Laser driven particle acceleration

**collaborators**

**ARDB, SLAC**

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Outline

• Introduction
  • Properties unique to laser acceleration
  • Available resources and expertise
  • Emergence of new technologies

• The physics concept and experiment
  • The physics concept
  • The physics demonstration experiment

• Current and future research
  • The E163 experiment
  • Accelerator structure investigations
  • Multi-staged laser accelerator

• Future scientific impact
  • Candidate technology for a TeV scale collider
  • Soft X-ray attosecond physics
Vacuum laser acceleration

1. Energy gain through longitudinal electric field
   - gradient = longitudinal electric field
   - linear e-beam trajectory
   - no synchrotron radiation
   - energy scalable
   \[ \Delta U = \int E_z \cdot dz \]

   linear particle acceleration process

2. Dielectric based structure with vacuum channel
   - Gradient \( \rightarrow 1 \text{ GeV/m} \)

   very high peak electric fields
   vacuum channel
   NIR solid-state lasers

3. Inherent attosec electron pulse
   - 2 \( \mu \text{m} \) laser \( \rightarrow 6 \text{ fsec period} \)
   - 1 of phase = 20 attosec

   Unique opportunity for light sources
Emergence of new technologies

- **Efficient pump diode lasers**
  - NiLight
  - 60 W/bar, 50% electr. efficiency

- **Ultrafast laser technology**
  - < 10 fs

- **Leveraging investment in telecom**
  - 30 W/bundle, 40% electr. efficiency

- **High power fiber lasers**
  - NUFERN
  - IMRA mJ 500 fsec laser

- **New materials**
  - High strength magnets
  - Nd:Fe
  - New ceramics
  - Nanotubes

- **Nanotechnology**
  - High purity optical materials and high strength coatings

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Particle accelerator research at Stanford

1st Klystron (Varian, 1930s')

The superconducting linac
In HEPL, 1960

1st Linac 1946

The 2-mile collider (SLAC)

LEAP, 1997-2004

Demonstration of the FEL, 1977
Available resources at Stanford/SLAC

Lasers, Optics and photonics

Materials science and nanofab capabilities

Ultrafast light and Xray science at SLAC

Accelerator and diagnostics expertise at SLAC

The gravitational wave detector

Fundamental science questions

Strong interaction and partnership with
- industry
- national labs
- other universities worldwide

Medicine
Chemistry
Biology
...
Laser acceleration concept

The diagram illustrates the laser acceleration concept, showing a dielectric waveguide structure with a laser beam entering and leaving. The accelerating force is applied to an electron bunch moving through the vacuum channel. The conceptual idea is described by Pantell in 1979.

Mathematical expression:
\[ \Delta U = \int E_z \cdot dz \]

The LEAP experiment
(Laser Electron Accelerator Project)

The field-terminating boundary

\[ \int_{-\infty}^{0} E_z \cdot dz > 0 \]

Electron beam

Laser beam

8 µm thick gold-coated Kapton tape

Stepper motors

Spectrometer

Camera

Optical phase of the laser

Electron energy

Accelerating phase

Decelerating phase

Broadening of the initial energy spread of the electron beam

Normalized charge per unit energy

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The SCA-FEL facility

<table>
<thead>
<tr>
<th>SCA beam parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy</td>
</tr>
<tr>
<td>$T_{\text{electron}}$</td>
</tr>
<tr>
<td>Charge per bunch</td>
</tr>
<tr>
<td>Energy spread</td>
</tr>
<tr>
<td>$\lambda_{\text{laser}}$</td>
</tr>
<tr>
<td>$E_{\text{laser}}$</td>
</tr>
</tbody>
</table>

Beam Energy: 30 MeV
Duration of electron pulse: ~2 psec
Charge per bunch: ~5 pC
Energy spread: ~20 keV
Wavelength of laser: 800 nm
Energy per pulse of laser: 1 mJ/pulse

Commercial, tabletop amplified sub-ps/sec mJ/pulse laser sources
Tomas Plettner and LEAP Accelerator Cell

The key was to operate the cell above damage threshold to generate Energy modulation in excess of the noise level.
We accelerated electrons with visible light

Visible-Laser Acceleration of Relativistic Electrons in a Semi-Infinite Vacuum

T. Plettner and R. L. Byer
Stanford University, Stanford, California 94305, USA

Colby, B. Cowan, C. M. S. Sears, J. E. Spencer, and R. H. Siemans
SLAC, Mento Park, California 94025, USA
(Received 19 April 2005; published 22 September 2005)

• confirmation of the Lawson-Woodward Theorem

\[ \int_{-\infty}^{+\infty} E_z \, dz = 0 \]

• observation of the linear dependence of energy gain with laser electric field

\[ \Delta U \propto |E_{laser}| \]

• observation of the expected polarization dependence

\[ |E_z| \propto |E_{laser}| \cos \rho \]
High-Harmonic Inverse-Free-Electron-Laser Interaction at 800 nm

Christopher M. S. Sears, Eric R. Colby, Benjamin M. Cowan, Robert H. Siemann, and James E. Spencer
Stanford Linear Accelerator Center, Menlo Park, California 94025, USA

Robert L. Byer and Tomas Plettner
Stanford University, Stanford, California 94305, USA
(Received 4 March 2005, published 2 November 2005)

FIG. 2. Example data run with 1500 laser on events. The solid curve is the least squares fit to all data points and gives the mean interaction of 18 keV. The dashed curve is the maximum estimate and gives the peak interaction of 25 keV. The width of cross correlation is 2.2 ps rms.

FIG. 4. IFEL gap scan data, with 164 runs total. Comparison to simulation (solid line) shows very good agreement to the shape and spacing of resonance peaks. The harmonic numbers are given next to each peak. Simulation has been rescaled vertically by 0.67 to better visualize overlap.

* graduate student C.M. Sears
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The E163 experiment at SLAC

Accomplished milestones so far
- construction of the experiment hall
- installation of the E163 control room
- commissioning of the laser system
- installation and commissioning of the RF gun

Expected 1st experiment in spring 2006
The next step: staged accelerators at E163

- focusing triplet
- optical buncher
- compressor chicane
- laser
- optical accelerator

The triplet
The IFEL
The compressor chicane
Accelerator structure
Accelerator structure research

Photonic bandgap fiber structures

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS, VOLUME 4, 651301 (2001)

Photonic band gap fiber accelerator

Xintian Edeo Lin*

Planar waveguide structures

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS, VOLUME 8, 073402 (2005)

Distributed grating-assisted coupler for optical all-dielectric electron accelerator

Zhiyu Zhang,* Sami G. Tanaziz, and Ronald D. Ruth

Current experimental fiber accelerator structure research

R. Ischebeck, R. J. Noble, B.Cowan*, M. Lincoln*, C. Sears*
Energy efficiency of laser accelerators, single and multiple bunch operation

Energy efficiency of laser driven, structure based accelerators

R. H. Siemann

Coupling Efficiency vs bunch charge

optimum efficiency about 1 fC

Beam loading calculations vs N

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Application of modern technologies

Lasers and photonics

200 fsec Yb:fiber laser; S. Sinha*

comb offset detection with Ti:Sapphire lasers; T. Plettner

PBG structure coupler

S. Fan et al., PRL 80, 5, 960-963 (1998)

Materials science

Gamma Radiation Studies on Optical Materials

Eric Colby, Member, Gary Luan, Member, Thomas Plettner and James Spencer, Member, IEEE

Fig. 1. Transmissivity spectra through 1.1 cm thick glass glass after Cd109 γ-irradiation. Spectra are stacked according to their order in the insert.

*grad. students

200 fsec Yb:fiber laser; S. Sinha*

**grad. students

200 fsec Yb:fiber laser; S. Sinha*

2 hr 1600°C
low Ar

2 hr 1700°C
low Ar

2 hr 1800°C
high Ar

Before HIP

YAG ceramic

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Envisioned laser-driven TeV-scale accelerator

**Optical Injector**
- Optical cycle e- bunch
- ~10⁴ electrons/bunch
- Ultra low emittance
- Laser-driven field emitters

**Pre-accelerator**
- Nonrelativistic
- Compress bunch

**Accelerator structures**
- Preserve emittance
- Periodic focusing
- Alignment and stabilization
- Coupling efficiency

**Electron beam**
- 1 fC/bunch
- Sub µm spot size
- ~10¹⁰ bunches/sec

**Initial focus of our research**
- Success of proof-of-principle exp.
- Research on dielectric structures

**Order-of-magnitude power estimate**
- 1 fC x 10¹⁰ x 1 TeV → 10⁷ W e-beam
- 20% coupling → 5x10⁷ W optical power
- 50% wallplug laser → 10⁸ W electricity
- 100 MW electricity

**Phaslocked Oscillators**
- 100 fsec, 1 GHz rep. rate
- Phaselocked to clock

**Power Amplifiers**
- NIR 1-2 µm wavelength
- 1 kW @ 50% efficiency
- ~50 kW/m optical power

**Collider area**
- Sub-Ångstrom spot size
- Multi-GHz rep-rate

**Optical clock**
- Ultrastable
- Attosec stability
- Low power

**Tungsten tip fsec field emitters**

**LIGO vibration isolation in ES3 at Stanford**
Soft X-ray attosecond physics

1° of optical phase at 2 μm \(\rightarrow\) 20 attosec

Preliminary model studies

- 1st initial feasibility study with the 1D FEL model
- Attosec bunching of 1fC helps enhance the gain
- “low” 1 MHz rep. rate \(\rightarrow\) low avg. power
- Further more refined studies under way
- It deserves a closer look

Prof. Byer’s dream…

The wizard of optics

Take advantage of ultra-low emittance laser-accelerator e-beam and new magnetic materials

compact attosec soft x-ray source with medical and chemistry applications
1st proof-of-principle Vacuum based laser acceleration demonstration

Conducting R&D on dielectric based accelerator structures

Envision an approach to a TeV scale laser driven particle accelerator
In 1954 Livingston noted that progress in high energy accelerators was exponential with time.

Progress was marked by saturation of the current technology followed by the adoption of innovative new approaches to particle acceleration.

Over the past two decades progress in Advanced Solid State Lasers has been driven by innovation. Laser sources coupled with related technologies enable new approaches to Advanced Electron Accelerators.
Selected publications


Backup slides
## TeV scale laser accelerator parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accelerator field wavelength</td>
<td>$\lambda$</td>
<td>2 $\mu$m</td>
</tr>
<tr>
<td>Laser pulse repetition rate</td>
<td>$f$</td>
<td>1 GHz</td>
</tr>
<tr>
<td>Bunches per laser pulse “macro-pulse”</td>
<td>$n$</td>
<td>10</td>
</tr>
<tr>
<td>Electrons / bunch</td>
<td>$N$</td>
<td>$\sim$6000 ($1$ fC)</td>
</tr>
<tr>
<td>Accelerator beam diameter</td>
<td>$\sigma$</td>
<td>0.1 $\mu$m</td>
</tr>
<tr>
<td>Beam diameter at IP focus</td>
<td>$\sigma$</td>
<td>0.1 Å</td>
</tr>
<tr>
<td>Transverse geometric emittance</td>
<td>$\varepsilon$</td>
<td>$10^{-11}$ m-rad</td>
</tr>
<tr>
<td>$\beta$ at IP</td>
<td>$\beta_0$</td>
<td>10 $\mu$m</td>
</tr>
<tr>
<td>Approximate luminosity at IP</td>
<td>$L$</td>
<td>$\approx \frac{nfN^2}{4\pi \sigma_x \sigma_y}$</td>
</tr>
</tbody>
</table>

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TeV scale laser accelerator pulse structure

- Target gradient $G = 1 \text{ GeV/m}$
- Laser pulse duration $T_{\text{laser}} = 1 \text{ psec}$
- Electron bunch duration $T_e = 20 \text{ attosec}$

1 fC/bunch

Total beam current $I_b = 10 \mu\text{A}$

Total beam power at 1 TeV $P_b = 10 \text{ MW}$
Soft X-ray attosecond physics - detail

Starting point
1-D FEL model
Design parameters must satisfy these conditions

Undulator design

Laser power required

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The laser accelerator and IFEL

- Back-of-ITR
- Puckup mirror (CH 24)
- Cerenkov cell
- Motor 1 (CH 21)
- Motor 2
- IFEL
- Upstream
- Downstream

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The tape boundary

1. Damage threshold
   - ignore it!
   - devise a “disposable” unit
   - materials retain their optical properties for a few picoseconds after a destructive laser pulse

2. Cell geometry
   - simplify to one semi-infinite boundary
   - make boundary thin enough to run e-beam through it
   - make boundary movable to present a new surface for each laser shot

3. Crossed laser beams
   - two laser beams too difficult? \( \rightarrow \) eliminate one of them
   - no more optical phase uncertainty problems
   - negligible transverse deflection forces

Improve on
- Operation tolerances
- Poor reliability
- Ease of operation

Conceptual drawing of the improved setup

\[ \Delta U = \int_{-\infty}^{0} E_z dz \]
The tape boundary

a) Setup for the reflected spot measurements

b) Reflected pulse intensity versus laser pulse duration
Laser Electron Accelerator Program
Located in the Hansen Lab on Stanford Campus

The crossed-beam laser accelerator Cell and magnet for electron beam energy measurements.

The view of the 30 MeV super-conducting linear accelerator in the underground tunnel on campus in the HEPL lab.