Laser-Driven Dielectric-Structure Accelerators*

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* http://www-project.slac.stanford.edu/e163/DielectricAccelTalk.pdf
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Why is laser-driven acceleration in “vacuum” worth pursuing?

“Vacuum”:
- No plasmas, background gases; only solid objects
- Low-field \( a_0 = \frac{eE}{2\omega mc} \ll 1 \)

Physical and Technical Issues

What are the most promising laser acceleration methods?

Crossed-Gaussian Accelerator
Photonic Band Gap Accelerator
\( \rightarrow \) Laser-Driven Linear Collider Concept

What R&D is needed to make a working laser accelerator?

STELLA
Laser Electron Accelerator Project (LEAP)
E163, SPRC, and follow-on programs at ORION

General Roadmap
Requirements for Future
High Energy Linear Colliders

Near Term:
• Center-of-mass energy 0.5-1.0 TeV
• Luminosity $>10^{34}$ cm$^{-2}$ s$^{-1}$

Long Term:
• $>3$ TeV and readily extendable
• Luminosity $>10^{35}$ cm$^{-2}$ s$^{-1}$ and increasing with $\gamma^2$

*Compactness, power efficiency, reliability, affordability*

Linear optical-wavelength acceleration requires:

Sub-femtosecond electron bunches $\Rightarrow$ sub-fs radiation pulses

Very small emittance beams $\Rightarrow$ radiation sources are truly point-like
High Power Density $\Rightarrow$ High Field Strength

$Pf^2$

Source Frequency [GHz]

SPPS/FFT Beam
FFT Beam
NLCTA Beam

Source Power Density [TW/cm$^2$]

SLAC MBK
SLAC 5045
Mitsubishi C-band
SLAC X-band PPM
Haimson 17 GHz TK
CLIC 30 GHz TBA
UMDC/CRCP 34 GHz G-K
LLNL 140 GHz Ubtron
HEPL SCA FEL
1 K CO2 Laser
1 TW CO2 Laser
Vanderbilt FEL
Boeing FEL
10 GW Er Fiber Laser
1 TW: Sapphire Laser
LANL RA FEL

Source Wavelength

*28.5 GeV, 1e10 ppp, 1$\mu$m x 1$\mu$m x 600$\mu$m (20$\mu$m for SPPS) beam

**350 MeV, 1e10 ppp, 1$\mu$m x 1$\mu$m x 1 mm beam

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FIG. 1. Observed values of damage threshold at 1053 nm for fused silica (●) and CaF$_2$ (○). Solid lines are $\tau^{1/2}$ fits to long pulse results. Estimated uncertainty in the absolute fluence is ±15%.


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Electrical Efficiency of Coherent Power Sources

SLAC PPM Klystron
- $\lambda = 2.624$ cm
- $\Gamma_t = 3 \mu$s
- $P_{ave} = 27$ kW
- $\eta = 65\%$

Yb:KY(WO$_4$)$_2$
- $\lambda = 1.028 \mu$m
- $\eta_{slope} = 86.9\%$
- $\eta_a = 22\%$
- $\eta_g = 43\%$ (theoretical)
- $\Gamma_t = 240$ fsec
- $P_{ave} = 22.0$ W

Yb:KGd(WO$_4$)$_2$
- $\lambda = 1.023 \mu$m
- $\eta_{slope} = 82.7\%$
- $\eta_g = 41\%$ (theoretical)
- $\Gamma_t = 176$ fsec
- $P_{ave} = 1.1$ W

Source Frequency [GHz]

Source Electrical Efficiency [%]

TUBES
(RF Compression, modulator losses not included)

FELs

LASERS

Yb:YAG

Yb:KY(WO$_4$)$_2$

Yb:KGd(WO$_4$)$_2$

Yb:Te:Al$_2$O$_3$

Cr$^{3+}$:ZnSe

Er Fiber

CO$_2$
Commerciaally Available High Efficiency Laser Diode Bars

300W (cw), $\eta_e=50\%$, $\lambda=780-1000$ nm

High Power Stacks

nLight Photonics' high power stacked bar module provides state-of-the-art power levels in a compact package. Starting with high power diode 1 cm bars, multiple modules are stacked to provide extremely high output power. These modules are water cooled to maximize output power without sacrificing the lifetime of the diode.

- **Optical**
  - Center Wavelength (Range): 780-1000 nm
  - CW Output Power: 300W (6 plates)
  - Center Wavelength Tolerance: ± 0.5 nm
  - Array Length: 1 cm

- **Electrical**
  - Total Conversion Efficiency: 50%
  - Threshold Current: 100 mA
  - Operating Current: 600 mA
  - Operating Voltage: < 12V
  - Series Resistance: 0.04Ω

- **Thermal**
  - Thermal Resistance: 0.35°C/W
  - Operating Temperature: 10°C to 40°C
  - Fluid Flow Rate: 300 ml/min/plate
  - Inlet to Outlet pressure drop: 30 psi
  - Deionized Water Resistivity: 5 - 2 MΩm-cm
  - Filter: < 20 μm

3900 W, $\eta_e=40\%$, $\lambda=792-812$ nm, (585 W ave.)
Stable optical phase-locking to a microwave reference has been demonstrated.

![Interference fringes](image1.png)

**Fig. 2.** White-light fringes resulting from the interference of the two continua generated by the two phase-locked IR laser pulses when the relative delay is properly adjusted to zero.

**Fig. 3.** Spectrally dispersed white-light fringes. Clear and well-defined fringes indicate that a stable phase relationship is conserved across all the generated visible spectrum.

Interference fringes of carrier phase-locked white light continua generated from a Ti:Sapphire laser.

Laser development is strongly driven by industry

• Lasers are a $4.8B/year market (worldwide), with laser diodes accounting for 59%, DPSS lasers $0.22B/year, and CO₂ lasers $0.57B/year [1] (in contrast, the domestic microwave power tube market is $0.35B/year, of which power klystrons are just $0.06B/year[2]).

• Peak Powers of TW, average powers of kW are available from commercial products

• The market’s needs and accelerator needs overlap substantially: Cost, reliability, shot-to-shot energy jitter, coherence, mode quality are needed by both

Fundamental Physics Considerations I

- Lawson-Woodward Theorem requires that one or more of:
  - Boundaries*
  - Gases
  - Periodic transverse motion of accelerated particles
  be present for linear acceleration ($\propto E$) to take place

- *Furthermore, since free-space modes are strictly TEM, efficient acceleration requires a structure that either strongly diffracts the TEM mode, or guides a TM-like mode $\Rightarrow$ boundaries must be very close to the beam ($r/\gamma\lambda<1$)

- Accelerating fields must not degrade transverse emittances $\Rightarrow$ fields must be rotationally symmetric
Fundamental Physics Considerations II

- Good coupling impedance $\Rightarrow$ strong fundamental-mode wakefield
- Stability against regenerative beam breakup $\Rightarrow$ minimal higher order mode wakefields
- Higher stored energy (Q) in structure $\Rightarrow$ Tighter dimensional tolerances
- Larger acceptance $\Rightarrow$ larger aperture
Basic Technical Considerations I

• For efficiency, accelerators should be designed at wavelengths to use the most efficient lasers
  – Yb:KGD(WO₄)₂, Yb:KY(WO₄)₂  \( \rightarrow \lambda \sim 1.0 \ \mu m \)
  – Erbium Fiber  \( \rightarrow \lambda \sim 1.5 \ \mu m \)
  – Cr⁺⁺:ZnSe  \( \rightarrow \lambda \sim 2.2-2.8 \ \mu m \)

• For economy of fabrication, accelerators should be designed at wavelengths were materials are low loss and amenable to lithographic or fiber drawing processes:
  – a-SiO₂  \( \rightarrow \lambda \sim 0.2-2.5 \ \mu m \)
  – c-Si  \( \rightarrow \lambda > 1.5 \ \mu m \)
Basic Technical Considerations II

- Structure materials should have
  - High damage threshold \(\rightarrow\) resistance to breakdown
  - High radiation resistance \(\rightarrow\) resistance to high-radiation accelerator environment
  - Excellent optical linearity, even under large applied electric fields \(\rightarrow\) minimal intensity-dependent dephasing
  - Good thermal conductivity, low thermal expansion \(\rightarrow\) thermally stable under changing operating conditions
  - Amenability to fabrication \(\rightarrow\) Lithography or fiber drawing
Short-Pulse Laser Damage of Dielectrics

• $t^{1/2}$ dependence for $t>10$ ps
• No $t$ dependence for $t<5$ ps
• “Laser Conditioning” raises threshold ~10%
• Some materials perform worse under vacuum

Radiation Resistance of Dielectrics

Radiation dose: 45 kGy (Si equivalent) (30 days at the exit of the FFTB vertical dipole)


Gamma-resistant Materials (no measurable change in transmission characteristics in the 0.8-3 µm range for a dose exceeding 100 kGy Si equivalent from a Co$^{60}$ source): c-SiO$_2$, c-Si, c-GaAs, Nd:YAG

Neutron damage studies (with a Cf$^{252}$ source) are planned.

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Progress in Precision Lithography

Dense, λ/10-sized features possible by standard semiconductor lithography

Source: 2001 ITRS - Exec. Summary, ORTC Figure

May 2001
- 90nm (1:1)
  790 Å, on Si
- 80nm (1:1)
  1560 Å, on Si
- 100nm (1:1.5)
  1025 Å, on SiON

2nd International Symposium on 157nm Lithography – May 14-17, 2001
Fiber Bundle Drawing

- Preform has essentially the same geometry as the finished bundle
- Dimensional drawdowns of 1000:1 routine

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http://www.crystal-fibre.com

http://www.infodotinc.com/neets/tm/107-5.htm

Examples of Dielectric Laser Accelerator Structures
First Example:
Interferometric Acceleration
(Inverse Transition Radiation Acceleration)

Interaction Length: $\sim 1000 \lambda \sim 0.1 Z_R$

$E_{1x} + E_{2x} = 0$ → no transverse deflection
$|E_{1z} + E_{2z}| > 0$ → nonzero electric field in the direction of propagation

The laser beams are polarized in the XZ plane, and are out of phase by $\pi$

Gradient limited to $\leq 70$ MeV/m for $\gamma \to \infty$ [R. Noble, 2001].

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\[
E_{x1} = \frac{E_{01} w_o}{w_1} \exp\left[-\frac{r_1^2}{w_1^2}\right] \cos(\psi_t)
\]

\[
E_{z1} = \frac{2E_{01} x_1}{k w_1^2} \exp\left[-\frac{r_1^2}{w_1^2}\right] \left(\sin(\psi_t) - \left[\frac{z_1}{Z_R}\right] \cos(\psi_t)\right)
\]

(paraxial approximation to first order in $1/w_0 k \sim 10^{-3}$)

\[
\psi_t = kz_1 - \omega t + z_1 r_1^2/(Z_R w_1^2) - \tan^{-1}(z_1/ Z_R) + \phi_o
\]

The LEAP Cell

(Analytic theory (Sprangle/Esarey/Krall/Ting 1996, green trace), and numerically integrated synchronous longitudinal (blue) and transverse (red) fields of crossed TEM$_{00}$ modes. Beam slits are not accounted for in this theory.)

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Vector Diffraction Code
A Matlab implementation of Huygen’s Principle in l.i.h. media

1. Construct or load incident fields

2. From incident fields, calculate surface currents on initial, discrete surface

3. Propagate to field points


The LEAP Cell

Analytic Theory

Vector Diffraction Calculation

Synchronous $E_z$

Synchronous $E_x$
Rayleigh-Helmholtz Reciprocity Theorem
(one of many reciprocity relations)


Colloquial Version, Narrowly Applied to Accelerators: If a structure accelerates beam, it will make the beam radiate, and the narrowband coupling impedance for each process will be the same.

Rigorous, general version: Given imposed quasistationary drive fields $E_o'$ and $E_o''$ on two objects and a bounding surface $S$ containing both objects within volume $V$, and $\varepsilon, \mu, \text{and} \sigma$ are all scalar and constant: (from S. Ballantine, Proc. IRE, 17(6), p.929ff, (1929).)

\[
\int\int\int [E_o' C'' - E_o'' C'] dv = \frac{c}{4\pi} \int\int [E' \times H'' - E'' \times H'] n dS
\]

\[ C \equiv \frac{c}{4\pi} \nabla \times H \]

Original version: “Let there be two circuits of insulated wire A and B and in their neighborhood any combination of wire circuits or solid conductors in communication with condensers. A periodic electromotive force in the circuit A will give rise to the same current in B as would be excited in A if the electromotive force operated in B.” Lord J. W. S. Rayleigh, Theory of Sound, v. II, Dover: New York, p. 145, (1894).
Accelerator vs. Radiator

Crossed-Beam Accelerator
Crossed Gaussian beams, \( w_0 = 64\mu \),
\( \theta = 11.5 \text{ mr} \)

CTR Radiator, viewed narrowband
10\(\mu\) x 10\(\mu\) x \(\lambda/30\) bunch, \(10^4\) particles

\[
E_{\{x,y\}} = \sum_{i=1}^{N=10^4} \frac{e\omega}{4\pi\varepsilon_0\gamma\beta^2c^2} \frac{\{x_i, y_i\}}{R_i} \sqrt{\frac{2}{\pi}} \exp\left(\frac{j\omega z_i}{\beta c}\right) K_1\left(\frac{R_i\omega}{\gamma\beta c}\right)
\]

\[
E_z = -j \sum_{i=1}^{N=10^4} \frac{e\omega}{4\pi\varepsilon_0\gamma^2\beta^2c^2} \sqrt{\frac{2}{\pi}} \exp\left(\frac{j\omega z_i}{\beta c}\right) K_0\left(\frac{R_i\omega}{\gamma\beta c}\right)
\]

\[
\vec{H} \approx \vec{Yk} \times \vec{E}
\]

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Crossed Gaussian and ICTR give qualitatively similar accelerating fields

Crossed Gaussian
Synchronous $E_z$

ICTR Synchronous $E_z$

Note: don’t take vertical scales too seriously
### Summary Properties

**TABLE A.1: Summary of crossed-Gaussian laser and field parameters.**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Future Value</th>
<th>Now Value</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron Energy</td>
<td>Eₑ</td>
<td>60 MeV</td>
<td>60 MeV</td>
<td></td>
</tr>
<tr>
<td>Laser Wavelength</td>
<td>λ</td>
<td>0.8 µm</td>
<td>0.8 µm</td>
<td></td>
</tr>
<tr>
<td>Laser focal spot size</td>
<td>w₀</td>
<td>50 λ</td>
<td>50 λ</td>
<td></td>
</tr>
<tr>
<td>Rayleigh Range</td>
<td>z_R</td>
<td>6.3 mm</td>
<td>6.3 mm</td>
<td></td>
</tr>
<tr>
<td>Slippage Length</td>
<td>z_s</td>
<td>2.8 mm</td>
<td>2.8 mm</td>
<td></td>
</tr>
<tr>
<td>Ideal Crossing Angle</td>
<td>θ</td>
<td>11.5 mrad</td>
<td>11.5 mrad</td>
<td>1/γ=8.3 mrad</td>
</tr>
<tr>
<td>Critical Energy</td>
<td>γₑ</td>
<td>68</td>
<td>68</td>
<td>(34 MeV)</td>
</tr>
<tr>
<td>Spot size on dielectric surface</td>
<td>w₁</td>
<td>51.3 λ</td>
<td>51.3 λ</td>
<td></td>
</tr>
<tr>
<td>Fluence x time on dielectric surface</td>
<td>F·Γ₁</td>
<td>2 J/cm²</td>
<td>0.5 J/cm²</td>
<td></td>
</tr>
<tr>
<td>Laser Pulse Energy</td>
<td>E₇</td>
<td>100 µJ</td>
<td>25 µJ</td>
<td></td>
</tr>
<tr>
<td>Laser Pulse Length</td>
<td>Γ₁</td>
<td>100 fsec</td>
<td>5 psec</td>
<td>FWHM</td>
</tr>
<tr>
<td>Peak Electric Field</td>
<td>E₀</td>
<td>5.9 GV/m</td>
<td>0.42 GV/m</td>
<td></td>
</tr>
<tr>
<td>Peak Axial Field</td>
<td>E₂</td>
<td>140 MV/m</td>
<td>9.8 MV/m</td>
<td></td>
</tr>
<tr>
<td>Energy Gain</td>
<td>ΔW</td>
<td>290 keV</td>
<td>20 keV</td>
<td>Ideal phase particle</td>
</tr>
<tr>
<td>Electron Beam Energy Spread</td>
<td>Γₑ</td>
<td>20 keV</td>
<td>20 keV</td>
<td>FWHM</td>
</tr>
</tbody>
</table>

But it should be noted that \( Z' = 3 \times 10^{-4} \, \Omega/\lambda \)!
Second Example: Photonic Band Gap Structures

\[ \epsilon_r = 2.13 \] (Silica)
\[ \text{DIA} = 1.4\lambda \]
\[ Z_c = 19.5\Omega \]
\[ \beta_g = 0.58 \]


- Can be designed to support a single, confined, synchronous mode
- All other modes at all other frequencies radiate strongly

\[ Z_c = \frac{|E_{\text{acc}}|^2 \lambda^2}{2P} \]

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2D Photonic Band Gap Structures

This geometry is designed for the lithographic process.

$\varepsilon_r = 12.1$
(Silicon)

Ben Cowan, ARDB, SLAC

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Impedance and Gradient Optimization

PC Waveguide Shunt Impedance for SOL Modes

\[ Z_c \sim \left( \frac{w}{\lambda} \right)^{-3.55} \]

Damage Factor vs. Pad and Guide Widths

Maximum Accelerating Gradient for 25 mm Segment

Ben Cowan, ARDB, SLAC
July 21, 2003
This geometry is designed for the fiber drawing process.

Mehdi Javanmard, ARDB, SLAC
July 21, 2003
Fabricated Examples


PCF structures vary according to application: (a) highly nonlinear fiber; (b) endlessly single-mode fiber; (c) polarization maintaining fiber; (d) high NA fiber. From René Engel Kristiansen (Crystal Fibre A/S), “Guiding Light with Holey Fibers,” OE Magazine June 2002, p. 25.
Hollow Fiber Bragg Accelerator

# Concentric layers \((\varepsilon_1, \varepsilon_2)\)

# Each layer \(\mathbf{n} \cdot \frac{\lambda}{4\sqrt{\varepsilon} - 1}\)

# \(v_{ph} = c\)

\[
R_{\text{int}} = 0.3 \lambda_0
\]

\[
R_{\text{int}} = 0.8 \lambda_0
\]

Levi Schächter, The Technion
Towards a Laser Linear Collider
Emittance and Beam Transport

If $a$ is the beam hole radius, the acceptance is

$$A = \frac{a^2}{\beta_{\text{max}}} = n \frac{\varepsilon_l}{\gamma}$$

$n \equiv$ clearance $= 25$ for $5\sigma$ beam

For a quad of length $l$ and gradient $G$

$$\varepsilon_l = \frac{a^2 eG l}{n} \frac{\cos \varphi}{2mc \left(1 + \sin \varphi\right)}$$

Example

$$G = 2.5kT/m; l = 1.0\, \text{cm}; \gamma = 2 \times 10^4 \implies f = 1.36m$$

$$\varphi = 45^\circ \implies L = 1.93m$$

$$a = 1.2\lambda = 2.4\, \mu\text{m}; n = 25 \implies \varepsilon_l = 7 \times 10^{-4} \pi \, \text{mm-mr}$$

R. Siemann, ARDB
While $\varepsilon_N = 7 \times 10^{-4} \pi \text{ mm-mr}$ is a very small emittance, the phase space density $Q/\varepsilon_N = 5 \times 10^5 e / 7 \times 10^{-4} = 0.12 \text{ nC/mm-mr}$, an order of magnitude lower than the phase space densities demonstrated by rf photoinjectors now.

First pass PARMELA simulations show this emittance is not unreasonable.
First-Pass Luminosity Calculation

\[ P_b = (nN) f_r \gamma mc^2 \]

\[ N_\gamma = 2.12 \frac{\alpha r_e (nN)}{\sigma_x + \sigma_y} \]

\[ L \propto \frac{N_\gamma P_b}{\gamma \sigma_y \left(1 + \sigma_y / \sigma_x\right)} \]

\[ \xi_1 = \frac{2r_e^2 N_\gamma}{\alpha \sigma_z \left(\sigma_x + \sigma_y\right)} \]

- Optical bunching within the short macropulses must be destroyed, otherwise beamstrahlung is unacceptably high. Can do this after acceleration with small \( R_{56} \).

**E_{CM} = 500 GeV**

<table>
<thead>
<tr>
<th>Laser</th>
<th>JLC/NLC</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>5\times10^6</td>
</tr>
<tr>
<td>( f_c )</td>
<td>50MHz</td>
</tr>
<tr>
<td>( P_b ) (MW)</td>
<td>10</td>
</tr>
<tr>
<td>( \sigma_x / \sigma_y ) (nm)</td>
<td>0.5/0.5</td>
</tr>
<tr>
<td>( N_\gamma )</td>
<td>0.22</td>
</tr>
<tr>
<td>( \sigma_z ) (( \mu )m)</td>
<td>120</td>
</tr>
<tr>
<td>( \sigma_z/c ) (psec)</td>
<td>0.4</td>
</tr>
<tr>
<td>( \xi_1 )</td>
<td>0.045</td>
</tr>
<tr>
<td>( L )</td>
<td>( 1\times10^{34} )</td>
</tr>
</tbody>
</table>

R. Siemann, ARDB

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Laser Linear Collider Cartoon

CW Injector
- Warm rf gun
- Cold Preaccelerator
- Optical Buncher
- 433 MHz x 5E05 e⁻/macropulse (600 μpulse/macropulse)
- ε_N~10⁻¹¹ m (but note Q/ε_N ~ 1 μm/nC)

Laser Accelerator
- λ=1-2 μ, G~1 GeV/m
- Photonic Band Gap Fiber structures embedded in optical resonant rings
- Permanent Magnet Quads (B’~2.5 kT/m)

An Acceleration Unit
- Resonant ring path length: λ_{rf}=23 cm
- Laser amplifier
- Optical resonator
- PBG accelerator structure

Optical Debuncher
- Final Focus I.P.
Experimental Efforts in Vacuum Laser Acceleration
The Inverse Free Electron Laser

STELLA (Staged Electron Laser Acceleration) experiment at the BNL ATF
(STI Optronics/Brookhaven/Stanford/U. Washington)

Multicell Linear Acceleration Experiments

**Multiple ITR Accelerators**
Y.-C. Huang, NTHU, Taiwan (at Brookhaven)

Expected gain: 250 keV over 24cm.

**Inverse Cerenkov Acceleration in Waveguide**
(Unfolded Fabry-Perot Interferometer)
A. Melissinos, R. Tikhoplav (U. Rochester, Fermilab)

Status: Structure has been fabricated with 80% power transmission measured. Nd:YAG drive laser is under construction at Fermilab now.
The LEAP Accelerator Cell
“Laser Electron Acceleration Project”
Stanford University (Appl Phys. & HEPL) / SLAC

crossed laser beams

High Reflectance Dielectric coated surfaces

Accelerator cell

Computed Field Intensity, $|E|^2$

Fused silica prisms and flats

~1 cm
The LEAP Accelerator Cell
The LEAP Experimental Setup

Diagnostics:
- spatial monitor
- streak camera

Electron beam

Vacuum chamber

Camera

doped YAG screen

Image intensified camera

spectrometer magnet

~ 1 m

~ 1 cm

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Precision Low-Charge Spectrometry

2 keV ($1:10^4$) resolution spectrometry with sub-picoCoulomb beams

Ce:YAG scintillator, ICCD
Timing Diagnostics
Three separate systems used, depending on circumstances

1. Coarse Timing (~1 nanosecond scale)
   PMT watches for bremsstrahlung x-rays from the beam
   Photodiode watches the laser
   → signals summed and transmitted on common cable; scope observation

2. Fine Timing (~5 picosecond resolution; relative, nondestructive)
   Rf cavity samples 11.8 MHz beam at 238th harmonic (2.812 GHz)
   Photodiode observes laser (82.7 MHz), generate 34th harmonic (2.812 GHz)
   → Phase comparison at 2.812 GHz, signal chopped at ~12 kHz and synchronously detected

3. Fine Timing (~50 picosecond resolution; absolute, destructive)
   Aerogel cell generates Cerenkov radiation from single e- pulse
   Laser passes through optically transmissive Cerenkov cell
   → C1587 Streak Camera (Γt=2 psec) observes both signals
Laser and Electron Beam
Timing and Position Overlap Diagnostics

- intensified gain camera
- XYBION 1SG350-U-E
- streak camera
- HAMAMATSU C-1587
- Cerenkov cell
- electron beam
- pellicle YAG screen holder
- tilt stage
E163: Laser Acceleration of Electrons at the NLCTA

- Create an extraction line in a separate hall attached to the NLCTA to test candidate laser acceleration structures
  - Phase I: Install the LEAP Crossed-Gaussian accelerator, commission the beamline, and complete the physics study of interferometric (ITR) acceleration
  - Phase II: Install an IFEL prebuncher, and conduct the first acceleration experiments, using the LEAP cell, or candidate single-cell PBG structures
    → With the completion of Phase II, the facility will then host the world’s highest brightness 0.8 μm electron injector
  - Phase III: Test multicell PBG structures
# Experimental Requirements

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Comment</th>
<th>Present Values</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Electron Beam Properties</strong></td>
<td></td>
<td></td>
<td>at HEPL</td>
</tr>
<tr>
<td>Bunch Charge</td>
<td>50 pC</td>
<td></td>
<td>5 pC</td>
</tr>
<tr>
<td>Beam Energy</td>
<td>60 MeV</td>
<td></td>
<td>28 MeV</td>
</tr>
<tr>
<td>Transverse Emittance</td>
<td>&lt; 2.5 π mm-mr</td>
<td>Normalized</td>
<td>10 π mm-mr</td>
</tr>
<tr>
<td>Bunch Length</td>
<td>&lt; 5 ps</td>
<td>FWHM</td>
<td>~5 ps</td>
</tr>
<tr>
<td>Energy Spread</td>
<td>&lt; 20 keV</td>
<td>FWHM</td>
<td>~20 keV</td>
</tr>
<tr>
<td>Pulse Repetition Rate</td>
<td>10 Hz</td>
<td></td>
<td>10 Hz</td>
</tr>
<tr>
<td><strong>Laser Beam Properties (for experiment)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pulse Energy</td>
<td>1 mJ</td>
<td></td>
<td>1 mJ</td>
</tr>
<tr>
<td>Pulse Wavelength</td>
<td>800 nm</td>
<td></td>
<td>800 nm</td>
</tr>
<tr>
<td>Pulse Length</td>
<td>0.1-10 ps</td>
<td>FWHM, variable</td>
<td>1.0-10 ps</td>
</tr>
<tr>
<td>Pulse Repetition Rate</td>
<td>10 Hz</td>
<td></td>
<td>10 Hz</td>
</tr>
<tr>
<td>Timing jitter w.r.t. electron beam</td>
<td>&lt; 1 ps</td>
<td></td>
<td>&lt;3 ps</td>
</tr>
</tbody>
</table>
E163 End-to-end Simulation

Electron generation and acceleration to 32.5 MeV: Parmela (UCLA/SLAC)

Electron transport through 2nd accelerator, chicane, dogleg, energy scraper: Elegant 14.6β2, with accelerator structure and collimator wakefields from analytic treatment in the NLC-ZDR, and initial magnet settings from 2nd-Order Transport optimization.

IFEL Interaction and Laser Acceleration: Genesis 1.3 (modified), Matlab Code

Remainder of Transport: Elegant 14.6β2
The LEAP Experimental Setup

- Camera
- Electron beam
- Vacuum chamber
- Doped YAG screen
- Diagnostics: spatial monitor, streak camera
- Image intensified camera
- Spectrometer magnet
- ~ 1 m
- ~ 1 cm

July 21, 2003
Anticipated Experimental Conditions

FIGURE 14. Null interaction time scan data sets: (left) with no collimation or charge thresholding, (center) with collimation only, and (right) with collimation and thresholding. Note that intensity per pixel has decreased an order of magnitude, but probe electron bunch has well defined energy characteristics. Bunch parameters and jitter are as in figures 12 and 13 above, but no laser interaction is present.

JITTERS ASSUMED: 5% Charge, 1% RF amplitude, 1 psec RF phase. (RMS).

July 21, 2003
Energy Collimator Installed at LEAP
Results from Last LEAP Run (June 2002)

July 21, 2003
FIGURE 12. Simulated time scan data set (left), and comparison energy profiles for laser at full overlap (red) and out of time (blue), on an expanded scale. The relative timing between laser and electron bunch is swept from $-5$ psec to $+5$ psec, with optimum overlap occurring at 0 psec (image #101). The laser pulse length is 5.0 ps FWHM, the laser-induced energy modulation amplitude is $\pm 20$ kV.

JITTER ASSUMED: 5% Charge, 1% RF amplitude, 1 psec RF phase. (RMS).
FIGURE 16. Charge density (left), simulated phase scan with jitter added (center), covering $10\pi$ of variation in the relative phase between IFEL and laser accelerator, and averaged spectra (right) at (1) bunching, (2) decelerating, (3) debunching, and (4) accelerating phase.

**JITTER ASSUMED:** 1% RF amplitude, 1 psec RF phase, 5% Charge. (RMS).

July 21, 2003
E163 Lattice Error Sensitivity

Integrated laser kick to probe bunch (normalized)

Nominal Interaction Strength

Elegant Error Analysis
k: 1.0%
a: 0.5%

Probability that performance is 75% of design or better: 34.7%

\[ F = \sum_{i=1}^{N} |\delta V_i| \]
E163 Enclosure
7/16/03

↑ Entrance labyrinth
Inside →
Outside →
Technical Roadmap

LEAP
1. Demonstrate the physics of laser acceleration in dielectric structures
2. Develop experimental techniques for handling and diagnosing picoCoulomb beams on picosecond timescales
3. Develop simple lithographic structures and test with beam

E163
Phase I. Characterize laser/electron energy exchange in vacuum
Phase II. Demonstrate optical bunching and acceleration
Phase III. Test multicell lithographically produced structures

Now and Future
1. Demonstrate carrier-phase lock of ultrafast lasers [NIST, Stanford]
2. Continue development of highly efficient DPSS-pumped broadband mode- and carrier-locked lasers [DARPA Proposal, SBIR Solicitation]
3. Devise power-efficient lithographic structures [SBIR Solicitation]
4. Devise stabilization and timing systems for large-scale machine [LIGO]
5. Much more!
High Average Power Diode Pumped Solid State Lasers

Stanford University (SPRC)

Power Scaling with high spectral and spatial coherence

Research Objectives:
• to improve the efficiency of diode pumped solid state lasers such as in-band pumping, reduction of loss in the laser materials, improved pumped efficiency, and operation of phased array spatial mode lasers.

• to scale the average power while maintaining coherence by extending the master oscillator, power amplifier approach to encompass cw, energy storage, and ultrafast pulse format operation.

Stanford Research Program (DARPA)

A. High Average Power CW Lasers
B. High energy Yb:YAG lasers for Remote Sensing
C. High average power ultrafast lasers
D. Optical damage and plasma studies with ultrafast lasers
Rapid, market-driven development has pushed lasers into competitive standing with microwave tubes with regard to average power, efficiency, and control, but with peak powers and field strengths that are vastly superior.

Efficient power coupling between optical fields and beam must be demonstrated in an energy- and economically-scalable structure

- **LEAP, E163, and the follow-on ORION VLA program**

Continued laser development to produce lasers with **all** properties matched to accelerator requirements is needed

- **DARPA-funded program at Stanford**

Continued work on higher damage threshold, linear materials is highly desirable

- **SPRC work on damage studies and optical ceramics**
“One of the authors (W.W.H.), in his study of cavity resonators, was motivated by a desire to find a cheap method of obtaining high energy electrons. This cavity acceleration work was put aside, largely because of the change in standard of success caused by the advent of Kerst’s betatron. . .

. . .By the end of the war many people were interested [in linear acceleration], possible reasons being: (a) wide-spread knowledge of cavity properties and technique, (b) the enormous pulsed powers made available by radar developments.”