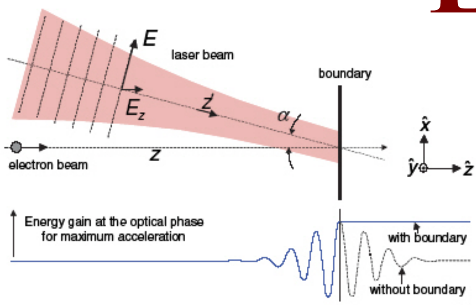
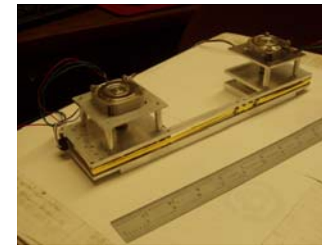
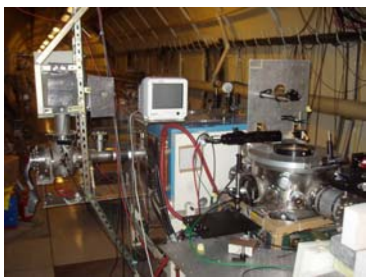
AARD subpanel Dec 21, 2005

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

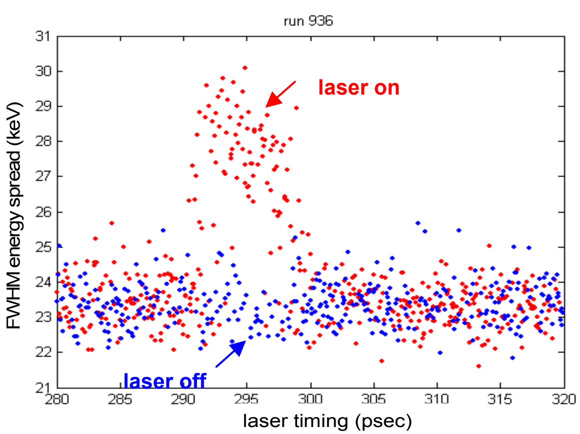
Zhiu Zhang†, Sami Tantawi†

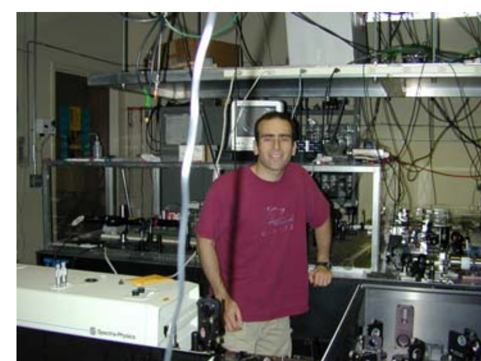
Techion Israeli Institute of Technology

Levi Schächter*

UCLA

J. Rosenzweig*



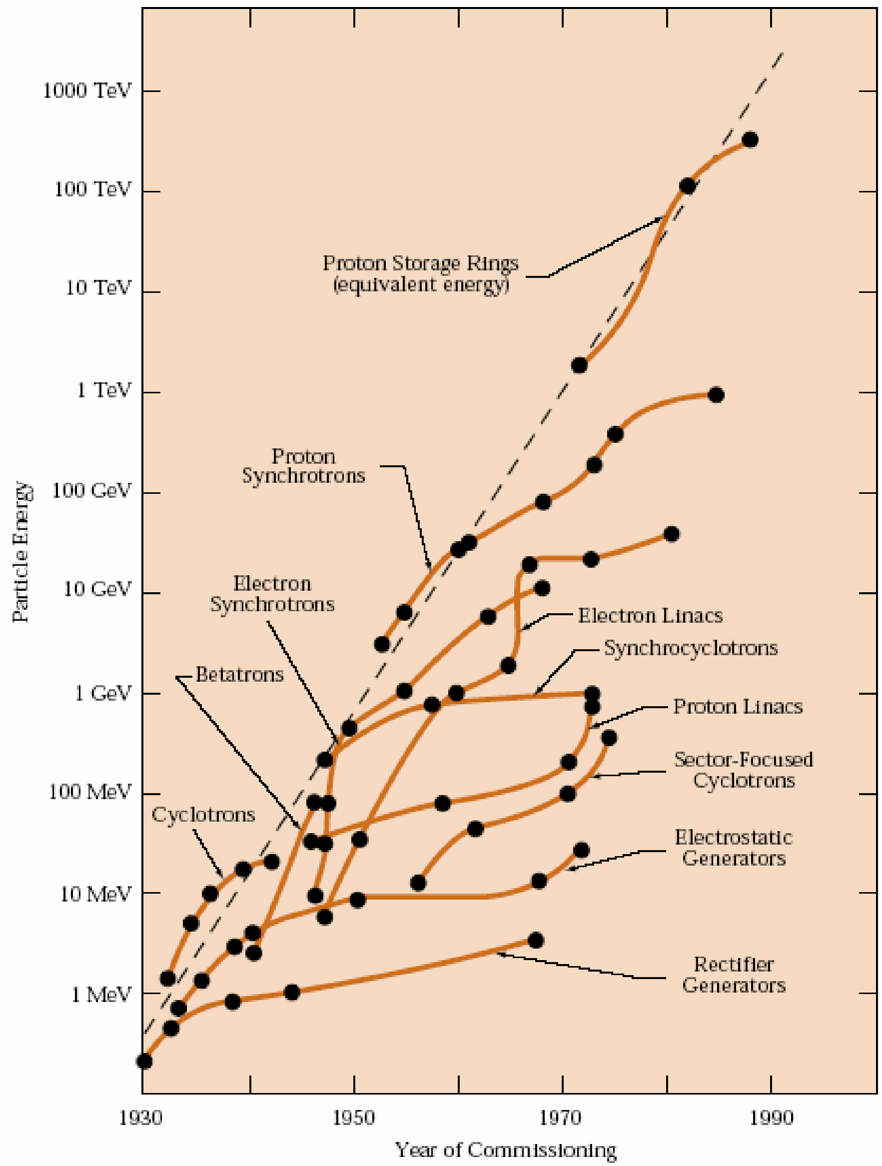


‡ grad students † postdocs and staff * faculty

Outline

- **Introduction**
  - Properties unique to laser acceleration
  - Available resources and expertise
  - Emergence of new technologies
- **The physics concept and experiment**
  - The physics concept
  - The physics demonstration experiment
- **Current and future research**
  - The E163 experiment
  - Accelerator structure investigations
  - Multi-staged laser accelerator
- **Future scientific impact**
  - Candidate technology for a TeV scale collider
  - Soft X-ray attosecond physics

The Livingston plot – 1954
Innovation leads to exponential progress



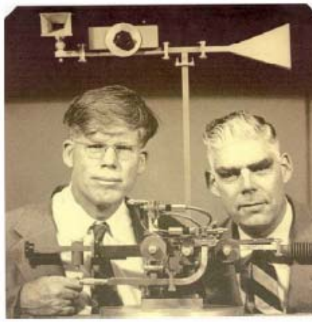
In 1954 Livingston noted that progress in high energy accelerators was exponential with time.

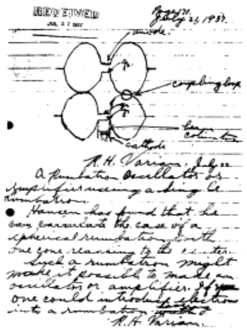
Progress was marked by saturation of the current technology followed by the adoption of **innovative new approaches** to particle acceleration.

Over the past two decades progress in Advanced Solid State Lasers has been driven by innovation. Laser sources coupled with related technologies enable new approaches to Advanced Electron Accelerators.

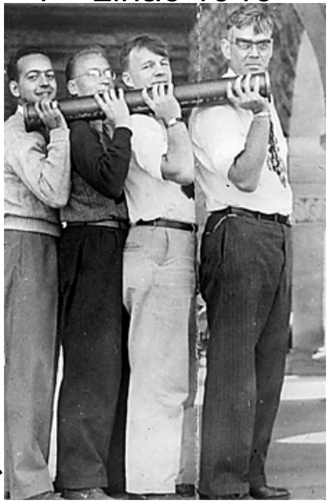
Particle accelerator research at Stanford

1st Klystron (Varian, 1930s')

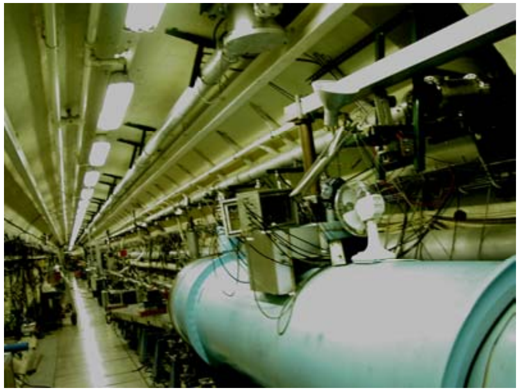




1st Linac 1946



The superconducting linac
In HEPL, 1960



Demonstration of the FEL, 1977

First Operation of a Free-Electron Laser*

D. A. G. Deacon,† L. R. Elias, J. M. J. Madey, G. J. Ramian, H. A. Schwettman, and T. I. Smi
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.

LEAP, 1997-2004

The 2-mile collider (SLAC)

Vacuum laser acceleration

1 Energy gain through longitudinal electric field

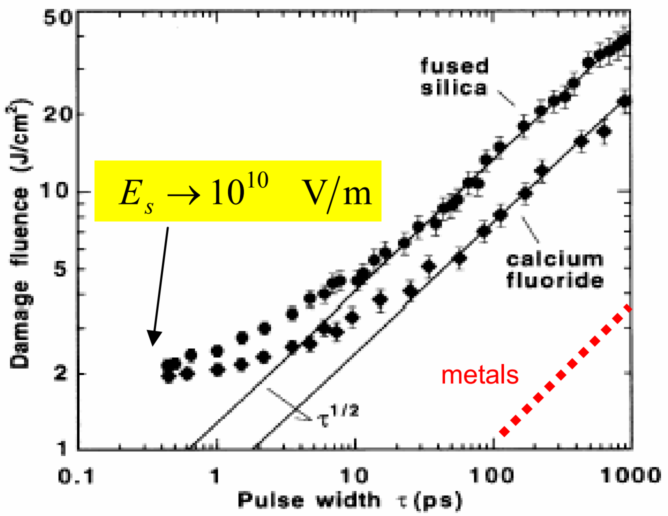
- gradient = longitudinal electric field
- linear e-beam trajectory
  - → no synchrotron radiation
  - → **energy scalable**

$$\Delta U = \int E_z \cdot dz$$

→ linear particle acceleration process

2 Dielectric based structure with vacuum channel

$$\text{Gradient} \to 1 \quad \text{GeV/m}$$



→ very high peak electric fields

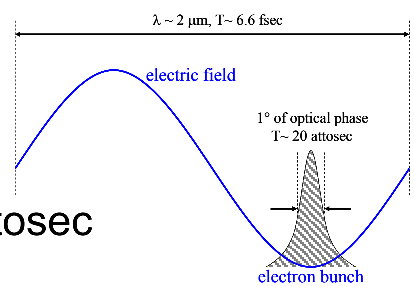
→ vacuum channel

→ NIR solid-state lasers

3 Inherent attosec electron pulse

2 μm laser → 6 fsec period

→ 1 of phase = 20 attosec



→ Unique opportunity for light sources

Emergence of new technologies

efficient pump diode lasers

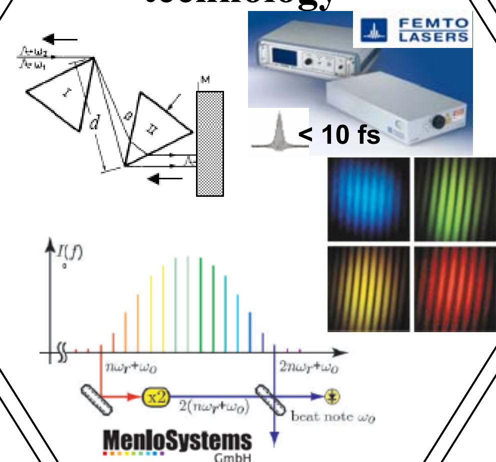
nLIGHT

60 W/bar, 50% electr. efficiency

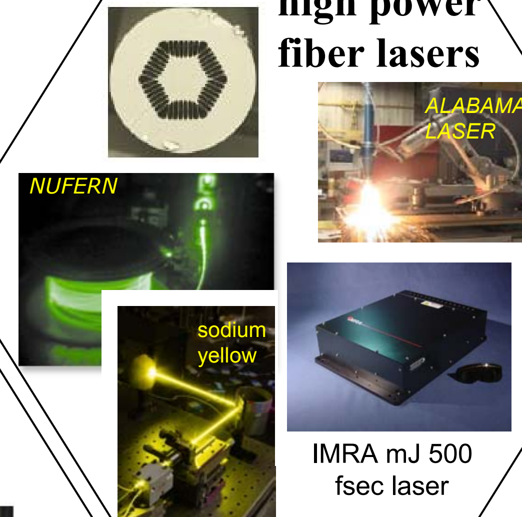
30 W/bundle, 40% electr. efficiency

Leveraging investment in telecom

ultrafast laser technology

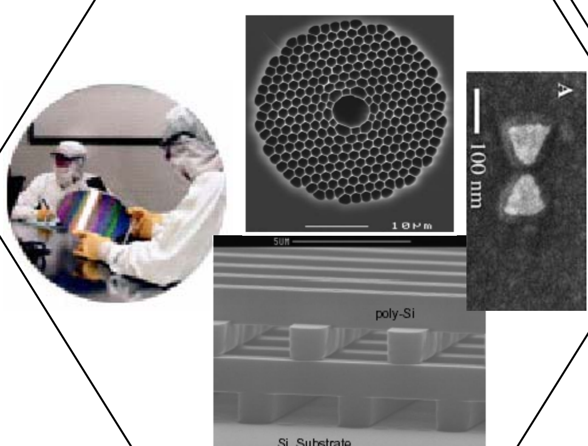


high power fiber lasers



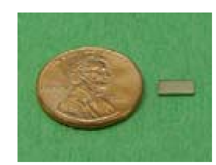
IMRA mJ 500 fsec laser

nanotechnology

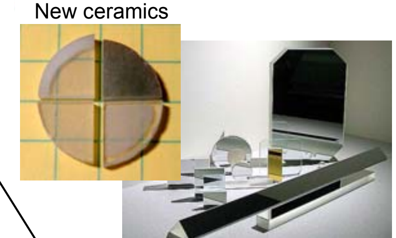


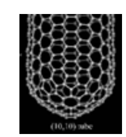
new materials

New ceramics



high strength magnets **Nd:Fe**

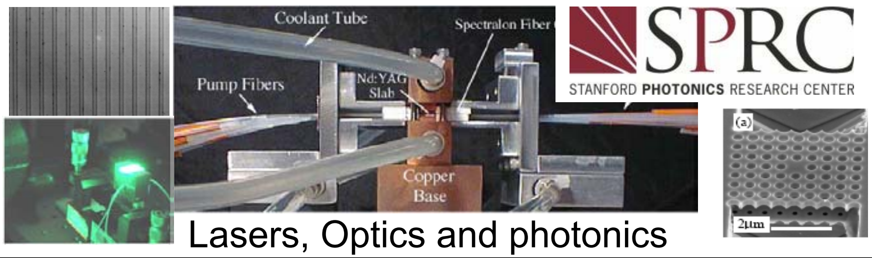




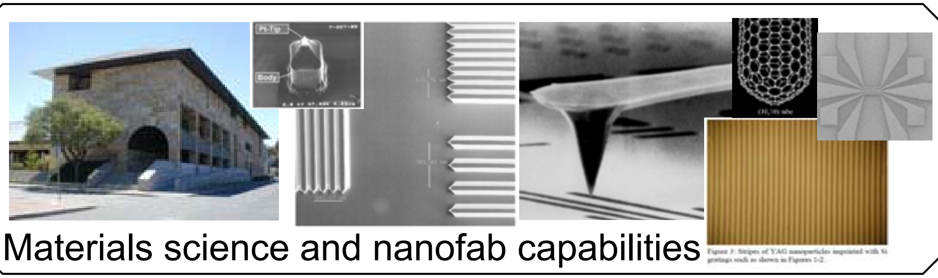
nano-tubes

high purity optical materials and high strength coatings

Available resources at Stanford/SLAC

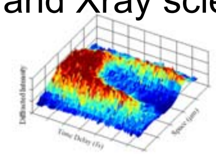


Lasers, Optics and photonics

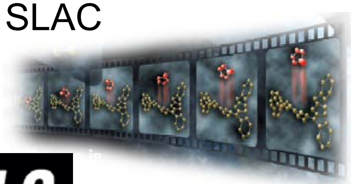


Materials science and nanofab capabilities

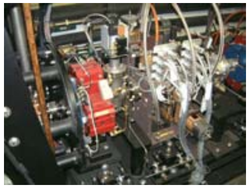
Ultrafast light and Xray science at SLAC



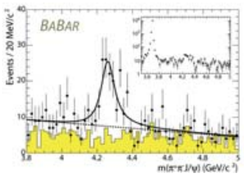
time evolution of 111 Bragg peak of InSb



Accelerator and diagnostics expertise at SLAC



The NLCTA beamline

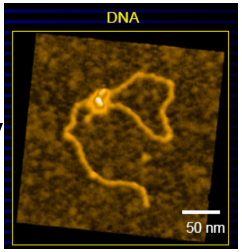


The gravitational wave detector

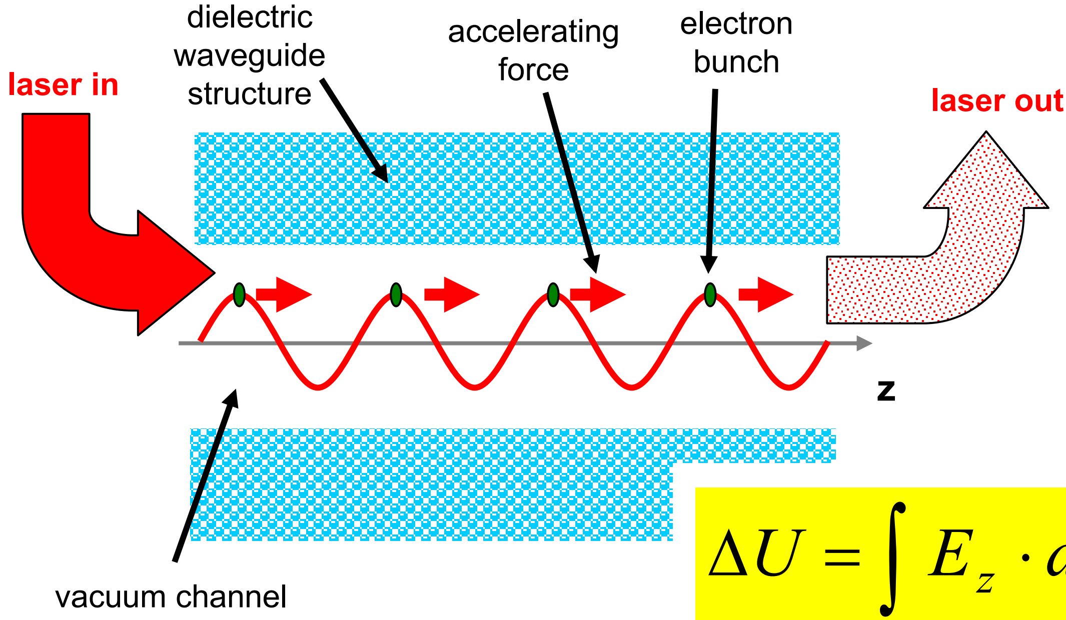
Fundamental science questions

Strong interaction and partnership with
- industry
- national labs
- other universities worldwide

Medicine
Chemistry
Biology
…

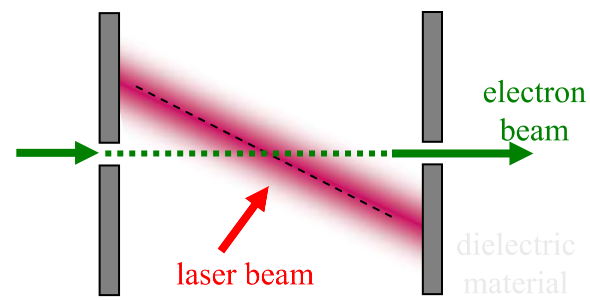


Laser acceleration concept

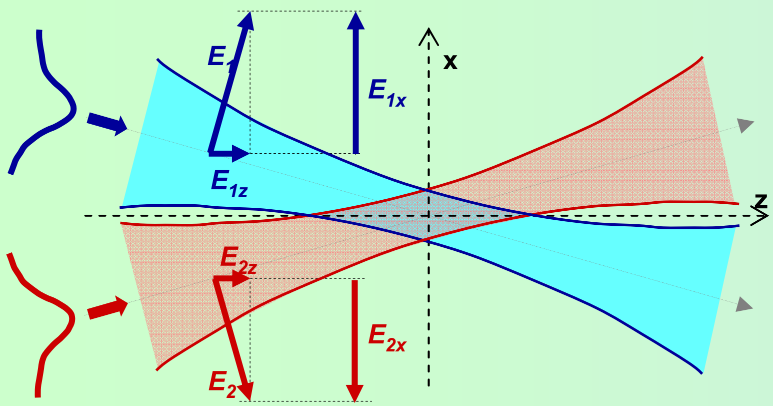


conceptual idea

Pantell, 1979



$$\Delta U = \int E_z \cdot dz \quad \xrightarrow{\text{boundary}} \quad \left| \int_0^d E_z(z')\,dz' \right| > 0$$



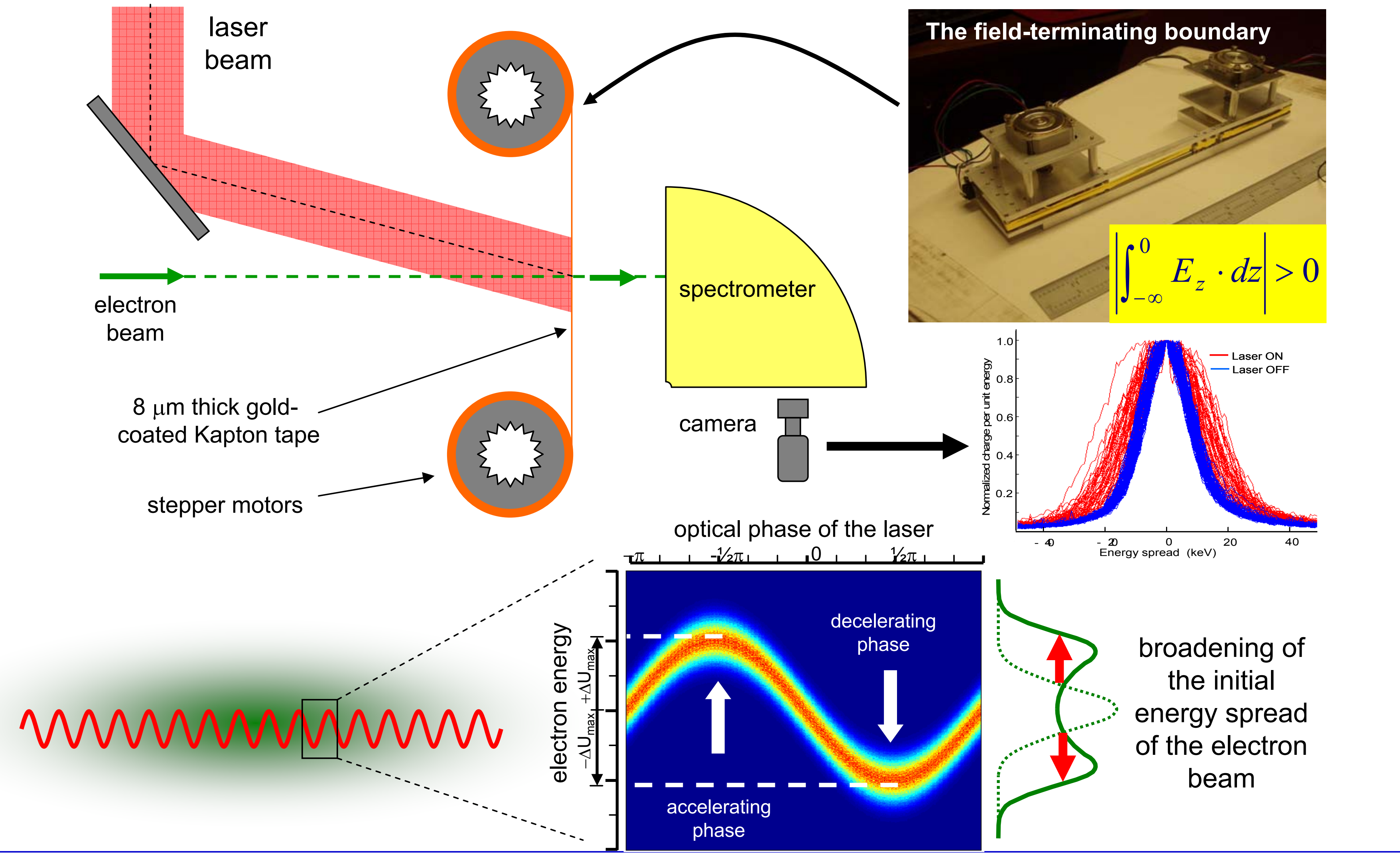
$$E_z = -\underbrace{\frac{2E_0 \sin\theta}{(1+\hat{z}^2\cos^2\theta)^{3/2}} \exp\left[-\frac{(\hat{z}/\theta_d)^2 \sin^2\theta}{1+\hat{z}^2\cos^2\theta}\right]}_{\text{Magnitude}} \times \underbrace{\cos\psi_t}_{\text{Phase}}$$

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

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

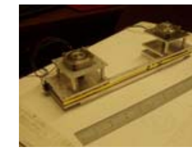
† P. Sprangle, E. Esarey, J. Krall, A. Ting, Laser Acceleration of Electrons in Vacuum, Optics Comm. 124 (1996) 69

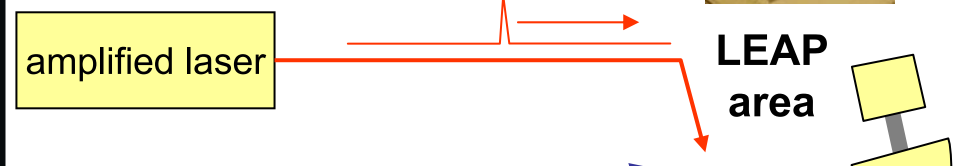
The LEAP experiment
(Laser Electron Accelerator Project)

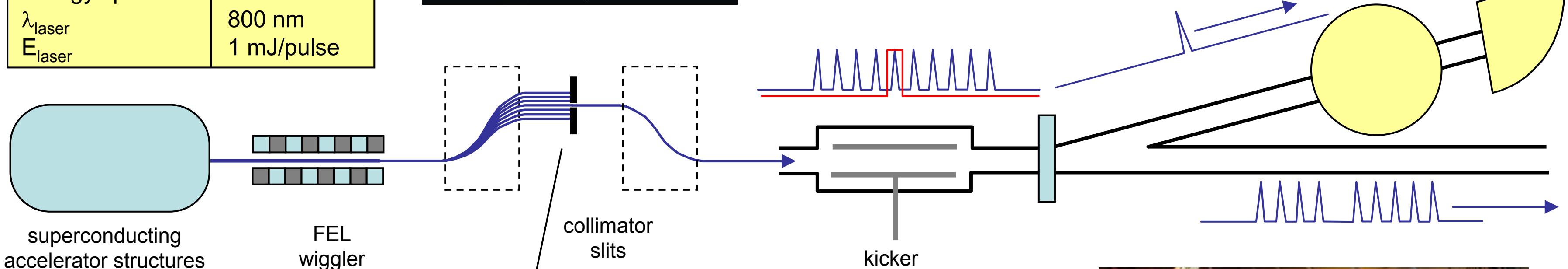


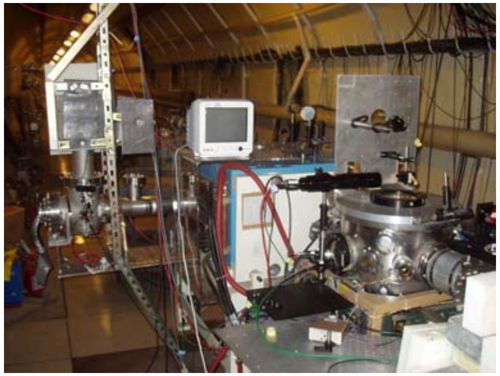
The SCA-FEL facility

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

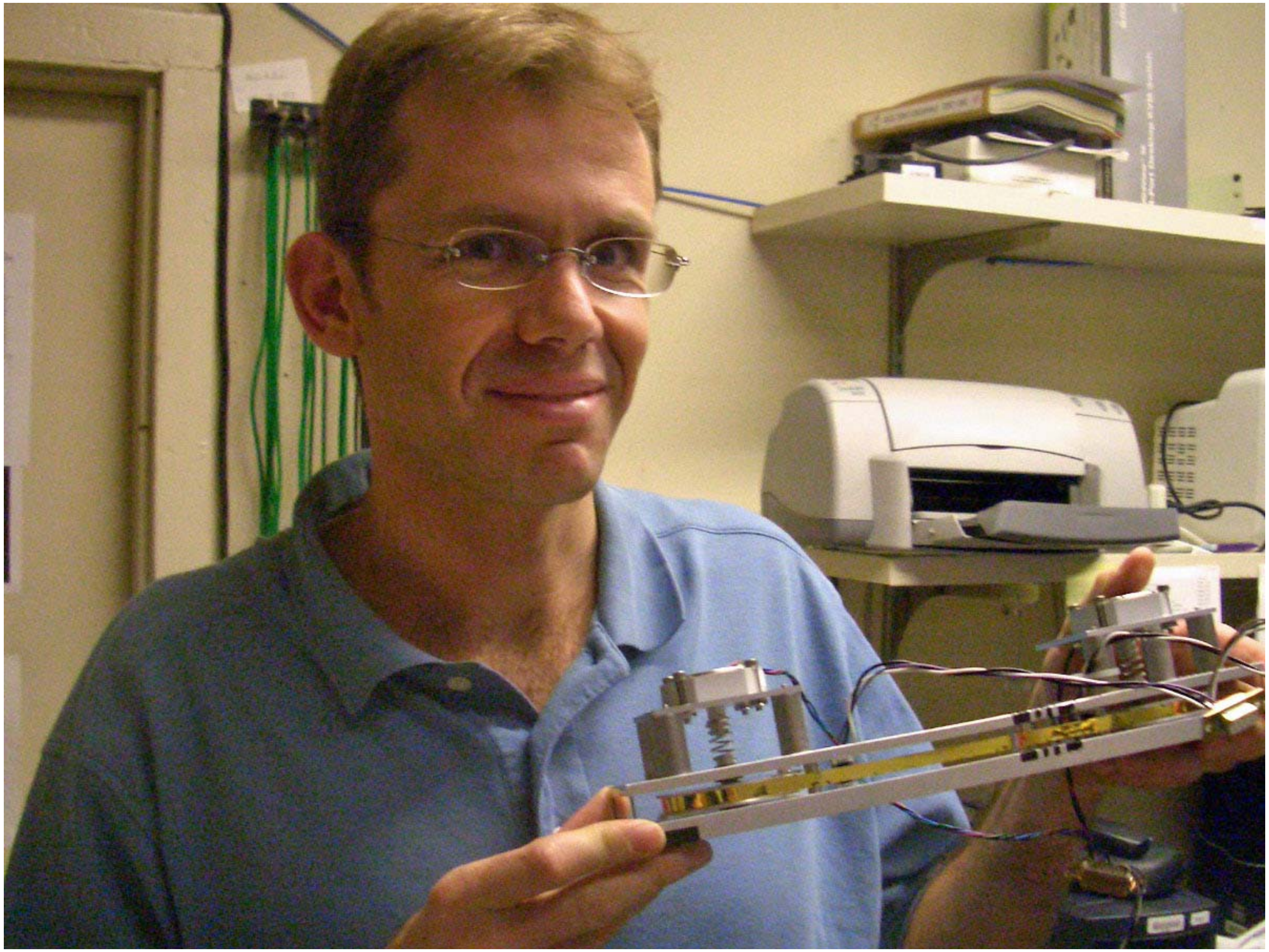








Tomas Plettner and LEAP Accelerator Cell



The key was to operate the cell above damage threshold to generate Energy modulation in excess of the noise level.

We accelerated electrons with visible light

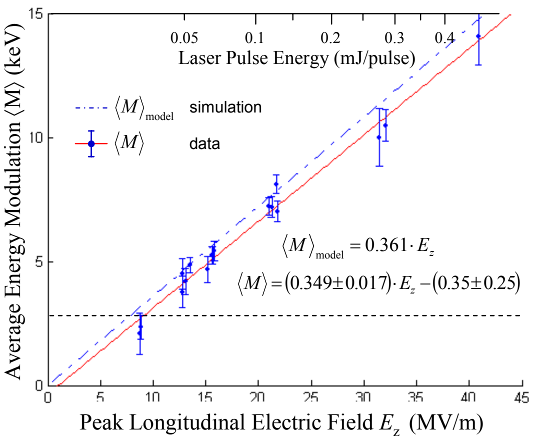
PRL 95, 134801 (2005) PHYSICAL REVIEW LETTERS week ending 23 SEPTEMBER 2005

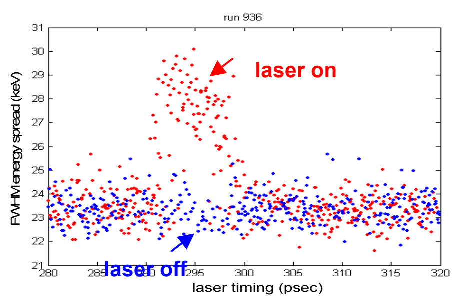
Visible-Laser Acceleration of Relativistic Electrons in a Semi-Infinite Vacuum

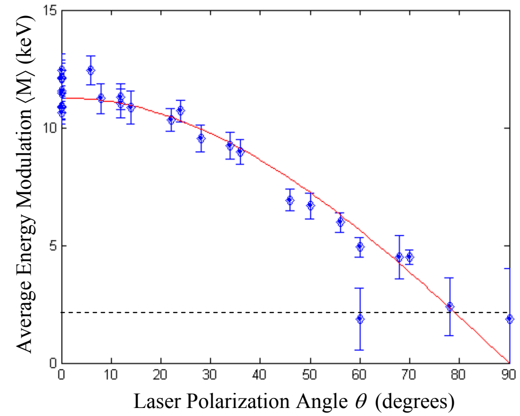
T. Plettner and R. L. Byer
Stanford University, Stanford, California 94305, USA

Colby, B. Cowan, C. M. S. 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 $\Delta U \propto |E_{laser}|$
- observation of the expected polarization dependence $|E_z| \propto |E_{laser}| \cos \rho$

laser-driven linear acceleration in vacuum

Visible light driven IFEL

PRL 95, 194801 (2005) PHYSICAL REVIEW LETTERS week endi… 4 NOVEMBE… 005

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

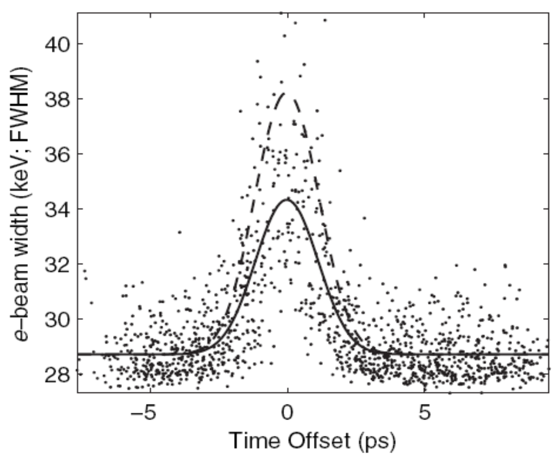


FIG. 2. Example data run with 1500 laser on events. The solid curve is the least squares fit to all data points and gives the mean interaction of 18 keV. The dashed curve is the maximum estimate and gives the peak interaction of 25 keV. The width of cross correlation is 2.2 ps rms.

Observation of harmonic interaction

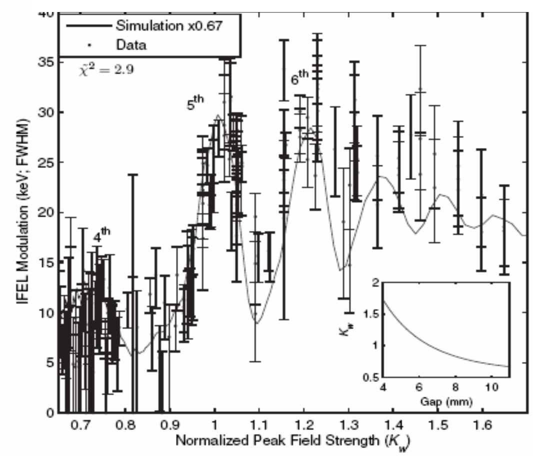


FIG. 4. IFEL gap scan data, with 164 runs total. Comparison to simulation (solid line) shows very good agreement to the shape and spacing of resonance peaks. The harmonic numbers are given next to each peak. Simulation has been rescaled vertically by 0.67 to better visualize overlap.

* graduate student C.M. Sears

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  - The E163 experiment
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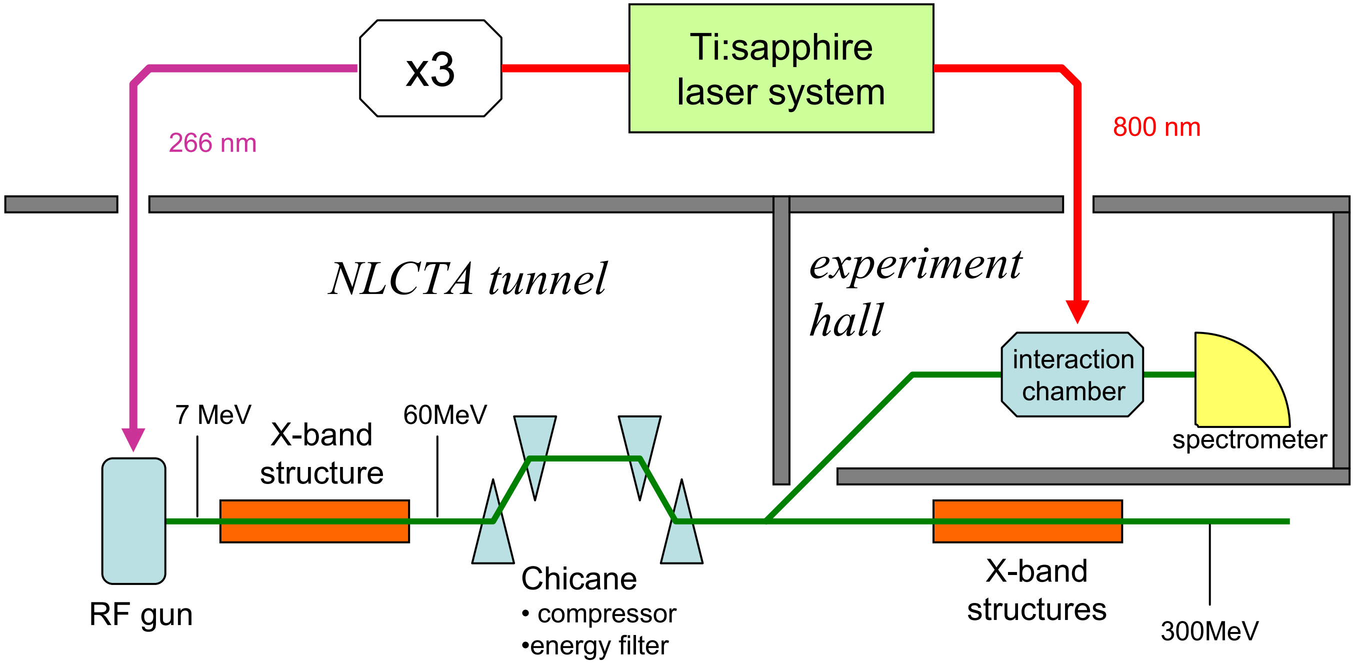
  - Multi-staged laser accelerator
- **Future scientific impact**
  - Candidate technology for a TeV scale collider
  - Soft X-ray attosecond physics

The E163 experiment at SLAC

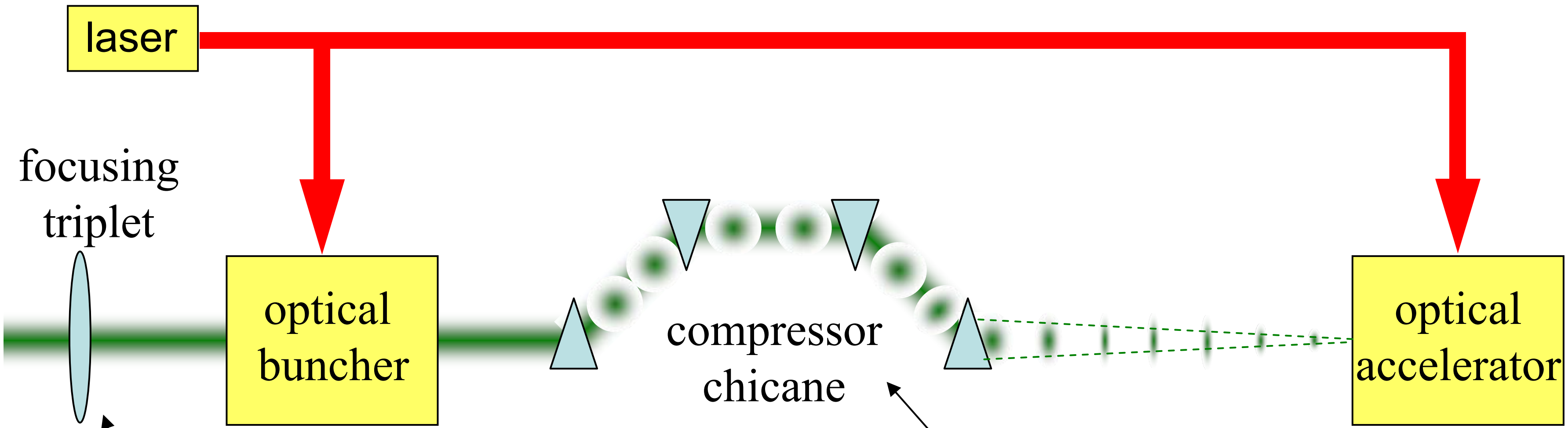


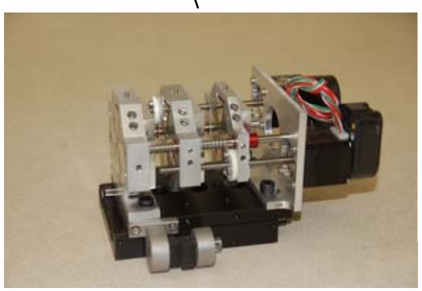
Accomplished mile stones so far

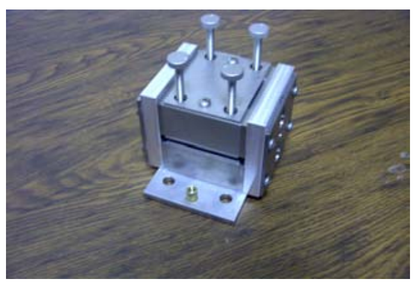
- construction of the experiment hall
- installation of the E163 control room
- commissioning of the laser system
- installation and commissioning of the RF gun

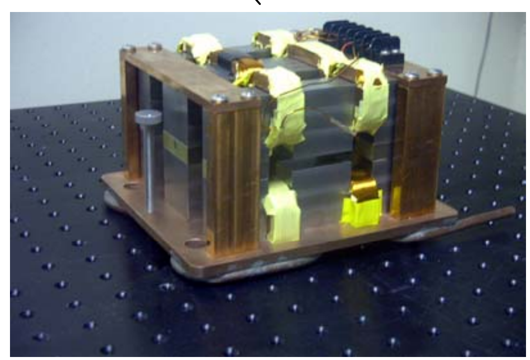
Expected 1st experiment in spring 2006

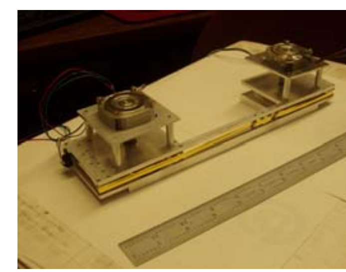
The next step: staged accelerators at E163




The triplet


The IFEL


The compressor chicane


Accelerator structure

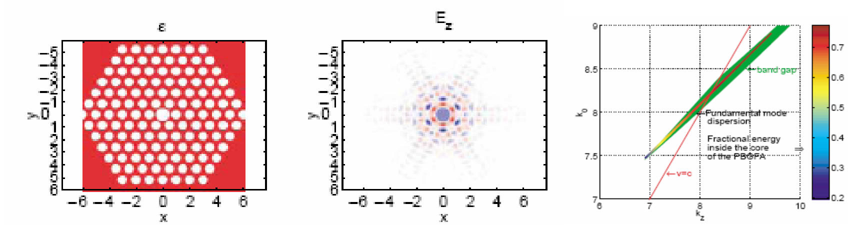
Accelerator structure research

Photonic bandgap fiber structures

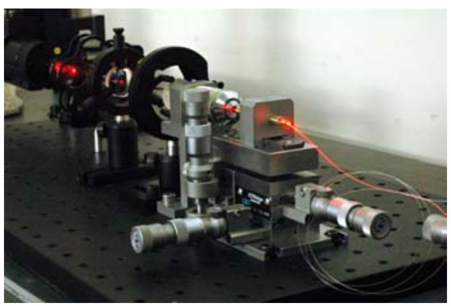
PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS, VOLUME 4, 051301 (2001)

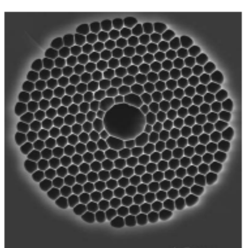
Photonic band gap fiber accelerator

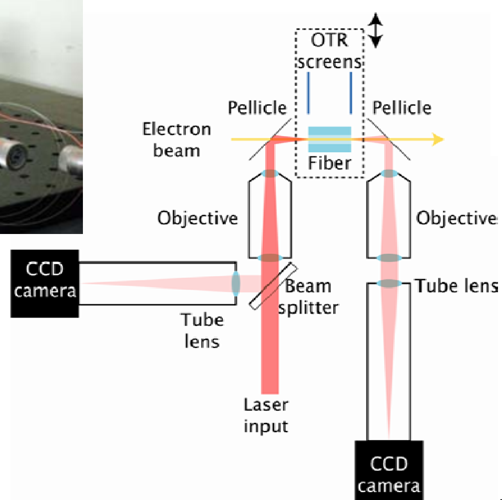
Xintian Eddie Lin*



Current experimental fiber accelerator structure research







R. Ischebeck, R. J. Noble, B.Cowan*, M. Lincoln*,C. Sears*

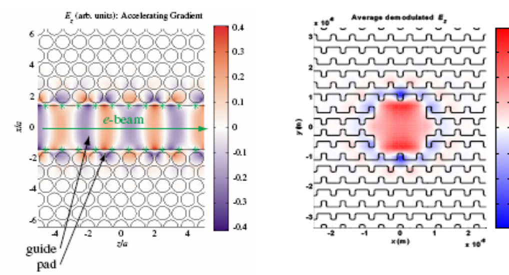
*grad. students

2 and 3-D photonic bandgap structures

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS, VOLUME 6, 101301 (2003)

Two-dimensional photonic crystal accelerator structures

Benjamin M. Cowan*



Planar waveguide structures

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 8, 071302 (2005)

Distributed grating-assisted coupler for optical all-dielectric electron accelerator

Zhiyu Zhang,* Sami G. Tantawi, and Ronald D. Ruth

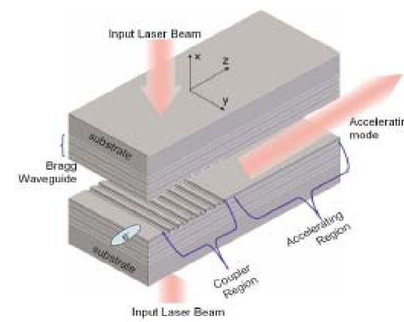


FIG. 1. (Color) Schematic diagram of a planar accelerator structure with distributed grating-assisted coupler (DGAC).

Energy efficiency of laser accelerators, single and multiple bunch operation

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS, VOLUME 7, 061303 (2004)

Energy efficiency of laser driven, structure based accelerators

R. H. Siemann

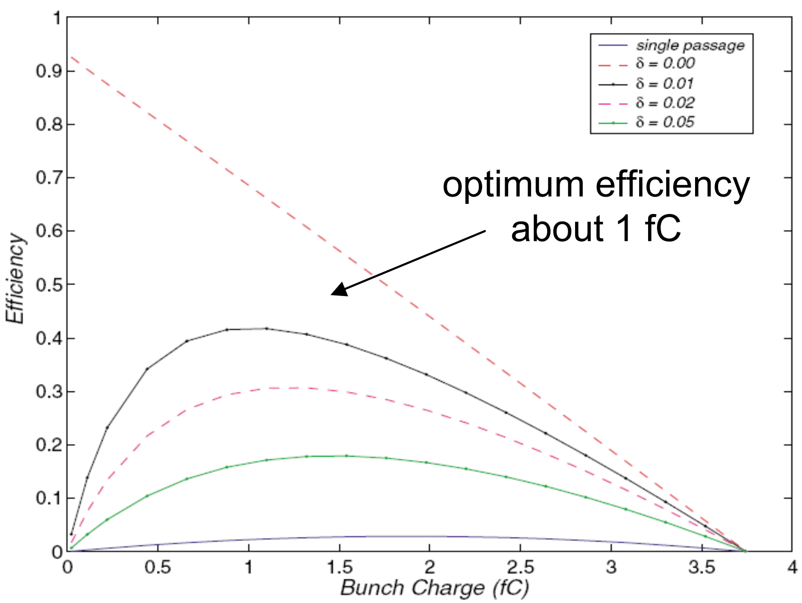
PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 8, 031301 (2005)

Energy efficiency of an intracavity coupled, laser-driven linear accelerator pumped by an external laser

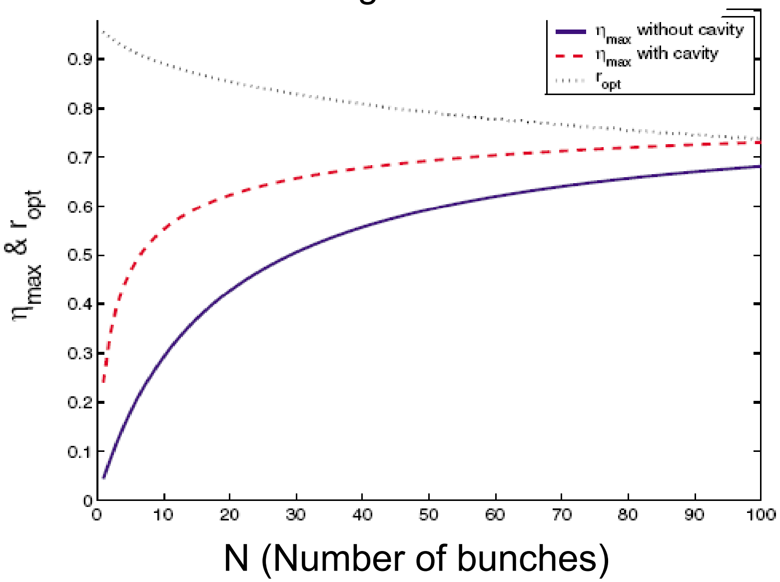
Y. C. Neil Na and R. H. Siemann
Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309, USA

R. L. Byer
Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305, USA
(Received 26 January 2005; published 11 March 2005)

Coupling Efficiency vs bunch charge



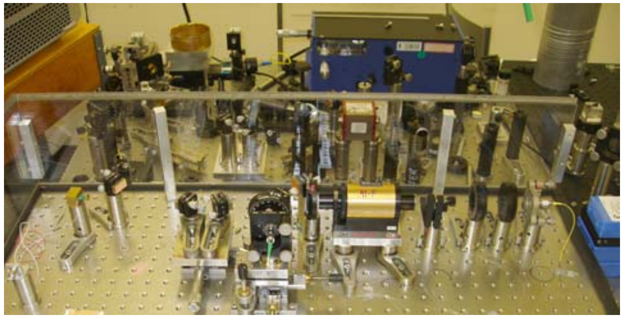
Beam loading calculations vs N



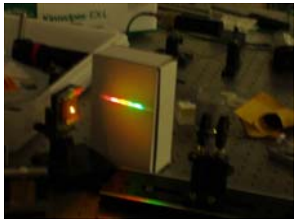
Application of modern technologies

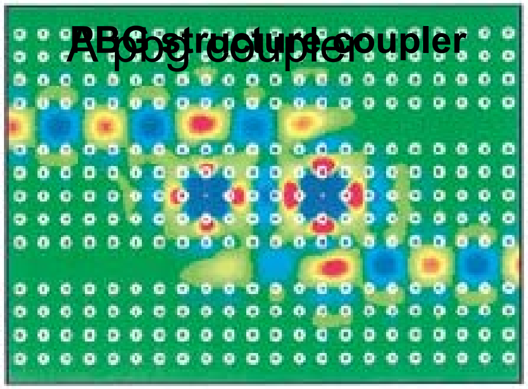
Lasers and photonics

200 fsec Yb:fiber laser; S. Sinha*



comb offset detection with Ti:Sapph lasers; T. Plettner





S. Fan et al, PRL 80, 5, 960-963 (1998)

Materials science

LASER AND PARTICLE GUIDING MICRO-ELEMENTS FOR PARTICLE ACCELERATORS*

T. Plettner, R. Gaume and J. Wisdom, Stanford University, Stanford, CA, USA
J. Spencer, SLAC, Menlo Park, CA 94025, USA

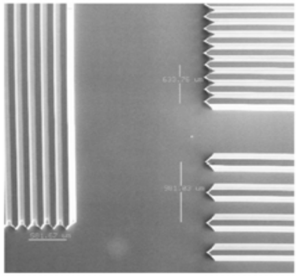
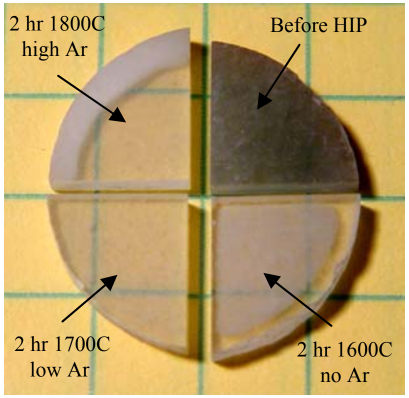


Figure 1: Different period structures printed on Si and cut for use as preforms for ceramic structures.

Figure 2: View of a 500 μm grating etched on (100) Si.

YAG ceramic



J. Wisdom*, R. Gaume

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*

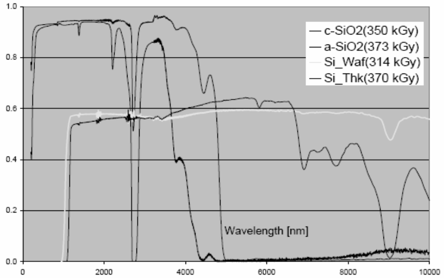


Fig. 6. Comparison of spectra from 0.20-10 μm for different forms of Si in Si equivalent dose. Spectra were matched at 3.2 μm.

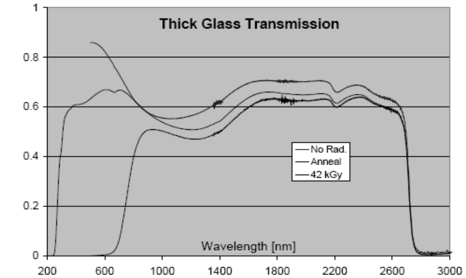


Fig. 1. Transmissivity spectra through 1.1 cm thick plate glass after Co^{60} γ-irradiation. Spectra are stacked according to their order in the insert.

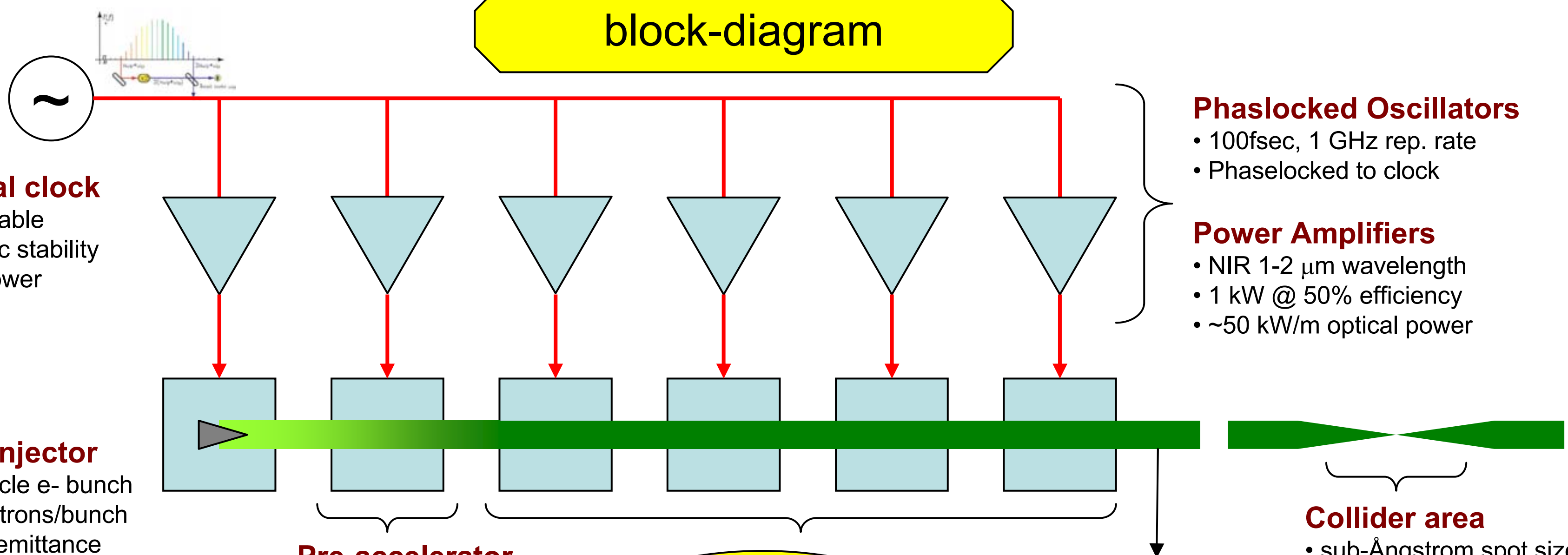
*grad. students

Outline

- **Introduction**
  - Properties unique to laser acceleration
  - Available resources and expertise
  - Emergence of new technologies
- **The physics concept and experiment**
  - The physics concept
  - The physics demonstration experiment
- **Current and future research**
  - The E163 experiment
  - Accelerator structure investigations
  - Multi-staged laser accelerator
- **Future scientific impact**
  - Candidate technology for a TeV scale collider
  - soft X-ray attosecond physics

Envisioned laser-driven TeV-scale accelerator

block-diagram



Phaslocked Oscillators
- 100fsec, 1 GHz rep. rate
- Phaselocked to clock

Power Amplifiers
- NIR 1-2 μm wavelength
- 1 kW @ 50% efficiency
- ~50 kW/m optical power

Optical clock
- ultrastable
- attosec stability
- low power

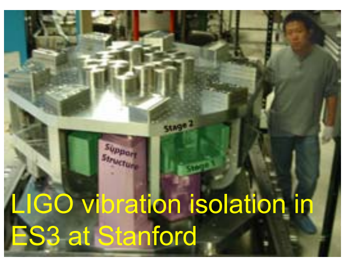
Optical Injector
- optical cycle e- bunch
- $\sim 10^4$ electrons/bunch
- ultra low emittance
- laser-driven field emitters

Pre-accelerator
- nonrelativistic
- compress bunch

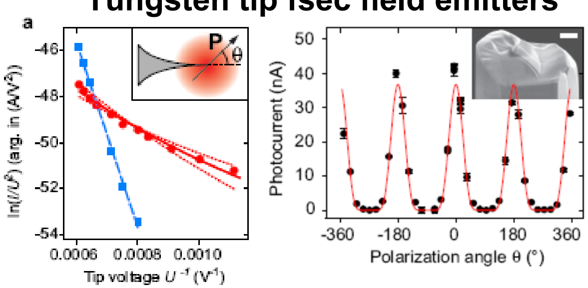
Accelerator structures
- preserve emittance
- periodic focusing
- alignment and stabilization
- coupling efficiency

Electron beam
- 1 fC/bunch
- sub μm spot size
- $\sim 10^{10}$ bunches/sec

Collider area
- sub-Ångstrom spot size
- multi-GHz rep-rate



Tungsten tip fsec field emitters



P. Hommelhoff et al

Initial focus of our research
- success of proof-of-principle exp.
- research on dielectric structures

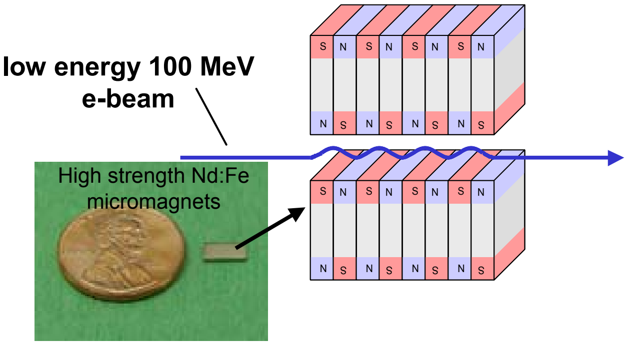
Order-of-magnitude power estimate
- 1 fC x 10^{10} x 1 TeV → 10^7 W e-beam
- 20% coupling → 5×10^7 W optical power
- 50% wallplug laser → 10^8 W electricity

100 MW electricity

Soft X-ray attosecond physics

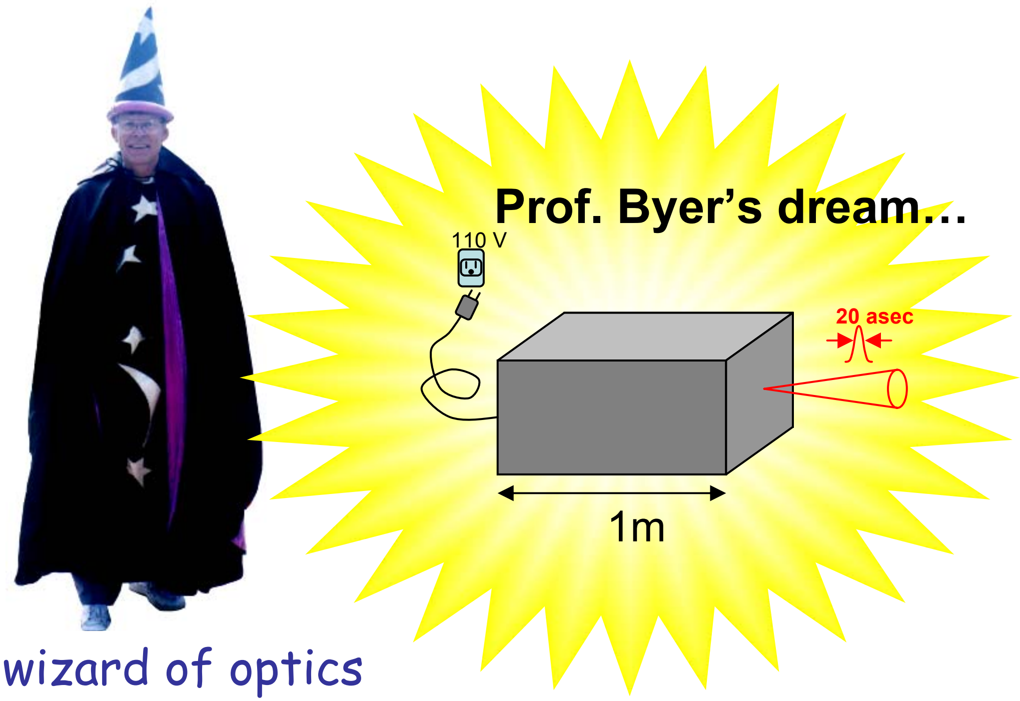
1° of optical phase at 2 μm → 20 attosec

attosec light sources



Take advantage of ultra-low emittance laser-accelerator e-beam and new magnetic materials

compact attosec soft x-ray source with medical and chemistry applications



The wizard of optics

Preliminary model studies

- **1st initial feasibility study with the 1D FEL model**
- **Attosec bunching of 1fC helps enhance the gain**
- **"low" 1 MHz rep. rate → low avg. power**
- **Further more refined studies under way**
- **It deserves a closer look**

Summary

1st proof-of-principle Vacuum based laser acceleration demonstration

Conducting R&D on dielectric based accelerator structures

Envision an approach to a TeV scale laser driven particle accelerator

Selected publications

1. Y.C. Huang, D. Zheng, W.M. Tulloch, R.L. Byer, “Proposed structure for a crossed-laser beam GeV per meter gradient vacuum electron linear accelerator”, Applied Physics Letters, 68, no. 6, p 753-755 (1996)

2. Y.C. Huang, T. Plettner, R.L. Byer, R.H. Pantell, R.L. Swent, T.I. Smith, J.E. Spencer, R.H. Siemann, H. Wiedemann, “The physics experiment for a laser-driven electron accelerator”, Nuclear Instruments & Methods in Physics Research A 407 p 316-321 (1998)

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

4. E. Colby, G. Lum, T. Plettner, J. Spencer, “Gamma Radiation Studies on Optical Materials”, IEEE Trans. Nucl. Sci. Vol. 49, No. 6, p. 2857-2867 (2002)

5. B. M. Cowan, “Two-dimensional photonic crystal accelerator structures”, Phys. Rev. ST Accel. Beams 6 101301 (2003)

6. R.H. Siemann, “Energy efficiency of laser driven, structure based accelerators”, Phys. Rev. ST AB. 7 061303 (2004)

7. T. Plettner, R. L. Byer, R. H. Siemann, “The impact of Einstein’s theory of special relativity on particle accelerators”, J. Phys. B: At. Mol. Opt. Phys. 38 S741–S752 (2005)

8. Y. C. Neil Na, R. H. Siemann, R.L. Byer, “Energy efficiency of an intracavity coupled, laser-driven linear accelerator pumped by an external laser”, Phys. Rev. ST. AB. 8, 031301 (2005)

9. T. Plettner, R.L. Byer, E. Colby, B. Cowan, C.M.S. Sears, J. E. Spencer, R.H. Siemann, “Visible-laser acceleration of relativistic electrons in a semi-infinite vacuum”, Phys. Rev. Lett. 95, 134801 (2005)

10. C.M.S. Sears, E. Colby, B. Cowan, J. E. Spencer, R.H. Siemann, T. Plettner, R.L. Byer, “High Harmonic Inverse Free Electron Laser Interaction at 800 nm”, Phys. Rev. Lett. 95, 194801 (2005)

11. 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)

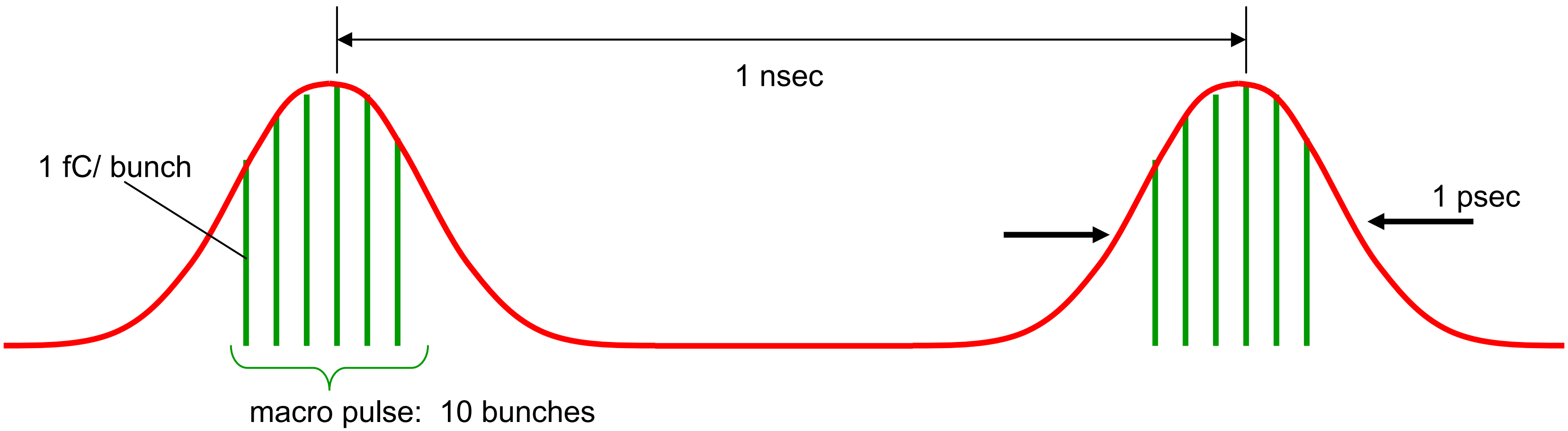
Backup slides

TeV scale laser accelerator parameters

accelerator field wavelength	λ	2 μm
laser pulse repetition rate	f	1 GHz } 10^{10}/sec
bunches per laser pulse "macro-pulse"	n	10 }
electrons / bunch	N	~6000 (1 fC)
accelerator beam diameter	σ	0.1 μm
beam diameter at IP focus	σ	0.1 Å
transverse geometric emittance	ε	10^{-11} m-rad
β at IP	β_0	10 μm
approximate luminosity at IP	$L \approx \frac{nfN^2}{4\pi\sigma_x\sigma_y}$	~10^{34}/cm^2-sec

TeV scale laser accelerator pulse structure

target gradient	G	1 GeV/m
laser pulse duration	T_{laser}	1 psec
electron bunch duration	T_e	20 attosec

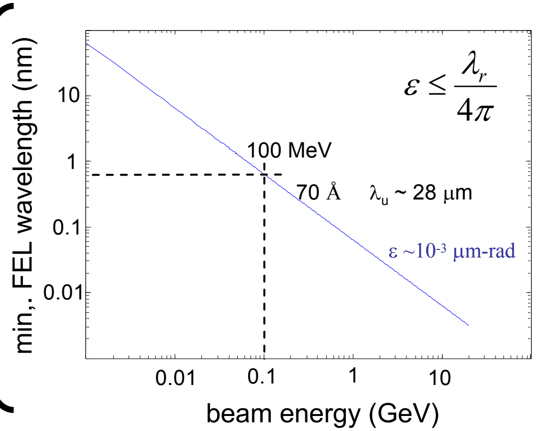


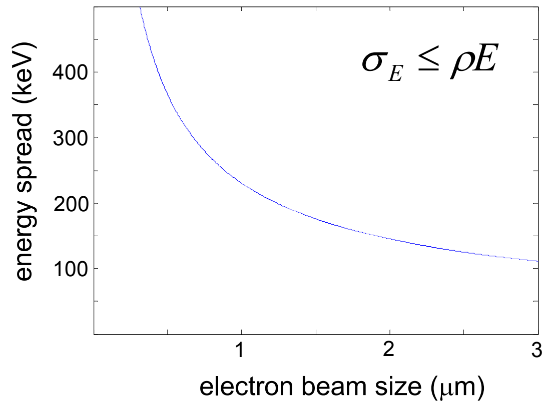
total beam current	I_b	10 μA
total beam power at 1 TeV	P_b	10 MW

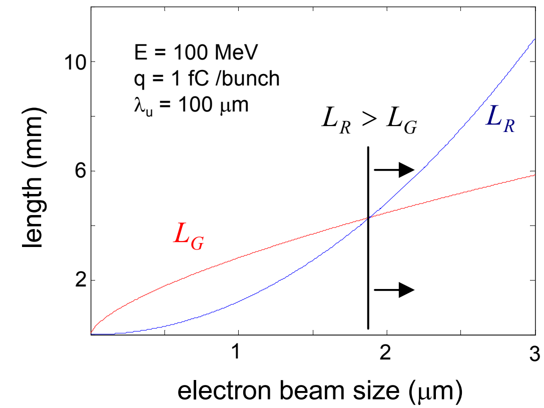
Soft X-ray attosecond physics - detail

Starting point

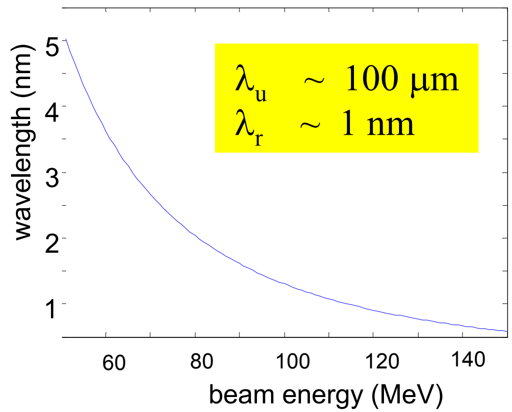
1-D FEL model
Design parameters must satisfy these conditions





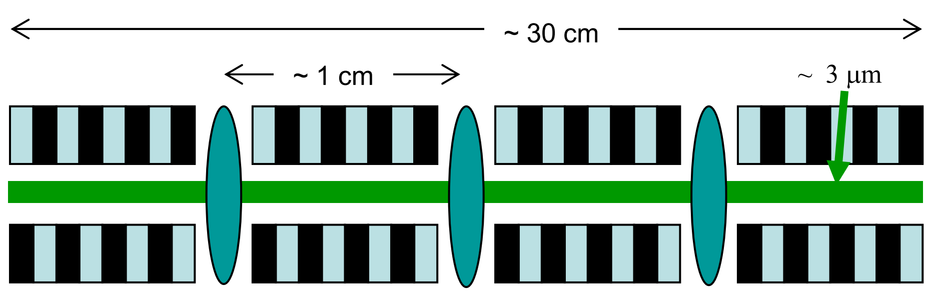


Undulator design



L_{FODO} ~ 1 cm $\quad L_G$ ~ 1 cm $\quad \varepsilon$ ~ 10^{-9} m-rad $\quad \lambda_b$ ~ 18 attosec

σ_{xy} ~ 3 μm $\quad L_{sat}$ ~ 30 cm $\quad q_b$ ~ 1 fC $\quad U_b$ ~ 10^{-7} J



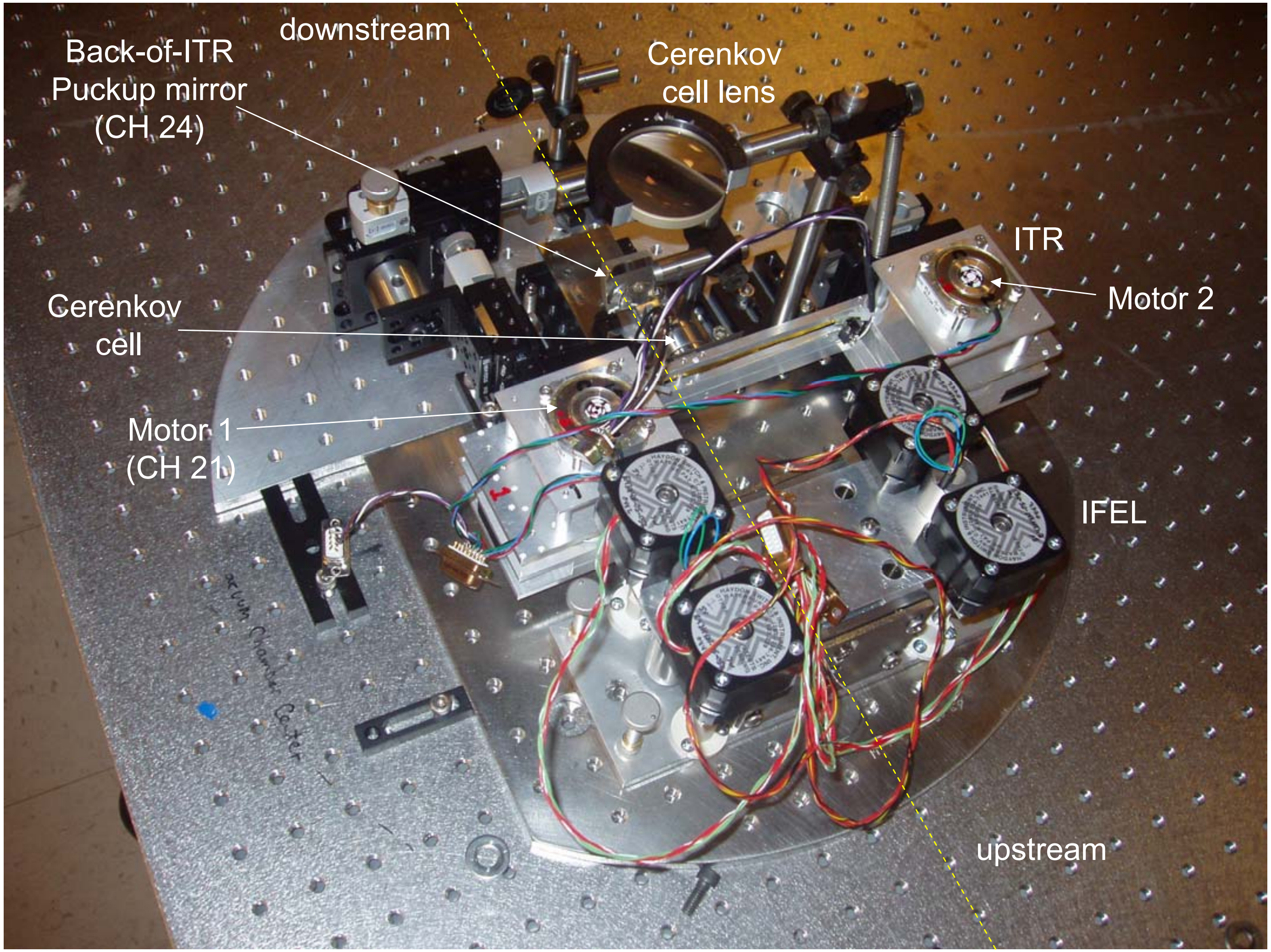
Laser power required

f_{rep} ~ 1 MHz
η_{acc} ~ 1%
P_{acc} ~ 10 W optical power
η_{laser} ~ 10 % wallplug efficiency
P_e ~ 100 W optical power

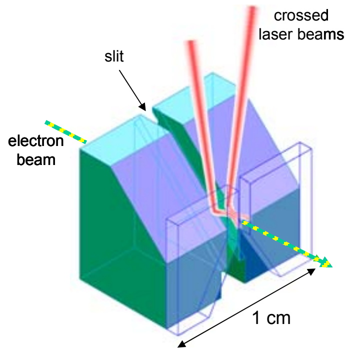
1% conversion efficiency

1% of $U_b = 10^{-7}$ J
U ~ 10^7 Photons
~ 1 nJ/pulse

The laser accelerator and IFEL



The tape boundary

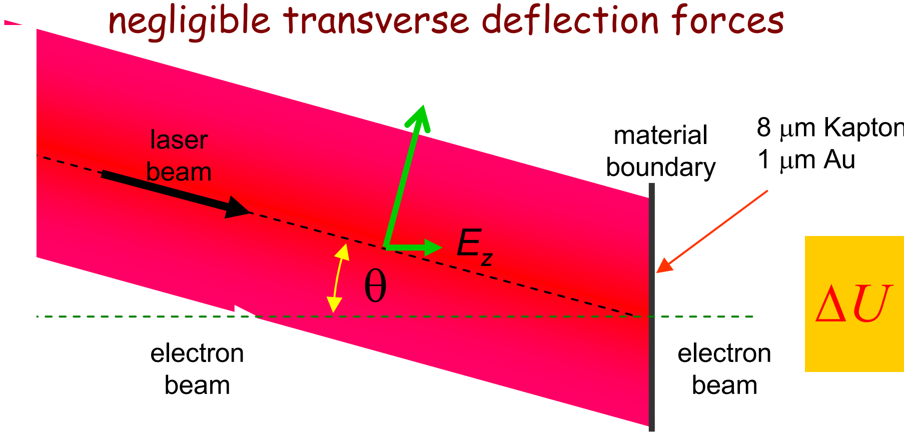


Improve on

- Operation tolerances
- Poor reliability
- Ease of operation

1. **Damage threshold**
   - ignore it!
   - devise a "disposable" unit
   - materials retain their optical properties for a few picoseconds after a destructive laser pulse
2. **Cell geometry**
   - simplify to one semi-infinite boundary
   - make boundary thin enough to run e-beam through it
   - make boundary movable to present a new surface for each laser shot
3. **Crossed laser beams**
   - two laser beams too difficult? → eliminate one of them
   - no more optical phase uncertainty problems
   - negligible transverse deflection forces

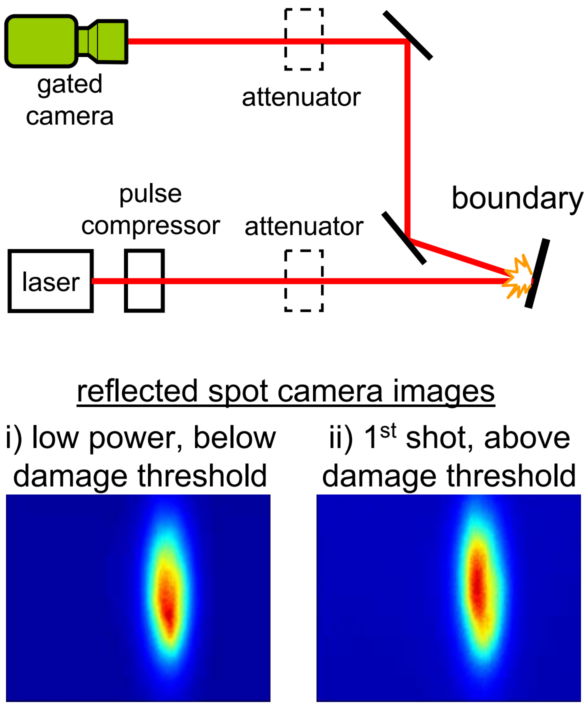
Conceptual drawing of the improved setup



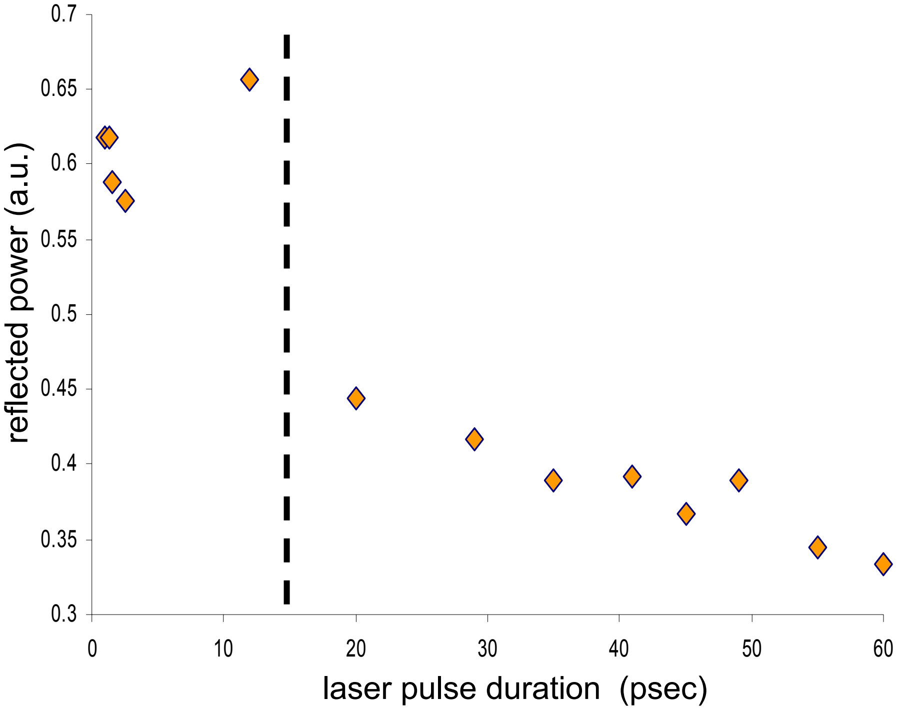
$$\Delta U = \int_{-\infty}^{0} E_z dz$$

The tape boundary

a) Setup for the reflected spot measurements

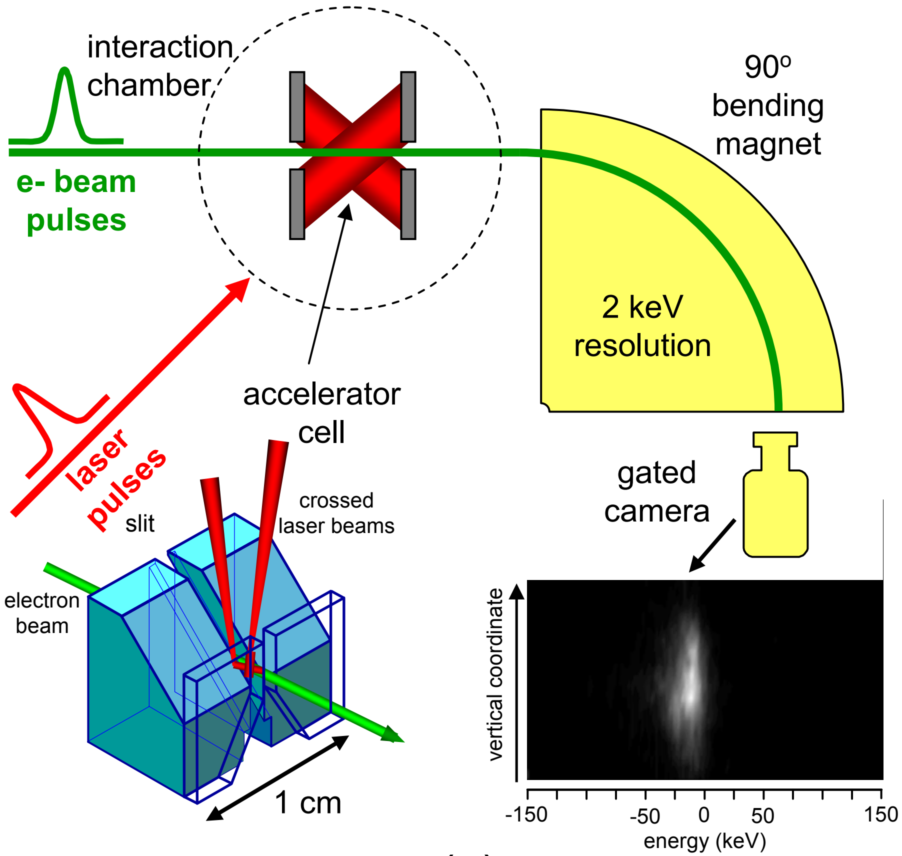


b) Reflected pulse intensity versus laser pulse duration

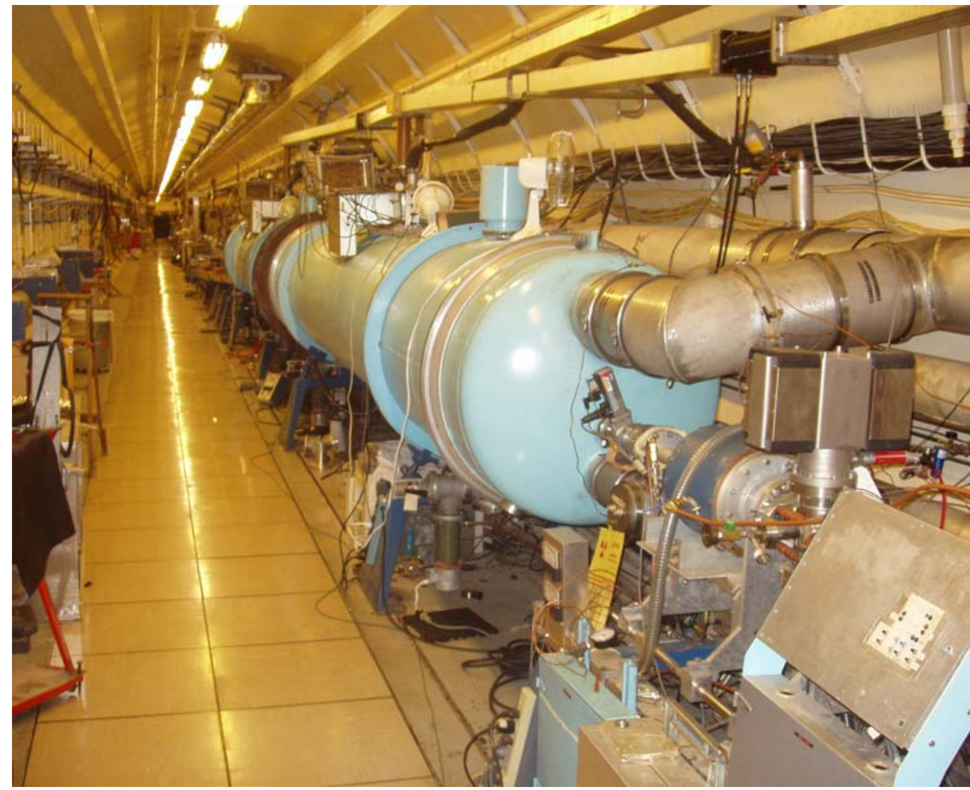


Laser Electron Accelerator Program

Located in the Hansen Lab on Stanford Campus



(a)



(b)

The crossed-beam laser accelerator Cell and magnet for electron beam energy measurements.

The view of the 30 MeV super-conducting linear accelerator in the underground tunnel on campus in the HEPL lab.