Laser Accelerators:
A Path toward Coherent Attosecond X-rays

Robert L. Byer,
Tomas Plettner, Eric Colby, Ben Cowan, Chris Sears, Jim Spencer
and
Robert H. Siemann

Department of Applied Physics
SLAC National Accelerator Laboratory
Stanford University

ABSTRACT

In 1947 W. W. Hansen and colleagues accelerated electrons with microwaves generated from a Klystron. That work led to the 3km linear accelerator at the Stanford Linear Accelerator Center completed in 1968.

In November 2005 we successfully accelerated electrons with a visible laser light. Today we are conducting experiments at SLAC to develop photonic bandgap dielectric based accelerator structures to efficiently couple laser radiation to electrons. The dielectric structures allow laser accelerators to operate at accelerating gradients of 1GeV/meter.

We have explored the possibility of laser accelerator driven coherent X-rays using a free electron laser. The approach looks promising because of the replacement of the traditional magnet based undulator with a laser driven dielectric based undulator.

Robert H. Siemann Symposium
July 7, 2009

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Laser Electron Accelerator Project – LEAP

The TeV-Energy Physics Frontier

Future Opportunities

Coherent X-ray lasers

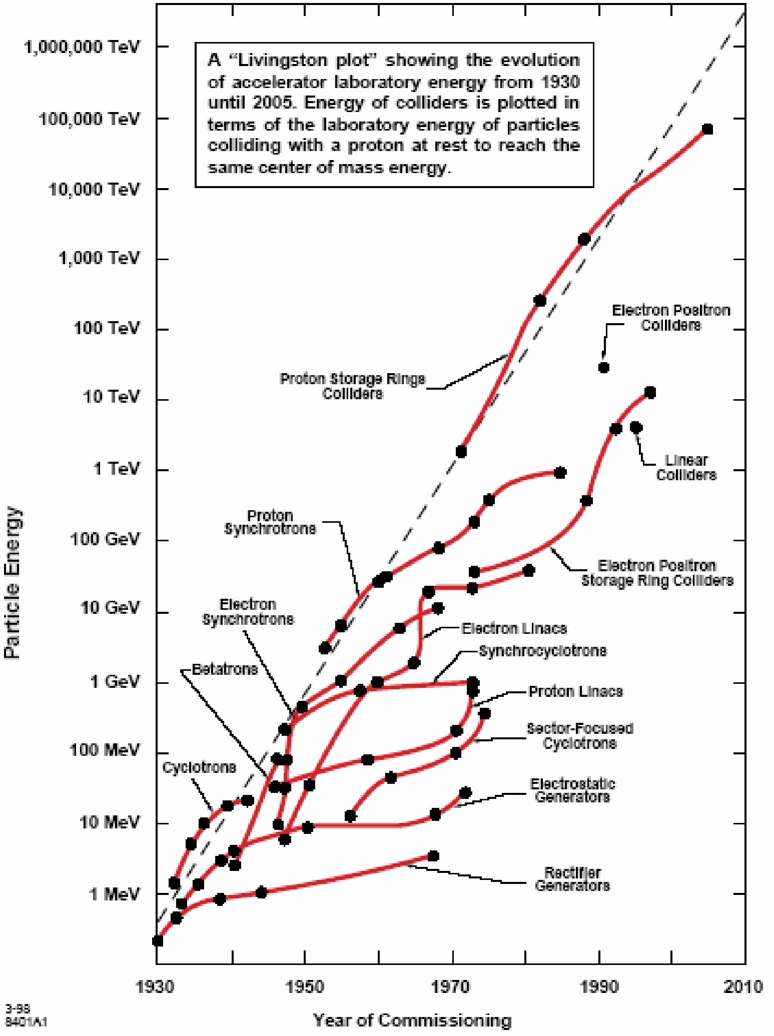
The Attosecond Physics Frontier

"Don't undertake a project unless it is manifestly important and nearly impossible."
Edwin Land – 1982

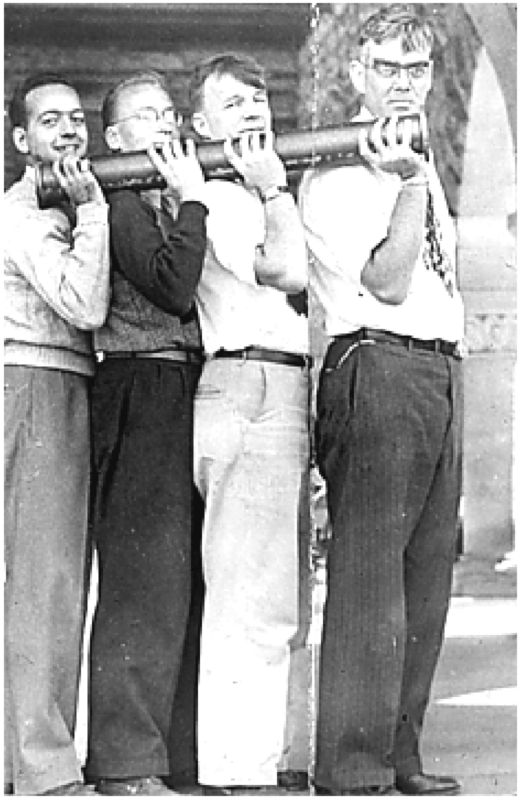
Professor Robert Siemann and Chris Sears

June 15, 2008 – Stanford Graduation Ceremonies

Livingston Plot of Particle Energy vs. Year



A "Livingston plot" showing the evolution of accelerator laboratory energy from 1930 until 2005. Energy of colliders is plotted in terms of the laboratory energy of particles colliding with a proton at rest to reach the same center of mass energy.



W. W. Hansen

1947

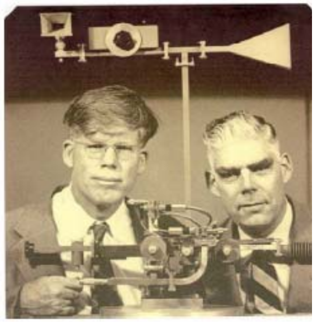
Mark 1

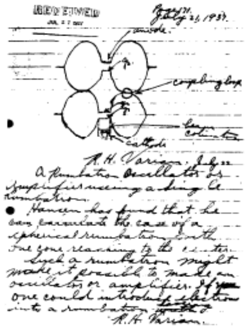
6 MeV

The First Linear Accelerator at Stanford - 1947

Particle accelerator research at Stanford

1st Klystron (Varian, 1930s')





RECEIVED
JUL 2 7 1937

July 21, 1937.

R. H. Varian. July 22

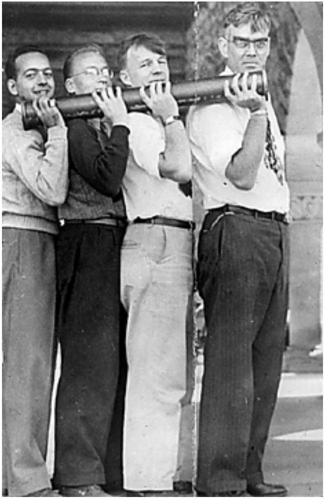
A Rhumbatron Oscillator or Amplifier using a single Rhumbatron.

Hansen has found that he can calculate the case of a spherical rhumbatron with the zone reaching to the center.

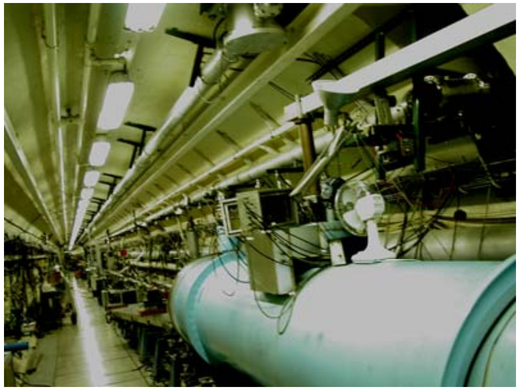
Such a rhumbatron might make it possible to make an oscillator or amplifier. If ~~you~~ one could introduce electrons into a rhumbatron ~~with~~

R. H. Varian.

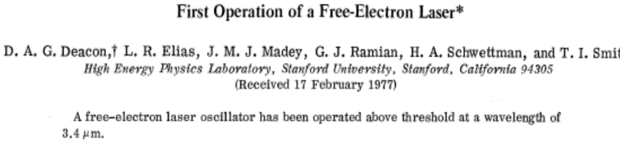
1st Linac 1946



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)

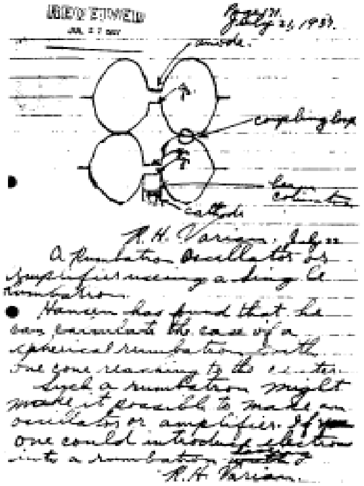
A free-electron laser oscillator has been operated above threshold at a wavelength of 3.4 μm.

LEAP, 1997-2004

The 2-mile collider (SLAC)

The Klystron tube

The “Microwave” Lab (Now HEPL and Ginzton Labs) played a crucial role on the development of particle accelerators and the corresponding RF technology



R. H. Varian. July 22

A Rumbatron Oscillator or Amplifier using a Ring Rumbatron.

Hansen has found that he can calculate the case of a spherical rumbatron with one zone running to the center.

Such a rumbatron might make it possible to make an oscillator or amplifier. If one could introduce electrons into a rumbatron [illegible]

R. H. Varian.

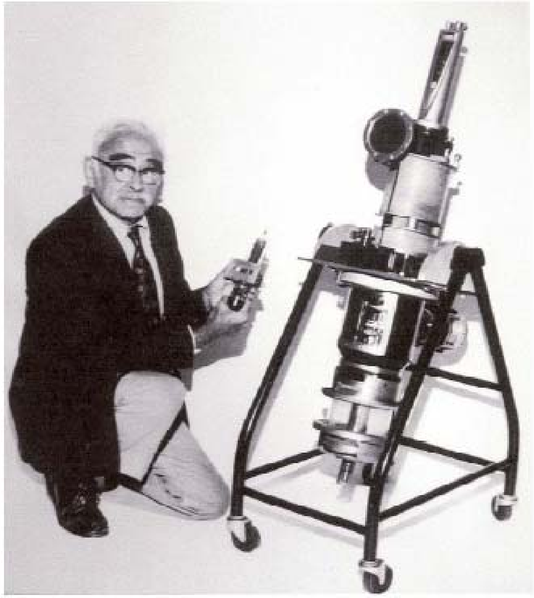
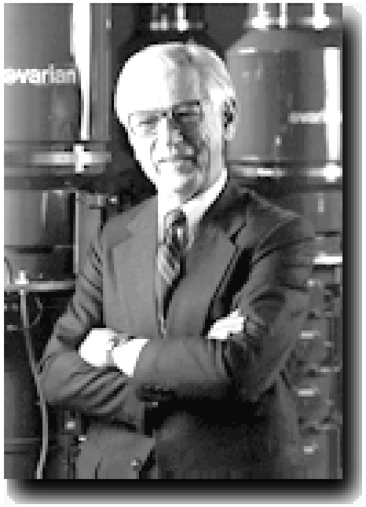


Fig. 10 Marvin Chodorow comparing the CV-150 to the Mark III klystron

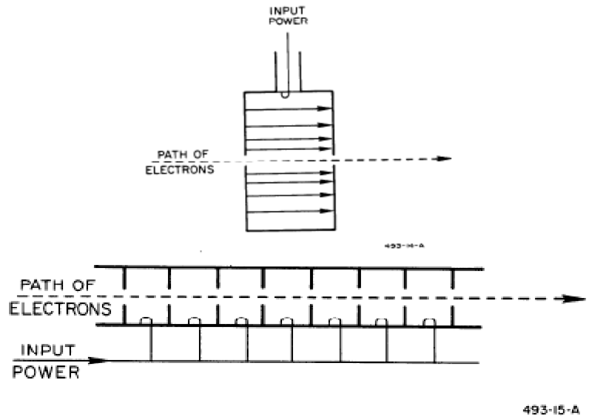
Marvin Chodorow & Klystron

W. W. Hansen – back right



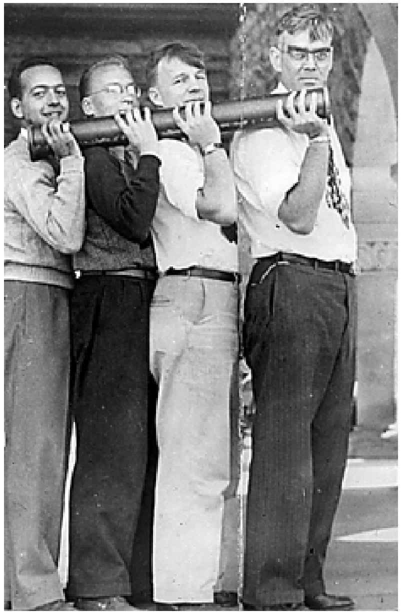
Ed Ginzton

The development of the linear accelerator at Stanford University

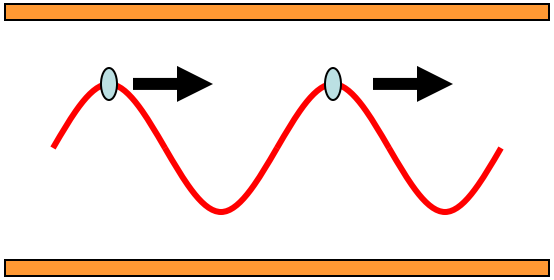


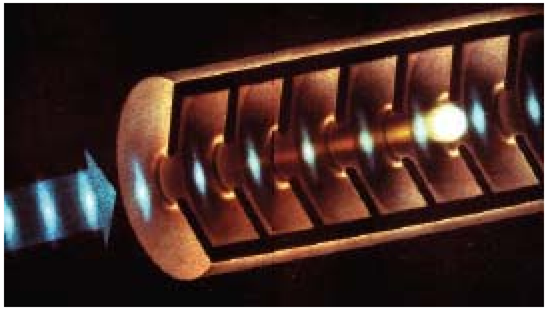
“we have accelerated electrons”

Hansen's report to the Office of Naval Research

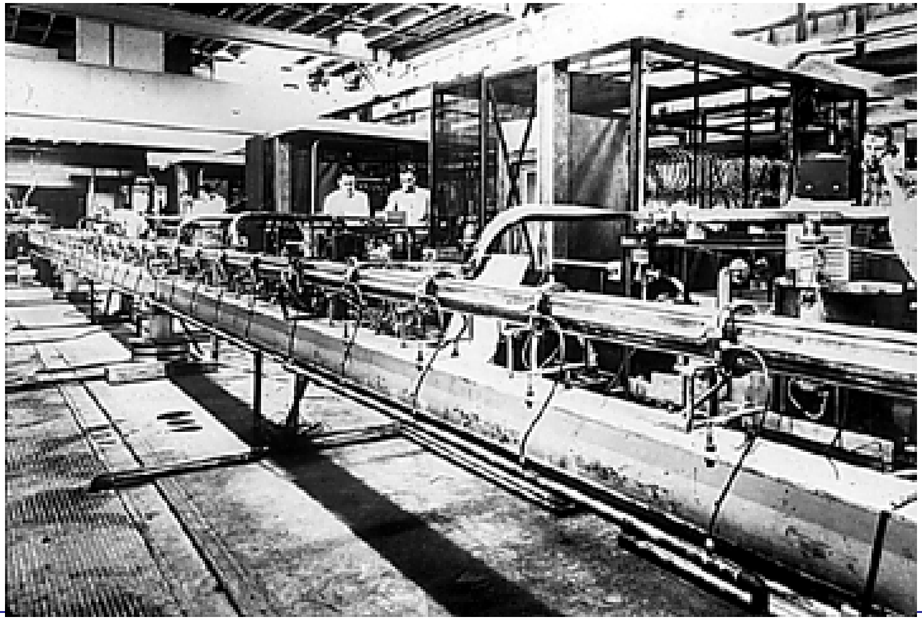


1947: **The Mark I**, 1m, 6 MeV





$$U = \int \vec{E} \cdot d\vec{r}$$



The Mark III

A high-energy physics research tool

1953: 400 MeV
1955: 600 MeV
1960: 1 GeV

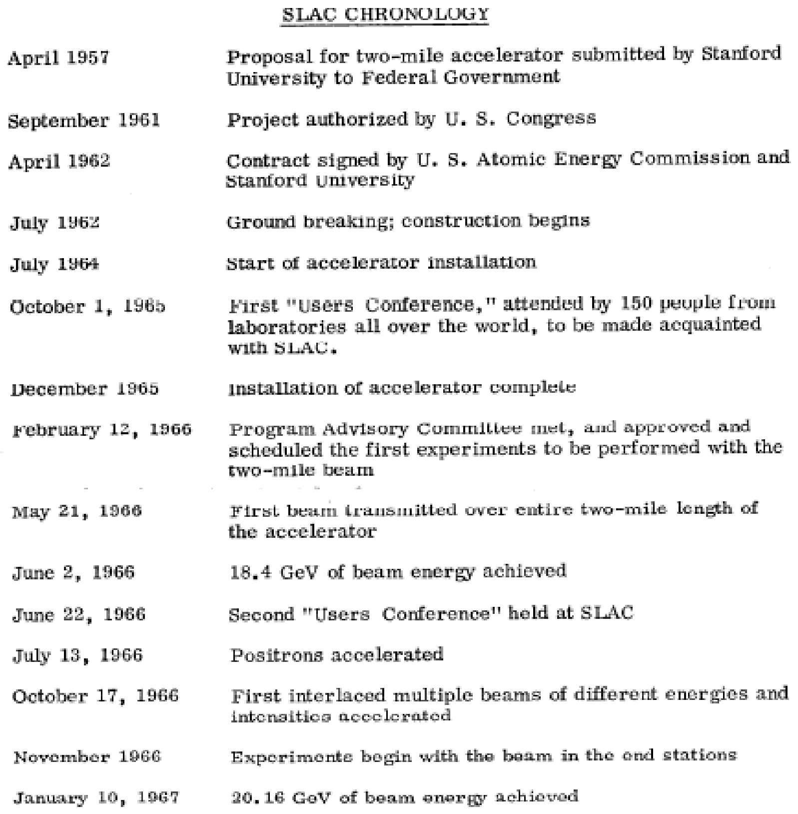
Meson Physics carried out by W. K.H. Panofsky

High resolution electron scattering from nuclei by R.Hofstadter

SLAC: The two-mile accelerator

"Project M"

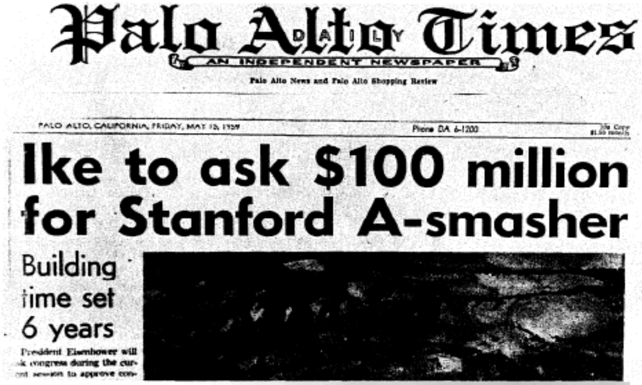
1955 first brainstorming and informal discussions



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	Experiments 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



Palo Alto Daily Times

AN INDEPENDENT NEWSPAPER

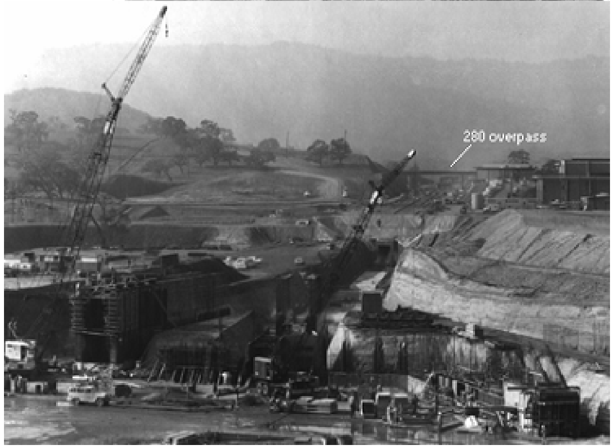
Palo Alto News and Palo Alto Shopping Review

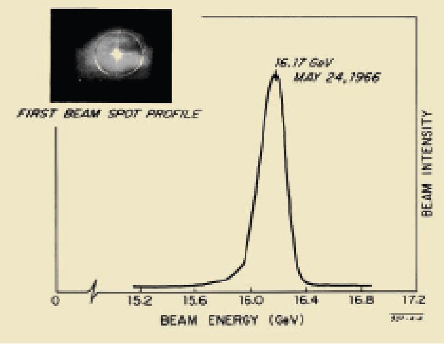
PALO ALTO, CALIFORNIA, FRIDAY, MAY 15, 1959 Phone DA 6-1200

Ike to ask $100 million for Stanford A-smasher

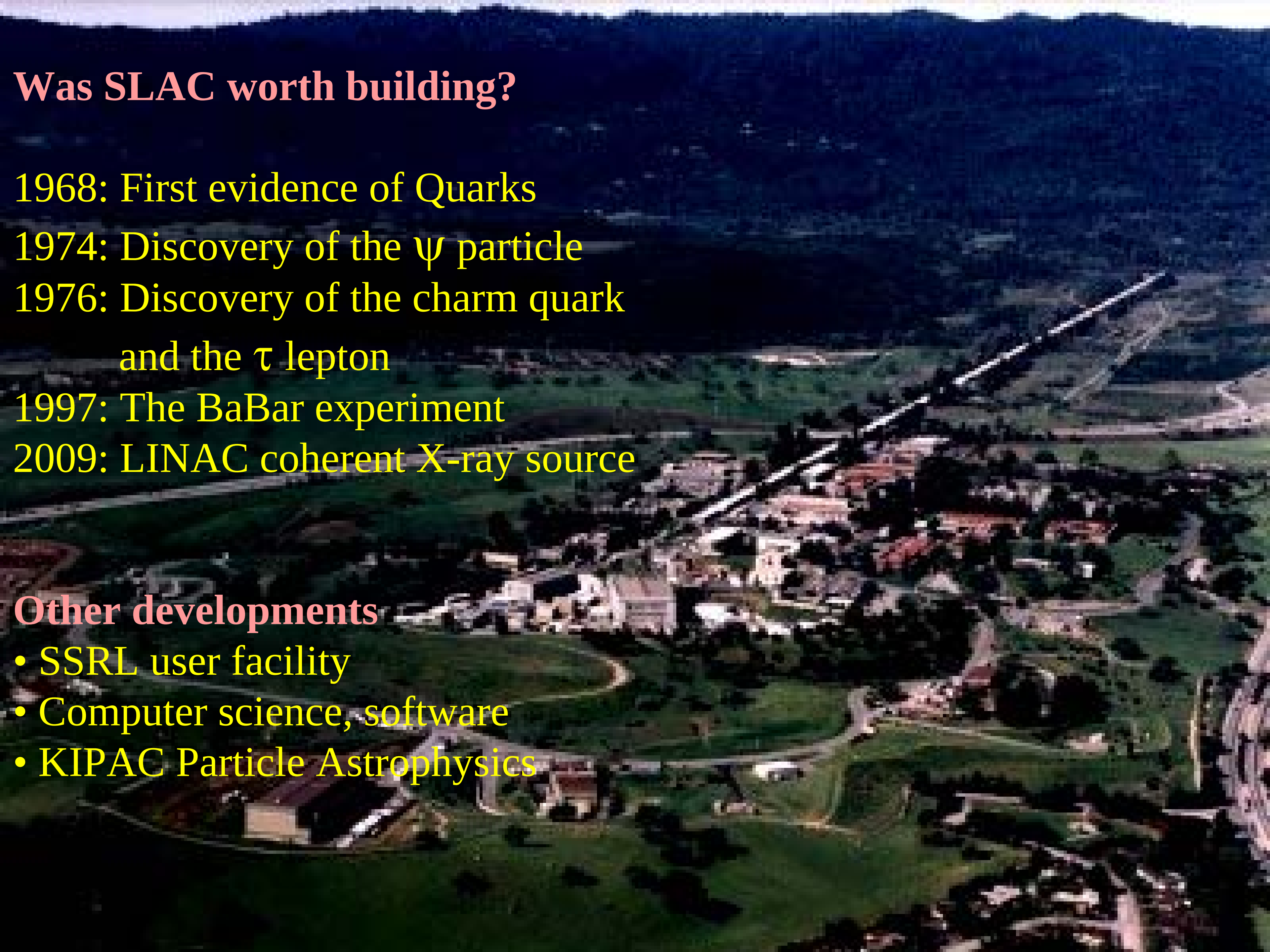
Building time set 6 years

President Eisenhower will ask congress during the current session to approve con-





First beam at SLAC, 1966



Was SLAC worth building?

1968: First evidence of Quarks

1974: Discovery of the ψ particle

1976: Discovery of the charm quark
and the τ lepton

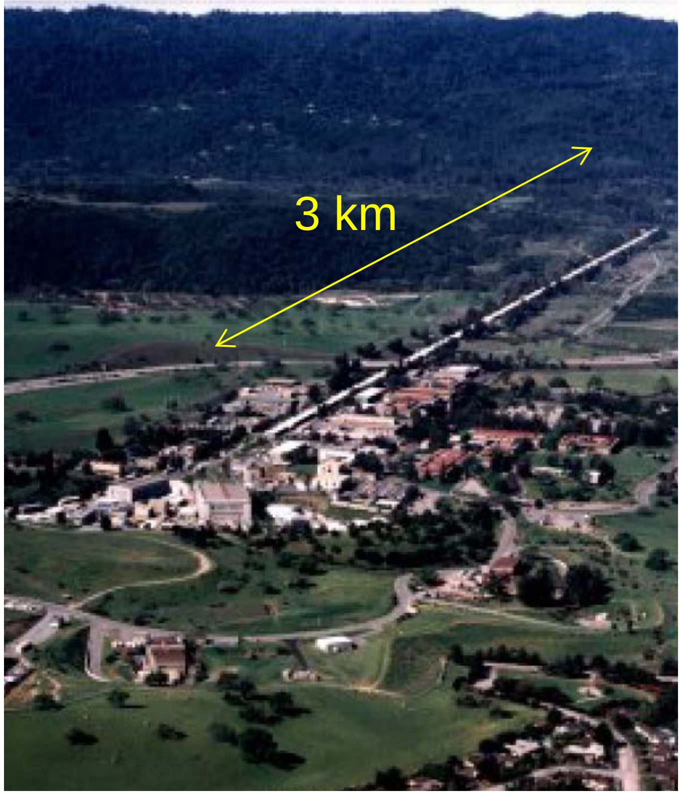
1997: The BaBar experiment

2009: LINAC coherent X-ray source

Other developments

- SSRL user facility
- Computer science, software
- KIPAC Particle Astrophysics

Existing and Proposed Linear Accelerators



Existing SLAC – 50 GeV

Proposed ILC Accelerator 1 TeV

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.

The Livingston curve

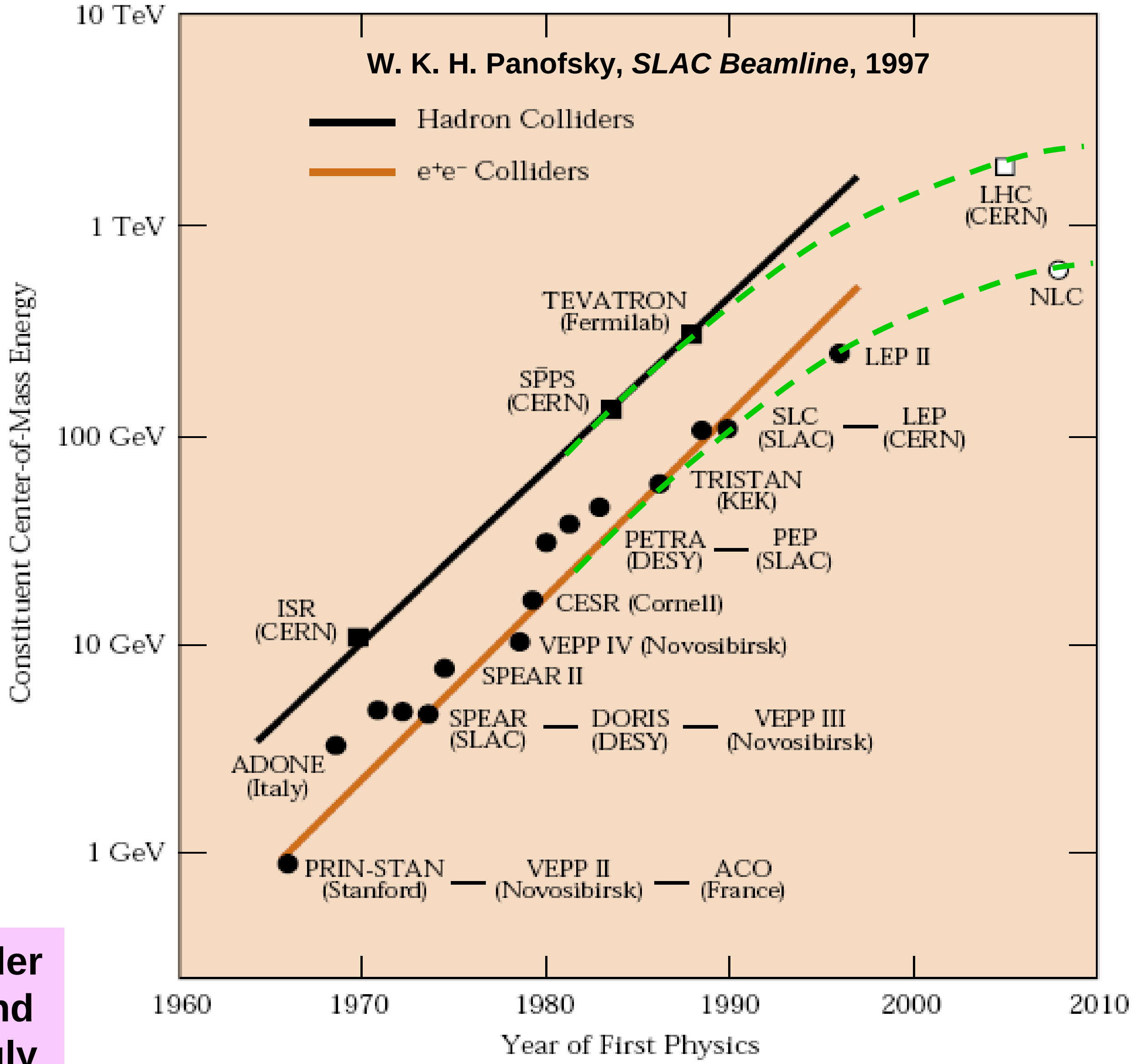
1. near-exponential growth in the beam energy up until about 1990

2. LHC and future NLC/ILC lie below the exponential growth curve

3. Exponential curve important for new physics

RF based accelerator technology is nearing its practical high-energy limit

For future high energy collider facilities beyond the LHC and ILC it becomes increasingly appealing to invest in new accelerator technologies

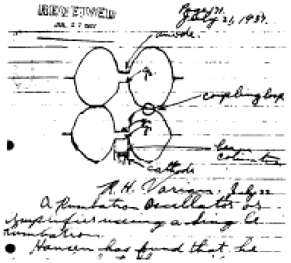


Future Goal

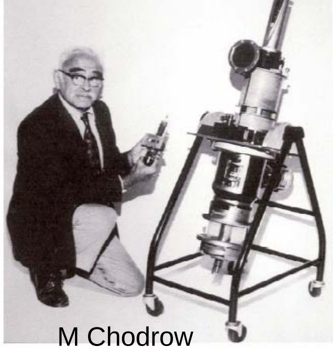
Maximum gradient ~ >1GeV/m

From Klystron to High power lasers

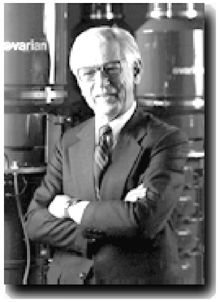
Klystron Microwave generators (1930s)



Varian brothers



M Chodrow



E.L. Ginzton

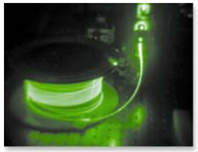
RF linear accelerator;
based on
Klystron technology
(1930s)

Diode pumped solid state lasers

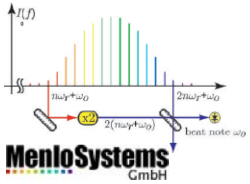
efficient pump diodes

60 W/bar, 50% electr. efficiency

high peak – power lasers



ultrafast laser technology



Features of interest to us

- **very compact, tabletop systems**
- **optical phase control**
- **pump diodes → 50% efficiency**
- **solid state gain medium → 80%**

Overall wallplug efficiency > 30%

possibility for ultra-short pulse operation (100 fsec or shorter)

Laser-driven particle acceleration

- Idea came about soon after the invention of high-peak power lasers (earliest articles go back to 1971)

- different laser particle acceleration concepts
    - ponderomotive
    - **linear electric field**
    - inverse cherenkov
    - inverse FEL
    - active gain medium
    - laser driven plasma wakefield
    - …

- experimental demonstrations are fairly "recent"

- still a controversial topic

NETWORKING IN THE IMMUNE SYSTEM • NANOTECH BATTERIES

SCIENTIFIC AMERICAN

How to Protect New Orleans from Future Storms

FEBRUARY 2006
WWW.SCIAM.COM

Big Physics Gets Small

Tabletop Accelerators Make Particles Surf on Plasma Waves

How to Stop Nuclear Terrorists

Guess Who Owns Your Genes?

CSI: Washington (George, that is)

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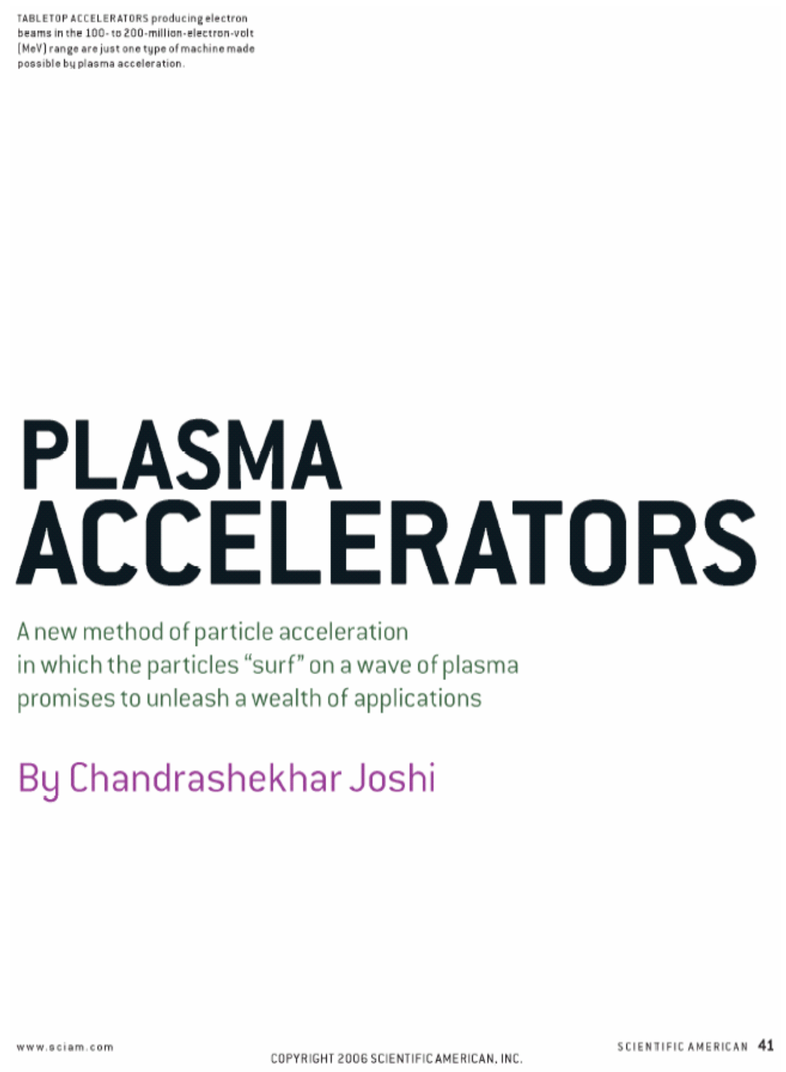

TABLETOP ACCELERATORS producing electron beams in the 100- to 200-million-electron-volt (MeV) range are just one type of machine made possible by plasma acceleration.

PLASMA ACCELERATORS

A new method of particle acceleration in which the particles “surf” on a wave of plasma promises to unleash a wealth of applications

By Chandrashekhar Joshi

www.sciam.com

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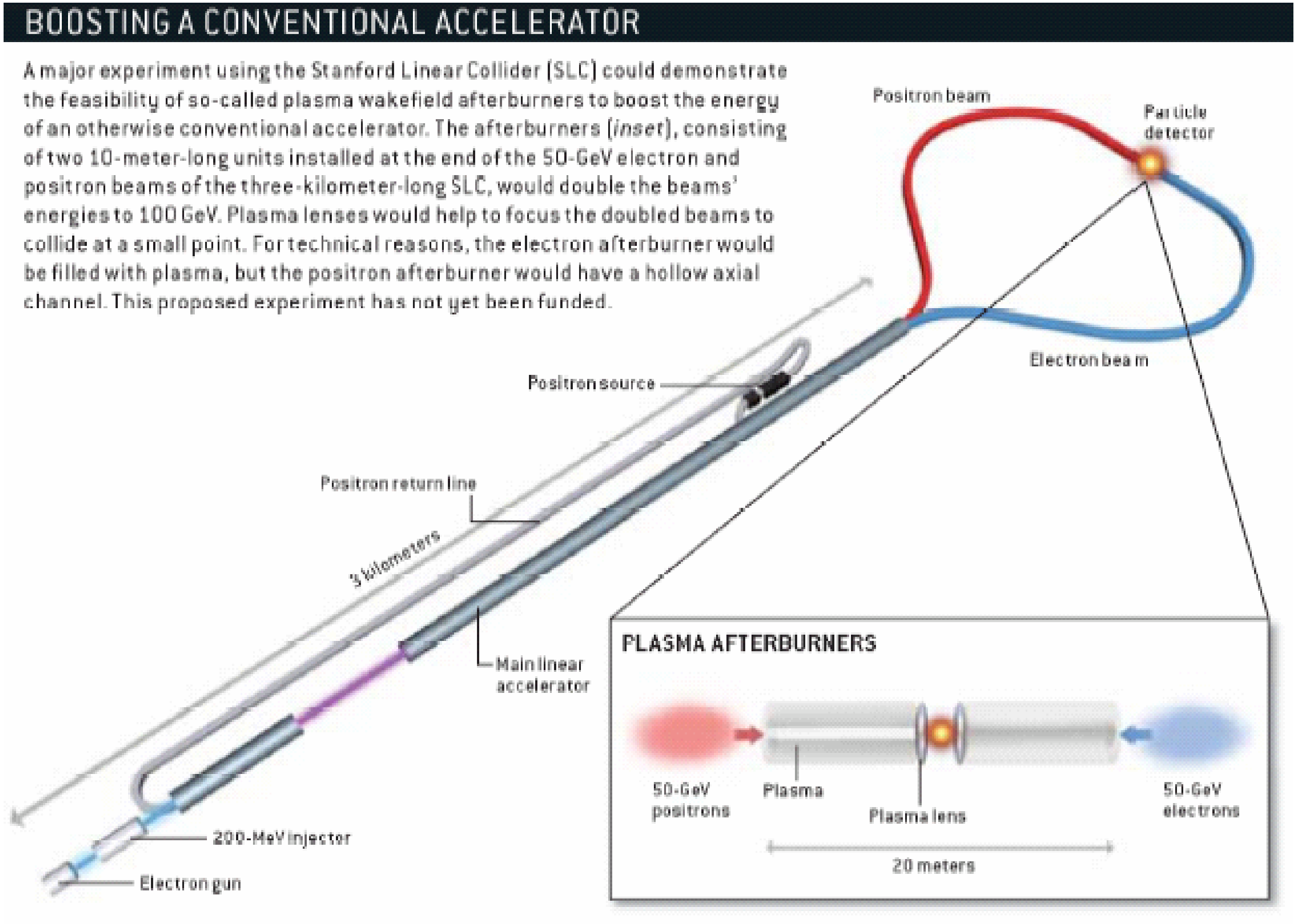
SCIENTIFIC AMERICAN 41

Wakefield Accelerator as a Booster for SLAC



BOOSTING A CONVENTIONAL ACCELERATOR

A major experiment using the Stanford Linear Collider (SLC) could demonstrate the feasibility of so-called plasma wakefield afterburners to boost the energy of an otherwise conventional accelerator. The afterburners (*inset*), consisting of two 10-meter-long units installed at the end of the 50-GeV electron and positron beams of the three-kilometer-long SLC, would double the beams' energies to 100 GeV. Plasma lenses would help to focus the doubled beams to collide at a small point. For technical reasons, the electron afterburner would be filled with plasma, but the positron afterburner would have a hollow axial channel. This proposed experiment has not yet been funded.

A few rules of the game

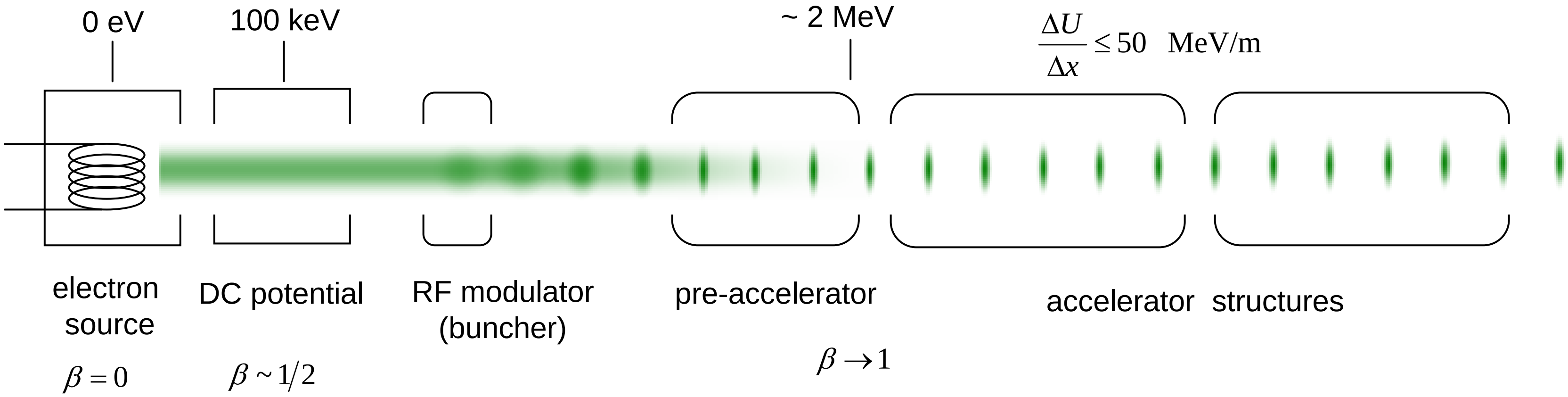
"An accelerator is just a transformer" – Pief Panofsky

"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

$\frac{\Delta U}{\Delta x} \le 50 \text{ MeV/m}$

electron source

DC potential

RF modulator (buncher)

pre-accelerator

accelerator structures

$\beta = 0$

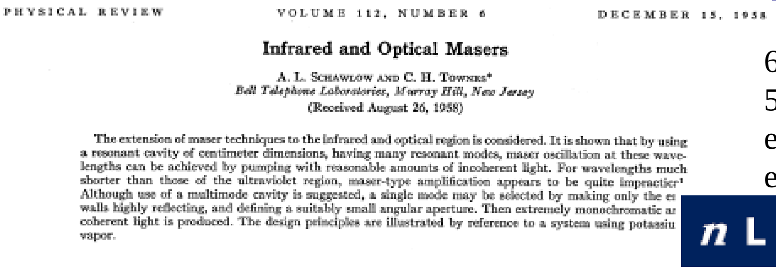
$\beta \sim 1/2$

$\beta \to 1$

1974 –sabbatical leave, Lund **1994** – SLAC summer school **2004** – **Successful 1st Exp**

“New” technology: the laser

Byer Group



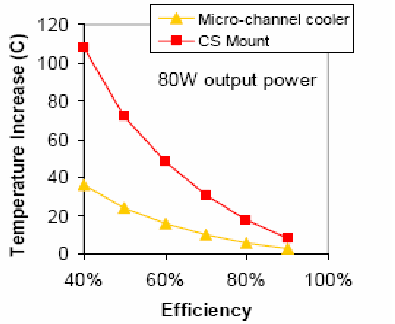
PHYSICAL REVIEW VOLUME 112, NUMBER 6 DECEMBER 15, 1958

Infrared and Optical Masers

A. L. Schawlow and C. H. Townes*
Bell Telephone Laboratories, Murray Hill, New Jersey
(Received August 26, 1958)

The extension of maser techniques to the infrared and optical region is considered. It is shown that by using a resonant cavity of centimeter dimensions, having many resonant modes, maser oscillation at these wavelengths can be achieved by pumping with reasonable amounts of incoherent light. For wavelengths much shorter than those of the ultraviolet region, maser-type amplification appears to be quite impractical. Although use of a multimode cavity is suggested, a single mode may be selected by making only the e walls highly reflecting, and defining a suitably small angular aperture. Then extremely monochromatic a coherent light is produced. The design principles are illustrated by reference to a system using potassiu vapor.

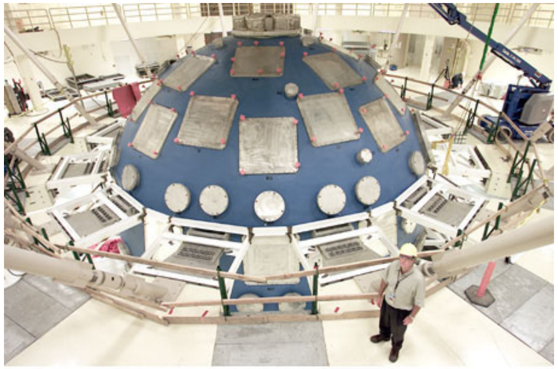
60 W/bar
50% now **78%**
electrical
efficiency



Improve efficiency of bar from 50%-80%

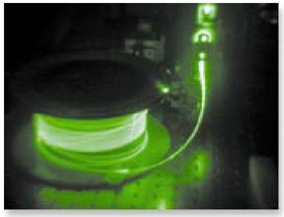
high power solid state lasers

The Hoya Production II laser glass melting campaign was completed,yielding over 1700 amplifier slab blanks



Target chamber with steel frameworks for catwalks being installed.

high power fiber lasers



NUFERN

ALABAMA LASER

modelocked laser technology

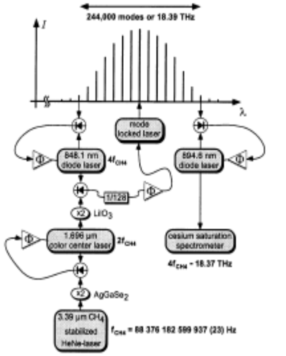


FIG. 1. Frequency chain that allows the comparison of the precisely known frequency of a methane stabilized He-Ne laser at 88.4 THz (3.39 μm) with the cesium D_1 transition at 335 THz (895 nm).

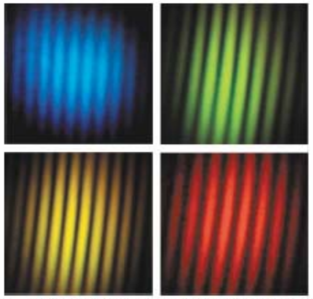
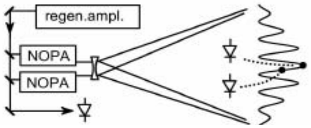
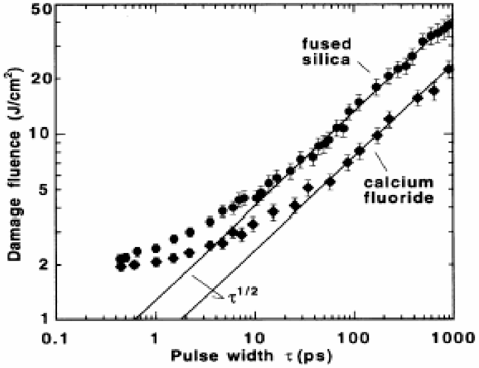


Fig. 2. Interference between two separate NOPAs for various center wavelengths.



damage threshold of dielectric materials



Stuart, et. al,, Phys Rev. Lett. Vol 74, No 12 p. 2248 (1995)

10 GV/m fields for 100 fsec laser pulses

Contents

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Laser Electron Accelerator Project – LEAP

- HEPL Experiments from 1997 – Nov 2004
- Future E163 Experiments at SLAC

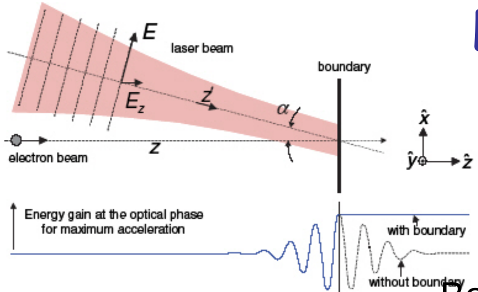
The TeV-Energy Physics Frontier

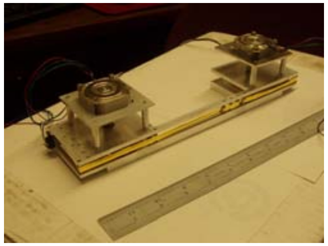
Future Opportunities

- Coherent X-ray lasers
- The Attosecond Physics Frontier

"Don't undertake a project unless it is manifestly important and nearly impossible." **Edwin Land – 1982**

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[†]

Technion Israeli Institute of Technology

Levi Schächter[*]

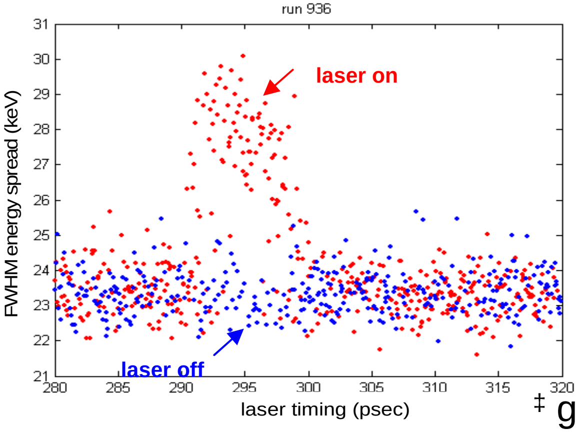
UCLA

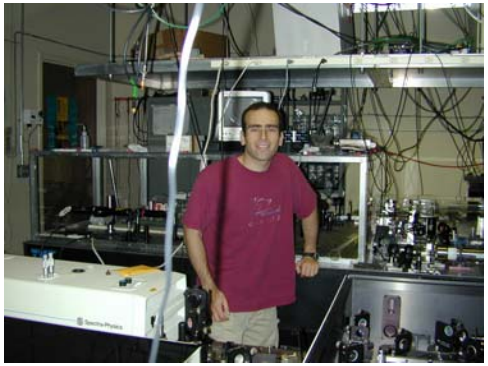
J. Rosenzweig[*]

and

DOE

David Sutter





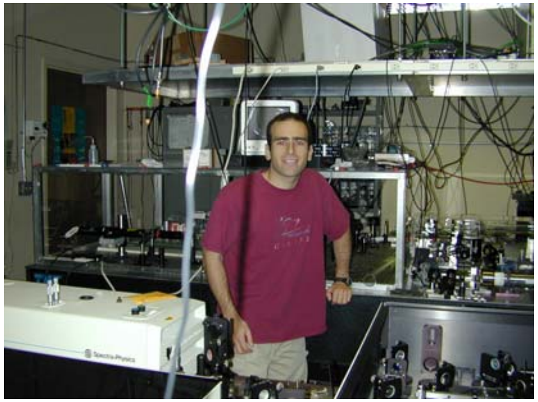
‡ grad students † postdocs and staff * faculty

Participants in the LEAP Experiment

Laser Electron Accelerator Program

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

Vacuum laser acceleration

1 Energy gain through longitudinal electric field

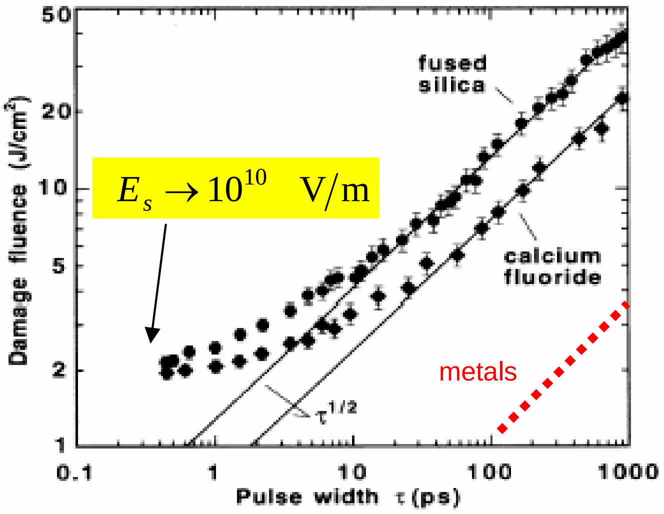
- gradient = longitudinal electric field
- linear e-beam trajectory
  - → no synchrotron radiation
  - → **energy scalable**

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

linear particle acceleration process

2 Dielectric based structure with vacuum channel

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



$E_s \to 10^{10} \quad \text{V/m}$

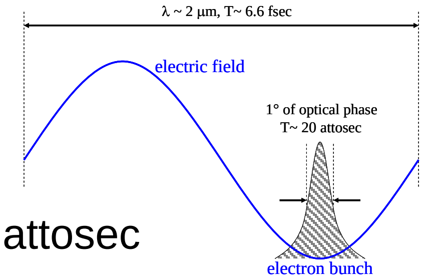
very high peak electric fields

vacuum channel

NIR solid-state lasers

3 Inherent attosec electron pulse

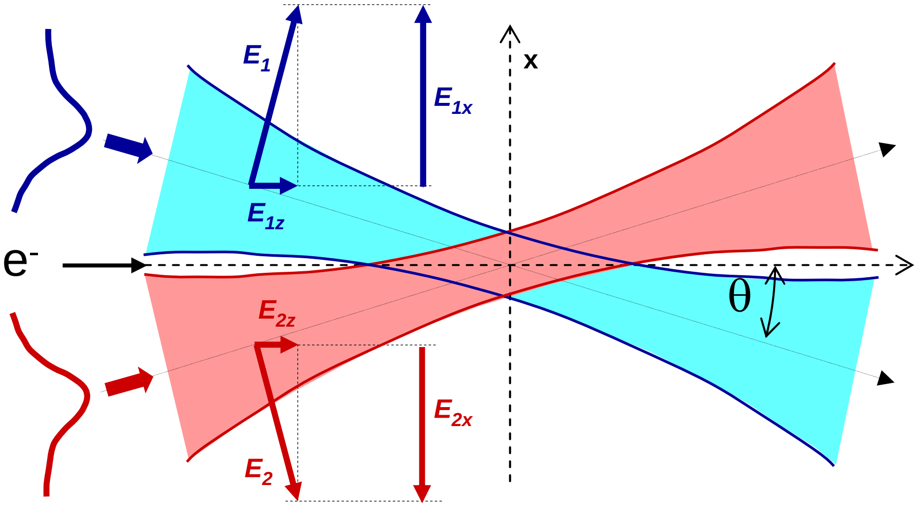
2 μm laser → 6 fsec period
→ 1deg of phase = 20 attosec



Unique opportunity for light sources

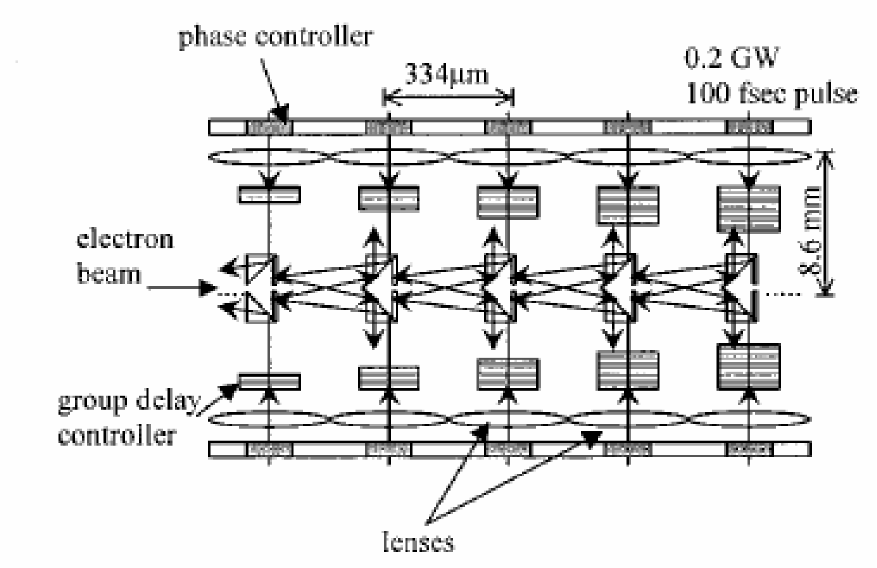
Proposed Crossed-Beam Laser Accelerator

The interaction length is limited by phase drift to less than 400 microns



(a)

The properly phased crossed laser beams have zero transverse field and only a longitudinal field component E_z.



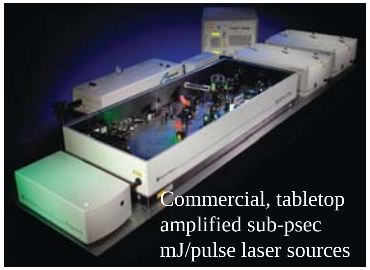
(b)

An early concept for resetting the phase every 334 microns to keep the electrons and the applied laser field phased.

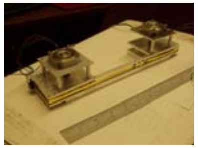
The Super Conducting Accelerator - FEL facility

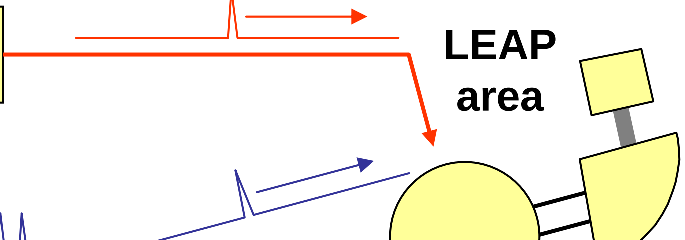
The SCA Accelerator provided a source of 30MeV electrons for LEAP

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



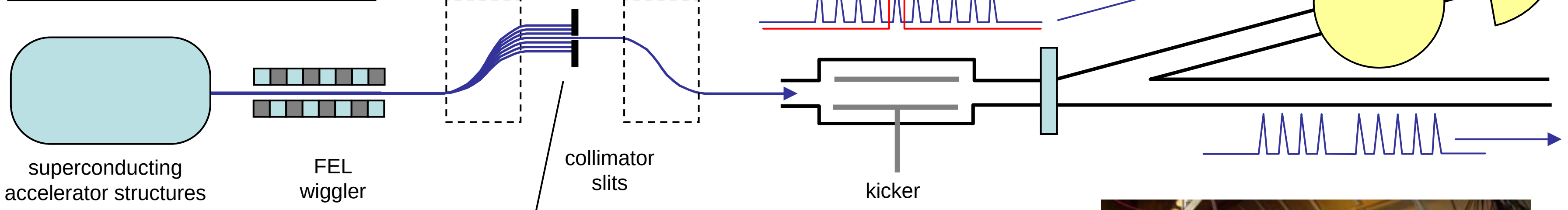
Commercial, tabletop amplified sub-psec mJ/pulse laser sources





amplified laser

LEAP area

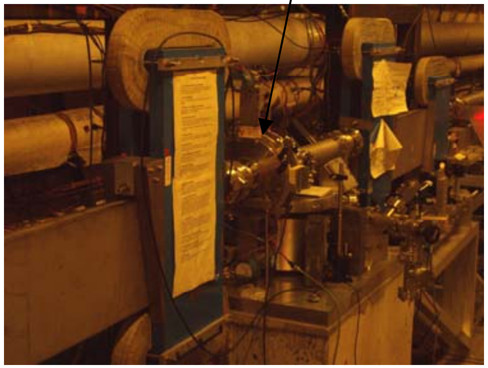


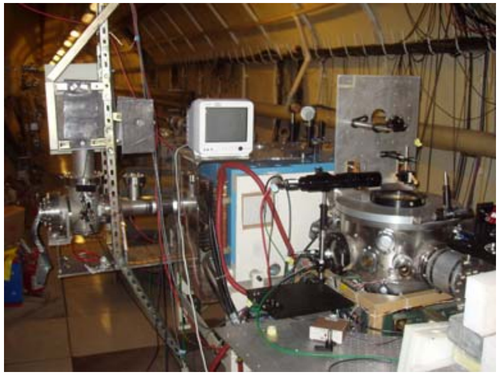
superconducting accelerator structures

FEL wiggler

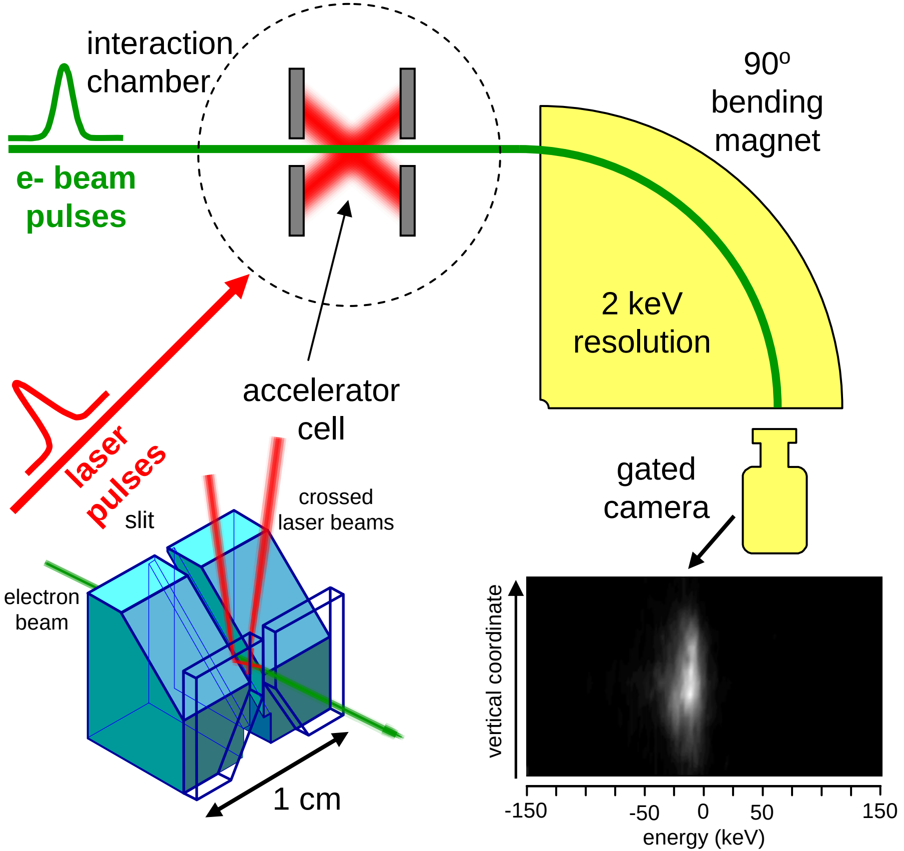
collimator slits

kicker

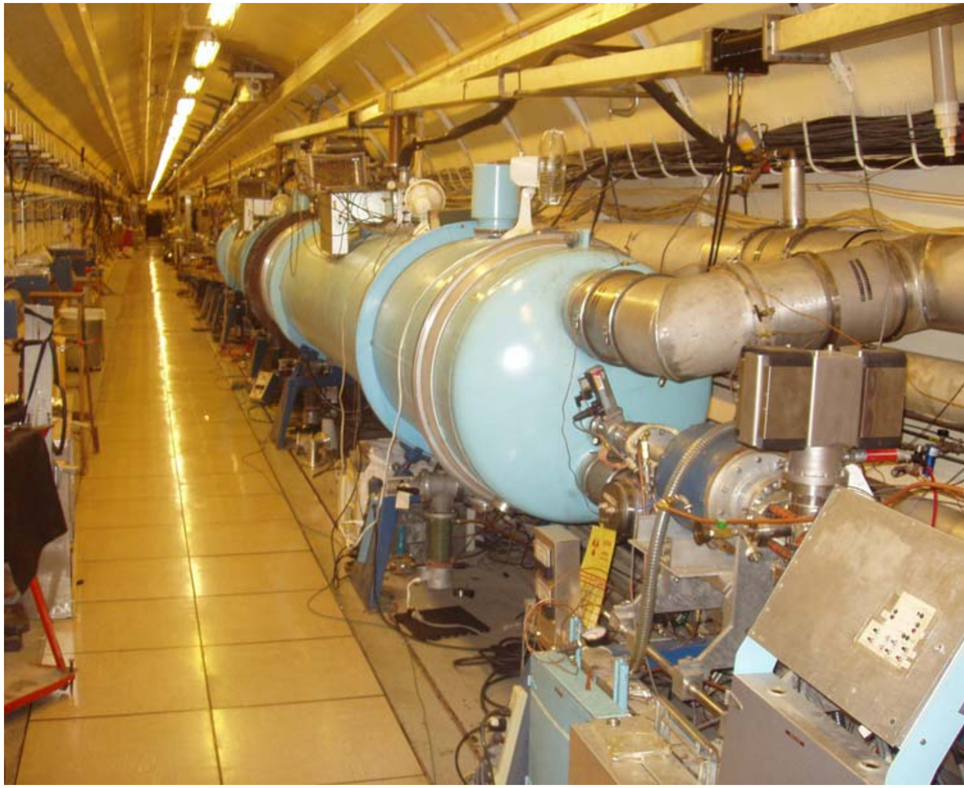




Laser Electron Accelerator Program
Located in the Hansen Lab on Stanford Campus



(a)

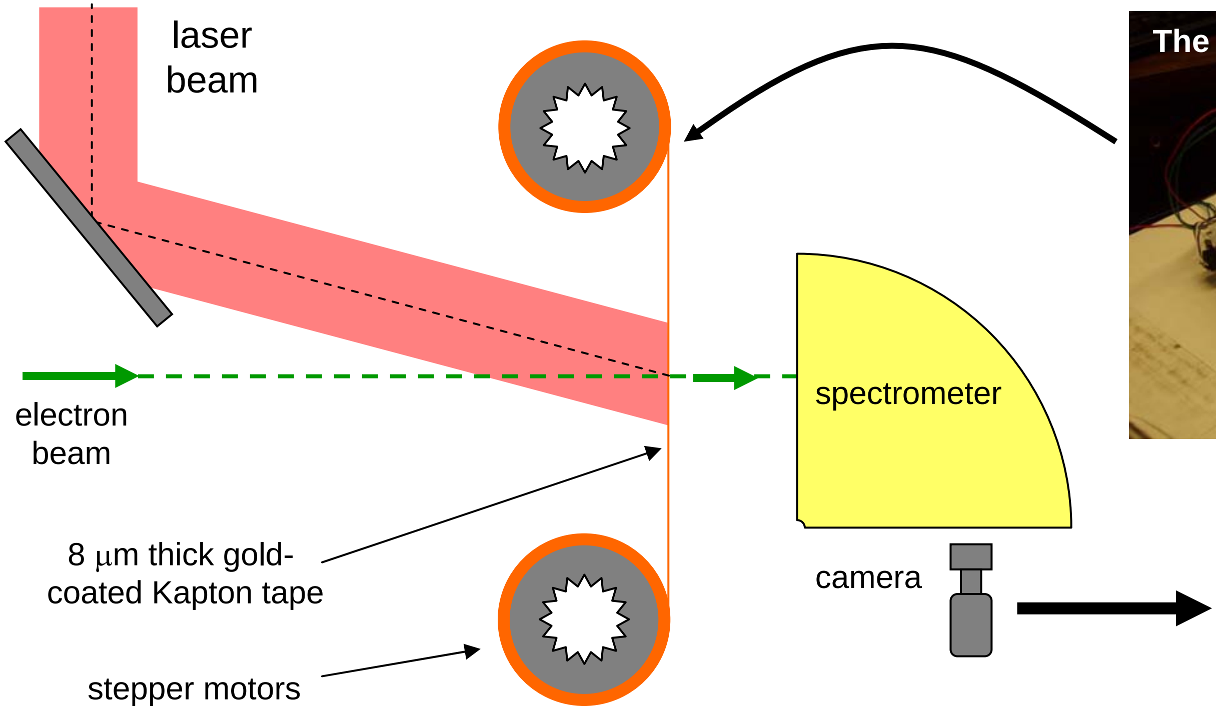


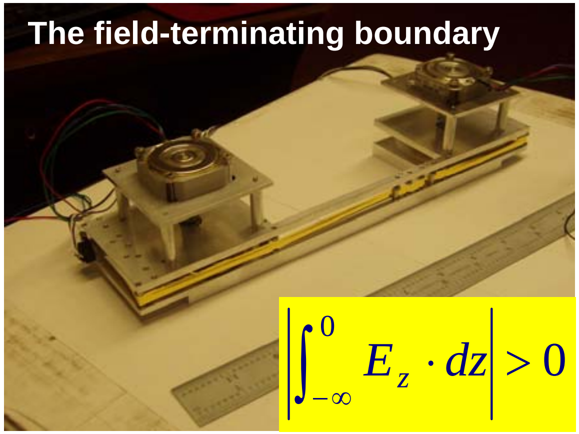
(b)

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

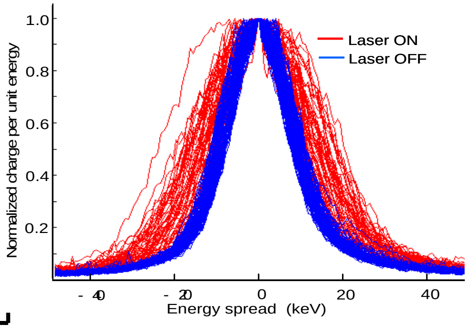
The view of the 30 MeV super-conducting linear accelerator in the underground tunnel on campus in the HEPL lab.

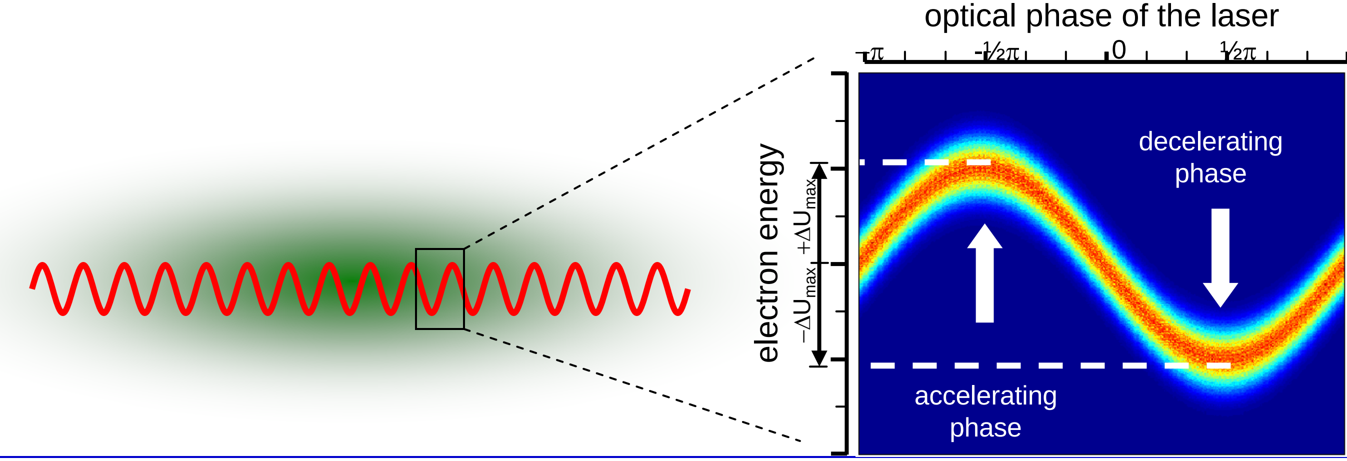
The LEAP experiment
(Laser Electron Accelerator Project)

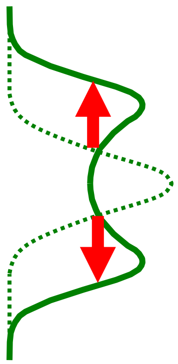



The field-terminating boundary

$$\left|\int_{-\infty}^{0} E_z \cdot dz\right| > 0$$



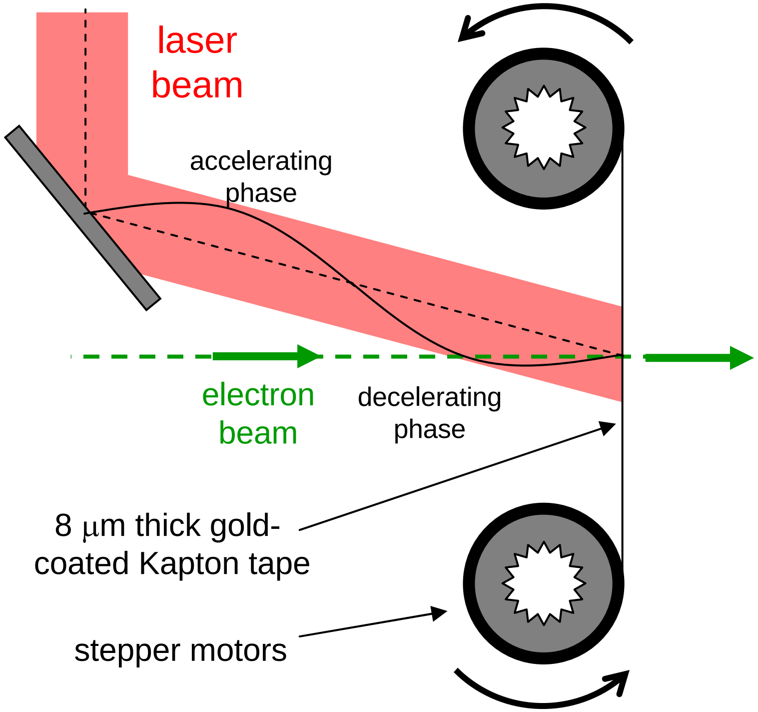


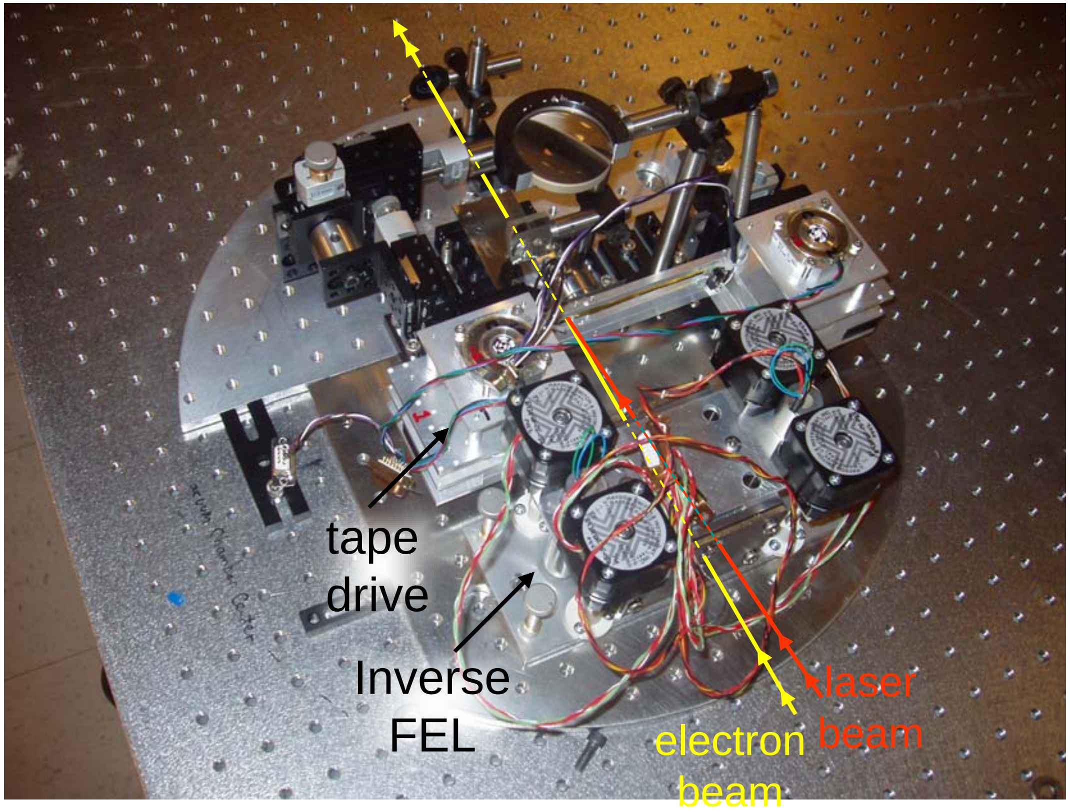


broadening of the initial energy spread of the electron beam

LEAP Experimental Success- November 2004

We have accelerated electrons with visible light!

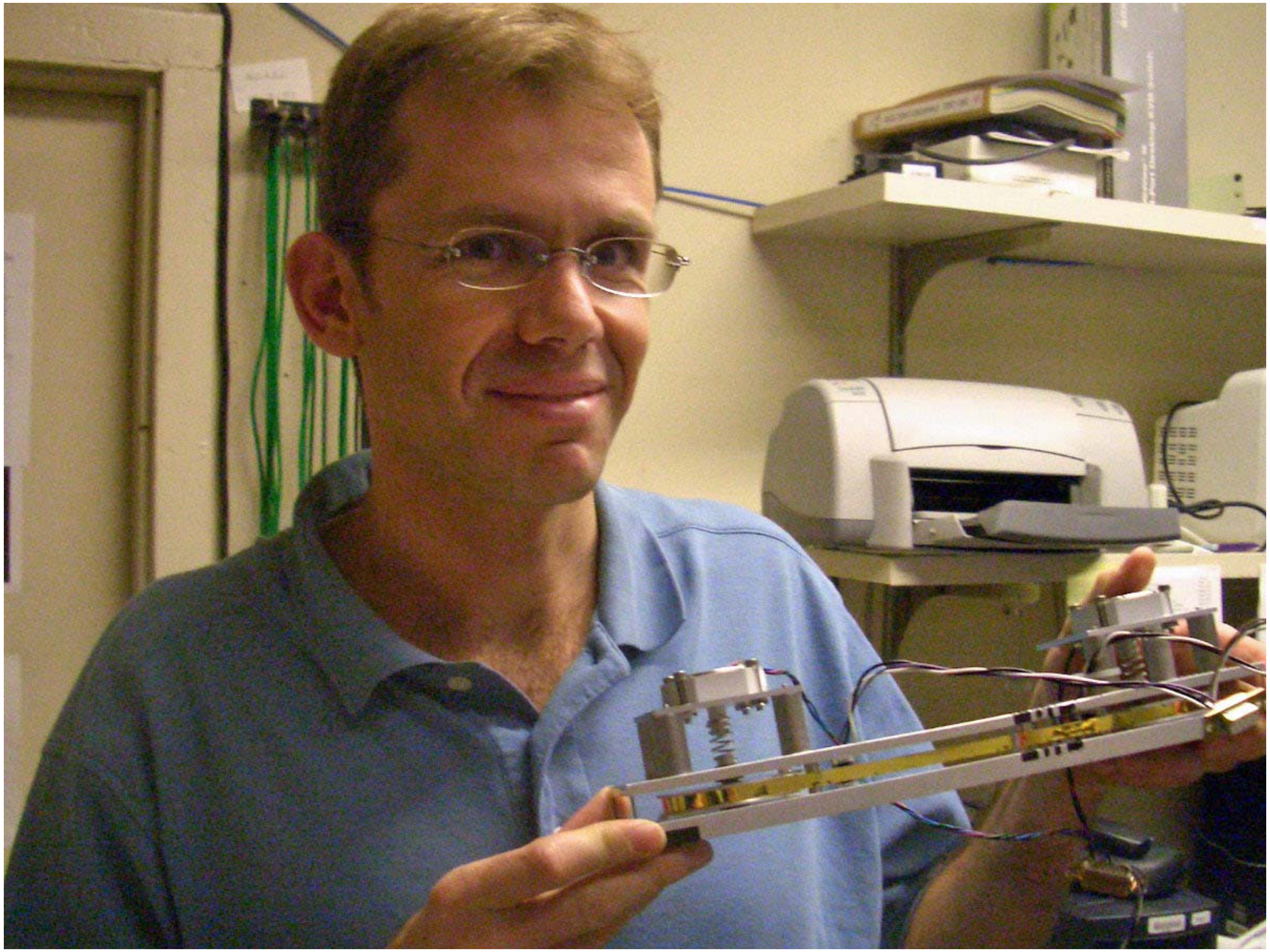




The simplified single stage Accelerator cell that uses gold coated Kapton tape to terminate the Electric field.

The LEAP experimental apparatus that Includes the LEAP single stage accelerator cell and the inverse FEL.

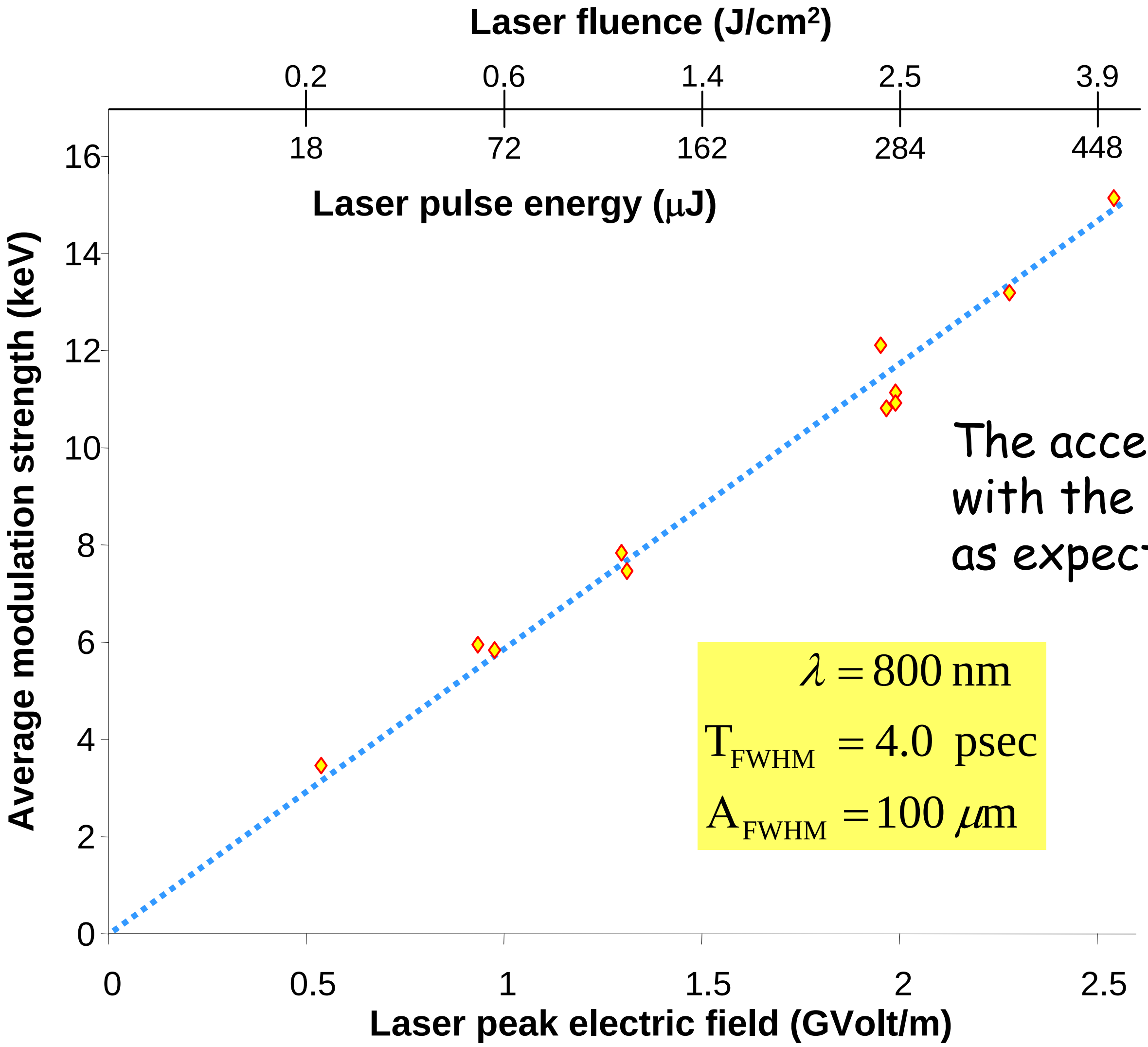
Tomas Plettner and LEAP Accelerator Cell



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

Energy Modulation vs Laser Peak Electric Field

(This is a modest laser with ~200 micro Joules in 4psec)



$$\lambda = 800\ \mathrm{nm}$$

$$T_{\mathrm{FWHM}} = 4.0\ \ \mathrm{psec}$$

$$A_{\mathrm{FWHM}} = 100\ \mu\mathrm{m}$$

The acceleration is linear with the applied laser field as expected from theory.

We accelerated electrons with visible light

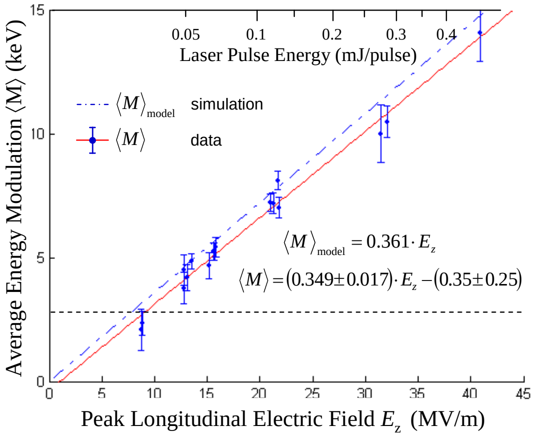
PRL **95,** 134801 (2005) PHYSICAL REVIEW LETTERS week ending 23 SEPTEMBER 2005

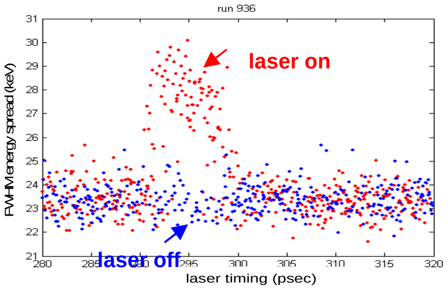
Visible-Laser Acceleration of Relativistic Electrons in a Semi-Infinite Vacuum

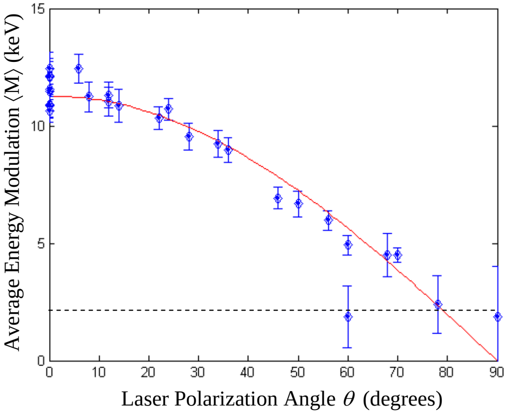
T. Plettner and R. L. Byer
Stanford University, Stanford, California 94305, USA

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)



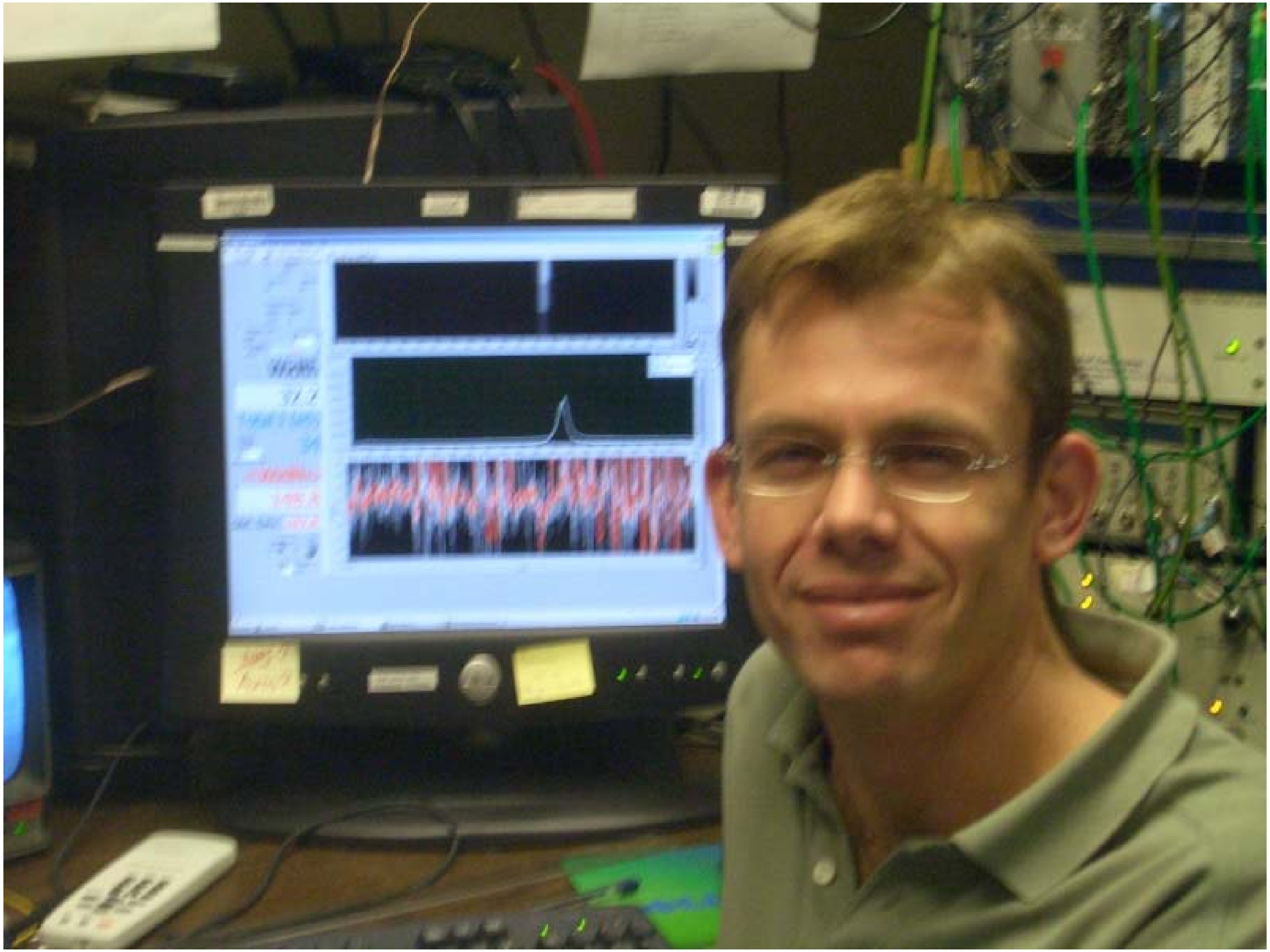




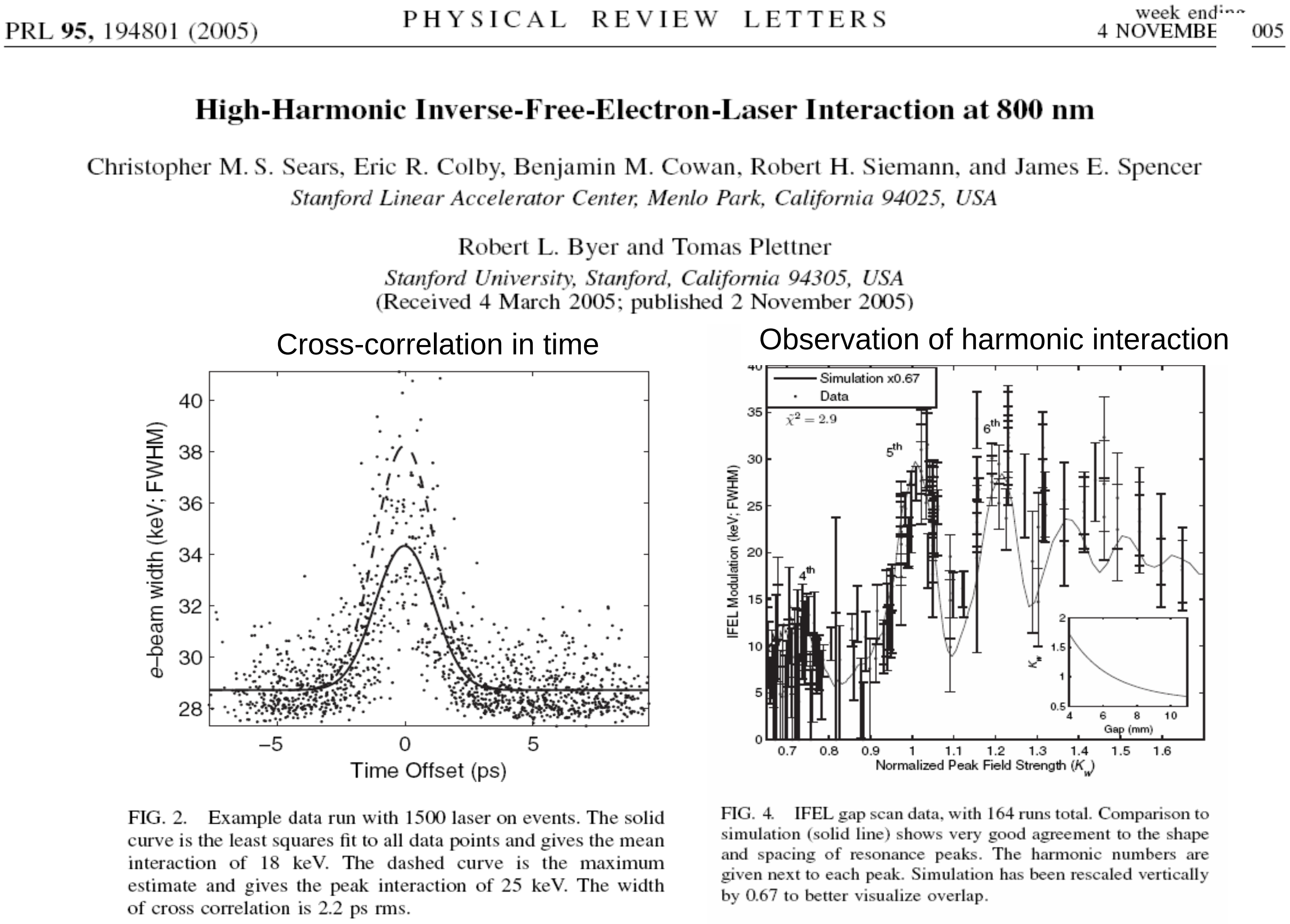
- confirmation of the Lawson-Woodward Theorem $$\int_{-\infty}^{+\infty} E_z dz = 0$$
- observation of the linear dependence of energy gain with laser electric field $$\Delta U \propto |E_{laser}|$$
- observation of the expected polarization dependence $$|E_z| \propto |E_{laser}| \cos\rho$$

laser-driven linear acceleration in vacuum

Tomas Plettner – Experimental Success



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.

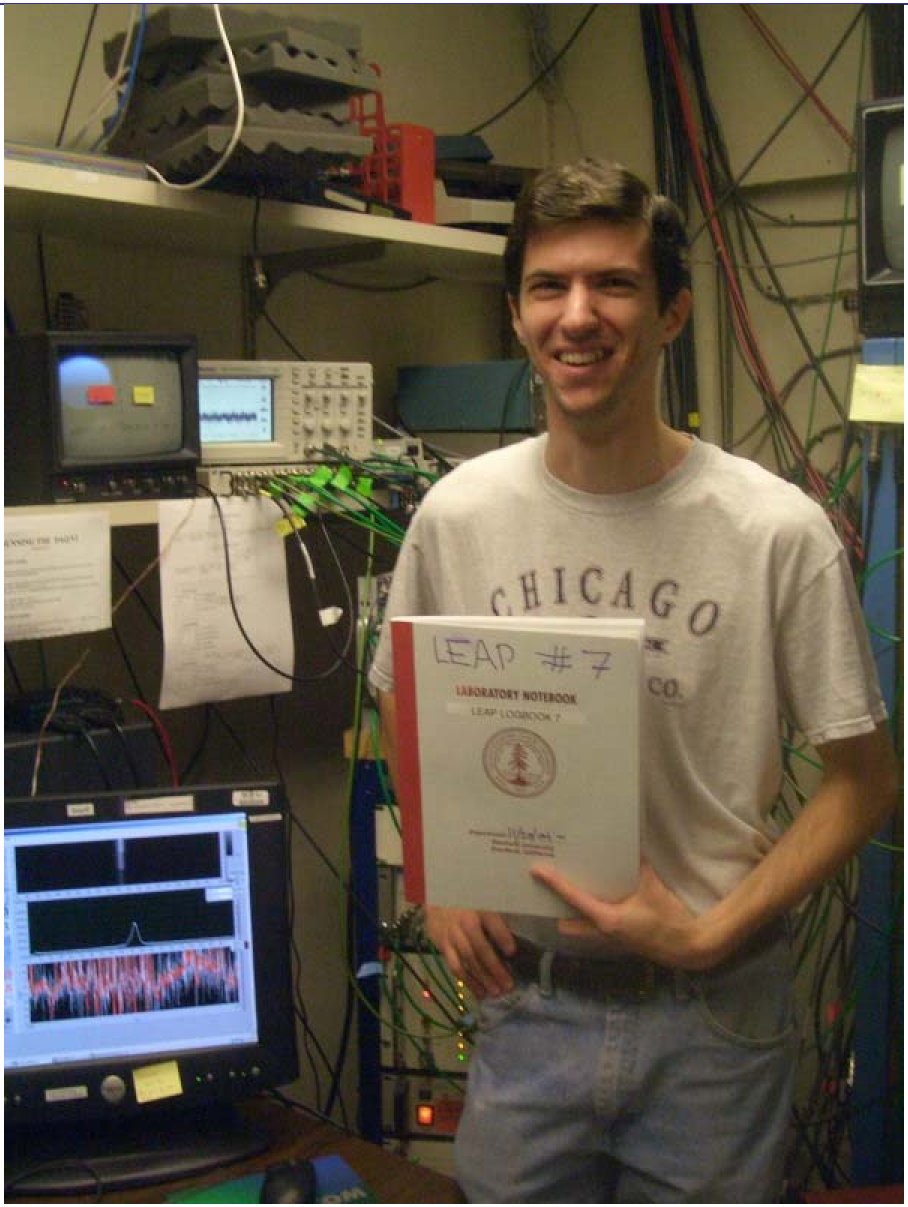
Observation of harmonic interaction

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.

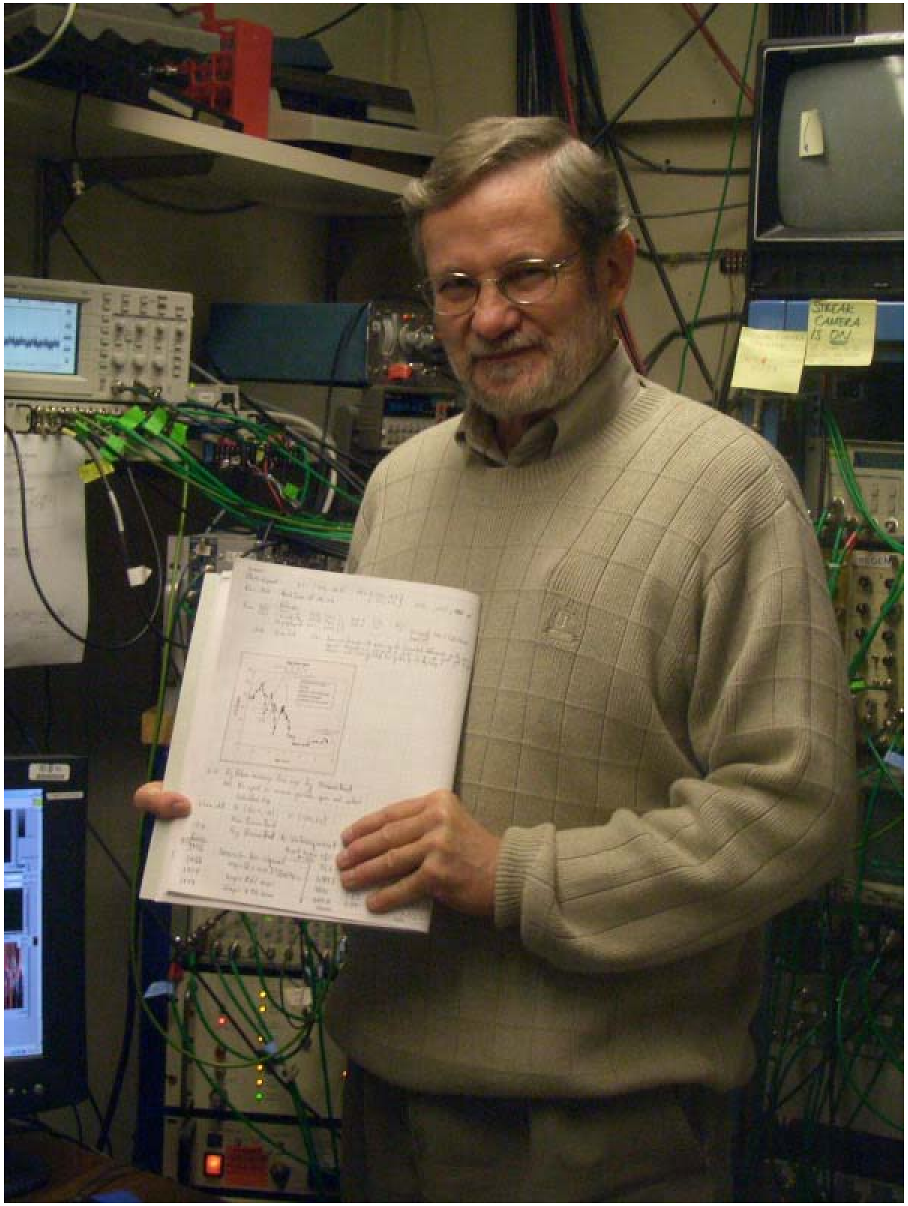
* graduate student C.M. Sears

AARD subpanel Dec 21, 2005

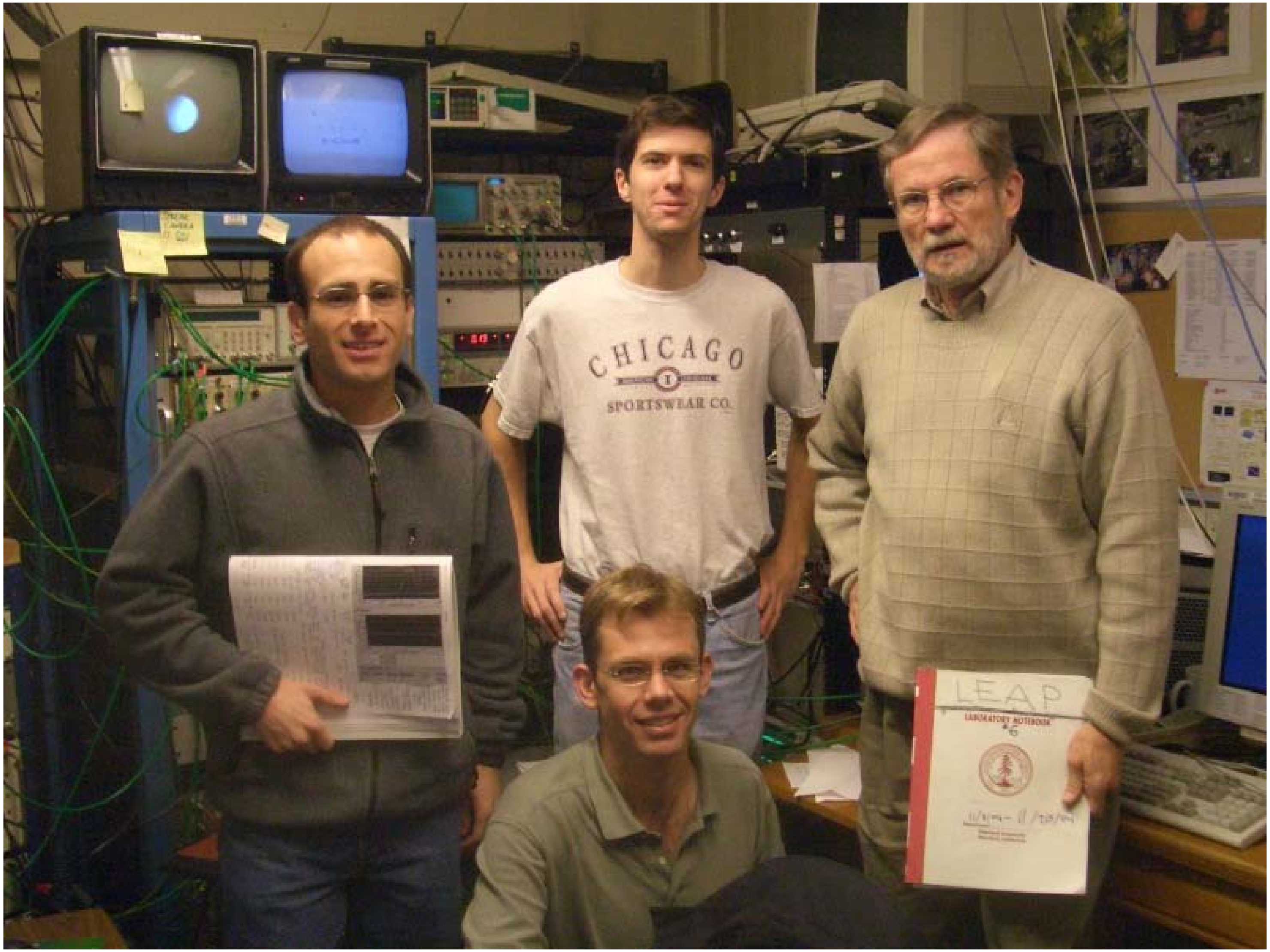
Chris Sears – LEAP Notebook #7



Jim Spencer – LEAP success!



LEAP Control Room – HEPL Nov 2004

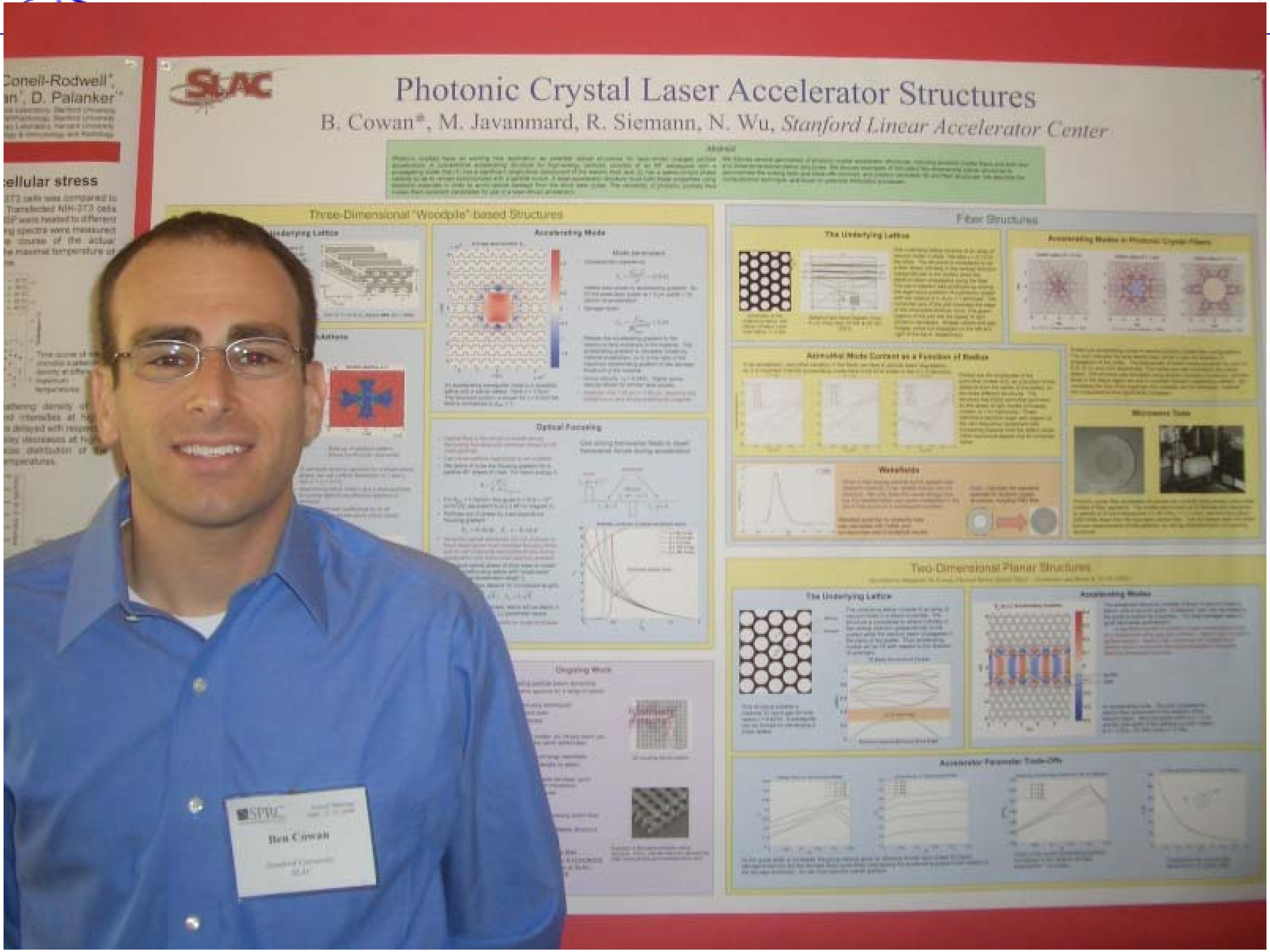


Ben Cowan Tomas Plettner Chris Sears Jim Spencer

LEAP Team – Feb 2006

Ben Cowan – detailed calculations of Accelerator Structures

Byer Group



Photonic Crystal Laser Accelerator Structures

B. Cowan*, M. Javanmard, R. Siemann, N. Wu, *Stanford Linear Accelerator Center*

Contents

"Don't undertake a project unless it is manifestly important and nearly impossible." **Edwin Land – 1982**

Historic Background

Laser Electron Accelerator Project – LEAP

  HEPL Experiments from 1997 – Nov 2004

  Future E163 Experiments at SLAC

The TeV-Energy Physics Frontier

Future Opportunities

  Coherent X-ray lasers

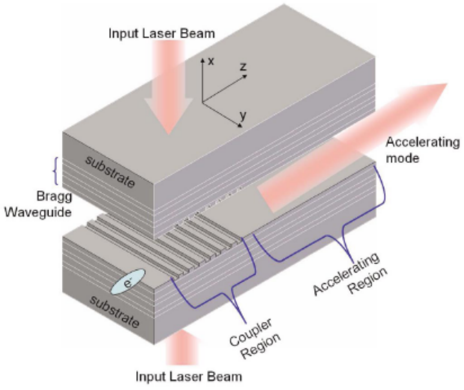
  The Attosecond Physics Frontier

Goal: Invent and Test Dielectric Accelerator Microstructures

KEY: Impedance match field to electrons using PBG structures

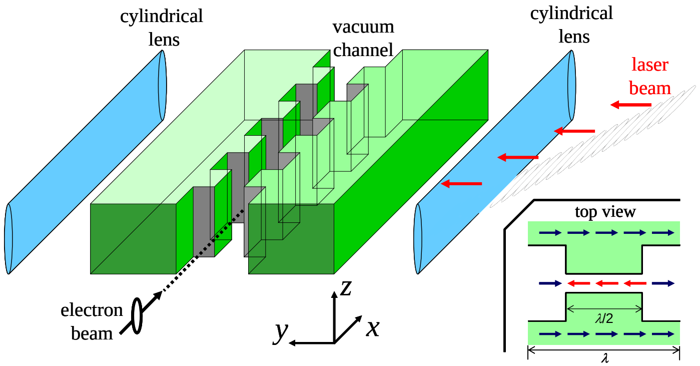
Byer
Group

Planar waveguide structures



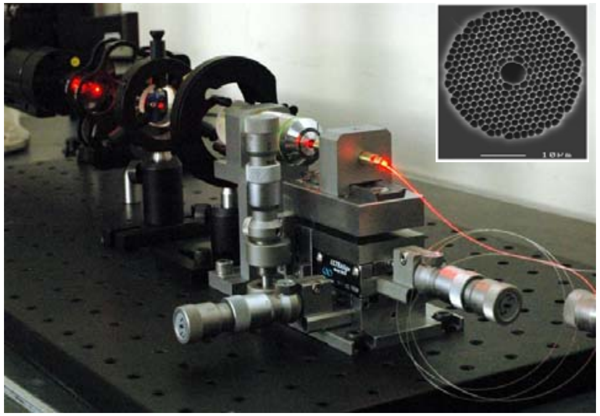
Z. Zhang et al. Phys. Rev. ST AB 8, 071302 (2005)

Periodic phase modulation structures



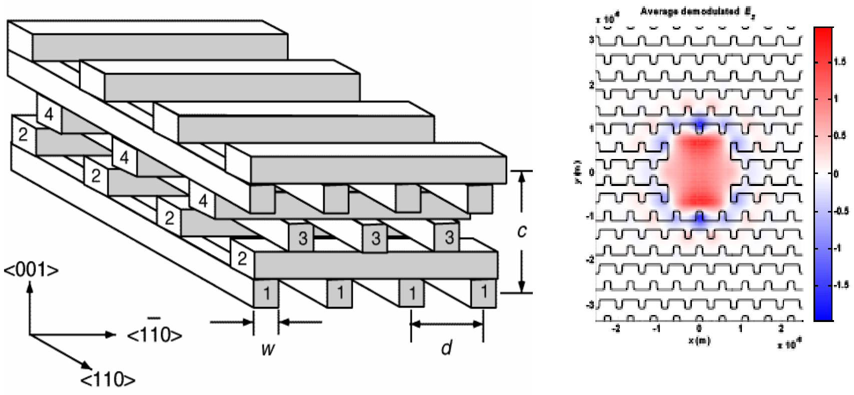
T. Plettner et al, Phys. Rev. ST Accel. Beams 4, 051301 (2006)

Hollow core PBG fibers



X.E. Lin, Phys. Rev. ST Accel. Beams 4, 051301 (2001)

3-D photonic bandgap structures



B. M. Cowan, Phys. Rev. ST Accel. Beams , 6, 101301 (2003).

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

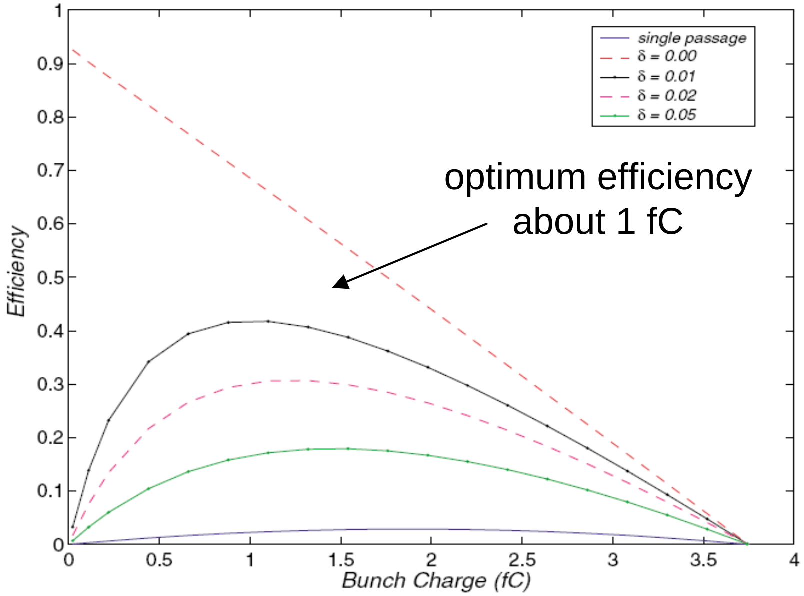
PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **8**, 031301 (2005)

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

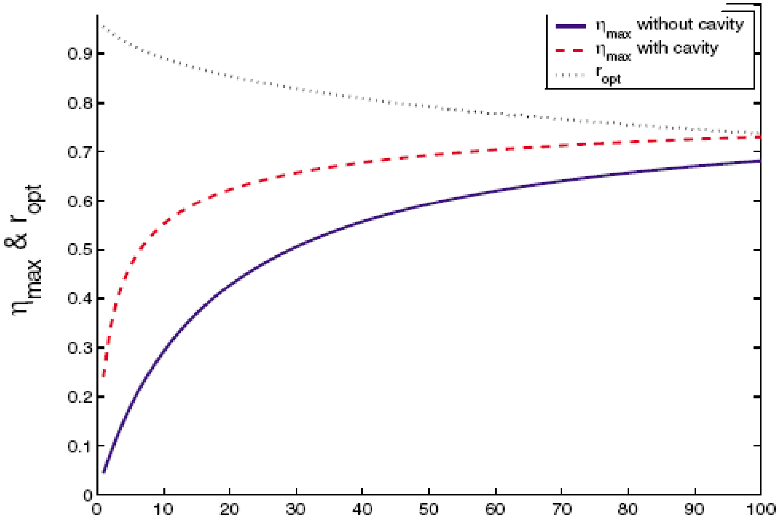
R. L. Byer
Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305, USA
(Received 26 January 2005; published 11 March 2005)

Coupling Efficiency vs bunch charge



optimum efficiency
about 1 fC

Beam loading calculations vs N

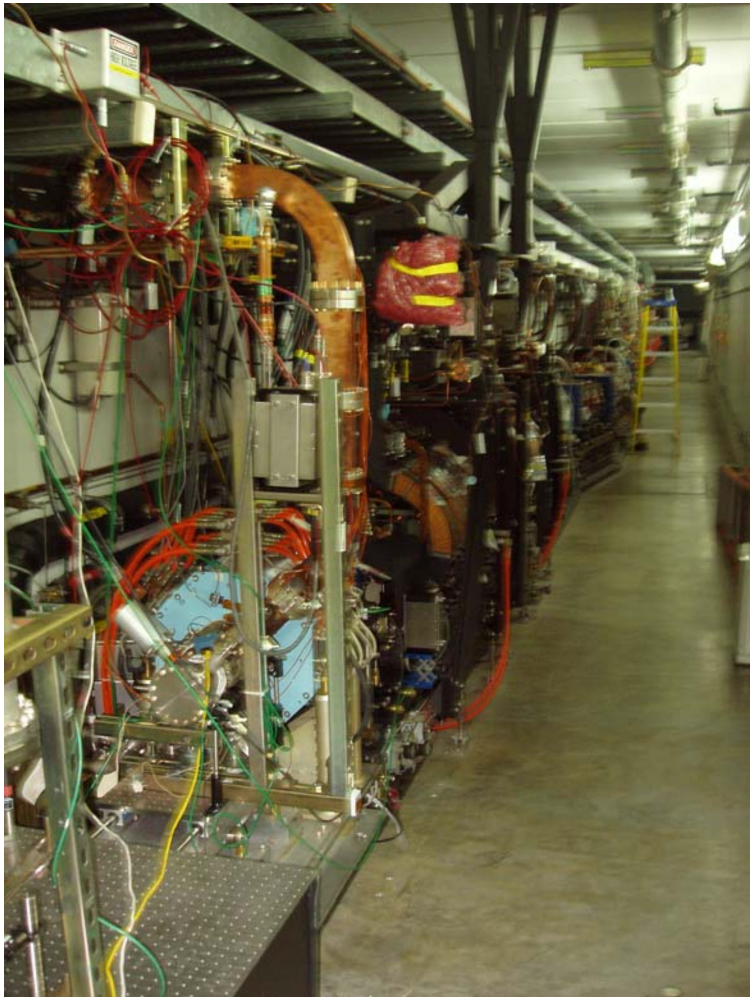


N (Number of bunches)

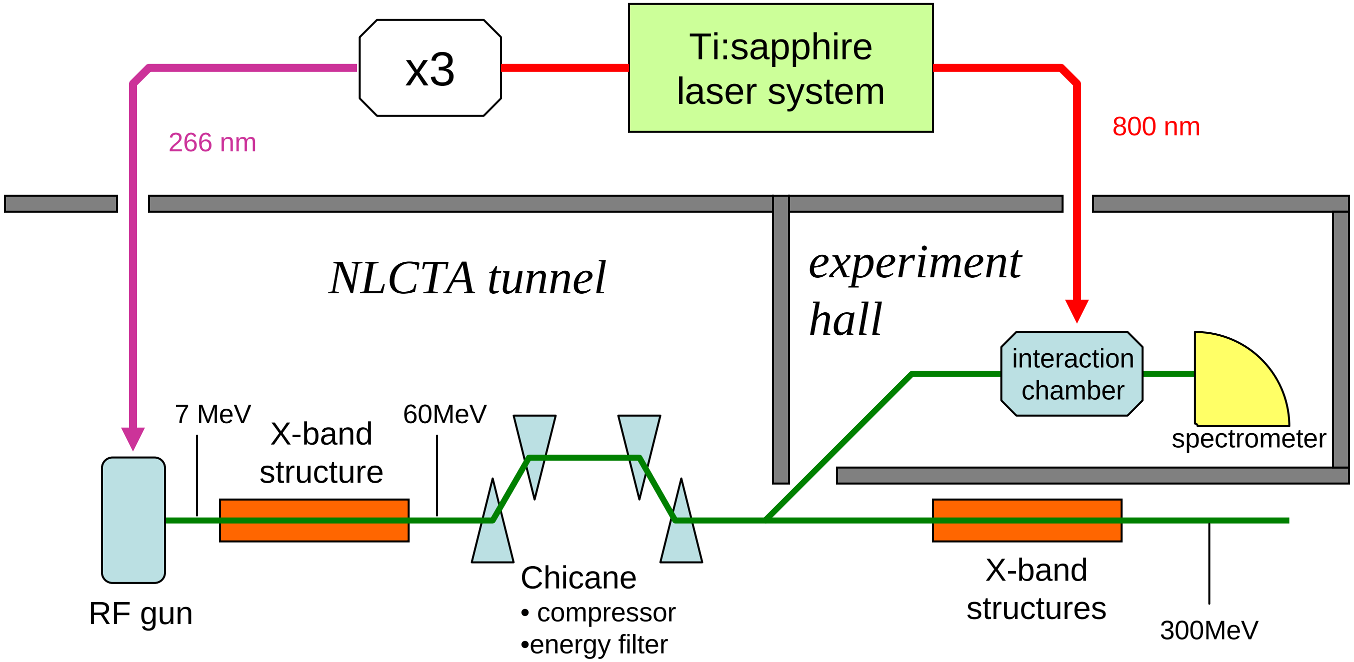
The E163 experiment at SLAC

The new E163 experiment hall

The NLCTA



The E163 experiment at SLAC



x3

Ti:sapphire laser system

266 nm

800 nm

NLCTA tunnel

experiment hall

interaction chamber

spectrometer

7 MeV

X-band structure

60MeV

RF gun

Chicane
- compressor
- energy filter

X-band structures

300MeV

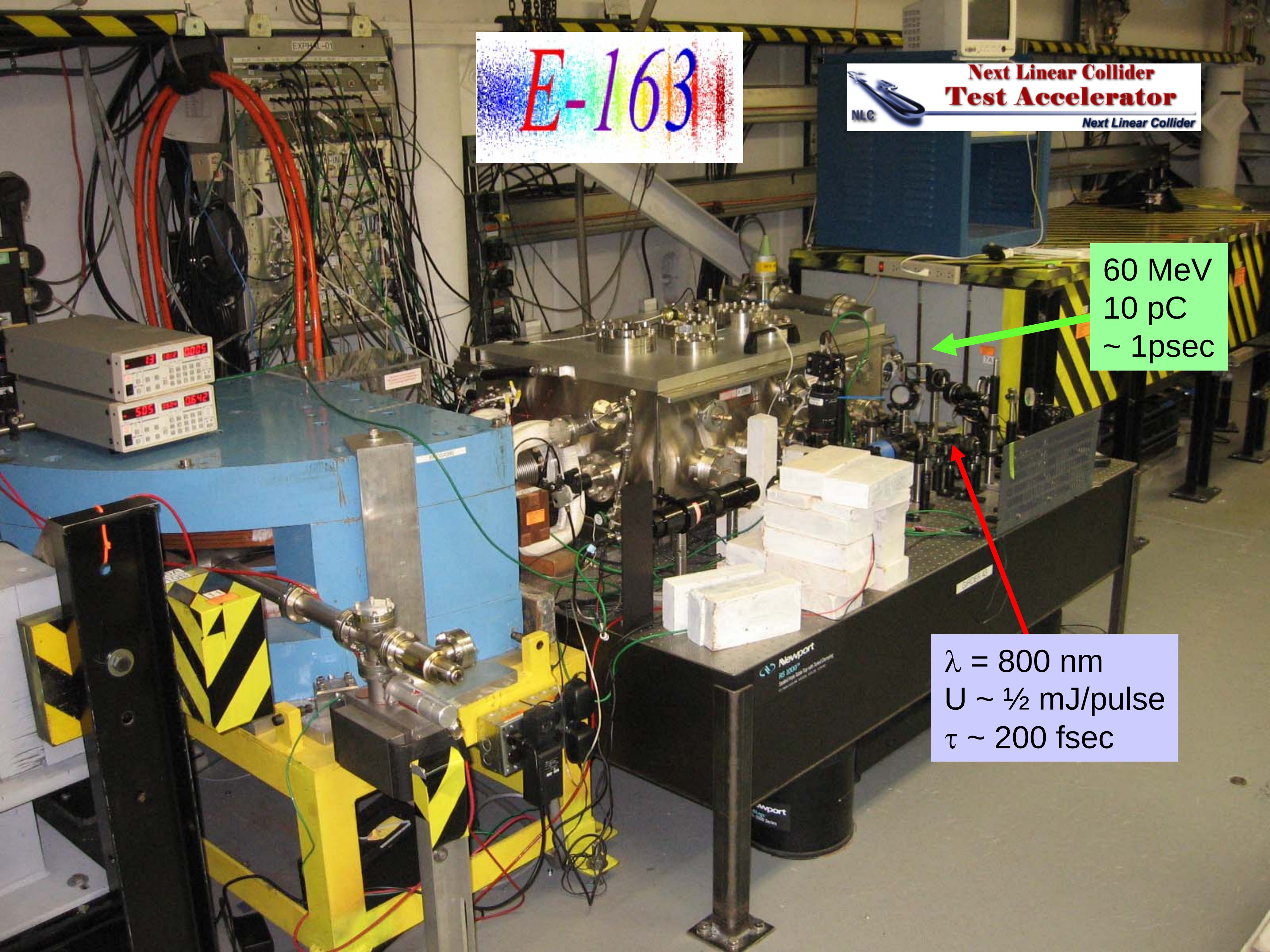
The new E163 experiment hall

The NLCTA

Accomplished milestones 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 autumn 2006



E-163

Next Linear Collider Test Accelerator

NLC Next Linear Collider

60 MeV
10 pC
~ 1psec

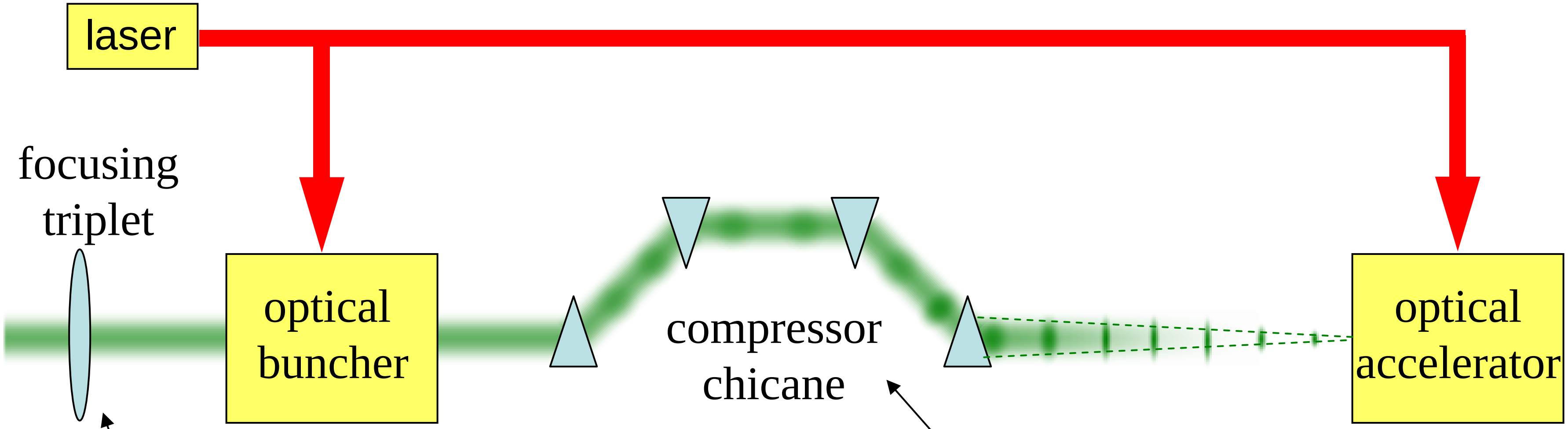
λ = 800 nm
U ~ ½ mJ/pulse
τ ~ 200 fsec

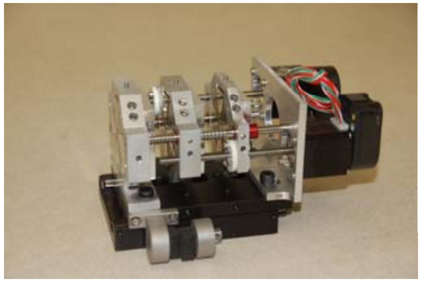
Eric Colby giving animated tour of NLCTA and E163

NLCTA Accelerator - Injector

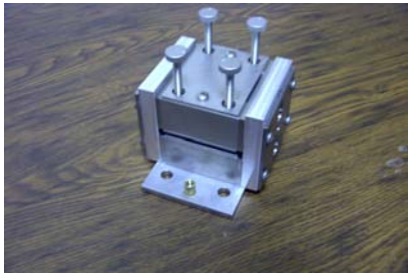
E163 Experimental area

The next step: staged accelerators at E163

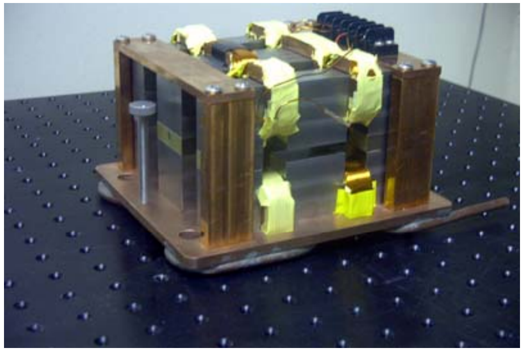




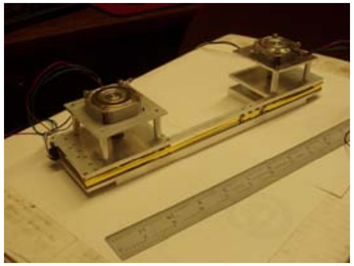
The triplet



The IFEL



The compressor chicane

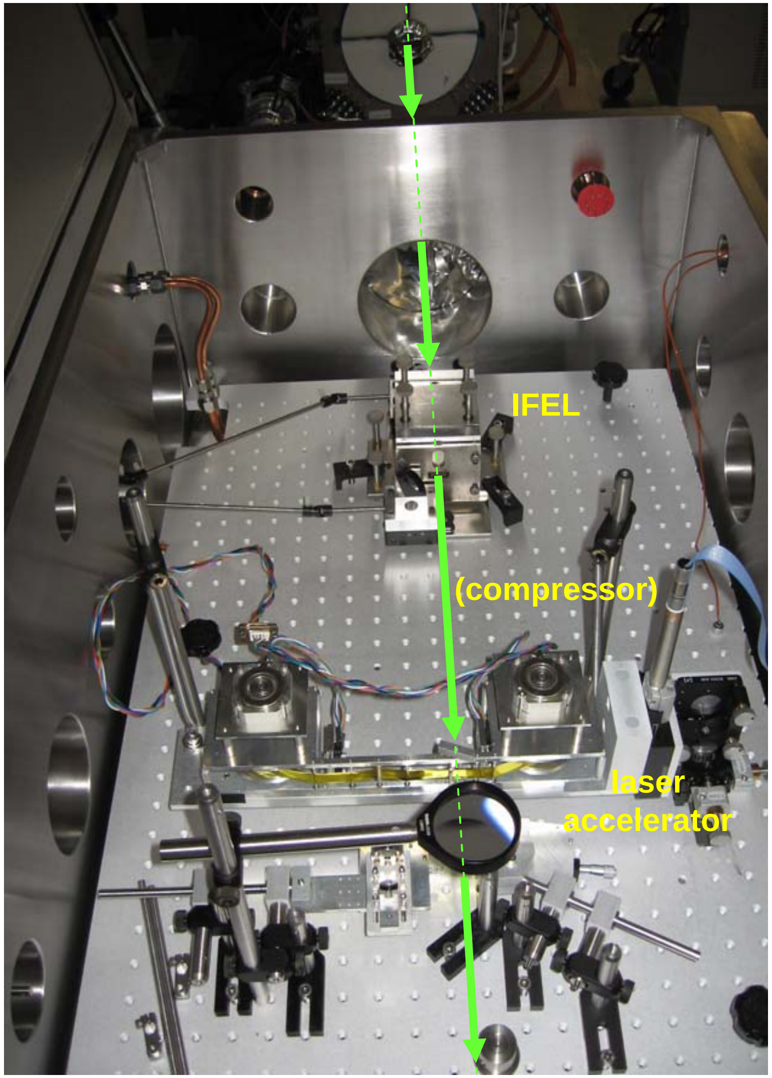


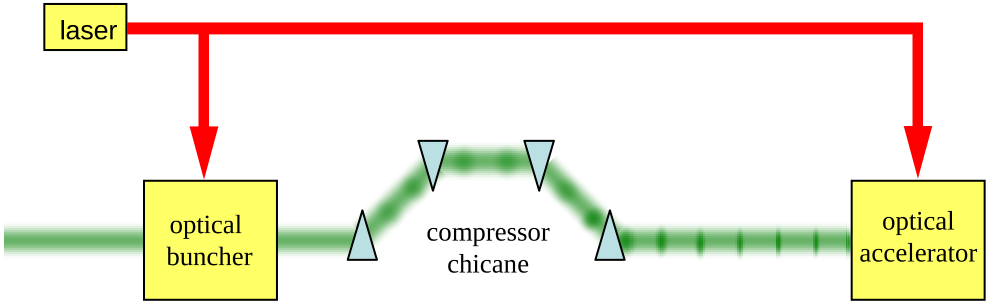
Accelerator structure

<500 attosecond electron compression in Inverse FEL

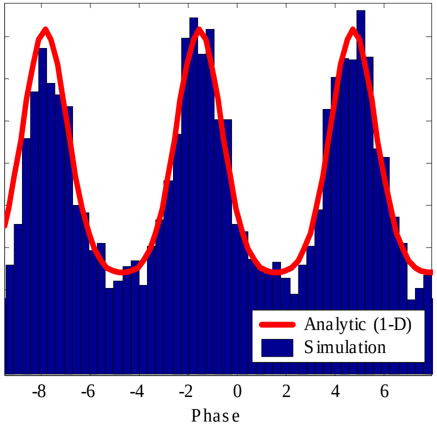
(Chris. M. Sears, PhD thesis SLAC June 2008**)**

We have achieved net acceleration of electrons with attosecond phase control

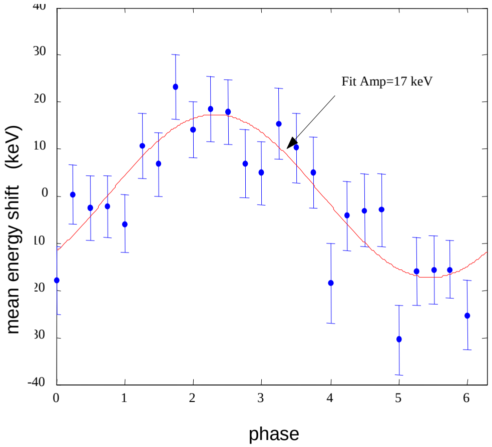




Expected bunching



Expected energy gain



Experiment features

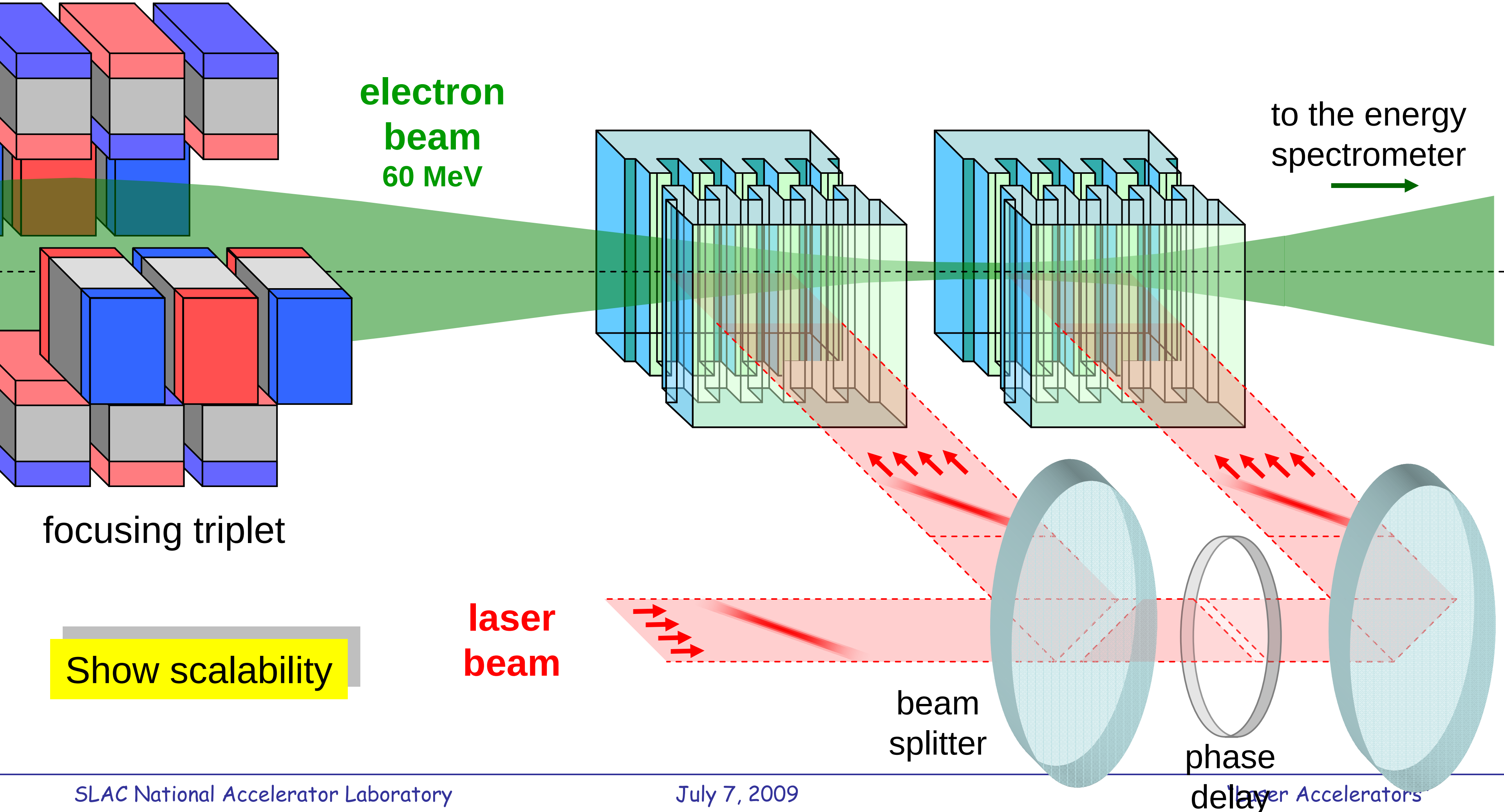
- IFEL modulates energy spread
- electron drift creates optical bunches
- second accelerator → net acceleration

Chris Sears Thesis Defense

Future Experiments

Goal: test multiple stage acceleration

Cascading of microstructure accelerators

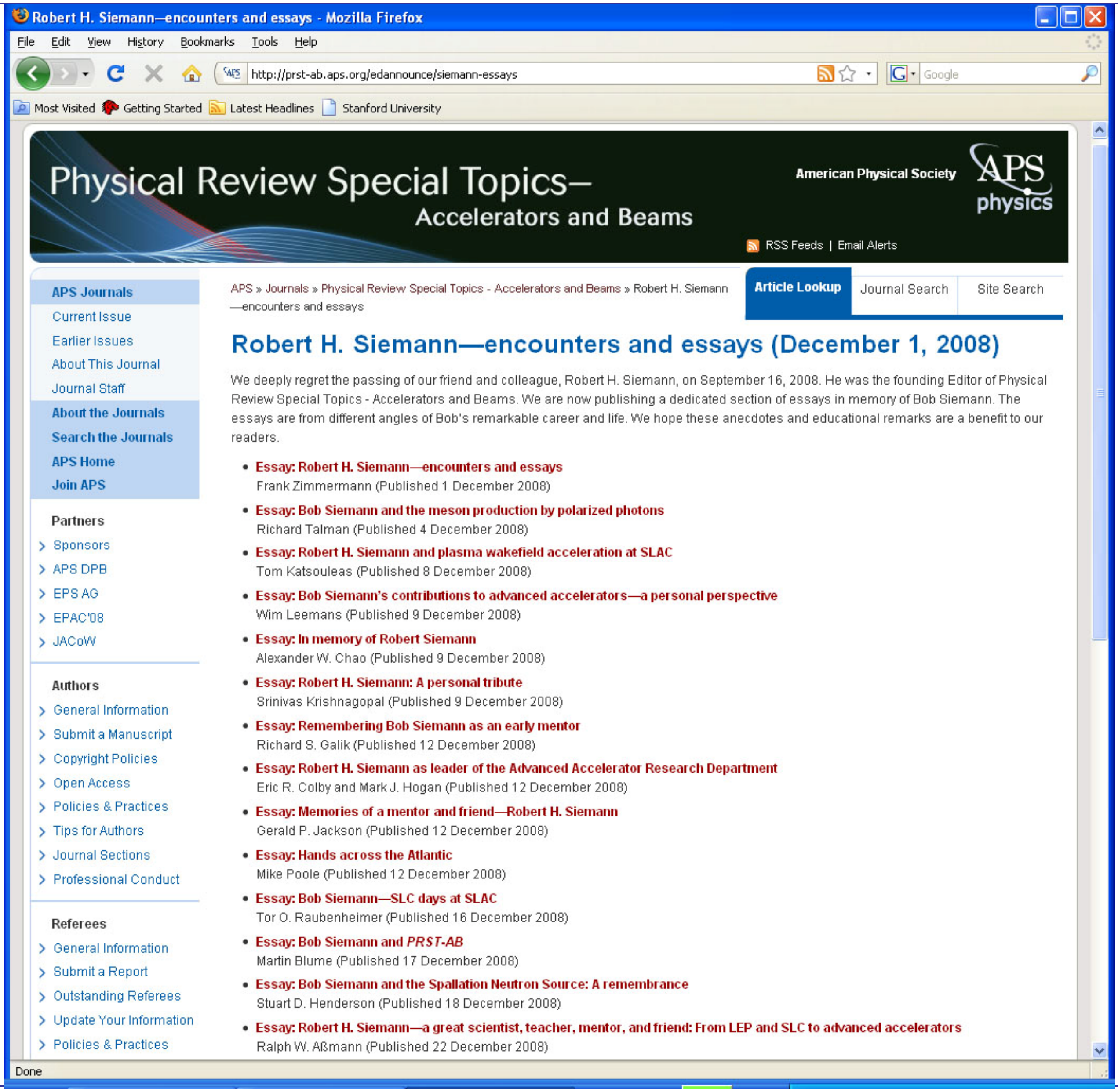


Show scalability

Professor Robert Siemann and Chris Sears

June 15, 2008 – Stanford Graduation Ceremonies

Robert H. Siemann – encounters and essays



Robert H. Siemann—encounters and essays (December 1, 2008)

We deeply regret the passing of our friend and colleague, Robert H. Siemann, on September 16, 2008. He was the founding Editor of Physical Review Special Topics - Accelerators and Beams. We are now publishing a dedicated section of essays in memory of Bob Siemann. The essays are from different angles of Bob's remarkable career and life. We hope these anecdotes and educational remarks are a benefit to our readers.

- **Essay: Robert H. Siemann—encounters and essays**
  Frank Zimmermann (Published 1 December 2008)
- **Essay: Bob Siemann and the meson production by polarized photons**
  Richard Talman (Published 4 December 2008)
- **Essay: Robert H. Siemann and plasma wakefield acceleration at SLAC**
  Tom Katsouleas (Published 8 December 2008)
- **Essay: Bob Siemann's contributions to advanced accelerators—a personal perspective**
  Wim Leemans (Published 9 December 2008)
- **Essay: In memory of Robert Siemann**
  Alexander W. Chao (Published 9 December 2008)
- **Essay: Robert H. Siemann: A personal tribute**
  Srinivas Krishnagopal (Published 9 December 2008)
- **Essay: Remembering Bob Siemann as an early mentor**
  Richard S. Galik (Published 12 December 2008)
- **Essay: Robert H. Siemann as leader of the Advanced Accelerator Research Department**
  Eric R. Colby and Mark J. Hogan (Published 12 December 2008)
- **Essay: Memories of a mentor and friend—Robert H. Siemann**
  Gerald P. Jackson (Published 12 December 2008)
- **Essay: Hands across the Atlantic**
  Mike Poole (Published 12 December 2008)
- **Essay: Bob Siemann—SLC days at SLAC**
  Tor O. Raubenheimer (Published 16 December 2008)
- **Essay: Bob Siemann and *PRST-AB***
  Martin Blume (Published 17 December 2008)
- **Essay: Bob Siemann and the Spallation Neutron Source: A remembrance**
  Stuart D. Henderson (Published 18 December 2008)
- **Essay: Robert H. Siemann—a great scientist, teacher, mentor, and friend: From LEP and SLC to advanced accelerators**
  Ralph W. Aßmann (Published 22 December 2008)

Laser Electron Acceleration Group

Chris McGuinness **Bob Siemann** **Bob Byer** **Eric Colby** **Chris Sears**

Rasmus Ischebeck **Chris Barnes** **Ben Cowan** **Tomas Plettner** **Jim Spencer**

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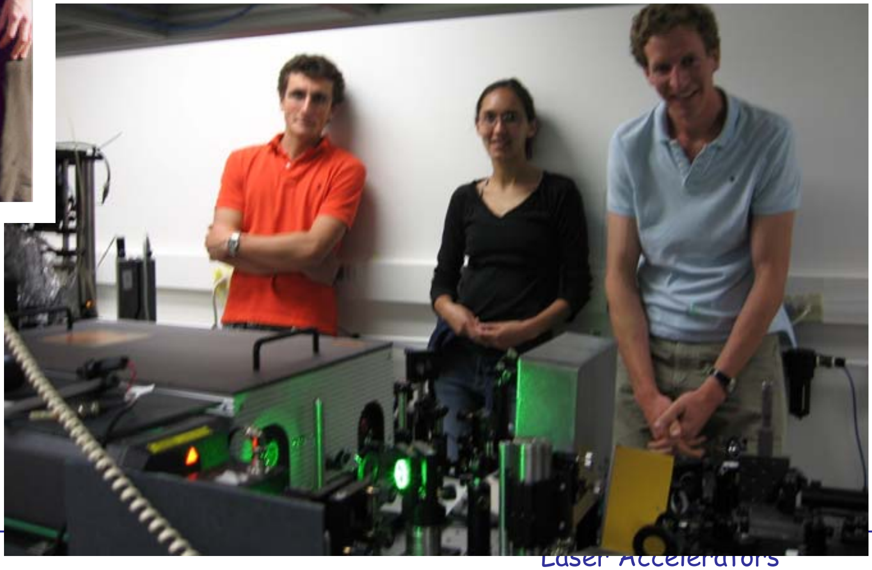


Contents

"Don't undertake a project unless it is manifestly important and nearly impossible." **Edwin Land – 1982**

Historic Background

Laser Electron Accelerator Project – LEAP

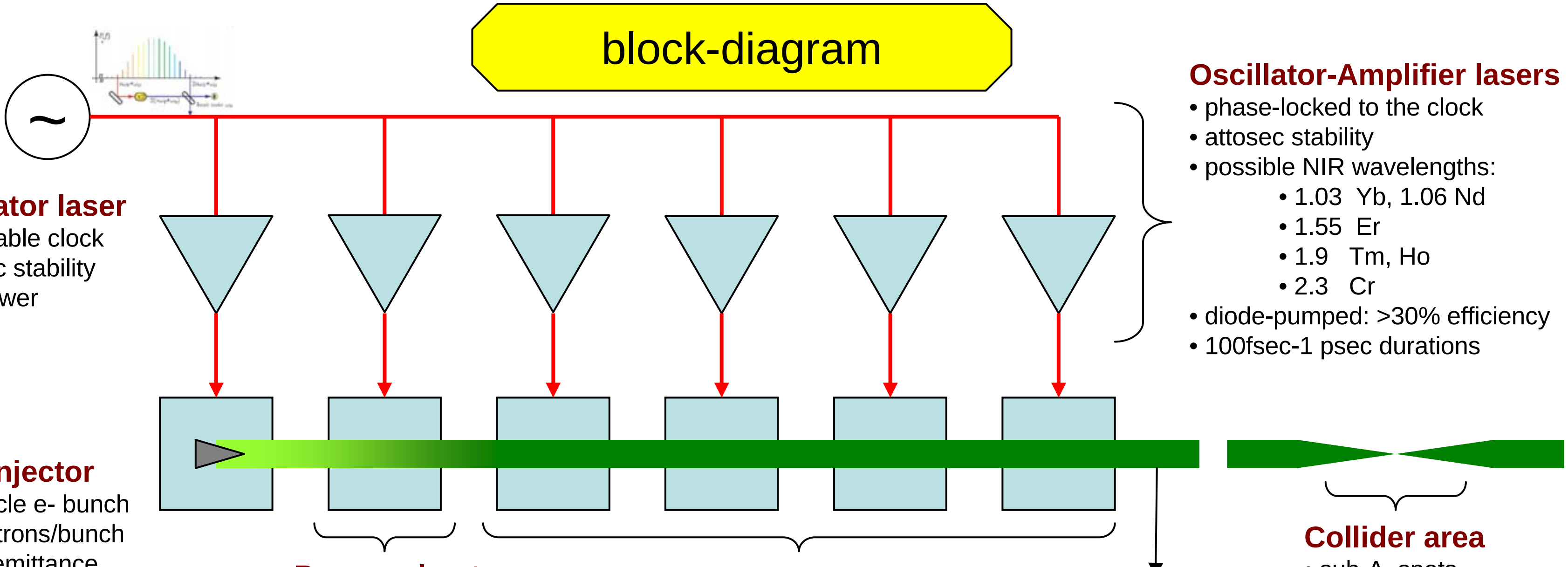
- HEPL Experiments from 1997 – Nov 2004
- Future E163 Experiments at SLAC

The TeV-Energy Physics Frontier

Future Opportunities

- Coherent X-ray lasers
- The Attosecond Physics Frontier

Envisioned laser-driven TeV scale collider



Oscillator laser
- ultrastable clock
- attosec stability
- low power

Oscillator-Amplifier lasers
- phase-locked to the clock
- attosec stability
- possible NIR wavelengths:
  - 1.03 Yb, 1.06 Nd
  - 1.55 Er
  - 1.9 Tm, Ho
  - 2.3 Cr
- diode-pumped: >30% efficiency
- 100fsec-1 psec durations

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

Pre-accelerator
- nonrelativistic
- preserve emittance
- compress bunch

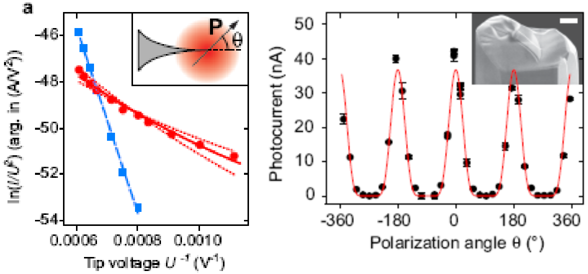
Accelerator sections
- relativistic
- preserve emittance
- periodic focusing
- alignment and stabilization

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

Collider area
- sub-A spots
- multi-MHz rep-rate

LIGO vibration isolation in ES3 at Stanford

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 → $2\text{x}10^7$ W optical power
- 50% wallplug laser → 10^8 W electricity

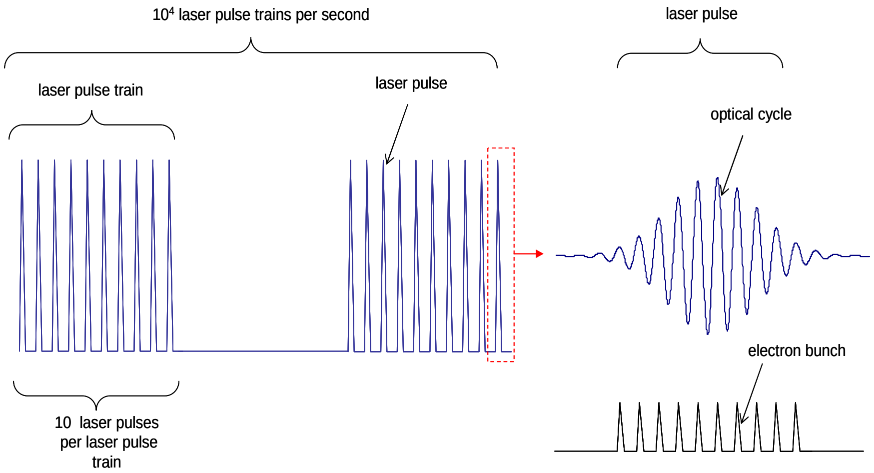
100 MW electricity

Laser beam parameters for TeV scale accelerator

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



	SLC	NLC	SCA-FEL	TESLA	laser-accelerator
f_{RF} (GHz)	2.856	11.424	1.3	1.3	3×10^4
f_m (Hz)	120	120	10	4	10^4
N_b	1	95	10^4	4886	10
Δt_b (nsec)	-	2.8	84.7	176	3×10^{-6}
f_b (Hz)	1.2×10^2	1.1×10^4	1×10^5	1.6×10^4	3×10^6
N_e	3.5×10^{10}	8×10^9	3.1×10^7	1.4×10^{10}	10^4
I_e (sec^{-1})	4×10^{12}	9×10^{13}	3×10^{12}	2×10^{19}	3×10^{10}

Requires 10kW/meter or 10MW/km and ~40% efficiency Laser Source!

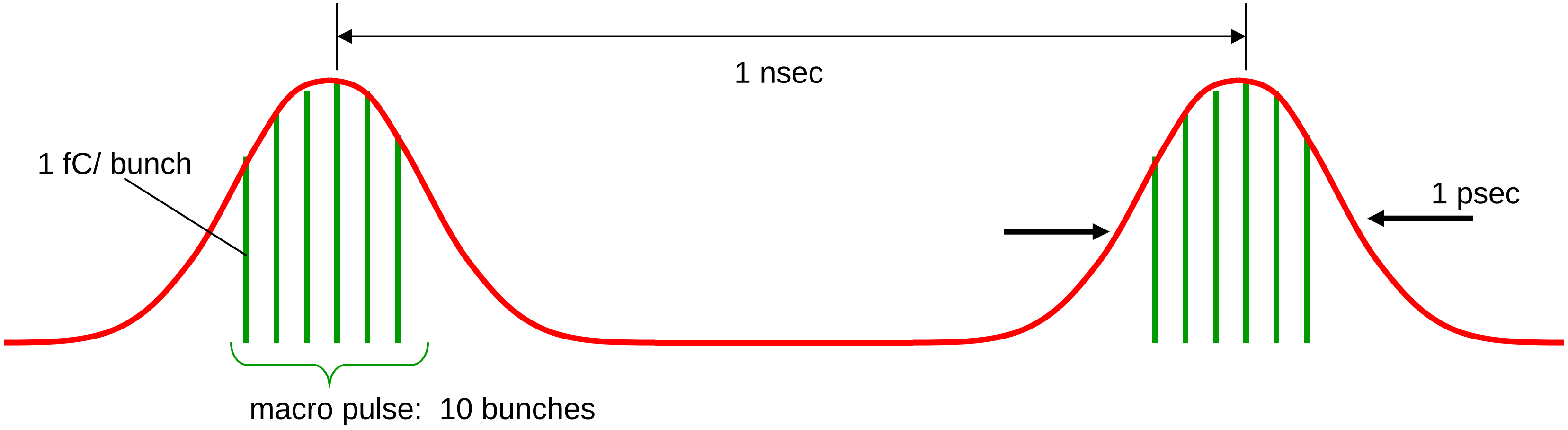
(~ 10 microjoules in 100fsec per micropulse)

Dramatic increase of

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

Envisioned parameters

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

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	$L \approx \dfrac{nfN^2}{4\pi\sigma_x\sigma_y}$	~10^{34}/cm^2-sec	

AARD subpanel Dec 21, 2005

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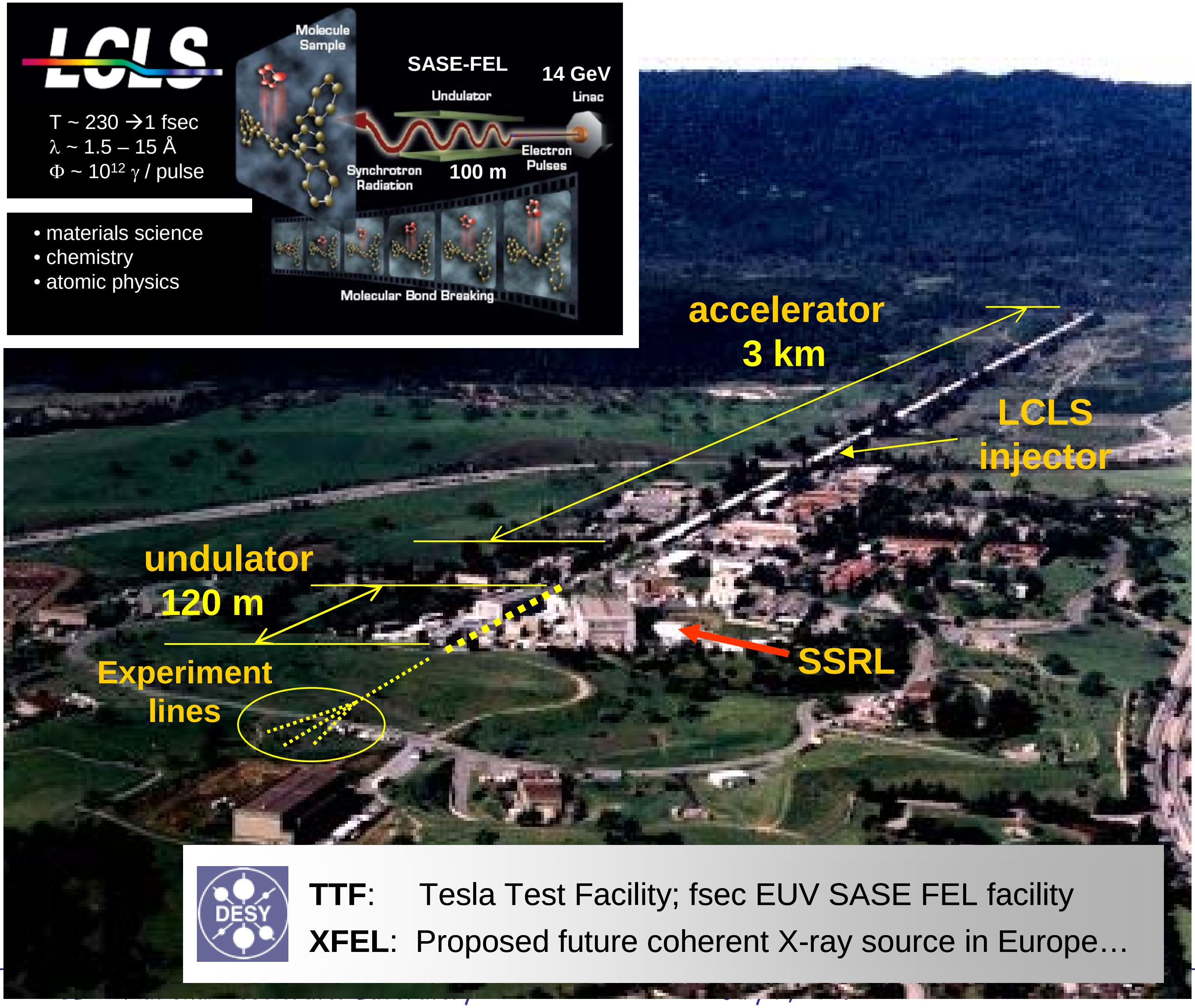
Coherent X-ray lasers

The Attosecond Physics Frontier

April 2009 - LCLS: Coherent 8KeV X-ray source- 1mJ at 10Hz!!

RF-accelerator driven SASE FEL at SLAC - 2009



TTF: Tesla Test Facility; fsec EUV SASE FEL facility

XFEL: Proposed future coherent X-ray source in Europe…

LCLS properties

- 1 km-size facility
- microwave accelerator
- λ_{RF} ~ 10 cm
- 4-14 GeV e-beam

- 120 m undulator
- 23 cm period
- 15-1.5 A radiation
- 0.8-8 keV photons
- 10^{14} photons/sec
- ~77 fsec

- **SUCCESS – April 09**
- **1mJ per pulse**
- **10 Hz**
- **8 keV X-ray photons**

Question: can we generate coherent X-rays With table top laser accelerator?

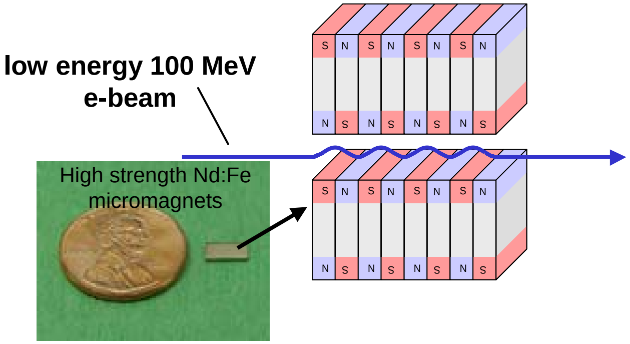
Reference: First suggestion that Laser accelerator could drive an X-ray FEL.

Y. C. Huang and R. L. Byer, "Ultra-Compact, High-Gain, High-Power Free-Electron Lasers Pumped by Future Laser-Driven Accelerators," in Free Electron Lasers 1996, G. Dattoli and A. Renieri, eds. (Elsevier Science B.V., 1997), pp. II-37-II-38.

Table Top Attosecond X-ray FEL Source

1° of optical phase at 2 μm → 20 attosec

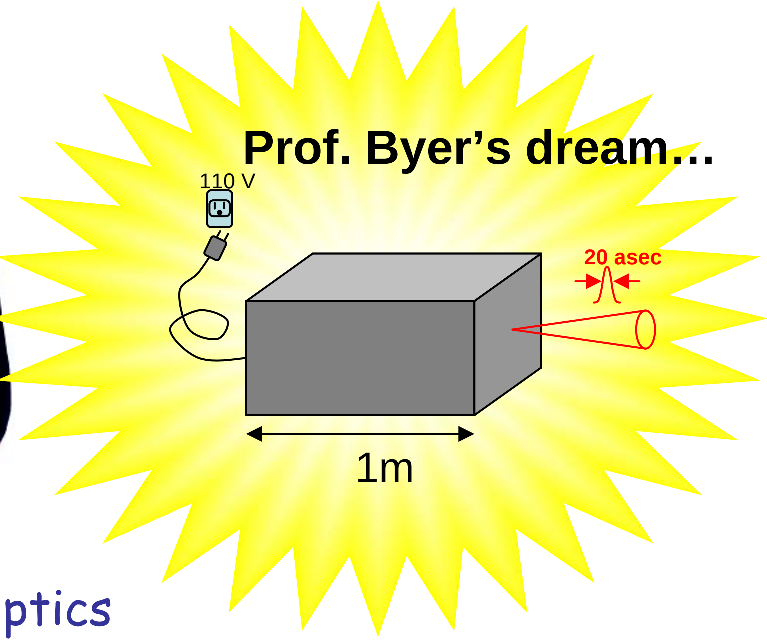
attosec light sources



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

Table Top attosec x-ray source with medical and chemistry applications

The wizard of optics

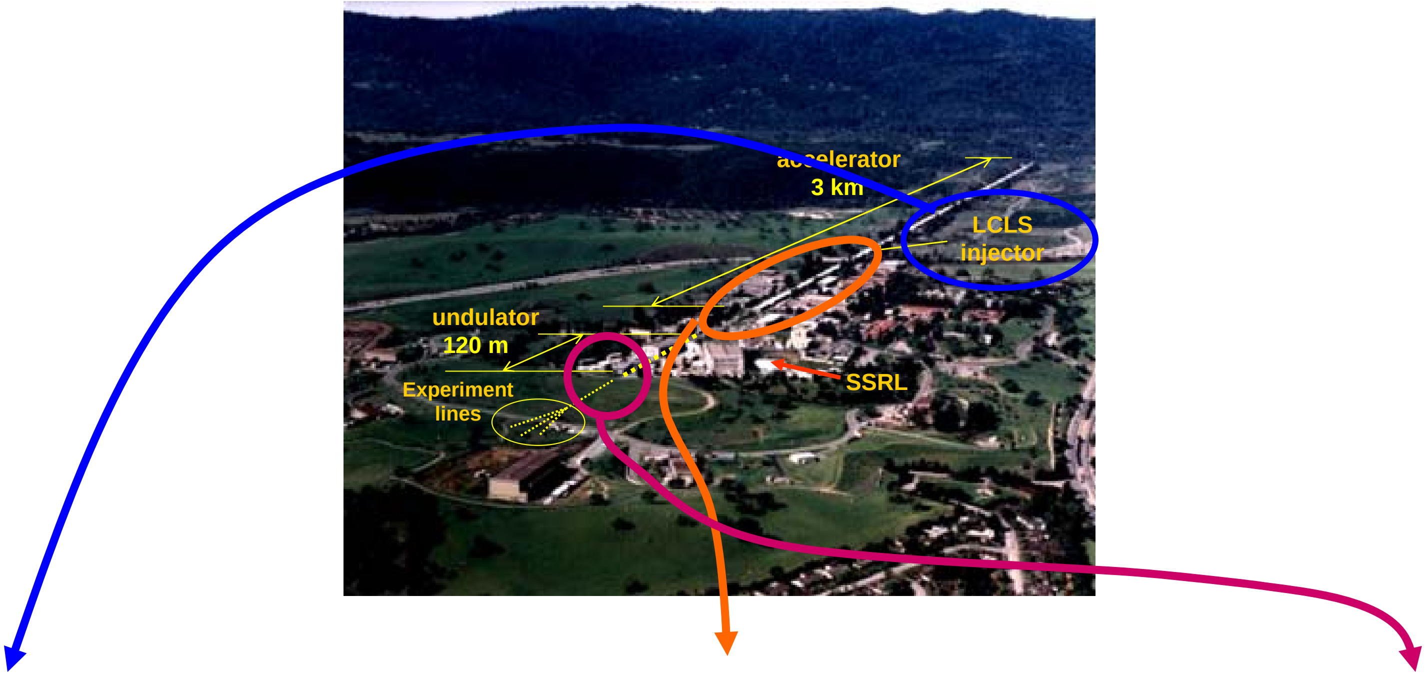


Preliminary model studies

- **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**

The Key Components of the SASE-FEL architecture

SASE – Self Amplified Spontaneous Emission



source of free particles → **accelerator section** → **undulator**

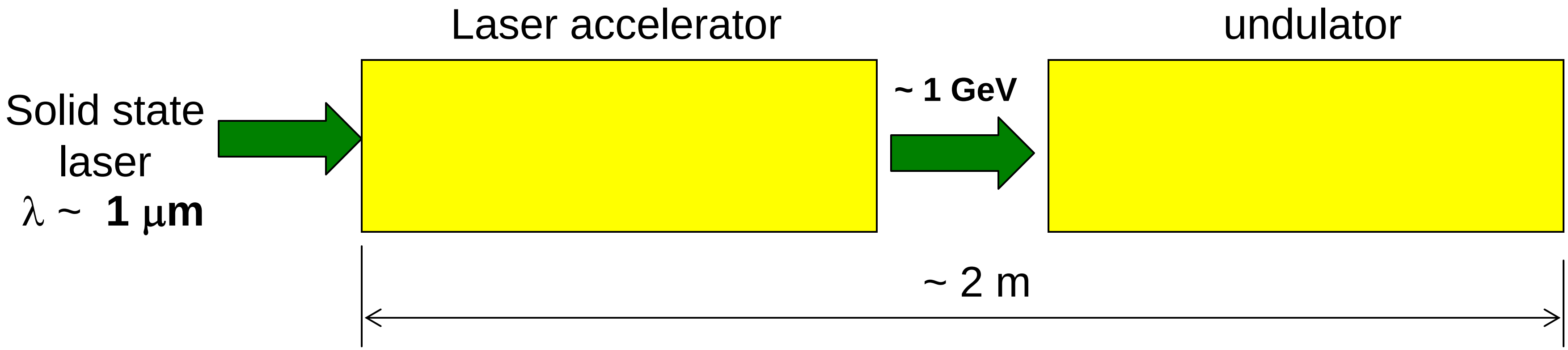
laser-driven
high rep. rate
very compact

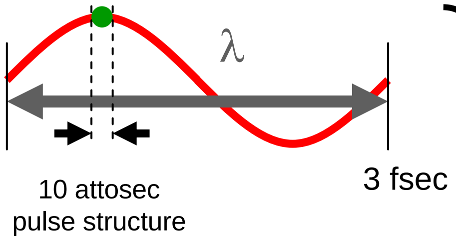
dielectric structure
based laser-driven
particle accelerators

dielectric structure,
laser driven

Question: Is it possible? A Table Top laser driven SASE-FEL

Concept: Summer 2007





Input electron beam

- ~ 1-2 GeV beam energy
- ~ **10 attosec pulse duration**
- ~ 1 pC bunch charge
- ~ 0.05% energy spread

Magnetic undulator

λ_u ~ 200 μm
L_u ~ 20-40 cm
B_0 ~ ½ - 1 T

Field envelope growth

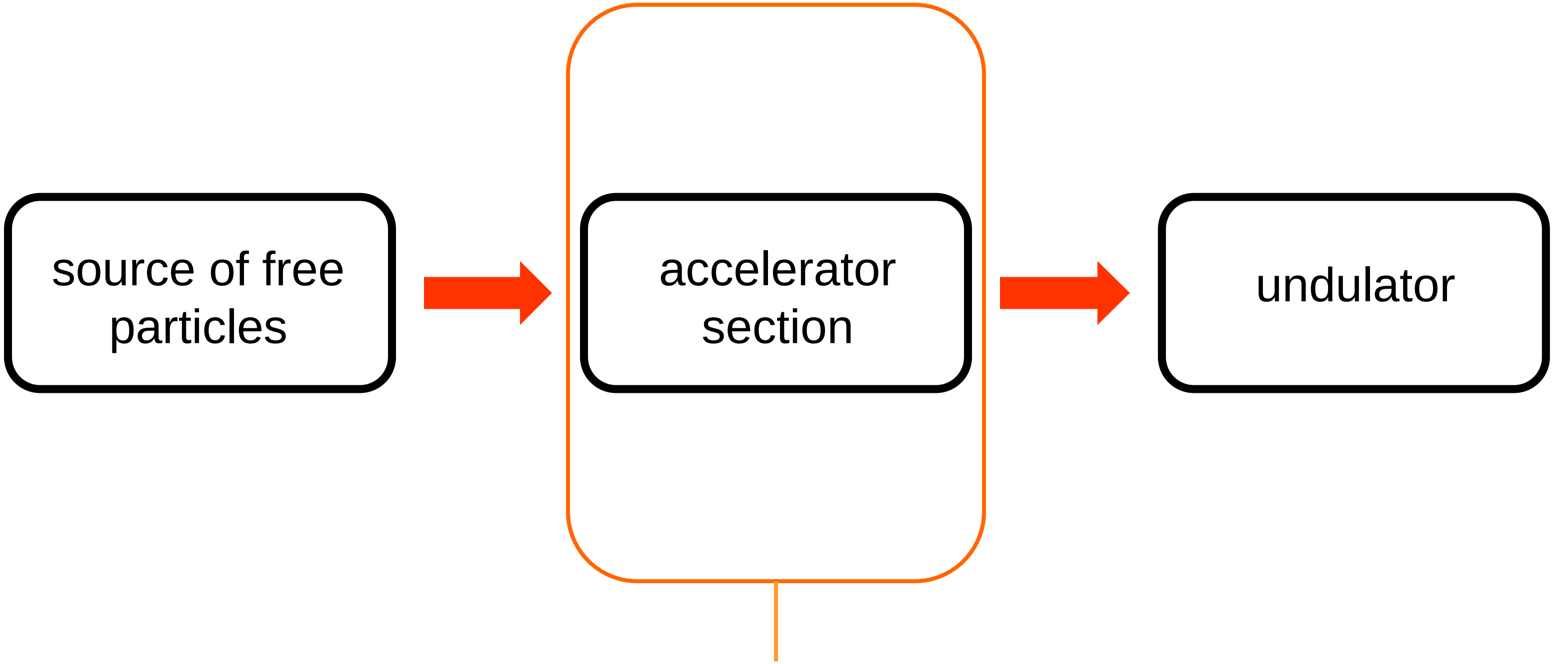
$$\frac{\partial}{\partial t}\tilde{E}(z',t) = -\chi_2 \left(\sum_{j\in\Delta} e^{-i\psi_j} \Big/ V_\Delta \right)$$

electrons per unit volume

Smallest possible beam size

$\phi_b < 500$ nm

Development of the three key laser-driven components

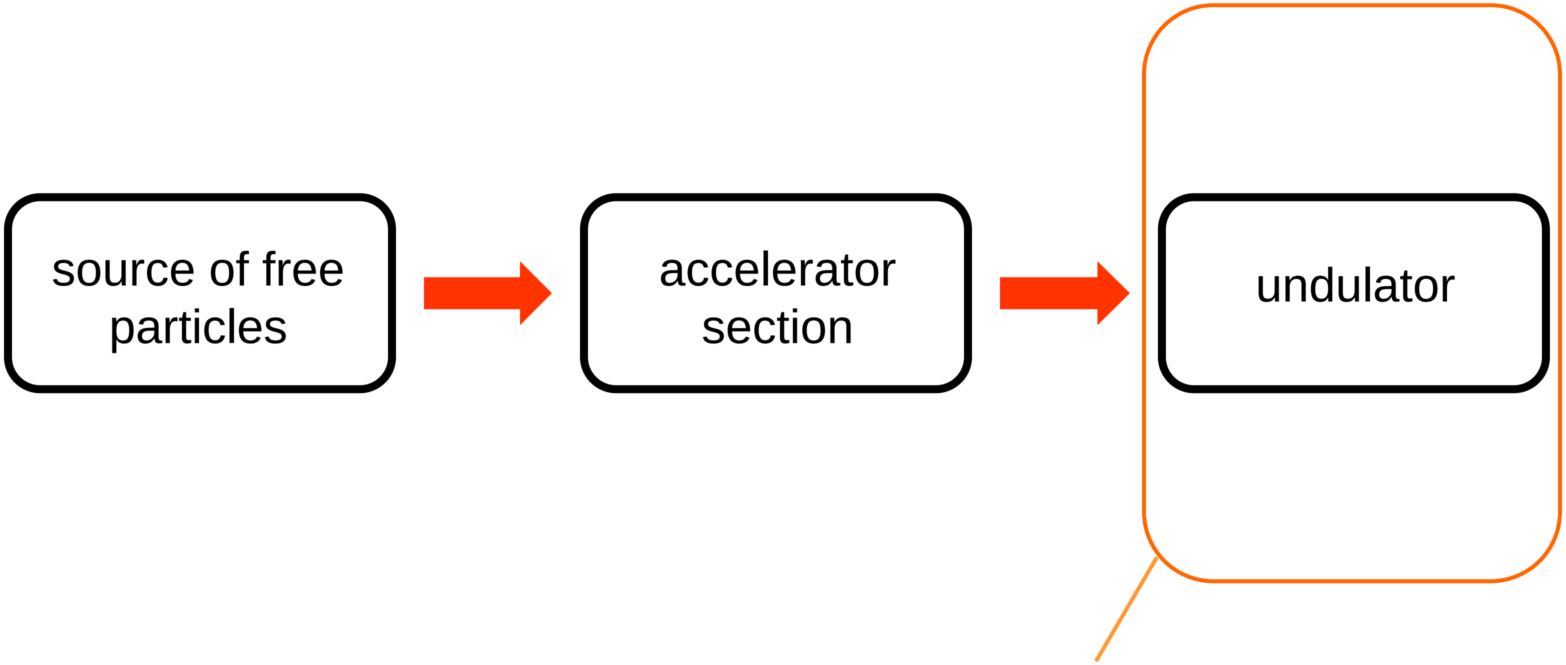


Objective:

develop MEMs based Dielectric laser-driven accelerator structures

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

Development of the three key laser-driven components



source of free particles

accelerator section

undulator

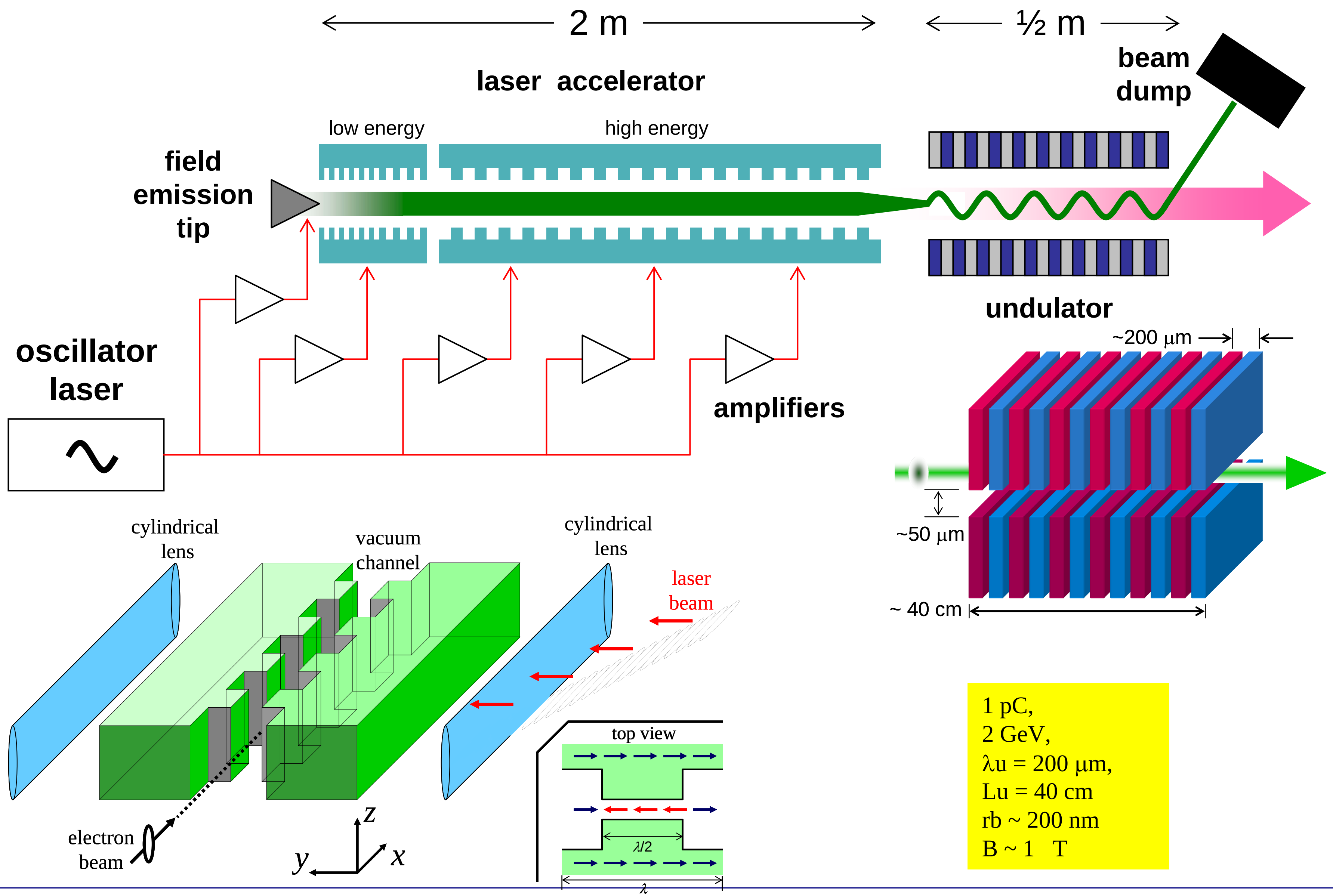
First Idea:

Periodic Magnetic Undulator

Field strength ~ 1 Tesla
Modulation Period ~ 0.1mm
Length ~ 30cm

Proposed parameters for laser driven SASE-FEL

(Theoretical Study of FEL operation)



1 pC,
2 GeV,
$\lambda u = 200\ \mu m$,
Lu = 40 cm
rb ~ 200 nm
B ~ 1 T

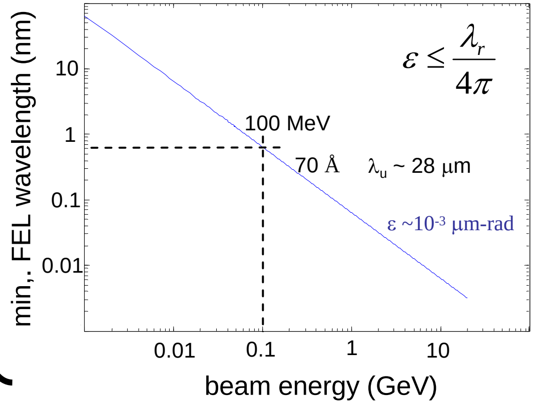
Byer Group

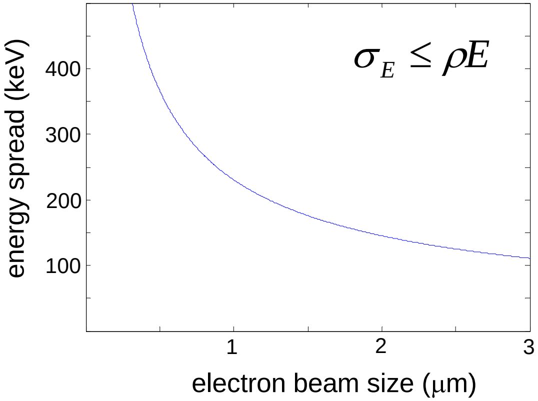
Attosecond X-ray FEL Source - detail

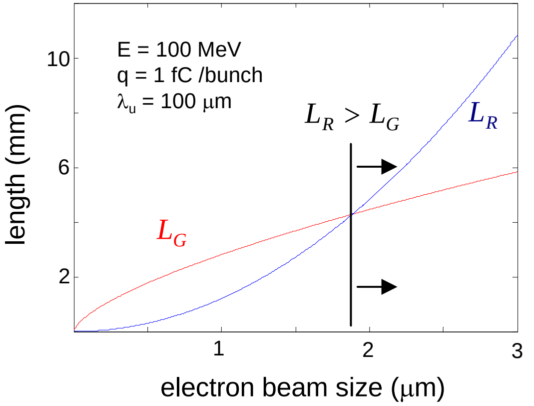
Starting point

1-D FEL model

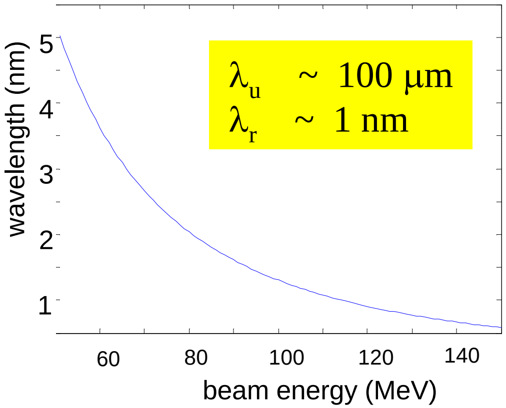
Design parameters must satisfy these conditions





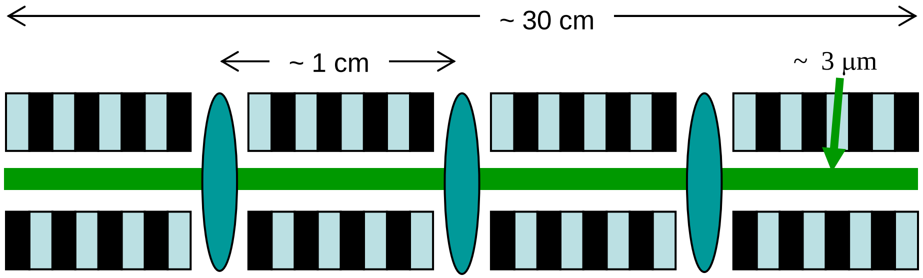


Undulator design



L_{FODO} ~ 1 cm L_G ~ 1 cm ε ~ 10^{-9} m-rad λ_b ~ 18 attosec

o_{xy} ~ 3 µm L_{sat} ~ 30 cm q_b ~ 1 fC U_b ~ 10^{-7} J



Laser power required

f_{rep} ~ 1 MHz

η_{acc} ~ 1%

P_{acc} ~ **10 W laser power**

η_{laser} ~ 10 % wallplug efficiency

P_e ~ **100 W electrical power**

1% conversion efficiency

1% of U_b = 10^{-7} J

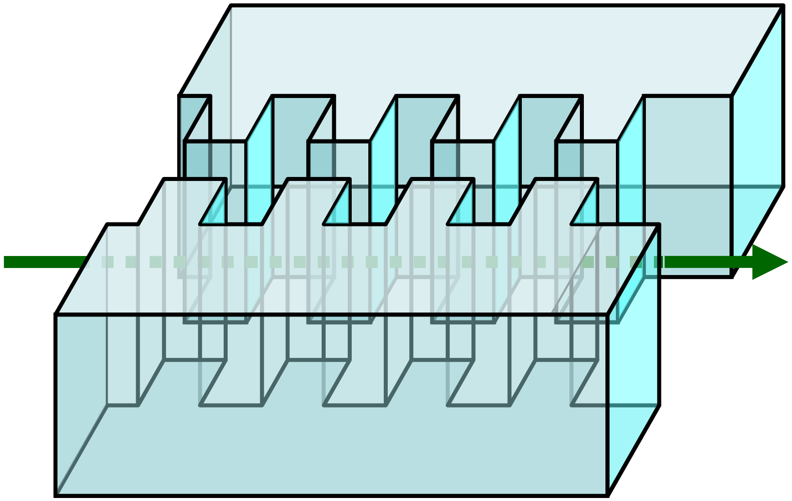
U ~ 10^7 Photons

~ 1 nJ/pulse

End of Story? NO! Plettner went away and thought real hard -

New Idea: Laser-Driven **Dielectric Undulator** for FEL

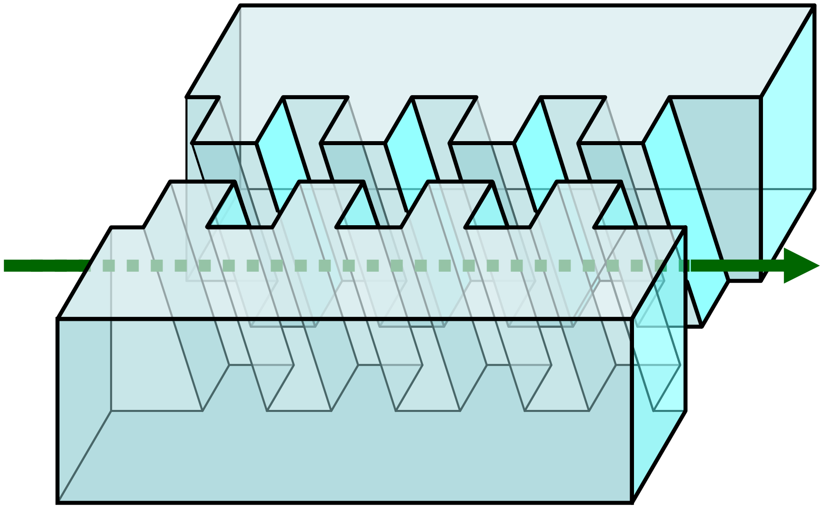
accelerator structure



$$\left\langle \vec{E}_{\perp} + \left(\vec{v} \times \vec{B}\right)_{\perp} \right\rangle = 0$$

$$\left\langle \vec{E}_{\parallel} \right\rangle \sim \tfrac{1}{2} E_{laser} \rightarrow \sim 4\,\mathrm{GeV/m}$$

deflection structure



$$\left\langle \vec{E}_{\perp} + \left(\vec{v} \times \vec{B}\right)_{\perp} \right\rangle \neq 0$$

$$\left\langle \vec{F}_{\perp} / q \right\rangle \sim \tfrac{1}{5} E_{laser} \rightarrow \sim 2\,\mathrm{GeV/m}$$

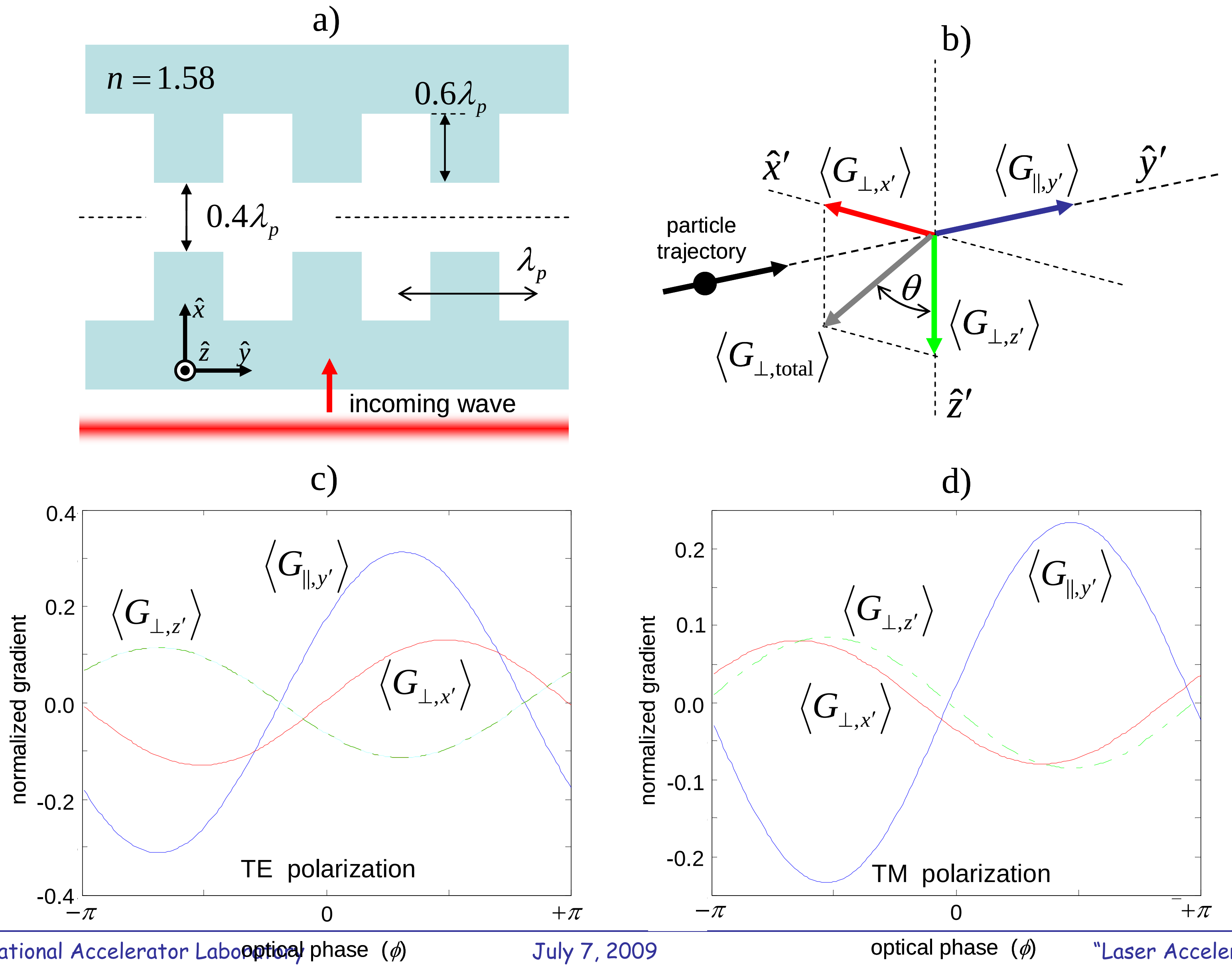
key idea

Extended phase-synchronicity between the EM field and the particle

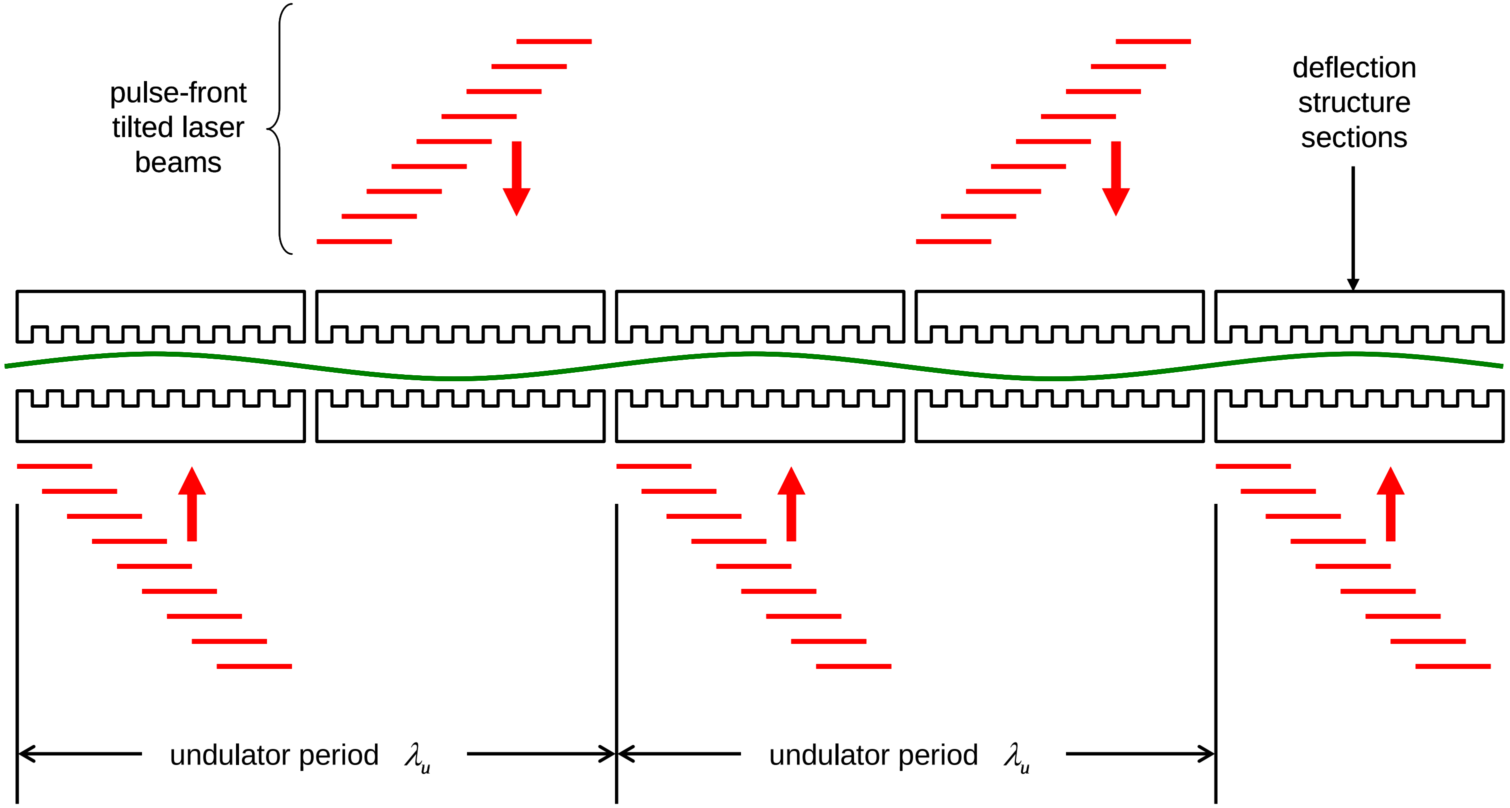
Use modelocked laser to generate periodic magnetic field

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

The calculated phase-synchronous force components

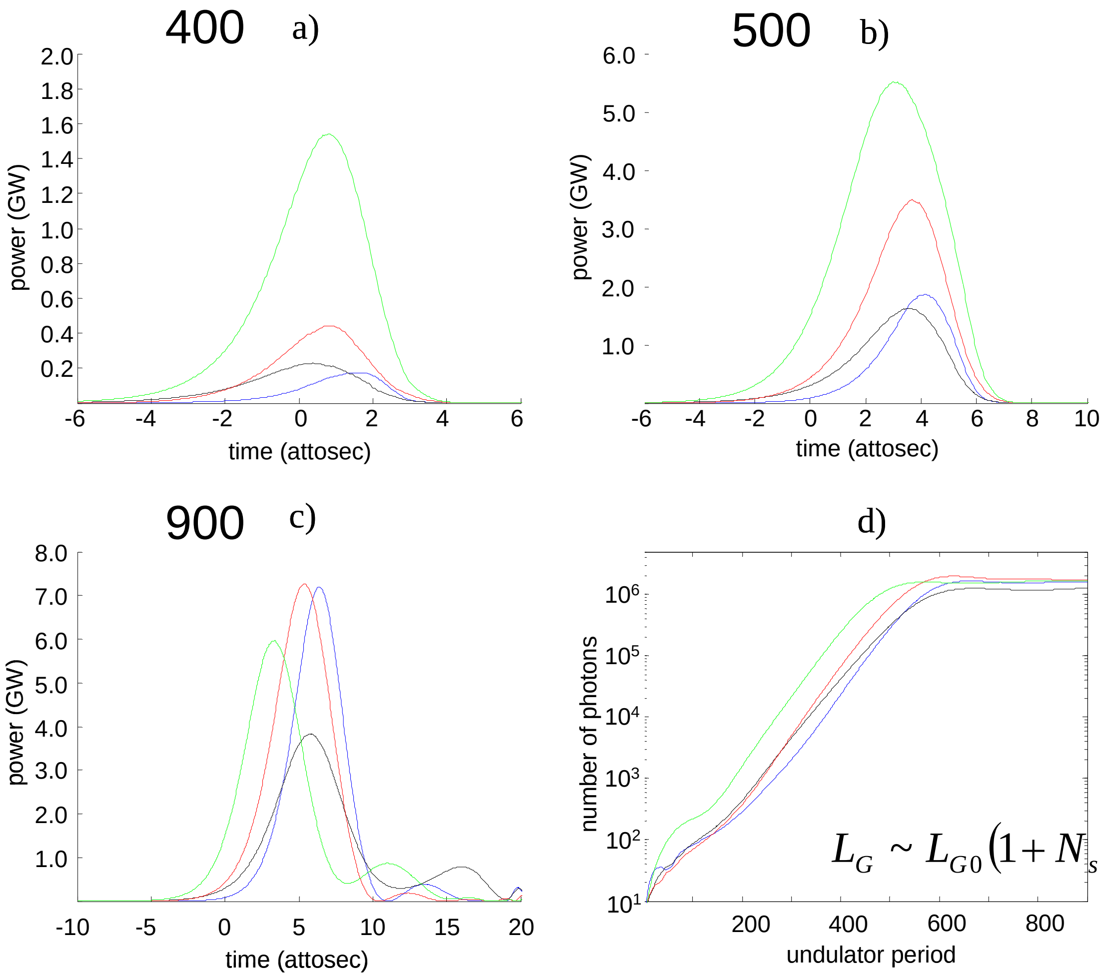


A dielectric structure laser driven undulator



- **same loss factor** as the laser accelerator: ~100 GV/m/pC
- **similar MEMS structure geometry** → fabrication compatibility

Calculated FEL Performance – 0.1 Angstrom X-rays (Pulse duration of X-rays – 5 attoseconds)



$$L_G \sim L_{G0}\left(1 + N_s \lambda_r / 3\sigma_b\right)$$

$$\rho_{eff} = U_{FEL} / U_{beam} \sim 5\times 10^{-4}$$

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

$$L_c \sim 21\lambda_r$$

$$\sigma_b \sim 136\lambda_r$$

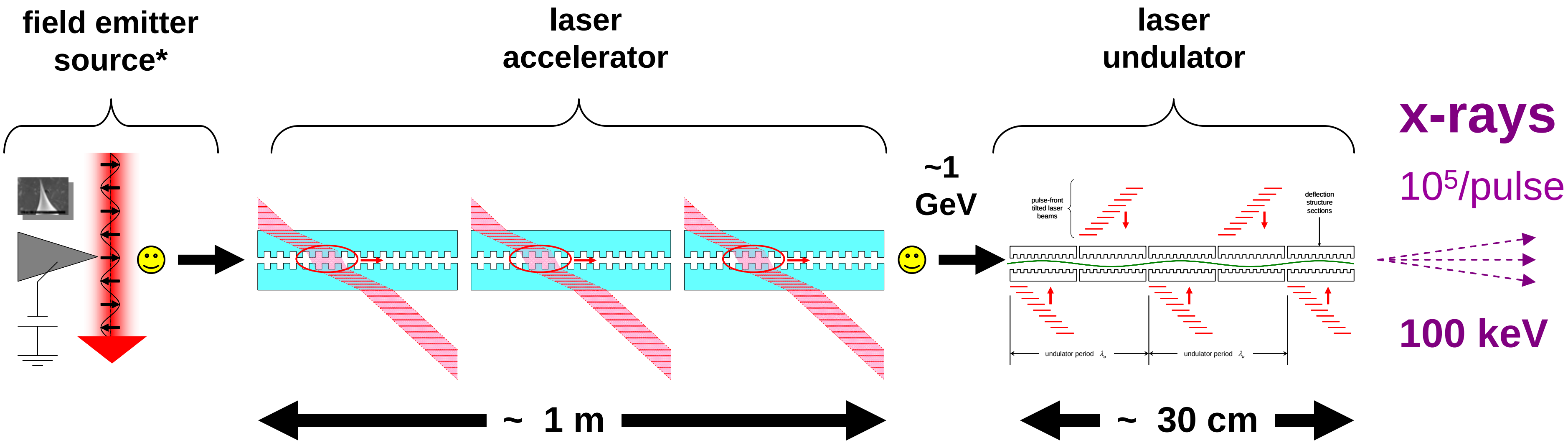
$$\downarrow$$

$$\sigma_b / L_c \sim 6$$

G. Dattoli, L. Giannessi, P.L. Ottaviani, C. Ronsivalle, J. Appl. Phys. 95, 3206 (2004)

Summary: possible table-top coherent X-ray source

Schematic of the tabletop radiation source



field emitter source*

laser accelerator

laser undulator

~1 GeV

x-rays

10^5/pulse

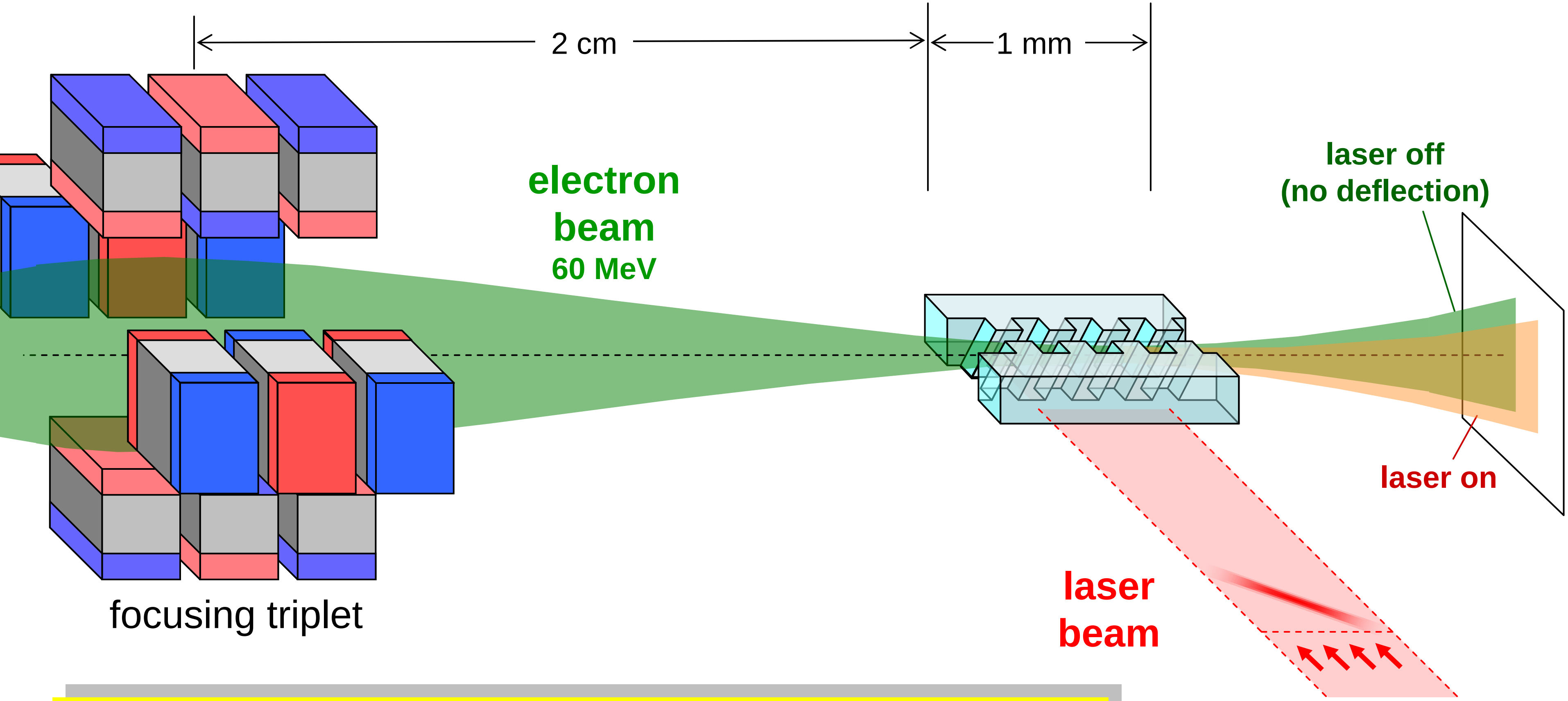
100 keV

~ 1 m

~ 30 cm

There is a path forward based on a modelocked laser driven dielectric structure

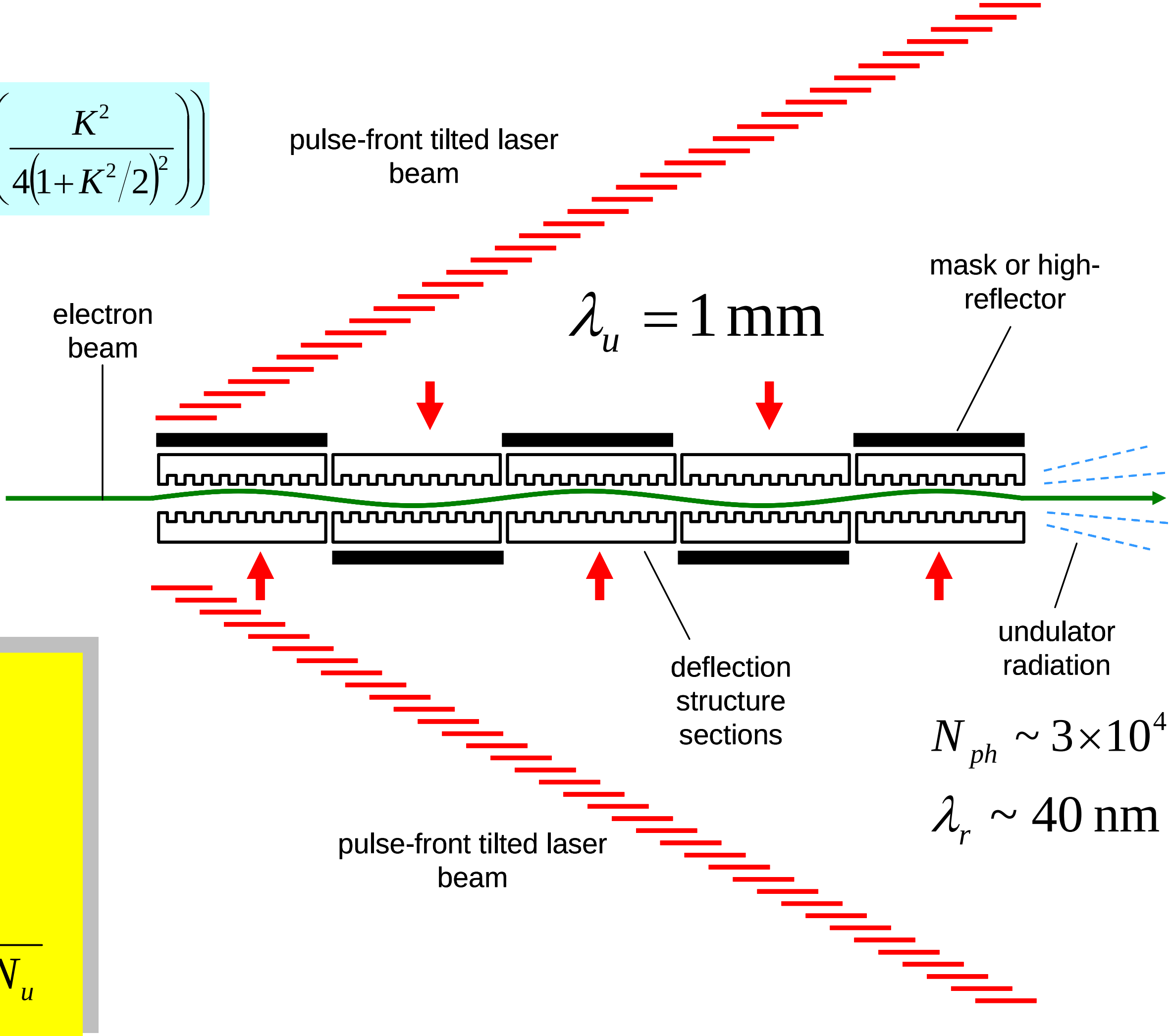
Test of laser-deflection Structure



Prove the concept of a phase-synchronous deflection force

Look for undulator radiation

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



<u>Prove the concept</u>

measure

$$\begin{cases} K \propto \lambda_u \\ \Delta\omega/\omega = 1/N_u \\ \Delta\theta = \sqrt{2\lambda_r/\lambda_u N_u} \end{cases}$$

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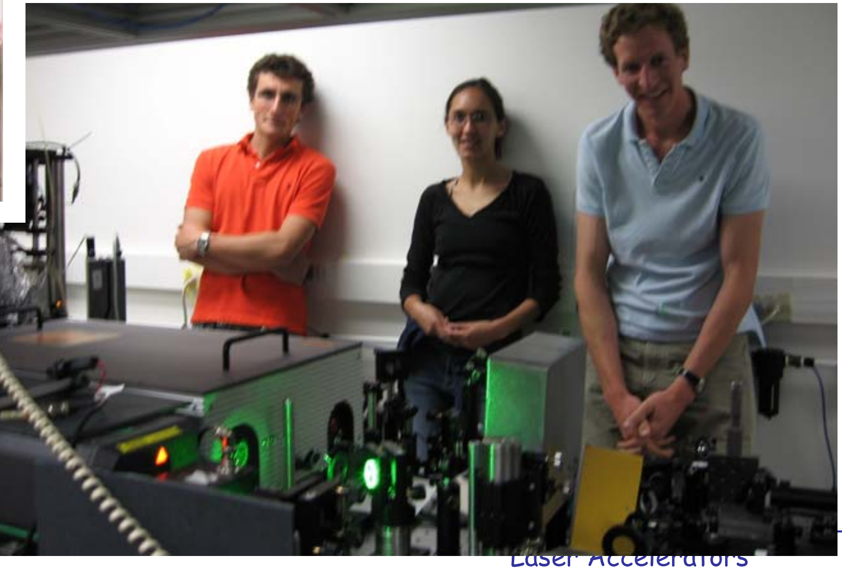
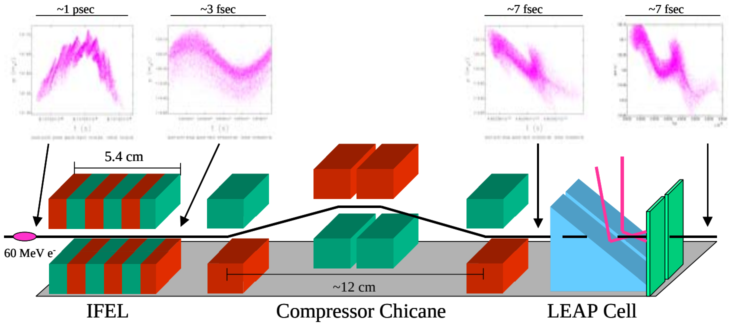


Challenges ahead

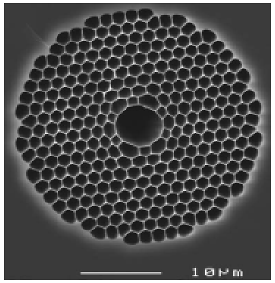
1



Staged acceleration

- precise control of optical phase
- control of focusing and steering of the electron beam

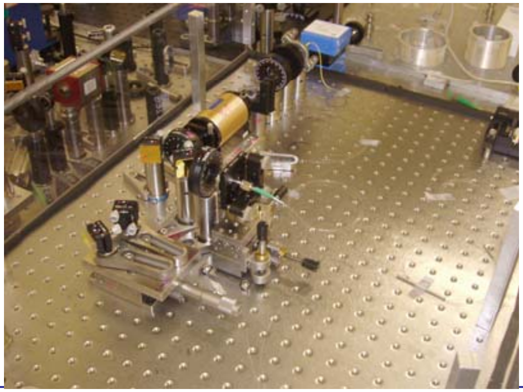
2



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

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)

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- Mike Hennessy (ES II)
- Todd Smith (HEPL)
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- R. Route, V. Drew
- B. Noble, D. Walz (ARDB, SLAC)
- Y.C. Huang, C. Barnes, S. Waldman, J. Wisdom
- S. Sinha, R. Gaume, S. Wong
- J. Rosenzweig

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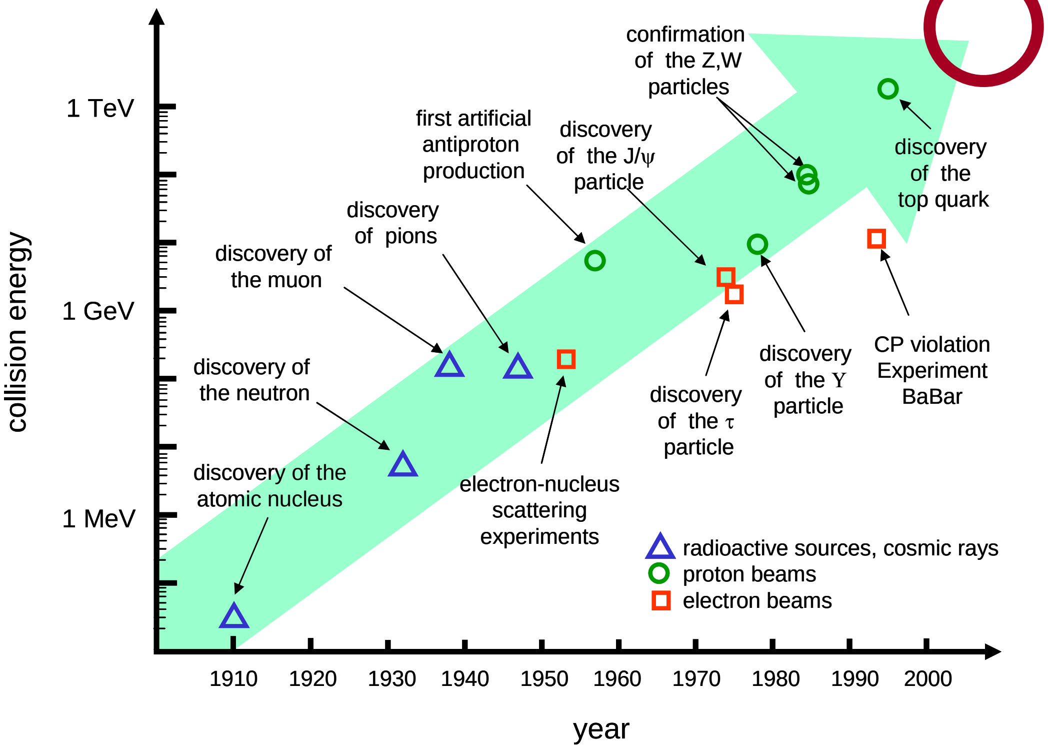
BACK UP SLIDES

Exploring the TeV-Energy Physics Frontier

historical trend of high energy physics experiments

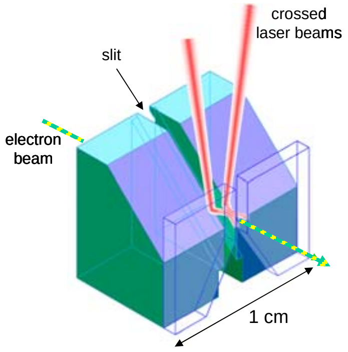


TeV e^+e^- collision experiments

- 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 tape boundary

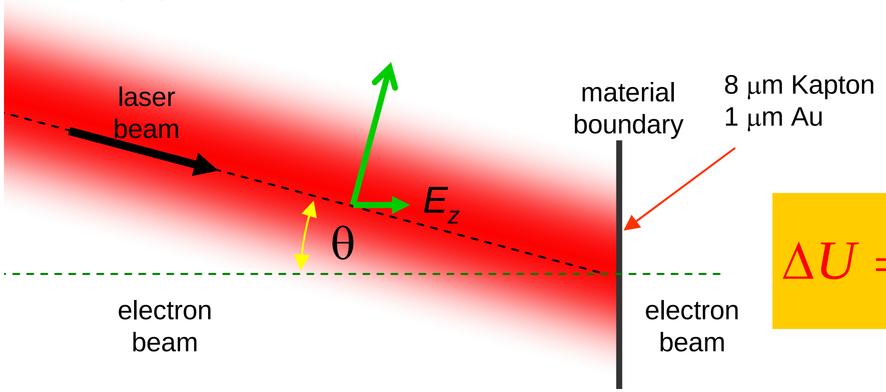


Improve on

- 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

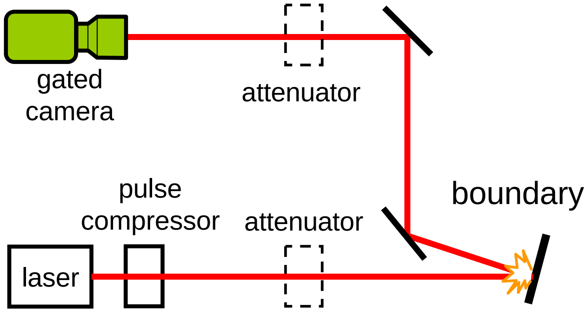
Conceptual drawing
of the improved setup



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

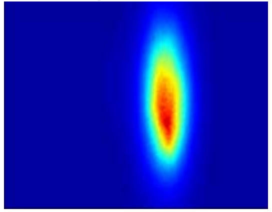
The tape boundary

a) Setup for the reflected spot measurements

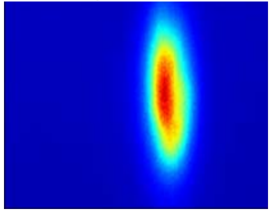


reflected spot camera images

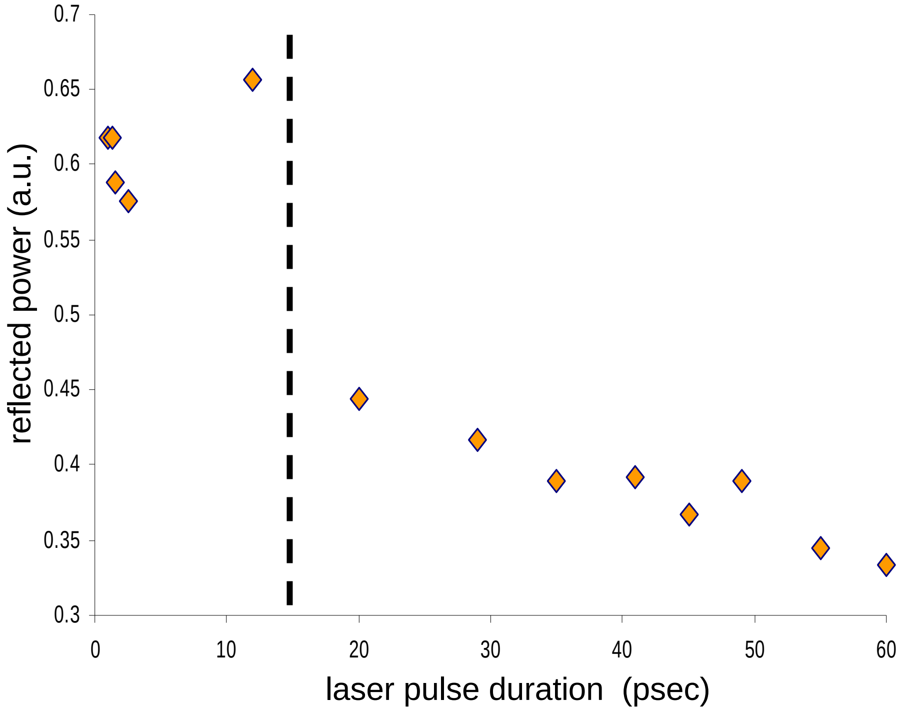
i) low power, below damage threshold



ii) 1st shot, above damage threshold

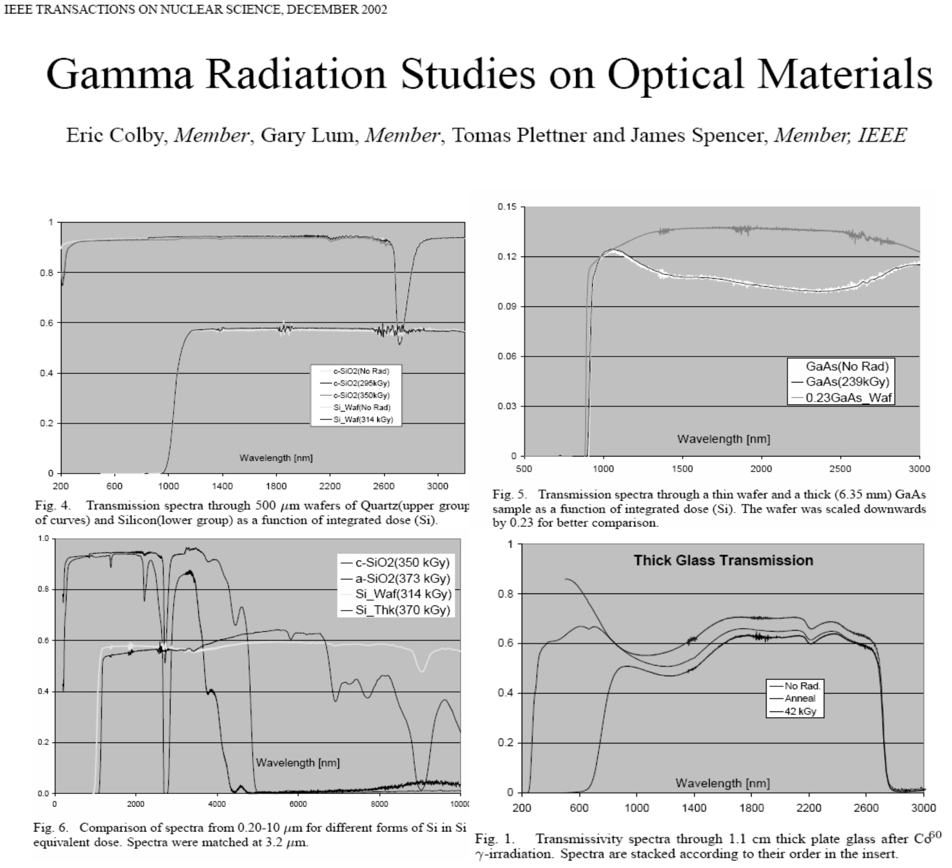


b) Reflected pulse intensity versus laser pulse duration



Laser damage and radiation damage studies

Radiation damage studies



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*

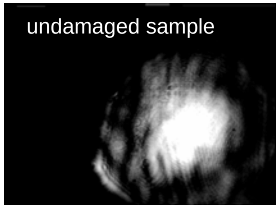
Fig. 4. Transmission spectra through 500 μm wafers of Quartz(upper group of curves) and Silicon(lower group) as a function of integrated dose (Si).

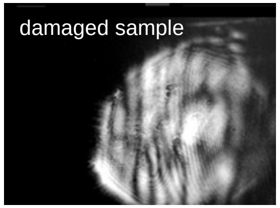
Fig. 5. Transmission spectra through a thin wafer and a thick (6.35 mm) GaAs sample as a function of integrated dose (Si). The wafer was scaled downwards by 0.23 for better comparison.

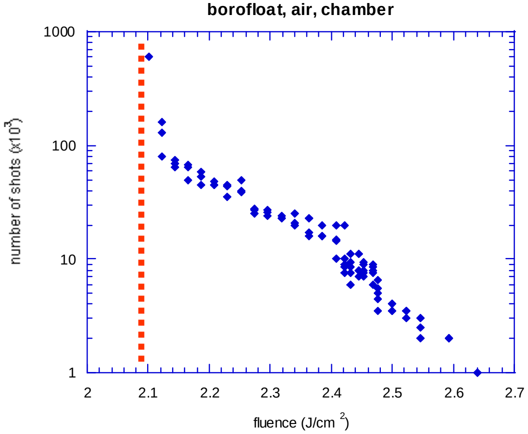
Fig. 6. Comparison of spectra from 0.20-10 μm for different forms of Si in Si equivalent dose. Spectra were matched at 3.2 μm.

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.

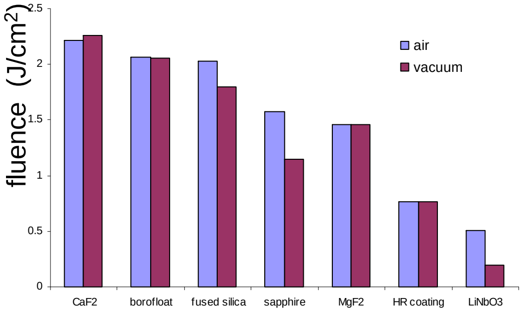
Laser damage threshold studies







material	damage threshold	
	air	vacuum
CaF_2	2.212	2.260
borofloat	2.064	2.054
fused silica	2.027	1.795
sapphire	1.574	1.152
MgF_2	1.455	1.455
800 nm HR	0.769	0.768
$LiNbO_3$	0.504	0.194



Laser research

OPTICAL PHASE LOCKING OF MODELOCKED LASERS FOR PARTICLE ACCELERATORS*

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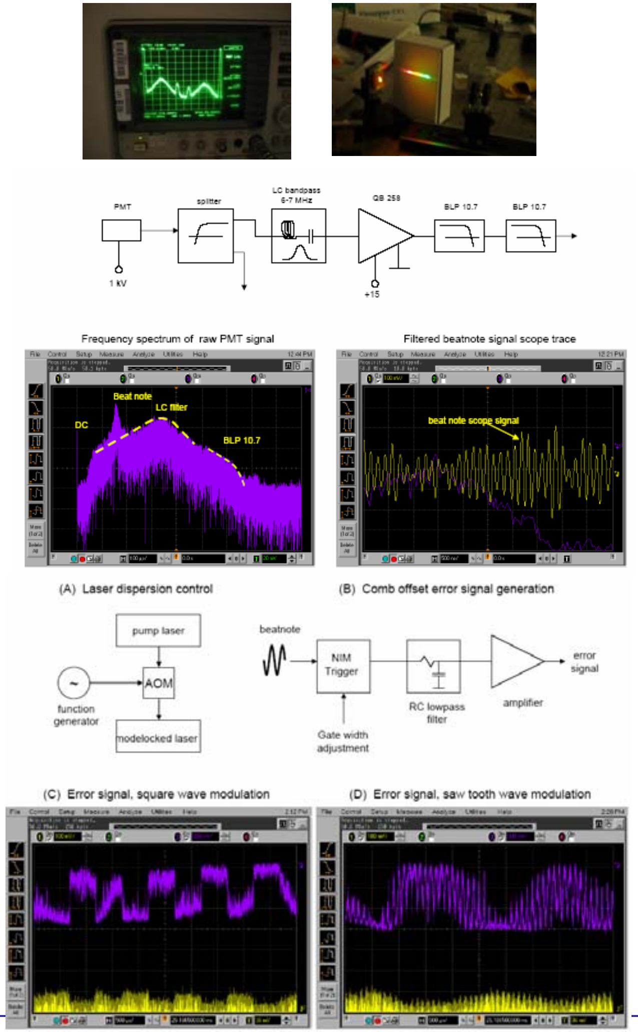

(A) Laser dispersion control

(B) Comb offset error signal generation

(C) Error signal, square wave modulation

(D) Error signal, saw tooth wave modulation