Accelerator Science at SLAC: Overview

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Outline

• Motivation
• Efforts in Next-Generation Accelerator Technologies
  – Short-Term and Medium-Term
    • High Gradient High Frequency RF
    • Advanced Computational Techniques
  – Long-term
    • Beam-Driven Plasma Acceleration
    • Laser-Driven Dielectric Structures
    • Seeding Techniques for FELs: Echo-7
• Capabilities
  – RF, Laser-Electron interaction, beam, plasma
• Opportunities
  – Opportunities—present and future—for SLAC’s users
A Broad Range of Science is Enabled by Accelerators

• High Energy Physics
  – Nature of matter, energy, and the forces that govern the universe
    • Linear colliders, storage ring colliders, factories
    ➔ Frontiers are *energy* and *luminosity*

• Basic Energy Sciences
  – Photon Science: structural biology, material science
    • Synchrotron light sources, FELs
    ➔ Frontiers are *wavelength*, *brightness*, *coherence*, and *time structure*
  – Neutron Science: material science, magnetic properties, spin
    • Spallation sources
    ➔ Frontiers are *energy* and *power*

• Medicine
  – Photon and hadron therapy, imaging
    • Linacs, cyclotrons, and synchrotrons
    ➔ Frontiers are *speed* and *dose accuracy*
Energy frontier advances have been revolutionary, not evolutionary, and depended on basic accelerator research conducted decades before the first major application.

**Example Timeline: Linear Accelerators**

- **1924** Linear AC acceleration concept: Ising
- **1928** First LF realization (DTL, 50 keV K ions): Wideroe
- **1947** First RF realization (Mark I, 4.5 MeV e\(^-\)): Hansen
- **1951** First application (Mark II, 49 MeV e\(^-\)): Nuclear Physics
- **1955** Other application (5 MeV for x-rays): Medicine
- **1967** First large-scale application (Project M, 20 GeV e\(^-\))

SLAC invests in a range of short, medium, and long-term accelerator techniques

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SLAC hosts US collaboration in high gradient research and has strong international collaboration with KEK and CERN.
HGRF Experimental Studies

- Basic Physics Experimental Studies
  - Single and Multiple Cell Accelerator Structures (with major KEK and CERN contributions)
    - single cell traveling-wave accelerator structures (Needs ASTA)
    - single-cell standing-wave accelerator structures (Performed at Klystron Test Lab)
  - Waveguide structures (Needs ASTA)
  - Pulsed heating experiments (Performed at the Klystron Test Lab, also with major KEK and CERN contributions)
- Full Accelerator Structure Testing (Performed at NLCTA, with CERN contributions)
  Can only be done at NLCTA at SLAC
Breakdown Probability for a Standing Wave Accelerator Structure Made of differing Materials

\[ \frac{a}{\lambda} = 0.22, \text{Pulse length} = 200\text{ns} \]

SLUO Meeting Sept. 17, 2009
Material Testing (Pulsed heating experiments)

- Economical material testing method
- Essential in terms of cavity structures for wakefield damping
- Recent theoretical work also indicate that fatigue and pulsed heating might be also the root cause of the breakdown phenomenon

Special cavity has been designed to focus the magnetic field into a flat plate that can be replaced.

$Q_0 \approx 44,000$ (Cu, room temp.)

$|\mathbf{E}|_{\text{TE}_{013}}$

$|\mathbf{H}|$
Some Testing Results showing Pulsed Heating Damages

Max Temp rise during pulse = 110°C

SEM Images Inside Copper Pulse Heating Region

Metallography: Intergranular fractures 500X
Fabrication and Testing of High Gradient Accelerator structure for CLIC main linac R&D

- Seven prototypes accelerator structures and Four of them were high power tested at SLAC.
- Six CERN made prototype structure were measured and high power tested at SLAC.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>11.424GHz</td>
</tr>
<tr>
<td>Cells</td>
<td>18+input+output</td>
</tr>
<tr>
<td>Filling Time</td>
<td>36ns</td>
</tr>
<tr>
<td>a_in/a_out</td>
<td>4.06/2.66 mm</td>
</tr>
<tr>
<td>vg_in/vg_out</td>
<td>2.61/1.02 (%c)</td>
</tr>
<tr>
<td>S11</td>
<td>0.035</td>
</tr>
<tr>
<td>S21</td>
<td>0.8</td>
</tr>
<tr>
<td>Phase</td>
<td>120Deg</td>
</tr>
<tr>
<td>Average Unloaded Gradient over the full structure</td>
<td>55.5MW→100MV/m</td>
</tr>
</tbody>
</table>

- Structure designed by CERN based on all empirical laws developed experimentally through our previous work
- Cells Built at KEK
- Structure was bonded and processed at SLAC
- Structure was also tested at SLAC
X-Band Deflectors for the LCLS
Time-resolved Electron Bunch Diagnostics

A 1 meter test deflector is being fabricated and will be tested this year

SLAC XL-4 Klystron, 50 MW, <1.6 us
3 dB splitter
20 MW 100 ns
20 MW 100 ns
bunch 13.6 GeV
Kick 42.6 MeV
2 x 94 cm

Prototype 1 meter structure
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CEBAF BBU - Solving the Inverse Problem

**CEBAF 12-GeV upgrade** –

- Beam breakup (BBU) observed at beam currents well below design threshold.
- Used measured RF parameters such as $f$, $Q_{\text{ext}}$, and field profile as inputs.

**Solutions to the inverse problem** identified the main cause of the BBU instability: **Cavity is 8 mm shorter** – predicted and confirmed later from measurements.

- The fields of the **3 abnormally high Q modes** are shifted away from the coupler.
- Showed that experimental diagnosis, advanced computing and applied math worked together to solve a real world problem as intended by SciDAC.

In collaboration with TJNAF
Advancing High Gradient R&D

HOM damping & Multipacting studies are needed for High Gradient Structures

In collaboration with ATR and CERN
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The Beam Driven Plasma Wakefield Accelerator

- Two-beam, co-linear, plasma-based accelerator
- Plasma wave/wake excited by relativistic particle bunch
- Deceleration, acceleration, focusing by plasma
- Accelerating field/gradient scales as $n_e^{1/2}$
- Typical: $n_e \approx 10^{17}$ cm$^{-3}$, $\lambda_p \approx 100$ µm, $G > MT/m$, $E > 10$ GV/m
- High-gradient, high-efficiency energy transformer
SLAC/UCLA/USC Experiments @ FFTB
Studied all aspects of beam-plasma interaction

Focusing & Matching $e^-$

Phase Advance $\Psi \propto n_e^{1/2}L$

L=1.4 m
$\alpha_0=14 \mu m$
$\epsilon_n=18\times10^{-5}$ m-rad
$\beta_n=6.1$ cm
$\alpha_0=0.6$


X-ray Generation


Wakefield Acceleration $e^-$


Electron Beam Refraction at the Gas–Plasma Boundary

$\theta \propto 1/\sin \phi$

$\theta \approx \phi$

BPM Data

Model

Nature 411, 43 (3 May 2001)

Wakefield Acceleration $e^+

* Acceleration gradients of \(~50\) GV/m (3000 x SLAC)
- Doubled energy of 45 GeV beam in 1 meter plasma
- Record Energy Gain
- Highest energy electrons ever produced at SLAC
- Significant advance in demonstrating the potential of plasma accelerators

A new facility to provide high-energy, high peak current $e^-$ & $e^+$ beams for PWFA experiments.

Beam Parameters Driven by Science Needs
Delivered to 100m area with three distinct functions:
1. Chicane for final stage of bunch compression
2. Final Focus for small spots at the IP
3. Experimental Area

Advantageous location:
- Preserves $e^+$ capability
- No bypass lines or interference with LCLS
- Linac setup virtually identical to SPPS/FFTB
FACET Experiments will accelerate a discrete bunch of particles with narrow energy spread

* Double Energy of a 25GeV Beam in ~1m
* Drive beam to witness beam efficiency of ~30% with small dE/E
PWFA Beyond Energy Doubling

* Collaboration development and future experimental directions will be subject of FACET workshop & proposal solicitation

* Some example directions already identified (see below)

* Higher transformer ratio with non-Gaussian bunches
  – Higher efficiency; Reduced number of stages for a collider

* Emittance growth from multiple sources
  – Hosing; Ion motion when $n_p/n_p \sim m_i/m_e$

* Plasma stability and tolerances (pulse format Hz to MHz)
  – Recombination, diffusion and heat transport

* Plasma lensing
  – Harness MT/m focusing; Investigate aberrations, integration, backgrounds
User Groups Help Define FACET Specs

* Strong collaborations with many years of experience in place
  * PWFA:
    * Joshi Group @ UCLA (20+ years PWFA & LWFA plasma physics)
    * Mori Group @ UCLA (Advanced computation/simulation)
    * Muggli Group @ USC (Experimental plasma physics)
    * Katsouleas Group @ Duke (Plasma theory)
  * DWA:
    * Rosenzweig Group @ UCLA (DWA theory & experiments)
    * Euclid Tech (Advanced materials)
    * Solid state, THz, magnetism
    * Stöhr/Siegmann Groups at SLAC (Solid state physics)
  * Expecting (and encouraging!) additional collaborations to form
A “drive” beam excites wake-fields in the tube, while a subsequent witness beam (not shown) would be accelerated by the Ez component of the reflected wakefields (bands of color).

For large wakes want high charge, short bunches and narrow tubes
The future of magnetic recording lies in smaller bits and faster switching.

FFT experiments demonstrated:

- Ultrafast precessional switching
- Increased damping at high magnetic fields from spin wave instabilities
- Generation of a NEW type of magneto-electronic anisotropy (PRL in press)
- Modification of electronic structure and non-linear conduction at high fields (unpublished!)

S. J. Gamble et al, Phys. Rev. Lett, in press

FACET offers important opportunities in material science, condensed matter physics and chemistry.
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Laser-Driven Structures

Motivation

- **High gradient** (>0.5 GeV/m) and high wall-plug power efficiency are possible
- **MicroJoule-class lasers** are needed (rack-mount devices– not gymnasium-sized devices!)
- Large-scale private sector R&D investment in telecom and semiconductor technologies provides **significant leverage** to DOE’s investment

**HIGH ENERGY PHYSICS**

- Short wavelength acceleration naturally leads to **attosecond bunches** and point-like radiation sources

**BASIC ENERGY SCIENCES**

- Structure Fabrication is by **inexpensive mass-scale** industrial manufacturing methods

**COMMERCIAL DEVICES**

Structure Candidates for High-Gradient Accelerators

**Maximum gradients based on measured material damage threshold data**

- **Photonic Crystal Fiber**
  - Silica, \( \lambda = 1053 \text{ nm} \), \( E_z = 790 \text{ MV/m} \)
- **Photonic Crystal “Woodpile”**
  - Silicon, \( \lambda = 1550 \text{ nm} \), \( E_z = 240 \text{ MV/m} \)
- **Transmission Grating Structure**
  - Silica, \( \lambda = 800 \text{ nm} \), \( E_z = 830 \text{ MV/m} \)

Luminosity from a laser-driven linear collider must come from **high bunch repetition rate** and **smaller spot sizes**, which naturally follow from the small emittances required.

Beam pulse format is (for example)

\[
(193 \text{ microbunches of } 1 \times 10^4 \text{ e}^- \text{ in } 1 \text{ psec}) \times 200 \text{ MHz}
\]

- Storage-ring like beam format
- **reduced event pileup**
- High beam rep rate=⇒ **high bandwidth position stabilization is possible**

**Table**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ILC Nom.</th>
<th>Fiber</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E_{\text{rms}} ) GeV</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>Bunch Charge ( a )</td>
<td>2.0E+10</td>
<td>3.8E+04</td>
</tr>
<tr>
<td># bunches/train ( N )</td>
<td>2320</td>
<td>159</td>
</tr>
<tr>
<td>Train repetition rate MHz</td>
<td>5.0E-06</td>
<td>20</td>
</tr>
<tr>
<td>Final bunch length psec</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Design wavelength micron</td>
<td>230609.58</td>
<td>1.89</td>
</tr>
<tr>
<td>Invariant Emittances micron</td>
<td>100.04</td>
<td>1e-04/1e-04</td>
</tr>
<tr>
<td>I. P. Spot Size nm</td>
<td>554/3.5</td>
<td>0.5/0.5</td>
</tr>
</tbody>
</table>

**Geometric Luminosity/cm²/s**

- **2.32E+34**
- **2.26E+34**

**Beam Power**

- MW 22.6
- 9.5

**Wall-Plug Power**

- MW 104.0
- 79.4

**Gradient**

- \( \text{MeV/m} \)
- 30
- 400

**Total Linac Length**

- km
- 33.3
- 2.5
Optical Accelerator Structures under Study

Photonic Band Gap Fibers
- Confines light by selective interference in dielectric lattice
- Made by conventional fiber drawing techniques in industry

Planar Grating Structure
- High gradient, wide aperture accelerator
- Producing structures at the Stanford Nanofabrication Facility

Bragg Planar Dielectric Structure
- Accelerating mode guided by two-sided Bragg multi-layer waveguide
- Grating couples laser from side and converts it to accel mode
- Producing structures at the Stanford Nanofabrication Facility

Silicon “Woodpile” Structure
- Producing structures at the Stanford Nanofabrication Facility
Attosecond Bunch Train Generation

First- and Second-Harmonic COTR Output as a function of Energy Modulation Depth (“bunching voltage”)

Demonstration of Staged Laser Acceleration

The first demonstration of staged particle acceleration with visible light!

Effective averaged gradient: 6 MeV/m (poor, due to the ITR process used for acceleration stage)
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Echo-Enabled Harmonic Generation Seeding for X-Ray FELs:

Echo-7 Experiment to be conducted at NLCTA in 2009-10

Using two modulators and two dispersion sections will up-shift the wavelength of the induced microbunching in the beam. The amplitude of the high frequency modulation is relatively large, 10-20%.

Evolution of the longitudinal phase space (one laser period is shown):
1. Energy modulation after first modulator
2. Tilted beamlets in the phase space after the first chicane
3. Energy modulation after the second modulator
4. Phase space after the second chicane
Generation of isolated attosecond x-ray pulse using echo mechanism

Echo modulation is performed with a few-cycle laser (200 nm) and augmented with an extra chirp due to a long wavelength (800 nm) laser.

Global phase space of the beam and the fine structure of microbunching before the radiator

Radiated power at 200th harmonic (1nm) of the Laser after 80 cm long radiator
Conclusion

• The focus is on developing next-generation techniques for high gradient acceleration
  – Program is comprehensive– EM design, plasma physics, photonic crystals, femtosecond beam control, material science, computational techniques, laser science, and more…

• Unique opportunities for collaboration
  – HGRF
  – Beam-driven plasma wakefield science
  – Laser-driven photonic band gap accelerator development
  – Seeding, advanced computation techniques, and more…

• Unique facilities are available
  – ASTA – high power rf, low energy electron beam
  – NLCTA – high power rf, moderate energy beam, lasers
  – FACET (soon) – high density high energy e-/e+ beams
Thank you!