Accelerator Research at FACET

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SLUO Annual Meeting
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Introduction

• Context
  – Why new accelerator techniques?
  – Challenges in accelerator research?

• Facility for Advanced Accelerator Experimental Tests (FACET)

• Proposals for FACET
  – Plasma wakefield acceleration
  – Dielectric wakefield acceleration
  – Crystal collimation

• Other SLAC experimental facilities for accelerator research
  – Accelerator Structure Test Area
  – NLC Test Accelerator
  – E-163 and Direct Laser Acceleration
Why New Acceleration Techniques?

- Accelerators have been primary tool to advance HEP frontiers
  - But accelerators have continued to increase in size and cost and appear to be approaching the limit that can be supported

- Need new technologies that are aimed at cost effective solutions

- Accelerator research very broad from materials to rf to nonlinear dynamics
  - Advances come from both fundamental research and directed R&D aimed at applications
**Primary Challenges for Accelerator R&D**

1. Beam power $\rightarrow$ average luminosity or brightness
   - Power (average current times energy) is frequently measured in megawatts and has both technical and physical limitations

2. Beam brightness and control $\rightarrow$ peak luminosity and radiation source brightness
   - Brightness is flux divided by 6-D phase space volume (emittance) which should be conserved after beam creation

3. Beam energy $\rightarrow$ energy reach or radiation wavelength
   - Critical problem for HEP requiring new cost-effective concepts
   - Novel concepts will enable new applications elsewhere as well

- Cost-effective approaches are needed across the field
- Paths to educate and attract more people to field
High Gradient Acceleration

- High gradient acceleration requires high peak power and structures that can sustain high fields
  - Beams and lasers can be generated with high peak power
  - Dielectrics and plasmas can withstand high fields

- Many paths towards high gradient acceleration
  - RF source driven metallic structures
  - Beam-driven metallic structures \( \sim 100 \text{ MV/m} \)
  - Laser-driven dielectric structures
  - Beam-driven dielectric structures \( \sim 1 \text{ GV/m} \)
  - Laser-driven plasmas
  - Beam-driven plasmas \( \sim 10 \text{ GV/m} \)

- FACET aimed at beam-driven plasma and dielectric acc.
Facility for Advanced aCcelerator Experimental Tests (FACET)

- FACET uses first 2/3 of SLAC linac → 23 GeV beams
- Compresses bunches in 3 stages → 10’s of microns
- Focuses beams to 10 micron spots transversely
- Unique beams with very high current density (~20 kA $I_{\text{peak}}$)
  - Fields of 10 V per Angstrom (100’s Tesla) → field ionize atoms
  - Intense THz radiation
Advanced accelerator research promises to improve the power and efficiency of today's particle accelerators, enhancing applications in medicine and high-energy physics, and providing potential benefits for research in materials, biological and energy science. Experiments on future acceleration techniques require high-quality, forefront facilities.

FACET—Facilities for Accelerator science and Experimental Test beams at SLAC—will study plasma acceleration, using short, intense pulses of electrons and positrons to create an acceleration source called a plasma wakefield accelerator. FACET will meet the Department of Energy Mission Need Statement for an Advanced Plasma Acceleration Facility.
FACET Users Workshop

Workshop on FACET experimental program Feb, 2010

FACET Users Workshop

March 18–19, 2010
Redwood Conference Room, Building 48
SLAC National Accelerator Laboratory
Menlo Park, California

Four working groups
- Plasmas Acc.
- Dielectric Acc.
- Crystals
- Materials

Announcements
Presentations from the Workshop are now available for download.
» view presentations
FACET Sector 20
Experimental Region

- **Positron Target**
- **LCLS Injector Vault**
- **Shield Wall**
- **Beam Dump**
- **Focal Point (IP)**
- **CTR/THz**

- Focal point is 2m downstream of the face of the last quadrupole
- Drift following focal point is 30m to the new LCLS shield wall
List of FACET Proposals

Unique facility has led to variety of 1st round proposals

- Multi-GeV Plasma Wakefield Acceleration Experiments
- Wakefield Acceleration in Dielectric Structures
- Study of Ultrafast Processes in Magnetic Solids following Excitations with Electron Beams
- Investigations of Optical Diffraction Radiation as a Non-intercepting Beam-size Monitor at High Energy and Charge Density
- Determination of the time profile of 50 fs long bunches by means of coherent Smith-Purcell radiation
- Afterburner Based on Particle Acceleration by Stimulated Emission of Radiation at FACET
- Letter of intent for a program of measurements for the CLIC study at the FACET facility
Promise of Plasma Acceleration

- 50 GV/m demonstrated
  - Potential use for linear colliders and radiation sources

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World-Wide Interest in Plasma Acc.

Plasma Acceleration on the Globe, T. Katsuoleas

- Laser Wake Expts
- Electron Wake Expts
- $e^-/e^+$ Wake Expts
Beam-Driven vs Laser-Driven

- Beam-driven accelerators could be cost effective for large installations
  - Electron beams couple better to structures than lasers
  - Use highly efficient rf system to generate drive beam
  - Electron beams easier to manipulate than rf
  - Consolidate main power sources

- But:
  - Not appropriate for compact installations
  - Complicated power handling
  - Little experience with large systems and difficult to demonstrate in advance
Concept of Beam-Driven Plasma Linac

- Concept for a 1 TeV plasma wakefield-based linear collider
  - Use conventional Linear Collider concepts for main beam and drive beam generation and focusing and PWFA for acceleration
    - Makes good use of PWFA R&D and 30 years of conventional rf R&D
  - Concept illustrates focus of PWFA R&D program
    - High efficiency
    - Emittance pres.
    - Positrons
  - Allows study of cost-scales for further optimization of R&D
**Example: PWFA Booster for FEL**

- Likely 1\textsuperscript{st} application of PWFA concept
- FERMI@Elettra is a single-pass FEL user-facility located next to the third-generation synchrotron radiation facility [ELETTRA](https://elettra.eu) in Trieste, Italy
- Start from FEL-1 and find a set of parameters for beam and undulator that boost energy by two and get 20nm down to 5nm – likely limited by CSR

<table>
<thead>
<tr>
<th>Parameter</th>
<th>FEL-1</th>
<th>PWFA</th>
<th>Units</th>
</tr>
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<tbody>
<tr>
<td>Wavelength</td>
<td>20</td>
<td>5</td>
<td>nm</td>
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<tr>
<td>Electron Beam Energy</td>
<td>1.2</td>
<td>2.4</td>
<td>GeV</td>
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<tr>
<td>Bunch Charge</td>
<td>0.8</td>
<td>0.25</td>
<td>nC</td>
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<td>Peak Current</td>
<td>0.85</td>
<td>15</td>
<td>kA</td>
</tr>
<tr>
<td>Bunch Length (FWHM)</td>
<td>400</td>
<td>2</td>
<td>fs</td>
</tr>
<tr>
<td>Norm. Emittance (slice)</td>
<td>0.8-1.2</td>
<td>1.5</td>
<td>mm-mrad</td>
</tr>
<tr>
<td>Saturation length</td>
<td>23</td>
<td>19</td>
<td>m</td>
</tr>
<tr>
<td>Peak power</td>
<td>2.3</td>
<td>130</td>
<td>GW</td>
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</table>
Challenges for Plasma-based Accelerators

- Luminosity drives many issues:
  - High beam power (20 MW) → efficient ac-to-beam conversion
  - Well defined cms energy → small energy spread
  - Small IP spot sizes → small energy spread and small $\Delta \varepsilon$

- These translate into requirements on the plasma acc.
  - High beam loading of e+ and e-
  - Acceleration with small $\Delta E/E$
  - Preservation of small transverse emittances – maybe flat beams
  - Acceleration of positrons
  - Bunch repetition rates of 10’s kHz with necessary plasma stability
  - Highly efficient power sources

Simulation of 25 GeV PWFA stage

Witness bunch

Drive bunch
FACET: Two-Bunch Operation

- Critical to demonstrate drive/witness acceleration
- Use notch collimator in Sector-10 bunch compressor to generate two separate bunches
- Technique works for either e-/e- or e+/e+
- Varying collimator shape and position allows flexibility in two-bunch format
# PWFA Experimental Program

<table>
<thead>
<tr>
<th>Experimental Tasks and Milestones</th>
<th>FY11</th>
<th>FY12</th>
<th>FY13</th>
<th>FY14</th>
<th>FY15</th>
<th>FY16</th>
<th>FY17</th>
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<tr>
<td>Accelerate e- bunch with sufficient charge</td>
<td>FACET</td>
<td>FACET</td>
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<td>Accelerate e- bunch achieving low energy spread</td>
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<td>Accelerate e- bunch with high efficiency</td>
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<td><strong>Demonstration of electron acceleration: high $\eta$, low $\Delta E$</strong></td>
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<td>Emittance preservation of e- bunch</td>
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<td><strong>Demonstration of a single stage of an electron PWFA-LC</strong></td>
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<tr>
<td>Acceleration of e+ bunch by e+ drive</td>
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<tr>
<td>Initial test of e+ acceleration in e- wakes</td>
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<td>Emittance preservation of e+ bunch</td>
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<tr>
<td>Upgrade Sector-20 chicane</td>
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<td>★</td>
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<tr>
<td>Accelerate e+ by e- drive; charge, low dE/E</td>
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<td>FACET</td>
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<tr>
<td>Accelerate e+ by e-, high efficiency, low emittance</td>
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<tr>
<td><strong>Selection of optimum positron acceleration mechanism for a PWFA-LC</strong></td>
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<tr>
<td>Upgrade injector with rf gun</td>
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<td>Plasma cell with jet and power removal</td>
<td>Study</td>
<td>Study</td>
<td>Eng.</td>
<td>Eng.</td>
<td>FACET</td>
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<tr>
<td><strong>Design plasma cell with needed stability and cooling</strong></td>
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Plasma Wakefield Collaboration

- Growing group at SLAC:
  - Mark Hogan
  - Joel England
  - Selina Li
  - Mike Litos
  - Joel Frederico

- Collaborators from USC, UCLA, Duke and BNL
- Collaboration with BELLA laser-driven plasma acceleration experimental facility being built at LBNL
Dielectric Structures

- Unlike Cu, dielectric structures have higher breakdown limits approaching 1 GV/m at THz frequencies
  - Extensive damage measurements to characterize materials
  - Structures can be either laser driven or beam driven (wakefield)

- Beam-driven structures
  - Frequencies are in GHz regime and dimensions are cm-level
  - Higher gradients than metallic structures but more difficult wakes

  - Mechanism independent of particle charge
    → positrons may be easier than in plasma
Concept of Beam-Driven Dielectric Linac

3GeV module (15m)
(38 DWPE & 38 DLA \(\rightarrow\) fill factor=76%)

Drive beam becomes 80MeV, main beam gain 3GeV

1.33 GW output/Dielectric PETS;
5% rf transportation loss;
\(E_{load} = 267 \text{ MV/m} \ (I_b=6.5\text{A})\);

W. Gai, Argonne National Lab

### AWA Short Pulse (1.5TeV,e+)

<table>
<thead>
<tr>
<th></th>
<th>AWA Short Pulse (1.5TeV,e+)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average drive beam current</td>
<td>80 mA</td>
</tr>
<tr>
<td>Average drive beam power</td>
<td>68.8 MW</td>
</tr>
<tr>
<td>Average rf power to main linac</td>
<td>60MW</td>
</tr>
<tr>
<td>Average main beam current</td>
<td>10.4 (\mu)A</td>
</tr>
<tr>
<td>Average main beam power</td>
<td>15.6 MW</td>
</tr>
</tbody>
</table>

Competitive rf-beam efficiency for the short pulse TBA

\[ \eta_{bRF} = \frac{I_{beam} E_{load} L_s}{P_{rf}} \times \frac{T_{beam}}{T_f} = 26\% \]

\(T_{beam} = 16 \text{ ns} = 416 \text{ rf cycles (26 GHz)}\)
\(Q_{\text{total}} = 208 \text{ nC per pulse}\)
1 bunch / 2 rf periods, 0.5nC / bunch
Crystal Collimation

Deflection of 400 GeV Protons (W. Scandale et al.)

1 - “amorphous” orientation
2 - channeling (50 %)
3 - de-channeling (1 %)
4 - volume capture (2 %)
5 - volume reflection (98 %)

- Crystals are interesting because of very high field gradients
- Volume reflection may provide path to high energy collimation or radiation generation
ASTA Test Facility

- Designed for economical testing of TW, SW accelerator structures, and waveguides
- Versatile structure for future applications (beyond high gradient work)

From Two 50 MW Klystrons
Two experimental stations inside the enclosure, one with compressed pulse and the other without the benefit of the pulse compressor.

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NLC Test Accelerator
RF Testing and Beam Dynamics

- Injector: 65MeV, ~0.3 nC / bunch
- 3 downstream X-band RF stations
  - 2 pulse compressors (240ns - 300MW max), driven each by 2 50MW X-band klystrons
  - 1 pulse compressors (400ns – 300MW /200ns – 500MW variable), driven by 2 50MW X-band klystrons.
- Shielding Enclosure: suitable up to 1 GeV
- S-band rf gun for low emittance beam and IR/UV laser systems for diagnostics and beam manipulation
- Extensive diagnostics to measure beam properties

Echo-7 Experiment at NLCTA
SLAC Laser Acceleration Facilities

Scientific Goal: Investigate physical and technical issues of laser acceleration using dielectric structures
Accelerator structures at laser wavelengths (10,000x smaller than microwave)

Unique approach to beam acceleration:
- Leverage commercial laser technology (low power, high rep rate)
- Use semiconductor fab techniques for potential to mass produce structures
Summary

- SLAC Accelerator Research program has a variety of experimental accelerator research programs:
  - ASTA, NLCTA, ESTB and FACET

- FACET will be a unique user facility for accelerator R&D
  - High-energy, high-quality, intense beams

- Broad research program focused on beam-driven acceleration but also including accelerator diagnostics, beam dynamics and material studies
  - Many opportunities to engage in R&D programs

- First beam expected in June 2011