC-Irvine	C. Joshi	1986	ANL	ITT Venezuela
Mori	Warren	UCLA	C. Joshi	1987	Rutherford Laboratory	UCLA
Umstadter	Don	UCLA	C. Joshi	1987	Bell Labs	University of Michigan
Wilks	Scott	UCLA	C. Joshi	1989	LLNL	LLNL
Leemans	Wim	UCLA	C. Joshi	1991	LBL	LBL
Robin	David	UCLA	C. Pellegrini	1991	LBNL	LBNL
Wong	W.H.	UCLA	Clark	1991	UCLA	
Moore	James M.	UCLA	Clark	1992	IBM	
Sakawa	Youichi	UCLA	C. Joshi	1992	Nagoya University	Nagoya University
Savage, Jr.	Richard	UCLA	C. Joshi	1992	CalTech	CalTech
Wang	Zijie	UCLA	D. Cline I. Ben-Zvi	1992	BNL/UCLA	BNL
Williams	Ronald	UCLA	C. Joshi	1992	Florida A&M	Florida A&M
Hartmand	Spencer	UCLA	C. Pellegrini	1993	SLAC	Opti-Phase Corporation
Decker	Chris	UCLA	C. Joshi	1994	LLNL	LLNL
Everett	Matt	UCLA	C. Joshi	1994	LLNL	Private Industry
Brogle	Robert	UCLA	C. Joshi	1996	Areoject, Inc.	Optimight, Inc.
Davis	Joseph (Pepe)	UCLA	C. Joshi	1996	Optiphase, Inc.	Optiphase, Inc.
Lal	Amit	UCLA	C. Joshi	1996	Metrolaser, Inc.	Metrolaser, Inc.
Smolin	John	UCLA	C. Pellegrini	1996	IBM	IBM
Travish	Gilbert	UCLA	J. Rosenzweig	1996	UCLA	ANL
Colby	Eric P.	UCLA	J. Rosenzweig	1997	SLAC	SLAC
Liu	Yabo	UCLA	D. Cline	1997	Pharo Science & Applications, Inc.	PWARE, Inc.
Ramachandran	Sathyadev	UCLA	C. Cline T. Murphy (FNAL)	1997	FNAL	University of Houston

Last Name	First Name	Institute	Advisor	Year of Ph.D.	First Placement	Present Placement
Zhang	Renshan	UCLA	C. Pellegrini	1997	Hughes Corporation	
Barov	Nikolai	UCLA	J. Rosenzweig	1998	UCLA	UCLA
Hogan	Mark	UCLA	C. Pellegrini	1998	SLAC	SLAC
Terebilo	Andrei	UCLA	C. Pellegrini	1998	SLAC	SLAC
Tzeng	Kuo-Cheng	UCLA	C. Joshi	1998	Investment Banking	
Wharton	Kenneth R.	UCLA	C. Joshi	1998	LLNL	LLNL
Gordon	Dan	UCLA	C. Joshi	1999	NRL	NRL
Tremain	Aaron	UCLA	J. Rosenzweig	1999	UCLA	UCLA
Duda	Brian	UCLA	C. Joshi	2000	Lincoln Labs, MIT	Lincoln Labs, MIT
Hemker	Roy	UCLA	C. Joshi	2000	University of Tokyo	University of Tokyo
Anderson	Scott	UCLA	J. Rosenzweig	2002		LLNL
Murokh	Alexei	UCLA	J. Rosenzweig	2002		UCLA
Wang	Shuoqin	UCLA	C. Joshi	2002		Hughes Research Labs
Blue	Brent	UCLA	C. Joshi	2003		LLNL
Ho	Ching-Hung	UCLA/ANL	D. Cline J. Simpson	1992	Taiwan	Taiwan
Liu	Yabo	UCLA/BNL	D. Cline I. Ben-Zvi	1997	UCLA	UCLA
Rajagopalan	Sankaranaray	ULCA/SLAC	D. Cline P. Chen	1993	UCLA	Industry
Nantista	Christopher	UCLA/SLAC	D. Cline T. Lavine	1994	SLAC	SLAC
Lin	Zin-Tian	UC-San Diego	N. Kroll	1995		
Gou						
Lai	S.K.	U-IA/Columbia	A. Bhattacharjee	2000	Semi-Conductor Industry	Semi-Conductor Industry
hiou	C.H.	University of Southern California	T. Katsouleas	1997	Industrial Technology Investment Corporation	Star Capital Group
Ahn	T.C.	University of Southern California	T. Katsouleas	1998	Qualcom	Qualcom
	Hyo	Yale	V. Hughes	1992		

Yearbook Acronyms 2005

1DOF	One-degree freedom
AGS	Alternating Gradient Synchrotron
APS	American Physical Society
APT	Atom-probe tomography
ARDB	Accelerator Research Department B (SLAC)
ATF	Accelerator Test Facility
BLM	Beam Loss Monitor
BNL	Brookhaven National Laboratory
BPM	Beam Position Monitors
CAMAC	Computer Automated Measurements and Control
CAS	Captured and significantly accelerated
CBB	Collective Beam-Beam
CCD	Charged coupled device
CCR	Calabasas Creek Research, Inc
CDR	Center for Design Research
CNL	Crocker Nuclear Laboratory
CSR	Coherent synchrotron radiation
CTF3	CLIC Test Facility 3
DESY	Deutsches Elektronen Synchrotron
DLWC	Delayed Line Wire Chambers
DOE	Department Of Energy
DOE/HEP	Department of Energy/High Energy Physics
DOE/OETD	Department of Energy/Office of Electric Transmission & Distribution
DSAT	Dynamical Systems and Accelerator Theory
e-beam	electron beam
ECAE	Equal channel angle extrusion
EIT	Electromagnetic induced transparency
EO-flash	Electro-optical flash
EPW	Electron plasma wave
ESONE	European Standards On Nuclear Electronics
EUV	Extreme Ultra-Violet
FEL	Free Electron Lasers
FESEM-EDS	Field Emission Scanning Electron Microscope-Energy Dispersive Spectroscopy
FFAG	Fixed Field Alternating Gradient
FFTB	Final Focus Test Beam
FIB	Focused ion Beam
FNAL	Fermi National Accelerator Laboratory
FWHM	Full width at half maximum
GVD	Group Velocity Dispersion
HEP	High Energy Physics
HEPAP	High-Energy Physics Advisory Panel
HEPL-SCA	High Energy Physics Lab (Stanford) – Superconductivity Accelerator
HER	High Energy Ring
HOM	Higher Order Modes
HRC	Haimson Research Corporation

HTS	High Temperature Superconductor
I/O	Input/Output
IC	Ionization chambers
ICA	Independent component analysis
ICA	Inverse Cherenkov Acceleration
ICFA	International Committee for Future Accelerators
ICOOL	Ionization cooling
ICR	Interstrand contact resistances
ICS	Inverse Compton scattering
ID	Insertion Devices
IEEE	Institute of Electrical and Electronics Engineers, Inc
IFEL	Inverse Free Electron Laser
IFS	Institute for Fusion Studies
IIT	Illinois Institute of Technology
ILC	International Linear Collider
INFN	National Institute of Nuclear Physics
IP	Interaction point
IR	Intersection region
IREAP	Institute for Research in Electronics and Applied Physics University of Maryland
ISS	International (Neutrino Factory) Scoping Study
ITRP	International Technology Recommendation Panel
IUCF	Indiana University Cyclotron Facility
KIPAC	Kavli Institute for Particle Astrophysics and Cosmology
LANL	Los Alamos National Laboratory
LANSCE	Los Alamos Neutron Scattering Science Center
LASM	Laboratories for Applied Superconductivity and Magnetism
LBNL	Lawrence Berkeley National Laboratory
LCLS	Linac Coherent Light Source
LEAP	Laser-Electron Accelerator Project
LER	Low Energy Ring
LHC	Large Hadron Collider
LLNL	Lawrence Livermore National Laboratory
LOA	Laser Optical Accelerator
LSE	Long Solenoid Experiment
LWFA	Laser wakefield acceleration
LINAC	Linear induction accelerator
MCOG	Muon Collaboration Oversight Group
MIA	Model-Independent Analysis
MICE	Muon Ionization Cooling Experiment
MIG	Magnetron Injection Gun
MNRC	McClellan Nuclear Reactor Center
MO	Magneto optical
MSE	Materials Science and Engineering Department
MTA	MUCOOL Test Area
MUTAC	Muon Technical Advisory Committee
NERSC	National Energy Research Scientific Computing Center
NFMCC	Neutrino Factory and Muon Collider Collaboration
NIST	National Institute of Standards and Technology
NIU	Northern Illinois University
NLC	Next linear collider

NLCTA	Next Linear Collider Test Accelerator
NSA	National Security Agency
NSF	National Science Foundation
NUCAPT	Northwestern University Center for Atom-Probe Tomography
ORM	Orbit response matrix
OSC	Optical stochastic cooling
OST	Oxford Superconductor Technology
OTR	Optical transition radiation
PACs	Particle Accelerator Conferences
PBG	Photonic Bandgap
PBPL	Particle Beam Physics Laboratory
PBWA	Plasma beatwave accelerator
PCF	Photonic crystal fiber
PIC	Particle-in-Cell
PIT	Powder-in-tube
PMQ	Permanent magnet quadrupole
PMTs	Photomultiplier tubes
PPM	Periodic permanent magnet
PPRC	Polarized Photocathode Research Collaboration
PSR	Proton Storage Ring at Los Alamos
PSFC	Plasma Science and Fusion Center
RBK	Ribbon-beam klystrons
RF	Radio frequency
RHIC	Relativistic Heavy Ion Collider
RHT	Reaction heat treated
RRR	Residual resistively ratio
RS	Raman-seeded
SASE	Self-Amplified Spontaneous Emission
SBIR	Small business innovation research
SCA-FEL	Superconductivity Accelerator-Free Electron Laser
SCL	Space-charge-limited
seeded SM-LWFA	seeded self-modulated laser wakefield acceleration
SEM	Secondary emission monitors
SLAC	Stanford Linear Accelerator Center
SLC	Stanford Linear Collider
SNR	Signal-to-noise ratio
SNS	Spallation Neutron Source
SOI	Silicon on Insulator
SRF	Superconducting RF
STELLA-LW	The Staged Electron Laser Acceleration – Laser Wakefield
SWABSiC	Surface Wave Accelerator Based on Silicon Carbide
TAMU	Texas A&M University
TESLA	TeV Energy Superconducting Linear Accelerator
TL	Temperature-limited
UCLA	University of California Los Angeles
UIT	Undulator Induced Transparency
UIUC	University of Illinois at Urbana-Champaign
UMER	University of Maryland Electron Ring

VLA	Vacuum laser acceleration
VME	Versa Module Europa
VSO	VME Standards Organization
VUV	Vacuum UltraViolet
WMPT	Weighted macroparticle tracking
WSBB	Weak-Strong Beam-Beam