2006 Advanced Accelerator Conference
Lake Geneva, Michigan, July 14 2006

Structure Loaded Vacuum Laser-Driven Particle Acceleration Experiments at SLAC

"…the LEAP – E163 experiment"

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1 Stanford University
2 ARDB group , SLAC

Principal investigators: R.L. Byer and R.H. Siemann

About this talk

This talk will cover

1. **A brief overview about our research and objectives**
2. A brief summary of the proof-of-principle demonstration for laser-driven particle acceleration in a semi-infinite vacuum space
3. A description of the continuation of experiments with laser-driven particle acceleration in a semi-infinite vacuum space.
4. An overview of the buncher-accelerator two-stage experiment
5. A narrative of the work on photonic bandgap microstructures for laser acceleration

Overview of our research

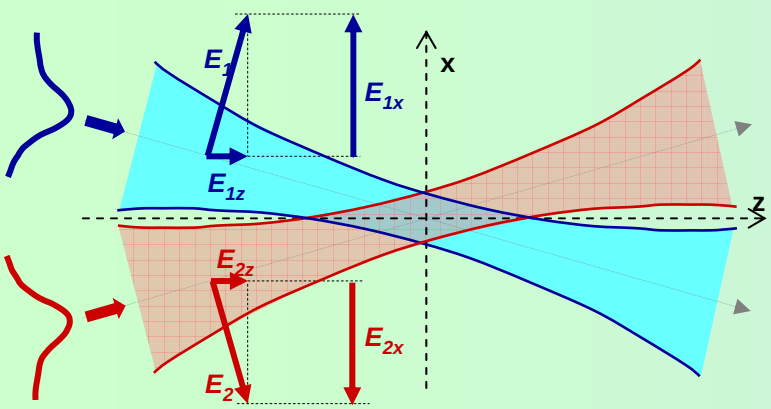
"**LEAP**" = **L**aser – **E**lectron **A**ccelerator **P**roject

Our primary objective:

To investigate and develop structure loaded vacuum laser-driven particle acceleration concepts

Our main research directions

I. Crossed laser beams in a structure loaded vacuum



$$E_z = -\underbrace{\frac{2E_0 \sin\theta}{(1+\hat{z}^2\cos^2\theta)^{3/2}} \exp\left[-\frac{\left(\hat{z}/\theta_d\right)^2 \sin^2\theta}{1+\hat{z}^2\cos^2\theta}\right]}_{\text{Magnitude}} \times \underbrace{\cos\psi_t}_{\text{Phase}}$$

$$\psi_t = \underbrace{k\cdot z\cdot\cos\theta - \omega\cdot t}_{\text{Plane Wave Phase}} + \underbrace{\frac{\hat{z}^3\cos^3\theta\cdot\tan^2\theta}{\theta_d^{\,2}\left(1+\hat{z}^2\cos^2\theta\right)}}_{\text{Math}} \underbrace{-2\cdot\tan^{-1}\left(\hat{z}\cos\theta\right)}_{\text{Gouy Phase}} + \phi_0$$

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

†P. Sprangle, E. Esarey, J. Krall, A. Ting, Laser Acceleration of Electrons in Vacuum, Optics Comm. 124 (1996) 69

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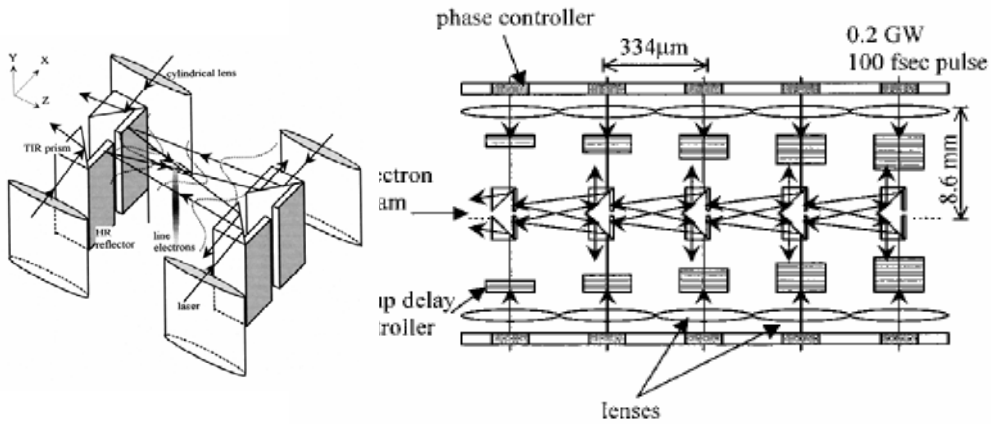
1995: proposed 1 GeV/m structure



- possible to fabricate
- could be powered with tabletop lasers

Y.C. Huang, et al, Appl. Phys. Lett. 68 (6) (1996) 753.

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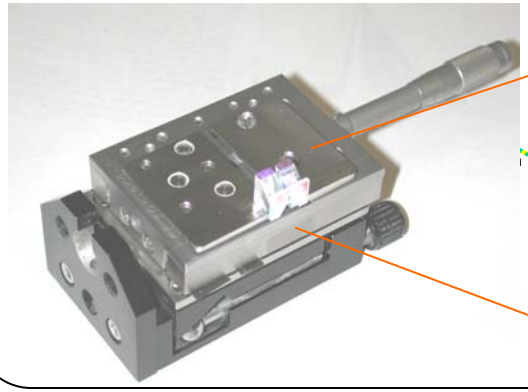
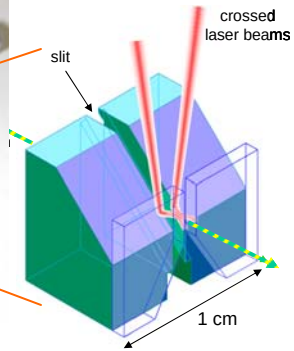
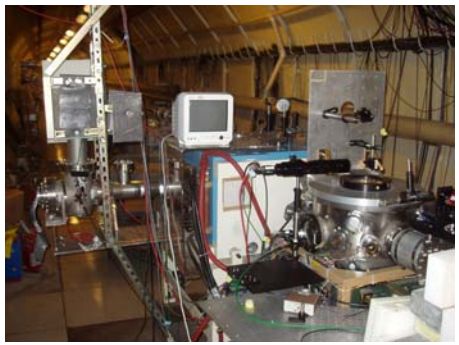
1997-2002: the single-cell x-laser beam accelerator experiment







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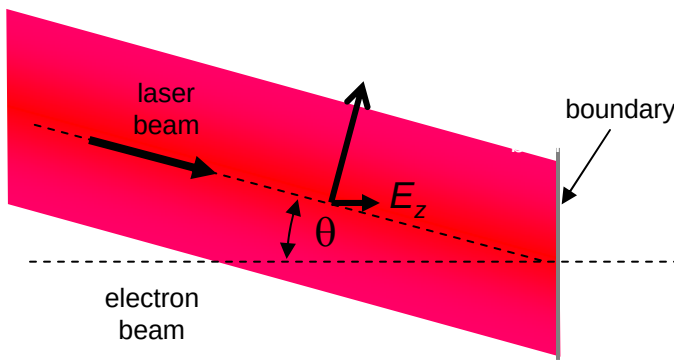
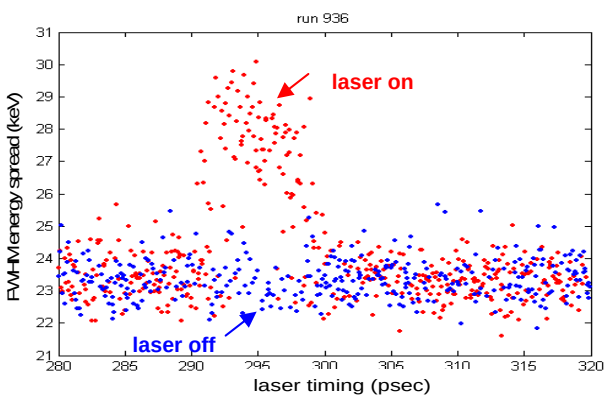
II. Single laser beam semi-infinite vacuum acceleration

2004: The successful proof-of-principle demonstration





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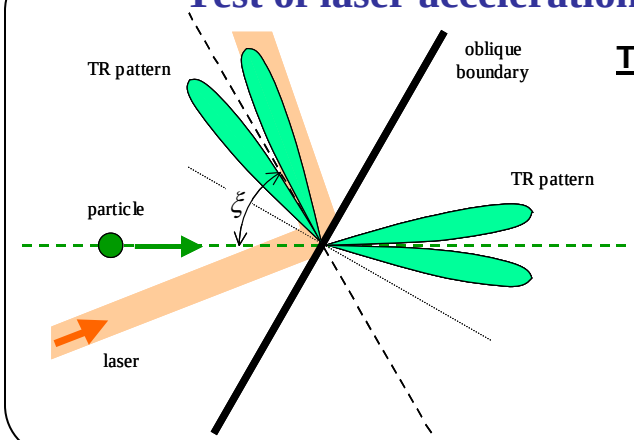
III. Further semi-infinite vacuum acceleration experiments

Test of laser acceleration as an inverse-radiation process



Test of different boundary conditions

- oblique orientation
- reflective
- absorptive
- transparent
- rough surfaces

$$\int_P \vec{E}_{laser} \cdot d\vec{x} \stackrel{?}{=} \oint_S \vec{E}_{laser} \cdot \vec{E}_{rad} \quad ds$$

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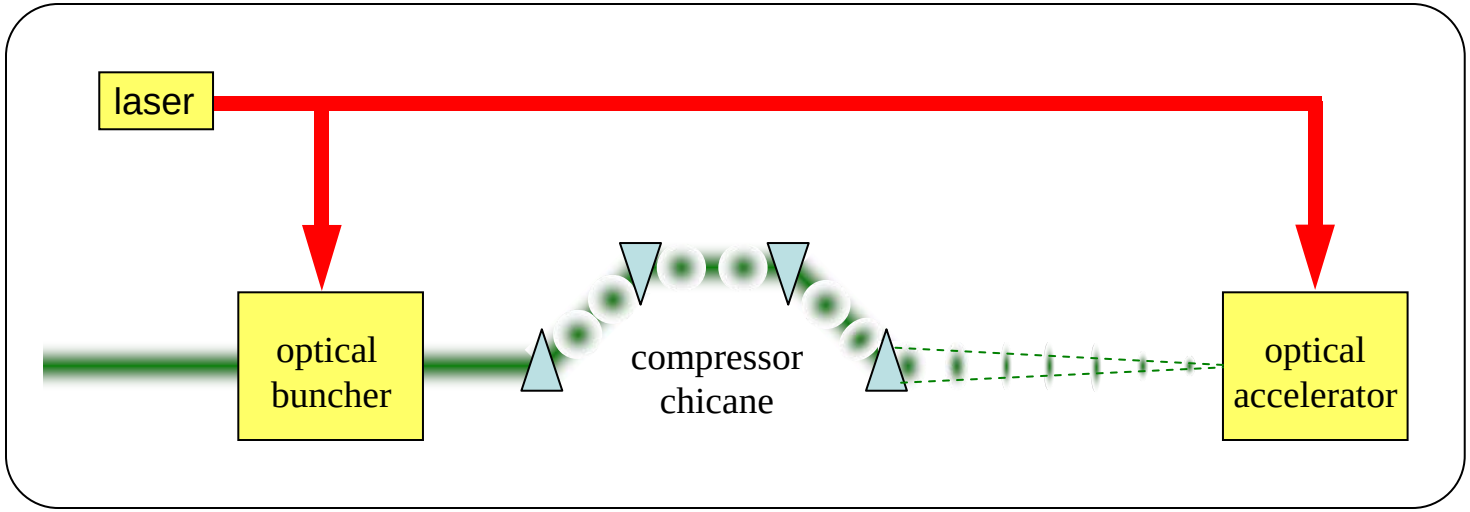
Our main research directions

IV. The buncher-accelerator two-stage experiment at λ=800 nm



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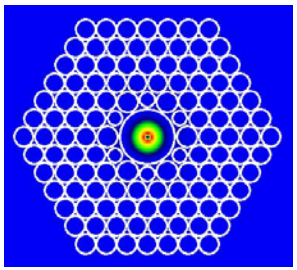
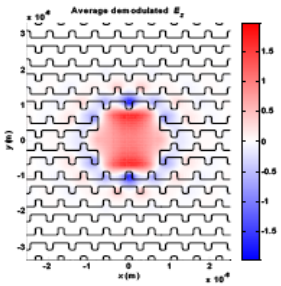
V. Ongoing work on photonic bandgap accelerator structures

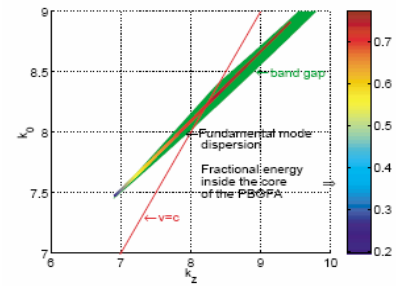
Initial stage of research and development



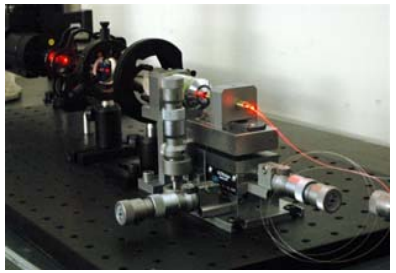
Field in a hollow core fiber



A 3-D PBG structure



Dispersion graph of trapped modes



Fiber accelerator test setup

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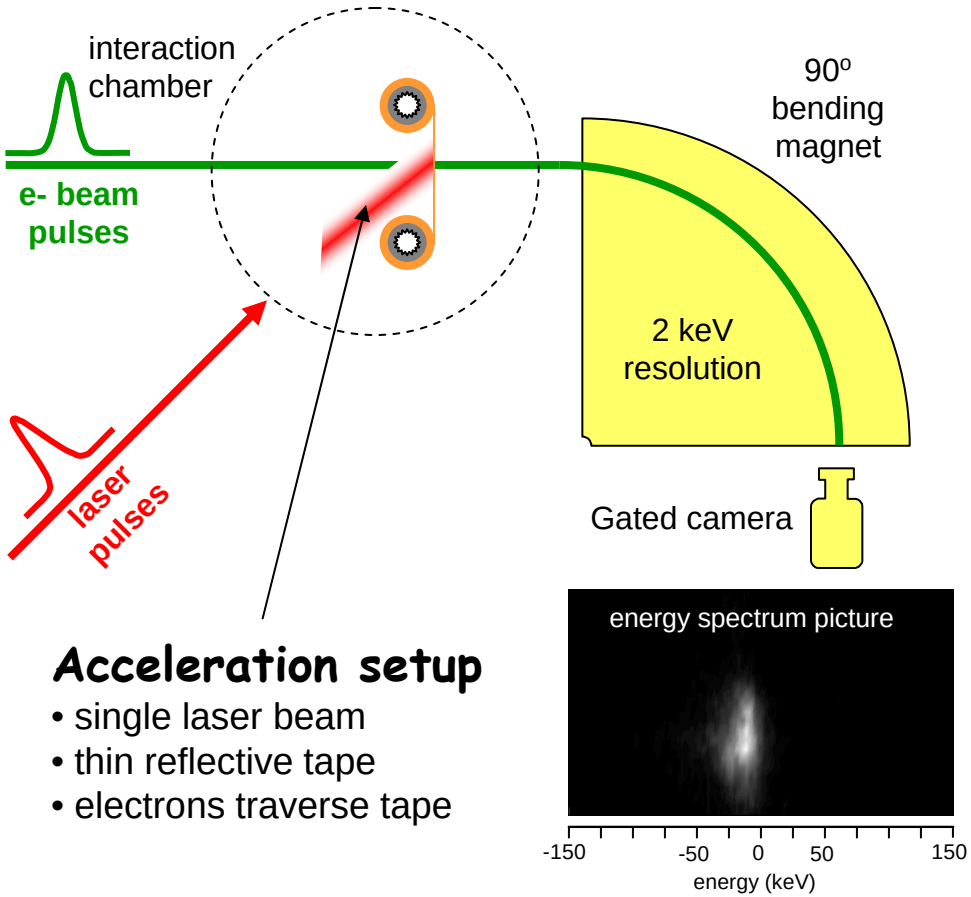
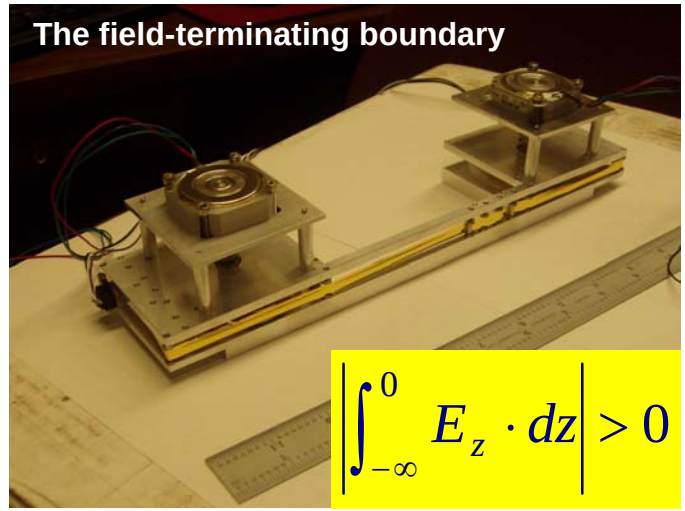
The proof-of-principle experiment

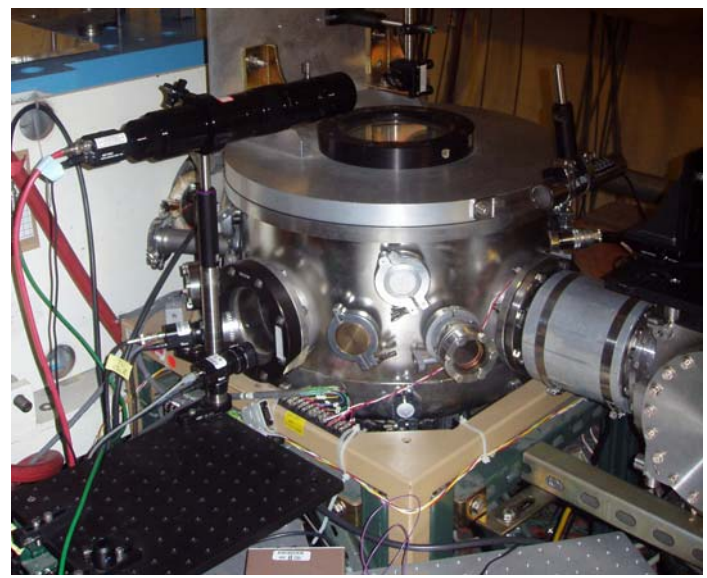
Demonstration of linear acceleration of relativistic electrons from a single laser beam in a semi-infinite vacuum



Acceleration setup

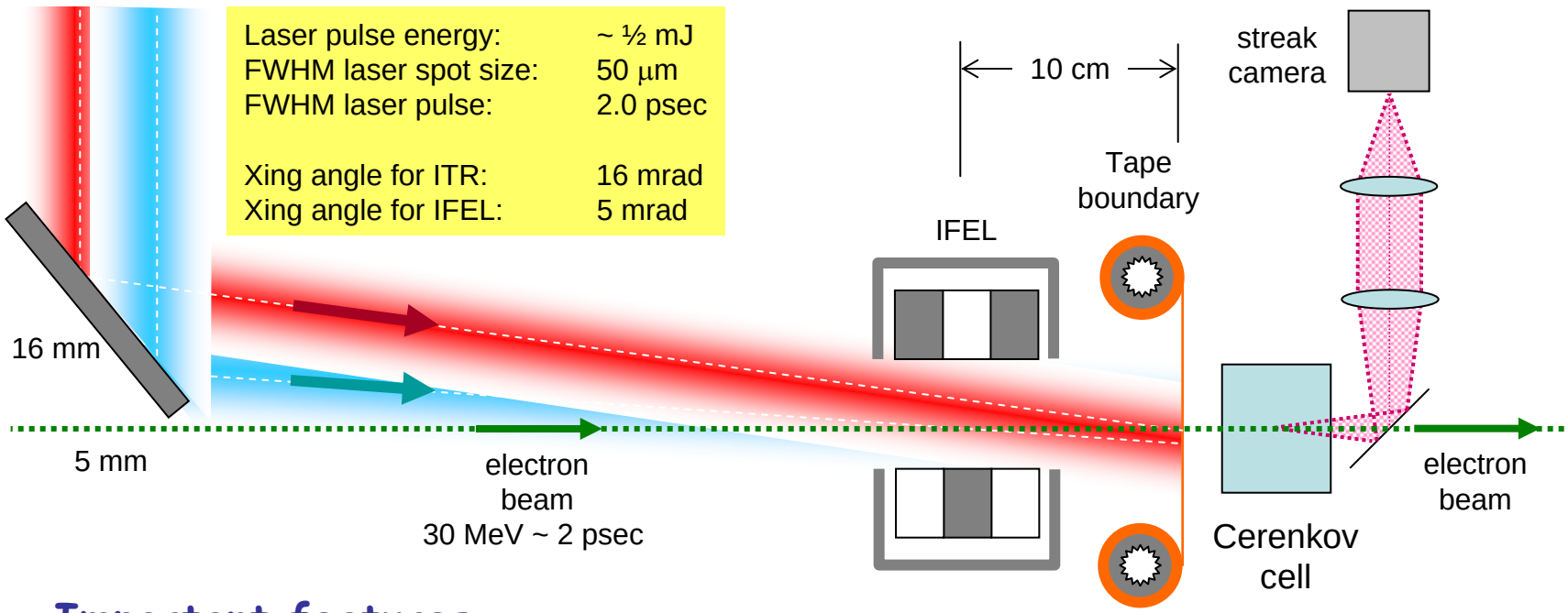
- single laser beam
- thin reflective tape
- electrons traverse tape





The proof-of-principle experiment

Schematic of the setup

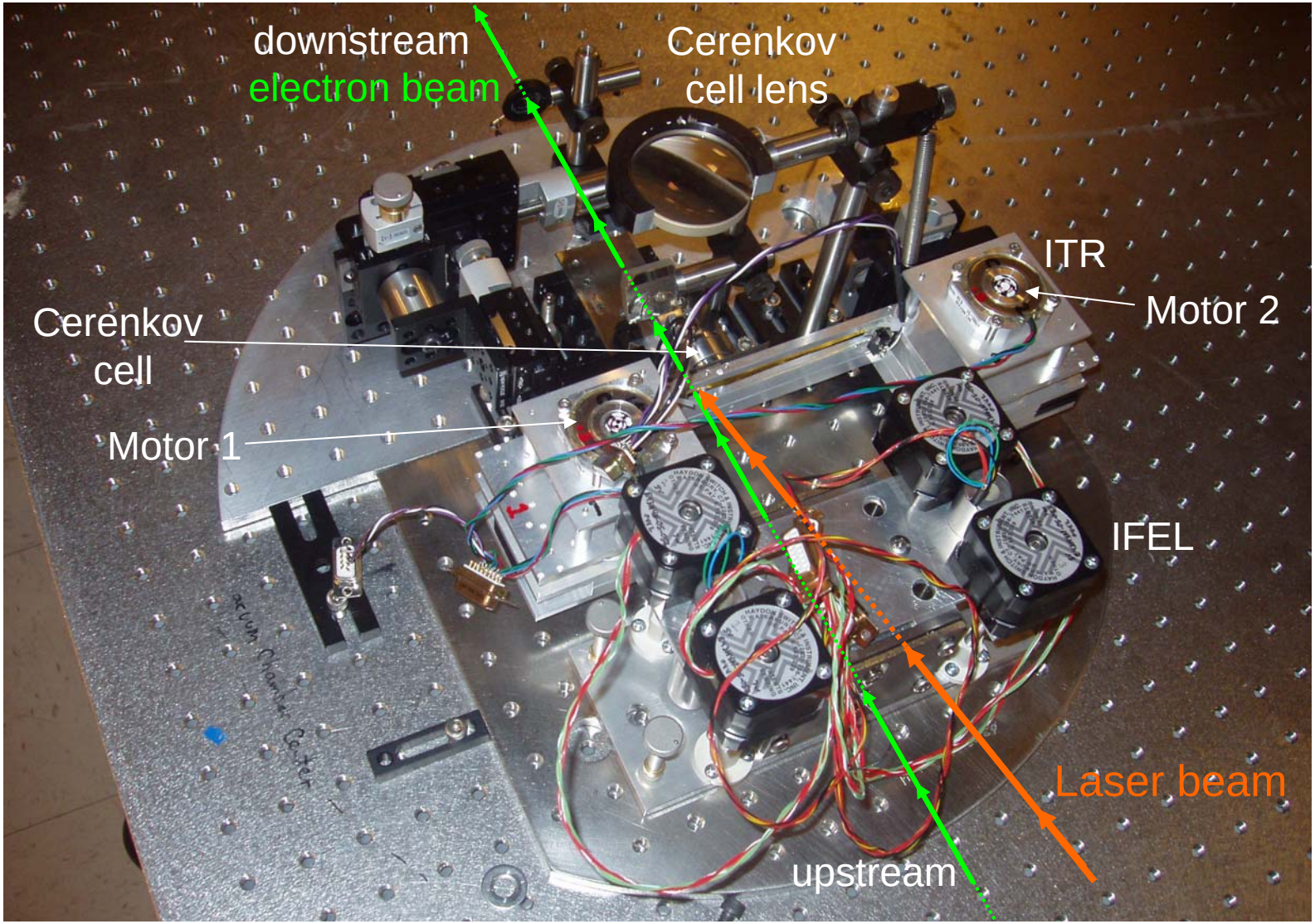


Important features

- coarse timing of the laser with respect to the electron beam from a Cerenkov cell singal
- two distinct operation modes: ITR and IFEL
- laser and electron beams cannot be simultaneously aligned for both the IFEL and the tape
- IFEL and ITR timing conditions are almost identical (within few psec)
- the IFEL produces a larger and easier to detect signal
- once correct laser timing is found laser beam is re-aligned for ITR operation

The proof-of-principle experiment

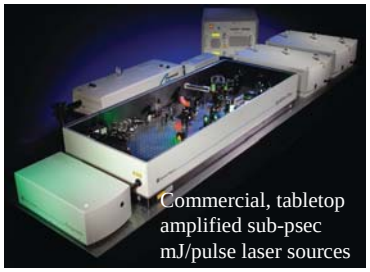
Birdseye view of the setup

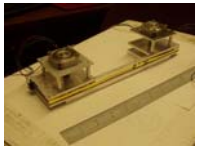


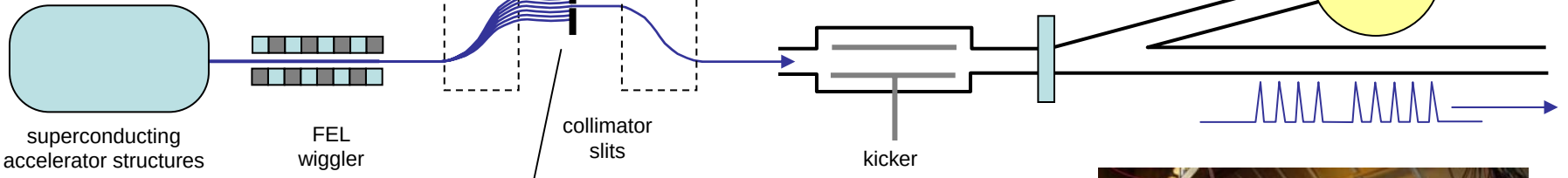
The proof-of-principle experiment

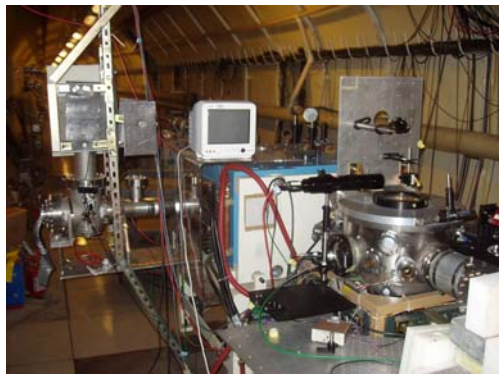
The SCA-FEL facility

SCA beam parameters	
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



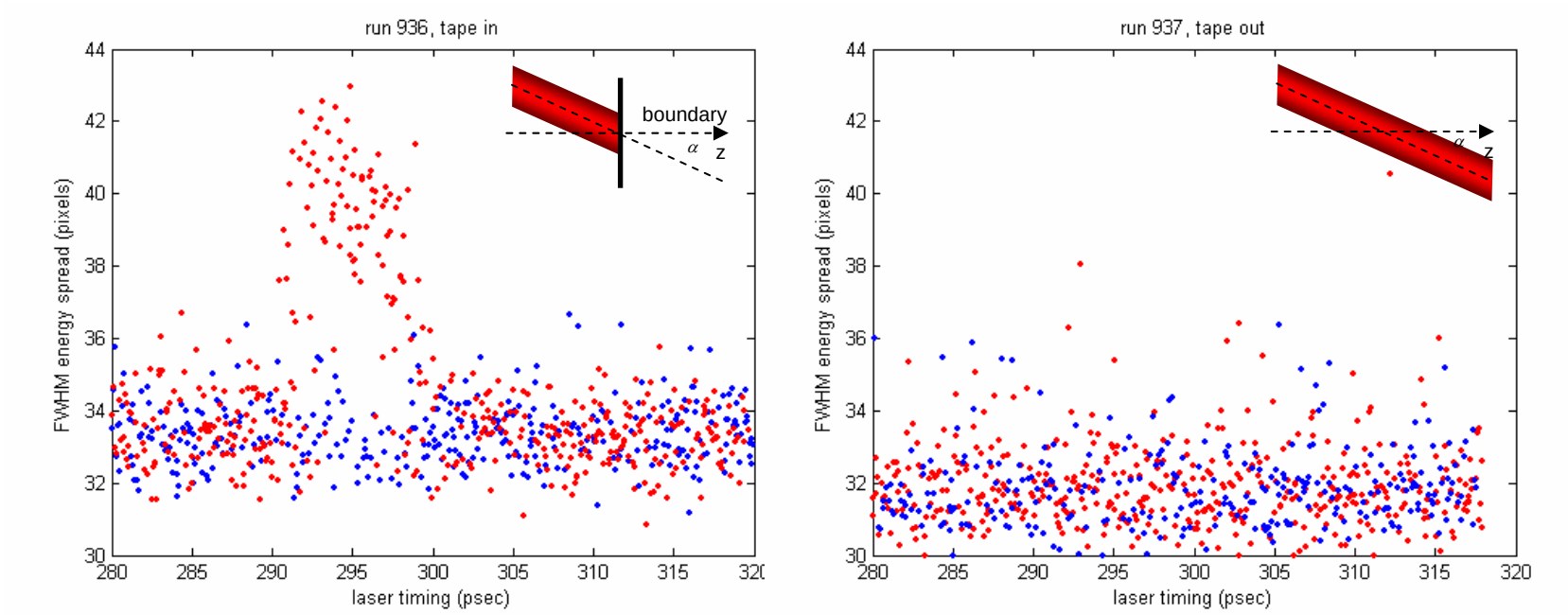






The proof-of-principle experiment

The effect of the boundary



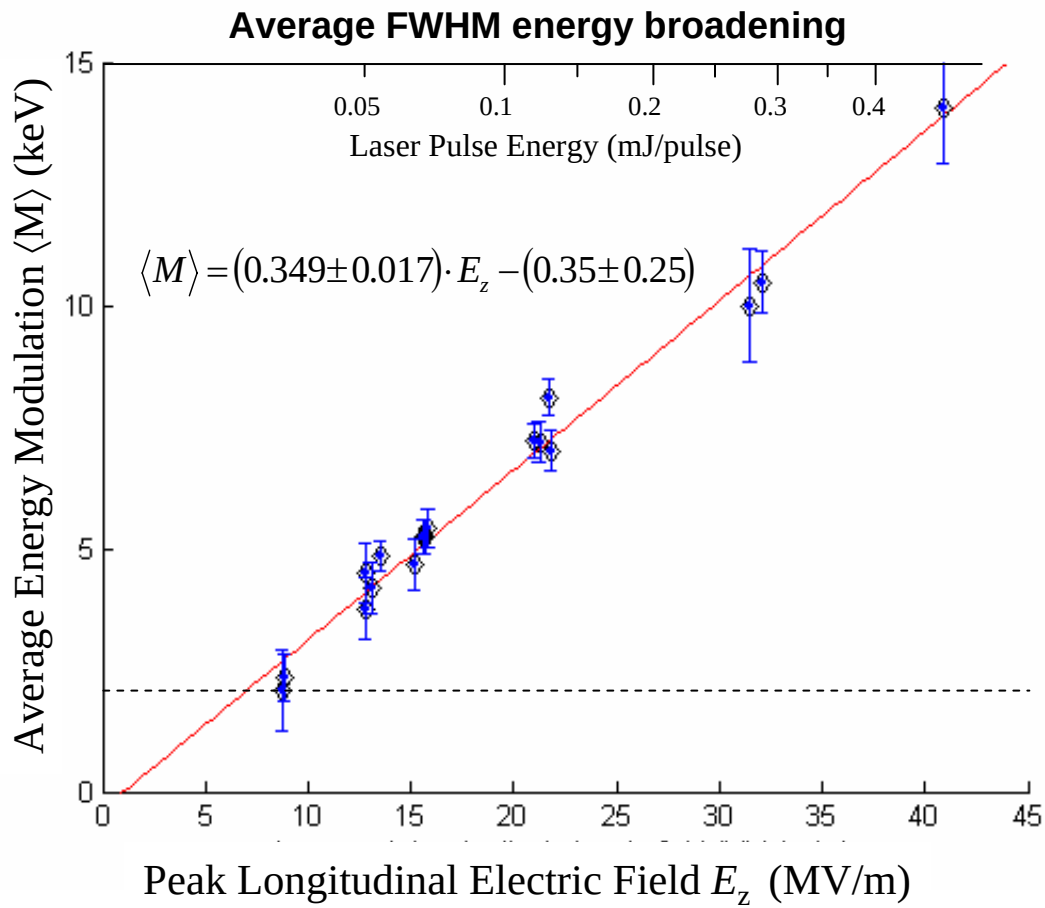
This confirms:

1. The Lawson-Woodward Theorem
2. No interaction from the IFEL

The proof-of-principle experiment

The dependence on the laser electric field amplitude

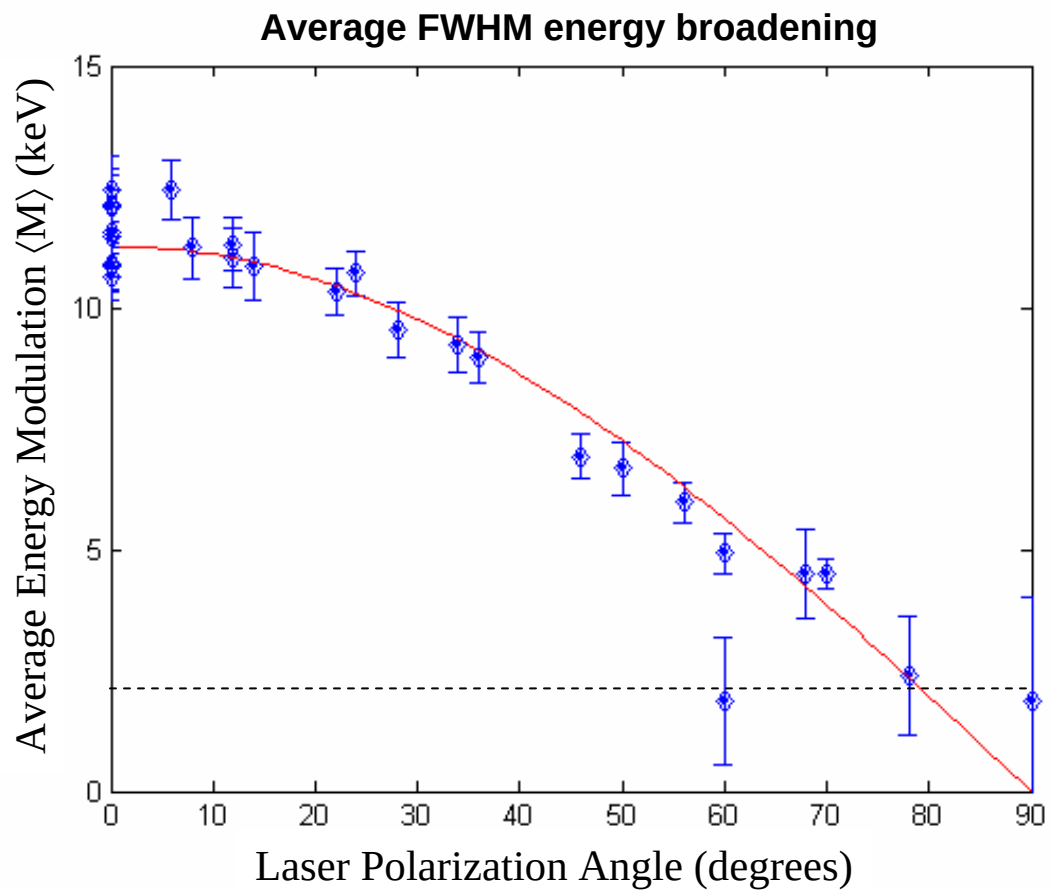
$$|U| \propto |E|_{laser}$$



The proof-of-principle experiment

The dependence on the laser electric field polarization

$$|U| \propto |\cos\phi|$$



T. Plettner, R.L. Byer, E. Colby, B. Cowan, C.M.S. Sears, J. E. Spencer, R.H. Siemann, "Proof-of-principle experiment for laser-driven acceleration of relativistic electrons in a semi-infinite vacuum", Phys. Rev. ST Accel. Beams 8, 121301 (2005)

IFEL Experiments at λ=800 nm

(graduate student C. M. Sears)

PRL **95,** 194801 (2005) PHYSICAL REVIEW LETTERS week ending 4 NOVEMBER 2005

High-Harmonic Inverse-Free-Electron-Laser Interaction at 800 nm

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

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

Cross-correlation in time

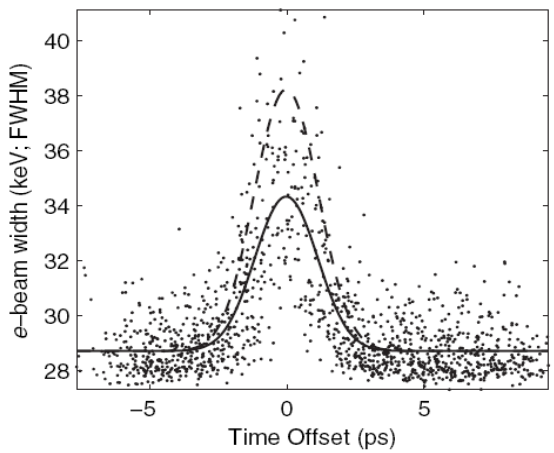


FIG. 2. Example data run with 1500 laser on events. The solid curve is the least squares fit to all data points and gives the mean interaction of 18 keV. The dashed curve is the maximum estimate and gives the peak interaction of 25 keV. The width of cross correlation is 2.2 ps rms.

Observation of harmonic interaction

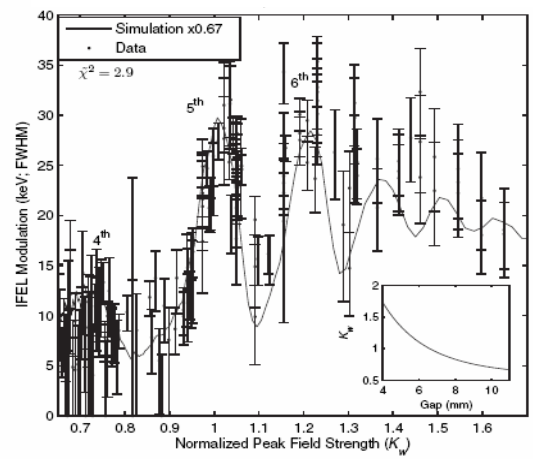


FIG. 4. IFEL gap scan data, with 164 runs total. Comparison to simulation (solid line) shows very good agreement to the shape and spacing of resonance peaks. The harmonic numbers are given next to each peak. Simulation has been rescaled vertically by 0.67 to better visualize overlap.

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Further semi-infinite vacuum acceleration experiments

A set of experiments that complement the initial proof-of-principle demonstration

- infinite flat boundary: very simple geometry
- ideal setting for a set of physics tests of laser-particle interaction
- direct test of the concept of laser-acceleration as an inverse-radiation process

$$\int_P \vec{E}_{laser} \cdot d\vec{x} \overset{?}{=} \oint_S \vec{E}_{laser} \cdot \vec{E}_{rad} \quad ds$$

- test of Inverse-transition radiation picture versus electric field path integral picture
  - o laser-electron-boundary angular dependence
  - o boundary type: transparent, reflective, absorptive, rough
- test of rare situations not applicable to this equivalence picture

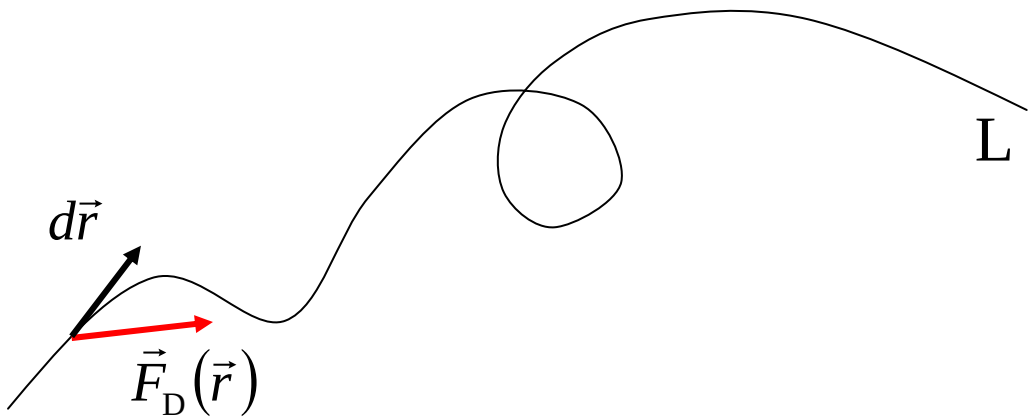
---

1. M. Xie, Proceedings of the 2003 Particle Accelerator Conference (2003)
2. Z. Huang, G. Stupakov and M. Zolotorev , “Calculation and Optimization of Laser Acceleration in Vacuum”, Phys. Rev. Special Topics - Accelerators and Beams, Vol. 7, 011302 (2004)

Further semi-infinite vacuum acceleration experiments

The Path Integral Method (PIM)

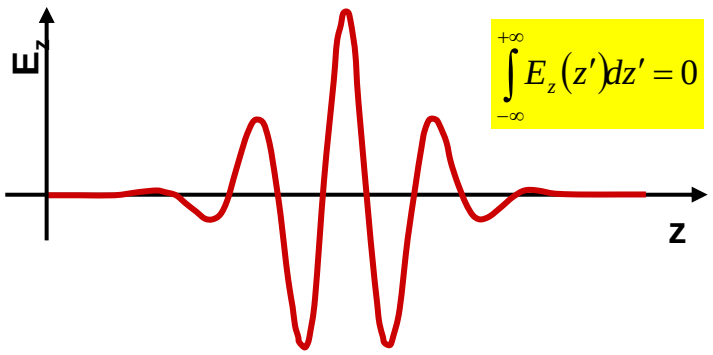
The mechanical work of the driving field on a charged particle is simply the path integral of its corresponding force



$$\Delta U_{\mathrm{P}} = \int_{\mathrm{L}} \vec{F}_{\mathrm{D}}(\vec{r}) \cdot d\vec{r} = q \int_{\mathrm{L}} \vec{E}_{\mathrm{D}}(\vec{r}) \cdot d\vec{r}$$

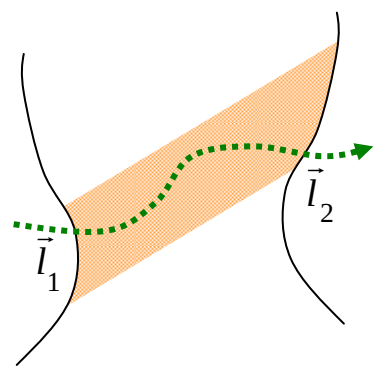
Further semi-infinite vacuum acceleration experiments

The Lawson-Woodward Theorem



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

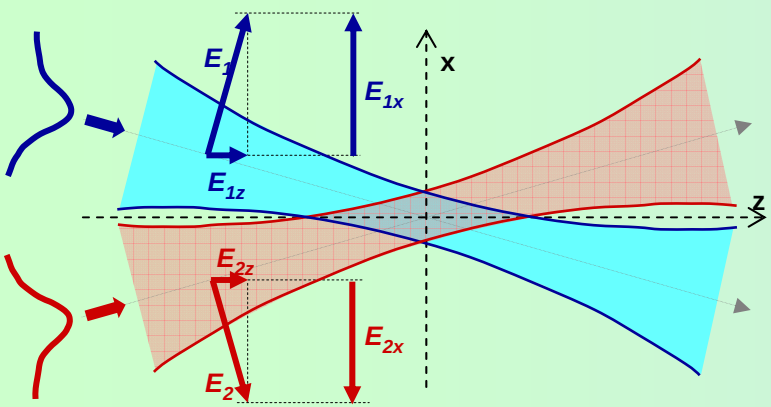
Limit the laser-electron interaction



$$\int_{\vec{l}_1}^{\vec{l}_2} \vec{E}(\vec{r}) \cdot d\vec{r} \neq 0$$

no knowledge of the properties of the boundary

crossed gaussian beams



$$E_z = \underbrace{-\frac{2E_0 \sin\theta}{(1+\hat{z}^2\cos^2\theta)^{3/2}} \exp\left[-\frac{\left(\hat{z}/\theta_d\right)^2 \sin^2\theta}{1+\hat{z}^2\cos^2\theta}\right]}_{\text{Magnitude}} \times \underbrace{\cos\psi_t}_{\text{Phase}}$$

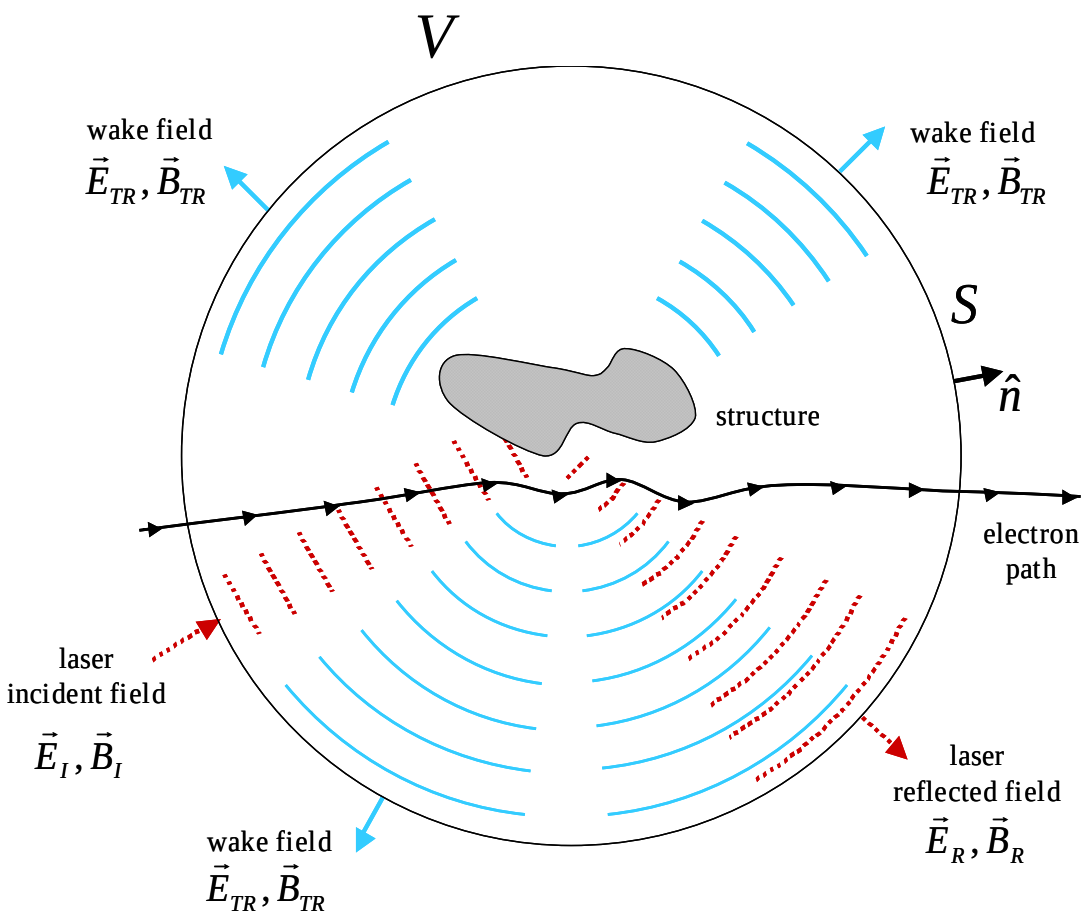
$$\psi_t = \underbrace{k \cdot z \cdot \cos\theta - \omega \cdot t}_{\text{Plane Wave Phase}} + \underbrace{\frac{\hat{z}^3 \cos^3\theta \cdot \tan^2\theta}{\theta_d^{\,2}\left(1+\hat{z}^2\cos^2\theta\right)}}_{\text{Math}} \underbrace{- 2 \cdot \tan^{-1}(\hat{z}\cos\theta) + \phi_0}_{\text{Gouy Phase}}$$

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

†P. Sprangle, E. Esarey, J. Krall, A. Ting, Laser Acceleration of Electrons in Vacuum, Optics Comm. 124 (1996) 69

Further semi-infinite vacuum acceleration experiments

The Inverse (Transition) Radiation Picture (ITR)



Special case of Poynting's Theorem

- mechanical work only on free charged particle
- no change of stored EM energy in volume V during the passage of the particle

$$\Delta U = \int_L \vec{E} \cdot d\vec{r} = -\frac{1}{\mu_0} \int_{-\infty}^{\infty} \oint_S \left(\vec{E} \times \vec{B}\right) \cdot \hat{n} ds dt$$

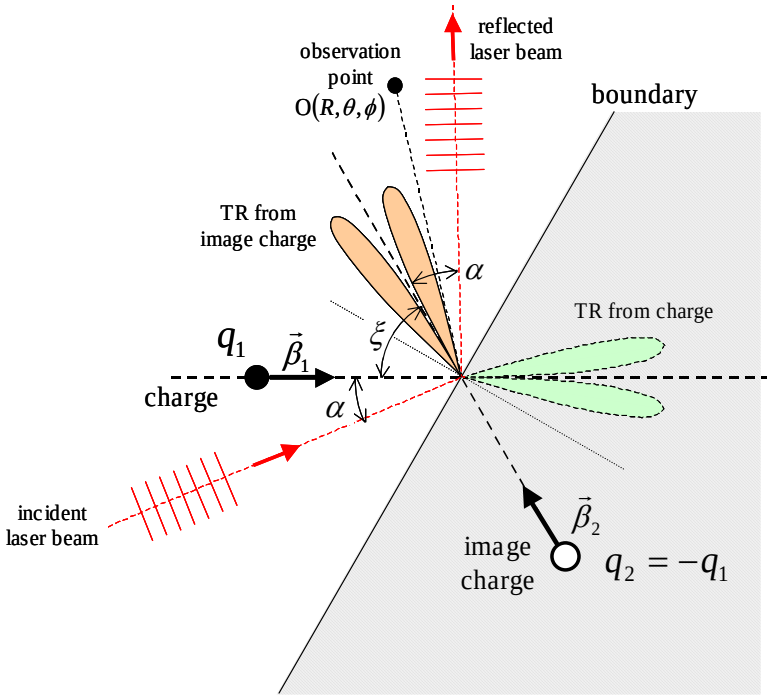
Fourier transform to frequency space

$$\Delta U = -\frac{1}{\pi Z_0} \int_{-\infty}^{\infty} \oint_S \left(\vec{E}_R(\omega) \cdot \vec{E}^*_{TR}(\omega)\right) ds d\omega$$

overlap integral of scattered laser field and particle's wake field

Further semi-infinite vacuum acceleration experiments

Planar infinite conductive boundaries at arbitrary orientations



T.R. E-field (q1 + q2) at y=0

$$\vec{E}_{TR} = -\frac{qZ_0 e^{i\omega R/c}}{4\pi R}\left(\frac{\beta\sin\theta'}{1-\beta\cos\theta'} + \frac{\beta\sin\theta}{1-\beta\cos\theta}\right)\begin{pmatrix}\cos\theta\\ 0\\ -\sin\theta\end{pmatrix}$$

$$\theta' = (\pi - \xi - \theta)$$

Assume a laser plane wave

$$\vec{E}_R(\vec{r}',t) = E_0\hat{P}_R\cos\left(\vec{k}\cdot\vec{r}' - \omega_0 t + \varphi_R\right)$$

Laser plane wave in spherical coordinates

$$E_R(\theta',\phi',\omega) = f(\theta',\phi',\omega)\hat{P}_R$$

$$= -\frac{2\pi\lambda E_0}{R'}\frac{\delta(\pi-\phi')\delta(\alpha-\theta')}{\sin\theta'}\frac{i}{2}\begin{pmatrix}\delta(\omega-\omega_0)e^{i(kR'+\varphi_R)}\\ -\delta(\omega+\omega_0)e^{i(kR'-\varphi_R)}\end{pmatrix}\hat{P}_R$$

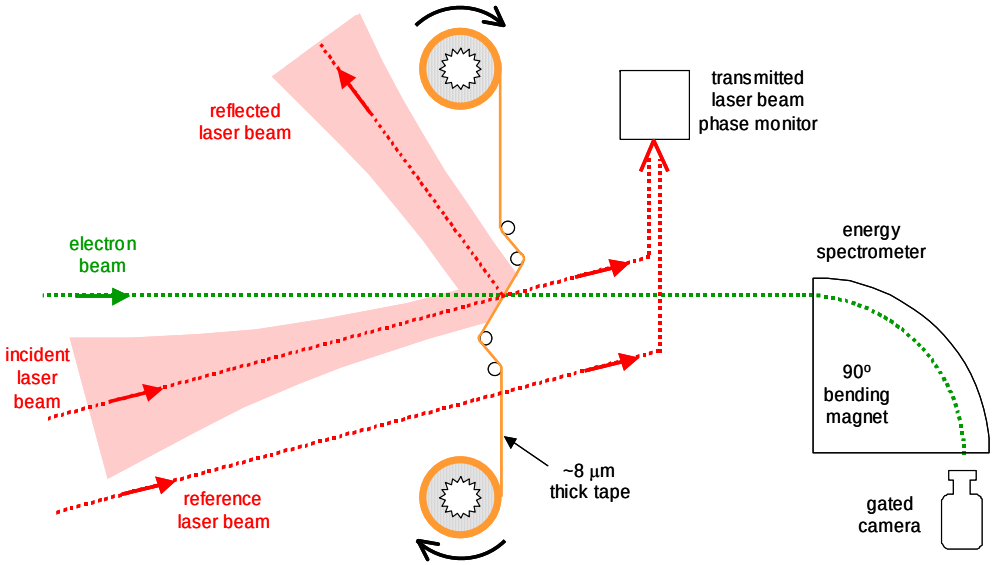
Energy gain from radiation overlap integral turns out to be equal to energy gain from field path integral

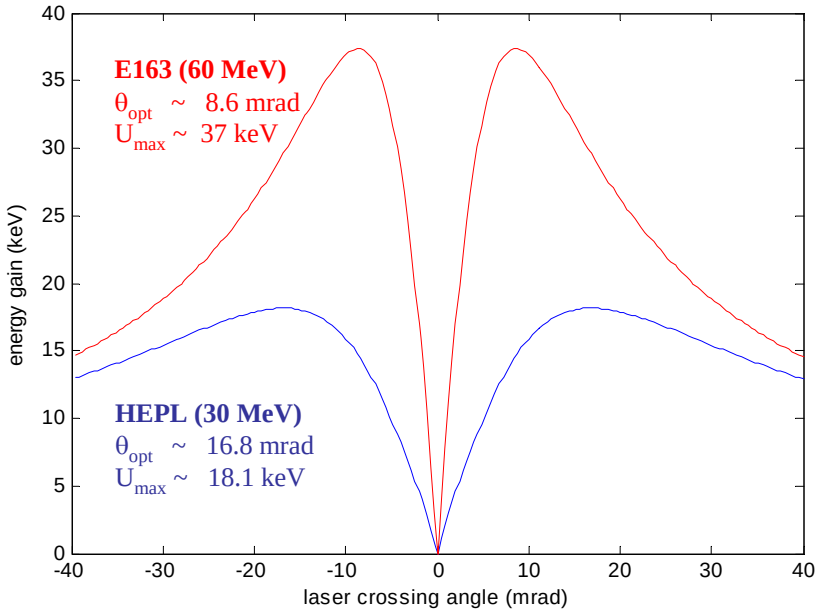
$$\Delta U = \frac{\lambda q E_0 \sin\varphi_I \cos\rho}{2\pi}\left(\frac{\sin\alpha}{\cos\alpha - 1/\beta} - \frac{\sin(\xi+\alpha)}{\cos(\xi+\alpha)+1/\beta}\right) \equiv A\cdot F(\alpha,\xi;\beta)$$

T. Plettner, “Analysis of Laser-Driven Particle Acceleration from Planar Infinite Conductive Boundaries”, SLAC-PUB-11637 (2006)

Further semi-infinite vacuum acceleration experiments

Experiment setup and expected dependence on laser crossing angle





λ = 800 nm
100 µm spot
T ~ 2 psec
½ mJ/pulse

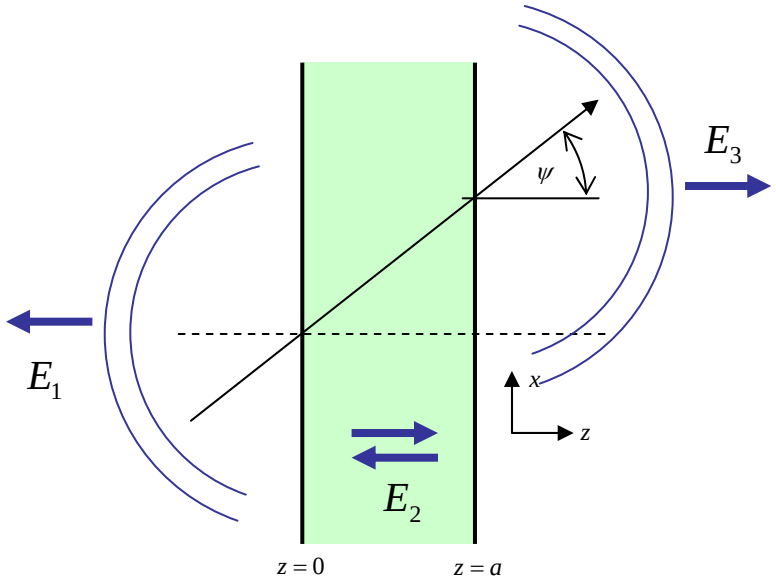
E_0 ~4.3 GV/m
α = 8.3 mrad
Gradient ~ 36 MeV/m
$Z_s = 5.76$ mm
Fluence: ~ 5 J/cm^2

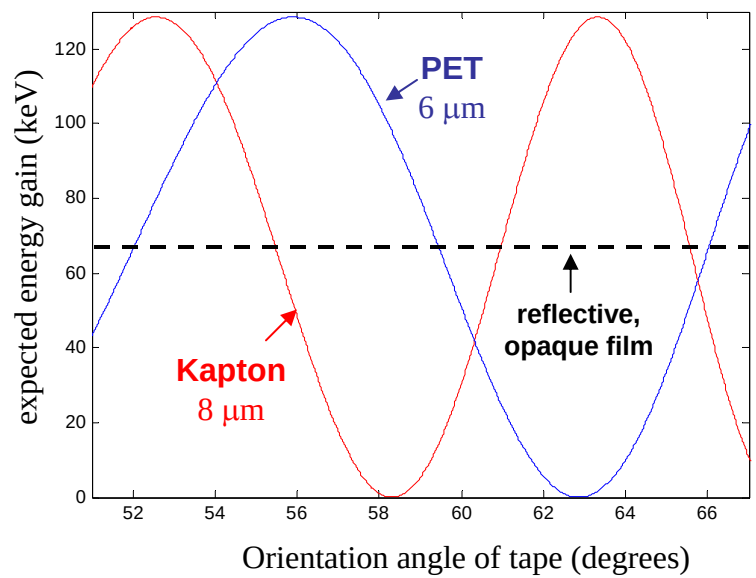
Optimum energy gain at $\theta=1/\gamma$

$$\Delta U_0 \sim \frac{qE_0\lambda\gamma}{2\pi}$$

Further semi-infinite vacuum acceleration experiments

Transparent phase retardation boundaries





$$E_{particle} = 2\pi i q c Z_0 \left(\frac{\omega \vec{v}}{c^2} - \frac{\vec{k}}{\varepsilon_j} \right) \frac{\delta\left(\omega - \vec{k}\cdot\vec{v}\right)}{k^2 - \left(\omega^2/c^2\right)\varepsilon_j}$$

$$\Delta U_{\max} \sim 2\Delta U_0$$

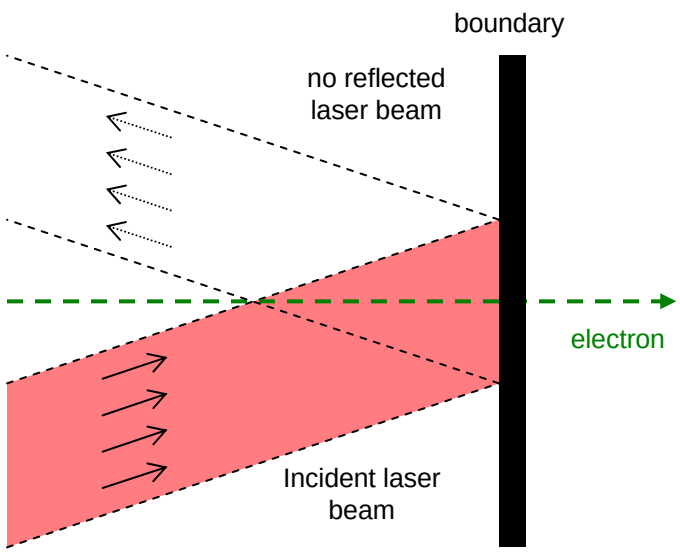
Energy gain from radiation overlap integral = energy gain from field path integral

$$\Delta U \sim \frac{qE_0\lambda}{\pi} \frac{\alpha}{\alpha^2 + 1/\gamma^2} \left\{ \sin\phi_L - \sin\left(ka\left(n\cos\theta_m - \cos\theta\right) + \phi_L\right) \right\}$$

T. Plettner, “Analysis of Laser-Driven Particle Acceleration from Planar Transparent Boundaries”, SLAC-PUB-11800 (2006)

Further semi-infinite vacuum acceleration experiments

Non-reflective black boundary



The Inverse Radiation Method does not apply in this situation since the boundary is absorbing electromagnetic energy energy

$$\Delta U = -\frac{1}{\pi Z_0}\int_{-\infty}^{\infty}\oint_S \left(\vec{E}_R(\omega)\cdot\vec{E}^*_{TR}(\omega)\right) ds\, d\omega = 0$$

The Path Integral Method predicts same effect as with reflective boundary

$$\Delta U_{\max} \sim \Delta U_0$$

Employing Poynting's Theorem…

Ohmic loss term

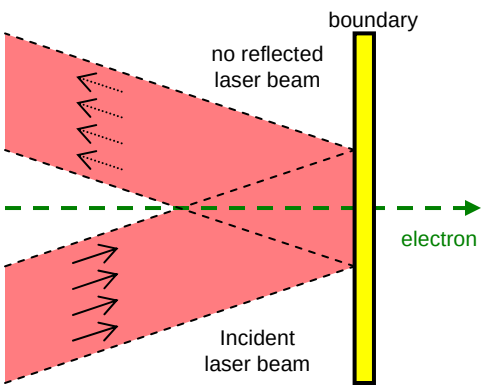
$$\Delta U_{\mathrm{P}} = \underbrace{-\Delta U_{\mathrm{EM}} - U_{abs} - \frac{1}{\pi}\int_{\omega}\int_{V} \sigma \tilde{E}_{L_{total}}(\omega)\cdot\tilde{E}^*_{P_{total}}(\omega)\, dv\, d\omega}_{} \underbrace{- \frac{1}{\pi Z_0}\int_{-\infty}^{\infty}\oint_S \left(\vec{E}_R(\omega)\cdot\vec{E}^*_{TR}(\omega)\right) ds\, d\omega}_{}$$

Electron's energy gain = - Energy absorbed by medium - EM energy radiated away

Further semi-infinite vacuum acceleration experiments

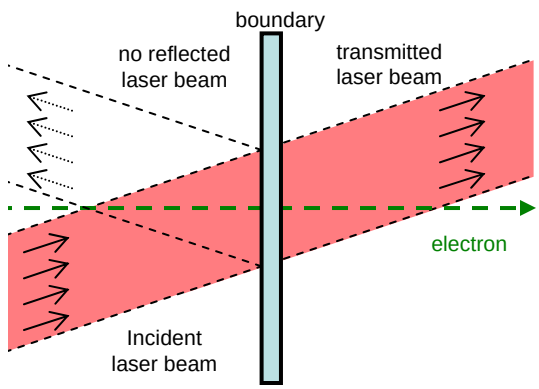
Summary of expected results with single-boundary experiments

a) reflective



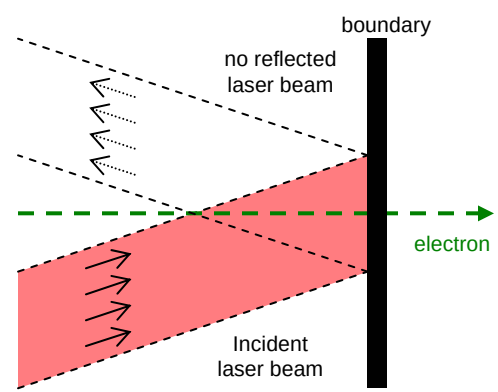
$$\Delta U_{\max} \sim \Delta U_0$$

b) transparent



$$\Delta U_{\max} \sim 0 \rightarrow 2\Delta U_0$$

c) absorbing



$$\Delta U_{\max} \sim \Delta U_0$$

$$\Delta U_0 \sim \frac{qE_0\lambda\gamma}{2\pi}$$

Inverse –radiation picture applies

more general formulation including loss is required

Poynting's Theorem

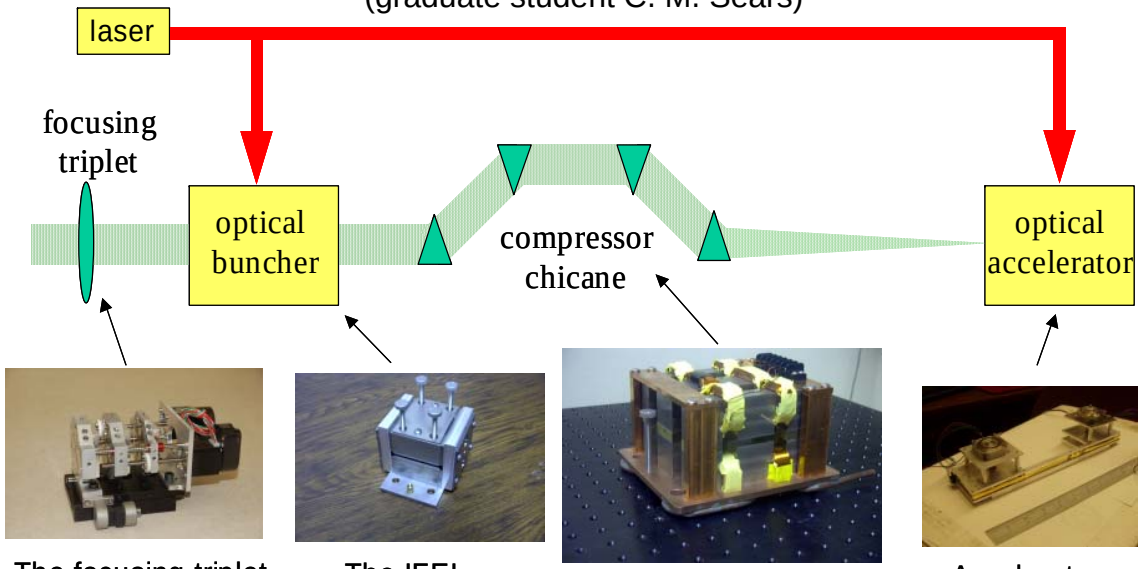
About this talk

This talk will cover

1. A brief overview about our research and objectives
2. A brief summary of the proof-of-principle demonstration for laser-driven particle acceleration in a semi-infinite vacuum space
3. A description of the continuation of experiments with laser-driven particle acceleration in a semi-infinite vacuum space.
4. **An overview of the buncher-accelerator two-stage experiment**
5. A narrative of the work on photonic bandgap microstructures for laser acceleration

Buncher-accelerator two-stage experiment

(graduate student C. M. Sears)

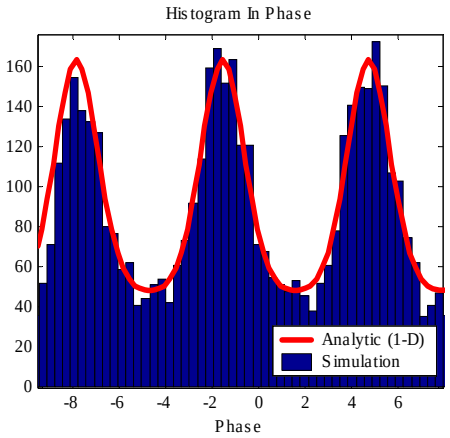


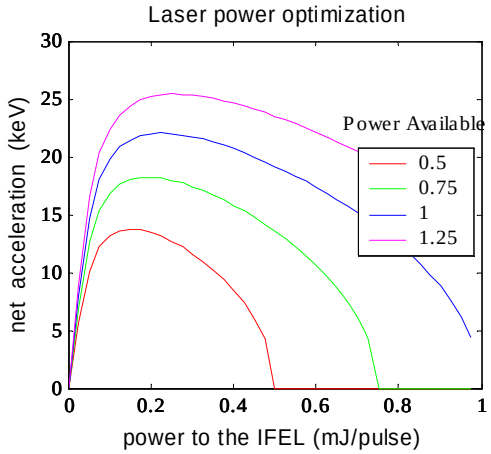
The focusing triplet

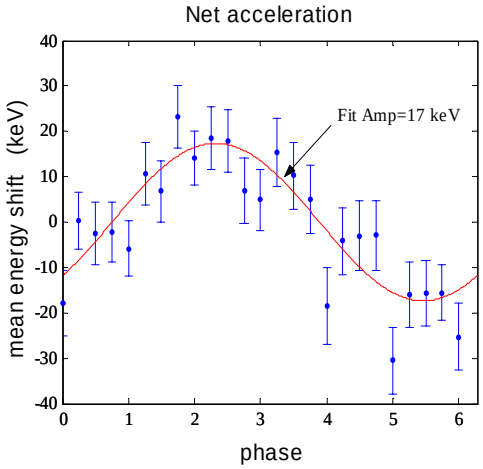
The IFEL

The compressor chicane

Accelerator structure







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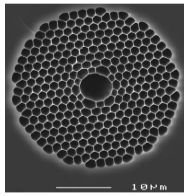
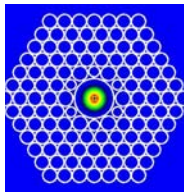
Photonic bandgap accelerator microstructure experiments

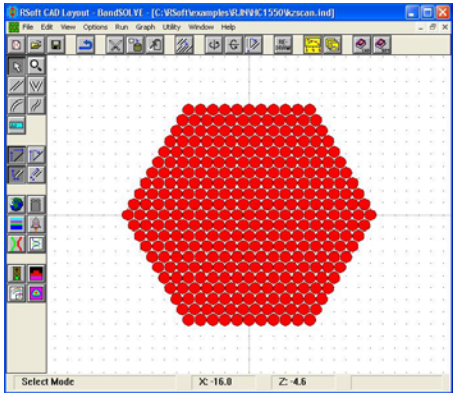
The Blaze Photonics HC-1550-02 fiber for laser-driven particle acceleration

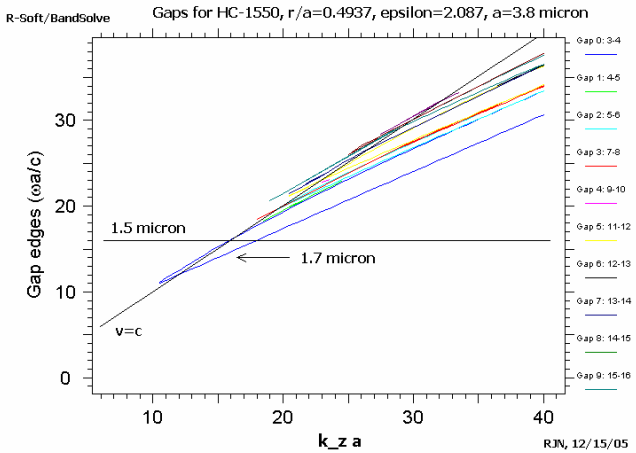
Modeling and studies with commercial software packages

R.H. Siemann, R. Noble, et. al









Proposed parameters for a laser-driven particle acceleration experiment with a PBG hollow core fiber

Parameter	value
Structure impedance	$Z_C = 1\Omega$
Damage factor	$D_F = 0.11$
Laser wavelength	$\lambda = 1.6\ \mu m$
Laser pulse energy	1 μJ
Laser pulse duration	1 psec
Laser group velocity	$\beta \sim 0.6$
Expected gradient	0.6 GeV/m
Structure length	0.5 mm
Energy gain	0.3 MeV

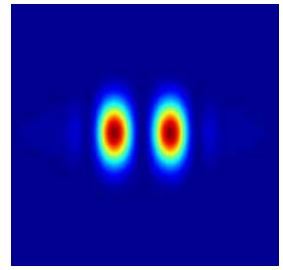
X.E. Lin, “Photonic band gap fiber accelerator”, Phys. Rev. ST Accel. Beams 4, 051301 (2001)

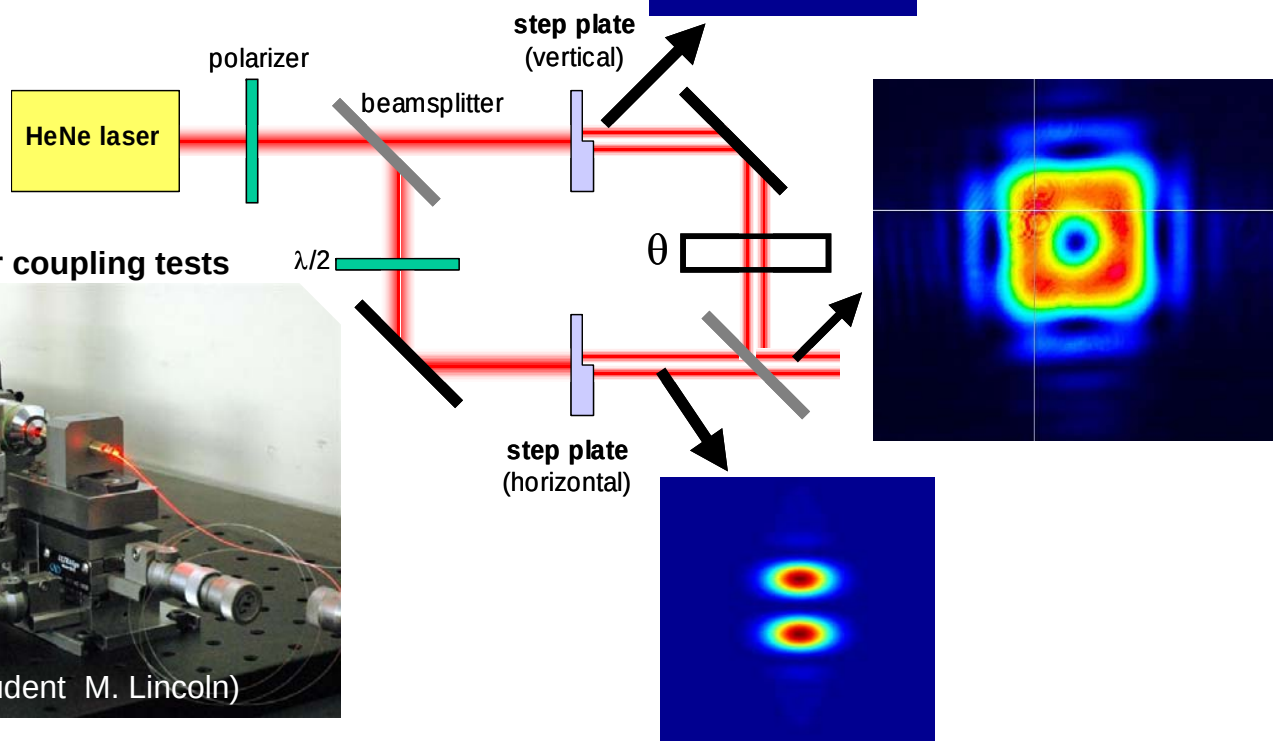
Photonic bandgap accelerator microstructure experiments

Simple optical tests with HeNe lasers

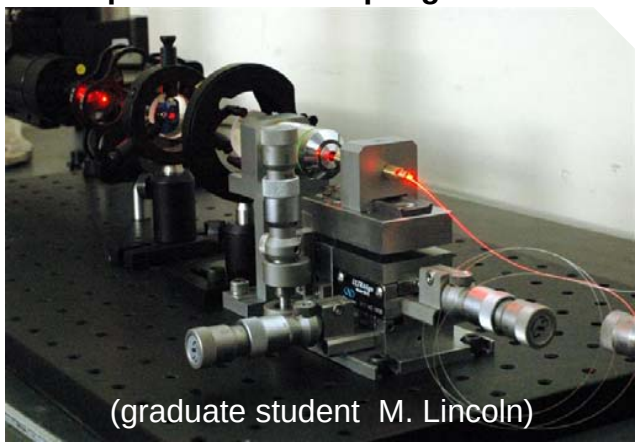
The generation of a TEM_{01}* donut mode

(graduate student P. Lu)





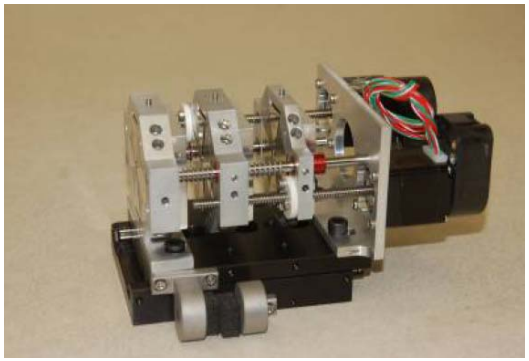
Free-space to fiber coupling tests



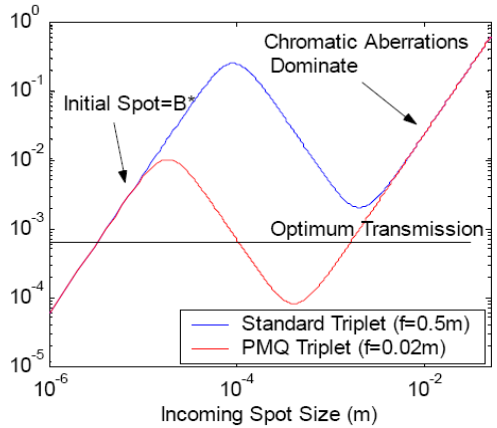
(graduate student M. Lincoln)

Photonic bandgap accelerator microstructure experiments

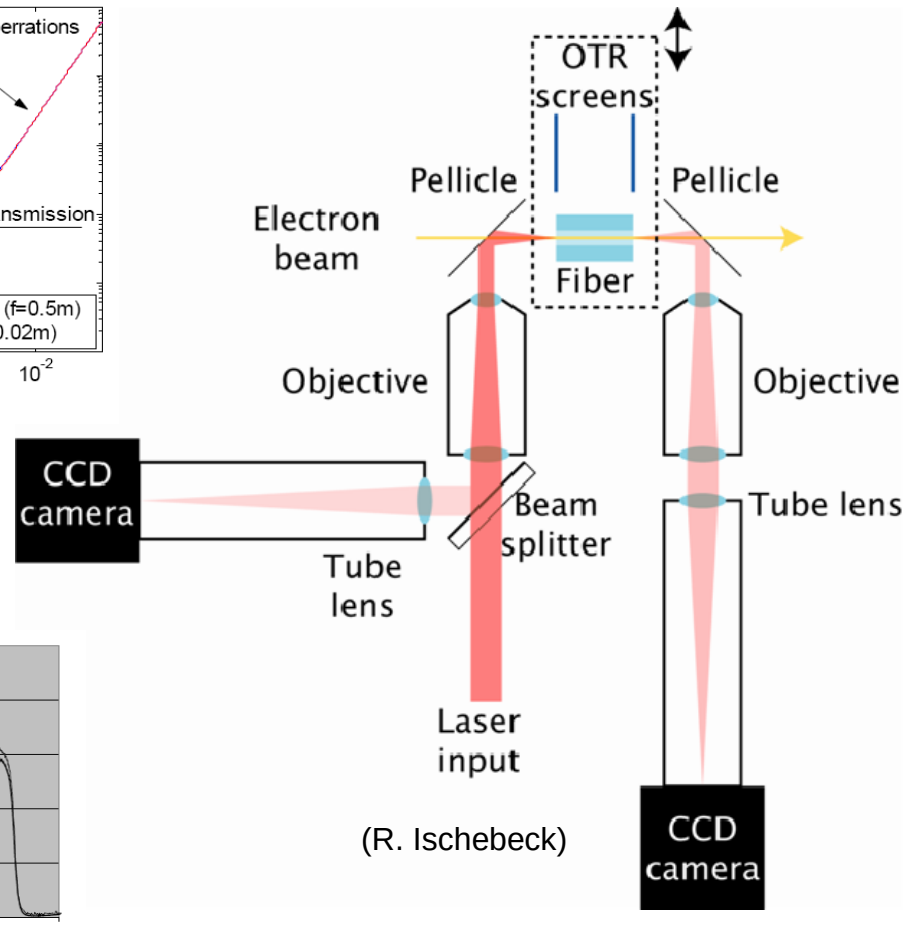
Focusing of the electron beam into the PBG structure



(graduate student C. M Sears)



Experiment setup



(R. Ischebeck)

IEEE TRANSACTIONS ON NUCLEAR SCIENCE, DECEMBER 2002

Gamma Radiation Studies on Optical Materials

Eric Colby, *Member*, Gary Lum, *Member*, Tomas Plettner and James Spencer, *Member, IEEE*

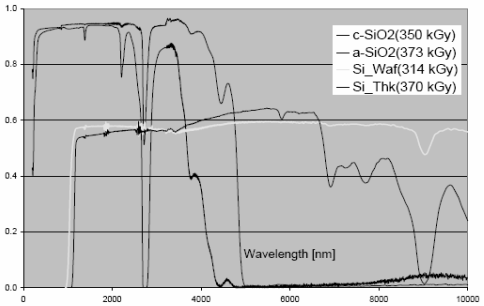


Fig. 6. Comparison of spectra from 0.20-10 μm for different forms of Si in Si equivalent dose. Spectra were matched at 3.2 μm.

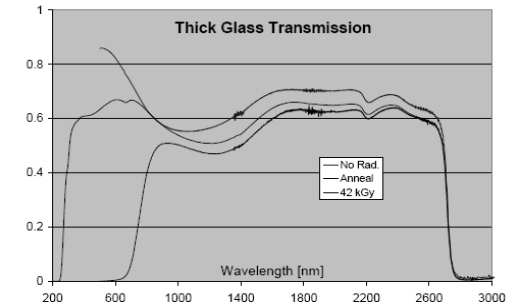


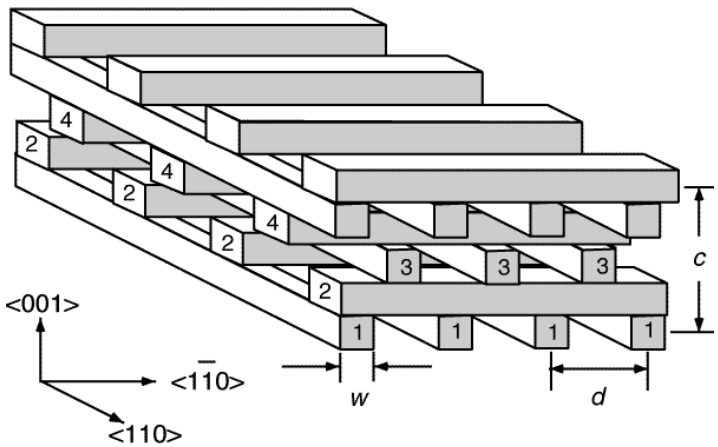
Fig. 1. Transmissivity spectra through 1.1 cm thick plate glass after Co^{60} γ-irradiation. Spectra are stacked according to their order in the insert.

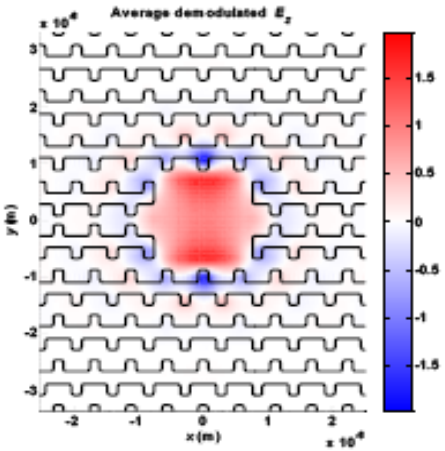
(J.E. Spencer)

Photonic bandgap accelerator microstructure experiments

The Woodpile 3-dimensional photonic bandgap structure

(graduate student B. Cowan)





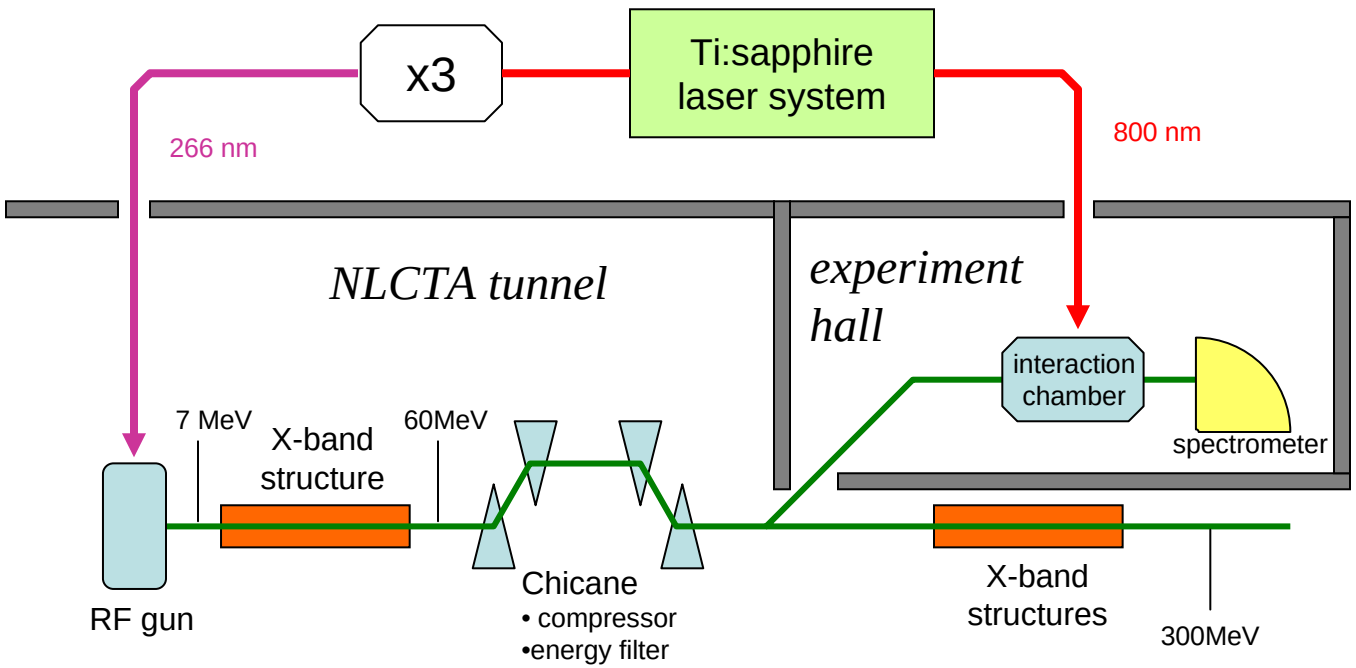
Present work

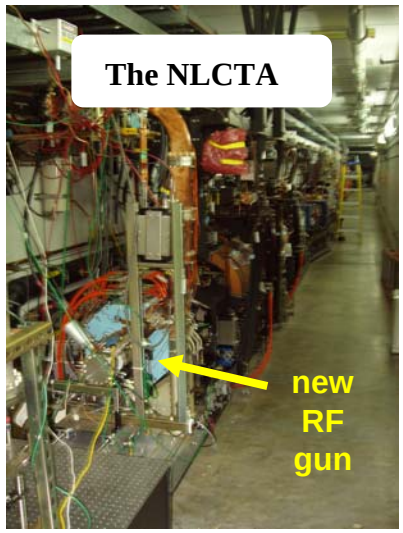
- EM field modeling work
- particle beam transport
- parameter optimization

- nanofabrication steps
- laser damage threshold measurements

Where all these experiments will take place

E. Colby





Status of the facility

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

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R. Route, V. Drew, D.L. Sawyer, J. Kiennitz

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M. Diggonet, S. Sinha, P. Lu

Varian machineshop and HEPL personnel
K. Merkle, M. Hennessy, P. Cruz

Collaborators

Other ADRB members and collaborators
M. Hogan, R. Iverson, J. Rosenzweig, E. Kirby, W.E. White

The NLCTA personnel

The Department of Energy

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