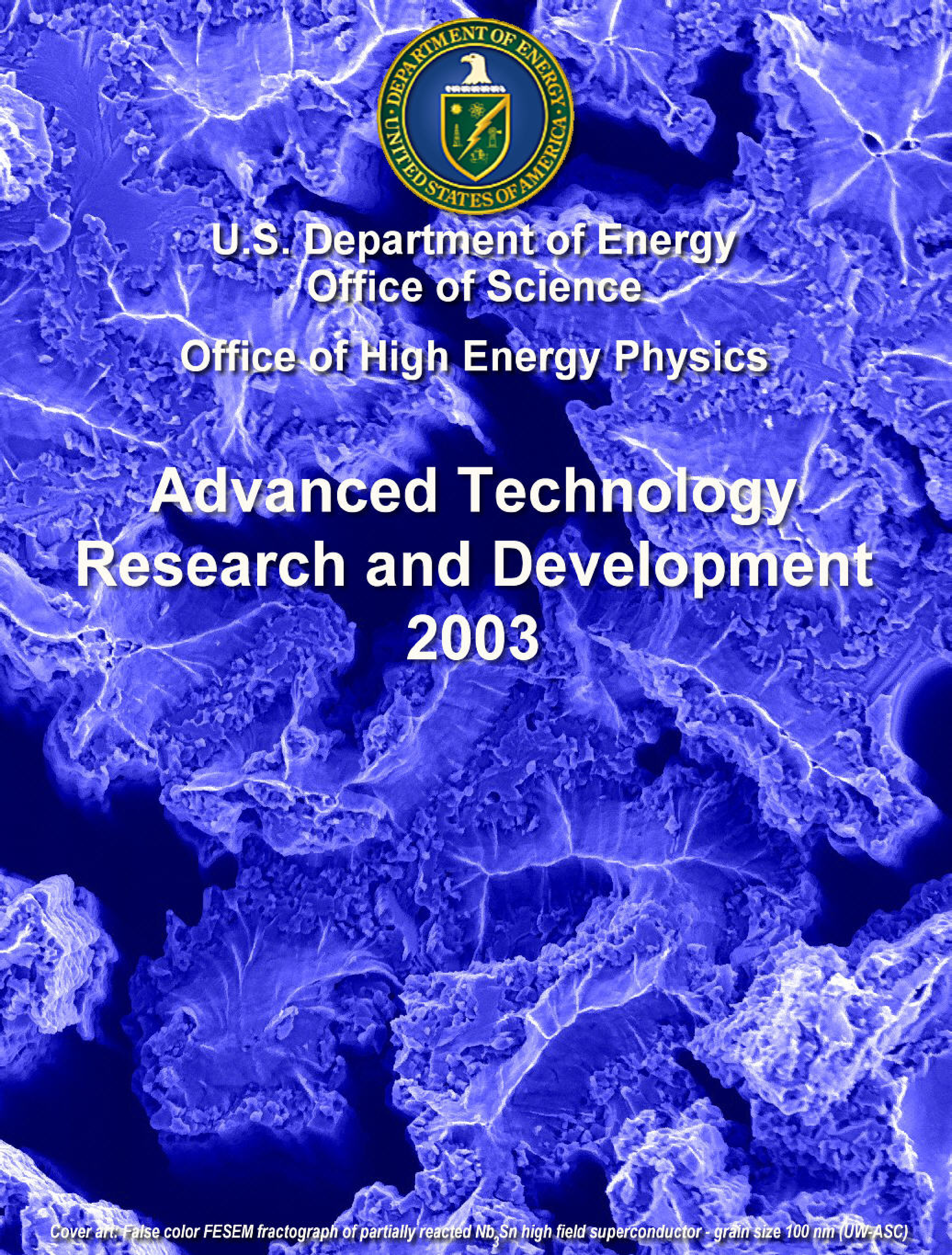
U.S. Department of Energy
Office of Science

Office of High Energy Physics

Advanced Technology Research and Development 2003



Cover art: False color FESEM fractograph of partially reacted Nb_3Sn high field superconductor - grain size 100 nm (UW-ASC)

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Introduction

We are pleased to provide the second "Year Book" of summaries of the research work supported by the Advanced Technology R&D Program of the Department of Energy's (DOE) Office of High Energy Physics (HEP). We found the first Year Book, published in 2000, to be of wide interest in the physics community and in government. We also have concluded that once every three years is about the right spacing for these reports. There have been changes and additions since 2000: the number of university grants has declined reflecting the budget times; information on Ph.D.'s granted under research sponsored by our program has been expanded to include Ph.D.'s earned in accelerator physics and technology at the DOE national laboratories under HEP funding; the name of the Division of High Energy Physics has been changed to "Office of High Energy Physics," reflecting a summer 2003 reorganization; and budget categories have been restructured so that what was called the "Washington Administered University Program" is now largely in "Accelerator Science."

The Program, by whatever name, continues in its mission to support a very broad range of accelerator science and technology ranging from the metallurgical optimization of superconductors to advanced accelerator concepts such as laser and plasma acceleration of charged particles. Overall the Advanced Technology R&D program was an approximately $24 million effort in FY03. The breakdowns in funding by topic and institutions supported are shown in Figures 1 and 2.

Additional R&D into the technologies for HEP accelerators and detectors is supported under the SBIR/STTR program which was funded at a level of about $16 million in FY03 and will climb to about $17 million in FY04. The SBIR/STTR funding is a set aside required by law. We have made a strong and largely successful effort to integrate this work into the overall accelerator and detector R&D needs of the HEP program. Descriptions of the work funded may be found in the relevant published abstracts of SBIR/STTR R&D which can be viewed on the Web at http://sbir.er.doe.gov/sbir/. Scroll down to "Award Data" where the abstracts of funded R&D from 1998 through the present can be found.

The criteria for the work that we categorize as "Advanced Technology R&D" is that it 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 the frontiers in these areas, with a specific focus on topics that may be applicable to high energy physics. The Program was first funded in 1982 as a primarily university based activity, although a few university grants for research in accelerator physics were in place as early as 1975. It was created on the recommendation of a 1980 HEPAP sub panel that the DOE HEP program provide a special venue for funding work in advanced accelerator physics and technology R&D, particularly topics of very high risk but with very high potential payoff, that were unlikely to be supported through our usual national laboratory technology R&D programs. The present Program, now funded primarily under the Accelerator Science budget, continues to follow this policy. As an example, we do not include the R&D in support of the Next Linear Collider (NLC) or the muon collider. The status of the latter will soon change back to long range R&D and will be included here next time. As the Advanced Technology R&D program evolved, it became clear that some of the topics could be carried out beneficially in the HEP supported national laboratories, and so funds separate from the University Program were found for the laboratories, as noted above, and this aggregate of R&D is now mostly captured in Accelerator Science.

Each of the research summaries included in this report was prepared by the principal investigator or the national laboratory manager for that research and represents the respective individual's view of the work performed. The summaries are snapshots of programs as of the summer 2003. Included at the end of each summary are lists of the group's recent talks and papers published, a list of current persons working on the research projects funded under the grant, and information on how to contact the Principal Investigator or Group Leader - should additional information about the research be desired.

We have again included two appendices with demographic data. Appendix A lists the current Ph.D. candidate graduate students supported in Fiscal Year 2003, and Appendix B lists all of the Ph.D. students who obtained their degrees under the HEP program. These are listed by institution and advisor; and we include year of degree, first employment following the degree, and current employment where known. It should be clearly understood that these lists of Ph.D. degrees awarded are only a subset of the degrees granted in the U.S. in accelerator physics and technology. In addition to High Energy Physics, the DOE supported national laboratory programs in Nuclear Physics and Basic Energy Sciences also have research activities that provide for Ph.D. thesis topics in accelerator physics and technology, and these Ph.D.'s are not included. Nor are the Ph.D.'s obtained under the National Science Foundation - supported work at Cornell, Michigan State and Indiana University. As a very rough guess, we think the total number of Ph.D.'s graduated in accelerator physics and technology since 1982 approaches 460. There are almost certainly errors and omissions in these tables. Please contact us with your corrections for the next edition.

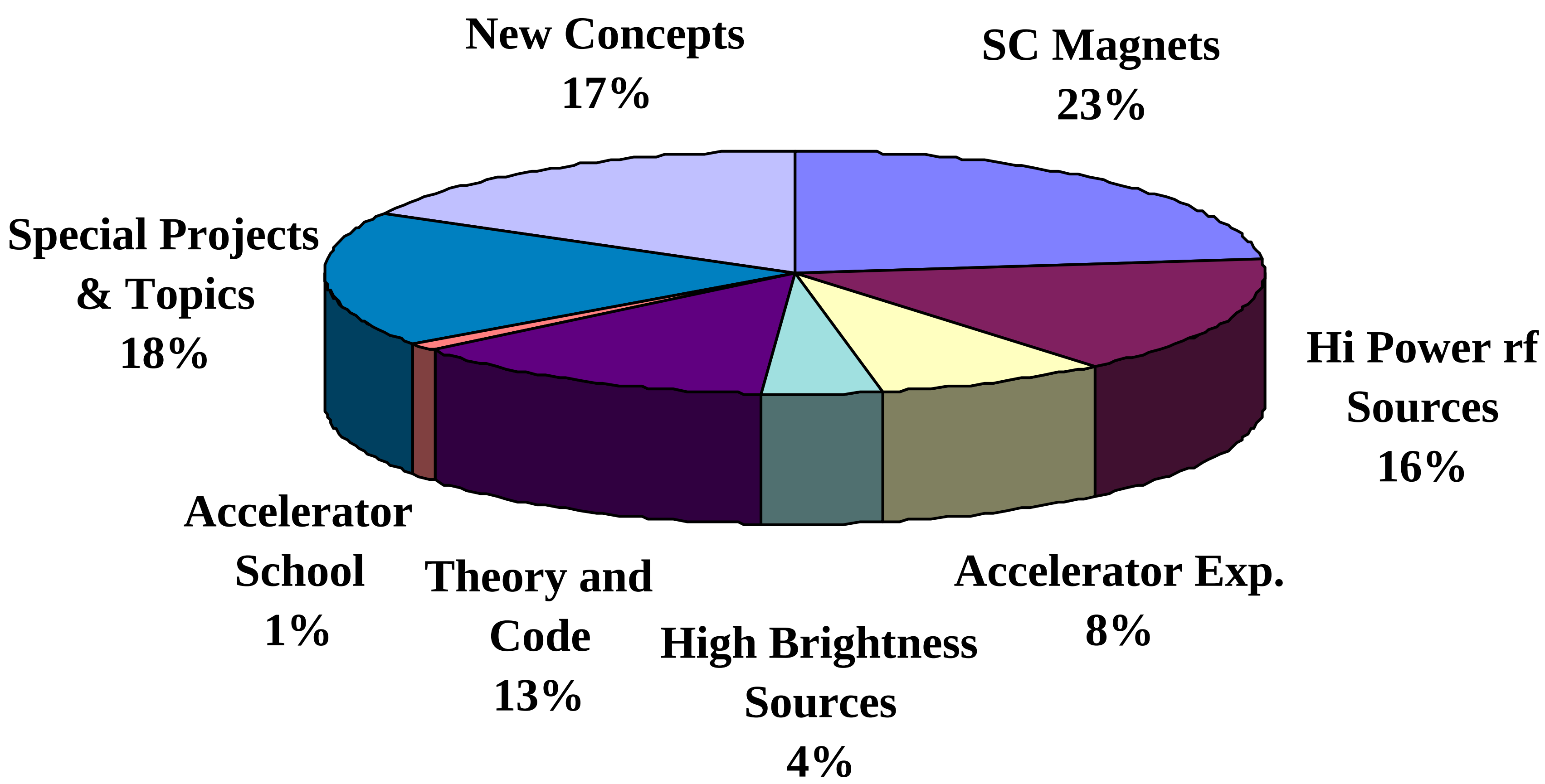
As for the first Year book, we are again most grateful to Ms. Melinda Adams of the University of Wisconsin-Madison who served as managing editor of this second year book project with the same dedication and skill as on the first, keeping us focused on our tasks, goals, and vital details. We would also like to acknowledge the work put in by Jerry Peters in assisting with the financial data and editing. Thanks are due also to the graphics and printing department at the Department of Energy for their help on the final production.

Finally, we are very grateful to all of the persons who encouraged us to prepare this second report and to all of those who have taken the time to contribute summaries to it.

David F. Sutter
Bruce P. Strauss

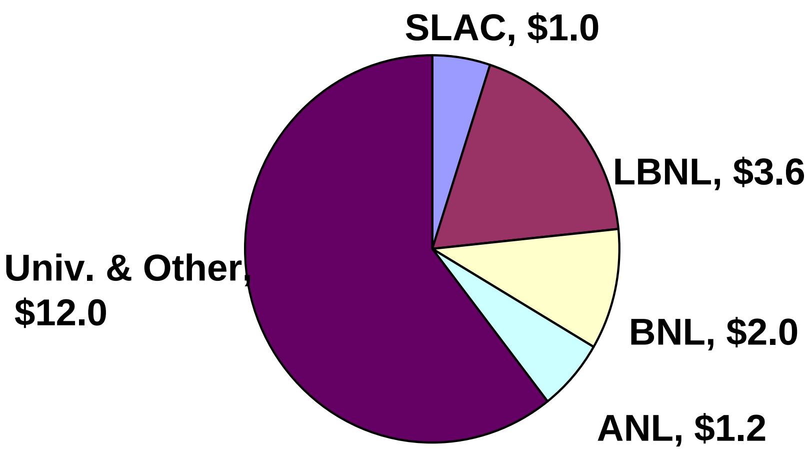
Germantown, Maryland
December, 2003

Advanced Technology R&D – Distribution of R&D Topics

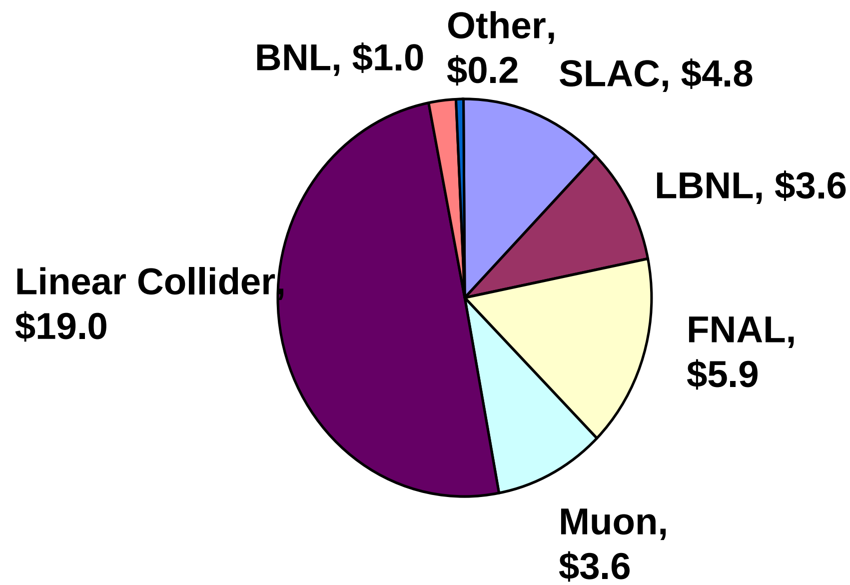


HEP- Accelerator Science & Development (M$) – FY 2003

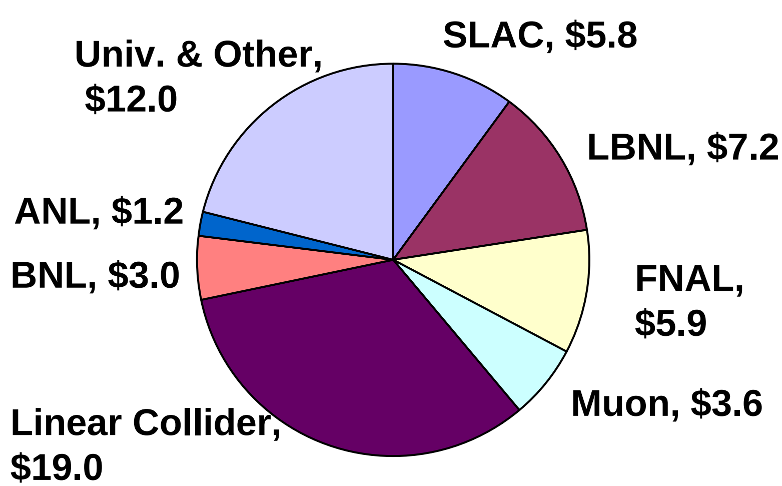
Accel. Science ($19.8)



Accel. Development ($38.1)



Total Accel. Sci. & Dev’t ($57.9)



University Groups

Experimental and Theoretical Research on Dielectric Wake Field Accelerators
A condensed report on part of the research being done recently on DOE grant
DE FG02-91ER40669

T. C. Marshall - Columbia University

Summary:

The project is a collaborative effort with Omega-P, Inc., located at Yale, and ATF, the users' facility located at Brookhaven. At these locations, experimental work is currently in progress, testing certain principles of wake field acceleration in dielectric wake field accelerators (DWA). Assistance to the project is provided by the participation of Dr. J.L. Hirshfield of Yale and Omega-P and his co-workers, together with the staff of ATF.

Experimental work is financed by related projects at Omega-P funded by the SBIR program. At Yale, there is a 6 MeV thermionic rf gun and beamline which uses a 10.5 Ghz former SLAC klystron for power. At ATF 50 MeV bunches are provided by a linac equipped with an rf photocathode. The experiment at Yale is testing the superposition of wake fields provided by a train of numerous bunches (gated by a "chopper") which passes through a DWA "resonator". At ATF, up to three drive bunches followed by one accelerated bunch 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 multimode, multibunch wake fields passing through dielectrics, and to investigate the limits of wake field superposition as a method to achieve high accelerating gradients from a train of "drive bunches" passing through a cylindrical structure. Also part of this project is an investigation of a new high power laser accelerator "LACARA", which will use a TW CO_2 laser pulse and a 6T solenoidal field provided by a "dry" superconducting magnet to accelerate a bunch of charge obtained from the ATF linac from 50 to 85 MeV in about 1m. This project has been delayed due to interruption of work on the magnet by the manufacturer (Everson Electric), but a new firm whas assumed the responsibility of finishing the magnet before the end of 2003. As this is a short report, no more will be said about these experimental projects now; instead we turn to some new promising studies which refine the concept of DWA using *rectangular microstructures* (dimensions transverse to the electron motion in the range of micrometers [mcm]) to obtain very high gradients and good stability.

Recent Accomplishments:

In the past two years, we have studied theoretically the use of tall, planar dielectric wake field structures having micron-scale dimensions. Such structures are capable of precision manufacture using microcircuit technologies, and have the capability of achieving very high field gradients: indeed, a series of ten, 3 fsec 2 pC periodically-spaced bunches has recently been modeled and found to drive up a wake field of >500 MeV/m in a structure 20 X 300 micrometers in cross section. The bunches are 10 micrometers wide, 300 micrometers tall, and dielectric slabs (k = 3.0) a few micrometers thick line the structure (Fig. 1). The wake field builds up by the superposition of wake fields from each "drive" bunch in the train, a desirable effect made possible by the very low dispersion in the rectangular structure and the dielectric. The wake field period in the structure must be chosen so as to match the period of the laser which provides the train of drive bunches.

A train of these bunches can be obtained beginning with a 500 MeV rf linac single-bunch source; this bunch then is processed using a LACARA accelerator "chopper," or possibly an

IFEL used as a "pre-buncher," so as to obtain a sequence of bunches each a few fsec in duration and spaced by the laser period. A TW CO_2 laser is used as a "modulator' of the original psec, nC bunch provided by the linac to form this sequence of fsec bunches, each having charge in the pC range. These bunches, the energy of which can be recycled, would in practice be followed by an *accelerated bunch* which is situated in the accelerating phase of E_z which follows the drive bunch train. In this way fields comparable with those achieved in laser plasma wake field accelerators can be set up, yet the energy is obtained largely from the rf linac source rather than the laser. We estimate that the dielectric is capable of handling the flux of radiant energy from the drive bunch train wake field. We have found that it is possible to distort the original circular cross section of the input bunches into a rectangular profile, using a quadrupole, and that the resulting rectangular profile is maintained for several cm of travel. (This distance would comprise one module of a staged high energy accelerator system; the drive bunches would be recycled in the linac and the accelerated bunch would proceed into the next stage.)

In Figures 2 a,b we show the wakefields set up by one drive bunch as it enters the structure (z=0) and moves to the right. This structure is only 120 micrometers in length, so that transient effects can be studied. Near the point of entry, one observes a region where the transition radiation from the entrance interferes with the (Cerenkov) wake field radiation. The latter travels with the bunch (almost at c) whereas the interference zone expands with the wave goup velocity (approximately $c/k^{1/2}$). Transition radiation is also emitted away from the entrance (not shown) and diminishes the energy of the bunch; however, since this radiation loss scales as the square of the bunch charge, it does not play an important role when pC bunches are used. Transition radiation from a DWA of finite length has been omitted in previous studies of wake fields. One observes in Fig. 2b that the zone of periodic wake fields expands to fill the region between the bunch and the transition radiation as the bunch moves onward. Thus the effect of transition radiation is important only for short structures energized by a lengthy train of drive bunches, because the trailing bunches there move mostly through the transition radiation zone and do not experience the orderly buildup of accelerating field.

In Figure 3a, we study the motion of a cloud of "test electrons" located at the position of the tenth drive bunch, which follows a series of nine, 500 MeV, 2 pC drive bunches. This figure shows that some of the test particles are lost to the walls as they fall into regions of unstable transverse motion; yet 71% survive a distance of 10 cm and lose appreciable energy (Fig. 3b) to the composite wake field (about 600 MeV/m, as shown in Fig. 4a [top portion]). In this example, the wake field spectrum is dominated by a few modes, having nearly the same periodicity (~20 micrometers). At an appropriate location (60.5 micrometers in this example) one may locate the bunch to be accelerated, where the transverse forces are stabilizing (F_x, F_y in the lower portion of Fig. 4a). Fig. 4b shows the motion of certain test particles located at the accelerated bunch, and Fig. 4c shows the initial and final x,y locations of these test electrons. The bunch motion is stable for 50 cm of travel, using no external devices. Excellent stability of the accelerated bunch is essential, as it must be accelerated along a sequence of modular structures driven by the drive bunches. A normalized emittance ~ 0.5 mm-mrad will assure that drive-bunch electrons will not hit the lateral walls in traveling a distance ~ 35 cm; whereas in the accelerated bunch all such electrons will have stable motion.

We have shown that tall, rectangular-profile, fsec bunches of charge can have remarkable stability in a planar dielectric microstructure while experiencing acceleration at a gradient about ten times as large as achievable in present accelerator structures. The bunch need not be as tall as the structure to enjoy the benefits of this configuration.

Publications 2001-2003:

1. T.C. Marshall, C. Wang, and J.L. Hirshfield, “Femtosecond planar electron beam source for micron-scale dielectric wake field accelerator”; ICFA Workshop on Laser-Beam Interactions, Stony Brook, June 2001; Published in: Phys. Rev. ST-AB, **4**, 121301 (2001)
2. R.B. Yoder, T.C. Marshall, and J.L. Hirshfield, “Energy-gain measurements from a microwave inverse free-electron-laser accelerator”, Phys. Rev. Lett. **86**, 1765 (2001)
3. J-M. Fang, et al, “An experimental test of a microwave inverse Cerenkov accelerator (MICA)”, in: *Proc. of the 2001 Particle Accelerator Conference*, p. 4020; P. Lucas and S. Webber, editors; IEEE 01CH37268 (2002)
4. C. Wang, J.L. Hirshfield, and T.C. Marshall, “Creation of narrow femtosecond sheet-like bunches for optical-scale dielectric slab accelerator structures”, in: *Proc. of the 2001 Particle Accelerator Conference*, p. 4035; P. Lucas and S. Webber, editors; IEEE 01CH37268 (2002)
5. Physical Review Special Topics – Accelerators and Beams **4**, 121301 (2002)
6. T.C. Marshall, “Summary of the working group on non-plasma accelerators”, paper T806 in: “Proceedings of the Snowmass 2001 Summer Study on the Future of Particle Physics”, editor: Norman Graf, Publ. by Stanford Linear Accelerator Center, Stanford CA, July 2002; SLAC Report SLAC-R-599, econf C010630
7. S.V. Shchelkunov, T.C. Marshall, et al., “Status report on the LACARA experiment” p. 349, AIP Conference Proceedings #647: Advanced Accelerator Concepts, Tenth Workshop, Editors C.E. Clayton and P. Muggli (2002)
8. T.C. Marshall et al., “Wake fields excited in a micron-scale dielectric rectangular structure by a train of femtosecond bunches” p. 361, AIP Conference Proceedings #647: Advanced Accelerator Concepts Tenth Workshop, Editors C.E. Clayton and P. Muggli (2002)

Papers Submitted:

To the Particle Accelerator Conference, May 2003 (written papers to be published in conference proceedings):

1. “Stability of electron orbits in the strong wake fields generated by a train of fsec bunches”
2. Experimental and Numerical Studies of Dielectric Wake Field Acceleration Devices’
3. “Numerical study of interference between transition radiation and Cerenkov wake field radiation in a planar dielectric structure”

Current Staff:

- T.C. Marshall, Professor of Applied Physics and principal investigator
- Dr. J-M. Fang, Research Associate (located at the Yale Beam Physics Laboratory)

Graduate Student:

- Mr. Sergey Shchelkunov, Graduate Research Assistant (located at ATF, Brookhaven); PhD. Degree candidate.

Past Doctoral Students Graduated

- Dr. J-M. Fang (1997), as above
- Dr. Iddo Wernick (1992), Staff Associate, Lamont-Doherty Geophysical Observatory, Palisades, NY
- In collaborations with Prof. Jay Hirshfield: Rodney Yoder, Yale, now at UCLA
- (all the above worked on different versions of the IFEL)

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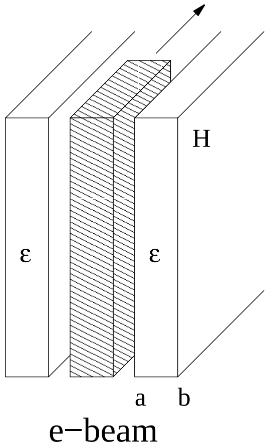

Fig. 1

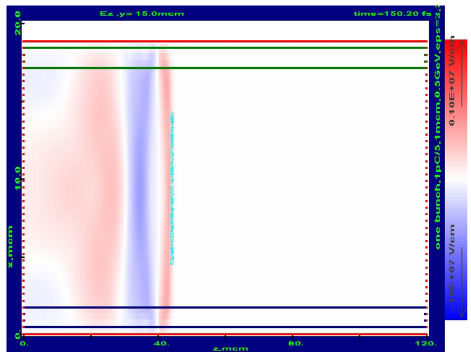

Fig. 2a

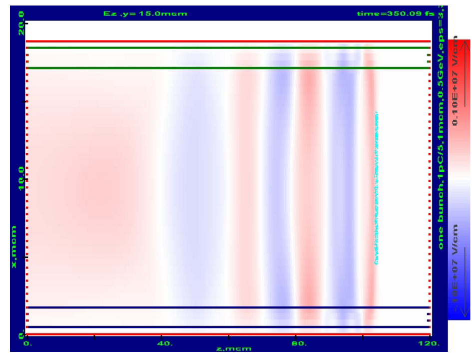

Fig. 2b

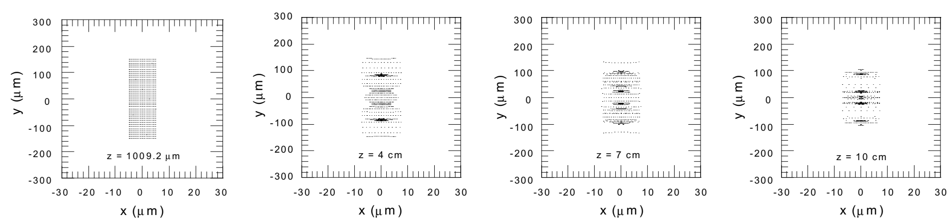

Fig. 3a

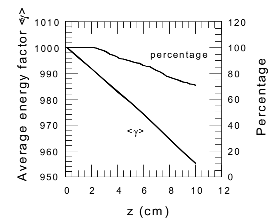

Fig. 3b

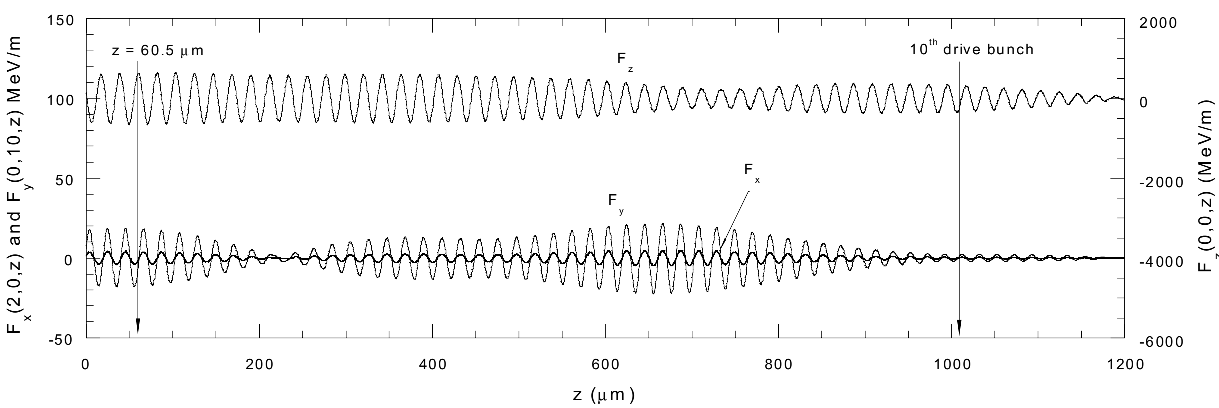

Fig. 4a

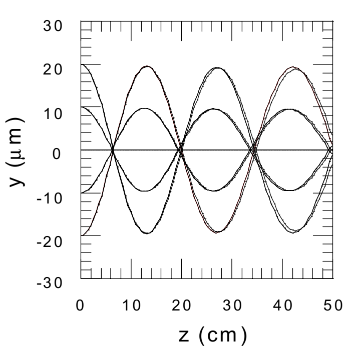

Fig. 4b

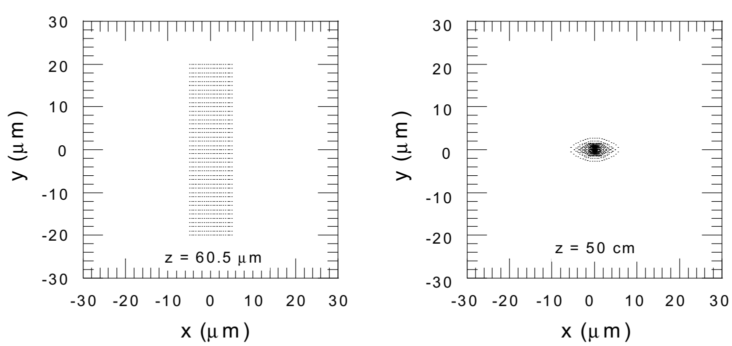

Fig. 4c

Electron Beam Transport in Advanced Plasma Wave Accelerators

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

Summary:

Experimental and computational studies are being conducted on the application of electron beams, CO_2 and YAG laser beams and plasmas, to advanced concepts in particle acceleration at the FAMU Laser Plasma Beam Physics (LPBP) Laboratory. The primary research goal is to study the very large electrostatic fields found in relativistic plasma waves by probing concurrently with a cross-propagating laser beam and a low energy electron beam. Previous computational studies have shown that the electron beam can be a sensitive diagnostic of the amplitude and other properties of the relativistic plasma waves, and thus may complement the laser beam diagnostic. The subject relativistic plasma waves are the basis of the plasma wave accelerator concept, which is being studied in many laboratories as a way to accelerate particles to very high energies over very short distances using accelerating gradients in excess of one gigavolt per meter. These acceleration gradients are orders of magnitude larger than those found in present technology particle accelerators. Therefore, 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.

The assembly of a new experimental facility, in which the interactions among an electron beam, laser beams and plasmas can be studied conveniently, is nearing completion in the FAMU LPBP Lab. Figure 1 is a schematic of the experimental layout and figure 2 shows the main interaction chamber. The CO_2 and YAG laser beams are focused into an interaction chamber in order to produce a plasma and also plasma waves in gases, such as He and Ar. The goal is to inject an initially cylindrical electron beam (5 to 50 keV) transverse to the plasma waves, which then scatter the electrons to create a distorted electron beam cross section. This distortion is to be measured on a fluorescing screen downstream, and is proportional to the amplitude and other spatial properties of the plasma waves, as predicted by computer simulations. The major components of the experiment have been tested individually recently, and are now being integrated and sequenced together. During these tests, we encountered some interesting experimental challenges that are leading to additional research, which we believe will lead to new opportunities for discovery and development.

Recent Accomplishments:

During the tests of the electron beam, it was observed that the electron beam produces a plasma as it propagates through the helium gas. This plasma, which we call the preionization plasma, is present in the focal volume of the CO_2 laser prior to the initiation of the laser ionization of the gas. We are continuing to study this preionization plasma to determine if it will enhance the laser ionization process by either reducing the threshold for ionization, or by allowing a higher plasma density to be attained for a constant CO_2 laser input. The emission characteristics of this low density preionization plasma were studied using a monochrometer system. A computational model was developed for use in determining the plasma temperature and density from the ratio of helium emission line intensities. A photo of the electron beam produced plasma and a summary of the computational model are shown in figures 3 and 4, respectively.

A plasma shutter has been developed which will shorten and control the CO_2 laser beam pulse before it is injected into the main interaction chamber. The plasma shutter operates by focusing the laser in a gas to generate a plasma which deflects and absorbs the trailing edge of the laser pulse. These studies show that the laser pulse width can be reduced substantially and the transmitted energy can be controlled by adjusting the gas pressure and gas species. Figures 5 and 6 show a laser produced breakdown plasma in the plasma shutter and a sample plot of the effect of pressure on laser energy, respectively. These studies are continuing with the use of various inert gases, the addition of diagnostics for side scattered visible and infrared radiation, and the injection of focused YAG laser light to initiate the breakdown.

In addition to accomplishing the above experimental tasks, we recently completed the assembly of a computerized beam viewing system which will be used to detect and analyze the distorted electron beam cross section. An apparatus for testing a gas jet plasma source has been built. This gas jet plasma source will be used as a future plasma source in which plasma waves will be created. A discharge tube plasma source has been built, which will be used for testing and calibrating the optical and spectroscopic instruments, and which will allow the control of gas species, density and temperature.

Computer simulations are performed continuously to model and analyze our experiments. A previous simulation shows that the originally circular cross section of the electron beam becomes distorted (figure 7) after passing through the plasma wave. We also perform computer simulations to study new advanced accelerator concepts. An example is a study of the acceleration of protons and ions to high energies by the type of longitudinal electrostatic fields that are found in relativistic plasma waves. Figure 8 shows a comparison of the trapping threshold and maximum energy gain for protons, and ions of helium and gold, along with the maximum energy for electrons. These simulations studies are continuing.

Publications:

1. R. L. Williams, “Studies on proton and ion interactions in plasma-based collective accelerators”, in Proceedings of the 2001 Particle Accelerator Conference, Chicago, Edited by Peter Lucas, IEEE Catalog Number 01CH37268C, Piscataway, NY (2001) page 3972.
2. R. L. Williams, A. Bowman, S. Brown, M. Blunt and J. Martinez, Jr., “Characteristics of a self-breakdown plasma shutter for CO_2 laser beams”, in preparation for submission to Review of Scientific Instruments.

Presentations:

1. R. L. Williams, (C. Lawyer, C. Blackwell, M. Ghebrebrhan and J. Martinez), “Electron beam propagation across plasma waves used in high gradient particle accelerators”, presented at the 44th Annual Meeting of the Division of Plasma Physics, APS, November 11-15, 2002, Orlando, FL. Bull. Am. Phy. Soc. **47(8)**, 282 (2002). (Students’ names in parenthesis were added to poster at the time of presentation, but are not on the previously submitted published abstract.)

Current Staff:

- Prof. Ronald L. Williams, Principal Investigator

Graduate and Undergraduate Students

• Arnesto Bowman	Graduate Student, pursuing Ph.D., physics
• Staci Brown	Undergrad Student, pursuing B.S., physics
• Michelle Blunt	Undergrad Student, pursuing B.S., mechanical engineering
• Jorge A. Martinez, Jr.	Undergrad Student, pursuing B.S., physics

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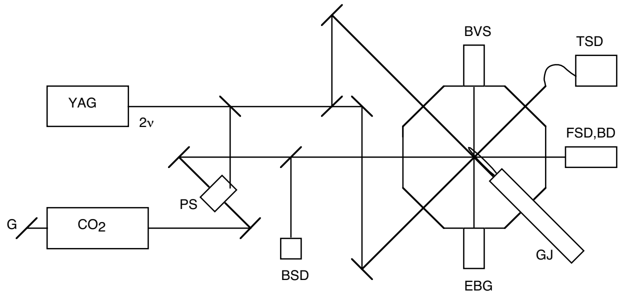

Figure 1. Experiment Schematic. YAG = YAG laser, TDS = Thomson scatter diagnostic, CO2 = CO2 laser, PS = plasma shutter, BSD = backscatter diagnostic, FSC,BD = forward scatter diagnostic, beam dump, EBG = electron beam gun, BVS = beam viewing system, GJ = gas jet plasma source.

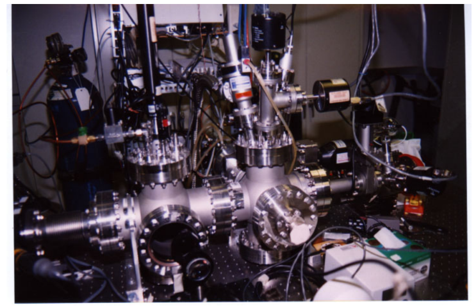

Figure 2. View of interaction chamber.

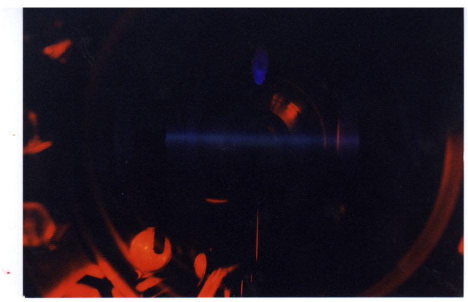

Figure 3. Electron beam produced preionization plasma. (Faint blue horizontal line.)

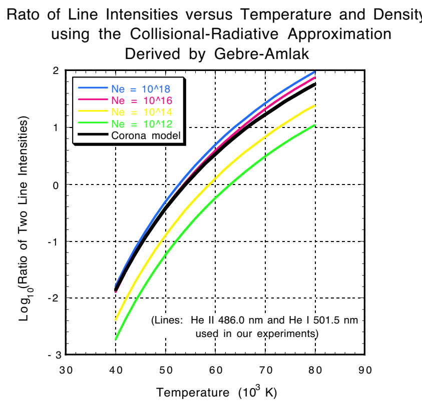

Figure 4. Summary of computational model for preionization plasma analysis.

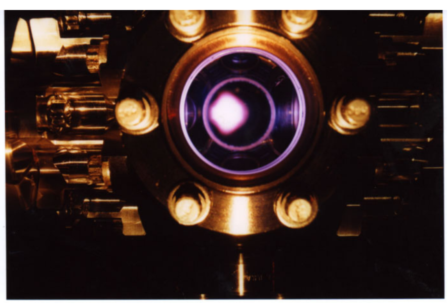

Figure 5. Laser produced breakdown of helium in plasma shutter.

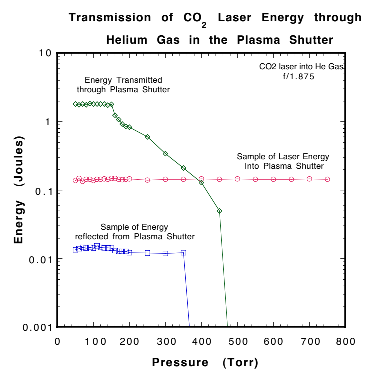

Figure 6. Laser energy in plasma shutter vs. gas pressure

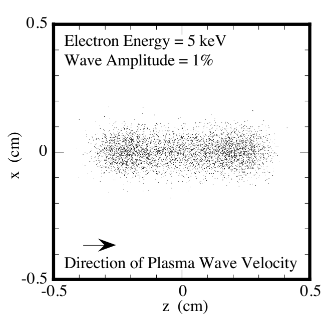

Figure 7. Cross section of electron beam after distortion by plasma wave. (Beam moves out of the page.)

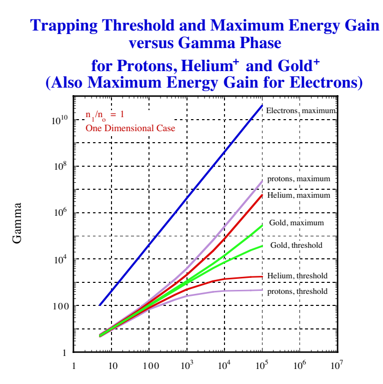

Figure 8. Trapping threshold and maximum energy for protons and ions.

Liquid Helium Fluid Dynamics Studies

S.W. Van Sciver **-** *Florida State University*

Summary:

The present report pertains to work carried out during the period 2001-2003 under the support of the US Department of Energy-Division of High Energy Physics. This work mainly involves experimental studies of liquid helium thermo-fluid dynamics with supporting analysis. The goal is to develop an improved understanding of He II for future particle accelerator applications. Major activities during this period include experimental investigations and analysis of:

1. High intensity transient heat transfer to static He II
2. Heat transport to forced flow He II at high Reynolds number
3. Heat and mass transfer in two-phase He II/vapor

The high intensity transient heat transfer experiments in static He II have been completed and the graduate student, David Hilton successfully defended his dissertation in April of 2003. A paper was presented at the LT23 conference in Hiroshima, Japan in August of 2002 (Ref. 7). After defending his dissertation, David has assumed a postdoc position in our group, while he prepares a more lengthy review article on second sound thermal shock and assists the new graduate student (Matthieu Dalban-Canassy) develop an experiment to measure second sound thermal shock in high Reynolds number forced flow He II. This experiment is a natural extension of the combined work of David Hilton and Sylvie Fuzier, as described below.

Our second main research activity involves experimental investigations of pressure drop and heat transfer in forced flow He II at high Reynolds number, up to 3×10^7. The graduate student on this project (Sylvie Fuzier) has successfully completed both experiments and is in the process of analyzing the data and developing a numerical model. Several publications have resulted from this work (Refs. 1 & 8) and Sylvie is in the process of preparing her dissertation with a projected completion in December 2003.

The third main activity involves the study of two-phase He II/vapor and a new graduate student (Xu Ting) has joined the group to pursue this project. We have modified our Liquid Helium Flow Facility to allow flow visualization of stratified two-phase flow. In addition to qualitative flow regime investigations, these experiments will also employ modern flow measurement techniques such as particle image velocimetry (PIV) to quantify flow fields and dynamic transitions. Experimental equipment is under construction with first experiments scheduled for end of summer 2003.

As part of our program activities, we continue to nurture collaborations with US and international HEP laboratories as well as provide assistance where needed. These collaborations enhance our program by giving insight into accelerator issues while expanding our research base through in-kind support. Over the past two years, our three significant collaborative projects are with DESY- Hamburg, CEA – Saclay and FermiLab.

Recent Accomplishments:

1. High Intensity Transient Heat Transfer to Static He II

These experiments were designed to understand the heat transport in He II resulting from high intensity thermal shock that could occur during a transient disturbance in a high current density superconducting magnet. The scientific goal is to successfully acquire clear and extensive direct measurements in He II of quantum turbulence induced by second sound shock pulses in a wide channel . The specific outcomes consist of measuring the heat transported by the second sound shock pulses and the development of localized turbulence as measured by the attenuation of second sound.

The first question we asked is: How much energy can be transported by second sound? To investigate this issue, we introduced high intensity thermal pulses (up to 400 kW/m^2) into a column of static He II while measuring the energy transported with a local, fast response thermometer at a distance from the heater. The energy transport fraction is defined as the ratio of the energy flux in the transported pulse to the input energy. If the energy fraction is unity, then essentially all the heat is carried by second sound. An energy fraction less than one indicates the presence of another heat transport mechanism, which in this case is thermal (Gorter-Mellink) diffusion. Figure 1 is a plot of the energy transport fraction versus initial pulse energy flux density for SSS pulses as measured in our experiment at 1.7 K. The black line is a power law fit to the data, the circled dots, with the power law given. The gray line is a power law fit to comparable data, the smaller crosses, extracted results published by Shimazaki, Iida, and Murakami . Accounting for pulse energy by plotting energy transport fraction versus initial pulse energy yields a breakpoint as a function of the initial pulse energy. At 1.7 K, this breakpoint energy is about 75 J/m^2. At higher fluxes, the energy transport fraction drops more rapidly that E^{-1}, which indicates a decreasing total energy flux carried by second sound. This result is suggestive of a dense quantum turbulence layer near the pulse heater, as a temperature gradient established in the turbulence.

The second set of experiments involved a local measurement of the quantum turbulence resulting from the passage of SSS pulses. In these experiments, quantum turbulence is observed as attenuation in second sound resonators located along the channel and operating transverse to the pulse propagation direction. The amplitude of the resonance is then a direct measure of the local turbulence and can be recorded continuously along the channel. Shown in Fig. 2 is an example of the measured attenuation (induced quantum turbulence). These measurements have never been performed before and there is no clear theoretical understanding to interpret the data. To parameterize the experiments, we have developed an electrical analogue based on the concept that the local turbulence is stored much as in a capacitor and dissipates due to conduction through a resistive medium (in this case, thermal diffusion in the He II). This “leaky capacitor fit” (LCF) to the excess attenuation coefficient measurements was then used to extract growth and decay characteristics of the corresponding induced turbulence . One parameter of interest is the vortex line length/volume that measures the local intensity of turbulence. In Fig. 2, this parameter peaks just below 1 Gm/m^3, which is small compared to the line density generated by less intense heat pulses of longer duration. Further research is needed to fully interpret these observations.

2. <u>Heat Transport to Forced Flow He II at High Reynolds Number</u>

The goal of these experiments is to understand the limits to heat transport in He II when the fluid is flowing at very high velocities approaching that of second sound. The experiment consists of a test section instrumented with pressure and temperature transducers and installed in the Cryogenic Helium Experimental Facility (CHEF) in our laboratory. The main part of the test section is a 0.85 m long, 10 mm ID tube, which is supplied by a large volume bellows pump capable of pushing He II at speeds greater than 20 m/s through the tube. These experiments have produced some exciting results. The forced flow pressure drop has produced friction factor data to $Re > 3 \times 10^7$ (see Ref. 5). The steady state and transient heat transfer experiments are also complete and the data is in analysis.

To study transient heat transfer, a new experimental test section has been built. It is made of a 0.85 m long, 10 mm ID smooth stainless steel tube equipped with two heaters, nine thermometers and three pressure transducers. The thermometers are inserted in the tube wall in contact with the flow and at various distances from the heaters ranging from 4 to 50 cm mostly downstream. Rectangular heat pulses of flux up to 400 kW/m^2 with duration between 1 and 20 ms were generated in a heater in the test section. The temperature evolution was recorded at several locations as the pulses were transported by forced convection. These data were recorded for a range of temperatures and flow rates.

Figure 3 shows typical transient results obtained. The heat pulses arrive faster at the measurement location when the flow velocities are higher as they are carried mainly by ordinary convection. The baseline for each pulse increases with the velocity and the distance downstream the heater. This is due to the Joule-Thomson effect: the pressure drop along the pipe leads to a raise in baseline temperature. More importantly, for the highest flow velocities, the shape of the pulses is closer to the initial rectangular shape generated at the heater than for the lower velocities. This could be due to a modification of He II heat transfer due to the increase of the main flow velocity. To investigate this suggestion, a numerical model has been developed for comparison with the experimental results. The He II heat conservation equation including the pressure terms is used and the equation is solved using an implicit finite difference scheme.

Figure 4 shows a comparison between the numerical model and the experimental results for one set of data. Reasonable agreement is seen between data and experiment. Further analysis is underway for other experimental cases. This analysis should lead to an improved understanding of the effect of forced flow on heat transfer in He II.

3. <u>Heat and Mass Transfer in Two-Phase He II/Vapor</u>

Work has begun on our new set of experiments in two phase He II/vapor. The principal feature to these new experiments is that we will employ modern flow visualization techniques to quantify the dynamics of flowing He II. As a first step to this work, we have designed and are having built a new flow test section to be installed in the liquid helium flow facility (LHFF). The section has a nominal 1" (25 mm) diameter and is equipped with two visualization sites each consisting of three optical windows: two for laser in and out and one at 90 degrees for image acquisition. The new test section is expected in late June, 2003 and we plan to begin experiments in late summer. To carry out these new visualization experiments, it has been necessary to modify the LHFF for optical access. This modification is complete (see Fig. 5) and the facility has been cold tested for operation.

Particle image velocimetry is one of the most advanced fluid dynamics techniques available to the research community. PIV involves taking two nearly simultaneous images of a particle seeded flow field. These images are collected by computer, which uses autocorrelation techniques to compute the local fluid velocity. With computing power available today, this process can be nearly real time. Although PIV is a well established technique for classical fluid dynamics investigations, we are the only group that is applying this research tool to He II. One of the challenges is to obtain suitable particles for seeding the flow. These developments will be part of our experimental program once the apparatus is operational.

<u>Collaborations</u>:

•<u>TTF Two Phase Flow Modeling and Experiments</u>: DESY employs a Post Doc (Xiang Yu), who is modeling He II two phase flow. We have contributed to the development of this model (5,6).

• <u>High Reynolds Number Forced Flow He II</u>: This work is supported by DOE; however, CEA has participated in the past by sending one engineer (B. Baudouy) to assist with the operation of the experiment and work on the analysis.

• <u>Cryogenics Experiments at FNAL</u>: FermiLab is planning to begin a program involving liquid helium two phase flow. The PI (S. Van Sciver) will advise this project and sit on the PhD student's committee.

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2. "He II level measurement techniques," D. Celik, D.K Hilton, T. Zhang and S.W. Van Sciver, Cryogenics 41, 355 (2001)
3. "Techniques for the detection of second sound shock pulses and induced turbulence in He II," D.K Hilton and S.W. Van Sciver, Cryogenics 41, 347 (2001)
4. "A study of the temperature dependent drag coefficient on a sphere in flowing He II," Y. S. Choi, M. R. Smith and S. W. Van Sciver, Advances ion Cryogenics, Vol. 47, 1335 (2002)
5. "Numerical simulation of two-phase Helium II stratified flow in cryogenic units of TESLA," X. Yu, S. Wolf, B. Peterson and S. W. Van Sciver, IEEE Trans. on Appl. Super. Vol. 12, 1368 (2002) (MT-17 Conference, Geneva)
6. "An experimental and numerical study of He II two-phase in the Tesla test facility," Y. Xiang, (S. W. Van Sciver), Cryogenics Vol. 42, 719 (2002)
7. "Quantum turbulence in He II induced by second sound shock pulses," Hilton, D. K., Van Sciver, S. W., 23rd International Conference on Low Temperature Physics, Hiroshima (20-27 August 2002), *Physica B*, Vol. 329-333, pp. 228-229 (2003).
8. "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

Current Graduate Students:

- Sylvie Fuzier – PhD graduate student in Mechanical Engineering
- Matteau Dalban-Canassy – PhD graduate student in Mechanical Engineering
- Xu Ting – PhD graduate student in Mechanical Engineering (current FSU Fellowship support)

Current Staff:
- Professor Steven W. Van Sciver – Principal Investigator
- David Hilton – Postdoc – former graduate student received PhD in Spring 2003

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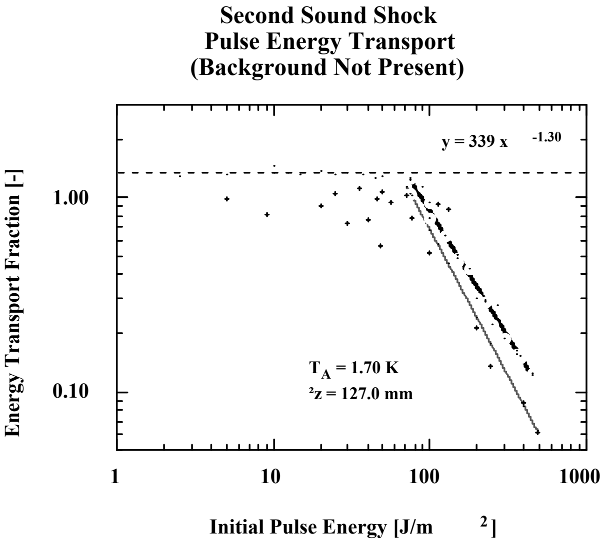

Fig.1. A plot of energy transport fraction versus initial pulse energy flux density for SSS pulses along the HeII liquid column. The black line is a power law fit to the data, the circled dots, with the power law given. The gray line is a power law fit to comparable data, the smaller crosses, extracted from Shimazaki, Iida, and Murakami.

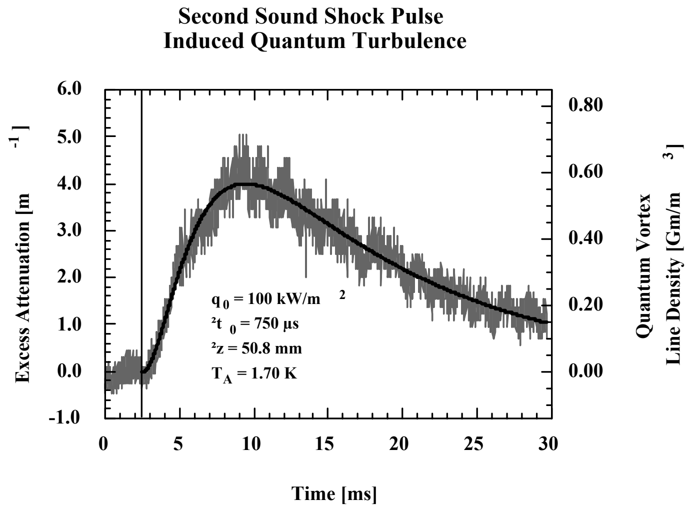

Fig.2. An example plot of the excess attenuation coefficient versus elapsed time at the position given above the second sound shock (SSS) pulse heater, revealing the quantum turbulence development induced by the specified pulse. The vertical line marks the arrival time of the pulse. The black curve superimposed on the gray data is the leaky capacitor fit (LCF).

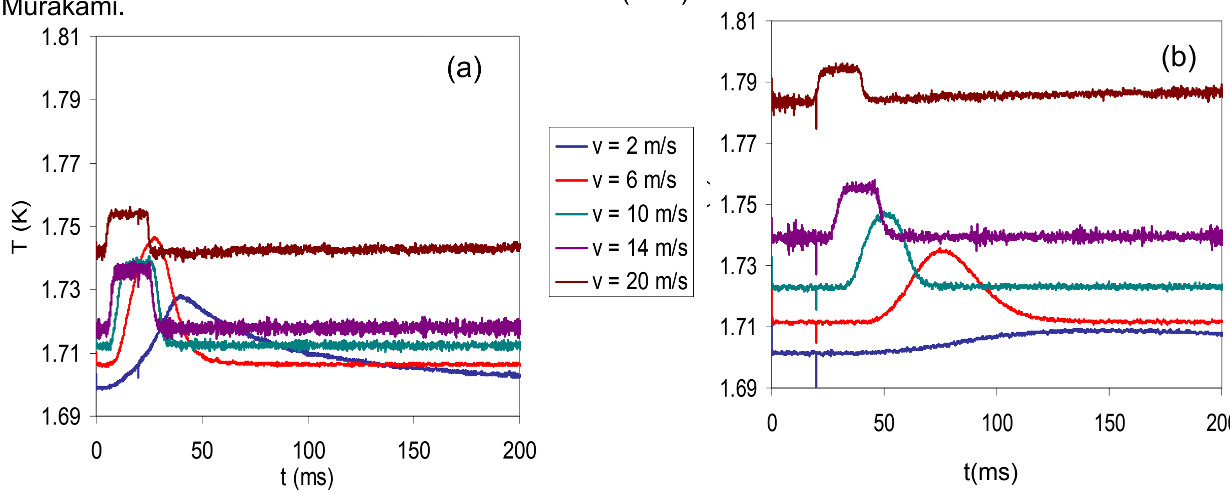

Fig 3. Temperature profile obtained 9.3 cm (a) and 39.3 cm (b) downstream of the heater which generates a heat pulse between t=0 and 20 ms

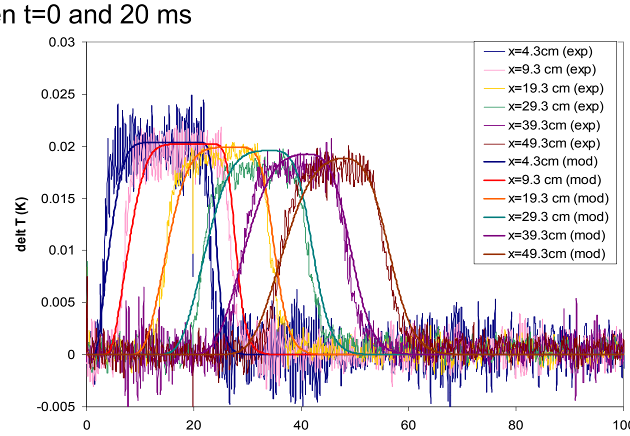

Fig 4. Comparison of the numerical (mod) and experimental results (exp) for a heat pulse of power 9.9 W/cm^2 and 20 ms duration received at several distances downstream the heater for a forced flow velocity of 14 m/s.

Fig. 5: Liquid Helium Flow Facility modified for visualization experiments

Neutrino Factory R&D at the Illinois Institute of Technology

Daniel Kaplan – Illinois Institute of Technology

Summary:

The long-term future of high-energy physics requires new accelerators. One option 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 Muon Collaboration explores the technological challenges of such facilities. At IIT, Sr. Research Associate Y. Torun is supported by DOE, and this report covers his work, which has focused on resolving critical experimental questions in Neutrino Factory R&D.

Targetry

The muon flux that can be produced depends on the pion yield and spectrum. The analysis of data from BNL AGS Experiment 910 on pion production, with 12.3 and 17.5 GeV/c protons on Be, Cu, and Au targets, was completed in 2001 and published [3], filling an important gap in our knowledge of production cross sections and removing a large uncertainty in the front-end design for a Neutrino Factory. For the Au target, the production peak was found to be at a pion momentum below the lower limit of reliable data existing before E910.

MuCool: Ionization Cooling

MuCool (FNAL-E904) is an R&D program on components of a Neutrino Factory muon ionization-cooling channel [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 a setup—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 are investigating the behavior of cavities in solenoidal magnetic field, radiation from the cavities and candidate instrumentation techniques.

Field Emission in rf Cavities

Field emission at surfaces limits accelerating gradients in many rf structures. The current density j from barrier penetration at a metal surface (work function ϕ) is given by $j(E) = (A/\phi\beta E)^2 \exp[-B\phi^{3/2}/(\beta E)]$, with E the nominal dc electric field at the surface, β the local field enhancement factor due to sharp features on the surface, and A and B constants [7]. 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 $n = E/j\ dj/dE \sim 2 + 67.4$ GV/m/(βE), 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, and spare rf power at 201MHz is not easily available. While definitive answers will require a prototype closely resembling the final design, many issues of cavity operation and diagnostics are qualitatively similar at 805MHz. Laboratory G at Fermilab was therefore set up 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 were used to 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 has been done in close collaboration with MuCool Collaboration members from Argonne, Fermilab, LBNL and the University of Illinois and MICE Collaboration members from CERN and Imperial College, London.

Recent Accomplishments:

The first cavity installed in Lab G was a six-cell open-iris prototype built at Fermilab. It was 1m long, with a titanium window at one end that was thin enough (125μm) to permit dark-current measurement. The field on the cavity irises was 2.6 times the on-axis field. During high-power conditioning with no magnetic field (B = 0), we measured large dark currents (approaching an ampere). The cavity was operated successfully with accelerating gradient 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 at LBNL 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. 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.

Some results are shown in the figures page. The dark-current plot (top right) from the first cavity spans about 14 orders of magnitude; different sets of points represent data taken at different times, showing the effects of conditioning. The data are consistent with Fowler-Nordheim field emission. The rf power level in the cavity is depicted in the middle-left panel together with discriminated photomultiplier-tube (PMT) pulses; the long discriminator-output logic pulse occurring during the tail of the rf pulse is due to multipacting. During conditioning or high-gradient operation, when the x-ray rate is too high for the PMT to follow individual pulses, one can still obtain useful information about cavity behavior from the raw PMT signal shown at the center of the middle row. The middle-right panel shows data from three different detectors; the slopes are consistent with the emission exponent described above. The bottom-right image was obtained using photographic paper placed against the cavity exit window and clearly shows individual emitters [7].

Due to limited funds, a significant portion of the instrumentation used in Lab G is borrowed, with various remote-control interfaces not integrated into a single system. To ease setup and data-taking, we have designed a supplemental data-acquisition system. 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. Thus far the system has been used to read pulse-height histograms for spectrum measurement; integration of other functions is in progress.

MICE: The International Muon Ionization Cooling Experiment

An experimental demonstration of ionization cooling is essential. A cooling experiment (MICE) using MuCool-developed components in a section of the “Study-II” channel [1] has been proposed [4,5] and is under active development [6,10]. 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 Study-II Neutrino Factory schematic and the layout of MICE are shown on the top-left and bottom-left figures respectively.) To measure beam emittance at the entrance and exit of the cooling section in MICE, 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, and led the software project [12]. A GEANT4-based architecture was built to combine, for the first time, the beamline elements, cooling hardware and particle detectors within the same framework. We also organized and performed measurements in Lab G to estimate backgrounds for the tracking detectors proposed for MICE.

MICE has 141 collaborators from 40 institutions (13 from the US) in 9 countries around the world. Efficient communication in such a diverse group requires a well-organized structure. We have set up and maintain the website [13], mailing lists, notes system and videoconferencing for the collaboration and serve on the collaboration steering group.

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3. I. Chemakin et al., Phys. Rev. C65 (2002) 24904
4. G. Gregoire et al., MICE-Note 21, Jan 2003, http://mice.iit.edu/mnp/MICE0021.pdf
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6. Y. Torun, "MICE: The International Muon Ionization Cooling Experiment," MICE-Note 33, May 2003, http://mice.iit.edu/mnp/MICE0033.pdf, to appear in PAC2003 proceedings
7. P. Gruber and Y. Torun, "A technique for imaging dark currents," MICE-Note 35, May 2003, http://mice.iit.edu/mnp/MICE0035.pdf, to appear in PAC2003 proceedings
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9. D. Li et al., "RF tests of an 805MHz pillbox cavity at Lab G of Fermilab," May 2003, to appear in PAC2003 proceedings
10. Y. Torun, "MICE Status," June 2003, presented at NuFact03 Workshop
11. M. M. Alsharoa et al., arXiv:hep-ex/0207031, to appear in Phys. Rev. ST Accel. Beams (2003)
12. http://www.mice.iit.edu/software/micegeant4.html
13. http://www.mice.iit.edu/

Current Staff:

- Faculty: Daniel M. Kaplan, Prof. of Physics, Principal Investigator
- Postdoctoral: Yagmur Torun, Sr. Research Associate
- Graduate student: Mohammad Al'Sharoa, Mechanical Engineering, PhD (supported by Joint University-Fermilab Doctoral Program in Accelerator Physics)
- Undergraduate: Hart Wilson (supported by ICAR)
- Past graduate student: Michael Boghosian, MS Mechanical Engineering

Graduate Student:

Mike Boghosian, MS, Mechanical and Aerospace Engineering in 2001. Currently an engineer at Gamma Technologies.

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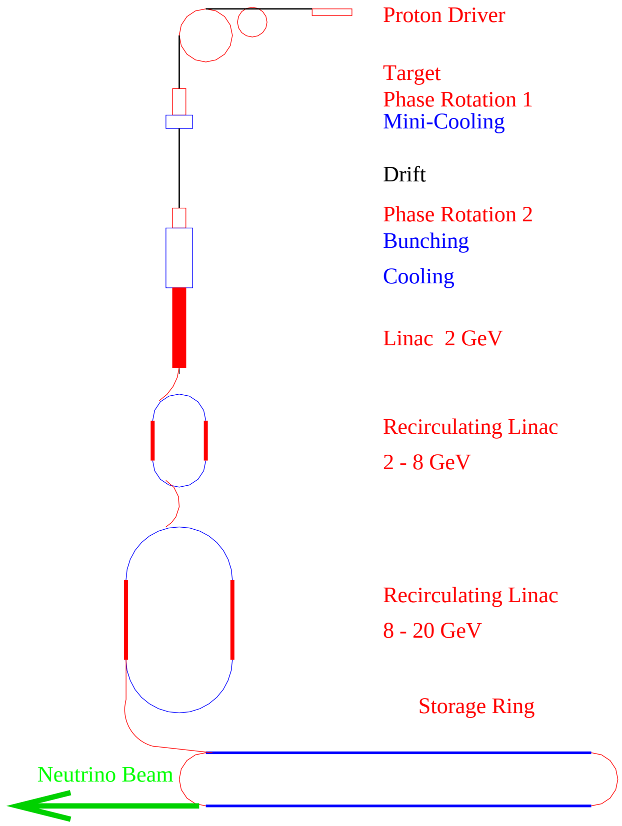
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Recirculating Linac
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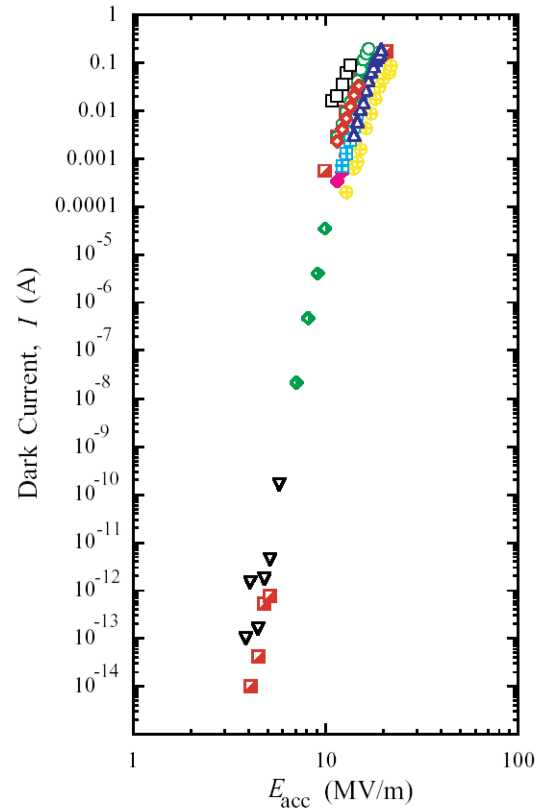
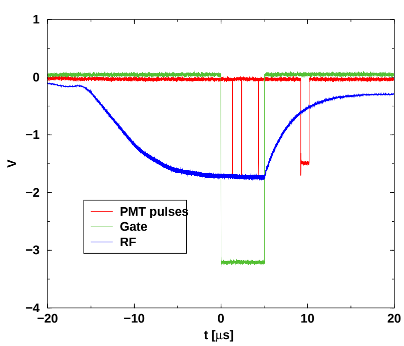
Neutrino Beam


Dark Current, I (A)
E_{acc} (MV/m)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V
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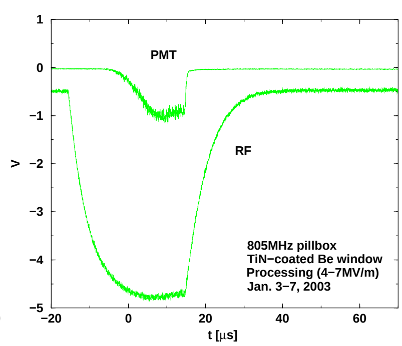
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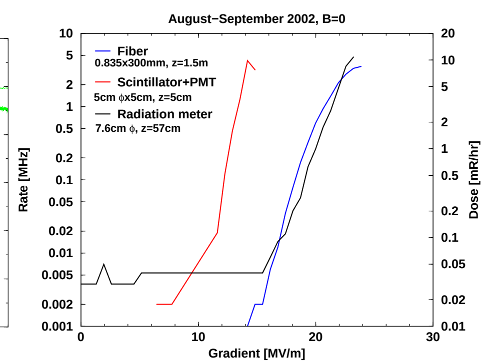
Jan. 3–7, 2003
V
t [μs]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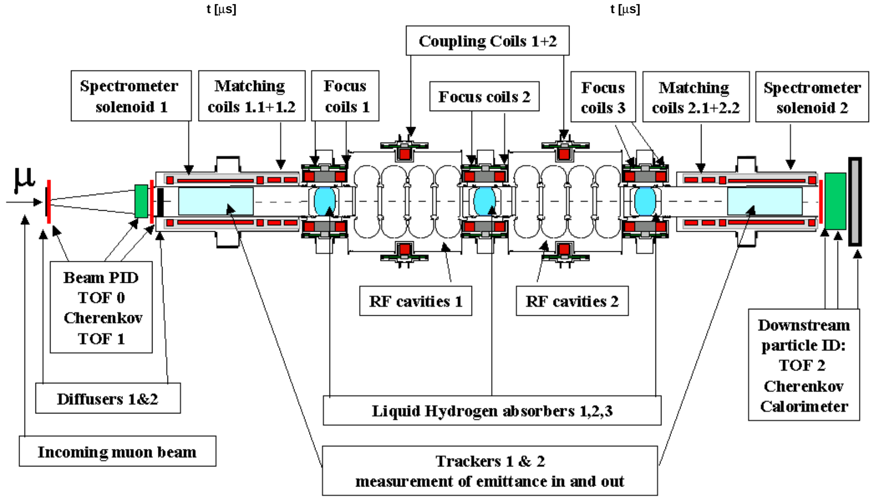
Gradient [MV/m]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μ
Beam PID
TOF 0
Cherenkov
TOF 1
RF cavities 1
RF cavities 2
Downstream particle ID:
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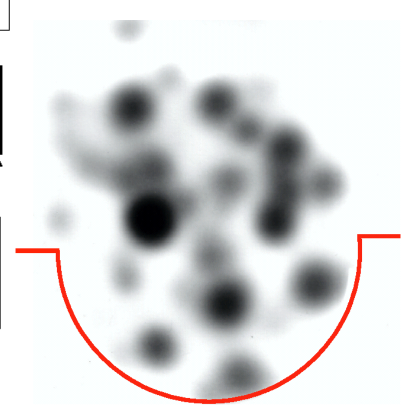
Trackers 1 & 2
measurement of emittance in and out



Advanced Accelerator Studies

G. Shvets – Illinois Institute of Technology

Summary:

Our theoretical/computational has recently relocated from Princeton Plasma Physics Laboratory (PPPL) to Illinois Institute of Technology (IIT). The focus of our work is on the development of plasma based and (to lesser extent) structure-based accelerating concepts, including laser-plasma, plasma channel, and microwave-based plasma 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, magnetic field generation in pre-formed and laser-ionized plasmas. Most important advances have been made in the following areas: (i) excitation of accelerating plasma waves using multiple counter-propagating laser beams; (ii) theory of Raman instabilities in plasma channels; (iii) generation of accelerating waves in magnetized plasma using Electromagnetically Induced Transparency (EIT) and Inverse Cherenkov Acceleration in Magnetized Plasma (ICAMP), (iv) development of laser-driven surface wave accelerator using solid-state materials with negative dielectric permittivity. These advances are briefly described below.

Recent Accomplishments:

Parametric Excitation of Accelerating Plasma Waves Using Multiple Laser Beams.

Ponderomotive excitation of electron plasma waves is known to be very effective in the counter-propagating laser geometry. The fractional density perturbation of the plasma wave is inversely proportional to the square of its wavelength, and is maximized when lasers propagate in opposite directions. Although the resulting short-wavelength plasma waves cannot accelerate relativistic electrons due to low phase velocity, they can nonlinearly interfere and produce the fast super-beatwave capable of relativistic acceleration. This super-beatwave can reach the amplitude of several GeV/m for modest laser beam intensities (below 10^{16} W/cm^2). Two configurations have been theoretically analyzed and simulated using PIC: (a) Colliding Beam Accelerator, where an ultra-short (half plasma period) laser beam collides with a long pulse, and (b) Colliding BeatWave Accelerator, where the pair of beatwave pulses collides with a low-intensity beam. In both configurations significant enhancement of the accelerating field is observed.

Wave-breaking of the short-wavelength plasma wave limits the peak accelerating field, resulting in the linear scaling of the accelerating field with plasma density. Therefore, colliding beam schemes are not practical for plasma density below 10^{19} cm^{-3}. With this in mind, we developed a novel scheme involving a moderately long (hundreds of fs) forward pulse and a counter-propagating beam detuned by 2 ω_p. A parametric instability results in a simultaneous generation of the coupled short- and long-wavelength plasma waves, of which the latter is used for acceleration. Simultaneous availability of Nd:Yag and Ti:S lasers in a number of laboratories makes this a viable proof-of-principle plasma acceleration scheme.

Raman Instabilities in Plasma Channels

Plasma channels are indispensable tools in developing practical laser-plasma accelerators. They are used for guiding laser beams over extended distances thereby increasing the length of the acceleration region. Stability of laser propagation in a channel is determined by parametric instabilities which include Raman Forward and Backward Scattering instabilities (RFS and RBS). In addition, RFS is responsible for generation of accelerating plasma waves in the self-modulated regime of laser wakefield accelerator. The physics of RFS in channels is complicated by two factors: (1) plasma wave frequency is not well defined because plasma density is non-uniform, and (2) plasma wake has a finite magnetic field which leads to the existence of non-local weakly-damped eigenmodes. We have investigated the spatio-temporal evolution of RFS in different channels, both deep and shallow. We have demonstrated significant reduction of the RFS growth rate due to phase mixing of plasma oscillations at different transverse locations. These calculations are now checked against particle simulations, and extended to include RBS instability. RBS in a plasma channel is an important element in developing the recently proposed technique for compressing the energy of a long laser pulse in the plasma via resonant backscattering. Princeton University graduate student Xiaohu Li was involved in this work. The recently hired postdoctoral associate Sergey Kalmykov will be contributing to it at IIT.

Generation of Accelerating Waves in Magnetized Plasma.

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 which 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. We are looking at the regime which corresponds to the slow group velocity of the resulting plasma waves. The incident microwave pulse is compressed in the plasma by the end converted into a predominantly longitudinal wave. Therefore, plasma is both the power compressor and the accelerator. External magnetuc field is necessary to enable coupling of the incident electromagnetic waves into the plasma.

The first configuration requires two magnetic fields: axial (along the beam and wave propagation) and transverse undulator. This configuration is based on the recently discovered by us (in collaboration with UC Berkeley) phenomenon of Undulator Induced Transparency (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 shows 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. The latter feature is due to our ability to control the phase velocity of the plasma wave using undulator strength or periodicity. Our discovery of electromagnetically-induced transparency (EIT) in plasma is of a fundamental importance because, previously, EIT was considered to be a purely quantum mechanical phenomenon that exists due to the interference of quantum mechanical transition amplitudes.

The second configuration we proposed is the Inverse Cherenkov Accelerator in Magnetized Plasma (ICAMP). Only transverse to the propagation direction magnetic field is used for coupling electromagnetic waves into the plasma. When the plasma and radiation frequencies are equal, the phase velocity of the resulting hybrid wave is equal to the speed of light. Particle in Cell simulations confirm a significant (by over an order of magnitude) compression of the electromagnetic energy in the plasma. Analytic and numerical investigations of the limits on accelerating gradients are presently carried out. The original linear theory is extended to the strong wave region where nonlinearities were shown to be important for the UIT configuration.

In addition to these topics, we have investigated several areas of fundamental interest to high-field laser plasma interactions. Motivated by the recent experiment at the Rutherford Appleton Laboratory that detected ultra-strong axial magnetic fields produced in underdense plasma during the propagation of a circularly-polarized laser pulse, we have developed an analytic theory describing magnetic field generation in the course of direct laser acceleration of electrons in an ion channel. In particular, we were able to explain this process as the resonant angular momentum transfer from laser to electrons.

Publications 2001-2003:

Refereed Journal Articles:

1. G. Shvets and X. Li, “Raman Forward Scattering in Plasma Channels", Phys. Plasmas, **8**, 8 (2001).
2. G. Shvets and N. J. Fisch, “Parametric excitations of fast plasma waves by counter-propagating laser beams", Phys. Rev. Lett. **86**, 3328 (2001).
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12. M. S. Hur, J. S. Wurtele, and G. Shvets, “Simulation of electromagnetically and magnetically induced transparency in a magnetized plasma”, Phys. Plasmas 10 (2003).
13. G. Shvets and M. Tushentsov, “Nonlinear propagation of electromagnetic waves in a plasma by means of electromagnetically induced transparency”, accepted to Journal of Modern Optics (2003).

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2. G. Shvets and J. S. Wurtele, "Electromagnetically induced transparency of magnetized plasma", Proceedings of 29th European Physical Society Conference on Plasma Physics and Controlled Fusion, Montreux, 17th –21st June 2002.
3. G. Shvets, J. S. Wurtele, and M. S. Hur, "Applications of magnetized plasma to particle acceleration", Proceedings of the Advanced Accelerator Concepts Workshop, June 23-28, 2002, Oxnard, CA.
4. M. S. Hur, J. S. Wurtele, and G. Shvets, "Magnetically induced transparency and its application as an accelerator", Proceedings of the Advanced Accelerator Concepts Workshop, June 23-28, 2002, Oxnard, CA.
5. P. Sharma and G. Shvets, "New effects in relativistic Thompson scattering", Proceedings of the Advanced Accelerator Concepts Workshop, June 23-28, 2002, Oxnard, CA.
6. G. Shvets, "Photonic approach to making a surface wave accelerator", Proceedings of the Advanced Accelerator Concepts Workshop, June 23-28, 2002, Oxnard, CA.

Current Staff:

- Gennady Shvets — Principal Investigator
- Sergey Kalmykov — Postdoctoral Associate (started June 2003)

Past Graduate:

- Xiaohu Li — Graduate Student, Princeton University (PhD, June 2001), present job: fixed income derivatives, Lehman Brothers (New York)

Current Graduate:

- Michael Tushentsov — Graduate Student, IIT (started June 2003), PhD candidate
- Yaroslav Urzhumov — Graduate Student, IIT (started January 2003), PhD candidate

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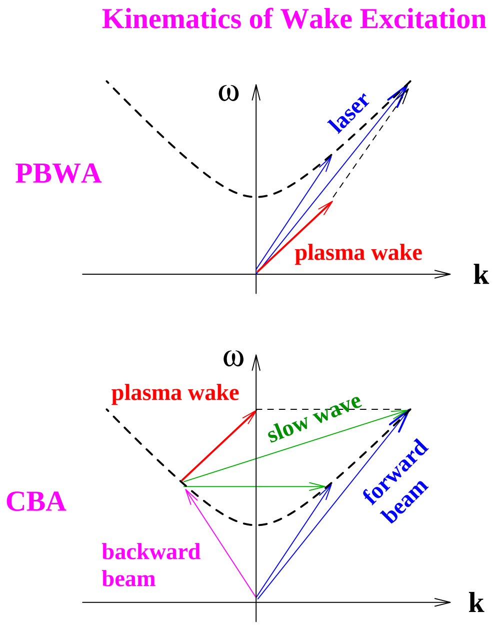
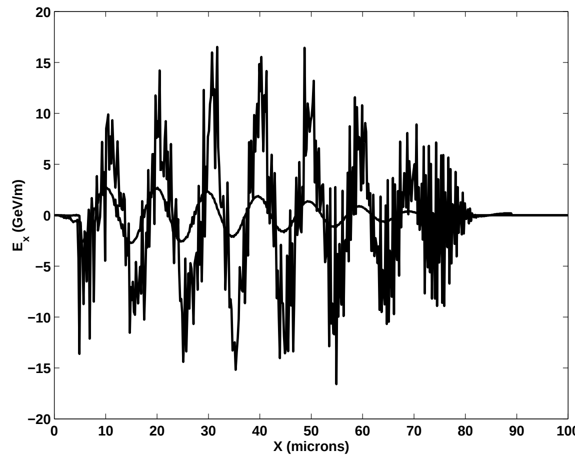
Theoretical Investigations of Plasma-Based Accelerators (PI: Gennady Shvets, IIT)

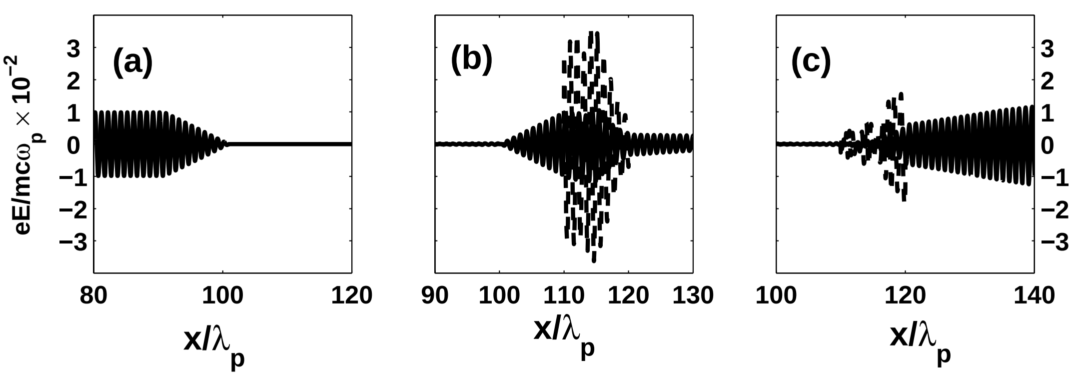
- **Generation of Accelerating Plasma Waves via Four-Wave Mixing (Super-Beatwave), Shvets et.al., Phys. Plasmas(2002).**



Accelerating field produced by the regular beatwave without pump (small wave) and with pump $a_2 = 0.03$ (large wave). Beatwave parameters: $\omega_0 = 10.5\ \omega p$, $\omega_1 = \omega_0 - \omega_p$, $\omega_p \tau_L = 25$, pump frequency: $\omega_2 = 11\ \omega p$, plasma density: $n = 10^{19}\ cm^{-3}$



- **Inverse Cherenkov Accelerator in Magnetized Plasma (ICAMP)**



Transverse (E_y) and accelerating (E_x) electric fields at different times: (a) t = 0, (b) t = 100 λ /c, and (c) t = 200 λ /c. Solid line: E_y, dashed line: E_x

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) space charge effects at high intensity synchrotrons such as the Proton Storage Ring (PSR) at LANL, the Fermilab Booster, and the compressor-synchrotron at the SNS, (2) the effect of space charge stop-band compensation of high intensity beams at the PSR, (3) physics of beam manipulation techniques for attaining high brightness beams, (4) spin dynamics in AGS and RHIC, (5) physics of beam cooling dynamics such as the optical stochastic cooling (OSC), (6) microwave instability induced by inductive insert at the PSR, (7) applications of the quadrupole-mode transfer function, (8) flat-beam photo-cathode, and (9) beam dynamics for recirculating linac for the high gain FEL source. In order to provide realistic space-charge stop-band compensation, we carry out the orbit response matrix method to model PSR and the Fermilab Booster. In the coming years, we are also collaborating with PSR and SNS on the feedback system study for the e-p instabilities. Our group has a close collaboration with scientists at ANL, BNL, Fermilab, SNS, and LANL. Some of these experiments were carried out at PSR, Fermilab Booster, and the AGS.

Our research can be important to future projects in nuclear and particle physics research using high brightness particle beams. Our accelerator physics group is important in training accelerator physics graduate and undergraduate students. 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 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, 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.

Recent Accomplishments:

In 2001-2003, the accelerator physics group at Indiana University has carried out research topics relevant to high intensity and high brightness beams. Some of our major findings can be summarized as follows.

- As the spin degree of freedom becomes more important in nuclear and particle research, acceleration of polarized beam in synchrotrons becomes an important task of accelerator physics. We have installed a solenoid partial snake to overcome imperfection spin resonances, and adiabatic excitation of coherent betatron oscillation with an rf dipole to overcome the intrinsic spin resonances. However, there are weak intrinsic and coupling spin resonances at the AGS can cause 60 % depolarization, resulting in 40 % 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 also observed higher order snake resonances.

- The dipole-mode beam transfer function has been carried out in to measure impedance, betatron tune, machine modeling, etc. Recently, we propose the quadrupole-mode beam transfer function method to measure (1) the rms beam emittance, (2) injection mismatch compensation for high energy accelerators, (3) beam properties measurement for high intensity beams and (4) shape changing impedance. However, our results show that the QTF does not have advantage over the rf dipole method in overcoming the intrinsic spin resonances.
- Many high brightness storage electron storage rings suffer coupled bunch instabilities induced by the parasitic modes of rf cavities. We have studied the effects of rf cavity voltage modulation on the longitudinal collective beam instabilities at Taiwan Light Source (TLS). Theoretical description of rf voltage modulation that includes the effect of non-zero synchronous phase has been developed. The characteristics of the quadrupole parametric resonance in single bunch and multi-bunch beam were studied and compared with theory. The formation of beamlets in the bucket helps to damp the coherent coupled bunch oscillation driving by parasitic modes of the rf system. In the presence of the rf voltage modulation, one observes great sensitivity of the horizontal beam size in dispersive region on the temperature of cooling water in rf cavities. This sensitivity can be used to calibrate the low level rf control feedback loop.
- We have carried out a series high intensity beam experiments at the high intensity Proton Storage Ring (PSR) at the Los Alamos National Laboratory (LANL). The ring is in many ways the predecessor of the future Spallation Neutron Source (SNS) under construction at Oak Ridge National Laboratory, which will operate at a beam power an order of magnitude higher than that currently delivered at the PSR. Still, the same fundamental space charge physics applies to both rings, and a good understanding of instabilities, emittance growth, and beam loss at the PSR is key to designing a stable and reliable higher intensity machine. Experimental observations of the PSR beam have been successfully used to benchmark theoretical and computational models. At the highest operating intensities, the PSR beam consistently experiences beam broadening in the vertical plane. We find that the experimental vertical beam profiles relax to a new equilibrium state at $4.37\cdot10^{13}$ protons per pulse independent of the initial injection painting scheme. We also find that the source of emittance blow-up arises essentially from the half-integer stop-band. Correction of the half-integer stop-band can minimize the emittance dilution.
- The stochastic cooling, invented by S. van der Meer in 1968, has been first experimentally demonstrated at the Intersecting Storage Ring (ISR) at CERN, and used for anti-proton cooling and collection facilities. The success of the stochastic cooling leads to many new discoveries in particle physics. Applications of the stochastic cooling to high energy storage rings encounter a few difficulties. First, the phase space areas of beams in a high energy accelerators are adiabatically damped, thus the stochastic cooling method becomes less efficient. Furthermore, the bunch length (σ_T) is shorter in high energy storage colliders, the cut-off frequency $1/\sigma_T$ for the coherent signal is extended upward to the GHz region. The Schottky signal has often been contaminated by the coherent beam signals. Without a good Schottky signal, it would be difficult to carry out the stochastic cooling. High energy charged particles emit photons in dipoles. The photon emission is a random process. Using the photons instead of microwave signals in beam cooling would solve the problem of coherent signal contamination, and may dramatically enhance the cooling rate. The optical stochastic cooling (OSC) has been proposed by Mikhailichenko and Zolotorev, (Phys. Rev. Lett., **71**, 4146 (1993)) with a quadrupole wiggler, and Zolotorev and Zholents with transit-time method (Phys. Rev. E**50**, 3087 (1994)). Although the basic principle of the optical stochastic cooling has been published in 1994, the requirements of the beam cooling section have not been fully analyzed. In particular, there are 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 *very* high 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.

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5. M.H. Wang, Y. Sato, and S.Y. Lee, "First experimental test of emittance measurements using the quadrupole mode transfer function," Particle Accelerator Conference, (2003).
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coherent half-integer resonance at the PSR," AIP Conference Proceedings, (2002); J. Holmes et al, "ORBIT: A code for collective beam dynamics in high intensity rings," AIP Conference Proceedings, (2002).
12. H. Huang, et al., "Overcoming and intrinsic depolarizing resonance with a partial snake at the Brookhaven AGS," submitted to the Phys. Rev. Lett. (2002).
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14. Nader Al Harbi, "Design of a CIS+ medical synchrotron," Master of Science Thesis, Indiana University, 2002.
15. S. Cousineau, "Understanding space charge and controlling beam loss in high intensity synchrotrons," Ph.D. Thesis, Indiana University (Jan. 2003)
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17. Nader Al Harbi, S.Y. Lee, "Design of a compact medical synchrotron," the Review of Scientific Instruments **74**, 2540 (2003).
18. S.Y. Lee, Y. Zhang, and K.Y. Ng, "Beam damping in optical stochastic cooling," Fermilab Technote FN-0718 (2003); submitted to Nucl Instru. Methods (2003).
19. S. Cousineau, et al., "Envelope and particle instabilities of space charge dominated beams in synchrotrons," Phys. Rev. Special Topics: Accelerators and Beams, **6**, 034205 (2003).
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22. P. Chou, M. H. Wang, and S.Y. Lee, "Effect of the rf cavity cooling-water temperature on electron beams with rf voltage modulation," the Physical Review Special Topics in Accelerators, **6**, 052803 (2003).

Current Staff:
- S. Y. Lee, Professor and Principal Investigator
- Nader Al-Harbi, M.S., August 2002
- V. Ranjbar, Ph.D., Oct. 2002
- S. Cousineau, Ph.D., January 2003

Current Graduate Students:

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- W. Guo, Ph.D.
- Y. Zhang, Ph.D.
- S. Wang, Ph.D.
- DaZhang Huang, Ph.D.
- Xiaobiao Huang, Ph.D.
- Y. Sato, Ph.D.
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Summary of Research on
Periodically Focused Intense Charged-Particle Beams

Dr. Chiping Chen - Intense Beam Theoretical Research Group
Plasma Science and Fusion Center
Massachusetts Institute of Technology

Summary and Recent Accomplishments:

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 and millimeter-wave sources that are considered as drivers for the Next Linear Collider (NLC).

The major breakthroughs in our research during 2001-2003 were:

a) *Discovery of a new confinement criterion for bunched beams.*

b) *Determination of the current limits in the periodic permanent magnet (PPM) focusing klystrons for NLC.*

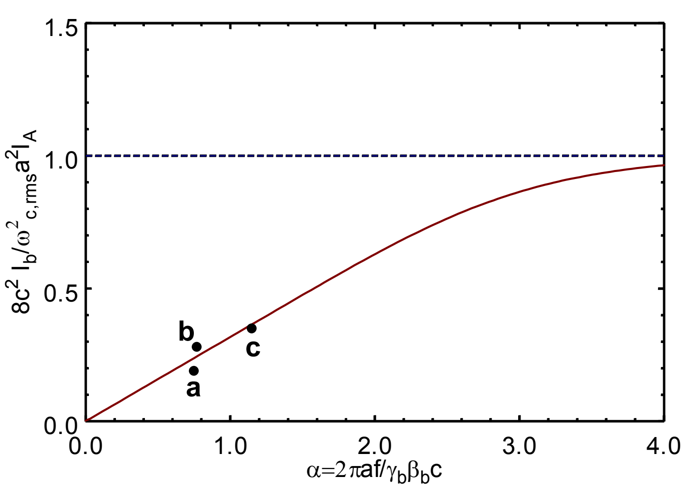
c) *Identification of a new mechanism for chaotic particle motion and halo formation in small-aperture alternating-gradient focusing systems.*

d) *Development and application of the Photonic Band Gap Structure Simulator (PBGSS) code for studies of PBG structures and for design PBG aided rf accelerator and rf sources.*

Results of the above breakthrough were reported in recent Particle Accelerator Conferences, APS Division of Plasma Physics Meetings, Advanced Accelerator Concepts Workshop, and other international scientific conferences.

Research Highlights:

Confinement of bunched beam in PPM klystrons



A plot of the maximum value of the self-field parameter (solid curve), $8c^2 I_b / \omega_{c,rms}^2 a^2 I_A$, for bunched beam confinement as a function of the parameter $\alpha = 2\pi a f / \gamma_b \beta_b c$. Shown in letters are the operating points for three SLAC PPM focusing klystrons: a) 50 MW XL-PPM, b) 75 MW XP, and c) Klystrino. The dashed line denotes the Brillouin density limit for an unbunched beam (from Hess and Chen, Phys. Lett. **A295**, 305, 2002).

Parameters for SLAC PPM Focusing Klystrons
(from Hess and Chen, Phys. Lett. **A295**, 305 2002)

PARAMETER	50 MW XL-PPM	75 MW XP	KLYSTRINO
f (GHz)	11.4	11.4	95
I_b (A)	190	257	2.4
γ_b	1.83	1.96	1.22
B_{rms} (T)	0.20	0.16	0.29
A (cm)	0.48	0.54	0.04
α	0.75	0.77	1.15
$\left.\frac{8c^2 I_b}{\omega_{c,rms}^2 a^2 I_A}\right\|_{exp}$	0.19	0.28	0.35
$\left.\frac{8c^2 I_b}{\omega_{c,rms}^2 a^2 I_A}\right\|_{cr}$	0.238	0.244	0.366

<u>2001-2003 Publications</u>

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Chiping Chen, Principal Research Scientist

Division Head
Richard Temkin, Senior Scientist

Administrative Support
Mary Pat McNally

Scientists
Chiping Chen
John A. Davies
Mark Hess
Bao-Liang Qian (now on the faculty of National University of Defense Technology, Changsa, Hunan, China.)

Graduate Students (all pursuing Ph.D.)
Ronak Bhatt
Enrique Henestroza
Ksenia Samokhvalova
Jing Zhou

<u>Recent Graduates:</u>
Yoel Fink, Ph.D. 2000, Assistant Professor, Dept. of Materials Science and Engineering, MIT

Mark Hess, Ph.D. 2002, Visiting Professor at Clark University, Spring 2003; currently Postdoctoral Research at Plasma Science and Fusion Center, MIT

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17 GHz High Gradient Accelerator Research

Richard Temkin – Massachusetts Institute of Technology

Summary:

The 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., 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. 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 mmmrad.

Recent Accomplishments:

- Routine operation of the Haimson Research Corp. 17 GHz rf accelerator with beam energy of over 17 MeV at 100 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 mm-mrad and brightness of up to 50 10^{12} A/m^2, in excellent agreement with theory.
- Theoretical design of 11 GHz and 17 GHz photonic bandgap cavities with a triangular lattice and a waveguide input coupler; fabrication and cold test of the cavities with excellent agreement between theory and experiment, showing the absence of high order (wakefield) modes.
- Educational activities and thesis research for graduate and undergraduate students; former students active in accelerator physics; visiting postdoctoral fellows.

Research Goals of this Program Include:

- Measurement of the bunch length of the electron beam, estimated to be about 180 fs, using a Smith-Purcell coherent radiation emission diagnostic.
- 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 up to 90 GHz.

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

In addition to the research funded at MIT, the Haimson Research Corporation (HRC) has been separately and independently funded (by the SBIR program of DOE HEP) to develop microwave source 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 35 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.

Interest in research on accelerators driven by very high frequency microwaves stems from the projected ability to operate such accelerators at higher gradients than present day or nearer term accelerators, such as the Next linear Collider that will operate at X-Band, 11.4 GHz. 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 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 improvement 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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2. M. A. Shapiro, W. J. Brown, I. Mastovsky, J. R. Sirigiri, And R. J. Temkin, "17 Ghz Photonic Band Gap Cavity With Improved Input Coupling," Phys. Rev. ST Accel. Beams Vol. 4, 042001 (2001).
3. M. A. Shapiro, W. J. Brown, C. Chen, J. R. Sirigiri, R. J. Temkin, "Measurement And Simulation Of A 17 Ghz Photonic Band Gap Structure For Accelerator Applications," PACS2001.-Proceedings-Of-The-2001-Particle-Accelerator-Conference-Cat.-No.01CH37268. Pp. 930-2 Vol.2 (2001).
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5. S. E. Korbly, W. J. Brown, M. A. Shapiro, R. J. Temkin, "Design of a Smith-Purcell radiation bunch length diagnostic," PACS2001.-Proceedings-of-the-2001-Particle-Accelerator-Conference-Cat.-No.01CH37268. 2001: pp. 2347-9 vol.3 (2001).

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15. E. I. Smirnova, C. Chen, M. A. Shapiro and R. J. Temkin, "An 11 GHz photonic bandgap accelerator structure with wakefield suppression," Particle Accelerator Conference PAC03, Portland, OR May, 2003 Paper TPAB029 IEEE Press (to be published, 2003).
16. A. Kesar, S. Korbly, I. Mastovsky, R. J. Temkin, J. Haimson, B. Mecklenburg "Initial testing of a field symmetrized dual feed 2 MeV, 17 GHz rf gun," Particle Accelerator Conference PAC03, Portland, OR May, 2003 Paper WPAB024 IEEE Press (to be published, 2003).
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18. E. I. Smirnova and C. Chen, "Asymptotic analysis of dispersion characteristics in two-dimensional metallic photonic band gap structures," J. Appl. Phys. 93, 5859 (2003).

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- Mr. Ivan Mastovsky, Research Scientist, MIT Plasma Science and Fusion Center
- Mr. William Mulligan, Engineer, MIT Plasma Science and Fusion Center
- Dr. Jake Haimson, Haimson Research Corp. and Visiting Scientist, MIT

Postdoctoral Associates:

- Dr. Amit Kesar, Ph. D. in Physics, Tel Aviv Univ.
- Dr. Jagadishwar Sirigiri, Ph. D. in Electrical Engineering, MIT

Graduates Students:

- Mr. Stephen Korbly, candidate for Ph. D. in Physics, MIT
- Ms. Evgenya Smirnova, candidate for Ph. D. in Physics, MIT
- Mr. Roark Marsh, candidate for PH. D. in Physics, MIT
- Mr. Kip Bishofberger, MIT Undergrad, now a Graduate Student, Elec. Eng. Dept., UCLA, working at Fermilab.

Former Students and Postdocs:

- Dr. Winthrop Brown, PH. D. Physics, 2001, currently, staff scientist at Lawrence Livermore National Laboratory.
- Dr. Seth Trotz, Ph. D. Physics, 1997, currently employed at MIT Lincoln Laboratory, Lexington, MA.
- Dr. Marco Pedrozzi, Postdoc 1998-1999, Scientist, Swiss Synchrotron Light Source.
- Dr. Jerome Gonichon, Ph. D. Universite Paris, 1995, Scientist, General Electric, France.

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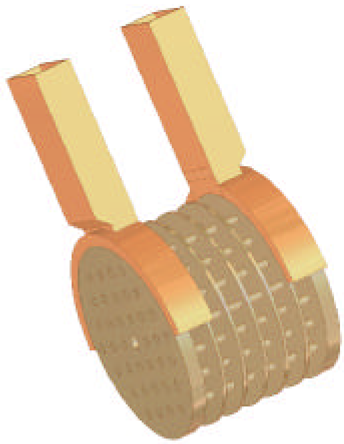
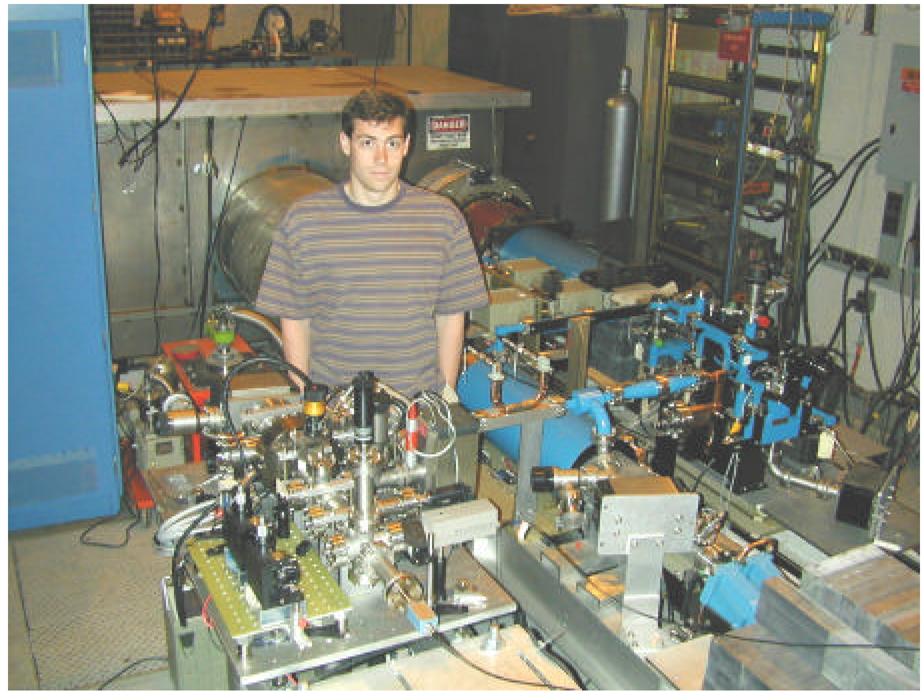
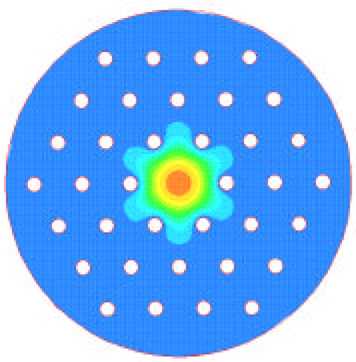
MIT High Gradient Accelerator Research



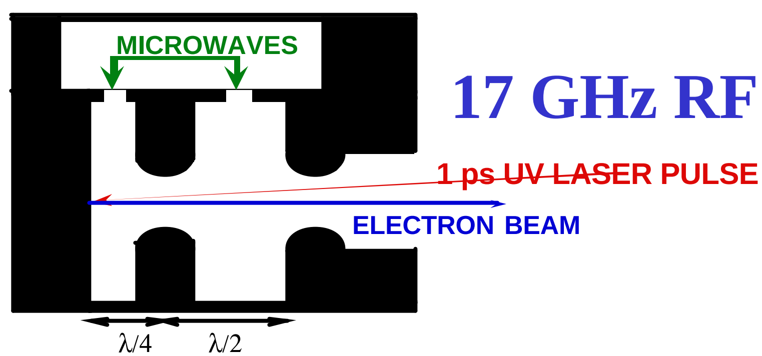
Photonic Bandgap Accelerator Structure



17 GHz, 25 MeV Haimson Accelerator



Photonic TM_{01} Cell



17 GHz RF Gun

Advanced Map Methods for the Description of Particle Beam Dynamics
Martin Berz, Michigan State University

Summary:

The work in the Beam Theory and Dynamical Systems Group in the Department of Physics and Astronomy at Michigan State University contributes to the 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 Muon Collaboration and the simulation of the FNAL Tevatron. Current work work is also directed toward the further development of the code COSY INFINITY, as well as the VUBeam on-line degree and course program in Beam Physics.

Recent Accomplishments:

As part of our activities and strong commitment to the muon collaboration, there is further development of our code COSY INFINITY, which is currently being used for muon simulation work at FNAL, CERN, BNL, UIUC, and MSU. Besides treating the full nonlinear Hamiltonian without the common approximation of expanding the square root and within a 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 precoolers 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 the need to simulate 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. The simulation tools are being prepared to allow optimization in terms of a figure of merit comprising emittance reduction, particle loss, and other parameters based on propagation of an extended ensemble of particles determined by a previous code. This work leads to the ability to offer relatively wide ranging adjustability of parameters like matching regions, linear optics of the FODO cell, higher harmonics and fringe fields of the focusing quads, and cavity phases and frequencies relative to those of the buncher as well as the possible need to use higher harmonics. As such, the resulting COSY tools complement the abilities of the other widely used muon simulation codes including GEANT and ICOOL which because of their design are computationally expensive and do not have far-reaching optimization capabilities.

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, there is a great need for support of user questions to allow for the effective use of the code. This support requires expert knowledge about the detailed workings of the code, and has continued to be one of the very time demanding aspects of the work in the group. The code also forms one of the backbones of the interactive homework system of VUBeam, MSU's Virtual University program in Beam Physics described below. Support is also being provided for the implementation of various new features that are being implemented in the code include the refinements to the methods for the verified integration of maps, the ability to treat detailed accelerating structures in connection with a collaboration with ANL, and various enhanced fringe field methods for the work on the Muon Collider described below, 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. These methods may lead to the development of computationally more favorable coordinate systems than the well-known curvilinear coordinates that have been extensively used in the past. Also, the development of more advanced preconditioners based on normal form methods is continuing.

Besides the conventional training of graduate students within the group at MSU, significant work is required for the maintenance of the VUBeam program, the on-line education initiative in Beam Physics supported by MSU's Virtual University. Over the last several semesters, more than 30 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 year, five of these students have completed Master's degrees, and various others have been paired up with suitable mentors at US National Laboratories and other locations to provide guidance and supervision for dissertation work.

Currently there are four on-line courses based on live lectures over the Internet and 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, these decks 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).

Publications 2001-2003:

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[16] C. O. Maidana, M. Berz, and K. Makino. “Muon beam ring cooler simulations using COSY INFINITY.” In Computational Accelerator Physics, 2003.
[17] M. L. Shashikant, M. Berz, and B. Erdelyi. “COSY INFINITYs EXPO symplectic tracking for LHC.” In Computational Accelerator Physics, 2003.
[18] K. Shamseddine and M. Berz. “Intermediate values and inverse functions on non-Archimedean fields.” International Journal of Mathematics and Mathematical Sciences, 30:165-176, 2002.
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[21] M. Berz and K. Makino. “Constructive generation and verification of Lyapunov functions around fixed points of nonlinear dynamical systems.” IJCR, 2002, in print.
[22] M. Berz and J. Hoefkens. “Verified high-order inversion of functional dependencies and superconvergent interval Newton methods.” Reliable Computing, 7(5):379-398, 2001.
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[25] 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, 2002, in print.
[26] J. Hoefkens, L. Diening, M. Berz, and B. Erdelyi. “The WebCOSY system for course management in distance education.” Journal of Computers in Mathematics and Science Teaching, 20(3):307-321, 2001.
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[28] M. Berz, K. Makino, and J. Hoefkens. “Verified integration of dynamics in the solar system.” Nonlinear Analysis, 47:179—190, 2001.
[29] M. Berz, B. Erdelyi, and K. Makino. “Fringe field effects in small rings of large acceptance.” Physical Review ST-AB, 3:124001, 2001.

Current Staff:

- Principal Investigator: Martin Berz
- Scientists: Kyoko Makino

Graduate Students:

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- Youn-Kyung Kim, pursuing PhD in Physics, MSU
- Johannes Grote, pursuing dual PhD in Physics/Mathematics, MSU
- Carlos Maidana, pursuing PhD in Electrical Engineering, MSU
- Pavel Snopok, pursuing PhD in Physics, MSU
- Alexey Poklonskyi, pursuing PhD in Physics, MSU
- Stephen Weathersby, pursuing MSc 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
- Chenghui Yu, pursuing PhD in Physics via VUBeam, Beijing
- Farzad Nekoogar, pursuing PhD in Physics via VUBeam, LBL

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.

Undergraduates:

- Laura Chapin

Past Graduates from this contract in 2001-2003:

Bela Erdelyi, PhD 2001, Postdoc, Fermilab
Jens Hoefkens, PhD 2001, Staff Scientist, GeneData
Jens von Bergmann, MSc 2001
Ralf Toenjes, MSc 2001
Jason Ong, MSc 2002 (VUBeam program)
Mandi Meidlinger, MSc 2002 (VUBeam program)
David Meidlinger, MSc 2002 (VUBeam program)
Reiko Taki, MSc 2003 (VUBeam program)
Mohamed Nasr, MSc 2003 (VUBeam program)

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

Steven H. Gold – Naval Research Lab

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 up to the design level. A power combiner/phase shifter assembly is being fabricated which will allow the power from the two output waveguides to be combined into a single waveguide, or split in any desired ratio and with any desired phase relationship between two waveguides.

Recent Accomplishments:

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. Thus far, high-power tests of three separate DLA structures have been carried out. The first two were traveling-wave and standing-wave DLA structures that were iris-coupled to the magnicon output waveguide. In both of these tests, the iris was the limiting factor, and iris breakdown limited the accelerating gradient to ~3–5 MV/m at drive powers of less than 1 MW. The third experiment tested a new input coupler that transitions from rectangular TE_{01} waveguide into the circular TM_{01} mode accelerating tube in a dielectric-free region of the cylindrical tube, after which there is a gradual transition into the dielectric-lined region. A traveling-wave configuration employing this new coupler experienced no breakdown up to 10 MW incident power. Next, the dielectric liner was inserted, and measurements made of the reflected and transmitted signals as a function of incident power (up to 5 MW). During these measurements, a progressive increase in the attenuation through the DLA structure was observed, as a function of incident power, starting at approximately 100 kW. 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 appear to result from the formation of a microwave-absorbing electron cloud near the dielectric surface due to single-surface multipactor. Future experiments will explore a variety of means to suppress electron multiplication by lowering the secondary emission coefficient of the dielectric surface, including the use of a thin TiN layer on the inner surface of the dielectric. The next high-power tests are scheduled for August 2003.

The second technology 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. Several high-power tests of active pulse compressor configurations have been carried out on the magnicon facility, with the two most recent tests carried out in 2002. The first of these recent tests was of a single-channel pulse compressor. In the self-breakdown regime of operation, 25 MW, 40-50 ns output pulses were obtained at a compression ratio of ~6x, while in triggered operation of the switch, 11-MW output pulses were obtained at a compression ratio of ~8x. Operation was limited by rf breakdown at higher powers. The second test was of a two-channel configuration, connected to the magnicon and to the high-power load by means of a quasioptical 3-dB hybrid coupler. In this configuration, the reflection from the two pulse compressor channels is directed to the load, so that the magnicon always sees a good rf match. (This is the same basic configuration used at SLAC in the SLED-II pulse compressor, to ensure that the klystrons always see a good rf match.) The test of a two-channel configuration demonstrated that the two channels, each with its own plasma switch tubes, could be switched simultaneously, and that switching had no effect on the rf phase relationship, so that the output of the two channels combined phase-coherently in the 3-dB hybrid, and was directed to the load. At a drive level of ~1 MW in a ~1 μs pulse, compressed output pulses of ~10 MW were observed with ~70 ns pulse length. This demonstrated the feasibility of this approach to active microwave pulse compression. However, operation at higher power levels was not possible, due to rf breakdown. This was attributed to an insufficient bakeout period and an insufficient level of rf conditioning. The R&D is continuing, and measures are being taken to increase the breakdown threshold of the device. The next high-power tests will begin in June 2003.

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9. A.L. Vikharev, O.A. Ivanov, A.M. Gorbachev, V.A. Isaev, S.V. Kuzikov, S.H. Gold, A.K. Kinkead, and J.L. Hirshfield, "First high-power experiments on a two-channel x-band active rf pulse compressor," in *Proceedings of the 2003 Particle Accelerator Conference*, in press.
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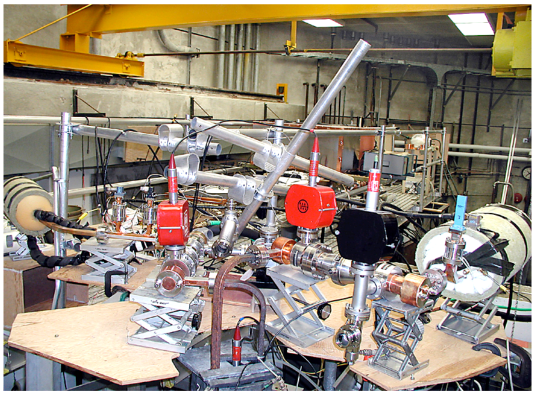
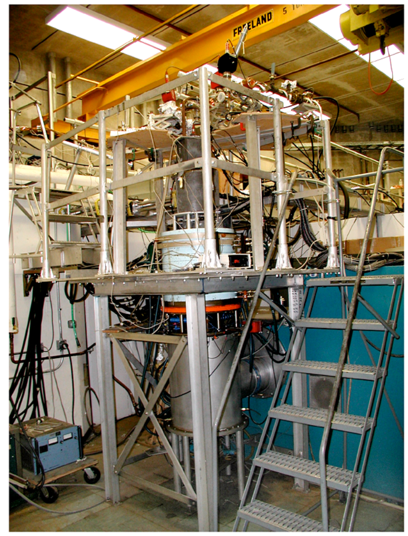
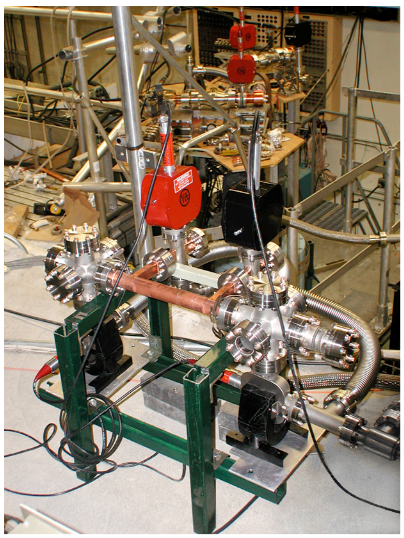
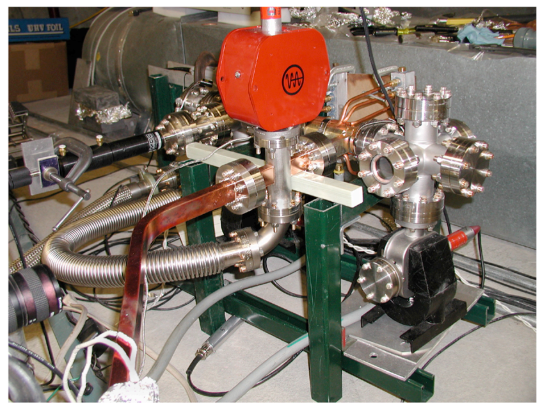


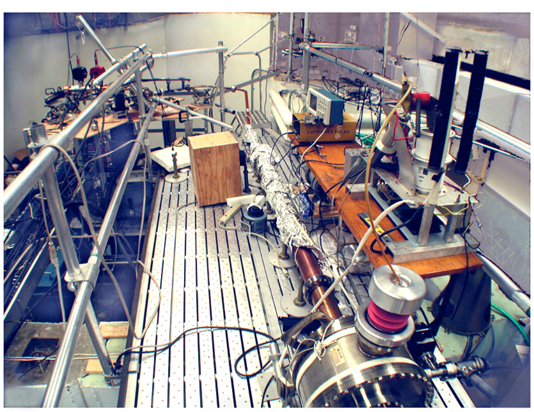
11.424-GHz Magnicon Amplifier (right) and output section (left)



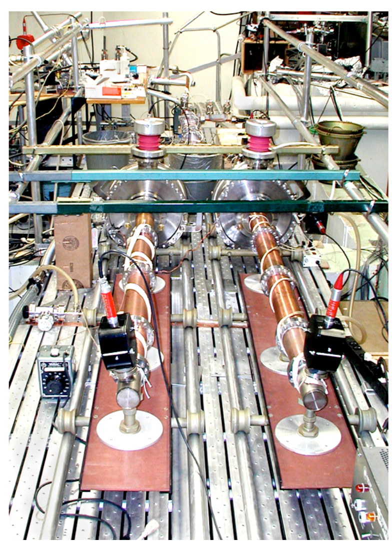


Dielectric-loaded accelerating structure test stand





One- and two-channel active microwave pulse compressors



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

P. Sprangle, Plasma Physics Division, Naval Research Laboratory

Summary:

Overview: The 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 is highly unstable, and the accelerated electron beam has a large energy spread. The current Tabletop Terawatt (T^3) laser at NRL, which produces a >10 TW, 400 fsec long pulse, is well-suited for SM-LWFA experiments and has also been used for optical guiding and all-optical electron injector experiments.

The general strategy for producing higher quality 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 $\lambda_p = 2\pi c/\omega_p$, 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 LIPA (Laser Ionization and Ponderomotive Acceleration) 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 group velocity of the laser pulse. 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.

Although optical injection, channel guiding, and "standard" LWFA acceleration have been demonstrated separately, the first integrated experimental demonstration of all of these components simultaneously is now in progress, using a 10 TW upgrade of the NRL Ti:sapphire femtosecond laser (TFL). This demonstration experiment includes a collaboration with Icarus, Inc., which is separately funded by a DOE SBIR grant.

Recent Achievements (Theoretical/Computational): Theoretical and computation studies since 2001 have covered a broad range of topics. A primary emphasis has been on modeling laser propagation and electron acceleration in channel-guided, "standard" LWFA's. 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 LWFA's 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. Most of the simulation studies in the past have emphasized the regime for an ideal, future LWFA, with phased electron injection into an ideal plasma channel. However, more recent channel-guided

LWFA modeling studies have centered on the regime of the TFL upgrade and have emphasized specific experimental difficulties that may be encountered in near term experiments. These include non-ideal electron injection spectra, electron transport and coupling into the plasma channel, electron deflection by capillary discharge fringing fields, and plasma channel degradation by laser-produced inner shell ionization. Other recent analytical and simulation studies of channel-guided LWFA's have demonstrated that a monoenergetic, unphased (long) electron pulse can produce a final electron spectrum with remarkably small energy spread, bunch length, and final emittance. The process that produces these high quality accelerated electron bunches involves pruning of electrons that move into defocusing portions of the wakefield, combined with strong phase bunching, rapid acceleration, and matching of the injection energy to the strength of the wakefield. These results have important practical implications for future LWFA's since they suggest that precisely-timed, ultrashort electron bunch injection may not be necessary.

LWFA acceleration involves a number of fundamental laser propagation, atomic physics and plasma physics effects. These fundamental studies have been an important component of the NRL program. A generalized model for treating both relativistic focusing and ponderomotive expulsion of electrons in uniform plasmas or plasma channels was developed and benchmarked against simulation models. Nonlinear pulse compression and photon deceleration (red shifting) in long plasma channels was observed in several simulation models and shown to have important implications for some LWFA parameter regimes. The possible use of short plasma channels as focusing (or defocusing) lenses was studied extensively with both analytical and simulation models. Plasma channel lenses could be used as optical elements in a LWFA at locations where the laser intensity is far above the damage threshold for conventional lenses or mirrors. Several studies of Raman instabilities in the long pulse regime were also carried out. A fundamental difficulty in treating Raman sidescatter correctly with the commonly-used quasi-static approximation was analyzed using both analytical and simulation models. A detailed study of Raman and self-modulation effects in channel-guided, long pulse (SM) LWFA's revealed a fundamental problem with rapid dephasing that appears to be the primary limitation for this accelerator concept. Finally, fundamental studies of photoionization were carried out, resulting in improved ionization models for the SIMLAC and TurboWAVE codes.

Simulations of both the LIPA and SM-LWFA optical injector concepts were carried out, primarily using TurboWAVE. These studies were closely linked to the NRL experimental program and in many cases also included a detailed analysis of electron transport for the injector to the plasma channel The SM-LWFA simulations show this approach as a viable option for near term experiments, although the quality of the beam produced is far from ideal. Recently, full 3-D simulations of a LIPA injector have been carried. At low gas densities, the simulations reproduce the expected strong correlation between energy and angle that make LIPA an attractive choice for a high quality, all-optical injector. At higher densities, space charge effects play an important role. The number of electrons accelerated increases substantially, and the plasma provides a substantial boost to the electron energy. However, the energy-angle correlation is smeared out, and the quality of the electron beam is significantly degraded.

Recent Achievements (Experimental): The NRL experimental program is focused on the investigation of laser guiding, electron acceleration, and optical injection for LWFA's using the T^3 laser. Highlights of the earlier experimental work included acceleration to 100 MeV in a SM-LWFA, demonstration of efficient optical guiding in long plasma channels, and the demonstration of the LIPA optical injection concept. There have been substantial recent improvements in the performance and reliability of the T^3 laser, including the upgrade to >10 TW, and dual beam (10 TW/2 TW) operation for injector/accelerator experiments.

Optical guiding experiments since 2001 have concentrated on characterizing the plasma channel inside the capillary discharge. Interferometric images were taken of the interior plasma channel inside a specially designed transparent discharge capillary constructed out of fused silica and having a square cross section. To analyze this data, a local density profile with square symmetry, 3rd order polynomial dependence on the transverse coordinates, and arbitrary axial dependence was assumed, allowing deconvolution of the local density from the interferograms. The analysis revealed the desired radial profile for optical guiding, but there was a significant drop in plasma density near the ends of the capillary and a small random transverse displacement in the centroid of the plasma channel. A time resolved Raman-backscatter diagnostic was also developed to probe the capillary plasma. A new chamber for guiding and acceleration experiments has recently been constructed, in preparation for LWFA experiments with the upgraded TFL laser. Initial experiments may provide the first simultaneous demonstration of optical and wakefield generation in the "standard" LWFA regime, which would be an important milestone in the development of a high quality LWFA.

Both the LIPA and SM-LWFA approaches are being investigated at NRL for all-optical injection. A two-beamline version of the T^3 laser with separate compression sections was constructed and demonstrates a capability that will be essential for future two-stage (optical injection *and* LWFA acceleration) experiments. Experiments during 2002 emphasized the SM-LWFA injector approach. The electron energy spectrum was measured and has sufficient energy to be useful for future LWFA experiments. A magnetic energy selector was designed that could be used to tune the injection energy for subsequent LWFA acceleration. Although LIPA experiments with the original 2.5 TW T^3 laser were successful in generating ~1 MeV electrons, the initial attempts with the >10 TW T^3 upgrade in 2002 encountered numerous problems with laser operation. These problems have largely been solved, and LIPA experiments during 2003 with the T^3 laser and a nitrogen gas jet have generated a peak in the electron yield at a 30 degree angle, with maximum electron energies at this angle of ~3 MeV. These results are consistent with the LIPA mechanism. However, substantial electron yield is also produced on the forward (0 degree) direction, with somewhat higher maximum electron energies (~8 MeV). TurboWAVE simulations are consistent with these results and suggest that both LIPA and SM-LWFA (or direct laser acceleration) mechanisms are involved. Although the beam quality is not as good as in earlier LIPA experiments, the more recent experiments produced sufficient electron energy for typical LWFA injector applications. Future channel-guided LWFA experiments with the TFL upgrade will use this "high density LIPA" optical injector. NRL also collaborated on experiments in Israel that used a solid wire in place of the gas jet as a target for an optical injector.

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High Energy Laser-Driven Acceleration Based on the Laser Wakefield Accelerator (LWFA)

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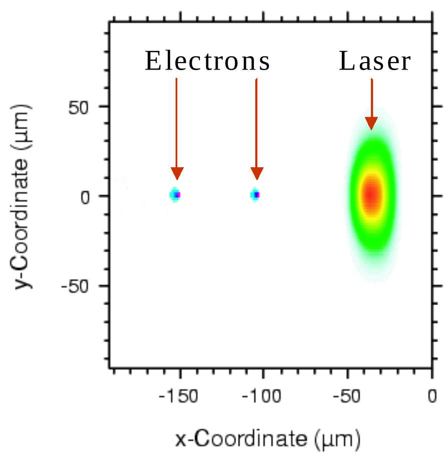
Research Areas

- Standard (short pulse) and self-modulated (long pulse) laser wakefield accelerators
- Optical guiding and electron acceleration in plasma channels
- All-optical electron beam injectors

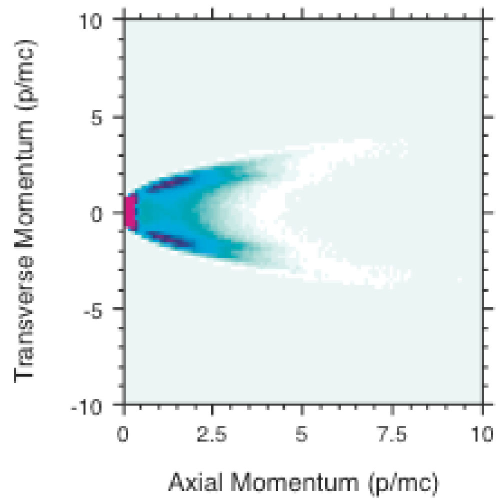
Research Tools

- Numerical models: TurboWAVE, SIMLAC, LEM, WAKE, Cyber-Ray
- Tabletop Terawatt Laser (T^3): 1.054 µm, 400 fs, >10 TW
- Ti:sapphire Fsec Laser (TFL): 0.8 µm, 50 fs, 1 TW (10 TW upgrade in progress)

Simulation of phase bunching and acceleration in channel-guided LWFA

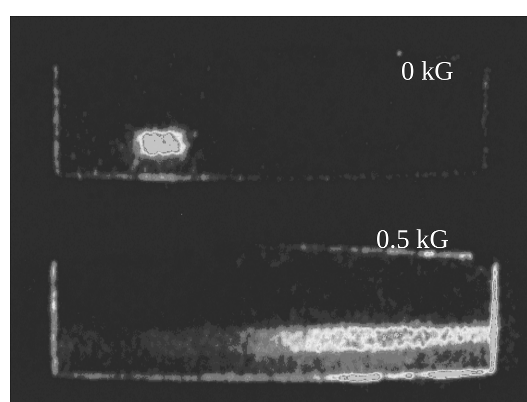


Transverse vs axial momentum in simulation of NRL all-optical injector



Current setup for the 2 beam (10 TW, 2 TW) T^3 laser optical injection experiments

Electron spectrometer images of optical injector energy spectrum



Instrumentation Standards

L. Costrell – NIST

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. Its function is that of standards development, processing and coordinating. Its first activity was the development of the NIM instrumentation system, through the Department of Energy 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 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 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 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 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 an 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 HEP 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 W. Ekin – National Institute of Standards and Technology

Summary:

Project Purpose: This project provides the electromechanical 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. Stress and strain management is one of the key base technologies that needs to be developed for these brittle ceramic materials. The project utilizes specialized measurement capabilities to study and develop models for understanding electromechanical properties. It serves industry primarily 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, and the stress-strain characteristics. 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. A textbook is also being written, entitled "*Experimental Techniques for Low Temperature Measurements*".

Recent Accomplishments:

The fabrication of the next generation of particle accelerators for high energy physics will require the development of a new Nb_3Sn superconductor able to carry extremely high current densities (J_c) at high magnetic fields. One technique for accomplishing this is to push the density of superconductor in the composite wire to new limits. Such an experimental, high-Nb composite was recently fabricated by *Oxford Superconducting Technology*. A concern in high-energy-physics community was that the conductor would have very low tolerance to mechanical strain. Our tests show that this conductor had electromechanical tolerance similar to standard Nb_3Sn composites. The irreversible strain, beyond which the conductor shows permanent degradation, had a relatively high value of 0.73 %. The peak critical current was measured at a strain of 0.29 %. This result clears the way for wire manufacturers to push the niobium density to even higher values, which could provide a significant extension of the magnetic field limit of the present accelerator magnets.

We carried out measurements of the effect of strain in Nb_3Sn tapes made by chemical vapor deposition and found results that seem to contradict the deviatoric-strain model. At a field of 11 Tesla and a strain of 0.26 %, the effect of axial strain on J_c amounts to about +15 %, whereas that of transverse compressive stress is only about –0.5 % at 170 megapascals. This result does not support the deviatoric-strain model, which would predict an increase of J_c with transverse stress, just the opposite of the sign of the effect observed and far different from the magnitude measured. One possibility to explain the results obtained is to consider a large hydrostatic strain effect, which was previously neglected by the deviatoric-strain model.

The axial strain measurements carried out on a new generation of Bi-2212 multifilamentary wires at 16.5 Tesla and 4 Kelvin, revealed that the tolerance to strain of this conductor has been greatly improved. The irreversible strain at which the critical current density starts to degrade is found to be as high as 0.5 %, representing an improvement by a factor of three with respect to early Bi-2212 wires made a decade ago. This new finding opens very promising perspectives for the use of Bi-2212 multifilamentary wires in fabricating large electromagnets for high-energy-physics accelerators. These new multifilamentary wires were designed so that the porosity of Bi-2212 powder is reduced. This resulted in a significant enhancement of both the critical current density and its tolerance to strain

We made a preliminary investigation of the electromechanical properties of newly discovered MgB_2 superconductor as a function of magnetic field. A nickel-sheathed MgB_2 tape was tested as a function of axial strain in high magnetic fields. MgB_2 was found to exhibit a small reversible increase of J_c as a function of strain, driven by an intrinsic strain effect on the effective upper critical field of this material. The data indicate that the strain sensitivity of MgB_2 is significantly smaller than that of Nb_3Sn superconductor. As the applied strain is increased beyond the irreversible strain limit of the conductor, J_c shows a dramatic drop as cracks form in the superconductor due to the application of strain.

Dr. Jack W. Ekin is presently in the process of finishing a textbook on experimental techniques for cryogenic measurements. This book covers the *design* of cryogenic measurement probes, and provides *cryogenic materials data* in the appendices for carrying out their construction. Topics include, for example, thermal techniques for designing a cryogenic apparatus, selecting materials appropriate for such apparatus, how to make high-quality electrical contacts to a superconductor, and how to make reliable critical-current measurements. The textbook is written for *beginning graduate students*, *industry measurement engineers*, and *materials scientists* interested in learning how to design successful low-temperature measurement systems. The appendices are written for *experts* in the field of cryogenic measurements and include electrical, thermal, magnetic, and mechanical properties of technical materials for cryostat construction; properties of cryogenic liquids; as well as temperature measurement tables and thermometer properties. These appendices aim to collect in one place many of the data essential for designing a new measurement apparatus.

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6. N. Cheggour, J. W. Ekin, C. C. Clickner, D. T. Verebelyi, C. L. H. Thieme, R. Feenstra, and A. Goyal, “Axial tensile strain effect on the critical-current density of Y-Ba-Cu-O coatings on deformation-textured Ni-based substrates,” Appl. Phys. Lett., submitted (2003).

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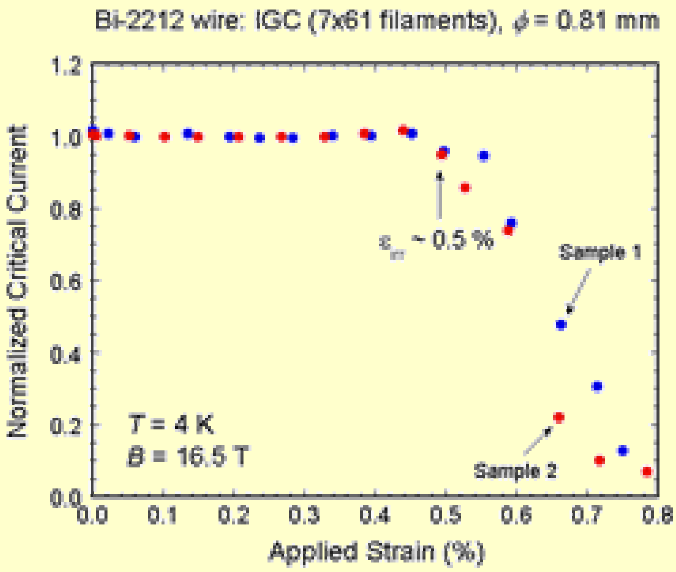
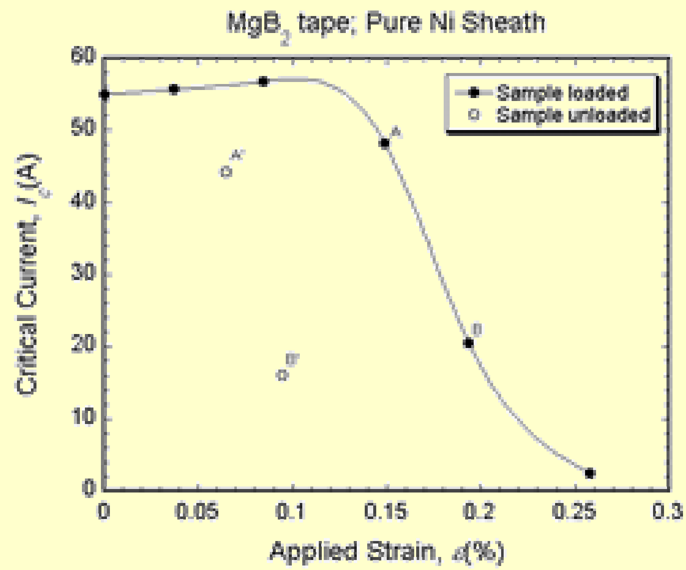
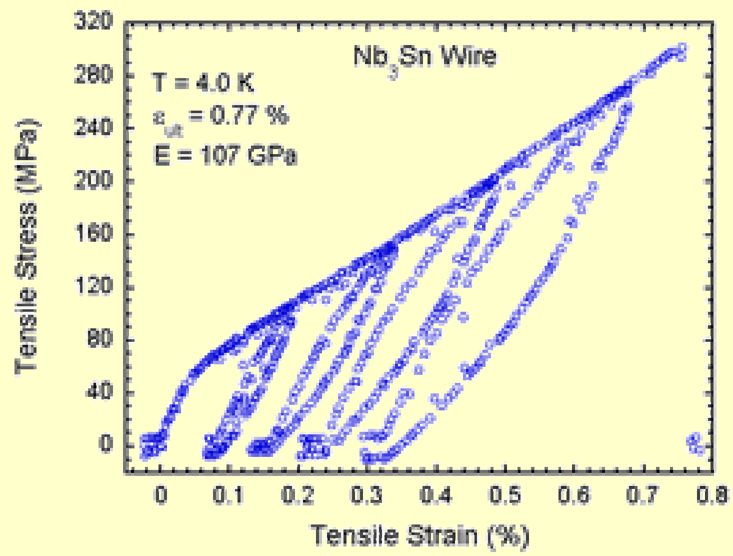
J_c(strain) Probe and results for Bi-2212 and MgB_2 conductors





NIST

Stress-strain Probe and results for Nb_3Sn composite



Critical-Current Metrology for Nb_3Sn Conductor Development

Loren F. Goodrich – National Institute of Standards and Technology-Boulder

Summary:

This 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 supported jointly by DOE/HEP and DOE/OFES, directly by purchase orders from U.S. companies and national laboratories, and internally by NIST.

For the High Energy Physics (HEP) program, this research project provides metrology on critical current of high-performance Nb_3Sn conductors. The requirements of the HEP high-field conductor development program call for conductors with higher current densities, less stabilizer, and larger wire diameters than ever before. These requirements create a series of challenges for routine, short-sample, critical-current (I_c) testing. It has become common for laboratories (including NIST) to observe 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 wires and/or wires that have less than 50 % stabilizer may require a new technique for measurement of I_c. 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:

1. Gave an invited presentation on the background on the International Thermonuclear Experimental Reactor (ITER) critical-current standard for testing Nb_3Sn conductors at the HEP Conductor Mini-Workshop at the 2002 Applied Superconductivity Conference.
2. Consulted on critical-current measurements of high-performance Nb_3Sn wires with a U.S. laboratory; these measurements resulted in a complete understanding of previous anomalous results.
3. Provided hysteresis loss measurements of high-performance Nb_3Sn wires for the HEP community.
4. We are preparing to participate in the upcoming interlaboratory comparison of critical-current measurement on reference Nb_3Sn conductors.
5. Measured critical currents of a few Nb_3Sn wires 0.8 mm and 1 mm in diameter with a new prototype specimen holder, and results indicated that no end splices were necessary.

<u>Supplemental Information</u>:

We recommended a number of changes to the ITER critical-current standard for testing Nb_3Sn including: (1) make it less likely to damage the conductor during the mounting stage, (2) have all current contacts soldered, (3) have more cooling surface area on the copper current contacts, (4) allow for interlaboratory exchange of mounted specimens, and (5) retain as much of the ITER I_c standard as possible. These features were incorporated into a new prototype design proposed by Dan Dietderich of Lawrence Berkeley National Laboratory (LBNL). The prototype design is still changing, but it was offered to the community as an alternative that others could use in their research. We at NIST have made two new sample holders following this prototype design. This prototype will allow us to conduct research to understand the parameters that affect the early specimen quench and to determine the best way to measure these materials. It could be that the lessons learned from this experimentation will clarify some issues and return us to the ITER I_c standard with little or no change.

NIST consulted on anomalous critical-current measurements of high-performance Nb_3Sn wires with a researcher at a U.S. laboratory. We recommended that additional, simple measurements be made on end-to-end sample voltage taps to verify whether a significant fraction of the sample current was bypassing the sample and flowing through the conductive mandrel, as described in a paper published in 1995 (*IEEE Trans. Appl. Supercond.* **5**, 3442-3444). The resulting measurements completely explained the observed anomalous results and verified the proposed explanation. These results were presented at the 2002 Applied Superconductivity Conference. The study supports the suggestion that end-to-end sample voltage measurements, which we have long recommended, are an important diagnostic for routine testing. Without these diagnostic voltage taps, this subtle effect of the bypass current can create highly misleading results.

Timely measurements of magnetic hysteresis loss were provided by us on Bruce Zeitlin's (Supergenics LLC) new conductor design (BAZ fin) that showed promise for meeting the HEP magnetization goals without having to resort to very large numbers of restack elements. These results were presented by Bruce Zeitlin at the November 2002 HEP Workshop. We made these measurements 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 are preparing to participate in the upcoming interlaboratory comparison of critical-current measurement on reference Nb_3Sn conductors. This comparison will be organized by personnel from LBNL. We have purchased, received, and calibrated a new 14/16 T magnet with NIST funding that will be used for routine critical-current measurements to high magnetic fields.

The main difficulty in routine measurements of critical-current in high-performance Nb_3Sn wires is that the specimen quenches (reverts to the normal state) at currents lower than expected, with little or no voltage drop over the center part of the specimen. This may be due to damaged regions near the current contacts, conductor inhomogeneity, conductor instability, contact heating, or sample motion. Damaged regions, inhomogeneity, and contact heating could lead to regions of apparent lower I_c near the current contacts that have been observed on some specimens. We at NIST and others have observed lower critical currents near the ends of the coil specimen that can cause the observed early quenches at low currents. We have observed that adding Nb_3Sn "splice wires" in parallel with the specimen on the current contact and in these regions increases the quench current of a given specimen. Other laboratories have also independently come to this same conclusion that "splice wires" can help in some cases.

Our measurements of critical current on a few Nb_3Sn wires 0.8 mm and 1 mm in diameter with the new prototype specimen holder indicated that no end splices were necessary. These early results suggest that the new prototype holder may be less likely to damage the ends of the specimen during the mounting stage. The I_c measurements were made in fields from 10 T to 16 T inside a re-entrant Dewar so that the specimen could be held in a helium bath at 4.2 K while the magnet was being held near 2.2 K with a Lambda refrigerator. We did observe early specimen quenches at the lower magnetic fields, but more complete curves were acquired at the higher magnetic fields (14 T to 16 T). We made these measurements without "splices," and the specimen did not show any regions where the I_c was significantly lower than at the center of the specimen coil. The source of the early quenches at fields of 10 T to 12 T has not yet been determined, but these results indicate that the source may be more intrinsic to the wire.

Publications (2001-2003):
None – HEP funding just began in October 2002

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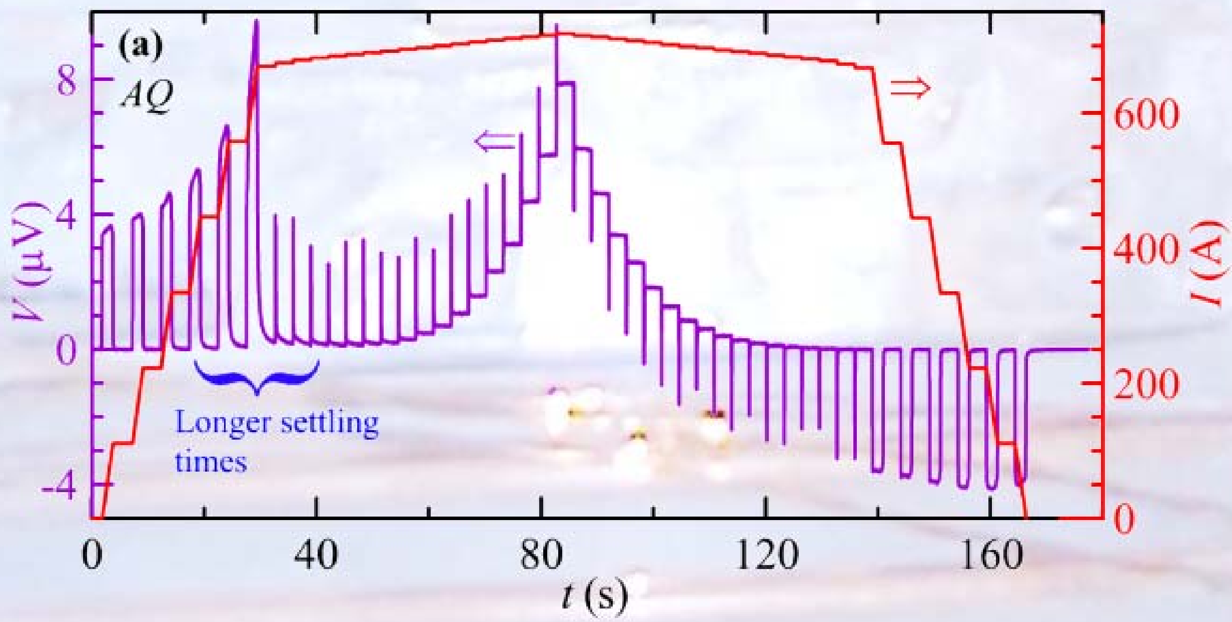
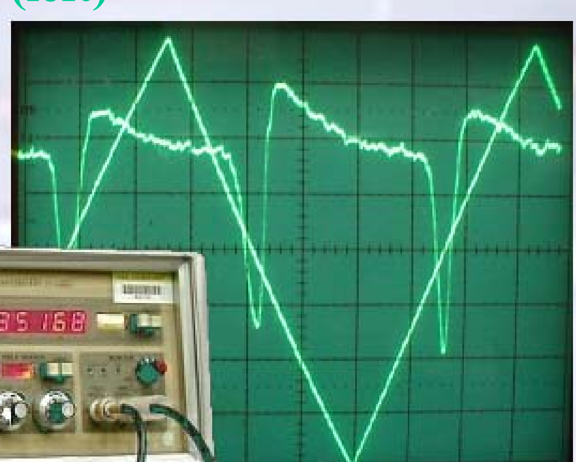


V(t) and I(t) curves indicating variable mutual inductance and settling times

Prototype holder for specimen mounted on ITER style mandrel

NMR calibration of new 52 mm bore 14/16 T Magnet (left)



Materials, Strands, and Cables for Superconducting Accelerator Magnets

E.W. Collings and M.D. Sumption - Ohio State University

Summary:

As part of LASM/OSU's multi-year efforts, a number of areas in conductor development have been investigated, including proximity effects in NbTi strands, bridging in Nb_3Sn strands, interfilamentary resistance in NbTi strands, and AC loss and contact resistance measurements in NbTi, Nb_3Sn, Nb_3Al/Cu, and Bi:2212 cables. Further, a development program in Nb_3Al strand (including microstructural, phase diagram, and transport property studies) has been carried out, with a strong connection to strand manufacturers. OSU was intimately involved with the development of the first Bi:2212 Rutherford cable, and has been responsible for suggesting and testing various innovations for Rutherford cable configurations made with NbTi and Nb_3Sn strand. OSU has also studied the flux jump stability of Nb_3Sn and Nb_3Al strands, taking into account geometrical, ramp rate, and cooling effects, and is investigating the transport stability of a new generation of Nb_3Sn and Nb_3Al conductors. The overall program has focussed on the research and development of high performance strands and cables for HEP dipole and quadrupole applications. These efforts have resulted in well over 100 scientific and technical publications in journals and conference proceedings. This work has resulted in alterations in the design of NbTi fine filament strands (for proximity effect suppression), the acceptance in some applications of cored cables, and in the definition of HT protocols for existing cables. LASM/OSU has also acted as the development and processing center for Nb_3Al strands in the US, and has been a partner in the development of Nb_3Sn and Bi-related conductors. In almost all cases these efforts have been collaborative in nature, working closely with both national laboratories and industry.

Recent Accomplishments:

The last three-year period has led to developments in materials, strands, and cables; these efforts are described below.

Materials: Nb_3Al

The materials aspects of Nb_3Al are being studied in various ways at LASM/OSU. The first area of interest is a reinvestigation of the phase diagram for this system. A new phase diagram has been proposed, as shown in Fig. 1, which delineates an extended bcc solid solution and displays a different character of the phase diagram (compared to past diagrams) near stoichiometry. The second aspect of the these Nb_3Al studies is microstructural. Information at the 0.1-1 μm size level is being used to correlate with phase diagram studies. At the same time ongoing work is studying the laminar defect structure created by the bcc-A15 conversion (at the 10s of nm scale, see Fig. 2). This is being compared/correlated to XRD peak broadening to distinguish between grain refinement or size and laminar spacing size. A third area of interest is the evolution of the XRD pattern (in-situ) during the MRHQT initial up-ramp (post quench, during the initial stages of bcc-A15 conversion). XRD patterns have been taken as a function of time (a full pattern every 30 seconds) illuminating the development of phases formed during this conversion (Fig. 3). Overall, OSU aims to use information from the variety of approaches described above to optimize of the stoichiometry of the Nb_3Al phases with desired heat treatment schedules, as well to increase flux pinning and J_c.

Materials: Nb_3Sn

A number of studies in support of strand development are being pursued. Important questions being addressed include an investigation of the level of both Sn and ternary alloy distribution within the Nb/Cu array of internal-Sn rod-in-tube type conductors. These factors affect both transport properties (and thermodynamic properties) as well as the loss properties, as described below. A Ta barrier-split internal-Sn subelement is shown in Fig. 4, along with the analysis of the Sn content behind the barrier.

Strands: Considerations for d_{eff}

One of the strand design goals important to HEP applications is the minimization of the effective filament diameter, because this helps determine both the level of flux jumping and the dipole field quality. One scheme for d_{eff} reduction in Nb_3Sn based conductors is the use of a spilt subelement for internal-Sn rod-in-tube design strands. In order to asses both the actual and expected effectiveness of this split, OSU has investigated the magnetization, AC loss, χ_{DC}, and d_{eff} for these split subelement strands. Calculations have been made determining expected d_{eff} values for unsplit and split annular subelement geometries. Results have been obtained using both analytical and numerical techniques, and the results show that in general, d_{eff} for unsplit annular subelements (the typical geometries) this should be about 18 % higher than the outer radius of the annulus, an effect which stems in part from the standard definition of d_{eff}. It is also shown that, optimally, the d_{eff} for split subelement strands should be about 45 % of the unsplit value. Experimental investigation of existing strands made in this way do not fully live up to this expectation, although subelement splitting does seem to be reducing magnetization and d_{eff} in some cases.

Strands: Flux Jump Stability

While low d_{eff} values are of interest for their influence on loss and field quality, the most crucial aspect of d_{eff} is its influence on strand flux jump stability. LASM/OSU has investigated flux jump stability in both Nb_3Sn and Nb_3Al strands of various designs, under various conditions. Flux jump quantification with cooling type has been addressed, as well as some initial experimental work on the level of benefit from exterior Cu for present generation strands. Recent effort has also applied Mints-related expressions relating the ramp-rate induced electric field to flux jumping in experimental measurements of Nb_3Sn conductors. This was combined with field and temperature dependencies of critical current to described the influence of ramp rate on the character and position of the occurrence of flux jumping within the *M-H* loop. These studies will help predict both the occurrence and the strength of flux jumping, which has significant consequences for HEP magnet operation.

Strands: I_c and Measurement Stability

HEP type conductors are far from cryostable; they operate using a current margin approach in practice. As the current densities increase (with currents reaching 1200 A at 12 T) the strands are increasing less stable, and in fact become difficult to measure. Some of this is attributable to measurement technique, some of it is related to intrinsic strand “measurability”. OSU’s initial efforts in this area focus on the need to distinguish between these two possibilities, and understand more fully the role of stabilizer fraction and RRR. These factors are important for both Nb_3Sn and Nb_3Al strands. Experimental work (transport up to 15 T and 1200 A) as well as the application of theory, are being pursued to address these issues.

Cables: Loss Measurement

The limitation and moderation of loss in Rutherford cables while at the same time retaining sufficient current sharing is an ongoing and important goal for the DOE. OSU’s effort in this topic has moved from the area of NbTi-based cables to that of Nb_3Sn based cables with higher post-cabling curing/heat treatments and in some cases “added Cu” configurations where the Cu intended for stabilization and/or protection may be part of the cable structure (Fig. 5). The use of resistive cores in the context of Nb_3Sn cables is also a very active issue being pursued at OSU. Loss measurements and effective resistvities for both Cu-added cables and cored cables have been investigated, and at least from a loss point-of-view have been seen to be viable (i.e., give target R_c values in the neighborhood of 15-25 $\mu\Omega$).

Cables: Loss Analysis

In order to treat cases of cored cables with various core widths and or thicknesses, as well as mixed strand, added Cu, or other unusual cable geometries, an FEM analysis method based on an anisotropic continuum approach, rather than a network model, has been developed. The tensor definitions of this system are simple enough to be translated into presently available commercial software, with the cable regions indicated in Fig. 6. Current distributions and loss vs core width are shown in Figs 7 and 8, where the diamond-like paths of crossover currents are reproduced. Calculations based on this model (Fig. 9) show that HEP goals can be achieved with the use of these new geometry cables, and that continuum-approach based FEM models can be helpful predictors of loss.

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19. M.D. Sumption and E.W. Collings, "Stability and Flux Jumping of Internal-Sn, Nb_3Sn Conductors (and a Model System MgB_2)," Presented at the ASC 2002.
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24. M.D. Sumption, E.W. Collings, R.M. Scanlan, and A. Nijhuis, "AC Loss in Nb-Sn Based Rutherford Cables with Mixed Strands and Cu/SS Resistive Cores," Presented At The ASC 2002.
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26. M.D. Sumption and E.W. Collings, "Stability and Instability in High Performance (Metastable) Composite Strands During I-V Measurement," submitted to Physica C 2003.

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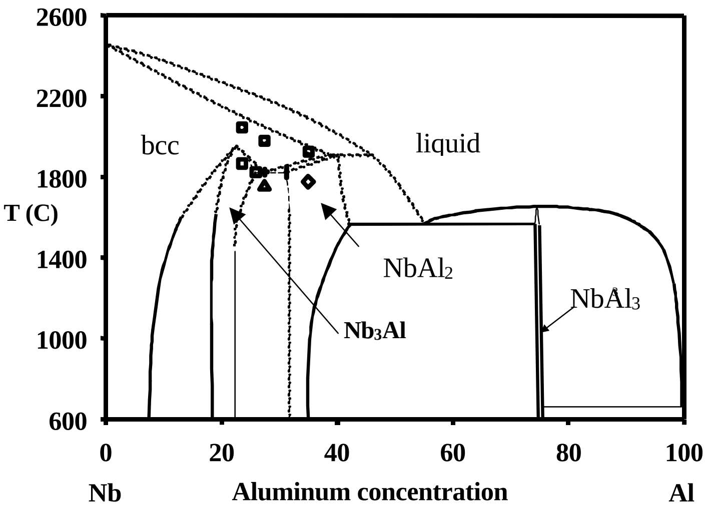

Figure 1. Proposed new Nb_3Al phase diagram.

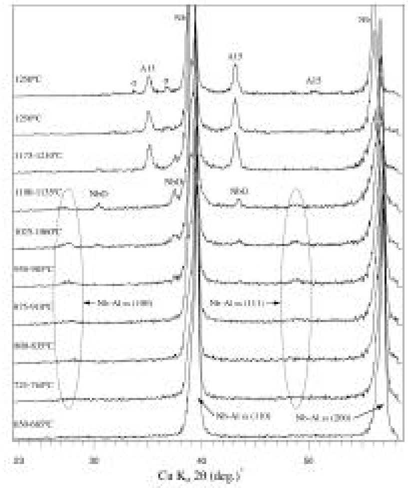

Figure 2. XRD taken as a function of time during initial stages of MRHQT.

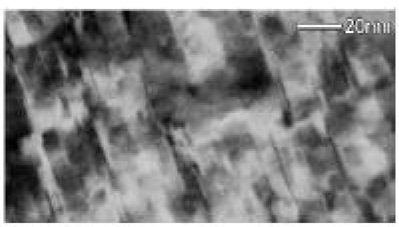

Figure 3. TEM of Al-rich planar defects.

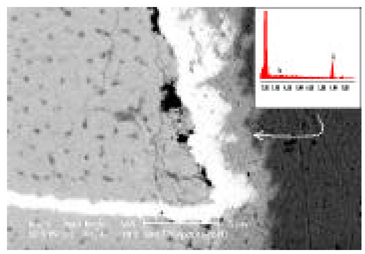

Figure 4. BSE of Nb_3Sn RIT Internal Sn conductor with Sn concentration outside barrier.

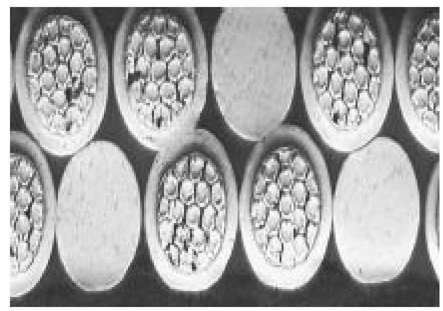

Figure 5. Mixed strand cable (Nb_3Sn-based).

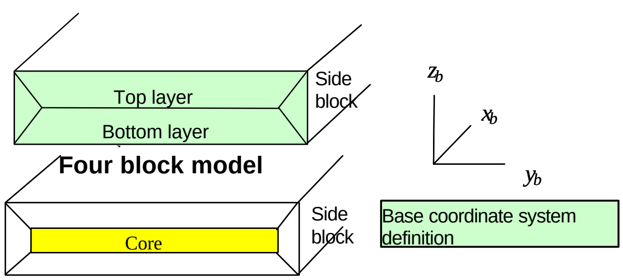

Figure 6. Geometry of the four-block model and the core model for Rutherford cables.

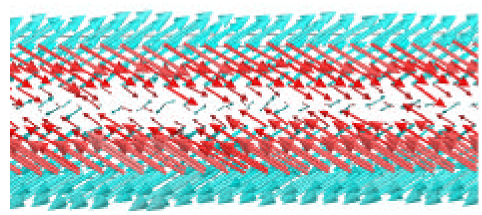

Figure 7. Longitudinal view of current paths in a Rutherford cable.

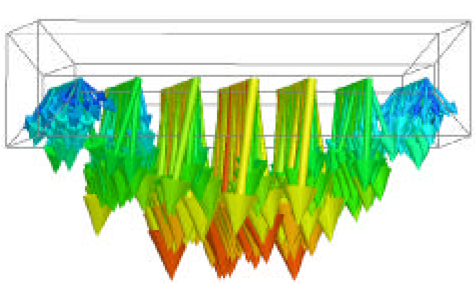

Figure 8. Cross sectional view of currents in four-block model

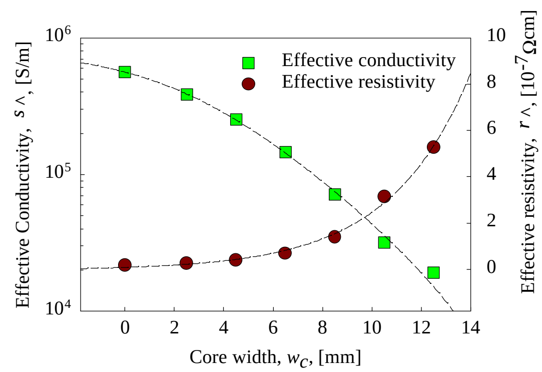

Figure 9. FEM anisotropic continuum model-calculated loss as a function of core width.

Nonlinear Dynamics and Collective Processes in Intense Charged Particle Beams

Ronald C. Davidson – 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 High Energy Physics Division, we have conducted detailed theoretical studies of critical problem related to the basic equilibrium, stability and transport properties of intense charged particle beams for high energy physics applications (see 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 Accomplishments:

(a) Publication of a 583-page graduate-level treatise entitled *An Introduction to the Physics of Intense Charged Particle Beams in High Energy Accelerators* (World Scientific, Singapore, 2001); (b) development and application of a kinetic formalism based on the nonlinear Vlasov-Maxwell equations to describe the equilibrium and stability properties of intense charged particle beams propagating through a periodic focusing lattice; (c) development and application of a macroscopic warm-fluid model to describe intense beam propagation and stability properties; (d) development and application of a 3D multispecies nonlinear perturbative particle simulation code for investigation of collective processes in intense charged particle beams; (e) nonlinear delta-f simulation studies of the electron-proton two-stream instability in high intensity proton beams; (f) nonlinear delta-f simulation studies of intense charged particle beams with large temperature anisotropy; (g) kinetic investigations of collective two-stream interactions based on the Vlasov-Maxwell equations; (h) development of a Hamiltonian averaging technique and canonical transformation for investigating the general class of periodically-focused beam distribution functions that solve the nonlinear Vlasov-Maxwell equations; (i) development of Hamiltonian averaging techniques and application to periodic focusing systems and coherent beam-beam interactions; (j) development of a macroscopic fluid approach to coherent beam-beam interactions; (k) nonlinear estimates of beam emittance growth due to the collective relaxation of space-charge nonuniformities; (l) development of a guiding-center Vlasov-Maxwell description of intense beam propagation through a periodic focusing field; (m) development of a single-parameter characterization of the thermal equilibrium density profile for intense charged particle beams; (n) investigations of chaotic particle dynamics and phase-space structure for intense beam propagation in a periodic focusing lattice, including the implications for halo formation; (o) investigations of the kinetic equilibrium and stability properties of intense sheet beams; (p) development of a self-consistent model of nonlinear charge and current neutralization of an ion beam pulse in a pre-formed plasma; and (q) investigations of longitudinal drift compression for high intensity particle beams.

Selected 2001-2003 Refereed Publications (see also http://nonneutral.pppl.gov for a complete list of publications and electronic link to the papers):

1. "*An Introduction to the Physics of Intense Charged Particle Beams in High Energy Accelerators",* R. C. Davidson and H. Qin (World Scientific, Singapore, 2001).
2. "*Physics of Nonneutral Plasmas*", R. C. Davidson (reissued by World Scientific, Singapore, 2001).
3. "Guiding-center Vlasov-Maxwell description of intense beam propagation through a periodic focusing field," R. C. Davidson and H. Qin, Physical Review Special Topics on Accelerators and Beams **4**, 104401 (2001).
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5. "Nonlinear charge and current neutralization of an intense ion beam pulse in a preformed plasma," I. D. Kaganovich, G. Shvets, E. Startsev and R. C. Davidson, Physics of Plasmas **8**, 4180 (2001).
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7. "Analytical and nonlinear perturbative simulation studies of intense charged particle beams for heavy ion fusion," R. C. Davidson, H. Qin, W. W. Lee and S. Strasburg, Nuclear Instruments and Methods in Physics Research **A464**, 358 (2001).
8. "Stabilizing influence of axial momentum spread on the two-stream instability in intense heavy ion beams," R. C. Davidson, H. Qin, I. Kaganovich and W. W. Lee, Nuclear Instruments and Methods in Physics Research **A464**, 493 (2001).
9. "3D multispecies nonlinear perturbative particle simulation of intense charged particle beams," H. Qin, R. C. Davidson and W. W. Lee, Nuclear Instruments and Methods in Physics Research **A464**, 477 (2001).
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11. "Warm-fluid collective mode excitations in intense charged particle beams --- test particle simulations," S. Strasburg and R. C. Davidson, Nuclear Instruments and Methods in Physics Research **A464**, 524 (2001).
12. "Paul trap configuration to simulate intense beam propagation over large distances through a periodic focusing quadrupole field," R. C. Davidson, P. C. Efthimion, R. Majeski, H. Qin and G. Shvets, Nuclear Instruments and Methods in Physics Research **A464**, 502 (2001).
13. "Beam emittance growth from the collective relaxation of space-charge nonuniformities," S. M. Lund, J. J. Barnard, R. C. Davidson and E. P. Lee, submitted for publication (2002).

14. "Nonlinear delta-f simulation studies of intense charged particle beams with large temperature anisotropy," E. A. Startsev, R. C. Davidson and H. Qin, Physics of Plasmas **9**, 3138 (2002).
15. "Hamiltonian formalism for solving the Vlasov-Poisson equations and its application to periodic focusing systems and the coherent beam-beam interaction," S. I. Tzenov and R. C. Davidson, Physical Review Special Topics on Accelerators and Beams **5**, 021001 (2002).
16. "Longitudinal drift compression and pulse shaping for high-intensity particle beams," H. Qin and R. C. Davidson, Physical Review Special Topics on Accelerators and Beams **5**, 034401 (2002).
17. "Renormalization group reduction of nonintegrable Hamiltonian systems," S. I. Tzenov, New Journal of Physics **4**, 6.1 (2002).
18. "Implications of the electrostatic approximation in the beam frame on the nonlinear Vlasov-Maxwell equations for intense beam propagation," R. C. Davidson, W. W. Lee, H. Qin and E. Startsev, Physics of Plasmas **9**, 340 (2002).
19. "Kinetic description of intense beam propagation through a periodic focusing field for uniform phase-space density," R. C. Davidson, H. Qin and S. I. Tzenov, Physical Review Special topics on Accelerators and Beams **5**, 084402 (2002).
20. "Overview of theory and modeling in the heavy ion fusion virtual national laboratory," R.C Davidson, A. Friedman, C. M. Celata, D. R. Welch, et. al., Laser and Particle Beams **20**, 377 (2002).
21. "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 **20**, in press (2002).
22. "Study of drift compression for heavy ion beams," H. Qin and R. C. Davidson, Laser and Particle Beams **20**, 411 (2002).
23. "Nonlinear delta-f simulation studies of intense charged particle beams with large temperature anisotropy," E. Startsev, R.C. Davidson and H. Qin, Laser and Particle Beams **20**, 585 (2002).
24. "Paul trap simulator experiment to simulate intense beam propagation through a periodic focusing quadrupole field," R. C. Davidson, P. C. Efthimion, E. Gilson, R. Majeski, and H. Qin, American Institute of Physics Conference Proceedings **606**, 576 (2002).
25. "Two-stream instabilities in guiding-center plasmas for antihydrogen recombination schemes," R. Stowell and R. C. Davidson, American Institute of Physics Conference Proceedings **606**, 73 (2002).
26. "Wall-impedance-driven collective instability in intense charged particle beams", R. C. Davidson, H. Qin and G. Shvets, Physical Review Special Topics on Accelerators and Beams **6**, submitted for publication (2003).
27. "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,** in press (2003).
28. "Comparison of quantum mechanical and classical trajectory calculations of cross sections for ion-atom impact ionization of negative- and positive-ions," I. D. Kaganovich, E. A. Startsev and R. C. Davidson, Physical Review **A**, submitted for publication (2003).
29. "Analytical theory and nonlinear delta-f perturbative simulations of temperature anisotropy instability of intense charged particle beams", E. A. Startsev, R. C. Davidson and H. Qin, Physical Review Special Topics on Accelerators and Beams **6,** submitted for publication (2003).
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32. "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).
33. "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).
34. "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).
35. "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).
36. "Paul trap simulator experiment," E. Gilson, R. C. Davidson, P. Efthimion, R. Majeski and H. Qin, Laser and Particle Beams **21**, in press (2003).
37. "Electron cyclotron resonance plasma source for heavy ion beam charge neutralization," P. Efthimion, E. Gilson, L. Grisham, P. Kolchin, R. C. Davidson, S. Yu and B. G. Logan, Laser and Particle Beams **21**, 1 (2003).
38. "Analytical and numerical studies of heavy ion beam transport in the fusion chamber," I. Kagonovich, E. A. Startsev and R. C. Davidson, Laser and Particle Beams **20**, 497 (2003).

Invited Papers and Conference Proceedings:

During 2001 –2003, 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, and twenty papers describing this research have been published in the Proceedings of the 2001 and 2003 Particle Accelerator Conferences.

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• Hong Qin	Co-Principal Investigator
• W. Wei-li Lee	Co-Investigator
• Eward A. Startsev	Co-Investigator
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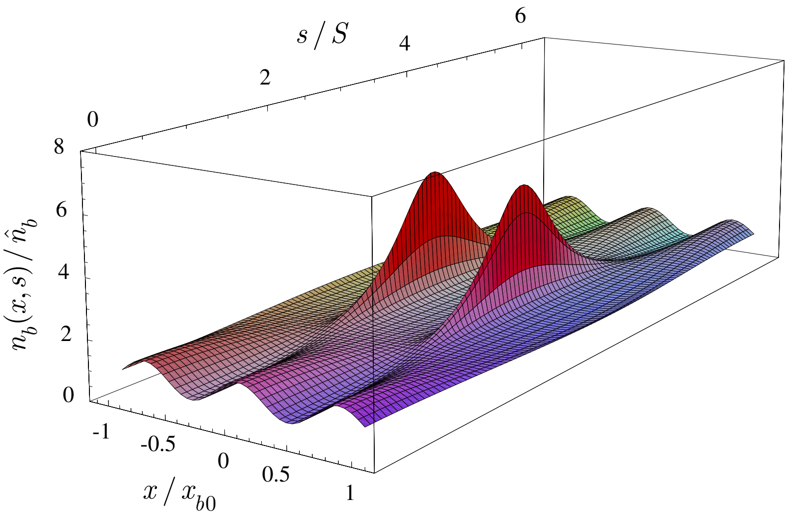

Fig. 1. Plot of normalized beam density as a function of spatial coordinates for a matched space-charge-dominated one-dimensional sheet-beam in a FODO lattice. Note that there are large-amplitude density compression peaks and density rarefactions for the matched solution. [see "Kinetic Description of Intense Beam Propagation Through a Periodic Focusing Field for Uniform Phase-Space Density," R. C. Davidson, H. Qin and S. I. Tzenov, Physical Review Special Topics on Accelerators and Beams **5**, 084402 (2002).]

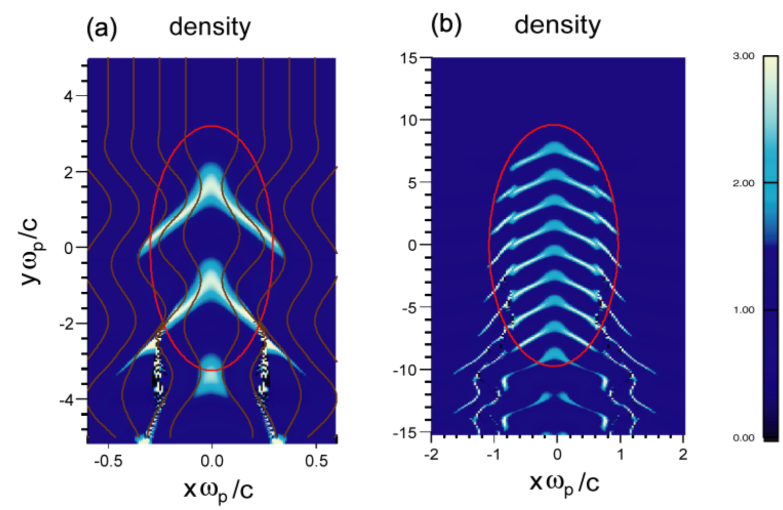

Fig. 2. Neutralization of an ion beam pulse during steady-state propagation of the beam pulse through a cold, uniform, background plasma. The beam propagates in the y-direction. The beam density has a flat-top profile, and the red lines show the beam pulse edges. Shown in the figures are contour plots of the normalized electron density (n_e/n_p). The brown contours show the electron trajectories in the beam frame. The beam velocity is $V_b=0.5c$, and the beam density is $n_b=0.5n_p$. The beam pulse duration normalized to the electron plasma period is 1.9 for (a) and 6.4 for (b). The excitation of plasma oscillations is evident in Fig. 2(b). [see "Nonlinear Charge and Current Neutralization of an Intense Ion Beam Pulse in a Preformed Plasma," I. D. Kaganovich, G. Shvets, E. Startsev and R. C. Davidson, Physics of Plasmas **8**, 4180 (2001).]

The Laser-Electron-Accelerator Project at Stanford University

R. L. Byer – Stanford University

Summary:

The research program described herein addresses key technical issues unique to using lasers to accelerate charged particles. Major aspects include the development of efficient, rugged structures to couple the laser radiation to the particle beam, the pursuit of key material and fabrication technologies for making such structures, and the pursuit of key laser technologies for powering these structures.

The Laser Electron Acceleration Project (LEAP), begun more than six years ago, has succeeded in developing the experimental apparatus and expertise to conduct laser electron acceleration experiments and material damage studies. Progress has proceeded at a rate limited by the scant availability of accelerator time to conduct experiments. Over the three years covered by this proposal, we will construct a new experiment at the Stanford Linear Accelerator Center (SLAC) using the Next Linear Collider Test Accelerator (NLCTA) as the electron beam source. We will also continue aggressively pursuing structure designs suitable for lithographic or standard fiber drawing techniques, especially Photonic Band Gap structures (PBGs). We will continue work to understand technical issues influencing the phase stability of lasers, both in phase-locking and in phase-stable (linear) amplification.

The SLAC directorate approved the modification and installation of LEAP at the NLCTA in July of 2002, and SLAC designates this effort as experiment E-163[i]. SLAC is providing partial support for the photoinjector source, rf power system, construction of a dedicated shielded enclosure, laser room, and portions of the laser and beamline systems. E-163 is the first element of a broader program to develop an extensive advanced accelerator research facility at the NLCTA known as ORION[ii]. The development of E-163, and ultimately ORION, will provide a long-lived facility with infrastructure specifically suited for conducting a wealth of advanced acceleration experiments, including laser acceleration.

The LEAP Experiment at the SCA FEL Facility

The first objective of the LEAP project was to perform a proof-of-principle experiment for vacuum laser acceleration. During its first 6 years of funding LEAP was carried out at the SCA-FEL facility at Stanford University and has made significant progress toward the vacuum laser-acceleration proof-of-principle experiment. The work during this period led to the development of the instrumentation for the proof-of-principle experiment and yielded valuable insights on the required experimental conditions. This section describes the experiment and summarizes this progress.

The ultra low energy spread of the electron beam associated with superconducting accelerators was the major reason for the original decision to carry out the LEAP experiment at the SCA-FEL facility, whose linear accelerator structures are capable of delivering a 32 MeV beam. The LEAP experiment is located downstream from the SCA beam line components on a separate electron beam line with beam transport optics specially tailored to our particular beam demands. The electron beam is focused into a fused silica accelerator cell where the electron beam interacts with the laser beam. A high resolution energy spectrometer is located immediately downstream of the accelerator cell. Figure 1 shows a block diagram of the LEAP experiment in the SCA-FEL facility. (See Montage)

The physical effect that we seek to demonstrate takes place in the accelerator cell whose purpose is to circumvent the Lawson-Woodward theorem[iii] by providing a confined region of space for the laser electric field to interact with the electron beam. The accelerator cell, shown in Figure 2, is an arrangement of optical components that couple a laser field pattern into a vacuum space that is designed to produce a longitudinal electric field along the electron beam path. (See Montage)

The energy spectrum of the electron beam is measured with a spectrometer that consists of a ½ m radius, 90^{o} bending magnet with a YAG fluorescent screen viewed with an intensified gated camera at the focal plane. The energy spectrometer and the camera optics allow for the energy characterization of individual electron bunches (with only a few picoCoulombs of charge) to within a 2 keV (0.07%) resolution. .

<u>Recent Accomplishments</u>:

- High-resolution energy characterization of individual electron bunches
  Since the expected energy modulation effect is in the order of tens of keV the ability to resolve the energy spectrum to a few keV with bunch charges of just a few picoCoulombs is crucial for the success of the experiment. The energy spectrometer and the camera optics allow for the energy characterization of individual electron bunches to within a 2 keV resolution.
- Electron beam transmission through the dielectric accelerator microstructure
  Owing to the relatively large transverse emittance of the electron beam at the SCA-FEL facility, of about 0.5 mm-mrad, it was at first unclear whether there would be sufficient electron beam transmission through the LEAP accelerator cell. The LEAP cell acts as an emittance filter with a maximum physical acceptance on the order of 0.15 mm-mrad. In spite of the significant beam loss observed from the cell there was sufficient electron beam to observe an energy spectrum and to carry out the experiment.
- Development of spatial and temporal beam overlap diagnostics
  A very important achievement of the LEAP experiment at the SCA-FEL facility was the development of the spatial and temporal beam overlap monitors, critical for performing any laser acceleration experiment. (See Montage)
- Implementation of the energy collimator
  As stated earlier the introduction of an energy filter enabled a significant reduction of the electron beam's energy spread and its shot-to-shot jitter observed at the energy spectrometer. The energy spread of the filtered beam was observed to be reduced to 20 keV with a jitter of 5 keV, which brings the beam's spectrum properties within range for observing the expected maximum 20 keV laser induced energy modulation under ideal overlap conditions with the laser.

Present Situation

The benefits for running the initial phase of the experiment at the SCA-FEL facility have been enormous. The elements for running a proof-of-principle laser acceleration experiment were developed during this phase. In our view the key experimental conditions necessary for the successful observation of a 20 keV laser-induced energy broadening of the electron beam, assuming optimized beam overlap, have been met. These conditions are

- Spatial overlap; combination of spatial monitor and spatial collimator assure spatial overlap between the laser and the electron beam observed at the spectrometer.
- Temporal overlap; timing between laser and electron pulses inferred by the same streak camera system to reduce the timing uncertainty to ~60 psec. Laser timing scans over this window assure events that fulfill temporal overlap
- Narrowed energy spread with the help on the energy collimator
- Successful operation of the accelerator cell with 10 μm slit width

With optimized laser-electron beam overlap and in the absence of timing jitter a consistent laser-induced energy broadening of the electron beam is expected to be observable with the existing apparatus at the SCA-FEL facility. The remaining experimental uncertainty that could present a serious obstacle for succeeding at observation of the sought laser-induced energy broadening effect at this facility is the time structure of the electron beam and its possible timing jitter.

Future Outlook

The LEAP program's experimental demand for the electron beam quality and need for increased beam time have outgrown the capabilities of the SCA-FEL facility, whose focus has shifted primarily on FEL related activities in recent years. The development and testing of new diagnostics and experimental methods is time consuming, and has proceeded very slowly at the SCA-FEL facility due to the infrequent running of the accelerator. Further, the jitter and beam quality are such that the degree of collimation needed to produce beams of sufficient quality and stability to perform the experiment leads to insufficient bunch charge to make the measurement. These factors have led us to search for an accelerator test facility that is capable of accommodating our present and future long term needs. The move of LEAP to the NLCTA (as experiment E-163) will address these shortcomings. The significant improvement in beam quality (a factor of ten in transverse emittances and bunch charge, and a factor of two in energy) and the ability to run experiments on a schedule that is more closely determined by the experiment's needs, rather than the difficulties of staffing and running the accelerator, will meet the experimental requirements and greatly speed experimental progress.

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5. R. Siemann, "Laser driven linear collider beam-beam interaction," ARDB-325,1/31/03.
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9. Wanill Ha, Justin Mansell, Tomas Plettner, Jeffrey Wisdom, James Spencer, "Miniaturization techniques for accelerators," Proceedings of the 2003 Particle Accelerator Conference, Portland OR.

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[i] See http://www-project.slac.stanford.edu/e163.
[ii] See http://www-project.slac.stanford.edu/orion.
[iii] P. M. Woodward, J. IEEE **93**, Part IIIA, 1554 (1946); P. M. Woodward, J. D. Lawson, J. IEEE, **95**, Part III, 363 (1948), R. B. Palmer, in *Frontiers of Particle Beams*, M. Month, S. Turner, Eds., (Springer-Verlag, New York, 1988), p607ff.

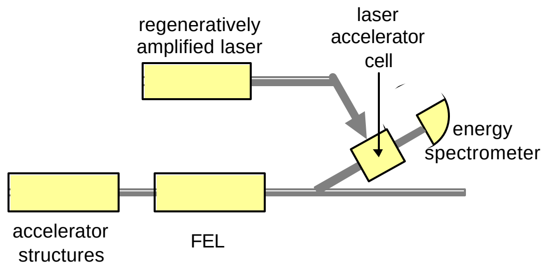

Figure 1: Block diagram of the LEAP apparatus in the SCA-FEL facility

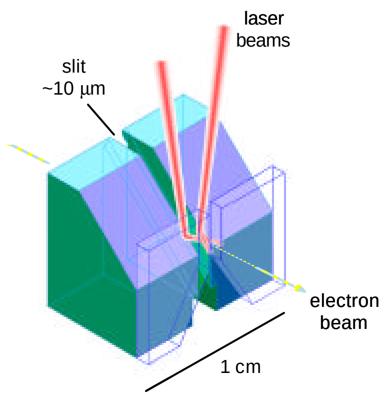

Figure 2: Perspective view of the LEAP accelerator cell.

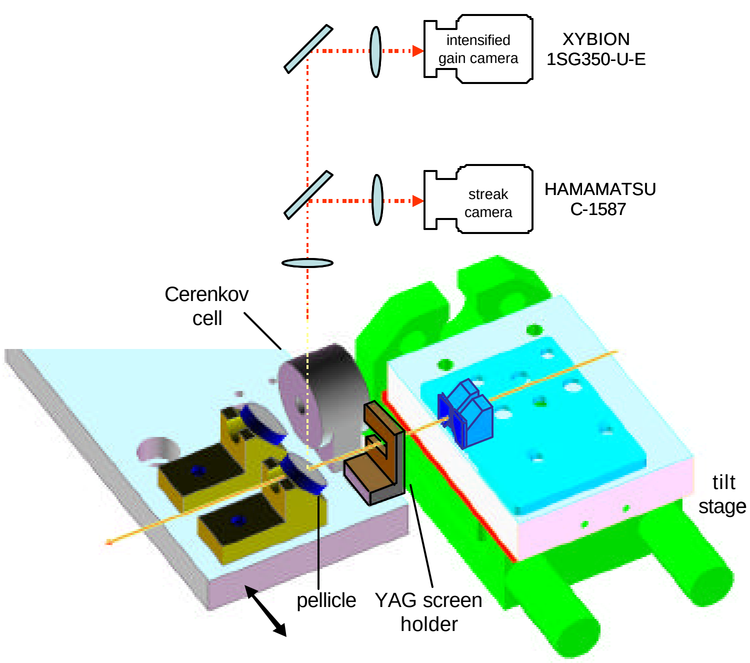

Figure 3: The spatial and temporal beam overlap monitors

Staged Electron Laser Acceleration-II (STELLA-II) Experiment

W. D. Kimura – STI Optronics, Inc.

Summary:

Electron accelerators are utilized in a wide range of applications. Besides being an important workhorse for physicists to understand the fundamental nature of matter, they are also used for many other applications in industry, medicine, and education. For example, accelerators can serve as sources to generate intense, tunable radiation over a wide spectrum. Microwave energy usually drives these accelerators. Laser light can also accelerate the electrons, but with potentially 1000 times higher acceleration gradients. This may someday enable creation of much higher energy electrons and/or more compact accelerators. A more compact device can help reduce the cost and increase the wider spread usage of these machines.

A laser-driven electron accelerator (laser linac) is becoming closer to reality. The Staged Electron Laser Acceleration (STELLA) program has been addressing key issues related to eventually developing a practical laser linac. One of these issues is staging the laser acceleration process where the laser beam repeatedly interacts with the electron beam (*e*-beam) in order to achieve high net energy gain. Staging is routinely done with microwave-driven accelerators; however, the laser light wavelength is orders of magnitude shorter than microwaves. This makes the mechanics of staging much more challenging because dimensions, tolerances, and stability requirements are correspondingly more stringent.

During an earlier effort (See Ref. 2 in Publications List), the STELLA experiment demonstrated for the first time staging between two laser-driven accelerators using a high-power CO_2 laser whose wavelength is 10.6 μm. This experiment was performed at the Brookhaven National Laboratory (BNL) Accelerator Test Facility (ATF). Both laser accelerators used the inverse free electron laser (IFEL) effect as the acceleration mechanism. An IFEL utilizes an array of magnets called an undulator or wiggler. The *e*-beam passing through the undulator follows an oscillatory trajectory. A high power laser beam is also directed collinear with the *e*-beam inside the undulator as depicted in Fig. 1. Depending on which optical phase the electrons interact with the laser field in the undulator, the electrons will experience either positive (decelerating) or negative (accelerating) electric fields. In STELLA, the electrons enter the 1st IFEL, called the buncher, distributed over all phases of the laser beam; hence, some of the electrons are accelerated and some are decelerated. After exiting the first undulator, these electrons are allowed to travel 2 m to the 2nd IFEL. During this transit, the faster electrons catch up with the slower ones resulting in bunching of the electrons into tiny groups of electrons. These groups or microbunches are only approximately 1 μm in length. In the 2nd IFEL, called the accelerator, these microbunches interact with a 2nd laser beam from the same ATF CO_2 laser with the peak power of this 2nd beam much higher than the laser beam driving the 1st IFEL. Depending on the phase that the microbunches intersect the laser beam in the 2nd IFEL, they once again can be either accelerated or decelerated. This phase delay adjustment is controlled by using movable mirrors to change the delay time for the arrival of the 2nd laser beam into the 2nd IFEL. Figure 2 shows one of the STELLA undulators. It is 33 cm along and uses rare-earth permanent magnets (PM) in its magnet array.

The first STELLA experiment proved that staging between two laser accelerators can be done. However, the quality of the *e*-beam after acceleration by the 2nd IFEL was not at a level needed for a practical laser linac. It is important that the electrons in the accelerated microbunches lie within a narrow energy spread. It is also important that as many electrons as possible are accelerated as a group. Trapping is the term given for capturing of the electrons within the laser beam optical field so that they can be accelerated as a group.

Thus, the goal of the second STELLA experiment (STELLA-II) was to demonstrate good trapping of the electrons and monoenergetic laser acceleration, i.e., a narrow energy spread of the accelerated electrons.

Figure 3 shows a schematic of the STELLA-II experimental layout. It differs from the first STELLA experiment in several important ways. First, a single laser beam from the ATF CO_2 laser drives both IFELs, rather than two separate laser beams. The ATF CO_2 laser was also upgraded to deliver higher peak power. Second, a chicane is used between the first and second undulators. The chicane is a 20-cm long, hybrid permanent-magnet/electromagnet device, which causes the electrons to travel through a "V"-shaped trajectory. Following this trajectory causes the electrons to bunch at the output of the chicane. Hence, the chicane replaces the 2-m drift space that was between the two IFELs during the first STELLA experiment. The electromagnets on the chicane also provide a means to adjust the phase delay between the microbunches and the laser field in the 2nd IFEL. Thus, this replaced the optical delay line that was used during the first STELLA experiment.

A third important change during STELLA-II was to use a gap-tapered undulator in the 2nd IFEL. Normally the separation distance between the two magnet arrays shown in Fig. 1 is constant along the length of the array. In a gap-tapered undulator the exit end of the undulator has a slightly smaller gap (specifically 11% for STELLA-II), which enables much higher energy gains. This higher gain makes it easier to separate and accelerate the microbunches from the untrapped electrons.

Figure 4 is a photograph of the STELLA-II experiment located on Beamline #1 of the BNL ATF. All the undulators and chicane were designed, manufactured, assembled, and characterized at STI Optronics, Inc. These devices are designed to be easily removed away from the beamline in order to make changes to the experiment and to allow others to use the beamline.

At the end of the beamline is an electron energy spectrometer, which is used to measure the energy spectrum of the *e*-beam. This energy spectrum is relative to the mean energy of the incoming *e*-beam, which for STELLA-II was set to 45.6 MeV. Hence, in the energy spectra discussed next, zero energy shift corresponds to 45.6 MeV.

The red curve in Fig. 5(a) shows the measured electron energy spectrum of the *e*-beam with no laser beam present. It is centered at zero energy shift and has a very narrow energy spread. Figures 5(b) and 5(c) give two examples of energy spectra with the laser beam present. In Fig. 5(b) we see that most of the electrons have been accelerated as a group to higher energy. In fact, $\approx$80% of the electrons have been trapped and gained over 7 MeV more energy (16% acceleration). The energy spread of these trapped electrons is 2.9% measured at full-width-at-half-maximum (FWHM). The over 16% energy gain is also the highest demonstrated to date for an IFEL.

Figure 5(c) is an example of lower trapping efficiency, but much narrower energy spread. The narrow peak of accelerated electrons centered at approximately 7 MeV energy shift has an energy spread of only 0.84% (FWHM). Roughly 14% of the electrons appear to be trapped.

The histograms in Fig. 5 are preliminary comparisons with the model. These predictions are very similar to the data. It is likely some of the differences between the model and data are because some of the parameters during the experiment cannot be easily determined with high accuracy. There is also jitter occurring where parameter values may randomly vary from shot to shot. Nevertheless, comparison with the model has already revealed some interesting facts. For example, the data seems to confirm what the model has predicted that at high enough laser intensity driving the tapered undulator there can be high trapping efficiency, but at the cost of larger energy spread. The model also indicates that the lower trapping efficiency for the narrow energy spread shot [i.e., Fig. 5(c)] may be because the *e*-beam focus inside the tapered undulator was not symmetric from the entrance to the exit, which led to many of the electrons loosing overlap with the laser beam prematurely.

Work to analyze the data and compare with the model is still continuing. The results of this analysis will help us devise ways to improve the trapping and acceleration process. The knowledge and experience gained from this experiment on staging, trapping, and monoenergetic acceleration can also be applied to other laser acceleration mechanisms. One mechanism that is particularly promising is laser wakefield acceleration (LWFA). Theoretical analysis was also performed during STELLA-II on possible LWFA experiments using the ATF CO_2 laser. The analysis uncovered some interesting new physics, which we hope to explore in the future.

Recent Accomplishments:

The STELLA-II experiment recently demonstrated a number of firsts: 1) 16% energy gain (7 MeV) in an inverse free electron laser (IFEL), which is the highest reported to date; 2) monoenergetic laser acceleration of these accelerated electrons with an energy spread of 0.84% full-width-at-half-maximum (FWHM); and 3) a high trapping efficiency of up to 80%.

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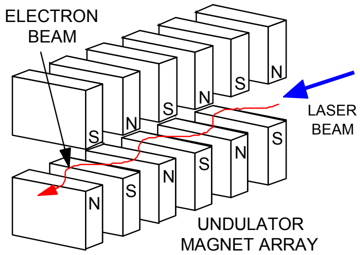


STELLA
Staged Electron Laser Acceleration

Fig. 1. In an inverse free electron laser (IFEL), an undulator is used to cause the electron trajectory to oscillate.

Fig. 2. Photograph of STELLA undulator. The magnet array is oriented vertical relative to Fig. 1.

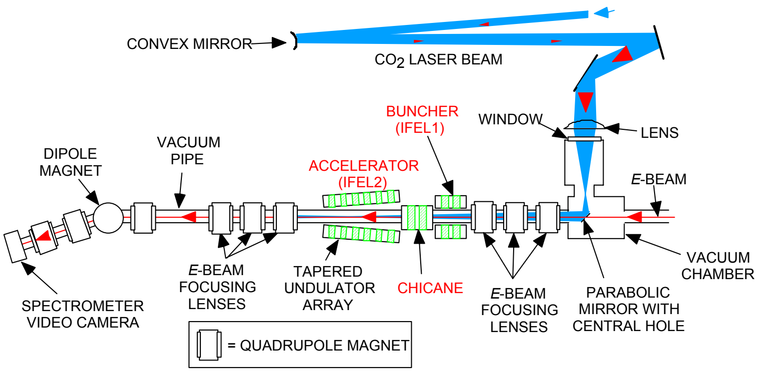
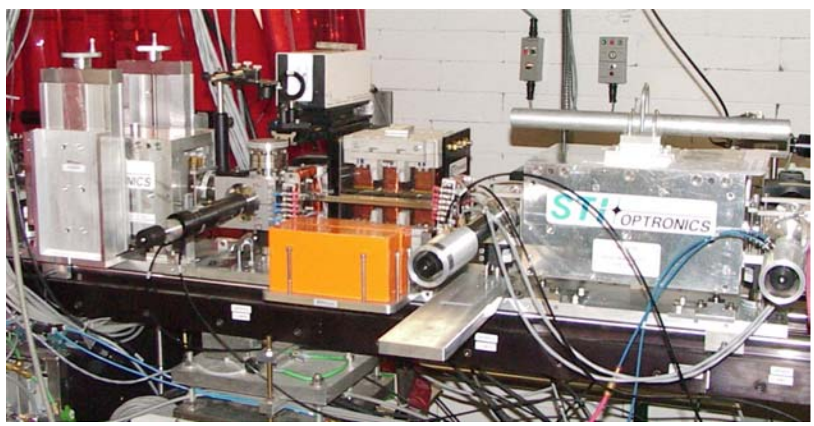
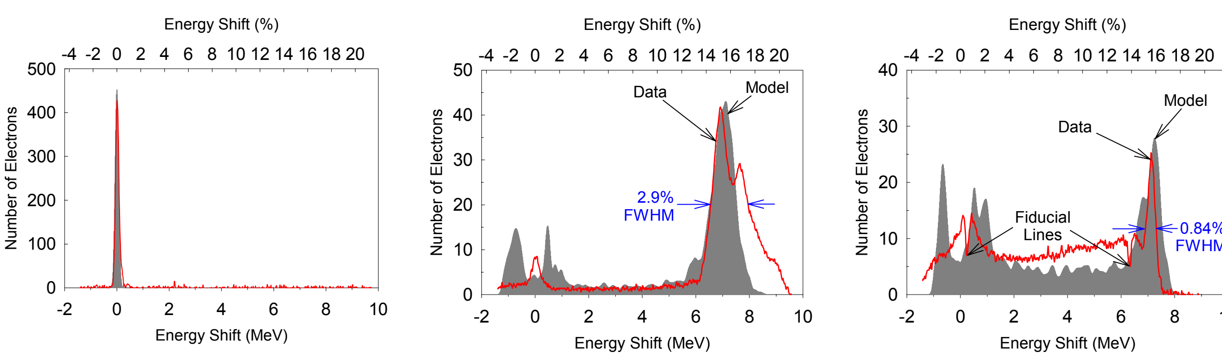


Fig. 3. Schematic diagram of STELLA-II experimental layout. The CO_2 laser beam enters the evacuated beamline through a large window and is focused at the center of the 2nd IFEL undulator (IFEL2). The *e*-beam travels through the IFELs and chicane to the energy spectrometer at the end of the beamline.

Fig. 4. Photograph of the STELLA-II experiment on Beamline #1 at the BNL ATF. The electrons and laser beam enter from the right. Starting from the right of the photo, the first device they enter is the buncher (IFEL1). Next in the middle is the chicane, which has been pulled away from the beamline. On the far left is the tapered undulator (IFEL2).





(a) (b) (c)

Fig. 5. Comparison of measured electron energy spectra (in red) with preliminary model predictions (histograms). (a) No laser beam present. (b) With laser showing high trapping efficiency (~80%) of electrons centered at ≈7 MeV energy gain. (c) With laser showing narrow energy spread (~0.84% FWHM) of electrons accelerated by ≈7 MeV.

New Technology for Future Colliders

Peter McIntyre, Texas A&M University

Recent Accomplishments

- Developed designs for dipoles to 16 Tesla field strength, in which Lorentz forces are managed so that they do not limit superconducting performance.
- Validated stress management design on a first prototype dipole.
- Devised technique for natural suppression of multipoles produced by superconducting filaments in the coil, making it use present Nb_3Sn strand for magnets.
- Devised manufacturing technology to reduce cost of high-performance Nb_3Sn superconducting strand.
- Invented the first workable approach to accelerator-driven thorium-cycle fission power, which could meet the world's energy needs for a thousand years.

The Accelerator Research Lab (ARL) at Texas A&M University is developing new technology for the colliders of the future. For hadron colliders, ARL is developing a new approach to *NbSn dipole technology* that provides stable performance to 16 Tesla, reduces by half the amount of expensive superconductor, and relieves requirements on filament size in the superconducting strands. ARL has also assisted a local company to develop a new approach to the fabrication of *internal-tin Nb_3Sn superconducting wire*, in which the billet size can be increased from ~30 kg to ~400 kg and the manufactured price can be reduced by a factor of three.

ARL has introduced a wholly new concept *for accelerator-driven thorium-cycle nuclear(ADTC) fission power* that could prove to be the greatest practical outcome from high energy research. The ADTC reactor could provide a new future for nuclear power: it cannot melt down, it eats its own long-lived waste isotopes, it operates as a sub-critical assembly, it does not produce an inventory of bomb-capable isotopes, and there is enough thorium in known reserves to power the entire Earth for a thousand years.

Nb_3Sn dipole technology A primary focus of our effort is a new approach to the design of high-performance Nb_3Sn dipoles for future hadron colliders. The performance of a hadron collider is paced by that of the superconducting magnets that bend and focus its particle beams. The strength of the magnetic field in the dipoles determines the beam energy that can be attained in a given circumference ring. The field quality in the magnet aperture determines the brightness of the beams for collisions and the time for which collisions can be sustained.

ARL has pioneered new technology for these magnets [1] using the superconducting alloy Nb_3Sn. Nb_3Sn makes it possible to attain a field strength up to 16 Tesla – twice that of the NbTi alloy that has been used in all colliders to date. Thus a given collider circumference could reach twice the collision energy.

But Nb_3Sn is a difficult material. It is brittle: it must be formed during a high-temperature annealing process within the strands of the superconducting cables after the magnet coils have been formed; and the coil must withstand immense magnetic stresses that are produced as the magnetic field reacts against the windings. It is very expensive – today high-performance Nb_3Sn strand costs ~$1,000/kg, compared to ~$100/kg for NbTi. Lastly the filament size within the strands is ~10 times larger than that in NbTi, resulting in larger error fields produced by magnetization effects as the magnets are energized from the field strength where beams are injected to the field strength for high-energy collisions. In order to take advantage of Nb_3Sn for hadron colliders, we must develop designs that require a minimum amount of superconducting cable, we must suppress the field errors from filament magnetization, and we must devise more cost-effective manufacturing technology to reduce its price. ARL is addressing all three issues.

ARL has pioneered a dipole design that controls the mechanical environment of the coil so that the immense stresses at high field are not communicated through the coil:

- The superconducting windings are arranged in a *block coil structure*. The coil windings are configured as simple racetrack pancakes which are easy to manufacture and can be readily assembled within the flux return shell. Unlike cos θ dipole configurations, the block coil structure is intrinsically scalable, so that the smaller dipole aperture needed for an ultimate energy collider can be provided by a smaller dipole coil, with dramatic reductions in the requirements for expensive superconductor. LBNL has recently used this block-coil structure to attain a new world record in dipole field strength – 16 Tesla.
- ARL has pioneered a technique of *stress management* in which a high-strength support matrix, integrated within the coil, bypasses the immense magnetic stresses on the inner windings past the outer windings so that the maximum local stress never exceeds the strength limits of the fragile superconductor and insulating materials. Mechanical shear is released within the coil package by surrounding each coil block with mica paper so that it rides without shear within the support matrix.
- The coil is preloaded within the flux return using an arrangement of *expansion bladders* with which a uniform preload can be delivered to all elements of the coil. The bladders are filled with a low-melt metal alloy while the dipole is warmed to 100^{o}C, the liquid metal filling the bladders is pressurized to deliver uniform hydraulic load throughout the coil structure, and the dipole is cooled to freeze the metal filling and lock in the preload through the remainder of the dipole's life. This simple procedure assures uniform delivery of immense preload, relaxes tolerances on fabricated parts, and simplifies assembly procedures.
- Magnetization field errors are suppressed using a *flux plate*, closely coupled to the dipole aperture, which strongly suppresses the multipole fields produced by filament magnetization at injection fields. This provision is uniquely possible with a block-coil configuration, and relaxes the difficulties from filament effects so that the fatter filaments of Nb_3Sn produce no greater effects than the thinner filaments in present NbTi dipoles.

These innovations have enabled us to design a dipole that requires half the amount of superconductor of other dipole designs with comparable field strength, relaxes requirements on filament size in the superconducting strands, eliminates the need for extra copper to be compounded in the strands, and relaxes dimensional tolerances and assembly procedures for the structural elements. The design can be scaled to the aperture actually needed for a collider [2], so that full cost advantage can be realized at ultimate energy.

In 2001 we built and successfully tested a first model NbTi dipole embodying several of these innovations [3]. It achieved design field without intermediate quenches (training), and exhibited excellent AC loss performance. During 2002 we developed the fabrication tooling and fixtures to build our first Nb_3Sn model dipole. The dipole is being fabricated during 2003 and will be tested at LBNL in spring 2004.

Nb_3Sn Superconductor Manufacturing Technology

Internal-tin Nb_3Sn wire has reached an impressive level of performance – 3,000 A/mm^2 in the superconducting cores at 12 Tesla field in liquid helium. While this performance meets the requirements for high-field dipoles described above, it comes at a price: $1,000/kg! This compares to ~$100/kg for NbTi that give comparable performance at low field strength.

The price of Nb_3Sn wire is not driven by materials ($80/kg) but by the fact that the complex sequence of steps in its fabrication must be repeated for every 30 kg billet. By contrast NbTi superconducting wire is fabricated in ~400 kg billets.

ARL has assisted a local company, ATC, to identify the elements of the fabrication sequence that limit billet size and to devise alternative ways to remove those limits. ATC is funded under DOE's SBIR program to develop a stepped-mandrel extrusion of the tin hole, eliminating the requirement for gun drilling. ATC has developed a continuous-tube-forming process [4] by which to apply Ta diffusion barrier and Cu sheath to subelements after they have been drawn nearly to the size for re-stacking. And finally ARL and ATC have devised a technique to transform the restack process from a batch assembly to a continuous process (cabling hex wire). These three developments have the potential to make it possible to process 400 kg billets of Nb_3Sn and reduce its price by a factor of three.

Accelerator-driven thorium-cycle fission power

The problems that drive public concerns about nuclear power are well known: reactors can melt down, reactors produce large inventories of long-lived radioactive waste, reactors use bomb-capable isotopes that could be diverted by rogue states or terrorists, and the recoverable uranium in the Earth would power our civilization for only ~100 years.

In 1950 E.O. Lawrence first proposed using proton beams to transmute thorium into ^{233}U and to stimulate that isotope to fission, providing an alternative route to fission power. In 1995 Rubbia suggested that such a reactor would have the attractive feature that it eats its own long-lived waste isotopes, and indeed could consume waste from conventional reactors. He also showed that the molten lead used for spallation, moderator, and heat exchange has sufficient thermal inertia to make meltdown impossible. Two problems prevented further development of ADTC: there is no feasible accelerator technology to produce the ~800 MeV, 14 MW proton beam that would be needed to drive a GW reactor, and a coaxial drive geometry would produce severe shadowing, in which fission products in the inner fuel elements absorb neutrons before they could reach the outer fuel elements so that only a fraction of the fuel could be used.

ARL has invented a new approach [5] that solves both problems. The isochronous cyclotron is a compact, efficient accelerator to produce 800 MeV proton beam. The PSI cyclotron in Switzerland has operated stably for the past 30 years, and produces 2 mA of proton beam. ARL adapted a magnetics design from Riken, in which the sector magnets of a cyclotron can be fashioned as a pair of superconducting coils, each bonded to a cold-iron pole piece, suspended in a vacuum aperture within a warm-iron flux return. By clever magnetics they showed that one can 'levitate' the coil assemblies so that the Lorentz forces on each coil are in equilibrium and the structure can be supported by low-heat-load tension elements. ARL extended that design to incorporate a stack of 10 such pole pieces, forming the apertures for 7 flux-coupled isochronous cyclotrons [6]. The footprint of this 7-beam accelerator is the same as that of a single-beam unit. Each cyclotron operates with the same accelerator performance achieved routinely at PSI. The seven beams are delivered into a 6-on-1 hexagonal pattern in the reactor core, providing the 14 MW needed for a GW reactor.

This 7-beam approach solves the problem of how to generate the necessary drive beams, but it also solves the shadowing problem. By distributing the proton drive in this hexagonal geometry, we homogenize the spallation drive of the core and reduce by a factor of 4 the mean distance from drive beam to fuel rod. Detailed simulations show that this eliminates shadowing and provides extremely uniform neutron flux, and power generation throughout the core.

Ironically, the ADTC development could have an important benefit for DOE's high energy research program. The logical place to develop the first prototype of the ADTC reactor would be at a DOE accelerator lab. If that were done, the ADTC reactor could deliver up to 1 gigawatt of electric power for use by lab programs. Since (present and future) accelerator facilities are typically paced by electric power consumption, this could provide a way to control operating cost for the research program while developing a technology that could solve Earth's energy needs for a thousand years.

Staff

Co-Principal Investigators: Peter McIntyre and Al McInturff (who divides his time between Texas A&M University and LBNL).

Post-doctoral associate: Akhdior Sattarov

Technicians: Ray Blackburn, Nick Diaczenko, Tim Elliott, Bill Henchel, Andrew Jaisle

Graduate students: Joong Byeon (Ph.D. Physics), Eichii Hirose (Ph.D. Physics), Patrick Noyes (M.S. Physics), Don Smith (Ph.D. Applied Physics), Amanda Woodward (Ph.D. Physics)

Undergraduates: Dakota Blair, Nikita Guo, Taylor Giles, Michael Hatridge, Matt Watkins

Recent graduates: Rainer Soika (2002 Ph.D Physics), now at BNL.

Recent Publications

1. R. Blackburn *et al., "*Construction and testing of block-coil high-field dipoles for future hadron colliders," Proc. 2002 Appl. Superconductivity Conf., Houston, Aug. 4-9, 2002.

2. A. McInturff, P. McIntyre, and A. Sattarov, "Microbore dipole for future hadron colliders," Proc. 2001 Snowmass Workshop on Future Facilities for High Energy Physics, T202, Snowmass, CO, June 30-July 21, 2001.

3. C. Battle *et al., "*Testing of TAMU1: a single-aperture block-coil dipole," Proc. 2001 Particle Accel. Conf., Chicago, June 18-22, 2001.

4. X. Fu *et al., "*Continuous tube forming of the Ta diffusion barrier and Cu stabilizer on internal-Nb_3Sn subelement," Proc. 2003 International Crogenic Materials Conf., Anchorage, AL, Sept. 22-26, 2003.

5. M. Admas *et al.,"*Accelerator-driven thorium cycle power reactor: design and performance calculations," Proc. Global-2003, ANS/ENS International Winter Meeting and Nuclear Technology Expo, New Orleans, LA Nov. 16-20, 2003.

6. P. McIntyre and A. Sattarov, "Superconducting sector magnets for a flux-coupled isochronous cyclotron stack," Proc. 2002 Appl. Superconductivity Conf., Houston, Aug. 4-9, 2002.

Contact Information

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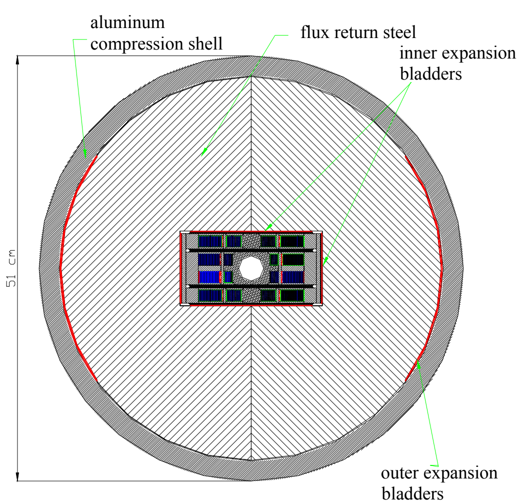

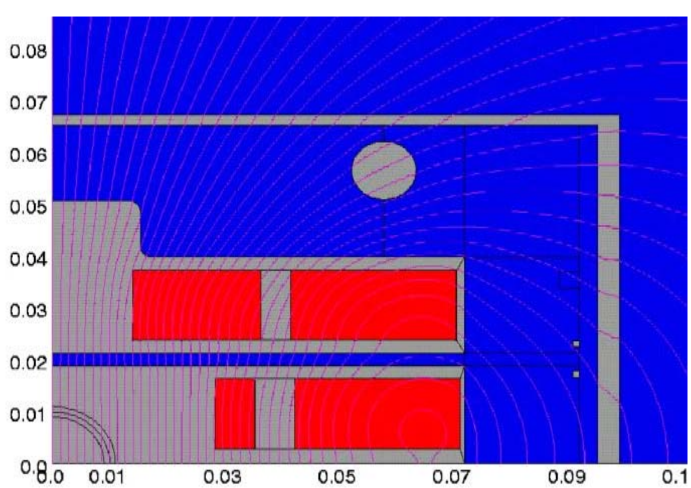

New Technology for Future Colliders – Texas A&M University

Fig. 1. Beginning the winding of a 2-winding pancake coil.

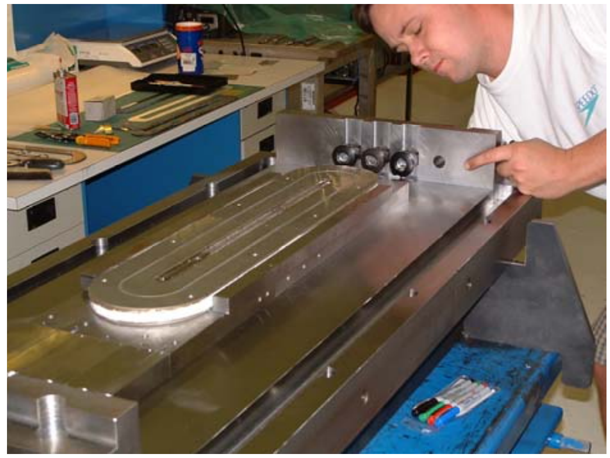

Fig. 2. Assembling the completed coil in the fixture for reaction heat treatment.

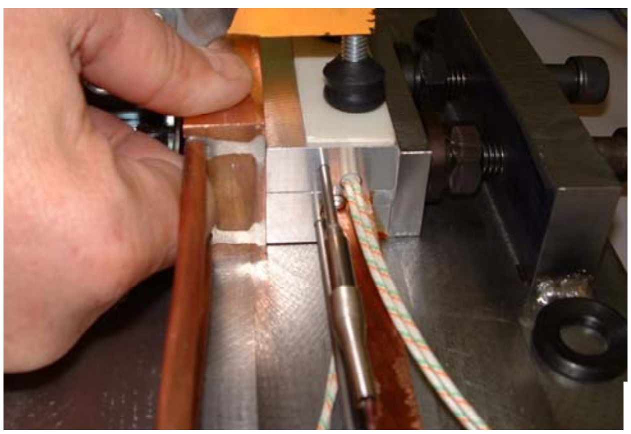

Fig. 3. Preparing a Nb_3Sn-NbTi lead splice for soldering.

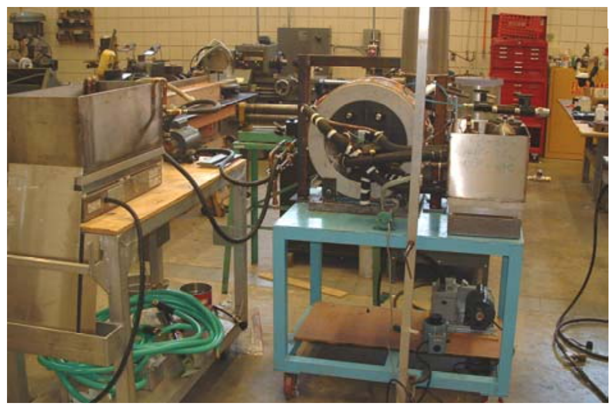

Fig. 4. Pressurizing the expansion bladders that preload the coil within the flux return.

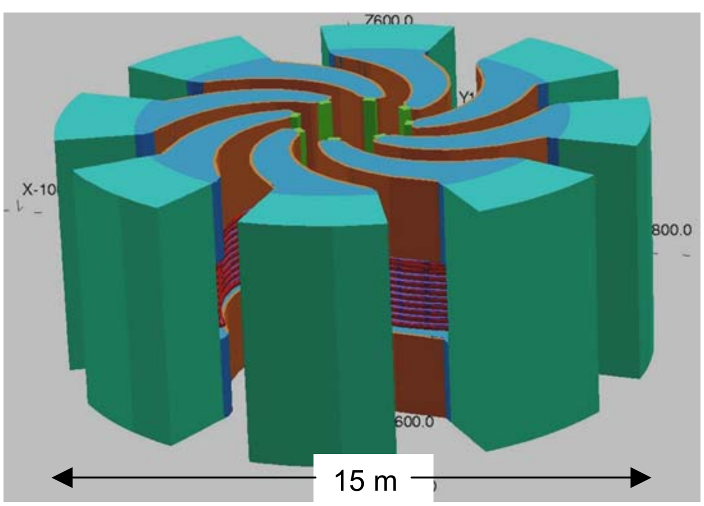

Fig. 5. The seven-beam isochronous cyclotron for ADTC.

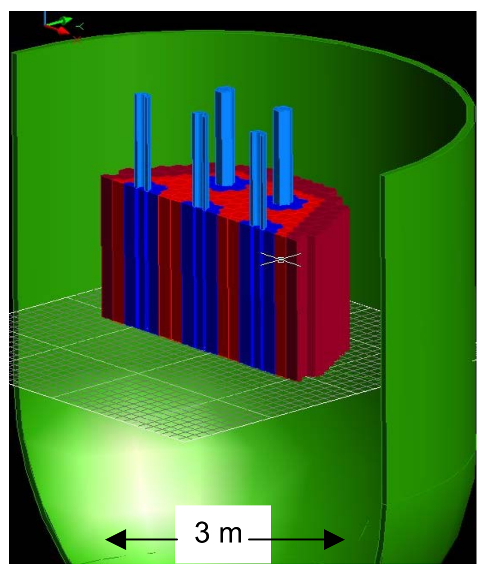

Fig. 6. Cross-section of the core of a 1 GW ADTC reactor.

Advanced Accelerator Concepts

Jonathan S. Wurtele – PI - UC Berkeley

Summary:

The development of a new generation of colliders beyond the LHC is central to 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. Indeed, the prospects for high-energy physics may be limited by our ability to build new machines. Looking beyond the NLC, our group explores neutrino factories, muon colliders, plasma-based acceleration, and plasma lenses.

Our UC Berkeley 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 environment 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. We investigate new ideas, based on autoresonance, for the beatwave excitation of wakefields. Autoresonant excitation significantly decreases the sensitivity of the beatwave scheme to density fluctuations or experimental uncertainty in the average density.

Undergraduate research is also an important component of the program. The activities of undergraduates include numerical investigation of the beam quality expected in all-optical laser-plasma accelerators, 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 critical beam physics problems for neutrino factories and muon colliders. There are significant challenges in the production, cooling, acceleration (and, for the collider, collision) of the intense muon bunches. Recently we have studied beam dynamics in muon cooling channels. 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 also 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. The concepts for manipulation of phase space and the numerical techniques used to study them can be applied in other circumstances. An example of this is beam conditioning for free-electron lasers.

A second thrust of our research is in plasma-based accelerating structures and lenses. We analyzed the hollow plasma channel as an accelerating structure, including, for example, the evaluation of instabilities from beam coupling higher-order azimuthal modes. The asymptotic growth rate of the resultant beam breakup instability was analyzed and a method for reducing the growth was proposed. We developed a method to predict emittance growth and damping of betatron oscillations in the so-called overdense plasma lens. In this lens the beam pinches in its

self-magnetic field. The low order moments of the phase space distribution of the beam exhibit the collisionless relaxation typical of collections of self-gravitating masses. Our theoretical and numerical techniques capture this physics and yield predictions in agreement with the results of particle-in-cell simulations.

Recently we have conducted pioneering 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 by 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 that the electromagnetic pump can be replaced by a static wiggler. The wiggler-based system is suitable for ion acceleration with controllable phase velocity and a gradient >20 MeV/m. Another novel concept arising from the study of electromagnetic pulse propagation in magnetized plasmas is that of magnetic resonance waveguides. We envision guiding microwaves in homogeneous plasmas using spatially varying magnetic fields. This concept is confirmed in simulations. These waveguides are created dynamically---and can be readily reconfigured by changing external magnetic fields.

Recent Publications:

1. P. Mardahl, H.J. Lee, G. Penn, J. S. Wurtele and N.J. Fisch, *Intense laser pulse amplification using Raman backscatter in plasma channels*. Physics Letters **A296**, 109 2002.
2. H.J. Lee, P. Mardahl, G. Penn and J. S. Wurtele, *Simulation of intense laser pulse amplification in a plasma*, IEEE Trans. Plasma Science, 2002.
3. C. Kennel, L. Capuano, P. Colestock, F. Cordova, J. Drake, N. Fisch, L. Fisk, R. Fonck, R. Frosch, G. Gloeckler, Z. Mikic, A. Narath, C. Pellegrini, S. Prager, A. Sessler, R. Socolow, R. Rosner J. Van Dam, and J. Wurtele, *An assessment of the Department of Energy's Office of Fusion Energy Sciences Program,*. National Academy Press, 2001.
4. W. Fawley, G. Penn, and J. Wurtele*, Helical channels for longitudinal compression of muon beams*, PAC-2001-FPAH092, Aug 2001, Proc. IEEE Particle Accelerator Conference (PAC2001), Chicago, Illinois, 18-22 Jun 2001.
5. W. Fawley, G. Penn, A. Sessler, and J. Wurtele*, Studies of the front end of a neutrino factory,* PAC-2001-FOAC011, Aug 2001. 3pp. Proc. IEEE Particle Accelerator Conference (PAC2001), Chicago, Illinois, 18-22 Jun 2001.
6. Rajendran Raja, et al., *The program in muon and neutrino physics: super beams, cold muon beams, neutrino factory and the muon collider,* FERMILAB-CONF-01-226-E, Aug 2001. 130pp. Contributed to APS / DPF / DPB Summer Study on the Future of Particle Physics (Snowmass 2001), Snowmass, Colorado, 30 Jun - 21 Jul 2001.
7. G. Penn, *Muon capture and cooling dynamics, capture in solenoidal channels (invited paper).* PAC-2001-TOAA001, Aug 2001. 5pp. Presented at IEEE Particle Accelerator Conference (PAC2001), Chicago, Illinois, 18-22 Jun 2001.
8. M.S. Hur, J.S. Wurtele, G. Shvets, *Simulation of electromagnetically and magnetically induced transparency in a magnetized plasma*, Phys. Plasmas **10**, 3004 (2003).
9. R.R. Lindberg, A.E. Charman, J.S. Wurtele *Comparison of the laser wakefield accelerator and the colliding beam accelerator*, Proceedings of the 10th Advanced Accelerator Concepts Workshop (AAC 2002), Mandalay Beach, California, 23-28 Jun 2002. Published in AIP Conf. Proc. 647, 727-736 (2003).
10. G. Shvets, J.S. Wurtele, and M.S. Hur, *Applications of magnetized plasma to particle acceleration*, 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, 681-689 (2003).
11. G, Shvets and J.S. Wurtele *Transparency of magnetized plasma at the cyclotron frequency*, Phys. Rev. Lett. **89**,115003 (2002).
12. H.J. Lee, P.J. Mardahl, G. Penn, and J.S. Wurtele, *Simulation of laser pulse amplification in a plasma by a counterpropagating wave*, IEEE Trans. Plasma Sci. **30**, 40-41 Part 1 (2002).
13. A. Wolski, G. Penn, A. Sessler, and J. Wurtele, *Beam conditioning for FELs: consequences and methods*, LBNL-53899, submitted for publication.
14. P.H. Stoltz, J.R. Cary, G. Penn, and J. Wurtele, *Efficiency of a Boris-like integration scheme with spatial stepping*, Phys.Rev.ST Accel.Beams **5**:094001,2002
15. The Muon Collider/Neutrino Factory Collaboration (Mohammad M. Alsharoa et al.), *Recent progress in neutrino factory and muon collider research within the muon collaboration,* Phys.Rev.ST Accel.Beams **6**:081001 (2003). e-Print Archive: hep-ex/0207031.
16. G. Penn, P.H. Stoltz, J.R. Cary, and J. Wurtele, *Boris push with spatial stepping*, J.Phys**. G29**,1719-1722 (2003).
17. Vladimir Gorgadze , Thomas A. Pasquini , Joel Fajans and Jonathan S. Wurtele, *Injection into electron plasma traps*, to appear in Proc. Nonneutral Plasma Workshop, Santa Fe, 2003.

Current Staff:

• Wurtele, J.S.	Principal Investigator
• Friedland, L.	Visiting Professor (Hebrew University)
• Hur, M.-S.	Postdoctoral Researcher
• Penn, G.	Research Scientist (50%)
• Charman, A.	Graduate Student (Ph.D., Physics, UCB)
• Geddes, C.	Graduate Student (Ph.D., Physics, UCB, Wim Leemans Research advisor)
• Gogardze, V	Graduate Student (Ph.D., Physics, UCB)
• Lindberg, R.	Graduate Student (Ph.D., Physics, UCB)
• Peinetti, F.	Visiting Graduate Student (Ph.D., Physics, Univ. of Turin)
• Rebaum, J.	Undergraduate Researcher
• Halquist, N.	Undergraduate Researcher

Recent Graduates

1. Carl Schroeder (Ph.D., Physics, UCB 1999) Postdoctoral appointment at UCLA, currently Staff Scientist, LBNL.
2. Ekatryna Backhaus (Ph.D., Physics, UCB 2001) High school science teacher, mother.
3. Bo Wu (Ph.D., Physics, UCB, Prof. A. Neureurther (EECS), research advisor, 2002) employed in semiconductor industry.
4. Emi Kawamura (Ph.D. Physics, UCB, 2003.)

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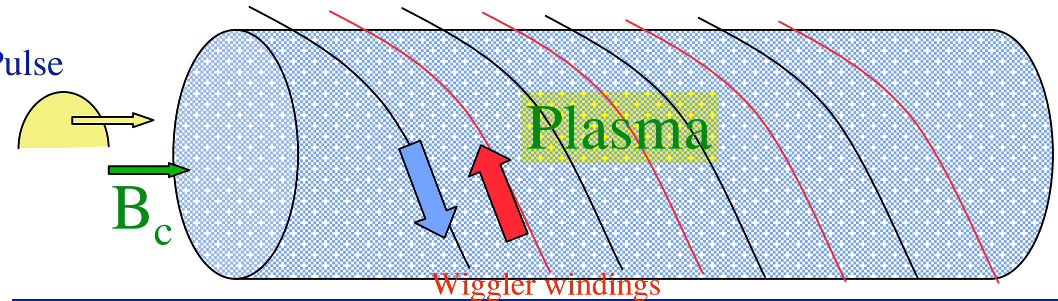
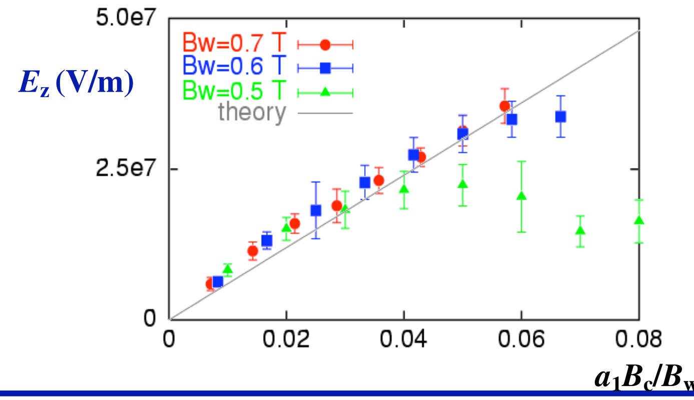
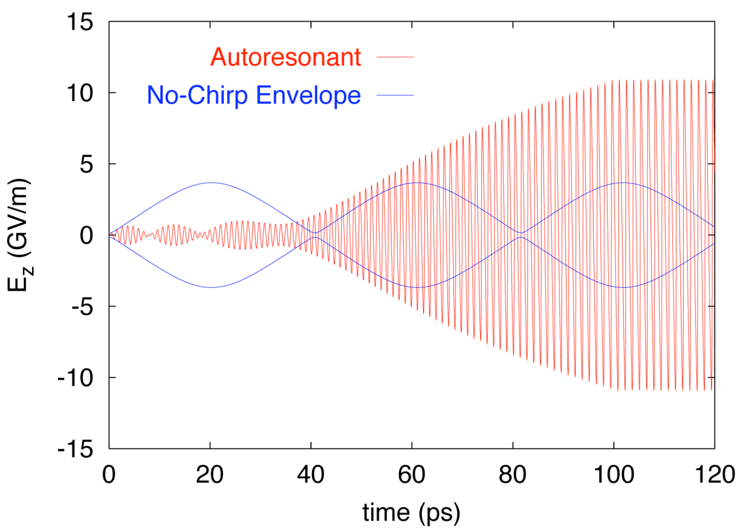
Ion acceleration using plasma EIT: schematic (below) and comparison of expected gradient between simulation and simple theoretical model for the accelerating gradient (right) (Hur et al, Phys. Plasmas 10, 3004 (2003))



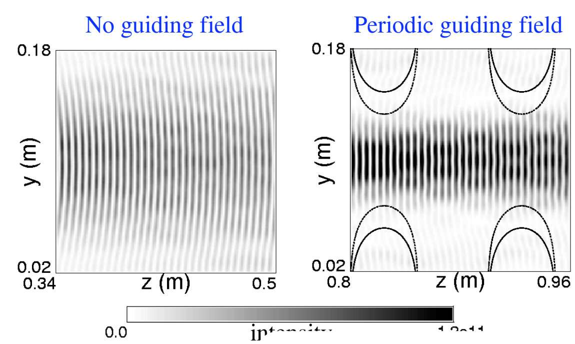




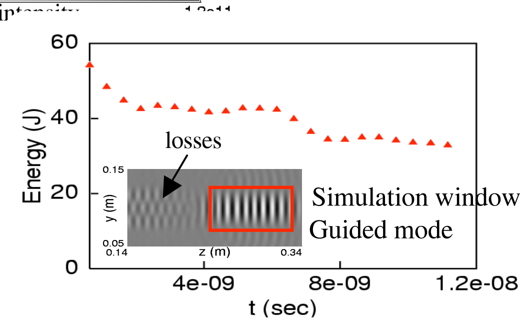
Autoresonant excitation of beatwaves (red curve) compared to envelope of resonant exicitation (blue curve). The technique significantly reduces sensitivity to density errors. (R. Lindberg, et al., submitted for publication 2003).

Magnetic Resonance Waveguides: Simulation and theory

(M.S. Hur and J.S. Wurtele)



Above: particle-in-cell simulation of a magnetic resonance waveguide, in which high frequency microwaves are transported tens of diffraction lengths without metal walls in a homogeneous plasma. Right: pulse energy evolution.



Advanced Accelerator Physics Research at UCLA

David B. Cline – University of California-Los Angeles

Summary:

The Advanced Accelerator Physics Research at 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 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 MICE (Muon Ionization Cooling Experiment), and studies at the 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, Fermilab, and SLAC) and at TRIUMF in Canada. The advanced concepts investigated include beam monitors, beam focussing 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 research program is rich in providing training and hands-on experience to graduate students and postdoctoral trainees in accelerator physics.

Recent Accomplishments:

1) The completion of the E150 plasma lens experiment at SLAC where the first focus of positrons by a plasma lens was observed. The results are published in Physical Review Letters, Phys. Rev. Lett. 87, 244801 (2001).
2) First acceleration of a staged advanced accelerator system STELLA (Staged Electron Laser Acceleration) at the BNL ATF. During April 2003 running, all "bugs" were eliminated at STELLA-II and the new STELLA-II system repeatedly obtained significant energy gain. This is important for a realistic use of an advanced accelerator system.
3) 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).
4) Measurements of transverse emittance dependence on laser uniformity. Results are published in Phys. Rev. ST-AB, 5, No. 9 (2002).
5) 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.
6) Successful feasibility study for a novel laser vacuum acceleration system at the BNL ATF using a tight laser beam.
7) 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.
8) The Higgs Factory Study for Snowmass 2001 (D. Cline and G. Hansen).
9) The development (with FNAL) of a Fast-Timing Trigger System (to 10 ps) for MuCool.
10) 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.
11) 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.

Plasma Lens Experiment E150 at SLAC

A small team from UCLA made significant contributions to the hardware and software of the plasma lens experiment at the SLAC FFTB (Final Focus Test Beam). The collaboration observed the 29 GeV electron and positron beam focusing through self-ionized or laser induced plasma at the FFTB. The positron beam-focusing plasma gave the first results, and the highest energy ever recorded was through the electron beam focusing through plasma. The specifications include a beam intensity of 1-3 x 10^{10} particles per pulse, a beam transverse size of 7 micron (horizontal) by 3 micron (vertical), and beam length of 0.7 mm in RMS. Plasma was generated by beam self-ionization or pre-ionization by a high power laser in a pulsed hydrogen or nitrogen gas jet. Two papers were published on the results.

STELLA Program
STELLA is a collaboration between UCLA, STI Optronics, Inc. and BNL to demonstrate staged laser acceleration of micro-bunches produced by a laser-energy-modulation process. STELLA has demonstrated the staging of two laser accelerations. The UCLA role in the project was to design and build the coherent transition radiation diagnostics to measure the femto-second micro-bunch. UCLA was also in charge of the analysis for femtosecond beam dynamics including space charge and coherent synchrotron radiation effects, e-beam optics preparation and e-beam tuning. In addition the UCLA team helped install the elements of the system, setup the laser optics and helped with laser alignment. A continuing program after STELLA-II and STELLA-III will be proposed which will demonstrate the staging of laser wakefield accelerations. The program will take several years to complete.

Vacuum Laser Acceleration and Compton Scattering Experiments
UCLA is successfully carrying out a feasibility study to demonstrate a novel laser acceleration by using a tight laser beam. The most prominent feature of the dynamic trajectories is that the incident electron beam can be captured into the intense field region rather than expelled from it as predicted by the conventional ponderomotive potential model. Essential conditions in this acceleration are: 1) very intense laser field ($a_0 > 5$), 2) small incident angle and 3) small injection electron momentum. With these conditions, an energy gain of > 20 MeV can be observed.

UCLA has collaborated with BNL and TMU on a Compton scattering experiment. The collaboration used an upgraded CO2 laser and an electron beam to obtain the new record for a Compton scattering X-ray signal, 1.7×10^8 X-ray signal/pulse using a 14 GW laser and a 60 MeV electron beam. This signal is a factor of 7 more then the one obtained in 1999. The collaboration has employed a plasma channel to increase the interaction length and then increase the X-ray signal.

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 (DLWC). The experiment has been restructured and a new run has been scheduled for April/May 2003.

b) Simulation of Neutrino Factory Front End
UCLA completed front end simulation for the neutrino factory feasibility studies with possible site locations at Fermilab and at BNL. The simulation covers the complete channel from the target through the phase rotation channel with the induction linacs (linear accelerator) to the end of the ionization cooling channel which gives the transverse phase space cooling. UCLA studied the muon polarization and its correlation to the arrival time by implementing the Muon Spin Tracking Code in the ICOOL ray tracing simulation code. The ratio of muons to the primary protons in

the six dimensional acceptance of the acceleration channel, and the muon polarization and its correlation to the arrival time, are the figures of merit of the channel. The simulation contributed to show the clear feasibility of the neutrino factory designs.

c) Conversion of a Neutrino Factory to a Higgs Factory

Professors D. Cline and G. Hansen lead an effort to study the possible “conversion of a neutrino factory to a Higgs factory”. One goal of the effort was to prepare a report for Snowmass 2001. A workshop was held at UCLA on February 28 to March 1, 2001 to start the study of the Higgs Factory. As was learned from the UCLA meeting, the key to a Higgs Factory is:

i) Stacking the many bunches in the neutrino factory into one μ^+ and one μ^- bunch.
ii) The ring cooler of Balbekov to reduce the emittance and size of the $\mu^\pm$ beam
iii) A final cooler storage ring using a Lithium lens insert. (This novel concept is entirely due to the UCLA team.)

d) 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 (SYNCH) 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 (ICOOL).

e) Study of Neutrino Factory Storage Ring

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

f) BNL Targetry Experiment E951

UCLA contributed to the initial observation of the feasibility of the liquid mercury jet target with the extremely high energy density primary proton beam for the neutrino factory and for the muon collider. The work included: a) a study on the accuracy of the transverse position controller of the target box (xy_mover.ps) at the test beam line, and b) picture taking and analysis of the Fast Speed Camera data which is capable of taking 16 frames with a 1 microsecond or longer time interval. In the April 2001 beam run, the first experimental results were obtained at the A3 primary beam line at BNL. The results show the maximum speed of the splashed mercury jet at around 50 m/s which is well within a manageable range inside the designed hardware system of the pion capture solenoid.

g) 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.

<u>Publications 2001-2003:</u>

1. E150 collaboration, "Plasma focusing of high energy density electron and positron beams", a contributed paper to the 18th International Conference on High Energy Accelerators (HEACC'01), in March 2001 in Tsukuba, Japan.

2. E150 collaboration, "Observation of plasma focusing of a 28.5 GeV positron beam", Phys.
3. Rev. Lett. **87**, 244801 (2001).
4. 3) W. Kimura, L. Campbell, C. Dilley, S. Gottschalk, D. Quimby, M. Babzien, I. Ben-Zvi, J. Gallardo, K. Kusche, I. Pogoreslky, J. Skaritka, A. van Steenbergen, V. Yakimenko, D. Cline, P. He, Y. Liu, L. Steinhaner, R. Pantell, “First staging of two laser accelerations”, Phys. Rev. Lett. **86**, No. 26, (2001).
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12. F. Zhou, D. Cline, Y.Ho, B. Liu, “A proposal for novel vacuum laser acceleration experiment at the BNL ATF”, to be presented at PAC03, Portland, (2003).

Current Staff:

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Dr. Yasuo Fukui	Asst. Res. Physicist	Mr. Xiaofeng Yang	Elec. Dev. Engineer
Dr. Alper Garren	Res. Physicist	Dr. Feng Zhou	Postdoctoral Associate

Current Graduate Students:

- Ping He Ph.D. Student
- Shao Lei Ph.D. Student

Past Graduate Students:

- Patrick Kwok, Masters of Science, March 1996, job unknown.
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STELLA-II Experiment at BNL

STELLA-II uses a single, high-power CO_2 laser beam to drive an inverse free electron laser (IFEL) buncher and IFEL accelerator. This differs from the first STELLA experiment, which used two separate laser beams to drive these devices. Using a single beam greatly reduces phase jitter and drift during the acceleration process. A conceptual drawing of the STELLA-II experiment is shown in Fig. 1.

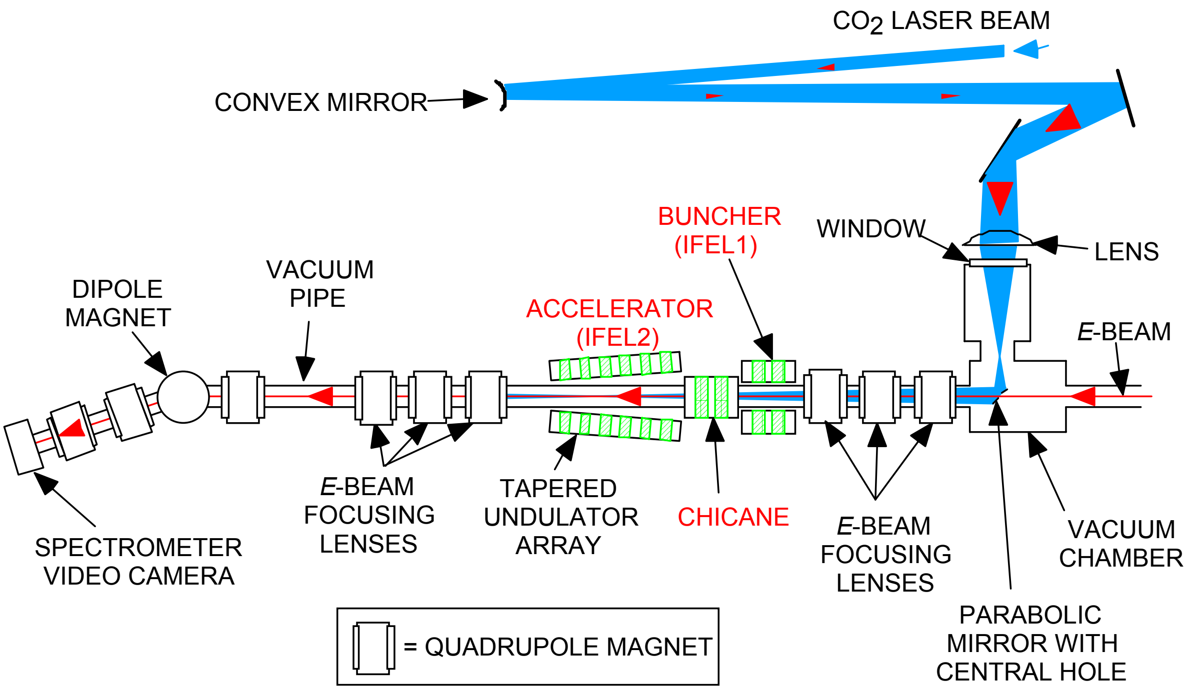

Figure 1. Conceptual Drawing of the STELLA-II Experiment.

Conceptual Diagram of the Higgs Factory and the Neutrino Factory

A conceptual diagram of the primary component systems making up a Higgs factory and neutrino factory are illustrated in Figure 2.

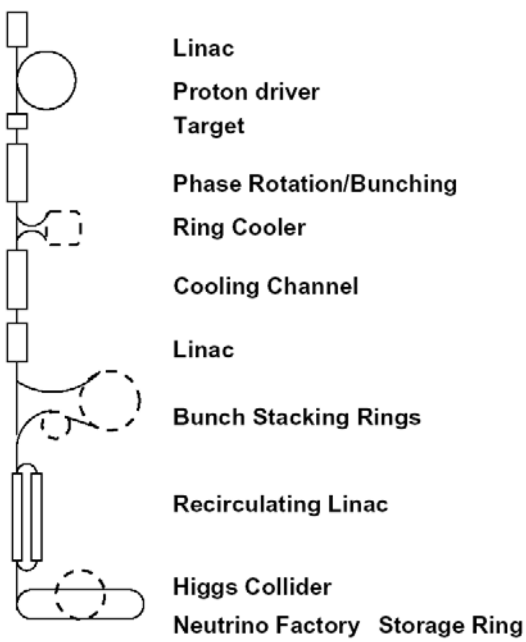

Figure 2 Schematic Diagram of a Higgs Factory and Neutrino Factory

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

P.I.: Professor C. Joshi, Co-P.I.s: Professor W. B. Mori,C. E. Clayton – UCLA

Summary:

The UCLA Plasma Accelerator Group has a strong program that continues to generate and develop new ideas involving the role of plasmas in future particle accelerators. Since the last report this group has had many notable successes, including first acceleration of injected electrons in the Neptune laboratory and the demonstration of acceleration of positrons at SLAC. The experiments have been supported by a strong theory and simulations program.

Recent Accomplishments:

On the experimental side the main accomplishment has been the successful completion of the NEPTUNE facility for Advanced Accelerator R & D and the use of this facility to demonstrate the acceleration of injected 10 MeV electrons to 50 meV using the Plasma Beat Wave Acceleration (PBWA) technique. The other accomplishment has been the demonstration of extremely non-resonantly excited relativistic plasma waves for particle acceleration. Both of these experiments have been supported by some of the largest particle-in-cell (PIC) code simulations carried out to-date using the code TURBOWAVE.

This group has also been extremely active in E157/E162 and E164 experiments on the Final Focus Test Beam (FFTB) at SLAC. The goal of these experiments is to develop the infrastructure needed to eventually attempt an energy doubler experiment using the Plasma Wakefield Acceleration (PWFA) schemes. To this end we have been working on acceleration and focusing of both electron and positron beams using plasmas. Meter scale acceleration modules for both electrons and positrons have now been demonstrated with peak gradients on the order ~ 100 MeV/m. The peak gradient is expected to scale inversely with square of the drive bunch length. Thus the current effort is on reducing the bunch length from 700 μm to 70 μm, thereby increasing the peak accelerating gradient to 10 GeV/m.

The present experiments on the FFTB are expected to finish by FY04. Serious discussions are underway as to how this work might be continued either in the SLC arcs and/or using the proposed ORION facility.

A nominally 50 MeV Inverse Cherenkov Accelerator (IFEL) experiment is currently underway utilizing the TW capability of the CO_2 laser at NEPTUNE. The experience gained here will be extremely useful in fielding a 330 μm IFEL buncher experiment for the Phase II experiments in Neptune. This buncher will produce a series of < 30 μm wide microbunches that will be spatially and temporally synchronized with the beat-driven RPW for "monoenergetic" acceleration.

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42. C. V. Filip et al., "Non-resonant beat-wave excitation of constant phase-velocity, relativistic plasma waves for charged particle acceleration," prepared for submission to Phy. Rev. E.

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- Co-P.I.: Dr. Chris Clayton
- Co-P.I.: Professor Warren Mori

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- Ken Marsh, Principle Development Engineer
- Dr. Sergei Tochitsky, Senior Development Engineer

Past Graduates:

Shuoqin Wang, Ph.D. degree, 2002, employed at Hughes Research Labs
Brent Blue, Ph.D. degree, 2003, employed at Lawrence Livermore National Laboratory

Current Graduates:

Ph.D. Graduate Students: Catalin Filip — Ph.D. expected graduation date: Sept. 2003
Ritesh Narang — Ph.D. expected graduation date: Sept. 2003
Michail Tzoufras, Jay Sung, Devon Johnson, Miaomiao Zhou
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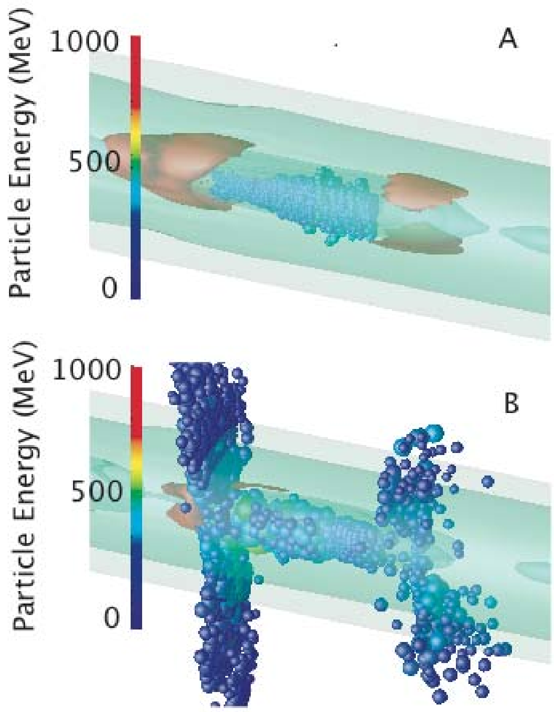

Figure 1: Self trapped acceleration of electrons by a 50 fs (FWHM), 10^{19} W/cm^2 laser pulse in a parabolic density plasma channel after (A) 5 mm and (B) 8 mm propagation.

Theoretical and Experimental Studies in Accelerator Physics

James Rosenzweig and Claudio Pellegrini - UCLA Dept. of Physics and Astronomy

Summary:

The activities on this grant encompass the research interests of Profs. James Rosenzweig and Claudio Pellegrini. Prof. Rosenzweig has led the development of the Neptune photoinjector, its associated basic beam physics and diagnosis work, and its (non-beatwave) plasma acceleration program. Prof. Pellegrini has led the effort to develop a high gradient inverse free-electron laser experiment for Neptune. 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 experiments), both PI's have off-campus experimental programs partially or fully supported my this grant at BNL, FNAL, LLNL and SLAC.

Some of the highlights of the last year's research include:

1. The Neptune photoinjector has been used in next generation plasma beatwave accelerator experiments using Prof. Joshi's MARS laser, a two-frequency CO_2 system. Over 50 MeV electrons were observed, having been accelerated from 11 MeV.
2. Basic beam physics studies at the Neptune photoinjector have continued. A complete experimental and computational study of transverse phase-space bifurcation during chicane compression of an intense 11 MeV electron beam from 4.5 to 0.65 ps was performed. A UCLA-developed single shot, slit-based phase space reconstruction method allowed direct examination of the phase space distribution; detailed simulations indicated a novel space-charge effect due to configuration space folding of the beam was the dominant mechanism driving this previously unknown effect.
3. Neptune was used for initial studies of the velocity bunching (VB) concept, which may help avoid the pitfalls of magnetic compression. Pulses as short as 0.4 ps were observed using coherent transition radiation (CTR). This version of the VB scheme is under study for use at the ORION advanced accelerator facility.
4. Two state-of-the-art photoinjector guns (for Neptune and ORION) have been fabricated at UCLA with SLAC collaboration. A new type of photoinjector which is scalable to high frequency and higher beam energy, based on hybrid standing-traveling wave rf structure is now under joint development with industry.
5. An inverse free-electron laser experiment which utilizes the TW Mars laser and the photoinjector at Neptune is now being installed. This ultra-high power laser beam is handled well by small f-number focusing, which produces a large Guoy phase shift during the IFEL interaction. An undulator that mitigates these problems has been constructed in collaboration with the KIAE-Moscow. Over 60 Mev beam is expected from this IFEL.
6. A new dogleg compressor beamline has been constructed at Neptune, which allows generation of a beam with a long ramp and sharp fall. The nonlinear dynamics of this system required novel use of sextupole correctors. This beam should be useful for a high-transformer ratio plasma wakefield accelerator (PWFA) experiments at Neptune, with a similar system now under study for ORION. An rf deflection mode cavity is now under development with INFN-Frascati which will allow 100 fsec resolution pulse profile measurements on these beamlines.
7. Photocathode development has proceeded, with magnesium cathode studies currently underway at Neptune. Plans are now being made to study diamond film cathodes.
8. The VISA SASE FEL, a UCLA-led collaboration at the BNL ATF, observed saturation of the 4-m FEL. A novel nonlinear compression mechanism in the ATF dogleg was found to be

responsible for anomalously high gain. This experiment was only under-stood through benchmarking of start-to-end simulations using PARMELA, Elegant, and GENESIS to measurements of emittance, energy spread and pulse length.

9. A new chicane compressor system has been developed and is now being installed at the BNL ATF. We will study basic compression-related processes such as coherent edge radiation (CER) using this device. It will also enable a new round of high gain, chirped FEL experiments using the VISA undulator, and sextupole correction.
10. A VB experiment at the LLNL/UCLA PLEIADES inverse Compton scattering experiment has been performed, with 0.3 psec beam observed. The next stage of these experiments will to attempt to preserve the beam emittance during compression.
11. A novel, extremely short focal length final focus system based on very high gradient (>300 T/m) permanent magnet quadrupoles (PMQs) is now being constructed for use in PLEIADES, to enhance the scattering luminosity. This system, which is tuned by longitudinal positioning of the PMQs, is also under study for use in beta-matching for beam-plasma experiments, such as plasma wakefield acceleration, and plasma assisted inverse Compton scattering (for polarized positron sources).
12. The FNAL/UCLA plasma wakefield acceleration experiments at the FNAL A0 photoinjector were continued. A witness beam was created that allowed sampling of >150 MV/m accelerating fields in the blowout regime.
13. A new method of creating phase-locked, fsec beam pulses in plasma waves by trapping background plasma electrons has been developed at UCLA for an experimental demonstration at A0 in summer 2003. This scheme uses only a drive beam PWFA that traverses a sharp density gradient in the plasma. By appropriate tailoring of the density profile in simulations, it has been found that a very low emittance, small energy spread electron beam can be “injected” into the plasma wave. Further, it has been shown that this system can be scaled to high plasma density to produce beams of unprecedented brightness.
14. A dielectric-based resonant laser accelerator, to be operated at either 10 or 340 microns at Neptune, has been studied analytically and computationally, and is now undergoing design.
15. Fundamental analytical and computational studies of plasma wakefields in the extreme blowout regime have been performed. Novel aspects of coherent radiation (CER, near-field CTR, coherent synchrotron radiation instability) and space-charge dominated beam physics have also been studied through theory and simulation. Computational capabilities in the group have been greatly enhanced by our development of Beowulf parallel computing cluster.

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2. "Properties of an ultra-short gain length, saturated, self-amplified spontaneous emission FEL," A. Murokh, et al., accepted for publication in Physical Review E.
3. “Velocity bunching experiment at the Neptune Laboratory,” P.Musumeci, R.J.England, M.C.Thompson, R.Yoder, J.B.Rosenzweig, in Advanced Accelerator Concepts, Ed. C. Clayton and P. Muggli (AIP Conf. Proc., 2002).
4. “Plasma electron fluid motion and wave breaking near a density transition,” R. J. England, J. B. Rosenzweig, and N. Barov Phys. Rev. E 66, 016501 (2002).
5. “Experimental characterization of nonlinear harmonic radiation from a visible self-amplified spontaneous emission free-electron laser at saturation,” A. Tremaine, Phys. Rev. Lett. 88, 204801 (2002)

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7. “Plasma density transition trapping as a possible high-brightness electron beam source,” M.C. Thompson, J.B. Rosenzweig, in Advanced Accelerator Concepts, Ed. C. Clayton and P. Muggli (AIP Conf. Proc., 2002), also submitted to PRST-AB.
8. “Experimental characterization of nonlinear harmonic radiation from a visible self-amplified spontaneous emission free-electron laser at saturation,” A. Tremaine, Phys. Rev. Lett. 88, 204801 (2002)
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14. “Energy loss of a high charge bunched electron beam in plasma I: analysis,” J.B. Rosenzweig, N. Barov, M.C. Thompson, and R.B. Yoder, submitted to PRST-AB
15. “Energy loss of a high charge bunched electron beam in plasma II: simulations, scaling, and accelerating wake-fields,” J.B. Rosenzweig, N. Barov, M.C. Thompson, and R.B. Yoder, submitted to PRST-AB.
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- England, J. (Rosenzweig)
- Lim, J. (Rosenzweig)
- Musumeci, P. (Pellegrini)
- Thompson, M. (Rosenzweig)

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Alex Murokh, (Rosenzweig, 2002). UCLA postdoc.

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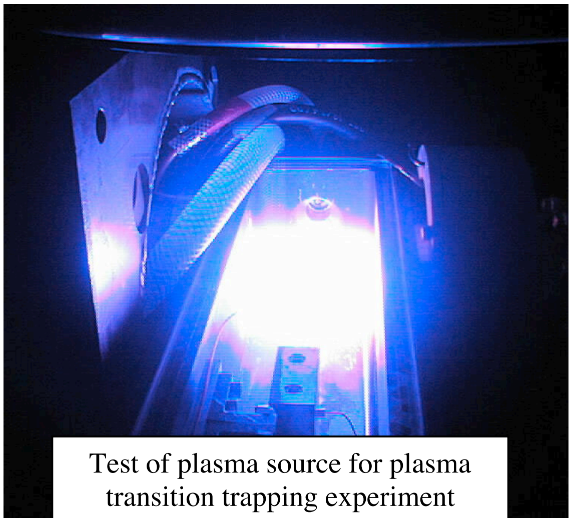
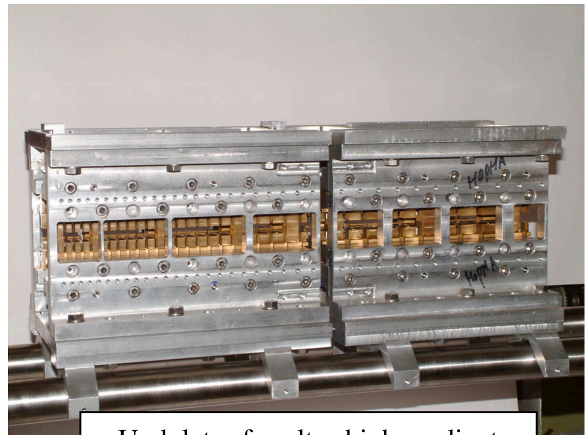
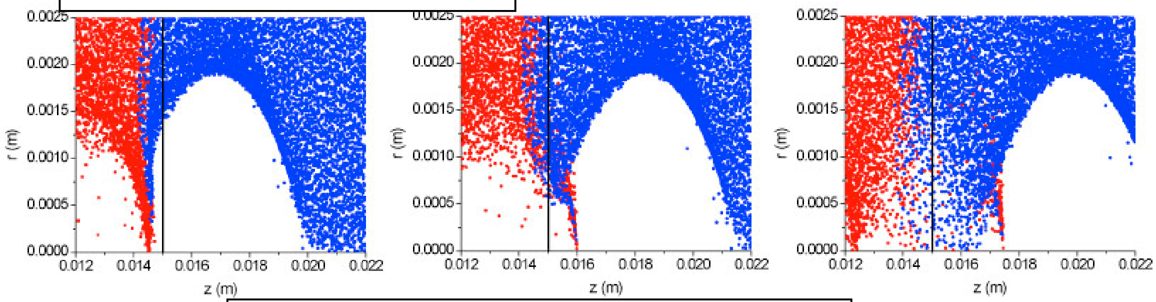


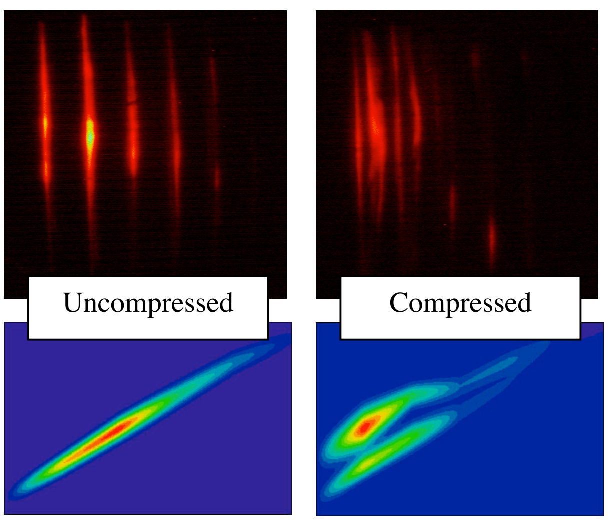
Test of plasma source for plasma transition trapping experiment



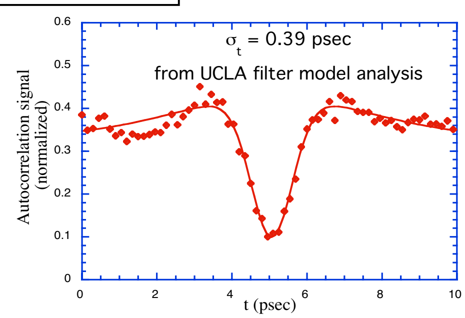
Undulator for ultra-high gradient IFEL experiment at Neptune



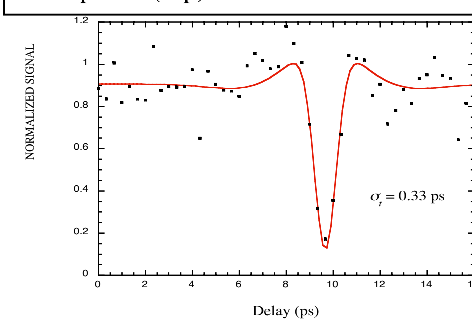
Simulation of plasma transition trapping process (initially upstream electrons shown in red)



Slit images (top) and associated transverse phase space reconstructions (bottom) from Neptune chicane compression experiment



CTR measurement of velocity-bunched beams at Neptune (top) and LLNL PlEIADES (bottom)



Chaotic Dynamics in Accelerator Physics

John R. 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 beam (actually, non neutral plasma) cooling through application of microwave fields. 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 a set-based message passing system that has recently been used to allow for dynamic load balancing.

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*. Three laser pulses are used in this scheme. The *drive pulse* is of larger amplitude and generates a wake field. It is followed by the *forward injection pulse*, a smaller pulse of transverse polarization. A third pulse is injected axially in the reverse direction. This *backward injection pulse* has the same polarization as the forward injection pulse. Because its polarization is transverse to that of main drive pulse, it passes through the main drive pulse with little interaction. However, when it hits the forward injection pulse, it creates a beat potential that moves particles up in phase space to the trapping region of the wake field.

Our simulations show that this process can produce very good beams. After nearly 2 mm of propagation we find beams of length 10.6 fs, while the relative rms energy spread is $\sigma_{p_x}/\langle p_x\rangle$=6.2%. The faster particles are at a relativistic factor of γ=83 with average of $\langle\gamma\rangle$=77.5. This implies an average acceleration gradient of 22 GV/m. The rms width of the beam is 1.25 μm. The measured transverse emittance is $\varepsilon\equiv\sigma_{p_y}\tilde{\sigma}_y/\langle p_x\rangle$ = 0.0077πmm-mrad. This implies a normalized emittance $\varepsilon_N = \varepsilon\gamma$= 0.596$\pi$mm-mrad.

However, in the last year we found that injection is much more ubiquitous. First, we noted that at large values of the pump field, the accelerating potential takes on more favorable dynamical properties, in that the fraction of longitudinal phase that is both accelerating and transversely focusing increases from roughly 50% to more than 80%. This, combined with the fact that at larger pump field, particles may be injected to lower energy and be accelerated, implies that at larger pump field it becomes much easier to optically inject particles into a wake field. Thus, we have now observed injection in a two-pulse scheme, where the optical injection occurs due to a phase kick that is caused by the backward pulse. Subsequently, we observed in simulations of longer regions that there can be spontaneous particle injection several accelerating buckets back from the pump pulse, apparently due to transverse wave breaking. We are currently pursuing this area of study, as we believe that a combination of optical techniques might lead to beamlet trains well suited for high-energy physics experiments.

With these discoveries, the tables turned, in the sense that we seem to have shown that with existing schemes it is difficult to produce single, well-formed beamlets. Inevitably, wave breaking occurs far enough back in the tail of the accelerating potential. As there remain technological uses for single, well-formed beams, we have at the same time begun re-examining the various injection schemes with the goal of producing single, well-formed beams. In the last few months we have been pursuing a new injection method that shows promise for doing just that. This method relies on having two forward pulses of the same polarization, with one trailing the other by a distance of roughly 1 1/2 plasma wavelengths. The first pulse creates the accelerating wake potential, while the second removes it, because it is out of phase. Then only a single accelerating field region is produced. Ultimately, a single backward pulse causes particles to be injected in this wake through phase-kick injection. Our preliminary results indicate that this scheme will allow one to produce single, well-formed pulses.

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.

Lastly, we are continuing our studies of equilibrium and crystallization of beams. This work comprises the thesis of Jinhyung Lee. This work is potentially of very high interest, as it indicates that one may be able to cool pure electron plasmas and beams using a combination of synchrotron radiation and microwaves. In the last year we were able to significantly reduce the computational requirements for studying such systems by removing the synchrotron time scale from dynamical equations through a perturbative expansion.

Finally, we again note that this work is synergistic with other work being carried out in our group and in collaboration with others. In collaboration with Peter Stoltz, who was funded by DOE at Tech-X Corporation to work on muon collider modeling, we developed a new method for spatial integration through accelerator lattices. In collaboration with David Bruhwiler, also at Tech-X Corporation, we have discovered that tunneling ionization can strongly modify the expectations from advanced accelerator experiments planned at SLAC. We note once again that 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.

Recent Accomplishments:

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

Development of the theory for microwave cooling of strongly magnetized electron plasmas and use of this theory to demonstrate that cooling to the crystalline state can take place on hour time scales

Publications 2001-2003:

Refereed Journal Articles or Conference Proceedings

1. D. L. Bruhwiler, R. Giacone, J. R. Cary, J. P. Verboncoeur, P. Mardahl, E. Esarey and W. P. Leeman, "Particle-in-cell simulations of plasma accelerators and electron-neutral collisions," Phys. Rev. ST/AB 4, 101032 (2001).
2. D.L. Bruhwiler, R. Giacone, J.R. Cary, J.P. Verboncoeur, P. Mardahl, E. Esarey and W. Leemans, "Modeling beam-driven and laser-driven plasma wakefield accelerators with XOOPIC," in Advanced Accelerator Concepts, AIP Conf. Proc., Vol. 569, ed. P.L. Colestock and S. Kelley (AIP, Melville, NY, 2001), pp. 591-604.
3. W. Wan and J. R. Cary, "Finding four dimensional symplectic maps with reduced chaos," Phys. Rev. ST/AB 4, 084001 (2001).
4. P. H. Stoltz, J. R. Cary, G. Penn, and J. Wurtele, "Efficiency of a Boris-like integration scheme with spatial stepping," Phys. Rev. ST/AB 5, 094001,1-9 (2002).
5. C. Nieter and J. R. Cary, "VORPAL: a versatile plasma simulation code", submitted to J. Comp. Phys. (2003).
6. 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," accepted for publication, Phys. Plasmas (2003).

Non–refereed Conference Proceedings

1. Bruhwiler, D. Dimitrov, P.E. Catravas, E. Esarey, W.P. Leemans, B.A. Shadwick, P. Mardahl, J.P. Verboncoeur, J.R. Cary, R.E. Giacone, "Particle-in-cell simulations of gas ionization by short intense laser pulses," paper MOPC006, Proc. Particle Accelerator Conference (Chicago, 2001).
2. K. Sonnad, J.R. Cary, "The effect of nonlinear transport on beam halo formation," paper RPAH065, Proc. Particle Accelerator Conference (Chicago, 2001) available at http://accelconf.web.cern.ch/AccelConf/p01/PAPERS/RPAH065.PDF.
3. C. Nieter, J.R. Cary, "VORPAL - a multidimensional code for simulating advanced acceleration concepts," paper RPAH110, Proc. Particle Accelerator Conference (Chicago, 2001) available at http://accelconf.web.cern.ch/AccelConf/p01/PAPERS/RPAH110.PDF.
4. J. Lee, J.R. Cary, "Cooling of non-neutral plasma by energy exchange," paper FPAH091, Proc. Particle Accelerator Conference (Chicago, 2001) available at http://accelconf.web.cern.ch/AccelConf/p01/PAPERS/FPAH091.PDF.
5. R.E. Giacone, J.R. Cary, E. Esarey, W.P. Leemans, D. Bruhwiler, P. Mardahl, J.P. Verboncoeur, "Simulations of electron injection into plasma wake fields by colliding laser pulses using XOOPIC," paper FPAH149, Proc. Particle Accelerator Conference (Chicago, 2001) available at http://accelconf.web.cern.ch/AccelConf/p01/PAPERS/FPAH149.PDF.
6. D. A. Dimitrov, D. L. Bruhwiler, W. Leemans, E. Esarey, P. Catravas, C. Toth, B. Shadwick, J. R. Cary, and R. Giacone, "Simulations of laser propagation and ionization in l'OASIS experiments, Proc. Tenth Workshop, Advanced Accelerator Concepts, C. E. Clayton and P. Muggli, eds., AIP Conference Proceedings, Vol. 647 (Mandalay Beach, June 2002).
7. J. R. Cary and C. Nieter, "VORPAL an arbitrary dimensional hybrid code for computation of pulse propagation in laser-based advanced acceleration concepts," Proc. 18th Annual Review of Progress in Applied Computational Electromagnetics (Monterey, CA, 2002).

8. C. Nieter and J. R. Cary, "VORPAL as a tool for the study of laser pulse propagation in LWFA," Proc. ICCS 2002, P.M.A. Sloot, C.J.K. Tan, J.J. Dongarra, A.G. Hoekstra(Eds.), Lecture Notes in Computer Science, 2331, p. 334 (Springer Verlag, Berlin, 2002).

Contributed Papers for Scientific Meetings (2001-2003)

21 papers. Details not given to conserve space.

Current Staff Supported Under This Grant:

- Prof. John R. Cary (Principal Investigator)
- Dr. Rodolfo Giacone (Research Associate)
- Mr. Kiran Sonnad (Graduate Research Assistant pursuing Ph.D.)
- Mr. Jinhyung Lee (Graduate Research Assistant pursuing Ph.D.)

Previous Staff Supported Under This Grant:

Name	Position	Date graduated or left	Subsequent position	Current position
David L. Bruhwiler	Graduate Research Assistant	Ph. D. June 1990	Grumman Research	VP, Tech-X Corporation
William E. Gabella	Graduate Research Assistant	Ph. D. June 1991	UCLA	Vanderbilt FEL Lab
Carson Chow	Postdoctoral Research Associate	June 1994	Postdoc, Boston University	Professor of Mathematics, U. Pittsburg
Peter H. Stoltz	Graduate Research Assistant	Ph. D. June 1996	Princeton Plasma Physics Lab	Member Technical Staff, Tech-X Corporation
Scott Hendrickson	Graduate Research Assistant	Ph. D. June 1996	Kaiser Technologies	Director, Business Development, Tech-X Corporation
Weishi Wan	Postdoctoral Research Associate	June 1997	Postdoc, FNAL	Staff Member, LBNL

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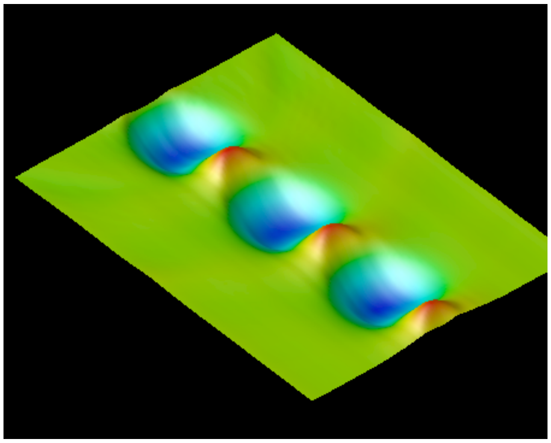

Fig. 1. A 3D rendering of the potential energy of a laser wake field for a=1.7. The direction of laser propagation is to the right and down.

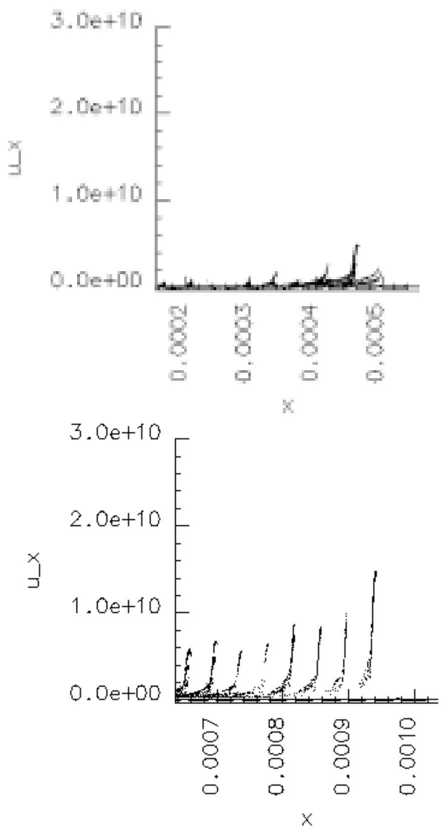

Fig. 2. Longitudinal phase space during the injection process through acceleration, showing the generation and acceleration of beamlets.

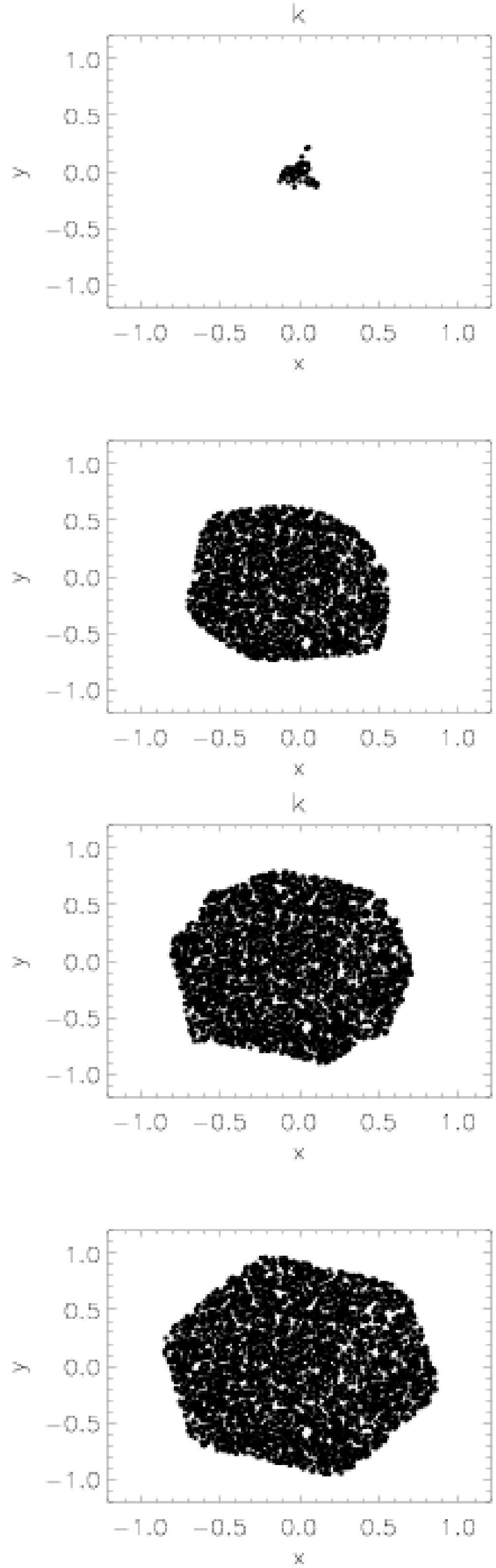

Fig. 3. Increase of the dynamic aperture through correct choice of phase between linear and nonlinear elements.

Study of the Stability of Particle Motion in Storage Rings

Jack Shi – University of Kansas

Summary:

During the past year, the beam-dynamics group at the University of Kansas has focused on a study of long-range and head-on beam-beam effects in storage-ring colliders. Topics include the collective beam-beam instability in hadron colliders and its implication to bunch-current limit and development of the global and local compensation of long-range beam-beam interactions with magnetic multipole correctors based on a minimization of nonlinearities in one-turn and/or sectional maps of a storage-ring collider.

Recent Accomplishments:

Study of Beam-Beam Effects in HERA with an Extreme Large Beam-Beam Tune Shift

HERA Accelerator Studies 2000 has been conducted to understand the effect of a large beam-beam tune shift of the electron beam on emittance growth and luminosity reduction in HERA. In the experiment, the vertical beam-beam parameter of the positron beam was varied from 0.068 to 0.272 by changing the vertical beta-function of the positron beam at interaction point (IP) from 1.0 to 4.0 m. When the beta-function is 4.0 m, a record total incoherent beam-beam tune shift of 0.544 (with two IPs) was achieved. The emittance of the positron beam and the luminosity were measured as functions of the beam-beam parameter at HERA IPs, H1 and ZEUS. To have a better understanding of those measurements, we have reconstructed the HERA experiment with a self-consistent beam-beam simulation. This study also served a detail benchmark of our beam-beam simulation code with the experimental measurement. In the simulaton, both the emittance and luminosity were calculated as functions of the beam-beam parameter of the positron beam. A remarkable agreement between the experiment and the simulation was obtained. In the experiment, the coherent tune was also measured at the beam-beam parameter of 0.272. Table 1 lists the coherent tune measured in the experiment and calculated by the simulation and it shows a very good agreement between the experiment and the simulation. Contrary to the traditional belief, the coherent beam-beam tune shifts in this case are much smaller than in the case of two symmetrical Gaussian beams. To understand such small coherent tune shifts, eigen-frequencies of the coherent oscillation were derived for the un-symmetrical case of a beam-beam interaction based on the assumption of rigid Gaussian beams. It was found from the derived eigen-frequency formula that the small coherent tune shift in this case is due to a severe mismatch between two beams as a result of the emittance blowup of the positron beam. With the enlarged positron-beam emittance obtained from the simulation or experiment, however, the coherent tune shift calculated from the derived formula does not agree well with the experimental or simulation result (see Table 1). The discrepancy here is due to a non-Gaussian distribution of the positron beam. A study of the dynamics of particle distributions during the beam-beam simulation showed that the distribution of the positron beam deviated from a Gaussian distribution with a significant drop at beam core and a growth of beam tails. Compared with the distribution of the positron beam, a Gaussian beam has more particles in the core. The coherent beam-beam tune shift calculated from the derived formula is therefore larger than the real tune shift of the positron beam.

Table 1: Coherent tune in HERA Accelerator Studies 2000 when the vertical beta-function of the positron beam at IPs is 4.0m. The beam-beam parameter for the positron and proton beam are (0.041, 0.272) and (0.00003, 0.00001), respectively. ``Gaussian Beam'' is the tune calculated with the measured positron-beam emittances by using the derived formula for two non-symmetrical Gaussian beams.

	$\nu_{e,x}$	$\nu_{e,y}$	$\nu_{p,x}$	$\nu_{p,y}$
Lattice Tune	52.169	52.246	31.291	32.297
Experiment	52.160	52.233	31.291	32.297
Simulation	52.162	52.232	31.291	32.297
Gaussian Beam	52.156	52.227	31.291	32.297

Study of Collective Beam-Beam Instability in Hadron Colliders

The collective beam-beam effect in hadron colliders has been studied with a self-consistent beam-beam simulation by using the particle-in-cell method. It was found that when the beam-beam parameter exceeds a threshold, a collective beam-beam instability characterized by an enhanced emittance growth due to the dynamics of the counter-rotating beam occurs. After the onset of this collective beam-beam instability, the phase-space area near the origin could become unstable for beam centroids, and the two colliding beams could develop a spontaneous chaotic coherent oscillation. A study of the dynamics of beam distributions showed that after the onset of this chaotic coherent beam-beam instability, the beam distributions could significantly deviate from a Gaussian due to beam halo. The formation of the beam halo is a result of chaotic transport of particles from beam cores to beam tails.

In the current luminosity upgrade for HERA, the luminosity is expected to increase roughly by a factor of 4.5. To achieve this goal, the beta-functions at IPs of both beams have been reduced and the beam currents will be increased. These measures will increase the beam-beam parameter of the electron beam from (0.012, 0.03) to (0.034, 0.052). To exam whether a luminosity reduction could occur due to beam-beam interactions, the beam-beam effect in the HERA upgrade has been studied with a self-consistent beam-beam simulation by using the particle-in-cell method. It was found that beam-beam interactions in the HERA Upgrade could induce a chaotic coherent beam-beam instability that could result in an emittance blowup on the proton beam and a significant luminosity reduction. A study of the dynamics of beam-beam tune spread of the electron beam showed that this coherent beam-beam instability is due to an overlap of the electron beam and the 4th-order incoherent beam-beam resonance. A simulation with a slightly different working point of the electron beam that moves the electron-beam core away from those 4th-order resonances was therefore performed. It confirmed that this coherent beam-beam instability could be avoided by eliminating the crossings of major beam-beam resonance with a different working point. To determine the threshold of the onset of the coherent beam-beam instability, the emittance growth of the proton beam was studied as a function of bunch current of the proton beam in the case of one IP. It was found that the threshold is at 50% design proton-beam current. This further confirms the effect of the 4th-order resonance on the coherent beam-beam instability since at 50% design proton-beam current the electron beam avoids the crossing of the 4th-order resonance.

Such the collective beam-beam instability has been observed in a recent beam experiment on HERA (HERA High-Luminosity Studies, Feb. 21-23, 2003). In the experiment, the emittance of the proton beam and the luminosity were measured and compared at two different working points of the positron beam. When the working point of the positron beam is at (0.14, 0.21), the positron beam is away from the 4th-order resonance and does not cross any major beam-beam resonance. In this case, no emittance growth of the proton beam or the luminosity reduction were observed. When the working point of the positron beam was moved to (0.215, 0.296), on the other hand, the positron beam overlaps with the 4th-order resonance of $2\nu_x + 2\nu_y = 1$ and a more than 30% emittance growth of the proton beam was observed. The phenomena observed in the experiment agree remarkably with the prediction from the beam-beam simulation. It should be noted that in HERA the beam-beam parameter of the positron beam is over 20 and 100 times larger than that of the proton beam in the horizontal and vertical direction, respectively, and the two rings have a very different working point. Traditionally, the beam-beam effect in such situation is considered as a typical strong-weak or very un-symmetrical case. This study showed that the traditional boundary between the strong-strong and strong-weak beam-beam interactions is no longer valid in the nonlinear (non-integrable) regime of beam-beam interactions. For high-intensity beams, the nonlinear beam-beam perturbation could dominate beam dynamics and the collective (coherent) beam-beam instability could occur in both the cases of strong-strong (symmetrical or nearly symmetrical) and strong-weak (very un-symmetrical) beam-beam interactions.

Development of Multipole Compensation of Long-Range Beam-Beam Interactions With Minimization of Nonlinearities in Poincaré Maps of a Storage-Ring Collider

In the case of multi-bunch operation in the Tevatron, serious long-range beam-beam effects are due to many non-localized parasitic collisions that are distributed around the ring. In the case of LHC, on the other hand, the long-range beam-beam effects are due to localized parasitic collisions inside interaction regions. To control the non-localized or/and localized long-range beam-beam perturbations, we proposed a compensation scheme for long-range beam-beam interactions by using magnetic multipole correctors based on a minimization of nonlinearities in one-turn or sectional maps of a storage-ring collider. This multipole compensation scheme can be used for both global and local compensation of long-range beam-beam interactions and for a beam-based compensation of long-range beam-beam interactions if the one-turn or sectional maps can be extracted in beam dynamics experiments.

With LHC as a test model, the effectiveness of the multipole compensation of long-range beam-beam interactions was studied in terms of improvement of dynamic aperture and reduction of emittance growth. Head-on and long-range beam-beam interactions at IP1 and IP5 were included in the study. Cases of with or without multipole field errors in the lattice were studied. In the case of the nonlinear lattice, we studied 50 different cases of random multiple components of the field errors in order to improve the statistical significance of the simulation that involves random field errors. Dynamic aperture was studied with 100,000-turn tracking, and the emittance growth was examined with a self-consistent beam-beam simulation with a million particles. The study showed that both the global and local multipole compensation of long-range beam-beam interactions is very effective in increasing the dynamic aperture and improving the linearity of the phase-space region near the closed orbit. With a few groups of multipoles correctors, nonlinear terms in one-turn or sectional maps, including long-range beam-beam interactions, can be minimized order-by-order, and, consequently, the nonlinearity of the system in the phase-space region that is relevant to the beams is significantly reduced. In the case of localized parasitic collisions, such as in LHC, our study showed that both the wire compensation scheme proposed by Koutchouk and our multipole compensation scheme are very effective in eliminating long-range beam-beam effects. With the multipole compensation, however, the overall nonlinearities in the system, including both the long-range beam-beam interactions and magnetic field errors in the lattice, can be treated systematically with a same group of multipole correctors, since the field errors and long-range beam-beam interactions can be simultaneously considered in the maps. In the case of distributed parasitic collisions such as in the Tevatron, no other viable solution is currently available for a compensation of nonlinear long-range beam-beam interactions. The multipole compensation scheme proposed here opens up a possibility for the reduction of nonlinear long-range beam-beam effects in this case.

Publications 2001-2003:

1. L. Jin and J. Shi, "Effect of electron-beam compensation of beam-beam tune spread on beam-size growth in Tevatron", in *Proc. of the Workshop on the Beam-Beam Effect in Circular Colliders*, Edited by T. Sen and M. Xiao, FERMILAB-Conf-01/390-T, Fermilab, 2001, p. 157.
2. J. Shi, "Beam-beam effects with offset head-on collision", LHC Beam-Beam Study Report, SL/AP, CERN, (2001).
3. D. Yao and J. Shi, "Evolution of averaged action variables in weakly non-integrable Hamiltonian systems", J. Phys. A, 4999 (2001).
4. L. Jin, J. Shi, and W. Herr, "Study of the wire compensation of long-range beam-beam interactions in LHC with a strong-strong beam-beam simulation", in *Proc. of the 8th European Particle Accelerator Conference*, Paris, June 2002.
5. J. Shi, O. kheawpum, and L. Jin, "Global compensation of long-range beam-beam interactions with multipole correctors", in *Proc. of the 8th European Part. Accel. Conf.*, (2002).
6. J. Shi, L. Jin, and O. Kheawpum, "Multipole compensation of long-range beam-beam interactions with minimization of nonlinearities in Poincaré maps of a storage-ring collider", submitted to Phys. Rev. E, (2003).
7. L. Jin and J. Shi, "Importance of beam-beam tune spread to the collective beam-beam instability in Hadron colliders", submitted to Phys. Rev. E, (2003).
8. 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 Part. Accel. Conf.*, Portland (2003).
9. J. Shi, L. Jin, and M. Minty, "Collective beam-beam instability in strong-weak case of beam-beam interactions", to be submitted to Phys. Rev. E, (2003).
10. J. Shi, L. Jin, and O. kheawpum, "Chaotic coherent oscillation due to beam-beam interaction of Hadron beams", to be submitted to Phys. Rev. E, (2003).

Current Staff:

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Lihui Jin	Ph.D. Graduate Student, Sept. 1999 -- present.
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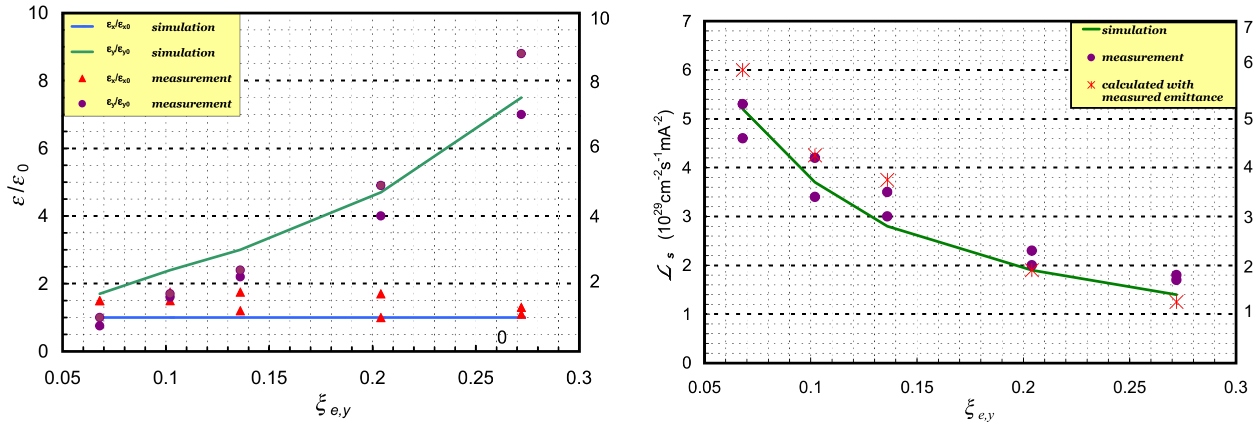

Figure 1: Experimental measurement and simulation result of HERA 2000 Study. Emittance growth (left figure) of the e^+ beam and the specific luminosity (right figure) of HERA as functions of $\xi_{e,y}$, the vertical beam-beam parameter of the e^+ beam. ϵ_0 is the nominal emittance of HERA. Discrete points are from the experiment and continuous curves from the simulation. For each $\xi_{e,y}$ where the measurement was performed, two data points correspond to the measurement at H1 and ZEUS. In the emittance plot, the upper (lower) curve is the vertical (horizontal) emittance.

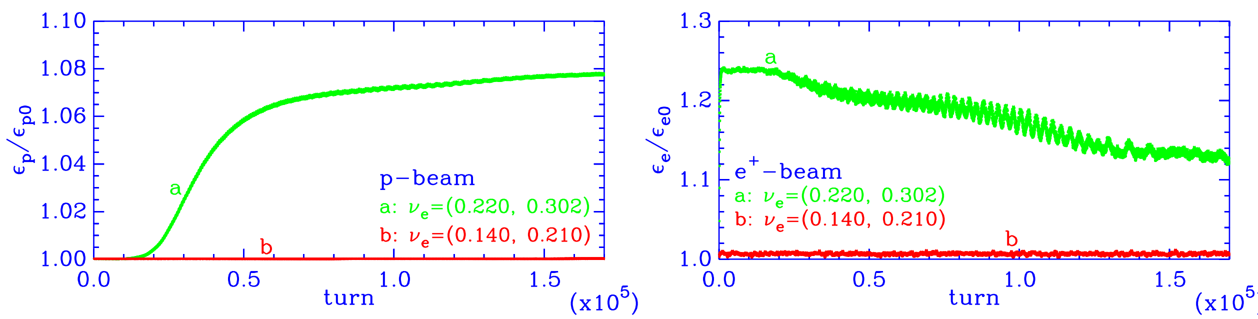

Figure 2: Self-consistent beam-beam Simulation of the emittance growth of the p (left figure) and e^+ (right figure) beam in HERA at two different working points of the e^+ beam. a: The working point of the e^+ beam is at $\vec{\nu}_e = (0.220,\ 0.302)$ and the e^+ beam overlaps with the 4th-order resonance of $2\nu_x + 2\nu_y = 1$. The emittance growth of both the beams is due to the onset of the chaotic coherent beam-beam instability. b: $\vec{\nu}_e = (0.140,\ 0.210)$ and the e^+ beam is away from the resonance. In this case, both the beams are stable. In both cases, the working point of the p beam is $\vec{\nu}_p = (0.294,\ 0.298)$. The beam-beam parameter is $\vec{\xi}_e = (0.016,\ 0.024)$ and $\vec{\xi}_p = (0.0014,\ 0.0004)$ for the e^+ and p beam, respectively. HERA 2003 Experimental Result: In case a, the proton beam emittance increases $\sim$30% while in case b, no emittance increase was observed.

University of Maryland Dynamical Systems and Accelerator Theory Group

Alex J. Dragt and Robert L. Gluckstern - University of Maryland

Summary:

The University of Maryland Group has been carrying out long-term research work in the general area of Dynamical Systems with a particular emphasis on applications to Accelerator Physics. This work is broadly divided into two tasks:

- The Computation of Charged Particle Beam Transport,
- The Computation of Electromagnetic Fields and Beam-Cavity Interactions.

Each of these tasks is described briefly below. Work is devoted both to the development of new methods and the application of these methods to problems of current interest in accelerator physics including the theoretical performance of present and proposed high energy machines.

In addition to its research effort, the Dynamical Systems and Accelerator Theory Group is actively engaged in the education of students and post-doctoral research associates. There are currently 12 Ph.D. physicists working in the field of Accelerator Physics who were trained in our Group.

Task A. 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 SLAC B factory and for final focus systems in the SLAC Test Beam Facility and the NLC, and are being used in the design of the LHC and in the design of high current accelerators for neutron spallation sources, neutrino factories, and muon colliders. They are also being used at LANL both for multimillion macroparticle intense beam simulations and 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 (900 pages currently written) and in the "MaryLie 3.0 User's Manual, A Program for Charged Particle Beam Transport Based on Lie Algebraic Methods" (870 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.

Recent Accomplishments:

- Computation of Maps for real Magnets (work done with M. Venturini and A. Wolski at LBNL). Work has and 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 Linear Collider and other machines, permanent magnet elements in the Tevatron recycler, low beta quads in the LHC, and dipoles in the 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, NLC, and TESLA applications. The use of elliptical cylinders is being explored for the CESER-c superferric wiggler magnets. Finally a method that employs the surface of a bent box with straight ends is being developed for magnets with large orbit sagitta.

- Construction of a Hybrid PIC-Lie Beam Transport Code including Space Charge Effects [work done with R. Ryne (LBNL) and other members of the DOE Accelerator Physics SciDAC consortium]. Work is being carried out on the construction of a Hybrid PIC-Lie code that incorporates both the full linear and nonlinear beam-line element library of MaryLie through 5^{th} order and standard PIC routines for space-charge effects. The code also includes 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 highly parallel version has been developed for use on the largest tera-scale computers at NERSC, and applications are being made to the SNS and the Fermilab booster.
- Lie-Algebraic Treatment of General Maps. A method has been found for classifying and representing *all* analytic maps, and it has been shown that any such map can be uniquely factorized into a symplectic (Hamiltonian) and nonsymplectic (dissipative) part. Thus there is now a unified theory of both Hamiltonian and dissipative effects. This factorization is currently being applied to the one-turn map for the PEP-II ring including all linear and nonlinear Hamiltonian effects and all dissipative synchrotron radiation effects.

Task B. Computation of Electromagnetic Fields and Beam-Cavity Interactions:

- 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 are now being applied to the understanding of possible halo formation and other resonant effects in circular accelerators, including the Spallation Neutron Source (SNS) rings being designed at BNL. This work is being carried out in collaboration with A. Fedotov, a former Maryland graduate student and post-doc who is now on the SNS staff at BNL. The resonant behavior and resulting instability is shown in Fig. 13 of Reference B2 (attached to this report).
- A second area of continued work is the study of coupling impedances in beam pipes and its importance in understanding beam current limitations in circular accelerators. Present activities include an attempt to obtain an analytical formulation of 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. This work is being carried out in collaboration with F. Ruggiero and B. Zotter at CERN, and is relevant to the impedance measurements now being made at CERN by F. Caspers, L. Vos and others.
- A third area of recent activity is a study of the evolution of a mismatched spherically symmetric beam bunch in a focussing channel using the Vlasov equation supplemented by the Boltzmann equation to include intra-beam collisions. The purpose of the work is to understand a variety of mismatched collective modes as well as the details of the approach to thermal equilibrium. This work is being carried out in collaboration with R. Ryne and J. Qiang at LBNL. In addition, we are studying numerical methods to achieve fast and accurate time evolution of charged particle bunches in beam pipes.

Publications 2001-2003:

Task A:

1. A.J. Dragt, P. Walstrom, et al., “Computation of charged-particle transfer maps for general fields and geometries using electromagnetic boundary-value data,” Proceedings of the 2001 International Particle Accelerator Conference (2001).
2. A.J. Dragt and P. Johnson, “The propagation of quantum relativistic wavepackets in electromagnetic fields,” Proceedings of the 2001 International Particle Accelerator Conference (2001).
3. M. Venturini, A. Wolski, and A.J. Dragt, “Wigglers and single-particle dynamics in the NLC damping rings,” Proceedings of the 2003 International Particle Accelerator Conference (2003).
4. R. Ryne, A. Adelmann, P. Colella, J. Qiang, D. Serafini, R. Samulyak, S. Habib, T. Mottershead, F. Neri, P. Walstrom, V. Decyk, A.J. Dragt, “MaryLie/IMPACT: a parallel 5th order beam optics code with space charge,” Proceedings of the 2003 International Particle Accelerator Conference (2003).

<u>Task B</u>:

1. R.L. Gluckstern and B. Zotter, “Analysis of shielding charged particle beams by thin conductors,”PRSTAB **4**, 024402 (2001).
2. A.V. Fedotov, J.A. Holmes and R.L. Gluckstern, “Instabilities of high order beam modes driven by space charge coupling resonances,” PRSTAB **4**, 084202 (2001).
3. T. S. Wang, S.S. Kurennoy and R.L. Gluckstern, “Space charge impedance of r-f shielding wires and external ceramic and conducting pipes,” PRSTAB **4**, 104201 (2001).
4. A.V. Fedotov, R.L. Gluckstern and J. Wei, “Effect of space charge on stability of beam distributions in the SNS ring,” Proceedings of the Particle Accelerator Conference, Chicago, IL, June 2001, p. 2851.
5. J.A. Holmes, V. Danilov, J. Galambos, A.V. Fedotov and R.L. Gluckstern, “Resonant beam response in the PSR accumulator ring,” Proceedings of the Particle Accelerator Conference, Chicago, IL, June 2001, p. 3188.
6. S. Krinsky and R.L. Gluckstern, “Statistical correlation and intensity spiking in the SASE FEL,” Nucl. Instr. and Meth. In Physics A**483**, 57 (2002).
7. S. Krinsky and R.L. Gluckstern, “Analysis of statistical correlations and intensity spiking in the self-amplified spontaneous-emission free-electron laser,” PRSTAB **6**, 050701 (2003).
8. A.V. Fedotov, R.L. Gluckstern, I. Hofmann, and H. Okamoto, “Application of envelope instability to circular machines,” Proceedings of the Particle Accelerator Conference, Portland, OR, May 2003.

<u>Current Staff:</u>

- Dragt, A.J., Professor of Physics and Principal Investigator
- Gluckstern, R.L., Professor of Physics and Co-Principal Investigator
- Johnson, P.R., Postdoctoral Research Associate
- Cooper, B., Ph.D. Graduate Student
- Mitchell, C., Ph.D. Graduate Student
- Palastro, J., Ph.D. Graduate Student
- Papadopoulos, C., Ph.D. Graduate Student
- Roberts, M., Ph.D. Graduate Student
- Saranchak, D., Ph.D. Graduate Student

<u>Past Ph.D. Students now in Accelerator Physics:</u>

- **David Douglas**, Ph.D. 1982

Employment: Previously employed by the Lawrence Berkeley Laboratory. Currently employed by the Thomas Jefferson National Accelerator Laboratory.

- **Etienne Forest**, Ph.D. 1984
  Employment: Previously employed by the Lawrence Berkeley Laboratory. Currently employed by the KEK High Energy Physics Laboratory, Tsukuba, Japan and an Associate Professor at the Graduate University for Advanced Studies, Kanagawa, Japan.

- **Robert Ryne**, Ph.D. 1987
  Employment: Previously employed by Lawrence Livermore National Laboratory. Then employed by the Los Alamos National Laboratory. Currently employed by Lawrence Berkeley National Laboratory.

- **Govindan Rangarajan**, Ph.D. 1990
  Employment: Previously at Lawrence Berkeley Laboratory. Now a member (Associate Professor) of the Mathematics Faculty, Indian Institute of Science, Bangalore, India.

- **Rui Li**, Ph.D. 1990
  Employment: Thomas Jefferson National Accelerator Laboratory.

- **Dan Abell**, Ph.D. 1995
  Employment: Previously employed by Brookhaven National Laboratory. Presently employed by Tech-X.

- **Alexei Fedotov**, Ph.D. 1997
  Employment: Brookhaven National Laboratory.

- **Marco Venturini**, Ph.D. 1998
  Employment: Previously employed by Stanford Linear Accelerator Center. Currently employed by Lawrence Berkeley National Laboratory.

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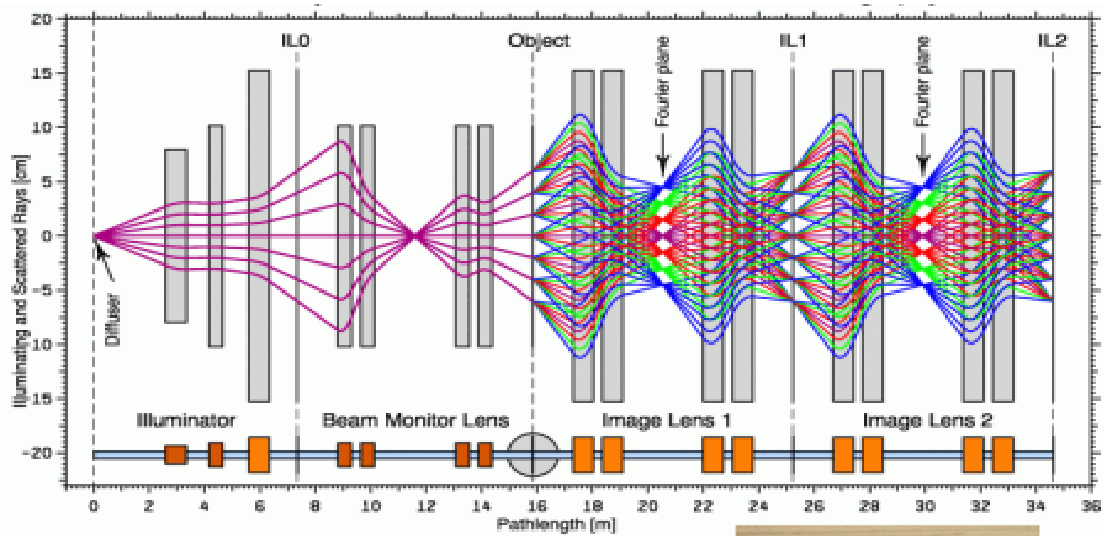
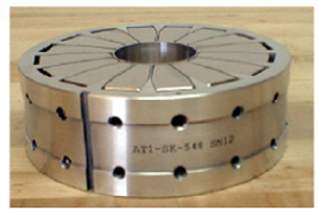
University of Maryland DSAT Group Montage

MaryLie Simulation of Beam Line for Proton Radiography



- Past experiments at ANL and BNL
- Recent proton microscope expt at LANL
  - Used 4 permanent magnet quads
  - Designed by T. Mottershead, LANL



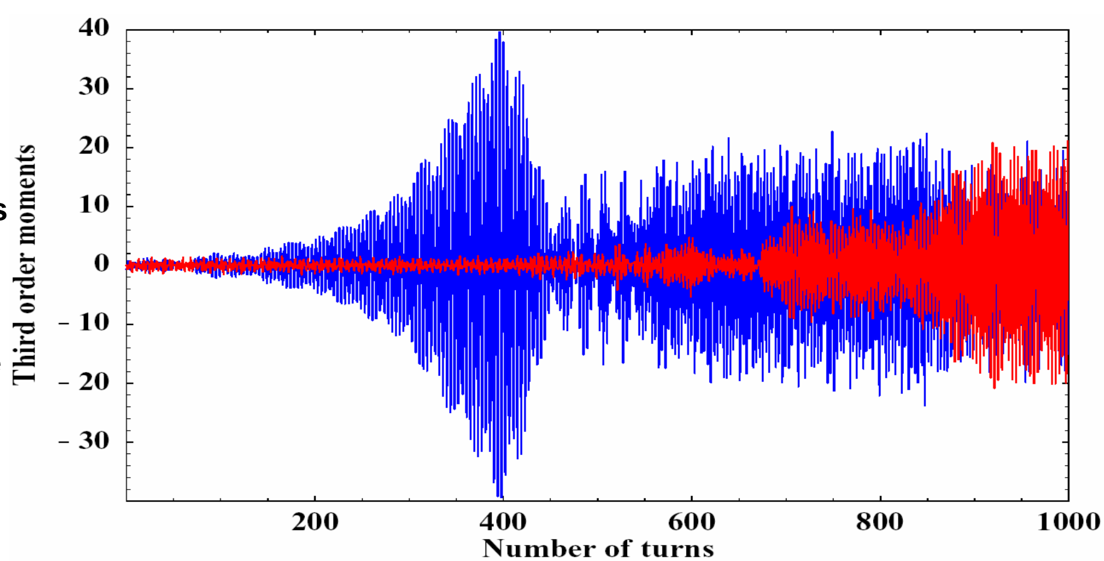
Comparison with experiment: Realistic modeling of fringe fields and aberration effects

Designed with MaryLie; Performed as Predicted

First microscope results

Magnified image 9 meters from the object. The edge resolution has been measured to be about 3 microns rms.

Time evolution of $\langle x^3 \rangle$ (blue) and $\langle y^3 \rangle$ (red) beam moments showing possible unstable behavior in the SNS storage ring



Study of High-Power Gyrotrons with Applications to linear Accelerators (Task B)

W. Lawson, V.L. Granatstein, M. Reiser, P.G. O'Shea - University of Maryland

Summary:

The purpose of the TASK B program is to evaluate gyroklystron amplifiers as RF drivers for high-energy linear accelerators with rf frequency in the range 17.1 to 91.4 GHz. This frequency range is higher than is presently used in HEP accelerators. The higher rf frequency is expected to enable larger accelerating gradients so that accelerator length can be kept within tolerable limits as final energy is increased to the TeV range.

An early accomplishment of the program was the demonstration of a frequency doubling gyroklystron with output peak power of 30 MW at a frequency of 20 GHz. The present thrust of the program is to significantly increase the output power. To this end, a 17.14 GHz, frequency doubling gyroklystron is being developed which is expected to have output power approaching 100 MW in microsecond pulses; such performance would significantly surpass the performance of conventional klystrons in terms of the output power density parameter (peak power divided by wavelength squared). One innovation required to achieve the increased power capability is the use of a co-axial circuit in the gyroklystron.

A preliminary experiment on a 3-cavity coaxial gyroklystron without the frequency doubling feature performed well producing output pulses of 80 MW at 8.57 GHz (reference 1). More recently, initial operation of a 3-cavity, coaxial, gyroklystron has been achieved with the frequency-doubling feature in operation so that output was at 17.14 GHz. Peak output power was limited to 27 MW by instability in the gyroklystron input cavity in which azimuthal non-uniformity in the electron beam is believed to be a dominant factor.

Recent Accomplishments:

During the past two years, the existing non-stationary, self-consistent, large-signal code MAGY, which is widely used for designing gyrotron oscillators and amplifiers, was generalized to account for the azimuthal non-uniformity of cathode emission and the radial thickness of annular electron beams. So far, this generalization has been accomplished in the version of MAGY developed for cylindrical cavities. Results of the studies of these effects in gyrotron oscillators are published in Refs. 2 and 3. It is planned to modify MAGY so that these new effects can be explored in coaxial circuits.

Also during the past two years, our group participated in the development of an inverted magnetron injection gun for our experiments with relativistic gyroklystrons. This development is ongoing at Calabazas Creek Research Co. and is sponsored by a DOE SBIR Phase-II Grant. The inverted electron gun will allow us to support the coaxial insert axially and hence to avoid interception of the electron beam by the radial pins which are presently supporting the insert.. This new inverted gun should allow us to double our repetition rate at full beam power and would be a suitable configuration for the high repetition rates that would be required in an actual linear collider. Results of our collaboration with CCR were reported in Refs. 4 and 5.

Other theoretical work includes improved design of high-power microwave components (tapers, mode converters, etc) and the design of space-charge-limited (SCL) Magnetron Injection Guns (MIGs). This study is ongoing, but if we can design an SCL-MIG with sufficiently high beam quality, we will have solved the most pressing problem today in large-emitter MIGs, i.e. the severe azimuthal variations in beam current density, which are caused by temperature and work-function variations.

The experimental work has focused on a number of areas. Our central theme has been to prepare our experimental system to be a driver for the accelerator section which was designed at 17.136 GHz and delivered to the University of Maryland by the Haimson Research Corporation (HRC). To this end we have modified our three-cavity frequency-doubling gyroklystron, which produced about 27 MW of peak power, to include an additional gain cavity (reference 6) . We also modified the output section of the tube to increase the TE02 mode purity from about 96% to over 99.9% (Reference 7). This four-cavity system should have had a gain of about 60 dB, which would allow us to use the TWT amplifier chain that we purchased to drive the accelerator, thereby enabling us to use feed-forward techniques to reduce the phase-variation of the gyroklystron output. Unfortunately, the increasing non-uniformity of the beam current due to continuing degradation of the MIG performance forced us to operate with a greatly-reduced average velocity ratio to avoid instabilities, resulting in a performance of the 4-cavity circuit was no better than that of the 3-cavity tube.

We adopted long-term and short term strategies to overcome the MIG difficulties. The long term strategies involve the SCL MIG designs described above and our interaction with industry described below. The short-term strategy was to redesign the input cavity, where the instabilities were observed, to improve the stability of the circuit in that region. Those modifications have been implemented and the hot-testing of the new 4-cavity tube is commencing.

We have collaborated with industry to modify the design and manufacturing processes in large emitters to reduce temperature and work-function variations. We have constructed an emitter testing/processing station where we can measure temperature uniformity and activate cathodes. We continue work on radial extraction of power from the output cavity and have designed and cold-tested a cavity which extracts power through the inner conductor with more than 98% efficiency. This type of cavity should enable our system to be zero-drive stable and would greatly reduce the size and complexity of the mode-conversion system required to convert the output power into standard rectangular waveguide for injection into the HRC accelerator section. Finally, it would be essential to use this type of cavity if we were to convert to an inverted MIG configuration.

The final experimental system under construction at this point is the feed-forward system to reduce phase-ripple due to systematic variations in beam voltage and other repeatable gyroklystron variations. We have developed software, based on LabView, which reads in the phase variation information that is output from a balanced mixer. The software then outputs a voltage profile to two arbitrary waveform generators which in turn control PIN diodes which modify the input amplitude and phase in the drive chain, to compensate for the phase variation of the gyroklystron.

Publications 2001-2003:

1. G. S. Nusinovich, A. N. Vlasov, M. Botton, T. M. Antonsen, Jr., S. Cauffman and K. Felch, “Effect of the azimuthal inhomogeneity of electron emission on gyrotron operation”, Physics of Plasmas, **8**, pp. 3473-3479, (2001).

2. W. Lawson, R. L. Ives, M. Mizuhara, J. M. Neilson, and M. E. Read, "Design of a 10 MW, 91.4 GHz frequency-doubling gyroklystron for advanced accelerator applications," IEEE Trans. Plasma Sci., **29**, pp. 545-558 (2001).
3. W. Lawson, "The application of scattering matrices to re-entrant cavities," Int. J. Electronics, **88**, pp. 1131-1140, (2001).
4. M. Read, L. Ives, G. Miram, P. Borchard, L. Falce, W. Lawson, G. Nusinovich, V. Granatstein and K. Gunther, "Advanced magnetron injection guns for coaxial gyrotrons and gyroklystrons", 27th Int. Conf. on Infrared and Millimeter Waves, Sept. 22-26, 2002, San Diego, CA, Conf. Digest, R. J. Temkin, Editor, pp.337-338.
5. M. E. Read, R. L. Ives, G. Miram, G. S. Nusinovich, W. Lawson, B. Hogan, and V. L. Granatstein, "Inverted magnetron-injection electron gun for the relativistic gyroklystron at the University of Maryland", Advanced Accelerator Concepts: Tenth Workshop, Mandalay Beach, CA 2002, Eds. C. E. Clayton and P. Muggli, AIP Conf. Proc. 647, pp.416-420.
6. I. Spassovsky, E.S. Gouveia, S.G. Tantawi, B.P. Hogan, W. Lawson and V.L. Granatstein, "Design and cold testing of a $TE_{01(circular)}$ to a $TE_{02(rectangular)}$ mode converter" IEEE Trans, Plasma Sci. **30,** pp. 787 - 793 (2002)
7. W. Lawson, "On the frequency scaling of coaxial gyroklystrons," IEEE Trans. Plasma Sci.,**30**, pp. 876-884 (2002).
8. G. S. Nusinovich, O. V. Sinitsyn, M. Yeddulla, L. Velikovich, T. M. Antonsen, Jr., A. N. Vlasov, S. Cauffman and K. Felch, "Effect of the radial thickness of electron beams on mode coupling and stability in gyrotrons", Physics of Plasmas **10**, August 2003 (to be published).

Current Staff (TASK B):

- Reiser, M. Co-Principal Investigator, Prof. Emeritus and Senior Research Scientist
- Granatstein, V.L. Co-Principal Investigator, Professor, Electrical and Computer Engineering
- Lawson, W. Co-Principal Investigator, Professor, Electrical and Computer Engineering
- O'Shea, P. G. Co-Principal Investigator, Professor, Electrical and Computer Engineering
- Nusinovich, G. Senior Research Scientist

Hogan, B.	Assistant Research Engineer	
Schoonover, J.	Administrator	
Bharathan, K.	Graduate Student	Seeking a Ph. D. in Electrical Engineering
Gouviea, S.	Graduate Student	Seeking a Ph. D. in Physics
Raghunathan, H.	Graduate Student	Seeking an M.S. in Electrical Engineering
Ngogang, R.	Graduate Student	Seeking an M.S. in Electrical Engineering

Previous Graduate Students (TASK B):

Student	Degree	Year	First / Current Employment
M. Skopec	M.S.	1989	NIH
S. Miller	M.S.	1990	?
J. P. Calame	Ph. D.	1991	NRL
S. Tantawi	Ph. D.	1993	SLAC
H. W. Matthews	M.S.	1994	Signia-IDT

• V. Specht	M.S	1994	NSWC
• M. K. E. Flaherty	M.S	1994	Johns Hopkins APL
• J. P. Anderson	M.S	1997	Raytheon / Ph. D. Student at MIT
• J. Cheng	Ph. D	1998	?
• M. Castle	Ph. D	2001	Johns Hopkins APL
• B. Huebschman	M.S	2002	Army Reserve (activated)

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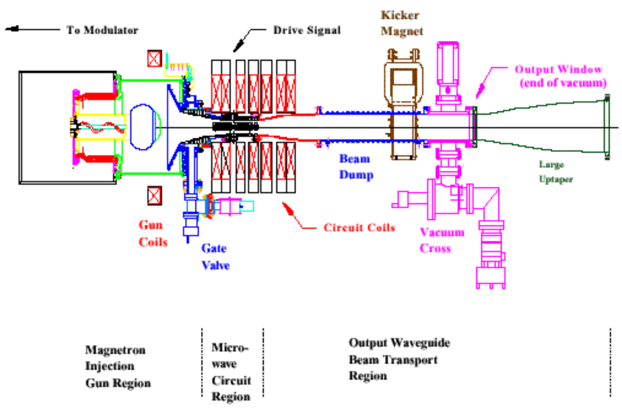

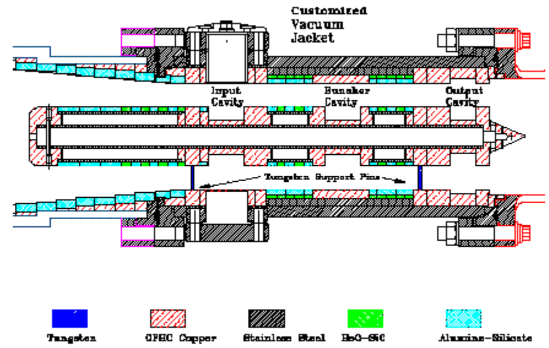

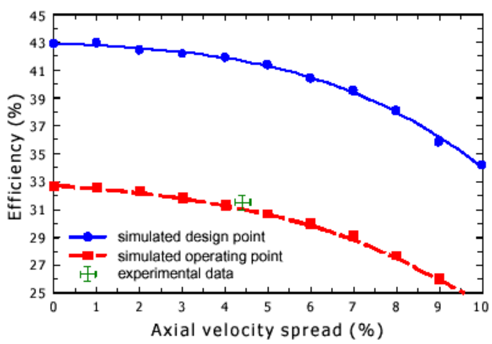

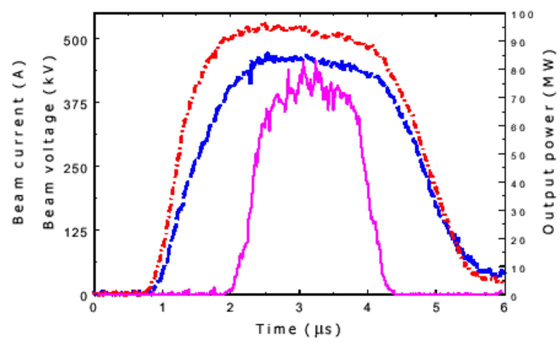

High-Power Gyrotrons with Applications to linear Accelerators

Application of Plasma Waveguides to Advanced High Energy Accelerators

H.M. Milchberg and T.M. 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 focusing of laser pulses in gases of atomic clusters.

Self-focusing of intense laser pulses in a clustered gas

Gases of atomic clusters are interaction media for laser pulse propagation with a variety of applications. Clusters are aggregates of typically 10^5-10^6 atoms, which are exploded by the laser pulse, leaving tenuous plasma. The gases are efficient absorbers of laser energy because the interaction with the laser pulse occurs at near solid density. We have found a new form of laser self-focusing in these gases that makes them attractive for laser plasma acceleration. To study the laser- cluster interaction we have developed a new experimental diagnostic, Single Shot Supercontinuum Interferometry, (SSSI) capable of measuring, with femtosecond time resolution, the ensemble average polarizability in a gas of intense laser-heated clusters. Using this diagnostic we have inferred the cluster explosion dynamics. The time evolution of the polarizability is characteristic of competition in the optical response between super-critical and sub-critical density regions of the exploding cluster. The results are consistent with complementary time-resolved Rayleigh scattering measurements. There is a significant macroscopic implication of this cluster evolution: a gas of exploding clusters causes nonlinear propagation of an intense laser pulse owing to the space and time dependence of the ensemble polarizability. In particular, a self-focusing effect has been observed experimentally and strongly contrasts with the ionization-induced refraction and beam spreading usually observed in non-clustered gases. We have also developed a numerical model of laser propagation in a gas of exploding clusters that supports the experimental findings. The mode is based on a Gaussian optics description of the laser pulse and a uniform density description of the exploding cluster. Our studies have shown that cluster gases can efficiently absorb laser energy in a small spatial region leaving behind a plasma channel whose density can be tailored by varying the cluster density and size. Recently we have demonstrated experimentally that this effect can be exploited to create plasma waveguides using short pulse lasers without the need of line-focusing optics. These channels can be created at sufficiently low density to allow access to the resonant regime of plasma wake generation.

Effective coupling of high intensity lasers to a pre-formed funnel-mouthed plasma waveguide

The injection of laser pulses into hydrodynamically preformed plasma channels is hindered by the conditions at the entrance of the channel. In particular, neutral gas and down tapered channel wall prevent efficient coupling of the laser pulse. To solve this problem, we have grafted a plasma lens onto the channel using an auxiliary formation pulse. This eliminates the neutral gas near the channel entrance, which refracts the pulse when ionized, and provides a focusing element to funnel the high intensity laser into the channel. The funnel plasma was produced by focusing a 100 mJ portion of the 100 ps Nd:YAG pulse through the same lens used to inject intense ultrashort Ti:Sapphire laser pulses into a plasma waveguide. The funnel generation pulse and injection pulse counterpropagate with respect to the axicon-focused waveguide generation pulse. Images of the injection pulse with and without the funnel showed an improvement in coupling efficiency. The process of coupling was simulated using the code WAKE. It was found that for the optimal gas jet target, the averaged on-axis peak intensity inside the channel can reach 10^{18} W/cm^2.

3D Modeling of Laser Plasma Interaction

Plasma based particle acceleration requires the generation of plasma wave wakes which maintain their coherence over long distances. For example in Laser Wake Field Acceleration (LWFA) schemes the laser pulse must propagate tens of centimeters, which corresponds to many Rayleigh lengths, and in Plasma Wake Field Acceleration (PWFA) the particle beam must be propagated many meters. These wakes and their effect on the driver (Laser or particle beam) can be simulated efficiently in the quasistatic approximation. In this approximation the driver does not evolve during the time a plasma electron spends in the driver. We have developed, in collaboration with colleagues at UCLA, a 3D plasma acceleration simulation code QUICKPIC.

Current Staff

• Howard M. Milchberg	Co-Principal Investigator
• Thomas M. Antonsen Jr.	Co-Principal Investigator
• Jianwei Liu	Ph.D. Candidate (experiment)-DOE funded
• Kiyong-Kim	Ph.D. Candidate (experiment)-DOE funded
• Vinod Kumarappan	postdoc (experiment) - NSF funded
• Hua Sheng	Ph.D. Candidate (experiment)-NSF and Sematech funded
• Andrew York	Ph.D. Candidate (experiment)-starts Jan. 2004 under DOE support, supported fall 2003 by TA
• James Cooley	Ph.D. Candidate (theory)-DOE funded
• Ayush Gupta	Ph.D. Candidate (theory)-NSF funded
• Jianzhou Wu	Ph.D. Candidate (theory)-NSF funded
• John Palastro	Ph.D. Candidate (theory)-DOE funded

Recent Graduates:

Zhigang Bian Ph. D. 2003 (Lucent Technology), I Alexeev, Ph. D. 2003 (Naval Research Lab), J. Fan (Ph. D. 2002) (NEC Labs), E. Parra (Ph. D. 2003) (National Inst. of Health)

Publications: 2001-2003

1. "Measurement of the average size and density of clusters in a gas jet," Kim KY, Kumarappan V, Milchberg HM, APPL PHYS LETT 83 (15): 3210-3212 OCT 13 2003
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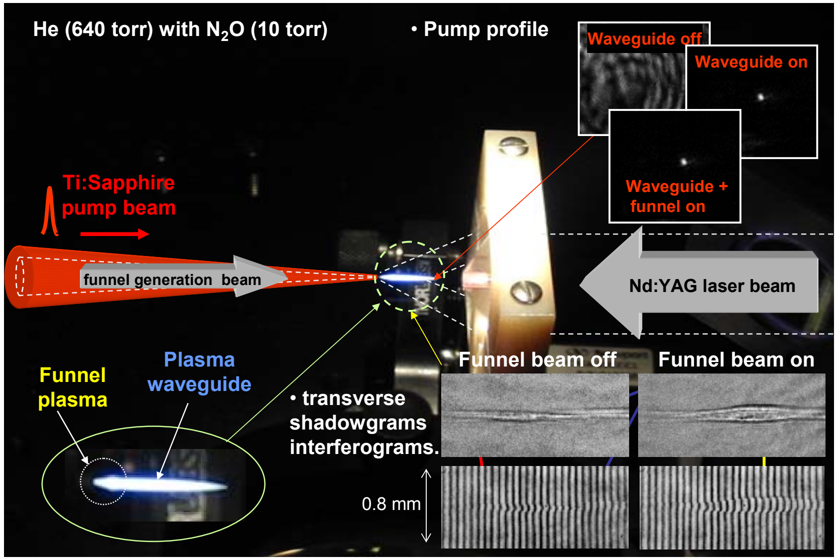
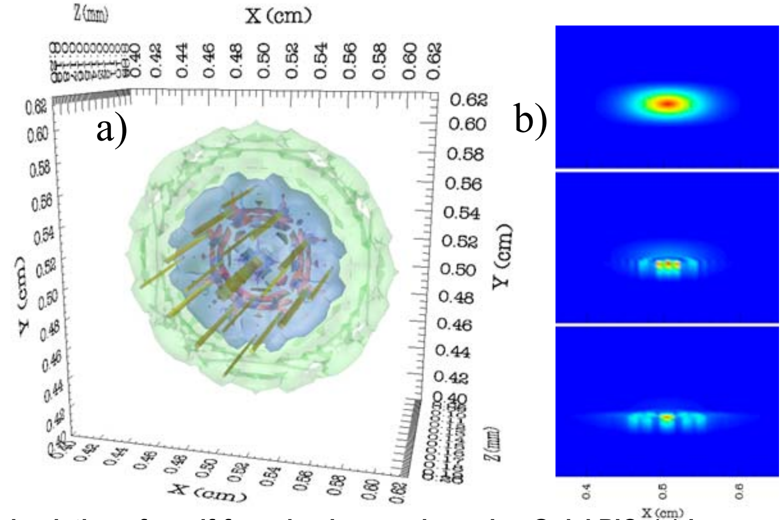
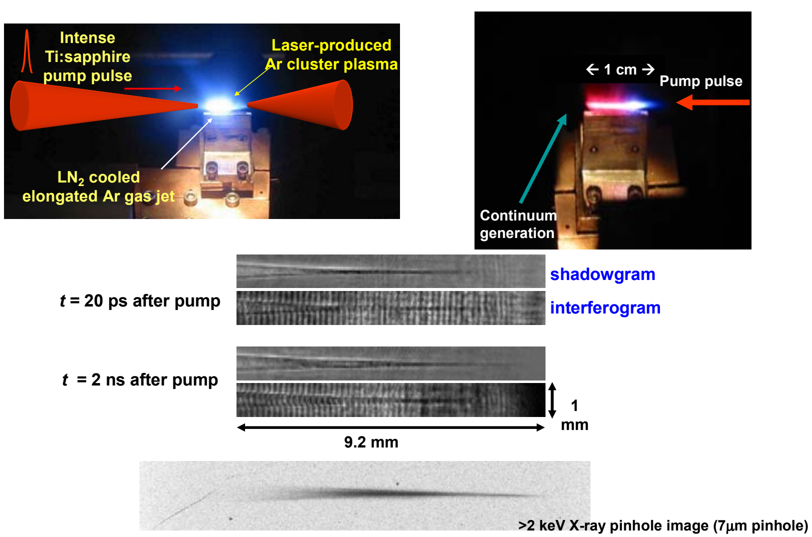
Plasma waveguide with a funnel generation beam



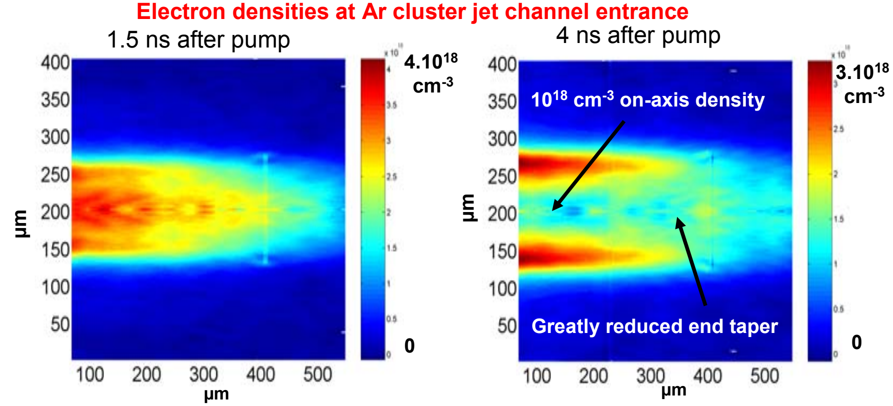


3D simulation of a self-focusing laser pulse using QuickPIC (a) Iso-surface of laser intensity for 7.6Pcr laser and plasma density (yellow) (b) Mid-plane view of laser intensity at three different propagation distances.

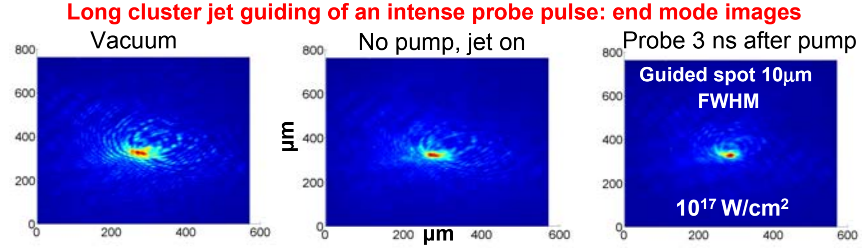
Long, stable plasma generation in elongated cluster jet



Electron densities at Ar cluster jet channel entrance



Long cluster jet guiding of an intense probe pulse: end mode images



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

P. G. O'Shea, M. Reiser, R. Kishek, and I. Haber - Institute for Research in Electronics and Applied Physics, University of Maryland

Summary:

During the past decade, our research in TASK A has focused on the physics of intense, space-charge dominated beams. This work is of vital importance for the development of more intense high quality beams for such applications as spallation neutron sources, high-energy physics colliders, and light sources. In our program, we have studied phenomena relating to emittance growth, longitudinal instability, and equipartitioning in beams of increasing intensity and complexity. We have been a leader in the application of thermodynamic principles to the study of beams. A hallmark of our program has been the use of low-energy electron beams to model the space-charge physics and the close connection between theory, simulation and experiment.

In the early phases of this research, we have focused our efforts on linear beam systems with solenoidal focusing. In the past few years, we have begun the study of intense beams in a dispersive lattice with strong focusing. This work culminated in the construction of the University of Maryland Electron Ring (UMER) now in its final stages of construction. Generally, circular accelerators and rings have been limited to lower intensities than linear accelerators to avoid destructive resonances in a circular lattice. At higher intensities, collective effects will dominate over single particle effects. Because of the lack of experimental data, almost all of our understanding in this region is based on theory, simulation and conjecture. UMER currently under construction is a low-cost flexible electron model of high-intensity recirculators and rings.

Recent Accomplishments:

- Near completion of the construction of UMER, and the acquisition of beam data along more than ½ a turn.
- One of our goals for UMER diagnostics is to be able to map 6-D phase space. All the diagnostics have been improved and are now operational: **Beam position monitors** (BPM) have been constructed and their electronics improved to achieve sub-mm spatial resolution with ns time resolution; combined-function moveable **view-screen/BPM** units now reside in every in-line diagnostic chamber. The **slit-slit transverse phase space monitor** with ns temporal resolution has been similarly redesigned and rebuilt. Energy spread can be measured with resolution of sub-eV in energy, sub-ns in time, and mm transversely.
- All the magnets and diagnostics are now computer-controlled, and the lab computers have all been networked. Control and data-processing software has been enhanced.
- Sophisticated alignment equipment has been acquired and is now in routine use for aligning UMER sections and magnets during installation. Mechanical alignment now conforms with our specified tolerances.
- Combinations of measurements, theory, and simulation led to better understanding of the initial conditions exiting the gun and how they influence beam distributions downstream. We have discovered that the cathode grid leads to an interesting hollow velocity distribution that persists for a relatively long time past the gun.
- Advanced algorithms for steering and injection have been developed and tested.
- Development of a new method of introducing spatial and temporal perturbations to the beam, namely by using photo-emission from a laser beam incident on the thermionic cathode.
- We have initiated collaborations with potential outside users of UMER. Projects include using UMER to study the evolution of beam halo (Wangler, LANL); using UMER as a model

system for galactic dynamics (Kandrup, U. Florida, Bohn NIU); exploring beam anisotropy (Hofmann, GSI)

The research also benefits from partial support funded by the DOE Heavy ion Fusion Program

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Complete list at http://www.ipr.umd.edu/ebte/ring/index.html

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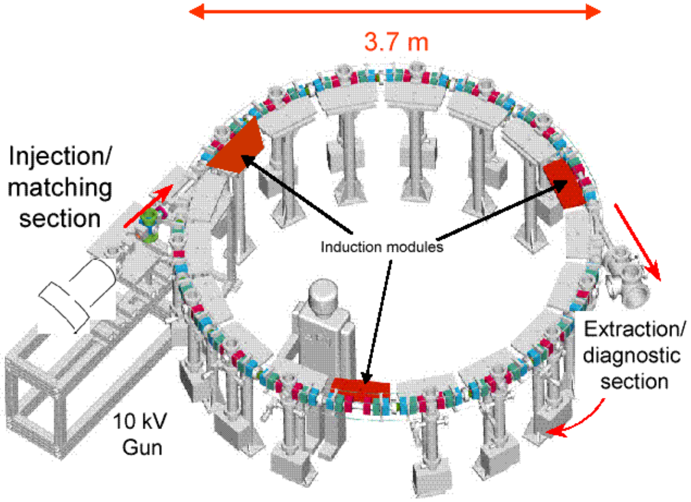
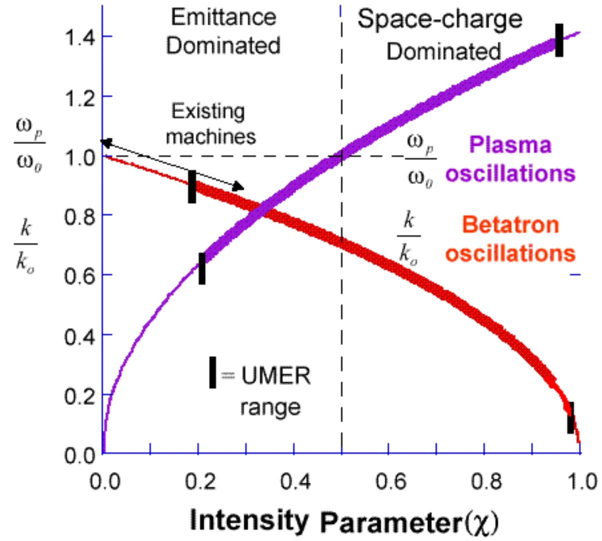
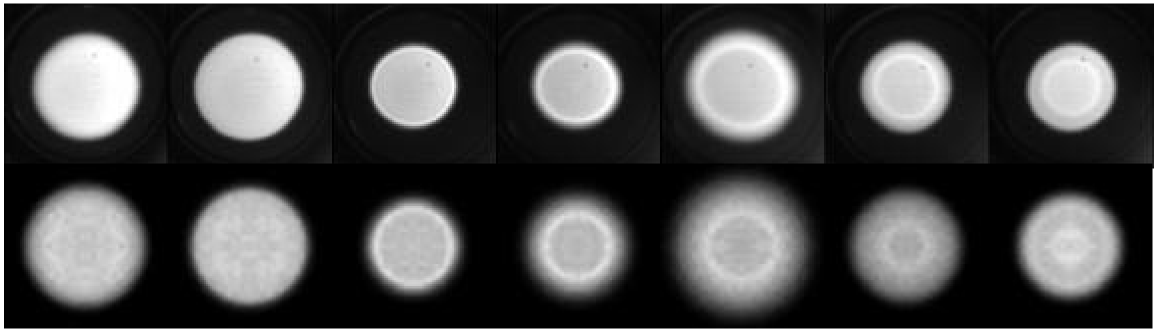


University of Maryland Electron Ring



The new high-intensity range accessible by UMER



Space charge waves

Investigations of Beam Dynamics Issues at Current and Future Accelerator

J.A. Ellison- University of New Mexico

Summary and Recent Accomplishments:

There are many significant problems in beam dynamics that are at the forefront of what is understood in dynamical systems, stochastic processes and scientific and high performance computing. This makes it an ideal area for interaction between universities and accelerator labs. The Advanced Technology R&D Program at DOE makes this possible. We have an ideal situation because our mathematics and statistics faculty is an excellent source of expertise in the underlying areas of mathematics, UNM has a high performance computing center, and we have close collaborations with researchers in accelerator labs as well as mathematical scientists at other universities. The investigation has several foci: Beam-Beam Interaction, Nonlinear Longitudinal Collective Effects, Coherent Synchrotron Radiation (CSR), Spin and Polarization, and Space Charge. A significant aspect of our work involves the study of the Vlasov and Vlasov Fokker-Planck Equations including existence of equilibria, linearized behavior about equilibria, development of a weakly nonlinear theory and a study of fully nonlinear effects such as solitary waves and weak turbulence. My total research effort is devoted to the projects stated above. In addition I teach courses in mathematical areas important to the analysis of the grant projects. Collaborators are crucial to the success of our work. The following are people with whom we are currently working or with whom we have detailed research plans in place related to the topics of the grant. Alejandro Aceves (UNM), Paul Alsing (UNM), Desmond Barber (DESY), Pat Colestock (LANL), Scott Dumas (U. of Cincinnati), Klaus Heinemann (DESY), Georg Hoffstaetter (Cornell), Tanaji Sen (Fermilab), Mathias Vogt (DESY) and Bob Warnock (SLAC).

I. Weak-Strong Beam-Beam (WSBB)

We have developed a long time perturbation theory for quasi-periodic maps with a small parameter, ε. This is an extension of our work on the method of averaging for flows in Physica D, 146 p. 341--366, (2000). It is rigorous perturbation theory in the sense of asymptotics; we use a cut-off Diophantine condition to handle the small divisor problem and this allows us to partition the frequency (tune) space into nice sets that are far-from-low-order-resonance (FFLOR) and near-to-low-order-resonance (NTLOR). Each set has an associated flow that approximates the dynamics for that set of tunes.

An important class of problems in beam dynamics is formulated in terms of Kick-Lattice maps. We have applied our perturbation theory in the case where the lattice is linear and the kick is a perturbation of size ε. The one frequency case has been completed and applied in detail to the 1 DOF WSBB [12]. The approximate dynamics is given by a one degree-of freedom (DOF) autonomous Hamiltonian flow, which is therefore integrable. We are in the process of extending this to the two DOF case [16]. Here we find that the tune space is partitioned into three primary sets. In the FFLOR sets the kick causes a tune spread. Near to low order resonance lines but far from the crossing of two such lines the kick significantly changes the dynamics however the approximating flow is integrable. Near to the crossing of two low order resonance lines the dynamics appears to be generically non-integrable. A signature of non-integrability is chaos and we have found evidence of this near the ¼-¼ resonance. This is illustrated in the attached figure that shows an associated Poincare′ Map with a stochastic layer in red resulting from one initial condition.

Boocha is working with Sen to develop a detailed WSBB code for the Tevatron including long-range effects. Here the major issues are accuracy and speed. We have developed a fast evaluation of the complex error function and are evaluating several parallel and high performance options. See Ref. [18].

II. Strong-Strong Beam-Beam (SSBB)

We have developed two approaches to calculating the evolution of two counter-rotating bunches under the SSBB interaction. One tracks particles (WMPT) and the other computes the density evolution (PF-Vlasov). The one DOF case is discussed in detail in [2,3,7]. Vogt has developed a two DOF WMPT code for hadrons. The force calculation is based on the Fast-Multipole-Method of Greengard [3,8], which we have made parallel using a force decomposition idea [11,18]. Sobol has developed a parallel two DOF PF-Vlasov code [17]. The goal here is an accurate calculation of the phase space density.

An important issue is the existence of equilibrium solutions. With Warnock, we have made considerable progress in the lepton case [1,5,13]. We study a nonlinear integral equation that is a necessary condition on the equilibrium phase space distribution function of stored, colliding electron beams. It is analogous to the Haissinski equation, being derived from Vlasov-Fokker-Planck theory, but is quite different in form. The equation is analyzed for the case of the Chao-Ruth model of the beam-beam interaction in two DOF, a so-called strong-strong model with nonlinear beam-beam force. We prove existence of a unique solution, for sufficiently small beam current, by an application of the function space version of the implicit function theorem. We have not yet proved that this solution is positive, as would be required to establish existence of an equilbrium. There is, however, numerical evidence of a positive solution. We expect that our analysis can be extended to more realistic models. The hadron case is more difficult and an exact equilibium probably does not exist. However our analysis below does indicate the existence of quasi-equilibria.

Our perturbation approach to the “Kick-Lattice” WSBB [12,16] has been extended to the SSBB case. In [4] we treat the one DOF case and in [14] the two DOF case. Just as in the WSBB case, the approximation we obtain is a flow; a Vlasov equation that is the new model referred to in the title of [14]. This clarifies the approximations in the pioneering work of Yokoya, et al. and Alexahin. The power of our approach is evidenced by the fact that the approximating Vlasov equation has exact equilibria, the associated linearized equations have uncoupled azimuthal Fourier modes, which leads to a singular integral equation, and the setting is ready-made for the development of a weakly nonlinear theory for a study of the coupling of the π and σ modes. A new approach to the numerical solution of this singular integral equation (the usual approach is due to Oide-Yokoya) is discussed in related work on the linearized Vlasov equation for longitudinal motion of a bunched beam [9].

III. Coherent Synchrotron Radiation

There are two points at which coherent synchrotron radiation (CSR) could be of concern in linear colliders. First, it may cause transverse (x-plane) emittance degradation in bunch compressors, since energy changes due to CSR get mapped into transverse coordinates through dispersion. Second, it might cause longitudinal bunch instabilities in the damping rings, possibly leading to a quasi-periodic, sawtooth behavior of the bunch length. Damping ring designs contain around 100 meters of wigglers (to reduce the damping time to a manageable value), and CSR in the wigglers may produce a large coupling impedance that could induce the feared instability. We are working on the bunch compressor, as a Vlasov-Maxwell problem, and have plans to investigate CSR in wigglers.

Warnock has been studying general aspects of CSR for some years, and has recently produced a successful model of CSR-induced instabilities in storage rings, in collaboration with M. Venturini (PRL, **89**, 224802 (2002)). The model explains recurrent bursts of CSR as seen at several synchrotron light sources. The model is realized numerically through time-dependent integration of the nonlinear Vlasov-Fokker-Planck (VFP) equation, using a method developed by Warnock and Ellison, and previously applied to simulate the sawtooth mode in the SLC damping rings. This method goes far beyond linear Vlasov theory, in that it allows one to study nonlinear saturation of an instability, and effects on a long time scale after saturation, such as CSR bursts (separated by a fraction of the damping time) and the sawtooth. It is superior to macroparticle simulation, in that spurious numerical noise is largely suppressed. In addition, he has been investigating bunch compressor issues for some time and has made good progress; we recently joined him in this work and have been devoting considerable effort to its progress.

IV. Nonlinear Longitudinal Collective Effects

The purpose of this work is to derive an equation for the envelope of the longitudinal fluctuations in a storage ring, specifically in an unbunched, coasting beam, under the influence of the machine impedance. The scenario is that a given storage ring is run at the intensity limit for longitudinal stability such that the system is marginally stable, a situation likely common to many storage rings. Linear instability may occur and the mode oscillations will grow to the point where some type of nonlinearity brings the system into saturation and it comes to rest at marginal stability. It is this situation we wish to consider. The final result will be an equation describing the steady-state condition where the nonlinear spreading and subsequent dissipation of the fluctuations just balances the free energy injected by the machine impedance.

To illustrate the concepts we choose to consider an unbunched, coasting beam in the periodic system of a storage ring, focusing our attention only on the longitudinal degree of freedom. The procedure we develop should be applicable to bunched beams and transverse dynamics; however, the analytic description is somewhat simpler for the longitudinal case. Moreover, we restrict our analysis to the case of weak turbulence where the nonlinear interaction in the frequency domain can be limited to a bounded region. Starting from the Vlasov equation, we proceed by studying the behavior near an equilibrium being guided by a fixed point iteration procedure used in Plasma Physics (See “Chaos and Structures in Nonlinear Plasmas”, W. Horton and Y-H Ichikawa, World Scientific, 1996). The analysis take place in Fourier space corresponding to the azimuthal position and time, and a fixed point iteration yields an exact equation that when truncated at the appropriate order leads to a coupled set of nonlinear equations for the Fourier modes of the force due to the impedance. We are now studying an appoximation procedure that leads to a so-called kinetic wave equation that describes the differential flow of power across the frequency spectrum as the system approaches the steady state. This is joint work with Colestock and Vlaicu and will form a significant part of the latter’s Ph. D. thesis.

V. Spin Dynamics

The extensive manuscript [15] provides a rigorous discussion of the concept of spin tune on syncho-betatron orbits in storage rings and of the conditions for its existence. Spin motion on the periodic closed orbit of a storage ring can be analyzed in terms of the Floquet theorem for equations of motion with periodic parameters and the spin tune emerges in a Floquet exponent as an additional frequency of the system. To define spin tune on synchro-betatron orbits we exploit the important concepts of quasi-periodicity, the uniform precession frame and the uniform precession rate. These allow a generalization of the Floquet theorem whereby the uniform precession rate appears in a Floquet exponent as an additional frequency in the system in analogy with the case of motion on the closed orbit. The spin tune is a uniform precession rate obtained when certain conditions are fulfilled. Having defined spin tune we define spin-orbit resonance on synchro-betatron orbits, which allows an examination of its consequences. We give conditions (e.g. where small divisors are controlled by applying a Diophantine condition) for the existence of a spin tune and illustrate the various aspects of our description with several examples. The formalism also suggests the use of Fourier analysis to “measure” spin tune during computer simulations of spin motion on synchro-betatron orbits. In a related work, we are investigating adiabatic invariants for spin-orbit motion [10].

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- Professor James A. Ellison, Principal Investigator
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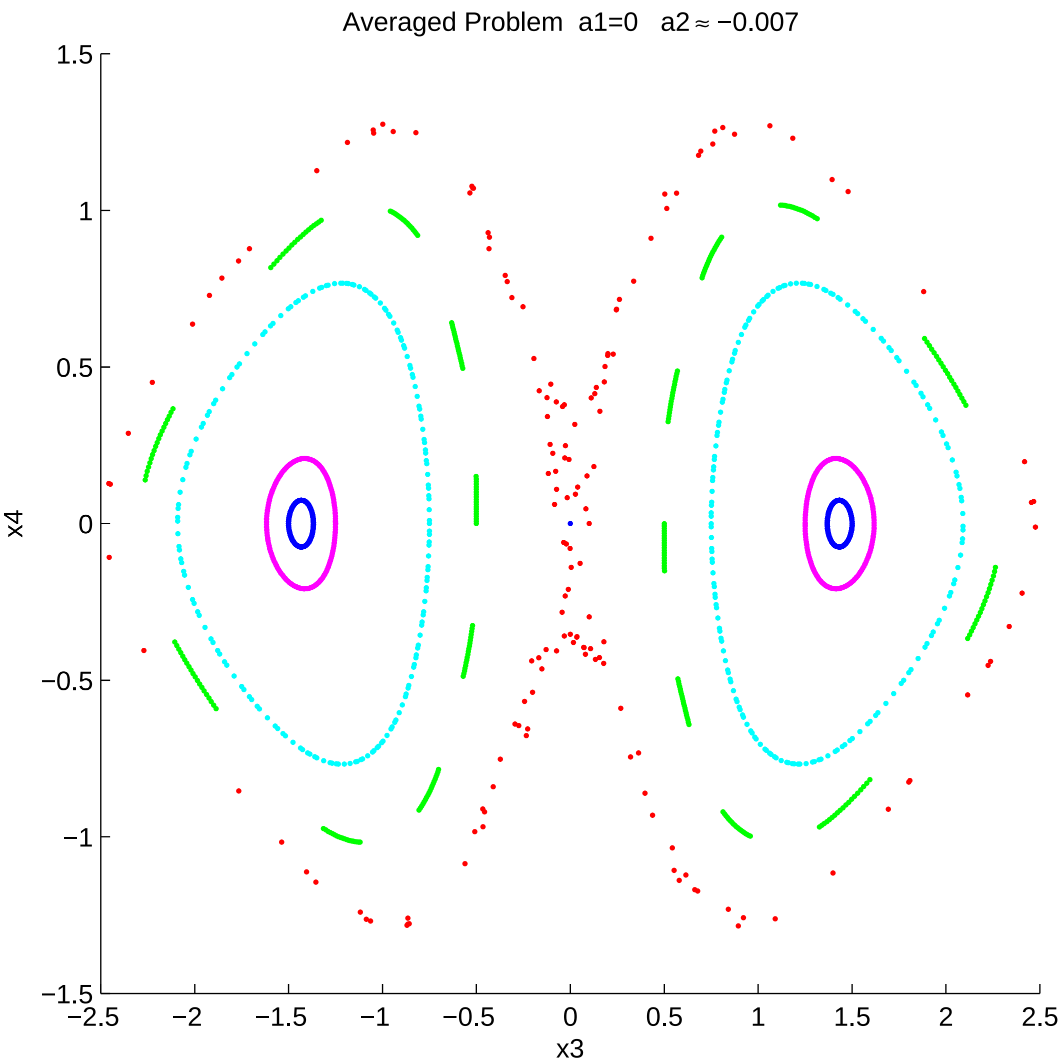

Averaged Problem a1=0 a2 ≈ −0.007
1.5
1
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−0.5
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−0.5
0
0.5
1
1.5
2
2.5
x3

An All-Optical Laser-Wakefield Electron Injector

Donald Umstadter - *University of Michigan, Ann Arbor*

Summary:

In conventional electron accelerators, electrons are accelerated by means of the electric fields of radio-frequency waves in metallic cavities. In recent years, we have been developing an alternative acceleration concept that might someday do the job in a much smaller space. In the plasma wakefield approach, for example, a terawatt laser beam is focused into a plasma, setting up fast (relativistic) waves in the plasma. If timed just right, electrons in the plasma can surf the plasma waves to high energies, as high as 100 MeV, in the distance of only a millimeter. One problem with this concept is the mismatch between the electron source (sometimes an external photocathode, sometimes uncontrolled electrons from the plasma itself) and the plasma wave used for acceleration.

The goal of this project is to investigate a new means of generating electrons in a controllable way, namely the use of a pair of crossed laser beams which position, heat, and synchronize the insertion of electrons into the plasma wave. This is predicted theoretically and numerically to result in a monoenergetic beam with femtosecond duration and extremely low transverse emittance. Besides potential applications to particle physics, ultra-high-gradient acceleration is also expected to benefit other DOE-funded research on x-ray light sources, the production of medical radioisotopes and the ignition of thermonuclear fusion reactions.

One of the most important outcome of this project thus far was demonstration of the principle of optical control of laser accelerators, namely, that one laser pulse could modify the properties (e.g., emittance and electron number) of an electron beam accelerated by a separate but synchronized laser pulse. [1,2,3,4,5] While this was done with a long duration laser pulse and thus did not result in a reduction of the energy spread, it did demonstrate that with the addition of a second pulse the energy of electrons could be increased and the beam emittance decreased.

Recent Accomplishments:

Another recent highlight was that, using our new 30-fs 10-TW laser system, we accelerated with a laser accelerator an electron beam with a record low divergence (0.2 degrees). This is more than 100 times lower than the 30-degree divergence that was reported recently by a French group using a laser with similar parameters [V. Malka et al., Science, 298, 1596 (2002)]. Our previous measurements of surprisingly low transverse emittance beams were explained theoretically by Chao et al. [Physical Review, Special Topics in Accelerators and Beams, **6**, 024201 (2003)].

We also studied the propagation of an intense (1×10^{19} W/cm^2) ultrashort (30 fs duration) laser pulse in plasma conditions that are similar to those that will be encountered in an injection experiment.[6,7,8] The plasma density was varied in such a way that the parameters of the interaction crossed for the first time the transition from the resonant to the self-modulated regime. In so doing, we found that under certain conditions, self-focusing into multiple filaments accompanies self-trapping and acceleration of electrons, both of which must be avoided if injection is to be successful. This same experiment demonstrated electron acceleration at a repetition rate of 10 Hz, which is an improvement of several orders-of-magnitude in the duty cycle of laser accelerators, bringing a practical injector closer to reality.

The acceleration of protons to MeV energies by the interaction of relativistically intense 10 TW, 400 fs laser pulse with a thin solid-density film was studied.[9,10] Deuterons were also accelerated to energies of about 2 MeV from a thin layer of deuterated polystyrene deposited on Mylar film.[11] These high-energy deuterons were directed to the boron sample, where they produced atoms of positron active isotope ^{11}C from the reaction $^{10}B(d,n)^{11}C$. The activation results suggest that deuterons were accelerated from the front surface of the target.

A method for the control of stimulated Raman scattering and hot electron production in short-pulse laser-plasma interactions was studied.[12] It relies on the use of a linear frequency chirp in non-bandwidth limited pulses. Theoretical calculations show that a 12% bandwidth will eliminate Raman forward scattering for a plasma density that is 1% of the critical density. The predicted changes to the growth rate are confirmed in two-dimensional particle-in-cell simulations.

These results were highlighted in the American Institute of Physics Bulletin of Physics News[13] and in *Photonics Spectra*.[14] Several reviews of these and related developments in the field of laser accelerators were also published.[15.16] This research was also discussed in sixteen invited talks, listed below, including an *Organization for Economic Cooperation Development* (*OECD) Global Science Forum Workshop on Compact High-Intensity Short-Pulsed Lasers : Future Directions and Applications* and a Plenary review at an *American Physical Society Meeting.*

<u>Invited Presentations on Laser Acceleration</u>

- *Symposium on Laser Accelerators, European Physical Society,* Geneva, Switzerland, July, 2002.
- *International Conference on Quantum Electronics*, Moscow, Russia, July, 2002.
- *Workshop on High-Brightness Sources*, Sardinia, Italy, Aug., 2002.
- *Nonlinear Optics: Materials, Fundamental and Applications*, Maui, Hawaii, August, 2002.
- 2002 *Annual Meeting of the American Physical Society Division of Plasma Physics*, Orlando, FL, 2002 (presented by *P. Zhang).*
- *AFRL/AFOSR Workshop on High Intensity Laser Interactions with Matter*, Wright Patterson Air Force Base, OH, December 16-17, 2002.
- “An all-optical electron injector,” Pedagogical Lectures on Advanced Methods for Acceleration with Emphasis on Recruiting other Physicists into the Field, *April 2002 American Physical Society Meeting*, Albuquerque NM, April 20-23, 2002.
- *OECD Global Science Forum Workshop on Compact High-Intensity Short-Pulsed Lasers : Future Directions and Applications*, JAERI Kansai Advanced Photon Research Center, Nara, Japan, May 28-30, 2001.
- *Second International Conference on Superstrong Fields in Plasmas*, Villa Monastero, Varenna (Lc), Italy, August 27 - September 1, 2001.
- “Relativistic particle acceleration via nonlinear laser-plasma interactions,” *31st Winter Colloquium on the Physics of Quantum Electronics,* Snowbird, Utah, Jan., 2001.
- *American Physical Society's Division of Atomic, Molecular and Optical Physics (DAMOP) 2001 Meeting*, London, Ontario, Canada, May 16-19, 2001.
- *Annual Meeting of the Optical Society of America*, Long Beach, CA, October 14 -18, 2001.
- *Advanced Acceleration Techniques Workshop American Physical Society Snowmass Meeting: The Future of Particle Physics*, Snowmass, CO, July, 2001.
- “Relativistic nonlinear optics of ultra-intense light,” *Conference on Lasers and Electro-optics (CLEO-QELS)*, Baltimore, MD, May 2001.
- *4th Symposium on Current Trends in International Fusion Research*, March 2001, Washington, DC.

- “Physics and applications of relativistic plasmas driven by ultra-intense lasers,” *Annual Meeting of the Division of Plasma Physics, American Physical Society,* Quebec City, Canada, October, 2000 (plenary review).

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• Anatoly Maksimchuk	Research Scientist
• Ping Zhang	Postdoctoral Fellow
• Ned Saleh	Graduate Student
• Shouyuan Chen	Graduate Student

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- Evan Dodd, Physics, now at Los Alamos National Laboratory

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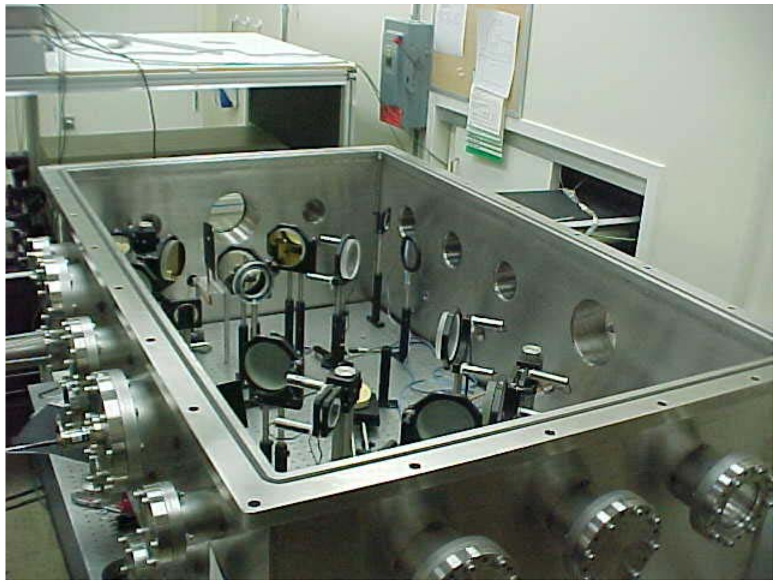
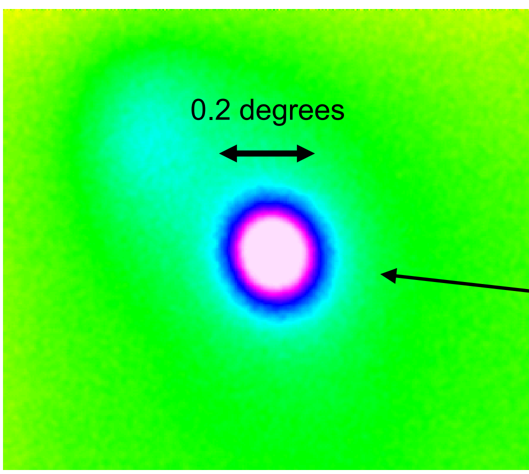
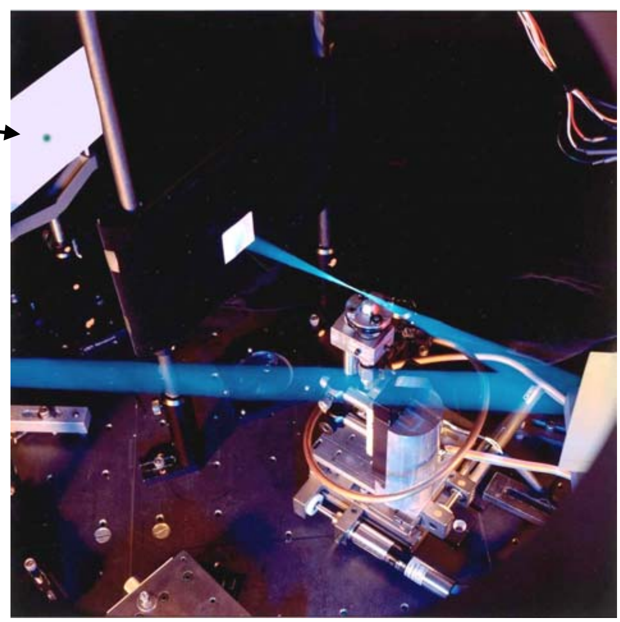


Vacuum chamber with optical elements for laser wakefield acceleration experiments.



Low divergence electron MeV-energy beam imaged with fluorescent screen and CCD camera.



Experimental apparatus: (from right to left) focusing optic, gas nozzle, laser light block and florescent screen.

Program for Plasma-Based Concepts for Future High Energy Accelerators

PI: Professor Thomas Katsouleas, and Co-PI Dr. Patric Muggli - University of Southern California

The USC program is focused on advancing plasma-based concepts for future high-energy accelerators. We are actively pursuing this goal through experiments, advanced computational modeling and theory.

Recent Accomplishments:

Highlights of accomplishments in this period include:

- Performance of the E-162 Plasma Wakefield Accelerator Experiment at the Stanford Linear Accelerator Center.
- Development 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.
- Development 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-162 Plasma Wakefield Accelerator experiment was designed to demonstrate high-gradient electron and positron acceleration at energies of relevance to high-energy colliders and over meter length scales. This experiment has produced a wealth of spectacular results and physics milestones. As described in the references that follow, the collaboration between USC, UCLA and SLAC achieved a number of firsts: These include the acceleration of electrons in the tail of a 30 GeV SLAC bunch by up to 280 MeV over 1.4 meters of plasma. The experiment ran parasitically with PEP-II operation at SLAC. In this mode, the SLAC linac delivered stably $2x10^{10}$ electrons per bunch which was a factor of two lower than the original design. Consequently, the acceleration measured was lower than the design by a similar factor but in very good agreement with the simulations performed for the actually delivered beam parameters. The good agreement bodes well for the collaboration's next experiment – E-164. Preliminary simulations indicate that the wakefield amplitude and acceleration gradient increase as the inverse square of the bunch length, and E-164 will test this scaling with bunch lengths 6 times shorter or more in upcoming runs in 2003-2004.

If plasma accelerators are to have an 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-162 accomplished important firsts on both of these fronts. By designing the incoming beam optics to match the theoretical Twiss parameters associated with the plasma's strong transverse focusing fields, the first demonstration of matched beam propagation and acceleration were achieved. Such matching will be important to preserving beam emittance in future plasma accelerators such as an Afterburner in which the beam may propagate over a hundred betatron oscillations. The 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. 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 PIC simulations (Fig. 1).

The plasma afterburner is a concept for impacting the energy frontier with a plasma accelerator placed at the interaction point of a linear collider. The concept is described in the USC thesis of Ms. Seung Lee who graduated during this contract period. Ms. Lee used simulations to support key foundations of the afterburner such as the scaling of the wakefields with shortened bunch length well into the non-linear regime, the beam loading of a significant number of particles (10^{10}) with modest energy spread, and the recovery of luminosity through plasma lensing. The interest in this original proposal has been spurred by experimental results on E-162 and elsewhere and is leading to work on a challenging but finite spectrum of remaining issues. Key among these are beam jitter and alignment tolerances, hosing instability limits and plasma source development.

The interaction between a positively charged high current beam with the low density electron cloud they create in circular accelerators has become a major concern in existing accelerators at high current and in the design of future circular accelerators (particularly LHC at CERN). Recently a meeting held at CERN under the title ECLOUD02 highlighted the fact that electron clouds lead to emittance blow-up and instability of beams in a number of accelerators world-wide, that the mechanisms of the e-cloud interaction are not well understood and that 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). Their 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. To this end, G. Rumolo from CERN visited USC for a month to collaborate on the code. An early milestone was reached recently: Using 16 processors at NERSC, the propagation of the beam through 50 turns (350 km) of the SPS at CERN was modeled. This is the relevant number of turns to begin to see the tune shift due to the cloud. Based on this preliminary work, it appears to be possible to develop a high-fidelity model capable of simulating hundreds or even a thousand turns in the near future. 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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31. B. E. Blue *et al.* “Plasma-wakefield acceleration of an intense positron beam,” Phys. Rev. Lett. **90**, 214801 (2003)

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- Mr. Ali Ghalam – PhD Student
- Mr. Erdem Oz – PhD Student
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- Mr. Reid Maeda - Undergraduate
- Mr. Bill Quillinan – Middle School Science Tchr.
- Mr. Paul Kim – HS Science Teacher

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1. Dr. Seung Lee (PhD, 2001) International Rectifier
2. Dr. Jerry Hoffman (PhD, 2001) Cymer Corp.

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"Channeled Laser Wakefield Acceleration: Toward GeV"

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Background and Overview

The experimental program is focused on development of a channeled Laser Wakefield Accelerator (LWFA), and of methods to diagnose, control and optimize its performance. In past years, we made the first femtosecond (*fs*)-time-resolved measurements of the resonant *[Siders 96]* and self-modulated *[LeBlanc 96]* Laser Wakefield Accelerators (LWFA's) in diffraction-limited focus geometry suitable for electron acceleration to MeV energies. We also demonstrated a fully ionized, preformed He plasma waveguide that transmits single terawatt laser pulses at 0.2×10^{18} W/cm^2 over more than *1 cm* (60 Rayleigh lengths) without distortion *[Gaul 00]*. In this funding period (2001-2003), we: (1) performed pump-probe experiments in the plasma waveguide *[Zgadzaj 03],* a pre-requisite to diagnosis of channeled LWFAs; (2) performed pump-probe experiments in clustered plasmas *[Shim 03]*, to explore more efficient ways of generating plasma channels; (3) upgraded our laser system from 1 TW to 5 TW to enable fully relativistic guided intensity (10^{18} W/cm^2), thereby laying the groundwork for dephasing-limited channeled LWFA up to GeV energies; (4) developed single-shot LWFA diagnostics *[LeBlanc00, Matlis 03]*, essential for evaluating shot-to-shot phase jitter and the feasibility of multi-staging; (5) made both experimental and theoretical progress toward Raman-seeded LWFA, a technique for coherently controlling the growth of a wakefield. Our current theoretical work is focused on improving efficiency of, and coherently controlling, LWFA by Raman seeding in both unguided and guided configurations *[Fomystkyi 03]*. This theoretical work supports a concurrent experiment in our laboratory *[Downer 02]*, while simultaneously exploring the feasibility of low-energy medical applications of LWFA *[Chiu 03, Kainz 03]*.

<u>Recent Accomplishments</u>

Pump-probe experiments in plasma channels. We implemented the first femtosecond pump-probe measurements in ~ 1 cm long preformed plasma channels. Experiments were performed in He plasma waveguides using 800 nm, 80 fs pump pulses of 0.2×10^{18} W/cm^2 peak guided intensity and single orthogonally-polarized 800 nm probe pulses at time delay Δt. Use of pump and probe pulses of the *same* wavelength, rather than traditional two-color pump-probe experiments, ensures group-velocity matching throughout channel transit, thus avoiding washing out of temporal pump-induced features, such as wakefields, that would occur with two-color experiments. Light exiting the channel was imaged with 100× magnification onto the entrance slit of an imaging spectrometer. A two-dimensional CCD recorded single-shot probe (+ pump leakage) spectra with ~1 μm spatial resolution along the dimension parallel to the slit. Thus both spatial and temporal modifications to the probe pulse are measured simultaneously.

Two main results were obtained in the first round of pump-probe experiments: (1) At time delays $|\Delta t| > 100$ fs, we observed frequency-domain interference (FDI) between the probe and a weak depolarized component of the pump. This technique provided sensitive homodyne-characterization of the mode structure of the weak, depolarized component of the pump that would otherwise be swamped by the main portion of the pump. A characteristic tilt was observed in the FDI fringes, which collaborator G. Shvets successfully modelled in terms of an asymmetric mode structure $E_{depol} \propto x \exp(-x^2)$ of the depolarized pump light. Quantitative analysis showed that most of the depolarization originates not in the main channel, but in short transitional regions near the entrance and exit where the channel is denser and narrower. (2) At $\Delta t \approx 0$, a blue-shift of the spectrum of the channeled probe pulses was observed, especially near the center ($x \approx 0$) of the guided mode, even though a blue-shift was not detected in the transmitted pump pulses. Analysis showed that the blueshift originated from un-ionized gas near the channel entrance. This not only confirms previous conclusions about full ionization within the He channel *[Gaul 00]*, but provides a much more sensitive diagnostic of residual un-ionized gas than diagnostics based on the guided pump pulse alone.

In future experiments, the same techniques will be used to measure non-Gaussian spatial structure and phase modulation induced on the probe by pump-induced wakefields and relativistic nonlinearities. Further details are described in the paper *[Zgadzaj 03].*

Optical nonlinearities in clustered plasmas. Our current method of generating channels is inefficient: He gas absorbs ~3% of a line-focused 1 joule Nd:YAG channel-forming laser pulse. Atomically clustered gases absorb intense laser light much more efficiently (~90%). Pre-expansion of the clusters by a pump pulse resonantly enhances absorption as the electron density n_e passes through $3n_{crit}$ *[Kim03]*. We proposed *[Tajima99]* that nonlinear optical response could also be resonantly enhanced in pre-expanded clustered plasmas, leading to new sources of short-wavelength radiation and new acceleration mechanisms.

We recently performed pump-probe experiments that simultaneously demonstrate resonantly enhanced linear absorption and third harmonic generation in pre-expanded clustered Ar gas. A 400 nm, 150 fs pulse pre-heated argon clusters near the throat of a pulsed nozzle. The clusters then freely expanded. A second intense 800 nm beam, propagating either collinearly with, or at a small angle to, the pump beam then probed the expanding clustered plasma. By varying the pump-probe time delay Δt, we observed a sharp resonance in the third harmonic production that contrasts with the relatively broad linear absorption resonance. The third harmonic resonance also occurs earlier in time than the corresponding linear absorption resonance *[Shim 03].* To explain the results, we developed a model of the nonlinear optical response of an expanding cluster *[Breizman 03, Fomytskyi 03aps]*. The elements of this model are: (1) The short pump pulse strips some electrons from the cluster, leaving behind a uniform sphere of ions and a smaller uniform sphere of remaining electrons; (2) the probe pulse field drives oscillations of the residual electron core against the ion background; (3) as the ions expand, their density becomes increasingly non-uniform, causing the oscillations of the electron core to become increasingly anharmonic.

Information obtained from this experiment will determine the optimum duration, timing and energy of the laser pulse needed to form a plasma channel in the clustered gas. By including *nonlinear optical* response, it will also elucidate the physics of cluster expansion more completely than experiments based solely on linear absorption.

Raman-seeded laser wakefield acceleration. Experiments are in progress to generate short-period wakefields in the "self-modulated" regime by simultaneously exciting a plasma with intense 800 nm main pulses and much weaker 870 nm seed pulses, which differ in frequency by the plasma frequency. Seed pulses have been generated by stimulated Raman scattering of the uncompressed amplified 800 nm pulses, compressed to ~ 300 fs with ~1% of the parent pulse energy, and characterized by frequency-resolved optical gating.

Meanwhile we completed theoretical modeling of Raman-seeded LWFA by 2D particle-in-cell simulations. The results show that, with a ~1% Raman seed, the main pulse intensity required for efficient self-modulated LWFA can be reduced below the threshold for relativistic self-focusing, thereby improving wakefield coherence and enabling higher repetition rate (>100 Hz) generation of nano-coulomb electron bunches *[Fomytskyi 03].* 2D simulations in a plasma channel showed efficient electron generation with Raman-seeded main pulse intensities as low as $a_0 \sim 0.3$ (~10^{17} W/cm^2 at 800 nm), and energy as low as 30 mJ, which implies repetition rates as high as 300 Hz for a conventional 10 W laser system. The possibility of such high repetition rates may help overcome a significant technical barrier to low-energy LWFA applications such as radiation oncology that are often casually advertised in review articles as future possibilities without serious analysis. To provide this missing serious analysis, we teamed up with collaborators at M.D. Anderson Cancer Research Center and analyzed comprehensively the potential impact of table-top LWFA sources on radiation oncology when energy windowing, beam delivery to the patient and source repetition rate are taken into account quantitatively ***[Chiu03, Kainz 03]***. A major conclusion of their analysis is that a threshold-lowering scheme such as Raman-seeding will be essential for achieving the threshold dose rate of 4 Gy/min in a ΔE ~ 5 MeV window that is generally accepted by the medical community.

Awards and Public Service (2001-2003)
The PI was elected a Fellow of the Optical Society of America in 2003. The PI served as Program Co-Chair of the 2003 Quantum Electronics and Laser Science (QELS 03) conference in Baltimore in June 2003, the largest laser science conference in the world, and completed a 3-year term as Topical Editor of the Journal of the Optical Society of America B. He served on the organizing committee of the 10th Advanced Accelerator Concepts workshop (2002), and currently serves on the organizing committee of the 11th workshop (2004).

Publications (2001-2003)

<u>**Refereed Articles**</u>

[**Breizman 03**] B. N. Breizman and A. V. Arefiev, "Electron response in laser-irradiated microclusters," *Plasma Phys. Reports* **29**, 642 (July 2003).

[**Chiu 03**] Chiu C, Fomytskyi M, Grigsby F, Raischel R, Downer MC and Tajima T, "Laser electron accelerators for radiation medicine: a feasibility study," submitted to *J. Med. Phys.* (2003).

[**Fomytskyi 03**] Fomytskyi M, Chiu C, Downer MC, Grigsby F, "Raman-seeded laser wakefield acceleration," submitted to *Phys. Plasmas* (2003).

[**Horton 03**] Horton W and Chiu C, "Laser Z-pinch dipole-target experiments to simulate space physics acceleration processes", submitted to *Phys. Plasmas* (2003).

[**Kainz 03**] Kainz KK, Hogstrom KR, Antolak JA, Almond PR, Bloch CD, Chiu C, Romytskyi M, Raischel F, Downer MC, Tajima T, "Dose properties of a laser accelerated electron beam and prospects for clinical application," *J. Med. Phys.* in press (2003).

[**Zgadzaj 03**] Zgadzaj R, Gaul EW, Matlis NH, Downer MC, Shvets G, "Femtosecond pump-probe study of preformed plasma channels," submitted to *J. Opt. Soc. Am. B* (2003).

<u>**Conference Proceedings Papers**</u>

[**Downer 02**] Downer MC, Chiu C, Fomyts'kyi M, Gaul EW, Grigsby F, Matlis NH, Shim B, Smith PJ, Zgadzaj R, "Plasma channels and laser pulse tailoring for GeV laser-plasma accelerators," *Advanced Accelerator Concepts X*, C. Clayton, C. Joshi, P. Muggli, eds. (American Institute of Physics, 2002), pp. 654-663.

[**Fomytskyi 03aps**] M. Fomyts'kyi and B. N. Breizman, "Third harmonic generation in laser-irradiated clusters," presented at *American Physical Society-Division of Plasma Physics*, Albuquerque, October 2003.

[**Gaul 02**] E. Gaul, F. Grigsby, N. M. Matlis, B. Shim, R. Zgadzaj, M. C. Downer, "Distortion-free guiding of 0.2 x 10^{18} W/cm^2 pulses through a fully-ionized 1.5 cm He plasma channel," *Ultrafast Phenomena XIII,* M. M. Murnane, N. F. Scherer, R. J. Dwayne Miller, A. M. Weiner, eds. (Heidelberg, Spring Verlag 2002), pp. 19-21.

[**Matlis 03**] N. H. Matlis, M. C. DOWNER, N. E. Andreev, "Optimized propagation of 10^{18} W/cm^2 pulses through sharply-bounded ionizing gas profiles," *Conference on Lasers and Electro-Optics* (CLEO '03), paper CThB1, Baltimore, MD, 5 June 2003.

[**Shim 03**] Shim B, Hays G, Downer MC and Ditmire T, "Time-resolved harmonic generation from noble-gas cluster explosions," presented at *American Physical Society-Division of Plasma Physics*, Albuquerque, October 2003.

<u>Invited Presentations</u>

M. C. Downer, "Guiding of intense femtosecond pulses in fully ionized plasma channels," American Physical Society - Division of Plasma Physics, Orlando, FL, November 2002.

M. C. Downer, "Review of progress in channeling laser pulses through plasmas," Particle Accelerator Conference (PAC 2003), Portland, Oregon, 12 May 2003.

<u>Personnel supported by DOE and/or contributing to this project (2001-2003)</u>

Senior scientists:

M. Downer (professor, principal investigator) – experimental program director
B. Breizman (senior scientist) - theory of laser-cluster interactions
*C. Chiu (faculty collaborator) - theory of Raman-seeded wakefield acceleration
G. Shvets (incoming faculty collaborator) - theory and simulation of laser-plasma physics

Graduate Students:

*Mikhailo Fomyts'kyi (doctoral student) - theory and simulation
*F. Grigsby (doctoral student) - Raman-seeded LWFA experiments and laser system modelling
*N. M. Matlis (doctoral student) - LWFA interferometry in differentially-pumped cell
*Bonggu Shim (doctoral student) - cluster plasma experiments
*R. Zgadzaj (doctoral student) - plasma channel experiments

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No theses yet awarded during the 2001-2003 funding period.

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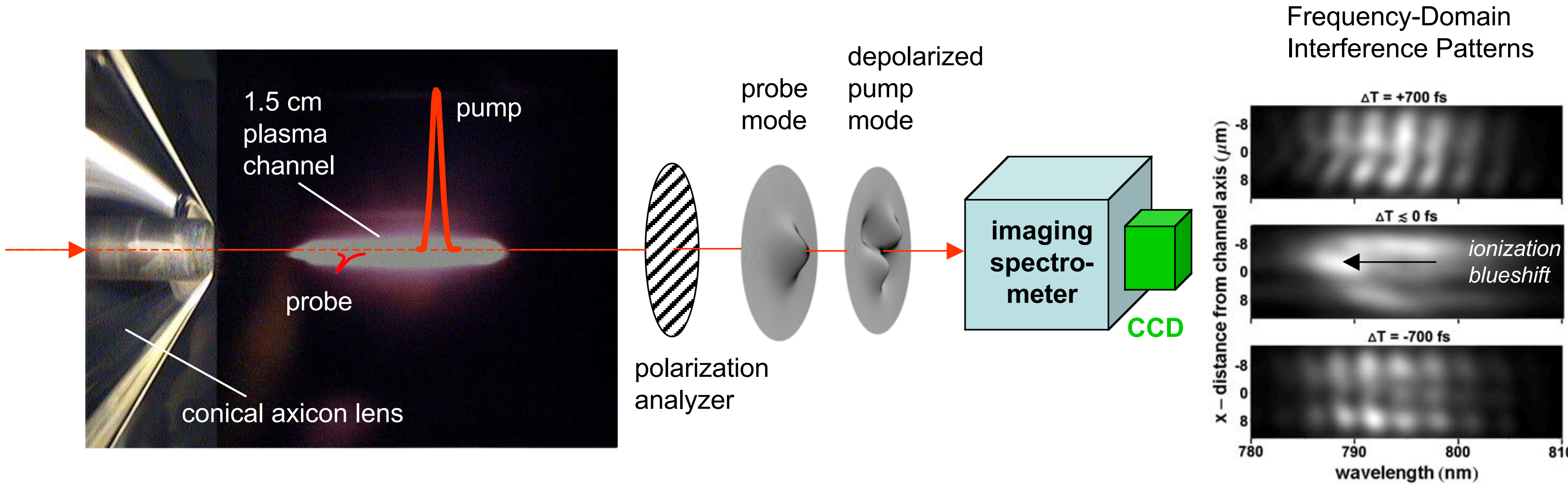
M. C. Downer - U. Texas - Austin
"Channeled Laser Wakefield Accelerator - toward GeV" (DEFG03-89-ER-40954)



- Preformed plasma channels capable of guiding intense fs laser pulses without optical distortion are essential to developing GeV-scale laser wakefield accelerators (LWFAs).
- Femtosecond pump-probe experiments were performed to characterize intense pulse propagation through the channel, & develop techniques for probing channeled LWFAs
- 80 fs, 800 nm pump pulse (I_{guided} = 0.2 x 10^{18} W/cm^2) and 800 nm probe co-propagate through channel formed when axicon lens line focuses a separate laser pulse.
- Tilt of frequency-domain interference fringes (e.g. ΔT = ±700 fs data) characterizes mode distortions of pulses accrued during channel transit
- Ionization blueshifts at ΔT~0 fs characterize residual un-ionized gas
- Future experiments will employ these same techniques to characterize channeled LWFAs created by pump pulses with (I_{guided} = 10^{18} W/cm^2).

R. Zgadzaj, E. Gaul, N. Matlis, M. Downer, G. Shvets, "Femtosecond pump-probe study of preformed plasma channels," submitted to J. Opt. Soc. Am. B (2003).

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 C. Larbalestier and Peter J. Lee – University of Wisconsin-Madison

Summary:

The Applied Superconductivity Center is the leading university center in the world for the study of superconducting strand. It has both a complete wire fabrication facility (including hydrostatic extrusion) and the facilities to fully characterize the strand for superconducting properties. Combining our own light microscope and high-resolution image analysis capabilities with the adjacent electron microscope facilities of UW Integrated Microscopy Resource, we can completely characterize the microstructural properties of the strands. Undergraduates and graduate students in our center obtain hands-on experience in all areas of strand fabrication and characterization. Not surprisingly graduates from our program working in industry have played an important part in the development of high performance commercial strand.

Under our High Energy Physics program we work with the accelerator community to improve the performance of superconductors for application in accelerator magnets. The center has played a leading role in the development of accelerator strand since the Tevatron Energy Saver Strand. In 1991 the Institute of Electrical and Electronic Engineers (Nuclear and Plasma Society) recognized the importance of this work by awarding Prof. David Larbalestier (jointly with R. M. Scanlan) the Particle Accelerator Conference Award for the development of High Current density Nb-Ti conductors for Accelerator Magnets.

The current aim of the program is to develop new high field superconductors for application in accelerator magnets of the type required for future hadron and muon colliders. We focus on understanding the factors controlling the critical current density and upper critical field performance of Nb_3Sn, MgB_2, Nb-Ti and Nb_3Al conductors and then devise processing strategies to incorporate the most favorable properties into conductors of these materials. A unique feature of the work is the alliance of detailed, local microstructural characterization and local electromagnetic characterization using very sensitive vibrating sample magnetometer and specific heat measurements to reveal the compositional sensitivity of the properties. The center organizes the superconductor material workshops that have so strongly stimulated the community working on accelerator applications of superconductors. The center also provides information to the community via its website at: http://www.asc.wisc.edu/. We are an active member of the new Conductor Development Program designed to facilitate the commercial production of high performance superconductor for the next generation of high energy physics applications.

Recent Accomplishments:

We have shown that the crucial change from the ITER CSMC generation of strands to the first generation high J_c strand was not in the Nb:Sn ratio but in the Sn (and Nb) to Cu ratio. The gap between the Nb_3Sn layer J_c of the ITER (high Cu, low hysteresis) strands and the high J_c strands is quite apparent as shown in the montage (upper left chart). Despite differences in the original Nb:Sn ratios of the many composites we have characterized, the Nb_3Sn layer J_c values for the high J_c strands are very close to each other. The importance of Cu:Sn ratio reduction in increasing J_c has important consequences. As the Cu content for bronze-process strand cannot be decreased below ~7:1, the advances seen in internal Sn strands since ITER will not repeated for bronze-process strands. In internal Sn strands the reduced Cu content in the sub-element means that, without sub-division of the filament pack, all the filaments within the sub-element will be coupled. Using Cu spacers within the sub-element can reduce the effective filament diameter but at the cost of increasing the Cu:Sn ratio and reducing J_c. Nb-Ta alloy spacers (or "fins") have recently been successfully introduced into internal Sn composites fabricated by Supergenics but there is considerable reaction between the Sn and the Nb-Ta fin (see center images in montage).

Chad Fischer completed his thesis studies on relationships between superconducting properties and Nb_3Sn reaction conditions in powder-in-tube Nb_3Sn conductors. The primary properties (T_c, H^* and H_{c2}) of the PIT strands reached optimum levels at 750°C. The flux pinning properties, however, reached optimum levels at 675°C and are greatly suppressed at higher reaction temperatures. Both the primary and flux pinning properties diminished for reaction times longer than 128 hours at 675°C. The results correlated to over reaction of the Nb barrier. Nevertheless, significantly higher T_c (17.55 K) and H* (26.7 T) values were observed compared to other manufacturing methods (e.g. high J_c optimized internal Sn with T_c ~16.5 and H^* ~ 24.5 T). The non-Cu J_c of the present designs are lower than recent internal-Sn strand (~2200 A/mm² at 12 T compared with 2900 A/mm²), largely reflecting their lower A15 fraction. The filaments, however, remain uncoupled and this suggests that the $d_{effective}$ can continue to be improved with further powder refinement. Mile Naus has combined the data from the PIT strands and high-Jc internal Sn strands and has shown a universal correlation between T_c and H^*_{Kramer} (see lower right hand chart in montage). This plot also suggest H^*_{Kramer} ~ 29 Tesla for stoichiometric A15.
Ti or Ta alloying of the Nb_3Sn is used to improve the high field critical current density, the Ti can be alloy with the original Nb filaments but this reduces ductility and increases the cost of the alloy. The Ti has also been introduced by incorporating it into the Sn core but this can lead to an inhomogeneous distribution of Ti which can have dramatic effects on the Nb_3Sn microstructure (as shown in the montage – lower left). We have also been collaborating with Mas Suenaga at BNL on his diffusion studies of internal Sn superconductors (John Ulrich – NSF REU and Matt Jewell – undergraduate). In this work we have shown that the Ti appears to segregate on the inside of the filament-pack ring in these low Cu:Nb ratio strands.

<u>Publications 2001-2003</u>:

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10. "Multifilamentary Nb_3Sn Wires reacted in hydrogen gas," M. Takayasu, R. G. Ballinger, R. B. Goldfarb, A. A. Squitieri, P. J. Lee, and D. C. Larbalestier, Advances in Cryogenic Engineering, 48 (B): 986-993, 2002.
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16. "Advances in superconducting strands for accelerator magnet application," Peter J. Lee and David C. Larbalestier, IEEE Proceedings 2003 Particle Accelerator Conference, 2003.

<u>Current Staff</u>:

- Principal Investigator: Prof. David Larbalestier
- Co-Principal Investigator: Dr. Peter Lee

Staff:

- Dr. Alexander Gurevich, 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.
- Melinda Adams, Outreach

Graduate:

- Matt Jewell, Masters student

Undergraduates:

- P. Burgardt
- B. Egan
- M. Jewell
- R. Mungall
- J. Wagner

Past Graduates from ASC from this contract in 2002-3:

- Chad Fischer, Masters

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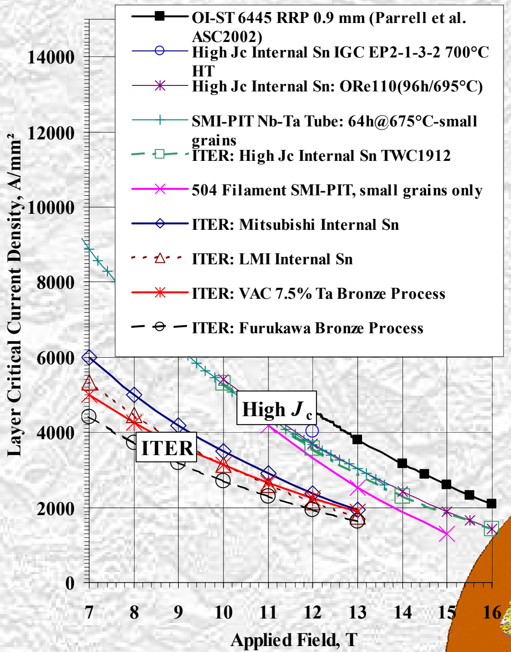
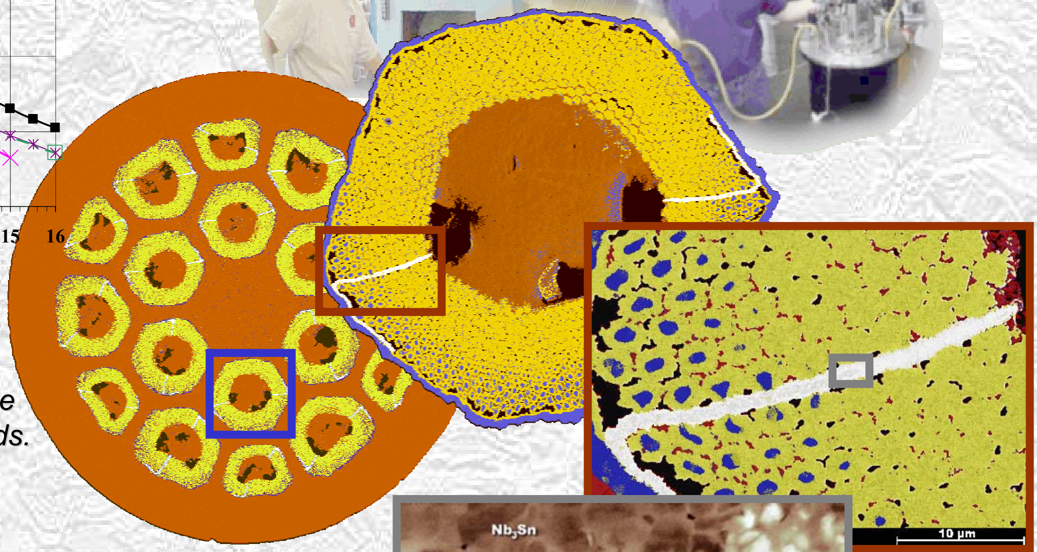
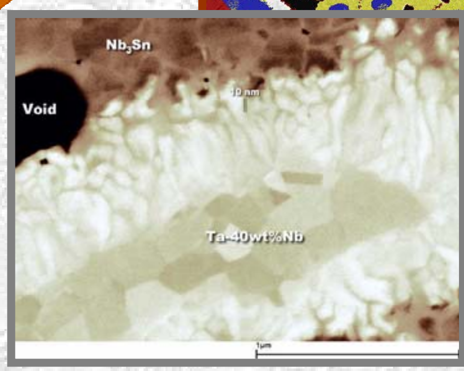
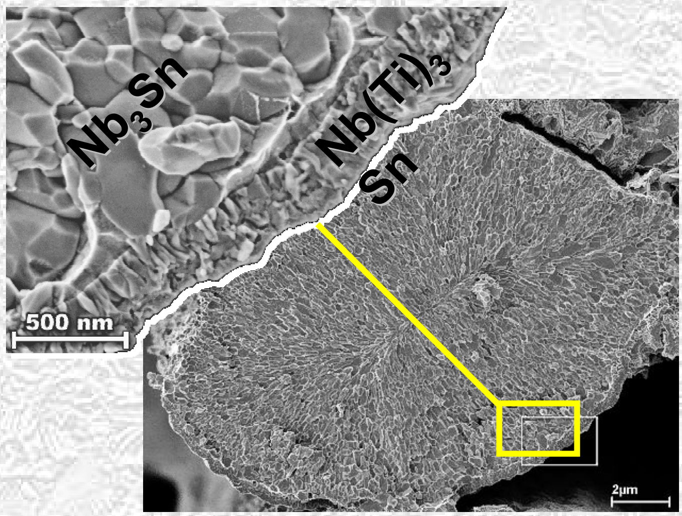


Comparison of Nb_3Sn Layer Critical in Nb_3Sn shows continued improvements in the intrinsic properties of the strands.

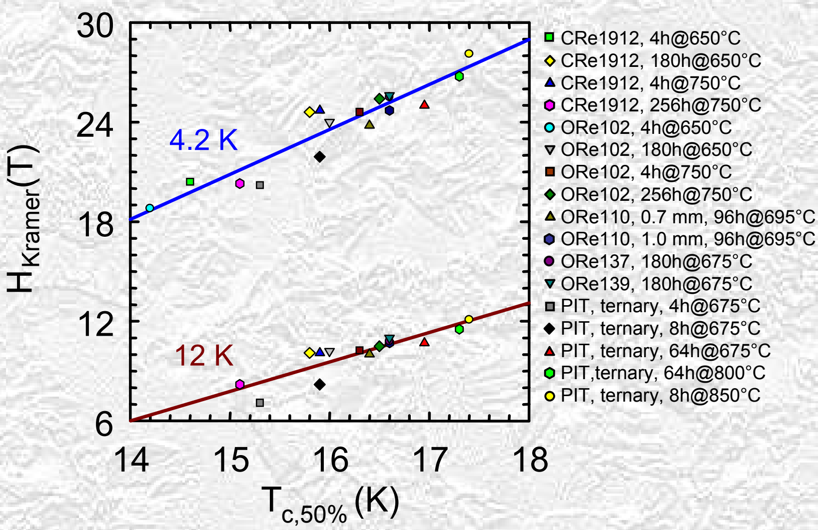




Successfully higher magnification electron backscatter images showing components of Supergenics Fin-divided high J_c Nb_3Sn strand. False colored to enhance atomic number contrast.



FESEM fractography reveals 2 distinct A15 layers (with and without Ti) produced in Sn(Ti) cored sub-element.



We have shown a universal correlation between T_c and H^*_{Kramer} for both internal Sn and PIT based high J_c Nb_3Sn. This plot also suggest H^*_{Kramer} ~ 29 Tesla for stoichiometric A15

Background is an image processed fracture surface from a MgB_2 sample

National Laboratories

Structure Based Wakefield Acceleration and High Current Electron Beam Generation at Argonne

Wei Gai - Argonne National Laboratory

Summary:

The advanced accelerator program at Argonne is focused on advancing the physics and technology of beams, particularly new approaches to beam acceleration and instrumentation important to the world high energy physics program, such as the development of new techniques for accelerating electron beams to high energies. We operate a unique high charge rf photocathode based linear accelerator, the Argonne Wakefield Accelerator (AWA).

The Advanced Accelerator group has been a pioneering research group working on wakefield phenomena for accelerator research, particularly emphasizing dielectric based beam- and rf-driven acceleration concepts. 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 NLC prototype design; generation of high current beams unique among rf photocathode based linacs, for example, we were the first to produce individual electron bunches with charge in excess of 100 nC; production and measurement of high accelerating gradients in both plasmas and dielectric structures; originated and demonstrated the principle of the wakefield step-up transformer using dielectrics. Our facility also serves as a user facility. A few notable examples of collaborative efforts are: the Tesla Test Facility photoinjector test with FNAL; the non-linear plasma wakefield experiment with UCLA; coherent Cherenkov and transition radiation with JPL and UCLA; and positron source measurements with APS; etc. Recently, we have received many requests to do advanced accelerator physics related experiments using the AWA facility. For example, DULY Research, Euclid Concepts and the University of Hawaii have already scheduled experiments related to high power rf generation, advanced collinear wakefield dielectric acceleration and laboratory astrophysics, respectively. Several other institutions are currently developing plans for experiments to be performed at the AWA.

The present focus is on accelerator research in areas that require intense, short-pulse electron beams; dielectric based wakefield acceleration in structures; plasma wakefield acceleration and focusing; generation of high power rf using dielectric lined waveguides or other types of slow wave structures; and enabling technologies of photocathode-based electron sources necessary to produce electron beams with the required characteristics for the all of the above. The technology we are developing, *wakefield acceleration*, involves using a train of low energy high current electron bunches (drive beam) to accelerate a second electron bunch (witness beam) to higher energy through the use of a dielectric loaded structure or plasma. In principle, an accelerating gradient in the several hundred MV/m regime is obtainable. We have constructed, and are presently operating, an experimental facility called the Argonne Wakefield Accelerator (AWA) to study the feasibility of these new acceleration methods. Based on our prior experience with high current photoinjectors, we have developed a third-generation, photocathode-based electron source capable of producing, for the same 100 nC-scale intensities, drive beams which are a factor of three shorter in duration and ten times smaller in emittance than the existing gun. The improvement in beam quality translates into significant increases in the performance level of our wakefield accelerator devices and makes them comparable to, or exceeding, those of conventional high frequency structures.

The group maintains a strong interest in accelerator theory and simulations. Along with beam dynamics simulations of the performance of the AWA accelerator systems, we have also been involved in theoretical and numerical studies of dielectric-based, decelerating structures for rf extraction, that have potential applications to CLIC-type two beam accelerators. We have also studied the application of wakefield physics and technology to high-energy physics, in particular for detection and measurement of high-energy cosmic rays.

The program maintains productive collaborations with other institutions. We have proposed and have now worked out a preliminary design for high precision wakefield measurements for NLC structures, particularly on the design of a high precision wakefield measurement system. We are also working with S. Gold at NRL and R. Ruth's Department at SLAC on high power testing of X-band traveling and standing wave dielectric accelerators, this collaboration has yielded many fruitful physics results The program has served as a training ground for Ph.D. thesis students. Currently, we have three Ph.D. students involved in our research.

The long-term goal of this program is the development of wakefield acceleration technology for high energy physics applications, and the demonstration of high gradient, sustained acceleration in a two stage accelerator (two beam acceleration mode), while investigating relevant physics and technology issues along the way. We have developed a coherent strategy to carry out this development. For the demonstration component of this goal, we plan to realize a 100 MV/m acceleration gradient over a meter long by accelerating a high-quality, 1nC beam to a total energy gain of 100 MeV using the wakefield technologies developed at Argonne.

Recent Accomplishments:

C*ommissioning of the new 1-1/2 cell L-band rf photocathode source.* This new rf gun design was based on our experience with the original AWA drive gun --- which at present is the highest current photoinjector in existence. This new gun will significantly improve the present AWA drive beam performance. The rms bunch length is three times shorter, while lowering the emittance by a factor of ten. The gun is currently operated at the designed gradient of 80 MV/m and vacuum in the range of 10^{-9} torr under full rf power (adequate for the use of high QE photocathodes). Electron beam with charge of 1 nC ~ 100 nC were generated using copper and magesium cathodes. The beam energy is 6 – 7.5 MeV. Initial beam characterization showed that beam has very low emittance as designed (40 mm-mrad for 20 nC). We have used a quartz Cherenkov radiator and measured the electron bunch length of ~ 15 ps for 20 – 70 nC beam which is in good agreement with the predictions. The immediate next steps are: high gradient testing of a short dielectric structure using 1 – 4 electron pulses; increase drive beam energy from 7.5 to 18 MeV by adding a linac tank in the beamline; implement a high QE CsTe cathode to be made at Las Alamos Lab; and detailed single and bunch train electron beam properties characterization. During this same period, a state of the art laser system was installed at the AWA with combination of Spectra Physics Tsunami oscillator, Spitfire Regenerative Amplifier, and two Ti:Sapphire Amplifiers (TSA 50), and KrF Excimer amplifier that generates, 1.5 – 15 mJ at 248 nm, 6 - 8 ps FWHM pulse length. Both laser amplitude and transverse beam stabilities have been greatly improved.

Development of an externally driven 11.424 GHz dielectric loaded structure. This is an exciting near term application of wakefield derived technology using an external rf power source to drive a dielectric structure. Based on our previous experience, obtained in development of a cold test prototype structure, we have constructed a dielectric loaded X-band traveling and standing wave structures. A series high power tests were conducted at NRL during this period, and a number of significant physics results were obtained that may impact the eventual use of these devices for future high energy accelerators. The initial test of a dielectric loaded traveling wave structure was made using a dielectric material with a permittivity of 20; this yields similar acceleration characteristics to the current NLC structure. The experiment achieved a maximum gradient of 3 – 5 MV/m before the onset of arcing in the coupling aperture. A postmortem analysis identified the origins of the low breakdown threshold in the coupling aperture: high rf field concentration near the coupler and copper flakes on the dielectric coupler surface deposited during installation of the tube. The same phenomena also occurred in the standing wave structure. Based on these initial test results, we redesigned the coupling scheme that uses a modular structure that initially converts the TE-mode from the feed waveguide to a TM mode in a copper cylinder. The TM mode rf power in turn propagates into the dielectric accelerating structure through a tapered section. Upon completion of the new modular coupling and dielectric structures using Alumina materials, a new round of experiments was performed at NRL. The goals of this test were to confirm that the new rf coupling scheme would function at high power without breaking down and to test the high power response of the Alumina structure. After two days of conditioning, the DLA structure could support an incident power of 5 MW at a 150 nsec pulse length with no signs of breakdown observed. Calculations show that this power level corresponds to a gradient of about 8 MV/m. One surprise uncovered during the test was an unexpected light emission from inner tubes of the structure. Our preliminary investigation into this phenomenon leads us to believe that we observed secondary electron emission (SEE) in the dielectric. We are now working on the interpretation of the data and investigating techniques (TiN coatings, etc.) to reduce the SEE. From this run we have drawn the following (preliminary) conclusions: (1) the redesigned DLA structure has eliminated the coupler-arcing problem; (2) no dielectric breakdown was observed; and (3) SEE appears to be absorbing rf power and producing light emission. Currently, a program has been setup to investigate TiN coating on inner radius of the dielectric tubes. Also, we are constructing a new set of modular structures with dielectric material MCT20 which may have a reduced sensitivity to SEE problems.

Other activities. In collaboration with SLAC, we developed a dielectric based decelerator as a power extraction device for CLIC. Working with DULY research, we have obtained Phase II SBIR funding. We have designed and fabricated a dielectric based power extraction device. An experiment was performed at the CLIC test facility, and produced up to 20 ~ 50 MW rf power at 21 GHz. A new round of high power testing at 15.6 GHz will be conducted at our AWA facility with a pulse train generated from the AWA gun. In addition to the above activities, we have also performed the first ever coherent transition/Cherenkov microwave radiation experiment (with JPL/UCLA) to simulate a cosmic ray showers. Another significant result obtained recently was the theoretical study and experimental demonstration of the physics of multiple beam driven, multimoded wakefield phenomena.

<u>Publications 2001-2003</u>:

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2. "Field analysis of a dielectric-loaded rectangular waveguide accelerating structure," L. Xiao, et al., Published in Phys. Rev. E, Vol 65, 2002.
3. "Wakefield acceleration in structures," M. Conde, in in Advanced Accelerator Concepts—Tenth Workshop, Mandalay Beach, CA, 22–28 June 2002, AIP Conference Proceedings 647, edited by C.E. Clayton and P. Muggli (American Institute of Physics Press, Melville, NY, 2002), pp. 63-70.

4. “High power testing of ANL X-band dielectric loaded accelerating structures,” J. Power et al., in *Advanced Accelerator Concepts—Tenth Workshop, Mandalay Beach, CA, 22–28 June 2002*, AIP Conference Proceedings 647, edited by C.E. Clayton and P. Muggli (American Institute of Physics Press, Melville, NY, 2002), pp. 556-564.
5. “A new high intensity electron beam for wakefield acceleration studies,” Conde et al., in Proceedings of 2003 Particle Accelerator Conferences, Portland, OR.
6. “A compact wakefield measurement facility,” J. Power et al, Proceedings of 2003 Particle Accelerator Conferences, Portland, OR.
7. “High power testing of X-band dielectric-loaded accelerating structures,” J. Power et al., Proceedings of 2003 Particle Accelerator Conferences, Portland, OR.
8. “Dipole wakefields in a dielectric-loaded rectangular waveguide accelerating structure,” C. Jing, et al., to appear in Physical Rev E, 2003.

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 Students:

- Betzel, G — MS Candidate, Physics, Northern Illinois U.,
- Geraskin, G — Ph.D. Candidate, Physics, Illinois Inst of Tech.
- Jing, C — Ph.D. Candidate, EE, Illinois Inst of Tech.
- Wang, H — Ph.D. Candidate, EE, Illinois Inst of Tech.

Recent Graduated Students:

- Zou, P (2002) — Ph.D., Currently Senior Staff Engineer, Intel Corp.

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Advanced Accelerator R&D at ANL

Fig 1. The newly commissioned RF photocathode gun.

Fig 2. The newly installed Ti:Sapphire UV laser system at the AWA.

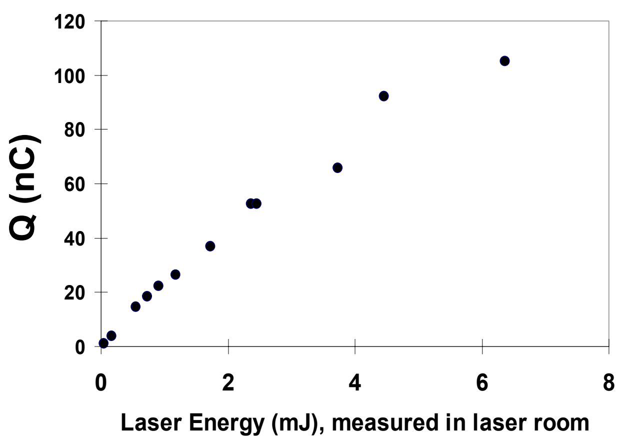

Fig 2. Measured single electron beam charges from the new gun. The measured pulse lengths (FWHM) are ~ 15 ps for charges up to 70 nC.

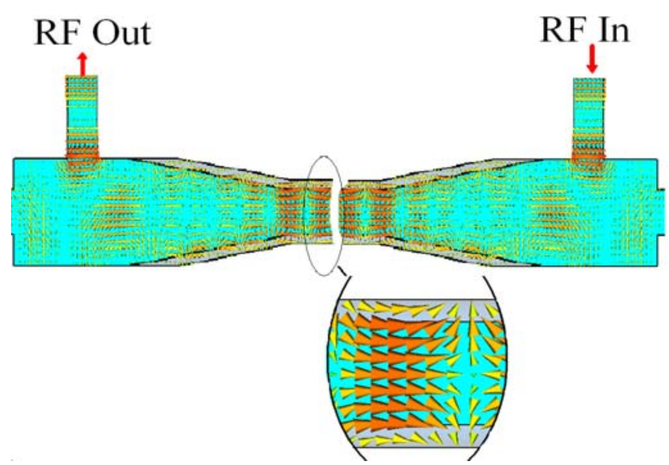

Fig 4. Numerical simulation of the newly designed dielectric accelerator that shows that all of the microwave energy goes through the dielectric loaded traveling wave accelerating structure with low fields around the coupler. A device built based on the design and high power tested at the NRL.

Accelerator Test Facility

Ilan Ben-Zvi - Brookhaven National Laboratory

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 0.5 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 1 to 8 ps, and a bunch compressor will extend the range soon down to 100 fs.

ATF users come from universities, small business and national laboratories mostly from the USA. 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 3 Physical Review (either PRL, PRE or PR-ST-AB) per year.

ATF experiments are serving all DOE divisions – High-Energy and Nuclear Physics as well as Basic Energy Science. The experiments cover various subjects, such as structure based laser acceleration (including 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, and Figure 4 shows the distribution of students according to school. 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. Figure 5 shows ATF users and members of its Program Advisory Committee (currently chaired by Prof. Chan Joshi) visiting the ATF during one of the recent ATF users meeting and Program Advisory Committee meeting.

The ATF staff improves continuously the performance of the facility. Among the equipment being commissioned as of June 2003 are the chicane bunch-compressor, a new computer-control system and the picosecond-terawatt CO_2 laser. Future plans include an energy upgrade to 120 MeV.

Internal R&D includes work on high-brightness electron beams, such as R&D on laser-photocathode RF guns, high-power CO_2 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 includes 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 CO_2 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 for the first time monoenergetic laser acceleration.

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.

Most recently, a 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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62. A. Tremaine, to be published in NIM A, to be published as of June 2003.
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Current Staff:

• Babzien, M.	Laser Engineer
• Ben-Zvi, I.	Principal Investigator, Senior Accelerator Physicist
• Corwin, T.	Mechanical Technician
• Davis, D.	Laser Technician
• Huang, J.-Y.	Accelerator Research Collaborator
• Kusche, K.	ESH&Q Officer
• Malone, R.	Senior Technology Architect
• Pavlishin, I.	Laser Research Associate
• Pogorelsky, I.	Laser Physicist
• Rodrigues, A.	Electronic Engineer
• Watanabe, T.	Accelerator Research Associate
• Woodle, M.	Mechanical Engineer
• Yakimenko, V.	Accelerator Physicist
• Zhou, F.	Accelerator Research Associate

Graduate Students:

- Ping He (Ph.D. student, UCLA)
- Dimitrios Nikas (Ph.D. student, Kent State)
- Sergey Shchelkunoff (Ph.D. student, Columbia University)
- Xiangyun Chang (Ph.D. student, University at Stony Brook)
- Yoshio Kamiya (Ph.D. student, Tokyo Metropolitan Univ.)
- Ronald Agutsson (M.Sc. student, UCLA)
- Gerard Andonian (Ph.D. student, UCLA)
- Carlo Vicario (Ph.D. student, University of Rome, La Sapienza)

Past Graduate Students:

- John Smedley (Ph.D. 2001, University at Stony Brook, now Research Associate at BNL)
- Sandra Biedron (Ph.D. 2001, University of Lund, now staff at ANL),
- Alex Murokh (Ph.D. 2001, UCLA, now Research Associate at UCLA)

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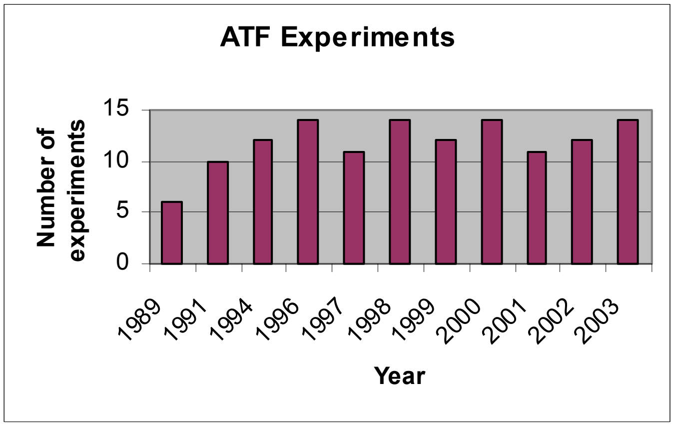


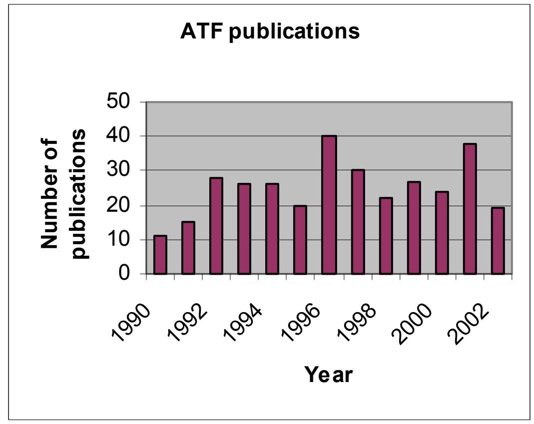
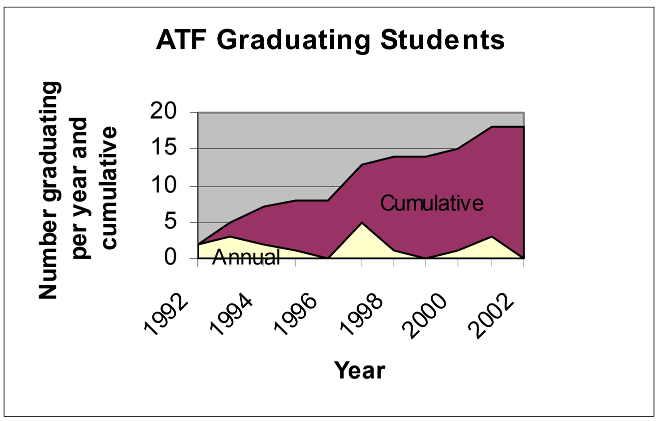


Figure1. The number of ATF experiments as a function of time.
Figure 2. ATF publications as a function of year, from 1990 to 2002.



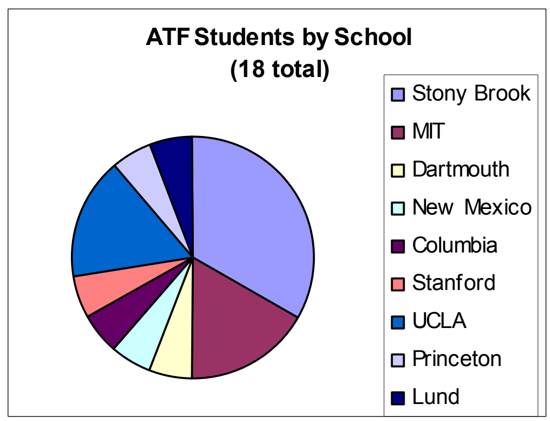


Figure 3. Graduate students by year of graduation (yellow) and cumulative total (red).
Figure 4. The distribution of 18 ATF graduate students by school.

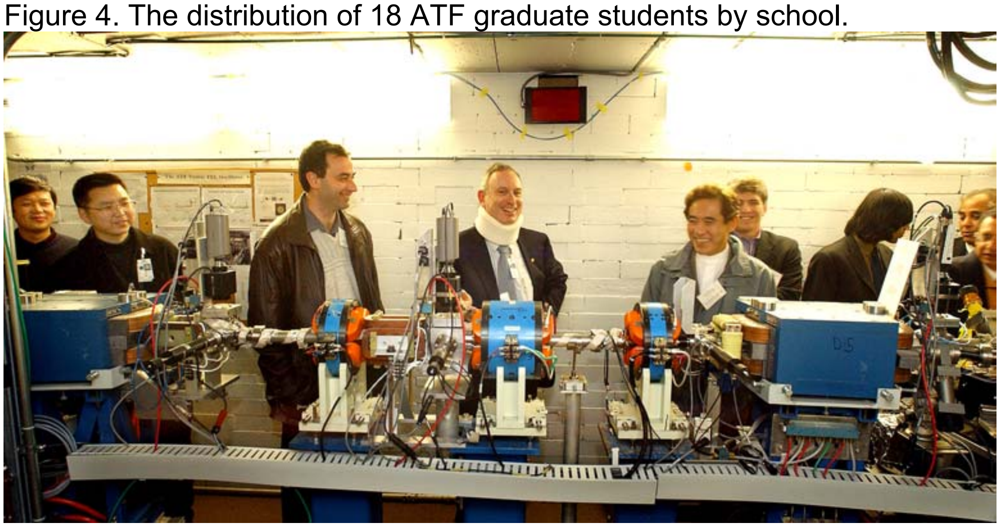


Figure 5. 2002 users' and Program Advisory Committee meeting at an ATF beamline.

Understanding limits to flux pinning in high-field superconductors for advanced accelerator magnets

Lance Cooley
University of Wisconsin – Madison (FY2000-2002)
Brookhaven National Laboratory (FY2003)

Summary:
This work explored flux-pinning mechanisms in Nb_3Sn and in other intermetallic superconductors to understand what the ultimate limits to accelerator magnet conductor performance might be. Four primary experiments were conducted: (1) An analysis of the flux-pinning properties of a powder-in-tube (PIT) Nb_3Sn strand showed that the usual flux-shear behavior gave way to more desirable core-pinning behavior when the temperature and field were adjusted to provide flux-line densities comparable to observed grain-boundary line length per unit area. (2) An investigation of the new superconductor $MgCNi_3$ uncovered extremely strong flux pinning, likely due to a nanostructure of precipitates. While such nanostructures are rare in intermetallic superconductors, this investigation suggested that very desirable pinning behavior, similar to that found in optimized Nb-Ti alloys, might be created by incorporating intragranular nanoprecipitates or nanoparticles in intermetallics such as Nb_3Sn. (3) Thin films of the new superconductor MgB_2 displayed mixed pinning behavior due to the competition between grain-boundary pinning and core pinning by nanoscale MgO precipitates. Thus, an alternative way to build core pinning in Nb_3Sn is to form a mixed nanostructure. (4) Simulations of the tin composition profile in PIT strands were carried out to understand the averaging effect of different experimental techniques. This suggested that HEP Nb_3Sn strands suffer large performance losses to the variation of tin content, which ranges from 18 to 25% in the superconducting A15 phase and is an inevitable consequence of diffusion reactions.

Recent Accomplishments:

(1) *Flux Pinning in PIT Nb_3Sn Strands with Grain Size Comparable to Flux-Line Separation*:

In collaboration with Lee and Larbalestier at Wisconsin, we examined a series of PIT Nb_3Sn strands with grain size between 50 and 120 nm. A series of short heat treatments (HT), 0.5 to 16 hours, at the manufacturer's recommended temperature of 675 °C were used to restrict grain growth. Scanning electron microscopy and digital image analysis conducted by Peter Lee showed that the initial layer of Nb_3Sn grains had ~50 nm size after the 0.5 h HT, which is about one-third that produced by the standard 47 h HT. Since the flux-line separation is 49 nm at 1 T field, it was thus possible to explore the limit of comparable grain size and flux-line separation, albeit within a very limited temperature range near the critical temperature T_c. Progressively larger grains were observed for longer heat treatment times.

We used magnetization measurements to determine the bulk pinning-force curves as a function of field and temperature. The central result from this experiment, published in [3], is that, by restricting temperature such that the irreversibility field H* was less than 1 T, the peak of the bulk pinning-force curve $F_p(H)$ was shifted to higher field for strands with smaller grains. Since Nb_3Sn is operated in HEP magnets at high fields, this shift is desirable. Other deviations from usual flux shear behavior were also observed at high temperatures when the grain size was less than 80 nm. These results suggest that the pinning force of grain boundaries can be directly summed in the limit that there are few flux lines per grain. However, this limit applied to only a very limited range of grain size and temperature, and flux shear behavior was obeyed to a high degree of accuracy outside of this range.

(2) *Core Pinning by Intragranular Nanoprecipitates in $MgCNi_3$*

A collaboration with others in the UW-ASC and with Princeton University analyzed a new superconductor, $MgCNi_3$. Analyses of magnetization data showed that this intermetallic superconductor has flux-pinning properties strikingly similar to the very desirable behavior found in Nb-Ti. Near T_c (about 7 K), $F_p(H)$ curve with the shape expected for flux shear and grain-boundary pinning was seen, the peak being at a low fraction (0.2) of the irreversibility field H*. However, the peak gradually shifted toward higher field as the temperature was reduced, until at 1.8 K it was at or slightly above 0.5H*. Such behavior has never been seen before in an intermetallic superconductor. And, since accelerator magnets operate at fields close to or above 0.5 H*, these measurements suggested that perhaps flux pinning could be adjusted to be more efficient even in the intermetallic Nb_3Sn.

Based on analyses of this same behavior in Nb48Ti by Meingast and Larbalestier [J. Appl. Physics 66:5971 1989], we concluded that there must be a significant volume fraction of core-pinning centers with a nanostructural scale comparable to that of the flux lattice at low temperature. These were confirmed by transmission electron microscopy, led by UW-ASC postdoctoral staff member Xueyan Song. At low temperatures, when flux lines are small in diameter, these precipitates provide strong interactions for all of the flux lines and give the core-pinning result. At higher temperatures, for which flux-line cores are much larger, the nanoscale variations of superconductivity became blurred, leaving underlying flux shear behavior. These results were published in [4]. The implication of these results is that a system of nanoprecipitates can easily defeat flux shear in an intermetallic superconductor. In addition, the strong pinning observed suggests that a nanoscale system of pinning centers might allow an intermetallic superconductor to move closer to ideal flux-pinning limits. This experiment is the basis for some of the new ideas we are pursuing.

(3) *Core Pinning Component in MgB_2 Thin Films*

After the discovery of superconductivity in MgB_2 in January, 2001, a large collaboration at Wisconsin was initiated to characterize initial samples and thin films. Of potential interest to DOE applications were the initial questions of what H*(T) is and whether the flux pinning properties provided insight to pinning mechanisms in intermetallic superconductors.
In one example, thin films with nanoscale grain size and high upper critical field H_{c2} also displayed unusual flux pinning behavior. In particular, Kramer plots were not linear, as expected for pinning by grain boundaries, but had a concave downward shape. Since this change would occur if direct summation and core pinning were dominant in at least part of the film, it was reasoned that nanoscale MgO particles, which were also present in the film, could provide potent core-pinning centers. By subtracting a linear background, a second component of the bulk pinning force was exposed, which indeed had the expected shape for core pinning.
It is believed that the high critical current density at 4.2 K of this film, above 1000 A/mm^2 at 10 T, is partly due to the presence of these strong core-pinning centers. Thus, in addition to intragranular core pinning centers found by experiment (2) above, a second possibility to defeat flux shear is to produce a fine nanostructure with nanoscale second phase particles. This work was publication number [5].

(4) *Calculations of the effects of tin gradients in PIT Nb_3Sn using a current-shell model*

An advantage of powder-in-tube Nb_3Sn for research is its tubular geometry, which is a very simple geometry for magnetization analyses when the field is parallel to the tube axis. Since the diffusion of tin is radially outward, a good model of the system of induced magnetization currents is given by concentric shells. Each shell can be considered to have slightly lower tin composition as the next shell inside it, since the innermost shell is next to the tin source and, according to the Nb-Sn phase diagram, must consist of the tin-rich limit of the superconducting phase. The outermost shell, next to unreacted Nb, must also consist of the tin-poor limit of the superconducting phase, and has the worst properties. Various gradients might occur between these extreme shells, which were simulated with increasing degrees of severity. Then from the radial variation of superconducting properties, it is possible to sum the magnetic moment of the shells, as would be measured in a magnetization experiment, and calculate resultant variations on the critical current density and other measured properties. While this work is still being finalized, it has already shown that properties derived from whole-sample currents, such as the irreversibility field, effectively average the tin composition profile, and are thus not as good as the properties that might be obtained if the stoichiometric composition Nb_3Sn were provided everywhere. Performance might increase by 25 to 50% by removing the gradients and their deleterious effects. This work will be submitted to J. Appl. Phys. in late 2003.

Selected Publications 2001-2003:

1. L. D. Cooley and P. J. Lee, "Shift of the flux-pinning force curve in Nb_3Sn thin films with very fine grain size," IEEE Trans. Appl. Supercond. vol. 11, pp. 3820-3827, 2001.
2. Cooley, L.D.; Eom, C.B.; Hellstrom, E.E.; and Larbalestier, D.C. "Potential application of magnesium diboride for accelerator magnet applications." In Proceedings of the 2001 Particle Accelerator Conference, edited by P. Lucas and S. Webber, v.1, pp. 203-207. Piscataway, NJ: The Institute of Electrical and Electronics Engi-neers, Inc., 2001.
3. L. D. Cooley, P.J. Lee, and D.C. Larbalestier, “Changes in flux pinning curve shape for flux-line separations comparable to grain size in Nb_3Sn wires,” Advances in Cryogenic Engineering (Materials) 48B, 925-932, 2002.
4. L.D. Cooley, X. Song, J. Jiang, D.C. Larbalestier, T. He, K.A. Regan, and R.J. Cava, “Core pinning by intra-granular nanoprecipitates in polycrystalline $MgCNi_3$,” Physical Review B vol. 65, p. 214518, 2002.
5. Lance Cooley, Xueyan Song, and David Larbalestier, “Improving flux pinning at high fields in intermetallic superconductors: clues from MgB_2 and $MgCNi_3$” IEEE Trans. on Appl. Supercond. vol. 13, pp. 3280-3, 2003
6. V. Braccini, L.D. Cooley, S. Patnaik, P. Manfrinetti, A. Palenzona, A.S. Siri, and D.C. Larbalestier “Significant enhancement of irreversibility field in clean-limit bulk MgB_2”, Applied Physics Letters, vol. 81, pp. 4577-9, 2002.
7. L. D. Cooley, P. J. Lee, and D. C. Larbalestier, "Conductor processing of low-Tc materials: the alloy Nb-Ti," Chapter B.3.3.2. of the *Handbook on Superconducting Materials*, ed. D. A. Cardwell and D. S. Ginley, Institute of Physics (London) 2002.

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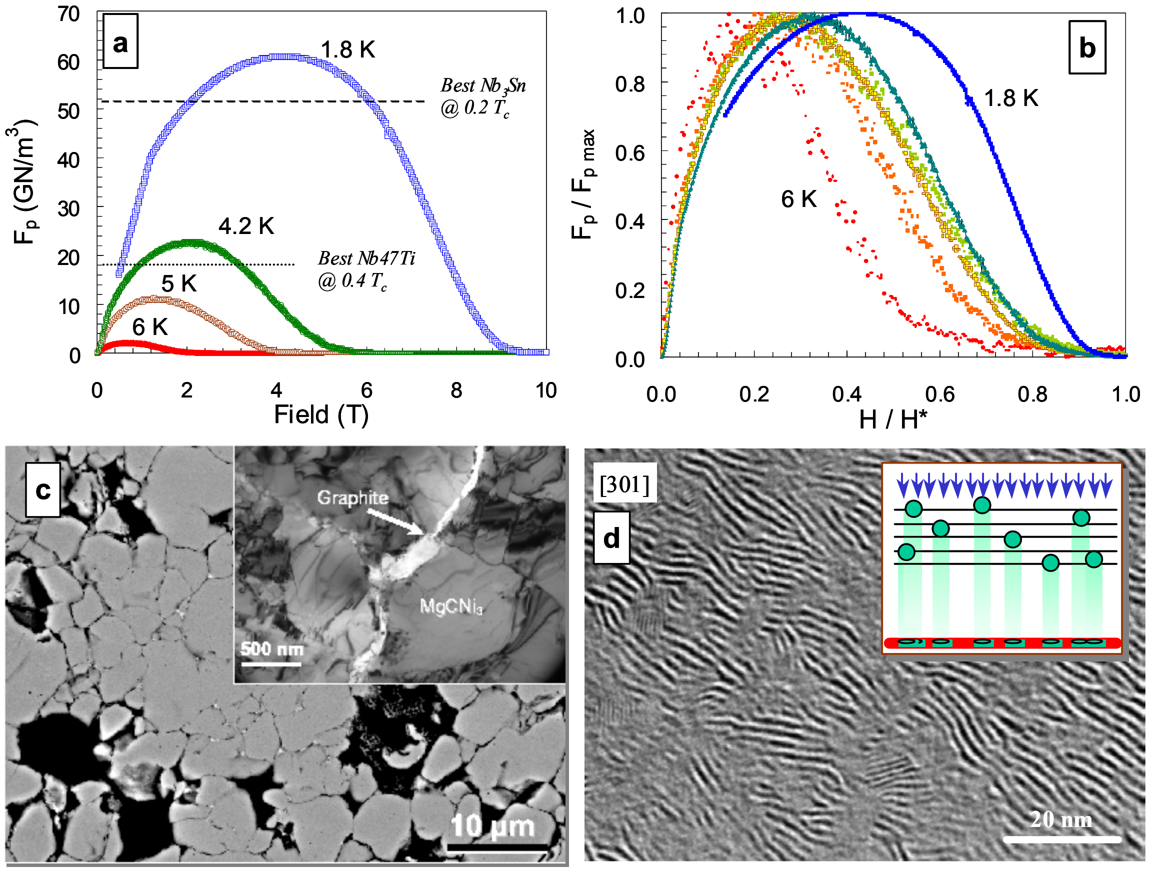

Fig. 1. Core pinning by intragranular nanoprecipitates in $MgCNi_3$. In plot (a), bulk pinning-force curves derived from magnetization data show very strong pinning, comparable to that in HEP conductors. In plot (b), a clear shift of the bulk pinning force curve shape with decreasing temperature is observed, from flux-shear behavior at 6.5 K to core pinning behavior at 1.8 K. The temperatures are (red to blue) 6.5, 6.0, 5.5, 5.0, 4.2, and 1.8 K. Transmission electron microscopy (courtesy X. Song) in (c) shows that clusters of $MgCNi_3$ grains are surrounded by thick carbon layers (carbon excess is required to get higher T_c). Based on these images, we assumed the magnetization currents flow over ~10 µm scales. While the $MgCNi_3$ grains in (c) do not show any evidence of a nanostructure to explain the flux-pinning properties, high-resolution imaging in (d) suggests the presence of many precipitates that interfere with the electron beam and produce Moiré fringe patterns. Domains in the fringe patterns (as illustrated in the inset) suggest the precipitate size is ~5 nm, comparable to the coherence length at low temperature but smaller than the coherence length near T_c. Thus, we believe that core pinning is effective at low temperature, which becomes smeared near T_c.

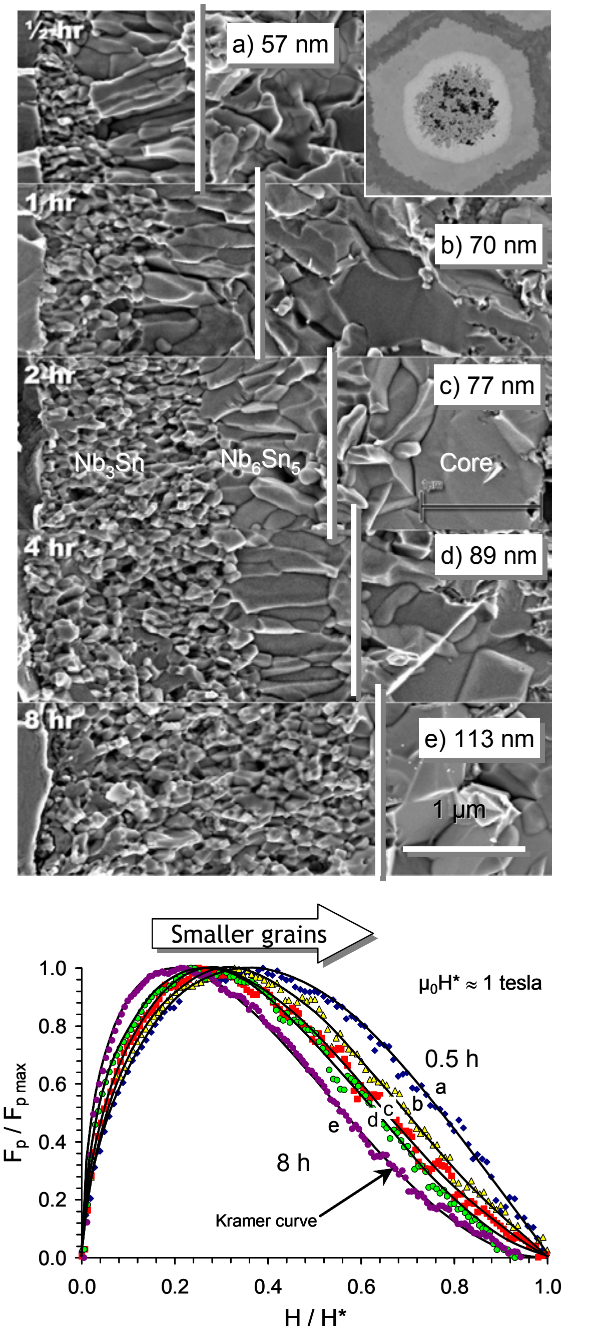

Fig. 2. Overview of PIT strand experiment. As shown in these SEM images (courtesy Peter Lee), the initial Nb_3Sn layer forms with 50 to 60 nm grain size after 0.5 h heat treatment at 675 °C. Longer times result in both significant layer growth and increase of the average grain size, as labeled on the images. Flux-pinning analyses at temperatures such that H^* = 1 T show that flux-shear behavior gives way to behavior more like direct summation as the grain size decreases, since the flux-line separation is comparable to the grain size.

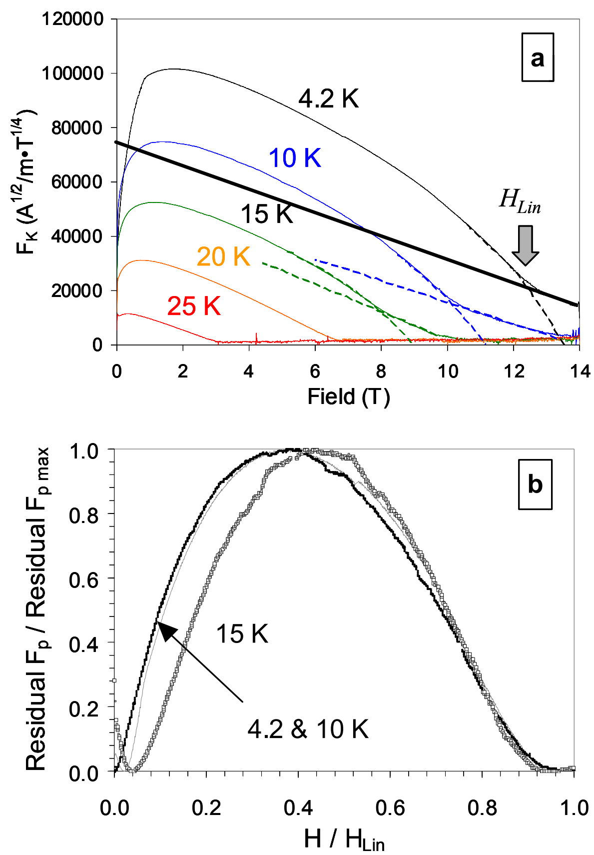

Fig. 3. Flux pinning analysis of the high-resistivity MgB_2 film. Kramer plots, which are proportional to $J_c^{1/2}$, are not linear but have concave downward curvature at low temperature, which would be consistent with linear dependence of $J_c(H)$. By subtracting a linear curve (shown for 4.2 K data in the top plot) and converting the resultant data to $F_p(H)$, curve shapes close to $h(1 - h)$ are seen, which is a signature of core pinning. This strongly suggests that MgO nanoprecipitates, which were observed by electron microscopy, are the dominant pinning center. This occurs despite also having MgB_2 grains with ~10 nm size, comparable to the flux-line separation. A possible explanation is that core pinning produces much stronger deformation of the flux lattice, bringing about a transformation from flux shear to direct summation.

Brookhaven National Laboratory Magnet Program

M. Harrison – Brookhaven National Laboratory

Summary:

The Superconducting Magnet Division (SMD) at Brookhaven National Laboratory (BNL) is developing “React & Wind” technology for future high field accelerator magnets. The program is based on two complimentary technologies: (a) racetrack coil magnets with “Rutherford” cables that operate at high currents and require fewer turns; and (b) slotted coil magnets with flexible cables that operate at lower currents and allow smaller bend radius. These technologies are being used to develop novel magnet designs for high field dipole magnets for main ring regions, and for high performance quadrupoles and dipoles for interaction regions.

High Temperature Superconductors (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 and 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 and Wind” technology must be used in making magnets with them.

BNL is also involved in developing magnet designs and technologies for an LHC (Large Hadron Collider) IR (interaction region) upgrade. The current plan is primarily based on Nb_3Sn superconductor (pole tip field in the range of 11-15 T); however, a significant part of the “React & Wind” magnet technology is common to both Nb_3Sn and HTS. This will allow BNL to adapt to HTS (from “coil R&D” to “magnet R&D”) if the HTS performance improves to the level needed. HTS technology, if developed in time, has the potential to offer major advantages in some scenarios.

Recent Accomplishments:

Nb_3Sn Cable Magnet Program:

The Nb_3Sn Cable Magnet Program at BNL is based on a rapid turnaround and cost-effective 10-turn coil program to scientifically develop various technologies. The coils have a minimum bend radius of 70 mm and a straight section of 300 mm, and require only 11 meters of cable to produce. One of these coils is shown in Fig. 1. Fig. 2 shows two of these coils in a common coil magnet configuration. The magnet structure is simple yet versatile enough to allow a variety of tests in various configurations (dipole, quadrupole, single coil test).

The next phase of this program is to build a ~12 T Nb_3Sn common coil magnet using “React & Wind” technology. This magnet, which is currently in the detail design phase, is being built to serve a dual purpose. In addition to testing future coils in a high background field configuration, it will also serve as a facility magnet for testing Nb_3Sn cable.

HTS Cable Magnet Program:

There has been steady progress in HTS cable (BSCCO 2212) and BNL's coil test program. For various HTS cable provided by Showa during the past several years, BNL has compared the critical current as a function of temperature, and noted a steady improvement in performance. As an end user of the HTS cable, BNL is pleased to see this progress.

There has also been a steady improvement in the uniformity of performance of HTS cable (BSCCO 2212) along the length. The present generation of cables shows much less variation (<10%, as per measurements in liquid nitrogen) in I_c and T_c along the length than the initial cables.

BNL has made several coils with HTS cable (BSCCO 2212) and HTS tapes (BSCCO 2212 and BSCCO 2223), and the results have been very encouraging thus far. The cable and coil test results for one case are given in Fig. 3, which shows the performance of HTS cable before coil winding (as measured in a short sample test fixture), and after coil winding. The measurements were taken in a background field provided by two "React & Wind" Nb_3Sn coils, in order to simulate the field and forces that would be present in a future high performance HTS magnet. The two curves in Fig. 3 indicate that no significant degradation in conductor performance has occurred as a result of the coil winding process. These results are encouraging given that the coil was made from Rutherford cable, and has a relatively tight bend radius of 70 mm.

Nb_3Sn Slotted Coil Program with Flexible Cable:

BNL is developing a technology where coils are wound in pre-machined slots on coil support tubes, using flexible pre-reacted Nb_3Sn cable. Reaction of the Nb_3Sn is a critical step, and the result is a cable that is flexible and free from breakage with normal handling. The cable is made from 0.33 mm diameter wires in a 6-around-1 configuration, with an overall diameter of 0.99 mm. It was placed in an oven for reaction of the Nb_3Sn, and the wires were prevented from sintering to one another by a coating of Mobil One motor oil. The cable was insulated with Kapton film, and wound onto a coil support tube.

A dipole coil using this small-diameter, pre-reacted Nb_3Sn cable has been built and tested successfully. This magnet is shown in Fig. 4. The slotted support tube subdivides the coil into many sectors, each independently supported, and can therefore control the Lorentz forces in high field magnets. This design has been used by BNL to build many successful helical dipole magnets for RHIC, using NbTi. The Nb_3Sn magnet quench performance is shown in Fig. 5. The highest quenches exceed 800 A and are near the short sample limit. This proof-of-principal result opens the door to a promising new approach to building high field magnets. While the Lorentz forces are high in any high field magnet, the slotted design inherently controls these forces, both in the 2D cross section and in the ends. A spacer plate atop each winding prevents the Lorentz force from crushing the slot.

Final Focus Magnet for Next Linear Collider:

For the Next Linear Collider, BNL is developing a final focus magnet that is sufficiently small so that the disrupted beam may pass outside the cryostat, despite the very small crossing angle. The design concept for this quadrupole magnet features two concentric coils - an inner coil consisting of five layers of single-strand conductor, and an outer coil consisting of four layers of seven-strand cable. The layers are wound on and bonded to a coil support tube using an 11-axis ultrasonic wiring machine. Because the magnet needs to be sufficiently small, one of the challenges is to wind small diameter coils with resultant tight bends in the conductor. BNL has performed several winding tests and the results have been quite promising. The first test coil consisted of a single layer dipole wound on a .075 inch diameter support tube (see Figure 6). This is by far the smallest magnet attempted to date using this technology. In a subsequent winding test, a 12 inch long double layer quadrupole coil was wound on a 1.5 inch diameter support tube (see Figure 7). With these tests, BNL has successfully demonstrated the ability to wind small diameter coils with the desired properties. Additional winding tests are planned and, later this year, BNL will produce and cold test a full-length (2 m) prototype of the inner coil.

Another challenge in the development of a final focus magnet is stabilization of the magnetic center. Because of offset sensitivity, cold mass motion relative to the cryostat, including that caused by ground motion and cryogenic system vibration, must be reduced to the nanometer level. BNL plans to perform vibration measurements in an effort to incorporate vibration minimization, including both active and passive damping systems, into future designs.

BNL has a diverse magnet program. In addition to the programs described above, it is examining rapid cycling superconducting magnets. Moreover, BNL is also looking into the application of the superconducting technology developed for accelerator magnets to other areas such as biological and medical sciences. It continues R&D on superconducting material and cable characterization.

Publications 2001-2003:

1. R. Gupta and M. Harrison, "*Interaction region magnets for VLHC*," International Conference on Magnet Technology (MT-17), Geneva, Switzerland (2001).
2. R. Gupta, et al., "*R & D for accelerator magnets with react and wind high temperature superconductors*", International Conference on Magnet Technology (MT-17), Geneva, Switzerland (2001).
3. J. Escallier, et al., "*Technology development for react and wind common coil magnets*", Particle Accelerator Conference (PAC), Chicago, IL (2001).
4. R. Gupta, et al., "*Next generation interaction region magnets for Hadron colliders*", Applied Superconductivity Conference, Houston, TX, (2002).
5. J. Cozzolino, et al., "*Magnet engineering and test results of the high field magnet R&D program at BNL*", Applied Superconductivity Conference, Houston, TX (2002).

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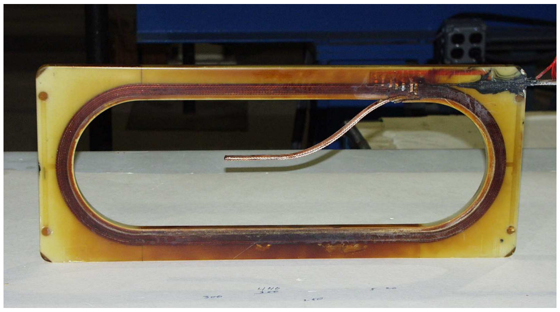

Fig. 1: A short 10-turn R&D coil built and tested using “React and Wind” technology.

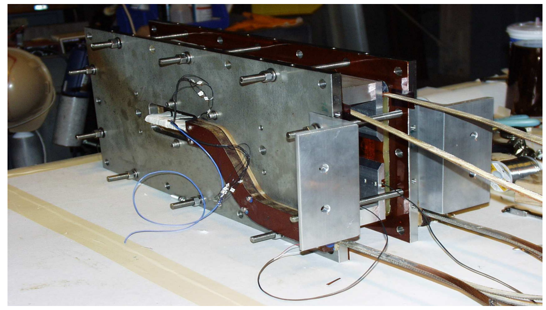

Fig. 2: An R&D magnet built using “React and Wind” technology.

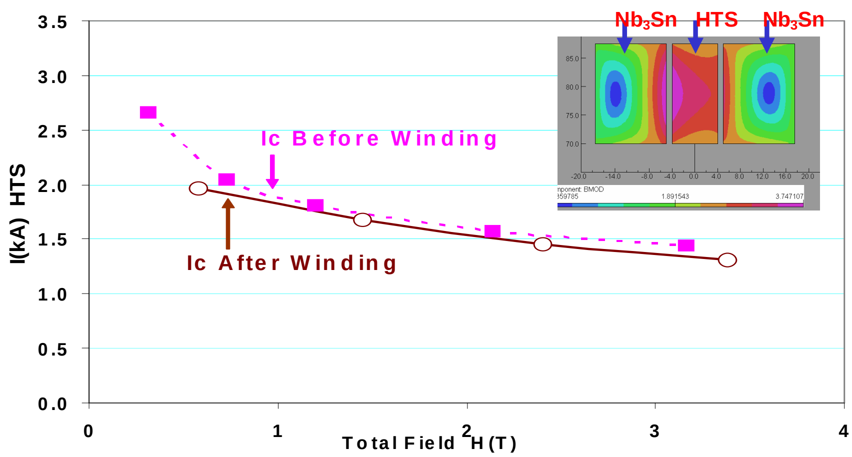

Fig. 3: Measured performance of HTS coil in a background field provided by two Nb_3Sn coils.

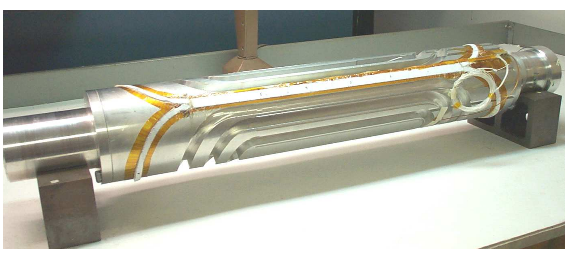

Fig. 4: Slotted magnet made with flexible Nb_3Sn cable.

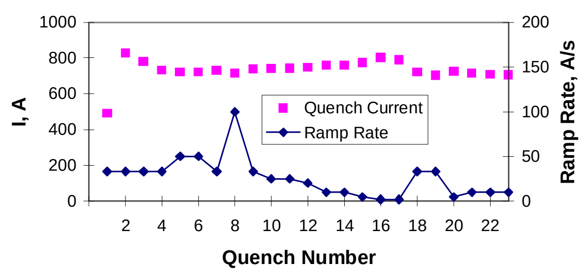

Fig. 5: Quench performance of slotted magnet made with flexible Nb_3Sn cable.

Figure 6: A single layer dipole coil test winding on a 0.75 inch diameter support tube.

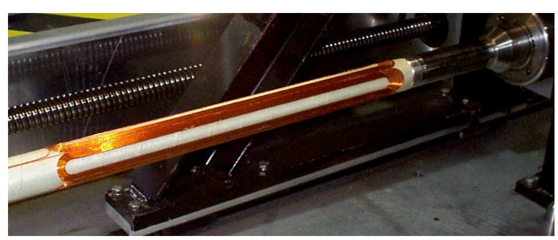

Figure 7: A double layer quadrupole coil test winding on a 1.5 inch diameter support tube. The coil length is 12 inches.

Fermilab Advanced Accelerator Magnet and Superconductor R&D Programs

A.V. Zlobin – Fermi National Laboratory

Summary:

Fermilab has a strong superconducting (SC) accelerator magnet R&D program, which is natural for a laboratory with the largest SC accelerator in the world, the Tevatron. The program goal is the development of new generation SC accelerator magnets with high operating fields and high operating margins for different applications. The possible applications include SC magnets for the Tevatron, particularly to replace some present dipoles and provide space for special devices, to replace existing low-β quadrupoles or to create a new interaction region (IR); SC magnets for a future Very Large Hadron Collider (VLHC); 2nd generation LHC IR dipoles and quadrupoles for luminosity upgrade; SC magnets for beam transfer lines, etc. In many cases, magnet requirements for upgrading existing and future machines push accelerator magnet technology to limits exceeding the present level based on NbTi superconductor. Our present SC Magnet R&D program is focused on Nb_3Sn accelerator magnets and explores two basic technologies used for brittle superconductors - wind-and-react and react-and-wind. Other superconductors and technologies will be also studied as soon as they become interesting for application in accelerator magnets. Fermilab has unique infrastructure to carry out short and full-scale model magnet R&D programs. The fabrication and test infrastructures include cable insulating machines, 2-m long and 15-m long winding machines, 1-m long coil HT oven, 6-m long epoxy impregnation facility, collaring/yoking presses, magnet test facilities with vertical (up to 4-m long) and horizontal (up to 15 m) cryostats with 1.8-4.5 K operation temperature, and a 30 kA power supply.

At the present time we are investigating two types of high-field dipole designs for the VLHC. One design is based on shell-type coils. This design approach is implemented in almost all NbTi SC magnets used in present high-energy accelerators. The other design is based on flat block-type coils arranged in the common-coil configuration. In this innovative design approach the coil radii are set by the aperture separation, not the aperture size, and hence, conductor bends are relatively gentle and friendly to brittle conductors such as A15's or HTS. Based on these basic design approaches, we have developed several innovative dipole magnets for the VLHC [1]. Fermilab participates in the U.S. LHC Accelerator Research Program (LARP). One of the LARP goals is to develop 2nd generation IR magnets for the LHC to replace the 1st generation magnets which have limited lifetime and will be one of the machine limiting systems. Contributions of Fermilab to LARP Magnet R&D include conceptual design studies of various magnet types. We will also participate in short and long model magnet R&D as well as in the design, fabrication and tests of full-scale prototypes of the LHC IR magnets. We expect strong connection between our basic high field program and the LARP magnet R&D program.

The development of new generation accelerator magnets requires advanced superconductors, structural materials and components. Fermilab is participating in national programs sponsored by DOE to encourage the development of improved superconductors and materials in U.S. industry. Fermilab has developed the adequate infrastructure to perform extensive material, superconductor and cable R&D. Our Short Sample Test Facility, which includes a 17 T solenoid in 2.2-4.2 K LHe dewar, three power supplies, control and DAQ systems, and a variable temperature insert, has been in operation for the last 5 years with testing rates of up to 40 samples per month. Our test current capability of single strands was recently upgraded to 2 kA. We also developed a 25 kA SC transformer for SC cable splice testing. A scanning electron microscope (SEM) and high-resolution optical microscope have been added to this facility in January 2001. A compact 28-strand cabling machine has been operated since February 2001.

Recent Accomplishments:
A series of single-bore cos-theta Nb3Sn dipole models based on the wind-and-react technique is being fabricated and tested. The magnet was designed for a nominal field of 12 T at 4.5 K of accelerator quality in a 43.5-mm diameter bore. Three short models were fabricated and tested in FY2001-2002. With these models we have achieved accelerator field quality but have not achieved yet the required field level. We are studying and optimizing the magnet technology and quench performance using half-coils and a magnetic mirror. Three mirror magnets were tested during January-May 2003. The next, the 5th dipole model, will be fabricated and tested in December 2003. Fabrication of common coil dipole models, based on a single-layer coil and a wide pre-reacted Nb_3Sn cable has also been started. This magnet was designed for a nominal field of 11 T at 4.5 K with accelerator quality field in a 40-mm bore. Mechanical models of this magnet have been fabricated and studied in FY2002. The 1st common coil short model has been fabricated and will be tested in July 2003. Experimental studies and optimization of react-and-wind techniques are performed using sub-sized cable and flat 1-m long racetrack coils. Two react & wind Nb3Sn racetracks have been fabricated and tested in FY2001-2002 and a third in FY2003. The last two racetracks reached 75-78% of their short sample limit. We are planning production and test of 2-3 model magnets per year. The goals are understanding and improvement of magnet technologies, quench performance, and field quality. When basic problems are understood, we plan to increase the production and tests of HFM models to 5-6 per year. We are also planning to develop infrastructure and start fabrication of long models starting in FY2006.

We are studying different Nb_3Sn strands produced using “Internal Tin”, “Distributed Tin”, “Modified Jelly Roll”, and “Powder in Tube” methods. Strand studies include measurements of critical current, magnetization, SEM studies and chemical analysis, and heat treatment optimization. Rutherford-type cables made of different Nb_3Sn strands are also being developed and studied. The studies include the effects of cable design and geometry on the critical current degradation due to cabling, cable bending and compression, cable stabilization with Cu tapes, and interstrand resistance measurements. We have accumulated a comprehensive data set on degradation of Rutherford-type cables made of different strands as a function of their packing factor.

High field Nb_3Sn magnets have significant coil magnetization effects due to large effective filament sizes. In order to reduce this effect, a simple passive correction technique based on thin iron shims has been developed and successfully tested. This approach leads to significant increase of the dynamic range of accelerator magnets and relaxes the requirements on the effective filament size in Nb_3Sn strands.

Insulation is one of the key elements of magnet design, which determines the electrical, mechanical, and thermal performance as well as lifetime of the magnet. Wind-and-react techniques impose demanding requirements on the magnet insulation which must withstand a long high-temperature heat treatment under compression. Ceramic insulation with a liquid ceramic binder, which meets these requirements, is being studied and optimized at Fermilab in collaboration with industry. Recently we have fabricated and tested a coil with a ceramic pre-preg. The react-and-wind technique allows using traditional insulating materials (Kapton, fiberglass). To avoid Ic degradation during cable insulation, we co-wind insulation tapes with the cable (instead of wrapping the cable) in our racetracks and common coil magnets.
Nb_3Sn coils are impregnated with epoxy to improve their mechanical and electrical properties. The low radiation limit for epoxy sets the lifetime of the magnet. Various commercially available polyimide solutions are being investigated to replace epoxy as an impregnation material for Nb_3Sn coils. The applicability of these solutions is determined by their viscosity and potlife. The mechanical, thermal and electrical properties of “ten-stack” samples impregnated with the polyimide solution Matrimid® 5292 have been measured and compared with epoxy-

impregnated samples. These studies will be continued on practice coils and then tested in model magnets.

Complicated end parts in case of wind-and-react techniques have to withstand the heat treatment and match the cable shape to avoid shorts. An optimization method for metallic end parts was developed at Fermilab and used together with the rapid prototyping techniques. This approach has reduced the time and cost of end part development. Water jet machining was used for end part fabrication resulting in the reduction of their cost by a factor of 3 (even more in the future) and the manufacturing time by a factor of 10 while providing good part quality.

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- Imbasciati L. – Ph.D., Vienna Technical University (Austria), 2003.
- Fratini M. – Laurea degree, Pisa University (Italy), 2001, now at CEA Saclay (France).
- Mattafirri S. - Laurea degree, Pisa University (Italy), 2002, now at LBNL.
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Figure 1: Single-bore two-layer cos-theta dipole (left), double-bore single-layer common coil dipole (center), large-bore 2nd generation LHC IR quadrupole (right).

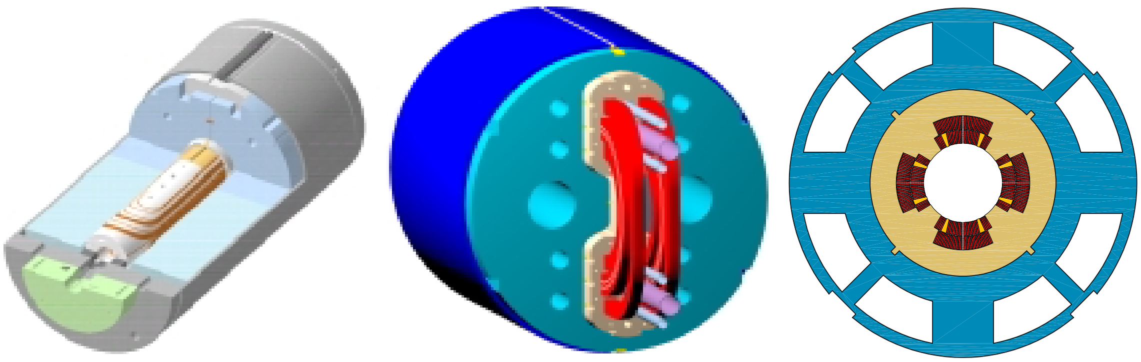

Figure 2: Cos-theta half-coil assembled with iron half-cylinders (left), mirror magnet with bolted skin (center), cos-theta model prepared to cold tests (right).

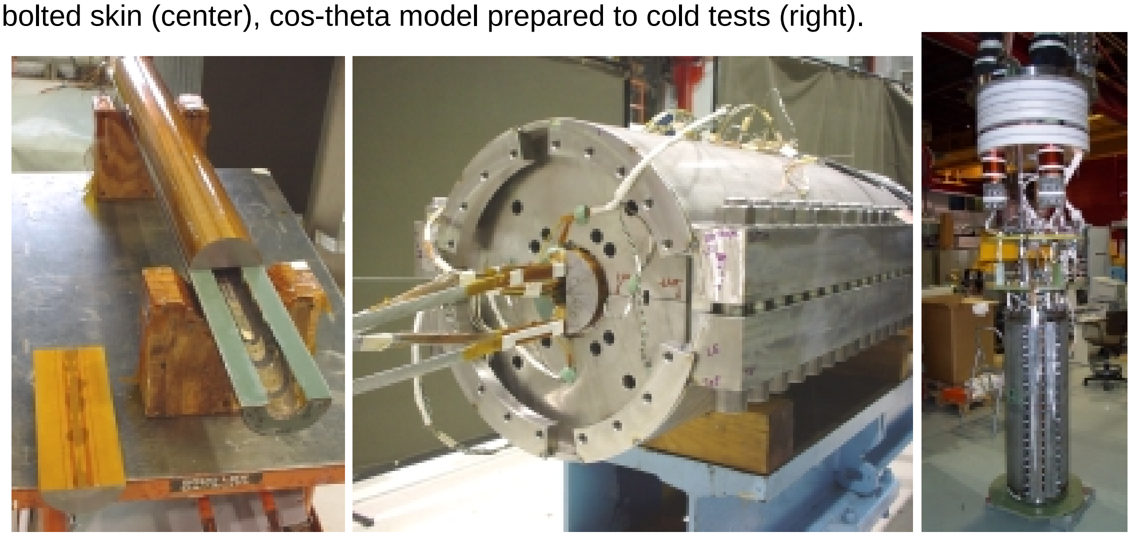

Figure 3: Collared coil of the common coil dipole after impregnation (left), flat racetrack coil winding (center), racetrack assembly prepared to cold tests (right).

Beam Electrodynamics Studies at Berkeley Lab

John Corlett – Lawrence Berkeley National Laboratory

Summary:

The interactions, electromagnetic in origin, between charged particle beams and their environment result in increasing variety and difficulty of the radiofrequency and microwave manipulations required by existing and future accelerators. This generates an acute need for specialists in electromagnetic interactions, components, and systems for the production, acceleration, control, and diagnostics of charged particle beams. The Beam Electrodynamics Group (BEG) provides core expertise and facilities for the study and control of the electromagnetic interactions between charged particle beams and their environment.

Accelerator physics and technology issues related to intense, short, well-focused charged particle bunches form a primary theme of the group's R&D. Interaction of these beams with accelerator components and diagnostic devices is always electromagnetic in origin, and so measurement and control will involve both low-level and high-power microwave and radiofrequency (rf) technology. Ultra-short (picosecond scale) bunches will have broad frequency spectra reaching up to tens 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 Lambertson Beam Electrodynamics Laboratory (LBEL), named for retired former group leader and mentor Glen Lambertson, provides experimental facilities for low-power test and measurement of rf and microwave devices and systems. The laboratory is equipped with network analyzers, spectrum analyzers, time-domain reflectometers, bead-pull apparatus, and beam impedance measurement apparatus. The BEG also maintains a workstation dedicated to running electromagnetic analysis and design software, including the fully three-dimensional code MAFIA, and 2-D codes including ABCI and URMEL. 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.

We draw upon this extensive knowledge and understanding of electromagnetic fields and waves, and on microwave and rf technologies, to design accelerator systems and components and to combat deleterious effects arising from beam-environment interactions.

Recent Accomplishments:

Recent accomplishments include development of novel radiofrequency accelerating structures for muon beams, including successful demonstration of high-power “pillbox” cavities with thin metallic windows, development of storage ring lattices for reducing the emittance of electron and positron beams, successful demonstration of a new optical technique for longitudinal density measurement of charged particle bunches, and analysis of the effects of harmonic cavities on instabilities in high-current storage rings.

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12. "Update to the NLC injector system design", J.C. Sheppard, S.D. Anderson, Y.K. Batygin, V.K. Bharadwaj, J.E. Clendenin, P. Emma, K.S. Fant, Z. Li, B. McKee, M.H. Munro, C.D. Nantista, N. Phinney, C.E. Rago, T.O. Raubenheimer, M.C. Ross, D.C. Schultz, C.M.

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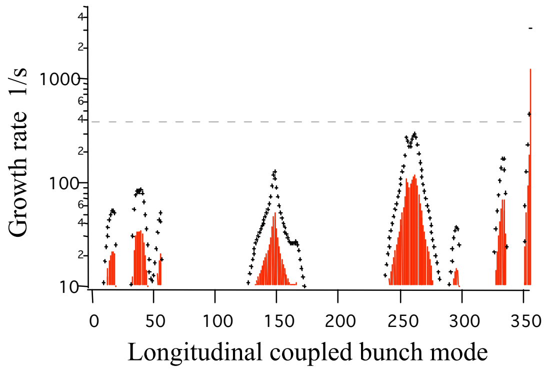
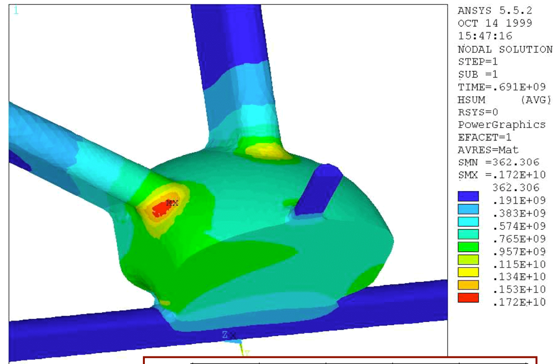
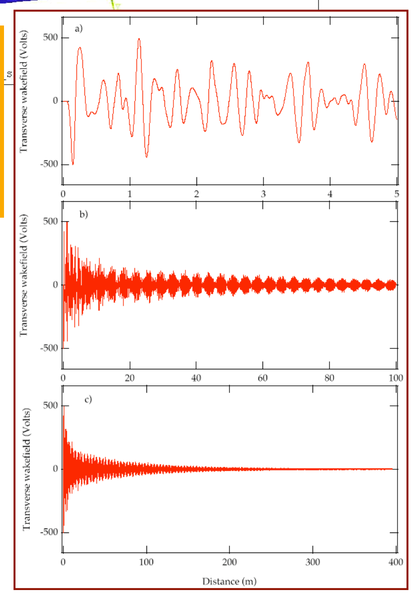
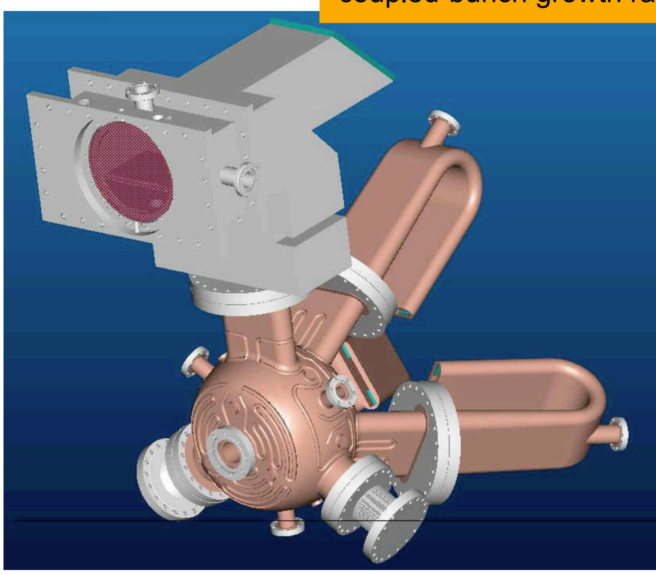
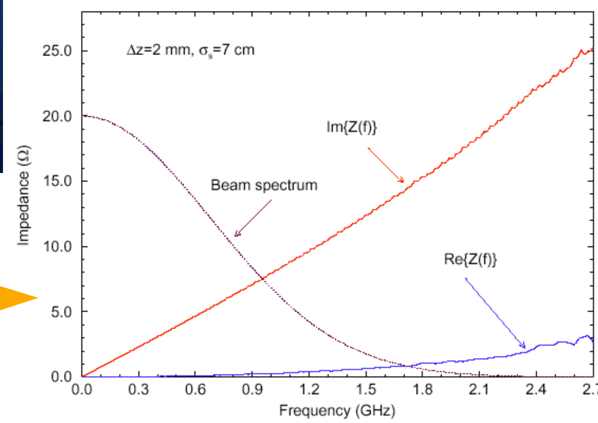




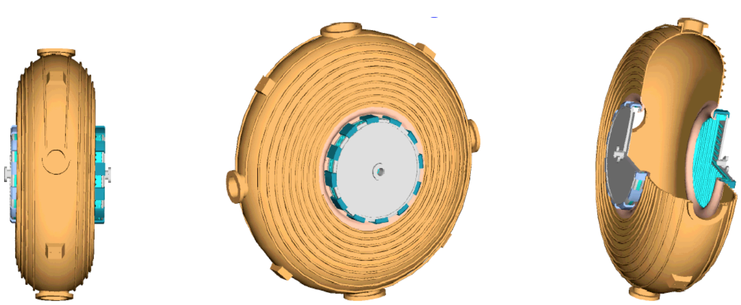


Higher-order-mode damped accelerating cavity design – including thermal analysis, wakefields, and resultant coupled-bunch growth rates





Impedance analysis of a collider interaction region



Conceptual design of a muon acceleration cavity

Advanced Accelerator R&D

Miguel A. 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:

* Developed a very detailed probabilistic model for the secondary electron emission process and fixed model parameters by fitting to measured data for stainless steel and copper. The model is fully incorporated into our electron-cloud simulation code POSINST.
* Extended POSINST to deal with very long bunches. With this improvement, the code is now applicable to high-energy, short-bunch storage rings (such as light sources or e^+e^- colliders), as well as to low-energy intense proton rings (such as spallation neutron sources).
* Calibrated POSINST against measurements at the APS and the PSR; agreement is within ~50% or better, depending on which quantity is studied.
* Applied POSINST to SPS simulations, and compared against other codes and measurements. Agreement is satisfactory.

* In collaboration with the AMAC group (LBNL), augmented beam-beam code from a gaussian description to a PIC description. In addition, code is fully parallel, allows for crossing angles collisions, bunch length effects, and parasitic collisions.
* Tested beam-beam code against measurements at RHIC with good agreement.
* Applied beam-beam code to TEVATRON and LHC simulations.

* 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. Additionally it allows to drastically reduce power requirement for the amplifier and to relax the requirements for the path length stability of the beam transport system.
* Applied the new scheme to cooling gold ions in RHIC; this work is presently pursued in collaboration with the particle-cooling group at BNL.

* Developed a unified framework for laser acceleration of relativistic electrons in vacuum, gases or plasmas, by combining the principle of alternating gradient acceleration and the concept of over-sized open optical waveguides.
* Identified and clarified the acceleration mechanism of inverse transition radiation acceleration within this scheme.
* Initiated the study of a proof-of-principle experiment to demonstrate this new acceleration scheme at BNL ATF.

* In collaboration with J. Wurtele's group (UCB), we have formulated the 3D coupled equations of laser-plasma interaction for stimulated Raman backscattering.
* Found a general formal linear solution for the propagation of the Raman-amplified short pulse laser in arbitrary inhomogeneous plasma.

* Developed a universal Hamiltonian perturbation technique, and found the system Green function for Raman pulse propagation and amplification.
* Continued the development of the theory of hollow plasma channels for laser acceleration; we can now calculate structure properties analytically in simple geometries, and simulate with both fluid and particle-in-cell (PIC) codes.
* Found a new phenomena in plasmas, namely induced transparency at the cyclotron frequency. Using this effect, we are investigating novel plasma-based ion accelerators with gradients in the range of 10-40 MeV/m and adjustable phase velocity of the accelerating wave.

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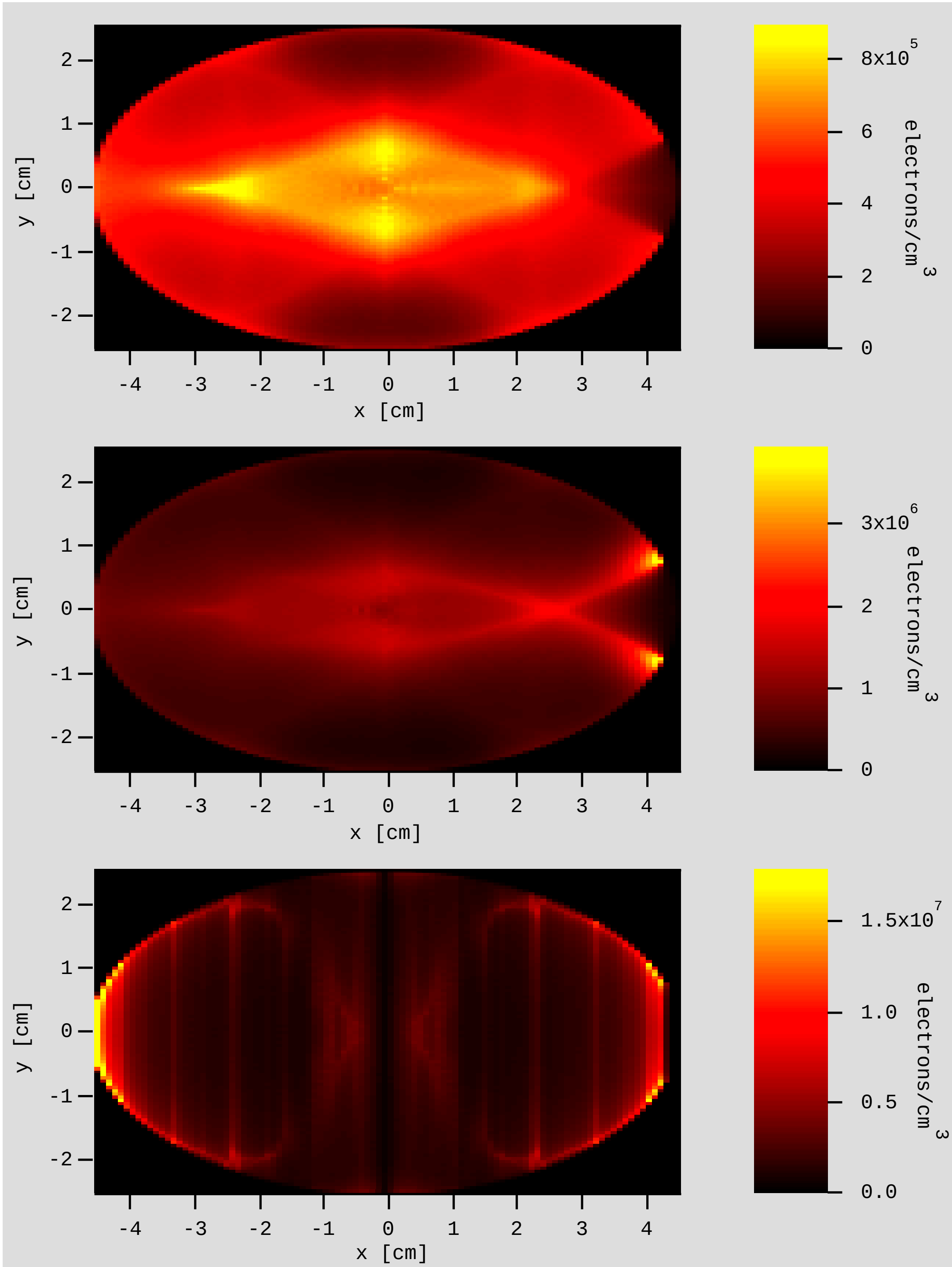

Color-coded plots of the simulated time-averaged electron cloud density in the arcs of the positron ring of PEP-II obtained with the simulation code POSINST. Top: in a field-free pumping section, assuming a photon reflectivity R~1. Center: same, except R=0. Bottom: in a bending magnet, R~1. The beam (not shown) is of size ~1 mm and travels perpendicular to the page at the center of the chamber. The antechamber slot is of full height 1.5 cm and is at the right side of the chamber.

Superconducting Magnet Program

S. Gourlay – Lawrence Berkeley National Laboratory

Summary:

The LBNL Superconducting Magnet Program (http://supercon.lbl.gov) is directed towards advancing all aspects of the technological infrastructure for high field magnet development relevant to possible future accelerators. Our mission statement guides the general activities of the program:

Develop and establish the technologies associated with high field superconducting magnets in order to provide cost-effective options for the next-generation high-energy physics accelerators. Apply our expertise towards achieving the goals of the High Energy Physics community.

Our recent progress has firmly established our program as a world leader in the development of high field dipole magnets using Nb_3Sn. In the past few years the LBNL Superconducting Magnet Program achieved a number of key milestones in both magnet fabrication and materials development work. Following the record-breaking success of RD3-b, a dual-bore, racetrack magnet that reached a field of 14.5 Tesla, a second racetrack dipole, RD3-c, incorporating a field quality geometry, was successfully tested in the spring of 2002. The calculated and measured geometric harmonics are given in the accompanying figure. The RD-3c magnet book that details all aspects of the design, modeling, construction, and test results is almost completed.

Recent Accomplishments:

Our current project is the construction of HD-1, a single-bore magnet using racetrack coils. HD-1 is designed to push the dipole field limit beyond 16 Tesla. The cross section and field profile in the coils are shown in the accompanying figure. The main magnet program is extensively supported by conductor studies and work on sub-sized model magnets. The sub-scale magnet program is now well underway with five tests completed and several more planned for this year. Sub-sized models are used to test support structure designs, investigate new coil geometries and evaluate cable designs. If new materials such as Nb_3Al, MgB_2 or Bi-2212 become available in sufficient quantity and with good properties, coils can be fabricated and tested in the sub-sized models.

Conductor studies include cabling work to reduce I_c degradation and techniques for cabling new conductor designs such as powder-in-tube, heat treatment studies to optimize the residual resistivity ratio and J_c, and the effect of transverse strain on degradation and the relationship of strain degradation to the conductor sub-structure. LBNL continues to provide significant cabling support for other magnet and cable development programs.

We continue to study ancillary issues that support high field magnet development. For example, in collaboration with industry, we are working on cost and performance improvement of conductor and insulation. In FY00 the Advanced Technology R & D Group of the DOE Office of High Energy Physics initiated a Conductor Development Program, which is managed by LBNL for the purpose of developing reliable commercial sources of high performance, low cost superconducting wire ($1.50/kA-m at 12T and 4.2K) for application in HEP-supported magnet development programs.

The program has several target specifications, the highest priority has been to attain a non-Cu critical current density (J_c) of 3,000 A/mm^2 at 12T and 4.2K. This was achieved in Nov. 2002 by one of the industrial sub-contactors, Oxford Superconducting Technologies. Our group was one of the first to be able to measure this high current conductor. A typical current versus voltage curve for 4.2K and 12.38T with self-field, is shown in the accompanying figure. The emphasis of the program is now turning to the second-priority goal – reducing the effective filament size to 40 microns without sacrificing the gains in J_c. Using the new knowledge gained from this research as a base, the program will then move into a fabrication scale-up phase where the performance and cost-effectiveness can be demonstrated in production-size quantities.

This year the group is working on two Laboratory Directed R&D (LDRD) projects. One is “Superconducting Magnet Systems for Ex-situ NMR Spectroscopy” and the other is “Short Period Superconducting Undulator Development.” Both projects are highly leveraged by the materials and techniques developed in the base program. In ex-situ NMR, a mobile magnet is scanned over an otherwise inaccessible object or subject in order to acquire magnetic resonance information. The quality of the ex-situ NMR data, and the development of ex-situ NMR techniques, would greatly benefit from the availability of higher field strength provided by Nb_3Sn. A fully optimized superconducting magnet using advanced conductors can be expected to achieve an additional increase of the field strength by a factor of at least 2-3 compared to other options.

Development of short-period, narrow-gap superconducting insertion devices is critical to applications in both future synchrotron radiation sources and in existing rings. The LDRD is addressing this requirement by developing and implementing beyond state-of-the-art Nb_3Sn superconductor/copper matrix technology.

The success of our program has been recognized internationally by the acceptance of Nb_3Sn as the material of choice for proposed LHC upgrades. The new LHC Accelerator Research Program will be an important application of the technology the LBNL group has been developing, helping to drive it well beyond state-of-the-art, significantly enhancing U.S. options in accelerator technology and providing opportunities for new applications.

<u>Publications 2001-2003</u>:

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2. Caspi, S., et al, “Nb_3Sn quadrupole magnets for the LHC IR,” presented at the Applied Superconductivity Conference (ASC), Houston, TX, August 4-9, 2002, SC-MAG #764, LBNL-49901.
3. Scanlan, R.M., et al, “Ac loss and interstrand contact resistance in bare and coated NbTi/Cu Rutherford cables with cores,” published in Superconductor Science and Technology, V14, I11, pg. 888-897. SC-MAG #776, LBNL-50185, 5/13/2002.
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15. Dietderich, D.R., et al, “New testing procedures, probe, and sample holder for testing high current Nb_3Sn conductor,” to be presented at the Cryogenic Engineering Conference (CEC), International Cryogenic Materials Conference (ICMC), September 22-26, 2003, Anchorage, Alaska, SC-MAG #804, LBNL-52546.
16. Dietderich, D.R., et al, “Test results of a 30mm period undulator fabricated with Nb_3Sn conductor,” to be presented at the Cryogenic Engineering Conference (CEC), International Cryogenic Materials Conference (ICMC), September 22-26, 2003, Anchorage, Alaska, SC-MAG #805, LBNL-52547.
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21. Sabbi, S., et al, “Superconducting magnet systems for ex-situ spectroscopy,” to be presented at the 18th International Conference on Magnet Technology, Morioka, Japan, October 20-24, 2003, LBNL-53130, SC-MAG#815.

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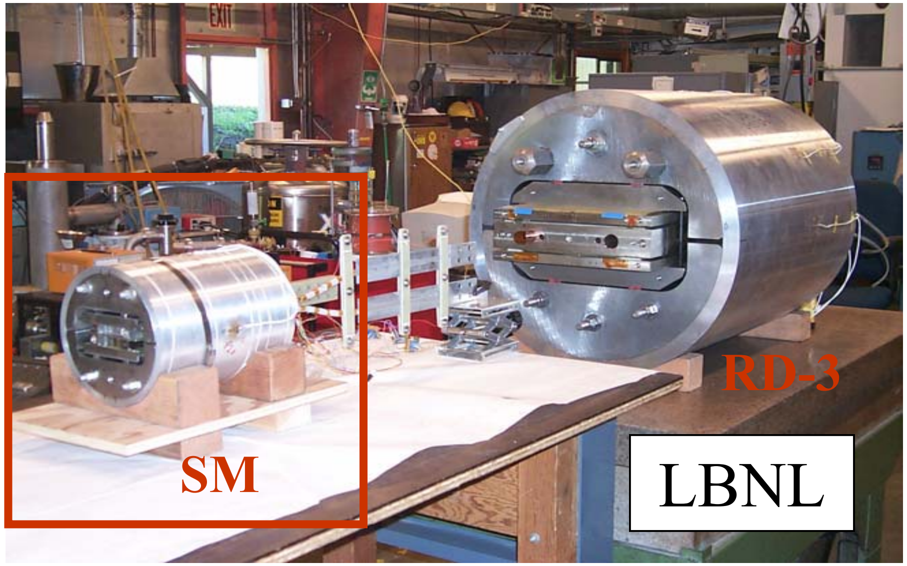
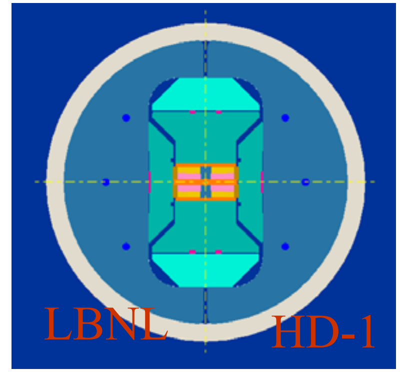
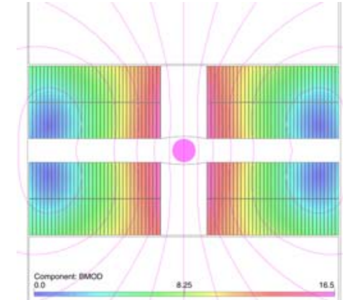






Coil cross-section with field profile

HD-1

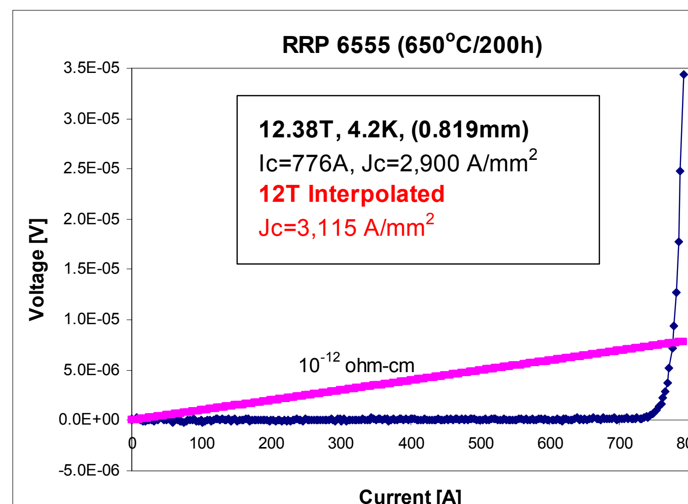
Bore field B_o> 16T
Maximum Stress~150MPa

SM Series Magnet Tests	Outcome
SM-02 Mixed Strand	Low quench performance
SM-03 Mixed Strand	Better performance
SM-04 CTC/FNAL Ceramic Insulation	Excellent performance
SM-05 Stress/Temperature Limits	Excellent performance

RD-3c Geometric Harmonics at 10^{-4} level in a 35mm bore

Normal	calculated	measured
b_3 (unit)	-5.44	-10.39
b_5 (unit)	-0.24	-0.02
b_7 (unit)	0.58	0.61
b_9 (unit)	<0.01	<0.01

I_{op}=10 kA,
R_{ref}=10 mm



Optical-Accelerator Experiments at Berkeley Lab

Wim Leemans – Lawrence Berkeley National Laboratory

Summary:

The l'OASIS Group (Laser Optics and Accelerator Systems Integrated Studies) of LBNL's Center for Beam Physics conducts experimental and theoretical R&D on the interaction of high intensity lasers with particle beams and plasmas. The current program is centered around the development of a 1 GeV laser driven accelerator and consists of three parts: (i) study of an all-optical injector via laser triggered injection of electrons in a plasma structure, (ii) guiding of high intensity laser beams (10^{18} W/cm^2) over macroscopic distances (1- 10 cm scale length) in a plasma channel and (iii) development of beam diagnostics with femtosecond resolution for measurement of the beam's phase space properties.

The experiments are done at the l'OASIS facility which houses a multi-terawatt Ti:sapphire laser system that can deliver five different beams to the target. One beam has peak power up to 10 TW in 50 fs, two of the beams have peak power at the 3 TW level, one beam contains up to 250 mJ in 200 ps and the fifth beam is a frequency doubled (blue, 400 nm) probe beam. A sixth beam is under construction and will deliver up to 100 TW peak power in a 40 fs duration pulse. All pulses are derived from a single oscillator pulse and hence are intrinsically synchronized, limited by path length variations. The facility has been equipped with a radiation shielded experimental cave and radiation interlock system, as well as a remote control room, allowing operation at high repetition rates while producing significant radiation doses. Electron beams containing a significant fraction of electrons with energy > 50 MeV are routinely produced and have been used to activate positron emitters such as ^{11}C and ^{18}F. A double focusing magnetic spectrometer was installed that allows careful parametric studies of the dependence of the electron energy spectrum on laser and plasma parameters.

The theory and computational efforts of the Group are focused on new concepts and analysis of ongoing experiments at the l'OASIS 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 (PIC) codes for self-consistent modeling of the laser-plasma interactions, including particle trapping and acceleration.

Recent Accomplishments:

We have succeeded in the first experimental demonstration of laser pulse shape effects on the electron yield in a laser driven accelerator [W.P. Leemans et al., Phys. Rev. Lett. **89**, 174802 (2002)]. Modeling of the self-modulated and Raman forward scattering laser instabilities in the presence of laser chirp supports the experimental observation that laser pulse shape is much more important in practical parameter regimes than laser chirp [C.B. Schroeder et al., Phys. Plasmas **10**, 285-295 (2003)]. We have observed 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. accepted; C.B. Schroeder et al., submitted]. This mechanism provides the opportunity to diagnose the laser accelerated beams at the exit of the accelerator. We also have succeeded in guiding laser beams with relativistic intensities using a preformed plasma channel created by the ignitor-heater method over more than 25 Rayleigh lengths [C.G.R. Geddes et al., in preparation]. As a first step towards implementing the "colliding pulse" optical injection method, [E. Esarey et al., Phys. Rev. Lett. **79**, 2682 (1997)], we also have observed electron yield enhancement when using a second laser pulse intersecting the driving laser pulse at an angle of 150˚. The colliding pulse injection method is expected to produce low emittance (1 π mm-mrad), low energy spread (1%), 40 MeV femtosecond electron bunches containing >10^7 electrons per bunch. Combining this injector with 5-10 cm long plasma channels will be attempted for a 1 GeV module using the new 100 TW, 10 Hz laser system.

<u>Publications 2001-2003</u>:

<u>Refereed Journals</u>

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2. D. L. Bruhwiler, R.E. Giacone, J.R. Cary, J.P. Verboncoeur, P. Mardahl, E. Esarey, W.P. Leemans, and B.A. Shadwick, "Particle-in-cell simulations of plasma accelerators and electron-neutral collisions", *Phys. Rev. Special Topics - Accel. Beams **4***, 101302, October 2001, LBNL-50725.
3. P.X. Wang, Y.K. Ho, X.Q. Yuan, Q. Kong, N. Cao, L. Shao, A.M. Sessler, E. Esarey, E. Moshkovich, Y. Nishida, N. Yugami, H. Ito, J.X. Wang, and S. Scheid, "Characteristics of laser-driven electron acceleration in vacuum", *Journal of Applied Physics,* Vol. **91**, pp. 856-866, January 2002, LBNL-49103.
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5. C.E. Clayton, B.E. Blue, E.S. Dodd, C. Joshi, K.A. Marsh, W.B. Mori, S. Wang, P. Catravas, S. Chattopadhyay, E. Esarey, W.P. Leemans, R. Assmann, F.J. Decker, M.J. Hogan, R. Iverson, P. Raimondi, R.H. Siemann, D. Walz, T. Katsouleas, S. Lee, and P. Muggli, "Transverse envelope dynamics of a 28.5 GeV electron beam in a long plasma:, *Phys. Rev. Lett. **88***, 154801, April 2002, LBNL-50726.
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9. E. Esarey, P. Catravas and W.P. Leemans, "Thomson scattering sources of fs x-rays based on laser wakefield accelerators", 21st ICFA Beam Dynamics Workshop on Laser-Beam Interactions, *Phys. Rev. Spec. Topics Accel. Beams (2002),* LBNL-50728.
10. W.P. Leemans, P. Catravas, E. Esarey, C.G.R. Geddes, C. Toth, R. Trines, C.B. Schroeder, B.A. Shadwick, J. van Tilborg, and J. Faure, "Chirp induced asymmetries and enhancement of electron yield in a laser plasma accelerator", *Physical Review Letters*, Vol. **89**, 174802, October 2002, LBNL-49856.
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13. C.B.Schroeder, E. Esarey, C. Toth, J. Faure, C.G.R. Geddes, J. van Tilborg, B.A. Shadwick, and W.P. Leemans, "Frequency chirp and pulse shape effects in self-modulated laser wakefield accelerators'', *Physics of Plasmas*, vol. **10**, no. 5, pp. 2039-2046, LBNL-52176, May 2003.
14. R.M.G. Trines, L.P.J. Kamp, T.J. Schep, W.P. Leemans, E.H. Esarey, and F.W. Sluijter, "Enhancement of fast-electron generation through suppression of Raman backscattering''*, Phys. Rev.*, LBNL-52175 (2002).
15. W.P. Leemans, C.G. R. Geddes, J. Faure, C. Toth, J. van Tilborg, C.B. Schroeder, E. Esarey, G. Fubiani, D. Auerbach, B. Marcelis, M.A. Carnahan, R. A. Kaindl, J. Byrd, and M. C. Martin, "Observation of THz emission from a laser-plasma accelerated electron bunch crossing a plasma-vacuum boundary", submitted to *Phys. Rev. Lett.*, April 2003, LBNL-52554.

16. D.L. Bruhwiler, D.A. Dimitrov, J.R. Cary, E. Esarey, W. Leemans and R.E. Giacone, “Particle-in-cell simulations of tunneling ionization effects in plasma-based accelerators”, *Physics of Plasmas*, vol. **10,** no. 5, pp. 2022-30, LBNL-52177, May 2003.
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<u>Current Staff</u>:

• Leemans, W. P.	Principal Investigator, Group Leader
• Esarey, E.	Staff Scientist, Deputy Group Leader
• Schroeder, C.	Scientist
• Faure, J.	Scientist
• Shadwick, B.A.	Scientist, part time

<u>Graduate Students</u>:

- G. Fubian, Ph.D., University of Paris, France, in progress
- C. G.R. Geddes, Ph.D., University of California, Berkeley, in progress.
- J. van Tilborg, Ph.D., Technische Universiteit Eindhoven, the Netherlands, in progress.
- R. Trines, Ph.D., March 2003, Technische Universiteit Eindhoven, the Netherlands.

<u>Past Graduate Students</u>:

- A. Reitsma, Ph.D. thesis, September 2002, Technische Universiteit Eindhoven, the Netherlands.
- A. Misuri, M.Sc. Thesis, July 2002, University of Pisa, Italy, LBNL-50940.
- B. Marcelis, M. Sc. Thesis, October 2002, Technische Universiteit Eindhoven, the Netherlands.
- J. de Groot, M. Sc. Thesis, June 2001, Technische Universiteit Eindhoven, the Netherlands.

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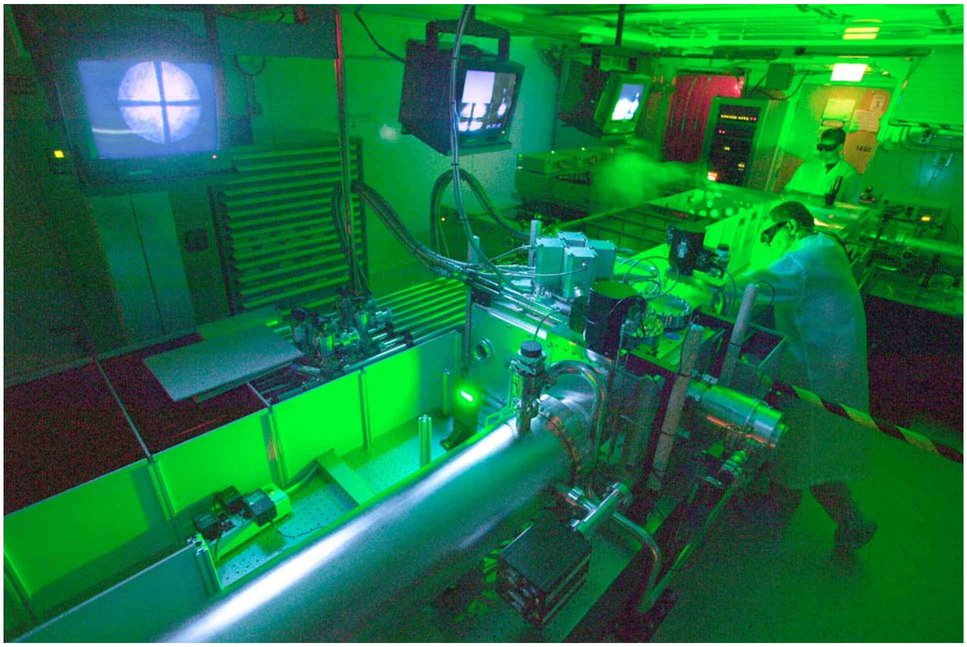

Figure 1: Photograph of the main amplifier for the 100 TW, 10 Hz upgrade of the Ti:sapphire laser system being commissioned at the l'OASIS laboratory. The green glow is from 532 nm radiation produced by the frequency doubled Nd:YAG pump lasers. The laser will be the main power source for the all-optical 1 GeV laser driven accelerator experiments at LBNL.

Los Alamos Accelerator Code Group

R. W. Garnett
Los Alamos National Laboratory

Summary:

FY 2002 was a transitional year for the Los Alamos Accelerator Code Group (LAACG). A new leader of the code group was appointed and a renewal proposal for continued funding was submitted to DOE. Additionally, new members were added to the group as part of a succession plan for maintenance of our codes and to help us reach near-term future goals. We continued our role as a national resource for members of the accelerator community who use and/or develop software for the design and analysis of particle accelerators, and beam transport systems. We continued to distribute accelerator design and simulation codes via the world-wide web and maintained an online compendium of accelerator codes which can be found at http://laacg1.lanl.gov/laacg/componl.html. We presently have over 1300 registered users world-wide using our codes and accessing our website. The code group resides in the Accelerator Physics and Engineering Group, LANSCE-1, at Los Alamos National Laboratory.

Continuing impact of the LAACG

The codes supported and maintained by the LAACG continue to have an impact on accelerator projects around the world. Our codes are currently being used in the design and simulation of accelerators and beam delivery systems presently funded through several divisions of the DOE Office of Science and other funding sources. Many of these projects are of national importance such as the Spallation Neutron Source (SNS) now being constructed at Oak Ridge National laboratory, at SLAC for LCLS and NLC, at BNL for RHIC, at universities such as UCLA, the University of Maryland, the University of Indiana, and Michigan State University, and several companies in industry including Advanced Energy Systems, Varian, and AccSys Technology, Inc.

A review of major conference and workshop proceedings (e.g. the International Linac Conference, the Particle Accelerator Conference, the European Particle Accelerator Conference, the International Conference on the Application of Accelerators in Research and Industry, and others) shows that, in any given year, several hundred papers are published for which the research presented involved codes developed and maintained by the LAACG. Several of these publications also include comparisons between codes, indicating that similar alternate software is being developed at other institutions. However, these codes are always benchmarked against the LAACG codes. Another trend that is visible is the development of software at other institutions that basically provides graphics interfaces and uses the LAACG codes as the calculation tools (or uses output from the LAACG codes as input for secondary calculations).

Present LAACG activities

Present LAACG activities include: (1) maintenance and enhancement of certain widely used software packages, including POISSON/SUPERFISH, PARMILA, PARMELA, PARMTEQ, and TRACE 3-D; (2) consultation, education, and gathering/dissemination of information related to computational accelerator physics; (3) the distribution of software and documentation via the Internet; and (4) maintenance of the official LAACG website. The continued high-level use of the above-mentioned codes, which have over 1300 registered users world-wide, demonstrates the great value of the LAACG to the national and international accelerator communities. Additionally, every year, the code group is pleased to grant the requests of instructors at universities and at special accelerator schools (USPAS, CERN) to use LAACG codes (POISSON/SUPERFISH, PARMELA, and TRACE 3-D) in the classroom as part of their graduate-level instruction in accelerator physics and engineering.

Many improvements to the codes have resulted through national and international collaborations with our users and through regular feedback regarding how the codes are serving the needs of the community. Future code enhancements such as including the capability to model low-energy superconducting accelerator structures and the transport of beams containing multiple charge states could impact the design of facilities such as the Rare Isotope Accelerator (RIA) now being planned by collaboration between Argonne National Laboratory and Michigan State University, or high-intensity driver-linac designs for applications such as accelerator transmutation of waste, fusion materials testing, etc. Codes like PARMELA have already been used to enhance the performance of existing machines such as the Stanford Linear Collider. Additionally, these codes may be required to help design the next- generation light source.

Descriptions of the LAACG-supported design codes

POISSON/SUPERFISH – *is a 2-D code package of more than 30 programs for the design of RF cavities, magnet components, electrostatic elements, and waveguide devices*. An over-relaxation method is used to solve the generalized Poisson's equation in two dimensions. Eigenfrequencies and fields for arbitrarily shaped two-dimensional waveguides in Cartesian coordinates and three-dimensional axially symmetric RF cavities in cylindrical coordinates can be determined. The package contains codes to generate a very accurate triangular mesh adjusted to conform to the problem geometry, to plot the fields and to evaluate auxiliary quantities of interest in the design of drift-tube linac (DTL) cavities, coupled-cavity linac (CCL) cells, radio-frequency quadrupole (RFQ) cavities and other devices. For example, the code calculates transit-time factors, power losses, and the effect of perturbations. Several codes are included for automatically tuning DTL, CCL, and RFQ cavities by iterating on a selected portion of the geometry.

PARMILA – *is a multi-particle design and transport code for ions historically used to design drift-tube linacs (DTLs).* The name comes from the phrase, "***P****hase* ***a****nd* ***R****adial* ***M****otion in* ***I****on* ***L****inear* ***A****ccelerators*". The code has been extended to also design coupled-cavity linacs, and elliptical-cavity superconducting linac structures. A "drift-kick" method is used to transform the beam, represented by a collection of particles, through the linac to study the beam dynamics performance of the design.

PARMELA – *is a multi-particle beam dynamics code used primarily for electron-linac beam simulations.* The name comes from the phrase, "***P****hase* ***a****nd* ***R****adial* ***M****otion in* ***E****lectron* ***L****inear* ***A****ccelerators.*" It is a versatile code that transforms the beam, represented by a collection of particles, through a user-specified linac and/or transport system. It includes several space-charge calculation methods. Particle trajectories are determined by numerical integration through the fields. This approach is particularly important for electrons where some of the approximations used by other codes (e.g. the "drift-kick" method commonly used for low-energy protons) would not hold. PARMELA works equally well for either electrons or ions although is computationally slower due to the numerical integrations. PARMELA can read field distributions generated by the POISSON/SUPERFISH group of codes. Members of the code group won a LANL 2000 Distinguished Copyright Award for this code.

PARMTEQ – *and several other RFQ design codes comprise this group of codes and are used to design high-performance radio-frequency quadrupole (RFQ) linacs.* PARMTEQ is an acronym for "***P****hase* ***a****nd* ***R****adial* ***M****otion in a* ***T****ransverse* ***E****lectric* ***Q****uadrupole*". The codes have been experimentally verified in some detail by working hardware at Los Alamos and at other laboratories around the world. As we learn more about linac performance, both experimentally and theoretically, we continue to update these codes. Partial and complete RFQ design-code distributions are available. A partial distribution contains the codes necessary to design the RFQ vane profile and analyze the beam performance including the effects of higher order multipole field components and image charges. A complete distribution also includes the code VANES and several related programs, which generate and analyze machine instructions for numerically controlled machining of the vanes. Multi-particle simulations of the RFQ design are also possible with these codes.

TRACE 3-D – *is an interactive first-order beam-dynamics program that calculates the envelopes of a bunched beam, including linear space-charge forces, through a user-defined transport system.* It provides an immediate graphics display of the envelopes and the phase-space ellipses in three dimensions. This code is extremely useful for laying out beam transport lines and for determining beam matching parameters.

POSTER – This graphics postprocessor is currently under development and is a new addition to the LAACG suite of codes. We anticipate making a version of this code available on the web soon. POSTER converts data files into Postscript form for plotting. It also includes several high-performance data processing/analysis capabilities. Its primary utility is to layout linacs, circular accelerators and beam lines that have been designed by the popular accelerator design codes. However, it has also been used to visualize results from multiparticle simulations and actual measured beam data. This postprocessor will be extended to provide a seamless interface to PARMILA, PARMELA, TRACE 3-D, MARYLIE, DIMAD, TRANSPORT, and TEAPOT. POSTER will read the input files for these codes and generate accurate physical layouts of beam lines and accelerator lattices. An online version of a users manual will also be available. POSTER has been used rather extensively for beam-line layouts completed as part of the Advanced Hydrotest Facility Project at LANL, as well as others.

Web site maintenance / compendium of accelerator codes

We have continued to maintain the official web site and online compendium of accelerator codes. The online compendium is still incomplete, with many pages not yet containing the required descriptive text or appropriate links. We have continued to make corrections, however this past year our main focus has been on creating a new website and acquiring a dedicated server running the Unix/Linux operating system. The new computer has been acquired and is up and running. It is presently being used for the website development and we hope to be able to make a connection available to our users soon. Switching to a Linux-based server will allow improved capabilities such as more secure operation, interactive submissions, online searching, and implementation of software not presently available under the MS-Windows environment to track our web site traffic. Dynamic web pages based on PHP templates will simplify the addition of new services and the maintenance of the pages.

Code distribution statistics in FY 2003

The number of code downloads were down this past year primarily because of increased LANL computer security. Improved firewalls have made it much more difficult for users to connect to our green (open partition) servers. A number of our unfulfilled code requests are for LAACG-licensed software. Approval to distribute this software must now be obtained on a case-by-case basis from LANL Industrial Business Development (LANL-IBD) after a mandatory review. Our code distribution statistics are shown below:

- Number of LAACG Web Site Visits: 8344

- Number of new code distributions:

  POISSON/SUPERFISH: 122
  PARMELA: 19 plus 15 unfulfilled commercial or foreign requests
  PARMILA: 10
  PARMTEQ/RFQ Codes: 4 unfulfilled commercial or foreign requests
  TRACE 3-D: 40

- Number of updated versions of the codes distributed:

  POISSON/SUPERFISH: 1562
  PARMELA: 252
  PARMILA: 53
  PARMTEQ/RFQ Codes: 28
  TRACE 3-D: 392

- Distribution Demographics:

  Academic Institutions: 26%
  Commercial Companies: 24%
  Government-Funded Labs: 45%
  Private Individuals: 5%

Recent Publications:

R. Garnett, "Status of the Los Alamos Accelerator Code Group," to be published in the Proceedings of the International Computational Accelerator Physics Conference 2002, Michigan State University, East Lansing, Michigan, October 15-18, 2002.

Current Staff:

Robert Garnett, Principal Investigator
Christopher Allen, Technical Staff Member
James Billen, Technical Staff Member
Frank Krawczyk, Technical Staff Member
Thomas Mottershead, Technical Staff Member (retired 2003)
Harunori Takeda, Technical Staff Member
Lloyd Young, Technical Staff Member (retired 2003)

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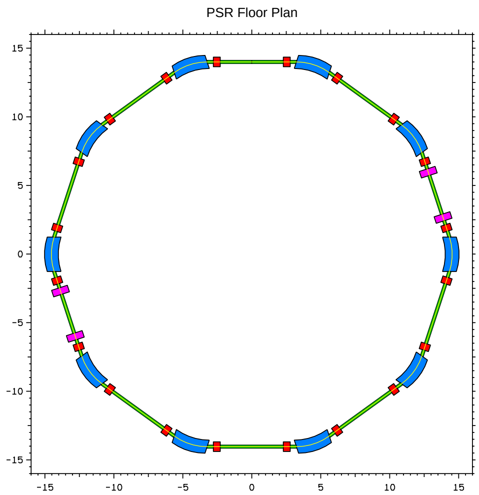
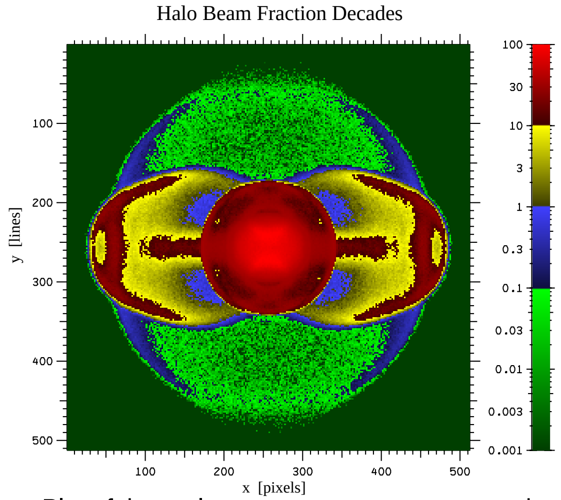
Los Alamos National Laboratory – Los Alamos Accelerator Code Group

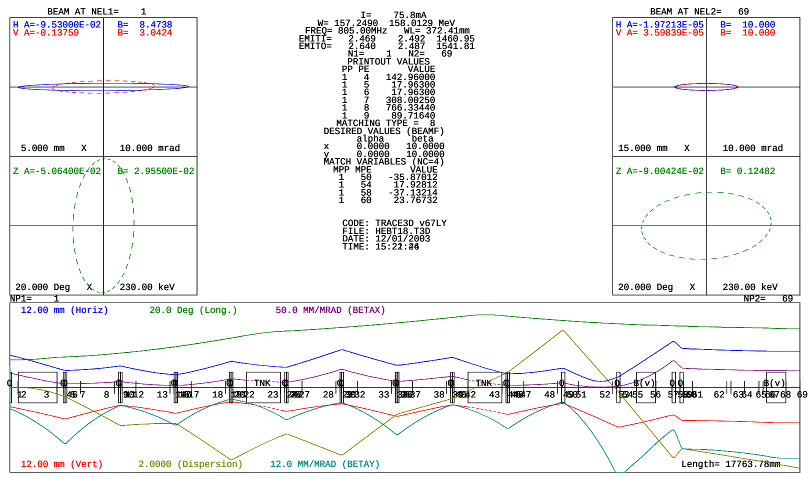
R. Garnett, C. Allen, J. Billen, F. Krawczyk C. T. Mottershead, H. Takeda, and L. Young

POSTER Plotting example of the LANSCE proton storage ring beam line layout.

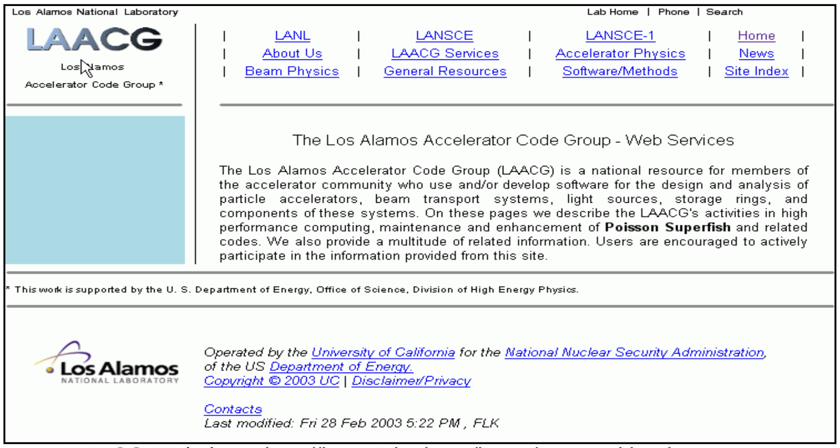




Plot of the real-space transverse cross-section of a beam containing a halo where the graded logarithmic color scale indicates halo beam fraction decades using POSTER.



TRACE 3-D simulation of a ring injection line to do correlated longitudinal injection painting.



LAACG Website at http://laacg1.lanl.gov/laacg/componl.html.

SLAC Accelerator Research Department B

Robert Siemann, Stanford Linear Accelerator Center

Overview:

SLAC Accelerator Research Department B (ARDB) performs experimental research in high gradient acceleration. High gradient RF, 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. Our collaborators in the ARDB research program and the ORION Center for Advanced Accelerator and Beam Physics Research are: Profs C. Joshi, W. Mori and J. Rosenzweig of UCLA, T. Katsouleas of USC, and R. Byer of Stanford.

Summary of Current Activities:

Plasma Wakefield Acceleration (SLAC Experiments E157, E162, E164 and E164X)
These experiments are studies of the interactions of electron and positron beams with plasmas performed by a UCLA/USC/SLAC collaboration. E157 was the first of these experiments. It was followed by E162 and E164, which have completed data taking, and the program will continue with E164X. All of these experiments take place in the SLAC Final Focus Test Beam (FFTB) using 28.5 GeV electron or positron beams. The FFTB and high energy beams are unique aspects of these experiments. The incoming and outgoing beams are well-characterized with a variety of detectors.

E157 and E162 used a 1.4 m long lithium plasma, and together they gave the opportunity to study many aspects of the beam-plasma interaction at the scale of interest to a plasma accelerator. There were eight data taking runs extending through 2001, and data analysis has been the recent focus of these experiments. Recently published results include: a concept for a plasma-wakefield based energy doubler [1], measurements of transverse focusing of electron beams[2,3],' X-ray production by electrons traversing the plasma [4], an overview of the high energy density plasma science that has been in these experiments [5], and transport and acceleration of positron beams [6,7]. Three graduate students (Brent Blue, UCLA, Seung Lee, USC, and Shoquin Wang, UCLA) received PhD degrees for their work on E157 and E162.

The next experiment in this series is E164, which completed data taking in November, 2003. The goal of E164 is to reach higher gradients by employing shorter bunches and higher density plasmas. The short, high current bunch, $1.5X10^{10}$ electrons in a 10 to 20 micron long bunch (!), is produced with a bunch compressor chicane in the SLAC linac. The plasma density must be increased to keep the plasma wavelength approximately the same as the bunch length. Data have been taken with lithium, hydrogen and xenon plasmas. Tunneling ionization of the plasma by the beam fields is routinely observed. The data from E164 are being analyzed at the present time. The experimental work will continue with experiment E164X that is tentatively scheduled to run in Spring 2004.

Laser Electron Acceleration Project (LEAP) and E163
The Laser Electron Acceleration Project (LEAP) is a Stanford/SLAC experimental program that has the goal of building accelerators based on near IR lasers in the 1 to 2 micron wavelength range. There is an enormous commercial market for near-IR lasers from telecommunications and laser machining, and this market is producing rapid advances and significant cost reductions. The LEAP goal is to develop accelerator structures and acceleration mechanisms that will benefit from these developments.

The first stage of LEAP has been a proof-of-principle experiment located at the superconducting accelerator on the Stanford campus. There was a one-week long run in June 2002, and significant amounts of data were taken, but there was no convincing evidence of acceleration. However, we have learned a great deal about techniques and instrumentation for laser acceleration experiments, and Tomas Plettner, a Stanford graduate student, received his PhD degree for this work.

SLAC experiment E163 has been approved to provide the electron beam needed for long-term progress. E163 would continue the proof-of-principle studies and follow that with demonstration of optical bunching at 1 micron and acceleration using a lithographically fabricated multi-cell structure. E163 is presently under construction. It calls for modifications of the SLAC Next Linear Collider Test Accelerator (NLCTA), and the building of a shielded enclosure for performing experiments. The shielding enclosure has been design for a 60 MeV, 1 nC beam. It is located to the north of the NLCTA and has been completed recently. The LEAP apparatus will be moved from the Stanford campus to SLAC when appropriate. The major E163 technical system is a photoinjector with associated drive laser and RF system. All of these are well on the way to completion, and E163 data taking could begin within a year.

There are important issues related to laser acceleration that can be addressed without an electron beam, and we continue to work on them. Recent activities included measurements of laser and radiation damage of materials [8], Inverse Free Electron Laser bunching of beams, lithographic fabrication of structures, general considerations for laser driven accelerators, and photonic crystal accelerators. Work in many of these areas has been presented at conferences, and papers on photonic crystal optical fibers [9] and lithographically fabricated photonic crystals have been published[10].

High Gradient RF Technology

This was the last year of activity in this area with the final analysis and publication of the results on surface pulsed heating of copper RF cavities [11]. The results are that damage was measured after 56 million pulses with a temperature rise of 120 K and after 86 million pulses with a temperature rise of 82 K. David Pritzkau received his PhD degree from Stanford and the 2003 APS Division of Physics of Beams PhD Prize for this work [12].

The ORION Center for Advanced Accelerator and Beam Physics Research and the ORION Facility

Advanced accelerator research, with its goal of understanding the physics and developing the technologies for reaching higher energies, is essential for the future of particle physics. The ORION Center is a Stanford/UCLA/USC/SLAC collaboration devoted to advanced accelerator and beam physics research. A critical mass of researchers from diverse scientific backgrounds will be brought together with state-of-the-art beams, apparatus and computing. The ORION Center holds the promise of significant advances through rapid assessment and development of new acceleration concepts.

ORION Center experiments will take place at the FFTB and the ORION Facility. The FFTB experiments will exploit the apparatus developed for E157, E162, etc. The ORION Facility is a proposed user-oriented facility for advanced accelerator research that will be based on the NLCTA. The facility will provide 60 MeV beams in a Low Energy Hall and nominal 350 MeV beams in a High Energy Hall. The E163 photoinjector is based on an ORION design, and it will serve the entire facility with modest upgrades. In addition, the E163 beam line will be the extraction line for the Low Energy Hall. Diagnostics and data acquisition systems developed for E157, etc and E163 will be available to researchers at the ORION Center.

Current ARDB Scientific Staff

Robert H. Siemann	Professor, SLAC and Stanford Applied Physics, Principal Investigator
Eric Colby	W. K. H. Panofsky Fellow
David Fryberger	SLAC Staff
Mark Hogan	SLAC Staff
Robert Noble	SLAC Staff
Dennis Palmer	SLAC Staff
Christopher Barnes	PhD Graduate Student (Stanford)
Benjamin Cowan	PhD Graduate Student (Stanford)
Mehdi Javenmard	PhD Graduate Student (Stanford)
Devon Johnson	PhD Graduate Student (UCLA)
Caolionn O'Connell	PhD Graduate Student (Stanford)
Christopher Sears	PhD Graduate Student (Stanford)
Ning Wu	PhD Graduate Student (Stanford)

Publications & References

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[2] C. E. Clayton *et al,* "Transverse Envelope Dynamics Of A 28.5 Gev Electron Beam In A Long Plasma", Physical Review Letters **88**, 154801 (2002)

[3] C. O'Connell *et al*, "Dynamic Focusing Of An Electron Beam Through A Long Plasma", Physical Review Special Topics – Accelerators and Beams **5**, 1121301 (2002)

[4] Shouqin Wang *et al,* "X-Ray Emission From Betatron Motion In A Plasma Wiggler", Physical Review Letters **88**, 135004 (2002)

[5] C. Joshi *et al,* "High Energy Density Plasma Science With An Ultra-Relativistic Electron Beam", Physics of Plasmas **9**, 1845 (2002).

[6] M.J. Hogan et al, "Ultrarelativistic-Positron-Beam Transport through Meter-Scale Plasmas", Physical Review Letters **90**, 205002 (2003).

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[11] D. P. Pritzkau & R. H. Siemann, "Experimental Study of RF Pulsed Heating on Oxygen Free Electronic Copper", Physical Review Special Topics – Accelerators and Beams **5**, 112002 (2002)

[12] David Peace Pritzkau, "RF Pulsed Heating", PhD in Applied Physics from Stanford University. David is now a Senior Test Engineer at Big Bear Networks in Sunnyvale, CA.

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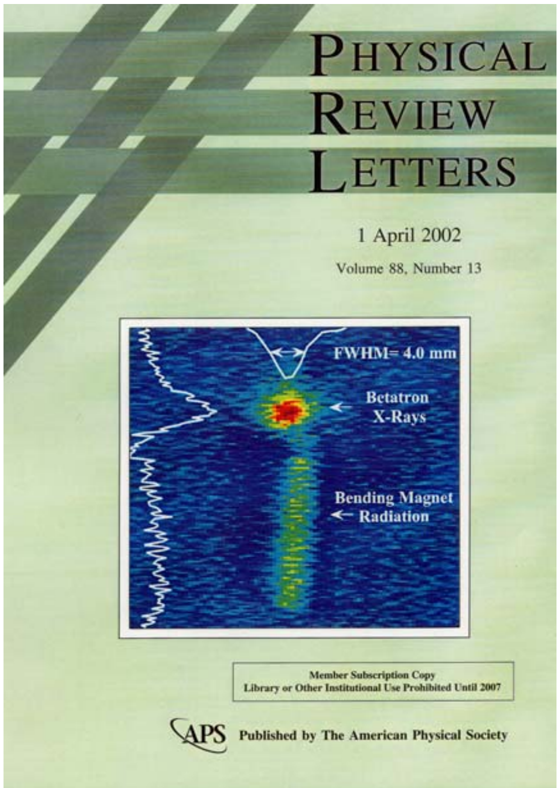
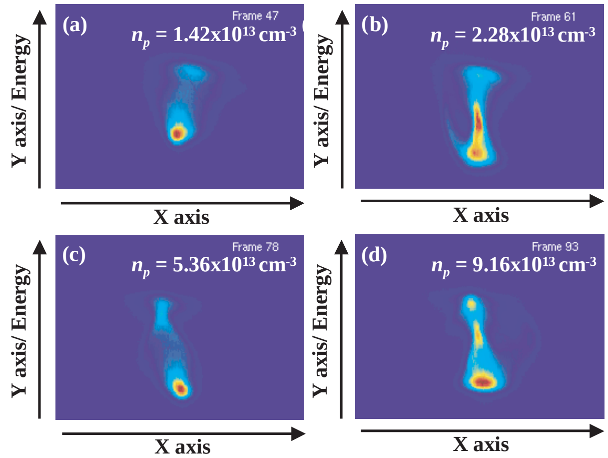
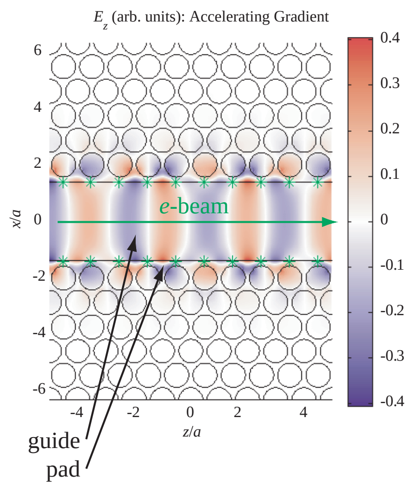
E-MAIL: Siemann@slac.stanford.edu



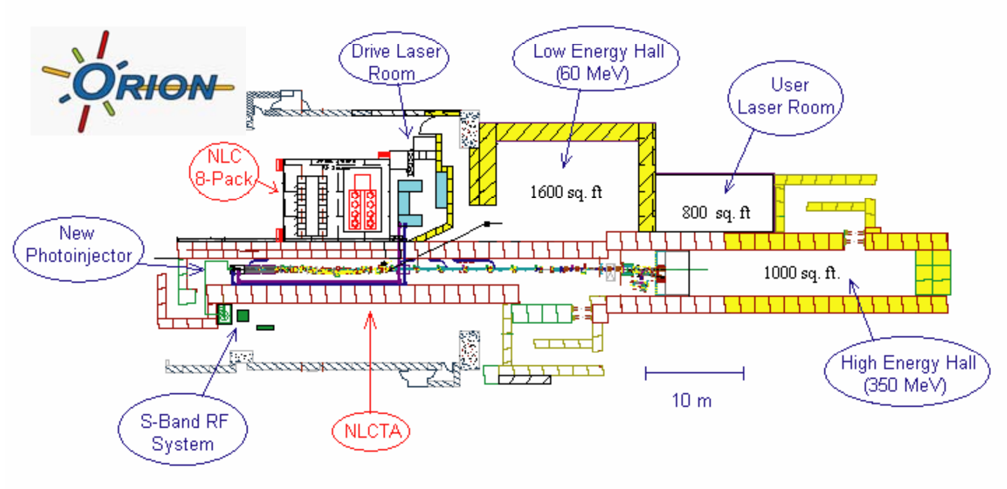
X-Ray emission from betatron motion in a plasma wiggler (S. Wang *et al* [4])



Dynamic Focusing of an Electron Beam in a Plasma (C. O'Connell *et al* [3])



Two-dimensional Photonic Crystal Accelerator Structure (B. M. Cowan [10])



Conceptual Layout of the ORION Facility at the NLCTA

Graduate Student Data

Appendix A: Current Students
Appendix B: Past Graduates

Appendix A

Current Graduate Students Data FY 2002

Last Name	First Name (MI)	Institute	Advisor
Shchelkunov	Sergey	Columbia University	T. C. Marshall
Bowman	Arnesto	Florida A&M University	R. L. Williams
Fuzier	Sylvie	Florida A&M University	S. W. Van Sciver
Dalban	Matteau	Florida A&M University	S. W. Van Sciver
Ting	Xu	Florida A&M University	S. W. Van Sciver
Beltran	C.	Indiana University	S. Y. Lee
Guo	W.	Indiana University	S. Y. Lee
Zhang	Y.	Indiana University	S. Y. Lee
Wang	S.	Indiana University	S. Y. Lee
Huang	DaZhang	Indiana University	S. Y. Lee
Huang	Xiaobiao	Indiana University	S. Y. Lee
Sato	Y.	Indiana University	S. Y. Lee
Breitzman	S.	Indiana University	S. Y. Lee
Korbly	Stephen	Massachusetts Intitute of Technology	Richard J. Temkin
Smirnova	Evgenya	Massachusetts Intitute of Technology	Richard J. Temkin
Marsh	Roark	Massachusetts Intitute of Technology	Richard J. Temkin
Bhatt	Ronak	Massachusetts Intitute of Technology	Chiping Chen
Henestroza	Enrique	Massachusetts Intitute of Technology	Chiping Chen
Samokhvalova	Ksenia	Massachusetts Intitute of Technology	Chiping Chen
Zhou	Jing	Massachusetts Intitute of Technology	Chiping Chen
Manikonda	Shashikant	Michigan State University	M. Berz
Kim	Youn-Kyung	Michigan State University	M. Berz
Grote	Johannes	Michigan State University	M. Berz
Maidana	Carlos	Michigan State University	M. Berz
Nekoogar	Farzad	Michigan State University, via VUBeam	M. Berz
Snopok	Pavel	Michigan State University	M. Berz
Poklonskiy	Alexey	Michigan State University	M. Berz
Robertson	Norman	Michigan State University, via VUBeam	M. Berz
Yu	Chenghui	Michigan State University, via VUBeam	M. Berz
Peng	X.	Ohio State University	E. W. Collings
Lee	E.	Ohio State University	E. W. Collings
Wu	X.	Ohio State University	E. W. Collings
Stowell	Ronald	Princeton University	Ronald C. Davidson
Cowan	B.	Stanford University	R. L. Byer
Sears	C.	Stanford University	R. L. Byer

Last Name	First Name (MI)	Institute	Advisor
Javanmard	M.	Stanford University	R. L. Byer
Barnes	Christopher	Stanford University	R.H. Siemann
O'Connell	Caolionn	Stanford University	R.H. Siemann
Wu	Ning	Stanford University	R.H. Siemann
Byeon	Joong	Texas A & M University	P. McIntyre
Hirose	Eichii	Texas A & M University	P. McIntyre
Smith	Don	Texas A & M University	P. McIntyre
Woodward	Amanda	Texas A & M University	P. McIntyre
Charman	A.	UC Berkeley	J. Wurtele
Geddes	C.	UC Berkeley	J. Wurtele / W. Leemans
Gogardze	V.	UC Berkeley	J. Wurtele
Lindberg	R.	UC Berkeley	J. Wurtele
Peinetti	F.	Visiting UC Berkeley from University of Turin	J. Wurtele
He	Ping	University of California-Los Angeles	David B. Cline
Lei	Shao	University of California-Los Angeles	David B. Cline
Andonian	G.	University of California-Los Angeles	James Rosenzweig
England	J.	University of California-Los Angeles	James Rosenzweig
Lim	J.	University of California-Los Angeles	James Rosenzweig
Musumeci	P.	University of California-Los Angeles	James Rosenzweig
Thompson	M.	University of California-Los Angeles	James Rosenzweig
Filip	Catalin	University of California-Los Angeles	Chan Joshi
Narang	Ritesh	University of California-Los Angeles	Chan Joshi
Tzoufras	Michail	University of California-Los Angeles	Chan Joshi
Sung	Jay	University of California-Los Angeles	Chan Joshi
Johnson	Devon	University of California-Los Angeles	Chan Joshi
Zhou	Miaomiao	University of California-Los Angeles	Chan Joshi
Huang	Chengkun	University of California-Los Angeles	Chan Joshi
Vandenbosch	Chad	University of California-Los Angeles	Chan Joshi
Ralph	Joe	University of California-Los Angeles	Chan Joshi
Lu	Wei	University of California-Los Angeles	Chan Joshi

Last Name	First Name (MI)	Institute	Advisor
Sonnad	Kiran	University of Colorado, Boulder	John R. Cary
Lee	Jinhyung	University of Colorado, Boulder	John R. Cary
Jin	Lihui	University of Kansas	Jack Shi
Anhault	Ben	University of Kansas	Jack Shi
Cooper	B.	University of Maryland, College Park	Alex J. Dragt
Mitchell	C.	University of Maryland, College Park	Alex J. Dragt
Palastro	J.	University of Maryland, College Park	Alex J. Dragt
Papadopoulos	C.	University of Maryland, College Park	Alex J. Dragt
Roberts	M.	University of Maryland, College Park	Alex J. Dragt
Saranchak	D.	University of Maryland, College Park	Alex J. Dragt
Cui	Y.	University of Maryland, College Park	P. G. O'Shea
Li	H.	University of Maryland, College Park	P. G. O'Shea
Harris	J.	University of Maryland, College Park	P. G. O'Shea
Huo	Y.	University of Maryland, College Park	P. G. O'Shea
Virgo	M.	University of Maryland, College Park	P. G. O'Shea
Bharathan	K.	University of Maryland, College Park	W. Lawson
Gouviea	S.	University of Maryland, College Park	W. Lawson
Kim	Kiyong	University of Maryland, College Park	H.M. Milchberg
Sheng	Hua	University of Maryland, College Park	H.M. Milchberg
York	Andrew	University of Maryland, College Park	H.M. Milchberg
Cooley	James	University of Maryland, College Park and Naval Research Laboratory	H.M. Milchberg (U of M) and Phillip Sprangle (NRL)
Wu	Jianzhou	University of Maryland, College Park	H.M. Milchberg
Palastro	John	University of Maryland, College Park	H.M. Milchberg
Gupta	Ayosh	University of Maryland, College Park	H.M. Milchberg
Liu	Jianwei	University of Maryland, College Park	H.M. Milchberg
Vlaicu	Irina	University of New Mexico	James A. Ellison

Last Name	First Name (MI)	Institute	Advisor
Sobol	Andrey	University of New Mexico	James A. Ellison
Saleh	Ned	University of Michigan, Ann Arbor	Donald Umstadter
Chen	Shouyuan	University of Michigan, Ann Arbor	Donald Umstadter
Fomyts'kyi	Mikhailo	University of Texas at Austin	M. Downer
Grigsby	F.	University of Texas at Austin	M. Downer
Matlis	N.M.	University of Texas at Austin	M. Downer
Shim	Bonggu	University of Texas at Austin	M. Downer
Zgadzaj	R.	University of Texas at Austin	M. Downer
Geraskin	G.	Argonne National Laboratory	Wei Gai
Jing	C.	Argonne National Laboratory	Wei Gai
Wang	H.	Argonne National Laboratory	Wei Gai
He	Ping	Brookhaven National Laboratory	Ilan Ben-Zvi
Nikas	Dimitrios	Brookhaven National Laboratory	Ilan Ben-Zvi
Shchelkunoff	Sergey	Brookhaven National Laboratory	Ilan Ben-Zvi
Chang	Xiangyun	Brookhaven National Laboratory	Ilan Ben-Zvi
Kamiya	Yoshio	Brookhaven National Laboratory	Ilan Ben-Zvi
Andonian	Gerard	Brookhaven National Laboratory	Ilan Ben-Zvi
Vicario	Carlo	Brookhaven National Laboratory	Ilan Ben-Zvi
Al'Sharoa	Mohammad	Fermi National Laboratory	Daniel Kaplan
Bordini	B.	Fermi National Laboratory	A. V. Zlobin
Tushentsov	Michael	Illinois Institute of Technology	Gennady Shvets
Urzhumov	Yaroslav	Illinois Institute of Technology	Gennady Shvets
Fubian	G.	Lawrence Berkeley National Laboratory	Wim P. Leemans
Geddes	C.G.R.	Lawrence Berkeley National Laboratory	Wim P. Leemans
van Tilborg	J.	Lawrence Berkeley National Laboratory	Wim P. Leemans
Trines	R.	Lawrence Berkeley National Laboratory	Wim P. Leemans

Appendix B
Past Graduate (PhD) Students and Placements

Last Name	First Name (MI)	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 Univ.	Krienan	1991	BNL	BNL
Zwart	G. Townsend	Boston Univ.	Krienan	1997	Bates	Bates
Zhang	Ge	Clark Univ./MIT	J. Davies J. Wurtele	1993		Lorel Corp.
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 U.	Columbia (Earth Sciences Inst.)
Lin	L-Y	Columbia	T.C. Marshall	1993	FOM Jutphaas (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	
Adler	Richard	Cornell Univ.	J. Nation	1980	AFWL	North Star Research, Inc.
Fenstermacher	Daniel	Cornell Univ.	J. Nation	1985	Harvard	
Providakes	George	Cornell Univ.	J. Nation	1985	Mitre Corp	
Anselmo	Antonio	Cornell Univ.	J. Nation	1987	Varian	
Greenwald	Shlomo	Cornell Univ.	J. Nation	1987	Israel Govt	Cornell University
Sheffer	Donald	Cornell Univ.	J. Nation	1991	Duke	
Koury	Daniel	Cornell Univ.	J. Nation	1992	Texas Instruments	
Davis	Timothy	Cornell Univ.	J. Nation	1993	Kionix, Inc.	Kionix, Inc.
Kuang	Erjia	Cornell Univ.	J. Nation	1994	Motorola, Far East	
Naqvi	Shahid	Cornell Univ.	J. Nation	1996	U. Chicago Radiology Stu	
Fletchner	Donald	Cornell Univ.	J. Nation	1999	Diamond Microelectronics	Diamond Microelectronics
Koyama	Taka	Cornell Univ.	R. Talman	1999		Intel
Kashikhin	V. V.	Fermilab	A. V. Zlobin	2002	St. Petersburg Technical University	Fermilab
Imbasciati	Linda	Fermilab	A. V. Zlobin	2003	Vienna Technical University	

Last Name	First Name (MI)	Institute	Advisor.	Year of Ph.D.	First Placement	Present Placement
Panek	John S.	Florida State Univ./NHMFL	S. W. Van Sciver	1998	Jet Propulsion Lab/ Cal Tech.	Goddard Space Flight Center
Hilton	David	Florida State Univ./NHMFL	S. W. Van Sciver	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 U.	R. Pollock/Lee	1989	Fermilab	Software Industry
Ellison	T.	Indiana U.	S.Y. Lee	1990	IUCF	Energy Storage Industry
Minty	Michiko G.	Indiana U.	S.Y. Lee/A. Krisch	1991	SLAC	DESY
Pei	A.	Indiana U.	R. Pollock/Lee	1992	BNL	Lucent
Ellison	M.	Indiana U.	S. Y Lee	1995	U. Colorado	Industry
Huang	Haixin	Indiana U.	S. Y. Lee	1995	BNL	BNL
Li	Derun	Indiana U.	S. Y. Lee	1995	UC San Diego	LBNL
Nagaitsev	Sergei	Indiana U.	P. Schwandt/ Lee	1995	Fermilab	Fermilab
Kang	X.	Indiana U.	S.Y. Lee	1998	U. Washington	UC Davis
Riabko	A.	Indiana U.	S.Y. Lee	1998	Software industry	Software industry
Bai	Mei	Indiana U.	S.Y. Lee	1999	BNL	BNL
Ranjbar	V.	Indiana U.	S. Y. Lee	2002	Indiana University	
Cousineau	S.	Indiana U.	S. Y . Lee	2003	Indiana University	
van Oort	Johannes	LBNL	S. A. Gourlay	2000		General Electric Company
Reitsma	A.	LBNL	W. P. Leemans	2002		Technische Universiteit Eindhoven
Hoffstaetter	Georg	Michigan State	Martin Berz	1994	Univ. of Darmstadt	DESY
Wan	Weishi	Michigan State	Martin Berz	1995	U. Colorado	ORNL
Makino	Kyoko	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

Last Name	First Name (MI)	Institute	Advisor.	Year of Ph.D.	First Placement	Present Placement
Chu	Yiu	MIT	J. Wurtele	1993	VCR Plus	TRW Corp.
Menninger	William	MIT	R.J. Temkin/ B.G.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	
Gonichon	Jerome	MIT	Richard Temkin	1995		General Electric, France
Lin	Chia-Lian	MIT	S. C. Chen/ A. Danly J.Wurtele	1995	Torrey Communications	Philips Corp.
Shvets	Gennady	MIT	J. Wurtele	1995	PPPL	PPPL
Hu	Wen	MIT	G. Bekefi/ R.J. Temkin	1997	Goldman Sachs	Goldman Sachs
Trotz	Seth	MIT	R.J. Temkin/ B.G. Danly	1997	Dartmouth	MIT Lincoln Laboratory
Catravas	Palmyra	MIT	H. Haus / J. Wurtele	1998	LBNL	LBNL
Volfbeyn	Pavel	MIT	W. Leemans / J. Wurtele	1998	LBNL	Harmonic, Inc.
Fink	Yoel	MIT	C. Chen/ J. Joannopoulos/ E. Thomas	2000	MIT	MIT, Faculty
Hess	Mark	MIT	C. Chen	2002	Visiting Prof. Clark University	MIT
Brown	Winthrop	MIT	Richard Temkin	2001		Lawrence Livermore National Laboratory
Gonichon	Jerome	MIT/ Univ. of Paris	C. Travier/ S.C. Chen/ B.G. Danly/ R.J. 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 U	E. W. Collings	1992	OSU	OSU
Buta	Florin	Ohio State U	E. W. Collings	2002		Hyper Tech Research

Last Name	First Name (MI)	Institute	Advisor.	Year of Ph.D.	First Placement	Present Placement
Russell	D. Patrick	Princeton	K. McDonald	1992	U. Wisc/Med Phys	
Strasburg	Sean	Princeton University	Ronald C. Davidson	2001		NRL
Kingsley	Lawrence	Rochester	A. Melissinos	1990	U. Toronto	Army Lab-NJ
Bamber	Charles	Rochester	A. Melissinos	1991	Rochester	
Plettner	Thomas	Stanford University	R. L. Byer	2002		Stanford University
Soika	Rainer	Texas A & M University	P. McIntyre	2002	BNL	
Bruhwiler	David	U. Colorado	J. R. Cary	1990	Grumman	Tech-X Corp.
Gabella	William	U. Colorado	J. R. Cary	1991	UCLA	Vanderbilt FEL
Hendrickson	Scott	U. Colorado	J. R. Cary	1996	Kaiser Technologies	Tech-X Corporation
Stoltz	Peter H.	U. Colorado	J. R. Cary	1996	PPPL	Tech-X Corporation
Li	Minyang	U. Houston	S. Ohnuma	1990	SSCL	
Machida	Shinji	U. Houston	S. Ohnuma	1990	KEK	KEK
Raparia	Deepak	U. Houston	S. Ohnuma	1990	SSCL	
Zhang	Peilei	U. Houston	S. Ohnuma	1991	SSCL	
Grossman	John	U. Maryland	C. Striffler	1981	NRL	NRL
Douglas	David	U. Maryland	A. Dragt	1982	LBNL	TJNAF (CEBAF)
Floyd	Linton E.	U. Maryland	M. Reiser, W. Destler	1983	NRL	Industry
Cremer	T.	U. Maryland	W. Destler	1984	Industry	
Forest	Etienne	U. Maryland	A. Dragt	1984	LBNL	KEK HEP Lab
Forest	Etienne	U. Maryland	Alex J. Dragt	1984	Lawrence Berkeley Laboratory	KEK High Energy Physics Laboratory
Loschialpo	Peter F.	U. Maryland	M. Reiser	1984	NRL	NRL
Milutinovic	Janko	U. Maryland	A. Dragt	1984	BNL	Wall Street
Lawson	Wesley	U. Maryland	W. Destler/ C. Striffler	1985	U. Maryland	U. Maryland, Faculty
O'Shea	Patrick G.	U. Maryland	W. Destler/ M. Reiser	1985	LANL	U. Maryland, Faculty
Schneider	Ralph F.	U. Maryland	M.J. Rhee	1985	Defense Threat Reduction Agency	Industry
Healy	Liam	U. Maryland	A. Dragt	1986	CERN	NRL, Celestial Mechanics Group
Chojnacki	Eric P.	U. Maryland	W. Destler	1987	ANL	Cornell
Kehs	R.A.	U. Maryland	V. Granatstein	1987	LLNL	LLNL

Last Name	First Name (MI)	Institute	Advisor.	Year of Ph.D.	First Placement	Present Placement
Ryne	Robert	U. Maryland	Alex J. Dragt	1987	LANL	LBNL
Aghamir	Farzin	U. Maryland	W. Destler	1988	UCLA	UCLA
Chang	Chu Rui	U. Maryland	M. Reiser	1989	SSCL	Industry
Park	Gun-Sik	U. Maryland	V. Granatstein	1989	Seoul Natl. Univ., Korea	Seoul Natl. Univ., Korea
Bleum	Hans	U. Maryland	V. Granatstein	1990	Industry	Industry
Li	Rui	U. Maryland	R. Gluckstern	1990	TJNAF (CEBAF)	TJNAF (CEBAF)
Rangarajan	Govindan	U. Maryland	Alex J. Dragt	1990	LBNL	Indian Institute of Science
Zhang	Xiaohao	U. Maryland	C. Striffler	1990		
Calame	Jeffrey	U. Maryland	V. Granatstein/ W. Lawson	1991	NRL	NRL
Lou	Wei Ran	U. Maryland	V. Granatstein / Y. Carmel	1991	Lucent Tech.	Lucent Tech.
Abe	David K.	U. Maryland	W. Drestler	1992	NRL	NRL
Kehne	David	U. Maryland	M. Reiser	1992	TJNAF	FM Technologies
Tantawi	Sami G.	U. Maryland	V. Granatstein	1992	SLAC	SLAC
Fischer	Richard P.	U. Maryland	V. Granatstein	1993	NRL	NRL
Wang	Dunxiong	U. Maryland	M. Reiser	1993	TJNAF	TJNAF
Zhang	Zexiang	U. Maryland	V. Granatstein	1993	Lucent Tech.	Lucent Tech.
Meyers	T.	U. Maryland	W. Destler	1994		
Rappaport	Harold	U. Maryland	C. Striffler	1994	U. Texas	U. Texas
Abell	Dan	U. Maryland	A. Dragt	1995	BNL	Tech-X Corporation
Brown	Nathan	U. Maryland	M. Reiser	1995	Gillespie Assoc.	Industry
Cheng	Wen-hao	U. Maryland	R. Gluckstern	1995	LBNL	Intel, Inc.
Allen	Chris	U. Maryland	M. Reiser	1996	Industry	LANL
Jiang	Shicheng	U. Maryland	A. Dragt	1996	Cable and Wireless, Inc.	Cable and Wireless, Inc.
Suk	Hyyong	U. Maryland	M. Reiser	1996	UCLA	UCLA
Fedotov	Alexei	U. Maryland	R. Gluckstern	1997	BNL	BNL
Cheng	J. P.	U. Maryland	W. Lawson	1998		
Clark	Thomas	U. Maryland	T. Antonsen	1998	NRL	NRL
Nikitin	Sergei	U. Maryland	T. Antonsen	1998	Quantronix Corp.	Quantronix Corp.
Venturini	Marco	U. Maryland	A. Dragt	1998	SLAC	LBNL
Bernal	Santiago	U. Maryland	M. Reiser	1999	U. Maryland	U. Maryland
Zou	Yun	U. Maryland	M. Reiser	2000	Industry	Industry
Castle	M.	U. Maryland	W. Lawson	2001		John Hopkins APL
Alexeev	I.	U. Maryland	H. Milchberg	2003	Naval Research Lab	

Last Name	First Name (MI)	Institute	Advisor.	Year of Ph.D.	First Placement	Present Placement
Bian	Zhigang	U. Maryland	H. Milchberg	2003	Lucent Tech.	
Parra	E.	U. Maryland	H. Milchberg	2003	National Inst. Of Health	
Fan	J.	U. Maryland	H. Milchberg	2002	NEC Labs	
Schuett	Petra	U. Maryland/ Hamburg	A. Dragt/ T. Wailand	1988	TU, Darmstadt	GSI, Darmstadt
Goodwin	J.E.	U. Michigan	Krisch	1990	Fermilab	
Anferov	V.A.	U. Michigan	Krisch	1992	IHEP	
Shoumkin	D.S.	U. Michigan	Krisch	1993	IHEP	
Chu	C.M.	U. Michigan	Krisch	1994	IUCF	
Koulsha	A.V.	U. Michigan	Krisch	1994	Industry/Russia	
Van Guilder	B.	U. Michigan	Krisch	1994	Montclair State College	
Blinov	Boris	U. Michigan	Krisch	1995	U. Michigan	U. Michigan
Alexeva	L. V.	U. Michigan	Krisch	1996	IHEP	
Crandall	D. A.	U. Michigan	Krisch	1996	Industry	
Varzar	S. M.	U. Michigan	Krisch	1996	IHEP	
Abedi-Khafri	M.	U. Oregon	Csonka	1985		
Watanobe	Hiroshi	U. Oregon	Csonka	1985	Colgate Univ.	
Chen	Li	U. Oregon	Csonka	1992		
Fisher	David L.	U. Texas	T. Tajima	1995	UTA Appl Phy Lab	UTA Appl Phy Lab
Ottinger	Michael	U. Texas	T. Tajima	1997	Turman State U.	Turman State U.
Chen	X.M. Jerry	U. Texas	T. Tajima	1999	Dupont Photmaks	
Hawksworth	David G.	U. Wisconsin, Madison	D. C. Larbalestier	1981	Oxford Magnet Tech.	Oxford Magnet Tech
Smathers	David	U. Wisconsin, Madison	D. C. Larbalestier	1983	Teledyne Wah Chang	TOSHOH SMD
Moffat	David	U. Wisconsin, Madison	D. C. Larbalestier	1985	Was in the field	Madison Software Co.
Larson	Delbert	U. Wisconsin, Madison	D. Cline/F. Mills	1986	U. Wisconsin	SAIC
Marken	Kenneth R.	U. Wisconsin, Madison	D. C. Larbalestier	1986	NIM Japan	Batelle-Columbus
Warnes	William H.	U. Wisconsin, Madison	D. C. Larbalestier	1986	Oregon State University, Faculty	Oregon State University, Faculty
Rosenzweig	James	U. Wisconsin, Madison	D. Cline / J. Simpson	1988	ANL	UCLA

Last Name	First Name (MI)	Institute	Advisor.	Year of Ph.D.	First Placement	Present Placement
Holmes	D. Scott	U. Wisconsin, Madison	S. W. Van Sciver	1989	Lake Shore Cryotronics	Consulting
Meingast	Christopher	U. Wisconsin, Madison	D. C. Larbalestier	1989	ITP, Forschungszentrum Karlsruhe, Germany	ITP, Forschungszentrum Karlsruhe, Germany
Muller	Henry	U. Wisconsin, Madison	D. C. Larbalestier	1989		Midwest Superconductors
Weisand, II	John G.	U. Wisconsin, Madison	S. W. Van Sciver	1989	SSC Laboratory	Cryogenics at SLAC
Daumling	Manfred	U. Wisconsin, Madison	D. C. Larbalestier	1990		NKT Research Center
McKinnell	Jim	U. Wisconsin, Madison	D. C. Larbalestier	1990	Oxford Superconducting Technology	HP
Seuntjens	Jeff	U. Wisconsin, Madison	D. C. Larbalestier	1990	Oxford Superconducting Technology	Singapore Fine Wire
Buckett	Mary	U. Wisconsin, Madison	D. C. Larbalestier	1991	3M	
Daugherty	Mark A.	U. Wisconsin, Madison	S. W. Van Sciver	1991	Los Alamos Natl. Laboratory	Private practice
Hampshire	Damian	U. Wisconsin, Madison	D. C. Larbalestier	1991		POHANG (Check Asc'00 attendee list)
Maddocks	James	U. Wisconsin, Madison	S. W. Van Sciver	1991		
Palkovik	John	U. Wisconsin, Madison	D. Cline/ F. Mills	1991	SSCL	
Stejic	George	U. Wisconsin, Madison	D. C. Larbalestier	1993	Eaton Corp.	Tesla Laboratories
Bonney	Laura	U. Wisconsin, Madison	D. C. Larbalestier	1994	FSU – NHMFL	Johns Hopkins University
Cooley	Lance	U. Wisconsin, Madison	D. C. Larbalestier	1994	NRC Fellow- NIST	Brookhaven National Laboratory
Huang	Yuenian	U. Wisconsin, Madison	S. W. Van Sciver	1994	Fermilab	Fermilab
Huang	Xiaodong	U. Wisconsin, Madison	S. W. Van Sciver	1994	NHMFL	Position in finance
Jablonski	Paul	U. Wisconsin, Madison	D. C. Larbalestier	1994	Teledyne Wah Chang	Precision Castparts Airfoils
Heussner	Robert	U. Wisconsin, Madison	D. C. Larbalestier	1997	HP	

Last Name	First Name (MI)	Institute	Advisor.	Year of Ph.D.	First Placement	Present Placement
Kadyrov	Earnest (Eric)	U. Wisconsin, Madison	D. C. Larbalestier	1997	Hewlett-Packard	Hewlett-Packard
Parrell	Jeff	U. Wisconsin, Madison	D. C. Larbalestier	1997	Oxford Superconducting Technology	
Cole	Benjamin	U. 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	Bo	UC Berkeley	J. Wurtele / A. Neureuther	2002	Semiconductor Industry	
Kawamura	Emi	UC Berkeley	J. Wurtele / C. Birdsall	2003		
Golden	Fletcher	UC-Irvine	Fisher/ Rostoker	1985	EG&G	
Irans	Ardeshir	UC-Irvine	Fisher/ Rostoker	1985	BNL	
Darrow	Chris	UCLA	C. Joshi	1986	LLNL	LLNL
Figueroa	Humberto	UCLA	C. Joshi	1986	ANL	ITT Venezuela
Mori	Warren	UCLA	C. Joshi	1987	Rutherford Laboratory	UCLA
Umstadter	Don	UCLA	C. Joshi	1987	Bell Labs	U. 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 U.	Nagoya U.
Savage, Jr.	Richard	UCLA	C. Joshi	1992	CalTech	CalTech
Wang	Xijie	UCLA	D. Cline/ I. Ben-Zvi	1992	BNL/UCLA	BNL
Williams	Ronald	UCLA	C. Joshi	1992	Florida A&M	Florida A&M
Hartman	Spencer	UCLA	C. Pellegrini	1993	SLAC	Opti-Phase Corp.
Decker	Chris	UCLA	C. Joshi	1994	LLNL	LLNL

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Everett	Matt	UCLA	C. Joshi	1994	LLNL	Private Industry
Brogle	Robert	UCLA	C. Joshi	1996	Aeroject, 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	UCLA	J. Rosenzweig	1997	SLAC	SLAC
Liu	Yabo	UCLA	David B. Cline	1997	Pharo Science & Applications, Inc.	PWARE, Inc.
Ramachandran	Sathyadev	UCLA	D. Cline/ T. Murphy (FNAL)	1997	FNAL	Univ. Houston
Zhang	Renshan	UCLA	C. Pellegrini	1997	Hughes Corp.	
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	Ken	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	U. of Tokyo	U. of Tokyo
Anderson	Scott	UCLA	J. Rosenzweig	2002		LLNL
Murokh	Alex	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	UCLA/SLAC	D.Cline/ P. Chen	1993	UCLA	Industry
Nantista	Christopher	UCLA/SLAC	D. Cline/ T. Lavine	1994	SLAC	SLAC
Lin	Xin-Tian	UCSD	N. Kroll	1995		

Last Name	First Name (MI)	Institute	Advisor.	Year of Ph.D.	First Placement	Present Placement
Gou	S. K.	U-IA/Columbia	Amitava Bhattacharjee	2000	Semiconductor Industry	Semiconductor Industry
Lai	C.H.	USC	T. Katsouleas	1997	Industrial Technology Investment Corp.	Star Capital Group
Chiou	T.C.	USC	T. Katsouleas	1998	Qualcom	Qualcom
Ahn	Hyo	Yale	V. Hughes	1992		