A Laser Driven Linear Accelerator:
A Pathway Toward Attosecond Coherent X-rays

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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 modelocked laser source. 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. Progress toward the accelerator and coherent X-ray source will be discussed.

Panel on Light Source Facilities
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Lawrence Livermore National Laboratory
Wednesday 9 January 2008

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Historic Background
- The Klystron and the Linear Acceleration of electrons
- Stanford Linear Accelerator Center – SLAC

The TeV-Energy Physics Frontier

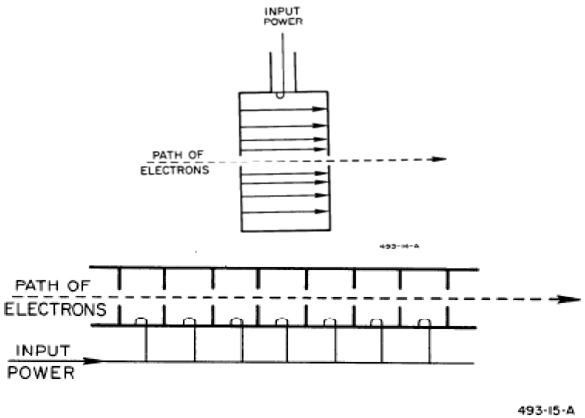
Laser Electron Accelerator Project – LEAP
- HEPL Experiments from 1997 – Nov 2004
- E163 Experiments at SLAC
  - Laser accelerator structures
  - Inverse FEL for electron pulse compression - <1 fsec electron pulse duration

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

Future Challenges
- Toward Table top Synchrotron sources

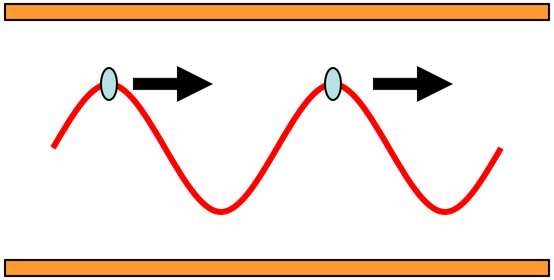
"Don't undertake a project unless it is manifestly important and nearly impossible." **Edwin Land – 1982**

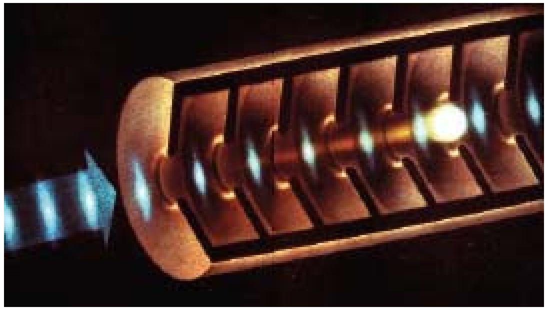
The development of the linear accelerator at Stanford University



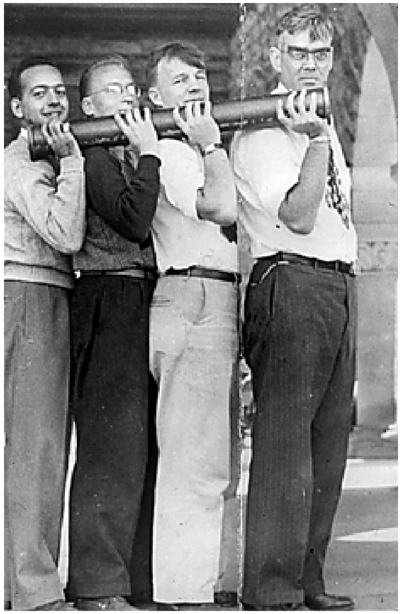
"we have accelerated electrons"

Hansen's report to the Office of Naval Research

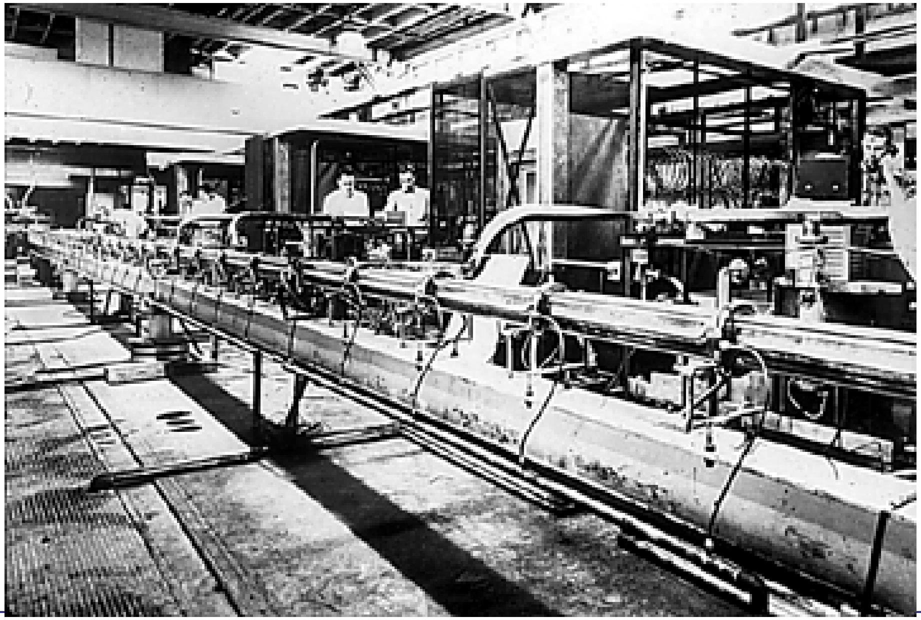




$$U = \int \vec{E} \cdot d\vec{r}$$



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



The Mark III

A high-energy physics research tool

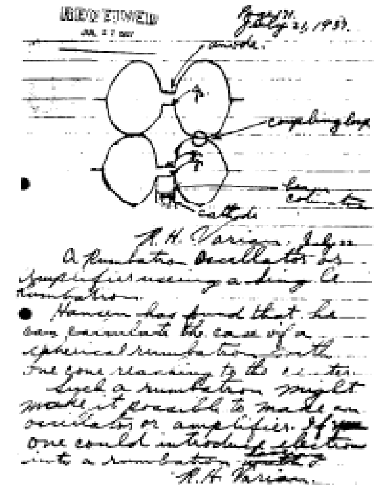
1953: 400 MeV
1955: 600 MeV
1960: 1 GeV

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

High resolution electron scattering from nuclei by **Robert Hofstadter**

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



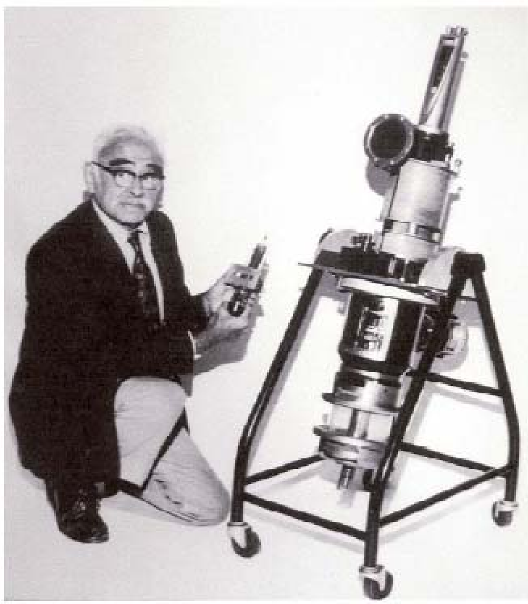
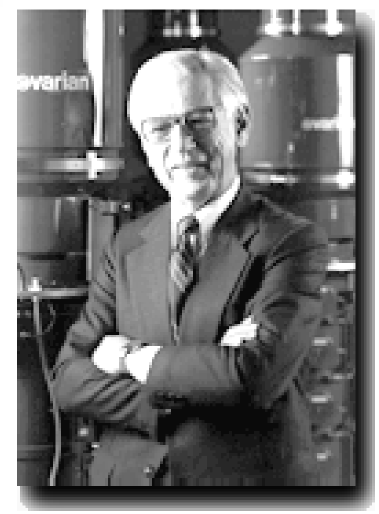


Fig. 10 Marvin Chodorow comparing the CV-150 to the Mark III klystron

Marvin Chodorow & Klystron

W. W. Hansen – back right



Ed Ginzton

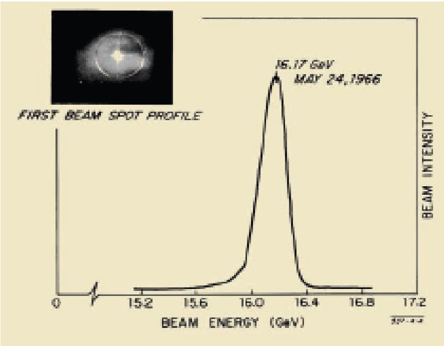
"Project M"

1955 first brainstorming and informal discussions

SLAC CHRONOLOGY

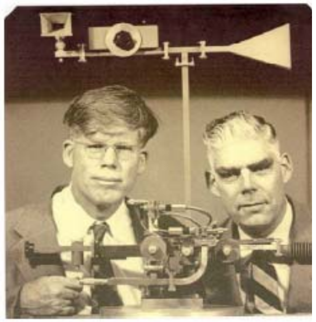
April 1957	Proposal for two-mile accelerator submitted by Stanford University to Federal Government
September 1961	Project authorized by U. S. Congress
April 1962	Contract signed by U. S. Atomic Energy Commission and Stanford University
July 1962	Ground breaking; construction begins
July 1964	Start of 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

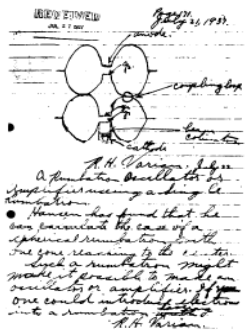
- $100M proposal
- numerous studies and reports
- > 10 years of effort



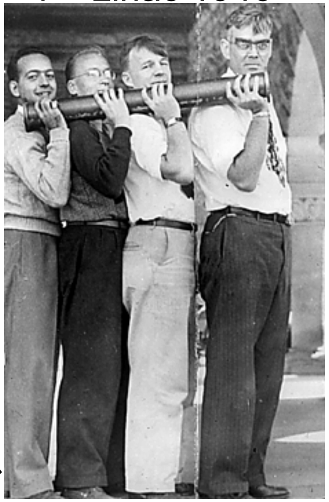
First beam at SLAC, 1966

1st Klystron (Varian, 1930s')

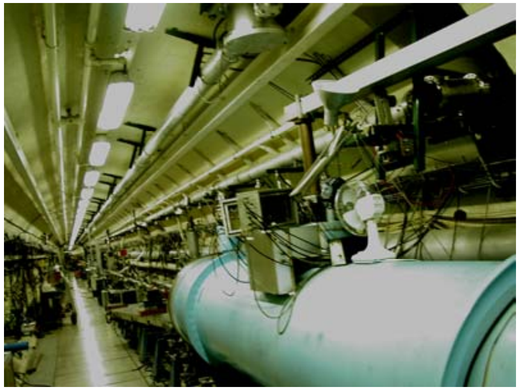




1st Linac 1946



The superconducting linac
In HEPL, 1960



The 2-mile collider (SLAC)

LEAP, 1997-2004

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. Smit
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.

SLAC – Particle Physics, Astrophysics & Photon Science

1968: First evidence of Quarks

1974: Discovery of the ψ particle

1976: Discovery of the charm quark and the τ lepton

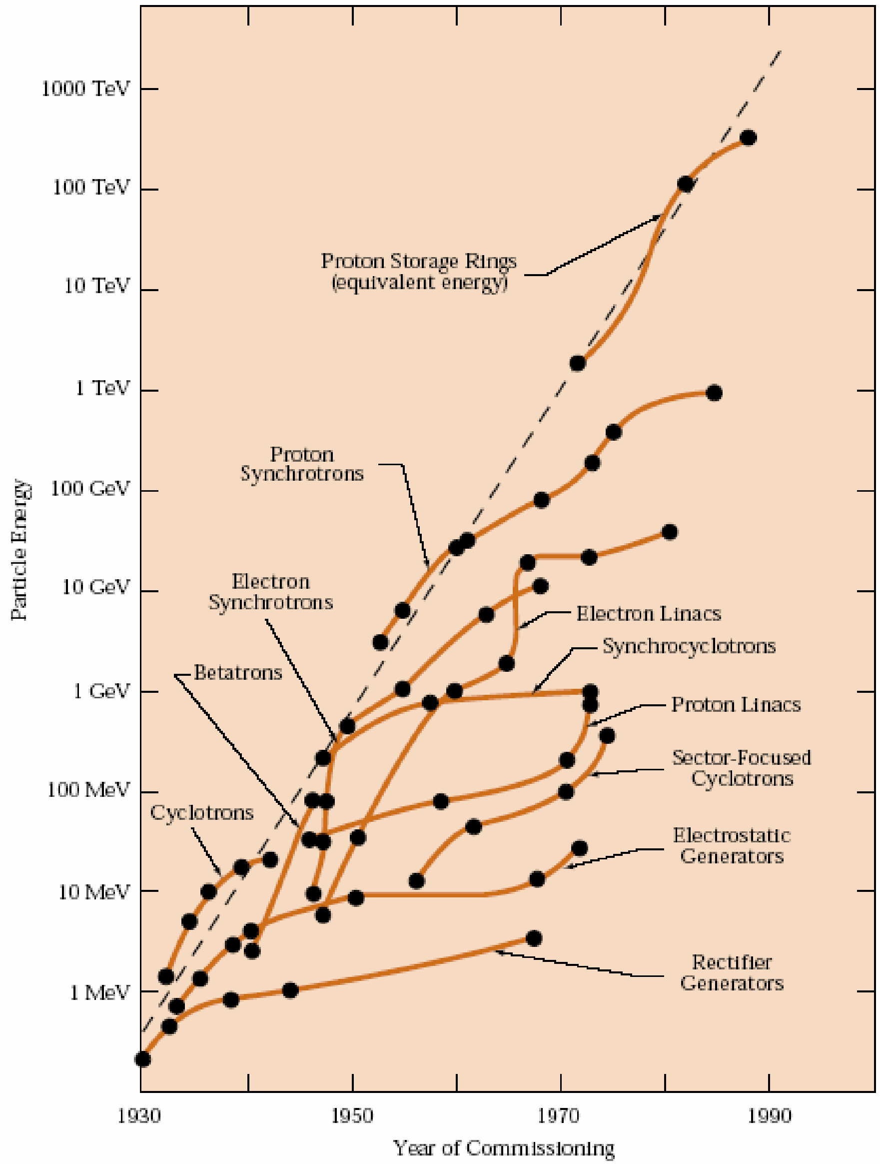
1997: The BaBar experiment

2006: LINAC coherent X-ray source

Other developments

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

The Livingston plot - 1954
Innovation leads to exponential progress



In 1954 Livingston noted that progress in high energy accelerators was <u>exponential with time.</u>

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

Laser sources coupled with related technologies enable new approaches to Advanced Electron Accelerators.

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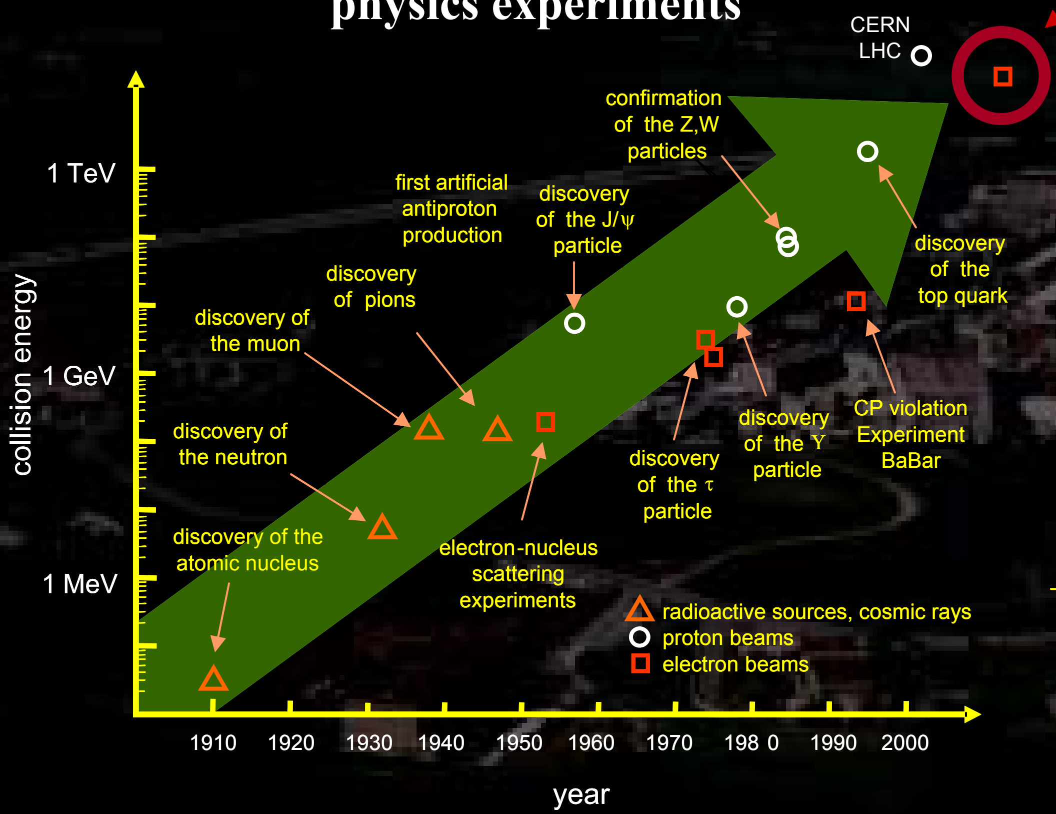
Future Challenges

Toward Table top Synchrotron Sources

What is next?

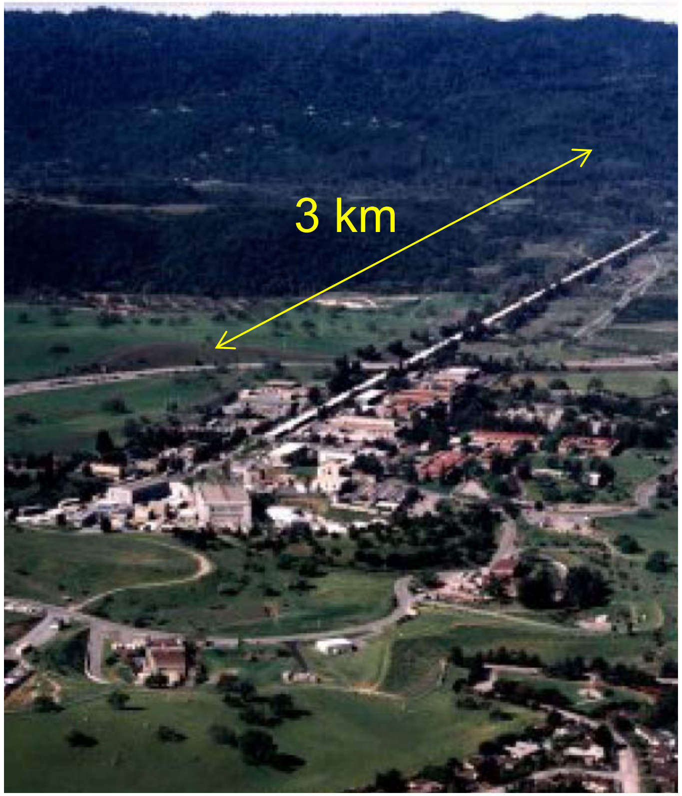
historical trend of high energy physics experiments

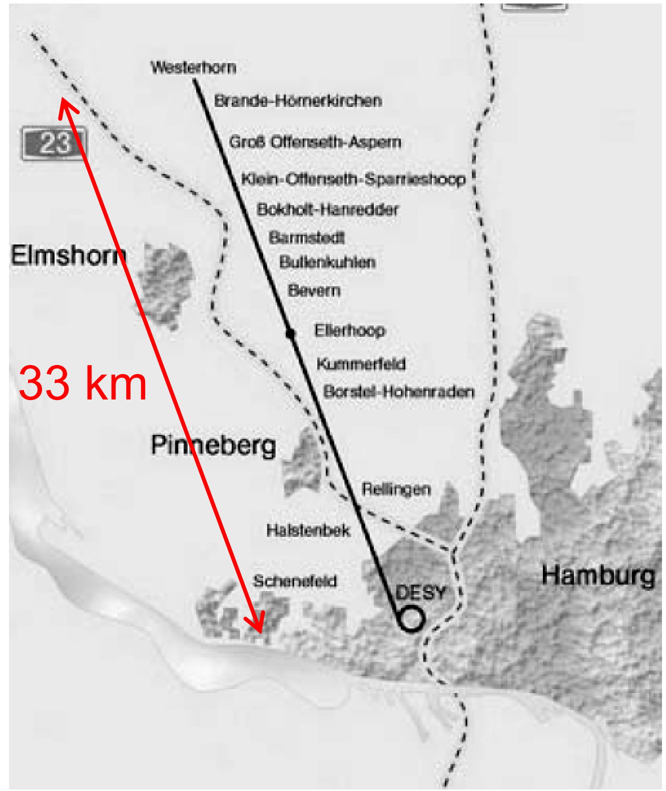


Future TeV e^+e^- collision experiments

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

The NLC ZDR Design Group and the
NLC Physics Working Groups
Snowmass `96 workshop





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.

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"
- very controversial topic

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

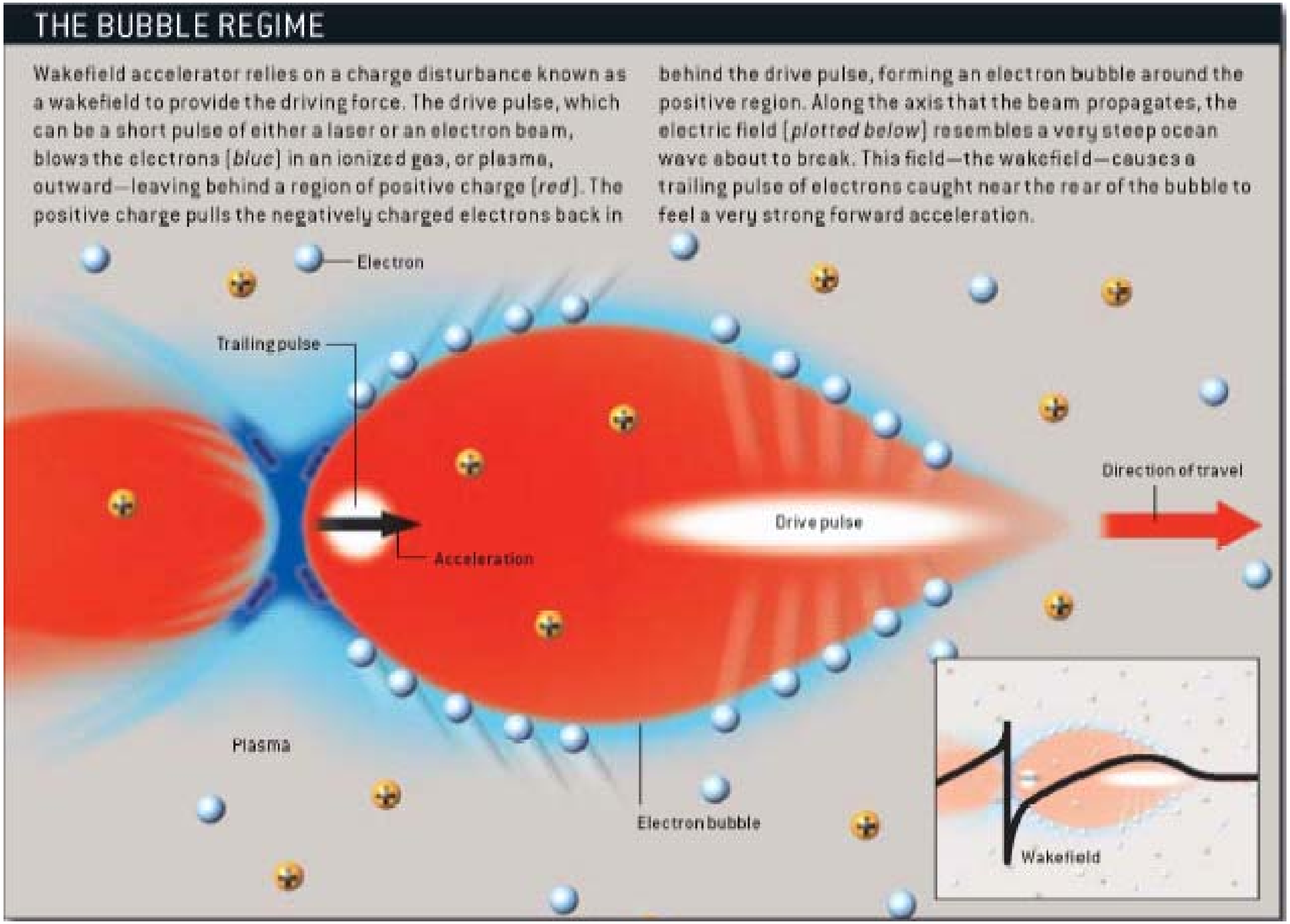
A new method of particle acceleration in which the particles "surf" on a wave of plasma promises to unleash a wealth of applications

By Chandrashekhar Joshi

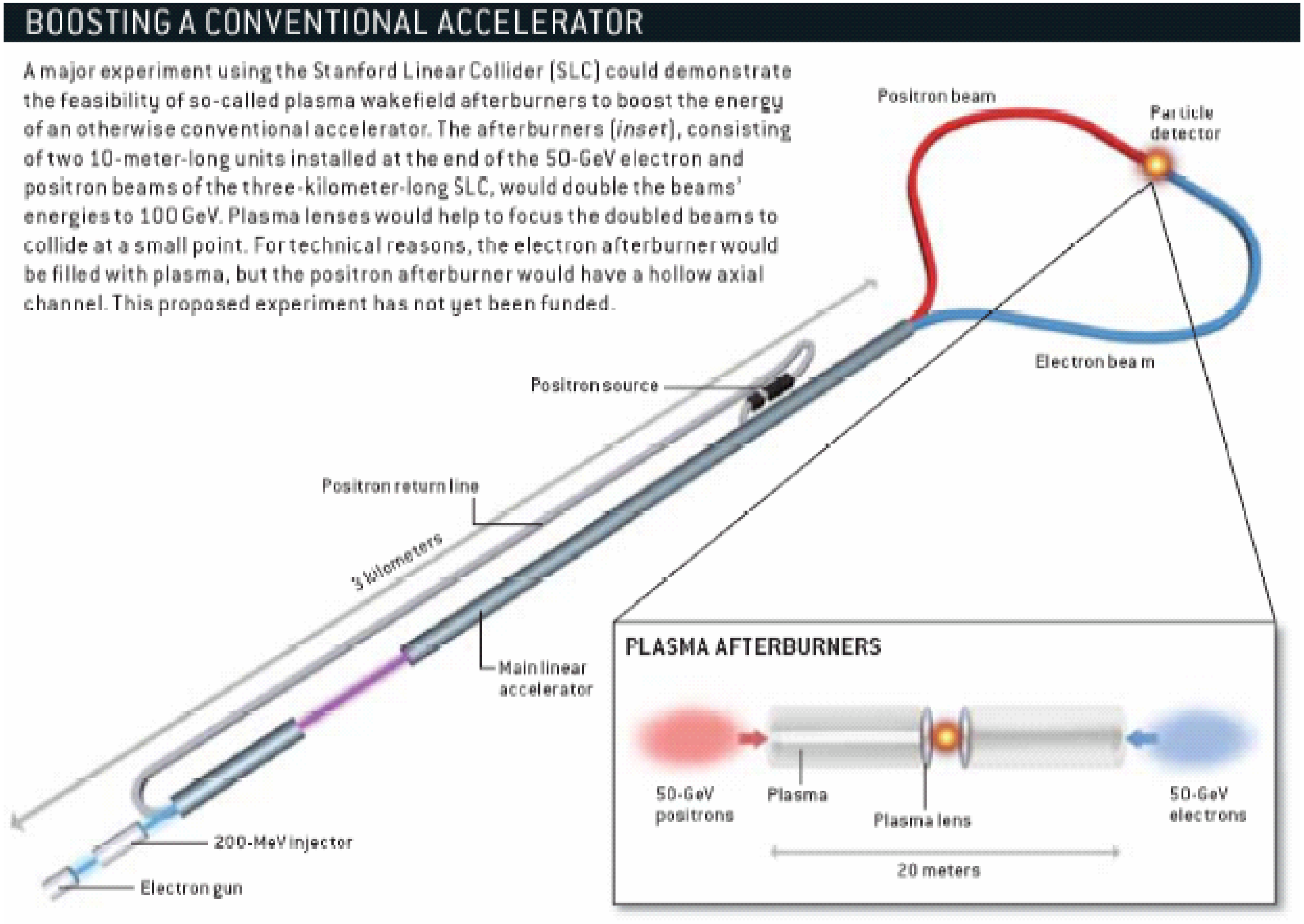
www.sciam.com

SCIENTIFIC AMERICAN 41

Principle of the Wakefield Accelerator



Wakefield Accelerator as a Booster for SLAC



A few rules of the game

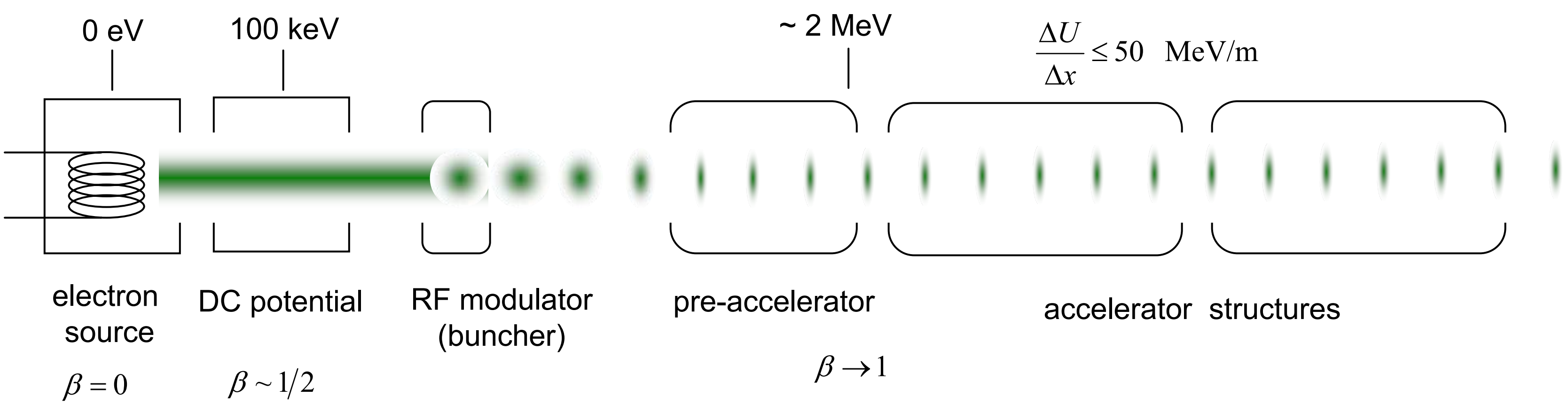
"An accelerator is just a transformer" – Pief Panofsky

"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" anon



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

Emergence of new technologies make Laser Acceleration Possible

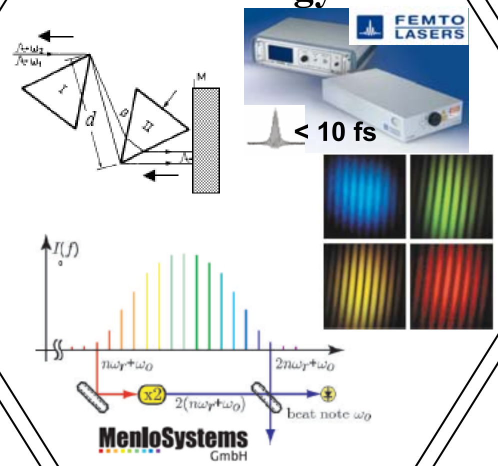
Leveraging investment in telecom

efficient pump diode lasers

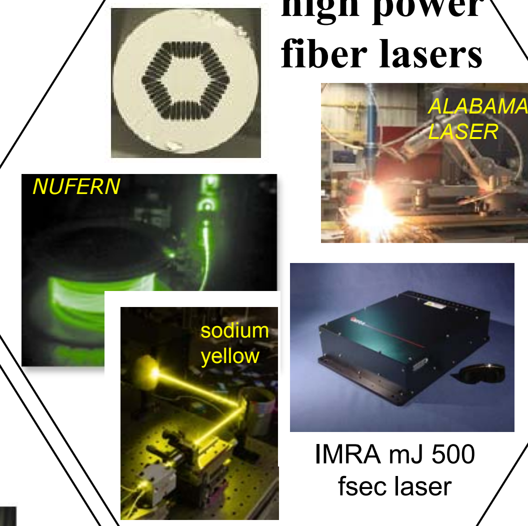
30 W/bundle, 40% electr. efficiency

60 W/bar, 50% electr. efficiency

ultrafast laser technology

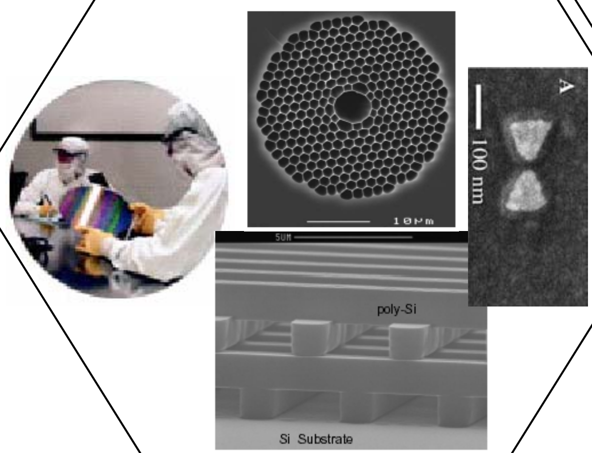


high power fiber lasers

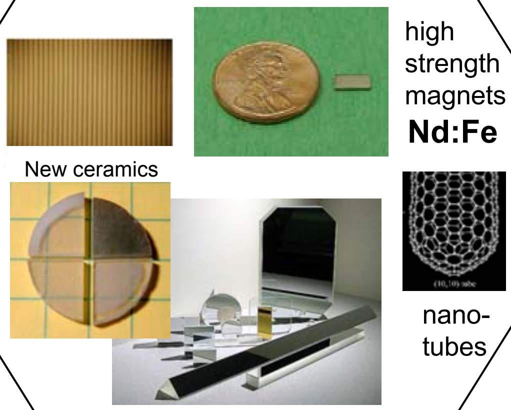


IMRA mJ 500 fsec laser

nanotechnology



new materials



New ceramics

high strength magnets **Nd:Fe**

nano-tubes

high purity optical materials and high strength coatings

Schematic of Future TeV scale Laser Accelerator

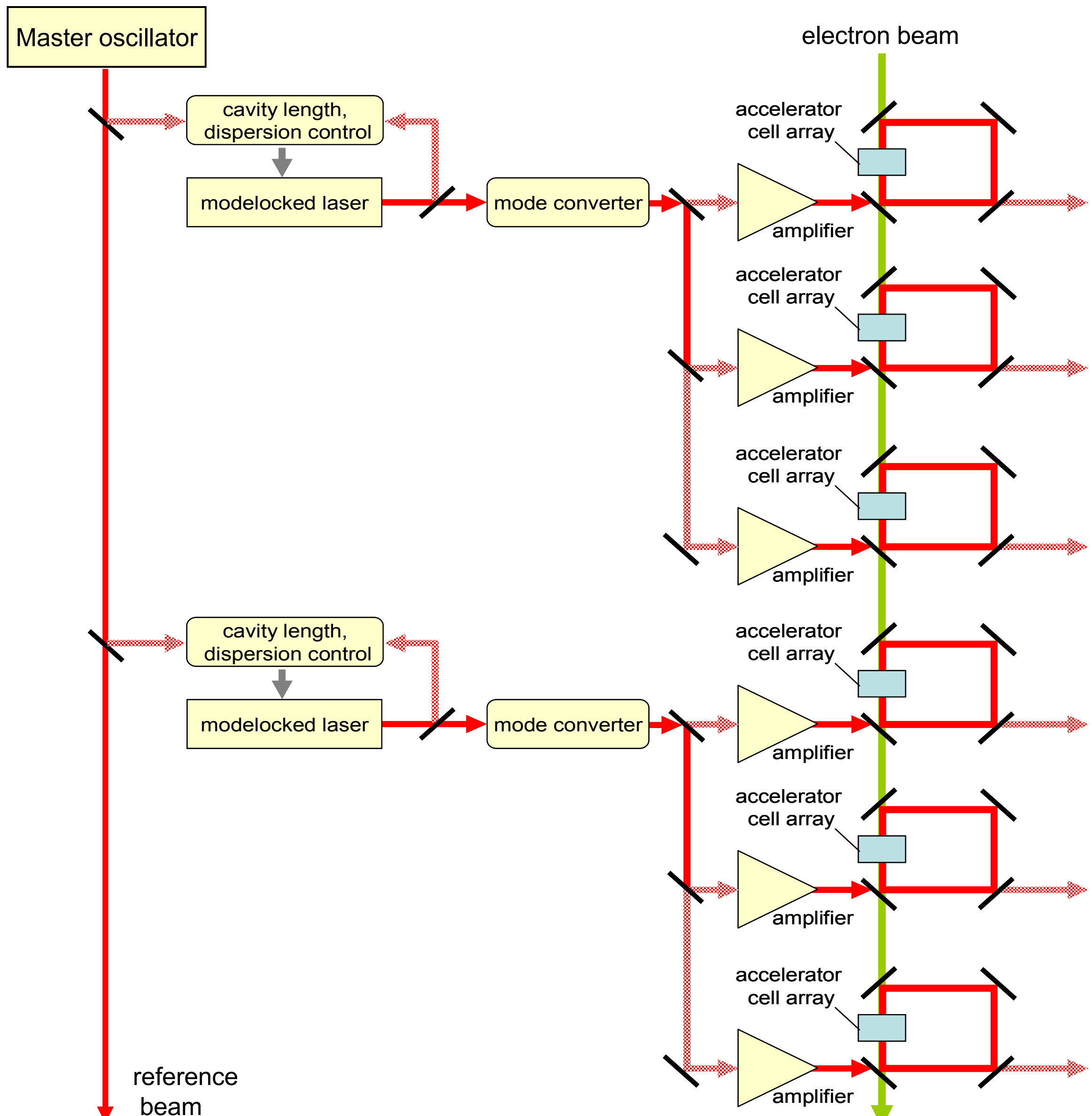
Proposed layout of the laser system for a TeV collider

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

local modelocked oscillators are phase-locked to the master oscillator

A mode converter transforms the TEM_{00} mode preferred by the laser to a TEM_{01} acceleration mode

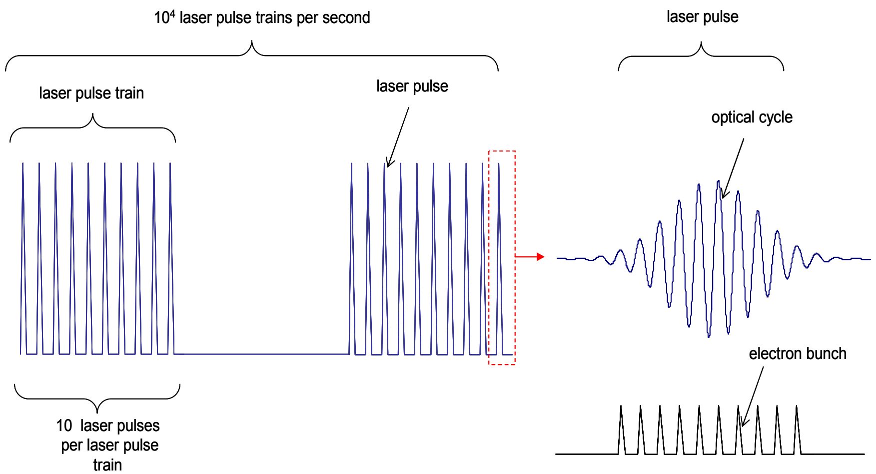
Laser amplifiers increase the power of the TEM_{01} mode from sub-watt to multiple tens of watts of average power mode



2. Low bunch charge problem

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

Laser pulse structure that leads to high electron bunch repetition rate

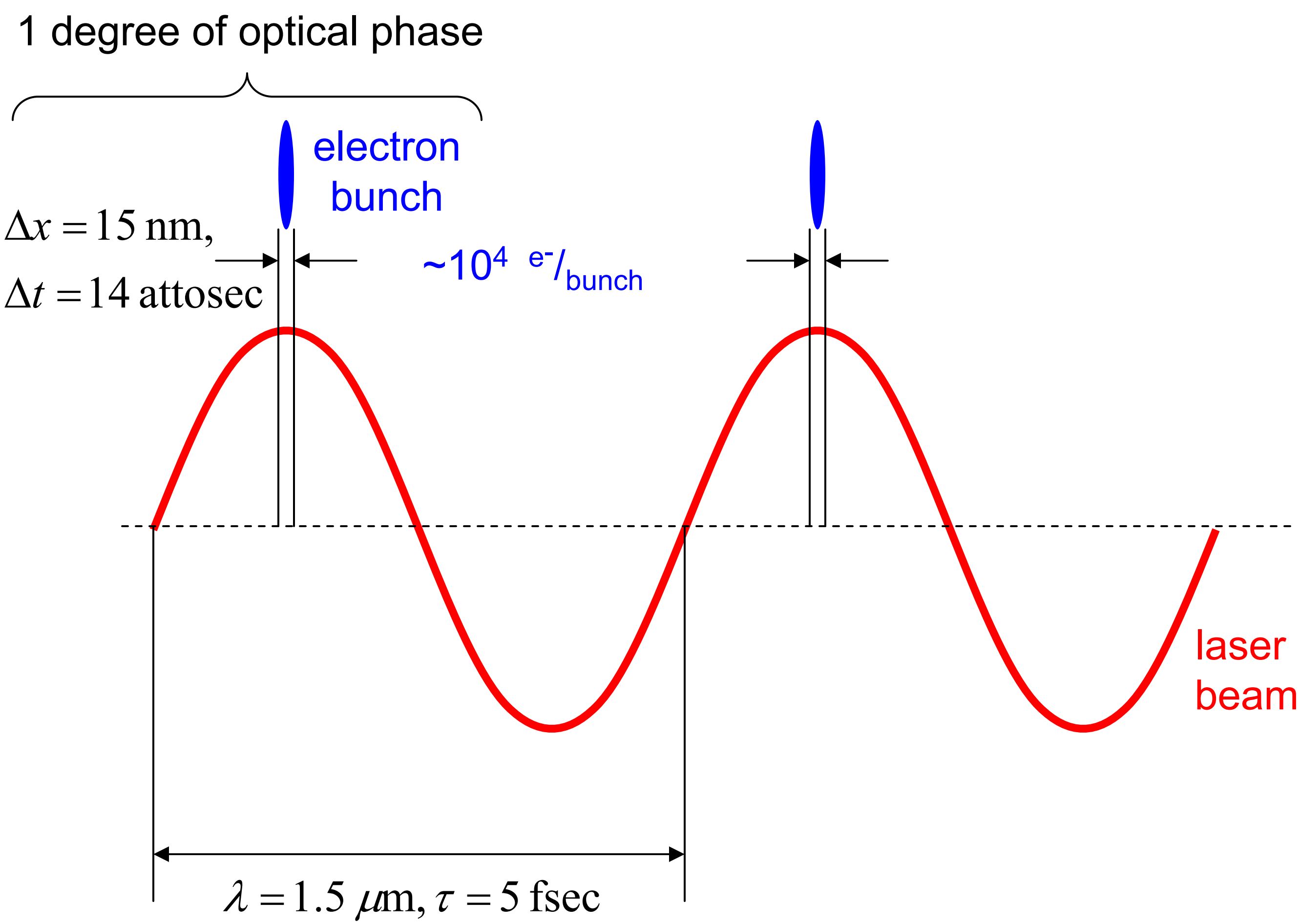


	SLC	NLC	SCA-FEL	TESLA	laser-accelerator
f_{RF} (GHz)	2.856	11.424	1.3	1.3	3×10^4
f_m (Hz)	120	120	10	4	10^4
N_b	1	95	10^4	4886	10
Δt_b (nsec)	-	2.8	84.7	176	3×10^{-6}
f_b (Hz)	1.2×10^2	1.1×10^4	1×10^5	1.6×10^4	3×10^6
N_e	3.5×10^{10}	8×10^9	3.1×10^7	1.4×10^{10}	10^4
I_e (sec^{-1})	4×10^{12}	9×10^{13}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

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

Dramatic increase of
- electric field cycle frequency
- macro pulse repetition rate

Atto Second Electron Bunches



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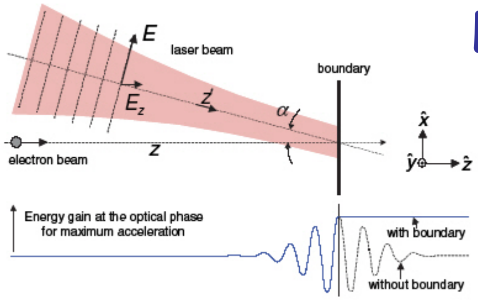
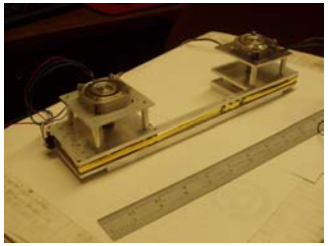
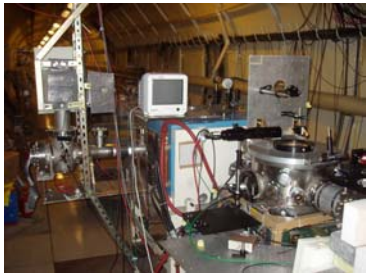


Laser driven particle acceleration



collaborators



ARDB, SLAC

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

Stanford University

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

ARDA, SLAC

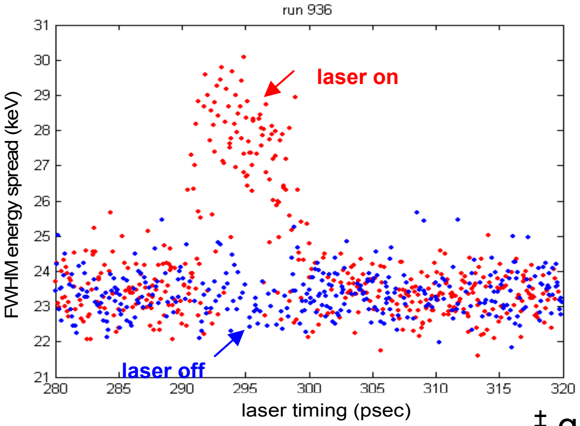
Zhiu Zhang†, Sami Tantawi†

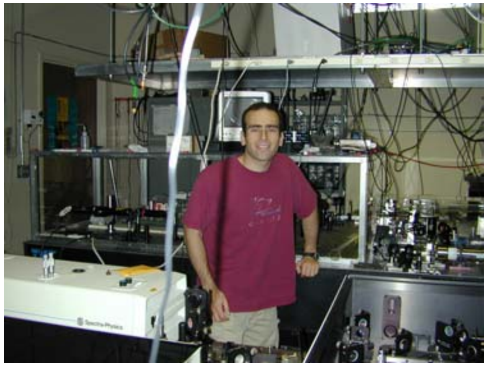
Techion Israeli Institute of Technology

Levi Schächter*

UCLA

J. Rosenzweig*



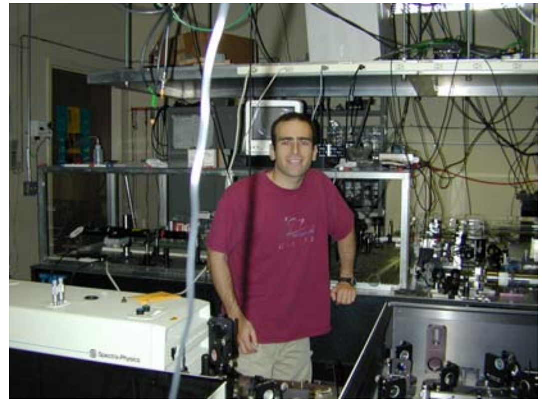


‡ grad students † postdocs and staff * faculty

Participants in the LEAP Experiment

Bob Siemann[2]

Chris Sears[2]



Ben Cowan[2]

Jim Spencer[2]

Tomas Plettner[1]

Bob Byer[1]

Eric Colby[2]

New students

- Chris Mcguinness[2]
- Melissa Lincoln[2]
- Patrick Lu[1]

Atomic Physics collaboration

- Mark Kasevich[3]
- Peter Hommelhoff[3]
- Catherine Kealhofer[3]

1 E.L. Ginzton Laboratories, Stanford University
2 Stanford Linear Accelerator Center (SLAC)
3 Department of Physics, Stanford University

Laser acceleration – Dielectric structure means high acceleration gradient

1 Energy gain through longitudinal electric field

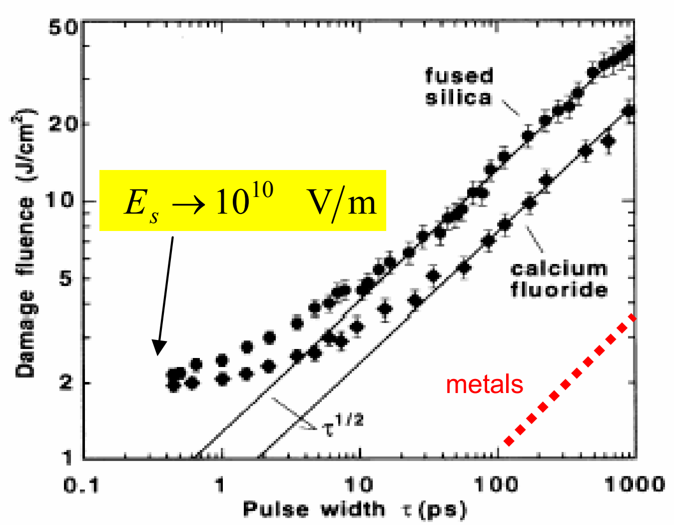
- gradient = longitudinal electric field
- linear e-beam trajectory
  - → no synchrotron radiation
  - → **energy scalable**

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

→ linear particle acceleration process

2 Dielectric based structure with vacuum channel

$$\text{Gradient} \rightarrow 1 \ \ \text{GeV/m}$$



→ very high peak electric fields

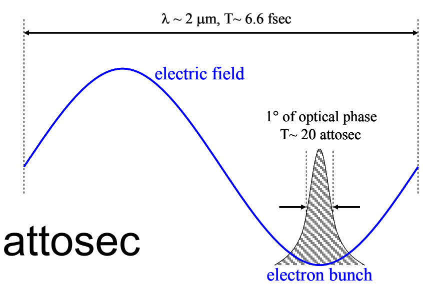
→ vacuum channel

→ NIR solid-state lasers

3 Inherent attosec electron pulse

2 μm laser → 6 fsec period

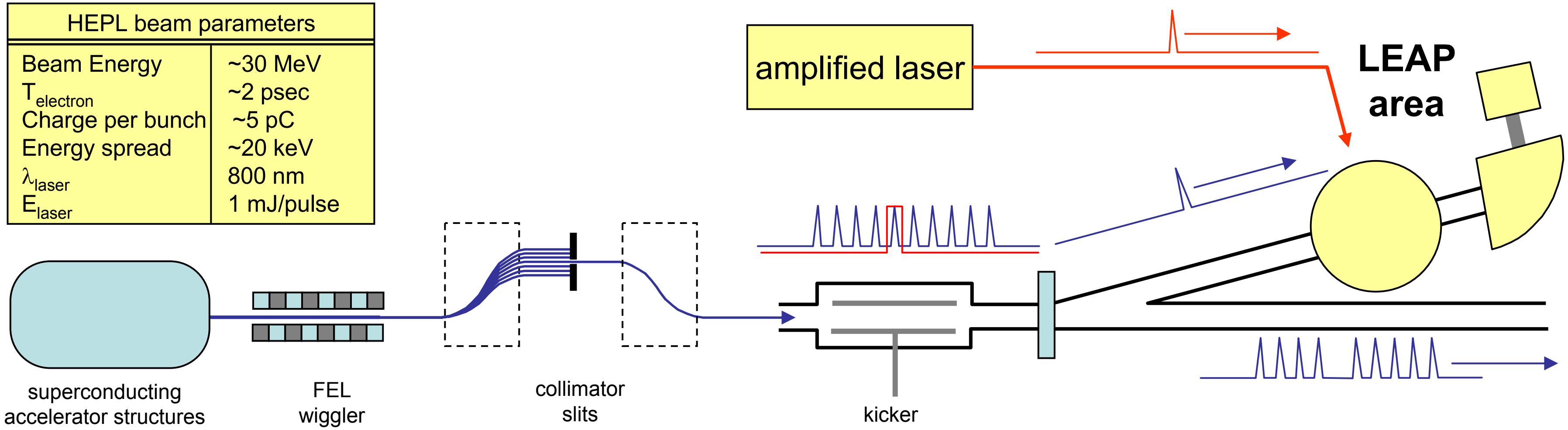
→ 1deg of phase = 20 attosec

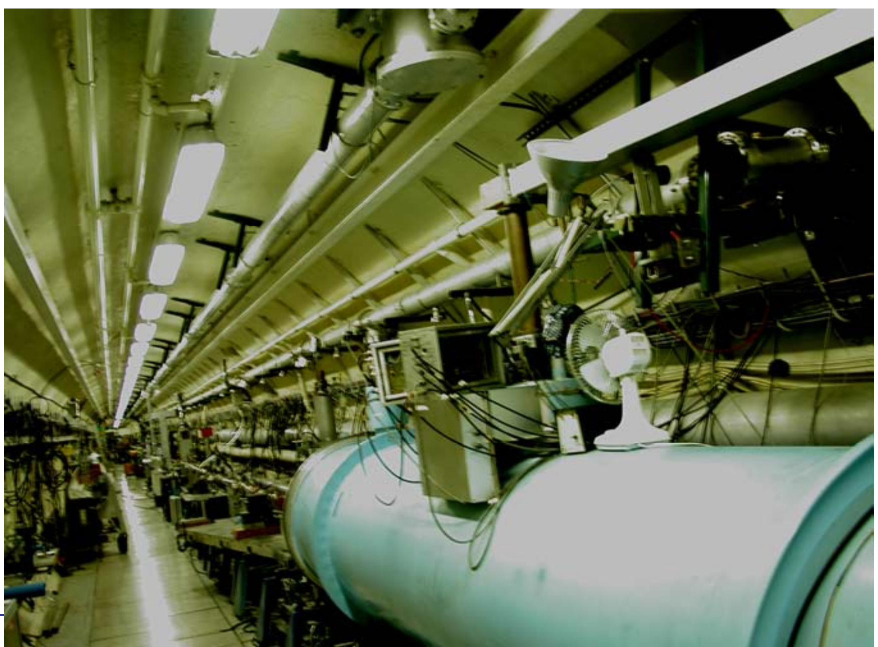


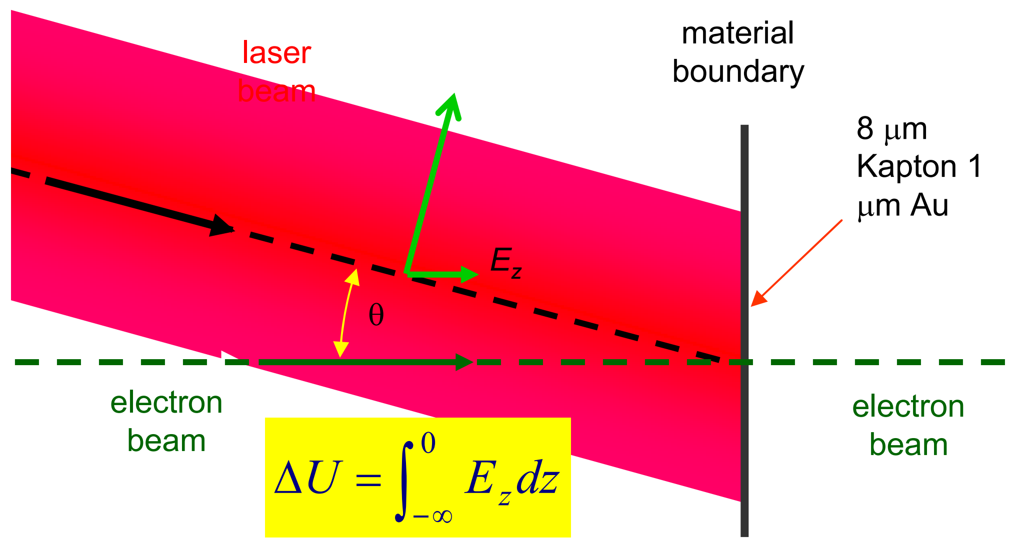
→ Unique opportunity for light sources

The proof-of-principle experiment

HEPL 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

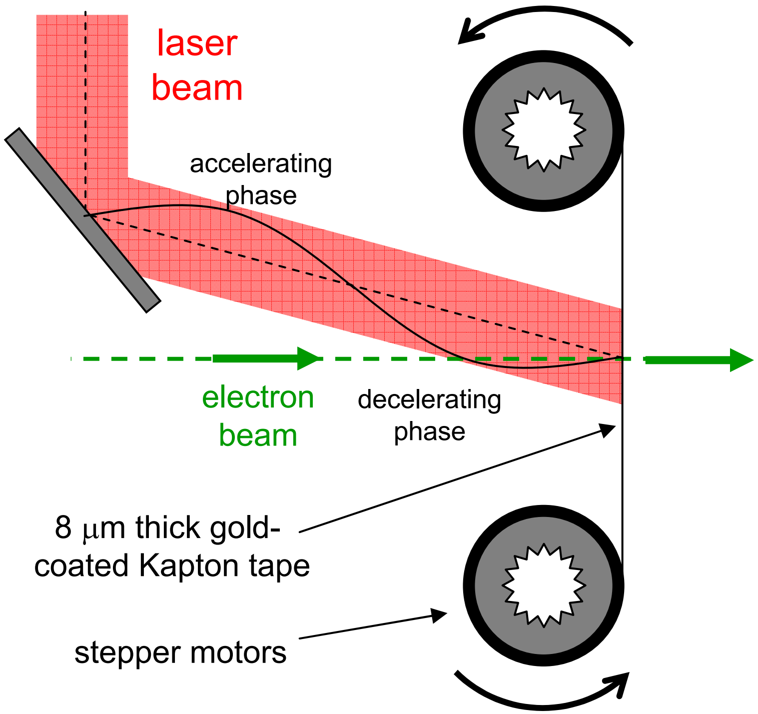




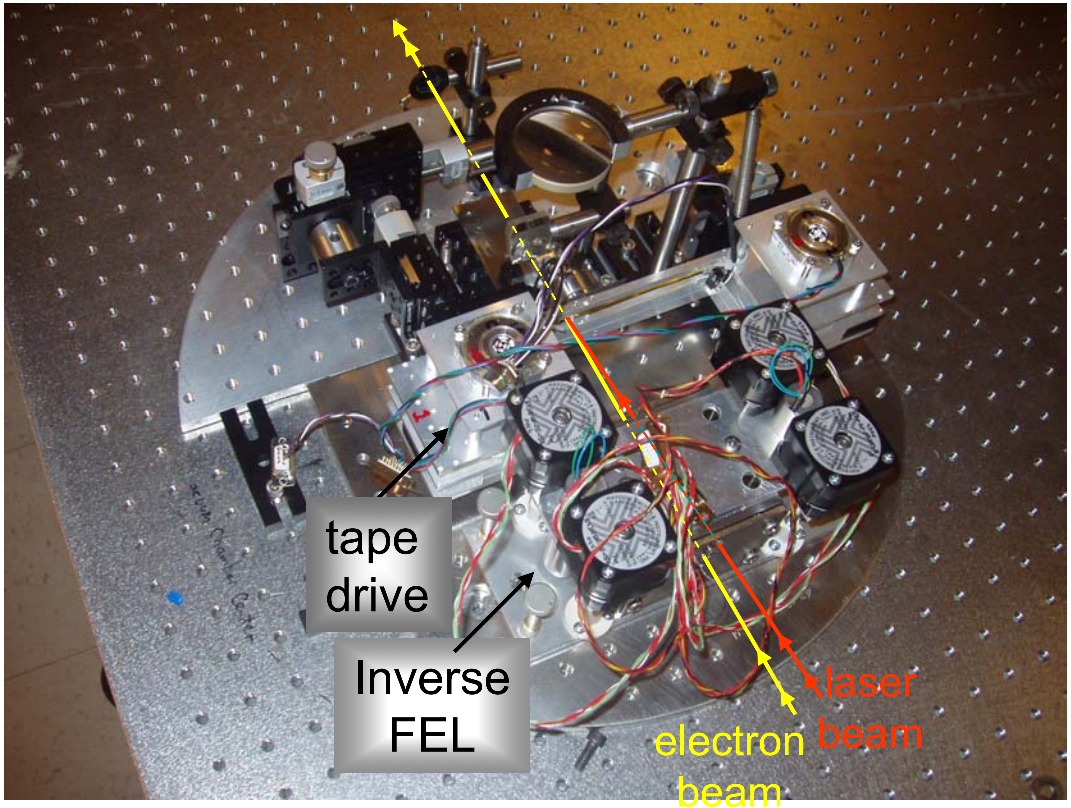


$$\Delta U = \int_{-\infty}^{0} E_z dz$$

We have accelerated electrons with visible light!

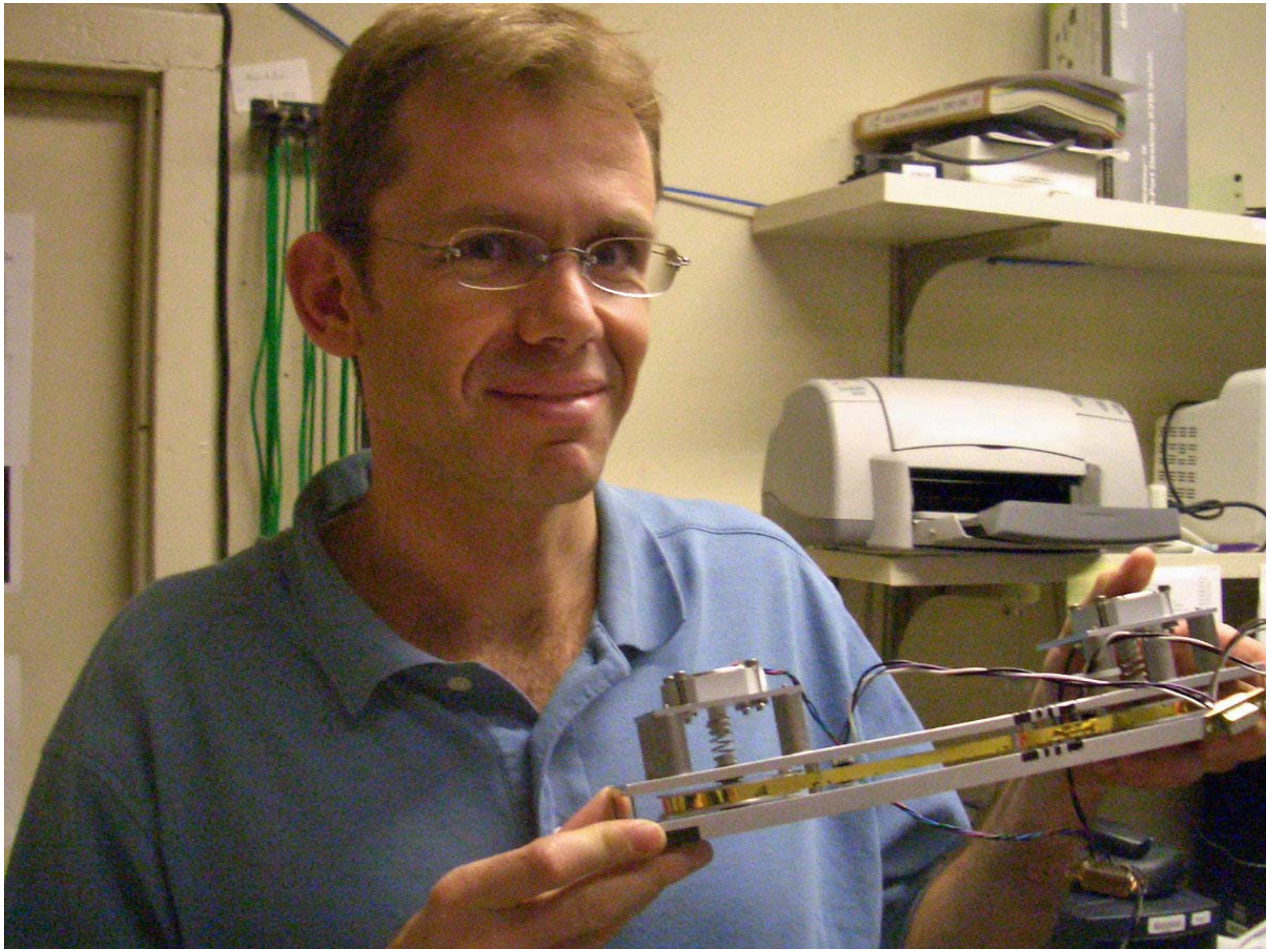


The simplified single stage Accelerator cell that uses gold coated Kapton tape to terminate the Electric field.



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.

Accelerated electrons – key experimental results

Byer Group

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

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

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Stanford University, Stanford, California 94305, USA

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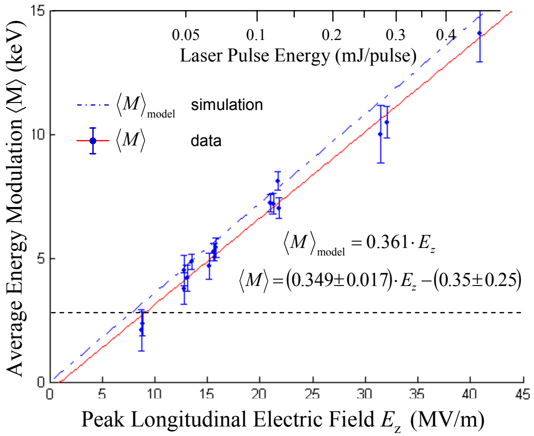
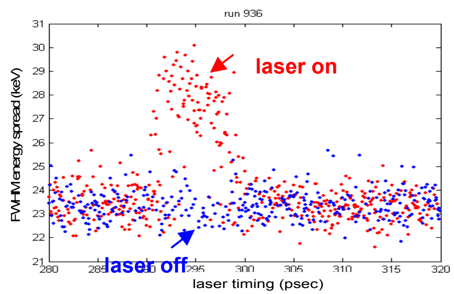
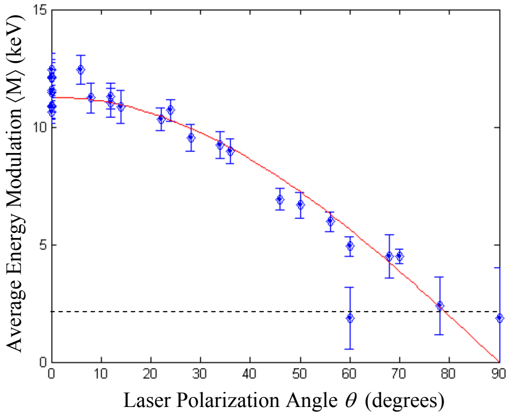
SLAC, Menlo Park, California 94025, USA

(Received 19 April 2005; published 22 September 2005)







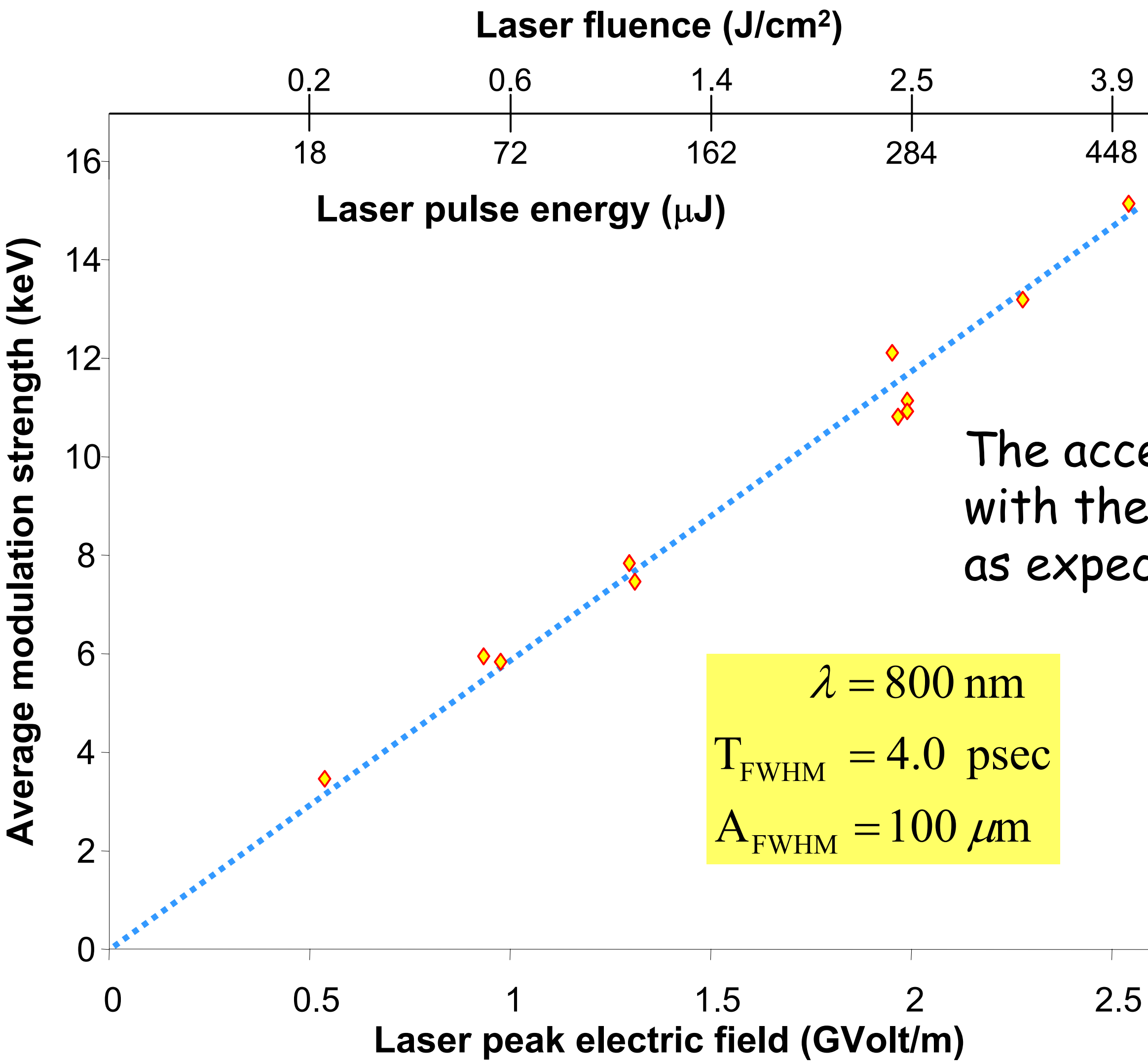
- **confirmation of the Lawson-Woodward Theorem** $\int_{-\infty}^{+\infty} E_z dz = 0$
- **observation of the linear dependence of energy gain with laser electric field** $\Delta U \propto |E_{laser}|$
- **observation of the expected polarization dependence** $|E_z| \propto |E_{laser}| \cos \rho$

laser-driven linear acceleration in vacuum

Energy Modulation vs Laser Peak Electric Field

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

E-163 Byer Group



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

2nd Success: Visible light driven IFEL

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

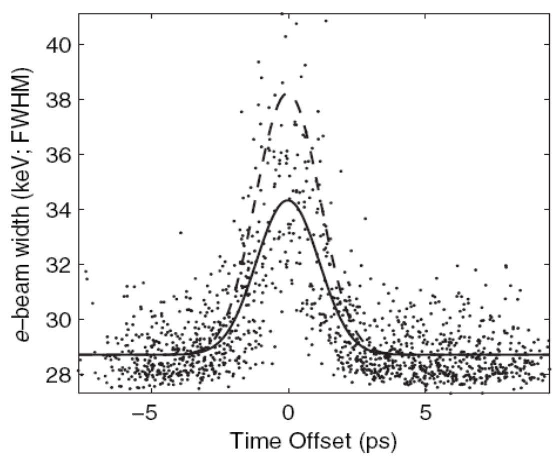


FIG. 2. Example data run with 1500 laser on events. The solid curve is the least squares fit to all data points and gives the mean interaction of 18 keV. The dashed curve is the maximum estimate and gives the peak interaction of 25 keV. The width of cross correlation is 2.2 ps rms.

Observation of harmonic interaction

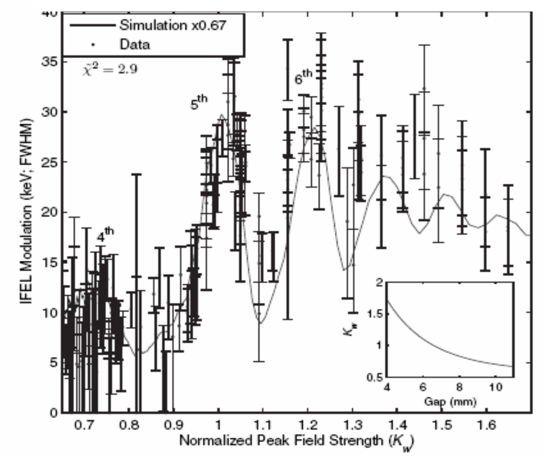


FIG. 4. IFEL gap scan data, with 164 runs total. Comparison to simulation (solid line) shows very good agreement to the shape and spacing of resonance peaks. The harmonic numbers are given next to each peak. Simulation has been rescaled vertically by 0.67 to better visualize overlap.

* graduate student C.M. Sears

Contents

Historic Background

The TeV-Energy Physics Frontier

Laser Electron Accelerator Project – LEAP

- HEPL Experiments from 1997 – Nov 2004
- **E163 Experiments at SLAC**
  - **Laser accelerator structures**
  - **Inverse FEL for electron pulse compression**

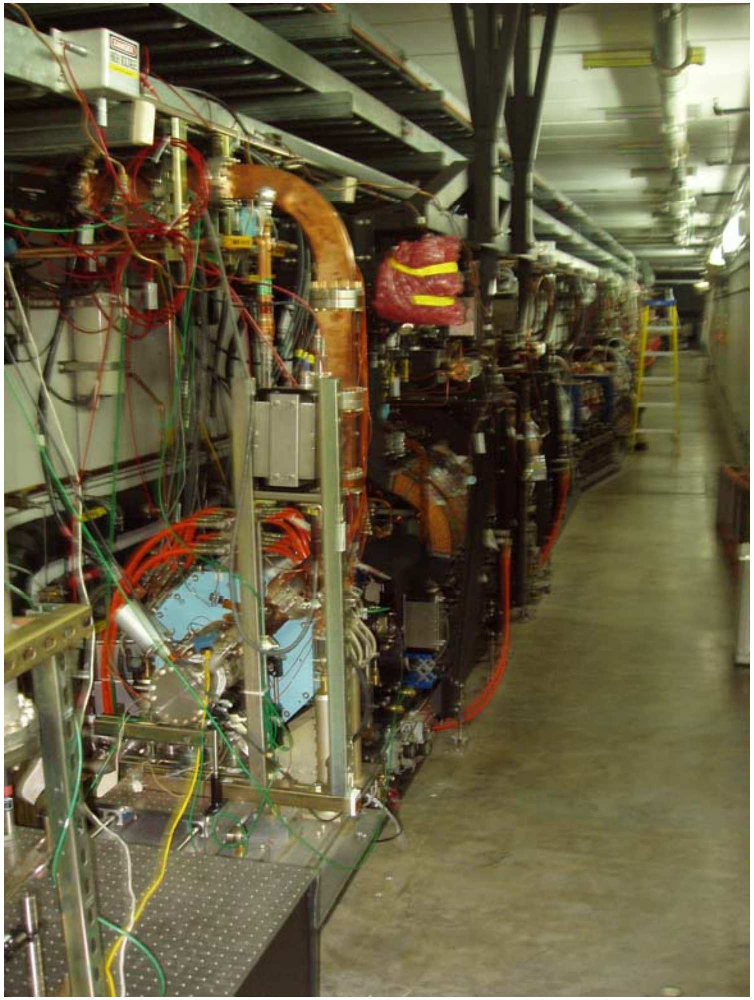
Coherent X-ray laser Generation

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

Future Challenges

The new E163 experiment hall - 2005

The **NLCTA**
Next Linear Collider Test Accelerator 360MeV




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
Newport

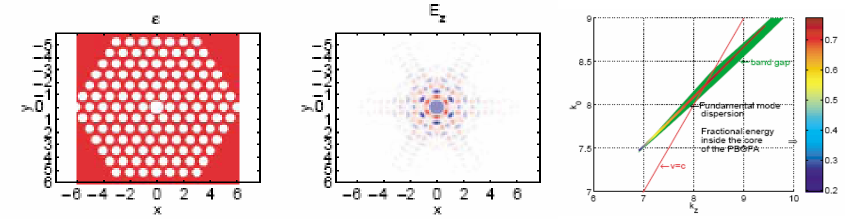
GOAL: Invent and Test Accelerator structures

Photonic bandgap fiber structures

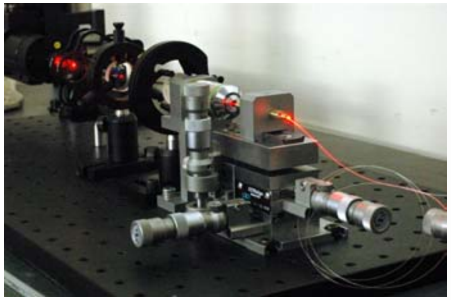
PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS, VOLUME 4, 051301 (2001)

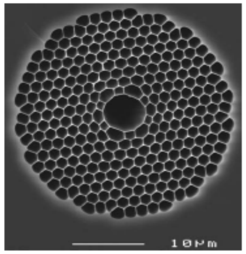
Photonic band gap fiber accelerator

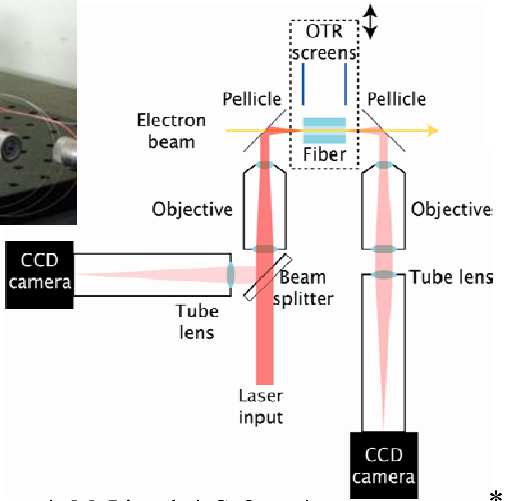
Xintian Eddie Lin*



Current experimental fiber accelerator structure research







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

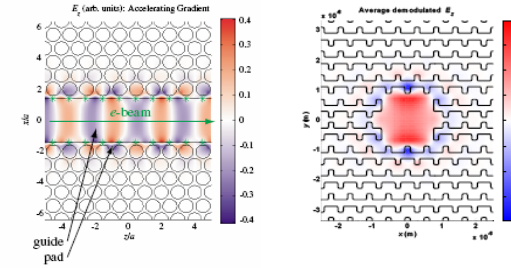
*grad. students

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

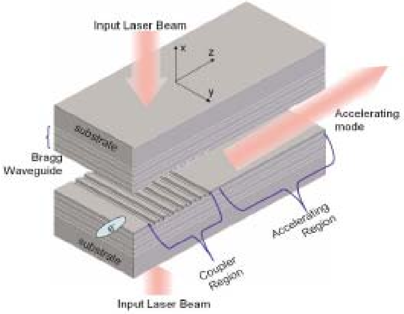


FIG. 1. (Color) Schematic diagram of a planar accelerator structure with distributed grating-assisted coupler (DGAC).

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

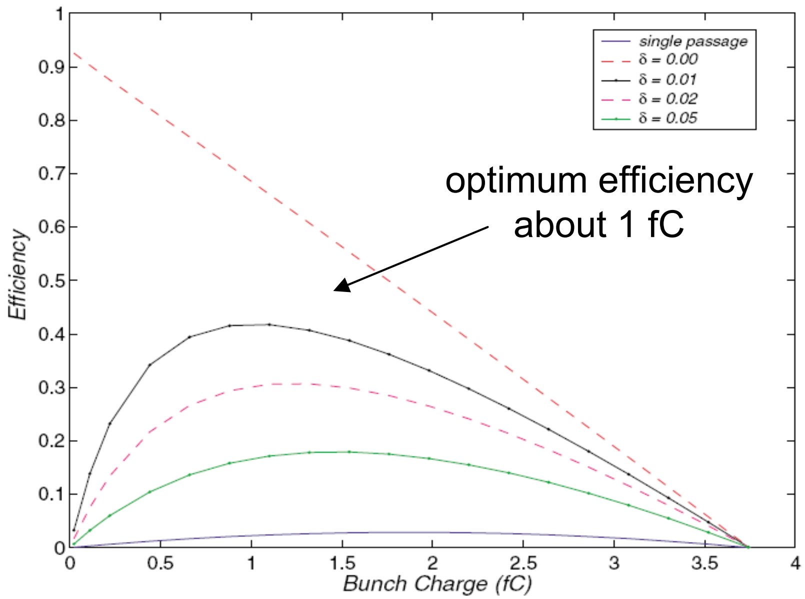
R. H. Siemann

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

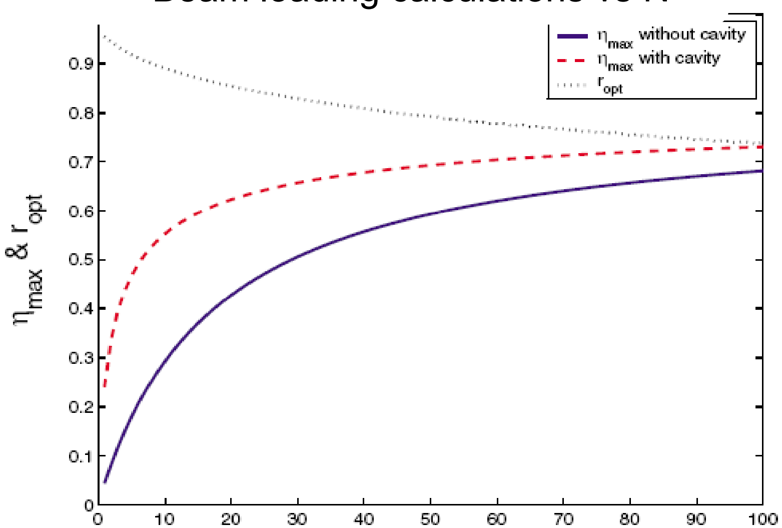
Energy efficiency of an intracavity coupled, laser-driven linear accelerator pumped by an external laser

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



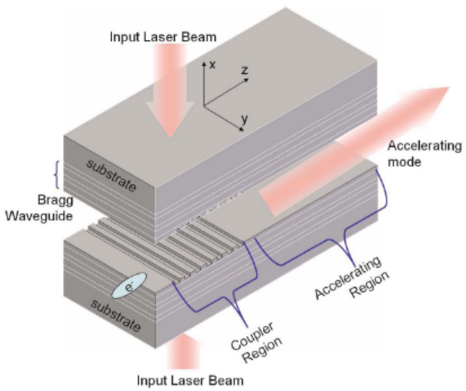
Beam loading calculations vs N



N (Number of bunches)

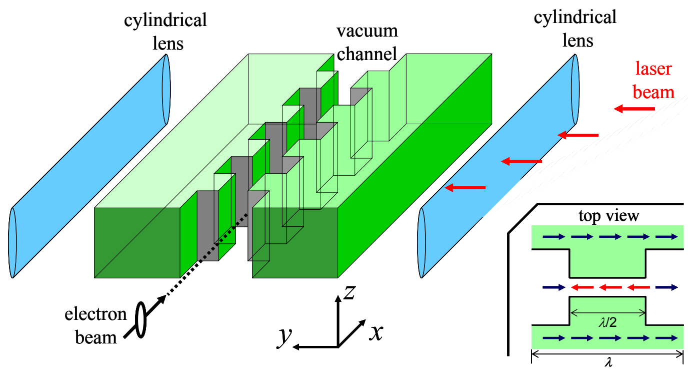
Many possible dielectric microstructure architectures

Planar waveguide structures



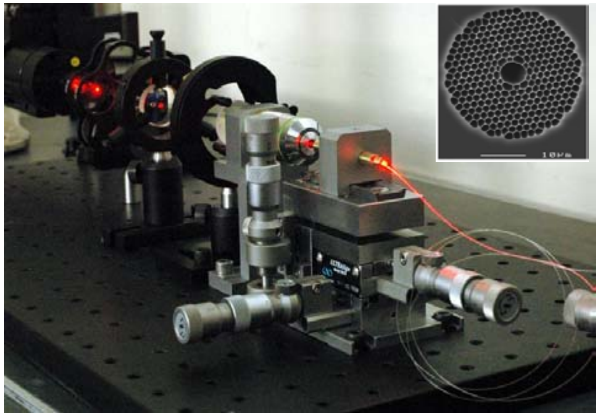
Z. Zhang et al. Phys. Rev. ST AB 8, 071302 (2005)

Periodic phase modulation structures



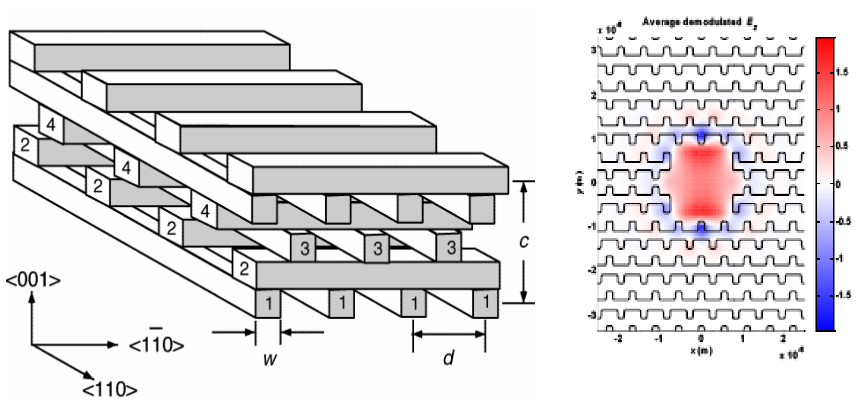
T. Plettner et al, Phys. Rev. ST Accel. Beams 4, 051301 (2006)

Hollow core PBG fibers



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

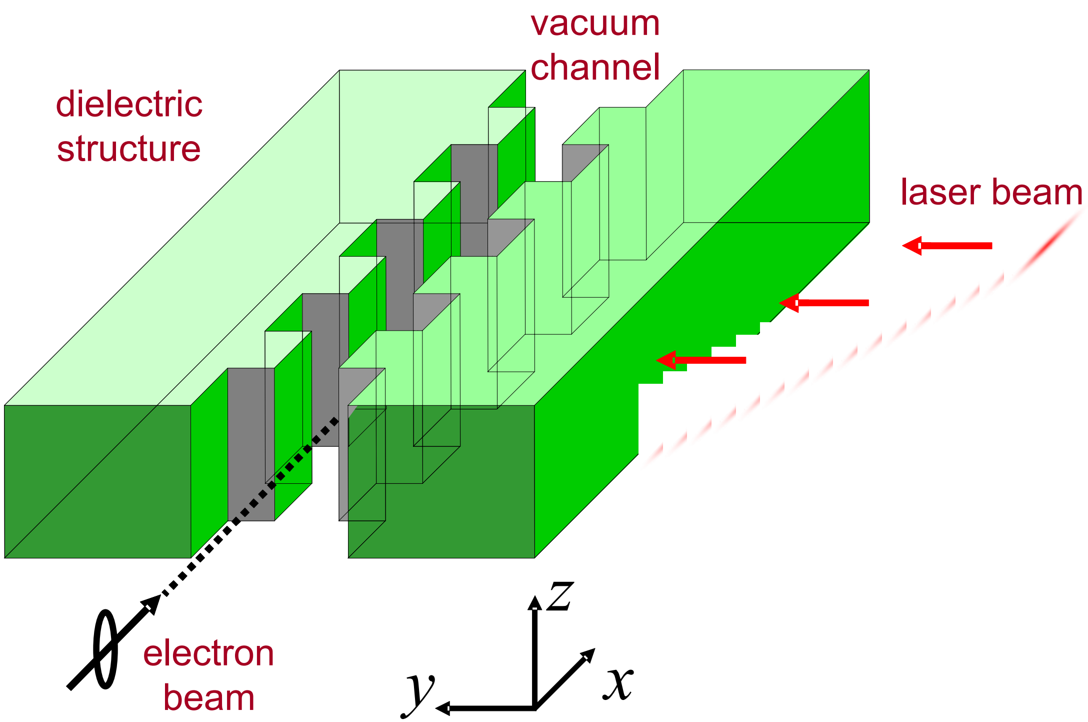
3-D photonic bandgap structures



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

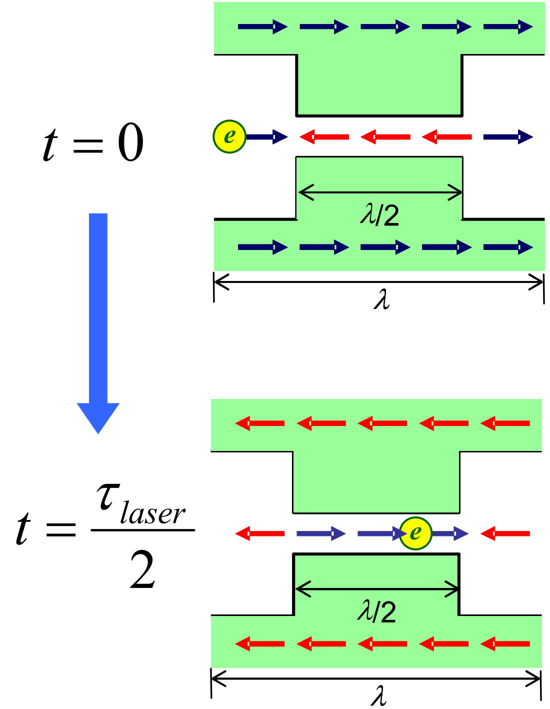
Main concept: quasi phase-matching of the EM field

perspective view



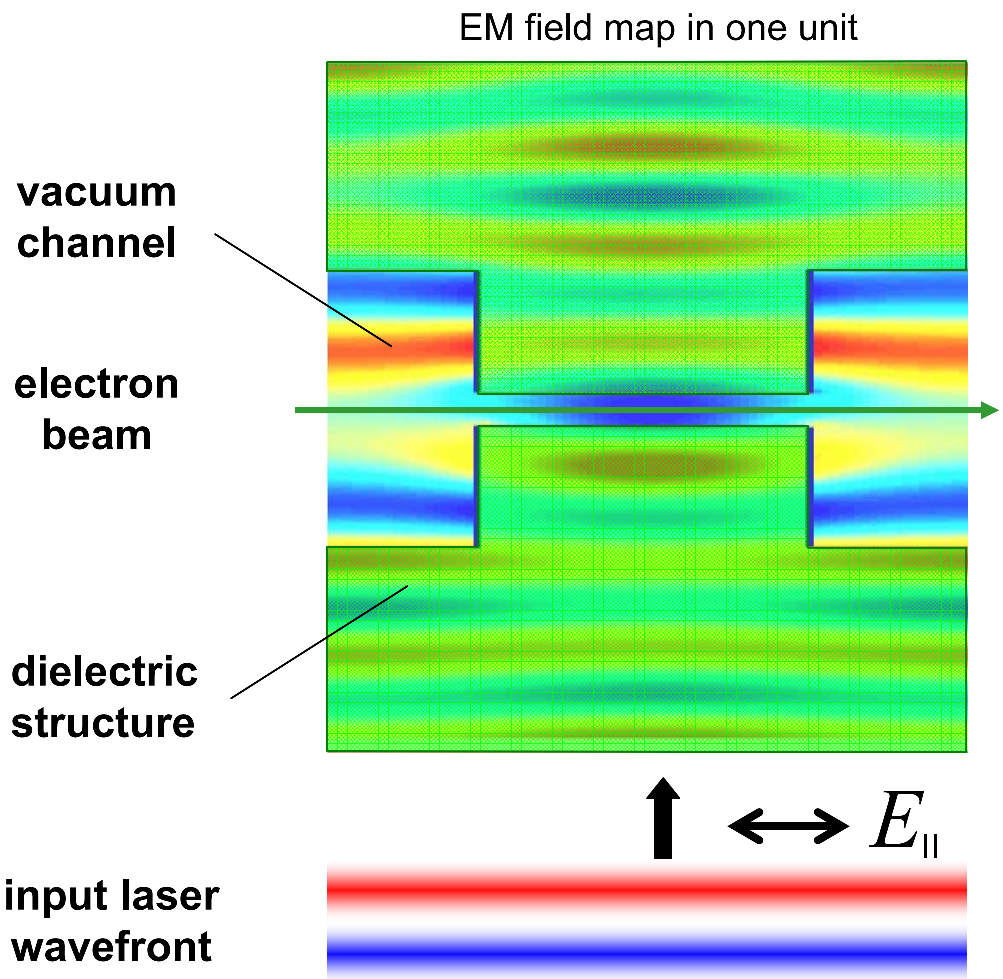
top view

traveling electron experiences accelerating force at all times



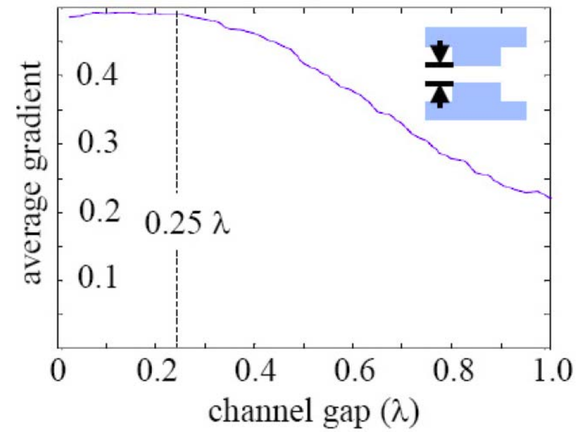
T. Plettner et al, Phys. Rev. ST Accel. Beams 4, 051301 (2006)

Transverse pumped phase-reset structure



$$\left\langle \vec{F}_{\perp} \right\rangle = 0$$

vacuum channel width < λ



$$\left\langle \vec{E}_{||} \right\rangle \sim \frac{1}{2} E_{laser}$$

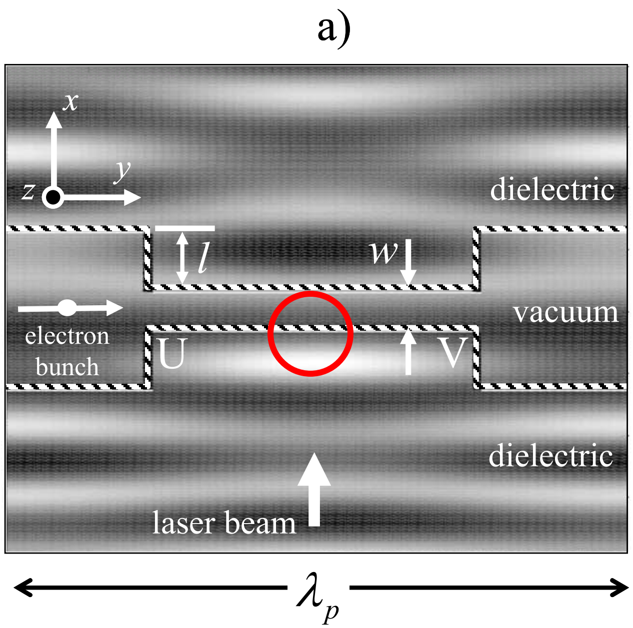
1 J/cm² fluence

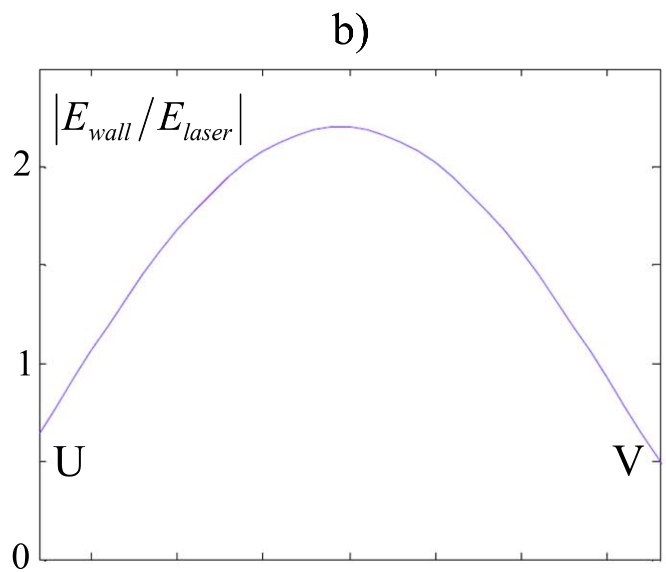
~10 fsec pulses

$$\left\langle G_{unloaded} \right\rangle \sim 4\,\mathrm{GeV/m}$$

The expected maximum gradients

Operate at the Breakdown Limit





$$\left\langle \vec{G}_{\perp,TE} \right\rangle \sim 0.15 |E_{laser}|$$

$$\left\langle \vec{G}_{\parallel,TE} \right\rangle \sim 0.3 |E_{laser}|$$

$\div 2$

$$\left\langle \vec{G}_{\perp,TE} \right\rangle \sim 0.07 |E_{max}|$$

$$\left\langle \vec{G}_{\parallel,TE} \right\rangle \sim 0.15 |E_{max}|$$

10 fsec laser pulse

1 J/cm^2 → $|E_{max}| \sim 25\,\text{GV/m}$ →

(At breakdown limit)

$$\left\langle G_{\parallel,TE} \right\rangle \sim 4\,\text{GV/m}$$

$$\left\langle G_{\perp,TE} \right\rangle \sim 2\,\text{GV/m}$$

Y. Min Oh et al, International Journal of Heat and Mass Transfer 49 (2006) 1493–1500

B. C. Stuart et al, Physical Review Letters 74, 2248 (1995)

M. Lenzner et al, "Femtosecond Optical Breakdown in Dielectrics", Phys. Rev. Lett. 80, 4076 (1998)

The most simplistic wakefield picture

The accelerator operates in reverse

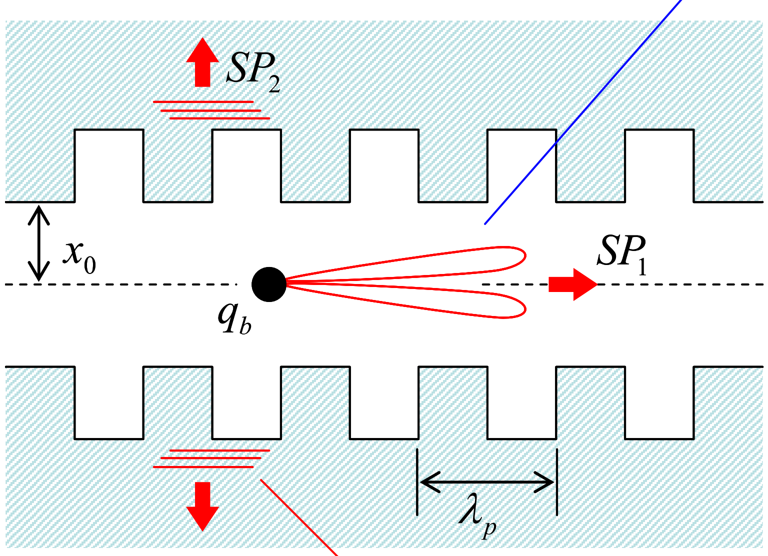
Assume a "perfect" dielectric (real index of refraction)

→ The loss factor mechanisms come from diffraction

fwd. Smith-Purcell [1]

$$4\pi x_0 / \lambda_p \sim 1/\gamma$$

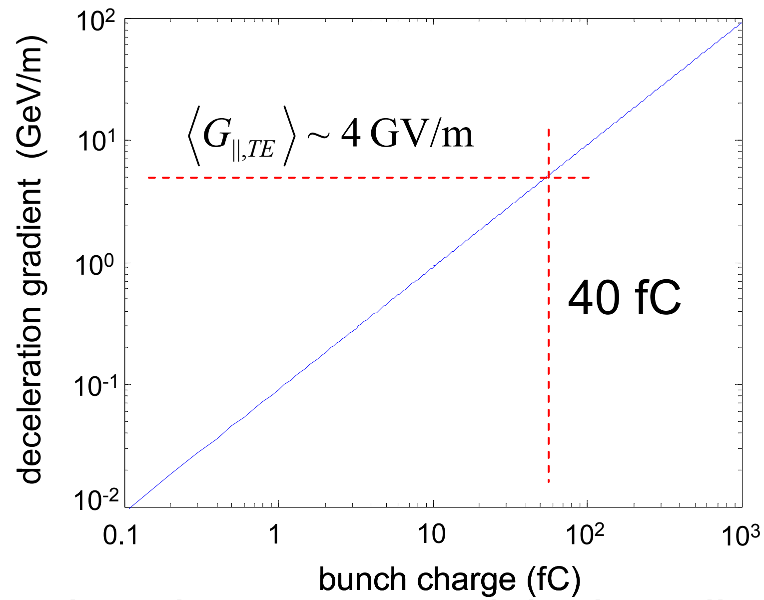
a)



beam loading [2,3,4]

$$qV = \frac{DL}{2Z_0}\left(E_L^2 - \left(E_L + E_W\right)^2\right)\tau_L$$

$$K_C \sim 100\ \mathrm{GeV/m/pC}$$



but I have neglected the broadband Cherenkov wake…

$$K_C \sim 100\ \mathrm{GeV/m/pC}$$

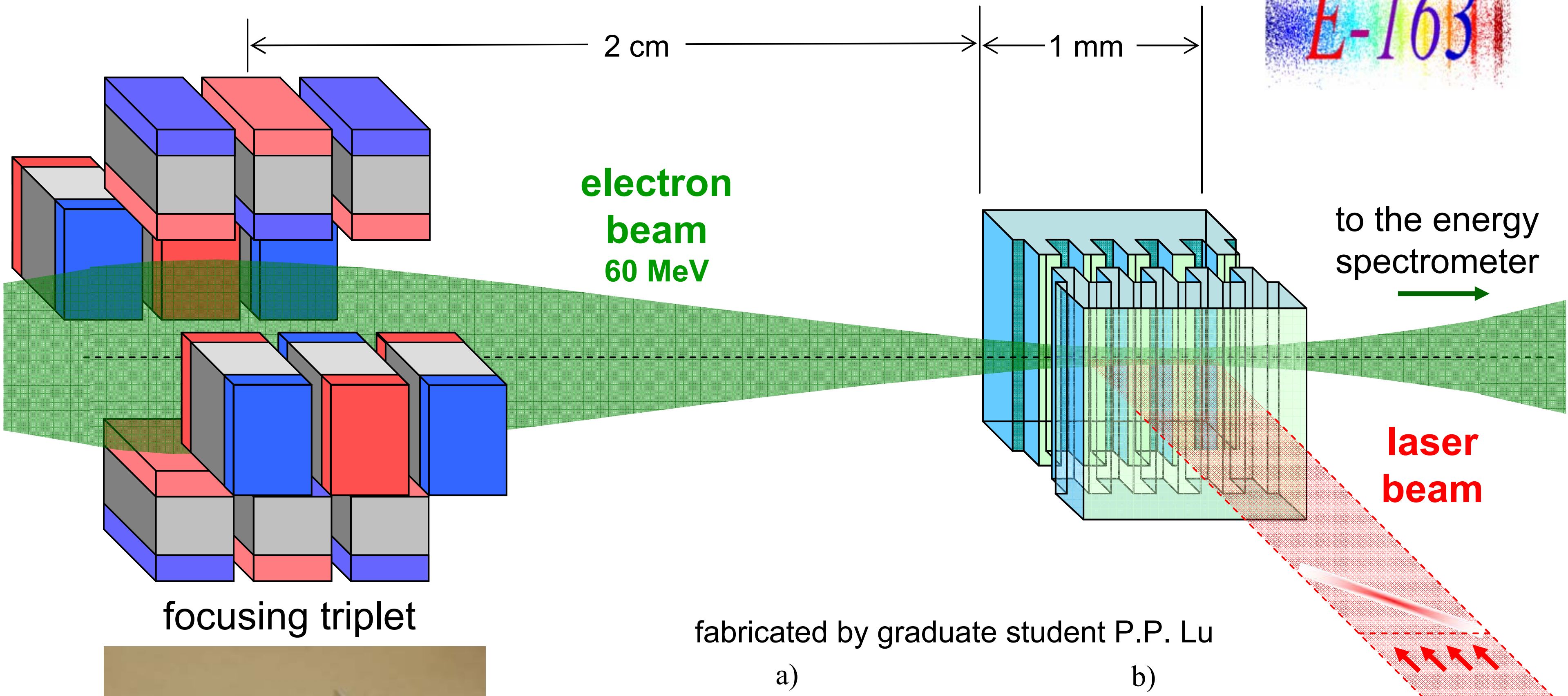
→ $Q_b \sim 20\ \mathrm{fC}$

[1] Phys. Rev. Lett. 74, 3808 (1995)
[2] Phys. Rev. STAB 6 02441 (2003)
[3] Phys. Rev. STAB 9, 111301 (2006)
[4] Phys. Rev. STAB 7, 061303 (2004)

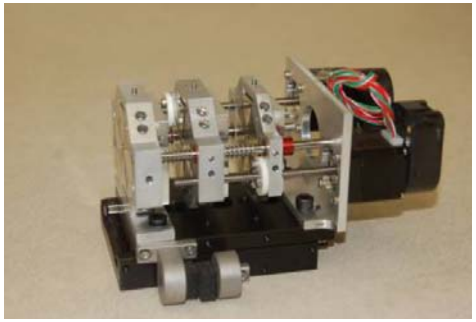
Transverse pumped phase-reset structure

Goal: test this structure at SLAC

Byer Group

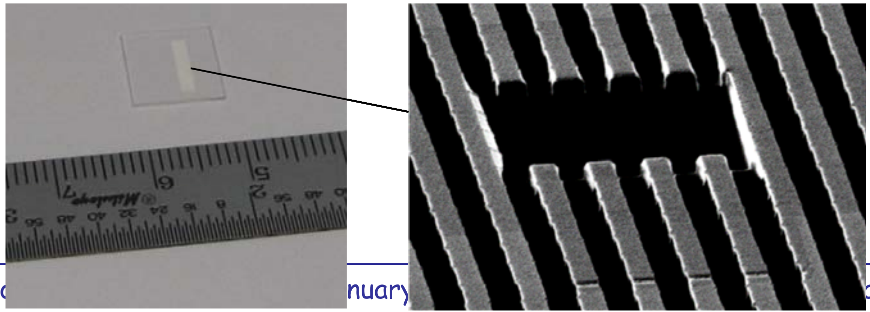


fabricated by graduate student P.P. Lu

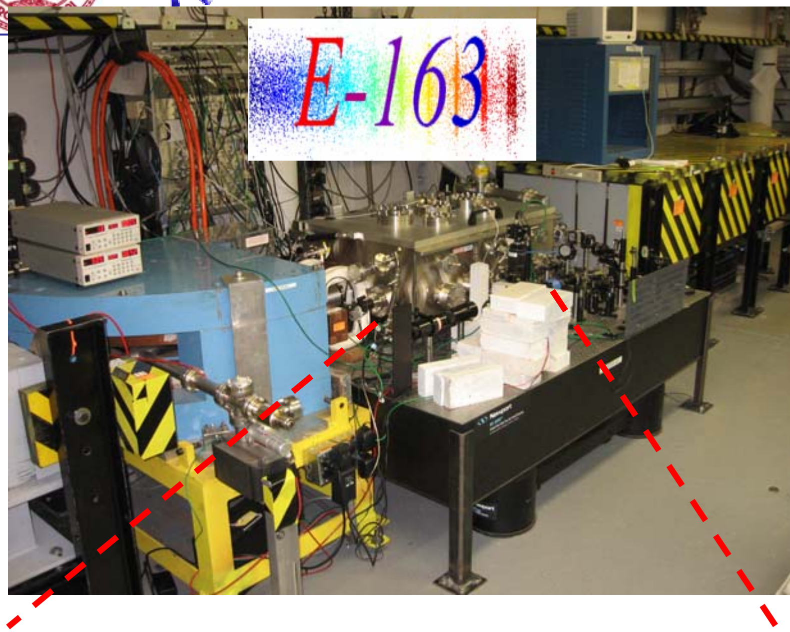


fabricated by graduate student C.M. Sears

a) b)

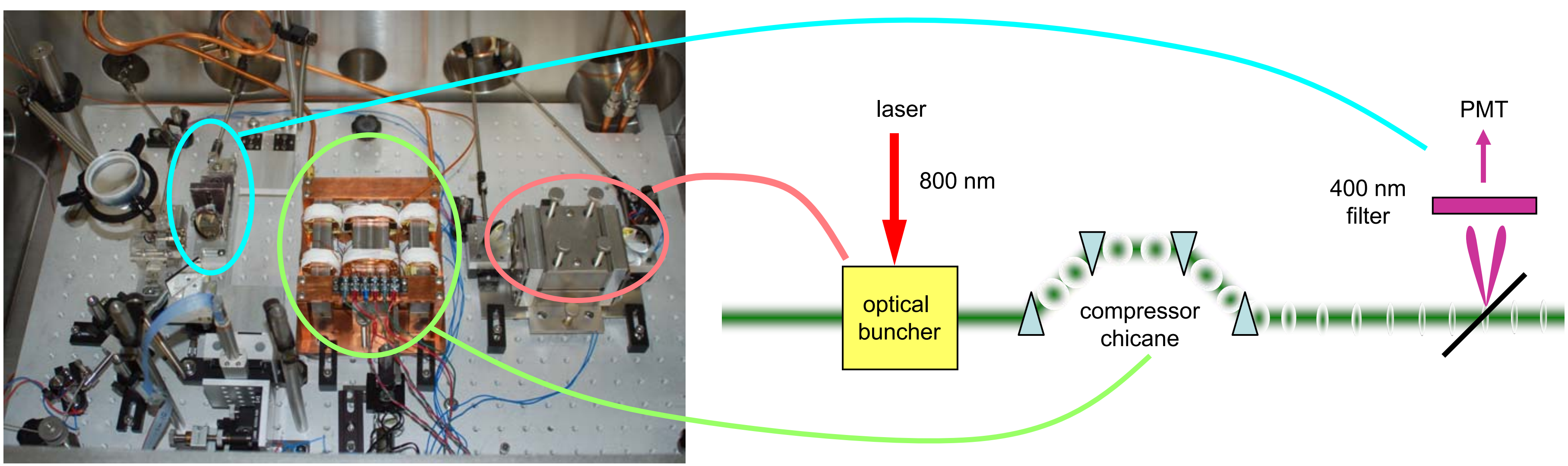


Present experiment at E163



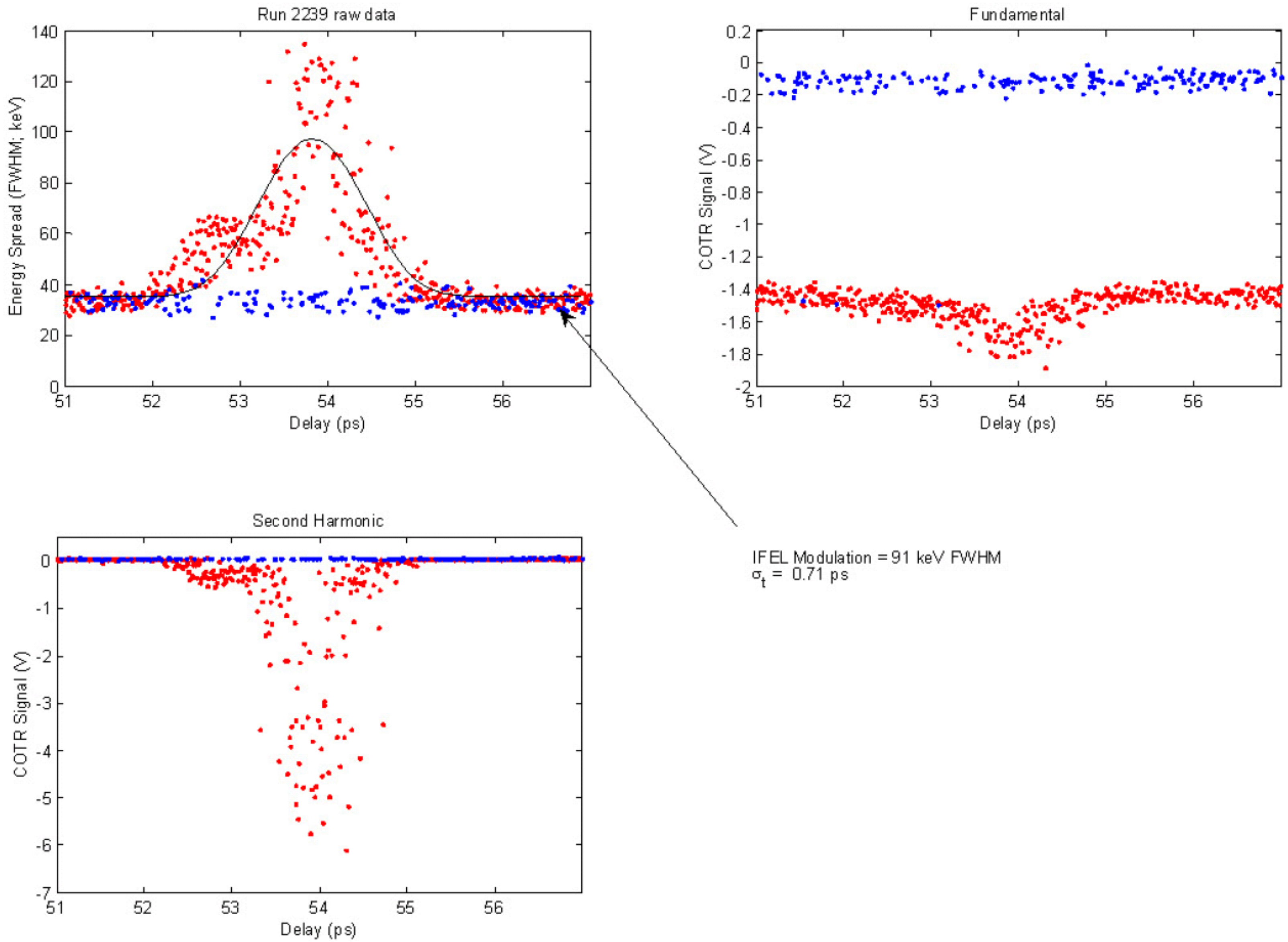
Micro-bunching of a 60 MeV electron beam at 800 nm from a 3-period IFEL

(Principal author: Chris Sears)



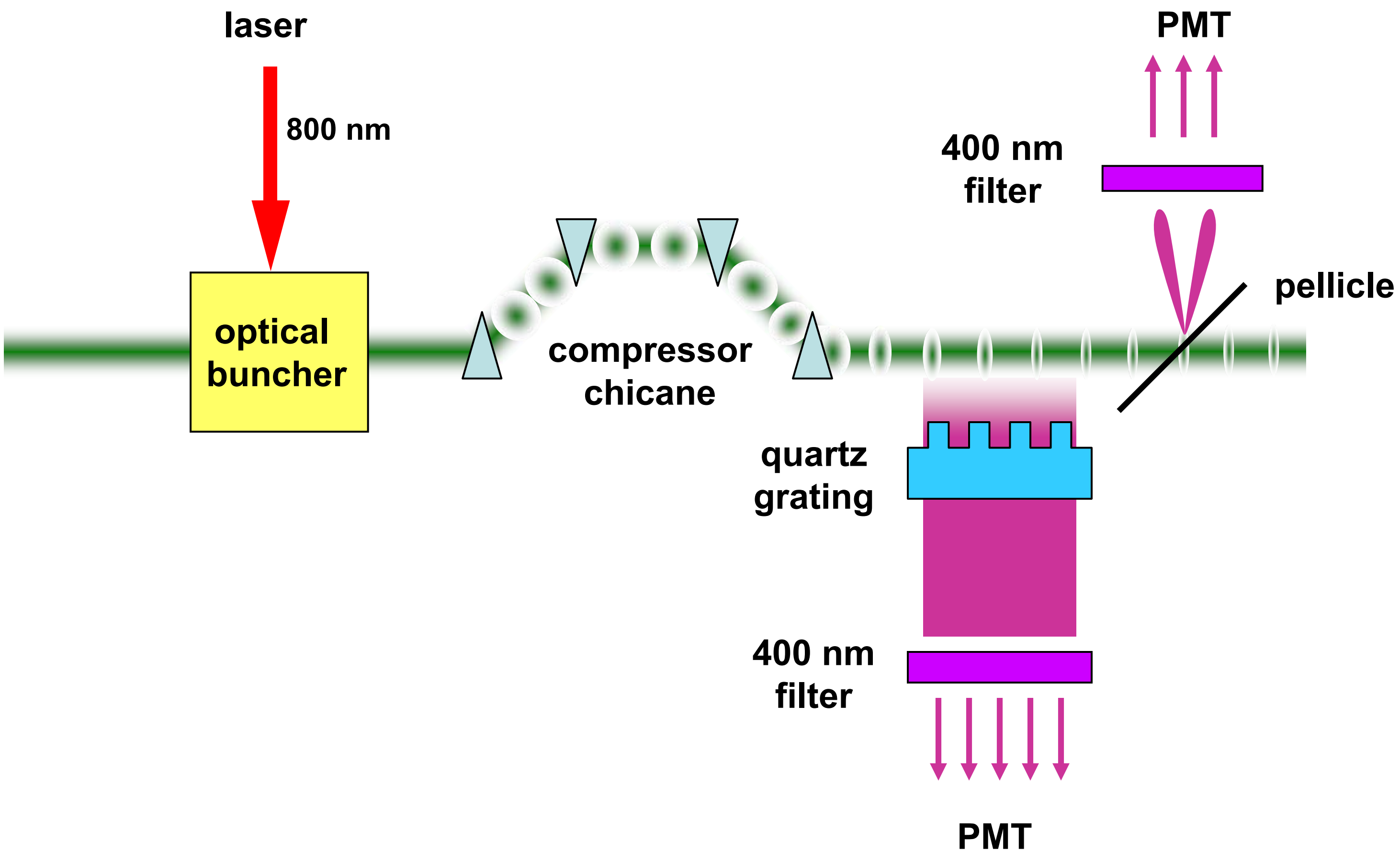
Present experiment at E163

Preliminary results provided by Chris Sears

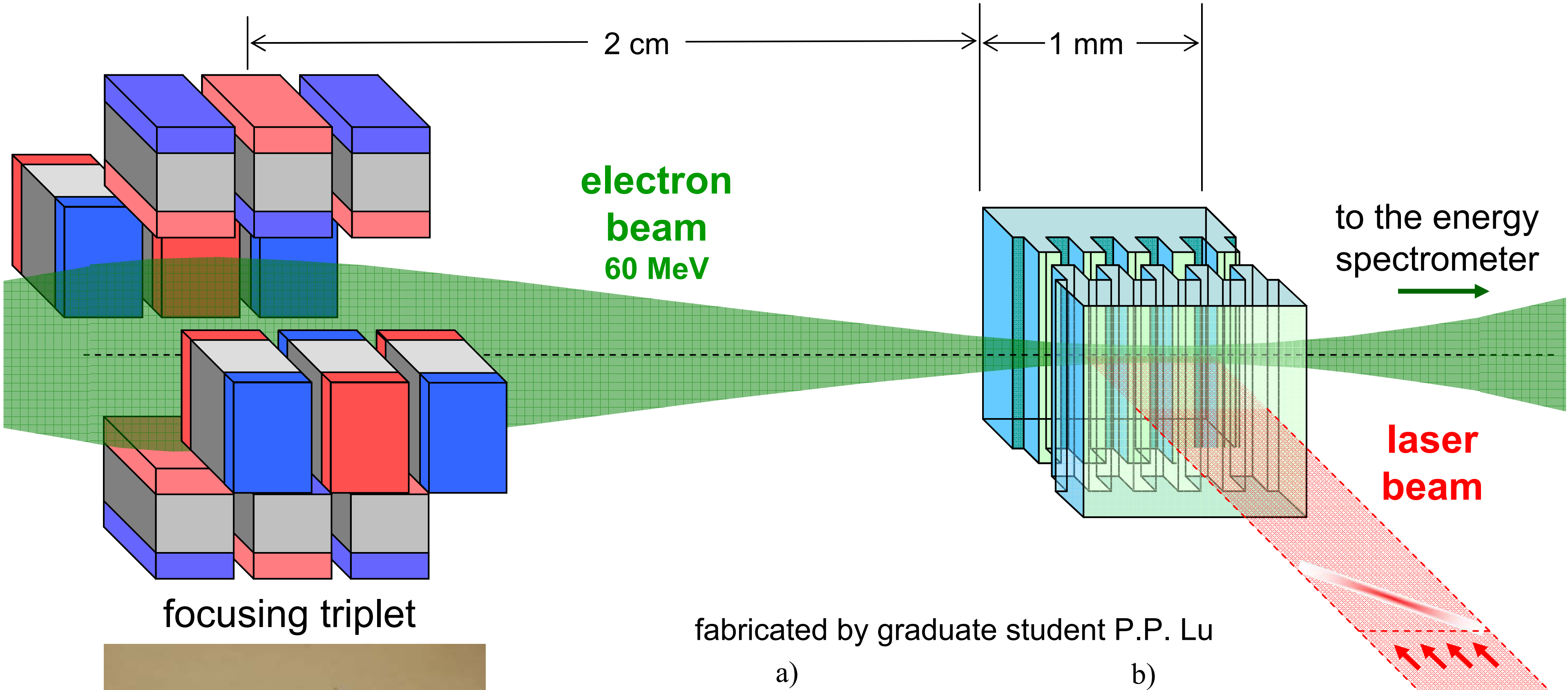


Observation of wakefields of the microbunched beam from a quartz grating

→ Beam position diagnostic
→ Inverse process of laser acceleration from the grating

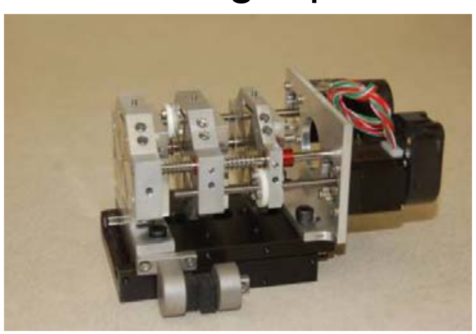


Laser-acceleration from a quartz-based mm-long accelerator microstructure



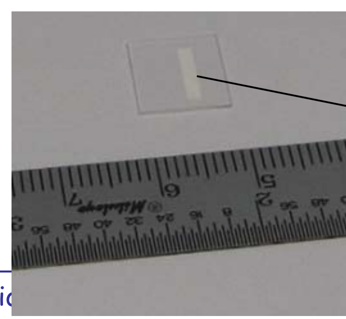
focusing triplet

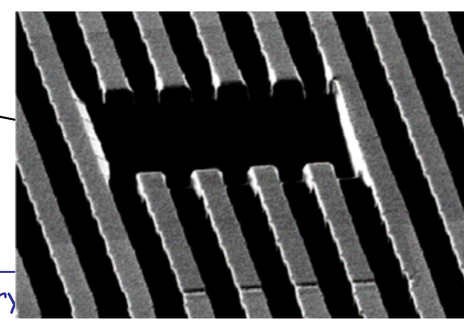
fabricated by graduate student P.P. Lu



fabricated by graduate student C.M. Sears

a) b)

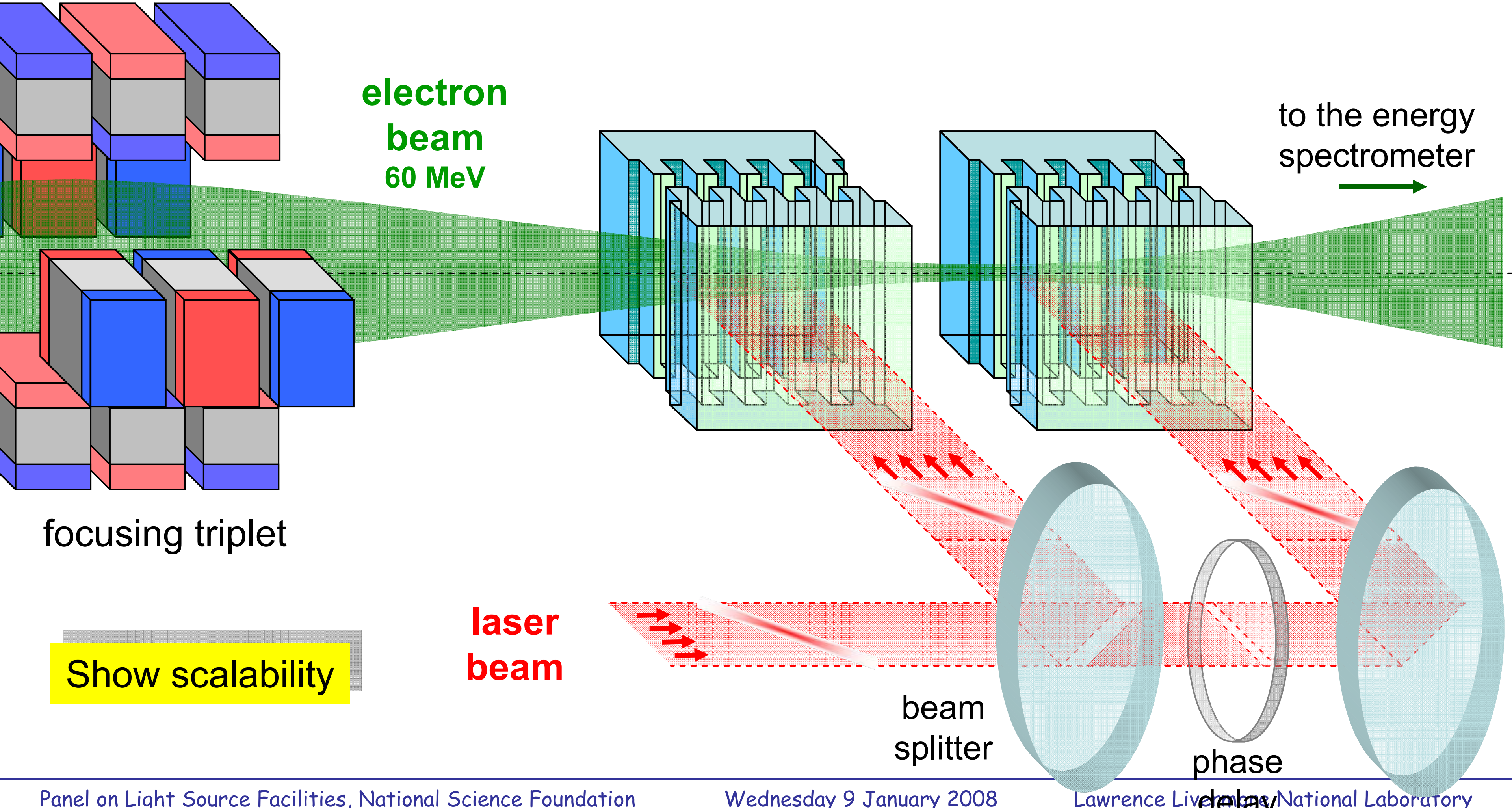




Goal: test multiple stage acceleration

E-163

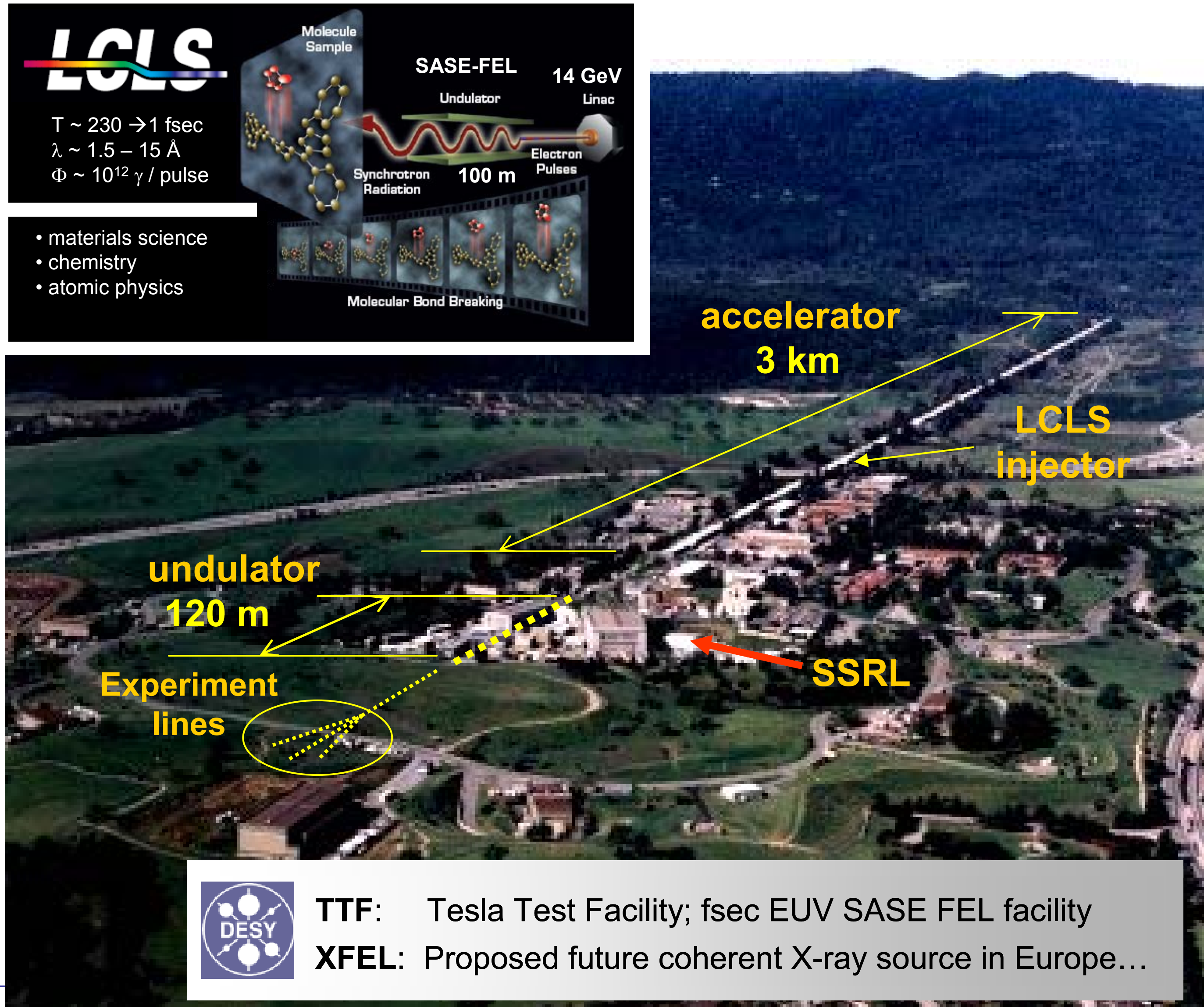
Cascading of microstructure accelerators



Show scalability

Contents

RF-accelerator driven SASE FEL facilities - 2009



TTF: Tesla Test Facility; fsec EUV SASE FEL facility
XFEL: Proposed future coherent X-ray source in Europe…

LCLS properties

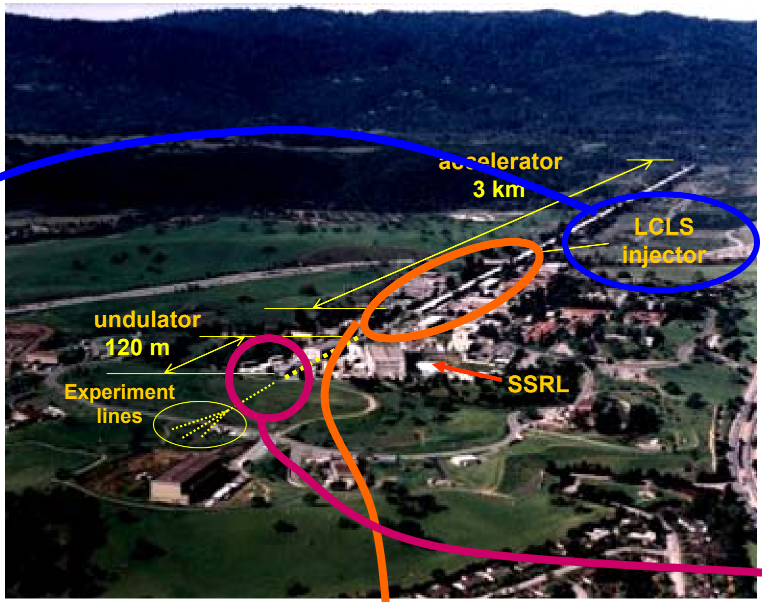
- km-size facility
- microwave accelerator
- λ_{RF} ~ 10 cm
- 4-14 GeV e-beam

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

- separate user lines
- 120 Hz pulse train

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

Motivation for an FEL application

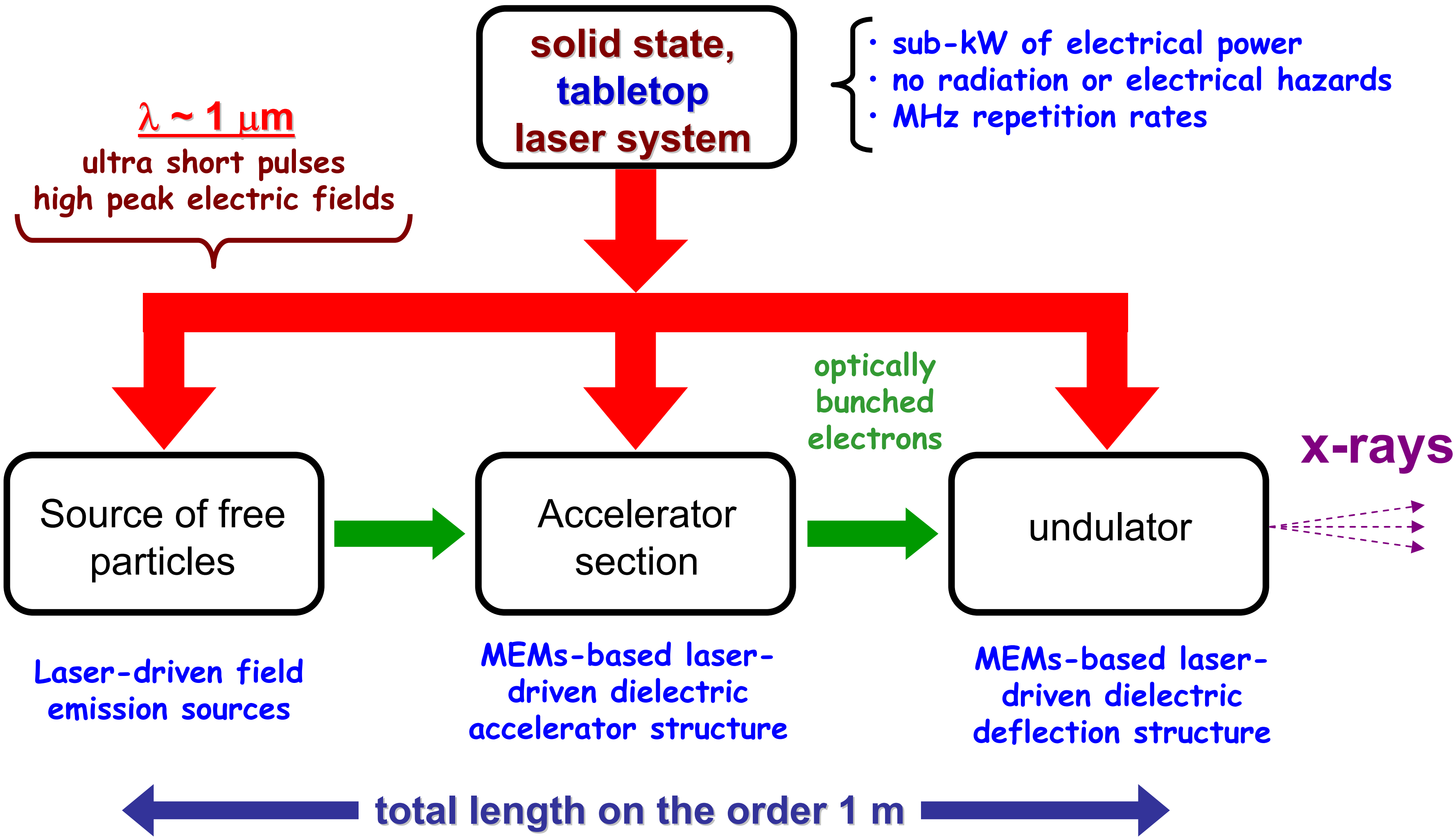
Attosecond Physics at hard X-ray energies

~ 1 GeV/m gradient	GeV electron beam in 1-2 m
Few-attosec pulse structure	Short undulator → preserve the few-attosec pulse structure on the photons
Possibility for MHz rep. rate	Modelocked lasers and low-power amplifiers

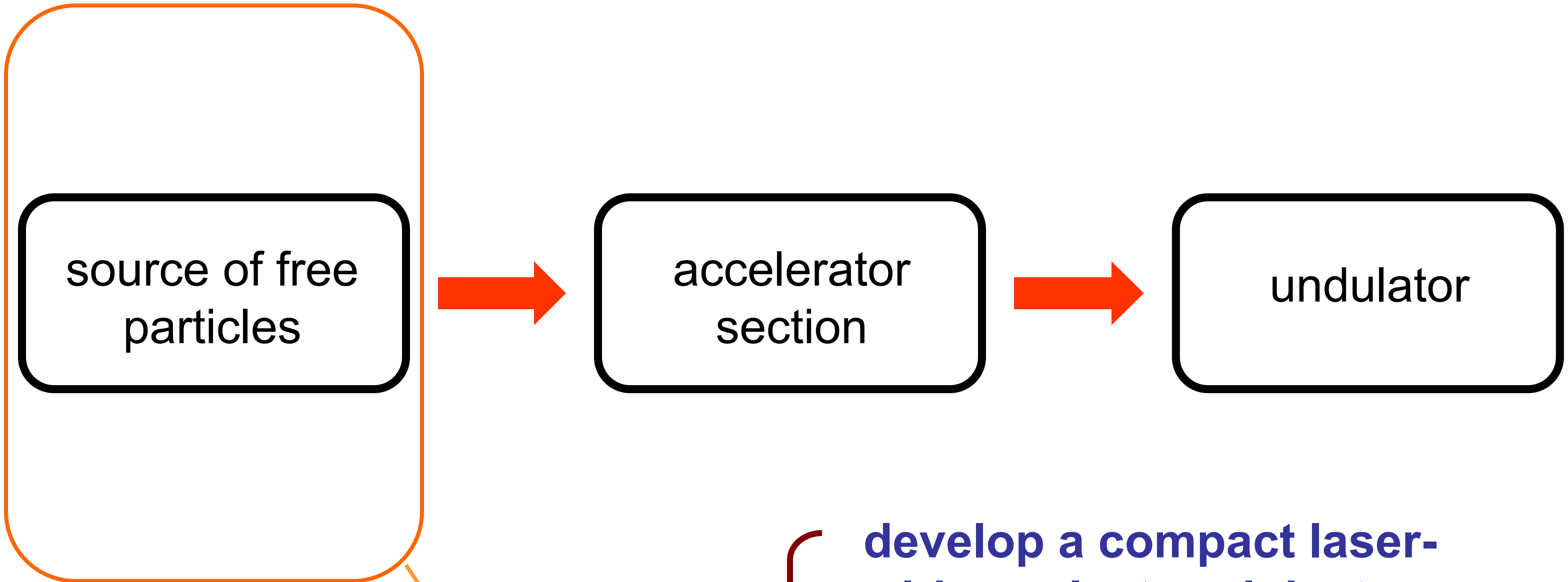
Requirements:
- **Suitable electron injector**
- **Matching short undulator**

Architecture of a laser-driven free-electron X-ray source

Byer Group



Development of the three key laser-driven components



Objective:

develop a compact laser-driven electron injector

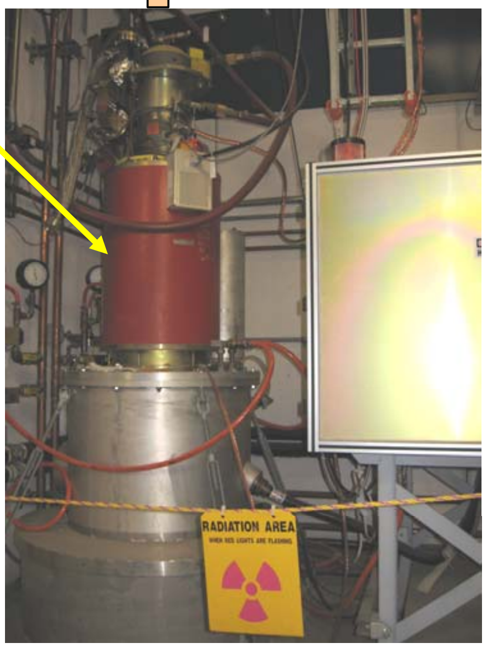
1. High rep. rate
2. Low power consumption
3. Ultra low emittance (~10^{-9} m-rad)
4. ~10 MeV in a few-cm structure

A conventional electron injector

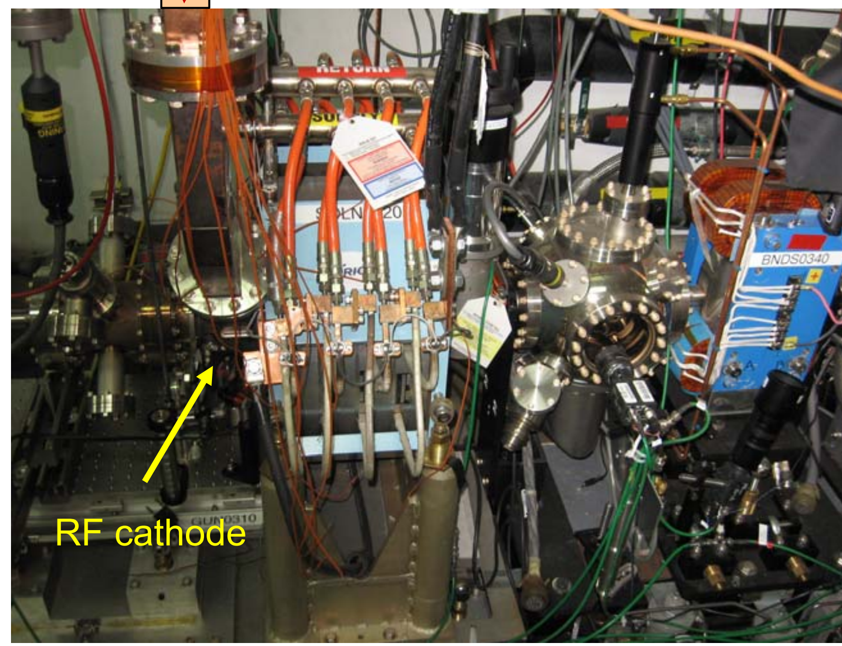
a room full of lethal and bulky equipment…

The klystron

- ~2 m tall
- **1/3 MV !**
- high power
- water cooling
- X-ray radiation
- **10 Hz** rep. rate

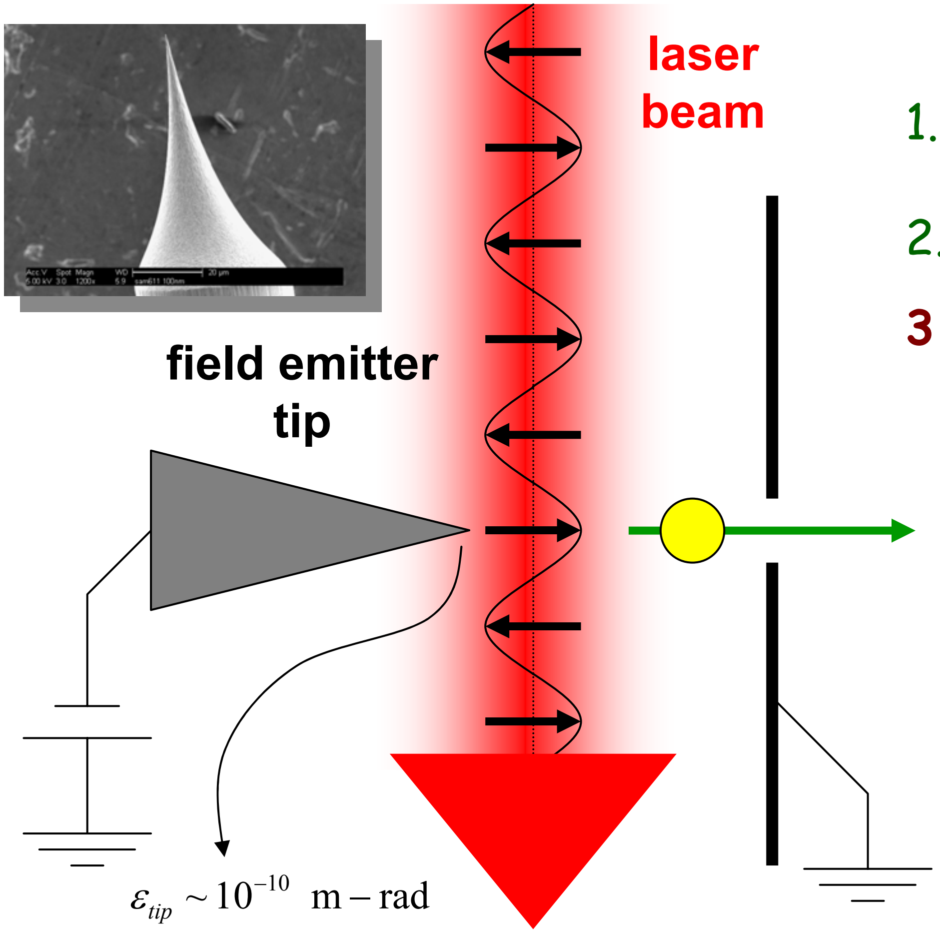


The NLCTA accelerator front end



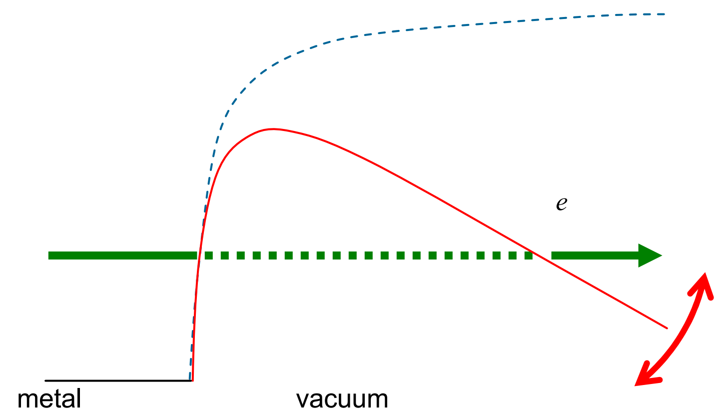
temporary source of relativistic electrons for present laser-acceleration experiments

P. Hommelhoff et al, Kasevich group



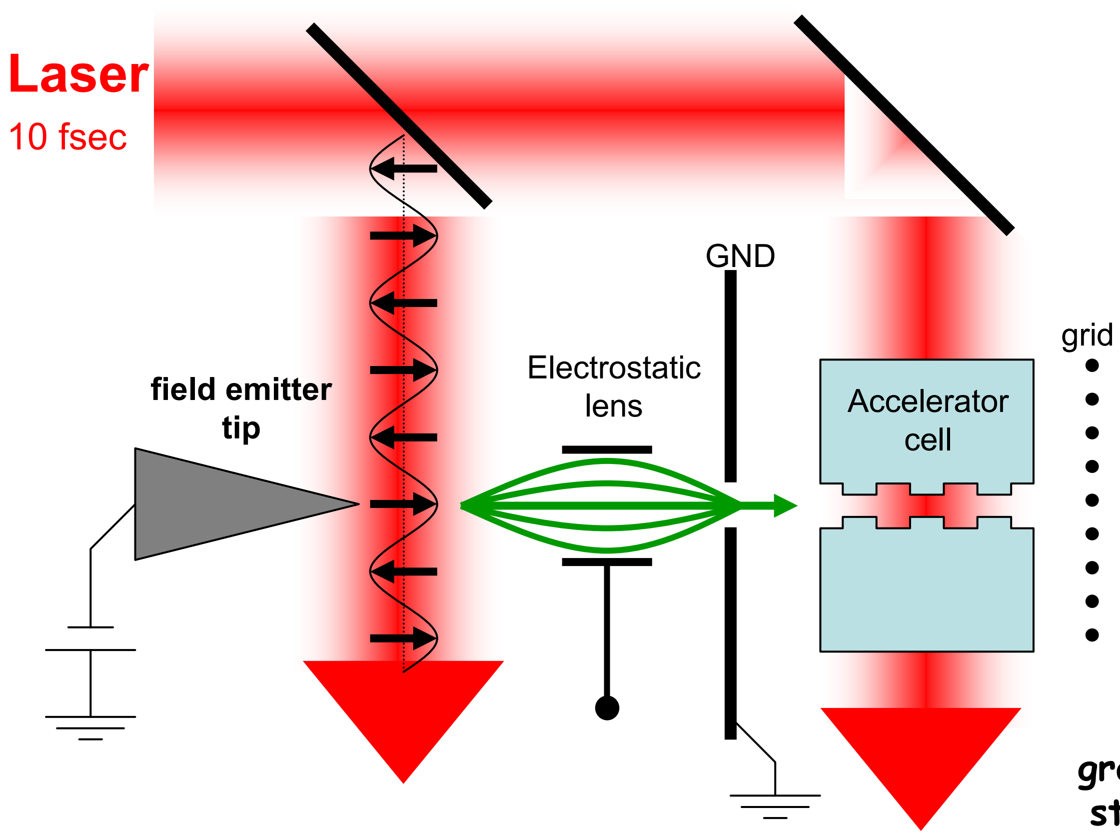
Field emission tip properties

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



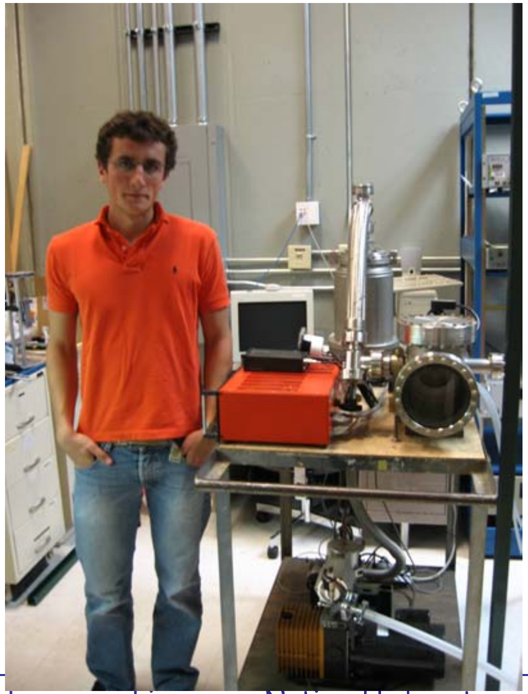
P. Hommelhoff, Y. Sortais, A. Aghajani-Talesh, M. A. Kasevich, "Field Emission Tip as a Nanometer Source of Free Electron Femtosecond Pulses", PRL 96, 077401 (2006)

Collaboration work with the Kasevich group



objectives

1. multiple-electron emission
2. focusing with electrostatic lens
3. verify ultra-low emittance
4. verify ~700 attosec bunch
5. modulate energy

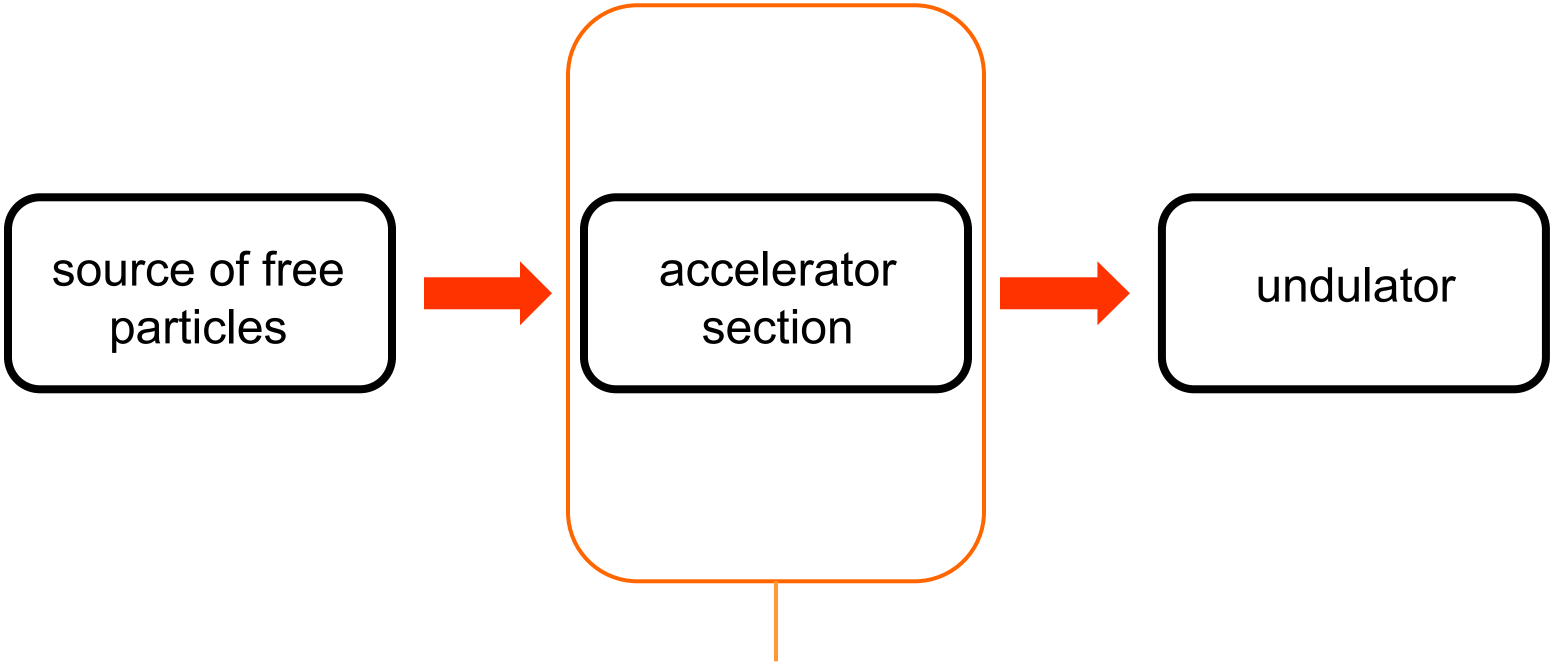


graduate student Anthony Serpry

Concept of field-emission arrays:

J.W. Lewellen, J. Noonan, "Field-emission cathode gating for rf electron guns", Phys. Rev. ST AB 8 033502 (2005)

Development of the three key laser-driven components

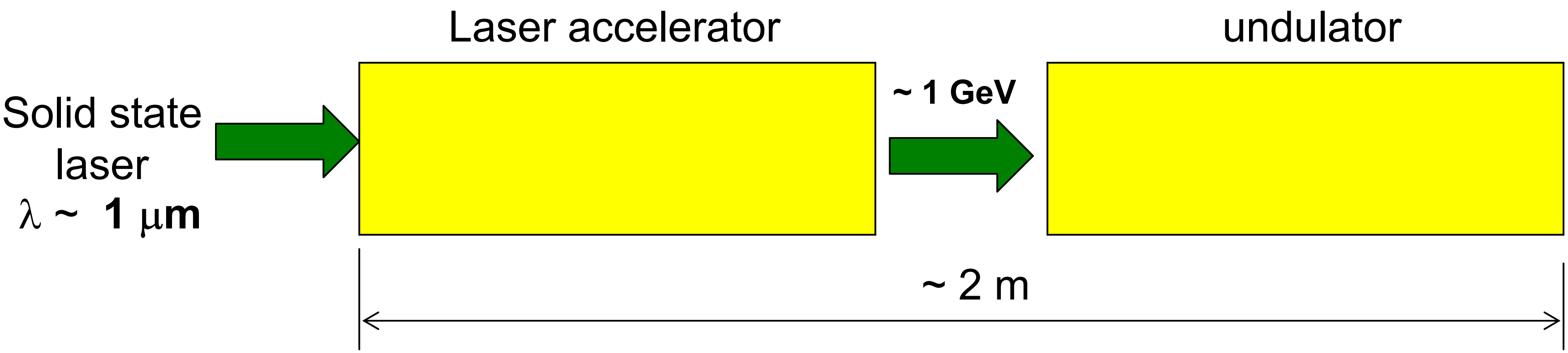


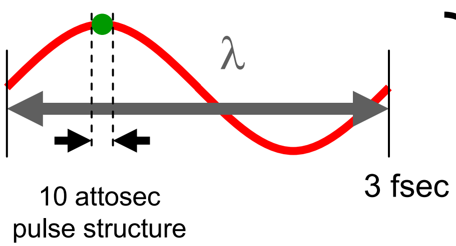
Objective:

develop MEMs based laser-driven accelerator structures

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

Proposed parameters for laser driven SASE-FEL





Input electron beam

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

undulator

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

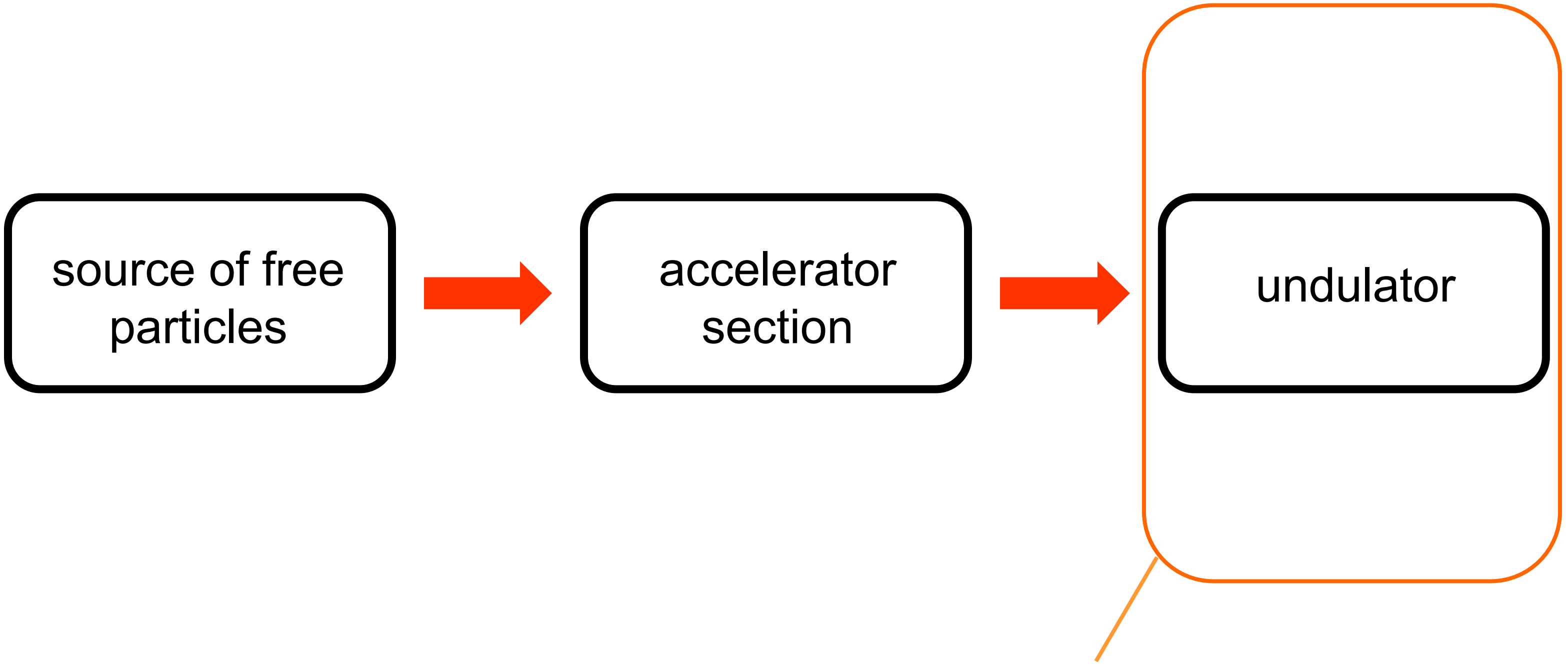
Field envelope growth

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

electrons per unit volume

Smallest possible beam size

$\phi_b < 500$ nm



First Idea:

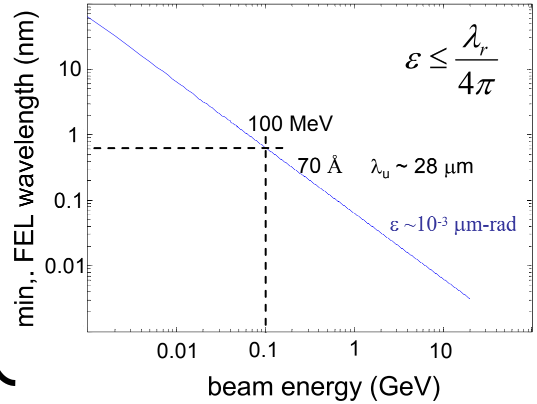
Periodic Magnetic Undulator

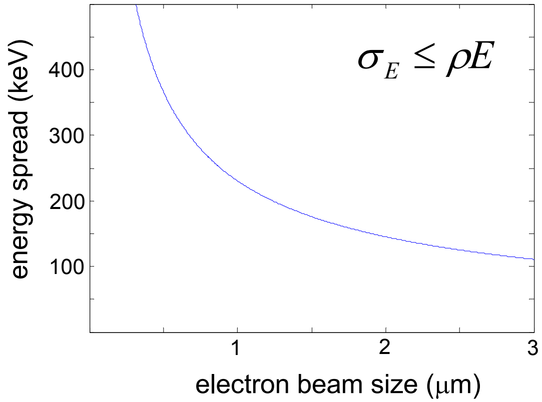
Field strength ~ 1 Tesla
Modulation Period ~ 0.1mm
Length ~ 30cm

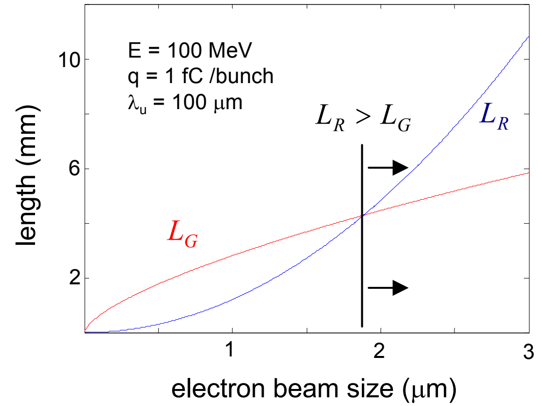
Attosecond X-ray FEL Source - First Approach

Starting point

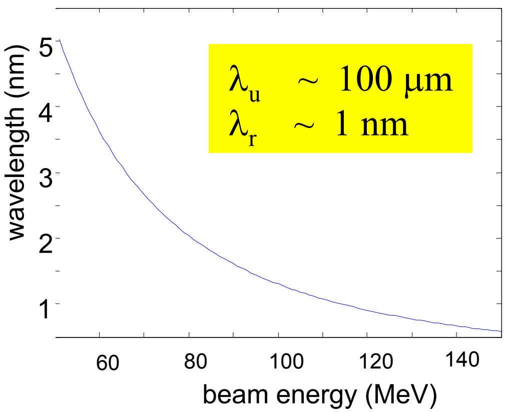
1-D FEL model
Design parameters must satisfy these conditions



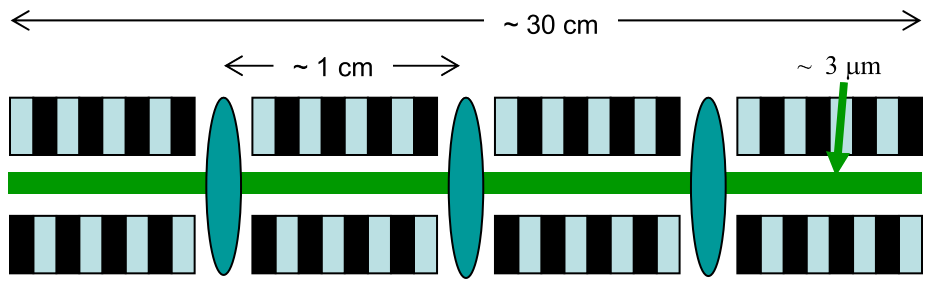




Undulator design



L_{FODO} ~ 1 cm L_G ~ 1 cm ε ~ 10^{-9} m-rad λ_b ~ 18 attosec
σ_{xy} ~ 3 µm L_{sat} ~ 30 cm q_b ~ 1 fC U_b ~ 10^{-7} J



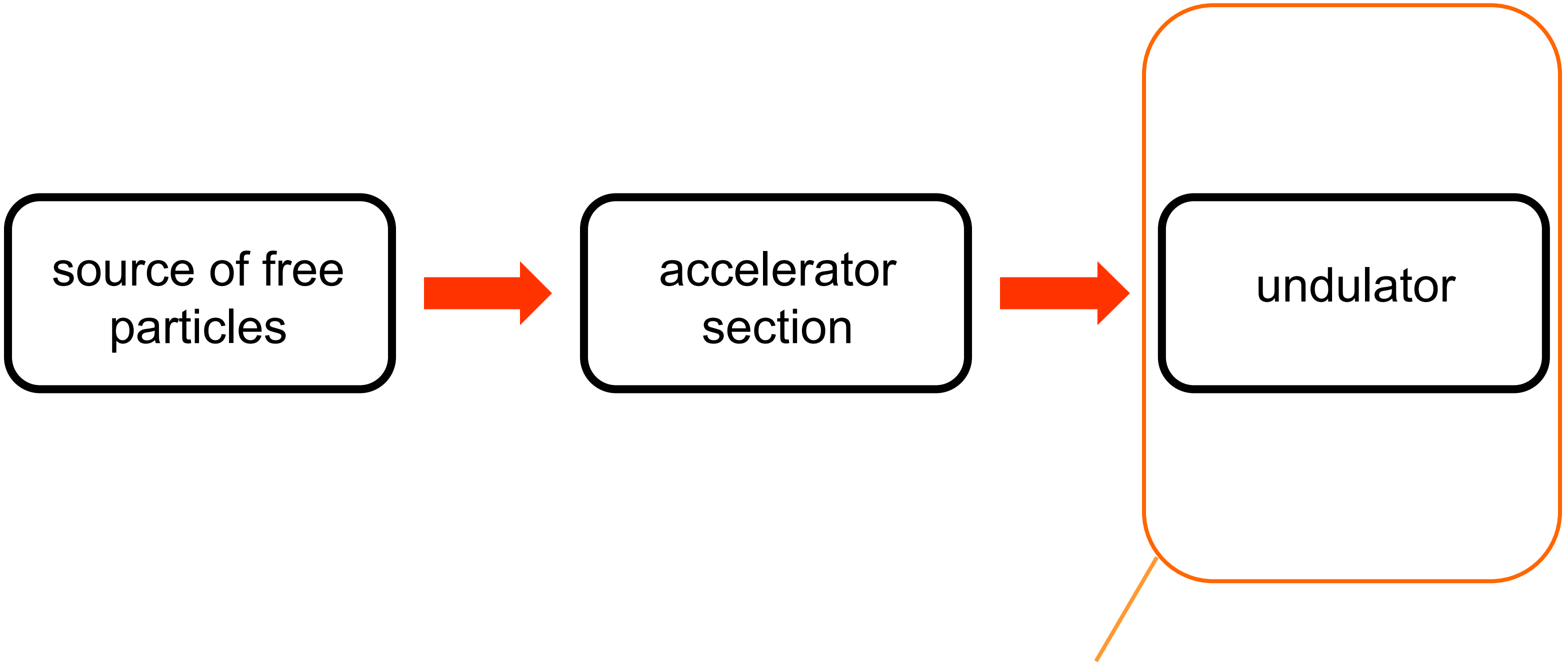
Laser power required

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

KEY IDEA: Use fsec laser to Drive Dielectric Undulator

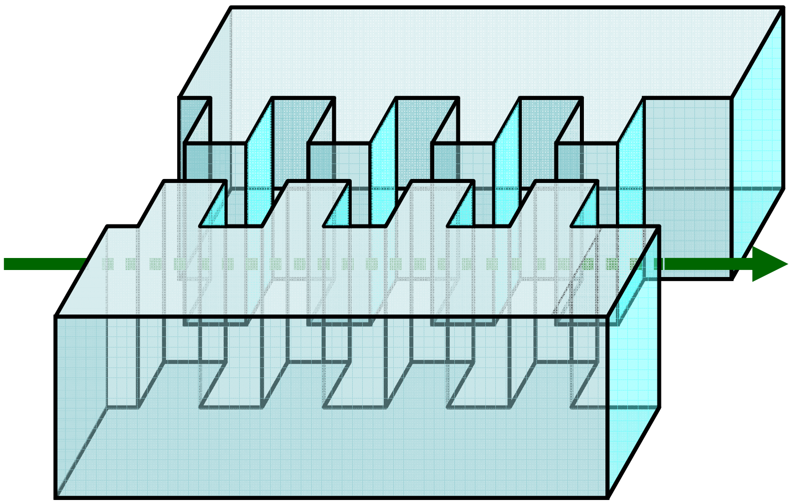


Objective:

develop MEMs based laser-driven deflection structures

1. Dielectric optical MEMs structures
2. High gradients (~ 1 GeV/m)
3. Possibility for compact undulators

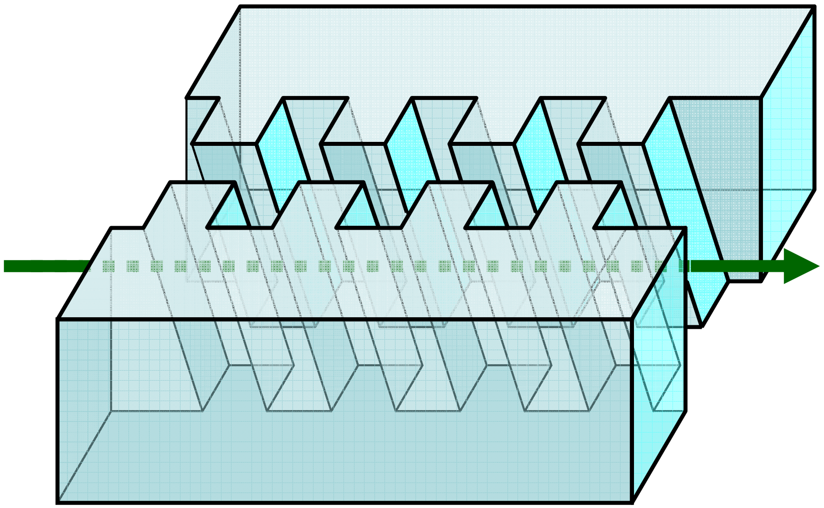
accelerator structure



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

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

deflection structure



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

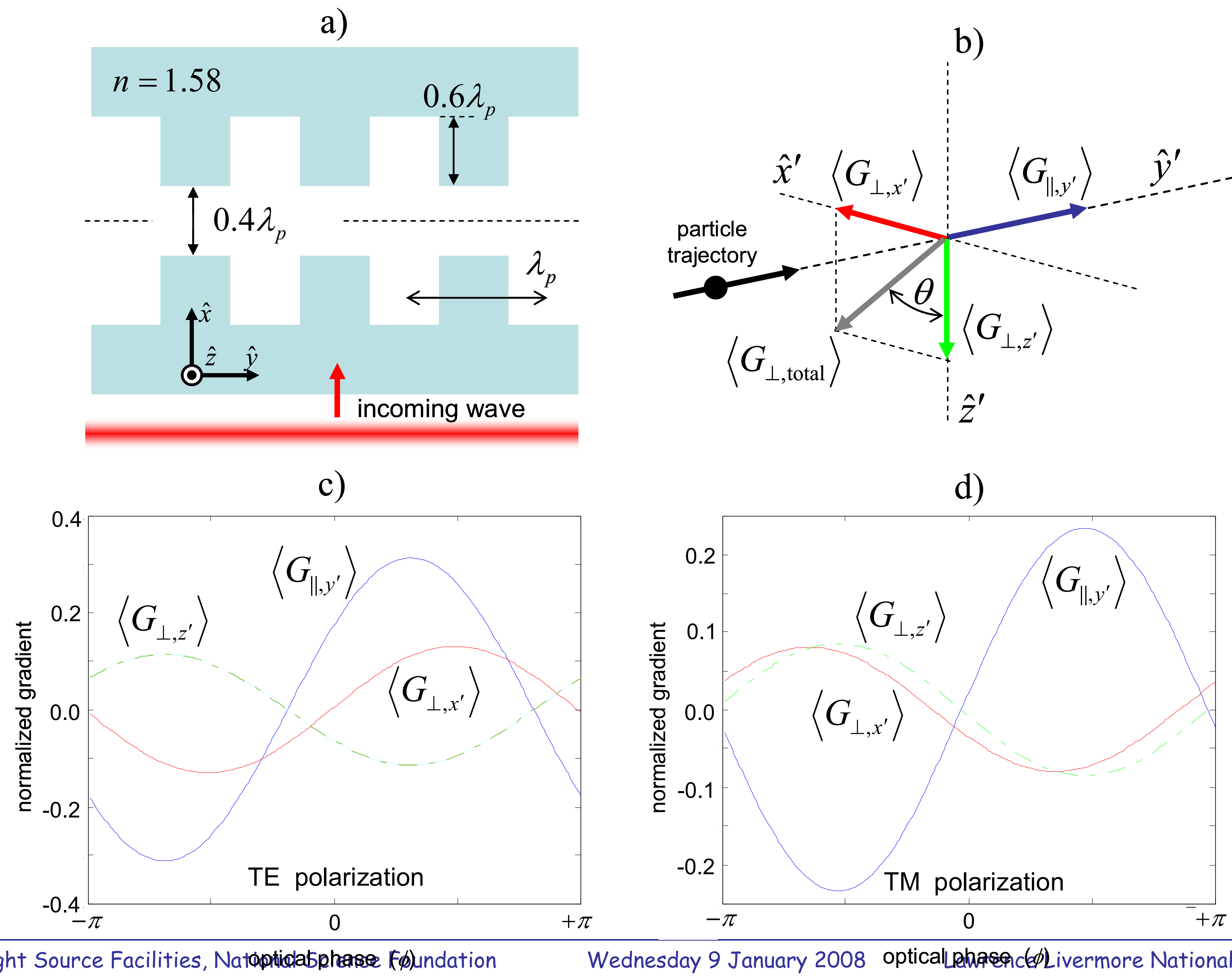
$$\left\langle \vec{F}_{\perp} / q \right\rangle \sim \tfrac{1}{5} E_{laser} \rightarrow \sim 2\,\mathrm{GeV/m}$$

key idea

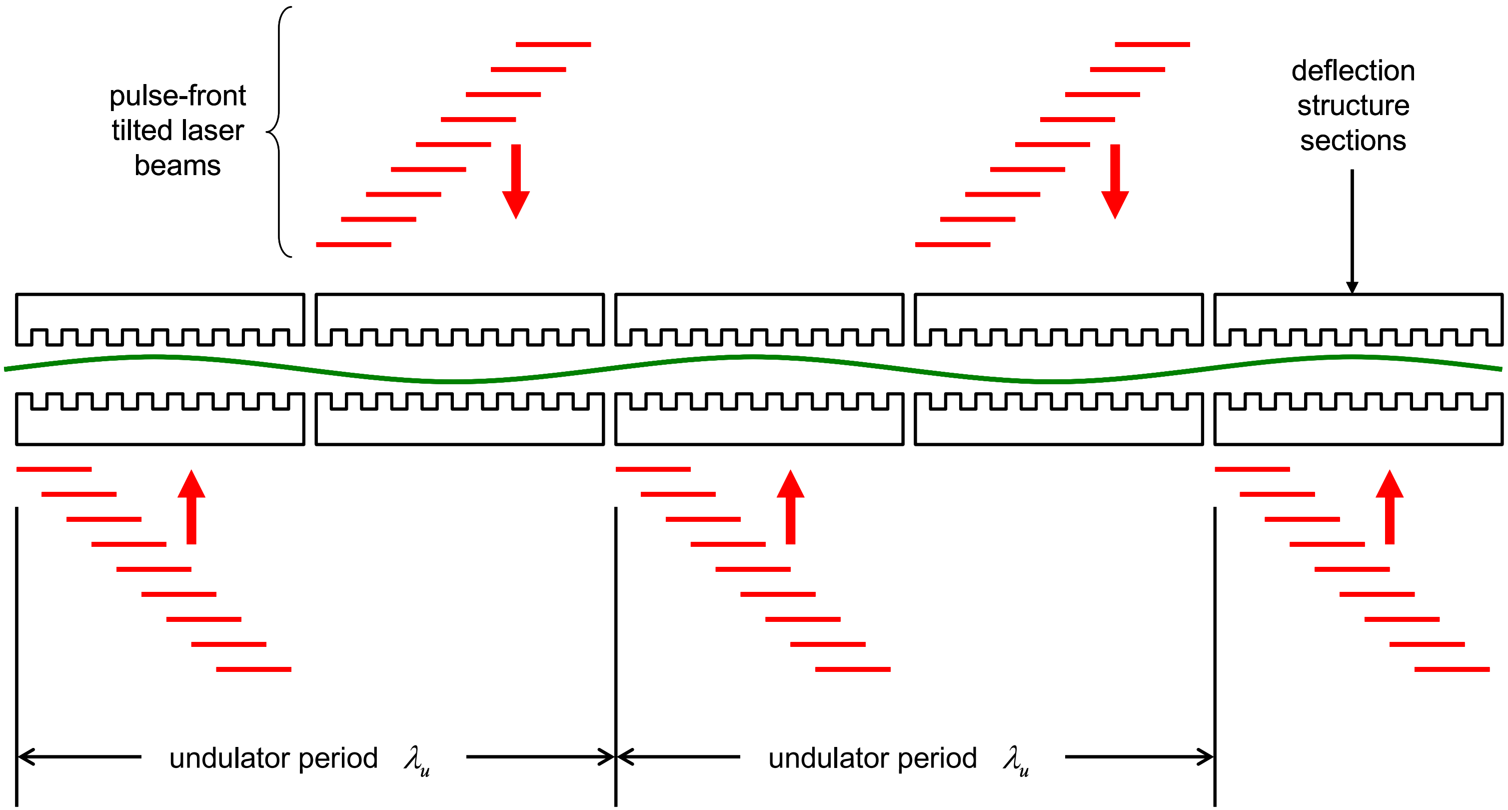
extended phase-synchronicity between the EM field and the particle

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 expected phase-synchronous force components



A dielectric structure undulator



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

1D model of Attosecond 120keV FEL

Byer Group

simulation parameters

$U_b = 2\ \text{GeV}$

$\tau_b = 5\ \text{attosec}$

$\varepsilon_N = 10^{-9}\ \text{m-rad}$

$Q_b = 20\ \text{fC}$

$\Delta\gamma/\gamma = 0.1\%$

$\sigma_r = 200\ \text{nm}$

$\beta^* = 4\ \text{cm}$

$\lambda_u = 0.3\ \text{mm}$

$K = 0.13$

short pulse regime

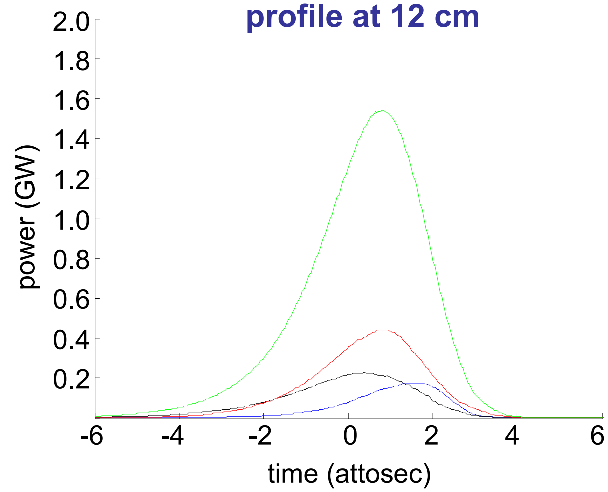
$L_c \sim 21\lambda_r$

$\sigma_b \sim 136\lambda_r$

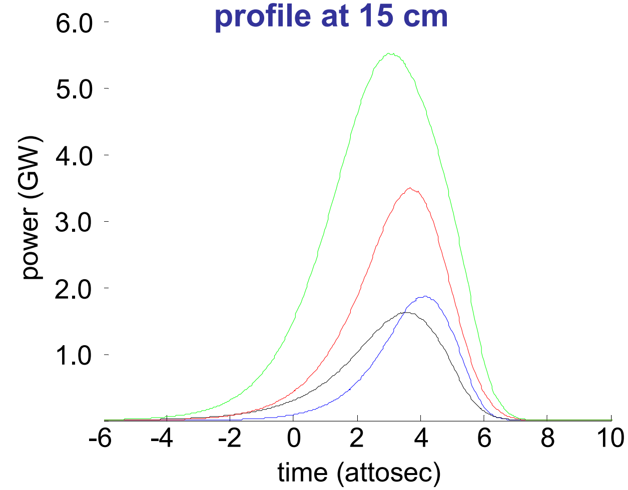
↓

$\sigma_b / L_c \sim 6$

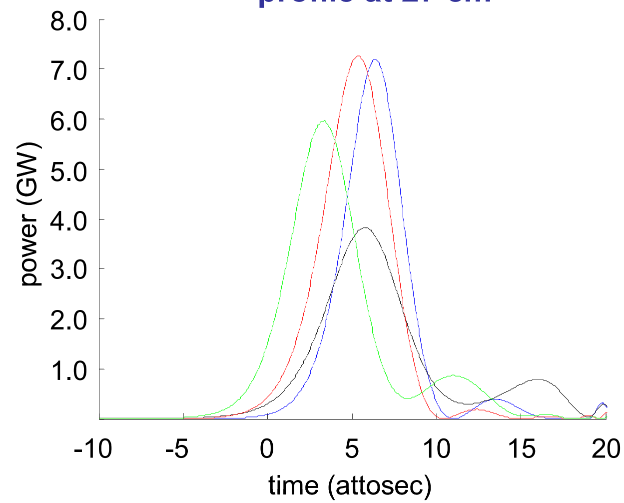
expected temporal profile at 12 cm



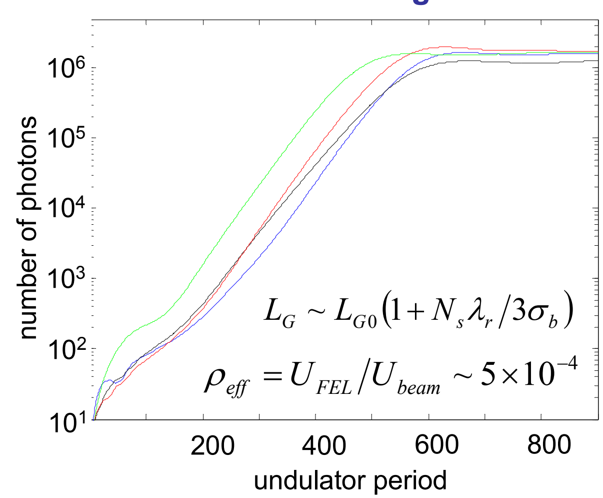
expected temporal profile at 15 cm



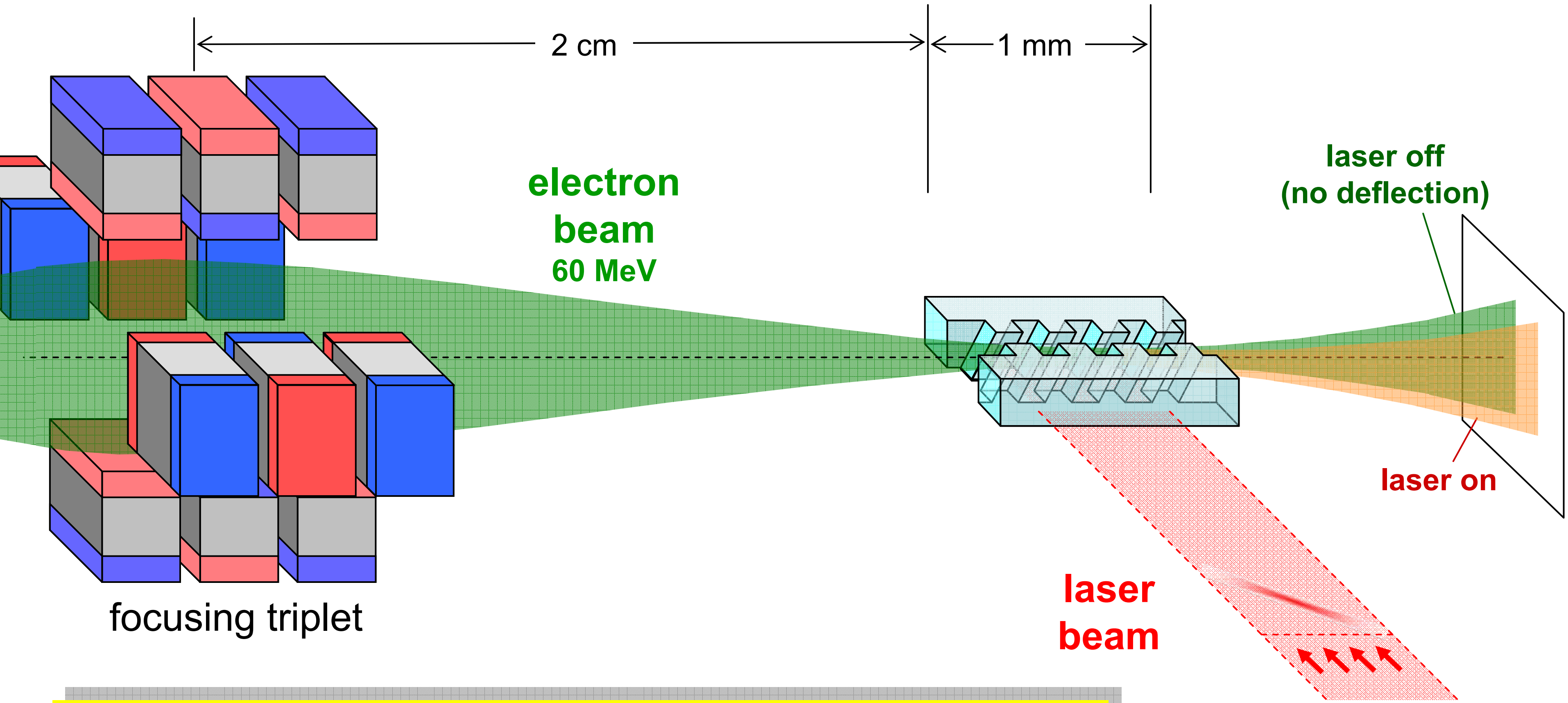
expected temporal profile at 27 cm



pulse fluence vs. undulator length



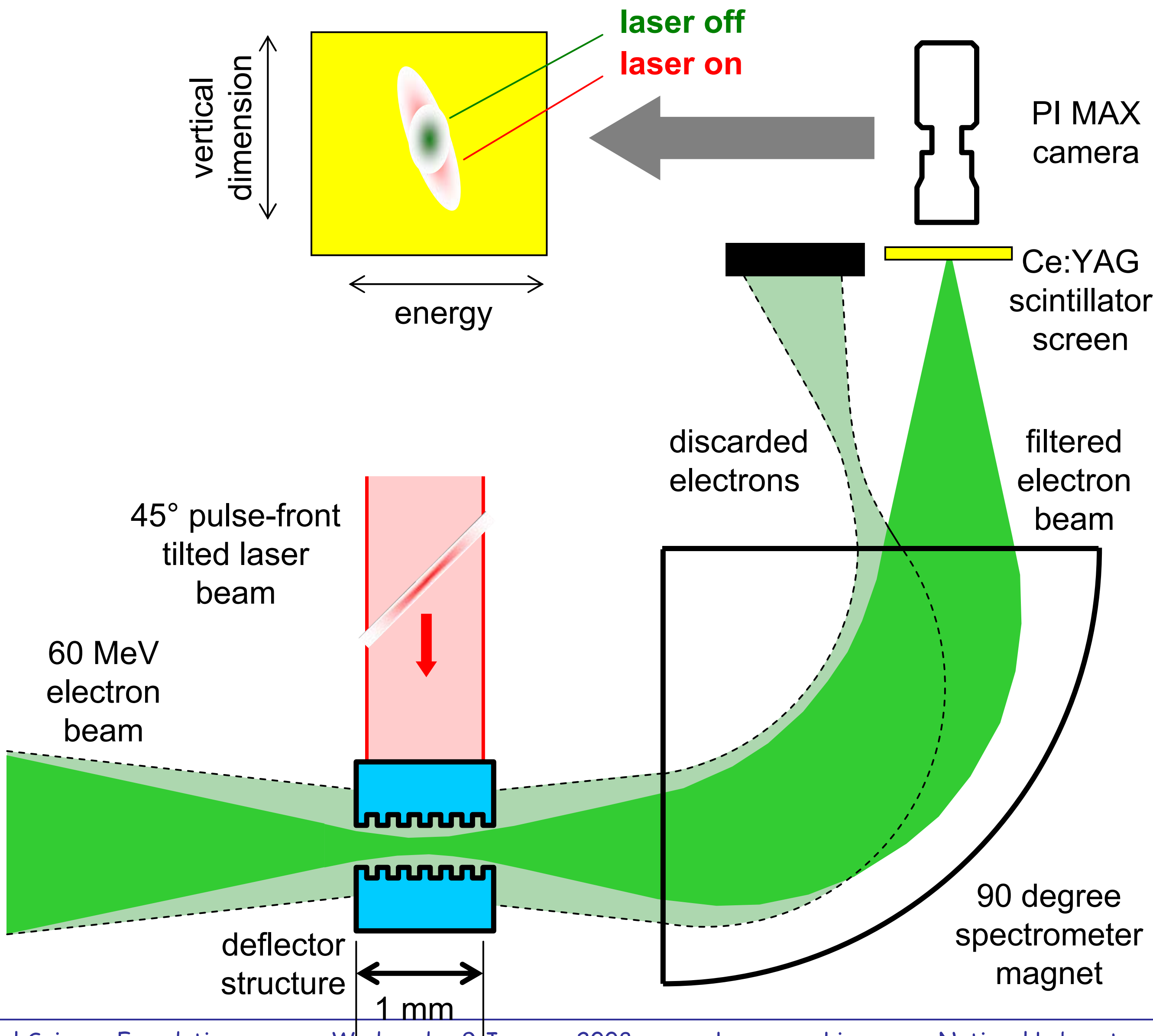
Test of laser-deflection Structure



Prove the concept of a phase-synchronous deflection force

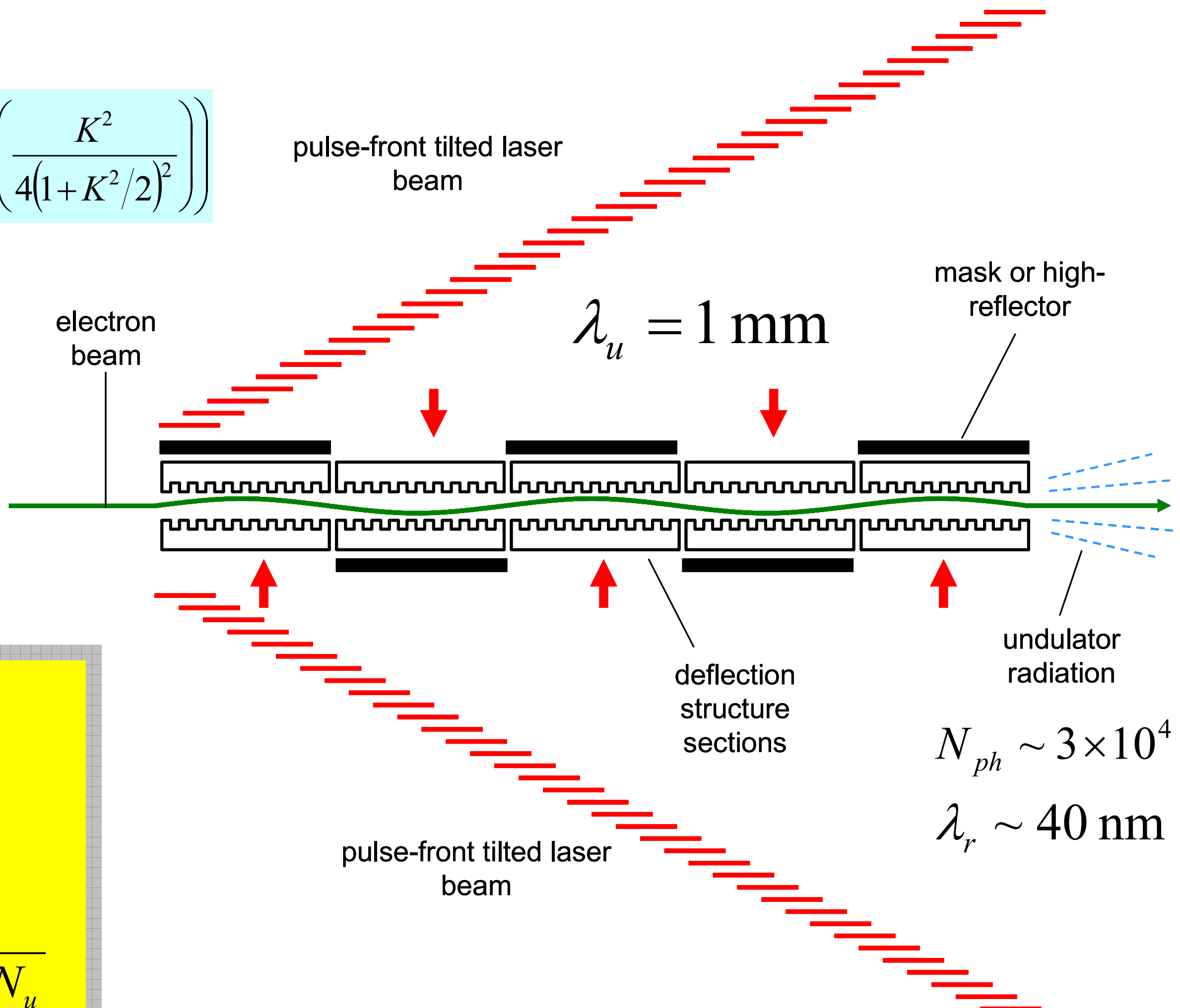
Measure Deflection of the Delectric Laser Driven Undulator

Near-future experiment at E163



Look for undulator radiation

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



Prove the concept

measure

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

Contents

Historic Background

The TeV-Energy Physics Frontier

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

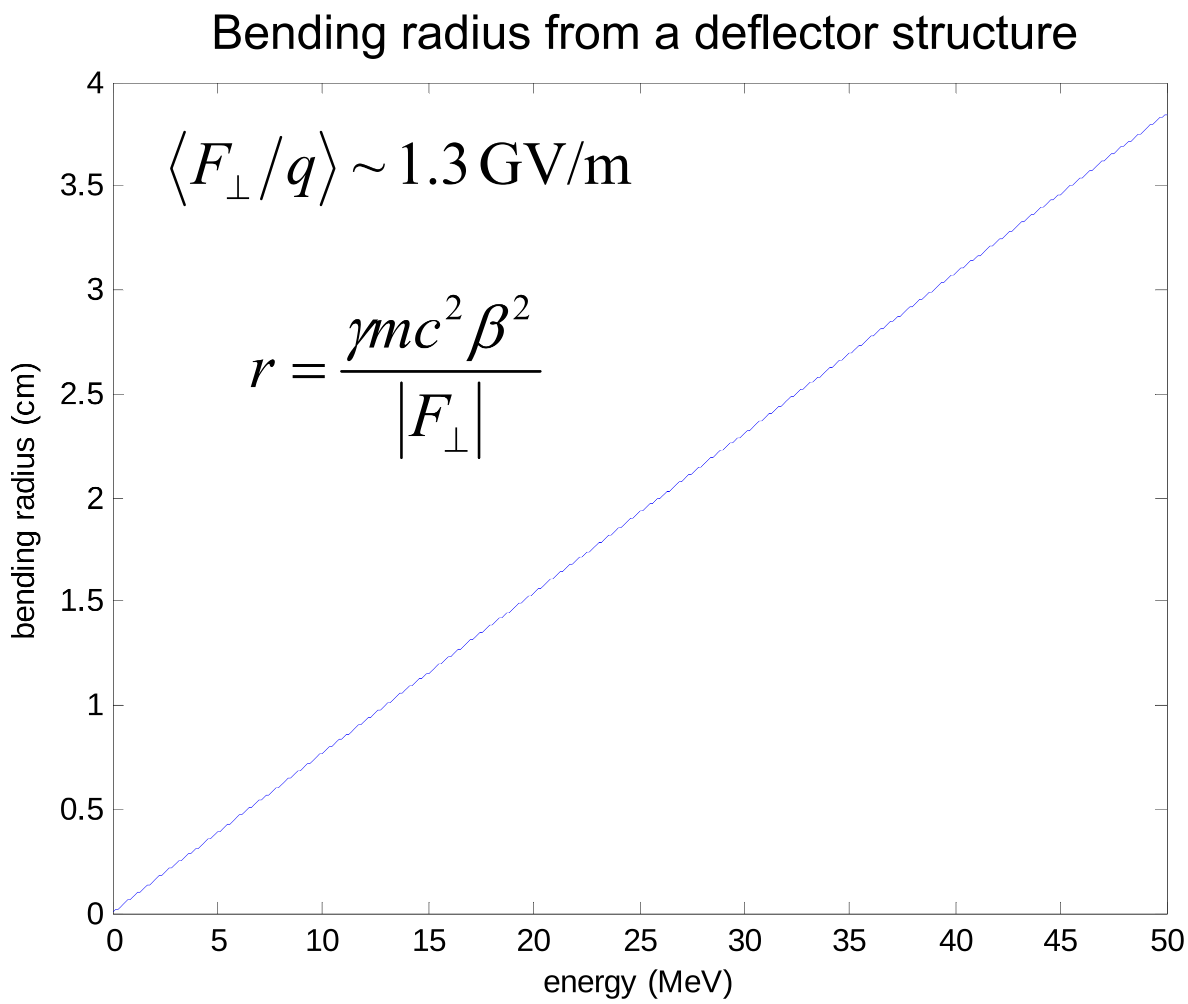
Coherent X-ray laser Generation
- Components of the X-ray laser
  - Dielectric Accelerator and Undulator Structures
  - FEL gain and efficiency

Future Challenges

Table Top Synchrotron Source

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

{Bending radius ~ 1m for 1GeV electron source}



Summary

Dielectric structure FEL
- injector
- accelerator
- undulator

Laser-driven

properties
1. photon energy of tens of keV
2. ~10^5 photons/pulse
3. 80 MHz → 10^{12} photons/sec

initial work
- laser-particle accelerators (LEAP/E163)
- field-emission injector
- modeling of the undulator and FEL process

future
- dielectric structure accelerators
- test a laser-driven deflector
- construct a low-energy pre-accelerator

Long-term experiments

Inject higher density of optically bunched electrons into the structure

- search for small-signal gain
- verify predicted beam loading and wakefield effects

Test other materials for dielectric structures

- verify index of refraction and transparency window
- perform laser-damage threshold tests
- radiation damage tests

Integration of the components

- cascading of ~10^3 mm-long accelerator sections
- cascading of ~10^2 sub-mm long deflection sections
- beam transport: steering and periodic focusing
- beam diagnostics: BPMs, etc

Refinement of the idea

- undulator optimization: periodic focusing, tapering, etc.
- seeding, resonator configuration
- harmonic generation

Acknowledgements

1. R. Ischebeck, E. Colby, R. Siemann, C.M. Sears, S. Fan, and Z. Huang
2. P. Hommelhoff and M. Kasevich for guidance on field-emission tips
3. H. Injeyan and R. Rice for discussing possible applications of the proposed X-ray sources
4. The NLCTA personnel at SLAC for guidance on operating the test accelerator

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1. **accelerator work**: supported by DOE DE-FG06-97ER41276
2. **light-source application**: supported by Northrop Grumman

Relativistic electron laser-acceleration group

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

Rasmus Ischebeck | Chris Barnes | Ben Cowan | Tomas plettner | Jim Spencer

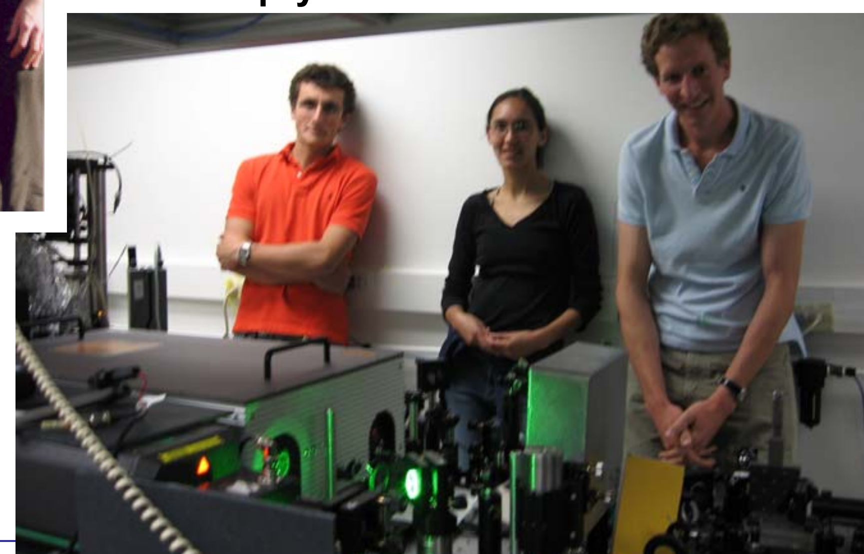
Bob Noble
Dieter Walz

past collaborators
Y.C. Huang
T.I. Smith
H. Wiedemann

Low-energy electron laser acceleration group

Mark Kasevich
Patrick Lu,
K-Xun Sun

Anthony Serpry | Catherine Kealhofer | Peter Hommelhoff



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)

The Livingston curve

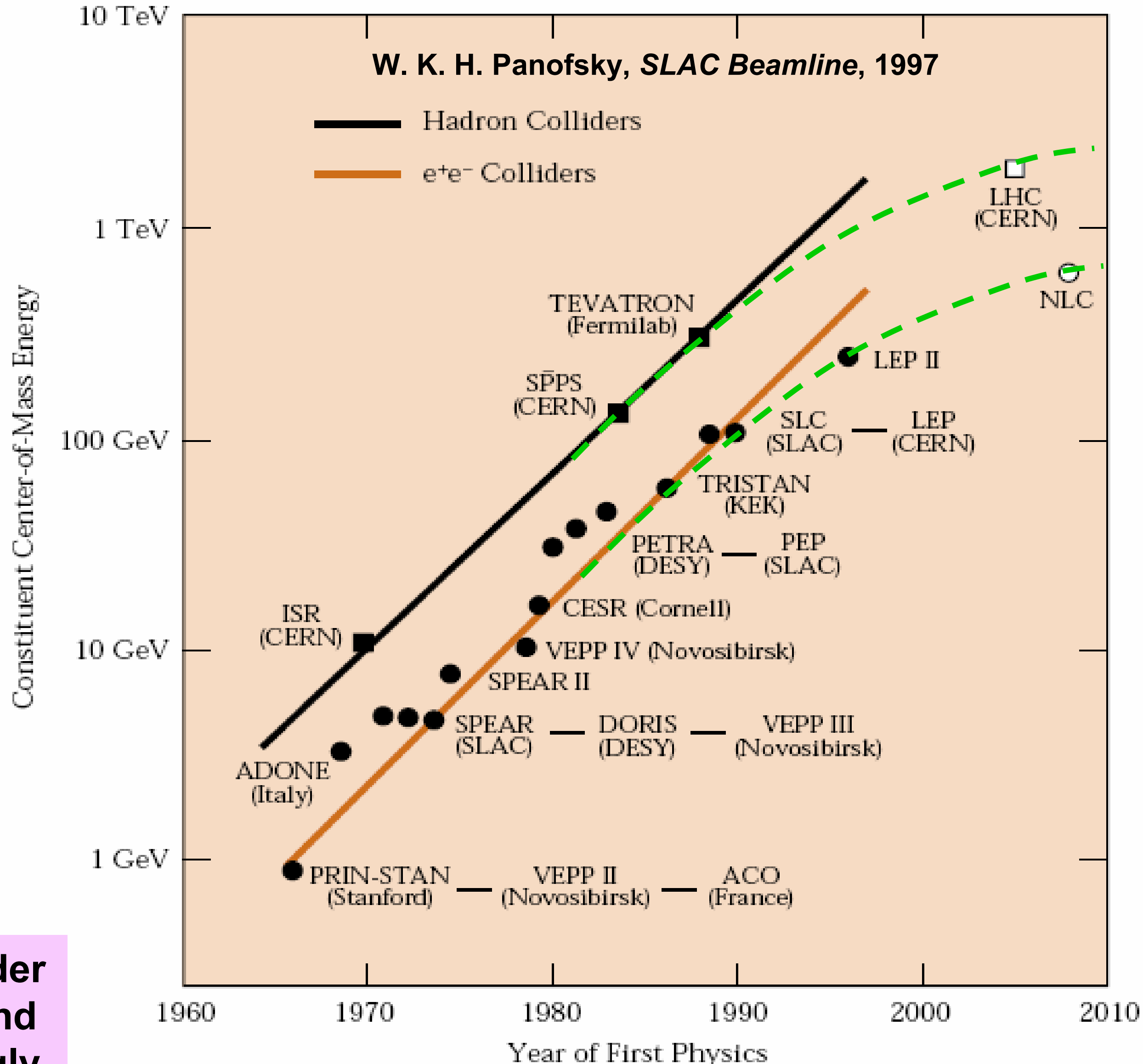
1. near-exponential growth in the beam energy up until about 1990

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

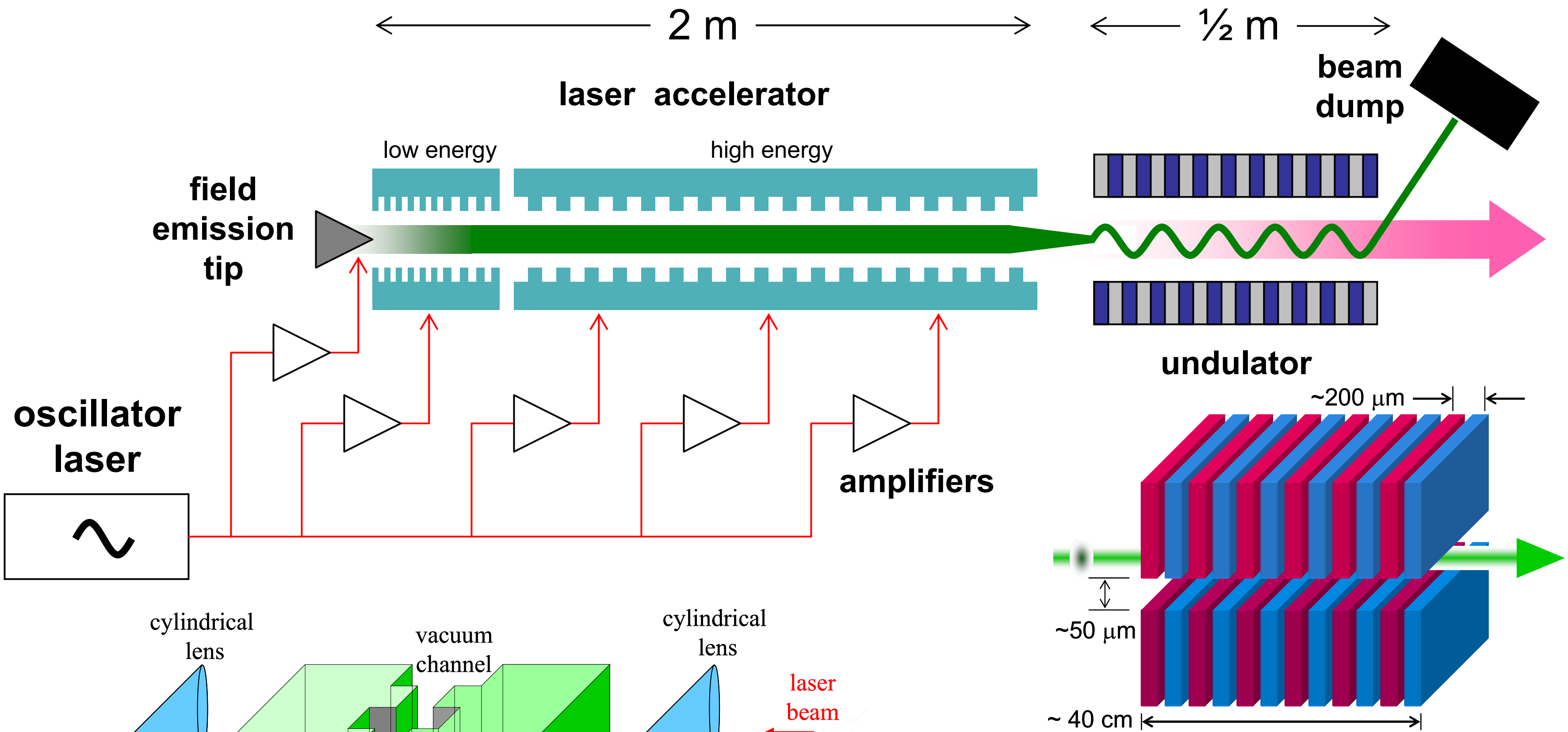
For future high energy collider facilities beyond the LHC and ILC it becomes increasingly appealing to invest in new accelerator technologies

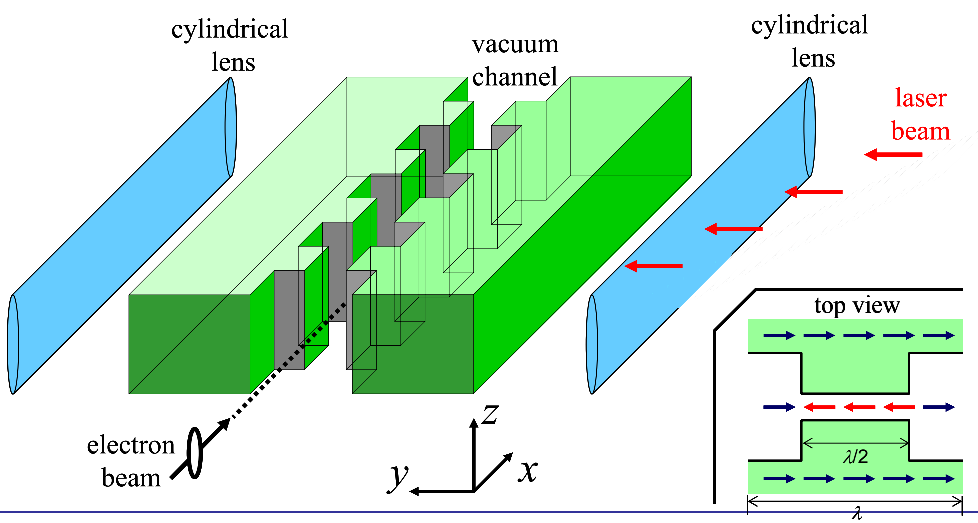


Future Maximum gradient ~ 1000 MeV/m

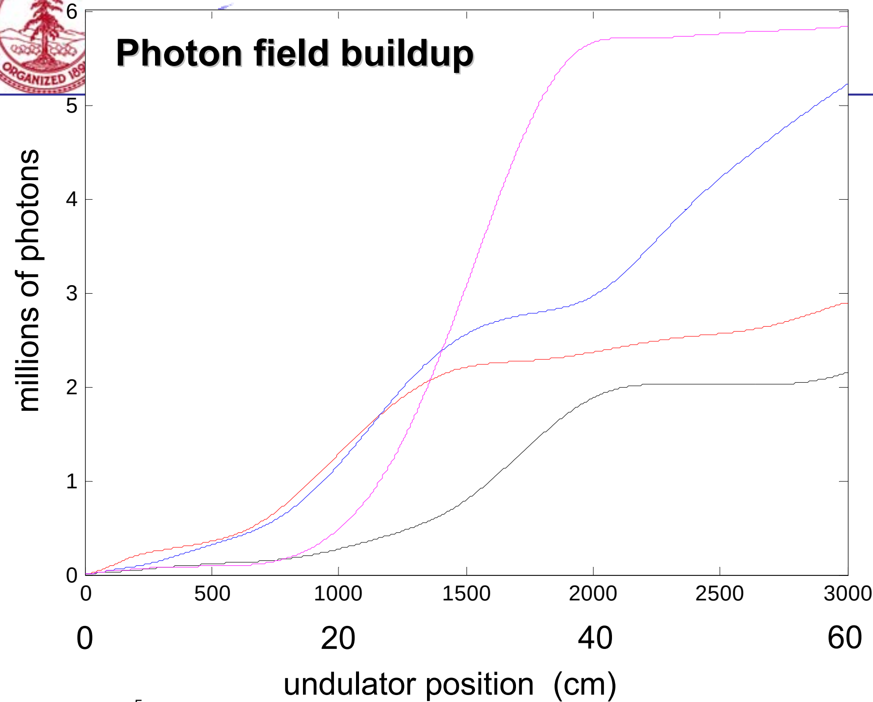
- BACK UP SLIDES

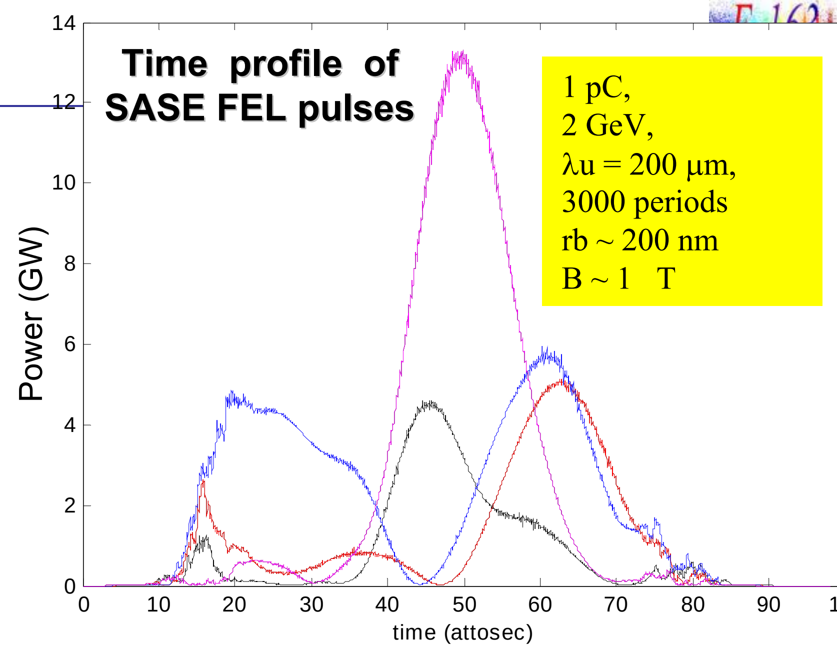
Proposed parameters for laser driven SASE-FEL

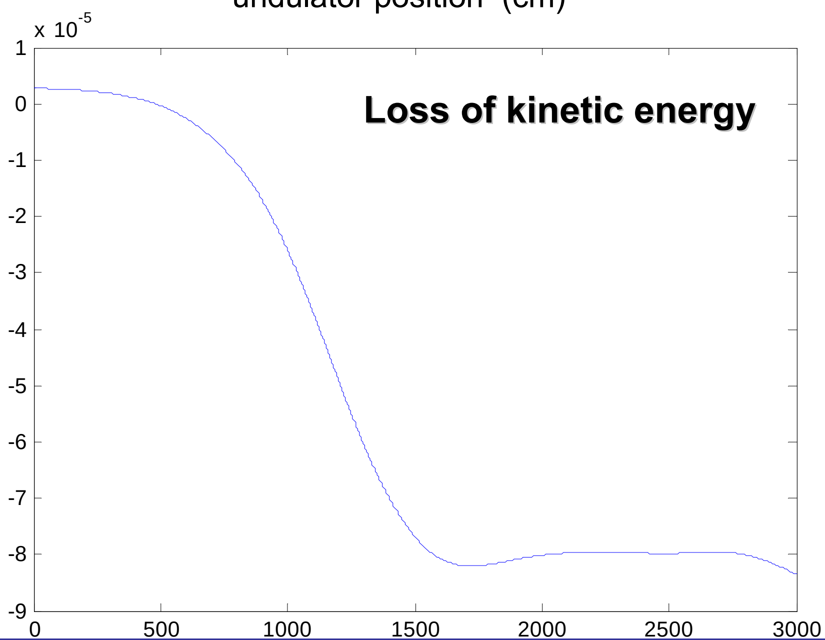




1 pC,
2 GeV,
$\lambda u = 200\ \mu m$,
Lu = 40 cm
rb ~ 200 nm
B ~ 1 T







$6x10^6$ photons

1 photon/electron

10 GW peak power

~15 attosec FWHM

~20 attosec timing jitter

Eγ~ 190 kev

Laser damage and radiation damage studies

Byer Group

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*

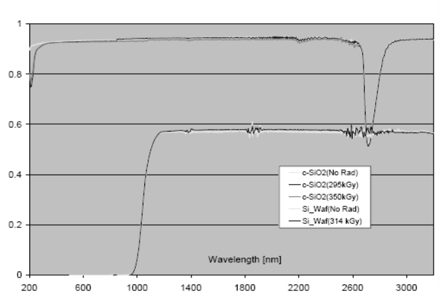


Fig. 4. Transmission spectra through 500 μm wafers of Quartz(upper group of curves) and Silicon(lower group) as a function of integrated dose (Si).

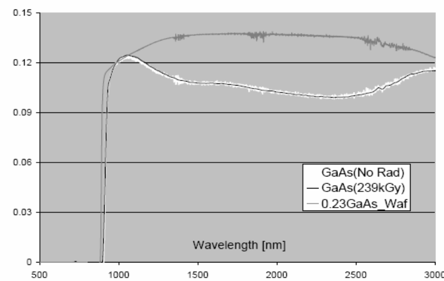


Fig. 5. Transmission spectra through a thin wafer and a thick (6.35 mm) GaAs sample as a function of integrated dose (Si). The wafer was scaled downwards by 0.23 for better comparison.

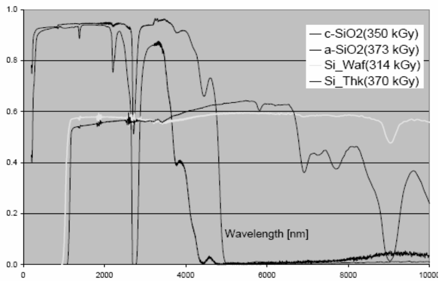


Fig. 6. Comparison of spectra from 0.20-10 μm for different forms of Si in Si equivalent dose. Spectra were matched at 3.2 μm.

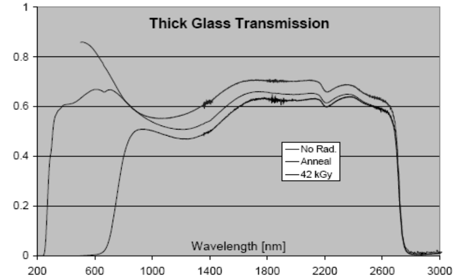
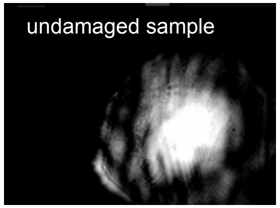
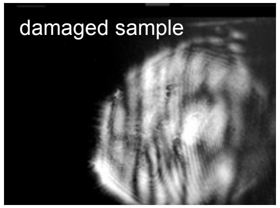
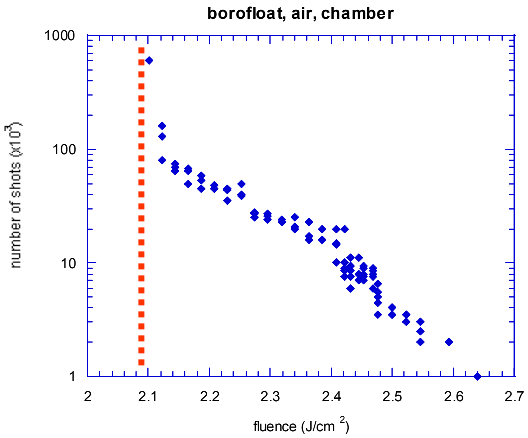


Fig. 1. Transmissivity spectra through 1.1 cm thick plate glass after Co^{60} γ-irradiation. Spectra are stacked according to their order in the insert.

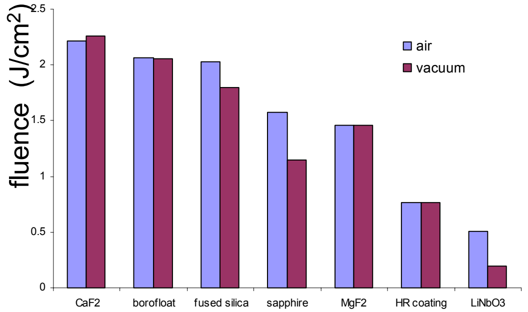
Laser damage threshold studies





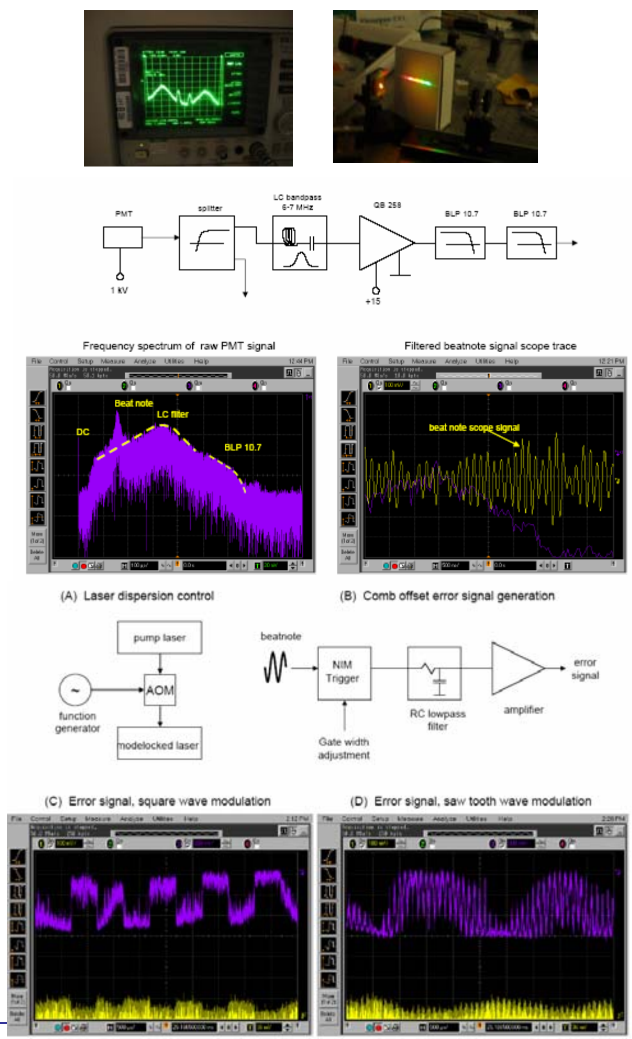


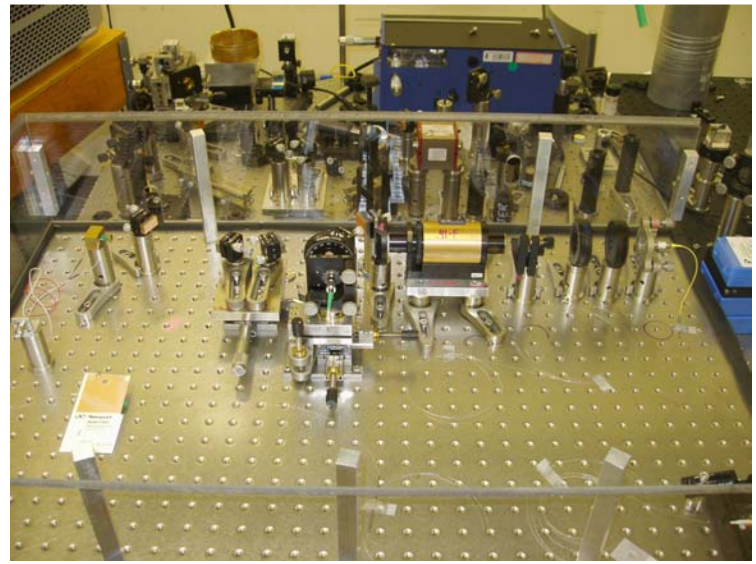
material	damage threshold air	vacuum
CaF_2	2.212	2.260
borofloat	2.064	2.054
fused silica	2.027	1.795
sapphire	1.574	1.152
MgF_2	1.455	1.455
800 nm HR	0.769	0.768
$LiNbO_3$	0.504	0.194

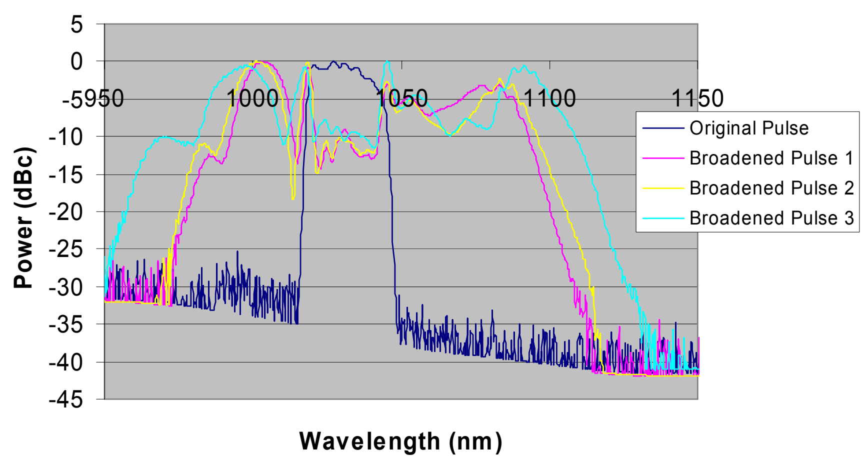


OPTICAL PHASE LOCKING OF MODELOCKED LASERS FOR PARTICLE ACCELERATORS*

T. Plettner, S. Sinha, J. Wisdom, Stanford University, Stanford, CA 94305
E. Colby, SLAC, Menlo Park , CA, 94025





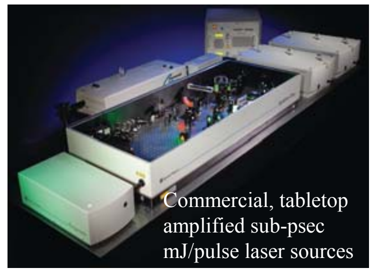


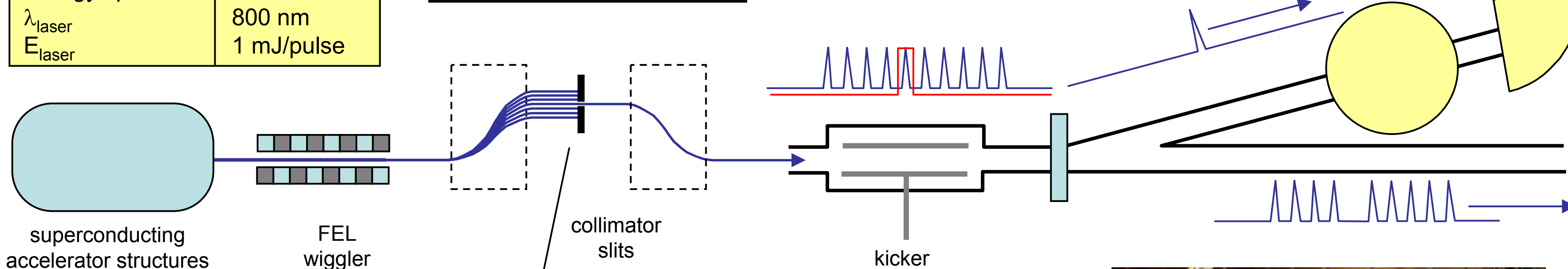
The SCA-FEL facility

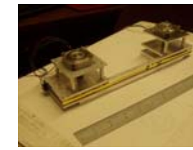
Byer Group

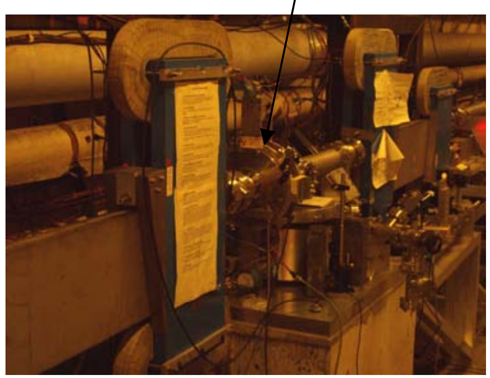
The SCA Accelerator provided a source of 30MeV electrons for LEAP

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

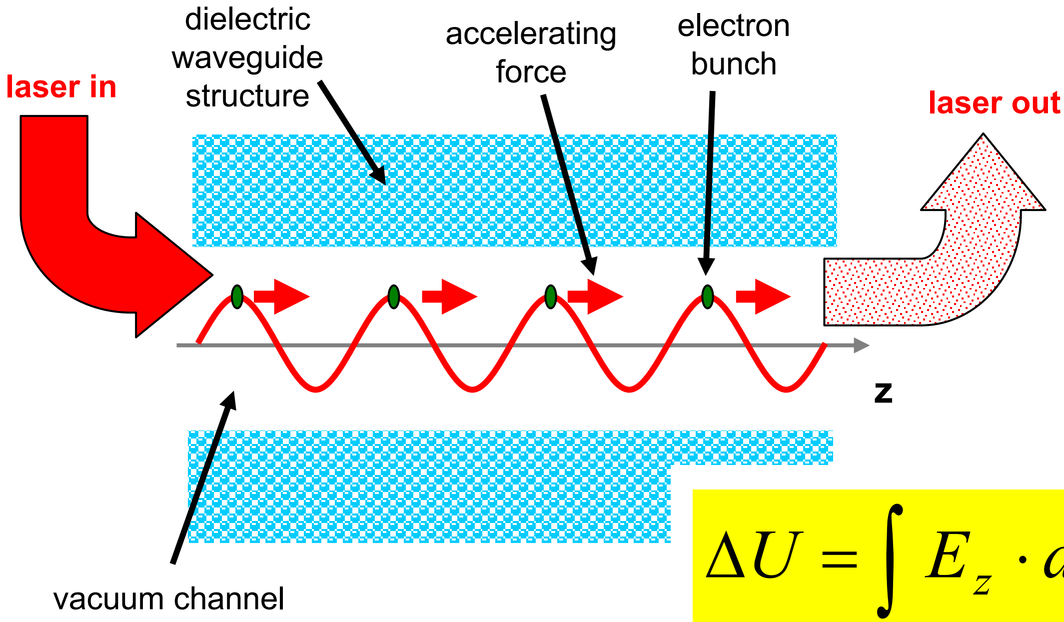






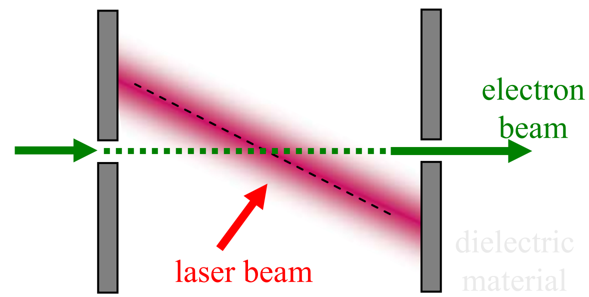


Laser acceleration concept

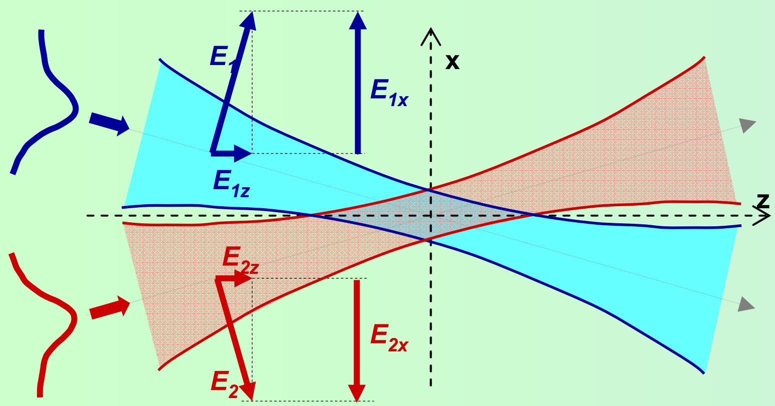


conceptual idea

Pantell, 1979



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



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

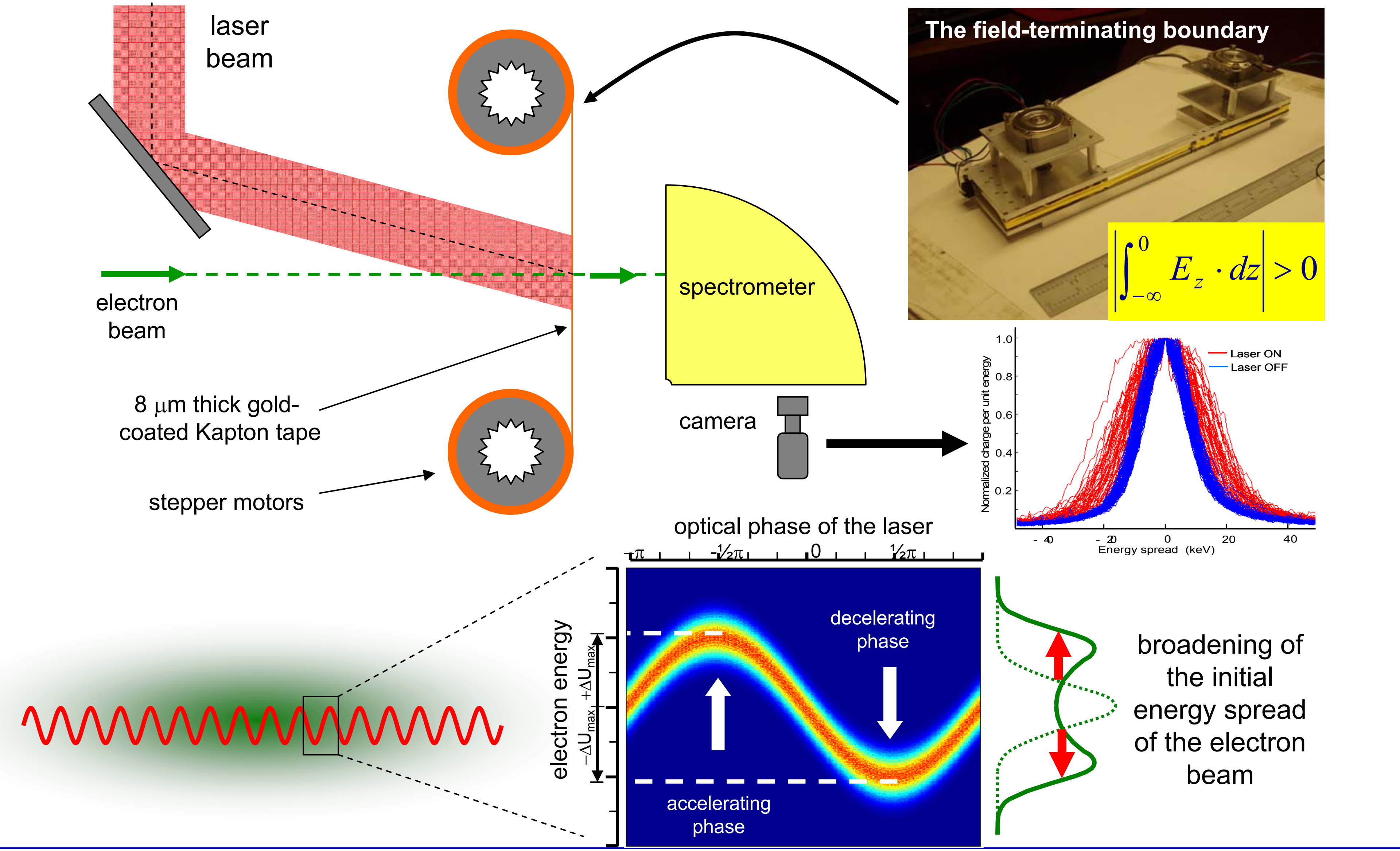
$$\psi_t = \underbrace{k\cdot z\cdot\cos\theta-\omega\cdot t}_{\text{Plane Wave Phase}}+\underbrace{\frac{\hat{z}^3\cos^3\theta\cdot\tan^2\theta}{\theta_d^{\,2}(1+\hat{z}^2\cos^2\theta)}}_{\text{Math}}\underbrace{-2\cdot\tan^{-1}(\hat{z}\cos\theta)+\phi_0}_{\text{Gouy Phase}}$$

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

†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)

Byer Group



"New" technology: the laser

Byer Group

PHYSICAL REVIEW VOLUME 112, NUMBER 6 DECEMBER 15, 1958

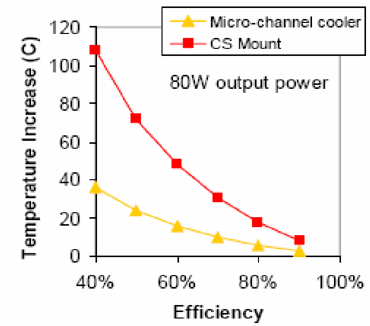
Infrared and Optical Masers

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 impractic 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

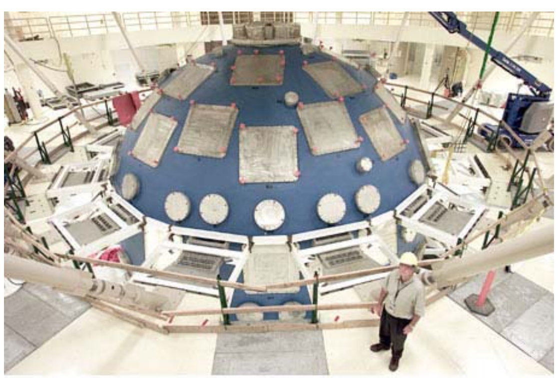
nLIGHT



Improve efficiency of bar from 50%-80%

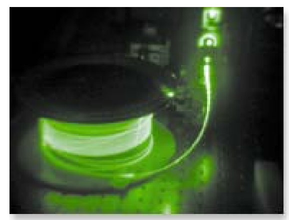
high power solid state lasers

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

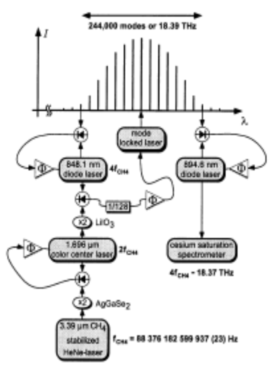


FIG. 1. Frequency chain that allows the comparison of the precisely known frequency of a methane stabilized He-Ne laser at 88.4 THz (3.39 μm) with the cesium D_1 transition at 335 THz (895 nm).

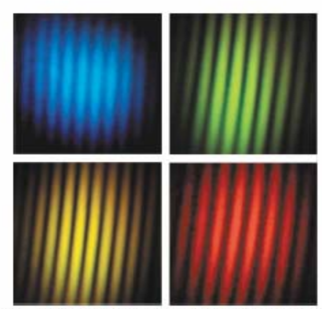
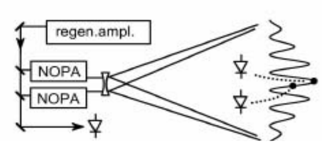
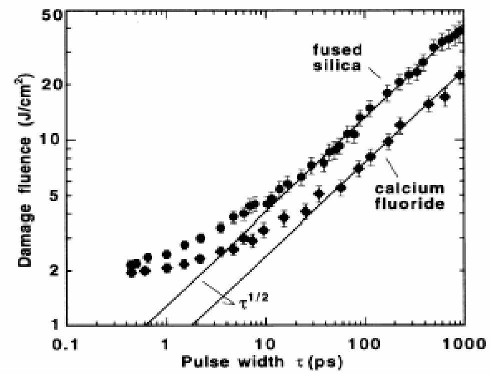


Fig. 2. Interference between two separate NOPAs for various center wavelengths.



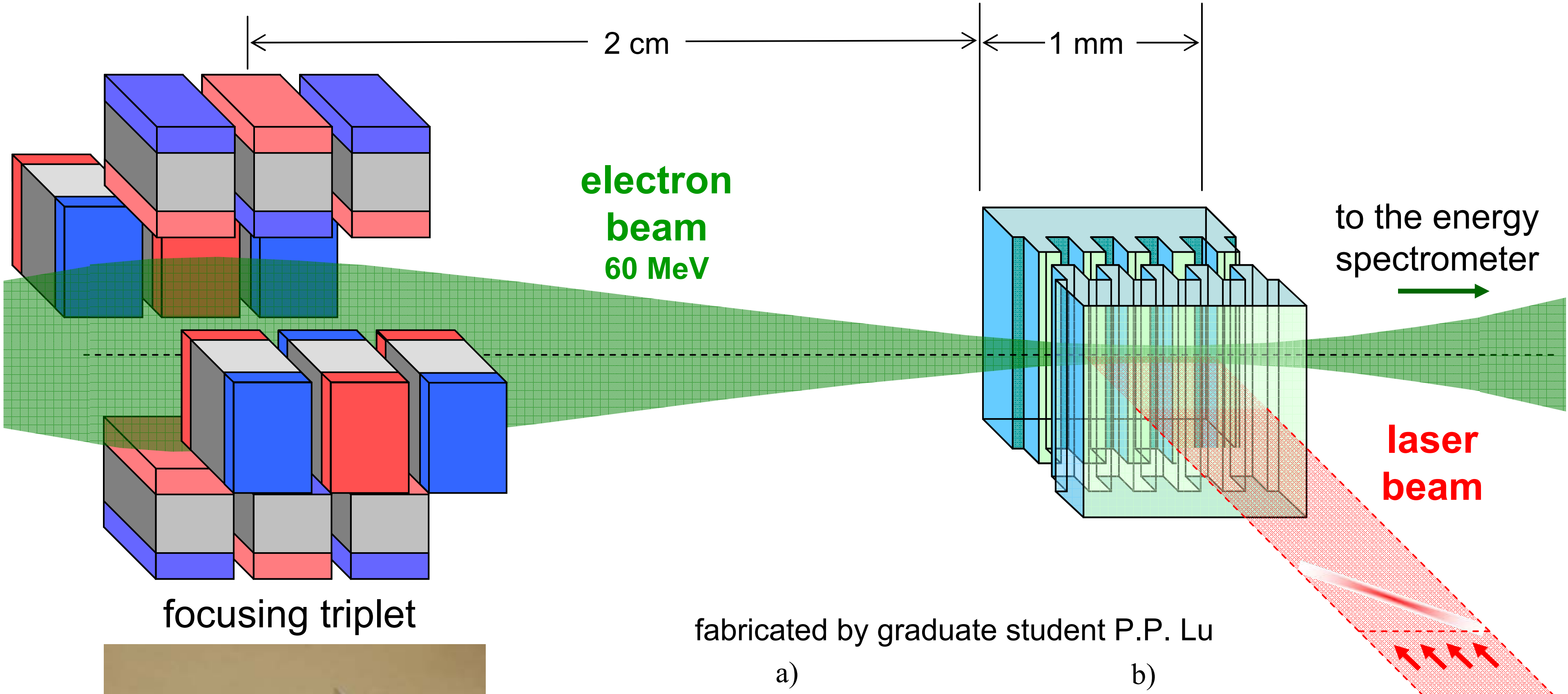
damage threshold of dielectric materials

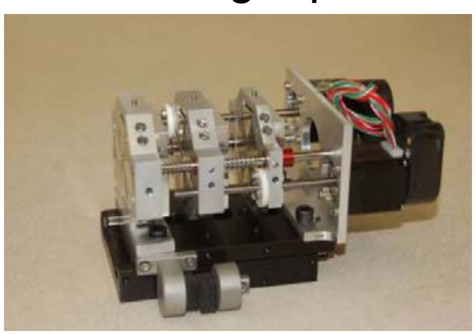


Stuart, et. al,, Phys Rev. Lett. Vol 74, No 12 p. 2248 (1995)

10 GV/m fields for 100 fsec laser pulses

Laser-acceleration from a quartz-based mm-long accelerator microstructure

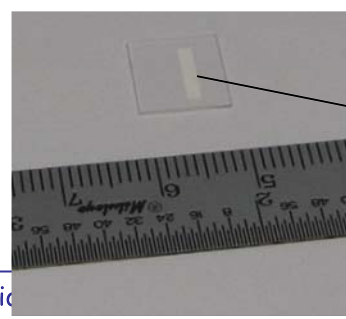




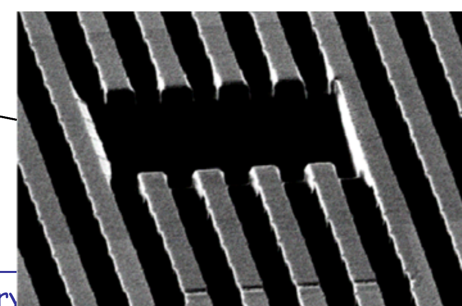
fabricated by graduate student C.M. Sears

fabricated by graduate student P.P. Lu

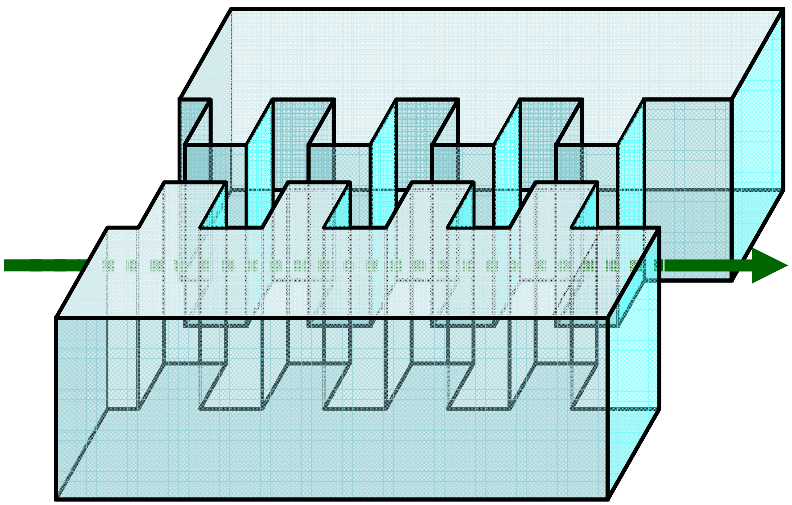
a)



b)



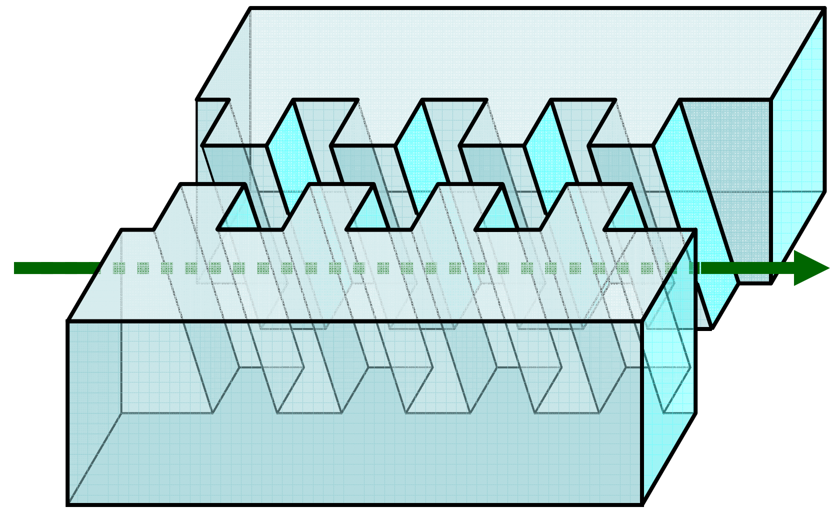
accelerator structure



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

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

deflection structure



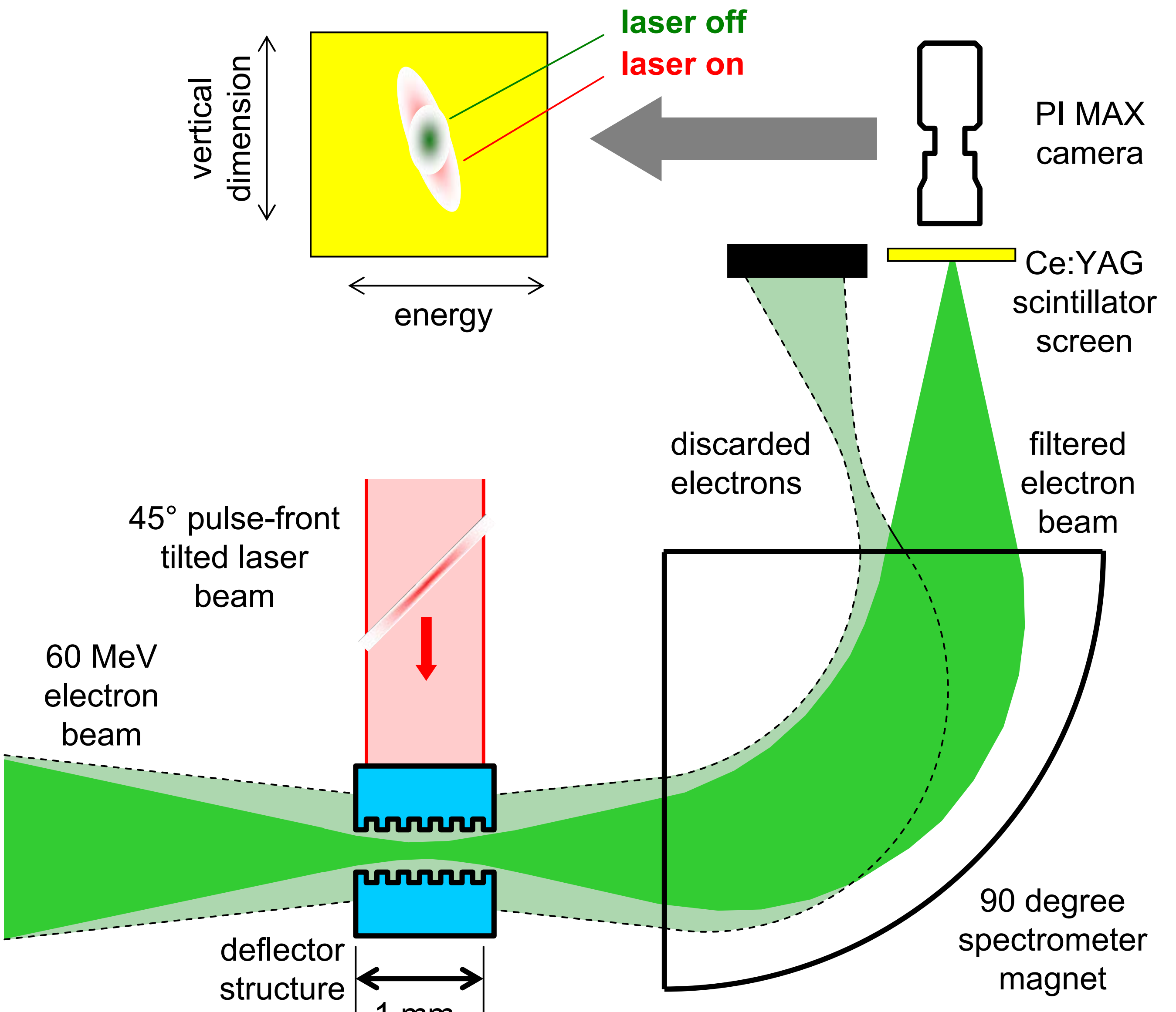
$$\left\langle \vec{E}_{\perp} + \left(\vec{v} \times \vec{B}\right)_{\perp} \right\rangle \neq 0$$

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

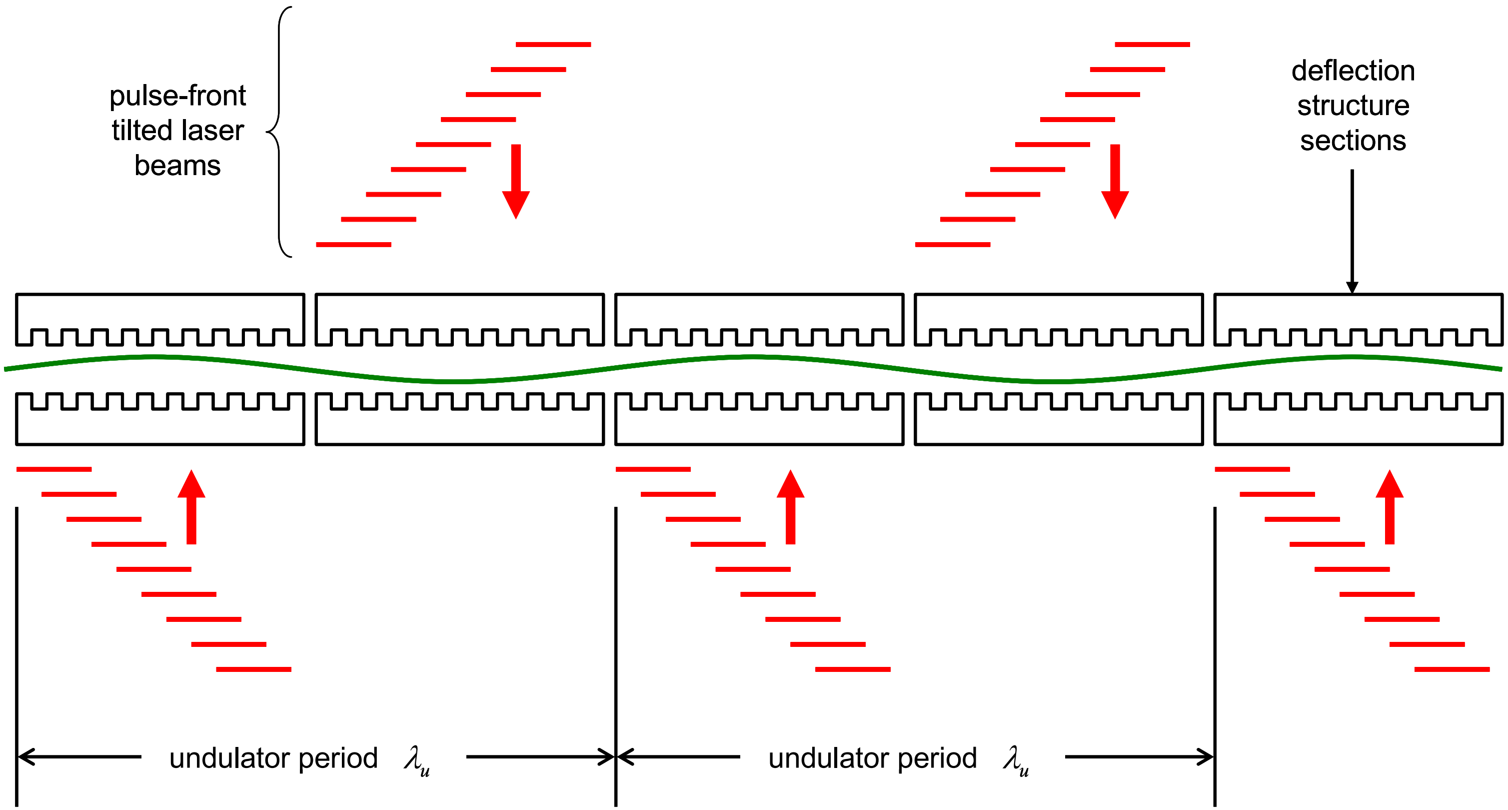
key idea

extended phase-synchronicity between the EM field and the particle

Near-future experiment at E163



A dielectric structure undulator



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

Calculated 120 KEV X-ray FEL Performance

simulation parameters

$U_b = 2\,\text{GeV}$

$\tau_b = 5\,\text{attosec}$

$\varepsilon_N = 10^{-9}\,\text{m-rad}$

$Q_b = 20\,\text{fC}$

$\Delta\gamma/\gamma = 0.1\%$

$\sigma_r = 200\,\text{nm}$

$\beta^* = 4\,\text{cm}$

$\lambda_u = 0.3\,\text{mm}$

$K = 0.13$

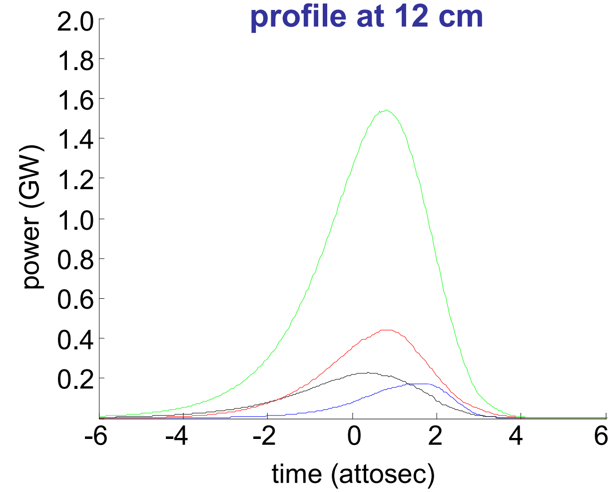
short pulse regime

$L_c \sim 21\lambda_r$

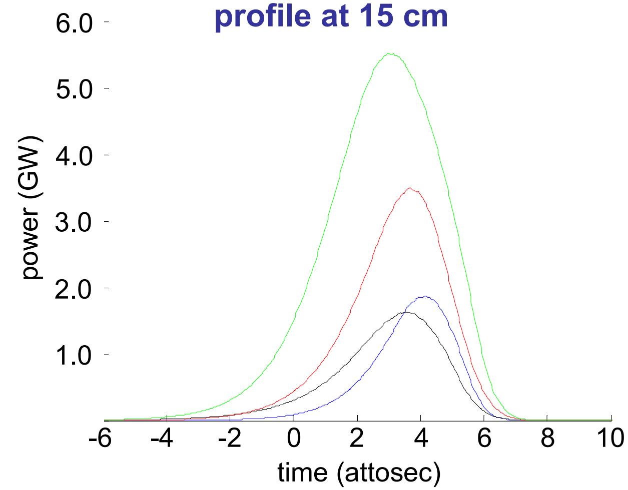
$\sigma_b \sim 136\lambda_r$

$\sigma_b / L_c \sim 6$

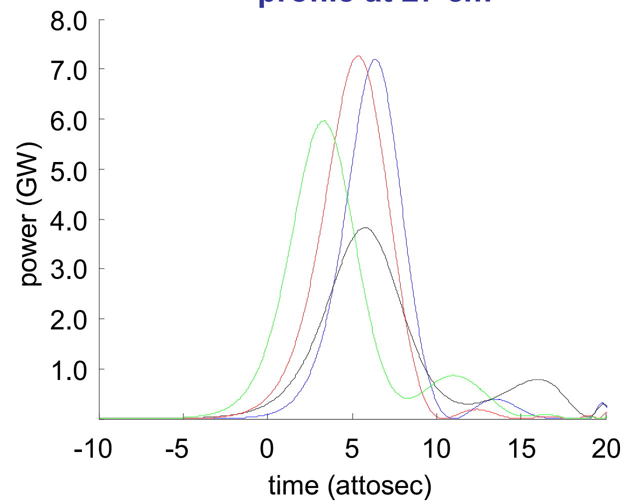
expected temporal profile at 12 cm



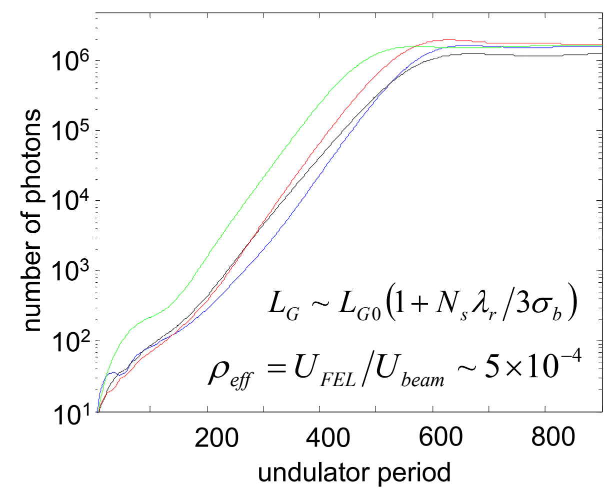
expected temporal profile at 15 cm

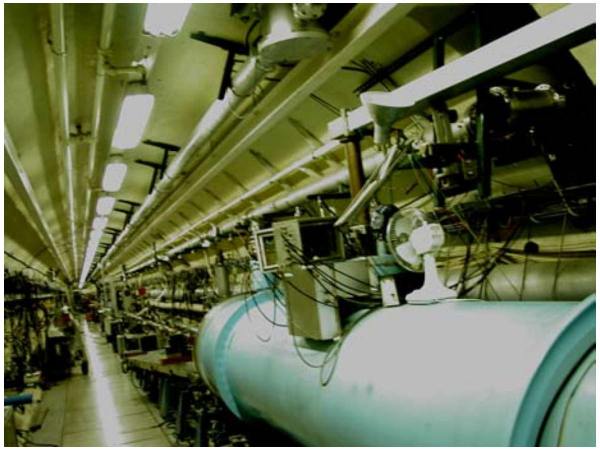


expected temporal profile at 27 cm

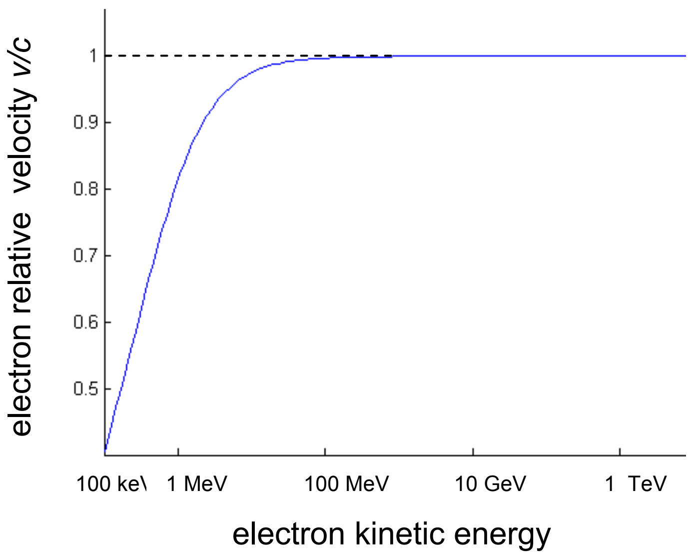


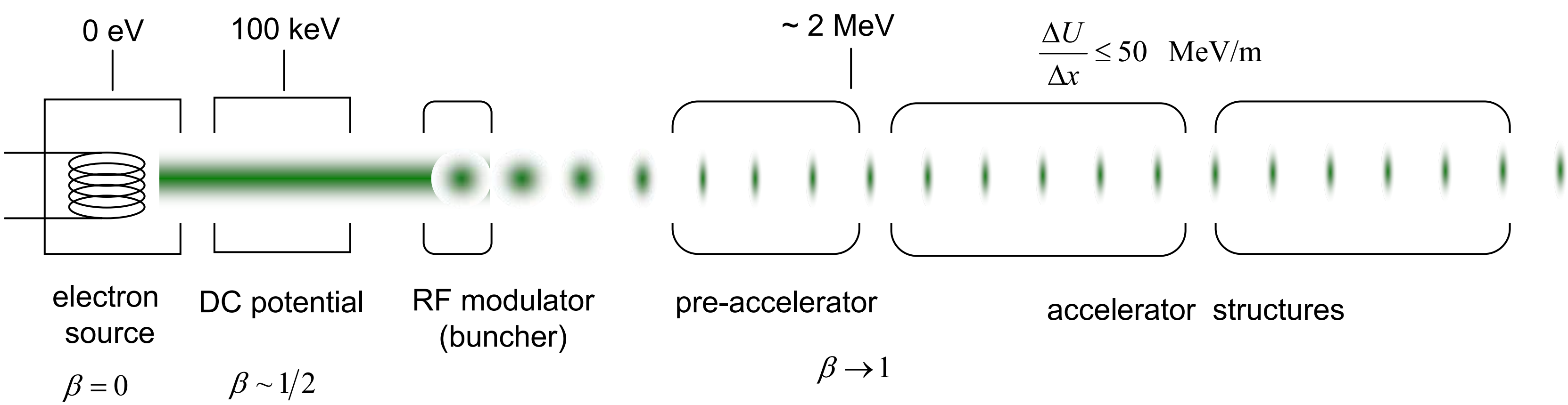
pulse fluence vs. undulator length





Superconducting Accelerator



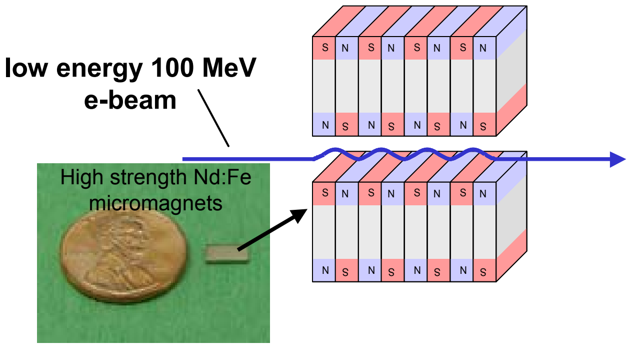


Schematic of a linear accelerator

Dream: Table Top Attosecond X-ray FEL Source

1° of optical phase at 2 μm → 20 attosec

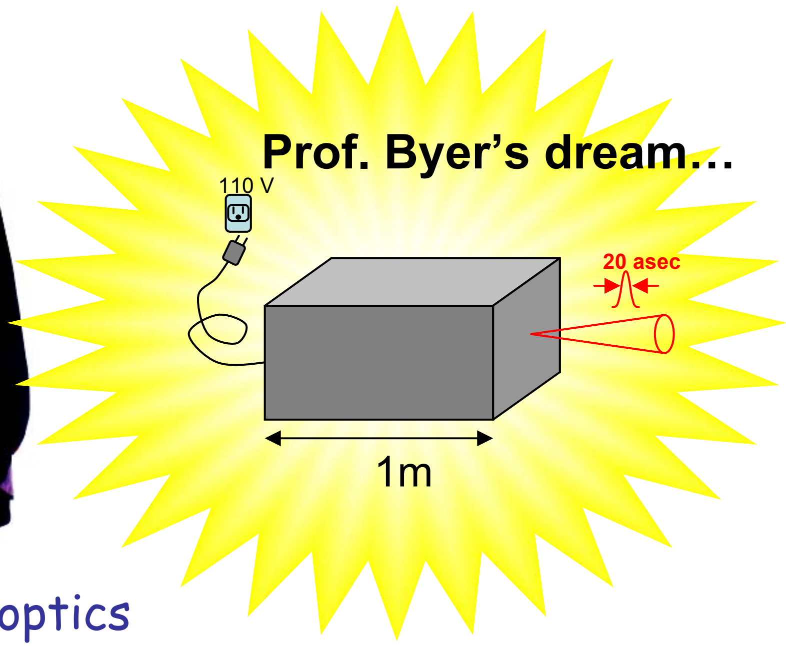
attosec light sources



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**