First Observation of Laser-Driven Particle Acceleration in a Semi-Infinite Vacuum Space

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1. Overview
   • Motivation for laser-driven particle acceleration
   • The physics concept
   • Overview of the LEAP experiment

2. The LEAP experiment
   • Important components of the LEAP experiment
   • The simplified acceleration geometry
   • The disposable boundary approach
   • The insertion of an IFEL as a timing monitor

3. Results
   • Confirmation of the Lawson-Woodward Theorem
   • Proof of the linear dependence on the electric field
   • Expected polarization dependence
   • Expected slow dependence on laser crossing angle

4. Future experiments
   • Test on different boundaries
   • Measurements below the laser damage threshold
   • E163 at SLAC

5. Summary
Motivation

historical trend of high energy physics experiments

Future TeV e+e− collision experiments
explore new accelerator technologies capable of

- substantial improvement of energy gradients
  $50 \text{ MeV/m} \rightarrow 1 \text{ GeV/m}$
- energy-scalable
- high luminosities at collision
- improved energy efficiency
- reliable and cost-effective technology
Laser driven particle acceleration in vacuum

Characteristics

- Crossing laser beams in vacuum
  - Longitudinal electric field of the laser pattern responsible for particle acceleration
- Dielectric accelerator structure
  - ~ 1 J/cm² damage threshold with ultra-short near IR lasers
  - with 100 fsec pulses peak fields of 10 GV/m possible
  - a 1 GeV/m gradient structure is possible
- The acceleration is linear
  - we are interested in a linear acceleration process $G \sim E_||$
- The electrons stay in vacuum
  - no beam deterioration from scattering with matter


The basic physics concept

Example: Longitudinal electric field from crossed laser beams*

![Diagram showing the longitudinal electric field from crossed laser beams.]

\[ E_z = -\frac{2E_0 \sin \theta}{(1 + z^2 \cos^2 \theta)^{3/2}} \exp \left[ -\left( \frac{z_0}{\theta} \right)^2 \frac{\sin \theta}{1 + z^2 \cos^2 \theta} \right] \cos \psi_i \]

\[ \psi_i = k \cdot z \cos \theta - \omega \cdot t + \frac{z^3 \cos^3 \theta \cdot \tan^2 \psi}{\theta^2 (1 + z^2 \cos^2 \theta)} - 2 \cdot \tan^{-1}(\hat{z} \cos \theta) + \phi_0 \]

\[ U(z) = \int_{z_0}^{z} E_z(z')dz' \]

Plot of the longitudinal E-field

**Limit the laser-electron interaction**

\[ \int_{-\infty}^{+\infty} E_z(z')dz' = 0 \]

\[ \int_{z_1}^{z_2} E_z(z')dz' \neq 0 \]

The Lawson-Woodward Theorem

The SCA-FEL Facility

<table>
<thead>
<tr>
<th>HEPL beam parameters</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy</td>
<td>~30 MeV</td>
</tr>
<tr>
<td>T_{electron}</td>
<td>~2 psec</td>
</tr>
<tr>
<td>Charge per bunch</td>
<td>~5 pC</td>
</tr>
<tr>
<td>Energy spread</td>
<td>~20 keV</td>
</tr>
<tr>
<td>λ_{laser}</td>
<td>800 nm</td>
</tr>
<tr>
<td>E_{laser}</td>
<td>1 mJ/pulse</td>
</tr>
</tbody>
</table>

Main advantages
- Convenience of location
- Low beam energy spread from the superconducting accelerator

Experiment is being moved to the NLCTA at SLAC
- dedicated accelerator test facility
- more possibilities for upgrades and expansions
- 60 MeV electron beam
- no electron macro pulse structure
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5. Summary
The LEAP experiment setup

Acceleration setup
- single laser beam
- thin reflective tape
- electrons traverse tape

1 m radius
90° bending magnet

2 keV resolution

interaction chamber
e- beam pulses
laser pulses

gated camera

energy spectrum picture
vertical coordinate
-150 0 50 150
energy (keV)
Problems with the old LEAP cell

- **HR coated fused silica with sharp edges in vacuum**
  - reduction of laser damage threshold to $\sim \frac{1}{4} \text{J/cm}^2$
  - max. energy gain of $\sim 20 \text{keV}$

- **Moving part of accelerator cell for variable slit**
  - internal alignment uncertainty once in operation
  - very difficult e-beam alignment (heavy loss of beam through a 10 micron slit)
  - poor transmission through the 10 $\mu$m slit

- **Crossed laser beams**
  - difficult alignment inside the cell space
  - optical phase uncertainty

**Diagram:** Crossed laser beams and electron beam through a slit, with a caption of interferometric alignment of prism surfaces.
The simplified acceleration geometry and the disposable 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? → 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

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**Diagram Notes**
- 8 µm Kapton
- 1 µm Au
- \( E_z \)
- \( \theta \)
The reflective boundary tape drive

- Stepper motor
- Au coated Kapton

Estimated duration of 1 track:
9:12 hrs. (552 min)
Use the IFEL as a psec-resolution timing diagnostic

Important features

- IFEL ~10 cm upstream of tape boundary
- Laser and electron beams cannot be simultaneously aligned for both the IFEL and the tape
- IFEL and ITR timing conditions are almost identical
- The IFEL produces a larger and easier to detect signal

See publication by C.M. Sears et al, "High Harmonic IFEL at 800 nm" (TPAE029)
Contents of the presentation

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Expected observations at the energy spectrometer

Electrons are not optically bunched

Electrons are distributed evenly over all the laser optical phases

We expect to observe a broadening of the initial energy spread of the electron beam that is related to the modulation strength of the laser
Data acquisition

Data was taken as laser time scans

- timing of laser shots scanned over a 20-30 psec timing window
- laser was randomly toggled on and off
- we look for changes of the energy width between laser-on and laser-off data

![Energy profiles with laser on and off](image)

**Legend:**
- Laser ON
- Laser OFF

![FWHM energy spread vs. laser timing](image)
Expected dependence of the laser-driven energy modulation

Effects we studied during the accelerator run:

1. The Lawson-Woodward Theorem
2. Laser peak electric field
3. Laser polarization
4. Laser crossing angle

Expected dependences

Numerical integration of the longitudinal electric field along the e-beam trajectory:

\[ U = \int_{-\infty}^{0} e \cdot E_z(z') dz' \]

\[ |U| \propto \sin \alpha \cdot Z_{slipage} \]

\[ |U| \propto |E|_{laser} \]

\[ |U| \propto \cos \phi \]
Confirmation of the Lawson-Woodward Theorem

This confirms:

1. The Lawson-Woodward Theorem
2. No interaction from the IFEL
Laser electric field strength dependence

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

Average FWHM energy broadening

\[ \langle M \rangle = (0.349 \pm 0.017) \cdot E_z - (0.35 \pm 0.25) \]

Laser Pulse Energy (mJ/pulse)

Average Energy Modulation (\(\langle M \rangle\)) (keV)

Peak Longitudinal Electric Field \(E_z\) (MV/m)
Laser polarization angle dependence

\[ |U| \propto |\cos \phi| \]

Average FWHM energy broadening

Average Energy Modulation (\langle M \rangle) (keV)

Laser Polarization Angle (degrees)
Laser crossing angle dependence

qualitatively
\[ |U| \propto \alpha \quad \text{for small } \alpha \]
\[ |U| \sim \text{const. for bigger } \alpha \]

ideally
\[ |U| \propto |\sin \alpha \cdot Z_{\text{slippage}}| \]

- measurement required realigning of laser and electron beam
- data set extended over several days
- electron beam conditions varied over this period of time
Did we do a modified plasma wakefield accelerator experiment?

From a plasma wakefield acceleration I would expect...

\[ I_{\text{threshold}} \]

\[ U = \text{constant} \]

\[ \tau_{\text{plasma lifetime}} \sim \frac{1}{2} \text{nsec} \]

But I observe...

\[ |U| \propto |E|_{laser} \]

\[ |U| \propto |\cos \phi| \]

\[ |U| \propto |\sin \alpha \cdot Z_{\text{slippage}}| \]

\[ \tau_{\text{interaction}} \sim 5 \text{ psec} \]
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5. **Summary**
Phase I: Single Cell Laser Acceleration

This is the continuation of the LEAP experiment

**objectives**

1. repetition of the tape boundary experiment
   verify
   • laser power, polarization & crossing angle
   • boundary type
   • reflected laser spot quality

2. switch to a dielectric single cell structure
   verify
   • laser-electron interaction length
   • laser crossing angle
   • accelerator aperture size
   • tolerances of the cell
The E163 experiment

Phase II: Optical buncher - accelerator cell staged experiments

See publication by C.M. Sears et al, "High Harmonic IFEL at 800 nm“ (TPAE029)
The E163 experiment

Phase III: Guided-Mode Structures

See publication by B. Cowan, “Photonic Crystal Laser-Driven Accelerator Structures” (TOPA010)
Summary

• we have laser-accelerated electrons in vacuum
  The laser wavelength was in the visible
  This was an energy-modulation experiment
  We employed a disposable boundary

• the effect is consistent with laser driven particle acceleration in vacuum
  It follows the Lawson-Woodward theorem
  \[ U \leftrightarrow |E_{laser}| \]
  \[ U \leftrightarrow |\cos \phi| \]
  \[ U \leftrightarrow |\sin \alpha \cdot Z_{slippage}| \]

• with the successful IFEL operation we have already started phase II of E-163
  The results from the IFEL alone are new

Acknowledgements

• The Department of Energy
• Mike Hennessy (ES II)
• Todd Smith (HEPL)
• The SCA personnel; George Marcus M. Galt, B. Armstrong, T. Kimura, D. Keegan, R. Swent, A. Schwettman, J. Haydon
• R. Route, V. Drew
• B. Noble, D. Walz (ARDB, SLAC)
• Y.C. Huang, C. Barnes, S. Waldman, J. Wisdom
Objective
Develop materials and micro-machining technologies for integrated micro-elements for laser driven particle accelerators. Our focus is on magnetic and optical micro-elements.

Summary of Work
We have focused on micromachining techniques on silicon and have begun exploring ceramic materials as components for laser driven particle accelerator structures. In addition, we have carried out studies on radiation sensitivity of various candidate materials.

Desired Properties of the Materials
- high laser damage threshold
- radiation resistant
- high melting point
- good thermal conductivity
- optical transparency
- inexpensive, machineable

Advantages of Si
- advanced micromachining technology
- possibility for integrated electronic circuits
- optically transparent 1.5-10 µm
- abundant and inexpensive
- high index of refraction
- good heat conductor
- radiation resistant

Problems
- limited geometry freedom with existing anisotropic etching techniques
- semiconductor: lower bandgap energy, easier multiphoton absorption and thus lower laser damage threshold

Advantages of Ceramics
- possibility for magnetic and optical materials from compatible substrates
- macroscopically amorphous: no restricted geometry limitations
- potentially higher degree of purity and less defect sites
- enhanced flexibility in mixing of different materials
- do not require expensive crystal growth step
- typical substrates like YAG: larger bad gap
- also transparent at visible wavelengths
- higher laser damage threshold
- higher melting points

Challenges
- optical ceramics fabrication technology is a relatively new topic
- micromachining technology on ceramics to sub-µm resolution has not been developed

*Supported by DOE grants DE-FG03-97ER41276 and DE-AC02-76SF00515.
Optical Phase Locking of Modelocked Lasers for Particle Accelerators

**Present accomplishments**
- Observed the comb offset from a commercial Ti:Sapphire modelocked laser
- Isolated a comb offset error signal
- Manipulated the comb offset with an electronic signal
- Constructed and tested a balanced cross-correlator
- We are presently switching to a 1 mm Yb:glass fiber modelocked laser

**Comb offset detection experiment**

**Beatnote detection circuitry**

**Two parameters for the control of the optical phase for modelocked lasers**
- **Pulse envelope timing and carrier-to-envelope phase**
  - Timing detection and control to within a fraction of an optical cycle (1 opt. cycle ~ 3 fsec)
  - Balanced cross correlator technique (40° of optical phase)
  - Frequency comb stabilization techniques:
    - Requires one octave of bandwidth.

**The balanced cross-correlator experiment**

**Future objectives**
- Repeat these measurements with the fiber laser
  - Feedback the comb error signal and stabilize the comb offset of a single laser
  - Construct a second identical fiber laser
  - Synchronize the pulse envelopes of the lasers to sub-fsec with the balanced cross-correl. technique
  - Eliminate residual phase jitter with an external interferometer unit controlling a variable path delay (e.g., a PZT)

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**Beatnote detection circuitry**

**Comb offset control**
- Error signal into AOM controls pump power and dispersion of laser
- AOM signal: 1.0 kHz, 0.2V square wave
- Comb offset:
  - Error signal into AOM controls pump power and dispersion of laser
  - Stabilize Comb offset

† Supported by DOE/W grants DE-FG03-97ER41276 and DE-AC02-76SF00515.
Side Note on laser ablation dynamics

**excitation stage**
- excited solid
- formation of electron-hole pairs
- Renormalization of the band structure
- Change of the optical properties
- Reduction of the band gap

**transition stage**
- Transformation into a liquid state
- ~100 nm layer of material with metallic properties

**rarefaction wave**
- Low-density shock wave traveling at the speed of sound of the material $c \approx 2500$ m/sec

**expansion phase**
- Expansion of the ablation front

**ejection phase**
- Ejection of monomers and molecular clusters

During the passage of the laser and the electron beam the surface of the tape is a metallic high reflector

$N_e \sim 10^{22}$ / cc.

http://www.ilp.physik.uni-essen.de/vonderLinde/Publikationen/ICONO98.pdf
We measured reflectivity of 1st ablation reflected spot vs. laser pulse duration.
Computation of the energy modulation strength

\[ QD = \sqrt{(FWHM_{ON})^2 - (FWHM_{OFF})^2} \]

averaged

\[ QD \approx \frac{42}{19} U_{mod} \approx 2U_{mod} \]