ABSTRACT

The dielectric laser acceleration (DLA) concept leverages well-established industrial fabrication capabilities and the commercial availability of tabletop lasers to reduce cost, while offering significantly higher accelerating gradients, and therefore a smaller footprint. In contrast to other novel accelerator schemes, desirable luminosities would be obtained by operating with very low charge per bunch but at extremely high repetition rates. This research has significant near and long-term applications, which we will discuss. And as a consequence of its unique operating parameter regime, the predicted energy loss due to beam-beam interaction is small.
Who we are

PIs: Eric R. Colby (50%), SLAC & Professor Robert L. Byer, Stanford

W. K. H. Panofsky Fellow
Joel England (90%)

Staff Physicists
James E. Spencer (50%)
Robert J. Noble (90%)

Staff Engineering-Physicist
Dieter Walz (10%)

Graduate Students
Chris McGuinness
Ken Soong
Edgar Peralta
Rachik Laouar (visiting)
Behnam Montazeri

Postdoctoral RA
Ziran Wu (50%)

E163 Collaborators
Tomas Plettner
Jamie Rosenzweig
Sami Tantawi (ATR)

What we do

Develop laser-driven dielectric accelerators into a useful accelerator technology by:

• Developing and testing candidate dielectric laser accelerator structures
• Developing facilities and diagnostic techniques necessary to address the unique technical challenges of attosecond laser acceleration

Motivation

• Lasers can produce far higher energy densities than can microwave sources, hence larger electric fields
• Dielectric materials can hold off field stresses of >1 GV/m for picosecond-class pulses
• Lasers are a large-market technology with rapid R&D by industry (DPSS lasers: ↑0.22 B$/yr vs. ↓0.060B$/yr for microwave power tubes)
• Short wavelength acceleration naturally leads to sub-femtosecond bunches
• Technology to handle laser materials lithographically is rapidly evolving ⇒ an all solid-state accelerator on a chip

Work supported by Department of Energy contracts DE-AC02-76SF00515 (SLAC) and DE-FG03-97ER41043-III (LEAP).
Novel Concepts: Progress of the last 30 years

- **Inverse Smith-Purcell Acceleration**
  ~0.05 MV/m, Bae et al, Tohuku U., 1987.

- **Inverse Cerenkov Acceleration**
  31 MV/m, Kimura et al, BNL-ATF, 1995

- **Inverse Free Electron Laser**

- **Inverse Transition Radiation**
  ~40 MV/m, Plettner et al, Stanford, 2005.


*ISP, IEEE IEDM, p307ff, (1987).*

*IFEL, PRL 92(5), 054801-1, (2004)*

*ITR, PRL 95, 134801,(2005)*

Compared to RF Accelerators

- Sources are typically freespace TEM, must match to guided TM
  - Power coupling requires special attention
- Accelerating fields are present for picoseconds, rather than microseconds
  - Waveguiding structures typically designed for high $v_g \approx 0.6$ to limit envelope slippage
  - Phase mask and swept-laser methods
- Metals have higher loss and lower damage threshold at optical frequencies than dielectrics

Compared to Laser-Driven Plasma-Wakefield Accelerators

- No-threshold linear process; typically $a_0 \approx 10^{-4}$ in solid-state structures
- Very strong coupling impedances
- $E_{\text{laser}} \sim nJ$ to $\mu J \Rightarrow P_{\text{laser}} \sim kW$ to MW $\Rightarrow$ higher rep rate $\sim 10 - 1000$ MHz
Contents

Introduction
  Laser Electron Accelerator Project - LEAP
  HEPL Experiments from 1997 - Nov 2004
  E163 Experiments at SLAC
    Laser accelerator structures
    Inverse FEL for electron pulse compression

Laser Accelerator Experiments
  Structures and expected performance (damage testing)
  Recent experiments
  Fabrication of woodpile and bi-grating structures

Coherent X-ray laser Generation
  Components of the proposed FEL X-ray laser
    Dielectric Accelerator and Undulator Structures
    FEL gain and efficiency

Future Challenges
  Darpa program: develop an accelerator on a chip
  Enable TeV scale physics affordable cost

"Don’t undertake a project unless it is manifestly important and nearly impossible.”    Edwin Land – 1982
1st Klystron (Varian, 1930s')

The 2-mile collider (SLAC)

1st Linac 1946

The superconducting linac In HEPL, 1960

LEAP, 1997-2004

Demonstration of the FEL, 1977

First Operation of a Free-Electron Laser

High Energy Physics Laboratory, Stanford University, Stanford, California 94305
(Received 17 February 1977)

A free-electron laser oscillator has been operated above threshold at a wavelength of 3.4 μm.
The “Microwave” Lab (Now HEPL and Ginzton Labs) played a crucial role on the development of particle accelerators and the corresponding RF technology.
“Project M”

1955 first brainstorming and informal discussions

**SLAC CHRONOLOGY**

- **April 1957**: Proposal for two-mile accelerator submitted by Stanford University to Federal Government
- **September 1961**: Project authorized by U. S. Congress
- **April 1962**: Contract signed by U. S. Atomic Energy Commission and Stanford University
- **July 1962**: Ground breaking; construction begins
- **July 1964**: Start of accelerator installation
- **October 1, 1965**: First "Users Conference," attended by 150 people from laboratories all over the world, to be made acquainted with SLAC.
- **December 1965**: Installation of accelerator complete
- **February 12, 1966**: Program Advisory Committee met, and approved and scheduled the first experiments to be performed with the two-mile beam
- **May 21, 1966**: First beam transmitted over entire two-mile length of the accelerator
- **June 2, 1966**: 18.4 GeV of beam energy achieved
- **June 22, 1966**: Second "Users Conference" held at SLAC
- **July 13, 1966**: Positrons accelerated
- **October 17, 1966**: First interlaced multiple beams of different energies and intensities accelerated
- **November 1966**: Experiment begin with the beam in the end stations
- **January 10, 1967**: 20.16 GeV of beam energy achieved

- **$100M** proposal
- numerous studies and reports
- > 10 years of effort
SLAC – Particle Physics, Astrophysics & Photon Science

1968: First evidence of Quarks
1974: Discovery of the $\psi$ particle
1976: Discovery of the charm quark and the $\tau$ lepton
1997: The BaBar experiment
2009: LINAC coherent X-ray source

Other developments
• SSRL user facility
• Computer science, software
• KIPAC Particle Astrophysics
What is next?

Future TeV $e^+e^-$ collision experiments

- Top Quark Physics
- Higgs Boson Searches and Properties
- Supersymmetry
- Anomalous Gauge Boson Couplings
- Strong WW Scattering
- New Gauge Bosons and Exotic Particles
- $e^-e^-$, $e^-\gamma$, and $\gamma\gamma$ interactions
- Precision Tests of QCD

The NLC ZDR Design Group and the NLC Physics Working Groups
Snowmass `96 workshop
The goal of the Laser Electron Accelerator Program - LEAP - is to invent a new approach that will allow TeV physics on the SLAC site. To achieve the goal we need an acceleration gradient of 1 GeV per meter.
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.

Laser sources coupled with related technologies enable new approaches to Advanced Electron Accelerators.
Emergence of new technologies make Laser Acceleration Possible

**Efficient pump diode lasers**
- 60 W/bar, 50% electr. efficiency
- 30 W/bundle, 40% electr. efficiency

**Ultrafast laser technology**
- < 10 fs
- 60 W/bar, 50% electr. efficiency

**Leveraging investment in telecom**

**High power fiber lasers**
- IMRA mJ 500 fs laser
- NUFERN
- ALABAMA LASER

**Nanotechnology**
- Sodium yellow
- Menlo Systems GmbH

**New materials**
- High purity optical materials and high strength coatings
- High strength magnets Nd:Fe
- New ceramics
- Nano-tubes

**Byer Group**

DPF 2011 August 8 - 12, 2011 "Laser Driven Dielectric Accelerators"
Proposed layout of the laser system for a TeV collider

A low-power ultra-stable master oscillator serves as a reference clock for the entire accelerator.

Local modelocked oscillators are phase-locked to the master oscillator.

A mode converter transforms the TEM\(_{00}\) mode preferred by the laser to a TEM\(_{01}\) acceleration mode.

Laser amplifiers increase the power of the TEM\(_{01}\) mode from sub-watt to multiple tens of watts of average power mode.
2. Low bunch charge problem

• Take advantage of high laser repetition rate
• Multiple accelerator array architecture

Laser pulse structure that leads to high electron bunch repetition rate

Requires 10kW/meter or 10MW/km and ~30% efficiency Laser Source!

(≈ 10 microjoules in 100fsec per micropulse)

Dramatic increase of

• electric field cycle frequency ~$10^{14}$ Hz
• macro pulse repetition rate ~1GHz

<table>
<thead>
<tr>
<th></th>
<th>SLC</th>
<th>NLC</th>
<th>SCA-FEL</th>
<th>TESLA</th>
<th>Laser-accelerator</th>
</tr>
</thead>
<tbody>
<tr>
<td>$f_{RF}$ (GHz)</td>
<td>2.856</td>
<td>11.424</td>
<td>1.3</td>
<td>1.3</td>
<td>3x10^4</td>
</tr>
<tr>
<td>$f_m$ (Hz)</td>
<td>120</td>
<td>120</td>
<td>10</td>
<td>4</td>
<td>10^4</td>
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<tr>
<td>$N_b$</td>
<td>1</td>
<td>95</td>
<td>10^4</td>
<td>4886</td>
<td>10</td>
</tr>
<tr>
<td>$\Delta t_b$ (nsec)</td>
<td>-</td>
<td>2.8</td>
<td>84.7</td>
<td>176</td>
<td>3x10^-6</td>
</tr>
<tr>
<td>$f_b$ (Hz)</td>
<td>1.2x10^2</td>
<td>1.1x10^4</td>
<td>1x10^5</td>
<td>1.6x10^4</td>
<td>3x10^6</td>
</tr>
<tr>
<td>$N_e$</td>
<td>3.5x10^10</td>
<td>8x10^9</td>
<td>3.1x10^7</td>
<td>1.4x10^10</td>
<td>10^4</td>
</tr>
<tr>
<td>$I_e$ (sec^-1)</td>
<td>4x10^12</td>
<td>9x10^13</td>
<td>3x10^12</td>
<td>2x10^19</td>
<td>3x10^10</td>
</tr>
</tbody>
</table>
"An accelerator is just a transformer" - Pief Panofsky

"All accelerators operate at the damage limit" - Pief

"To be efficient, the accelerator must operate in reverse”
- Ron Ruth, SLAC

“ It is not possible to accelerate electrons in a vacuum”
Lawson - Woodward theorem

“An accelerator requires structured matter - a waveguide - to efficiently couple the field to the electrons” Bob Siemann


0 eV  100 keV  ~ 2 MeV  \( \frac{\Delta U}{\Delta x} \leq 50 \) MeV/m

electron source  DC potential  RF modulator (buncher)  pre-accelerator  accelerator structures
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Structures and expected performance (damage testing)
Recent experiments
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Enable TeV scale physics affordable cost
Laser driven particle acceleration

collaborators

ARDB, SLAC
Bob Siemann*, Bob Noble†, Eric Colby†, Jim Spencer†, Rasmus Ischebeck†, Melissa Lincoln‡, Ben Cowan‡, Chris Sears‡, D. Walz†, D.T. Palmer†, Neil Na‡, C.D Barnes‡, M Javanmarad‡, X.E. Lin†

Stanford University
Bob Byer*, T.I. Smith*, Y.C. Huang*, T. Plettner†, P. Lu‡, J.A. Wisdom‡

ARDA, SLAC
Zhiu Zhang†, Sami Tantawi†

Techion Israeli Institute of Technology
Levi Schächter*

UCLA
J. Rosenzweig*

† grad students † postdocs and staff * faculty
Participants in the LEAP Experiment

Bob Siemann\(^2\)  Chris Sears\(^2\)  Ben Cowan\(^2\)  Jim Spencer\(^2\)

Tomas Plettner\(^1\)  Bob Byer\(^1\)  Eric Colby\(^2\)

New students
• Chris McGuinness\(^2\)
• Melissa Lincoln\(^2\)
• Patrick Lu\(^1\)

Atomic Physics collaboration
• Mark Kasevich\(^3\)
• Peter Hommelhoff\(^3\)
• Catherine Kealhofer\(^3\)

1 E.L. Ginzton Laboratories, Stanford University
2 Stanford Linear Accelerator Center (SLAC)
3 Department of Physics, Stanford University
1. Energy gain through longitudinal electric field

- gradient = longitudinal electric field
- linear e-beam trajectory
  → no synchrotron radiation
  → energy scalable

\[ \Delta U = \int E_z \cdot dz. \]

2. Dielectric based structure with vacuum channel

Gradient → 1 GeV/m

3. Inherent attosec electron pulse

Tm;Glass Fiber 2 μm laser → 6 fs period
  → 1 deg of phase = 20 attosec

- very high peak electric fields
- vacuum channel
- NIR solid-state lasers
- Unique opportunity for light sources
The properly phased crossed laser beams have zero transverse field and only a longitudinal field component $E_z$. The interaction length is limited by phase drift to less than 400 microns.

An early concept for resetting the phase every 334 microns to keep the electrons and the applied laser field phased.
The proof-of-principle experiment

<table>
<thead>
<tr>
<th>HEPL beam parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam Energy</td>
</tr>
<tr>
<td>T_{electron}</td>
</tr>
<tr>
<td>Charge per bunch</td>
</tr>
<tr>
<td>Energy spread</td>
</tr>
<tr>
<td>λ_{laser}</td>
</tr>
<tr>
<td>E_{laser}</td>
</tr>
</tbody>
</table>

Beam Energy: ~30 MeV
T_{electron}: ~2 psec
Charge per bunch: ~5 pC
Energy spread: ~20 keV
λ_{laser}: 800 nm
E_{laser}: 1 mJ/pulse

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

Material boundary:
- 8 \( \mu \)m Kapton
- 1 \( \mu \)m Au

Electron beam

Equation:
\[ \Delta U = \int_{-\infty}^{0} E_z dz \]
The LEAP experimental apparatus that includes the LEAP single stage accelerator cell and the inverse FEL.

The simplified single stage Accelerator cell that uses gold coated Kapton tape to terminate the Electric field.

We have accelerated electrons with visible light!
The key was to operate the cell above damage threshold to generate energy modulation in excess of the noise level.
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. Sears, J. E. Spencer, and R. H. Siemann
SLAC, Menlo 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
  \[ \Delta U \propto |E_{\text{laser}}| \]
- observation of the expected polarization dependence
  \[ |E_z| \propto |E_{\text{laser}}| \cos \rho \]
Early Optical Acceleration Experiments

We have showed that “direct” (no plasma) acceleration of electrons with light can be done with useful gradients and very simple geometries


Inverse Transition Radiation Acceleration

A single metal boundary illuminated by linearly polarized light at the transition radiation angle

Demonstrated:
• Acceleration of appreciable charge (q~10^7 e⁻) by visible light
• A peak longitudinal field of E_z>40 MV/m
• “Large” interaction distance: ~1 mm or ~1200λ

Harmonic Inverse FEL Acceleration

A 3-period variable-gap undulator

Demonstrated:
• Acceleration of appreciable charge (q~10^7 e⁻) by visible light
• Interaction between electrons and higher-order undulator resonances (4th, 5th, 6th)

This IFEL will be used to energy-modulate the beam as part of an optical prebuncher for staging experiments.
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Recent experiments
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SLAC provided access to the NLCTA test accelerator - 360MeV
The E163 experiment at SLAC

The new E163 experiment hall

The NLCTA
Next Linear Collider Test Accelerator 360MeV
Byer Group

DPF 2011
August 8 - 12, 2011

“Laser Driven Dielectric Accelerators”

- **60 MeV**
- **10 pC**
- **~ 1psec**
- **λ = 800 nm**
- **U ~ ½ mJ/pulse**
- **τ ~ 200 fsec**
Ben Cowan - detailed calculations of Photonic Crystal Accelerator Structures
**Goal:** Invent and Test Dielectric Accelerator Microstructures

*Key:* move to photonic bandgap structures

### Planar waveguide structures

![Planar waveguide structure diagram](image1)


### Periodic phase reset structures

![Periodic phase reset structure diagram](image2)


### Hollow core PBG fibers

![Hollow core PBG fibers](image3)


### 3-D photonic bandgap structures

![3-D photonic bandgap structures](image4)

Goal: Develop Theory for laser accelerator physics

Coupling efficiency higher than expected: charge \( \sim fC \) - need rep rate!

Energy efficiency of laser accelerators, single and multiple bunch operation

For the first time theoretical calculations showed that laser accelerators could be efficient.
Primary challenge for laser acceleration: mode is **transverse** electromagnetic—must develop longitudinal electric fields to accelerate.

**Structure Candidates for High-Gradient Accelerators**

*Projected maximum gradients based on measured material damage threshold data*

- **Photonic Crystal Fiber**
  - *Silica, \( \lambda = 1890 \text{ nm} \), \( E_z = 400 \text{ MV/m} \)*

- **Photonic Crystal “Woodpile”**
  - *Silicon, \( \lambda = 2200 \text{ nm} \), \( E_z = 400 \text{ MV/m} \)*

- **Transmission Grating Structure**
  - *Silica, \( \lambda = 800 \text{ nm} \), \( E_z = 830 \text{ MV/m} \)*

3D 2D 1D
Transmission Grating Accelerator

Elegant Variant: Fast Deflector

Silica, $\lambda=800\text{nm}$, $E_z=830\ \text{MV/m}$
Main concept: periodic phase-reset of the EM field

Reset the phase every ~300 microns in grating structure

Transverse pumped phase-reset structure

EM field map in one unit

vacuum channel

electron beam

dielectric structure

input laser wavefront

\[ \langle F_\perp \rangle = 0 \]

\[ \langle E_{\parallel} \rangle \sim \frac{1}{2} E_{laser} \]

1 J/cm² fluence

~10 fsec pulses

\[ \langle G_{unloaded} \rangle \sim 4 \text{ GeV/m} \]

\[ G_{loaded} \sim 2 \text{ GeV/m} \]
The expected maximum gradients
Operate at the Breakdown Limit

\[
\begin{align*}
\langle \bar{G}_{\perp,TE} \rangle & \sim 0.15 |E_{laser}| \\
\langle \bar{G}_{\parallel,TE} \rangle & \sim 0.3 |E_{laser}| \\
\langle \bar{G}_{\perp,TE} \rangle & \sim 0.07 |E_{\max}| \\
\langle \bar{G}_{\parallel,TE} \rangle & \sim 0.15 |E_{\max}|
\end{align*}
\]

10 fsec laser pulse

\[1 \text{ J/cm}^2 \quad \rightarrow \quad |E_{\max}| \sim 25 \text{ GV/m} \quad \rightarrow \]

(At breakdown limit)

A Compatible Electron Source

Field Emission Tip as a Nanometer Source of Free Electron Femtosecond Pulses

Peter Hommelhoff, Yvan Sortais, Anoush Aghajani-Talesh, and Mark A. Kasevich

Physics Department, Stanford University, Stanford, California 94305, USA
(Received 25 July 2005; published 21 February 2006)

I\sim 11 \text{ e}/\text{optical cycle} \Leftrightarrow <I>\sim 500 \mu \text{A}

B > 10^{13} \text{ A/m}^2 \text{ sr}^2

\text{500nm Scale bar}
Contents

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Laser Electron Accelerator Project - LEAP
HEPL Experiments from 1997 - Nov 2004
E163 Experiments at SLAC
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Laser Accelerator Experiments
  Structures and expected performance (damage testing)
  Recent experiments
    electron beam bunching
    staged acceleration
    radiation from PBGT fiber

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  Enable TeV scale physics affordable cost
Experimental Parameters:

- **Electron beam**
  - $\gamma=127$
  - $Q\approx 5-10$ pC
  - $\Delta \gamma / \gamma = 0.05\%$
  - Energy Collimated
  - $\varepsilon_N = 1.5 \, \pi \, \mu$

- **IFEL:**
  - $\frac{1}{4} + 3 + \frac{1}{4}$ period
  - 0.3 mJ/pulse laser
  - 100 micron focus
  - $z_0 = 10$ cm (after center of und.)
  - 2 ps FWHM
  - Gap 8mm
  - Chicane 20 cm after undulator
  - Pellicle (Al on mylar) COTR foil
<500 attosecond electron compression in Inverse FEL
(Chris. M. Sears, PhD thesis SLAC June 2008)

We have achieved net acceleration of electrons with attosecond phase control

**Experiment features**

- IFEL modulates energy spread
- electron drift creates optical bunches
- second accelerator → net acceleration
Staged Laser Acceleration Experiment

Total Mach-Zender Interferometer path length: \( \sim 19 \text{ feet} = 7.2 \times 10^6 \lambda \) !!

All-passive stabilization used (high-mass, high-rigidity mounts, protection from air currents)
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)

PBG Fiber Tests

Hollow-core photonic bandgap fiber structures

Focusing Triplet

2 cm

1 mm

input pellicle

output pellicle

laser beam
to the energy spectrometer

PBG fiber

Objective Parameters

• Working Distance > 10mm (geometrical constraints)
• NA_{objective} > 0.12 (NA_{fiber})

• Mitutoyo Infinity Corrected Objectives:
  • 100x → NA=0.5, WD=12mm
  • 20x → NA=0.4, WD=20mm

TEM00(lin) → TEM01* mode convertor output

e−
First Observation of Accelerating Modes in a PBG Fiber

- Commercially available fiber (Thorlabs HC-800-1, $533/m)
- Observed with optical spectrometer to measure SOL modes

Thorlabs HC-1550-2

A variety of optical-scale dielectric structures are under consideration.

PBG-fiber-based structures afford large apertures and length-scalability.

~2.5 GV/m

Planar structures offer beam dynamics advantages as well as ease of coupling power.

MAP

Logpile

Grating

Gil Travish, UCLA
The MAP structure consists of a diffractive optic coupling structure and a resonant cavity.

For gap $a$ and dielectric $b-a$, idealized resonance:

$$\cot \left[ k_z \sqrt{\varepsilon - 1(b-a)} \right] = k_z a \sqrt{\varepsilon - 1}/\varepsilon$$

Tuning: control “matching” layer $(b-a)$.

Gil Travish UCLA
For the first time, beam was transmitted through the optical-scale structure!

**Bunches from NLCTA Beamline**

Spot size = 96 x 83 μm²

\[ \varepsilon_x = 43 \text{ μm-rad} \]

\[ \varepsilon_y = 24 \text{ μm-rad} \]

Spectrometer Image (higher energy to the left)

- Electrons that lost energy while traveling through glass
- Electrons that made it through slope

- Theoretically, we expect peaks to be separated by 0.5 MeV

- With calibration of 1.776 KeV/pixel, we find separation of 0.337 MeV

Data analysis is ongoing
Working with optical wavelengths necessarily means that components built to confine fields in this range achieve nanometer and attosecond scale performance.

• Further applications of DLA
  • Optical undulators (~1 MeV)
  • Optical BPMs (Z. Wu, K. Soong),
  • Optical Structure Based beam focusing (B. Cowan)
  • Optical kickers and steering elements (K. Soong, C. McGuinness)
  • Attosecond-scale timing diagnostics
  • Internal-Beam Radiotherapy (UCLA-Travish, Yoder)
  • Optical BPMs (IIT-Technion—Schächter)
  • THz sources (Z. Wu)


MAP structure for IBRT. -- G. Travish, R. Yoder, UCLA.


Woodpile structure simulations as a BPM—Z. Wu

Woodpile structure designed to support deflecting mode—C. McGuinness
Contents

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  E163 Experiments at SLAC
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    Inverse FEL for electron pulse compression

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  Structures and expected performance (damage testing)
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... could we generate coherent X-ray photons with laser accelerators?

RF-accelerator driven SASE FEL facilities - 2009
(John Arthur, SLAC Tuesday PQE)

LCLS properties

- km-size facility
- microwave accelerator
- $\lambda_{RF} \sim 10 \text{ cm}$
- 4-14 GeV e-beam
- 120 m undulator
- 23 cm period
- 15-1.5 Å radiation
- 0.8-8 keV photons
- $10^{14}$ photons/sec
- $\sim 77$ fsec

- separate user lines
- 120 Hz pulse train

TTF: Tesla Test Facility; fsec EUV SASE FEL facility
XFEL: Proposed future coherent X-ray source in Europe...
The Key Components of the SASE-FEL architecture
SASE - Self Amplified Spontaneous Emission

source of free particles
laser-driven
high rep. rate
very compact

accelerator section
dielectric structure
based laser-driven
particle accelerators

undulator
dielectric structure,
laser driven
Architecture of a laser-driven free-electron X-ray source

- Source of free particles
  - Laser-driven field emission sources

- Accelerator section
  - MEMs-based laser-driven dielectric accelerator structure

- Undulator
  - MEMs-based laser-driven dielectric deflection structure

- x-rays

- solid state, tabletop laser system
  - $\lambda \sim 1 \, \mu m$
  - ultra short pulses
  - high peak electric fields
  - $\leq$ sub-kW of electrical power
  - no radiation or electrical hazards
  - MHz repetition rates

- total length on the order 1 m
1 degree of optical phase

$\Delta x = 15 \text{ nm}$, $\Delta t = 14 \text{ attosec}$

$\sim 10^4 \text{ e}^-/\text{bunch}$

$\lambda = 1.5 \mu\text{m}$, $\tau = 5 \text{ fsec}$
Development of the three key laser-driven components

source of free particles → accelerator section → undulator

Objective: develop a compact laser-driven electron injector

1. High rep. rate
2. Low power consumption
3. Ultra low emittance (~10^{-9} m-rad)
4. ~10 MeV in a few-cm structure
A laser-driven field-emission free-electron source

P. Hommelhoff et al, Kasevich group

Field emission tip properties

1. Laser-assisted tunneling of electrons from the atom to free space
2. Highly nonlinear
3. Potential for timed sub-optical cycle electron emission

Development of the three key laser-driven components

source of free particles \rightarrow accelerator section \rightarrow undulator

**Objective:**

1. Dielectric optical MEMs structures
2. High acceleration gradients (~ 1 GeV/m)
3. Mono-energetic, maintenance of low emittance
Investigate approaches for the FEL Undulator

Short Period Undulator with periodic magnets

source of free particles → accelerator section → undulator

First Idea:

Periodic Magnetic Undulator
Field strength ~ 1 Tesla
Modulation Period ~ 0.1mm
Length ~ 30cm
Discouraging! Magnetic Undulator not Matched to attosecond electron bunches

1 pC, 2 GeV, \( \lambda u = 200 \mu m \), \( Lu = 40 \) cm, \( rb \approx 200 \) nm, B \( \approx 1 \) T

Proposed parameters for laser driven SASE-FEL
(Theoretical Study of FEL operation - summer 2008)
New Idea: **Laser-Driven Dielectric Undulator for FEL**

**accelerator structure**

\[ \langle \vec{E} \rangle \sim \frac{1}{2} E_{\text{laser}} \rightarrow \sim 4 \text{ GeV/m} \]

**deflection structure**

\[ \langle \vec{E} + (\vec{v} \times \vec{B}) \rangle = 0 \]

\[ \langle \vec{E} \rangle \sim \frac{1}{5} E_{\text{laser}} \rightarrow \sim 2 \text{ GeV/m} \]

**key idea**

Extended phase-synchronicity between the EM field and the particle

Use modelocked laser to generate periodic deflection field

T. Plettner, “Phase-synchronicity conditions from pulse-front tilted laser beams on one-dimensional periodic structures and proposed laser-driven deflection”, submitted to Phys. Rev. ST AB
Proposed dielectric-based microstructure laser-driven undulator

T. Plettner and R. L. Byer
Stanford University, Stanford, California 94305, USA
(Received 18 April 2007; published 20 March 2008)

We describe a proposed all-dielectric laser-driven undulator for the generation of coherent short wavelengths and explore the required electron beam parameters for its operation. The key concept for this laser-driven undulator is its ability to provide phase synchronicity between the deflection force from the laser and the electron beam for a distance that is much greater than the laser wavelength. Because of the possibility of high-peak electric fields from ultrashort pulse lasers on dielectric materials, the proposed undulator is expected to produce phase-synchronous GV/m deflection fields on a relativistic electron bunch and therefore lead to a very compact free electron based radiation device.

DOI: 10.1103/PhysRevSTAB.11.030704 PACS numbers: 41.60.Cr, 41.75.Jv, 41.75.Ht, 42.25.Bs

Proposed few-optical cycle laser-driven particle accelerator structure

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(Received 2 October 2006; published 14 November 2006)

We describe a transparent dielectric grating accelerator structure that is designed for ultrashort laser pulse operation. The structure is based on the principle of periodic field reversal to achieve phase synchronicity for relativistic particles; however, to preserve ultrashort pulse operation it does not resonate the laser field in the vacuum channel. The geometry of the structure appears well suited for application with high average power lasers and high thermal loading. Finally, it shows potential for an unloaded gradient of 10 GeV/m with 10 fs laser pulses and the possibility to accelerate 10^6 electrons per bunch at an efficiency of 8%. The fabrication procedure and a proposed near term experiment with this accelerator structure are presented.

DOI: 10.1103/PhysRevSTAB.9.111301 PACS numbers: 41.75.Jv, 41.75.Ht, 42.25.Bs
Calculated FEL Performance - 0.1 Angstrom X-rays

- **400 periods, 12 cm**
  - Power (GW) vs. time (attosec)

- **500, 15 cm**
  - Power (GW) vs. time (attosec)

- **900, 27 cm**
  - Power (GW) vs. time (attosec)

- **Number of photons vs. undulator period**

**Parameters**:
- $U_b = 2$ GeV
- $\varepsilon_N = 10^{-9}$ m - rad
- $Q_b = 20$ fC
- $\Delta \gamma / \gamma = 0.1\%$
- $\sigma_r = 200$ nm
- $\beta^* = 4$ cm

**Equations**:
- $L_c \sim 21 \lambda_r$
- $\sigma_b \sim 136 \lambda_r$
- $\sigma_b / L_c \sim 6$
- $L_G \sim L_{G0} \left( 1 + N_3 \lambda_r / 3 \sigma_b \right)$
- $\rho_{eff} = U_{FEL} / U_{beam} \sim 5 \times 10^{-4}$

Summary: possible table-top coherent X-ray source

Schematic of the tabletop radiation source

field emitter source* → laser accelerator → laser undulator

- ~ 1 m
- ~ 30 cm
- x-rays
  - $10^5$/pulse
  - 100 keV

There is a path forward based on a modelocked laser driven dielectric undulator
Look for undulator radiation

\[ N_{ph} = \pi \alpha \frac{K^2}{\left(1 + K^2/2\right)^2} \left( J_1 \left( \frac{K^2}{4(1 + K^2/2)^2} \right) - J_0 \left( \frac{K^2}{4(1 + K^2/2)^2} \right) \right) \]

\( \lambda_u = 1 \text{ mm} \)

Prove the concept

\[
\begin{align*}
K &\propto \lambda_u \\
\Delta \omega/\omega & = 1/N_u \\
\Delta \theta & = \sqrt{2 \lambda_r/\lambda_u N_u}
\end{align*}
\]

measure

\( N_{ph} \sim 3 \times 10^4 \)

\( \lambda_r \sim 40 \text{ nm} \)
PROPOSED TABLETOP LASER-DRIVEN COHERENT X-RAY SOURCE*

T. Plettner*, R.L. Byer, Stanford University, Stanford, CA, 94305, USA

Abstract
We describe the concept of an all-dielectric laser-driven undulator for the generation of coherent X-rays. The proposed laser-driven undulator is expected to produce internal deflection forces equivalent to a several-Tesla magnetic field acting on a speed-of-light particle. The key idea for this laser-driven undulator is its ability to provide phase synchronicity between the deflection force and the electron beam for a distance that is much greater than the laser wavelength. A possible conceptual tabletop SASE-FEL device composed by such an integrated laser-driven accelerator-undulator system is explored.

INTRODUCTION
One of the potential main traits from future structure-loaded laser-driven particle accelerators is their promise for attosecond electron bunches and for higher gradients than RF particle accelerators. Therefore the possibility for employing such an accelerator as a compact electron source for a SASE-FEL device is interesting to explore. A meter long laser accelerator could deliver an optically bunched GeV energy electron beam into an undulator, and to preserve an all-tabletop system a matching compact undulator is highly desirable. To this end we propose a dielectric based laser-deflection structure that is MEMs based.

THE UNDULATOR
The key aspect of the proposed laser-driven undulator is the maintenance of phase synchronicity between the electromagnetic field and the travelling particle, which is designed to extend for a distance that is much larger than grooves of the vacuum channel are oriented at an angle \( \alpha \) with respect to the electron beam trajectory. These grooves introduce a phase modulation of the electromagnetic field in the vacuum channel that is responsible for the extended phase synchronicity condition with the electron beam. The period of the vacuum channel grooves, denoted by \( \lambda_p \) in Figure 1, is chosen such that its projection on the electron beam axis equals the laser wavelength \( \lambda \), such that \( \lambda_p = \lambda \cos \alpha \).

In the structure coordinates the particle velocity vector is given by \( \mathbf{v}(t) = c(\dot{\mathbf{y}} \cos \alpha + \dot{\mathbf{z}} \sin \alpha) \). The laser beam is a plane wave with the phase front at normal incidence the structure, travelling in the \( \hat{x} \)-direction.

![Perspective view of the deflection structure.](image)

A configuration of this type, where the periodic structure is oriented at an angle to the electron beam, satisfies the phase synchronicity condition for a non-zero deflection force acting on a speed-of-light particle [3].
Our long-term objective is to demonstrate a high-gradient dielectric-based extended accelerator structure on a chip.

The envisioned laser-driven particle accelerator will include the following components:
- A laser-driven electron injector and low-energy accelerator
- Dielectric loaded vacuum channel laser-accelerator sections
- Laser power couplers for the accelerator sections
- Steering and focusing elements
- Beam monitors

Our ultimate objective is the integration of all the parts into a scalable linear accelerator structure that can serve as the basis for a high-energy accelerator.
Photonic-based laser driven electron beam deflection and focusing structures

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MPQ, Garching, Germany
(Received 22 February 2009; published 26 October 2009)

We propose a dielectric photonic structure for ultrafast deflection and focusing of relativistic charged particle beams. The structure is designed to transform a free-space laser beam into a deflection force that acts on the free particles with the same optical phase over a distance of travel that is much greater than the laser wavelength. The proposed structure has a two-dimensional geometry and is compatible with existing nanofabrication methods. Deflection fields of GV/m magnitude and subfemtosecond switching speeds are expected to be possible from these dielectric structures. With these elements a submeter scale extreme ultraviolet synchrotron source seems feasible.

DOI: 10.1103/PhysRevSTAB.12.101302

PACS numbers: 41.75.Jv, 41.75.Ht, 42.25.Bs
Challenges ahead

1. Staged acceleration
   - precise control of optical phase
   - control of focusing and steering of the electron beam

2. Implementation of real accelerator microstructures
   - fabrication
   - coupling of the laser
   - electron beam transmission
   - survival of the radiation environment
   - heat removal

3. Laser technology
   - wavelength 2 μm
   - optical phase control
   - wallplug efficiency
   - lifetime
Monolithic Fabrication of an Integrated Structure

SiO$_2$ wafer
Fiber Couplers
Undulator
Accelerator Structures
Electron Source

Long Term Goal: Phased Accelerator structures on a chip
Contents

Historic Background

The TeV-Energy Physics Frontier

Laser Electron Accelerator Project - LEAP
  HEPL Experiments from 1997 - Nov 2004
  E163 Experiments at SLAC
    Laser accelerator structures
    Inverse FEL for electron pulse compression

Coherent X-ray laser Generation
  Components of the X-ray laser
    Dielectric Accelerator and Undulator Structures
    FEL gain and efficiency

Future Challenges
  DARPA program: DLAs to DLA driven FEL
  Enable TeV scale physics affordable cost
High Power Laser Technology for Accelerators

A joint International Committee on Future Accelerators (ICFA) and International Committee on Ultrahigh Intensity Lasers (ICUIL) whitepaper
Goal: evaluate prospects for laser accelerators
Climbing Mt. Parametrius

Shown here are more-detailed versions of the cover illustration, indicating the relative difficulty of the laser applications discussed in this whitepaper. Colliders for high-energy physics represent the presently aspirational pinnacle of laser power (*top*), but other applications are demanding in other parameters such as short pulses and repetition rate. Illustrations courtesy T. Tajima, University of München, DE.
ICFA and ICUIL Workshop Contributors

Contributors

Joint Task Force Members

The 2009-2011 membership of the JTF consists of members of the ICFA Beam Dynamics Panel (Ralph Assman, ICFA Beam Dynamics Panel chair Weiren Chou, Ingo Hofmann, and Kaoru Yokoya); the ICFA Advanced and Novel Accelerator Panel (Bruce Carlsten, Dino Jaroszynski, Wim Leemans, Akiro Noda, James Rosenzweig, Siegfried Schreiber and Advanced and Novel Accelerator Panel chair Mitsuru Uesaka); and ICUIL (Chris Barty, Paul Bolton, Robert Byer, Almantas Galvanauskas, Wim Leemans, and Wolfgang Sandner). Leemans is the chair of the JTF.

Workshop Participants

In addition to the task force members, the following scientists contributed to this document: Vincent Bagnoud, Jean-Paul Chambaret, Jean-Christophe Chanteloup, John Collier, Brigitte Cros, Jay Dawson, Hartmut Eickhoff, Eric Esarey, Erhard Gaul, Erion Gjonaj, Thomas Haberer, Manuel Hegelich, Kiminori Kondo, Thomas Kuehl, Yun Liu, Matthieu Somekh, Darren Rand, Tor Raubenheimer, David Richardson, Roland Sauербrey, Mike Seidel, Frank Stephan, Thomas Stoehlker, Toshi Tajima, Franz Tavella, Guenther Traenkle, Andreas Tuennermann, Bill White, Ingo Will, Xueqing Yan, Michalis Zervas, Bernhard Zielbauer.

Goal: Publish Workshop White Paper by end of 2011
Potential DLA-based collider parameters match well to general collider goals

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Selected publications


