Advanced Accelerator R&D

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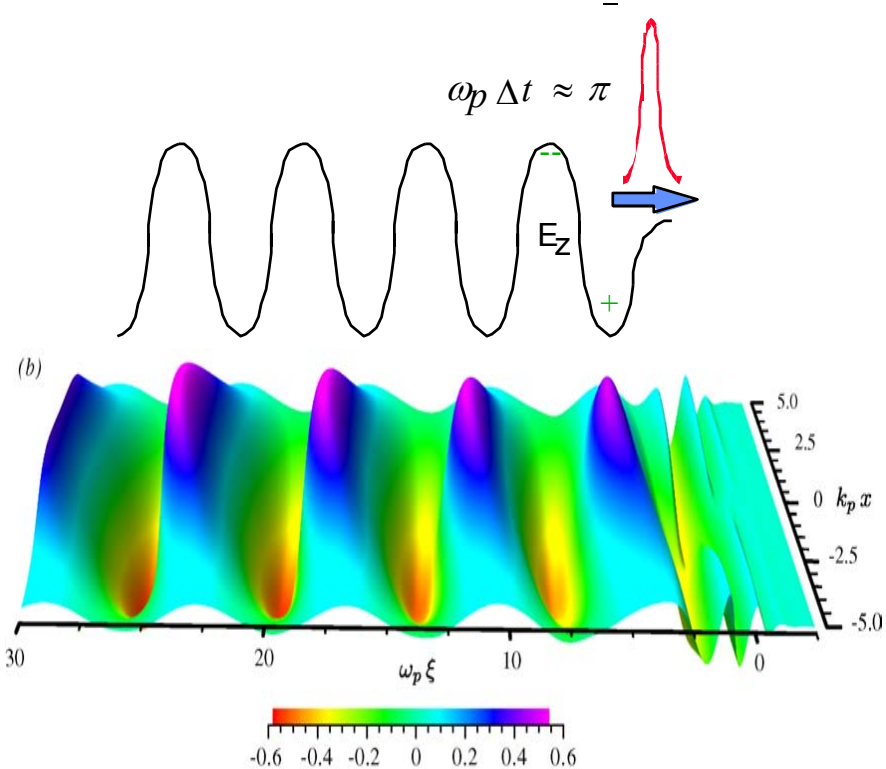
Plasma Accelerators Offer the Possibility of High-Energy Particle Beams at Affordable Scale

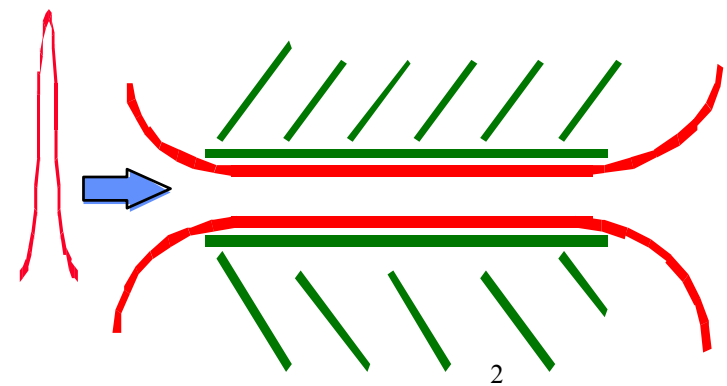
$$W = e\, E_z\, L_{int}$$

- Conventional RF accelerators: 10-100 MV/m, 100-1000 m for 10 GeV
- Laser-plasma based: 10 - 100 GV/m, 0.1 - 1 m for 10 GeV

Laser excites plasma wave: $E_z > 10$ GV/m



Laser channeling in plasmas increases L_{int}



$$n = 1 - \frac{\omega_p^2}{2\omega_l^2}$$

Optical injection

- Self-modulated laser wakefield
- Colliding pulse injector

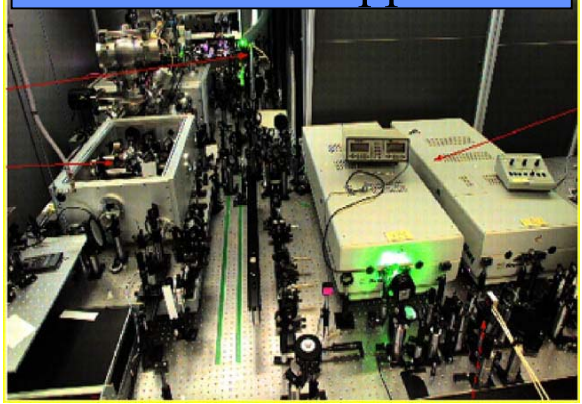
Impact and status of laser driven accelerator R&D

- Impact:
  - Compact GeV-class accelerator: applications in HEP and many areas of science
  - Laser technology for high energy physics
  - Training ground for future accelerator physicists
- Present status (at LBNL and/or other Laboratories)
  - Ultra-high gradient (10-100 GV/m): tens of MeV in mm-scale length accelerator ✓

    Note: highest gradient to-date with beam based is 100 MeV/m
  - Femtosecond electron bunches (coherent THz emission) ✓
  - High charge yield (multi-nC) ✓
  - Divergence x spot size at exit of accelerator < 0.1 mm-mrad ✓
- Open questions
  - Beam quality: is collider-relevant possible ?
  - Scalability: can plasma channels guide high intensity laser pulses over m-scale?
  - Efficiency: will lasers reach required wall-plug efficiency?

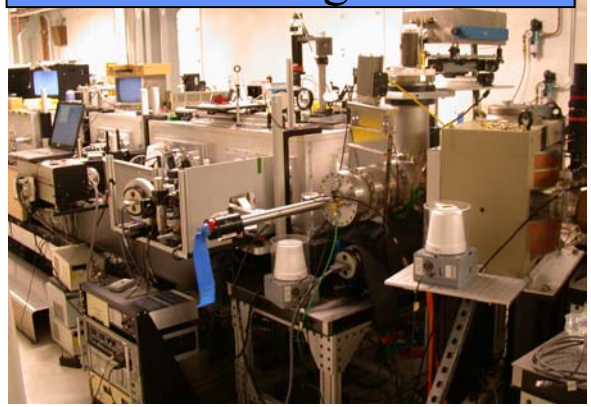
l'OASIS: An unparalleled facility dedicated to exploring laser acceleration

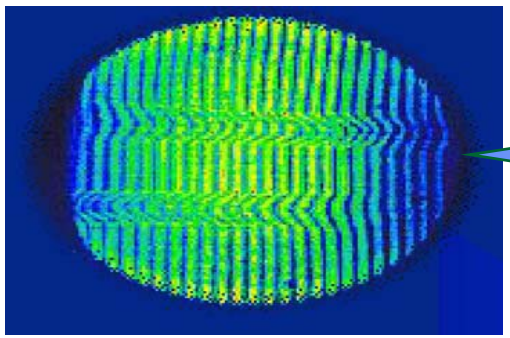
10 TW Ti:sapphire

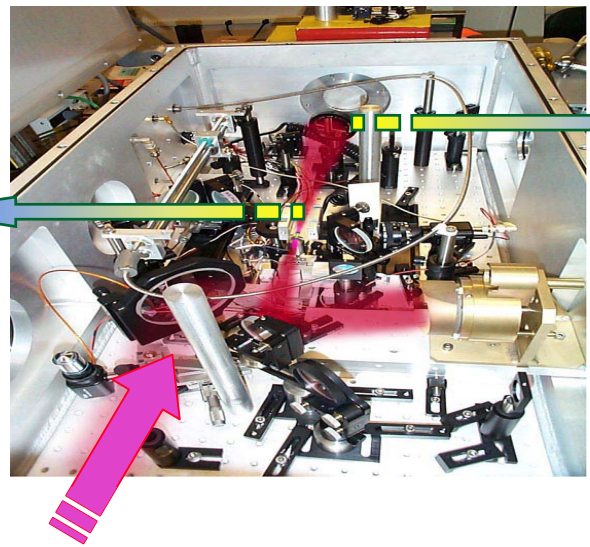


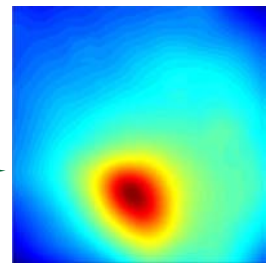
100 TW Ti:sapphire
(under construction)

Shielded target room







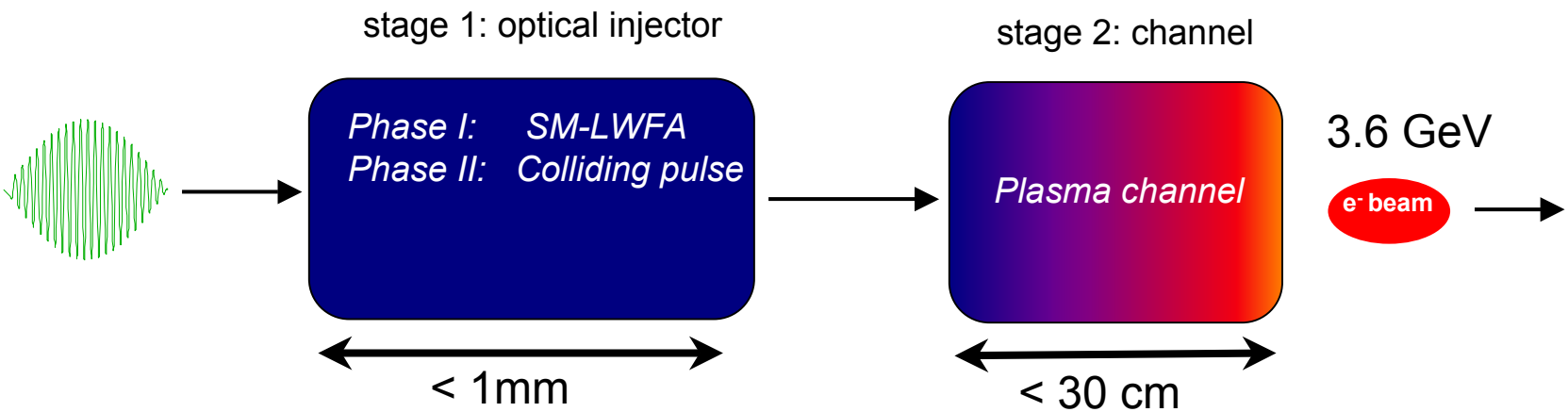


> 5 nC/bunch
10 - 20 fs pulse
at up to 10 Hz
@ 100 GeV/m

L'OASIS: Lasers Optical Accelerator Systems Integrated Studies

Development of > 1 GeV module requires 100 TW class laser system

Concept: Two stage all-optical accelerator module



Energy Gain: ΔW = **3.6 GeV**, E_{peak} = **23 GV/m**

Laser Pulse: **3.9 J**, 44 TW, 90 fs (2×10^{18} W/cm^{-2}, $\lambda = 0.8$ μm, $r_s = 36$ μm)

Plasma: $L_{channel} = 29$ cm, $n = 2.1 \times 10^{17}$ cm^{-3}

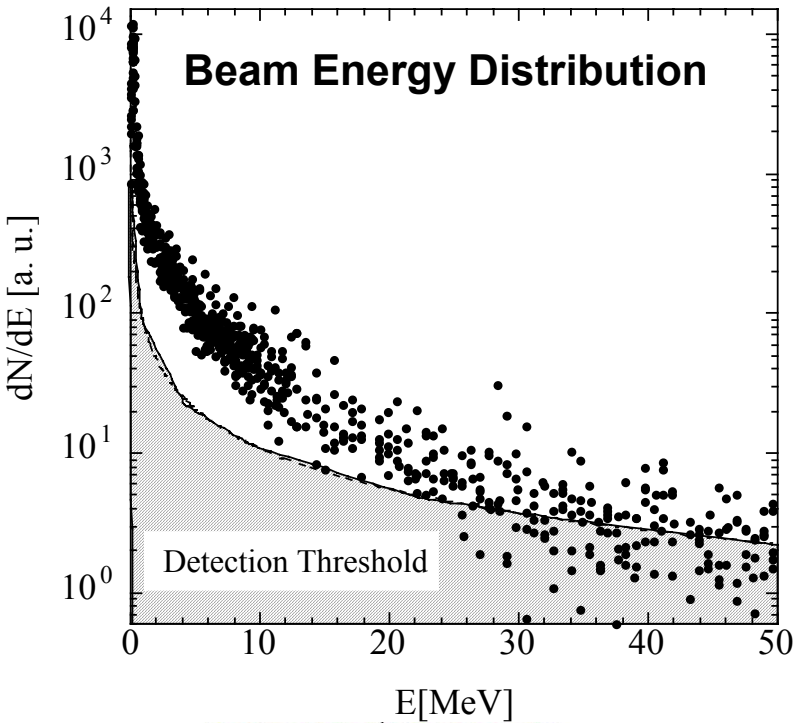
Note: 100 pC at 3.6 GeV = 0.35 J

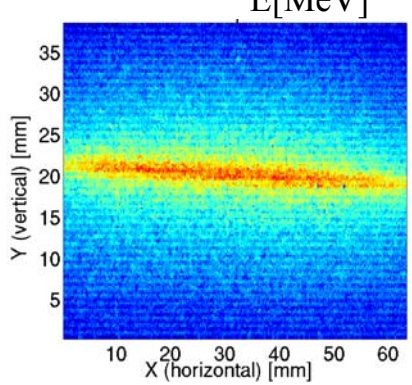
- Challenges:
  - Controlled injection
  - Long scale (10 - 100 cm) length plasma channel
  - Beam properties: energy spread, emittance, charge

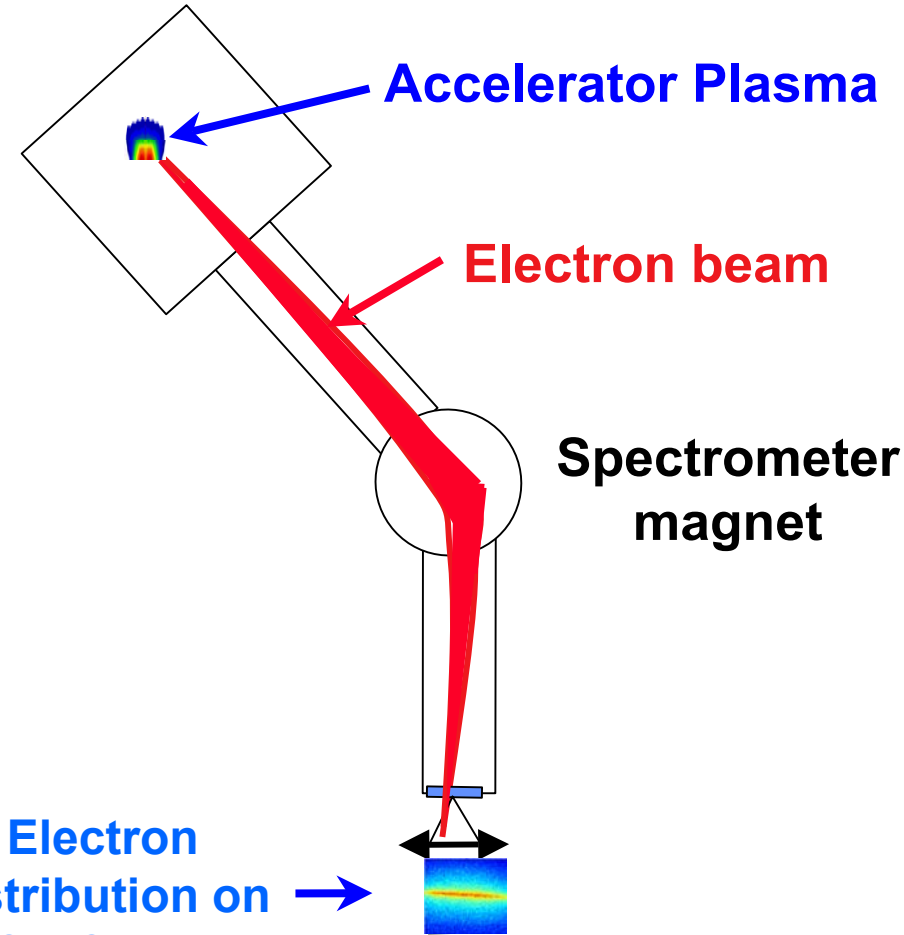
R&D program aims at developing physics and technology for future accelerators

- Controlling accelerator performance
  - Charge, energy (mean and spread), emittance
  - Laser power, plasma profile
- Development of 1 GeV module
  - Injector
  - Accelerating structure- plasma channel
  - Staging
- Modeling and simulation of non-linear physics

25 to 50 GeV/Meter Gradient Achieved in 1.5- to 2.0-Millimeter Plasma Structures

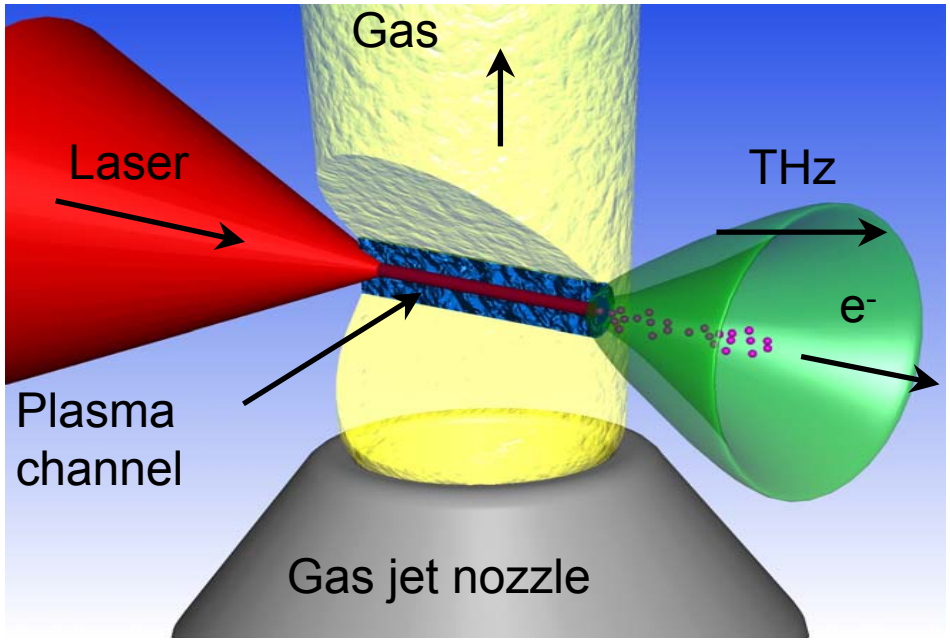




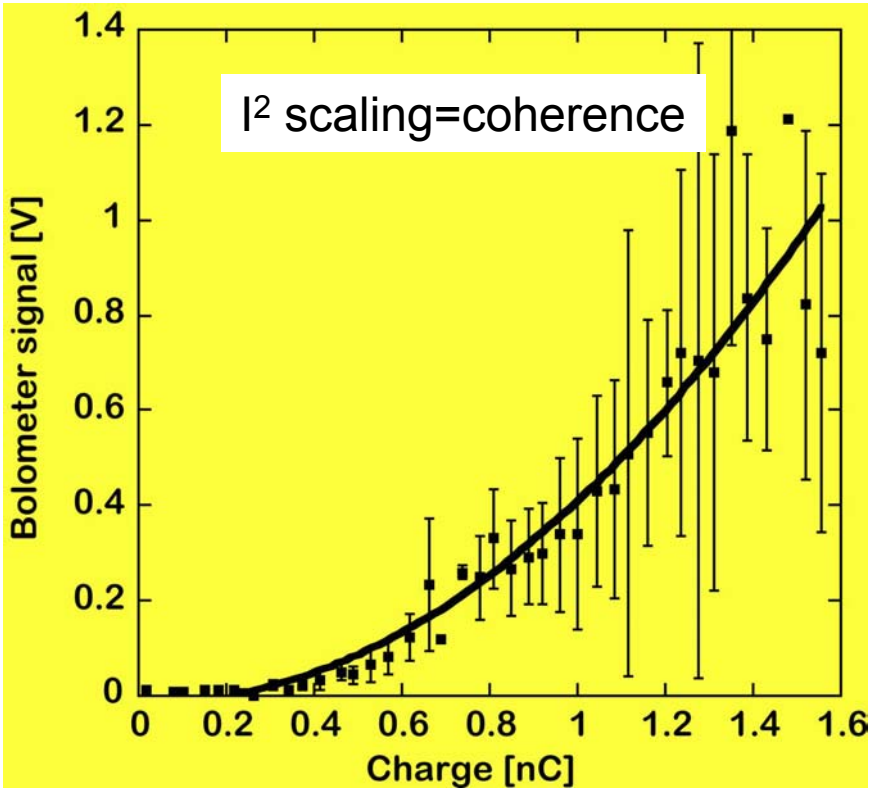


Goal is 1-GeV, 10-centimeter structure within two years

Novel diagnostics are being developed for laser driven accelerators



- Plasma edge becomes equivalent to metal foil, i.e. transition radiator
- Ultrashort bunch produces coherent THz signal

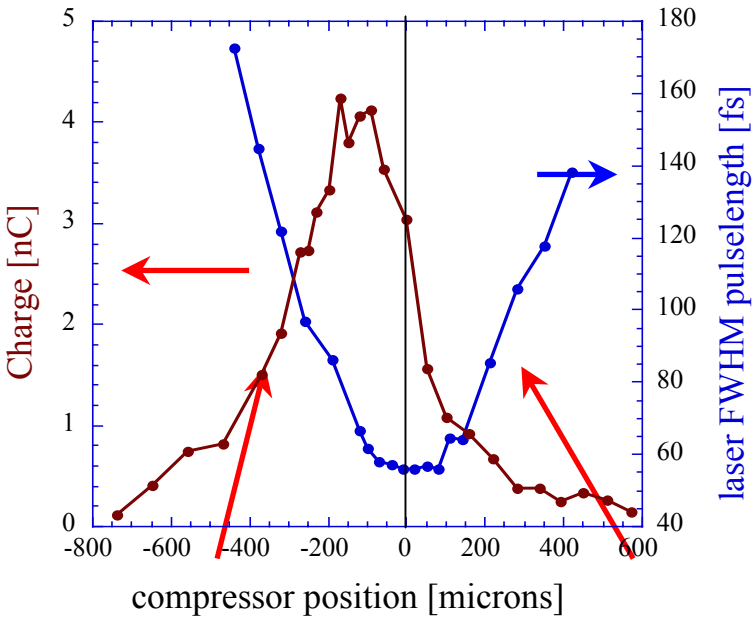


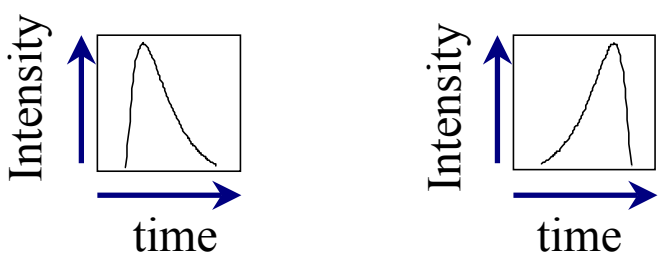
- Powerful beam diagnostic:
  - Radiation carries signature of beam
    - Energy
    - Charge
    - Bunch length
    - Emittance

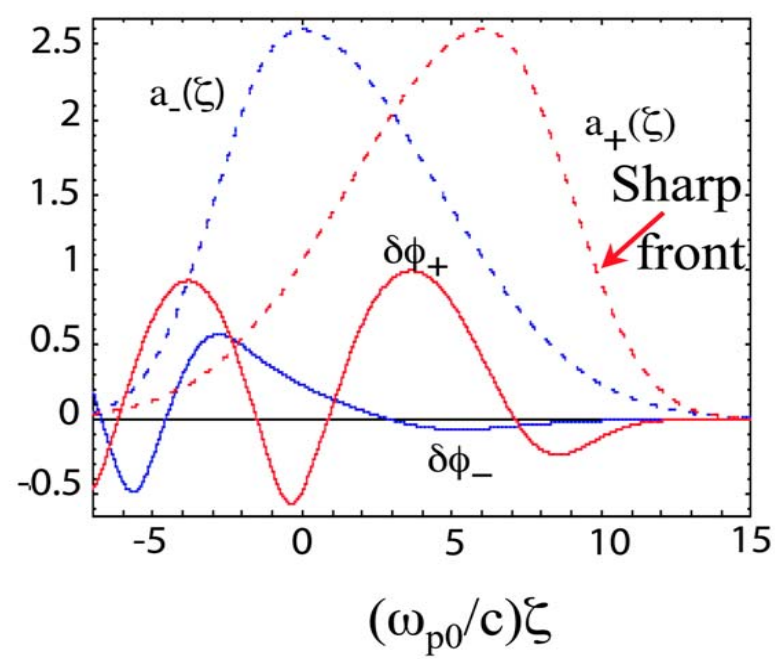
W.P. Leemans et al., submitted to Nature

Accelerator control: laser pulse shape

Asymmetry in electron yield vs. pulse duration





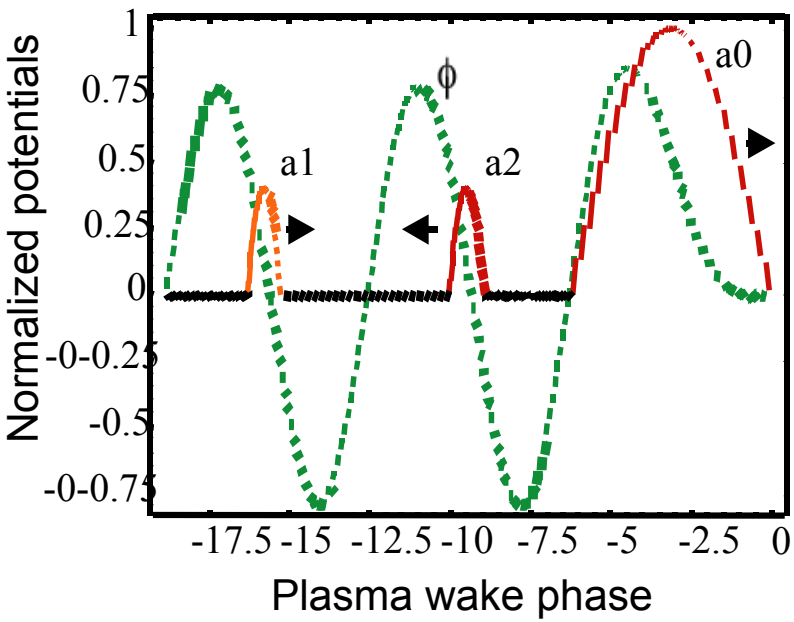


•Pulse shape depends on compressor position

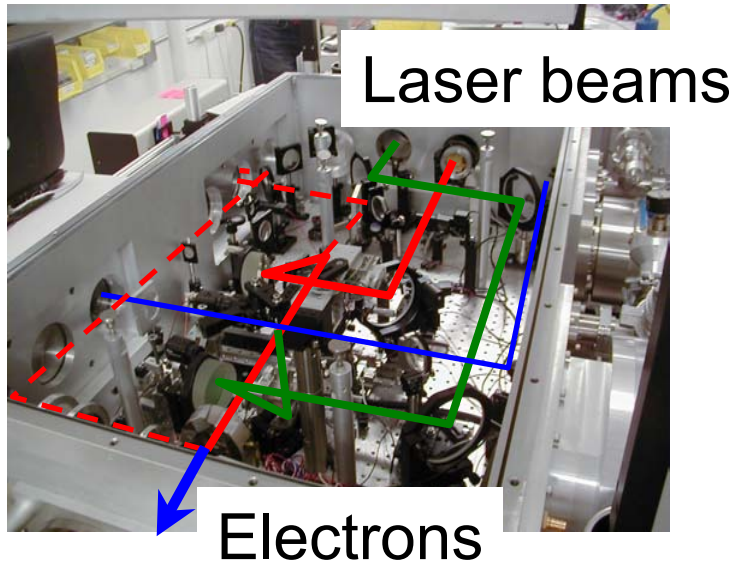
W.P. Leemans et al., PRL **89**, 174802 (2002).

Accelerator control: minimizing energy spread via laser triggered injection

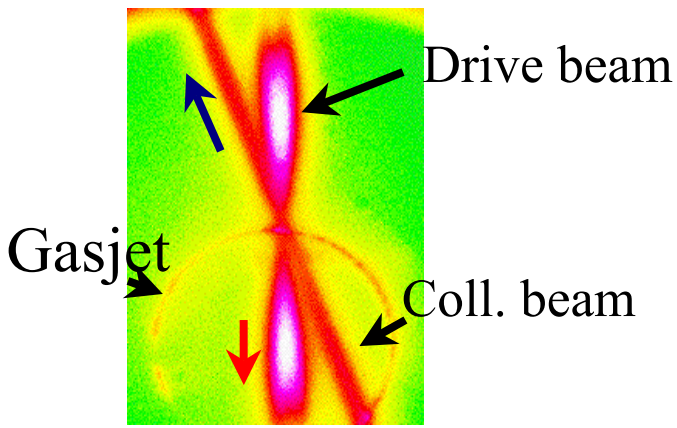
Colliding pulse injection



E.Esarey et al., PRL'97



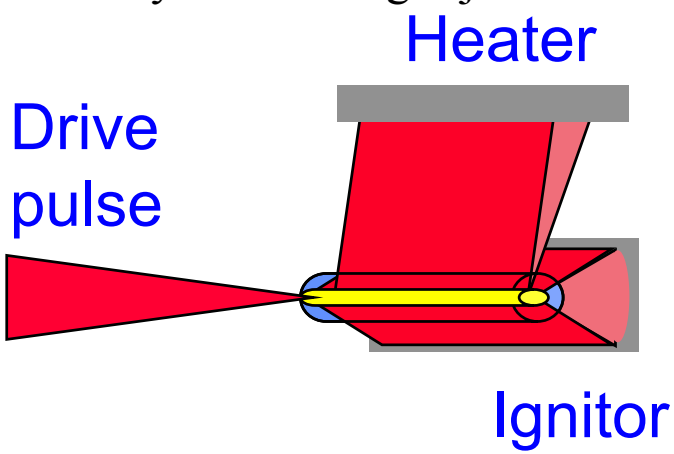
Top view



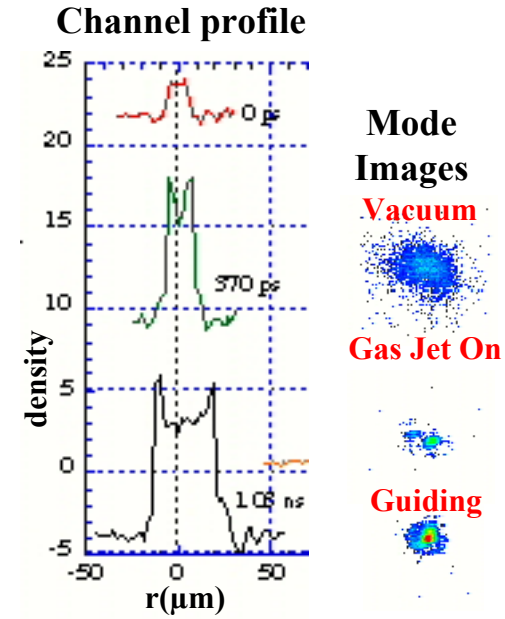
- Femtosecond bunches
- Few % energy spread
- 1-10 pC/bunch
- 40 MeV in 1 mm
- Emittance < 1 micron
- Observed enhancement of yield with 2 pulses

Accelerator control: plasma shape and profile

- Plasma channel: structure for guiding laser and supporting wake
- Hydrodynamically formed in gas jet



Guided 10^{17}W/cm^2 over 5-10 Z_R

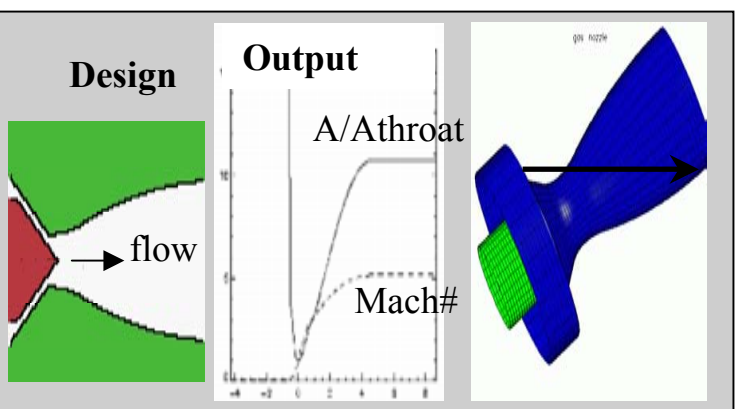


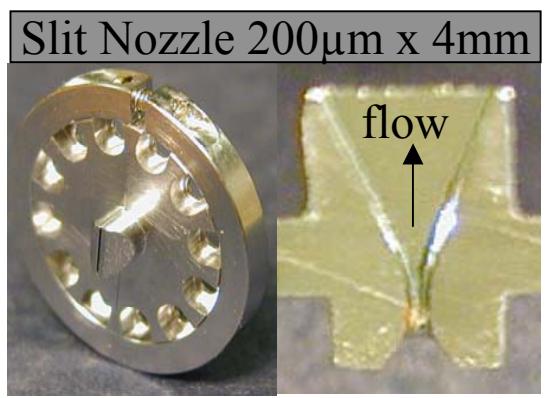
Volfbeyn, Esarey and Leemans, Phys. Plasmas '99

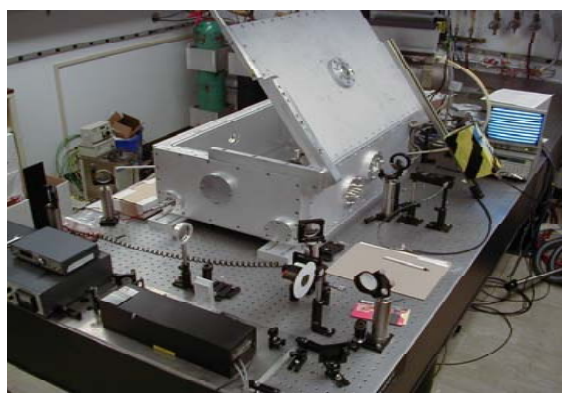
Design
- 1 and 3D model
- SciDAC

Development
- Slit nozzle
- Piezo+microvalves

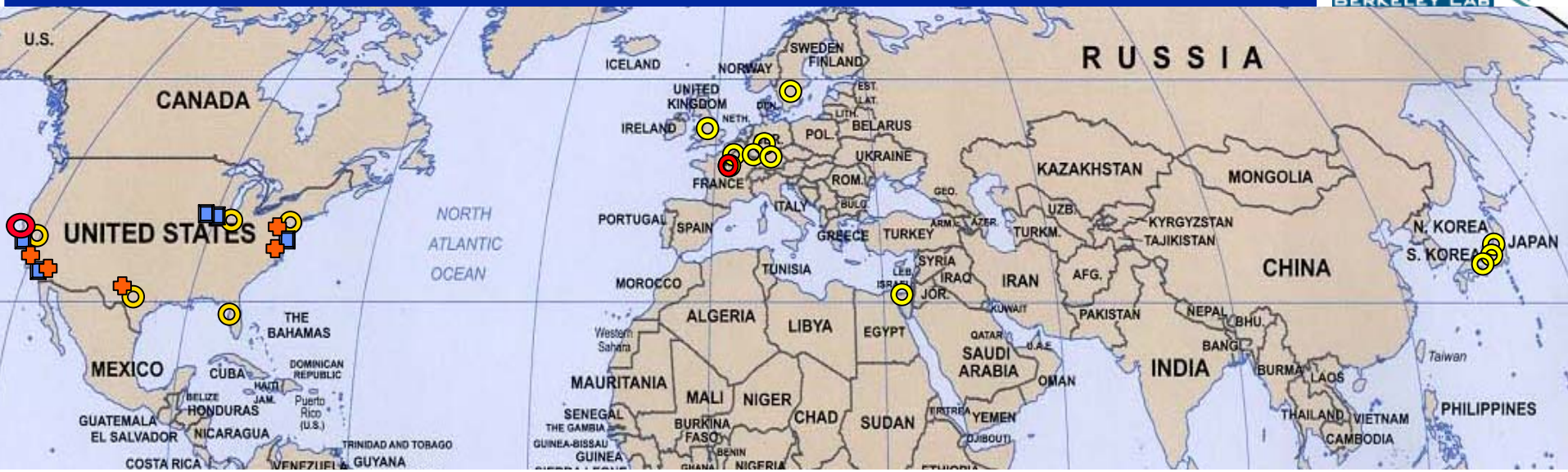
Testing
- Gas jet test stand
- Experiment







Laser facilities above 10 TW worldwide



:100TW, 10 Hz
:>10TW, <<10 Hz
:Beam driven

- DOE-HEP Investments in advanced accelerator facilities
  - Beam driven: ATF-BNL, AWA-ANL, A0-FNAL, UCLA, SLAC-FFTB/NLCTA
    - ⇨Wide parameter range
  - Laser-driven UT Austin, UMaryland, NRL, UCLA-Neptune, Stanford, LBNL
- Only facility with > 10 TW, 10 Hz laser system dedicated to HEP is at LBNL
- Major upgrade to 100 TW, 10 Hz facility
  - ⇨ Initiated by BER but funding cut in FY04

Advanced Accelerator program at LBNL

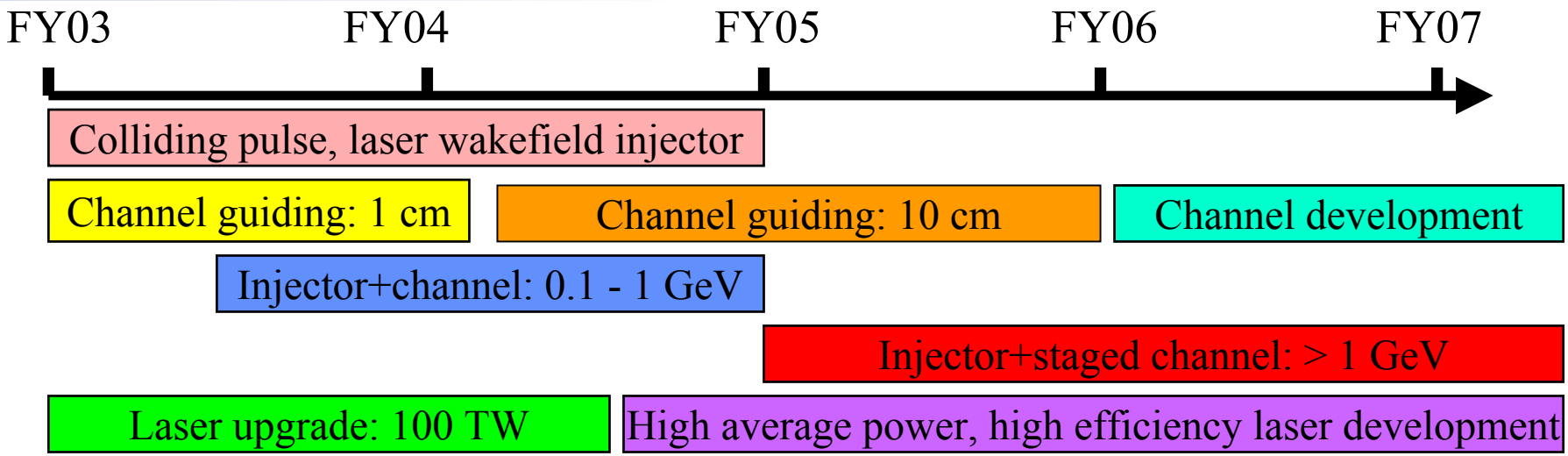
- **Development of 1 GeV in 10 cm laser driven accelerator**
  - Laser injection methods for high quality e-beams: colliding pulse
  - Long plasma channels for high energy
  - Novel diagnostics (bunch duration)
- **Comprehensive:**
  - Experiment-Theory-Simulation
  - Internal and external collaborations (e.g. SciDAC)
- **World-class research team:**
  - Refereed Journal Publications (1996-2002): 52 total (13 PRL, 1 Science)

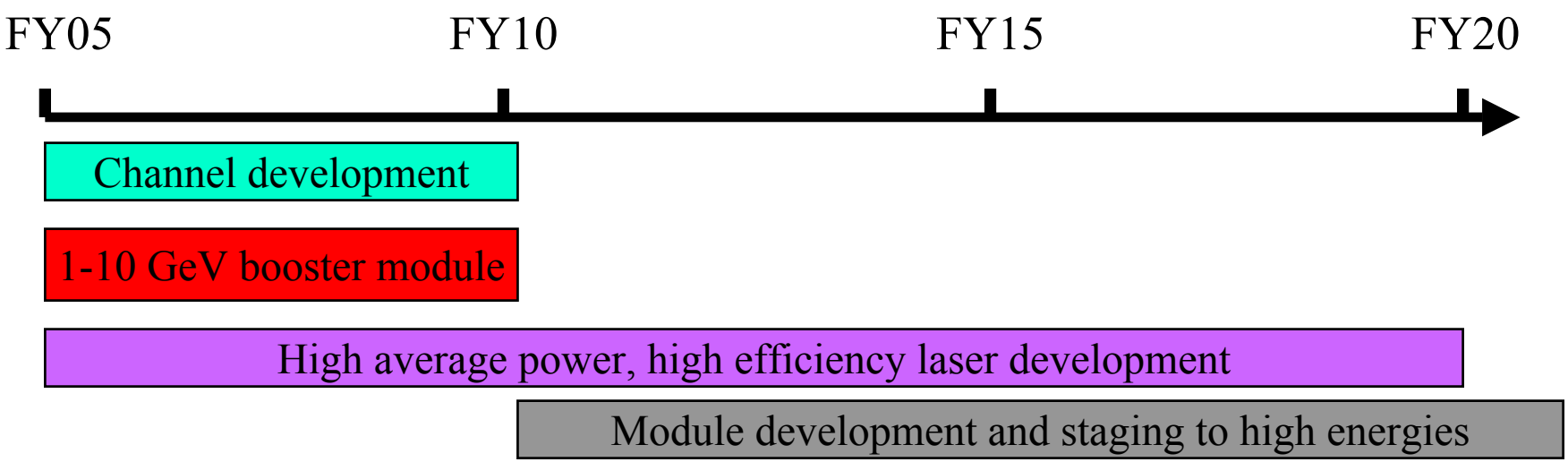
- **Unique, state-of-the-art, world-class facility:**
  - Multi-beam 10 TW, 10 Hz system
  - Upgrade to 100 TW, 10 Hz in progress.
  - Radiation shielded experimental areas, remote operation, control room

Only 100 TW, 10 Hz class facility in the world equipped for and dedicated to laser accelerator research

Such a facility is essential for 1 GeV laser accelerator R&D

Near and long term projection





L'OASIS Experimental Highlights with HEP relevance

- Development of state-of-the-art laser acceleration facility and Beam Test Facility
- Laser-based diagnostic for relativistic electron beams using Thomson scattering
  - W.P. Leemans et al., Phys. Rev. Lett. 77, 4182 (1996)
- Return current effects in plasma lenses for relativistic electron beams
  - R. Govil et al., Phys. Rev. Lett. 83, 3202 (1999)
- Laser channel production and guiding of > 10^{17} W/cm^2 using ignitor-heater method
  - P. Volfbeyn et al., Phys. Plasmas 6, 2269 (1999)
- Optical transition radiation to diagnose 30 GeV electron beams
  - P. Catravas et al., Phys. Plasmas 9, 2428 (2002)
- Cerenkov radiation from a 30 GeV beam to probe plasmas
  - P. Catravas et al., Phys. Rev. E 64, 046502 (2001)
- Fluctuational interferometry for measuring femtosecond bunches
  - P. Catravas et al., Phys. Rev. Lett. 82, 5261 (1999)
- Betatron oscillation of a 30 GeV beam propagating through a 1.4 m plasma
  - C. Clayton et al., Phys. Rev. Lett. 88, 154801 (2002)
- Gamma-neutron activation from a laser-driven accelerator
  - W.P. Leemans et al., Phys. Plasmas 8, 2510 (2001)
- Laser pulse shape effect on electron yield from a laser-driven accelerator
  - W.P. Leemans et al., Phys. Rev. Lett. 89, 174802 (2002)

L'OASIS Theory Highlights with HEP relevance

- **Colliding laser pulse method for electron injection**
  - E. Esarey et al., Phys. Rev. Lett. **79**, 2682 (1997); C.B. Schroeder et al.,PRE **59**, 6037 (1999)
- **Non-paraxial propagation of high intensity, short laser pulses in plasma channels**
  - E. Esarey et al., Phys. Rev. Lett. **84**, 3081 (2000)
- **Electron injection in wakefields by a density transition**
  - H. Suk et al., Phys. Rev. Lett. **86**, 1011 (2001)
- **Particle-in-cell code including the effects of ionization**
  - D. Bruhwiler et al., Phys. Rev. Spec. Topics Accel. Beams **4**, 101302 (2001)
- **Semi-analytic code for space charge effects in ultrashort electron bunches**
  - G. Fubiani et al., AIP Conf. Proc. **569**, 423 (2001)
- **First fully nonlinear Maxwell-fluid code for laser plasma interactions**
  - B. Shadwick et al., IEEE Trans. Plasma Sci. **30**, 38 (2002)
- **Synchrotron radiation from electron beams in plasma focusing channels**
  - E. Esarey et al., Phys. Rev. E **65**, 056505 (2002)
- **Two-stage laser wakefield accelerator**
  - A. Reitsma et al., Phys. Rev. Spec. Topics Accel. Beams **5**, 051302 (2002)
- **Frequency chirp and pulse shape effects on self-modulated lwfa's**
  - C.B. Schroeder et al., Phys. Plasmas, Jan (2003)
- **Ionization effect in the plasma afterburner concept**
  - D. Bruhwiler., Phys. Plasmas, submitted (2002)