First Observation of Laser-Driven Particle Acceleration in a Semi-Infinite Vacuum Space
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## Contents of the presentation

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 MeV/m $\rightarrow$ 1 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**
  - \(~1 \text{ J/cm}^2\) 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\(^1\)

- **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

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The basic physics concept

Example: Longitudinal electric field from crossed laser beams

\[ E_z = \frac{2E_0 \sin \theta}{(1 + z^2 \cos^2 \theta)^{3/2}} \exp \left[ \frac{\left(\frac{z}{\theta_0}\right)^2 \sin^2 \theta}{1 + z^2 \cos^2 \theta} \right] \times \cos \psi, \]

\[ \psi = k \cdot z \cdot \cos \theta - \omega \cdot t + \frac{z^3 \cos^3 \theta \cdot \tan^2 \theta}{\theta_0^2 (1 + z^2 \cos^2 \theta)} - 2 \cdot \tan^{-1}(\hat{z} \cos \theta) + \phi_0 \]

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

Plot of the longitudinal E-field

Limit the laser-electron interaction

The Lawson-Woodward Theorem

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

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

The SCA-FEL Facility

**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

<table>
<thead>
<tr>
<th>HEPL beam parameters</th>
<th></th>
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<tbody>
<tr>
<td>Beam Energy</td>
<td>~30 MeV</td>
</tr>
<tr>
<td>$T_{\text{electron}}$</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>$\lambda_{\text{laser}}$</td>
<td>800 nm</td>
</tr>
<tr>
<td>$E_{\text{laser}}$</td>
<td>1 mJ/pulse</td>
</tr>
</tbody>
</table>

Leak area

- superconducting accelerator structures
- FEL wiggler
- collimator slits
- kicker

amplified laser
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5. Summary
The LEAP experiment setup

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

- 2 keV resolution
- gated camera
- 1 m radius 90° bending magnet
- interaction chamber
- e-beam pulses
- laser pulses

energy spectrum picture

vertical coordinate

energy (keV)
Problems with the old LEAP cell

- **HR coated fused silica with sharp edges in vacuum**
  - Reduction of laser damage threshold to $\sim 0.25 \text{ J/cm}^2$
  - 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

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

8 µm Kapton
1 µm Au
The reflective boundary tape drive

estimated duration of 1 track
9:12 hrs.  (552 min)

stepper motor

stepper motor

Au coated Kapton

e-beam
Dual IFEL-ITR experiment operation

Use the IFEL as a psec-resolution timing diagnostic

Regen average power: ~ ½ W
FWHM laser spot size: 50 µm
FWHM laser pulse: 2.0 psec
Xing angle for ITR: 16 mrad

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)
Top view of breadboard

- Cerenkov cell
- Tungsten masks
- Alignment laser spot
- E-beam path
- ITR holder plate
- IFEL
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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

Optical phase of the laser

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
Expected dependence of the laser-driven energy modulation

- The Lawson-Woodward Theorem
- Laser peak electric field
- Laser polarization
- Laser crossing angle

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

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

Expected dependences:

- Laser angle: \( U \propto \sin \alpha \cdot Z_{\text{slippage}} \)
- Laser electric field: \( U \propto E_{\text{laser}} \)
- Laser polarization: \( U \propto \cos \phi \)
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 (M) (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…

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

\[ U = \text{constant} \]

\[ U = \text{constant} \]

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

But I observe…

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

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

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

\[ \tau_{\text{interaction}} \sim 5 \text{ psec} \]
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5. Summary
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
  \[ U \leftrightarrow |E_{\text{laser}}| \]
  \[ U \leftrightarrow |\cos \phi| \]
  \[ U \leftrightarrow |\sin \alpha \cdot Z_{\text{slippage}}| \]

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

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• B. Noble, D. Walz (ARDB, SLAC)
• Y.C. Huang, C. Barnes, S. Waldman, J. Wisdom
Laser and Particle Guiding Micro-Elements for Particle Accelerators*

R. Gaume, T. Plettner, J. Wisdom, Stanford University
J. Spencer, SLAC

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


Silicon micromachining

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

Optical quality surfaces

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

mm-deep trenches

Ceramics micromachining

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

Optically transparent bulk ceramic sample

Problems
- optical ceramics fabrication technology is a relatively new topic
- micromachining technology on ceramics to sub-\( \mu \)m resolution has not been developed.

50 \( \mu \)m spacing pattern imprinted with a Silicon preform

*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

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.

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 controllable path delay (e.g. a PZT)

Error signal generation
- Error signal into AOM controls pump power and dispersion of laser

Comb offset control
- AOM signal: 1.0 kHz, 0.2V square wave

Beatnote detection circuitry
- PMT splitter bandpass 6-7 MHz QB 258 10.7
- Beat note

Comb offset detection experiment
- Millenia V Tsunami
- Spectrum analyzer
- Comb offset 1064 nm
- BBO 532 nm

The balanced cross-correlator experiment
- PZT delay
  - Vpp = 60 mV
  - t = 240 attosec

δf

frequency (MHz)

Comb offset

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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~ 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

\[ N_e \sim 10^{22} / \text{cc.} \]

http://www.ilp.physik.uni-essen.de/vonderLinde/Publikationen/ICONO98.pdf
laser ablation dynamics experiment

We measured reflectivity of 1st ablation reflected spot vs. laser pulse duration

Reflectivity of the 1st high power pulse as observed by camera

Low power reflected beam

High power reflected beam

High power reflected beam

2nd laser shot
Computation of the energy modulation strength

\[ QD = \sqrt{\left(\text{FWHM}_{\text{ON}}\right)^2 - \left(\text{FWHM}_{\text{OFF}}\right)^2} \]

averaged

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