Future Linear Collider Applications with Dielectric Laser Accelerators

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ABSTRACT

The dielectric laser acceleration (DLA) concept leverages well-established industrial fabrication capabilities and the commercial availability of tabletop lasers to reduce cost, while offering significantly higher accelerating gradients, and therefore a smaller footprint. In contrast to other novel accelerator schemes, desirable luminosities would be obtained by operating with very low charge per bunch but at extremely high repetition rates. This research has significant near and long-term applications, which we will discuss. And as a consequence of its unique operating parameter regime, the predicted energy loss due to beam-beam interaction is small.

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AARD-Laser / E163

Who we are

PIs: **Eric R. Colby** (50%), SLAC & Professor Robert L. Byer, Stanford

W. K. H. Panofsky Fellow
Joel England (90%)

Staff Physicists
James E. Spencer (50%)
Robert J. Noble (90%)

Staff Engineering-Physicist
Dieter Walz (10%)

Graduate Students
Chris McGuinness
Ken Soong
Edgar Peralta
Rachik Laouar (visiting)
Behnam Montazeri

Postdoctoral RA
Ziran Wu (50%)

E163 Collaborators
Tomas Plettner (KLA Tencor)
Jamie Rosenzweig (UCLA)
Sami Tantawi (ATR)

What we do

Develop laser-driven dielectric accelerators into a useful accelerator technology by:

- Developing and testing candidate dielectric laser accelerator structures
- Developing facilities and diagnostic techniques necessary to address the unique technical challenges of dattosecond laser acceleration

Motivation

- Lasers can produce far higher energy densities than can microwave sources, hence larger electric fields
- Dielectric materials can hold off field stresses of >1 GV/m for picosecond-class pulses
- Lasers are a large-market technology with rapid R&D by industry (DPSS lasers: ↑0.22 B$/yr vs. ↓0.060B$/yr for microwave power tubes)
- Short wavelength acceleration naturally leads to sub-femtosecond bunches
- Technology to handle laser materials lithographically is rapidly evolving ➔ an all solid-state **accelerator on a chip**

Work supported by Department of Energy contracts DE-AC02-76SF00515 (SLAC) and DE-FG03-97ER41043-III (LEAP).

Novel Concepts: Progress of the last 30 years

- Inverse Smith-Purcell Acceleration

~0.05 MV/m, Bae *et al*, Tohuku U., 1987.

- Inverse Cerenkov Acceleration

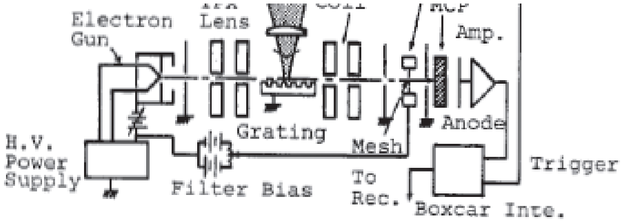
31 MV/m, Kimura *et al*, BNL-ATF, 1995

- Inverse Free Electron Laser

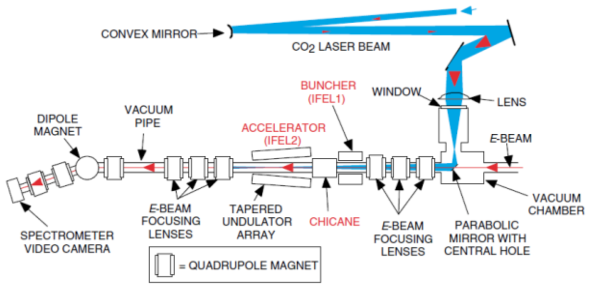
~14 MV/m, Kimura *et al*, BNL-ATF, 2004.

- Inverse Transition Radiation

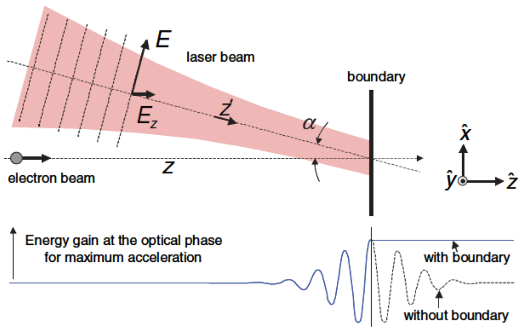
~40 MV/m, Plettner *et al*, Stanford, 2005.



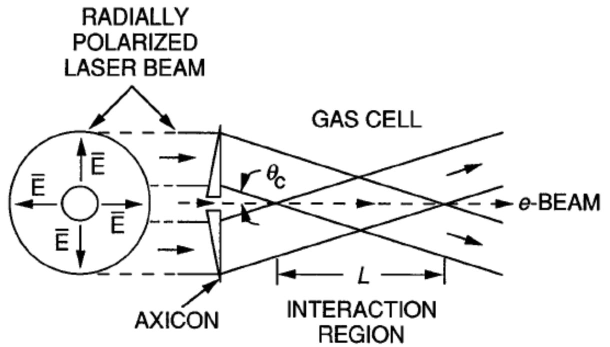
ISP, IEEE IEDM, p307ff, (1987).



IFEL, PRL **92**(5), 054801-1, (2004)



ITR, PRL **95**, 134801,(2005)



ICA, PRL **74**(4), p.546ff (1995)

Compared to RF Accelerators

- Sources are typically freespace TEM, must match to guided TM
  - Power coupling requires special attention
- Accelerating fields are present for picoseconds, rather than microseconds
  - : Waveguiding structures typically designed for high v_g~0.6 to limit envelope slippage
  - : Phase mask and swept-laser methods
- Metals have higher loss and lower damage threshold at optical frequencies than dielectrics

Compared to Laser-Driven Plasma-Wakefield Accelerators

- No-threshold linear process; typically a_0~10^{-4} in solid-state structures
- Very strong coupling impedances
- E_{laser}~nJ to **μJ** ➔ P_{laser}~**kW** to MW ➔ higher rep rate ~**10** – 1000 MHz

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  - E163 Experiments at SLAC
    - Laser accelerator structures
    - Inverse FEL for electron pulse compression

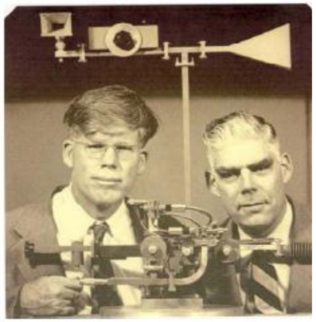
Laser Accelerator Experiments
- Structures and expected performance (damage testing)
- Recent experiments
- Fabrication of woodpile and bi-grating structures

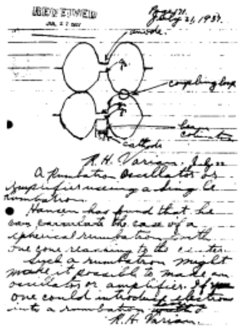
Coherent X-ray laser Generation
- Components of the proposed FEL X-ray laser
  - Dielectric Accelerator and Undulator Structures
  - FEL gain and efficiency

Future Challenges
- Darpa program: develop an accelerator on a chip
- Enable TeV scale physics affordable cost

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

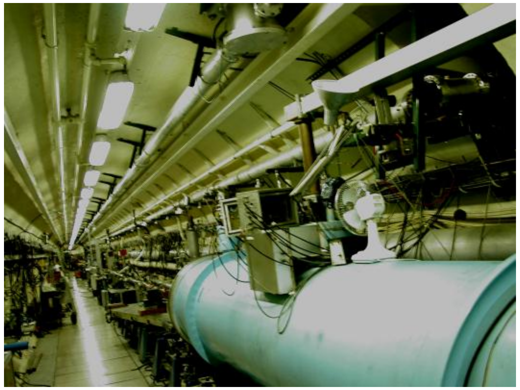
1st Klystron (Varian, 1930s')





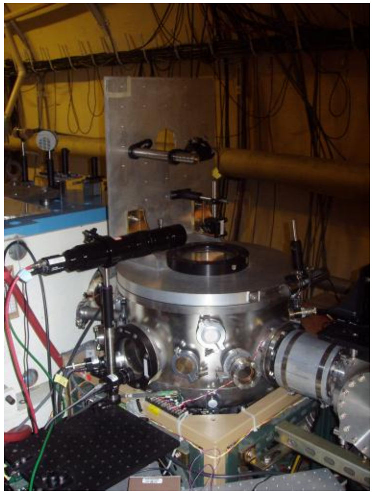
1st Linac 1946

The superconducting linac
In HEPL, 1960



The 2-mile collider (SLAC)

LEAP, 1997-2004

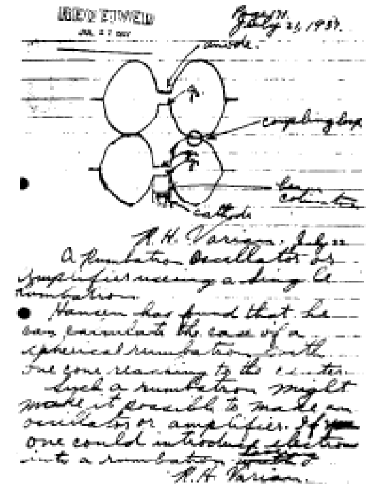


Demonstration of the FEL, 1977

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.



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

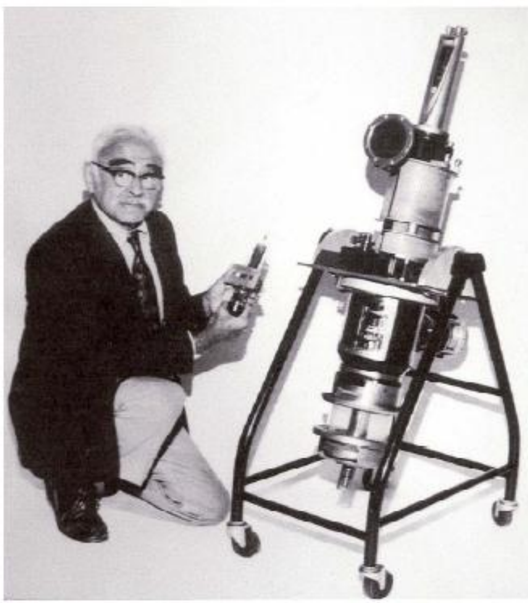
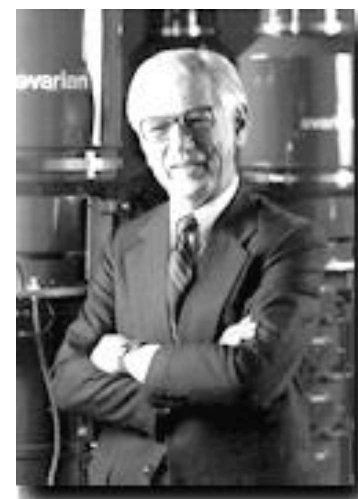


Fig. 10 Marvin Chodorow comparing the CV-150 to the Mark III klystron

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

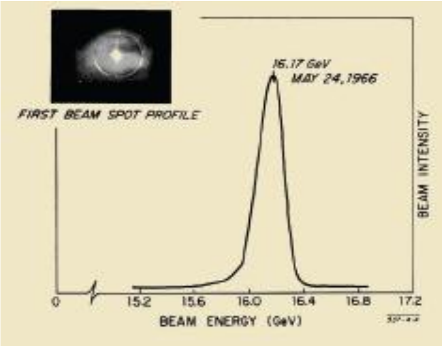
- $100M proposal
- numerous studies and reports
- > 10 years of effort


Palo Alto Times

AN INDEPENDENT NEWSPAPER

Ike to ask $100 million for Stanford A-smasher

Building time set 6 years



First beam at SLAC, 1966

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

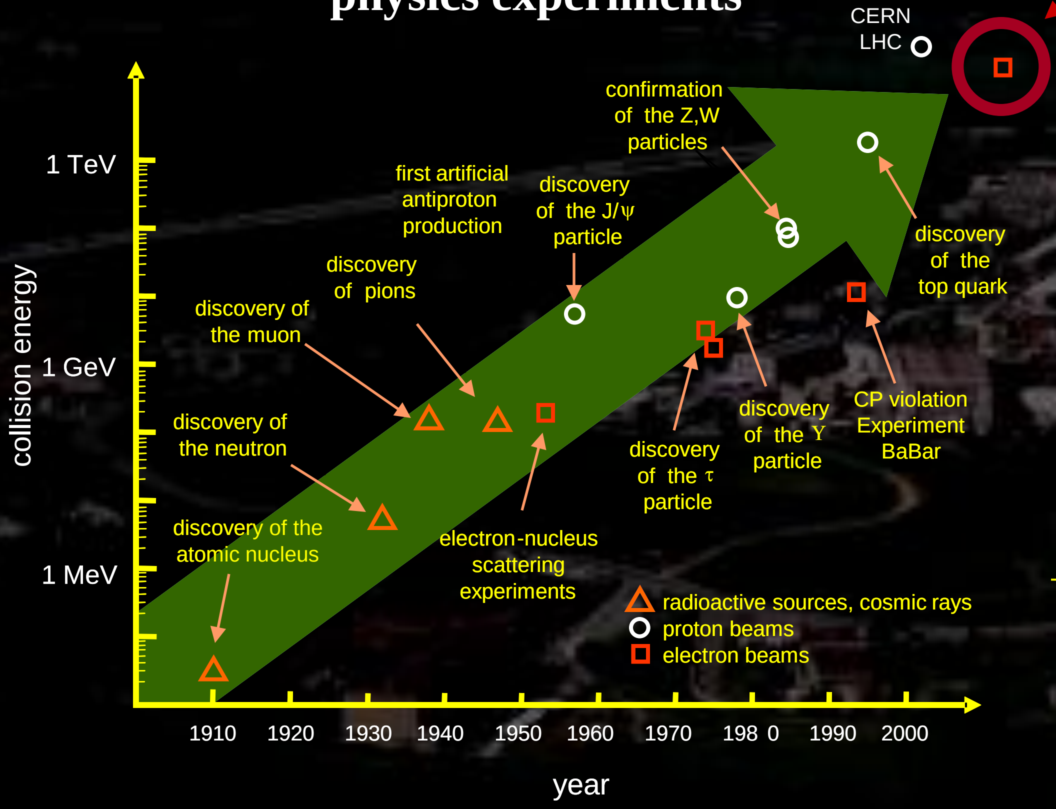
2009: LINAC coherent X-ray source

Other developments

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

What is next?

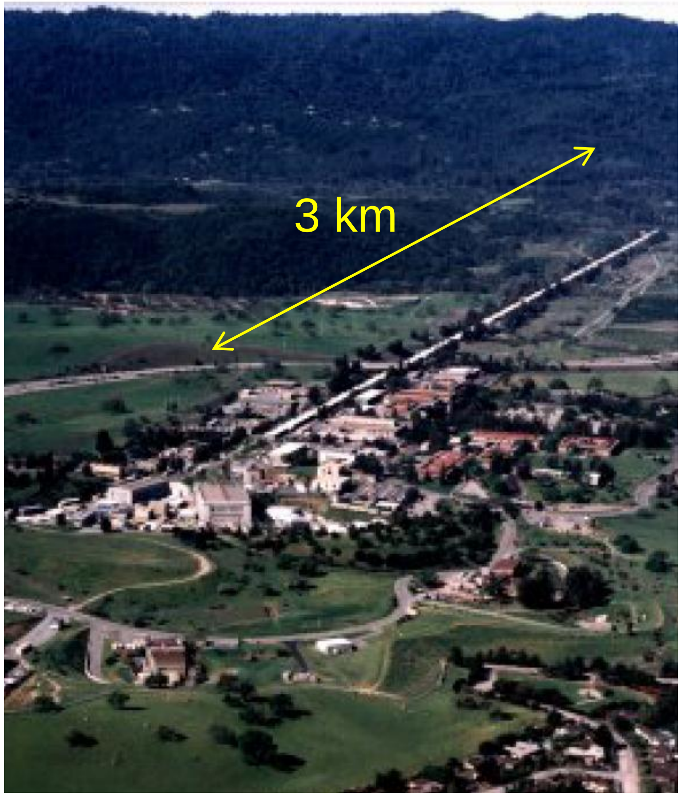
historical trend of high energy physics experiments

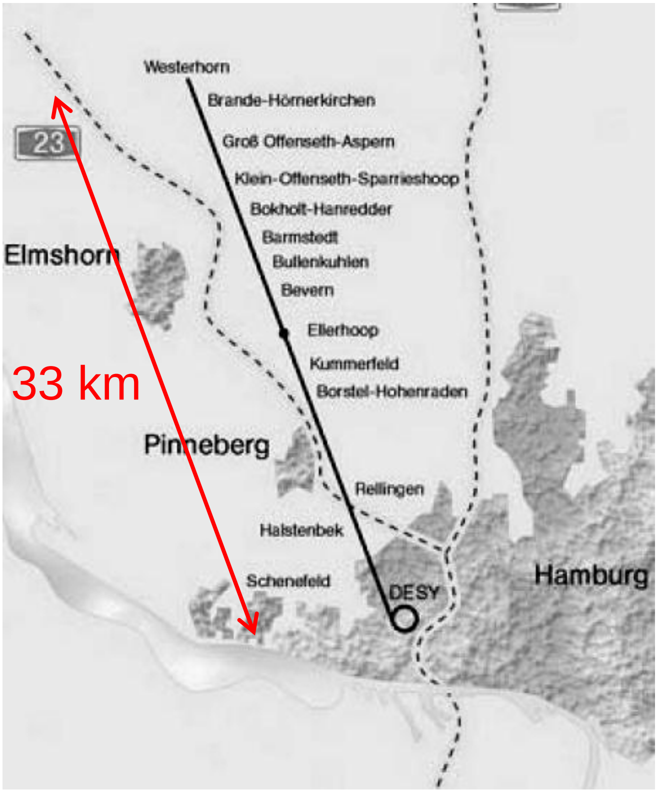


Future TeV e^+e^- collision experiments

- 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



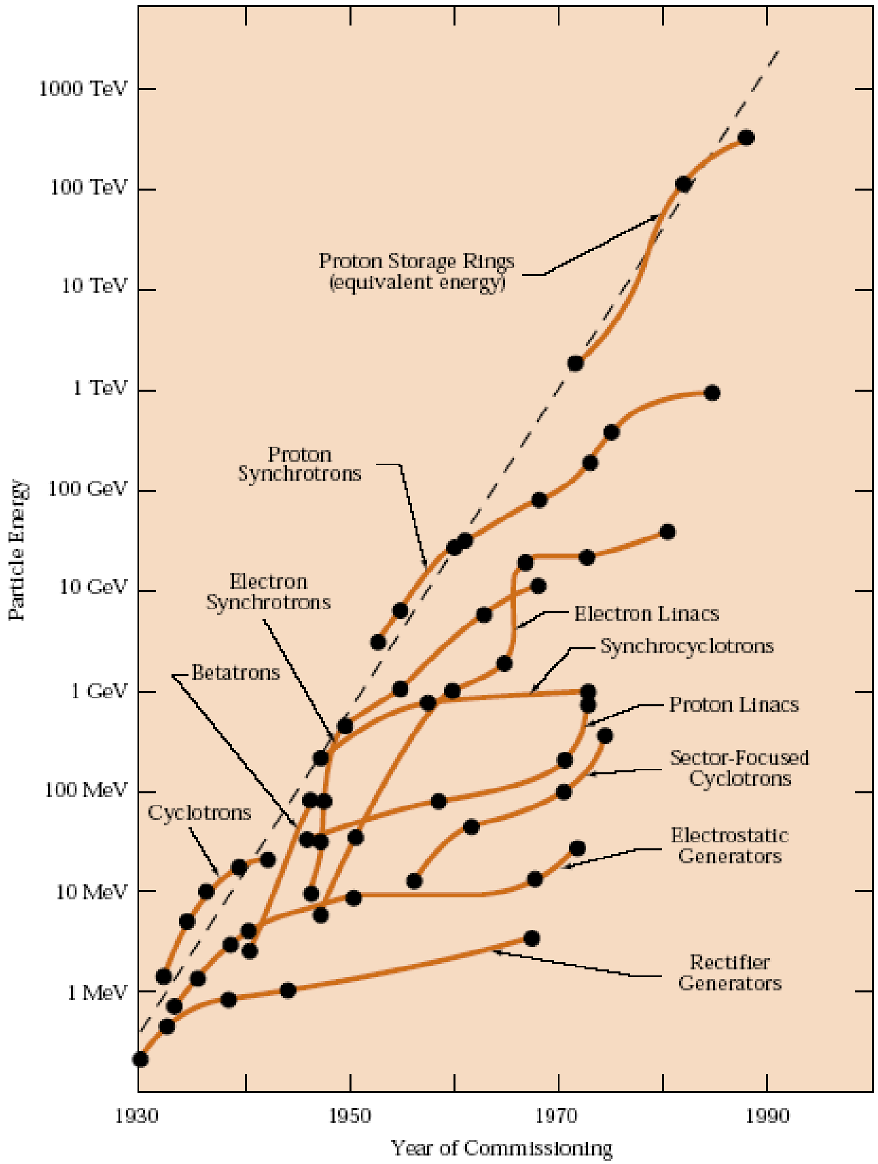


Existing SLAC – 50 GeV **Proposed ILC Accelerator 1 TeV**

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.

The Livingston plot – 1954
Innovation leads to exponential progress



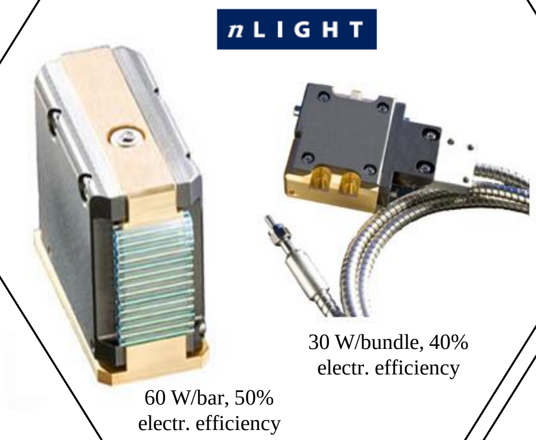
In 1954 Livingston noted that progress in high energy accelerators was <u>exponential with time.</u>

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.

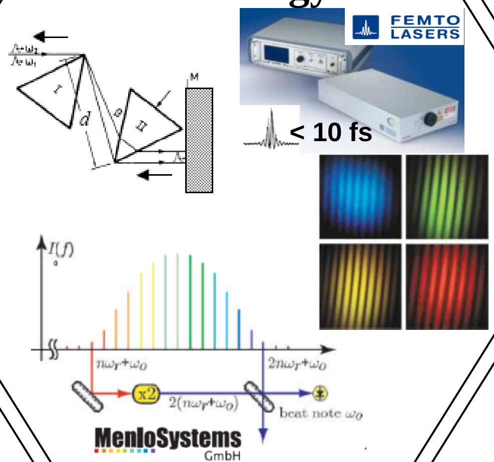
Emergence of new technologies make Laser Acceleration Possible

efficient pump diode lasers

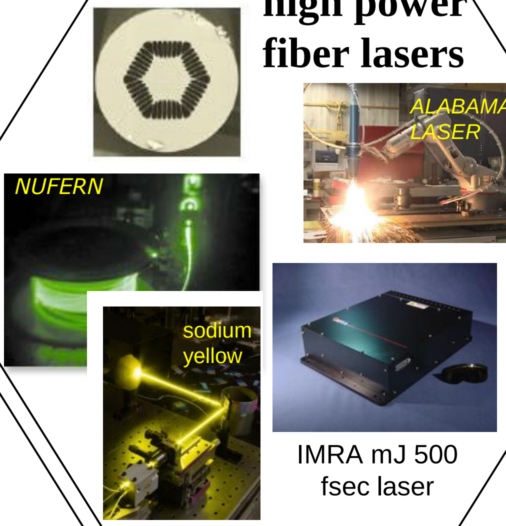


Leveraging investment in telecom

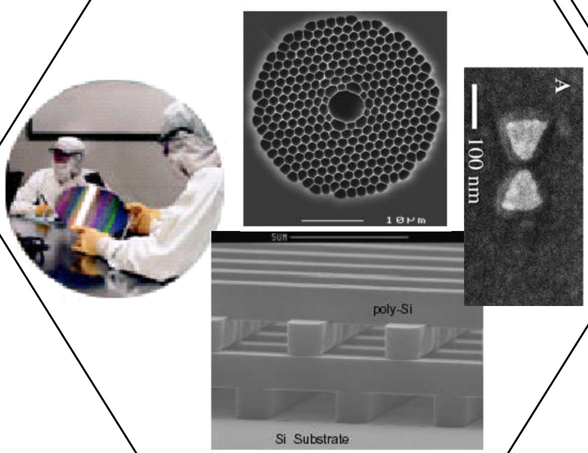
ultrafast laser technology



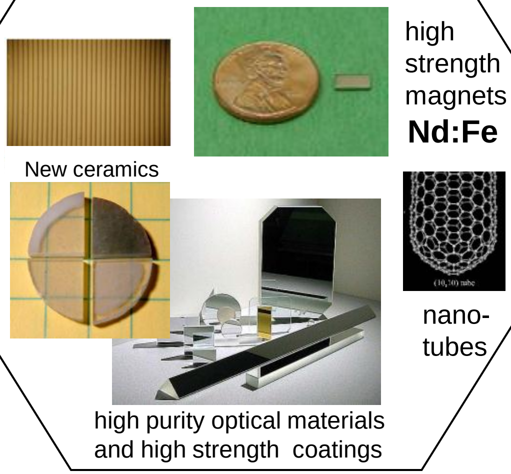
high power fiber lasers



nanotechnology



new materials



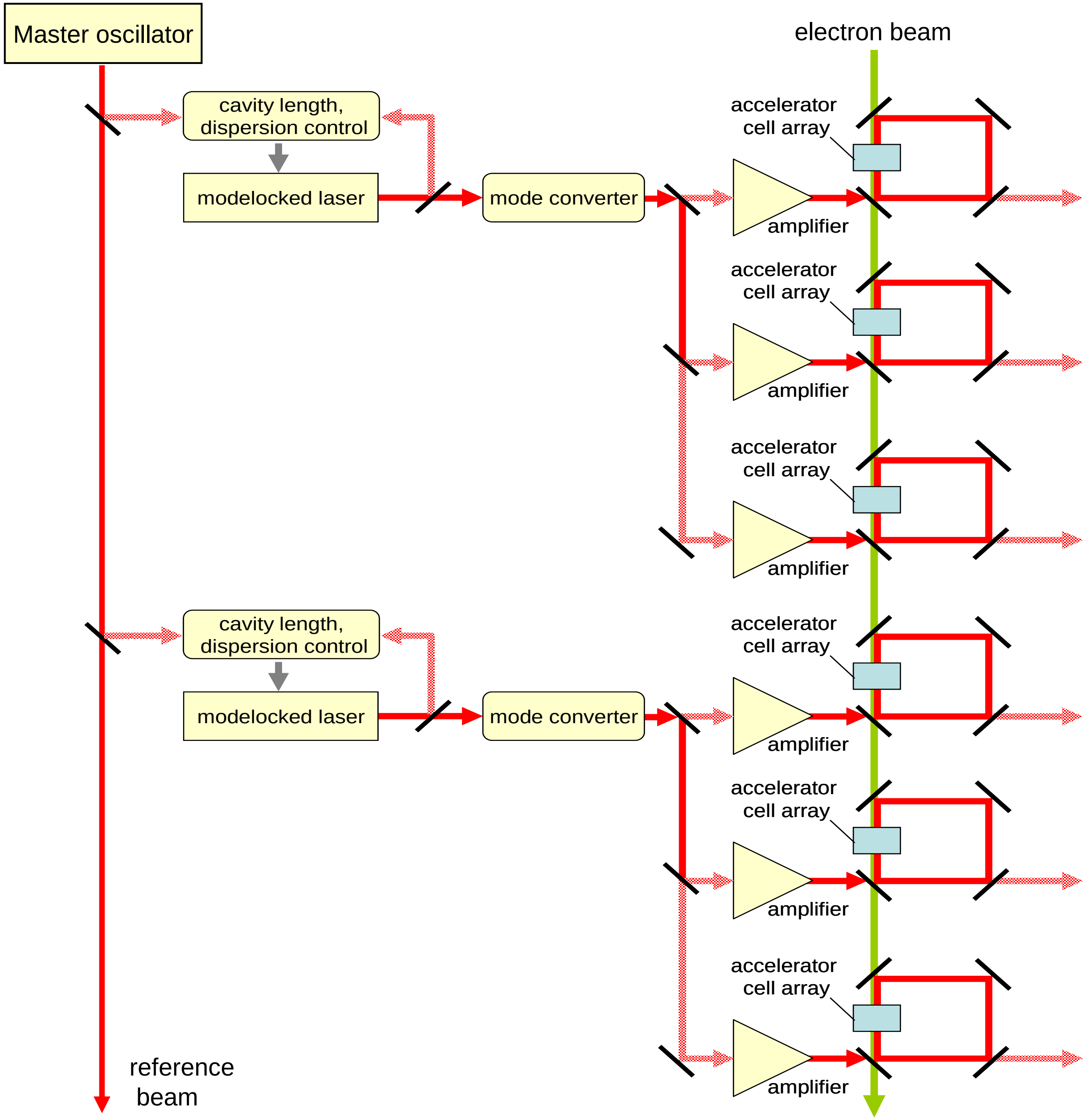
Proposed layout of the laser system for a TeV collider

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

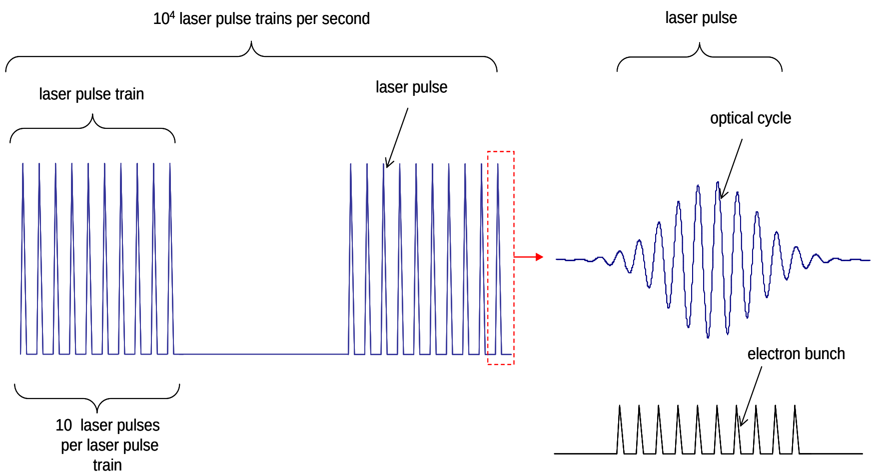


Laser beam parameters for TeV scale accelerator

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 ~30% efficiency Laser Source!

(~ 10 microjoules in 100fsec per micropulse)

Dramatic increase of

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

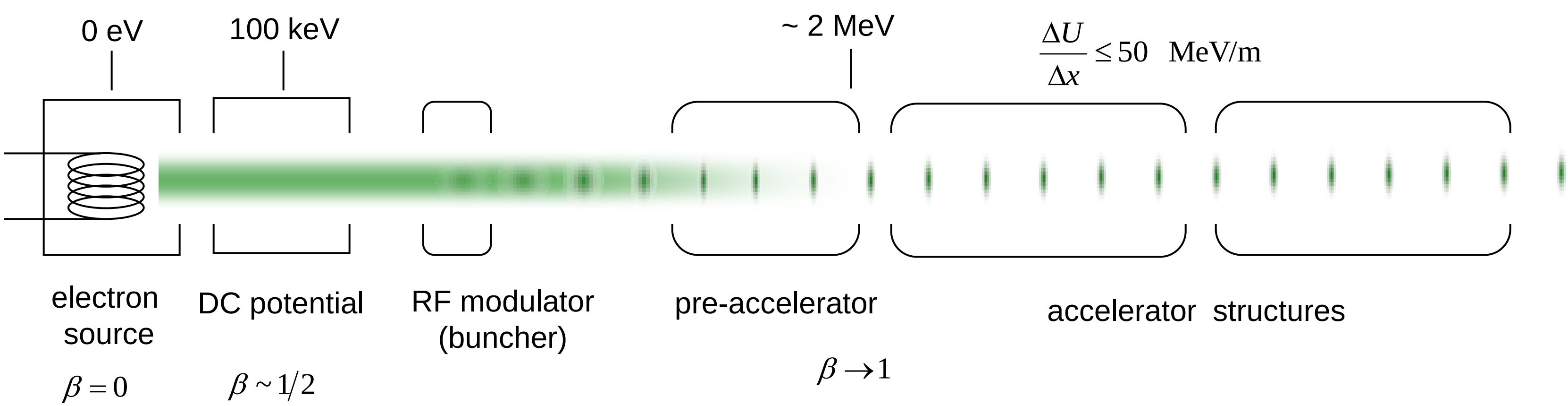
"An accelerator is just a transformer" – Pief Panofsky

"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



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

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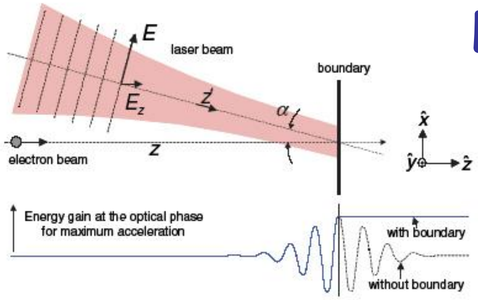
FEL gain and efficiency

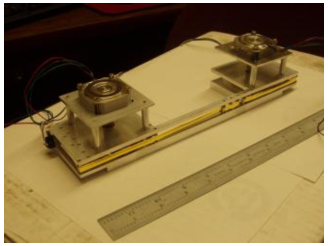
Future Challenges

Darpa program: develop an accelerator on a chip

Enable TeV scale physics affordable cost

Laser driven particle acceleration

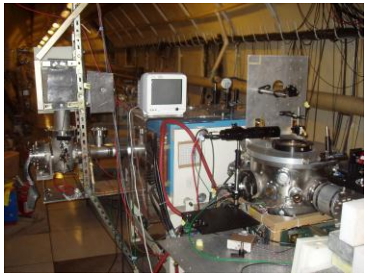




collaborators

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†

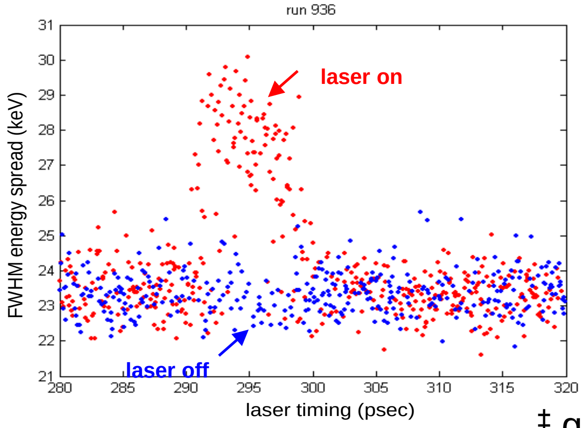


Stanford University

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

ARDA, SLAC

Zhiu Zhang†, Sami Tantawi†

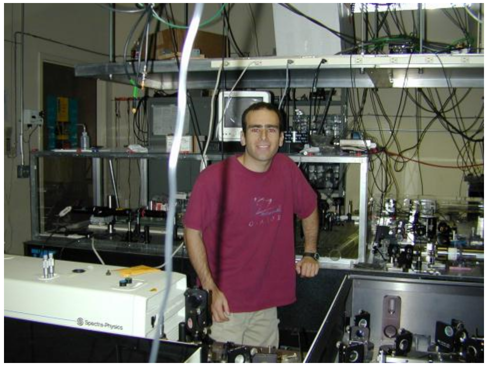


Techion Israeli Institute of Technology

Levi Schächter*

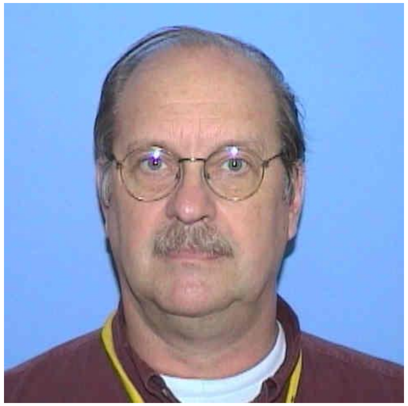
UCLA

J. Rosenzweig*



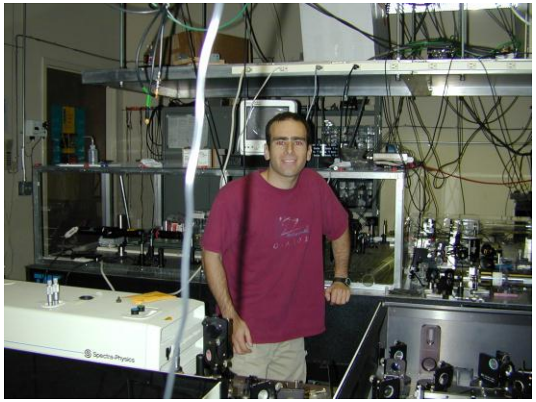
‡ grad students † postdocs and staff * faculty

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

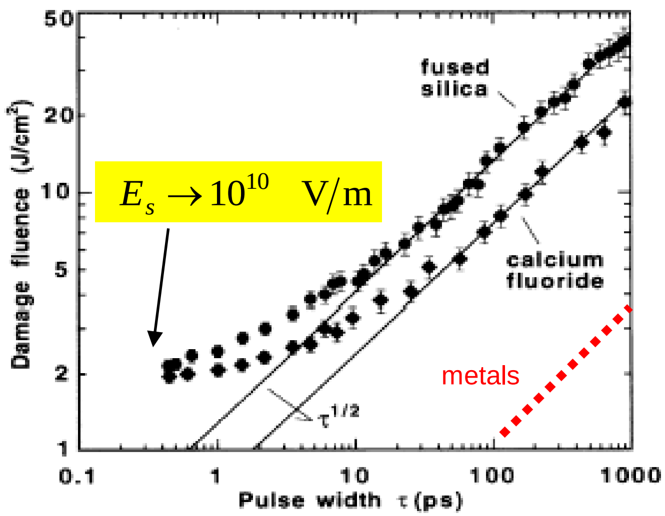
- gradient = longitudinal electric field
- linear e-beam trajectory
  - → no synchrotron radiation
  - → **energy scalable**

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

→ linear particle acceleration process

2 Dielectric based structure with vacuum channel

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

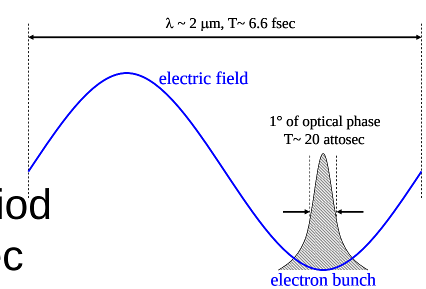


→ very high peak electric fields

→ vacuum channel

→ NIR solid-state lasers

3 Inherent attosec electron pulse



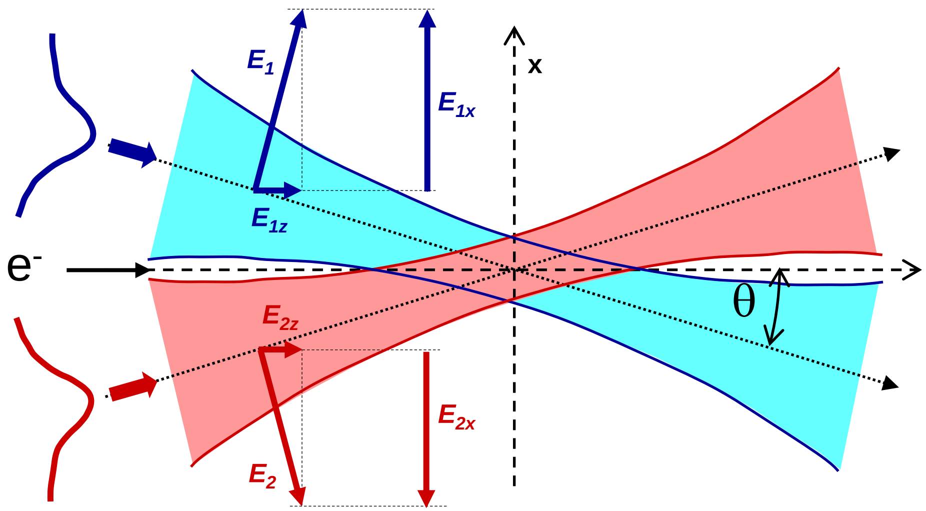
Tm;Glass Fiber 2 μm laser → 6 fsec period
→ 1deg of phase = 20 attosec

→ Unique opportunity for light sources

Early Proposed Crossed-Beam Laser Accelerator

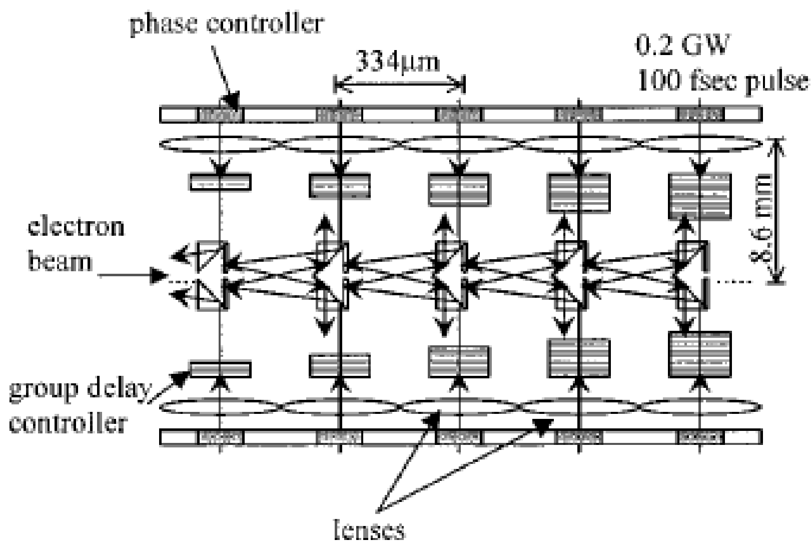
Low Impedance structures – feels like ancient history now

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.

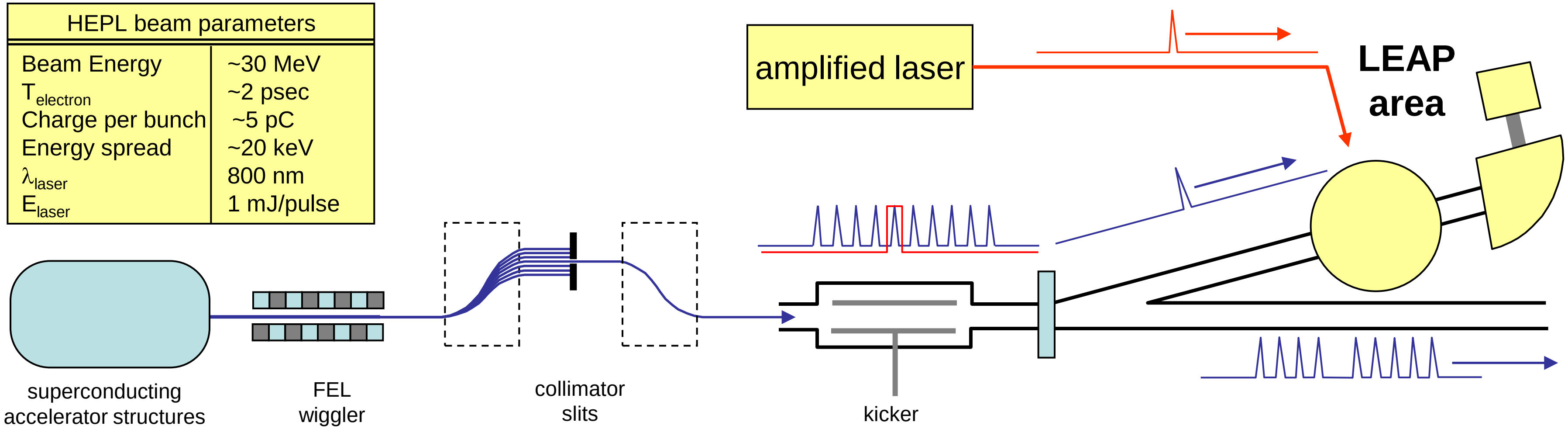


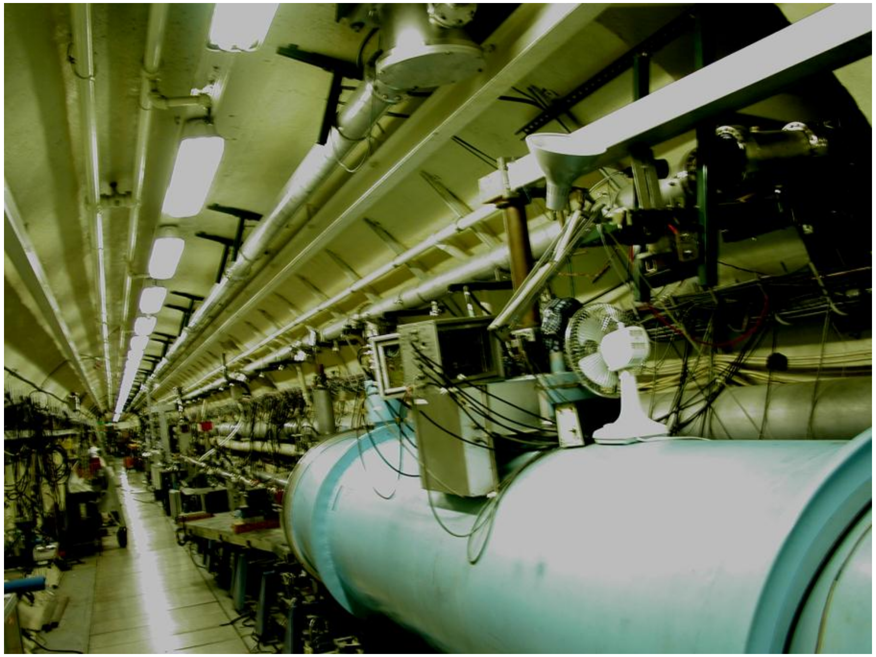
(b)

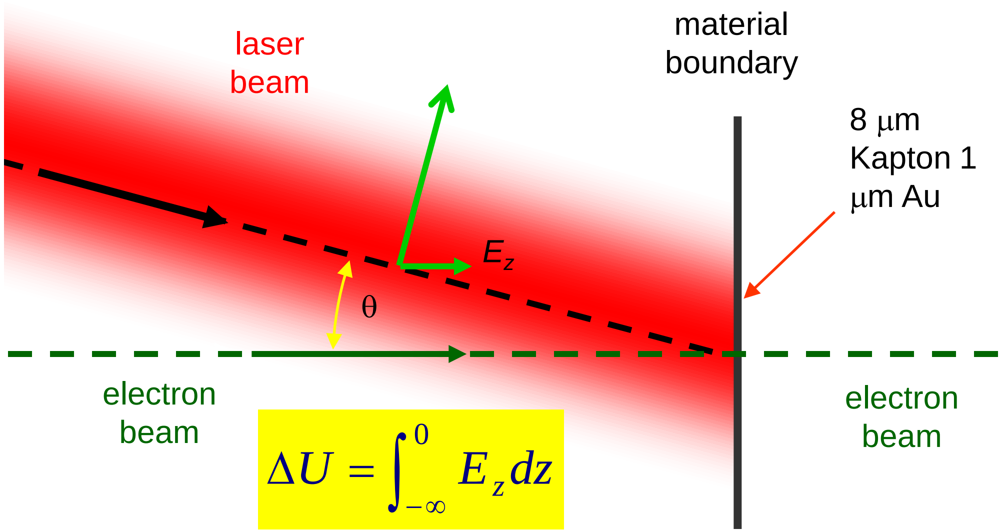
An early concept for resetting the phase every 334 microns to keep the electrons and the applied laser field phased.

The 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

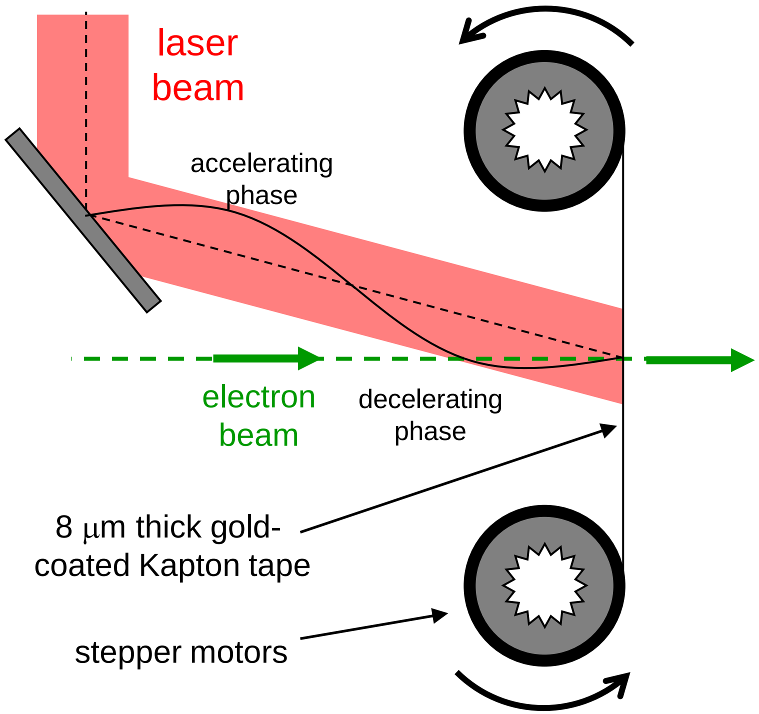


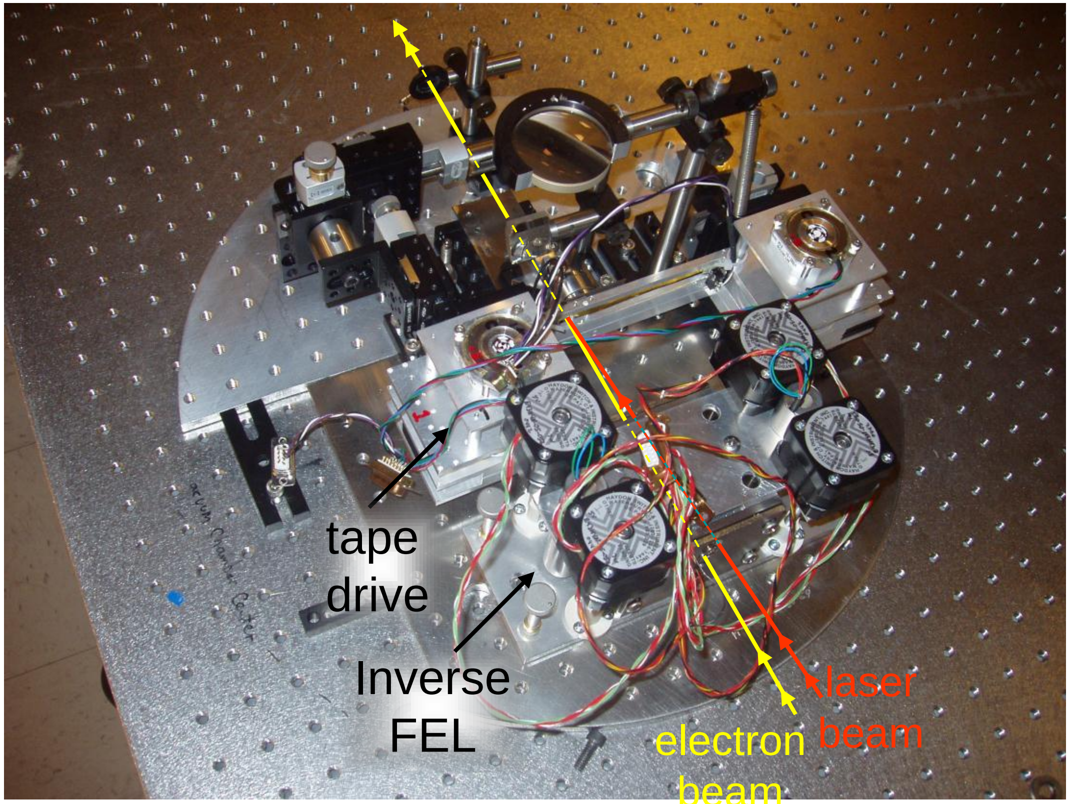




$$\Delta U = \int_{-\infty}^{0} E_z dz$$

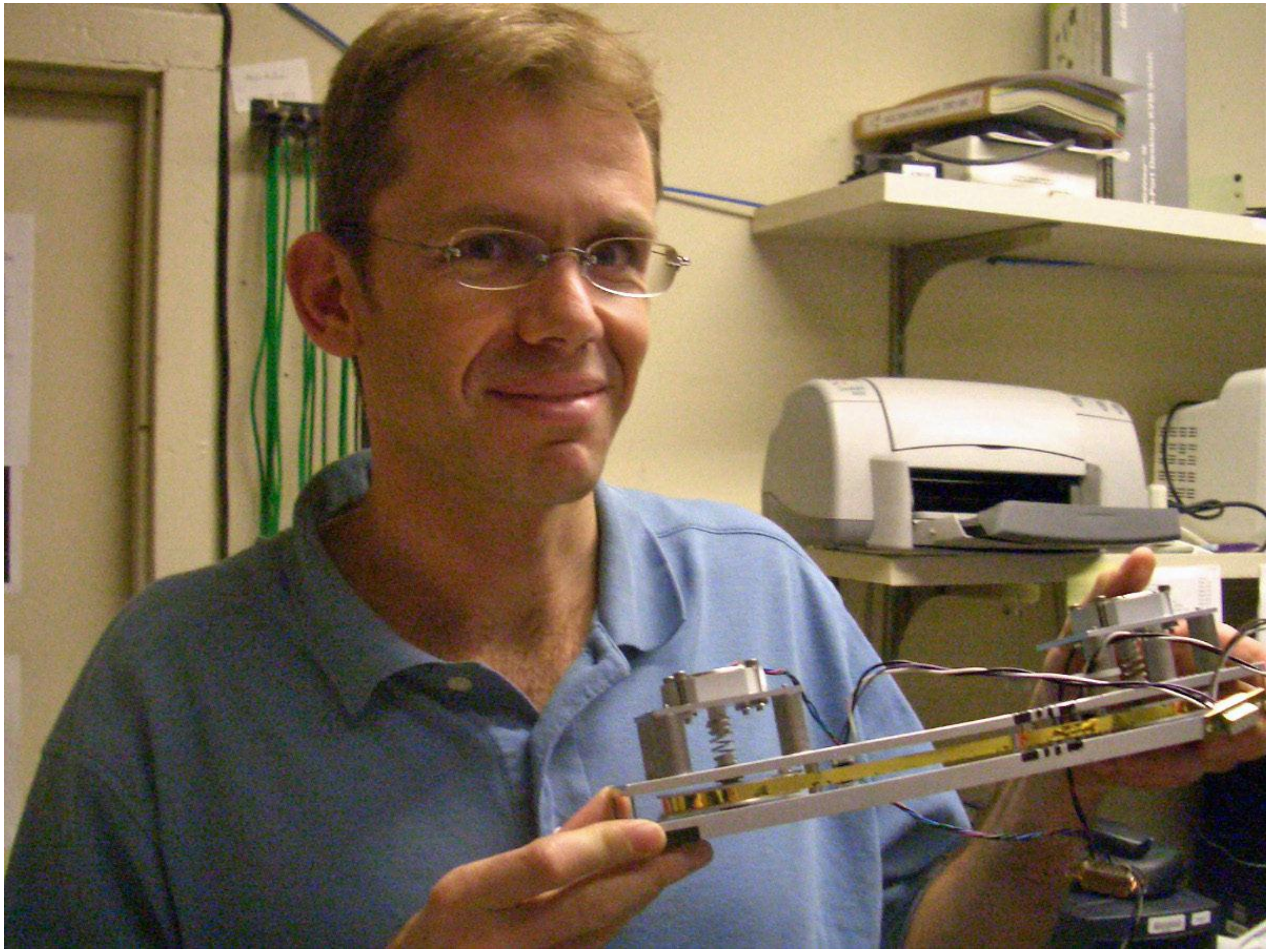
We have accelerated electrons with visible light!





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.



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

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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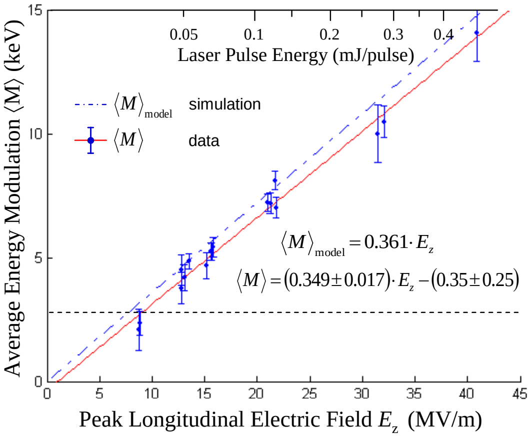
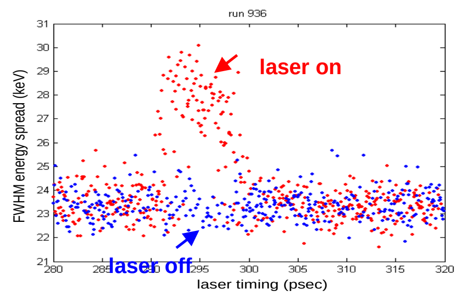
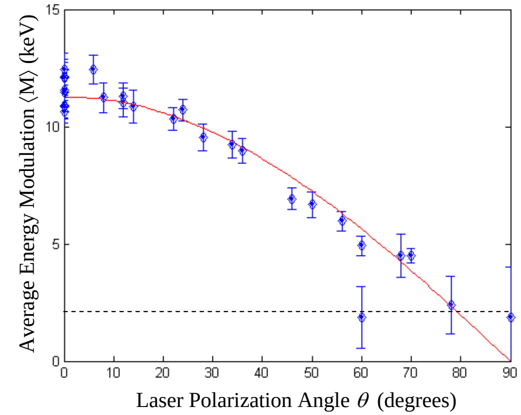
Colby, B. Cowan, C. M. S. Sears, J. E. Spencer, and R. H. Siemann
SLAC, Menlo Park, California 94025, USA

(Received 19 April 2005; published 22 September 2005)







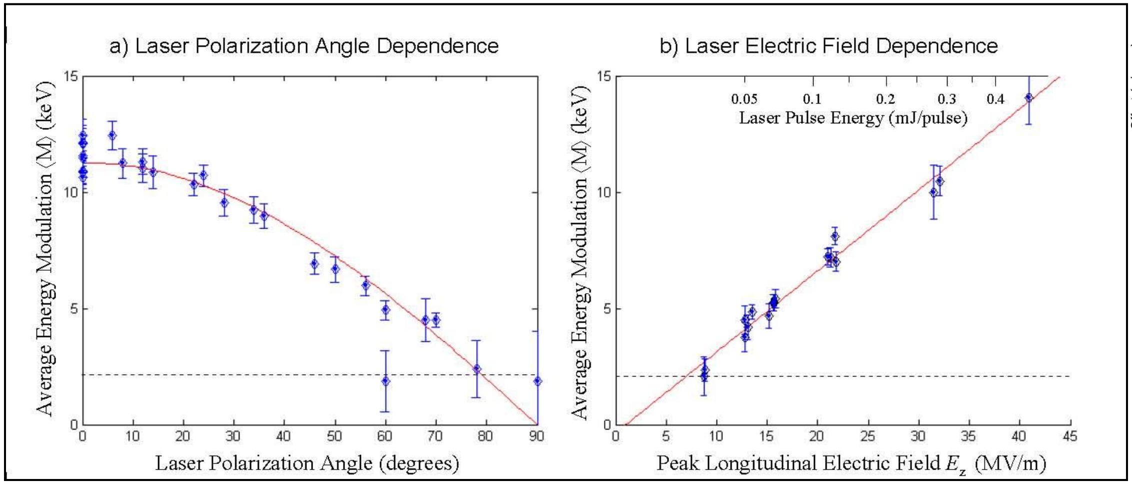
- **confirmation of the Lawson-Woodward Theorem** $\int_{-\infty}^{+\infty} E_z dz = 0$
- **observation of the linear dependence of energy gain with laser electric field** $\Delta U \propto |E_{laser}|$
- **observation of the expected polarization dependence** $|E_z| \propto |E_{laser}| \cos \rho$

laser-driven linear acceleration in vacuum

Early Optical Acceleration Experiments

We have showed that "direct" (no plasma) acceleration of electrons with light can be done with useful gradients and very simple geometries

T. Plettner, *et al*, *Phys. Rev*. Lett., **95**, 134801 (2005).



Inverse Transition Radiation Acceleration

A single metal boundary illuminated by linearly polarized light at the transition radiation angle

Demonstrated:

•Acceleration of appreciable charge (q~10^7 e^-) by visible light

•A peak longitudinal field of E_z>40 MV/m

•"Large" interaction distance: ~1 mm or ~1200λ

C. M. Sears, *et al*, *Phys. Rev. Lett*., **95**, 194801 (2005).

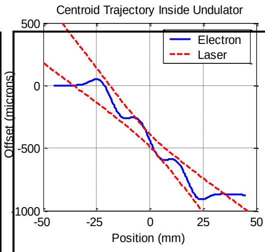
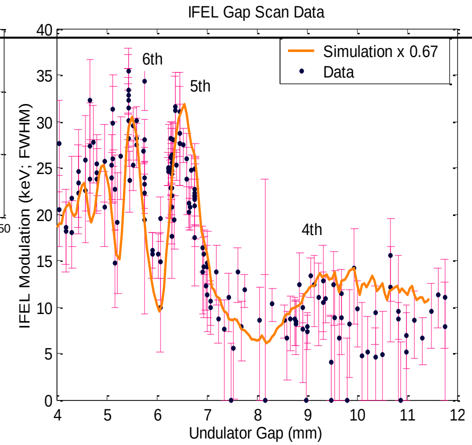


Figure 1: a) Above, laser & electron trajectories inside undulator for a gap of 5.4 mm. b) Left, gap scan data with simulation. The data shows clear peaks matching the simulation. Scan is composed of 164 separate runs with a fixed gap position for each run.



Harmonic Inverse FEL Acceleration

A 3-period variable-gap undulator

Demonstrated:

•Acceleration of appreciable charge (q~10^7 e^-) by visible light

•Interaction between electrons and higher-order undulator resonances (4^{th},5^{th}, 6^{th})

This IFEL will be used to energy-modulate the beam as part of an optical prebuncher for staging experiments.

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Introduction
- Laser Electron Accelerator Project – LEAP
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  - **E163 Experiments at SLAC**
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    - Inverse FEL for electron pulse compression

Laser Accelerator Experiments
- Structures and expected performance (damage testing)
- Recent experiments
- Fabrication of woodpile and bi-grating structures

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

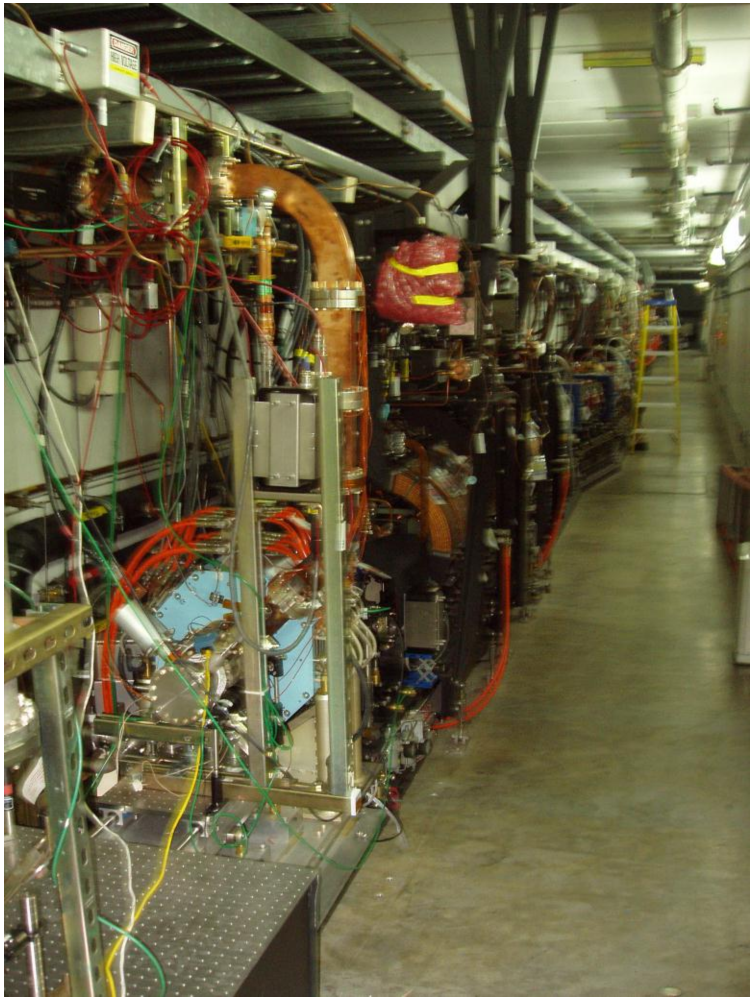
Future Challenges
- Darpa program: Development of an accelerator on a chip
- Enable TeV scale physics affordable cost

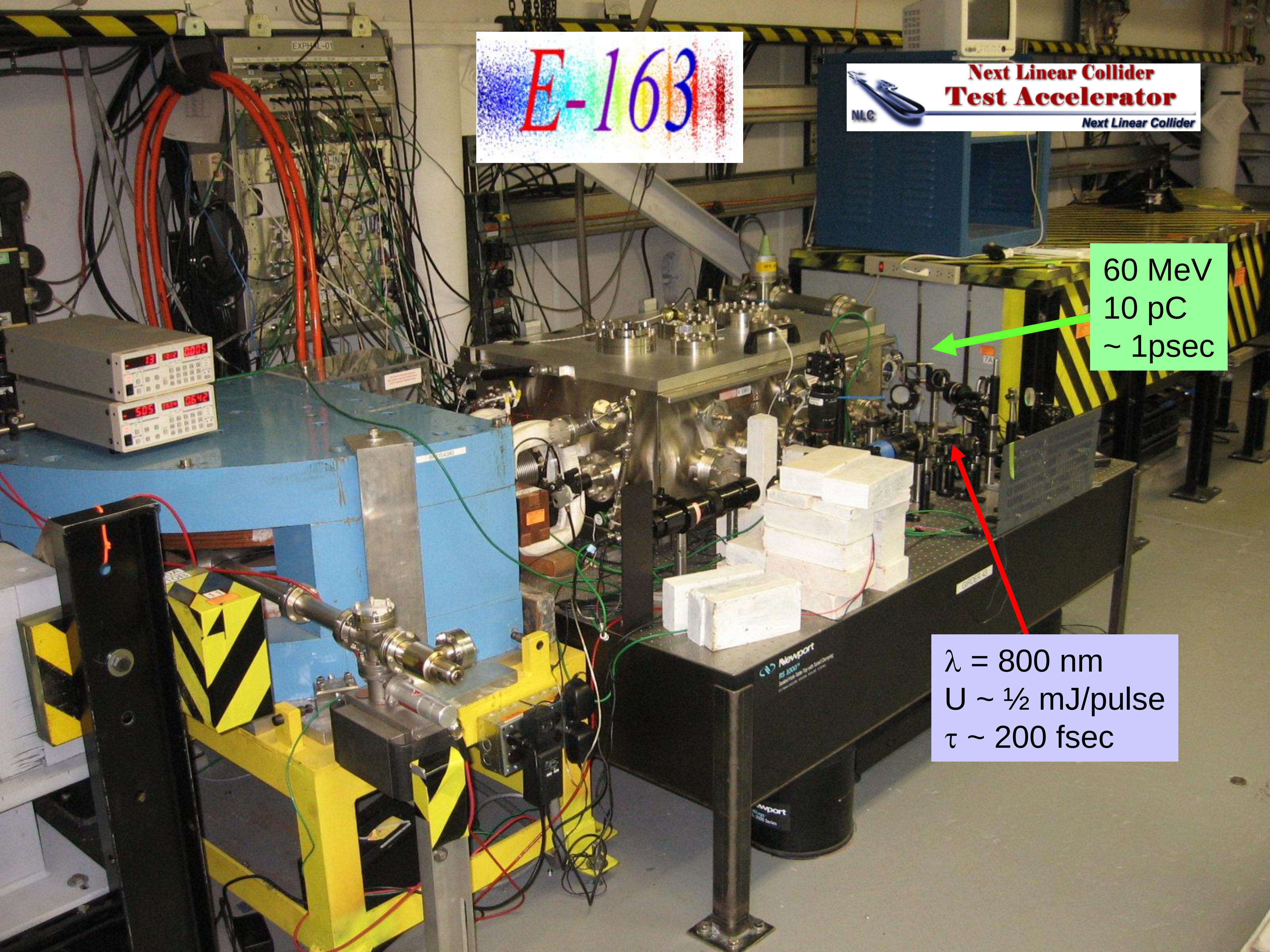
Move Experiment to SLAC: 1984 - 86

SLAC provided access to the NLCTA test accelerator – 360MeV

The new E163 experiment hall

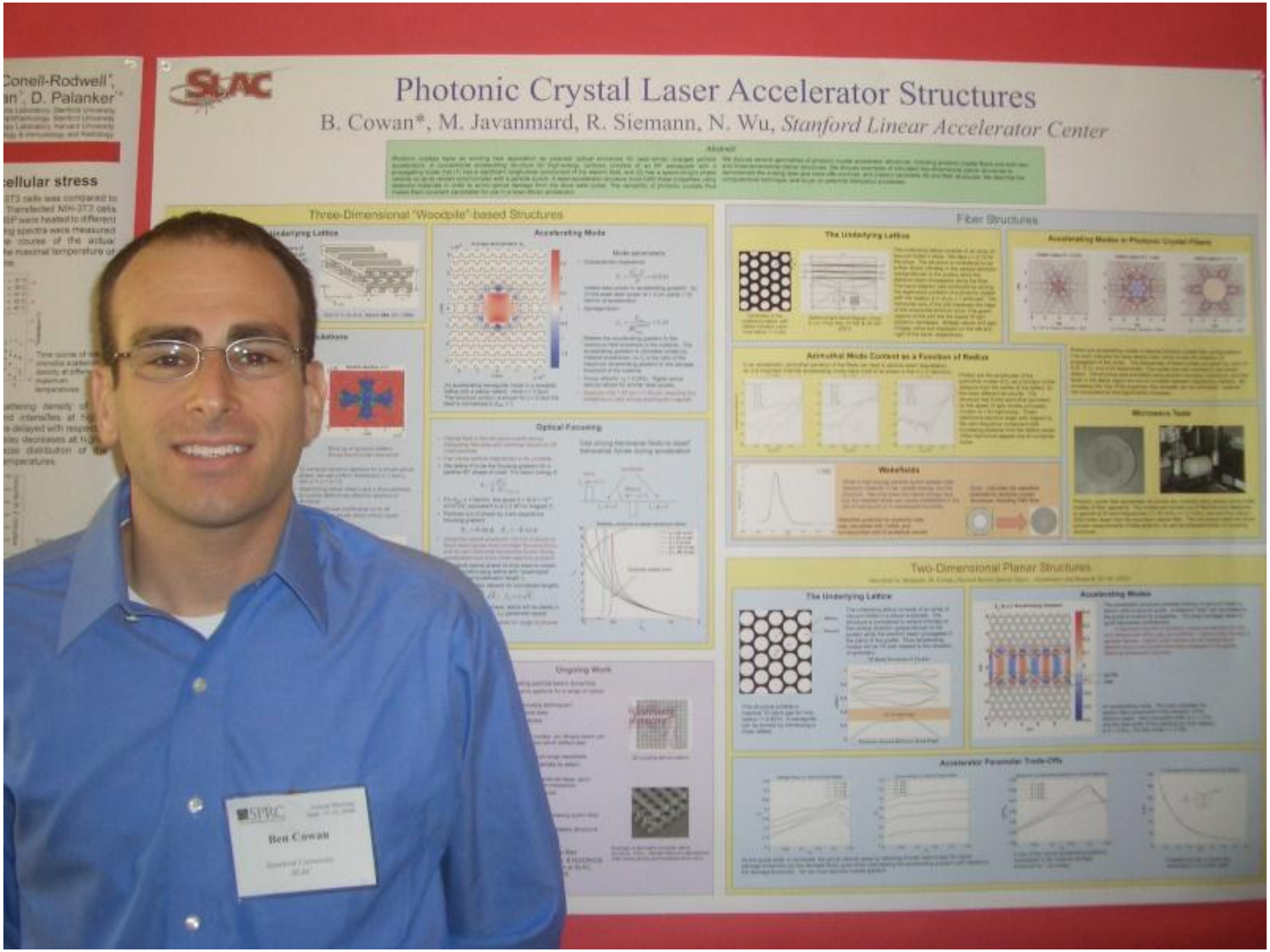
The **NLCTA**
Next Linear Collider Test Accelerator 360MeV




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

Ben Cowan – detailed calculations of Photonic Crystal Accelerator Structures

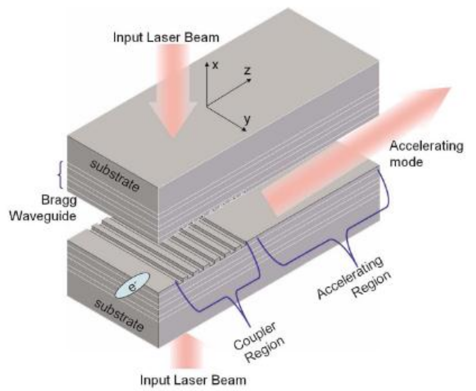
Byer Group



Goal: Invent and Test Dielectric Accelerator Microstructures

Key: move to photonic bandgap structures

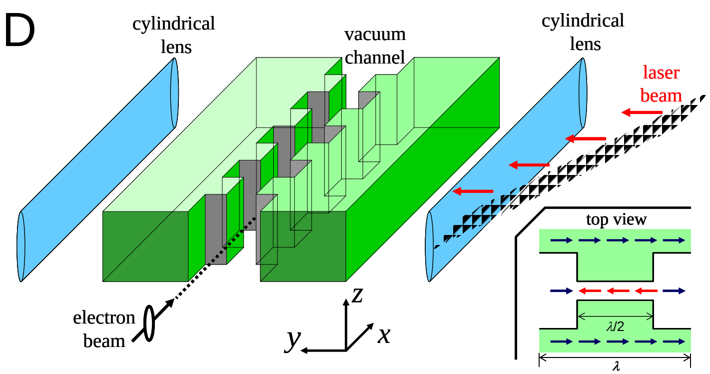
Planar waveguide structures



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

Periodic phase reset structures

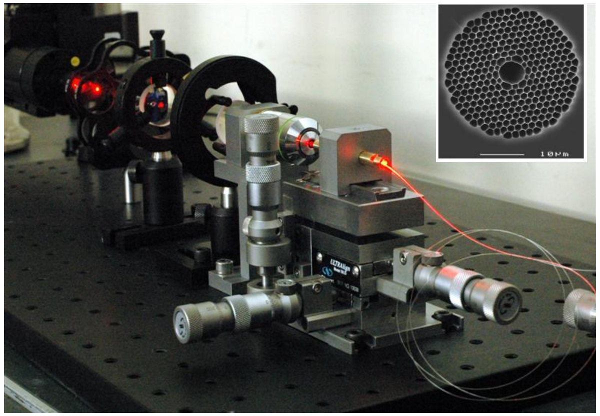
1D



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

Hollow core PBG fibers

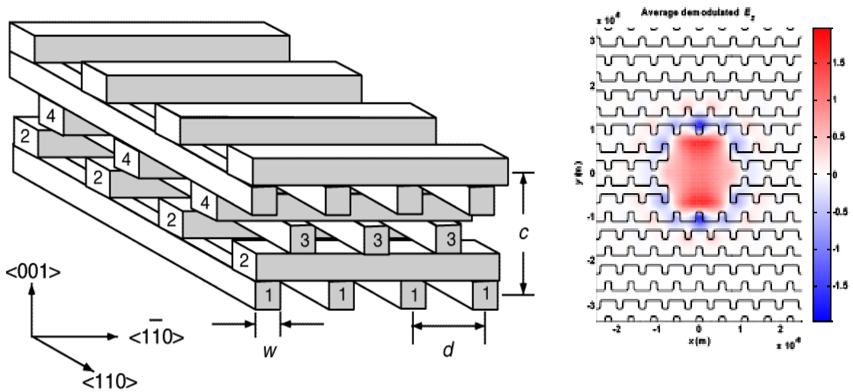
2D



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

3-D photonic bandgap structures

3D



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

Goal: Develop Theory for laser accelerator physics

Coupling efficiency higher than expected: charge ~fC – need rep rate!

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

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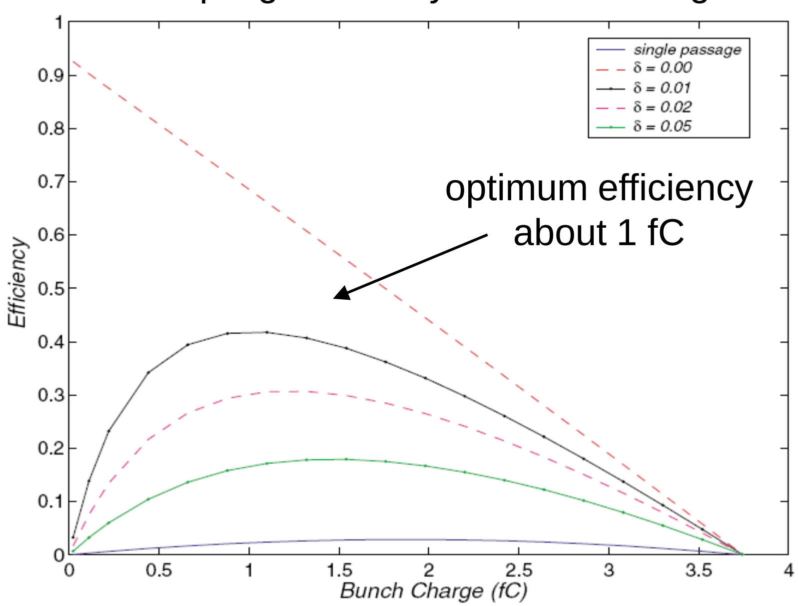
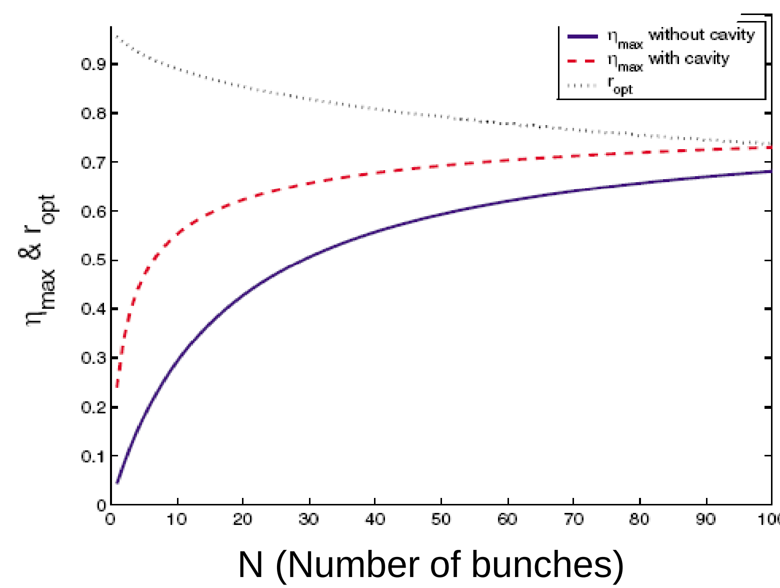
R. L. Byer
Edward L. Ginzton Laboratory, Stanford University, Stanford, California 94305, USA
(Received 26 January 2005; published 11 March 2005)

Coupling Efficiency vs bunch charge



Beam loading calculations vs N



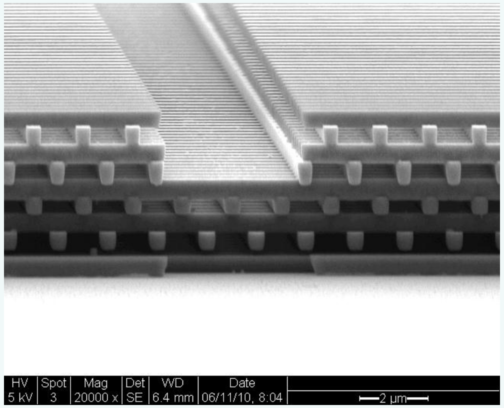
For the first time theoretical calculations showed that laser accelerators could be efficient

Dielectric Laser Acceleration

*Primary challenge for laser acceleration: mode is **transverse** electromagnetic—must develop longitudinal electric fields to accelerate*

Structure Candidates for High-Gradient Accelerators

Projected maximum gradients based on measured material damage threshold data

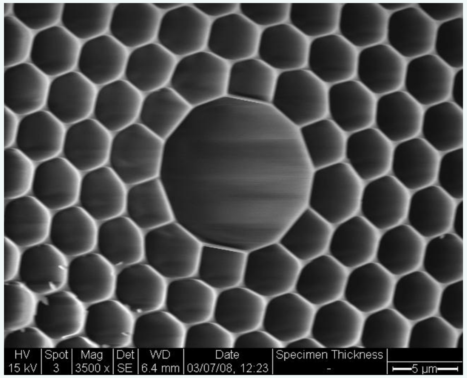


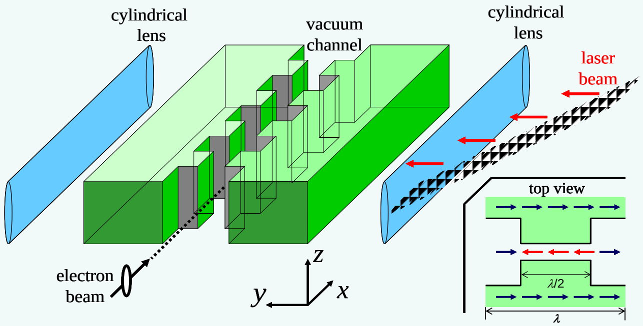
Photonic Crystal "Woodpile"

Silicon, λ=2200nm, ***E_z=400 MV/m***

Photonic Crystal Fiber

Silica, λ=1890 nm, ***E_z=400 MV/m***





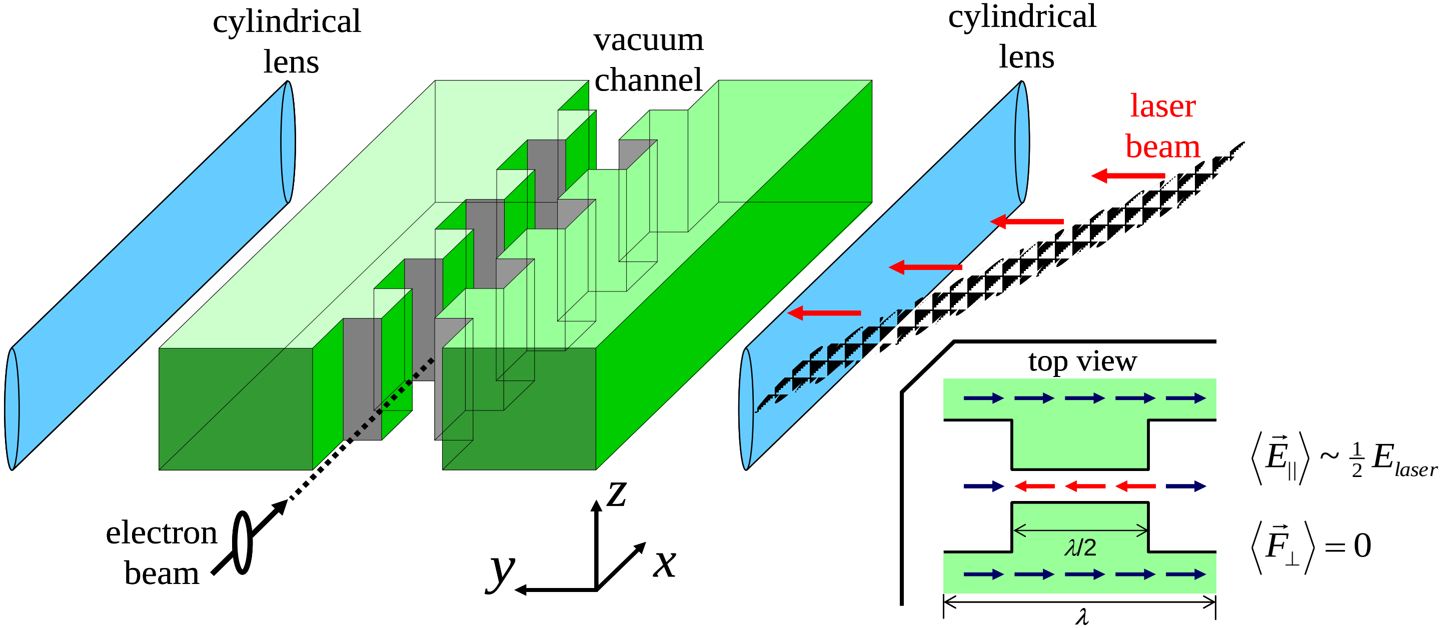
Transmission Grating Structure

Silica, λ=800nm, ***E_z=830 MV/m***

Waveguiding Structure | Waveguiding Structure | Phase Mask Structure

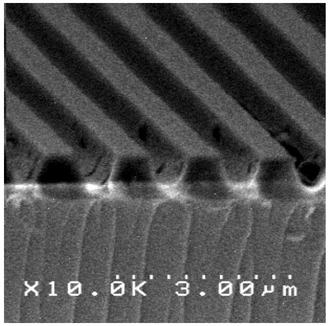
3D | 2D | 1D

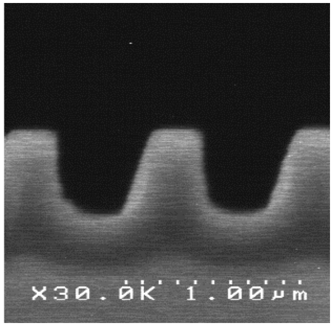
Transmission Grating Accelerator



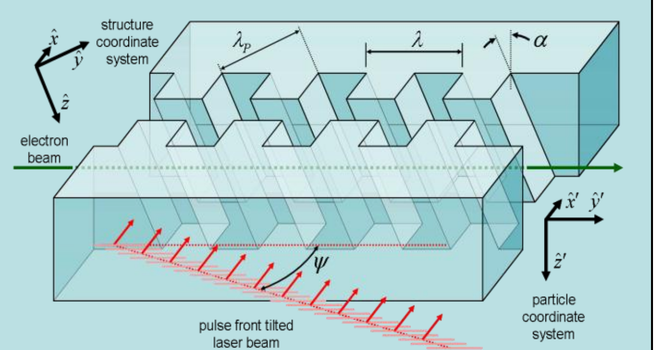
T. Plettner et al, Phys. Rev. ST Accel. Beams 4, 051301 (2006)

Silica, λ=800nm, E_z=830 MV/m





Elegant Variant: Fast Deflector

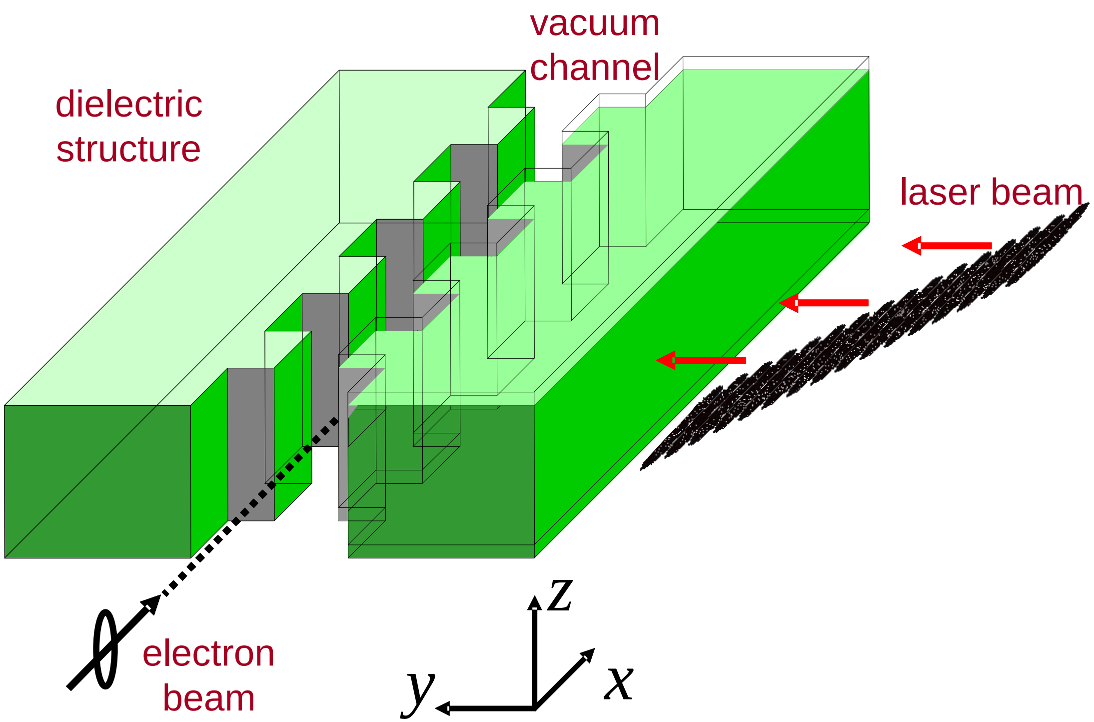


T. Plettner, *submitted to Phys. Rev. ST Accel. Beams*

Main concept: periodic phase-reset of the EM field

Reset the phase every ~300 microns in grating structure

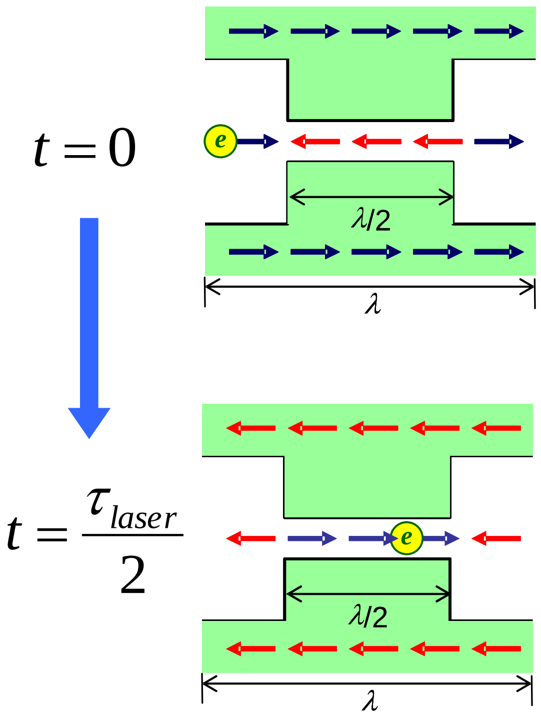
perspective view



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

top view

traveling electron experiences accelerating force at all times



Transverse pumped phase-reset structure

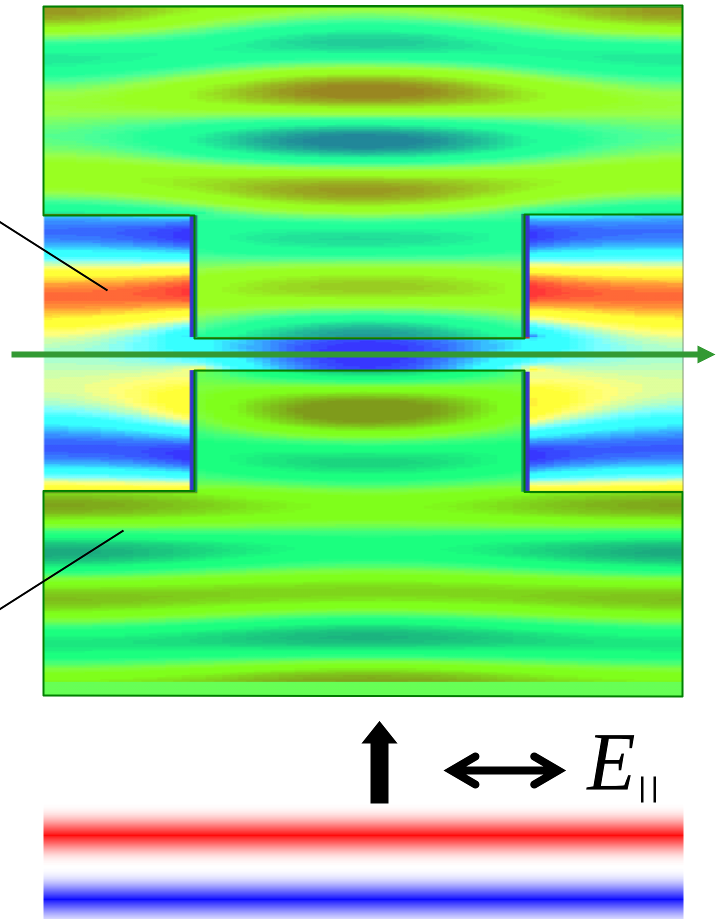
EM field map in one unit

vacuum channel

electron beam

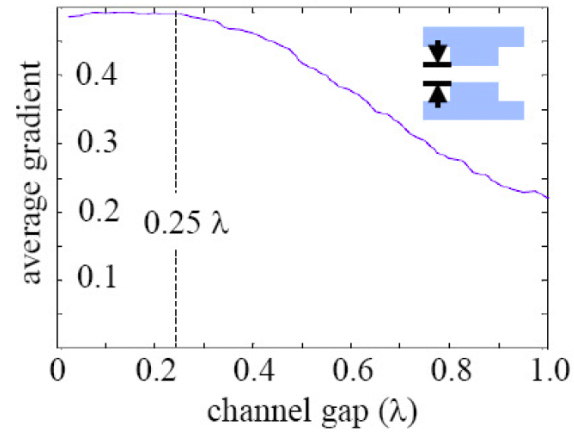
dielectric structure

input laser wavefront



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

vacuum channel width < λ



$$\langle \vec{E}_{||} \rangle \sim \tfrac{1}{2} E_{laser}$$

1 J/cm² fluence

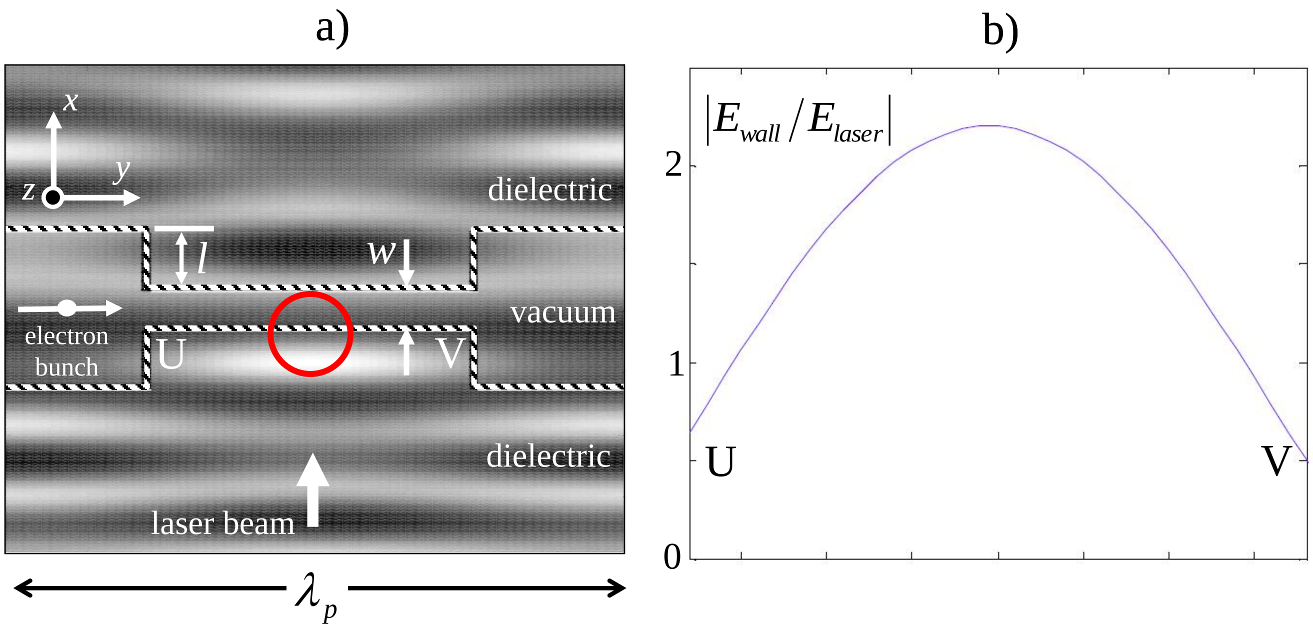
~10 fsec pulses

$$\langle G_{unloaded} \rangle \sim 4\,\text{GeV/m}$$

G_{loaded} ~ 2 GeV/m

The expected maximum gradients

Operate at the Breakdown Limit



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

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

$\div 2$

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

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

10 fsec laser pulse

1 J/cm^2 → $|E_{\max}| \sim 25\,\text{GV/m}$ → $\left\langle G_{||,TE} \right\rangle \sim 4\,\text{GV/m}$, $\left\langle G_{\perp,TE} \right\rangle \sim 2\,\text{GV/m}$

(At breakdown limit)

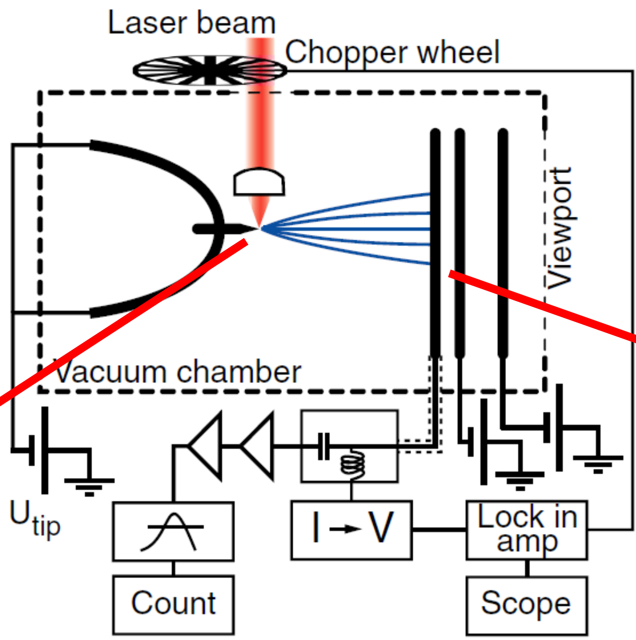
Y. Min Oh et al, International Journal of Heat and Mass Transfer 49 (2006) 1493–1500
B. C. Stuart et al, Physical Review Letters 74, 2248 (1995)
M. Lenzner et al, “Femtosecond Optical Breakdown in Dielectrics”, Phys. Rev. Lett. 80, 4076 (1998)

A Compatible Electron Source

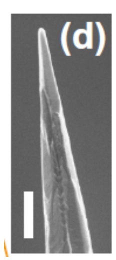
PRL **96,** 077401 (2006) PHYSICAL REVIEW LETTERS week ending 24 FEBRUARY 2006

Field Emission Tip as a Nanometer Source of Free Electron Femtosecond Pulses

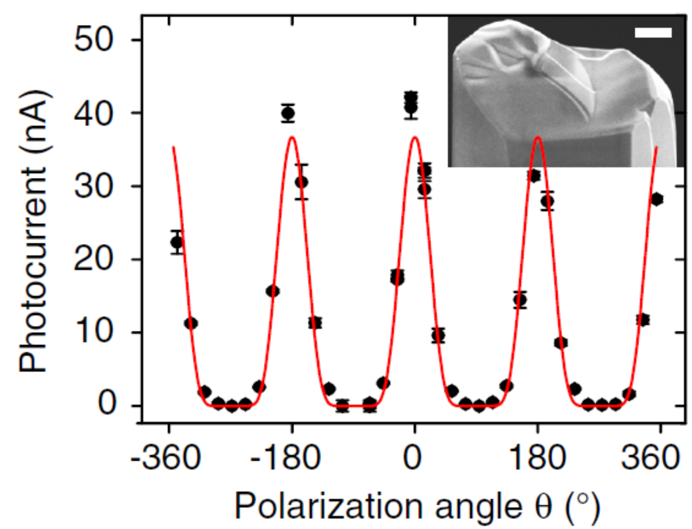
Peter Hommelhoff,* Yvan Sortais, Anoush Aghajani-Talesh, and Mark A. Kasevich
Physics Department, Stanford University, Stanford, California 94305, USA
(Received 25 July 2005; published 21 February 2006)



I~11 e-/optical cycle⇔<I>~500 μA
B>10^{13} A/m^2 sr^2



1μm
Scale bar



500nm
Scale bar

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Laser accelerator structures

Inverse FEL for electron pulse compression

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Structures and expected performance (damage testing)

Recent experiments

electron beam bunching

staged acceleration

radiation from PBGT fiber

Coherent X-ray laser Generation

Components of the proposed FEL X-ray laser

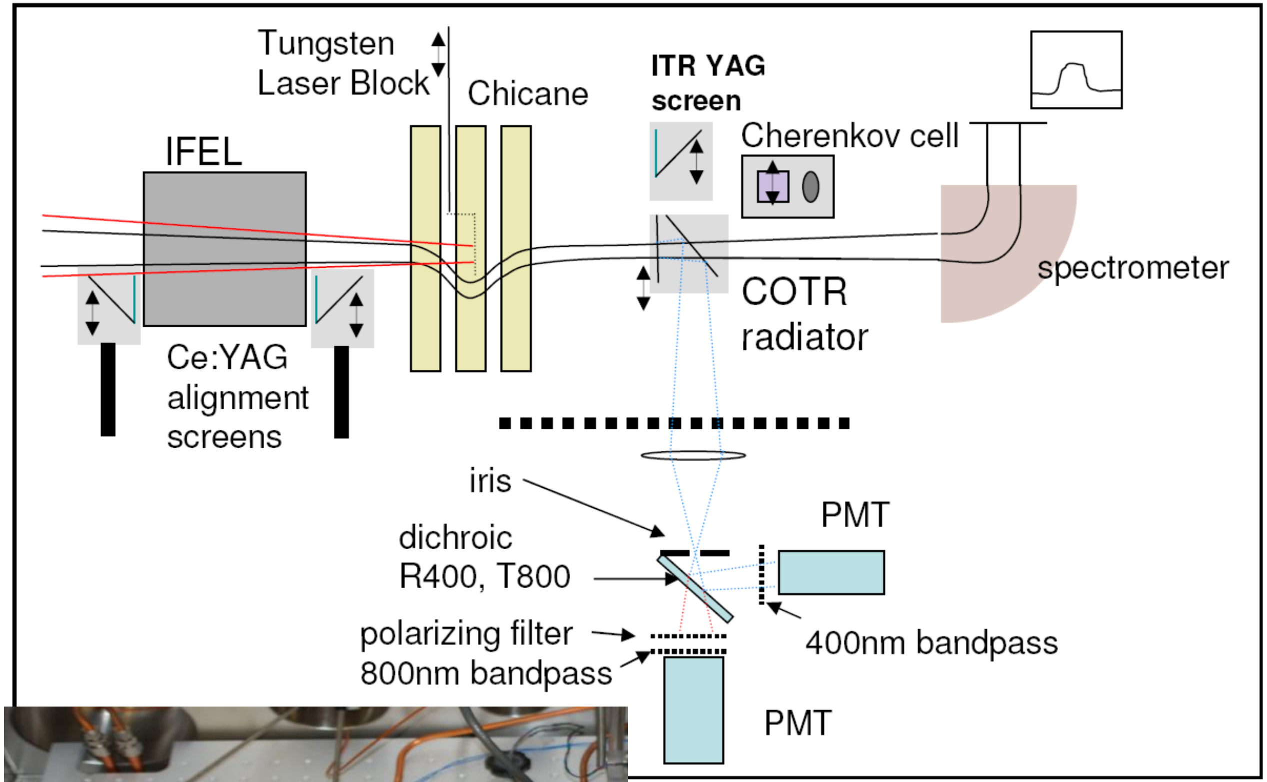
Dielectric Accelerator and Undulator Structures

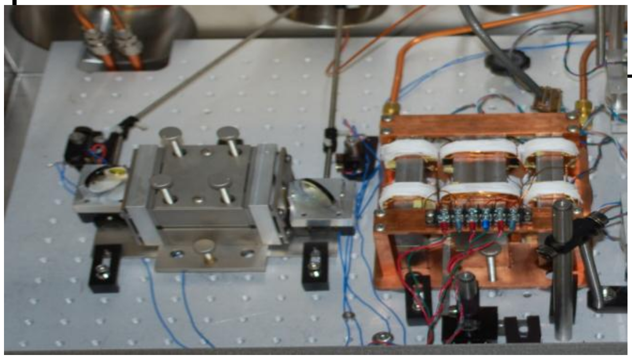
FEL gain and efficiency

Future Challenges

Darpa program: Development of an accelerator on a chip

Enable TeV scale physics affordable cost

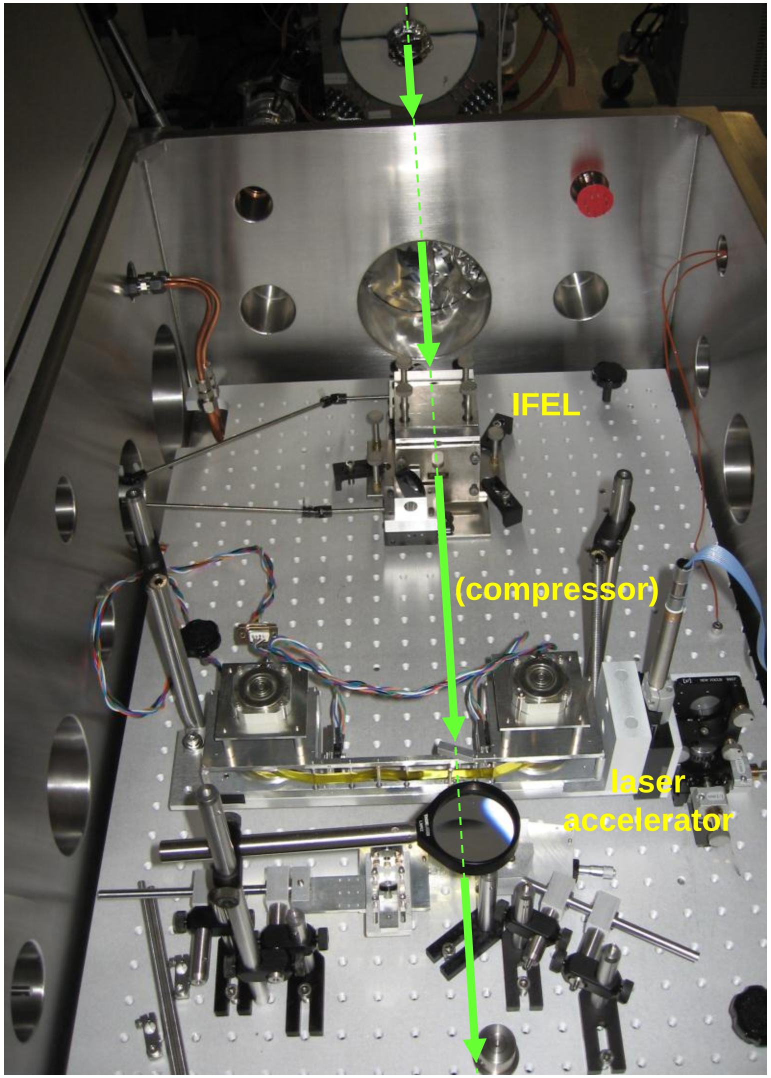


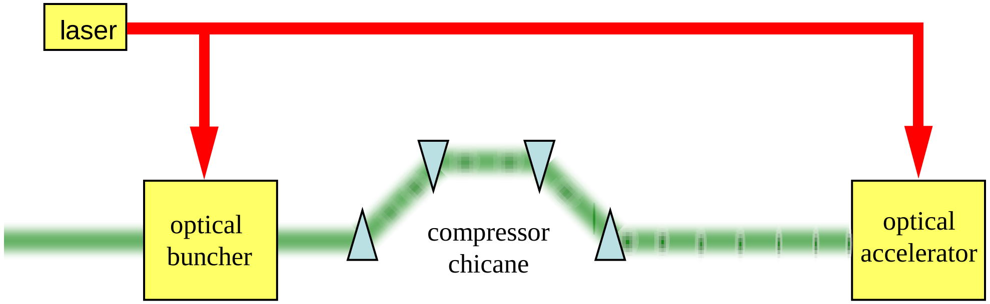


Experimental Parameters:

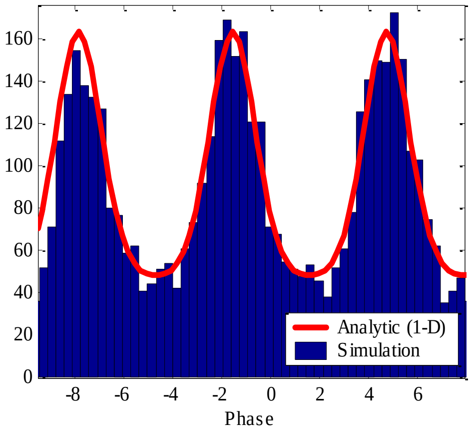
- Electron beam
    - $\gamma=127$
    - Q~5-10 pC
    - $\Delta\gamma/\gamma=0.05\%$
    - Energy Collimated
    - $\varepsilon_N=1.5\ \pi\ \mu$
- IFEL:
    - ¼+3+¼ period
    - 0.3 mJ/pulse laser
    - 100 micron focus
    - z_0=10 cm (after center of und.)
    - 2 ps FWHM
    - Gap 8mm
- Chicane 20 cm after undulator
- Pellicle (Al on mylar) COTR foil

We have achieved net acceleration of electrons with attosecond phase control

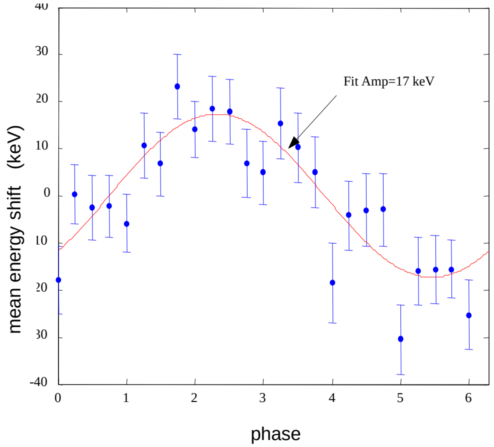




Expected bunching



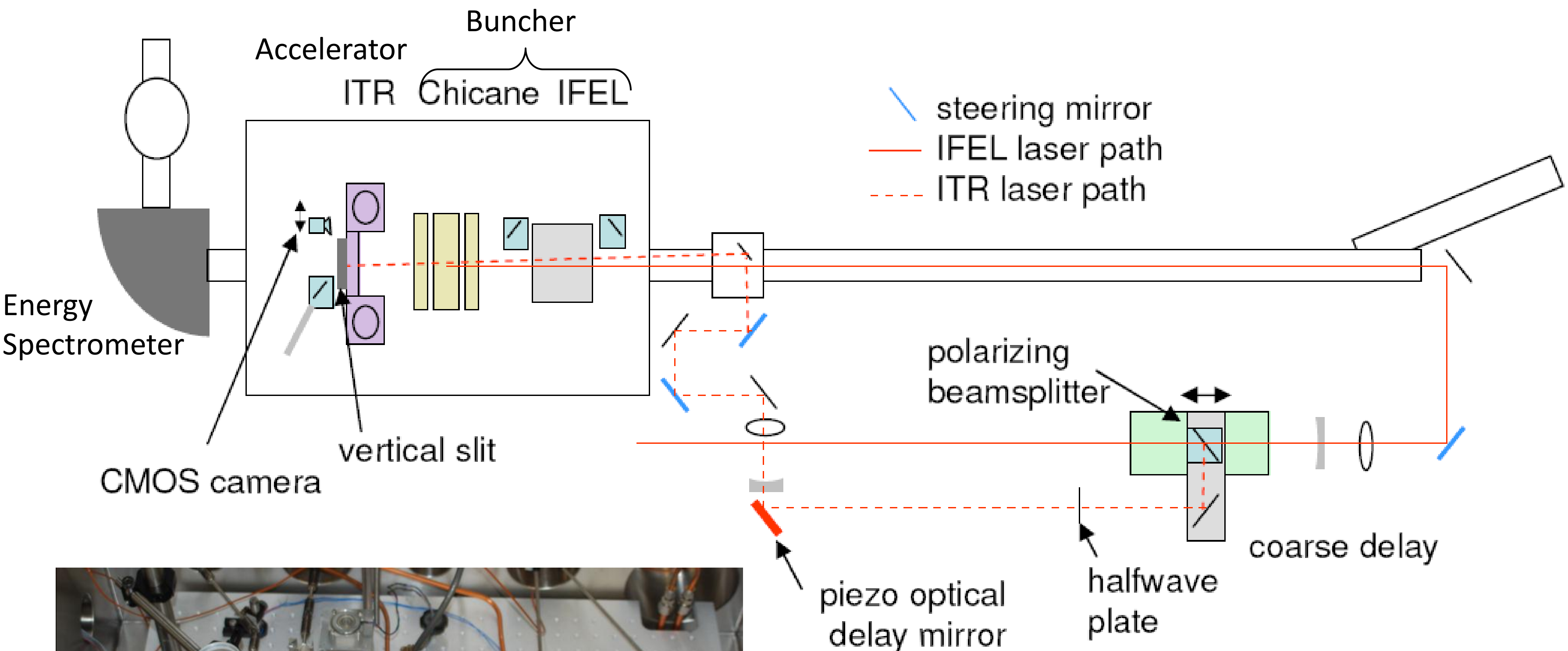
Expected energy gain

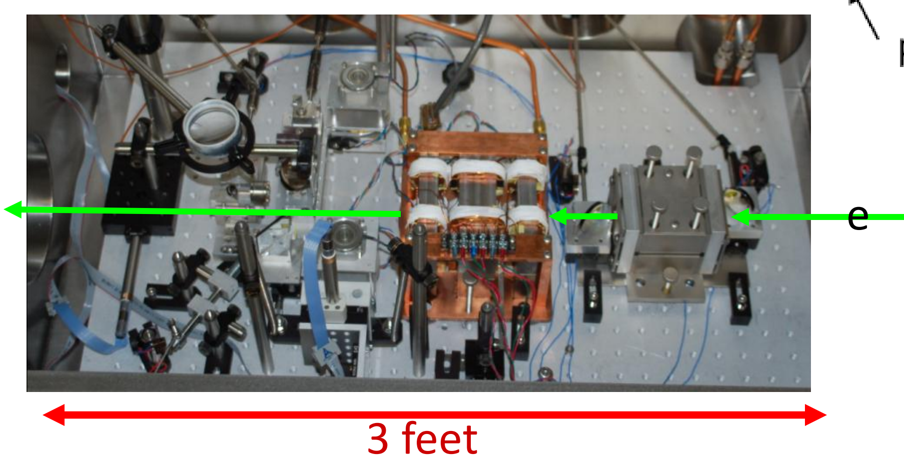


Experiment features

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

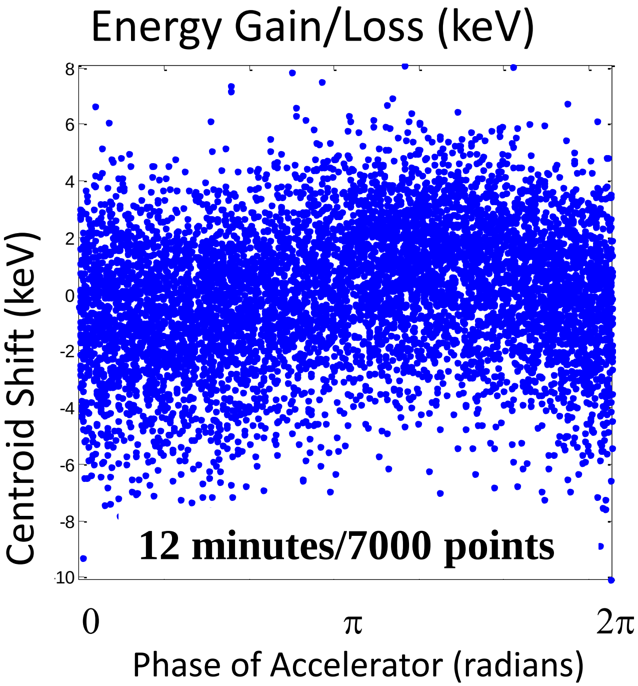
Staged Laser Acceleration Experiment



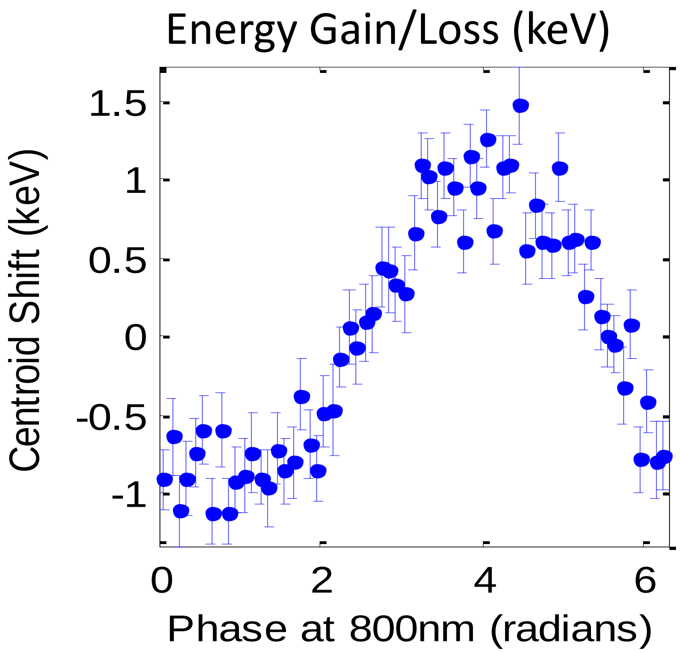


Total Mach-Zender Interferometer path length: ~19 feet = 7.2x10^6 λ !!

All-passive stabilization used (high-mass, high-rigidity mounts, protection from air currents)



Binned 500/events per point



C. M. Sears, "Production, Characterization, and Acceleration of Optical Microbunches", Ph. D. Thesis, Stanford University, June (2008).

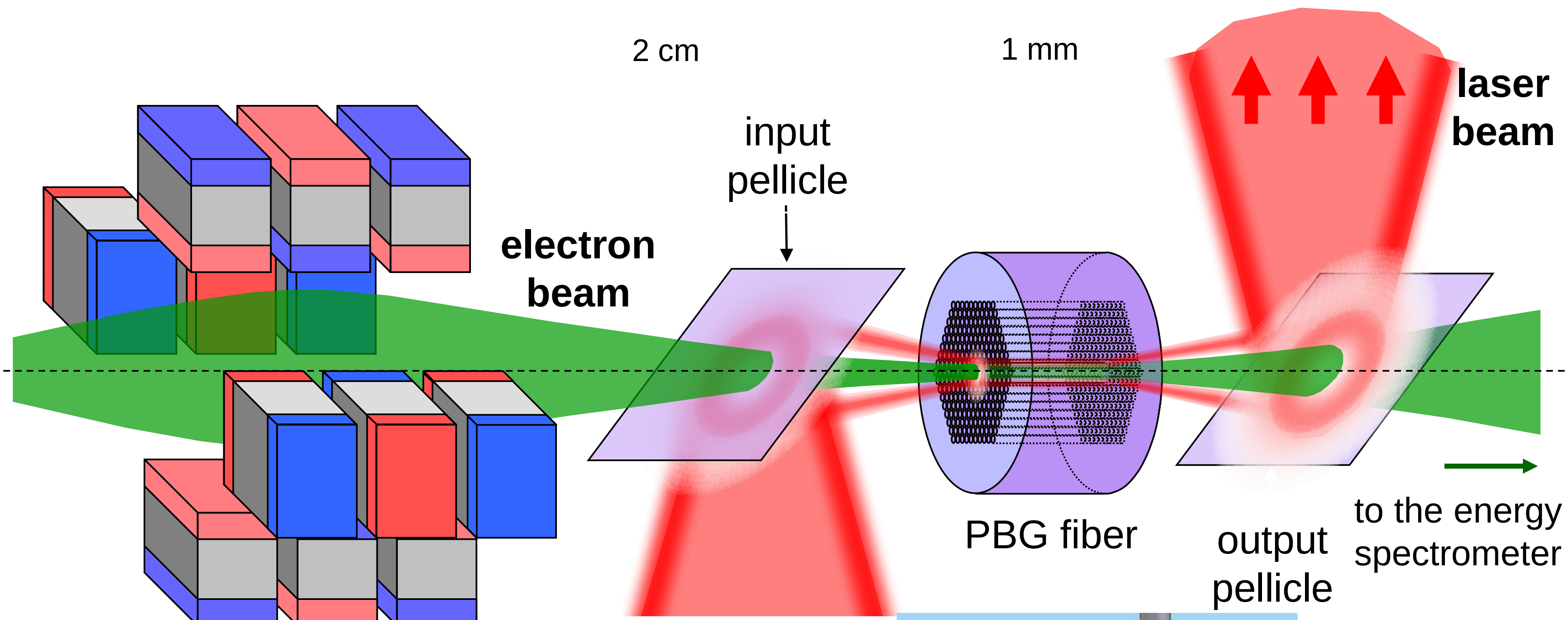
The first demonstration of staged particle acceleration with visible light!

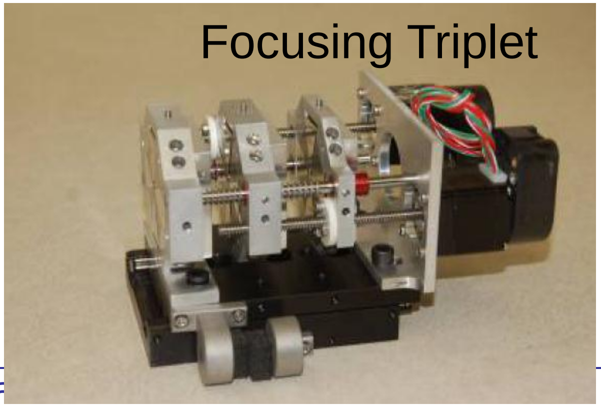
Effective averaged gradient: 6 MeV/m (poor, due to the ITR process used for acceleration stage)

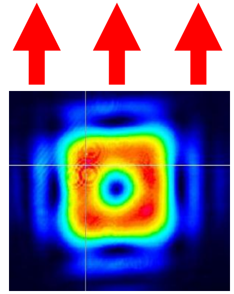
Professor Robert Siemann and Chris Sears

June 15, 2008 – Stanford Graduation Ceremonies

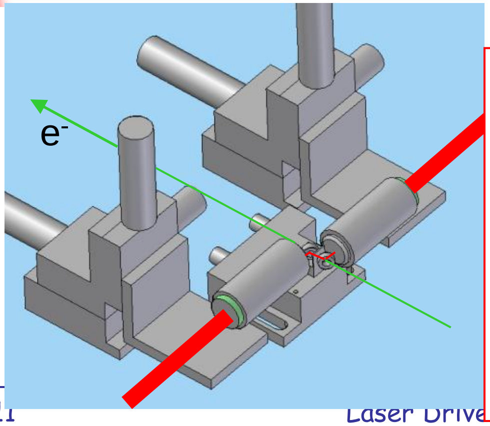
Hollow-core photonic bandgap fiber structures







TEM00(lin) → TEM01* mode convertor output

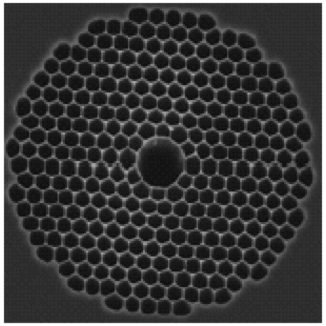


Objective Parameters

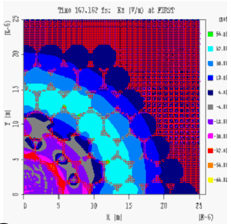
- Working Distance > 10mm (geometrical constraints)
- $NA_{objective} > 0.12$ (NA_{fiber})

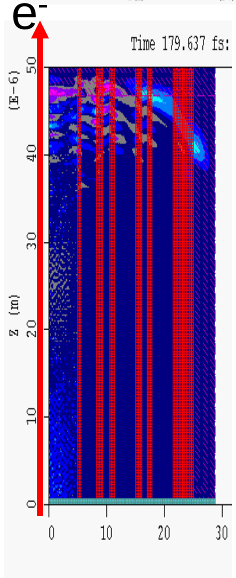
- Mitutoyo Infinity Corrected Objectives:
- 100x → NA=0.5, WD=12mm
- 20x → NA=0.4, WD=20mm

First Observation of Accelerating Modes in a PBG Fiber

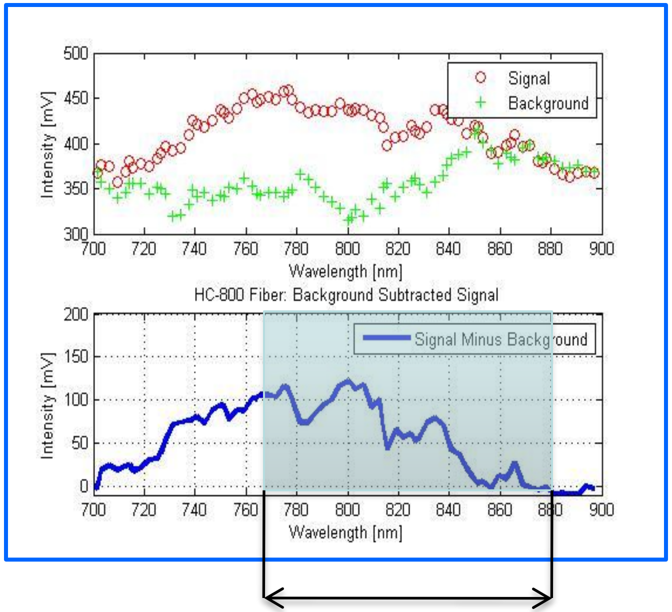


Thorlabs HC-1550-2

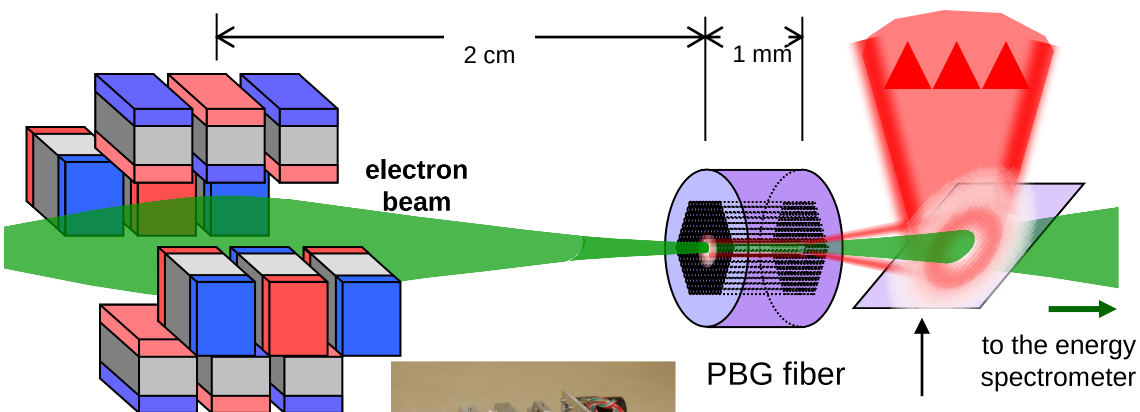




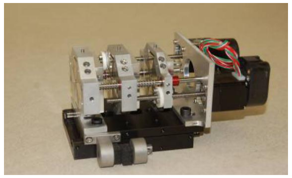
- Commercially available fiber (Thorlabs HC-800-1, $533/m)
- Observed with optical spectrometer to measure SOL modes



TE bandgap region



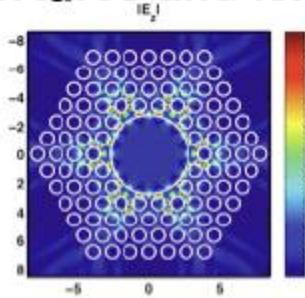
focusing triplet
K_q=0.5 kT/m



Joel England, *et al*, In preparation, (2011).

A variety of optical-scale dielectric structures are under consideration

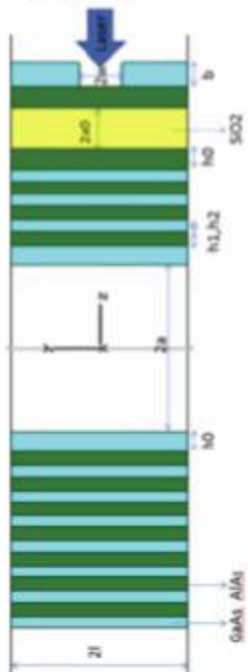
PBG-fiber-based structures afford large apertures and length-scalability



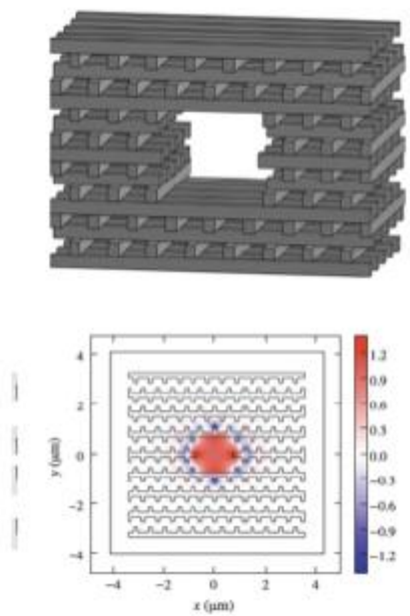
~2.5 GV/m

Planar structures offer beam dynamics advantages as well as ease of coupling power

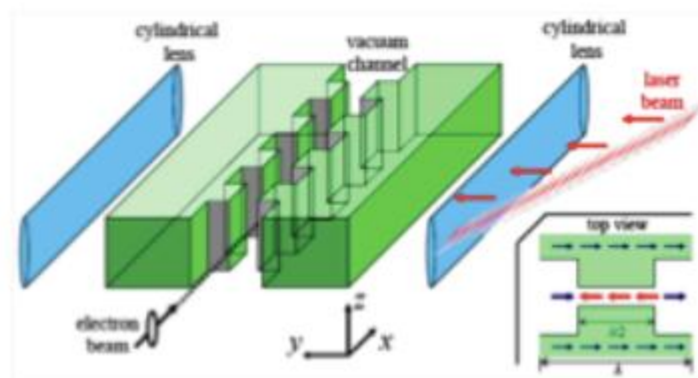
MAP



Logpile



Grating



Gil Travish, UCLA

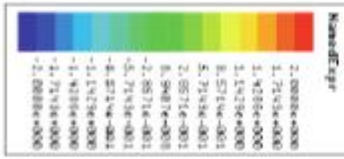
The MAP structure consists of a diffractive optic coupling structure and a **resonant cavity**

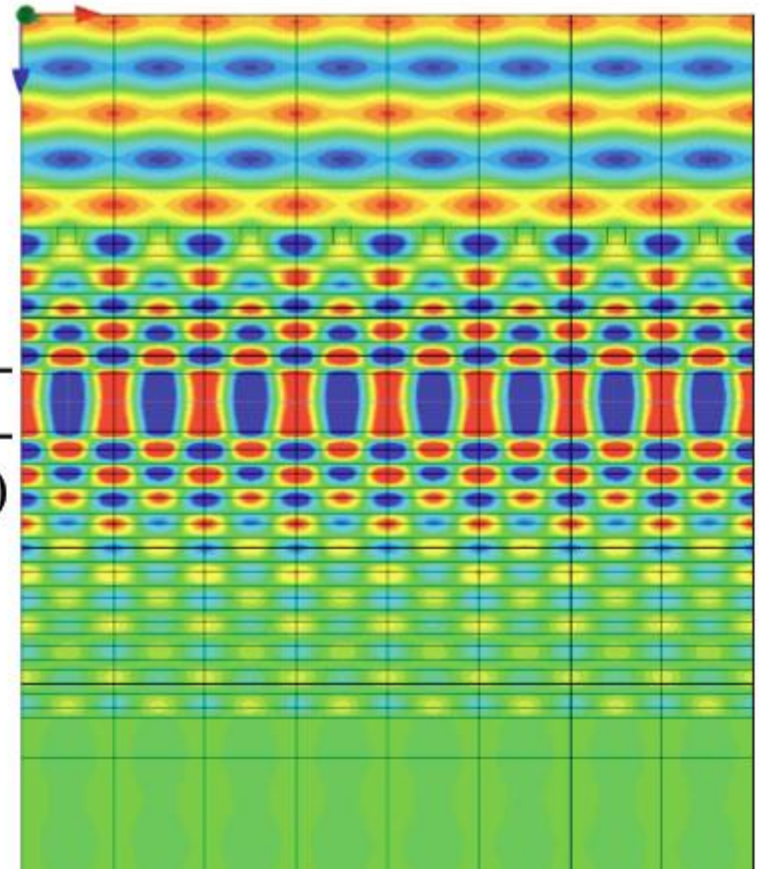
For gap *a* and dielectric *b*-*a* idealized resonance:

$$\cot\left[k_z\sqrt{\varepsilon-1}\left(b-a\right)\right]=k_z a\sqrt{\varepsilon-1}/\varepsilon$$

Micro
Accelerator
Platform

laser





e-beam

gap (1 optical wavelength)

$$E_z = E_0\cos(\omega z/c)$$

Tuning:
control “matching” layer (*b*-*a*).

Gil Travish UCLA

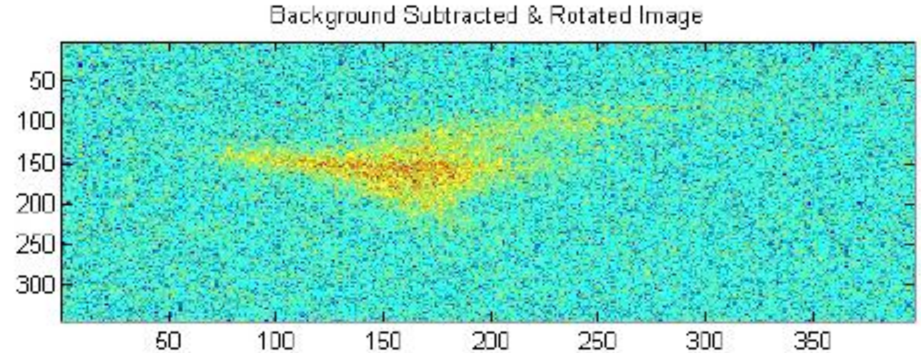
For the first time, beam was transmitted through the optical-scale structure!

Bunches from NLCTA Beamline

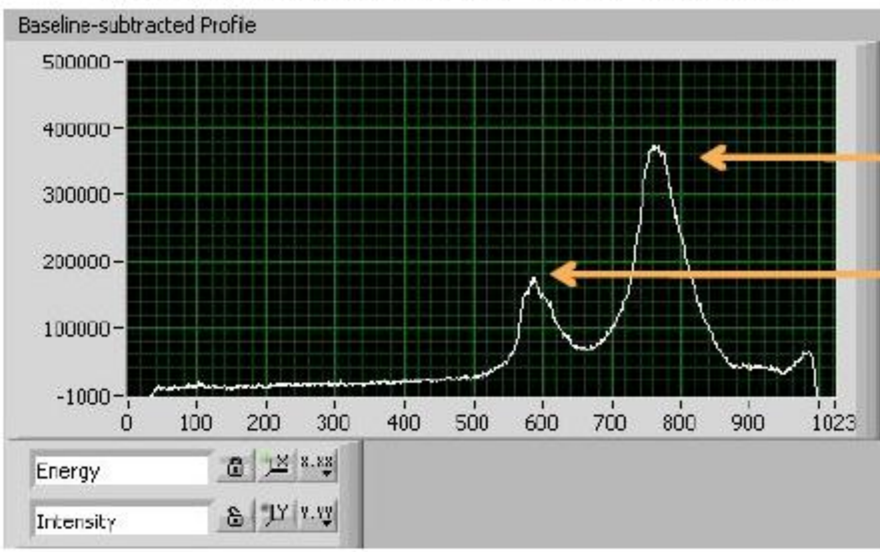
Spot size = 96 x 83 μm^2

ε_x = 43 µm-rad

ε_y = 24 µm-rad



Spectrometer Image (higher energy to the left)



electrons that lost energy while traveling through glass

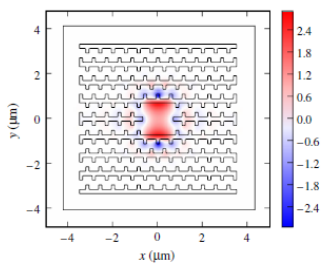
electrons that made it through slo

- Theoretically, we expect peaks to be separated by **0.5 MeV**
- With calibration of 1.776 KeV/pixel, we find separation of **0.337 MeV**

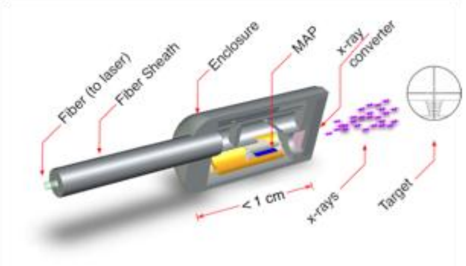
Data analysis is ongoing

DLA: Advanced Concepts

Working with optical wavelengths necessarily means that components built to confine fields in this range achieve nanometer and attosecond scale performance.

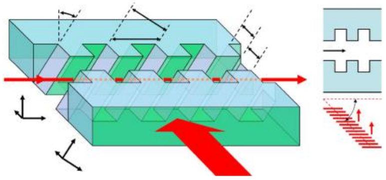


Woodpile structure designed with focusing field—B. Cowan, PRST-AB, 11, 011301, (2008).

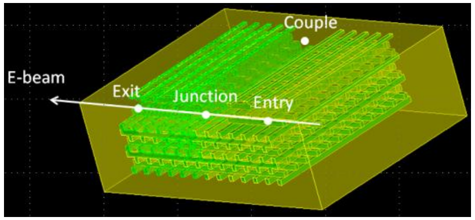


MAP structure for *I*BRT. -- G. Travish, R. Yoder, UCLA.

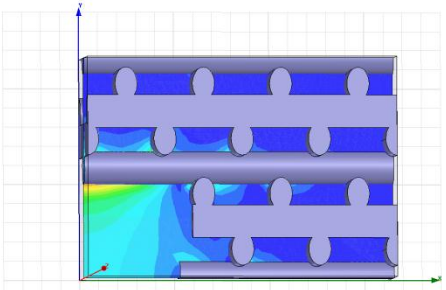
- **Further applications of DLA**
  - Optical undulators (~1 MeV)
  - Optical BPMs (Z. Wu, K. Soong),
  - Optical Structure Based beam focusing (B. Cowan)
  - Optical kickers and steering elements (K. Soong, C. McGuinness)
  - Attosecond-scale timing diagnostics
  - *Internal*-Beam Radiotherapy (UCLA-Travish, Yoder)
  - Optical BPMs (IIT-Technion—Schächter)
  - THz sources (Z. Wu)



Grating-based optical undulator– T. Plettner, PRST-AB, **11**, 030704 (2008).



Woodpile structure simulations as a BPM—Z. Wu



Woodpile structure designed to support deflecting mode—C. McGuinness

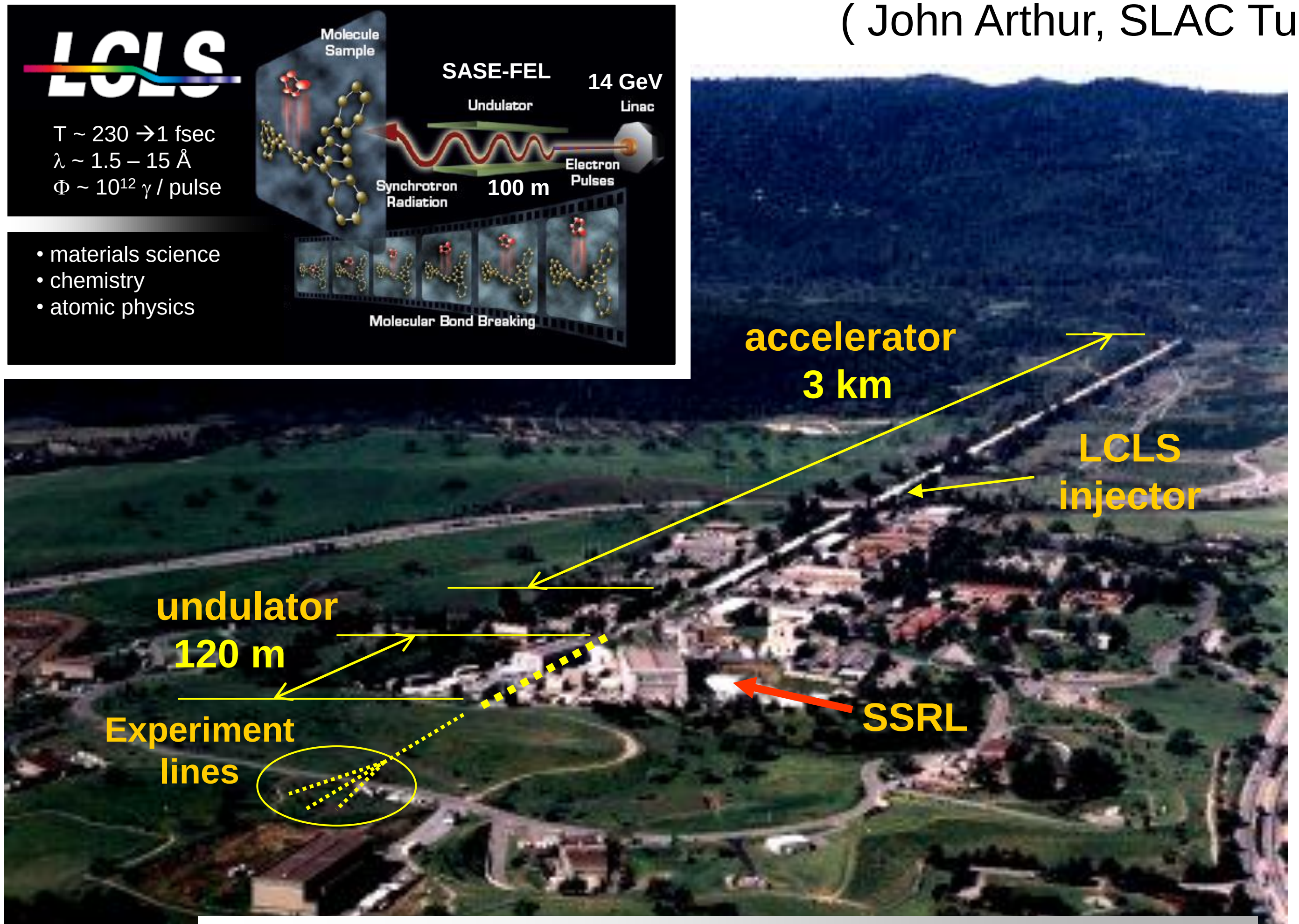
Contents

… could we generate coherent X-ray photons with laser accelerators?

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.

RF-accelerator driven SASE FEL facilities - 2009

(John Arthur, SLAC Tuesday PQE)



TTF: Tesla Test Facility; fsec EUV SASE FEL facility

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

LCLS properties

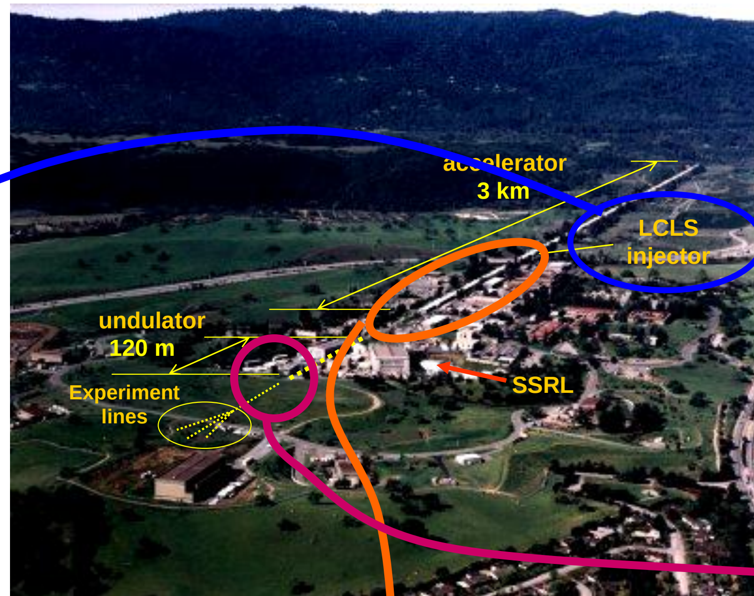
- km-size facility
- microwave accelerator
- λ_{RF} ~ 10 cm
- 4-14 GeV e-beam

- 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



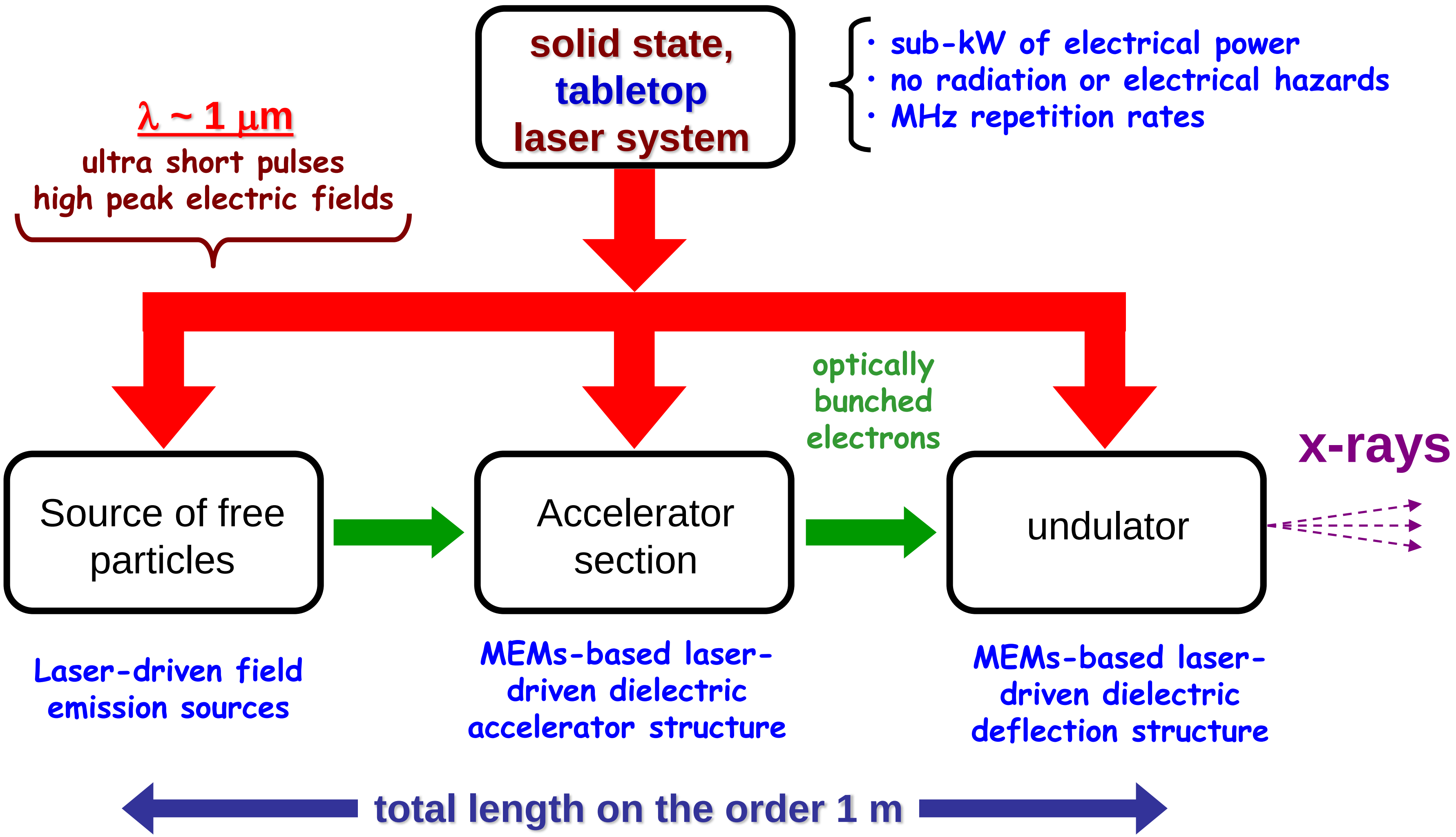
source of free particles → **accelerator section** → **undulator**

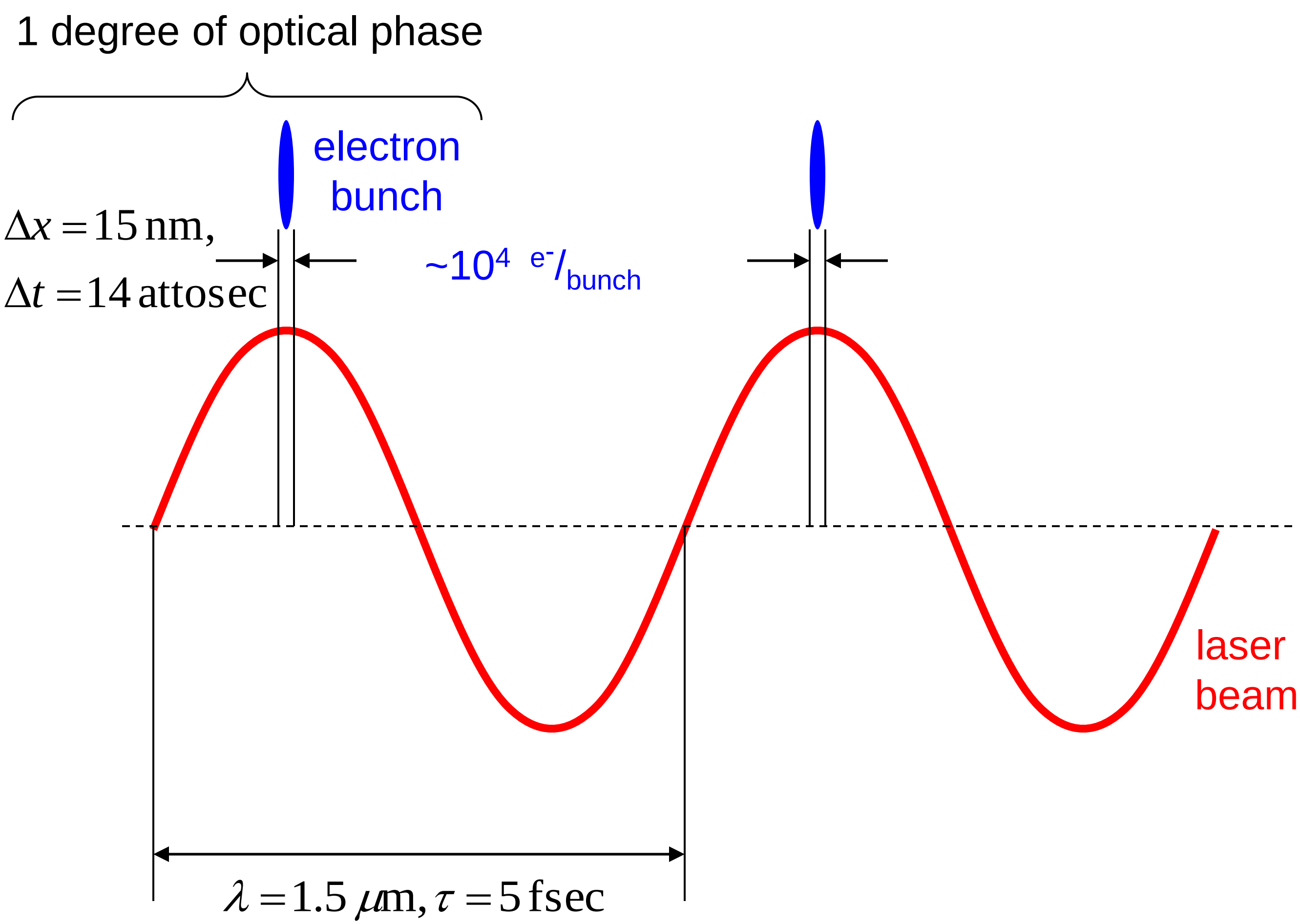
laser-driven
high rep. rate
very compact

dielectric structure
based laser-driven
particle accelerators

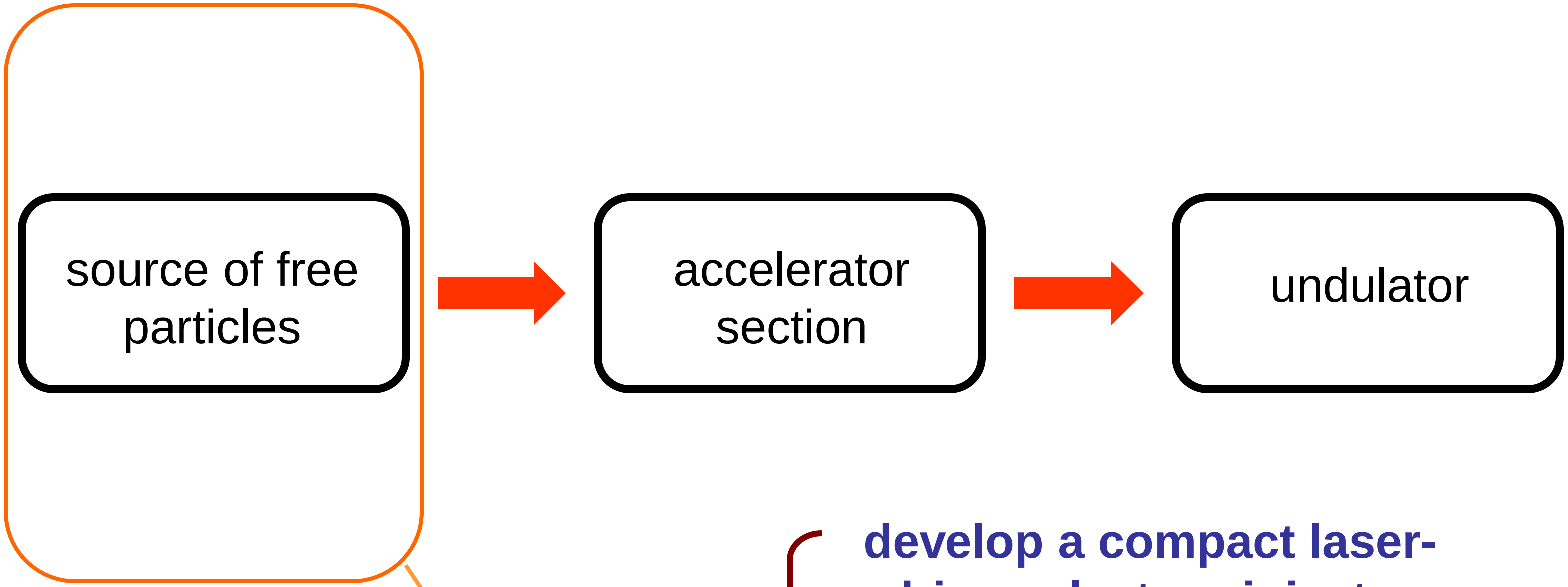
dielectric structure,
laser driven

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




1 degree of optical phase
electron bunch
$\Delta x = 15\,\text{nm},$
$\Delta t = 14\,\text{attosec}$
$\sim 10^4\ e^-/_{\text{bunch}}$
laser beam
$\lambda = 1.5\,\mu\text{m}, \tau = 5\,\text{fsec}$

Development of the three key laser-driven components



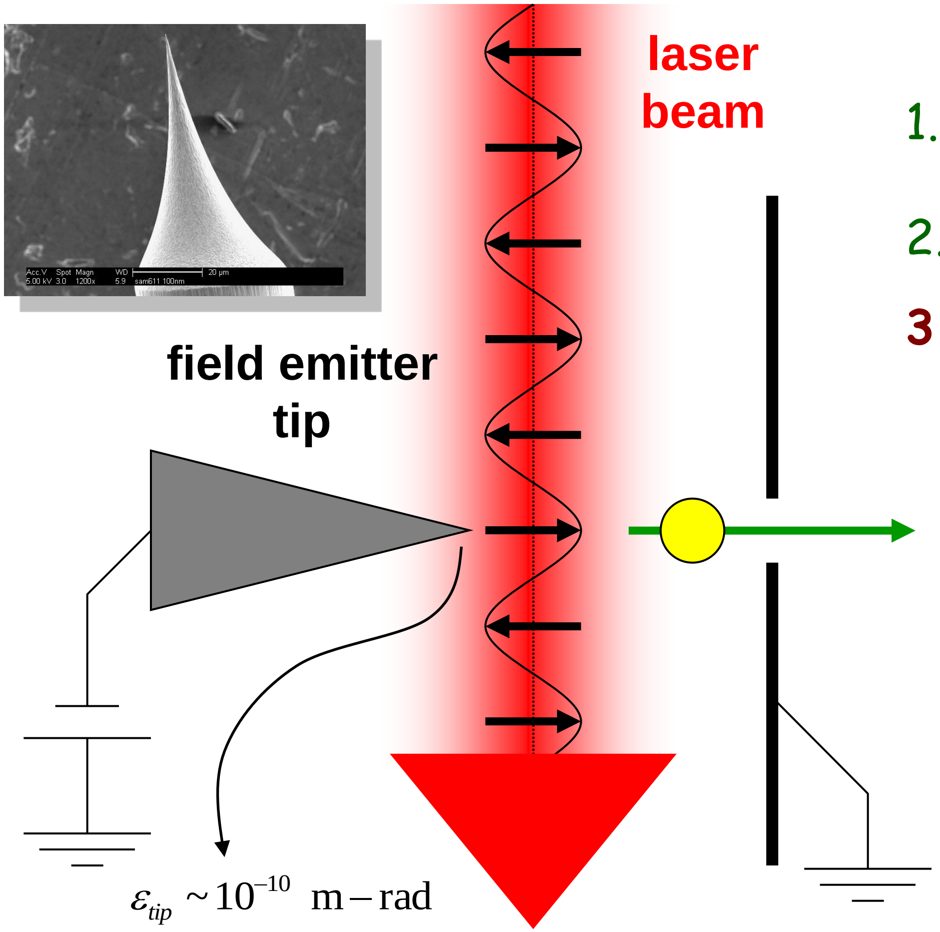
Objective:

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

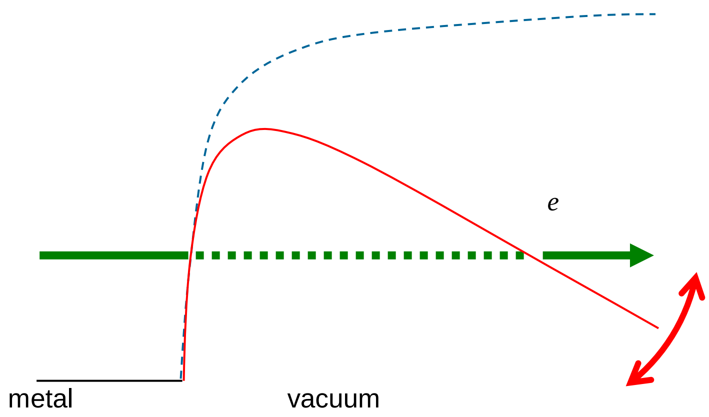
A laser-driven field-emission free-electron source

P. Hommelhoff et al, Kasevich group

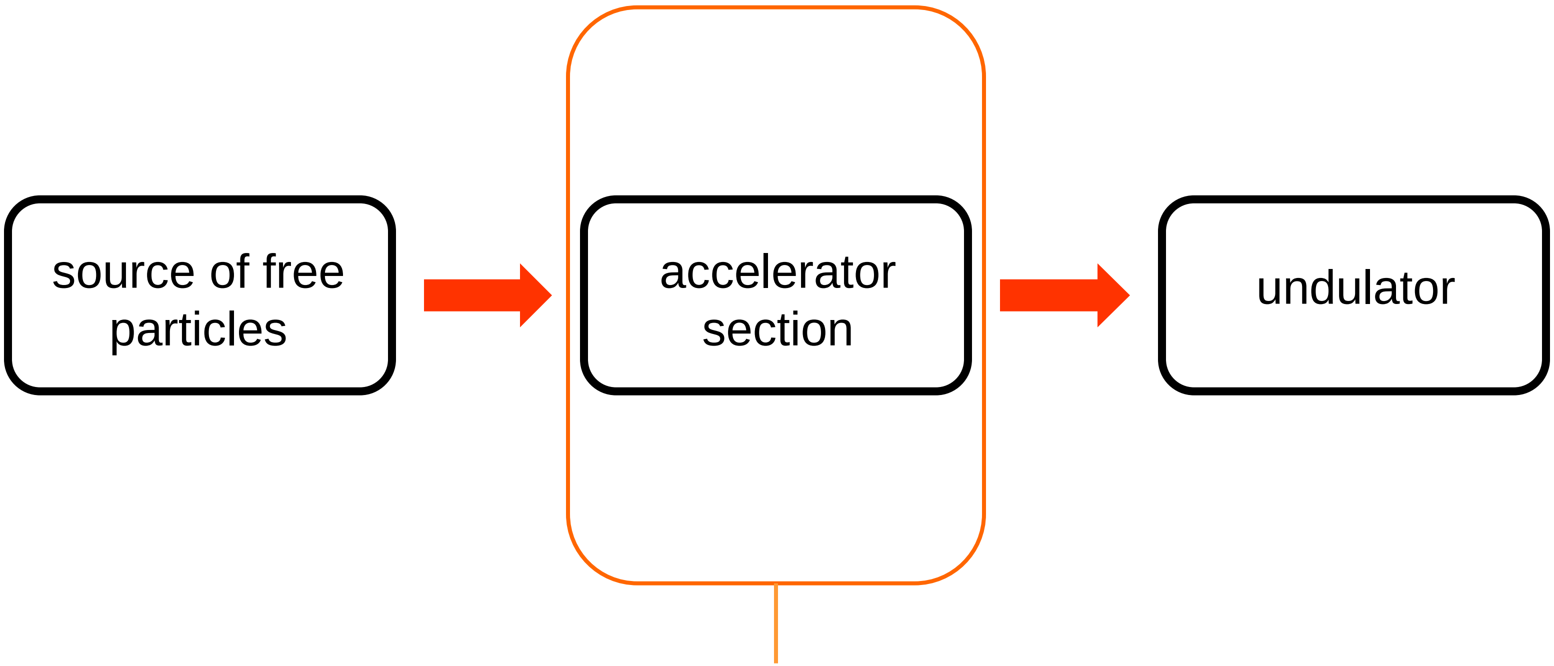


Field emission tip properties

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)

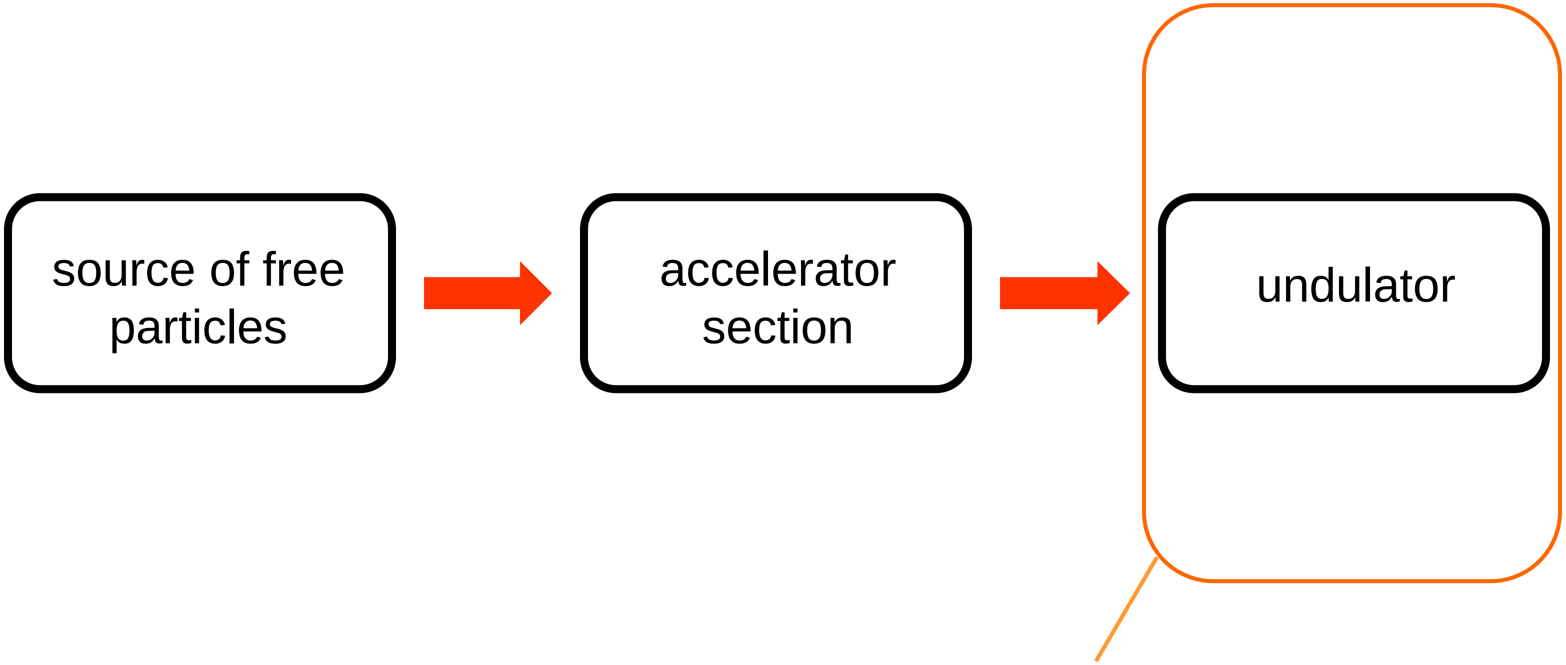


Objective:

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

Short Period Undulator with periodic magnets

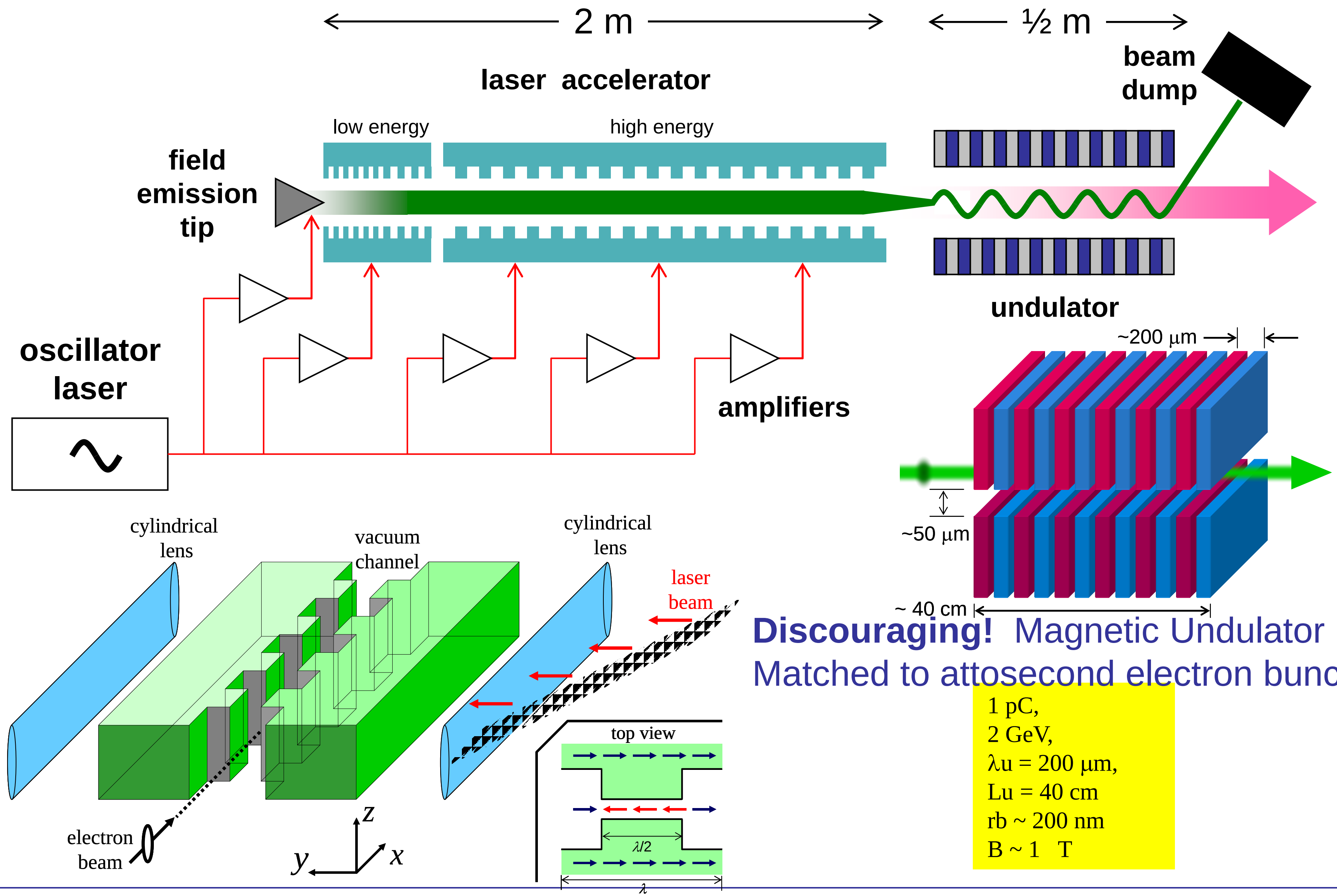


First Idea:

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 - summer 2008)

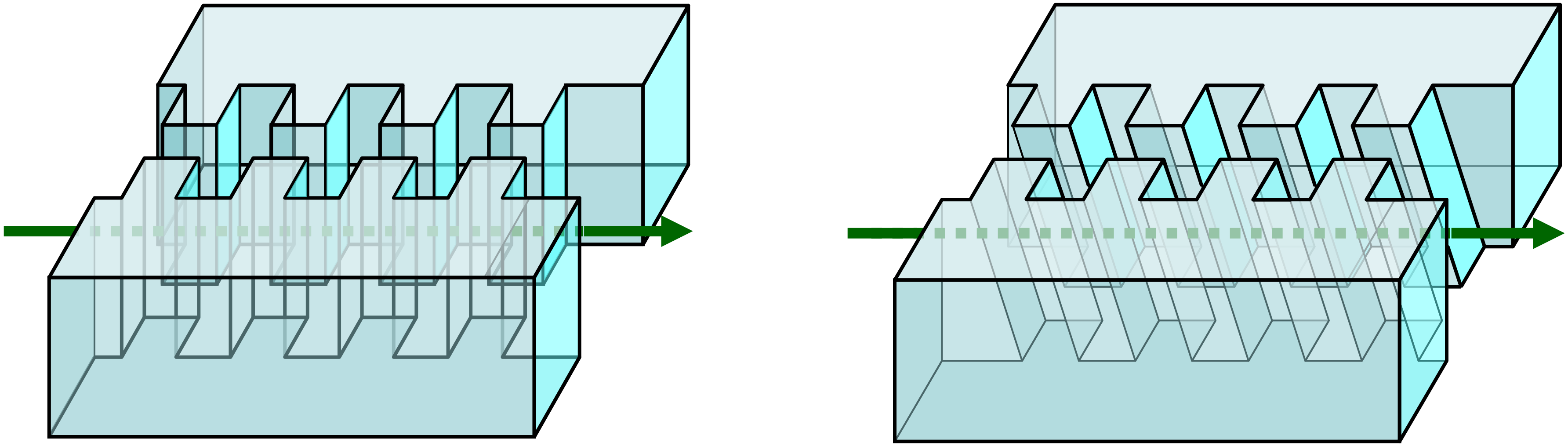


Discouraging! Magnetic Undulator not Matched to attosecond electron bunches

1 pC,
2 GeV,
λu = 200 μm,
Lu = 40 cm
rb ~ 200 nm
B ~ 1 T

New Idea: Laser-Driven Dielectric Undulator for FEL

accelerator structure | **deflection structure**



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

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

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

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

key idea

Extended phase-synchronicity between the EM field and the particle

Use modelocked laser to generate periodic deflection 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

Proposed Dielectric Grating Accelerator and Undulator Structure
Tomas Plettner 2006, 2008

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **11**, 030704 (2008)

Proposed dielectric-based microstructure laser-driven undulator

T. Plettner and R. L. Byer
Stanford University, Stanford, California 94305, USA
(Received 18 April 2007; published 20 March 2008)

We describe a proposed all-dielectric laser-driven undulator for the generation of coherent short wavelengths and explore the required electron beam parameters for its operation. The key concept for this laser-driven undulator is its ability to provide phase synchronicity between the deflection force from the laser and the electron beam for a distance that is much greater than the laser wavelength. Because of the possibility of high-peak electric fields from ultrashort pulse lasers on dielectric materials, the proposed undulator is expected to produce phase-synchronous GV/m deflection fields on a relativistic electron bunch and therefore lead to a very compact free electron based radiation device.

DOI: 10.1103/PhysRevSTAB.11.030704 PACS numbers: 41.60.Cr, 41.75.Jv, 41.75.Ht, 42.25.Bs

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS **9**, 111301 (2006)

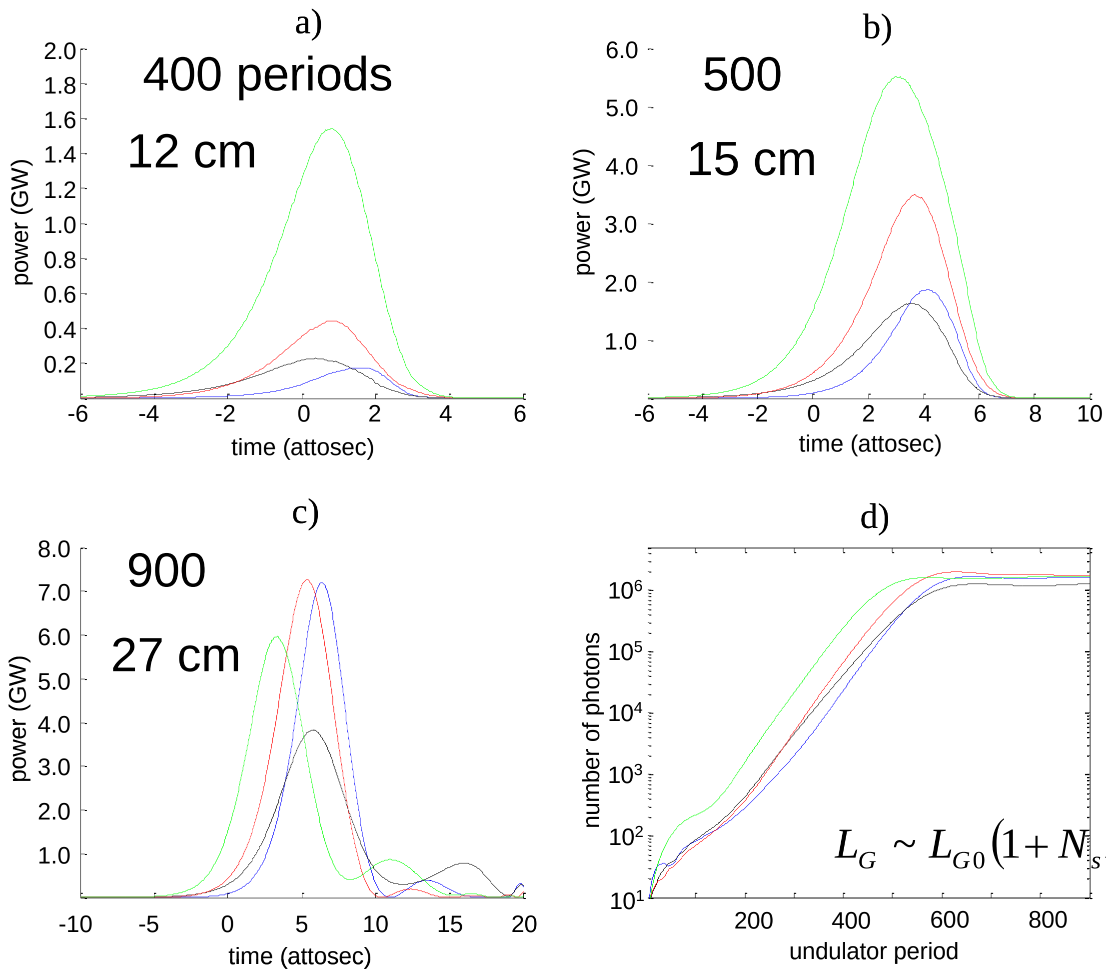
Proposed few-optical cycle laser-driven particle accelerator structure

T. Plettner, P. P. Lu, and R. L. Byer
E.L. Ginzton Laboratories, Stanford University, Stanford, California 94305, USA
(Received 2 October 2006; published 14 November 2006)

We describe a transparent dielectric grating accelerator structure that is designed for ultrashort laser pulse operation. The structure is based on the principle of periodic field reversal to achieve phase synchronicity for relativistic particles; however, to preserve ultrashort pulse operation it does not resonate the laser field in the vacuum channel. The geometry of the structure appears well suited for application with high average power lasers and high thermal loading. Finally, it shows potential for an unloaded gradient of 10 GeV/m with 10 fs laser pulses and the possibility to accelerate 10^6 electrons per bunch at an efficiency of 8%. The fabrication procedure and a proposed near term experiment with this accelerator structure are presented.

DOI: 10.1103/PhysRevSTAB.9.111301 PACS numbers: 41.75.Jv, 41.75.Ht, 42.25.Bs

Calculated FEL Performance - 0.1 Angstrom X-rays



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

$$L_c \sim 21\lambda_r$$

$$\sigma_b \sim 136\,\lambda_r$$

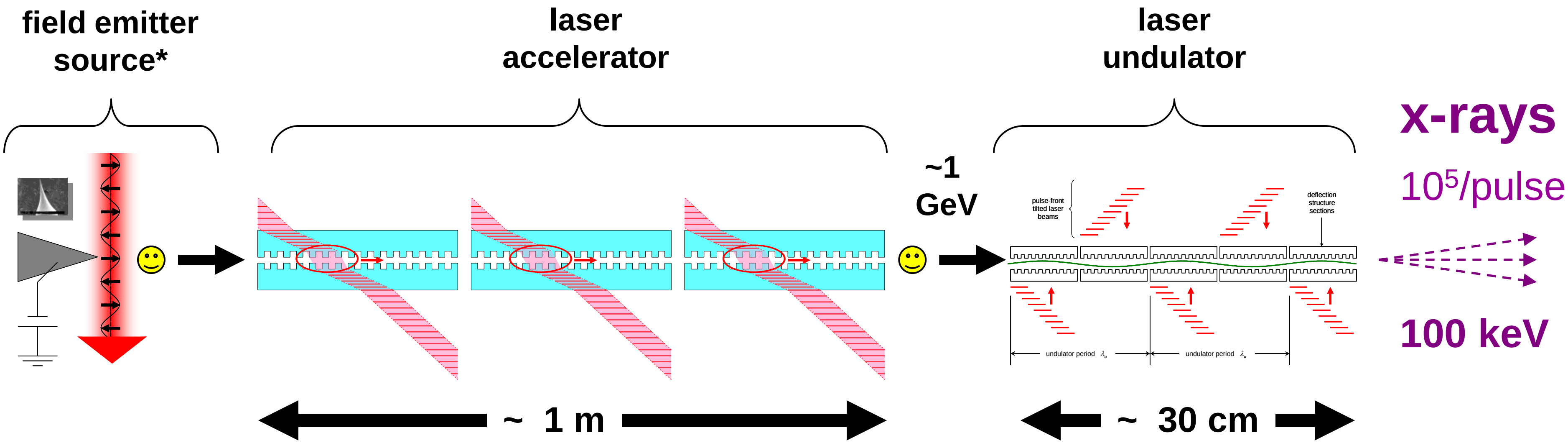
$$\sigma_b / L_c \sim 6$$

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

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

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

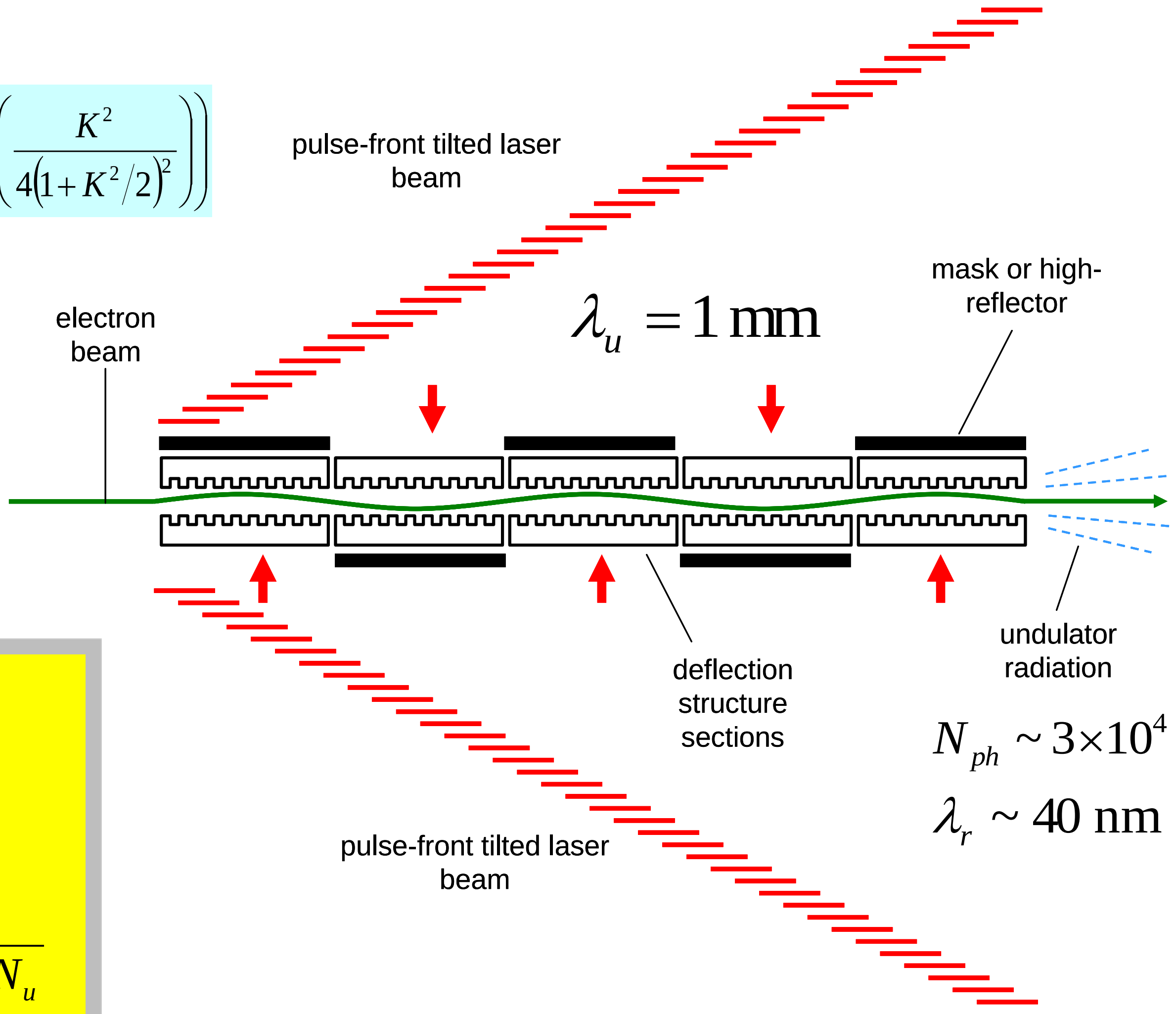
Schematic of the tabletop radiation source



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

Look for undulator radiation

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



$N_{ph} \sim 3\times10^4$

$\lambda_r \sim 40\ \text{nm}$

Prove the concept

measure

$$K \propto \lambda_u$$

$$\Delta\omega/\omega = 1/N_u$$

$$\Delta\theta = \sqrt{2\lambda_r/\lambda_u N_u}$$

Proposed Laser driven Undulator concept has been published (and patented)

Byer Group

PROPOSED TABLETOP LASER-DRIVEN COHERENT X-RAY SOURCE*

T. Plettner#, R.L. Byer, Stanford University, Stanford, CA, 94305, USA

Abstract

We describe the concept of an all-dielectric laser-driven undulator for the generation of coherent X-rays. The proposed laser-driven undulator is expected to produce internal deflection forces equivalent to a several-Tesla magnetic field acting on a speed-of-light particle. The key idea for this laser-driven undulator is its ability to provide phase synchronicity between the deflection force and the electron beam for a distance that is much greater than the laser wavelength. A possible conceptual tabletop SASE-FEL device composed by such an integrated laser-driven accelerator-undulator system is explored.

INTRODUCTION

One of the potential main traits from future structure loaded laser-driven particle accelerators is their promise for attosecond electron bunches and for higher gradients than RF particle accelerators. Therefore the possibility for employing such an accelerator as a compact electron source for a SASE-FEL device is interesting to explore. A meter long laser accelerator could deliver an optically bunched GeV energy electron beam into an undulator, and to preserve an all-tabletop system a matching compact undulator is highly desirable. To this end we propose a dielectric based laser-deflection structure that is MEMs based.

THE UNDULATOR

The key aspect of the proposed laser-driven undulator is the maintenance of phase synchronicity between the electromagnetic field and the travelling particle, which is designed to extend for a distance that is much larger than

grooves of the vacuum channel are oriented at an angle α with respect to the electron beam trajectory. These grooves introduce a phase modulation of the electromagnetic field in the vacuum channel that is responsible for the extended phase synchronicity condition with the electron beam. The period of the vacuum channel grooves, denoted by λ_p in Figure 1, is chosen such that its projection on the electron beam axis equals the laser wavelength λ, such that $\lambda_p = \lambda \cos\alpha$. In the structure coordinates the particle velocity vector is given by $\vec{v}(t) = c(\hat{y}\cos\alpha + \hat{z}\sin\alpha)$. The laser beam is a plane wave with the phase front at normal incidence the structure, travelling in the $\hat{x}$ - direction.

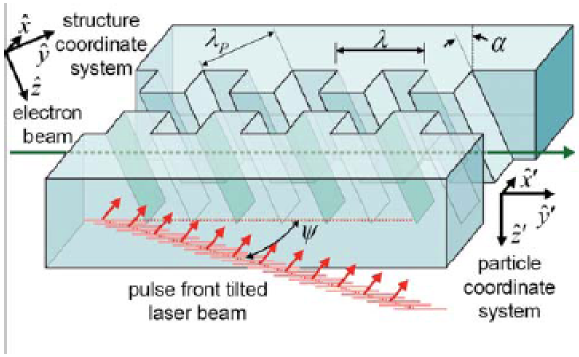


Figure 1: Perspective view of the deflection structure.

A configuration of this type, where the periodic structure is oriented at an angle to the electron beam, satisfies the phase synchronicity condition for a non-zero deflection force acting on a speed-of-light particle [3]. To

Vision for the Future

Our long-term objective is to demonstrate a high-gradient dielectric-based extended accelerator structure on a chip.

The envisioned laser-driven particle accelerator will include the following components:

- A laser-driven electron injector and low-energy accelerator
- Dielectric loaded vacuum channel laser-accelerator sections
- Laser power couplers for the accelerator sections
- Steering and focusing elements
- Beam monitors

Our ultimate objective is the integration of all the parts into a scalable linear accelerator structure that can serve as the basis for a high-energy accelerator.

Photonics Based (Grating) Deflection and Focusing Structure
Tomas Plettner et al 2009

Tomas Plettner[1]

PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 12, 101302 (2009)

Photonic-based laser driven electron beam deflection and focusing structures

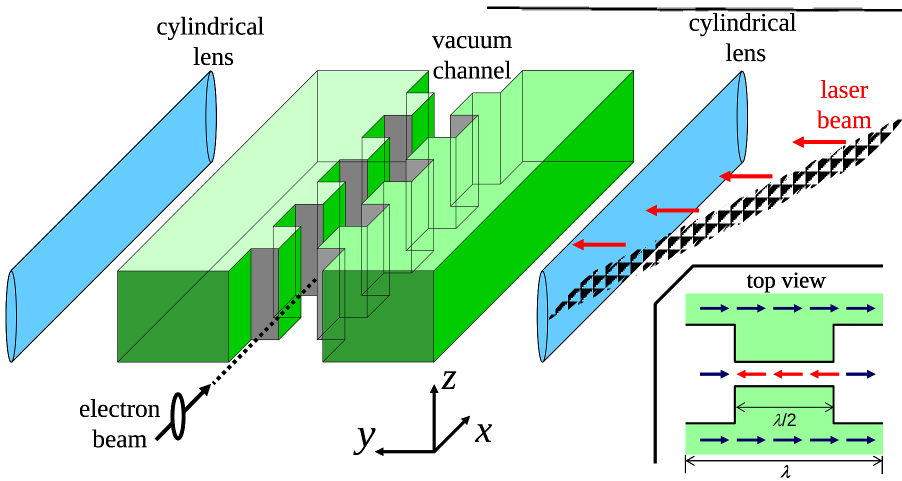
T. Plettner,* R. L. Byer, and C. McGuinness
E.L. Ginzton Laboratories, Stanford University, Stanford, California 94305, USA

P. Hommelhoff
MPQ, Garching, Germany

(Received 22 February 2009; published 26 October 2009)

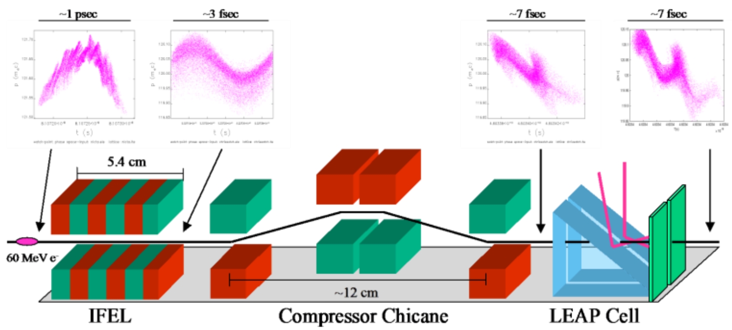
We propose a dielectric photonic structure for ultrafast deflection and focusing of relativistic charged particle beams. The structure is designed to transform a free-space laser beam into a deflection force that acts on the free particles with the same optical phase over a distance of travel that is much greater than the laser wavelength. The proposed structure has a two-dimensional geometry and is compatible with existing nanofabrication methods. Deflection fields of GV/m magnitude and subfemtosecond switching speeds are expected to be possible from these dielectric structures. With these elements a submeter scale extreme ultraviolet synchrotron source seems feasible.

DOI: 10.1103/PhysRevSTAB.12.101302 PACS numbers: 41.75.Jv, 41.75.Ht, 42.25.Bs



Challenges ahead

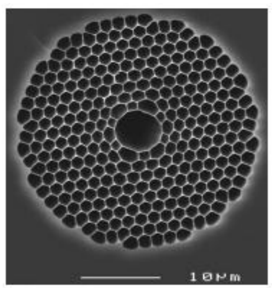
1



Staged acceleration

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

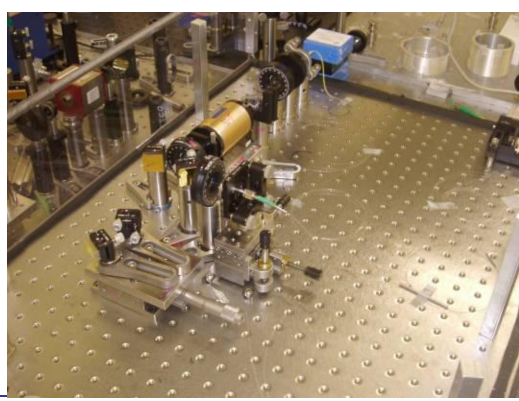
2



Implementation of real accelerator microstructures

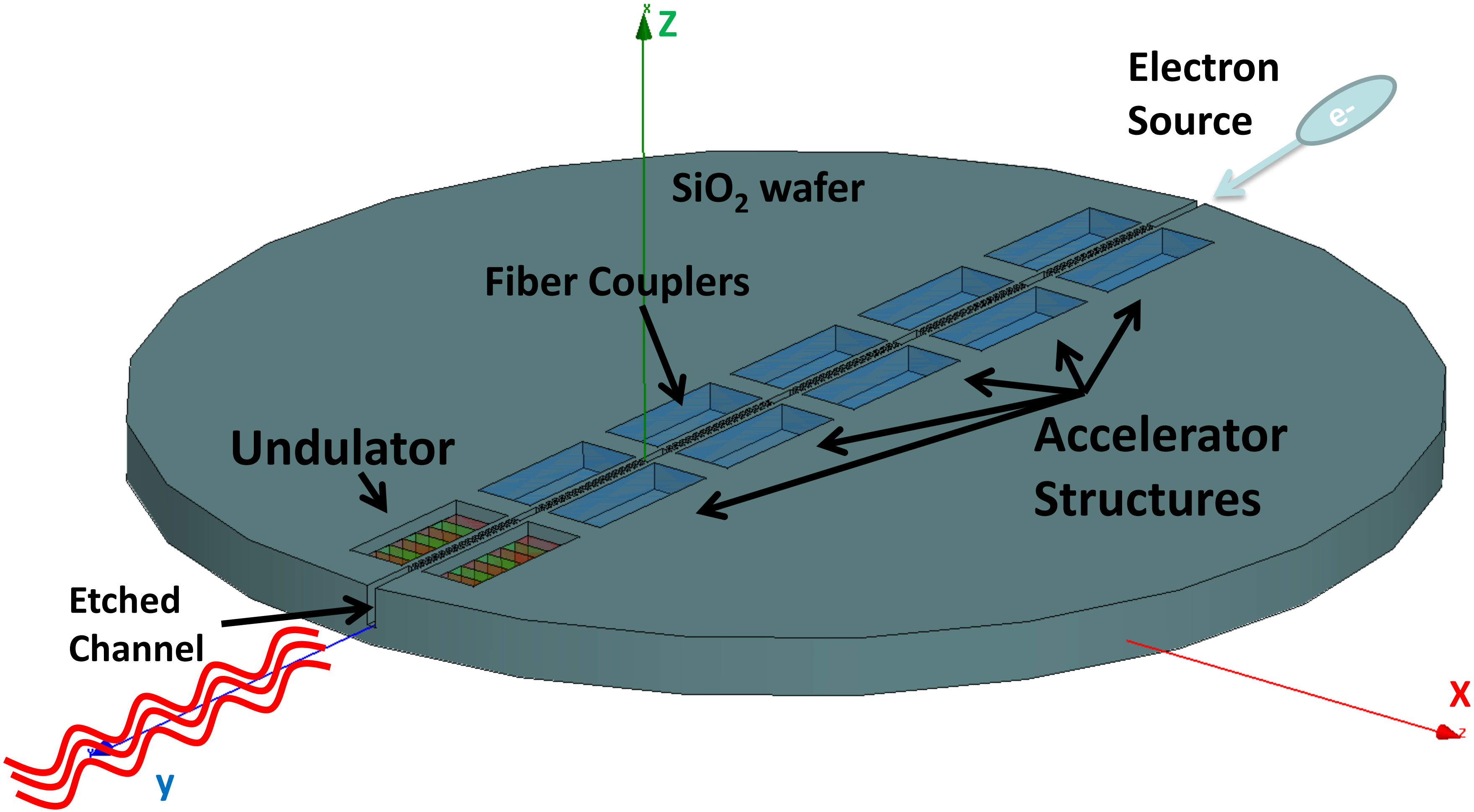
- fabrication
- coupling of the laser
- electron beam transmission
- survival of the radiation environment
- heat removal

3



Laser technology

- wavelength 2 μm
- optical phase control
- wallplug efficiency
- lifetime



Long Term Goal: Phased Accelerator structures on a chip

Contents

Historic Background

The TeV-Energy Physics Frontier

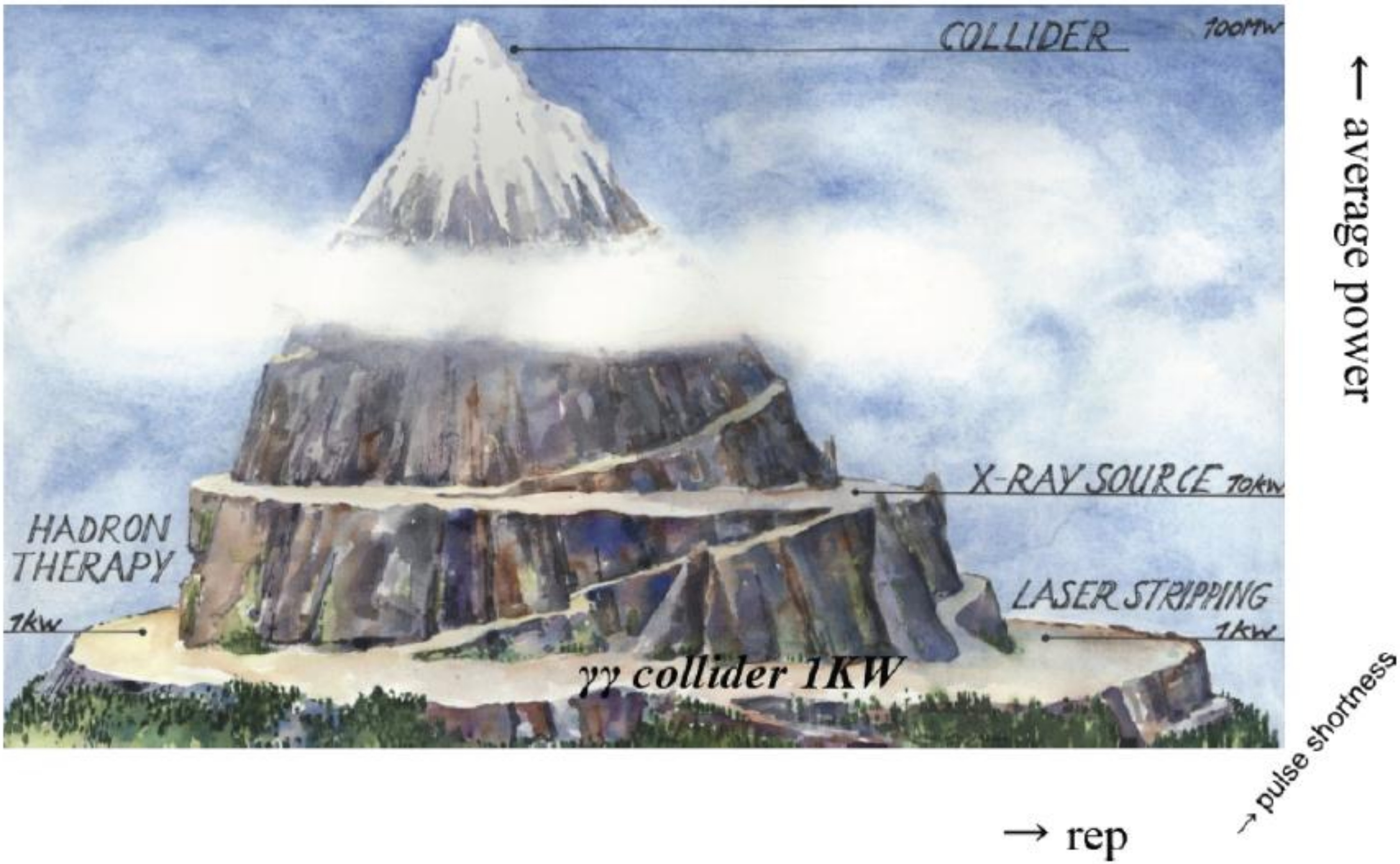
Laser Electron Accelerator Project – LEAP
- HEPL Experiments from 1997 – Nov 2004
- E163 Experiments at SLAC
  - Laser accelerator structures
  - Inverse FEL for electron pulse compression

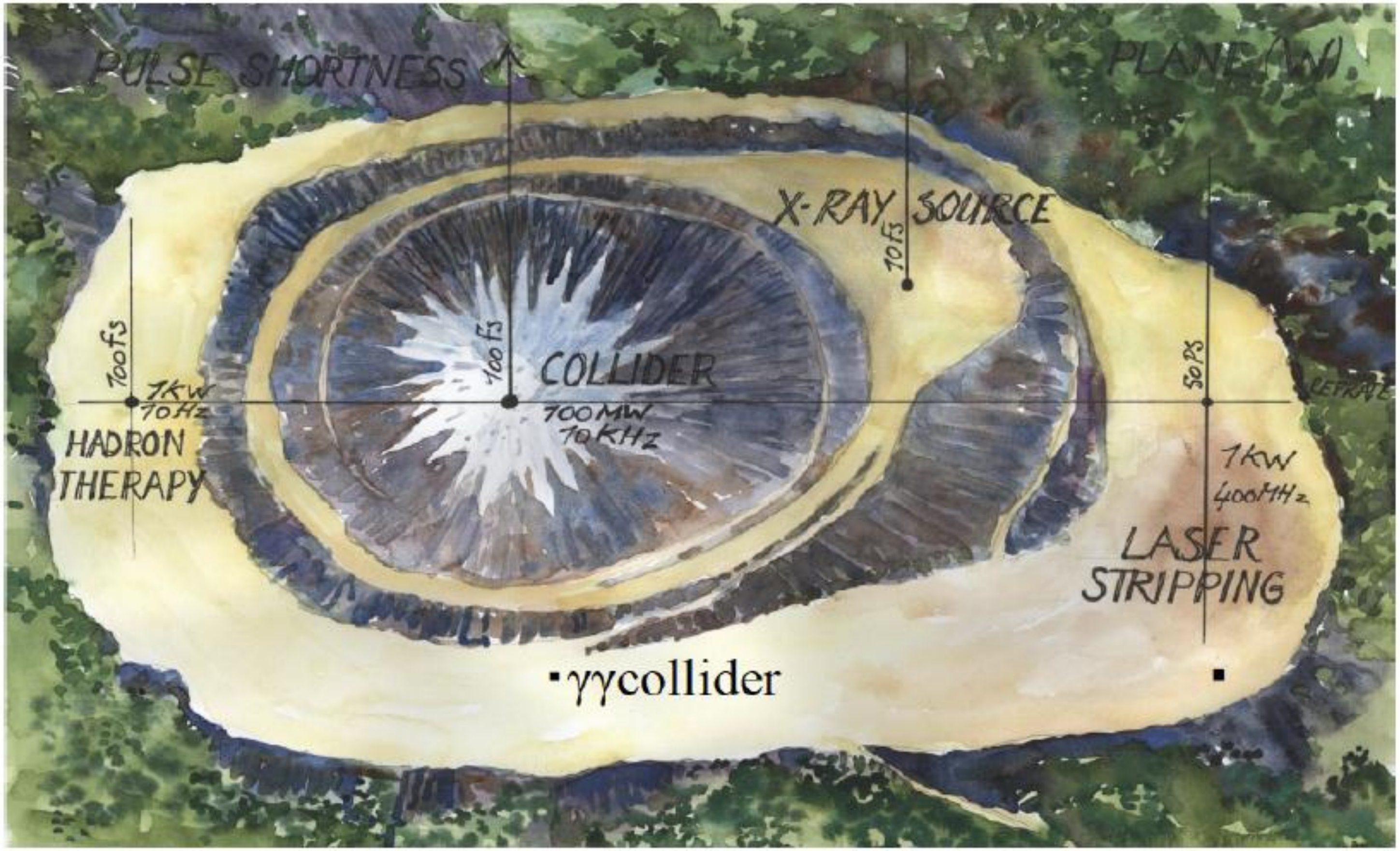
Coherent X-ray laser Generation
- Components of the X-ray laser
  - Dielectric Accelerator and Undulator Structures
  - FEL gain and efficiency

Future Challenges
- **DARPA program: DLAs to DLA driven FEL**
- **Enable TeV scale physics affordable cost**


HIGH POWER
LASER TECHNOLOGY
FOR ACCELERATORS
A JOINT INTERNATIONAL COMMITTEE ON FUTURE ACCELERATORS (ICFA) AND
INTERNATIONAL COMMITTEE ON ULTRAHIGH INTENSITY LASERS (ICUIL)
WHITEPAPER

Goal: evaluate prospects for laser accelerators





Climbing Mt. Parametrius

Shown here are more-detailed versions of the cover illustration, indicating the relative difficulty of the laser applications discussed in this whitepaper. Colliders for high-energy physics represent the presently aspirational pinnacle of laser power (*top*), but other applications are demanding in other parameters such as short pulses and repetition rate. Illustrations courtesy T. Tajima, University of München, DE.

Contributors

Joint Task Force Members

The 2009-2011 membership of the JTF consists of members of the ICFA Beam Dynamics Panel (Ralph Assman, ICFA Beam Dynamics Panel chair Weiren Chou, Ingo Hofmann, and Kaoru Yokoya); the ICFA Advanced and Novel Accelerator Panel (Bruce Carlsten, Dino Jaroszynski, Wim Leemans, Akiro Noda, James Rosenzweig, Siegfried Schreiber and Advanced and Novel Accelerator Panel chair Mitsuru Uesaka); and ICUIL (Chris Barty, Paul Bolton, Robert Byer, Almantas Galvanauskas, Wim Leemans, and Wolfgang Sandner). Leemans is the chair of the JTF.

Workshop Participants

In addition to the task force members, the following scientists contributed to this document: Vincent Bagnoud, Jean-Paul Chambaret, Jean-Christophe Chanteloup, John Collier, Brigitte Cros, Jay Dawson, Hartmut Eickhoff, Eric Esarey, Erhard Gaul, Erion Gjonaj, Thomas Haberer, Manuel Hegelich, Kiminori Kondo, Thomas Kuehl, Yun Liu, Matthieu Somekh, Darren Rand, Tor Raubenheimer, David Richardson, Roland Sauerbrey, Mike Seidel, Frank Stephan, Thomas Stoehlker, Toshi Tajima, Franz Tavella, Guenther Traenkle, Andreas Tuennermann, Bill White, Ingo Will, Xueqing Yan, Michalis Zervas, Bernhard Zielbauer.

Goal: Publish Workshop White Paper by end of 2011

Potential DLA-based collider parameters match well to general collider goals

		ILC Nom.	DLA
E_cms	GeV	1000	1000
Bunch Charge	e	2.00E+10	**1.00E+04**
# bunches/train	#	2820	**375**
train repetition rate	MHz	5.00E-06	**20**
final bunch length	psec	1.00	**1**
design wavelength	micron	230609.58	**0.8**
Invariant Emittances	micron	10/0.04	**1e-04/1e-04**
I. P. Spot Size	nm	554/3.5	0.5/0.5
Enh Lumi/ top1%	**/cm^2/s**	**4.34E+34**	**4.58E+34**
Beam Power	MW	22.6	6.0
Wall-Plug Power	MW	104.0	120.1
Gradient	MeV/m	30	830
Total Linac Length	km	33.3	1.2

E. Colby

Selected publications

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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)

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