Advanced Accelerator R&D

Prof. Tom Katsouleas

for the

E-157, E-162, E-163, E-164, LEAP Collaborations

- Extraordinarily high fields developed in beam plasma and beam-laser interactions
- Many questions related to
  -- basic physics of HED beams
  -- the applicability of plasmas and lasers to high energy accelerators and colliders

Address these questions via experiments ⇒

- E-150: Plasma lens (P. Chen et al.) demonstrated MT/m focusing fields
- E-157: First experiment to study Plasma Wakefield Acceleration (PWFA) of electrons over meter scale distances
- E-162: PWFA for positron beam drivers qualitatively different (flow-in vs. blow-out)
- E-164: Opportunity for dramatically shorter bunches in the FFTB in 2003 with correspondingly higher PWFA gradients (> GeV/m)
- E-163: Laser acceleration and staging utilizing an upgraded NLCTA and a pre-bunched beam
Example -- the

E-162 & E-164 Collaborations

R.H. Siemann, D. Walz

Stanford Linear Accelerator Center

B.E. Blue, C.E. Clayton, C. Huang, C. Joshi*, K.A. Marsh, W.B. Mori, S. Wang

University of California at Los Angeles
T. Katsouleas*, S. Lee, P. Muggli

University of Southern California
Physical Principles of the Plasma Wakefield Accelerator

- Space charge of drive beam displaces plasma electrons

- Plasma ions exert restoring force => Space charge oscillations

- Wake Phase Velocity = Beam Velocity (like wake on a boat)

- Wake amplitude $\propto \frac{N_b}{\sigma_z^2}$ (for $2\sigma_z \approx \lambda_p \propto \frac{1}{\sqrt{n_0}}$)

- 2D/3D PIC Simulations have born out this dependence

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Beam Propagation Through A Long Plasma

- Smaller “matched” beam size at the plasma entrance reduces amplitude of the betatron oscillations measured at the OTR downstream of the plasma
- Allows stable propagation through long plasmas (> 1 meter)

**E-157**

- \( \sigma_0 \) Plasma Entrance = 50 \( \mu \)m
- \( \epsilon_N = 12 \times 10^{-5} \) (m rad)
- \( \beta_0 = 1.16 \) m

**E-162 Run 2**

- \( L = 1.4 \) m
- \( \sigma_0 = 14 \) \( \mu \)m
- \( \epsilon_N = 18 \times 10^{-5} \) m-rad
- \( \beta_0 = 6.1 \) cm
- \( \alpha_0 = -0.6 \)

\[ \Psi \propto n_e^{1/2}L \]

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E-162: X-Ray Emission from Betatron Motion in a Plasma Wiggler

E-157: Electron Beam Refraction At Plasma–Gas Boundary

• Vary plasma – e⁻ beam angle $\phi$ using UV pellicle

• Beam centroid displacement @ BPM6130, 3.8 m from the plasma center

$\theta = \alpha (n_b/n_e)^{1/2} r_b$

$\theta \sim 1/\sin \phi$

$\theta \approx \phi$

P. Muggli et al., Nature 411, 2001

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Refraction of an Electron Beam: Interplay between Simulation & Experiment

Experiment
(Cherenkov images)

Laser off
Laser on

3-D OSIRIS
PIC Simulation

● 1st 1-to-1 modeling of meter-scale experiment in 3-D!

P. Muggli et al., Nature 411, 2001

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**OSIRIS Simulation**

- Average measured energy loss (slice average): $159 \pm 40$ MeV
- Average measured energy gain (slice average): $156 \pm 40$ MeV

$(\approx 1.5 \times 10^8 \text{ e}^-/\text{slic})$

**Experimental Data**

- $n_e = 1.6 \times 10^{14} \text{ cm}^{-3}$
- $n_e = 2.0 \times 10^{14} \text{ cm}^{-3}$
- $n_e = (2.3 \pm 0.1) \times 10^{14} \text{ cm}^{-3}$

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E-162: PWFA Different Mechanism For A Positron Beam

- **Electron Plasma**
  - Blow-out
  - Flow-in

- **Positron**
Preliminary Data on Energy Gain of a Positron Beam
With an eye towards the future and larger gradients, proposal for E-164…

We want to:

- Measure Accelerating Gradients in a PWFA > 1 GeV/m
- Test bunch length scaling

Approved -- begins 2003!

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Solid State Lasers - High Efficiency & Tremendous Fluence!

SLAC PPM Klystron
11.4 GHz, 3 µs pulse
$P_{ave} = 27$ kW, $\eta = 65\%$

Yb:KGd(WO$_4$)$_2$
290 THz, 112 fs pulse
$P_{ave} = 1.3$ W, $\eta = 28\%$

SLAC PPM Klystron
$10^{-5}$ TW/cm$^2$

Ti:Sapphire Laser
$10^8$ TW/cm$^2$

Source Efficiency

Source Fluence (TW/cm$^2$)

RF Tubes

Lasers

Source Frequency [GHz]
E-163 Laser Acceleration

- Crossed lasers interfere & produce $E_z$
- Boundaries terminate the interaction to give net acceleration

**Image Description**

- **LEAP Experiment**
  - (Stanford Campus)
  - $e^-$

- **Diagram**
  - Interaction Length: $\sim 1000 \lambda \sim 1 \text{ mm}$
  - Slit Width $\sim 10 \lambda$
  - Terminating Boundary
  - $e^-$ beam
  - Crossing angle: $\theta$
  - Waist size: $w_o \sim 100 \lambda$
E163 would move beyond P-o-P toward a real laser accelerator

Optical prebuncher to bunch electrons on the $\lambda = 1 \, \mu m$ scale

Multiple cell accelerating structure

Incoming plane waves

Lenslet arrays & Phase Control

LEAP cells
“We recommend that vigorous long-term R&D aimed toward future high-energy accelerators be carried out at high priority…” – HEPAP Subpanel, October 200

To this end, a group from SLAC, Stanford, UCLA and USC has proposed the ORION Center for Advanced Accelerator and Beam Physics Research

- The ORION Center addresses the gap between the promise of these new ideas and their realization for High Energy Physics
- ORION brings together the elements needed to explore the physics of different acceleration techniques
  - State of the art beams at the FFTB and upgraded NLCTA
  - A highly flexible electron source, specialized facilities for beam diagnosis and integrated computer simulations, etc.
  - A multi-disciplinary group of leading researchers in plasma science, lasers, beam physics, modeling and conventional accelerator technology
  - A shared set of broad physical and intellectual resources in a stable research environment
THE ORION CENTER

UCLA
Chan Joshi
Warren Mori
James Rosenzweig

USC
Tom Katsouleas

Stanford University
Organized Lab

Bob Byer
Bob Siemann
The ORION Center – The Facilities

- Unique facilities for advanced accelerator research

**FFT**B – 30 GeV $e^-$ & $e^+$ beams. New potential of $e^-$ beams with $\sigma_z < 100$ $\mu$m

**ORION** Facility (to be constructed in part with funds from the ORION Center Proposal) based on the NLCTA - $\sim$65 & 350 MeV $e^-$ beams
The ORION Facility – An Upgrade to the NLCTA for Advanced Accelerator Research

Low Energy Hall for experiments with $E \sim 65$ MeV, 3 beam lines

High Energy Hall for experiments with $E \sim 350$ MeV, 1 beam line

Chicane and beam transport used for tailoring longitudinal phase space

Laser room for experimental lasers

Injector – 1.6-cell RF gun

NLCTA
Plasmas Have Extraordinary Potential

Self modulated laser wakefield acceleration
E > 100 MeV
Accelerating Gradient > 100 GeV/m

A. Ting et al, NRL

P. Chen et al, SLAC

Plasma Focusing of e\(^+\) beams
Focusing Gradient > 1 MT/m
Advanced Accelerator R&D

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Plasma Acceleration:

- Extraordinarily high fields developed in laser and beam plasma interactions
- Many questions related to the applicability of plasmas to high energy accelerators and colliders
- E-157: First to study PWFA of electrons over meter scale distances, **E-162**: Positron beams and improved experimental apparatus, **E-164**: dramatically shorter bunches in the FFTB in 2003 and gradients (> GeV/m)!

Laser Acceleration:

- Laser developments in efficiency and peak power make them an attractive power source for accelerators
- **LEAP** is proof of principle laser acceleration experiment
- Future laser accelerators will need pre-bunched beam and staging ⇒ **E-163**

Continue to build on these collaborations at the ORION Center
Time Integrated & Time Resolved Focusing of Positrons

**Time Resolved “Streaks” of Cherenkov at Different Plasma Densities**

**Time Dependent Focusing Within a Positron Bunch**

- Laser OFF
- \( n = 2.4 \times 10^{11} \text{cm}^{-3} \)
- \( n = 2.2 \times 10^{12} \text{cm}^{-3} \)
- \( n = 3.8 \times 10^{12} \text{cm}^{-3} \)

Head

Tail

**SLAC SLUO July 2002**
OSIRIS Simulation

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($\approx 1.5 \times 10^8$ e$/\text{slice}$)

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Plasmas Have Extraordinary Potential

A 100 GeV-on-100 GeV e⁻e⁺ Collider
Based on Plasma Afterburners