Laser Accelerator on a Chip (>300MeV/m)

A Path to TeV Energy Scale Physics & Attosecond X-ray Lasers

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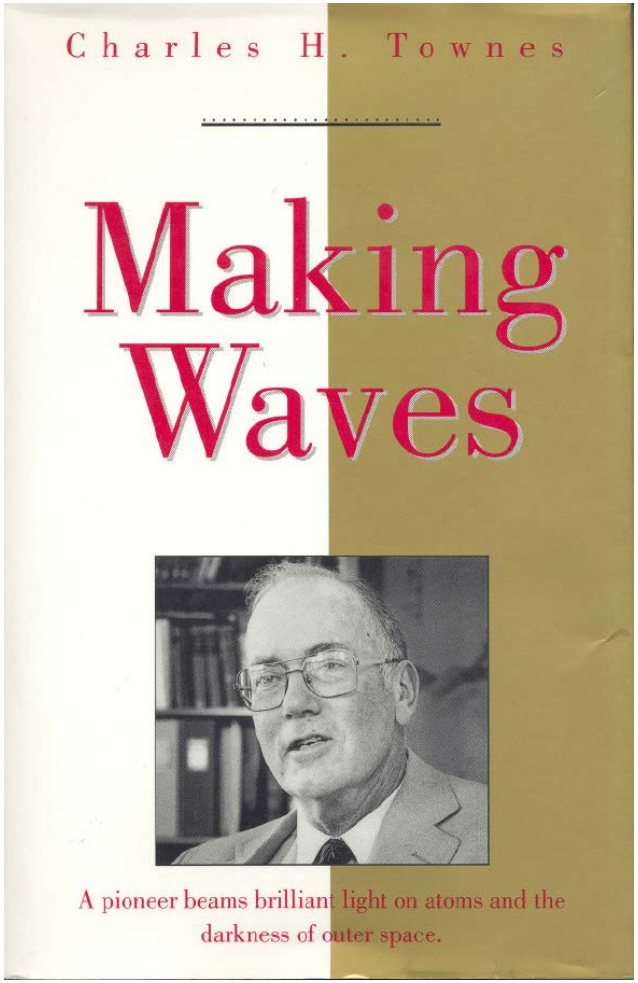
Abstract

We report on the first observation of high-gradient acceleration of electrons in a lithographically fabricated dielectric micro-structure driven by a modelocked Ti:sapphire laser. This approach shows promise for scaling to the energy and luminosity required for TeV energy scale physics and Attosecond X-ray Lasers.

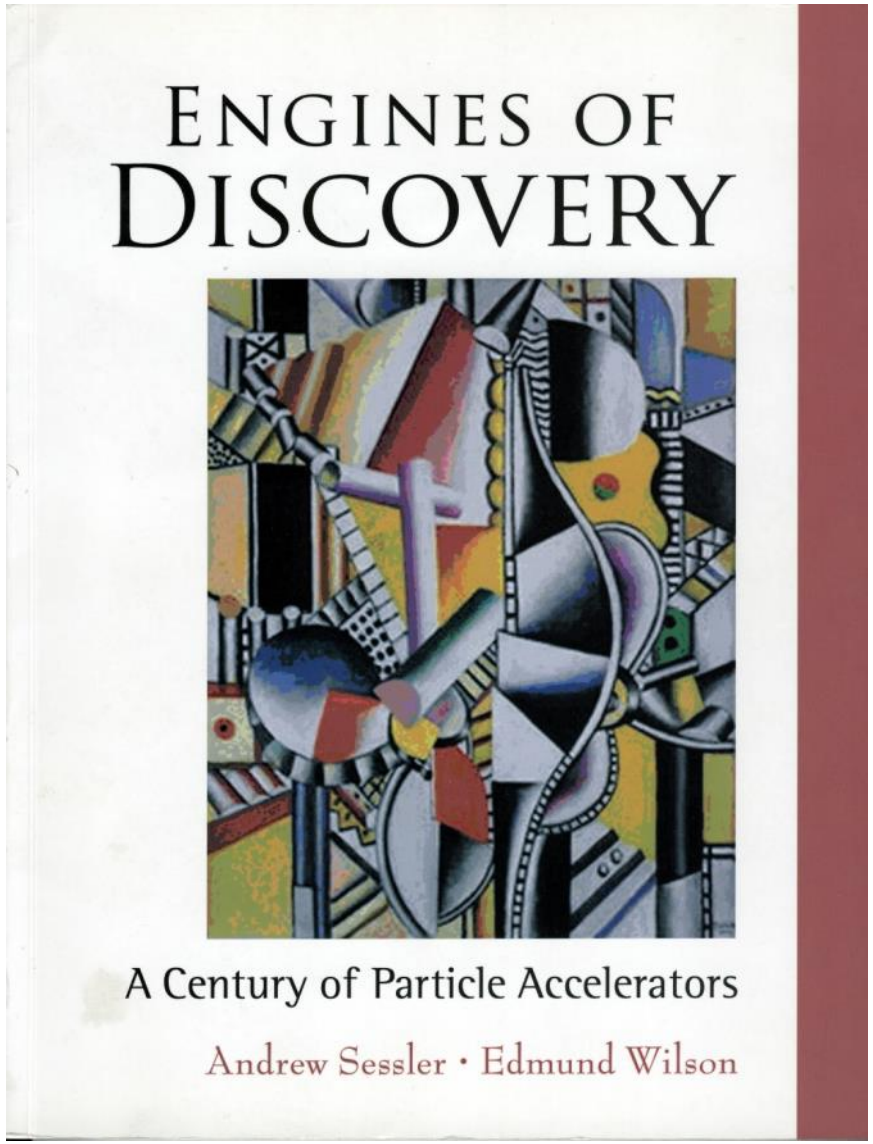
Fermi Lab Colloquium
January 29, 2014
Batavia, Illinois

Meeting the Challenges of laser accelerators for the 21st Century



Introduction	*Early Progress in Laser Accelerators*
Success!	*Laser Acceleration in Dielectric Structures*
Future Directions	*Laser Accelerator driven X-ray lasers*

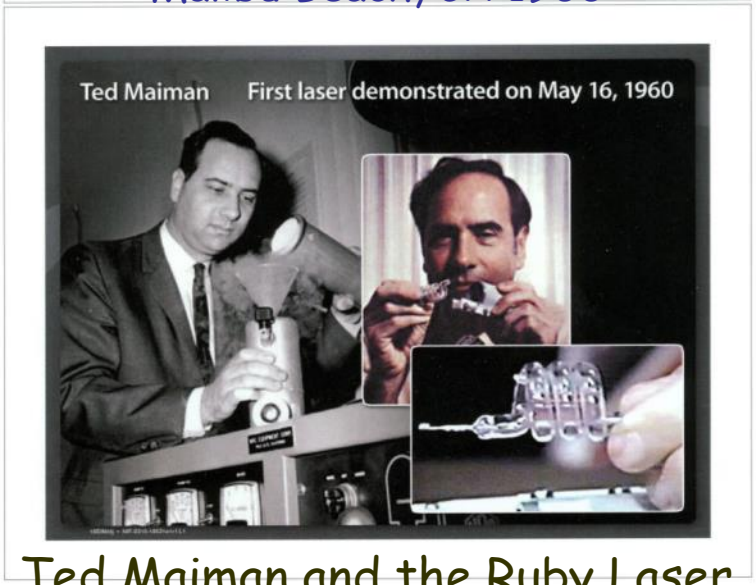
Re: The best 30seconds of my last ~ 5 years!



First came accelerators

Fifty years of Lasers

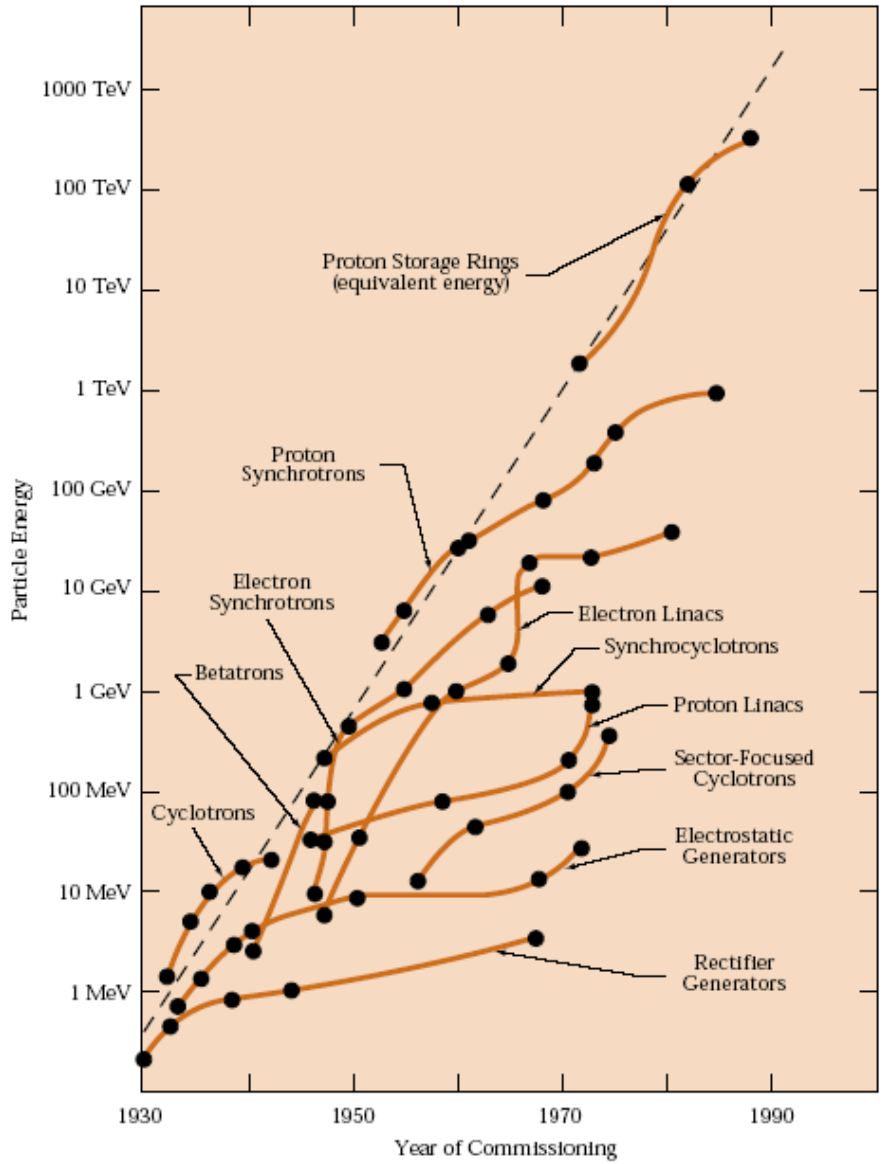
Malibu Beach, CA 1960



Ted Maiman and the Ruby Laser

then came Lasers

The Livingston plot – 1954
Innovation leads to exponential progress



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

Progress is marked by the saturation of the current technology followed by the adoption of **innovative new approaches** to particle acceleration led by scientists with a **vision** for the future and the **passion** to make it happen.

It is clear that there is a need for innovation in the next generation of advanced accelerators.

Will 2014 see a commitment to explore innovative new approaches to laser driven linear accelerators?

The Los Alamos Laser Acceleration of Particles Workshop and Beginning of the Advanced Accelerator Concepts Field

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University of California Los Angeles
Los Angeles, CA 90095, USA

Abstract. The first Advanced Acceleration of Particles–AAC–Workshop (actually named Laser Acceleration of Particles Workshop) was held at Los Alamos in January 1982. The workshop lasted a week and divided all the acceleration techniques into four categories: near field, far field, media, and vacuum. Basic theorems of particle acceleration were postulated (later proven) and specific experiments based on the four categories were formulated. This landmark workshop led to the formation of the advanced accelerator R&D program in the HEP office of the DOE that supports advanced accelerator research to this day. Two major new user facilities at Argonne and Brookhaven and several more directed experimental efforts were built to explore the advanced particle acceleration schemes. It is not an exaggeration to say that the intellectual breadth and excitement provided by the many groups who entered this new field provided the needed vitality to then recently formed APS Division of Beams and the new online journal Physical Review Special Topics- Accelerators and Beams. On this 30th anniversary of the AAC Workshops, it is worthwhile to look back at the legacy of the first Workshop at Los Alamos and the fine groundwork it laid for the field of advanced accelerator concepts that continues to flourish to this day.

Keywords: Advanced Accelerators, Laser Wakefield, Plasma Wakefields, Acceleration Theorems, Inverse Cherenkov, Inverse Free-Electron Laser, Near Field Acceleration, Far Field Acceleration.
PACS: 52.38 Kd, 52.59 Rz, 52.59 Sa, 41.60-m, 41.75 Hz, 41.75 Lx, 41.75 Jv

Although this is the 30th anniversary of the Advanced Accelerator Concepts (AAC) Workshop, our story actually began in 1980. The impetus for this adventure is best illustrated by this graph of the increase in energy of electron accelerators since their inception. The exponential energy increase of these accelerators based on microwave technology had saturated by 1980. At the time the two largest machines were the Tevatron –under construction at Fermilab and the Large Electron Positron Collider, LEP at CERN. Both were circular machines. The Superconducting Super Collider, SSC and the Large Hadron Collider, LHC both proton synchrotrons, were in the planning phase.

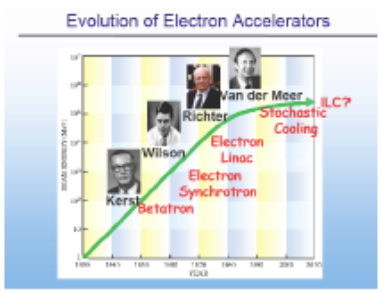

FIGURE 1. The exponential growth in the energy of electron machines based on

It was already recognized that the future accelerators

Plasma Accelerators at the Energy Frontier and on Tabletops

Charged particles surfing on electron density waves in plasmas can experience enormous accelerating gradients.

Chandrashekhar Joshi and Thomas Katsouleas

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d are expected
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ar, they should
unearth new classes of particles and enhance our understanding of the asymmetry between matter and antimatter,

(See the articles in PHYSICS TODAY by Andrew Sessler, January 1988, page 26, and by Jonathan Wurtele, July 1994, page 33.)

Small low-energy accelerators

The impact that much smaller low-energy particle accelerators have had on other branches of science and technology has been equally impressive. Accelerators are being used, among other applications, for materials science, structural biology, nuclear medicine, fusion research, food sterilization, transmutation of nuclear waste, and cancer therapy. The requirements for such machines are very different from those of high-energy accelerators, and they vary from one application to another. Nonetheless, many low-energy applications would benefit from extremely compact "tabletop accelerators" that could provide beams of GeV electrons, protons, or ions with energies of a few hundred MeV per unit charge.

In this article, we survey new approaches to charged-particle acceleration by collective fields in plasmas. These approaches show considerable promise for realizing plasma accelerators at the energy frontier as well as tabletop electron and ion accelerators. The plasmas would not only provide unprecedentedly high acceleration gradients; they would also serve to focus the accelerated beams down to very small spot sizes.

Instead of using RF waves to accelerate charged particles, as conventional accelerators do, plasma accelerators use plasma-oscillation waves excited by lasers or by "driver beams" of charged-particles. The accelerating gradients and focusing strengths that have been demonstrated in plasma experiments have been orders of magnitude greater than those achieved thus far by rf accelerators. The greater the accelerating gradient—if it can be maintained over sufficient distance—the shorter

Plasma and Fusion Research: Review Articles Volume 4, 045 (2009)

Surfing Plasma Waves: A New Paradigm for Particle Accelerators*)

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(Received 26 August 2008 / Accepted 6 February 2009)

Accelerator-based experiments have produced key breakthroughs in our understanding of the physical world. New accelerators, to explore the frontiers of Tera-scale Physics, appear possible, based on concepts developed over the last three decades in multi-disciplinary endeavors. The Plasma-Based Particle Accelerator is one concept that has made spectacular advances in the last few years. In this scheme, electrons or positrons gain energy by surfing the electric field of a plasma wave that is produced by the passage of an intense laser pulse or an electron beam through the plasma. This talk reviews the principles of this new technique and prognosticates how it is likely to impact science and technology in the future.

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Keywords: plasma wakefield accelerator, laser, relativistic electron beam, tera-scale physics

DOI: 10.1585/pfr.4.045

1. Introduction

More than a decade before Moore's law, depicting the number of transistors on an integrated circuit versus time was postulated, Livingston had graphed a similar relationship for maximum energies produced by high-energy particle accelerators. The updated version of the plot depicted in Fig. 1 came to be known as the Livingston curve. Since its first appearance in 1954, the Livingston curve has been the barometer of the future vitality of the field of high-energy physics much in the same way as Moore's law has been for the semiconductor industry. As did Moore's law, the Livingston curve showed that between 1930 and 1980 the maximum energy of electron accelerators roughly increased by a factor 10 per decade while the cost of increasing the energy dramatically went down roughly the same factor. The exponential increase depicted by the Livingston curve was possible because of continuous technological innovations for acceleration and focusing of charged particles as the existing technologies

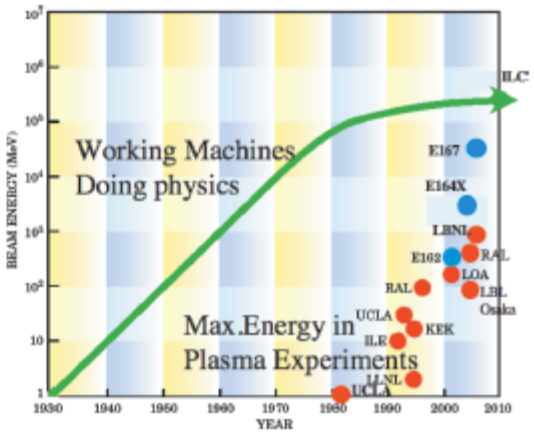

Fig. 1 Accelerator Moore's law. The exponential growth of electron beam energy, first noted by Livingston (green curve), began tapering off around 1980 as conventional

Surfing Plasma Waves

Experiments using lasers to excite the plasma wakefields have produced very impressive results. These have shown that electron beams with low divergence angles and narrow energy spreads can be generated with energies in the 1 GeV [9–11] range from plasma in a distance of about one centimeter. The titanium-sapphire lasers needed to produce such beams have tens of terawatts of power but the accelerator itself is extremely compact. The beam parameters are well suited for many applications that require "table-top" accelerators including in nuclear medicine, cancer therapy, structural biology and material science [12].

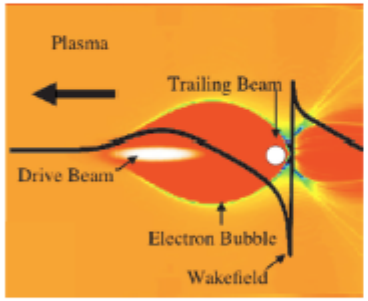

Fig. 3 Three dimensional computer simulation of an extremely nonlinear wakefield (black curve) excited in plasma by either an electron or a photon drive beam. The plasma electrons have been completely blown out of the red region by the drive beam. A second distinct trailing beam is placed where the wakefield is negative and is accelerated by it. The arrow shows the direction of the drive beam.

is no relative motion between the accelerating beam electrons (their mass is increased) and those that loose energy (their mass is reduced).

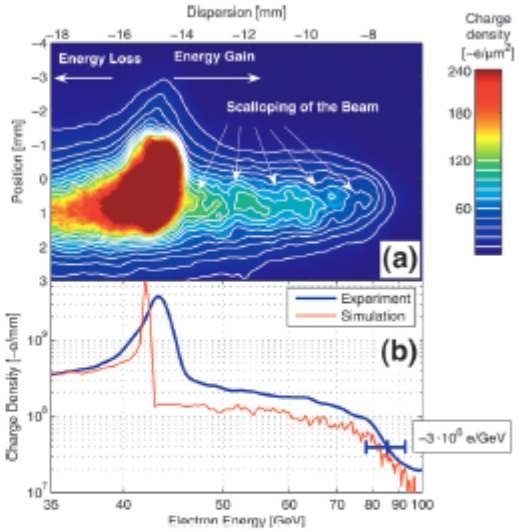

Fig. 4 (a) The energy spectrum of the initially 42 GeV electrons after passing through an approximately one meter long plasma observed in recent experiments at SLAC (b) A comparison between the measured spectrum and the simulated spectrum showing that some electrons are accelerated out to 85 GeV energy. (Blumenfeld *et al.*, Nature vol.445, p.741, 2007)

045-3

Mike Downer – Laser Wakefield Accelerator

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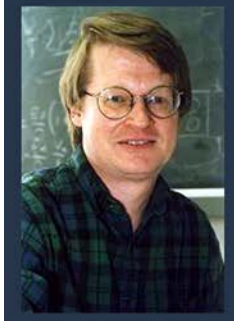

News

Downer group sets world record in laserplasma acceleration: 2 GeV

Prof. Downer wins Piper Award for Teaching Excellence

Downer lab intranet
(VPN connection required outside RLM)

We are an interdisciplinary experimental group overlapping atomic, plasma and condensed matter physics dedicated to measuring ultrafast phenomena at high light intensities

Prof. Mike Downer, Director

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College of Natural Sciences Distinguished Professor
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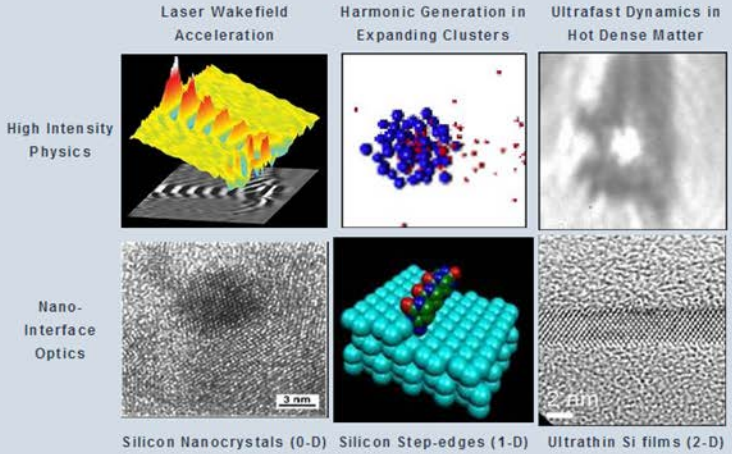

FemtoLab | Particle Accelerator That Ca | Quasi-monoenergetic laser | Google

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Quasi-monoenergetic laser-plasma acceleration of electrons to 2 GeV

Xiaoming Wang, Rafal Zgadzaj, Neil Fazel, Zhengyan Li, S. A. Yi, Xi Zhang, Watson Henderson, Y.-Y. Chang, R. Korzekwa, H.-E. Tsai, C.-H. Pai, H. Quevedo, G. Dyer, E. Gaul, M. Martinez, A. C. Bernstein, T. Borger, M. Spinks, M. Donovan, V. Khudik + *et al.*

Affiliations | Contributions | Corresponding author

Nature Communications **4**, Article number: 1988 | doi:10.1038/ncomms2988

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Abstract

Abstract • References • Author information

Laser-plasma accelerators of only a centimetre's length have produced nearly monoenergetic electron bunches with energy as high as 1 GeV. Scaling these compact accelerators to multi-gigaelectronvolt energy would open the prospect of building X-ray free-electron lasers and linear colliders hundreds of times smaller than conventional facilities, but the 1 GeV barrier has so far proven insurmountable. Here, by applying new petawatt laser technology, we produce electron bunches with a spectrum prominently peaked at 2 GeV with only a few per cent energy spread and unprecedented sub-milliradian divergence. Petawatt pulses inject ambient plasma electrons into the laser-driven accelerator at much lower density than was previously possible, thereby overcoming the principal physical barriers to multi-gigaelectronvolt acceleration: dephasing between laser-driven wake and accelerating electrons and laser pulse erosion. Simulations indicate that with improvements in the laser-pulse focus quality, acceleration to nearly 10 GeV should be possible with the available pulse energy.

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EMBL Conference: Microglia: Guardians of the Brain
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Meyerhofstr. 1, 69117 Heidelberg, Germany

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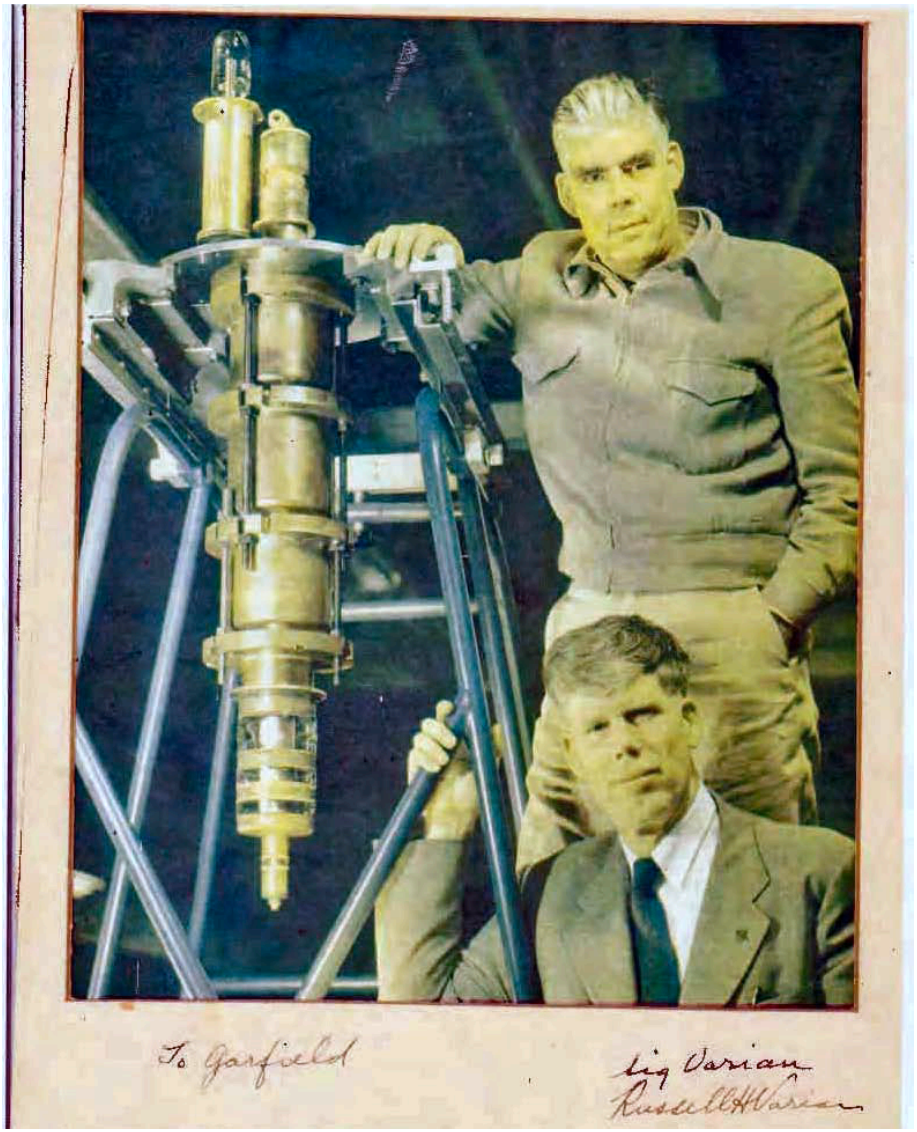
Developments in laser-driven plasma

Sig and Russ Varian with Klystron



Microwave Laboratory

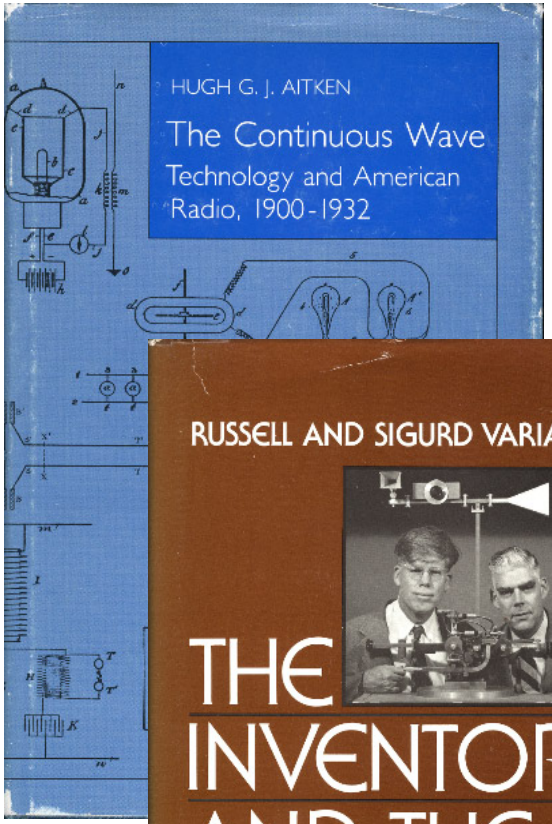
First Klystron 1937

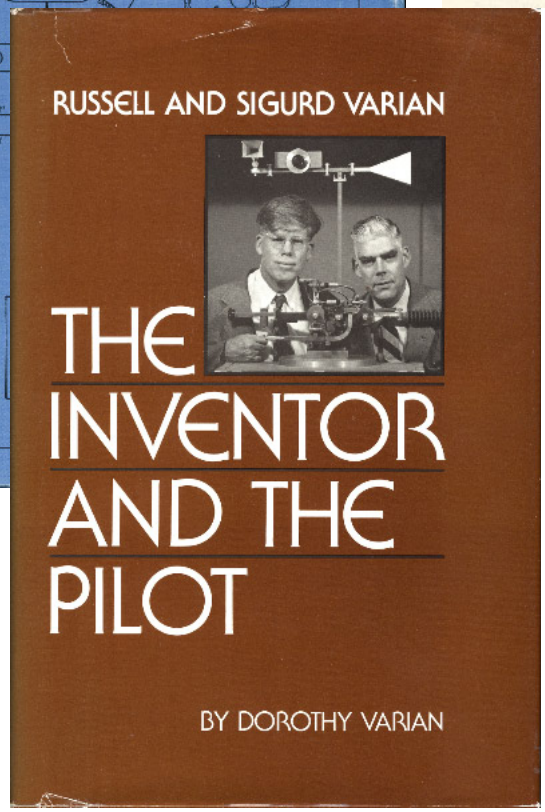
First Linear Accelerator 1947

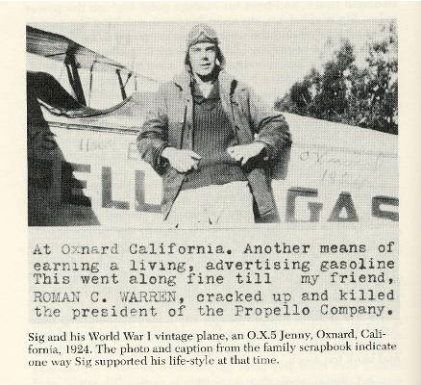
10 cells or 1m length

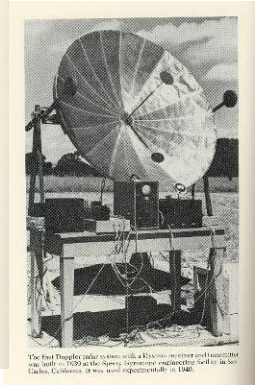
2MeV/m gradient

From Radio to Microwaves and Radar and on to Lasers

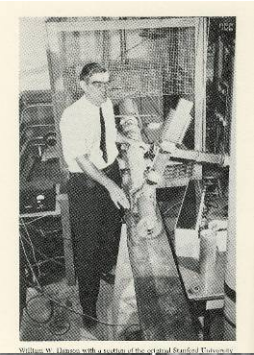








Doppler radar with klystron
-San Carlos, CA 1939



Varian Associates Staff
San Carlos CA 1948

The Mark I Linear Accelerator 1947

1meter – 2MeV/m gradient

A few rules of the game

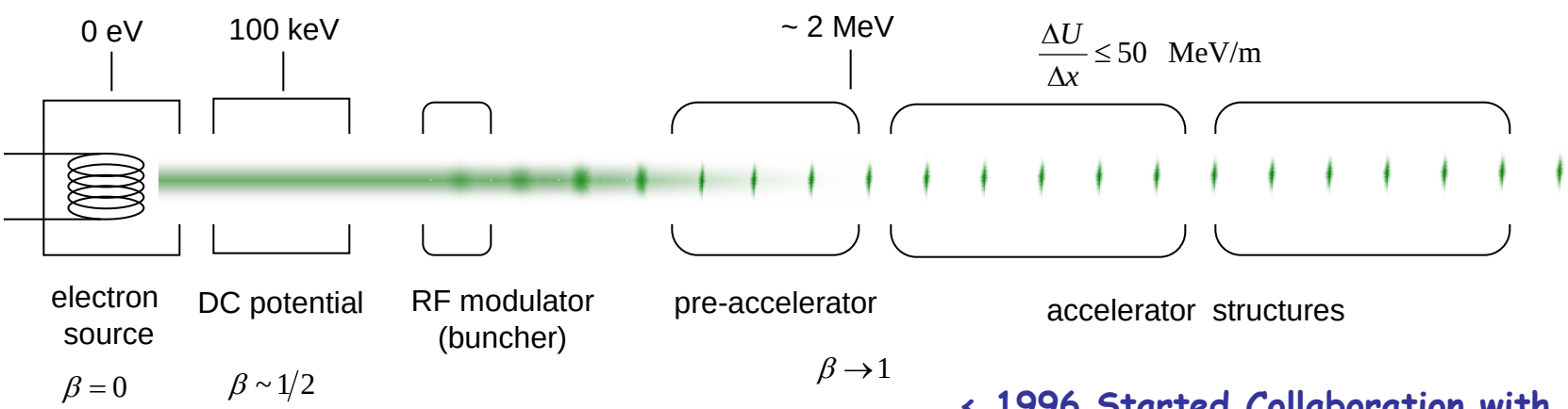
"An accelerator is just a transformer" – Pief Panofsky

"All accelerators operate at the damage limit" - Pief

"To be efficient, the accelerator must operate in reverse"
(Impedance Matching) - Ron Ruth, SLAC

" It is not possible to accelerate electrons in a vacuum"
Lawson - Woodward theorem

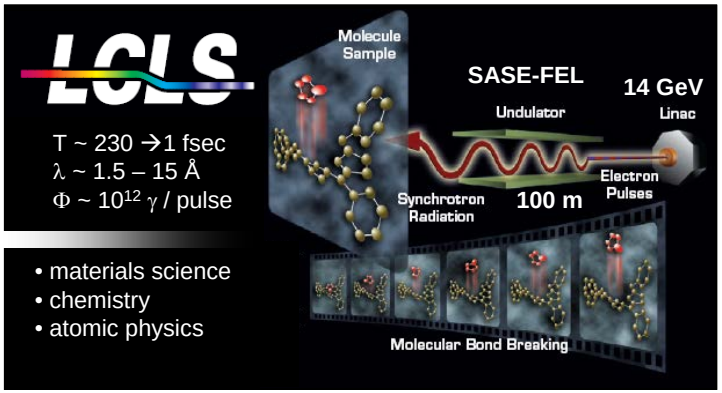
"An accelerator requires structured matter – a waveguide – to efficiently couple the field to the electrons" Bob Siemann

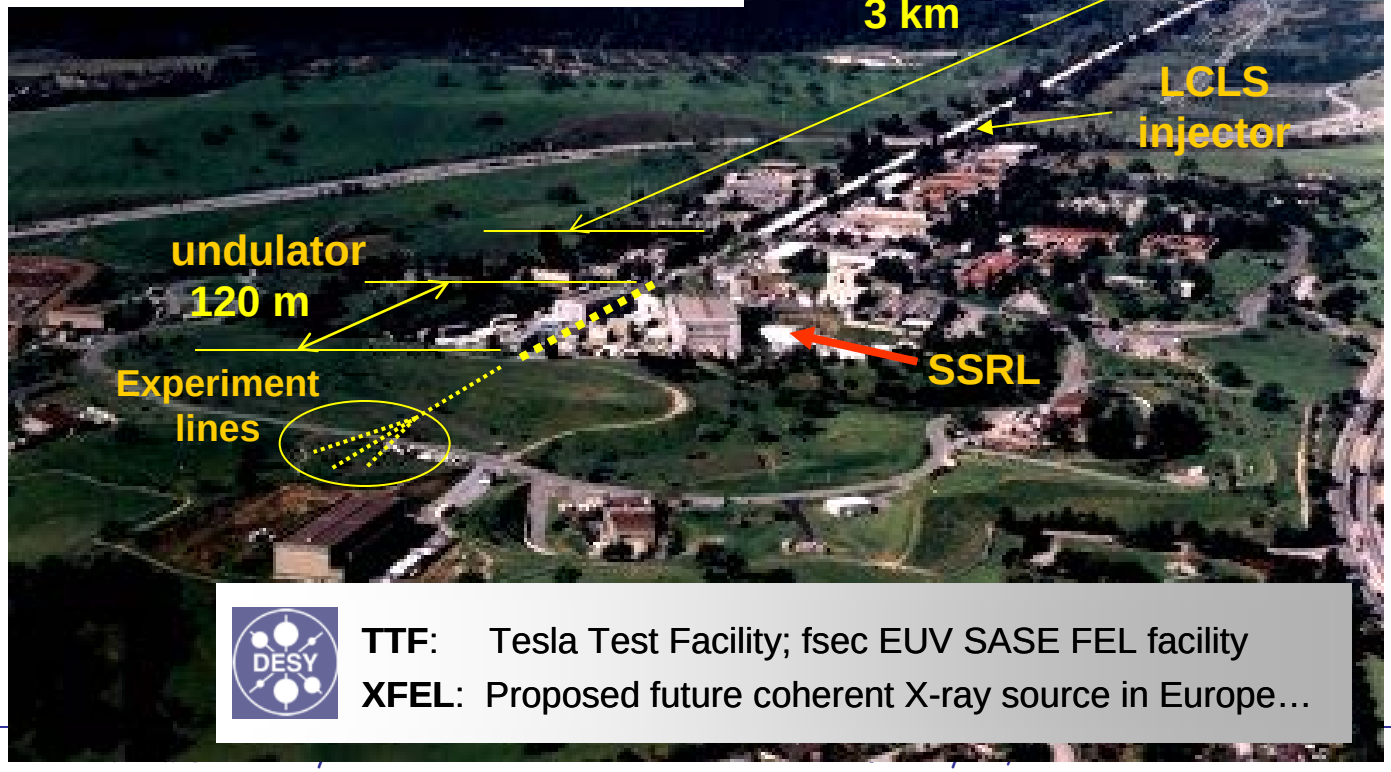


< 1996 Started Collaboration with SLAC >

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

RF-accelerator driven SASE FEL at SLAC - April 2009





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

LCLS properties

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

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

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

Emergence of new technologies make Laser Acceleration Possible

Byer Group

Leveraging investment in telecom

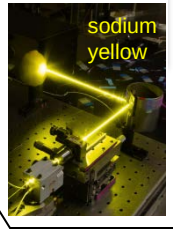
efficient pump diode lasers

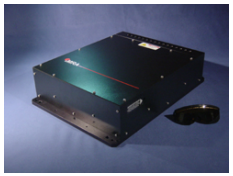
nLIGHT

60 W/bar, 50% electr. efficiency

30 W/bundle, 40% electr. efficiency

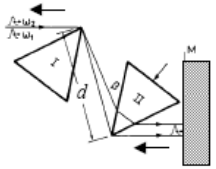
high power fiber lasers

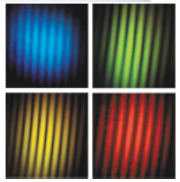


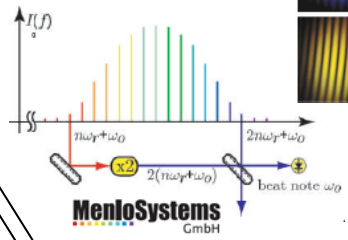


IMRA mJ 500 fsec laser

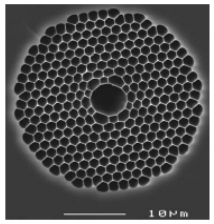
ultrafast laser technology

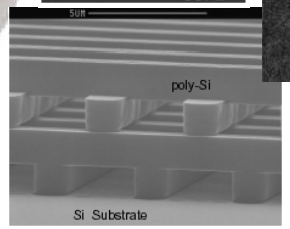






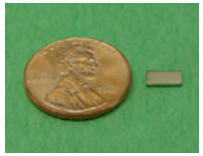
nanotechnology



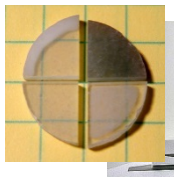


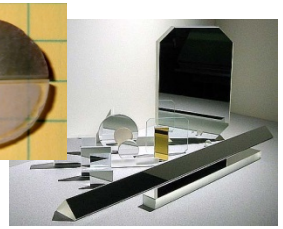
new materials

New ceramics

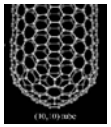


high strength magnets **Nd:Fe**





high purity optical materials and high strength coatings



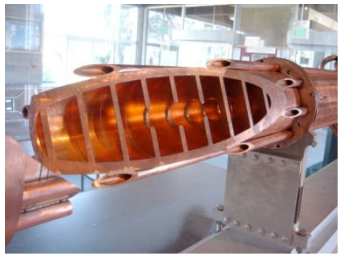
nano-tubes

Dielectric Laser-driven Accelerators (DLA)

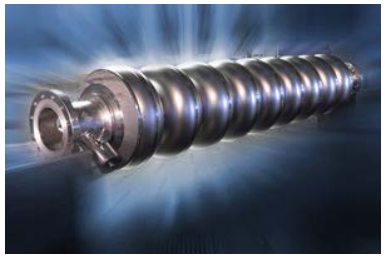
*The Economist, Oct 19th 2013

(R)Evolutionary Advancement

Traditional Manufacturing



Room temp.

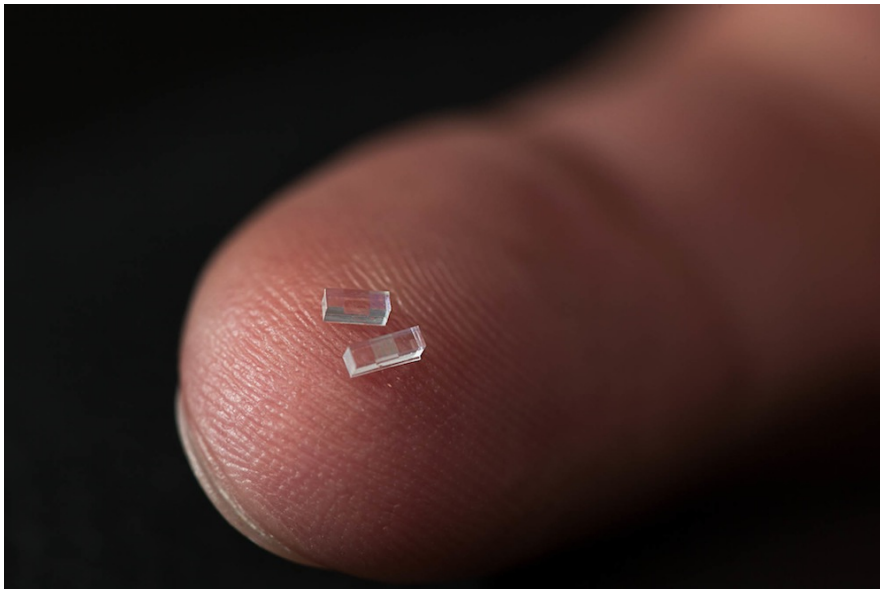


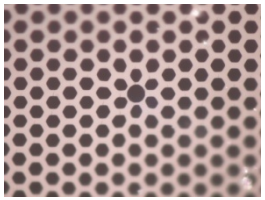
Super conducting

E_{acc} = 30 MV/m
λ = 10 cm

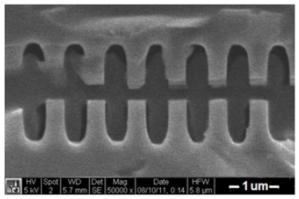
10E-4

Semiconductor Manufacturing

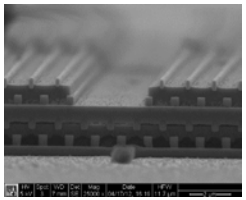




Fibers



Gratings



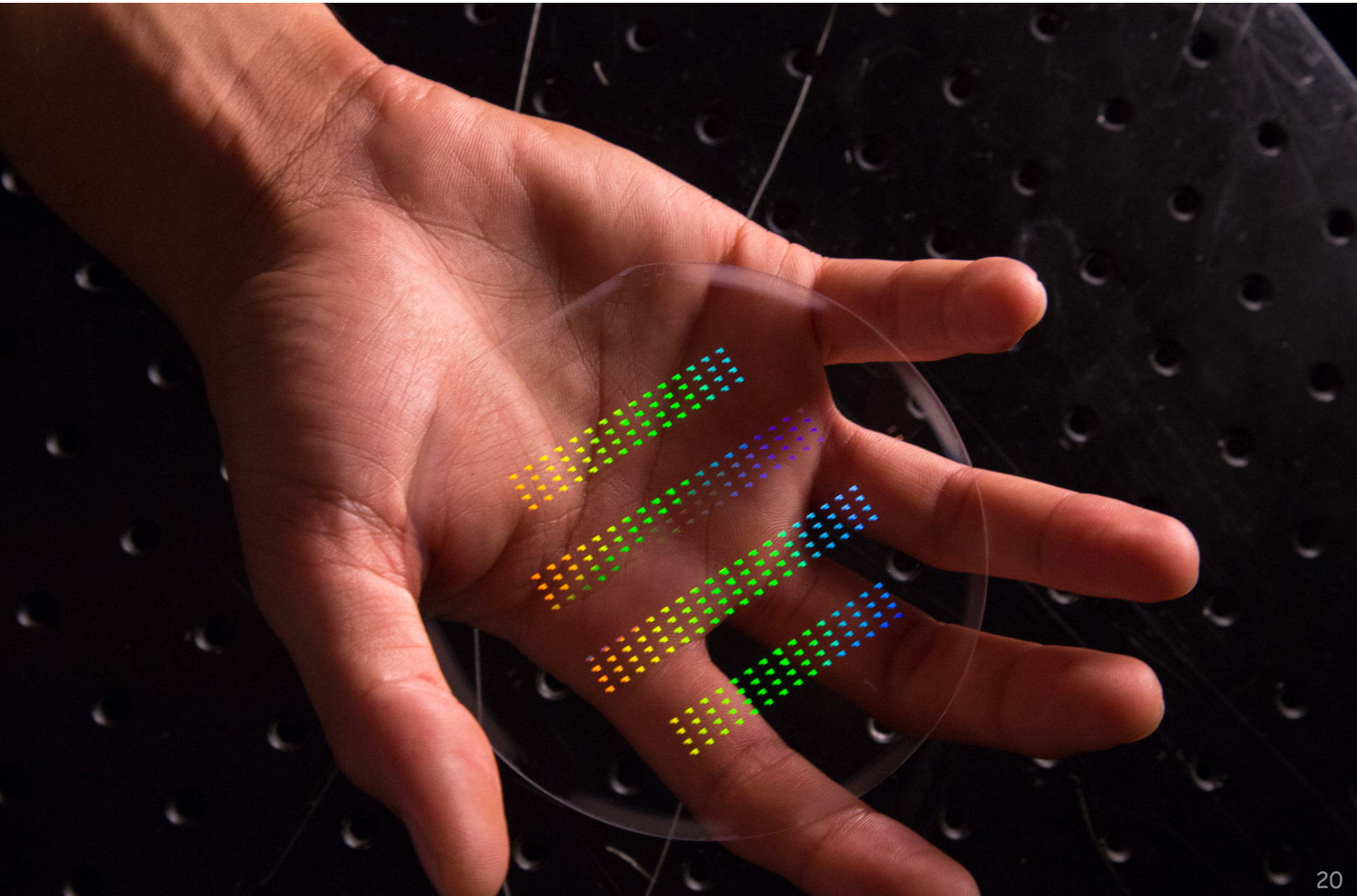
Crystals

E_{acc} = 2 GV/m*
λ = 1-10 μm

* in theory

240 Dielectric Laser Accelerators on a wafer

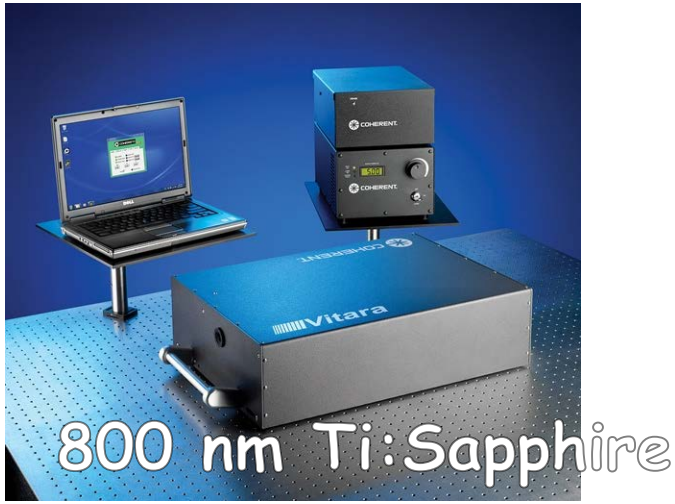
Byer Group

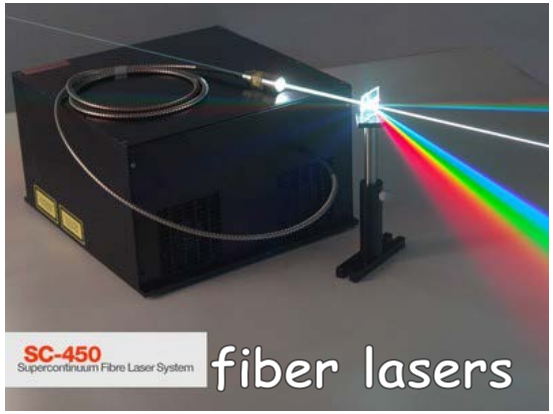


Laser-Powered

Byer Group

Relatively inexpensive and commercially developed!



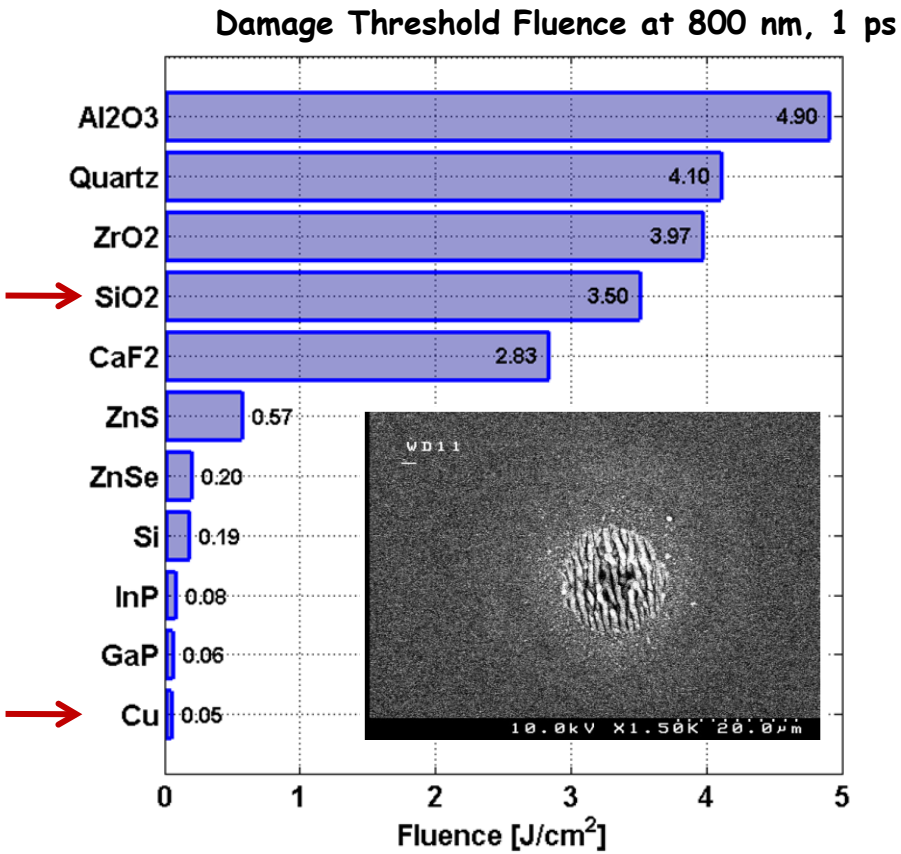


Dielectrics are highly resilient to damage

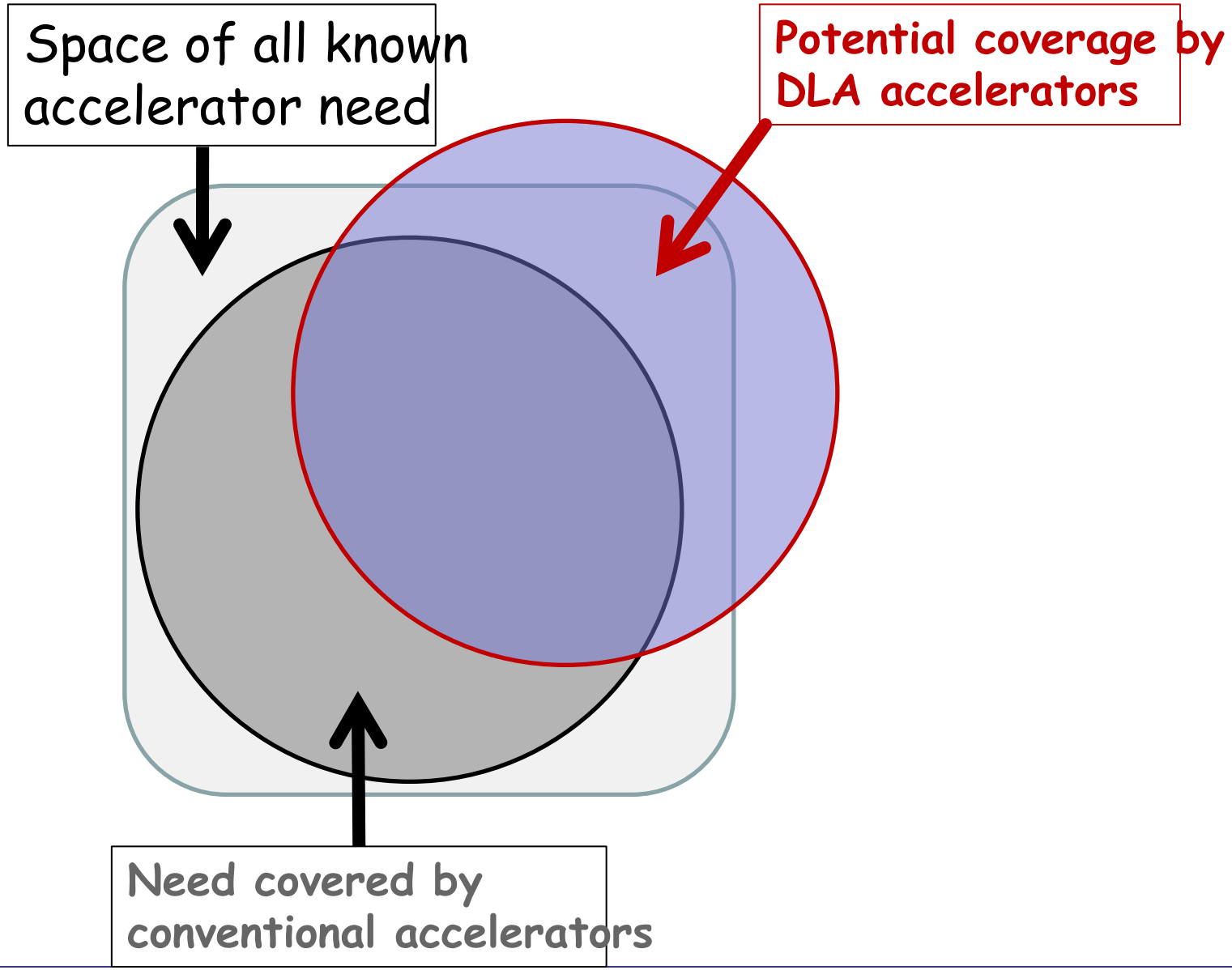
Proceedings of 2011 Particle Accelerator Conference, New York, NY, USA MOP095

EXPERIMENTAL DETERMINATION OF DAMAGE THRESHOLD CHARACTERISTICS OF IR COMPATIBLE OPTICAL MATERIALS*

K. Soong†, R.L. Byer, C. McGuinness, E. Peralta, Stanford University, Stanford, CA 94305, USA
E. Colby, SLAC National Accelerator Laboratory, Menlo Park, CA 94025, USA



Applications

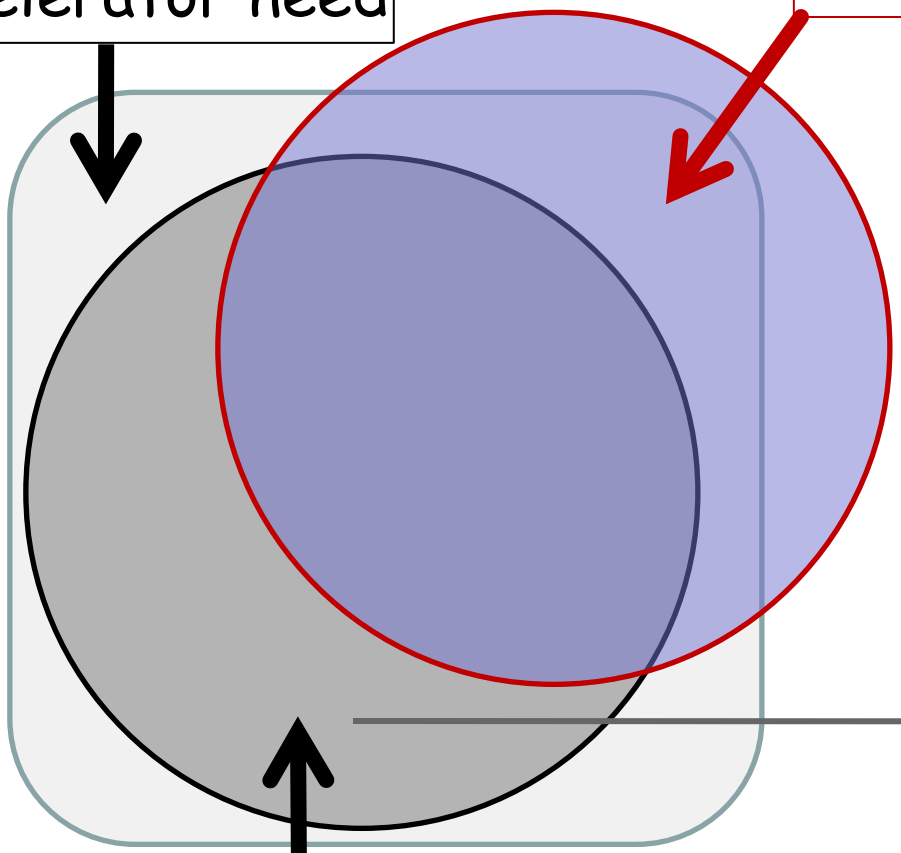


Applications

Byer Group

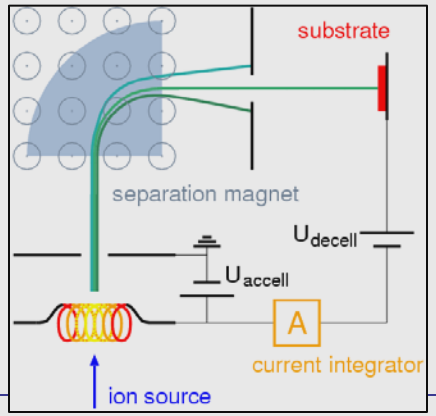
Space of all known accelerator need

Potential coverage by DLA accelerators

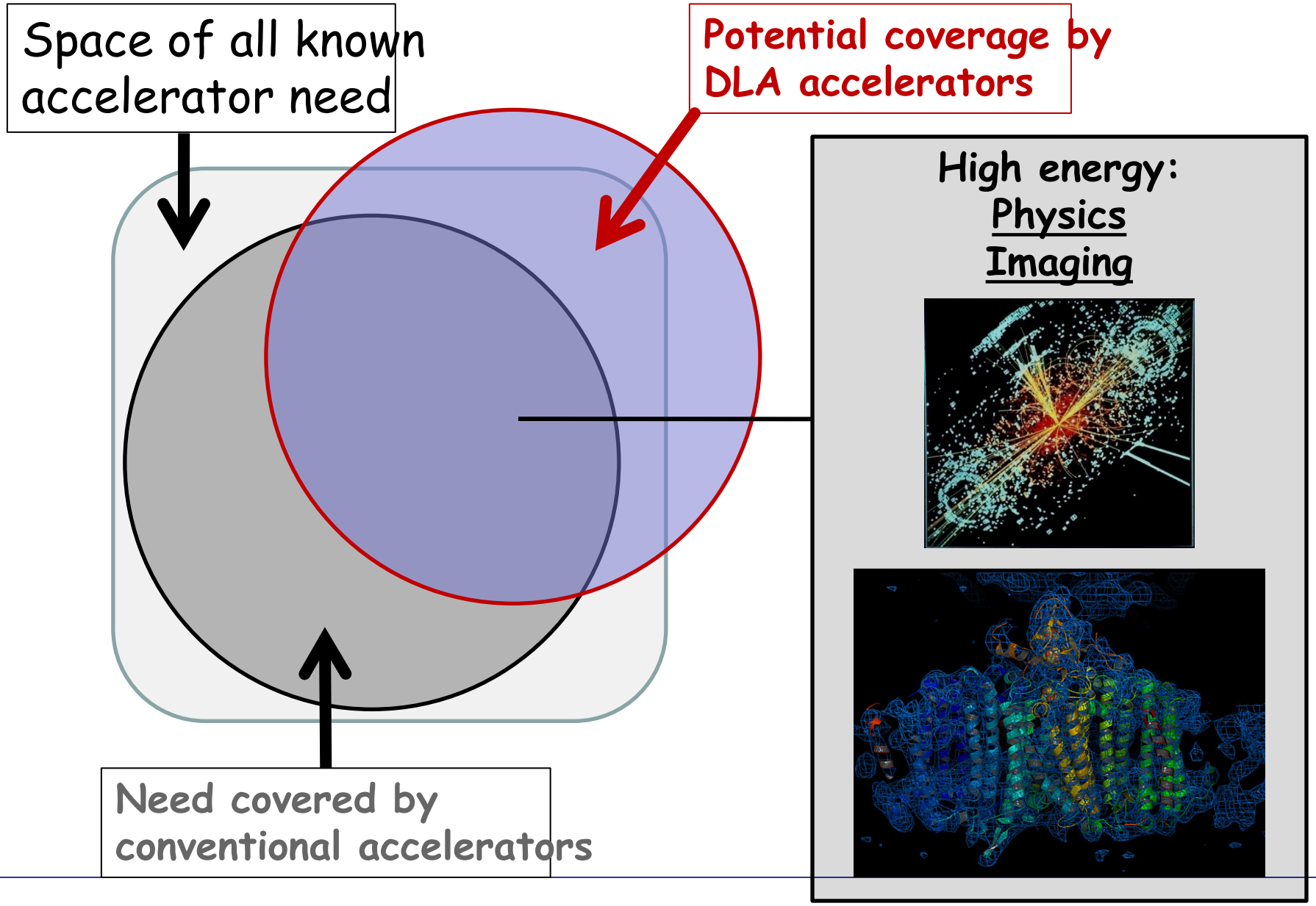


Need covered by conventional accelerators

High current:
Ion implantation



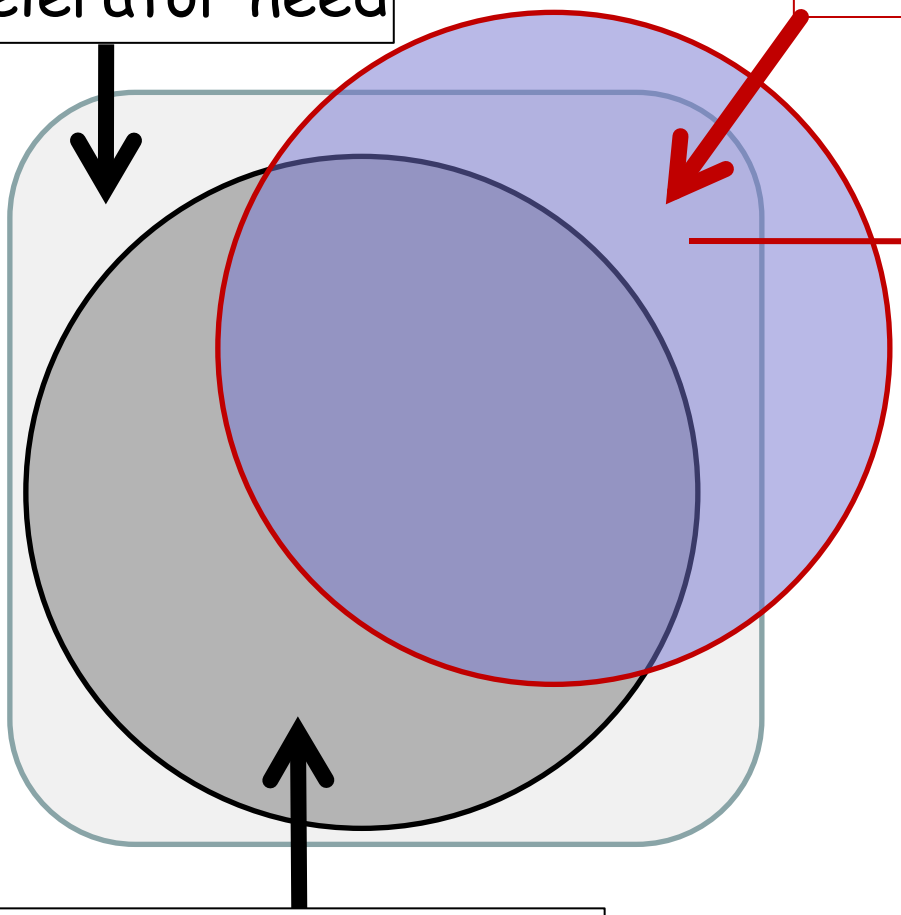
Applications



Applications

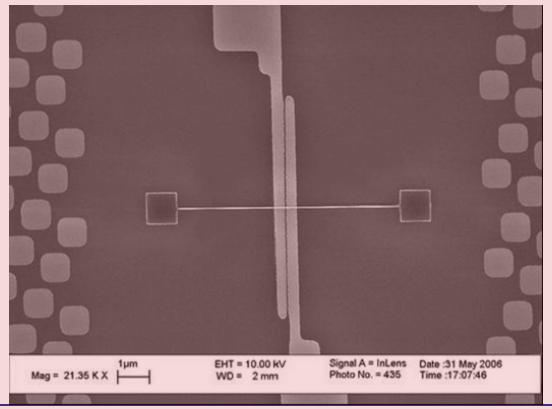
Space of all known accelerator need

Potential coverage by DLA accelerators

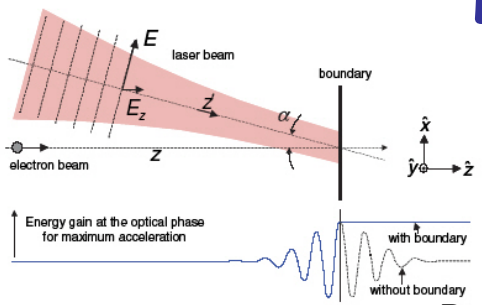


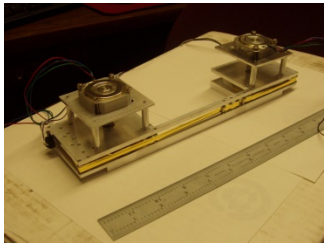
Need covered by conventional accelerators

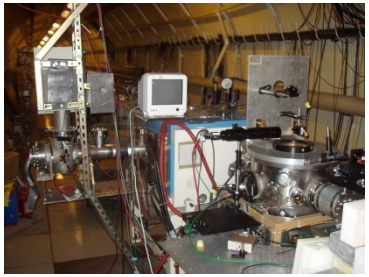
Compact/Efficient:
Medical
Commercial



Laser driven particle acceleration 1996 - 2004







collaborators

ARDB, SLAC

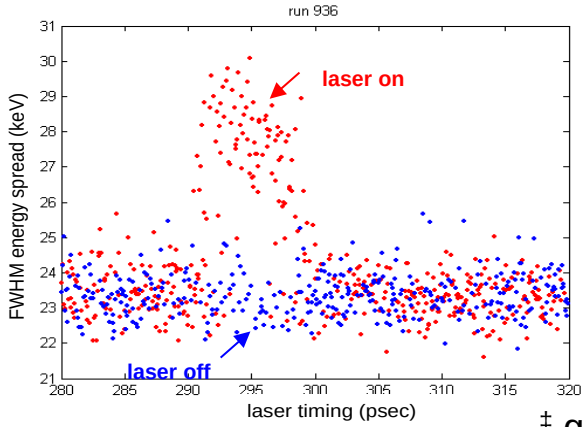
Bob Siemann*, Bob Noble†, Eric Colby†, Jim Spencer†, Rasmus Ischebeck†, Melissa Lincoln‡, Ben Cowan‡, Chris Sears‡, D. Walz†, D.T. Palmer†, Neil Na‡, C.D Barnes‡, M Javanmarad‡, X.E. Lin†

Stanford University

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

ARDA, SLAC

Zhiu Zhang†, Sami Tantawi†

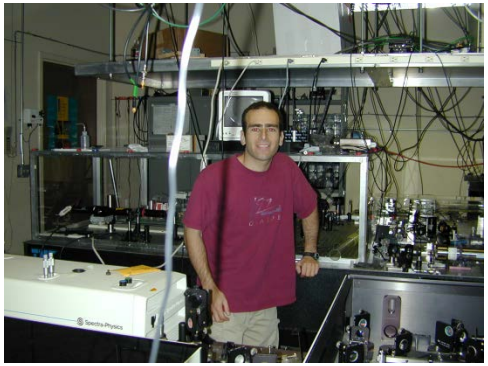


Techion Israeli Institute of Technology

Levi Schächter*

UCLA

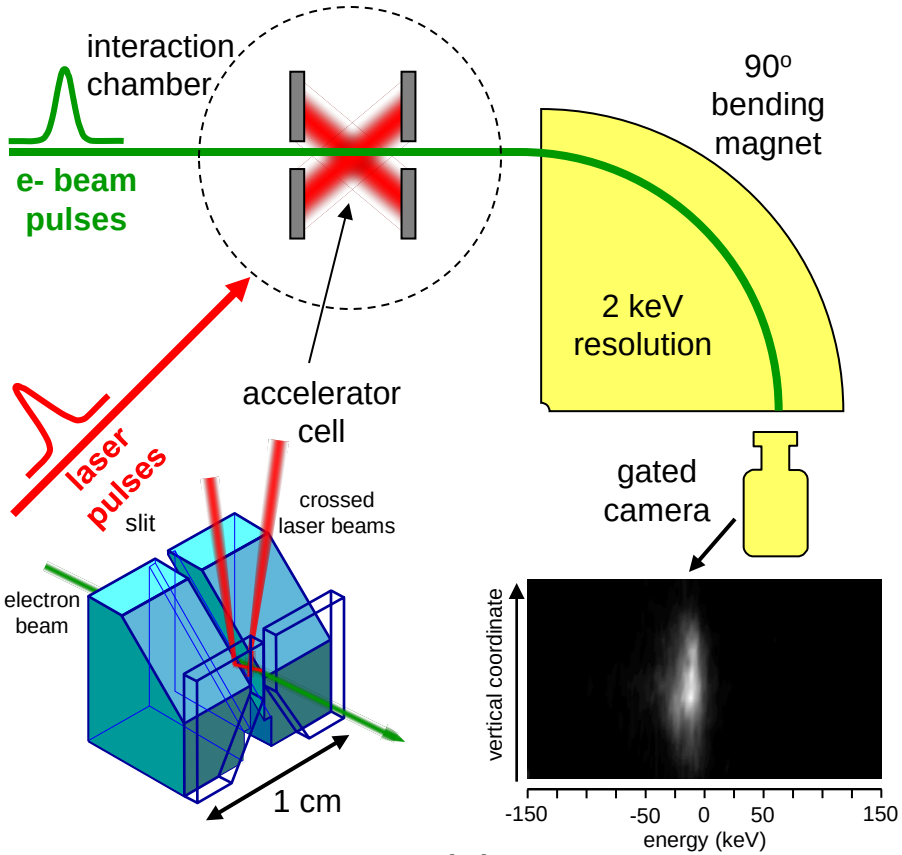
J. Rosenzweig*



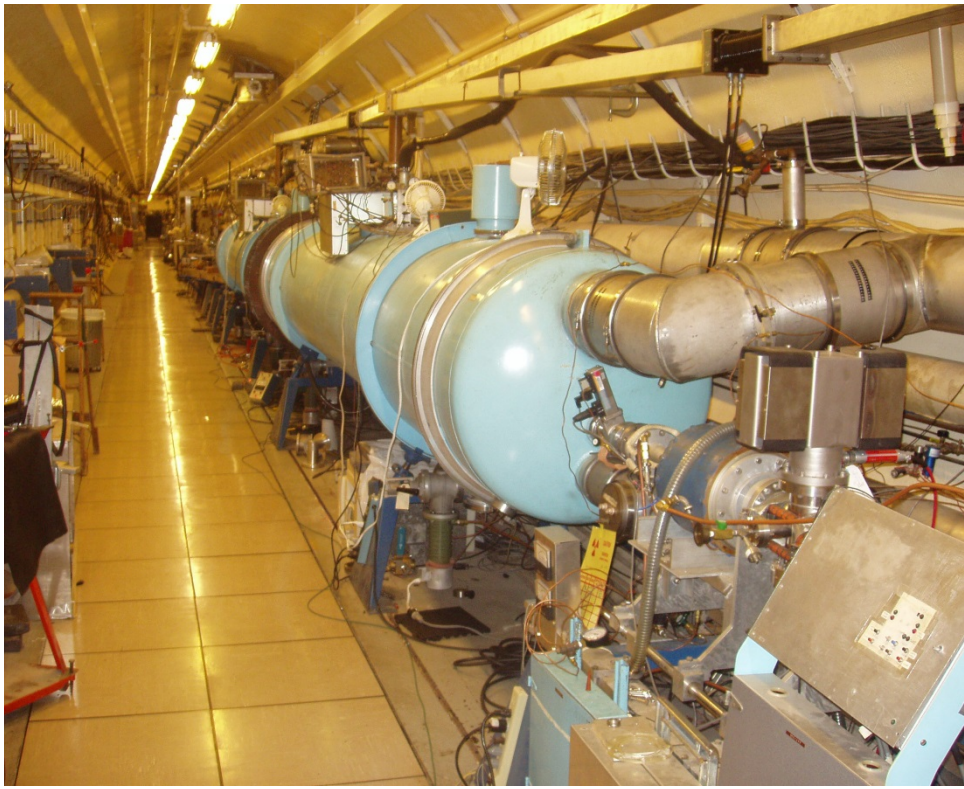
‡ grad students † postdocs and staff * faculty

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

Byer Group



(a)



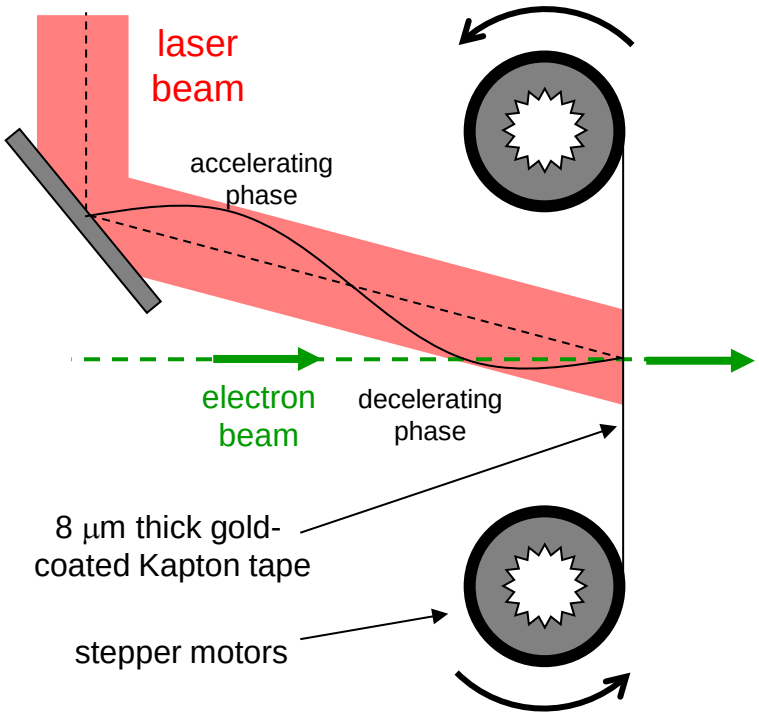
(b)

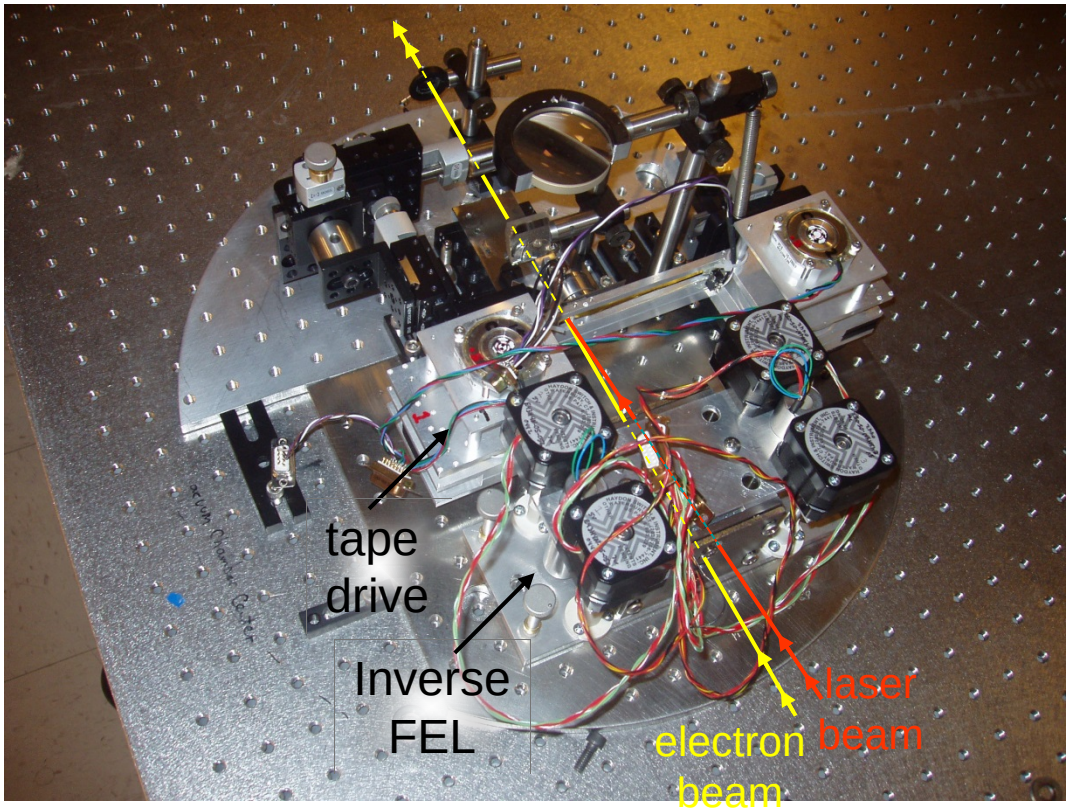
The crossed-beam laser accelerator Cell and magnet for electron beam energy measurements.

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

LEAP Experimental Success- November 2004

We have accelerated electrons with visible light!





Simplified single-stage Accelerator Cell - 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

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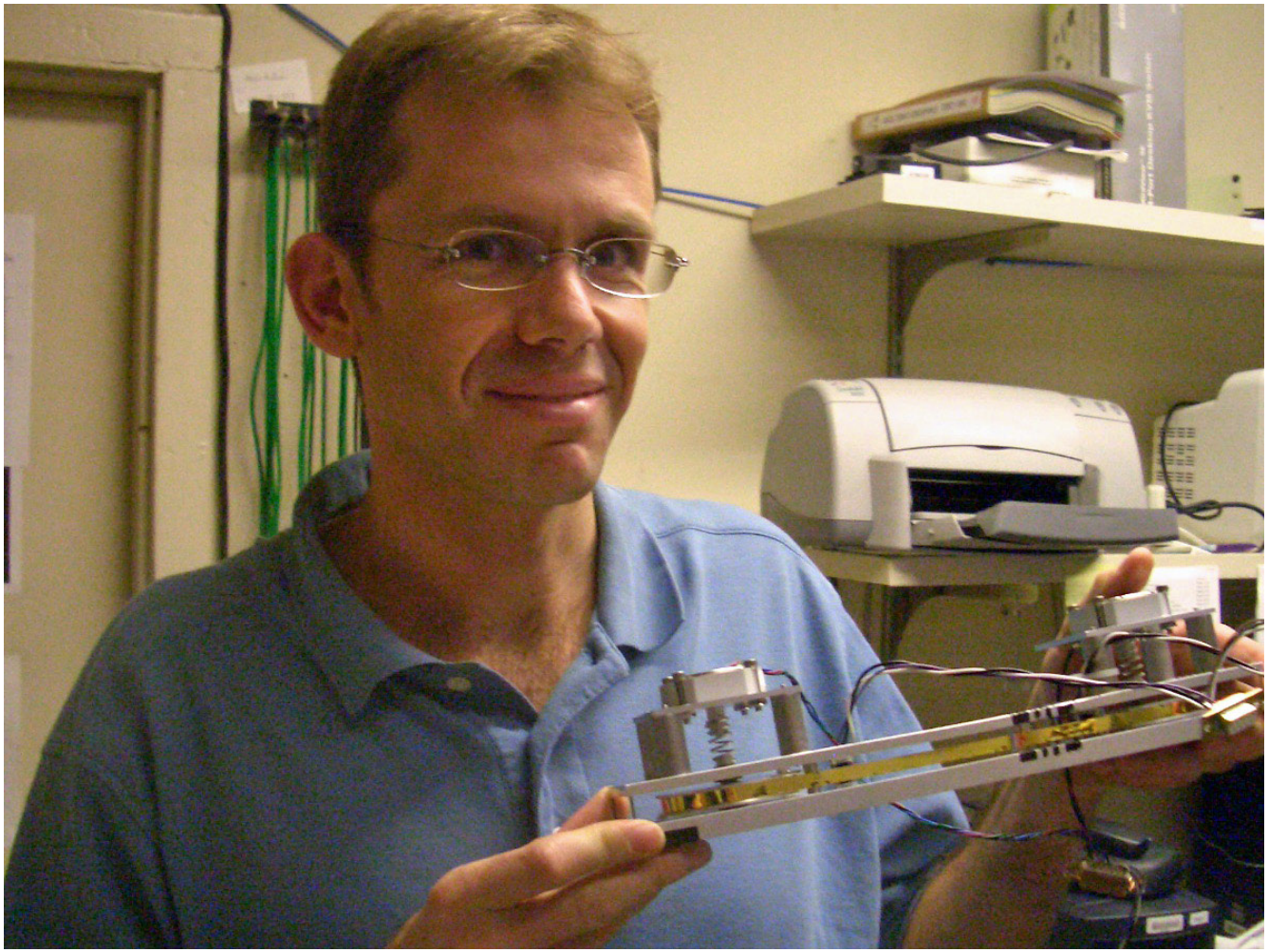


The key was to operate the cell <u>above</u> damage threshold to generate energy modulation in excess of the noise level.

1st Success: Accelerated electrons with visible light

Phys Rev Letts - Sept 2005

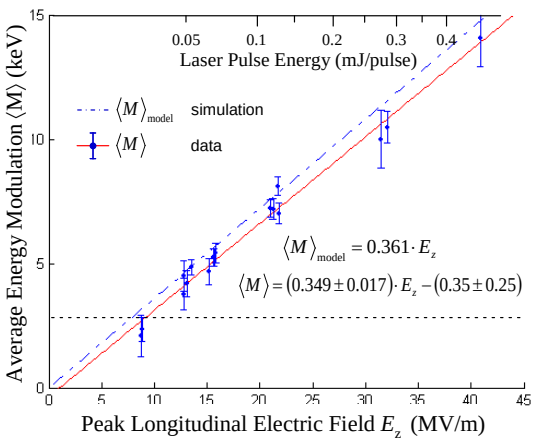
Byer Group

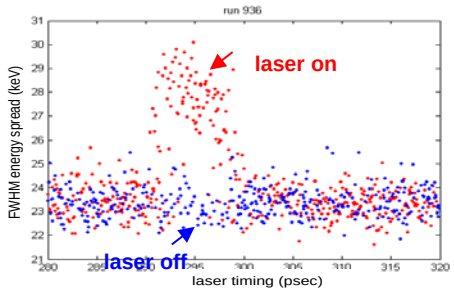
PRL 95, 134801 (2005) PHYSICAL REVIEW LETTERS week ending 23 SEPTEMBER 2005

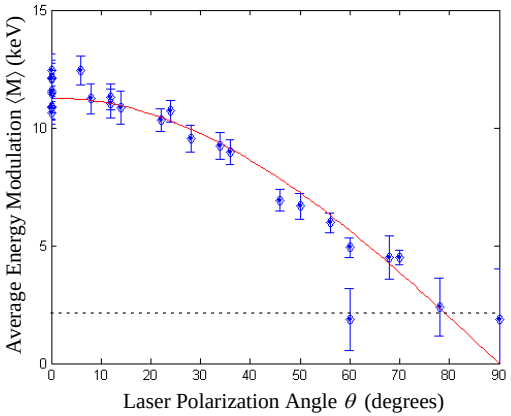
Visible-Laser Acceleration of Relativistic Electrons in a Semi-Infinite Vacuum

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

Colby, B. Cowan, C. M. S. Sears, J. E. Spencer, and R. H. Siemann
SLAC, Menlo Park, California 94025, USA
(Received 19 April 2005; published 22 September 2005)







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

laser-driven linear acceleration in vacuum

2nd Success: Visible light driven IFEL

Phys Rev Letts - Nov 2005

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

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

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

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

Cross-correlation in time

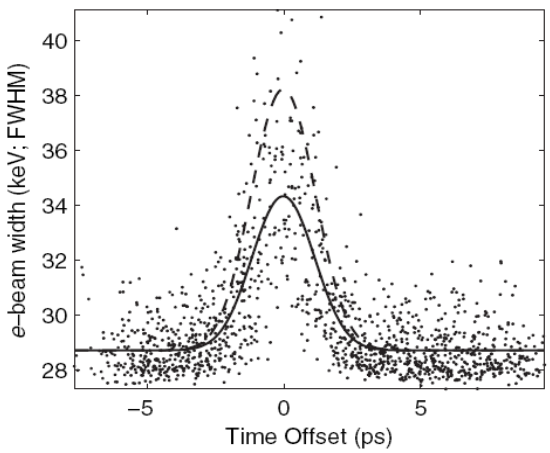


FIG. 2. Example data run with 1500 laser on events. The solid curve is the least squares fit to all data points and gives the mean interaction of 18 keV. The dashed curve is the maximum estimate and gives the peak interaction of 25 keV. The width of cross correlation is 2.2 ps rms.

Observation of harmonic interaction

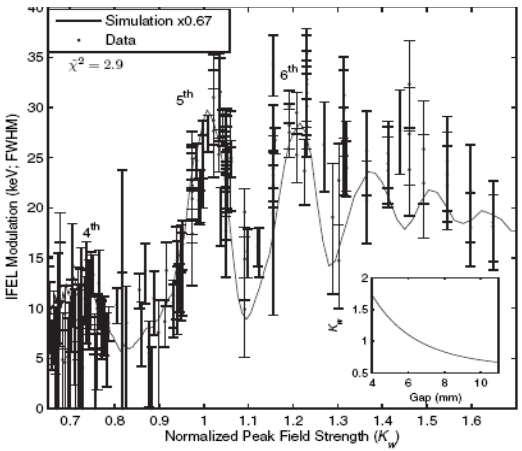
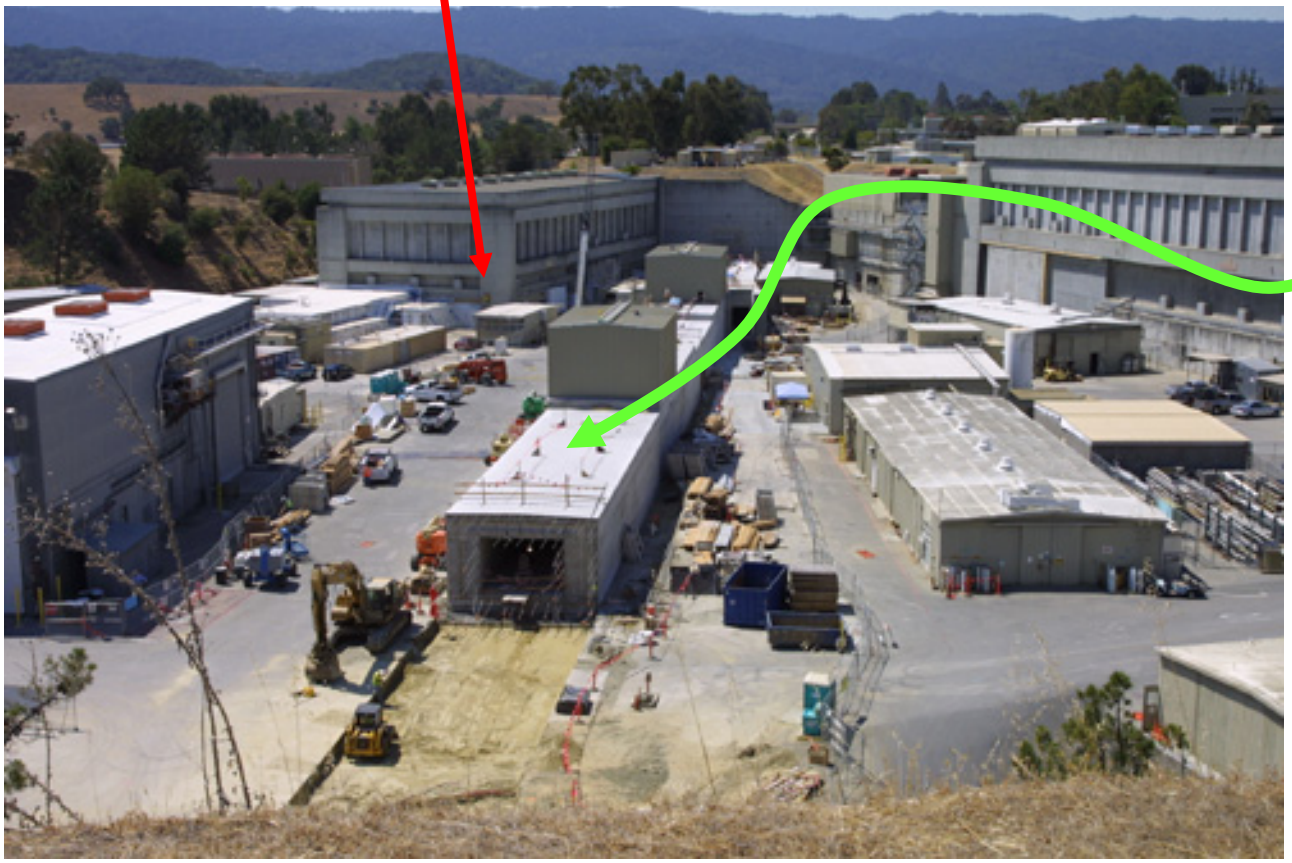


FIG. 4. IFEL gap scan data, with 164 runs total. Comparison to simulation (solid line) shows very good agreement to the shape and spacing of resonance peaks. The harmonic numbers are given next to each peak. Simulation has been rescaled vertically by 0.67 to better visualize overlap.

* graduate student C.M. Sears

Moved Experiment to SLAC: 2004 - 06

Byer Group

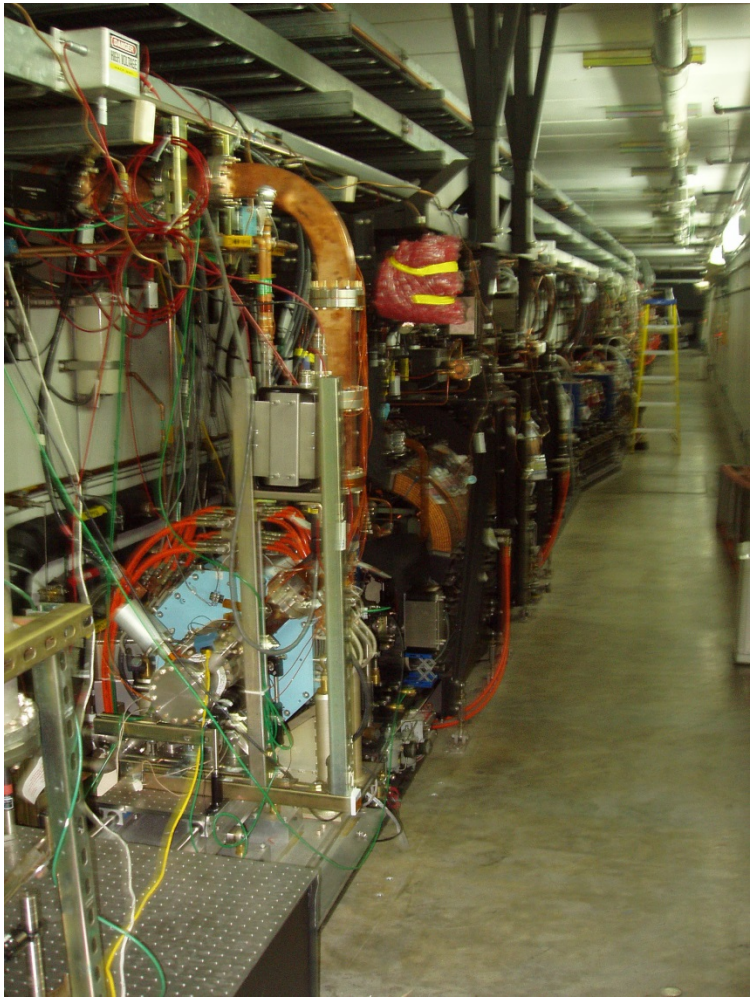


SLAC provided access to the NLCTA test accelerator – 60MeV

The E163 experiment at SLAC

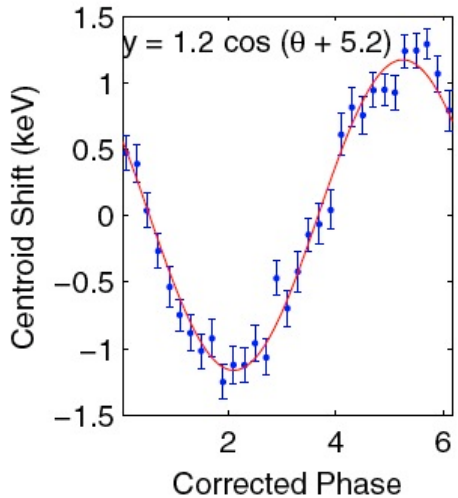
The new E163 experiment hall

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

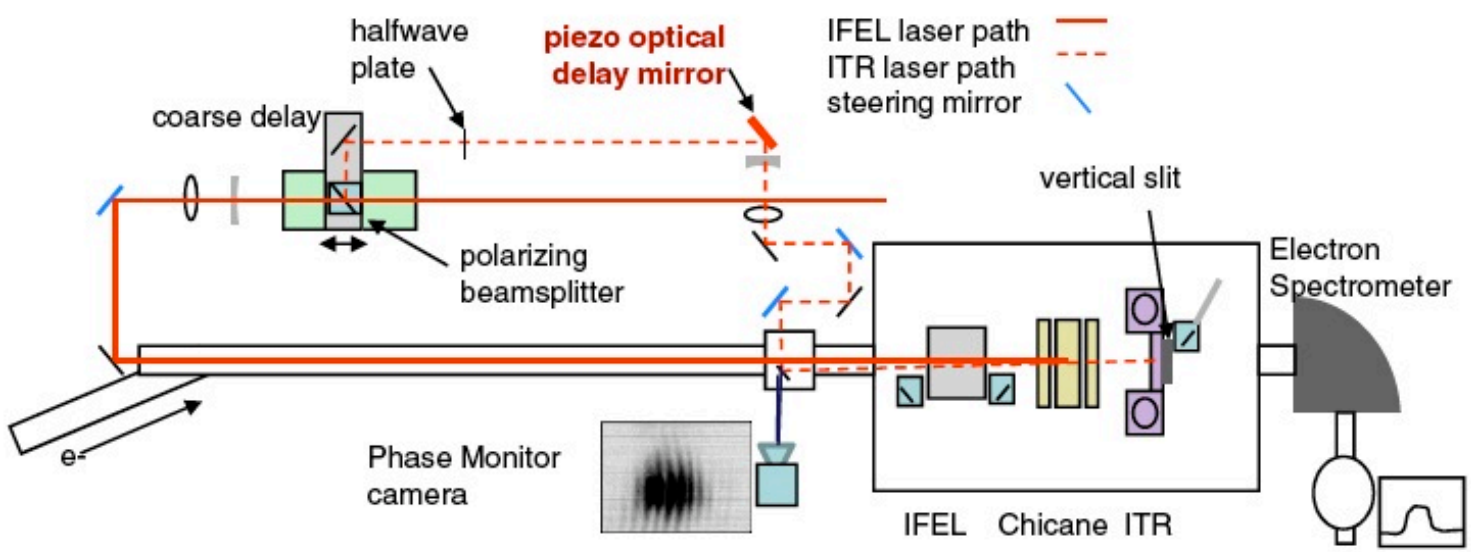
3rd Success: Bunching and Net Acceleration



Net laser acceleration of 1.2 keV demonstrated for **400 attosec microbunches** using inverse transition radiation (ITR) at a metal foil.

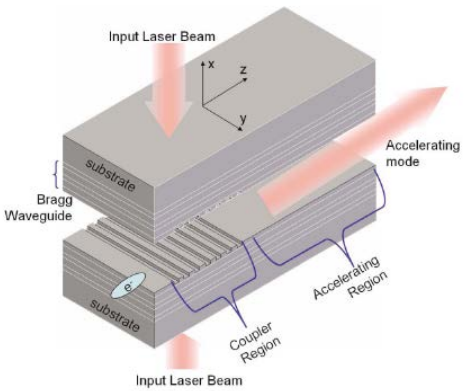
C.M.S. Sears, et al. "Production and characterization of attosecond electron bunch trains," PRST-AB **11**, 061301 (2008)].

C.M.S. Sears, et al. "Phase stable net acceleration of electrons from a two-stage optical accelerator." PRST-AB **11**, 101301 (2008).

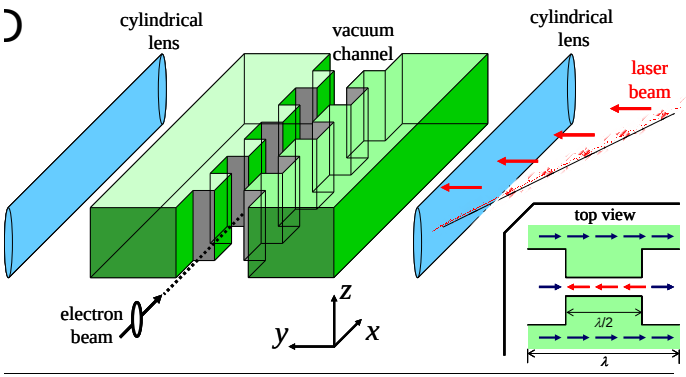


Professor Robert Siemann and Chris Sears

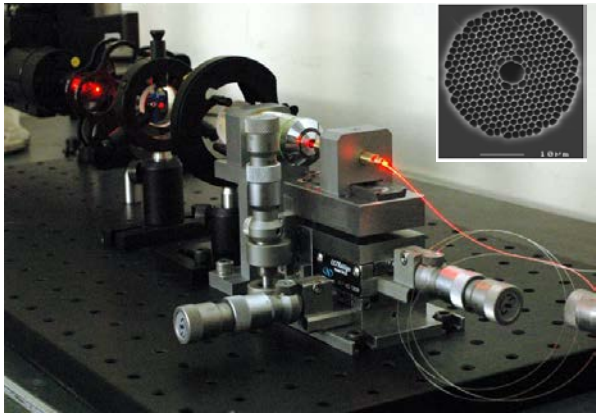
June 15, 2008 – Stanford Graduation Ceremonies



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

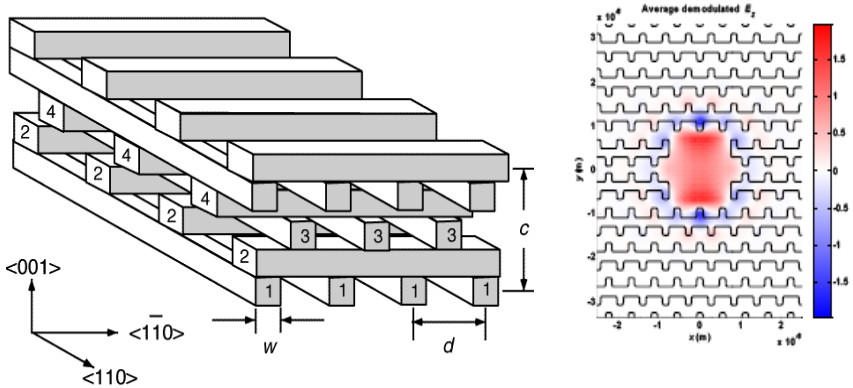


Hollow core PBG fibers



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

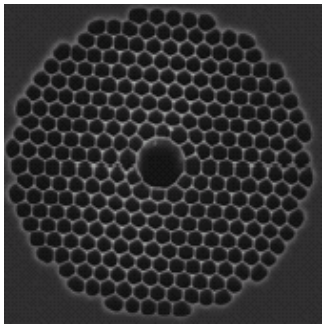
3-D photonic bandgap structures



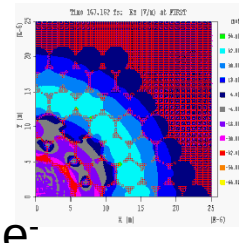
B. M. Cowan, Phys. Rev. ST Accel. Beams , 6, 101301 (2003).

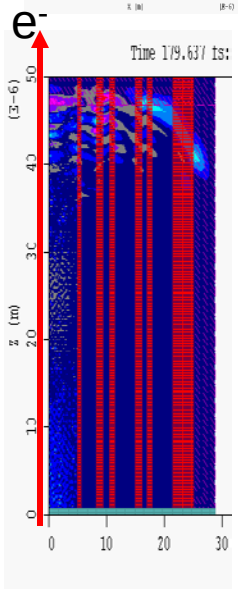
First Observation of Accelerating Modes in a PBG Fiber (Analog to Parametric Fluorescence)

Byer Group

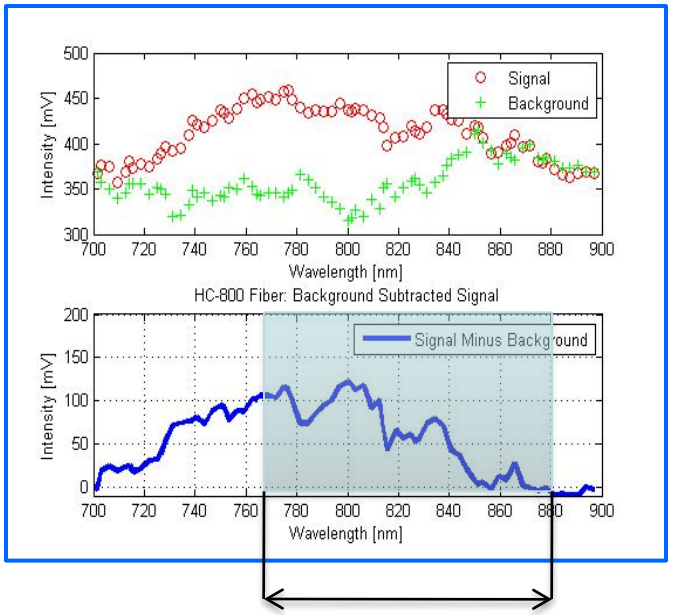


Thorlabs HC-1550-2

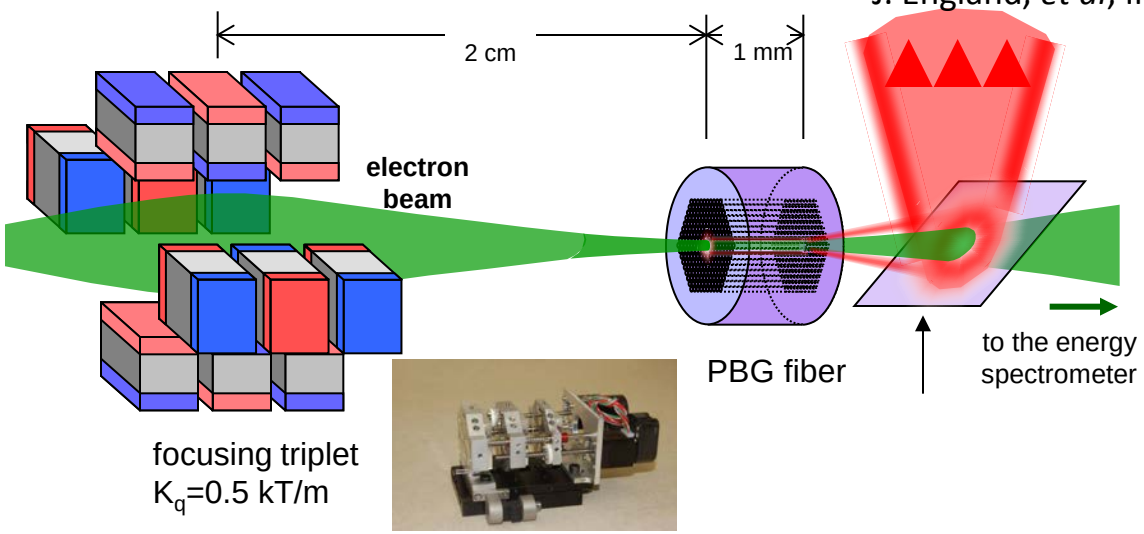




- Commercially available fiber (Thorlabs HC-800-1, $533/m)
- Observed with optical spectrometer to measure SOL modes



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



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)

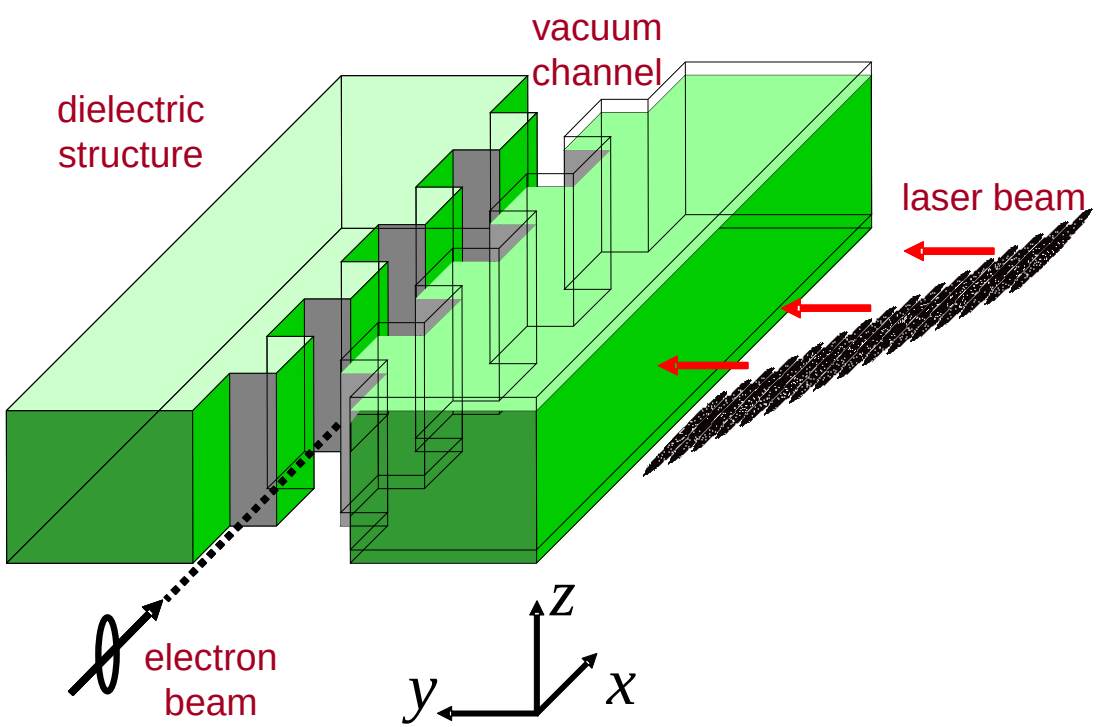
We describe a transparent dielectric grating accelerator structure that is designed for ultrashort laser pulse operation. The structure is based on the principle of periodic field reversal to achieve phase synchronicity for relativistic particles; however, to preserve ultrashort pulse operation it does 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

Main concept: periodic phase-reset of the EM field

Reset the phase every λ in grating structure

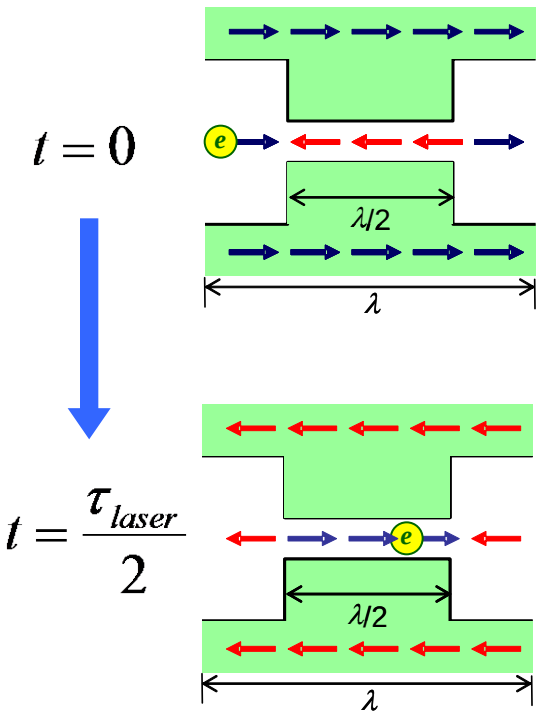
perspective view



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

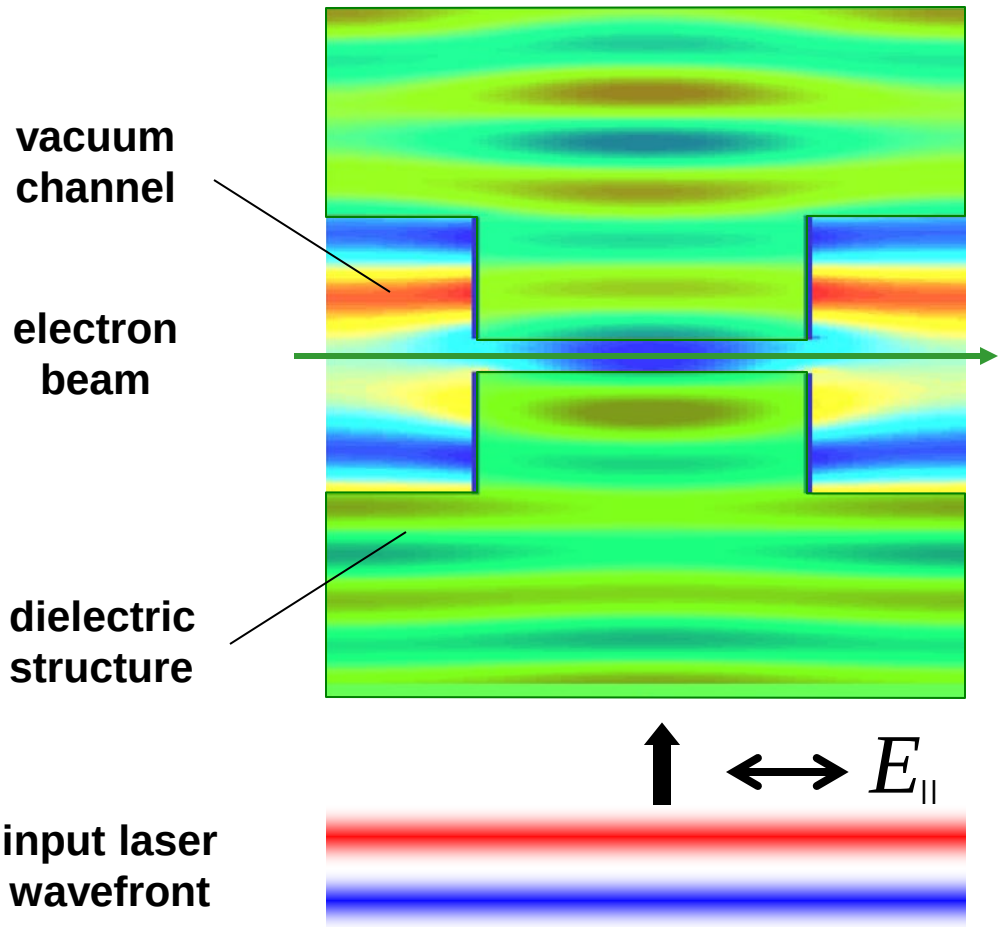
top view

traveling electron experiences accelerating force at all times



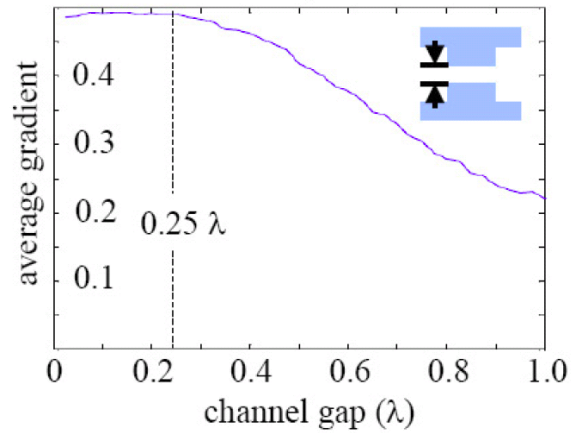
Transverse pumped grating phase-reset structure

EM field map in one unit



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

vacuum channel width < λ



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

1 J/cm² fluence

~10 fsec pulses

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

G_{loaded} ~ 2 GeV/m

Goal: Develop Theory for laser accelerator physics

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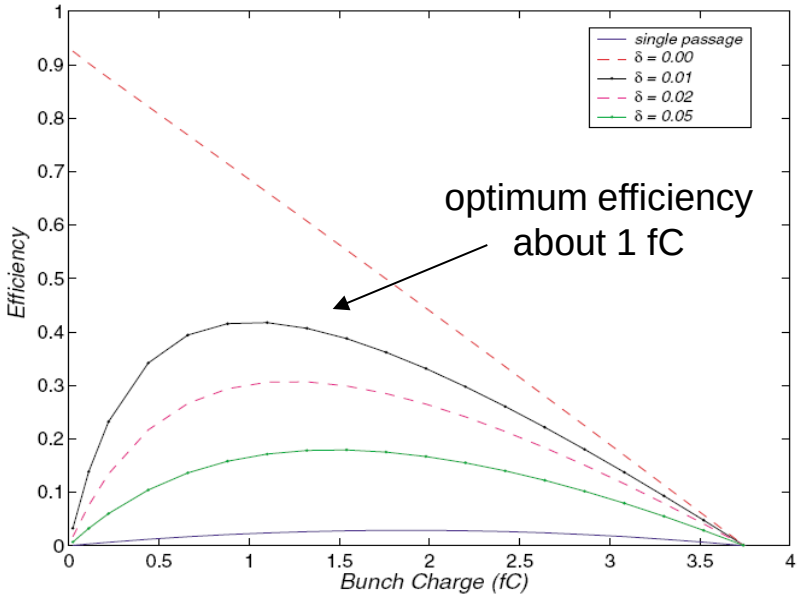
Energy efficiency of laser accelerators, single and multiple bunch operation

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

Energy efficiency of laser driven, structure based accelerators

R. H. Siemann

Coupling Efficiency vs bunch charge



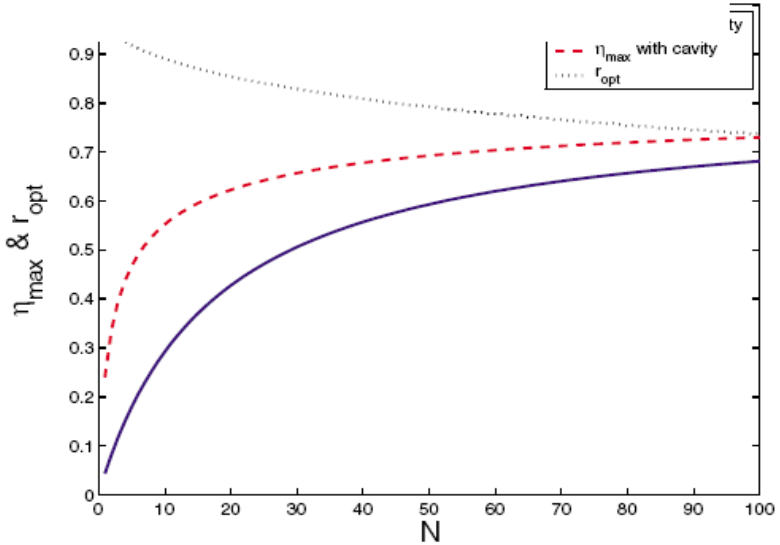
PHYSICAL REVIEW SPECIAL TOPICS - ACCELERATORS AND BEAMS 8, 031301 (2005)

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)

Beam loading calculations vs N



N (Number of bunches)

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

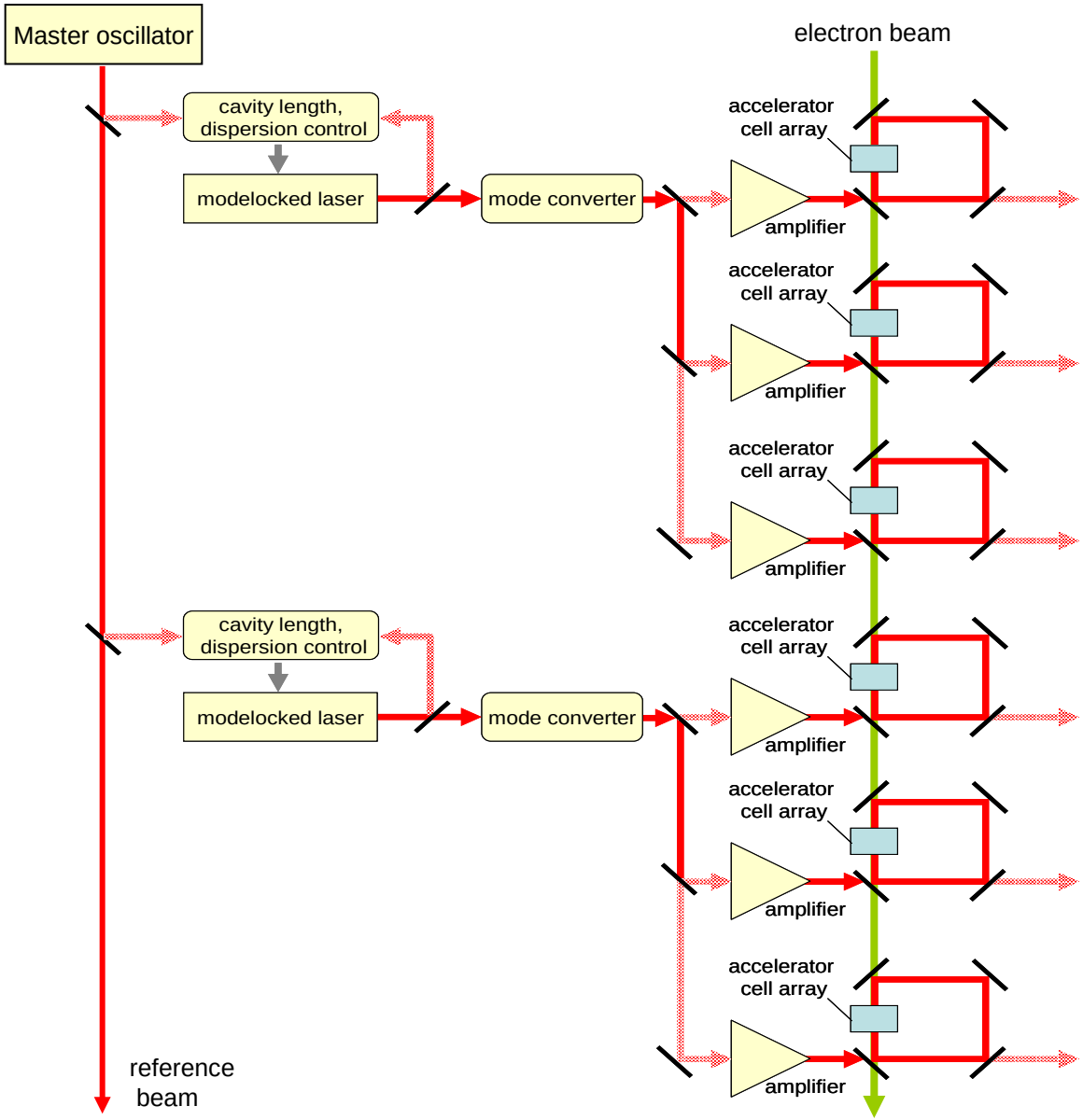
Proposed layout of the laser system for a TeV collider

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

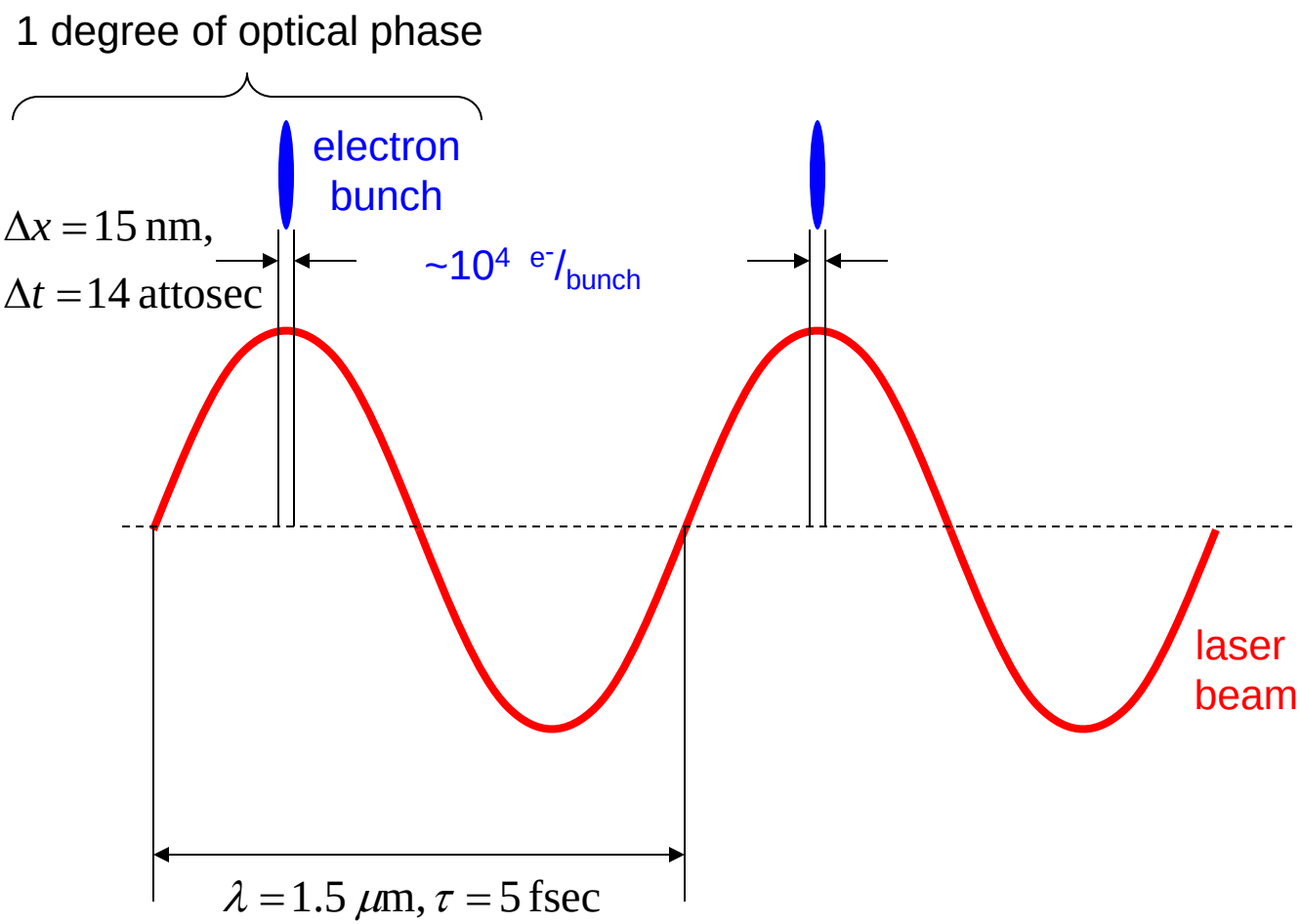
local modelocked oscillators are phase-locked to the master oscillator

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 Accelerators operate with **Attosecond** Electron Bunches



We have elected to develop Tm:fiber laser as driver for accelerators

TeV energy scale laser accelerators require ~ 150fsec phase-locked laser drivers -- ~ 10MW/km average power

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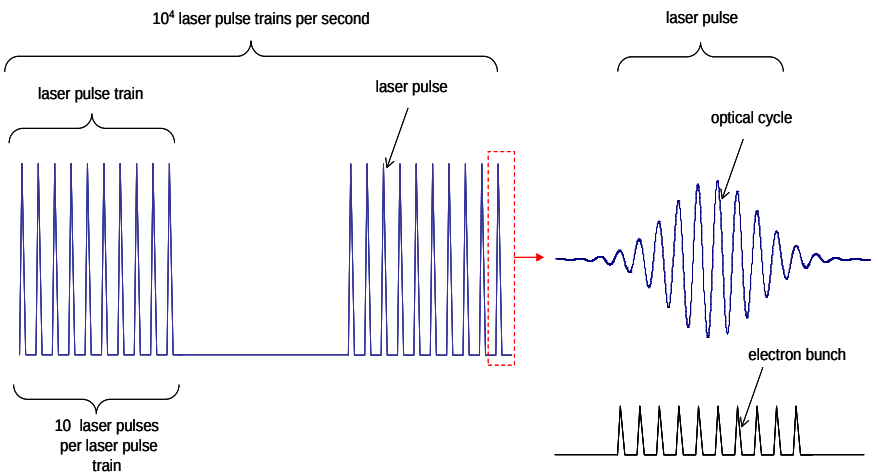
Tm:fiber laser at 2μm offers high-efficiency, ultrafast output

Low bunch charge problem

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

Laser pulse structure that leads to MHz electron bunch repetition rate



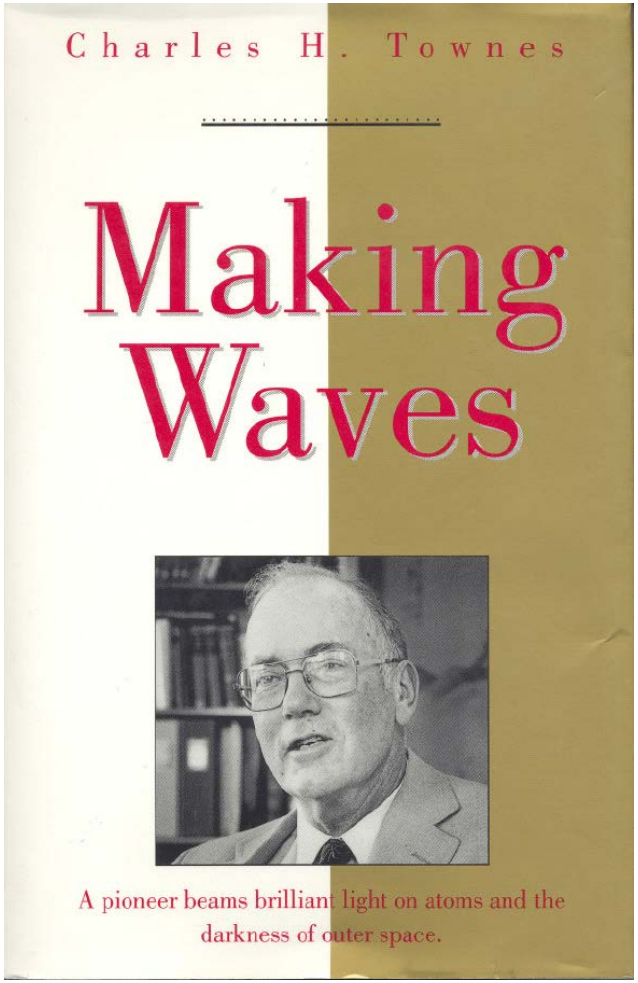
	SLC	NLC	SCA-FEL	TESLA	laser-accelerator
f_{RF} (GHz)	2.856	11.424	1.3	1.3	3×10^4
f_m (Hz)	120	120	10	4	10^4
N_b	1	95	10^4	4886	10
Δt_b (nsec)	-	2.8	84.7	176	3×10^{-6}
f_b (Hz)	1.2×10^2	1.1×10^4	1×10^5	1.6×10^4	3×10^6
N_e	3.5×10^{10}	8×10^9	3.1×10^7	1.4×10^{10}	10^4
I_e (sec^{-1})	4×10^{12}	9×10^{13}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

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

(~ 10 microjoules in 150 fsec per micropulse)

Dramatic increase of

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



Introduction *Early Progress in Laser Accelerators*

Success! ***Laser Acceleration in Dielectric Structures***

Future Directions *Laser Accelerator driven X-ray lasers*

Dielectric Laser Accelerator (DLA) Based Advanced X-Ray Sources

R. L. Byer, K. Soong, E. Peralta,
R. J. England, Bob Noble
Ben Cowan
Peter Hommelhoff

SLAC, Stanford, Tech-X, MPQ Collaboration

DARPA AXiS FY12 Year-End Review

MAX-PLANCK-INSTITUT FÜR QUANTENOPTIK

Who Are We?

Stanford University
(structures and testing)
Prof. Bob Byer (PI)
Prof. James Harris (co-PI)
Prof. Olav Solgaard (co-PI)
Ken Soong
Edgar Peralta
Behnam Montazeri
Ken Leedle
Chia-Ming Chan

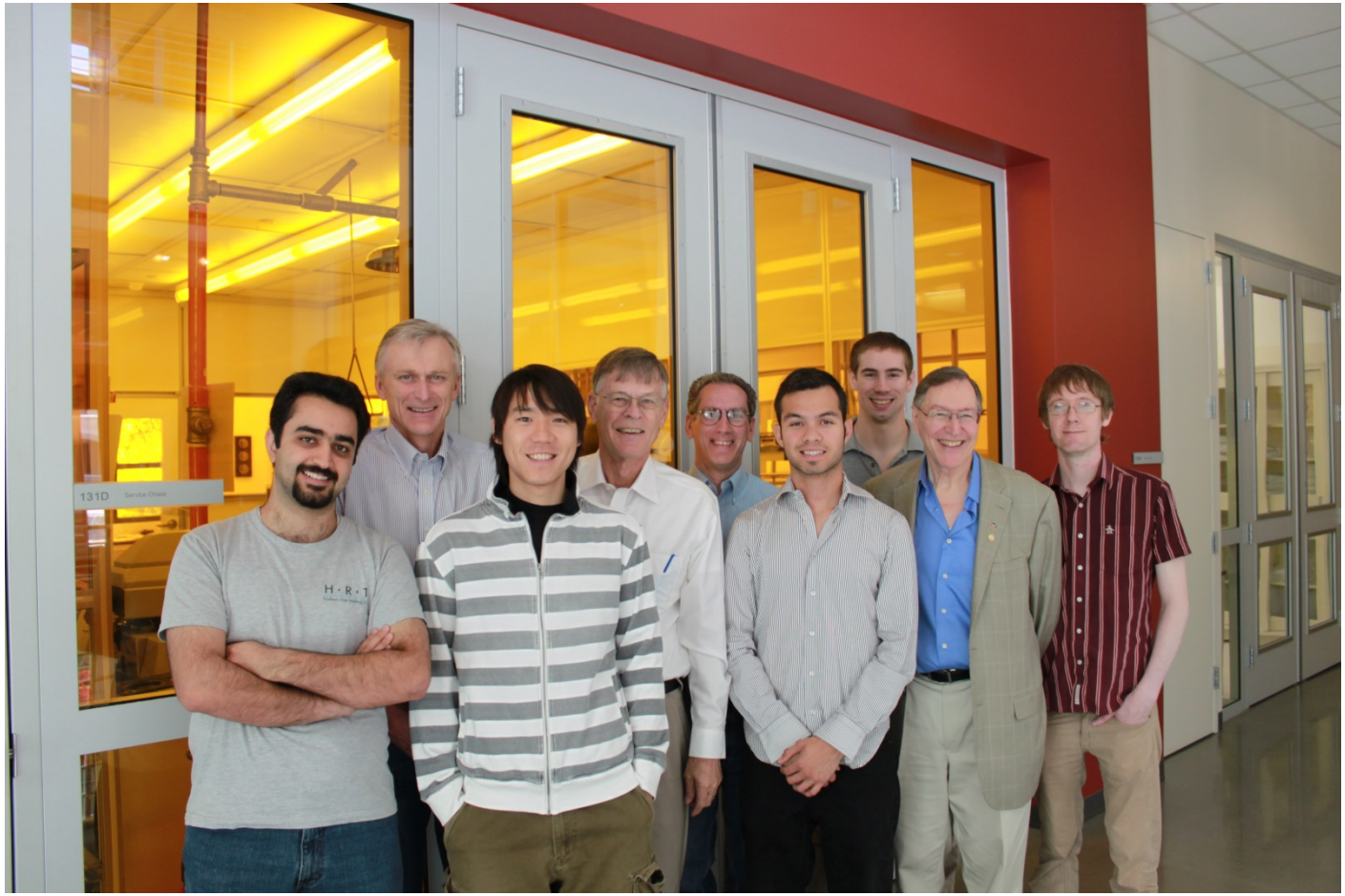
Max Planck Institute
(Injector and pre-accel)
Dr. Peter Hommelhoff
Johannes Hoffrogge

SLAC National Accelerator Laboratory
(accelerator testing of structures)
Dr. Joel England (Proj. Mgr.)
Dr. Bob Noble
Dr. Ziran Wu
Dr. Eric Colby

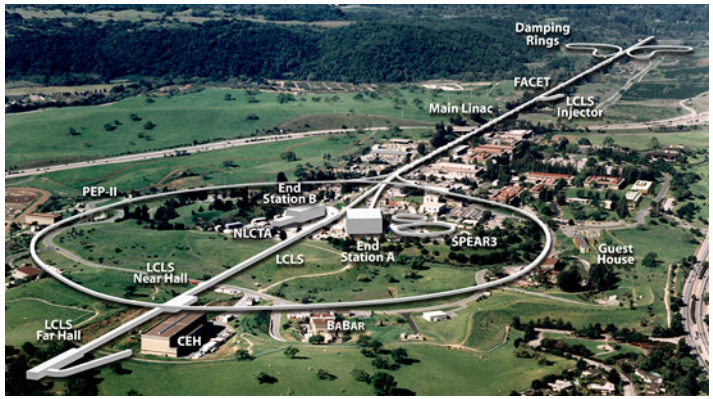
Tech-X Corporation
(Modeling structures)
Dr. Ben Cowan
Dr. Brian Schwartz
Dr. Dan Abell
Dr. Estelle Cormier

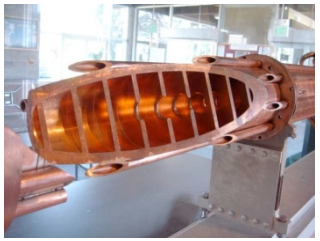
The 'Accelerator on a Chip' Team

Byer Group



Accelerator on a Chip Concept





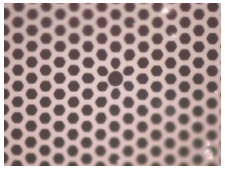
30 MV/m λ = 10 cm

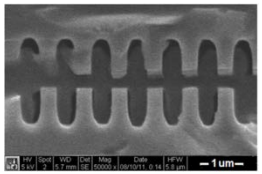
gradient

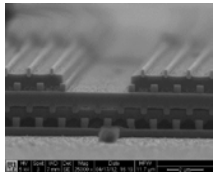
wavelength

x10^{-5}

1-2 GV/m λ = 1 μm







lower cost, more compact, higher gradient

laser-driven microstructures

- **lasers:** high rep rates, strong field gradients, commercial support
- **dielectrics**: higher breakdown threshold → higher gradients (1-5 MV/mm), leverage industrial fabrication processes

Long term goal: Fabrication of an Integrated Accelerator Machine on a Wafer

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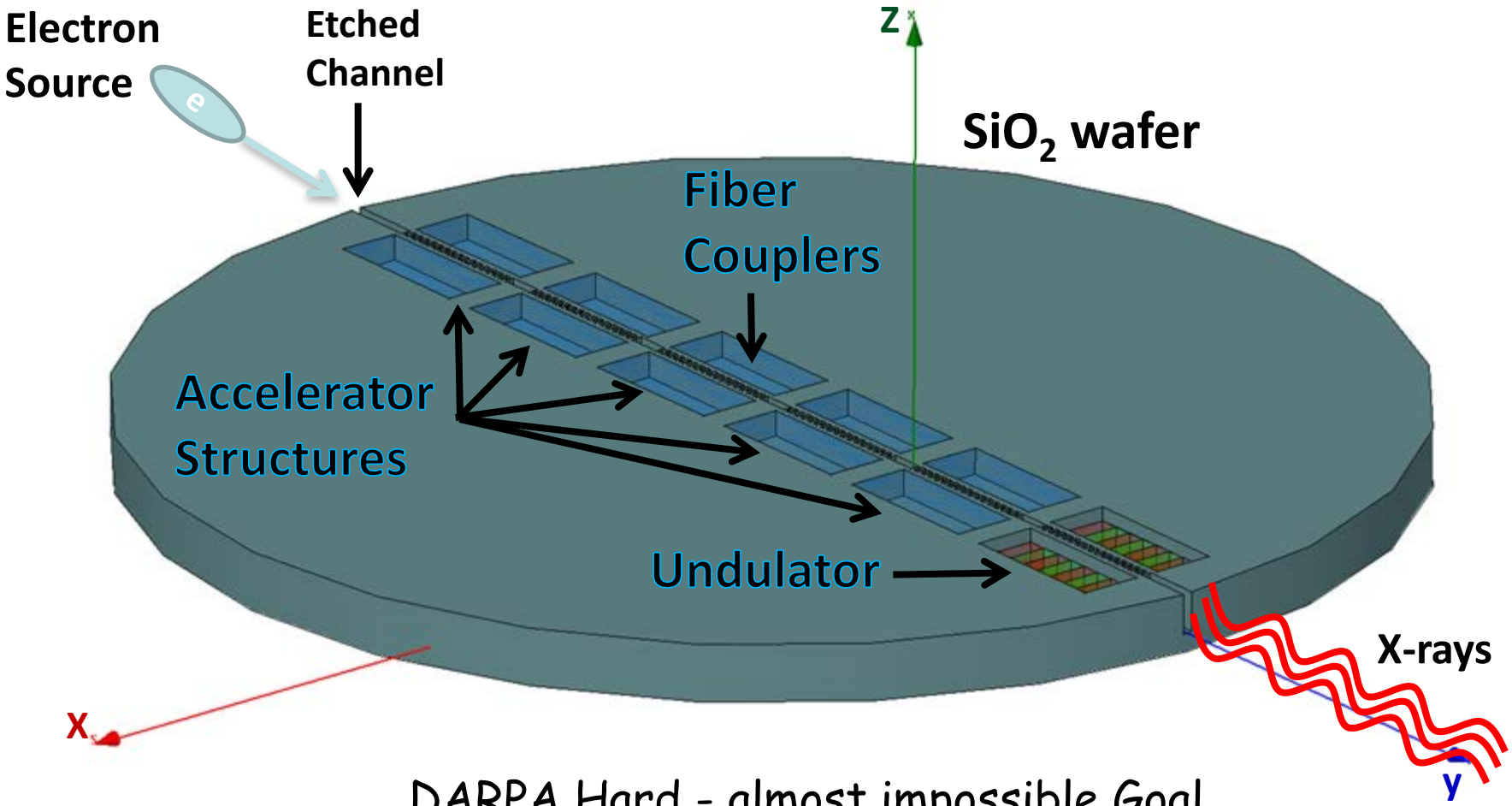

DARPA Hard - almost impossible Goal

Must innovate to accomplish this outcome

Laser Damage Threshold Studies

Motivation: higher damage threshold means higher acceleration gradient

Why search for optically robust materials?

$$\mathbf{E_{acc}} \propto \sqrt{\mathbf{F_{th}}} \cdot \mathbf{AF}$$

E_{acc} – Accelerating gradient
F_{th} – Damage threshold fluence
AF – Acceleration Factor
(ratio of accelerating field on axis to peak field in material)

Material studies → increase **F_{th}**
Structure design → increase **AF**

Increasing Gradient

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VOLUME 74, NUMBER 12 PHYSICAL REVIEW LETTERS 20 MARCH 1995

Laser-Induced Damage in Dielectrics with Nanosecond to Subpicosecond Pulses

B. C. Stuart, M. D. Feit, A. M. Rubenchik, B. W. Shore, and M. D. Perry
Lawrence Livermore National Laboratory, P.O. Box 808, L-443, Livermore, California 94550
(Received 24 August 1994)

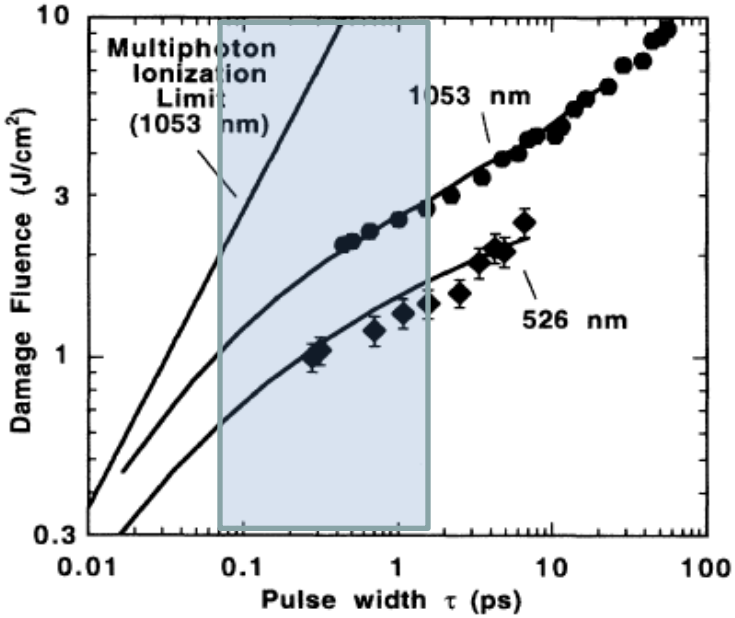


FIG. 4. Experimental and theoretical damage thresholds for fused silica at 1053 nm (●) and 526 nm (◆). The theoretical damage thresholds (solid curves) correspond to the formation of a critical density plasma ($\approx 10^{21}$ cm^{-3}), as discussed in the text. Relative errors in the experimental data are shown, estimated absolute error is ±15%.

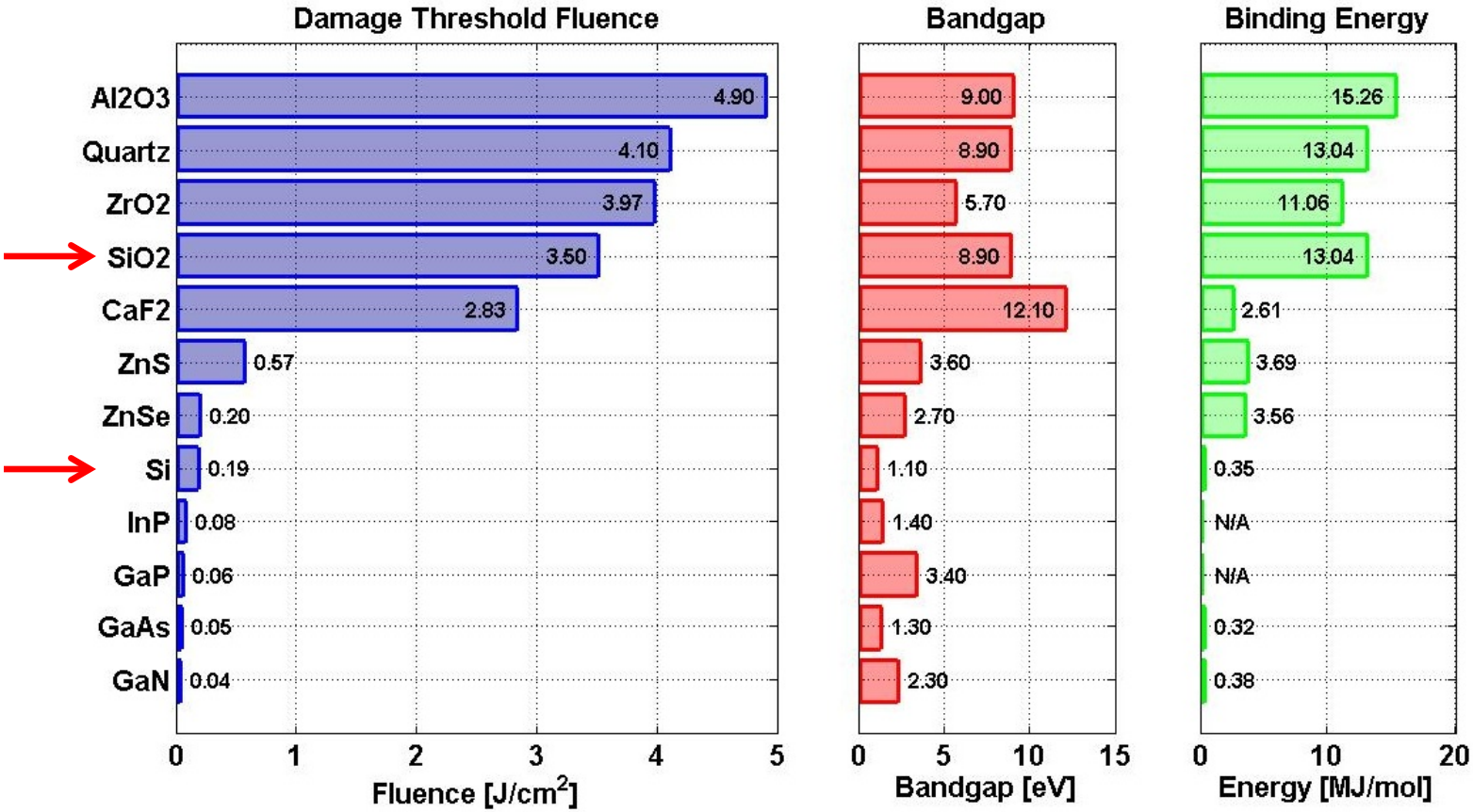
$$G \propto \eta \sqrt{\frac{F(\tau)}{\tau^{\frac{1}{2}}}}$$

Compressing the IR pulse from 2 ps to 20 fs can give us a **factor of 3 larger gradients.**

Laser Damage Threshold – Results

1 psec pulse duration and 1-2μm wavelength

The results of our on-going damage threshold experiments indicate that the most robust materials have a **large bandgap** and a **high lattice binding energy**



Grating prototypes of various gaps (fused silica)
(Edgar Peralta)

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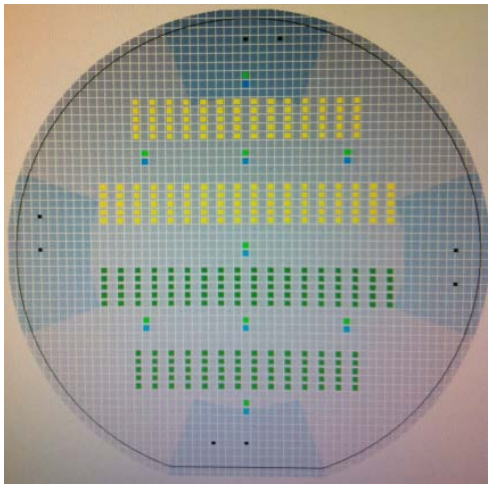
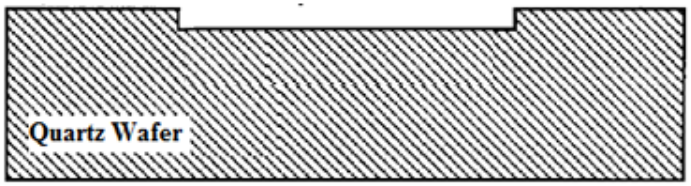
1) wafer layout

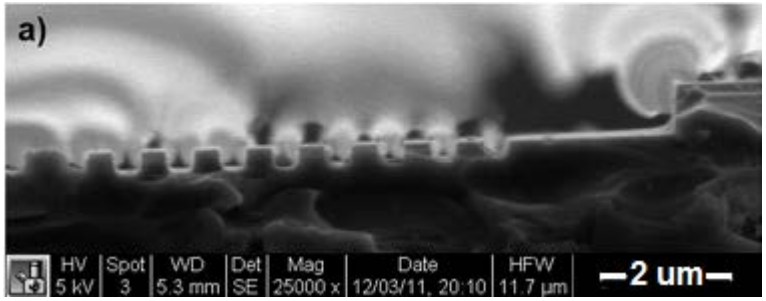


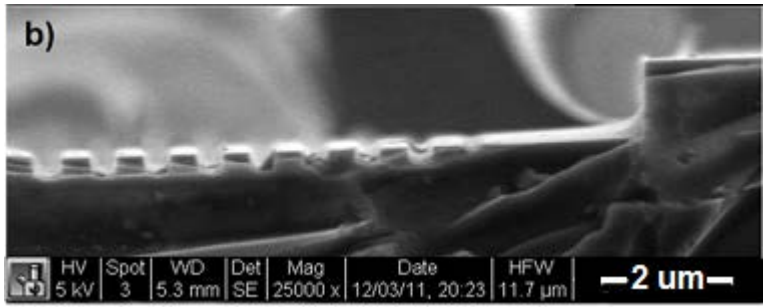
2 a) Etch trenches to set gap



2 b) Etch gratings inside trench

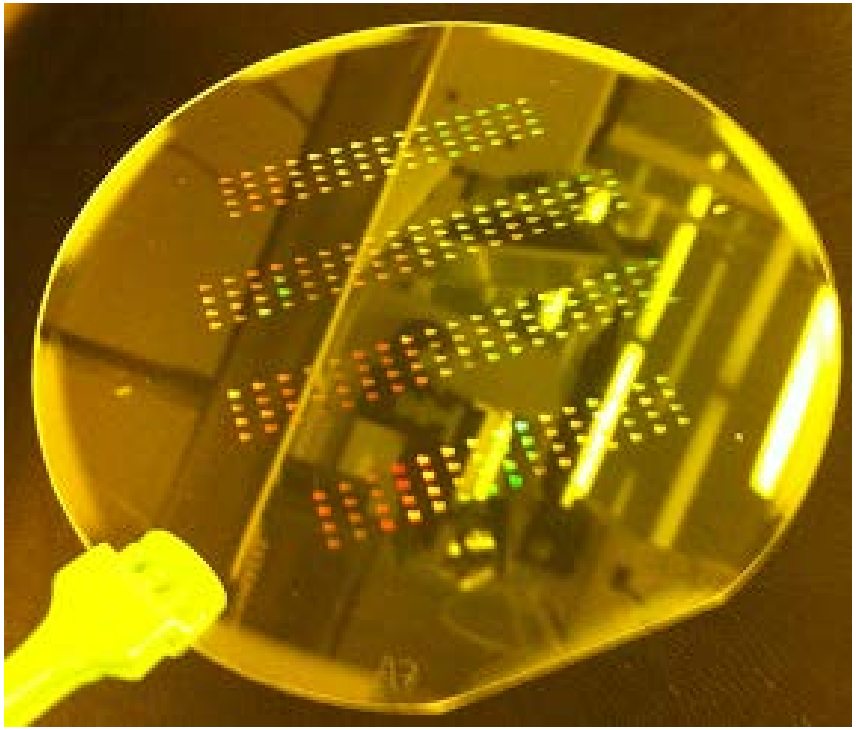
3) SEM Images of gratings near the edge of an 800nm (a) and a 1200nm (b) trench.



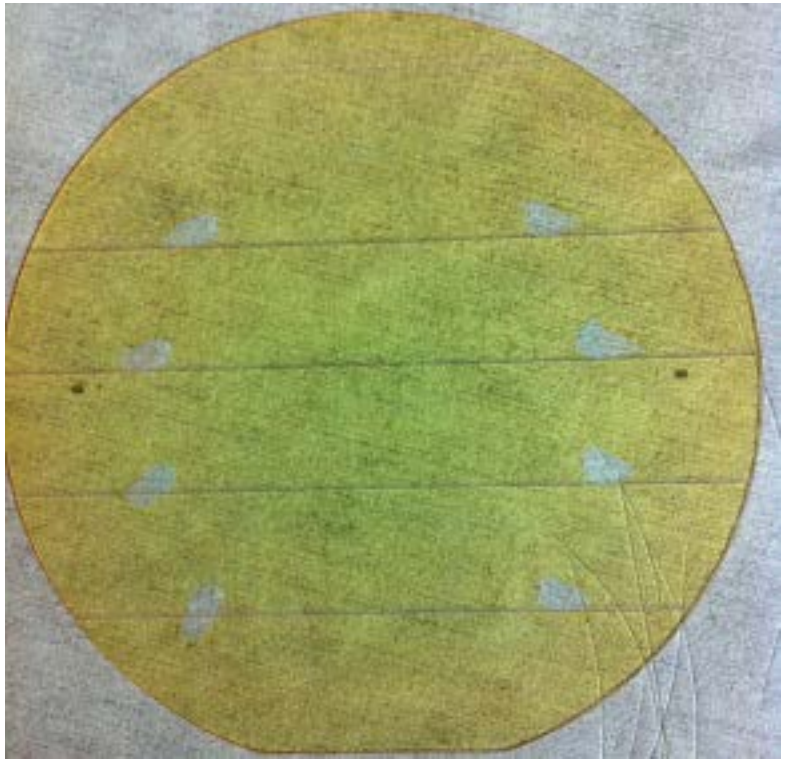


Finished Single Wafer

Etching – All done

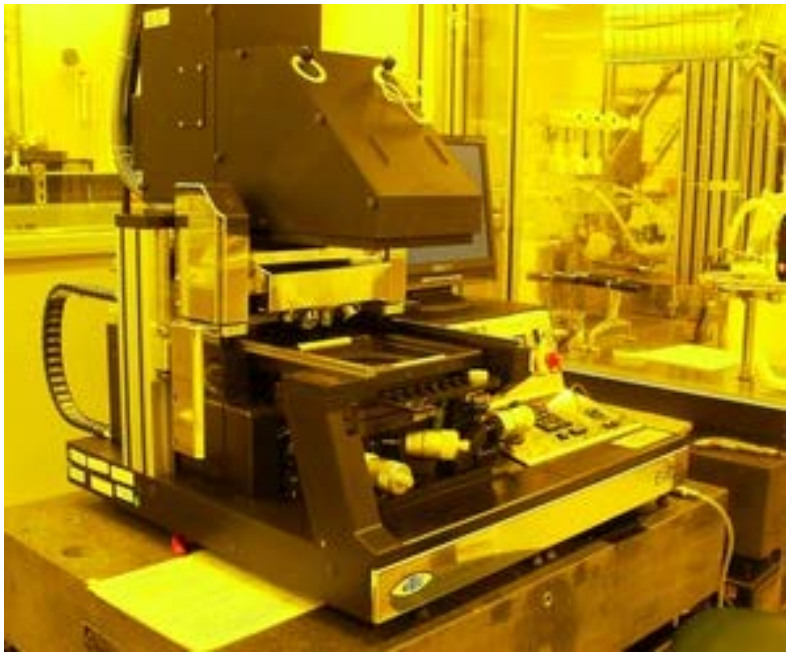


Alignment channel cuts

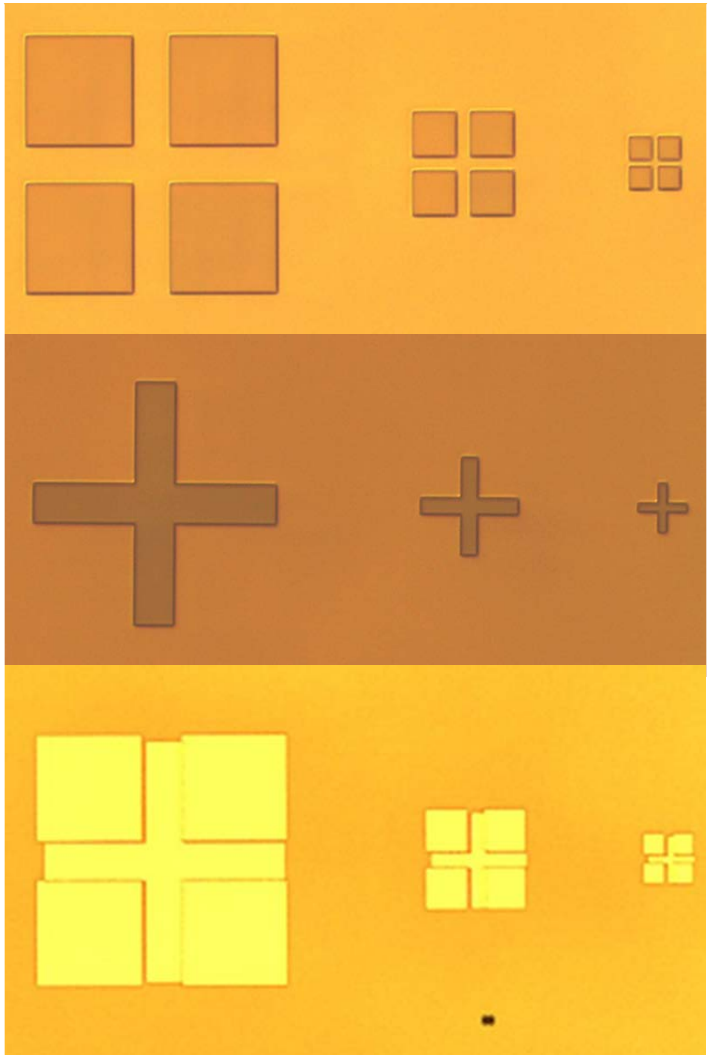


Machine-Assisted Bonding

EV Aligner Tool



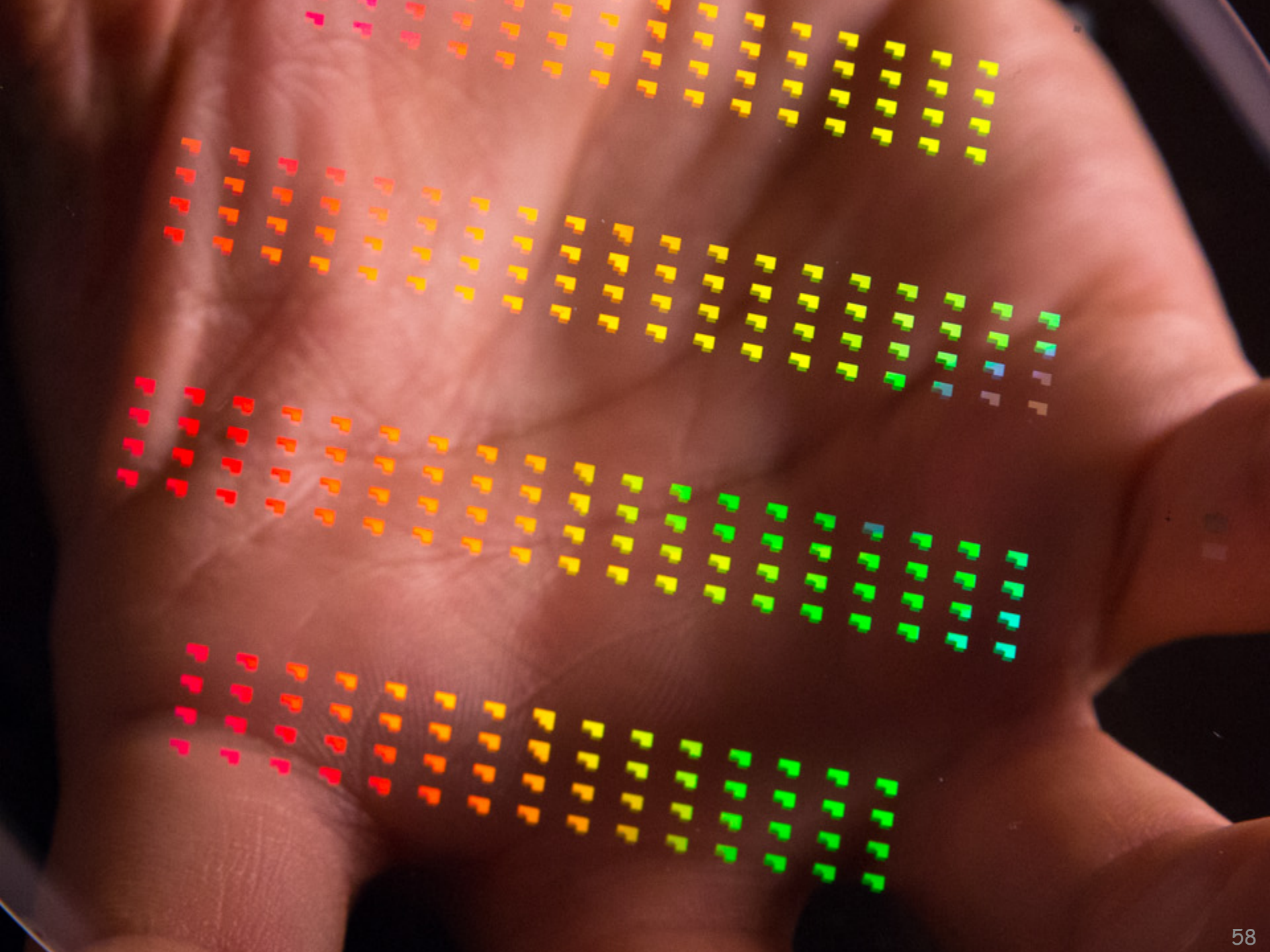
Alignment Marks



Wafer 1

Wafer 2

Bonded Wafer s



V5 FinishedTest Samples – Fused Silica
(tested in December and February runs)

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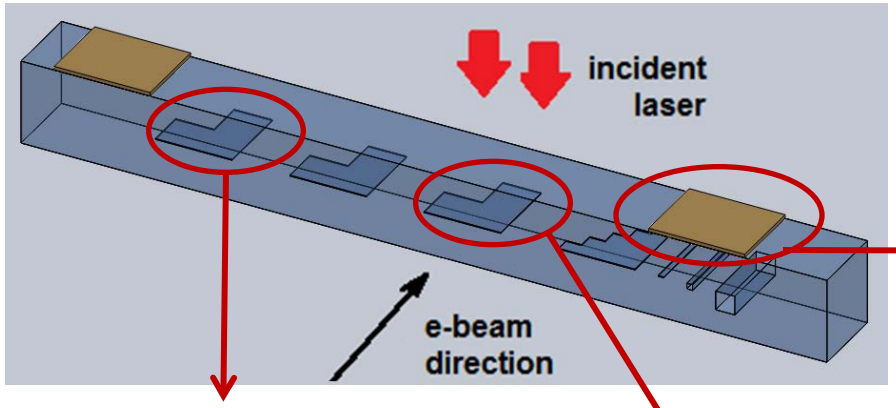

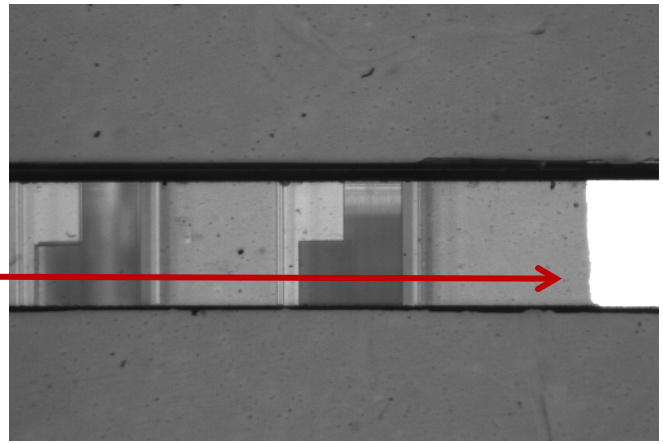

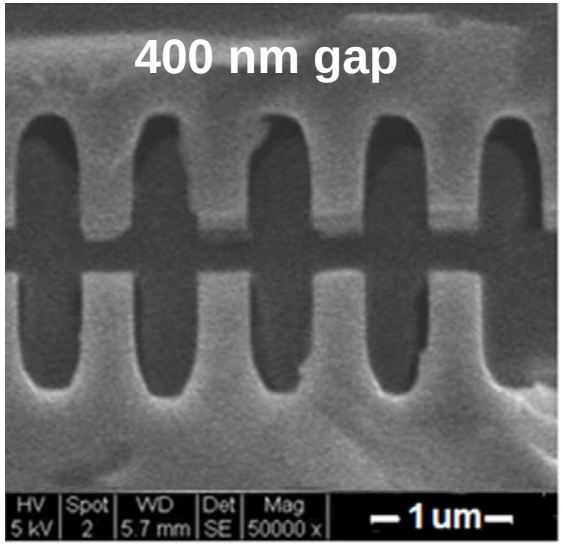

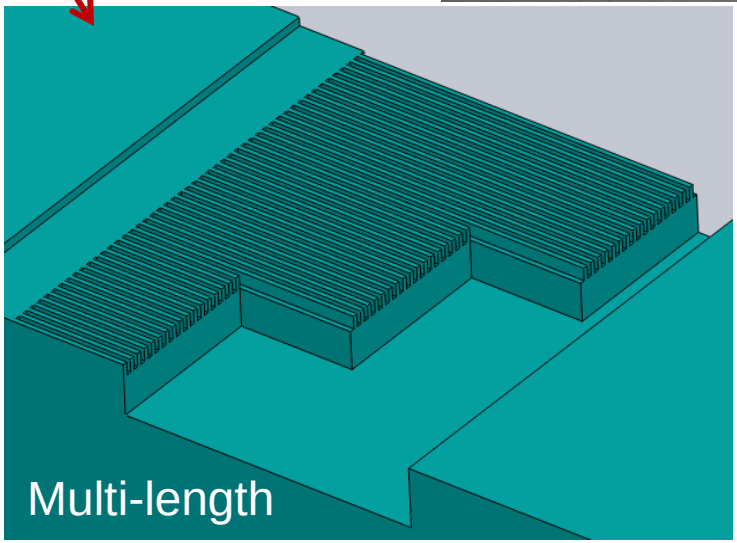

(one half shown only)

Features:

- Multi-length gratings
- 1x 400nm gap
- 1x 800nm gap
- Symmetric process
- Alignment channels
- IR reflectors
  (for laser alignment)

Experiment Schematic

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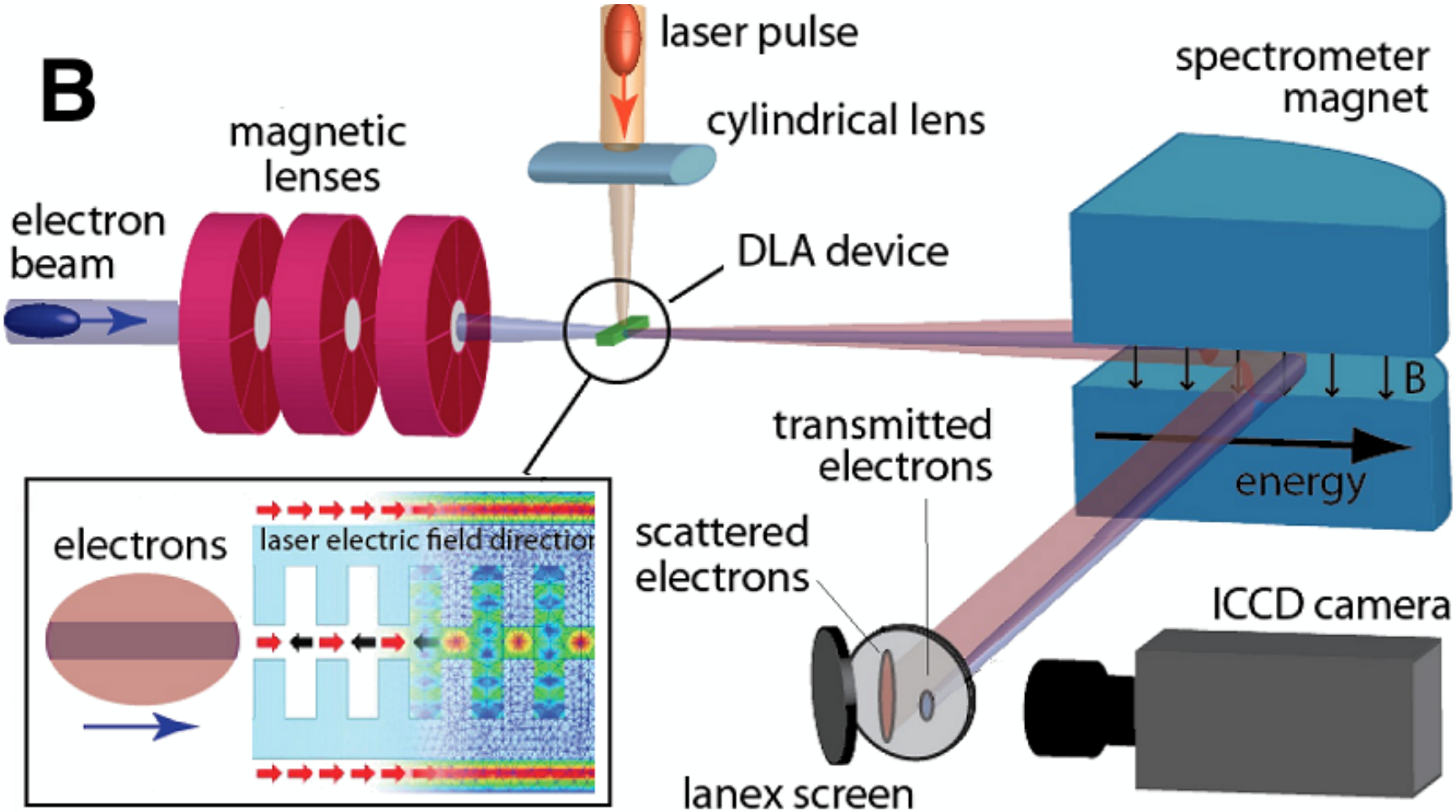
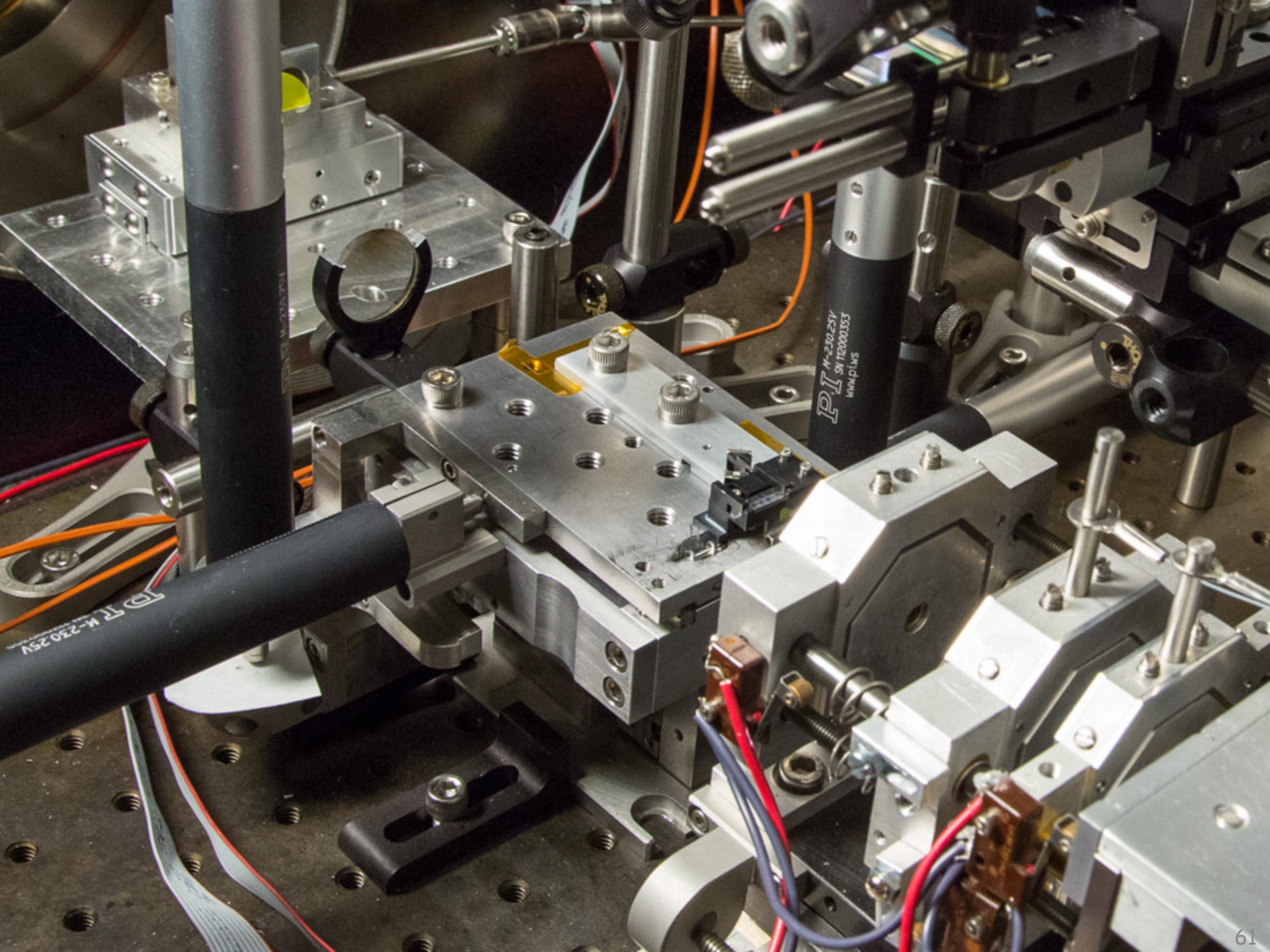


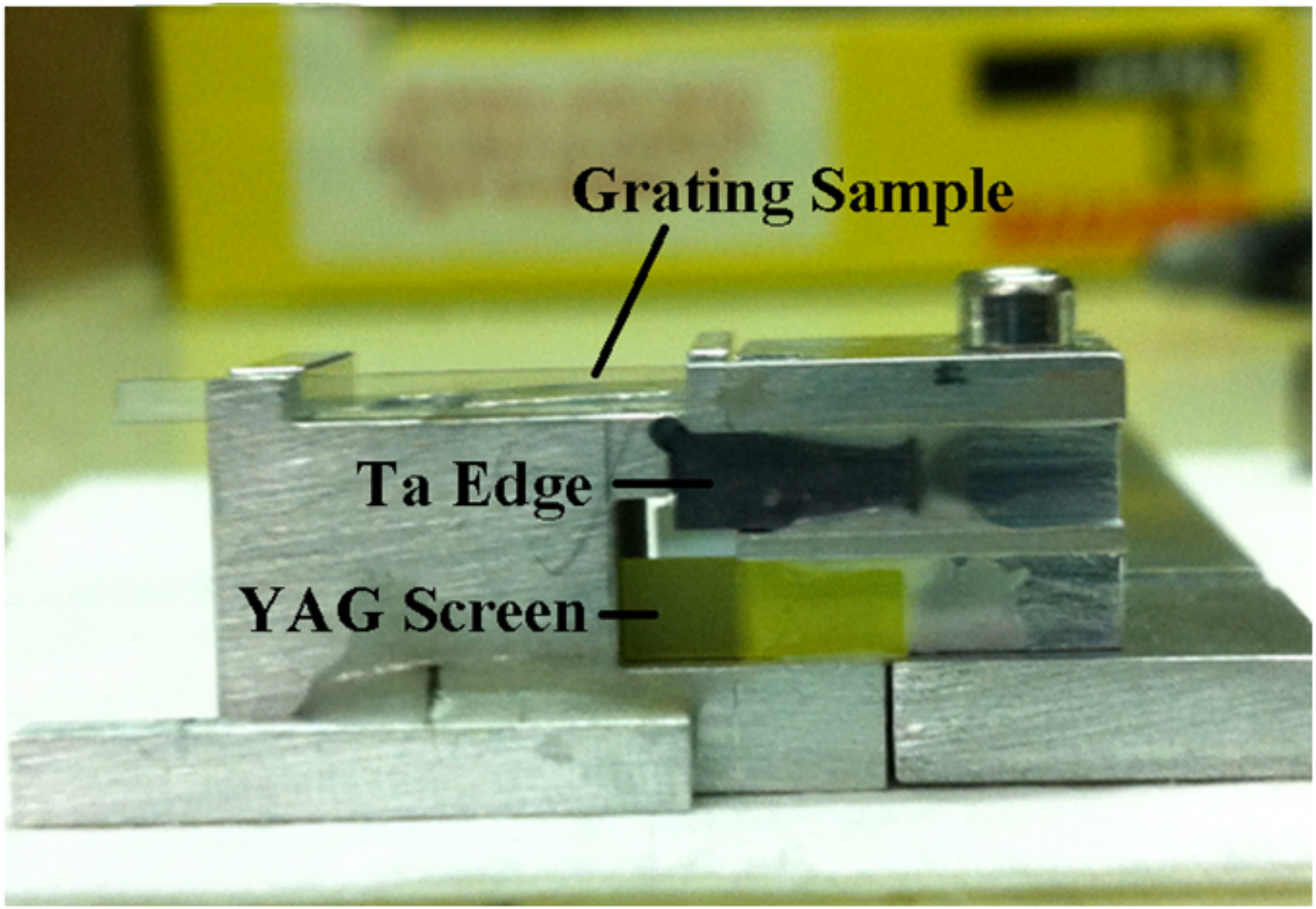

PI
M-230.25V
SN 112000353
www.pi.ws

Virtual Tour: Test Sample

Byer Group

Sample holder

~1 cm



Getting the 60MeV e-beam through the structure

1psec e-beam – 30 μm best focus!
However, we have a 400 nm aperture

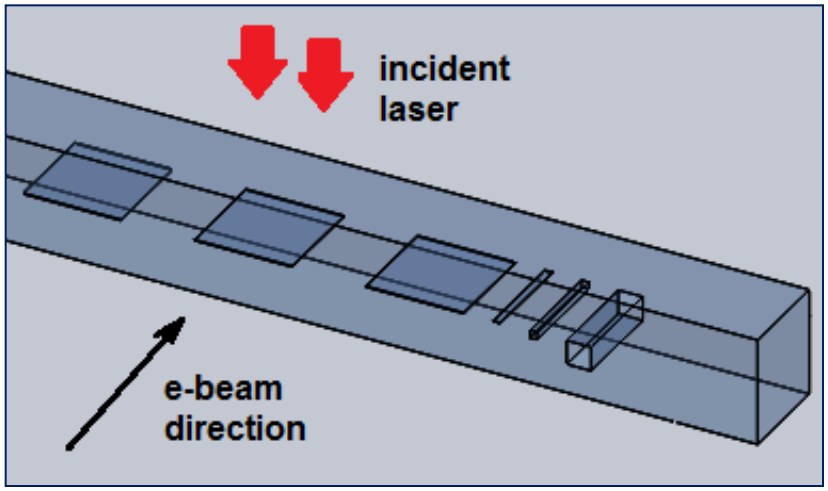
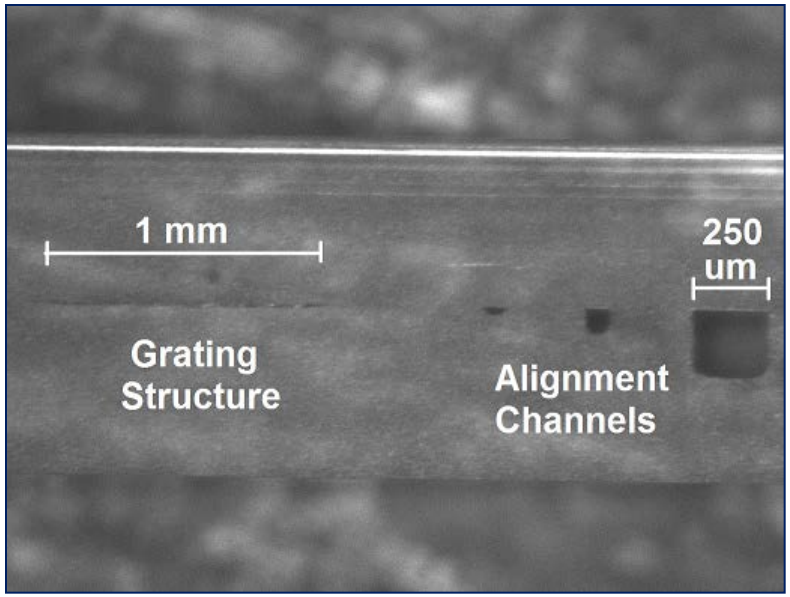


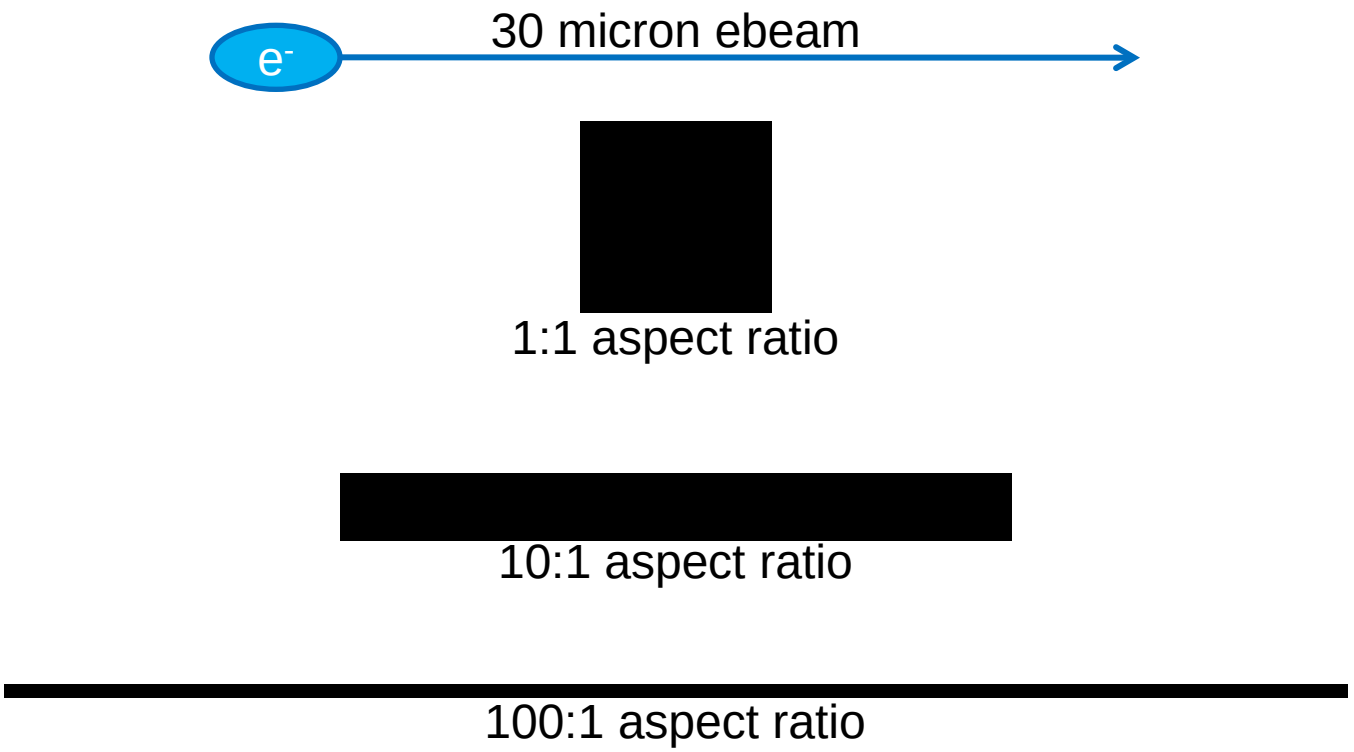
Diagram of test sample



Microscope image of test sample

Experimental Challenge

How hard is it to transmit through a 1000:1 aspect ratio channel?
The following gives a sense of scale.



1000:1 aspect ratio
(our structures)

Preliminary Results

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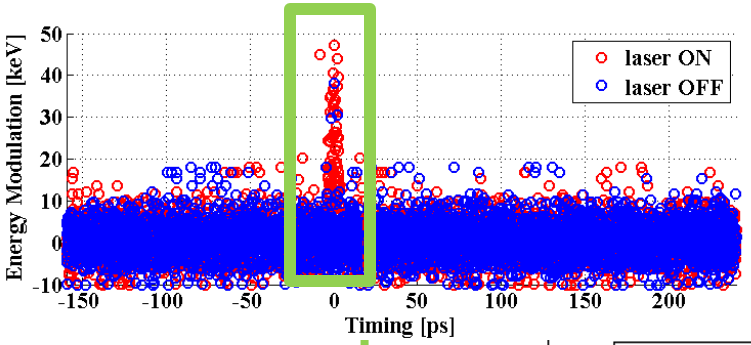
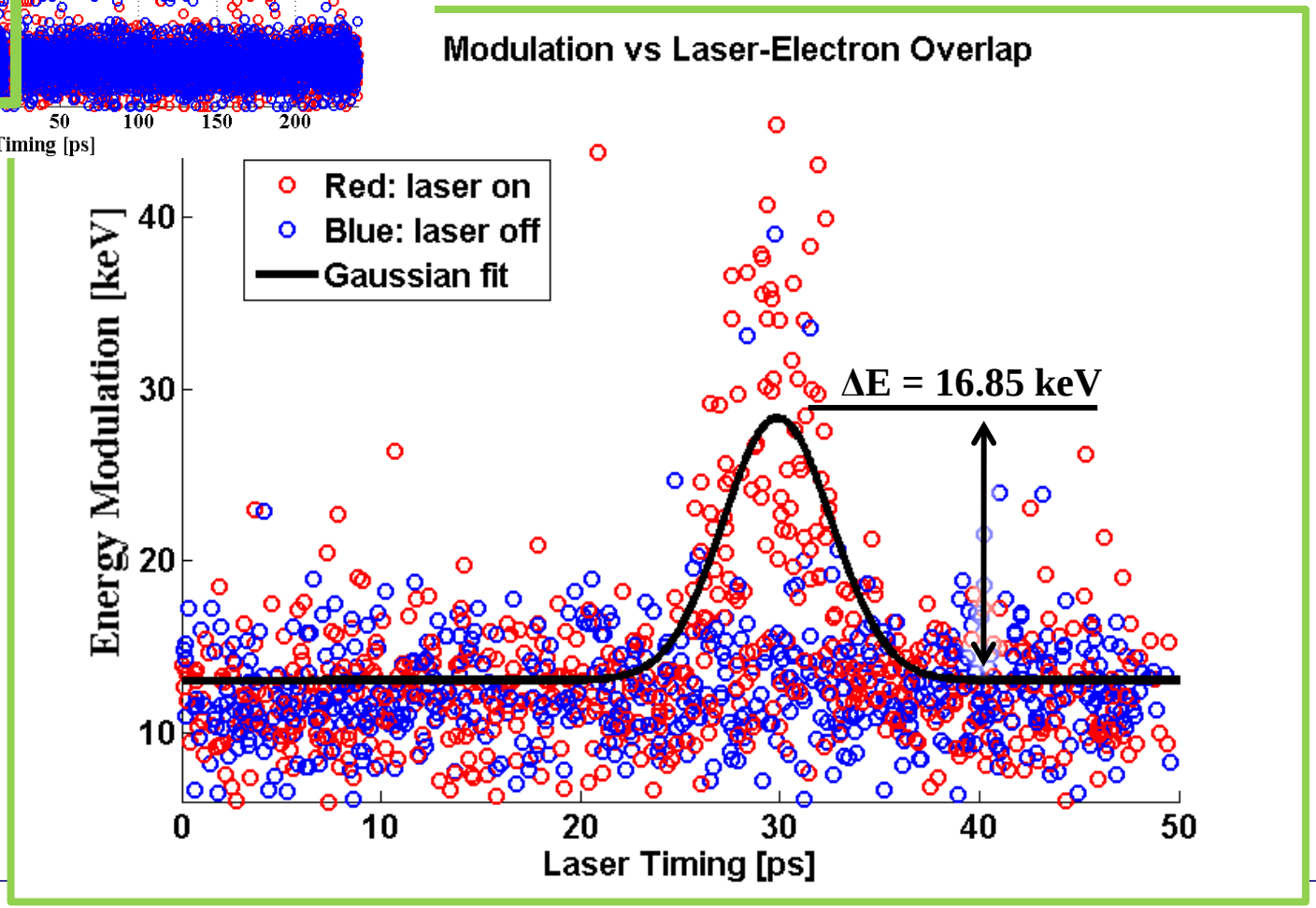
December 2012: We saw the first indication of acceleration at 33 MeV/m





Re: The best 30seconds of my last ~ 5 years!

Re: The best 30 seconds of my last ~ 5 years!

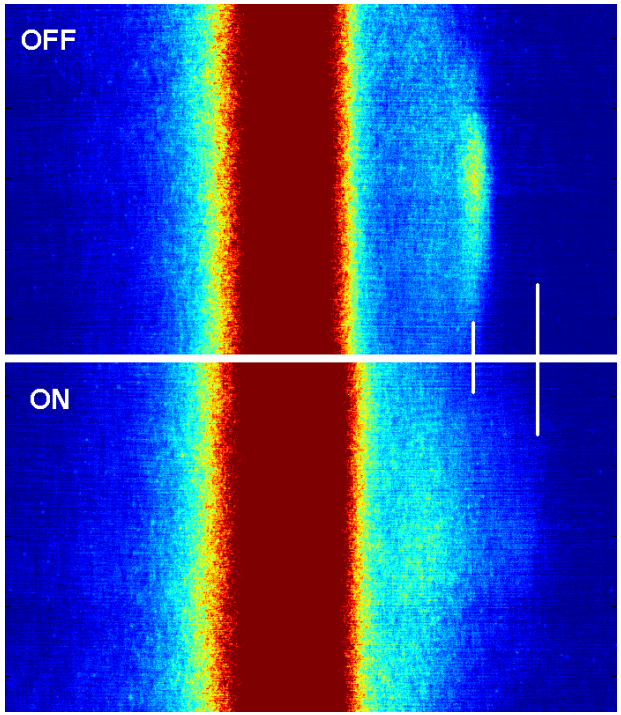
Byer Group

- 27 Feb 2013 23:57:39 -0800 (PST)
  From: **Edgar Peralta** <edgar.a.peralta@gmail.com>
  Date: Wed, 27 Feb 2013 23:57:09 -0800
  Subject: **Re: The best 30 seconds of my last ~5 years**
  To: Joel England <england@slac.stanford.edu>
  Cc: Robert Byer <rlbyer@stanford.edu>, "Soong, Ken" <kensoong@slac.stanford.edu>

  Here's another nice visual.
  On Wed, Feb 27, 2013 at 10:15 AM, Joel England <england@slac.stanford.edu> wrote:
  That's great, Edgar. If you can see the effect by eye from the raw data, that's about as convincing a demonstration as one could hope for.

- Joel

- R. Joel England
- SLAC National Accelerator Laboratory
- Dielectric Laser Acceleration Group
- Advanced Accelerator Research Department
- england@slac.stanford.edu
- 650-926-3706
- ----------



Timing is fixed which led to:

Excellent signal to noise – real time signal

Data confirms physics is correct

Gradient >100MeV/m

Preparation of publication is in process

60 MeV Electron Beam Transmission (400nm channel width, 0.5mm or 540 optical wavelengths long)

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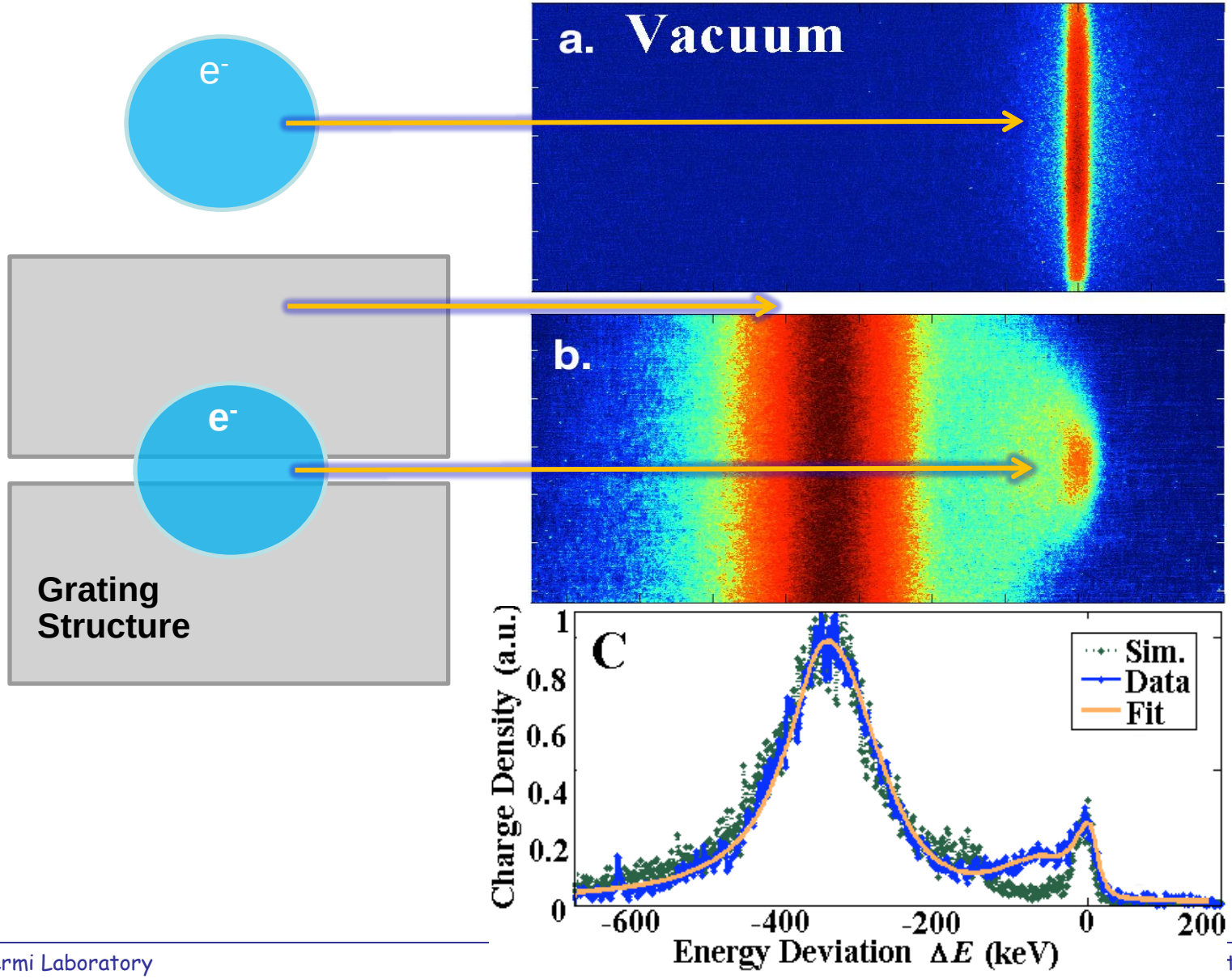

Electron energy spread by laser modulation (0.2mJ, 800nm, 1psec - focused to 0.35J/cm^2)

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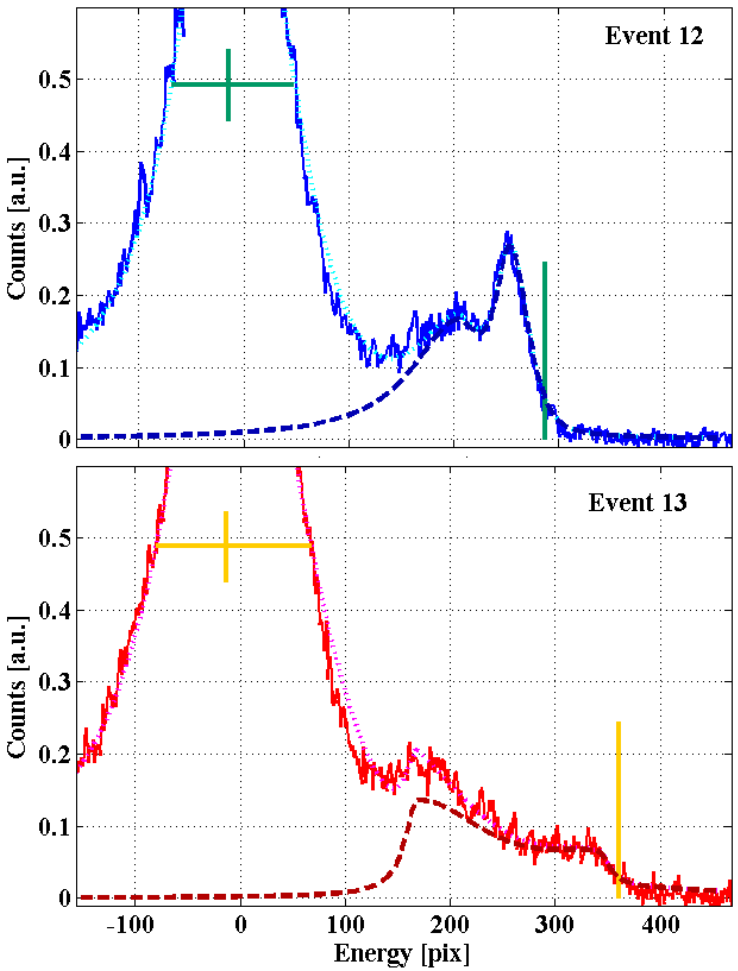

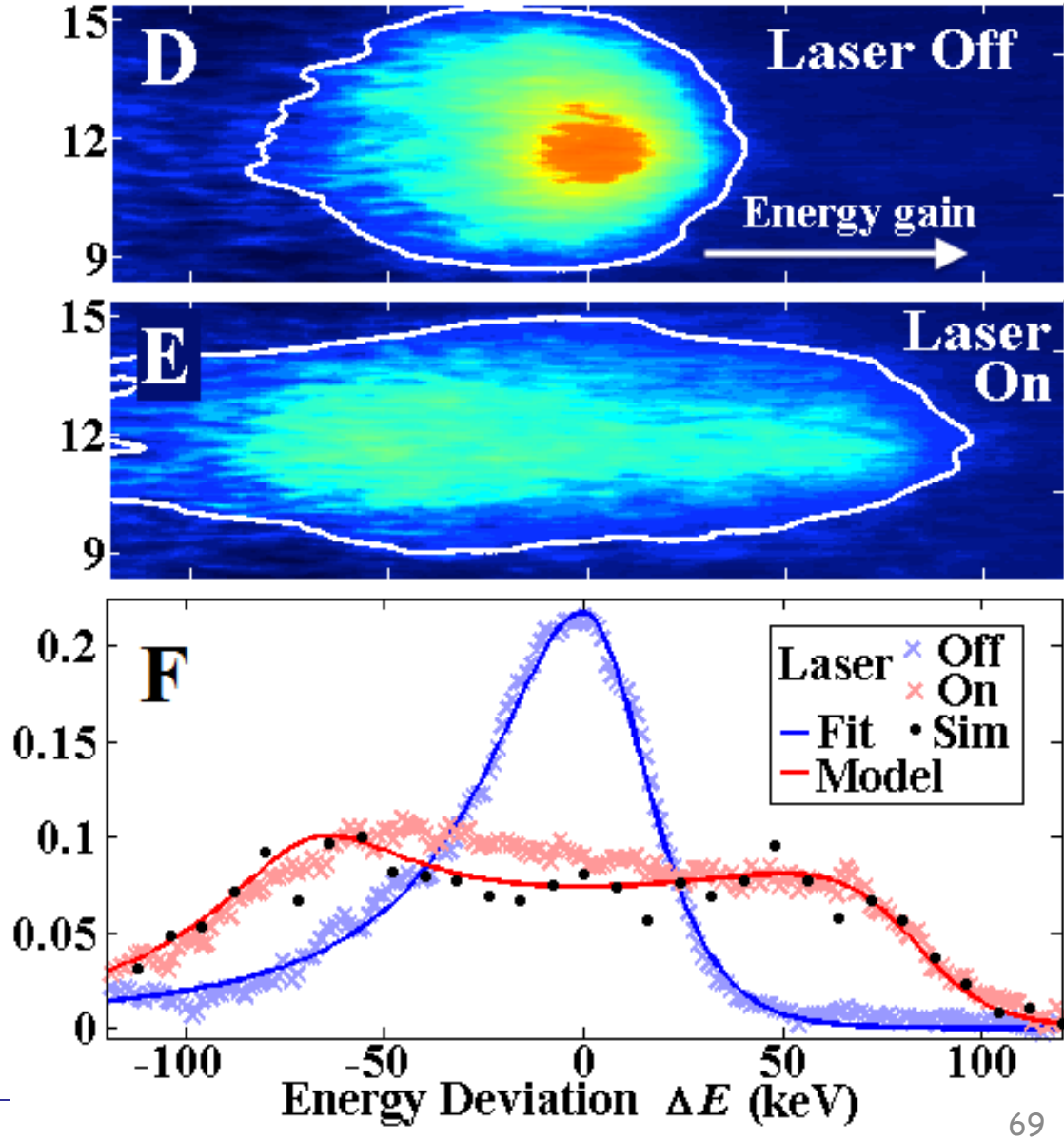

Ken Soong and Edgar Peralta at SLAC Experimental Hall

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A) Cross correlation of electron and laser pulses in time
B) Measured acceleration gradient vs Peak Electric Field

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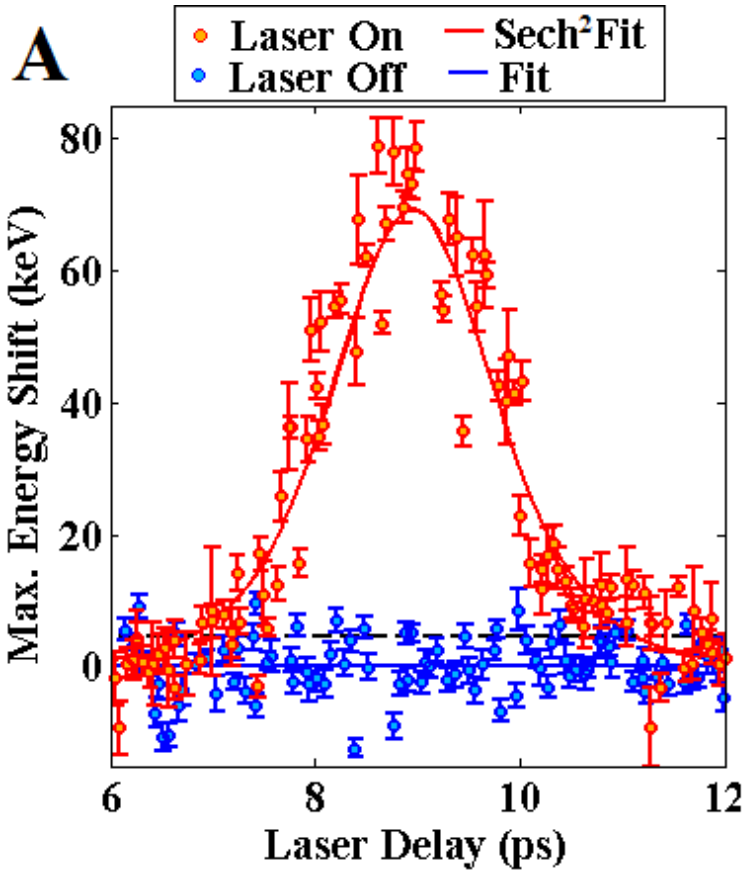
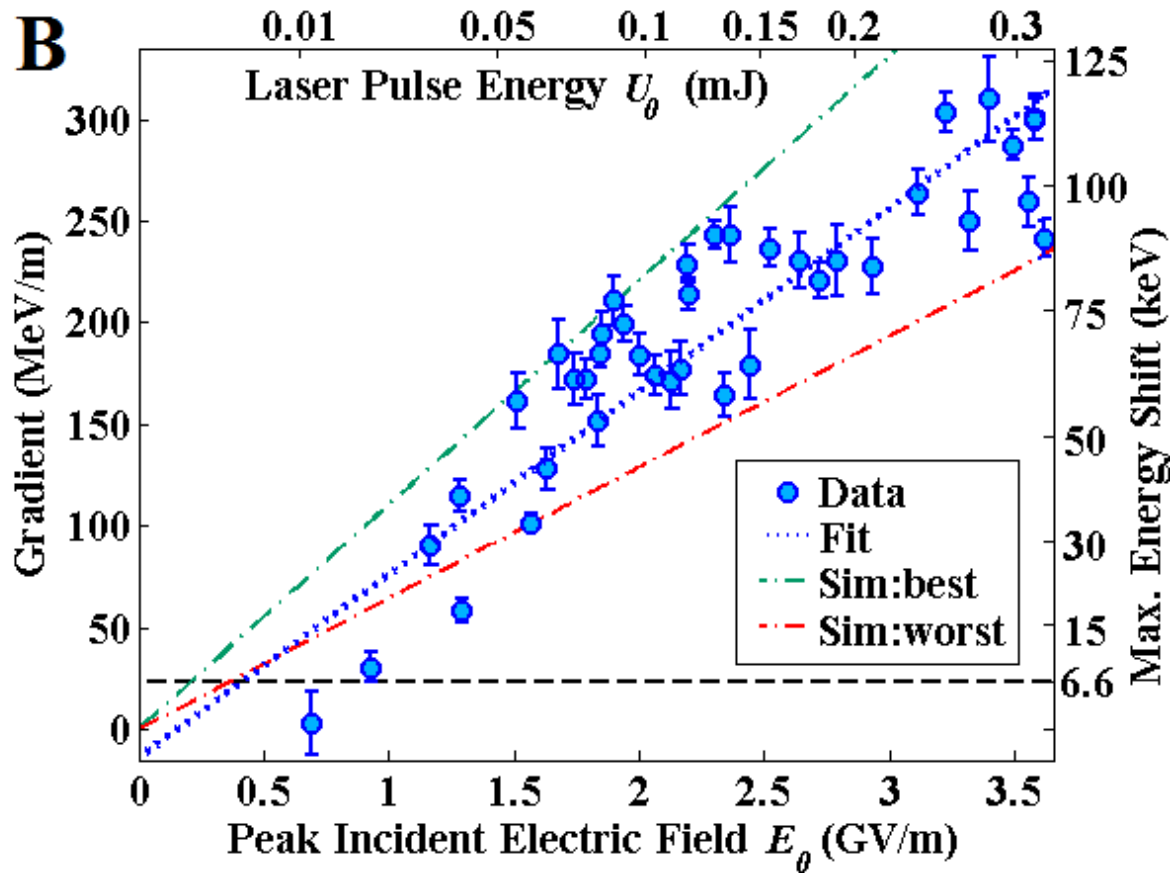
Measured: 300MeV/m gradient in fused silica structure





Upper and lower dashed lines (B) are calculated for aligned and misaligned structures
Fused silica structure damaged (gracefully) above 0.25mJ incident energy as expected

Party on Friday March 1, 2013 – Celebrating success!

Byer Group

Submitted for publication June 30 2013

High-Gradient (beyond 250 MeV/m) Acceleration of Electrons in a Laser-Driven Dielectric Micro-Structure

E. A. Peralta,[1,*] K. Soong,[1] R. J. England,[2] E. R. Colby,[2] B. Montazeri,[3] Z. Wu,[2] C. McGuinness,[1] J. McNeur,[4] R. L. Byer[1].

The enormous size and cost of current state-of-the-art accelerators based upon conventional radio-frequency (RF) technology has spawned an interest in developing new acceleration concepts that are more compact and economical. Micro-fabricated dielectric laser-driven accelerators (DLAs) are an attractive approach, as such structures can support accelerating fields one to two orders of magnitude higher than RF cavity-based accelerators. DLAs use lasers as a power source, which are smaller and cheaper than RF klystrons that power today's accelerators. In addition, DLAs are fabricated via mass-producible, low cost, lithographic techniques. We report the first observation of high-gradient (>250 MV/m) acceleration in a micron-scale DLA driven by an infrared laser. 60 MeV electrons are energy modulated over 563 ± 104 optical periods of a fused silica grating structure, powered by a 800 nm wavelength mode-locked Titanium:Sapphire laser. The observed results are in agreement with analytical calculations and electromagnetic simulations.

In a dielectric laser accelerator the large amplitude fields responsible for the accelerating force are provided by a laser pulse. Of particular interest are lasers that operate in the optical or near infrared (NIR) portion of the electromagnetic spectrum to take advantage of the low loss and high damage threshold of dielectric materials at these wavelengths. Direct laser acceleration of electrons using a NIR laser was demonstrated in a proof-of-principle inverse transition radiation experiment (1). That approach, however, requires a material bound-

An alternative way to satisfy the phase-velocity condition is by creating tailored longitudinal modes in near-field structures. One such approach, the inverse Smith-Purcell accelerator (7), has been demonstrated using a metallic grating (8), and more recently, in a dielectric grating with a NIR laser (9). These open structures do not support speed-of-light longitudinal eigenmodes and are therefore useful only at sub-relativistic particle energies (10). Additionally, they produce an exponentially decaying accelerating field pattern, which distorts the beam. To ad-

viously been shown. To circumvent these challenges, our demonstration employs a planar, phase-reset grating accelerator structure (15), which requires a relatively simple fabrication process and excitation mechanism.

The grating accelerator structure is fabricated out of fused silica (16) and designed to operate at the λ=800 nm wavelength of commercially available Titanium:Sapphire laser systems. The structure consists of two opposing binary gratings of period λ_P, separated by a vacuum gap of height g, where the electron beam travels perpendicular to the grating rulings. A scanning electron microscope (SEM) image of the structure's longitudinal cross-section is shown in Fig. 1A. To generate the required accelerating fields, a TM laser pulse is incident on the structure perpendicular to both the electron beam direction of propagation and the plane of the gratings. The laser pulse generates a series of grating diffraction modes inside the vacuum channel and by matching the grating period to the laser wavelength ($\lambda_P = \lambda$) we achieve phase synchronicity between the strong first space harmonic and the particle beam (10).

The structure essentially acts as a longitudinally periodic phase mask, where each grating pillar imparts a π-phase shift on the electric field, with respect to the adjacent vacuum space (Fig. 1B, inset). As a result, an electron launched at the correct phase (laser-electron timing) experiences net en-

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NATURE | LETTER near-final version

Demonstration of electron acceleration in a laser-driven dielectric microstructure

E. A. Peralta, K. Soong, R. J. England, E. R. Colby, Z. Wu, B. Montazeri, C. McGuinness, J. McNeur, K. J. Leedle, D. Walz, E. B. Sozer, B. Cowan, B. Schwartz, G. Travish & R. L. Byer

Affiliations | Contributions | Corresponding author

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The enormous size and cost of current state-of-the-art accelerators based on conventional radio-frequency technology has spawned great interest in the development of new acceleration concepts that are more compact and economical. Micro-fabricated dielectric laser accelerators (DLAs) are an attractive approach, because such dielectric microstructures can support accelerating fields one to two orders of magnitude higher than can radio-frequency cavity-based accelerators. DLAs use commercial lasers as a power source, which are smaller and less expensive than the radio-frequency klystrons that power today's accelerators. In addition, DLAs are fabricated via low-cost, lithographic techniques that can be used for mass production.

Editors' pick

'Taboo' topics in genetics

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Phys. Rev. Lett. 111, 134803 (2013) [5 pages]

Laser-Based Acceleration of Nonrelativistic Electrons at a Dielectric Structure

Abstract | References | No Citing Articles | Supplemental Material

Download: PDF (1,215 kB) Buy this article Export: BibTeX or EndNote (RIS)

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Received 15 July 2013; published 27 September 2013

See accompanying *Physics* Focus

A proof-of-principle experiment demonstrating dielectric laser acceleration of *nonrelativistic* electrons in the vicinity of a fused-silica grating is reported. The grating structure is utilized to generate an electromagnetic surface wave that travels synchronously with and efficiently imparts momentum on 28 keV electrons. We observe a maximum acceleration gradient of 25 MeV/m. We investigate in detail the parameter dependencies and find excellent agreement with numerical simulations. With the availability of compact and efficient fiber laser technology, these findings may pave the way towards an all-optical compact particle accelerator. This work also represents the demonstration of the inverse Smith-Purcell effect in the optical regime.

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DOI: 10.1103/PhysRevLett.111.134803
PACS: 41.75.Jv, 42.25.-p, 42.50.Wk

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Accelerator on a Chip

Byer Group

Joel and Bob,

I wanted to report back on last week's press release. It was a tremendous success by all standards, undoubtedly in the top 5 of all stories we've done in the past three years in terms of its reach and resonance. I'm sure you've seen a lot of the clips, but here's a list of some...

Forbes <http://www.forbes.com/sites/alexknapp/2013/09/29/researchers-build-a-particle-accelerator-on-a-chip/ >
Popular Science <http://www.popsci.com/article/technology/powerful-particle-accelerator-size-speck-glitter>
Popular Mechanics <http://www.popularmechanics.com/how-to/blog/cheaper-micro-sized-particle-accelerators-are-now-possible-15987492>
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IFLS <https://www.facebook.com/photo.php?fbid=673916955962652&set=pb.367116489976035.-2207520000.1380691349.&type=3&theater>
the Verge <http://www.theverge.com/2013/9/27/4777840/stanfords-new-linear-accelerator-is-just-three-millimeters-long>
Gizmodo <http://gizmodo.com/this-particle-accelerator-is-barely-bigger-than-a-grain-1426829083>
Physics <http://physics.aps.org/articles/v6/106>
ScienceDaily <http://www.sciencedaily.com/releases/2013/09/130927134714.htm>
Economist (Babbage Blog) <http://www.economist.com/blogs/babbage/2013/10/babbage-october-2nd-2013>
IBT <http://www.ibtimes.com/accelerator-chip-tiny-particle-collider-could-lead-portable-x-ray-technology-cheaper-accelerators>
Guardian Express <http://guardianlv.com/2013/09/accelerator-on-a-chip-to-yield-cheaper-particle-accelerators-and-x-ray-scanners/>
Pentagon Post <http://www.pentagonpost.com/scientists-demonstrate-accelerator-chip/83412290>
The Almanac <http://www.almanacnews.com/news/show_story.php?id=14520>
Design & Trend <http://www.designntrend.com/articles/8213/20130928/new-chip-accelerator-make-x-ray-technology-portable-stanford-slac-research-study.htm>
Examiner, <http://www.examiner.com/article/particle-accelerator-the-size-of-a-grain-of-rice-developed?cid=rss>
RedOrbit <http://www.redorbit.com/news/technology/1112960774/paving-the-way-for-tabletop-particle-accelerators-092813/>
Science Recorder <http://www.sciencerecorder.com/news/researchers-use-a-laser-to-build-a-particle-accelerator-on-a-tiny-glass-chip/>
PhysOrg <http://phys.org/news/2013-09-chip.html>

And that's just to name a few, there are really too many to list, particularly if you look beyond English-language sites. As evidence of how far and wide it's spread over the past week, the animation already has ~69,000 YouTube views (http://www.youtube.com/watch?v=V89qvy8whxY) and that number continues to climb.

Congratulations, I hope it helps cause conversations and leads to additional support for your ideas and your teams. It's certainly a huge value to the lab and the university's reputations to let the public know the types of technologies we're working on.

All the best and we look forward to hearing of your future success,
- Andy

Andy Freeberg, Media Relations Manager
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http://facebook.com/SLAC.National.Lab
http://twitter.com/SLACLab

I wanted to report back to you on last week's news release.
(September 27, 2013 at 10am)

It was a tremendous success by all standards undoubtedly in the top 5 of all stories done in the past 3 years in terms of its reach and response.

Andrew Freeberg, SLAC

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"Our ultimate goal for the structure is 1 billion electron volts per meter and we're already one-third of the way in our first experiment."
said Robert Byer, PI for the research.

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Researchers Demonstrate 'Accelerator on a Chip'

Technology could spawn new generations of smaller, less expensive devices for science, medicine

September 27, 2013

Menlo Park, Calif. — In an advance that could dramatically shrink particle accelerators for science and medicine, researchers used a laser to accelerate electrons at a rate 10 times higher than conventional technology in a nanostructured glass chip smaller than a grain of rice.

The achievement was reported today in *Nature* by a team including scientists from the U.S. Department of Energy's (DOE) SLAC National Accelerator Laboratory and Stanford University.

"We still have a number of challenges before this technology becomes practical for real-world use, but eventually it would substantially reduce the size and cost of future high-energy particle colliders for exploring the world of fundamental particles and forces," said Joel England, the SLAC physicist who led the experiments. "It could also help enable compact accelerators and X-ray devices for security scanning, medical therapy and imaging, and research in biology and materials science."

Because it employs commercial lasers and low-cost, mass-production techniques, the researchers believe it will set the stage for new generations of "tabletop" accelerators.

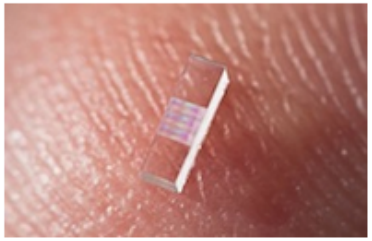
At its full potential, the new "accelerator on a chip" could match the accelerating power of SLAC's 2-mile-long linear accelerator in just 100 feet, and deliver a million more electron pulses per second.

This initial demonstration achieved an acceleration gradient, or amount of energy gained per length, of 300 million electronvolts per meter. That's roughly 10 times the acceleration provided by the current SLAC linear accelerator.

"Our ultimate goal for this structure is 1 billion electronvolts per meter, and we're already one-third of the way in our first experiment," said Stanford Professor Robert Byer, the principal investigator for this research.

SHARE

Nanofabricated chips of fused silica just 3 millimeters long were used to accelerate electrons at a rate 10 times higher than conventional particle accelerator technology. (Brad Plummer/SLAC)



The key to the accelerator chips is tiny, precisely spaced ridges, which cause the iridescence seen in this close-up photo

What Next? Plenty of work to do!

Current Challenges

Electron beam source, injector and buncher (Peter Hommelhoff)

Detailed modeling of structures (Ben Cowan)

*Silicon accelerator structure testing (Chia Ming Chan, Olav Solgaard)

*Beam position monitor and beam steering and focusing (Ken Soong)

Modelocked Tm :fiber oscillator/amplifier at 30% efficiency (Charles Rudy)

Future Directions

FEL Dielectric Undulator – test performance

Wave guide delivery of light from fiber laser amplifier to accelerator structure

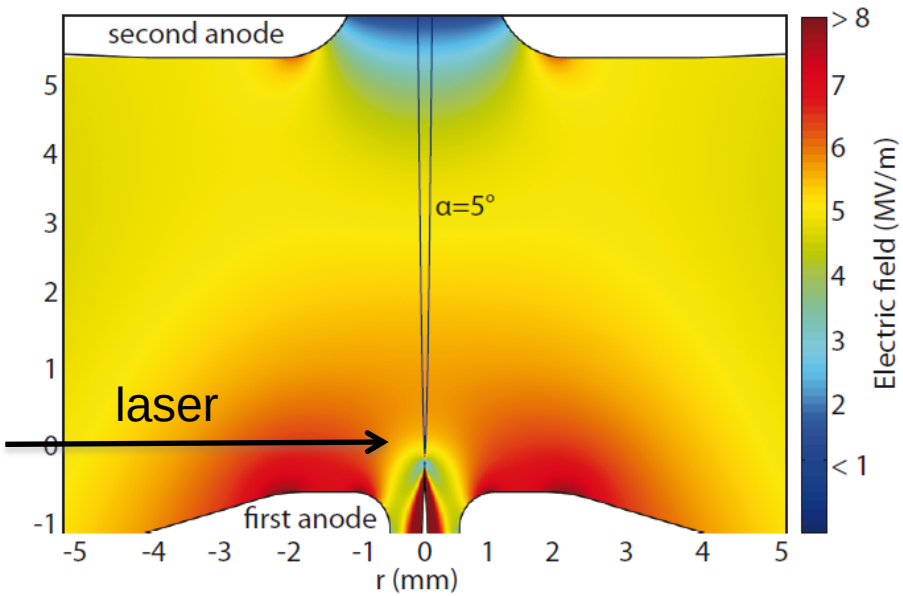
Multiple staged accelerator structures for energy scaling

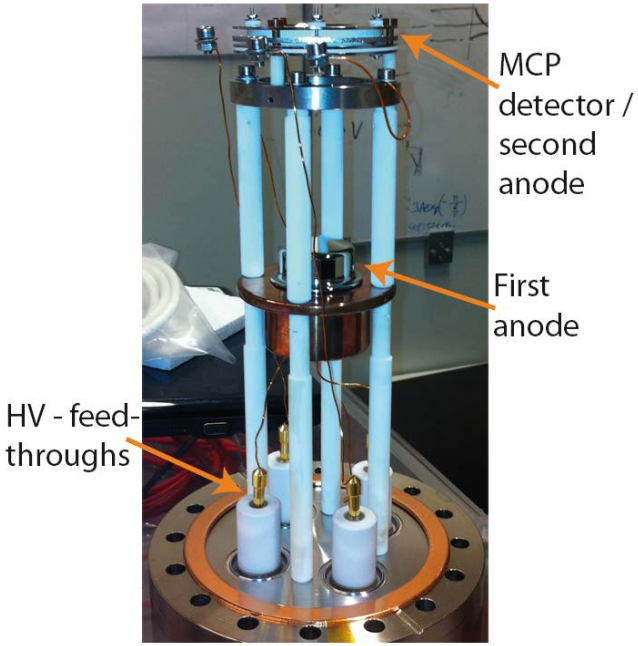
Complete FEL X-ray laser – sync pumped with “natural” photonic crystals as resonator mirrors

Supertip Emitter Source Development

Dr. Peter Hommelhoff, Johannes Hoffrogge, (MPQ)

- Optimized 30 keV structure found with the help of FDTD electric field simulations and particle tracking. Result:





Tip pointing through one anode, with second anode a few mm away (left). With this geometry, the field on electrons' path never drops below ~4MV/m

(a)Tungsten supertip electron source, (b) Mounted tip illuminated by a ultrafast laser

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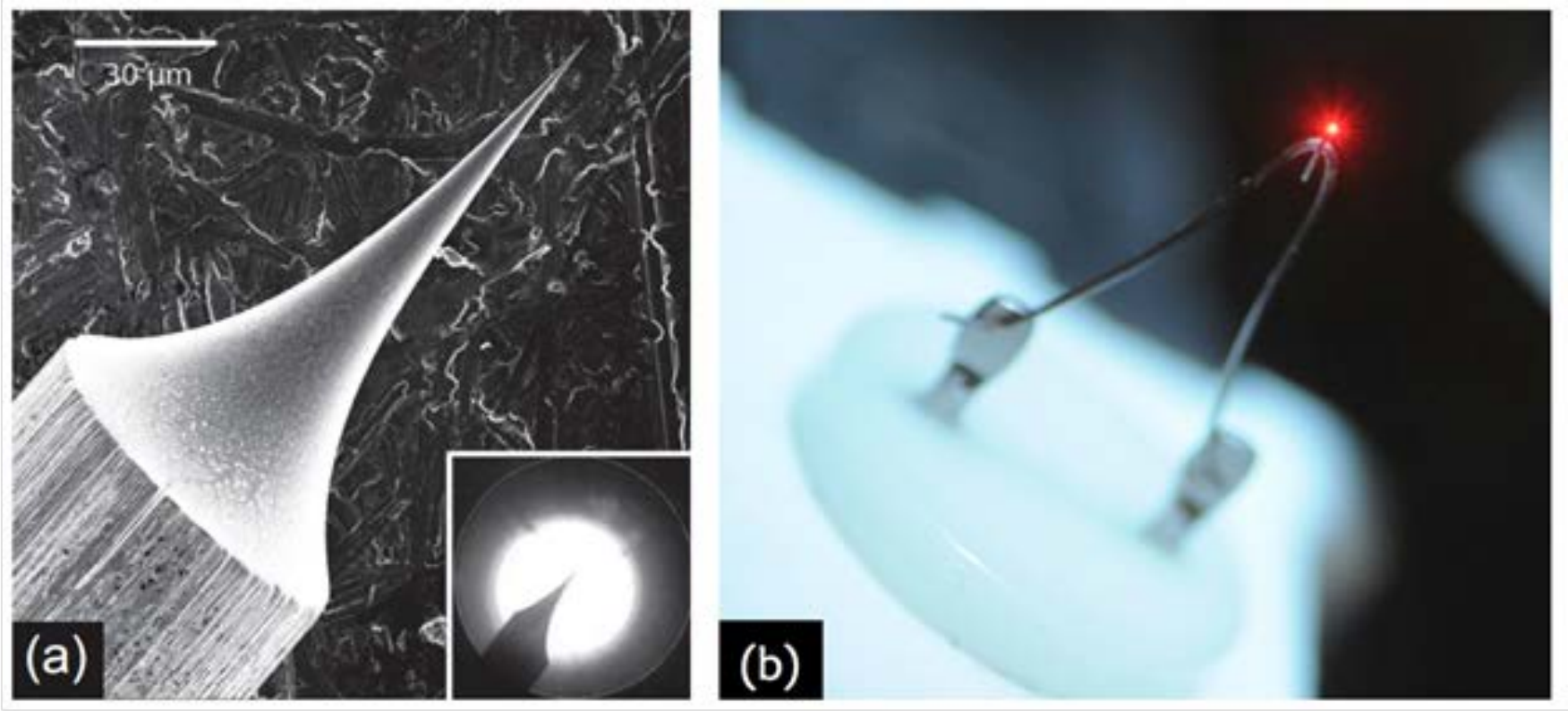

Courtesy P. Hommelhoff

Schematic of a Low-Beta Pre-Accelerator

Byer Group

PRL **111,** 134803 (2013) PHYSICAL REVIEW LETTERS week ending 27 SEPTEMBER 2013

Laser-Based Acceleration of Nonrelativistic Electrons at a Dielectric Structure

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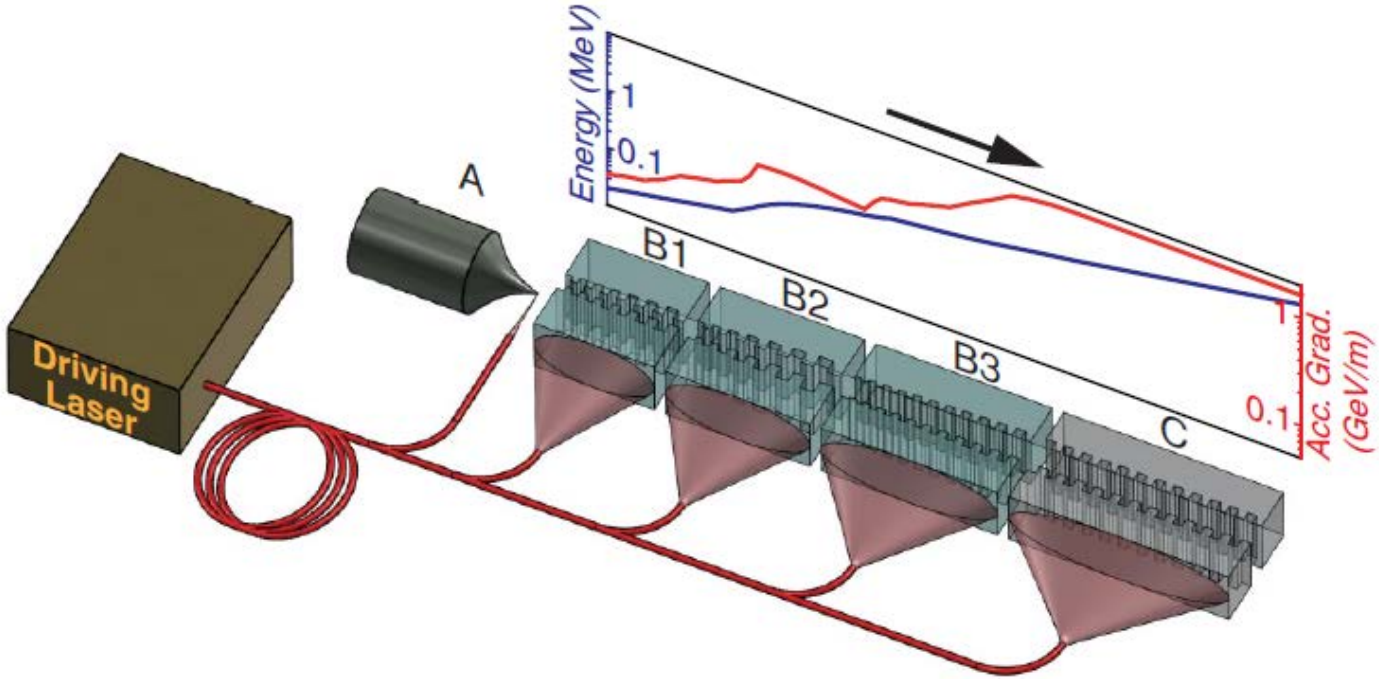
Peter Hommelhoff*
Department of Physics, Friedrich Alexander University Erlangen-Nuremberg, Staudtstrasse 1, 91058 Erlangen, Germany and Max Planck Institute of Quantum Optics, Hans-Kopfermann-Strasse 1, 85748 Garching, Germany
(Received 15 July 2013; published 27 September 2013)



Schematic of On-chip laser guiding to Accelerator Structure

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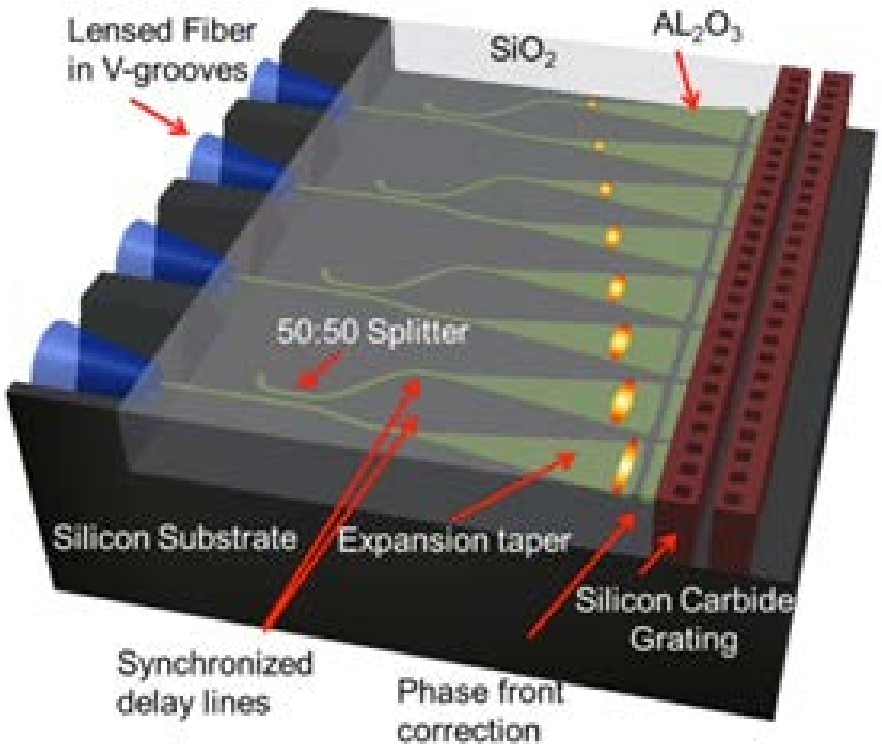
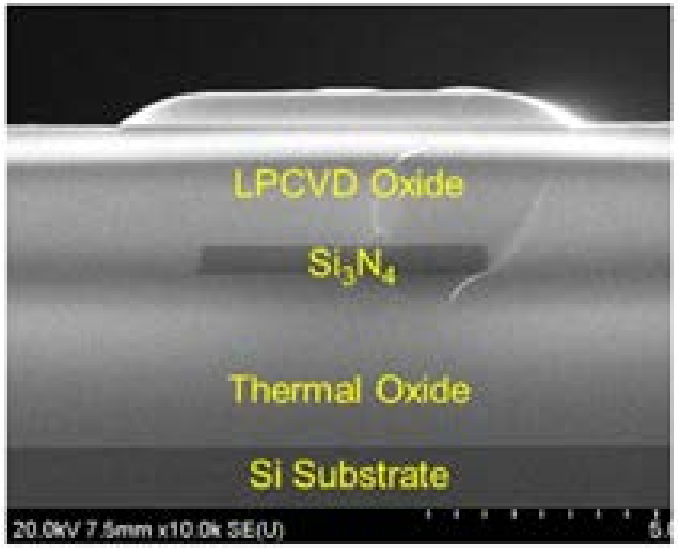
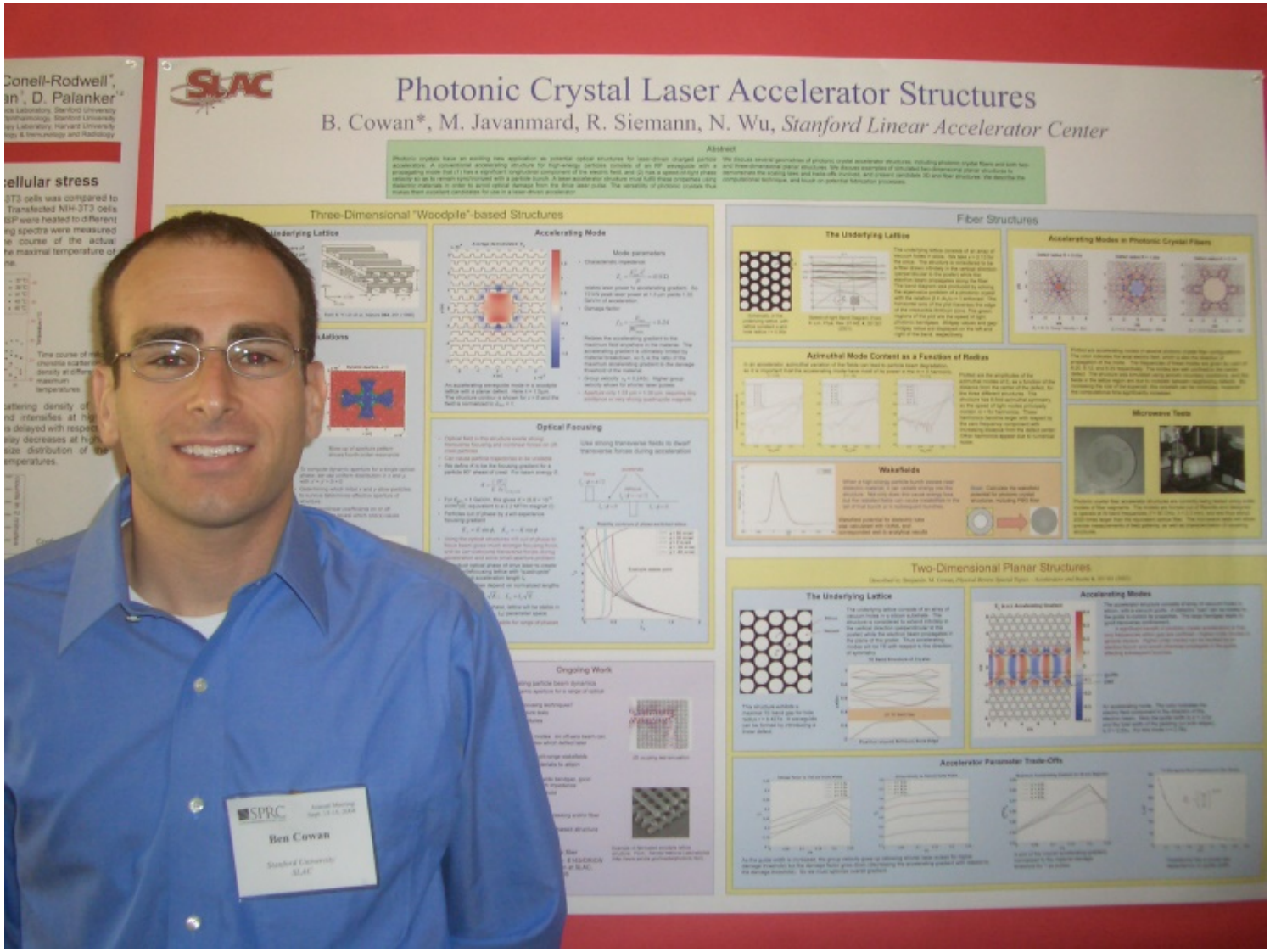




On chip Silicon-Nitride waveguide

Ben Cowan – detailed modeling
Photonic Crystal Accelerator Structures

Byer Group



Optical bunching in less than 1mm of acceleration
Ben Cowan – VORPAL simulations

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In addition, we increased the particle bunch length from 2 optical periods to 50. The introduction of the additional particles did not significantly increase the computation time, because particles in different physical regions are computed by different processor cores in a parallel simulation.

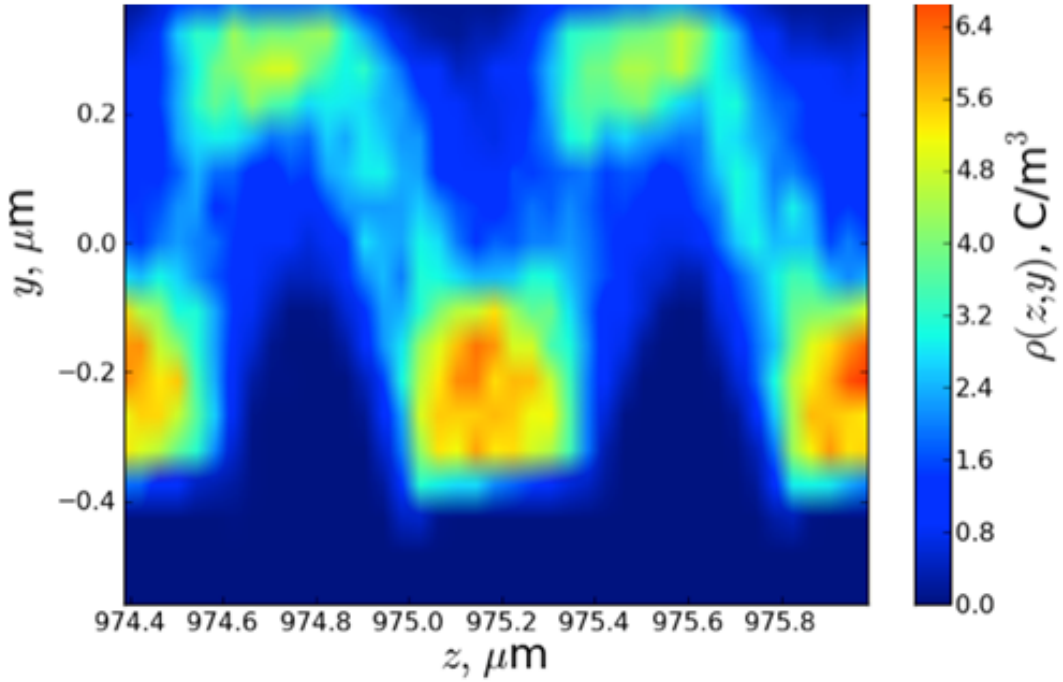


Fig. 9. Density modulation of electrons due to the transverse laser forces after ~1 mm of propagation.

With these changes, we obtained a remarkable result: electrons are optically bunched longitudinally due to the transverse forces from the laser field. For one interval of optical

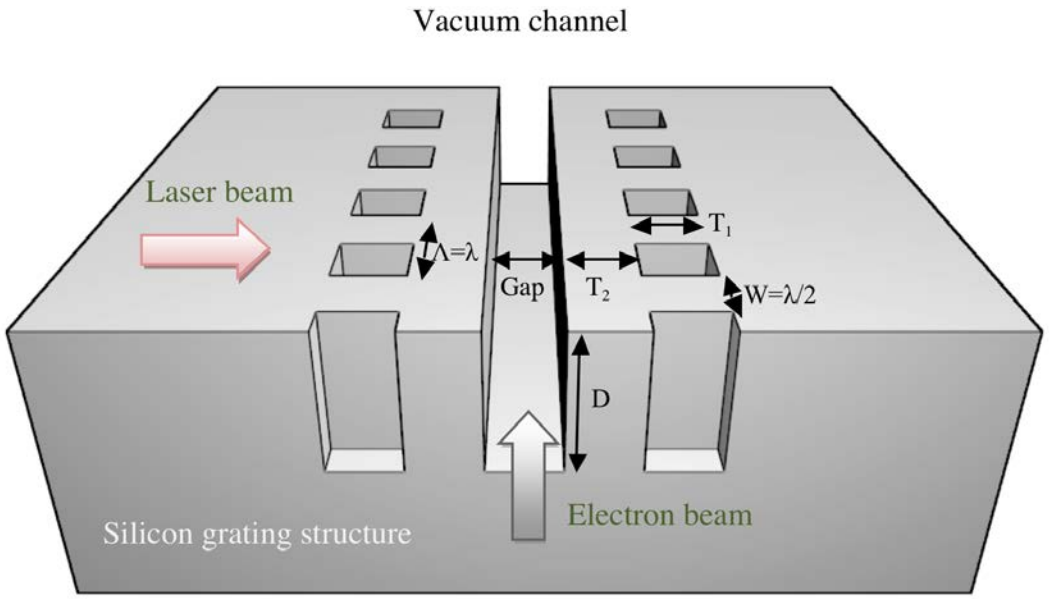
We expect to see 15 attosecond electron bunching in 1mm of structure

Innovative New Structures: Buried Grating in Silicon

Byer Group

Chia-Ming Chang, Prof. Olav Solgaard, E. Peralta

- Buried silicon grating structures for electron accelerators
- Grating design with <u>optimal gradient</u>
- Grating design with <u>wide electron channels</u> (wide gap)
- **FDTD simulations at 2μm wavelength – shows potential for 500MeV/m**
  - Parameters: electron channel gap, grating pillar height and slab height.



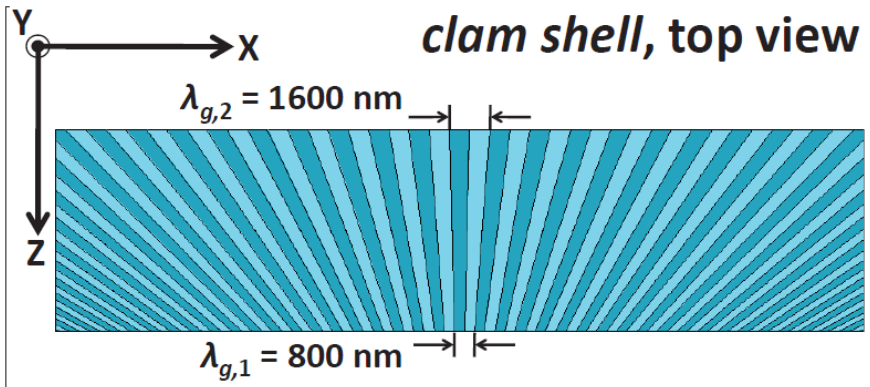
Plans are to test this structure in next run using 2μm laser driver

Structure Design: Grating-type Beam Position Monitor

Ken Soong idea and invention

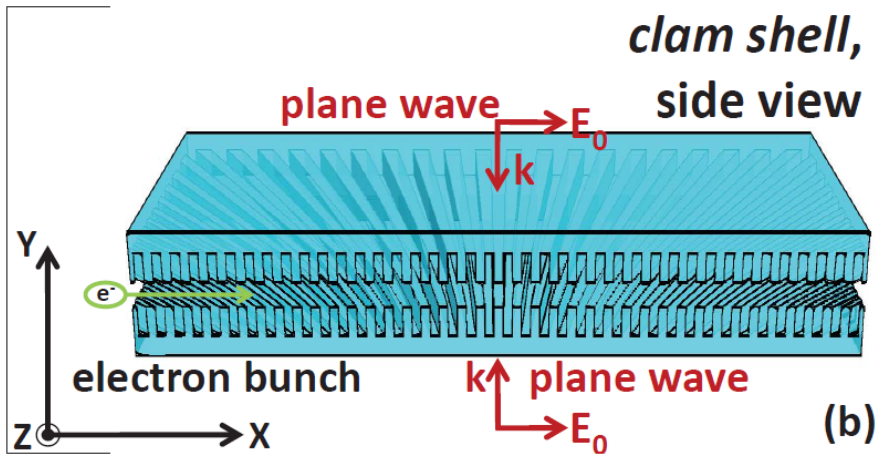
In order to stage 1 meter of accelerating structures, we will also need **focusing structures** and **deflecting structures**[1,2], as well as **beam position monitors**[3].

Recently developed BPM based on the principles of an **inverse grating accelerator structure**



BPM Design

(a)



(b)

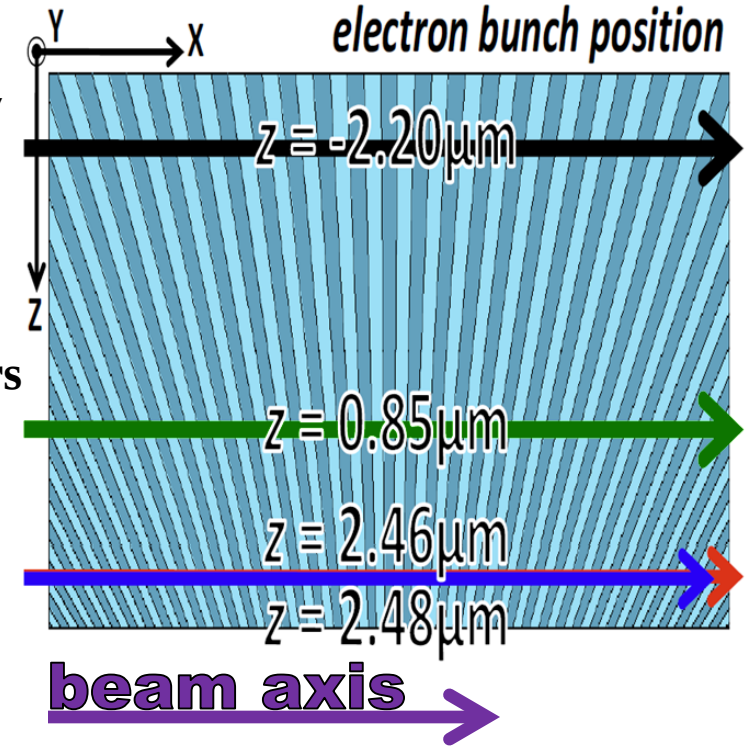
1. T. Plettner, *Phys. Rev. ST Accel. Beam* 12, 101302 (2009)
2. K. Soong, *SLAC Report* No. SLAC-PUB-14426 (2011)
3. K. Soong, *Optics Letters*, Vol. 37, Issue 5, pp. 975-977 (2012)

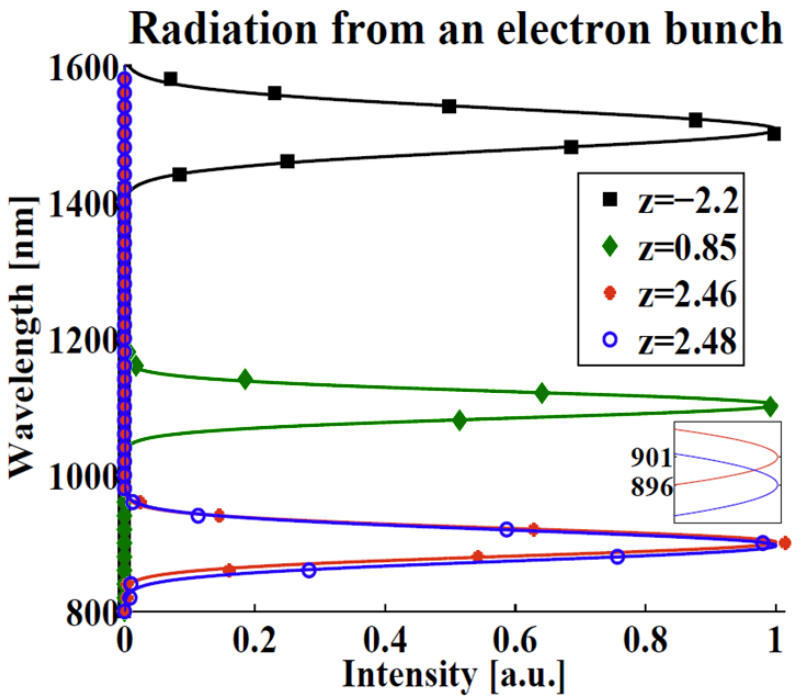
Structure Design: Grating-type BPM

First BPM design to encode beam position as a wavelength

→ Exploit the high resolution of spectrometer technology

Beam parameters
σ=20 nm
Q=10 fC
τ=0.1 fs





Simulation of performance

DLA Beam Position Monitor

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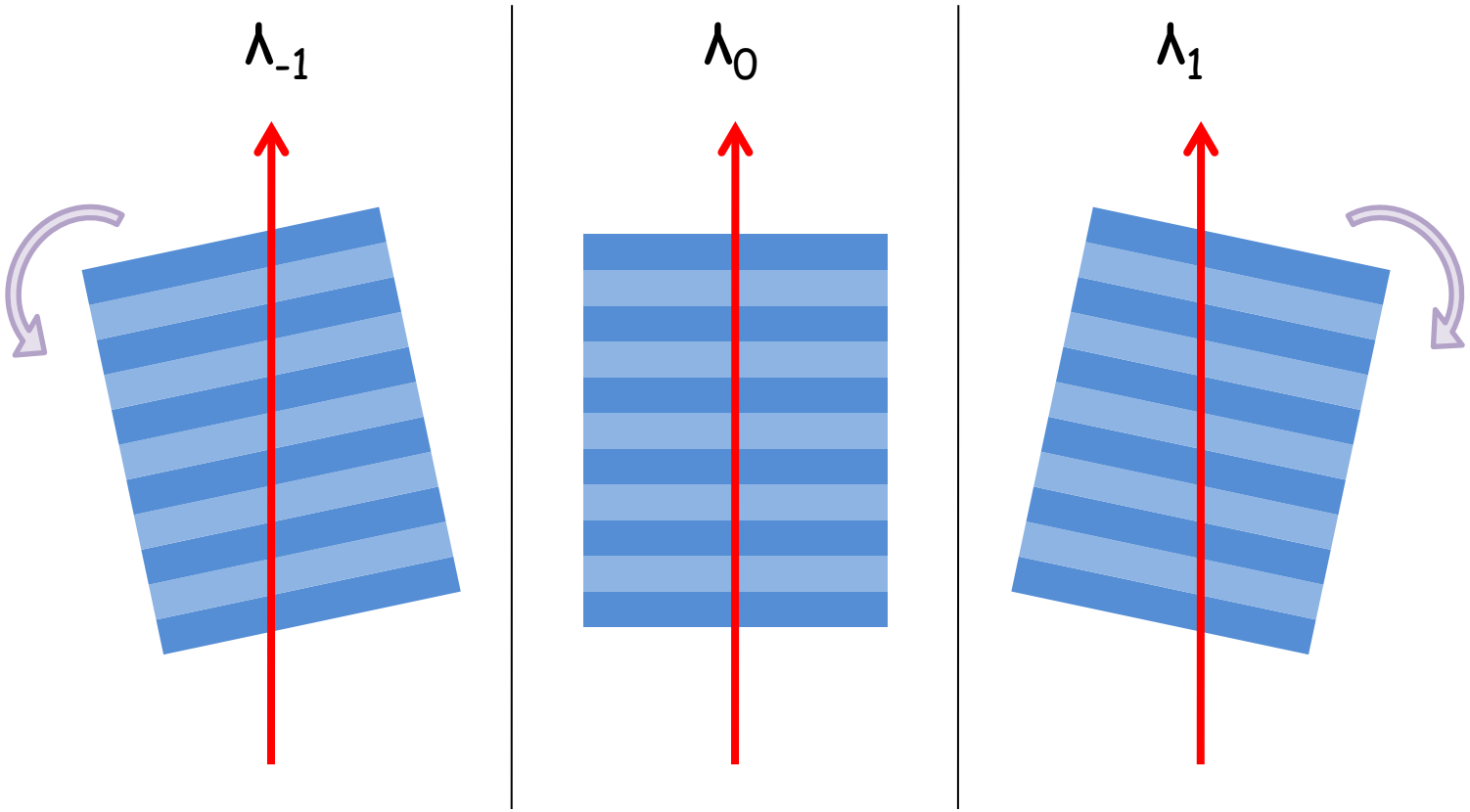
Verification of the grating-BPM concept: *geometry dependent radiation.*



By rotating a fixed period grating structure, we should be able to vary the radiation as:

$$\lambda = \frac{\lambda_0}{\cos\theta}$$

DLA Beam Position Monitor

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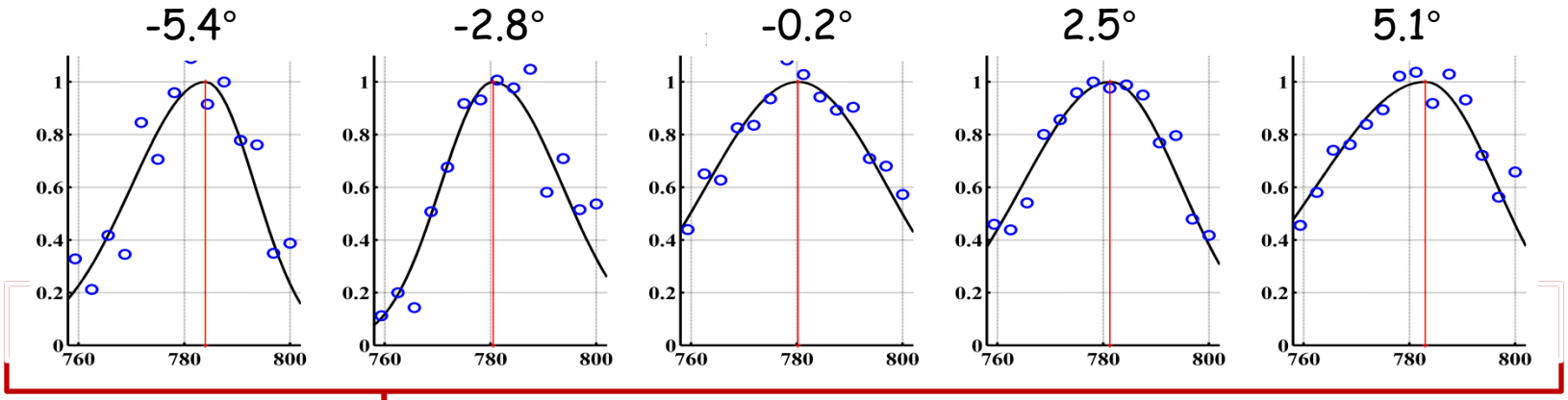
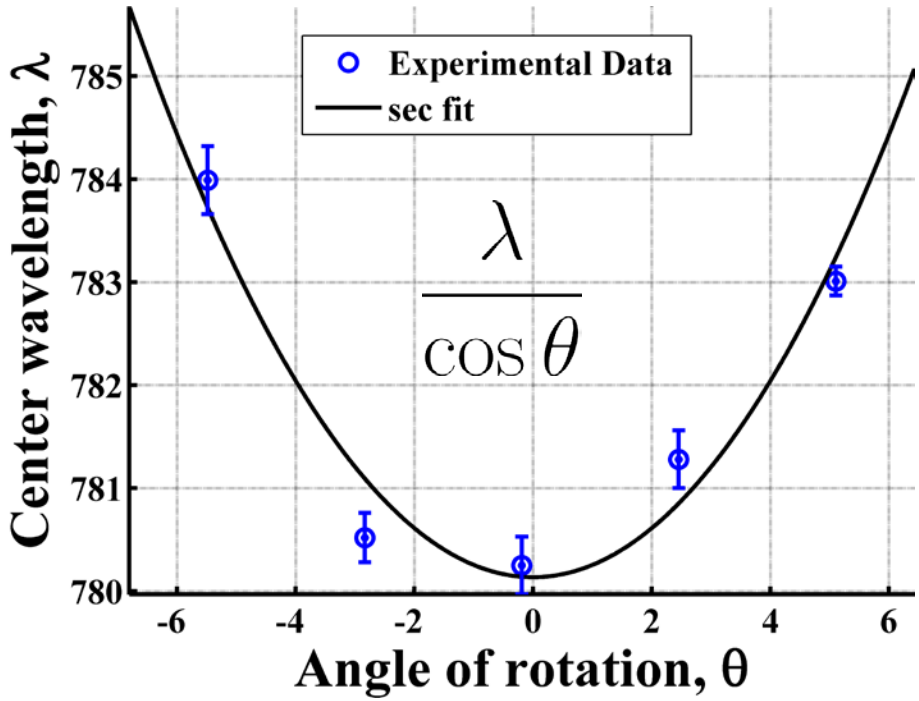
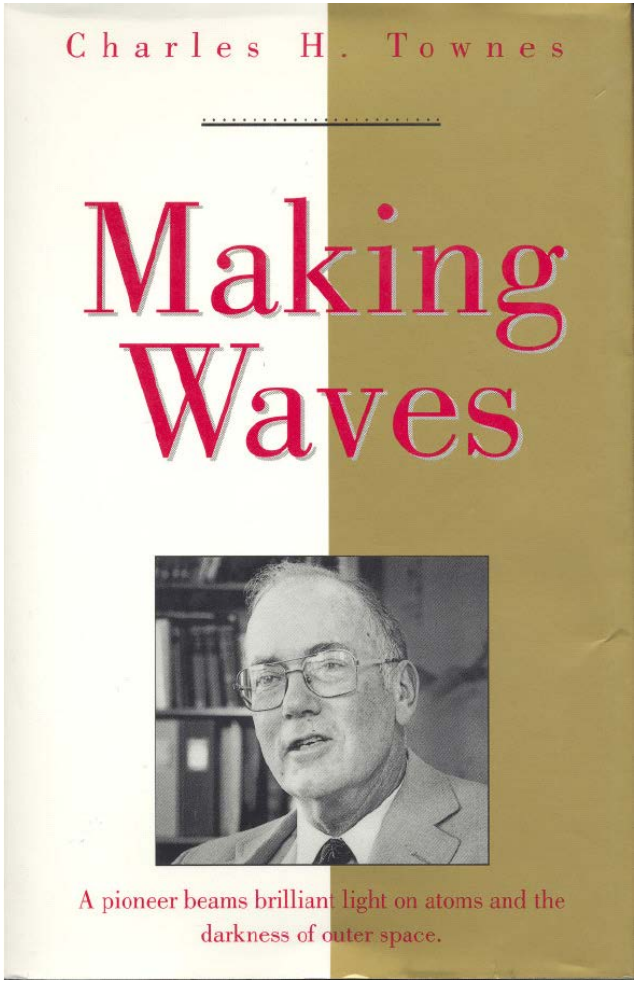
Spectrum vs. Rotation θ





Preliminary results verify a geometry dependent wakefield wavelength!



Introduction *Early Progress in Laser Accelerators*

Success! *Laser Acceleration in Dielectric Structures*

Future Directions ***Laser Accelerator driven X-ray lasers***

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

Byer Group

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

Photonic-based laser driven electron beam deflection and focusing structures

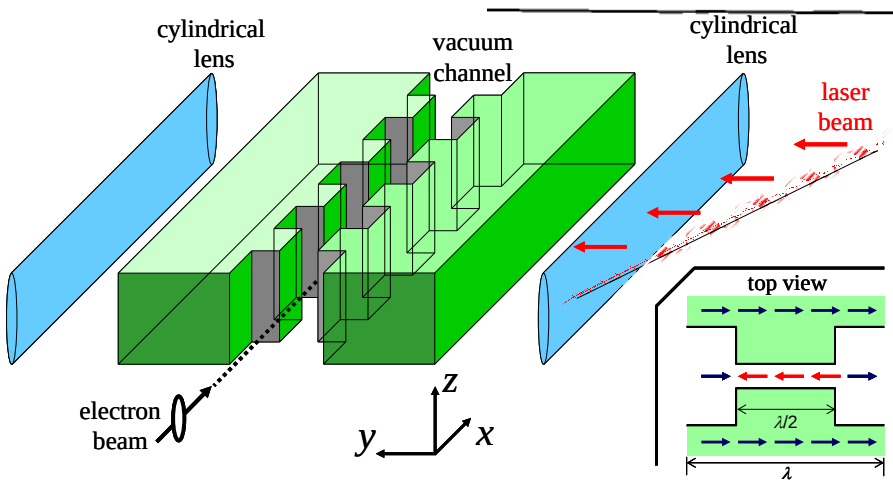
T. Plettner,* R. L. Byer, and C. McGuinness
E.L. Ginzton Laboratories, Stanford University, Stanford, California 94305, USA

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



GOAL: use Dielectric Laser Accelerator to build table top X-ray Laser

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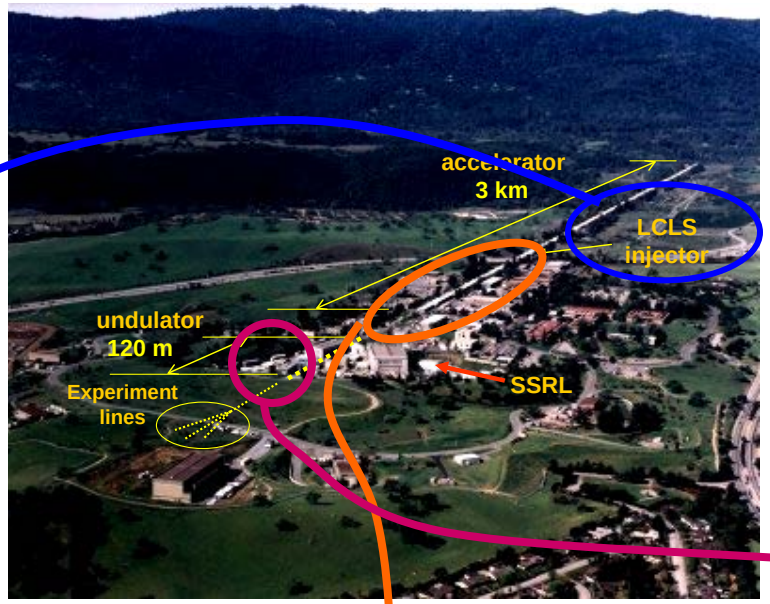


source of free particles → **accelerator section** → **undulator**

laser-driven
high rep. rate
very compact

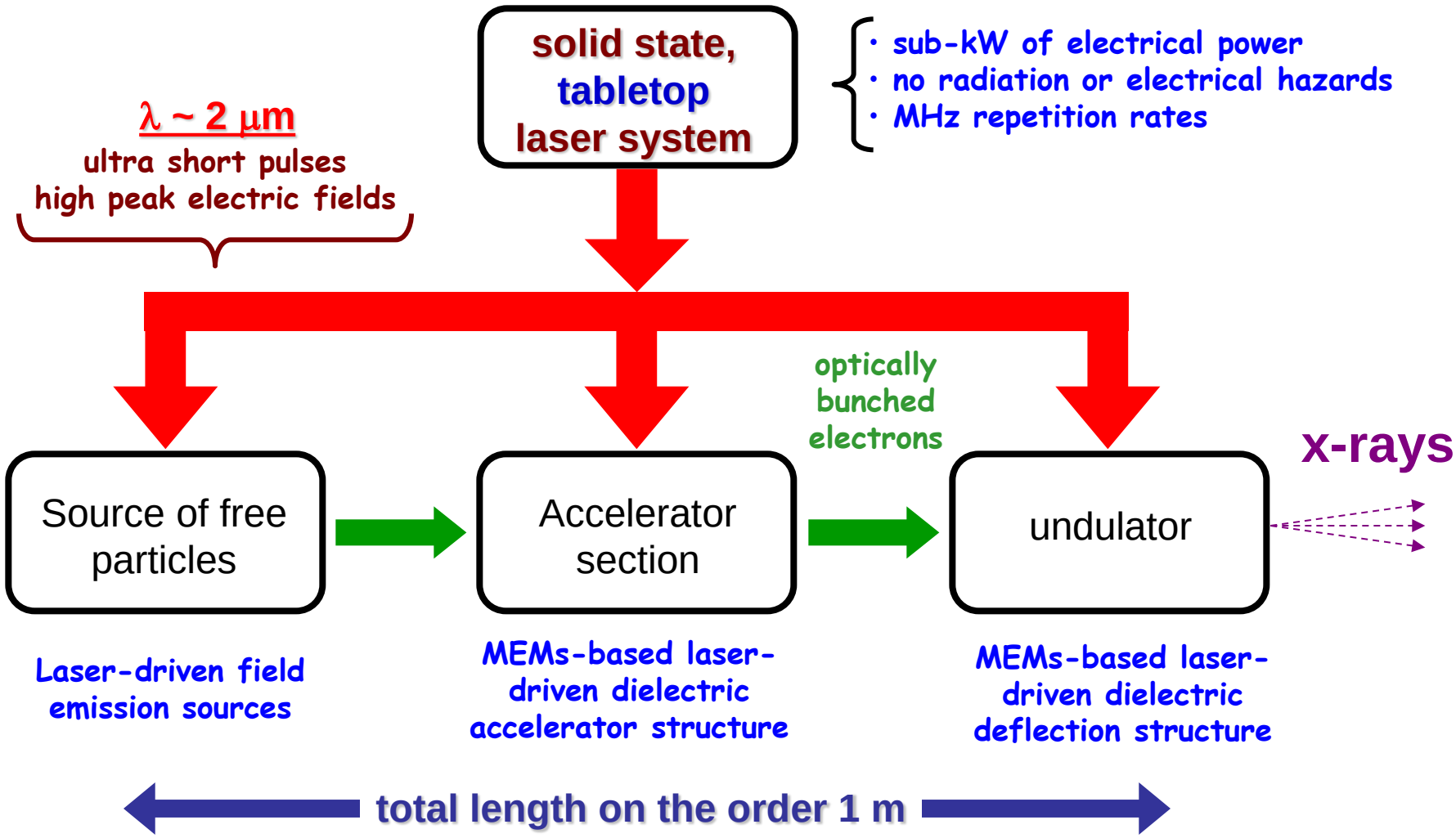
dielectric structure
based laser-driven particle
accelerators

dielectric structure,
laser driven

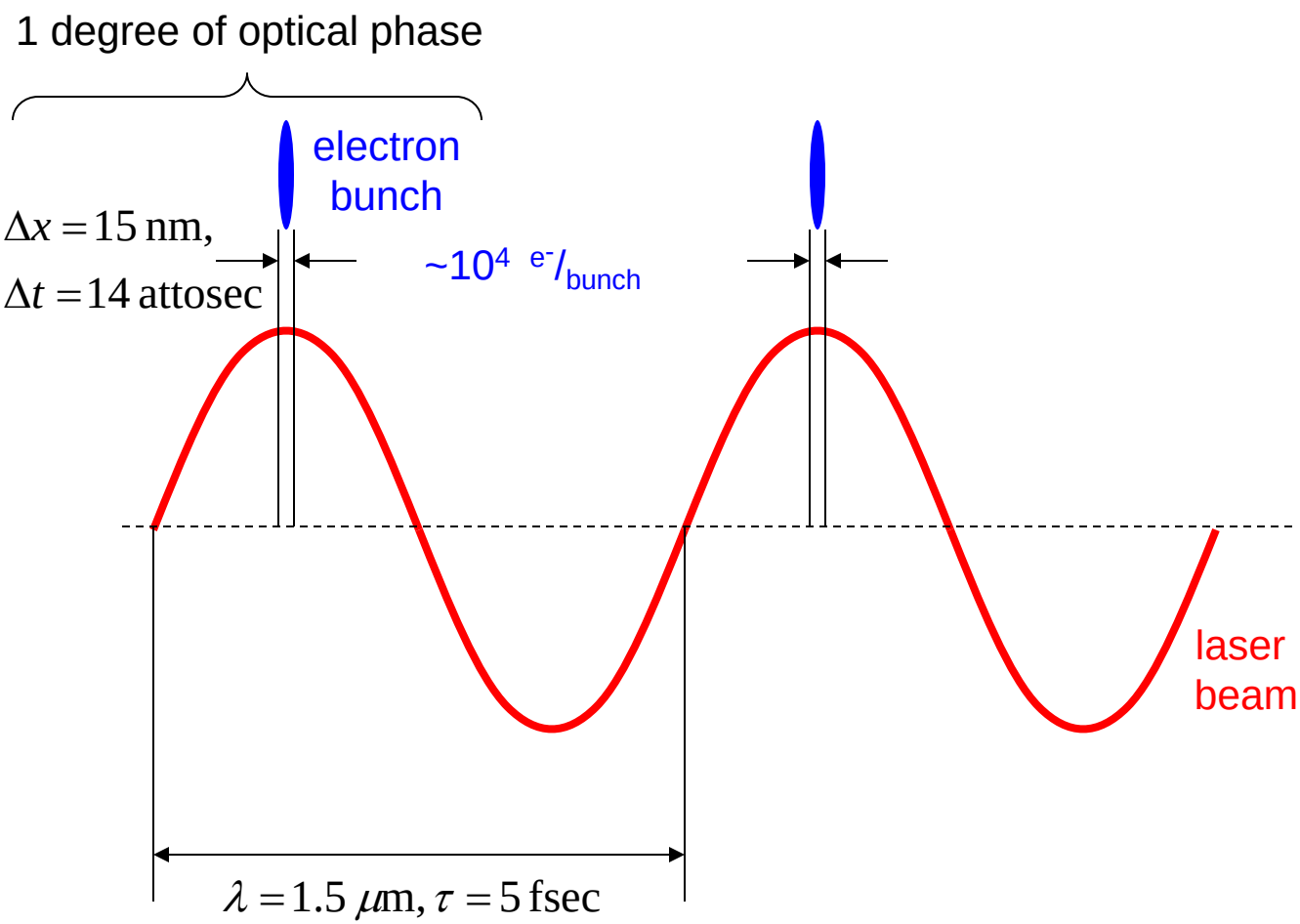
The Key Components of the SASE-FEL architecture

SASE – Self Amplified Spontaneous Emission

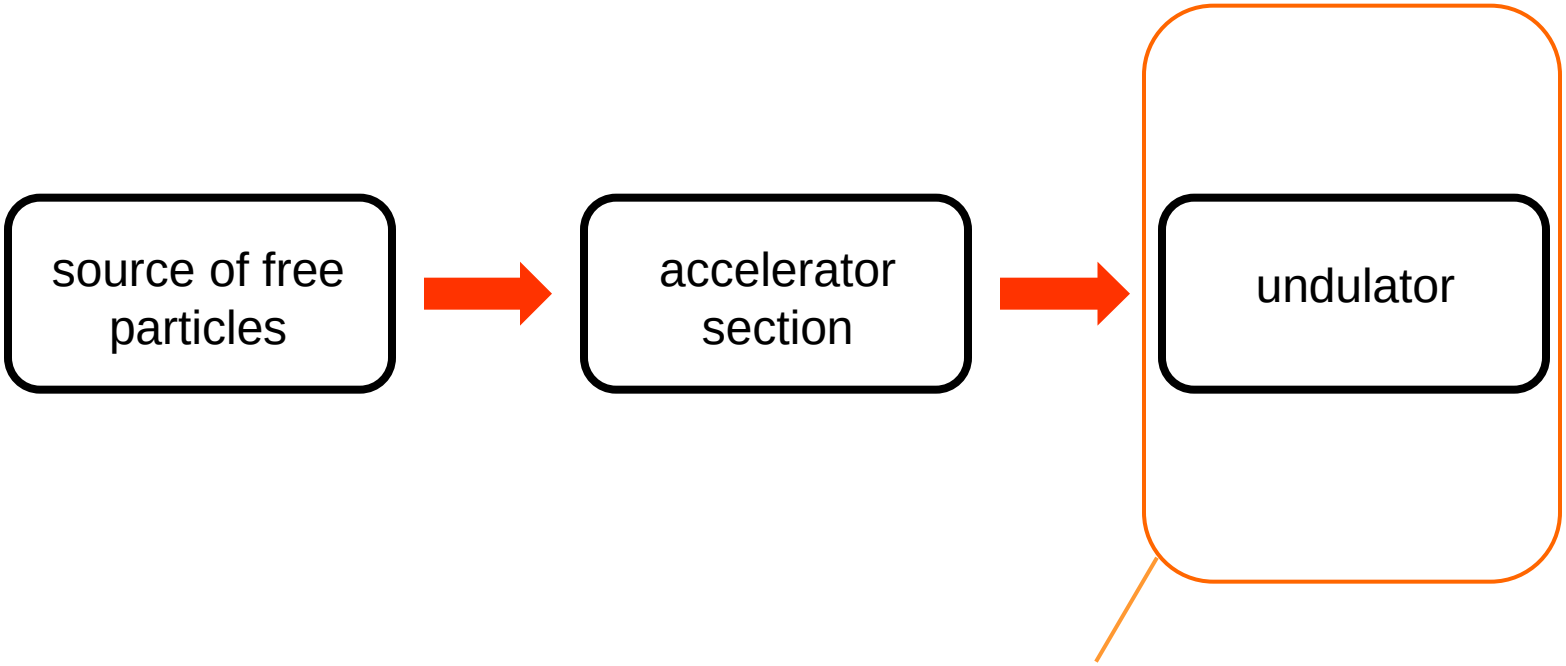
Architecture of a laser-driven free-electron X-ray source



Advantage Laser Accelerator: Atto Second Electron Bunches



Short Period Undulator with periodic magnets



First Idea:

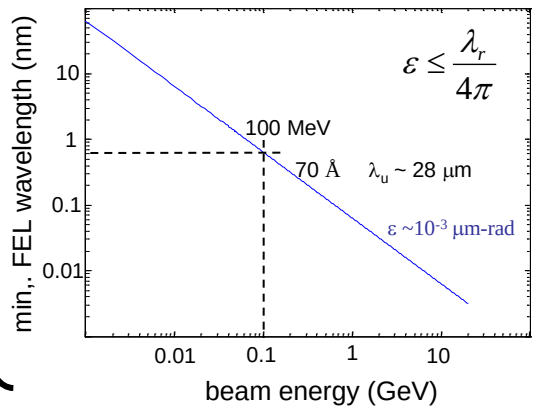
Periodic Magnetic Undulator

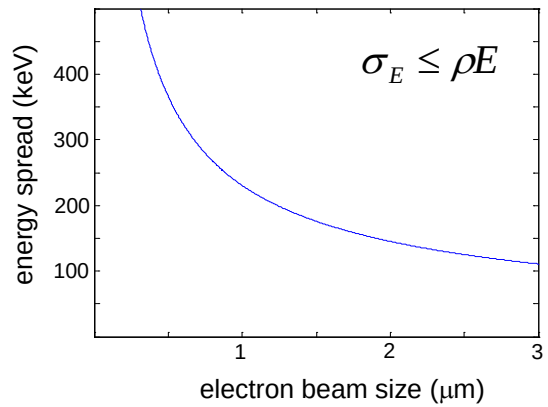
Field strength ~ 1 Tesla
Modulation Period ~ 0.1mm
Length ~ 30cm

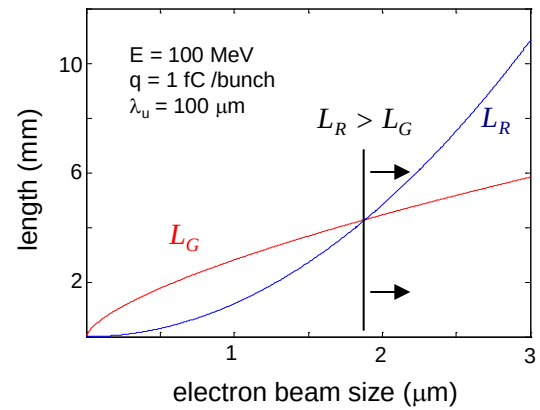
Magnetic Undulator based X-ray FEL Source
Plettner - Summer 2008

Starting point

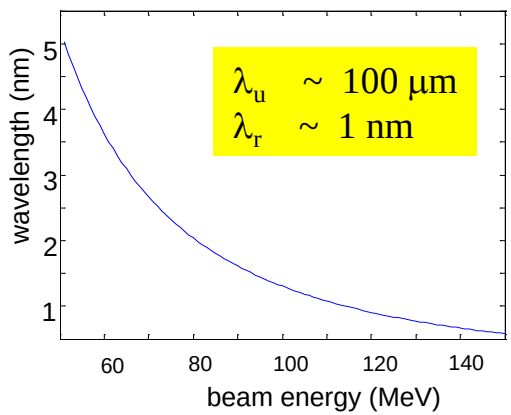
1-D FEL model
Design parameters must satisfy these conditions



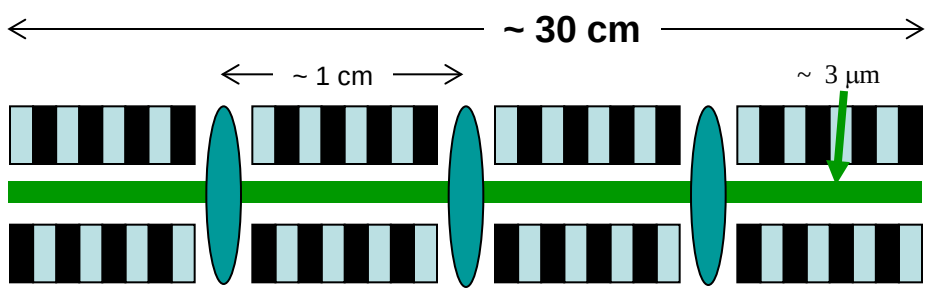




Undulator design



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



Laser power required

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

1% conversion efficiency

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

Magnetic Undulator based X-ray FEL Source

Not practical! Magnetic field to weak, structure too long

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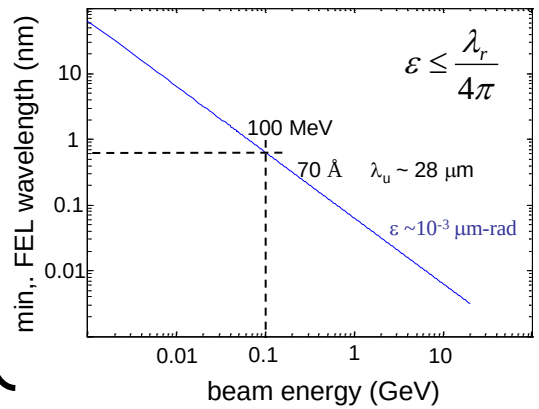
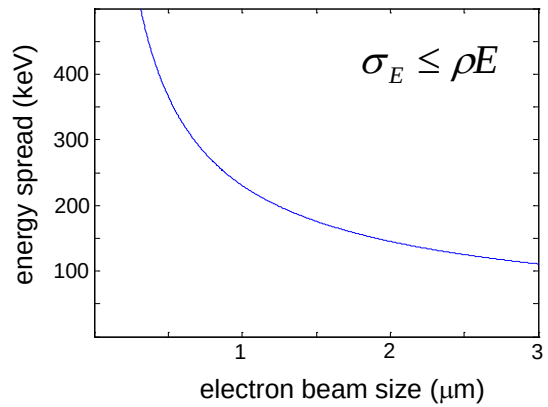
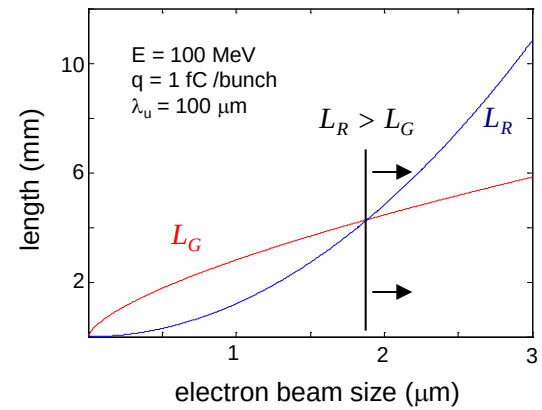
Starting point

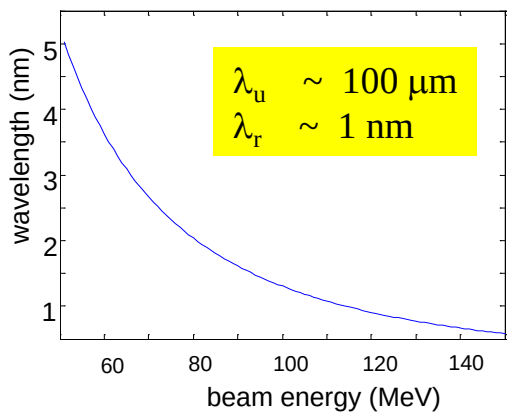
1-D FEL model
Design parameters must satisfy these conditions



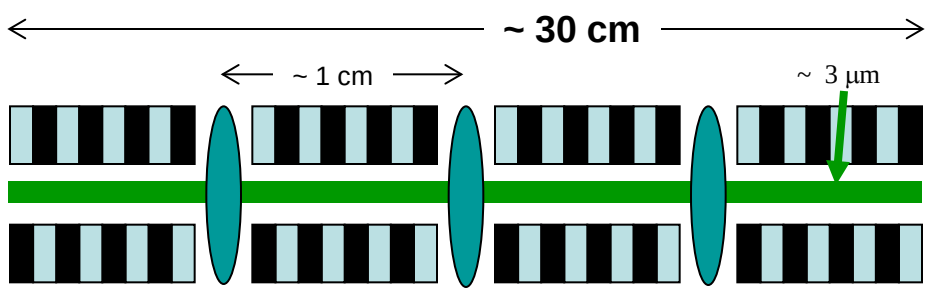




Undulator design



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



Laser power required

f_{rep} ~ 1 MHz
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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

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.

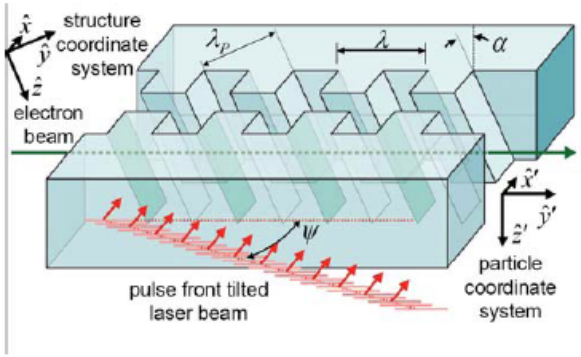
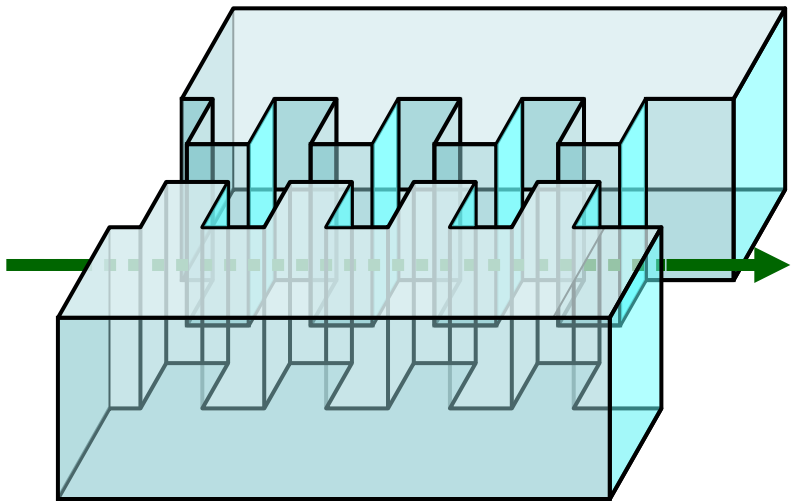


Figure 1: Perspective view of the deflection structure.

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

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

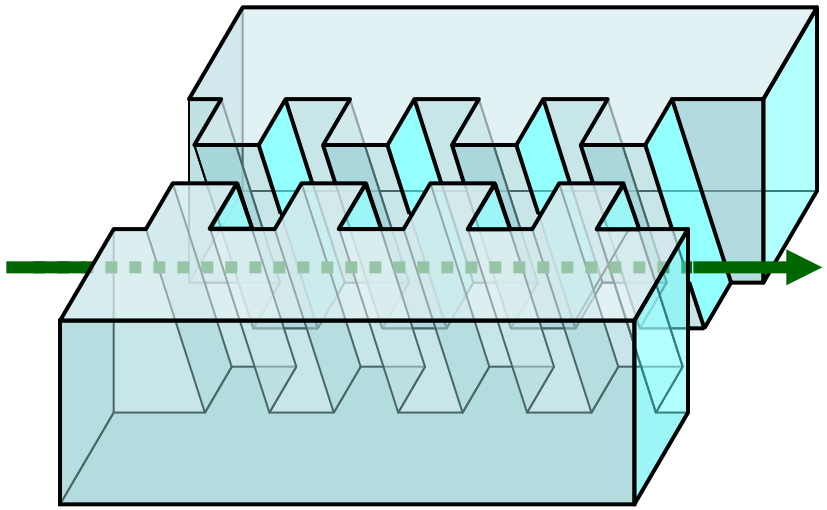
accelerator structure



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

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

deflection structure



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

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

key idea

Extended phase-synchronicity between the EM field and the particle

Use modelocked laser to generate periodic deflection field

T. Plettner, *"Phase-synchronicity conditions from pulse-front tilted laser beams on one-dimensional periodic structures and proposed laser-driven deflection"*, published Phys. Rev. ST AB

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

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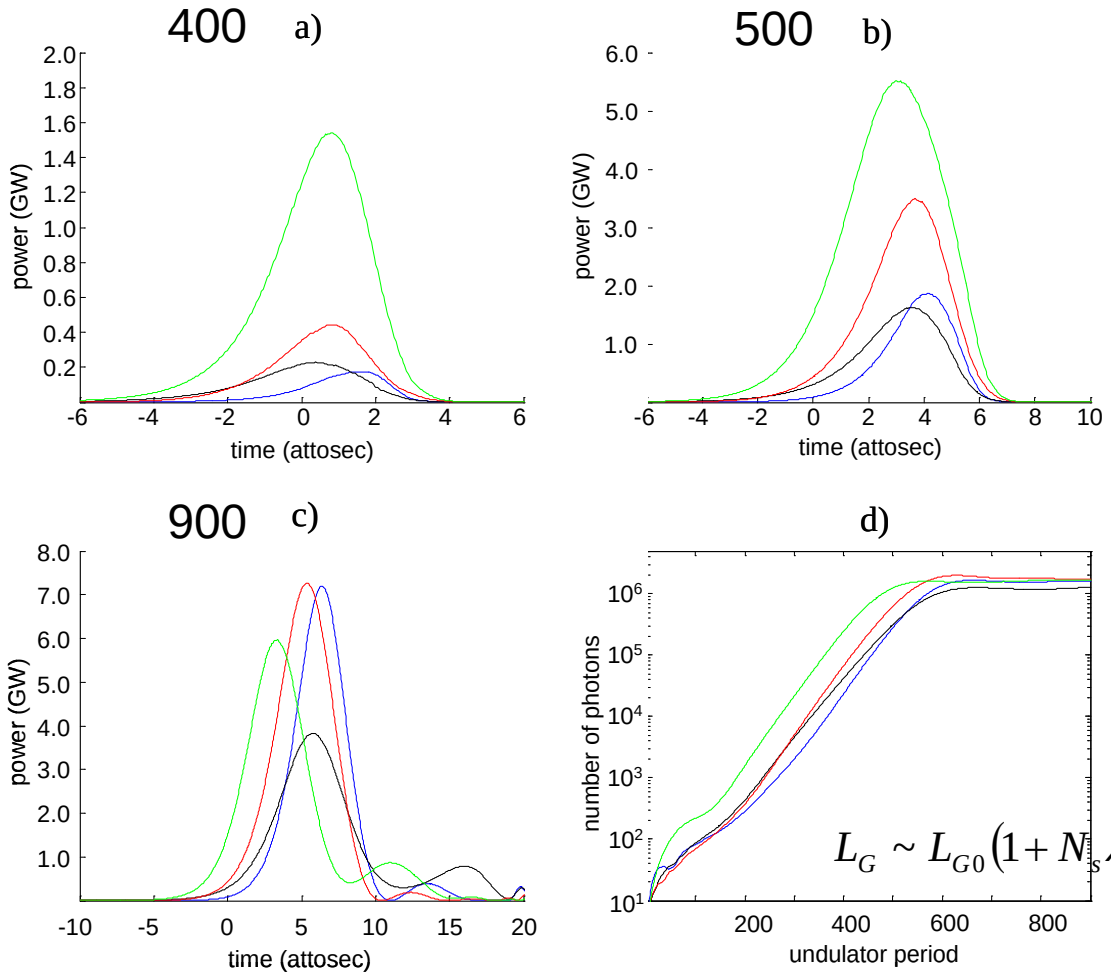


$$L_G \sim L_{G0}\left(1 + N_s \lambda_r / 3\sigma_b\right)$$

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

$$L_c \sim 21\lambda_r$$

$$\sigma_b \sim 136\lambda_r$$

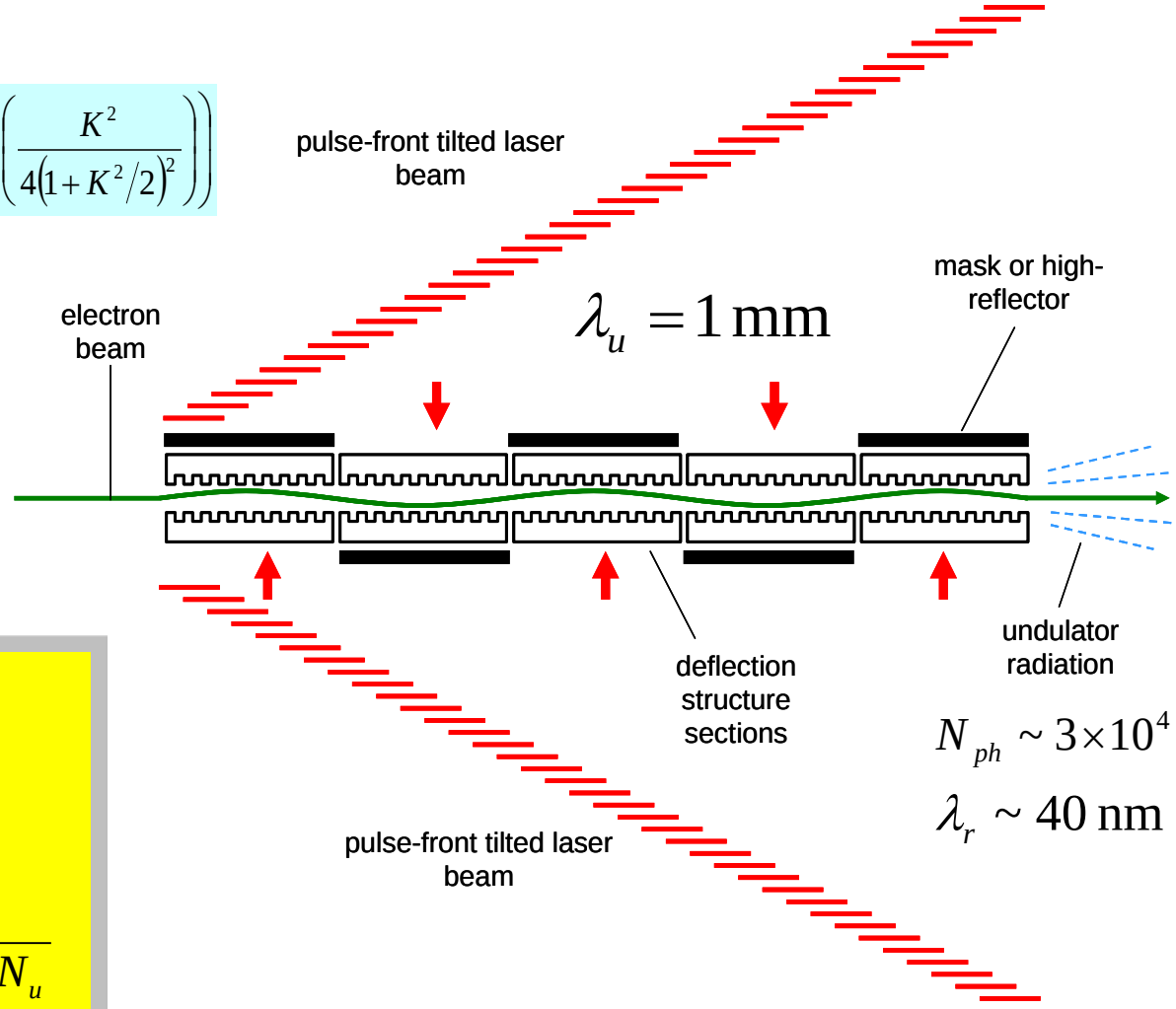
$$\sigma_b / L_c \sim 6$$

$$\rho_{eff} = U_{FEL}/U_{beam} \sim 5\times10^{-4}$$

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

Look for undulator radiation_

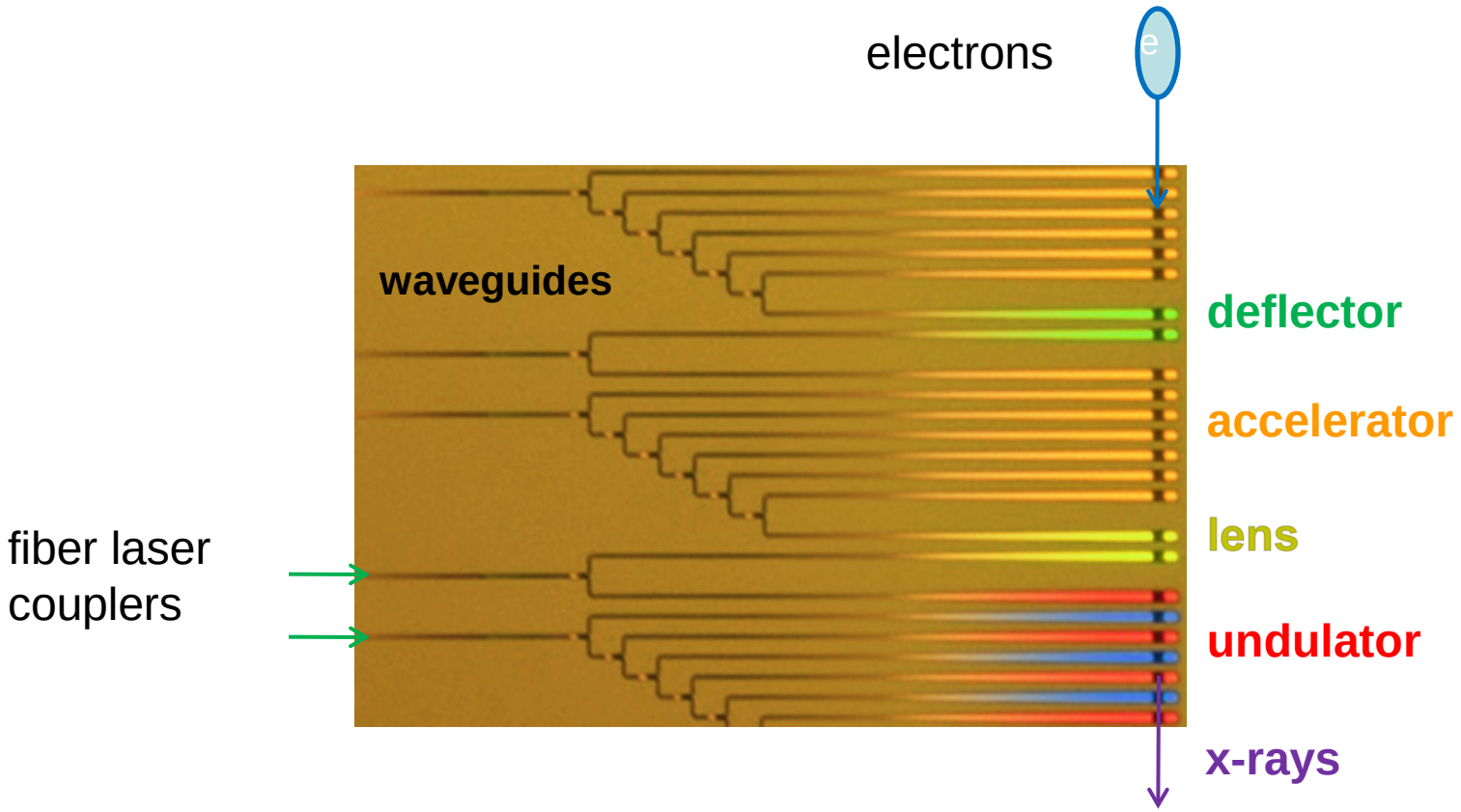
$$N_{ph} = \pi\alpha \frac{K^2}{\left(1+K^2/2\right)^2}\left(J_1\left(\frac{K^2}{4\left(1+K^2/2\right)^2}\right) - J_0\left(\frac{K^2}{4\left(1+K^2/2\right)^2}\right)\right)$$



Prove the concept

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

Accelerator on a Chip



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Prof. James Harris (co-PI)
Prof. Olav Solgaard (co-PI)
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Behnam Montazeri
Ken Leedle
Chia-Ming Chang

Max Planck Institute
Prof. Peter Hommelhoff
Johannes Hoffrogge
John Breuer

SLAC National Accelerator Laboratory
Dr. Joel England (Proj. Mgr.)
Dr. Bob Noble
Dr. Ziran Wu
Prof. Minghao Qi (visiting scientist)
Chunghun Lee (visiting student)

Tech-X Corporation
Dr. Ben Cowan
Dr. Brian Schwartz
Dr. Dan Abell
Dr. Estelle Cormier

UCLA
Dr. Gil Travish
Dr. Esin Sozer
Josh McNeur

Accelerator Team at E163 Experimental Hall

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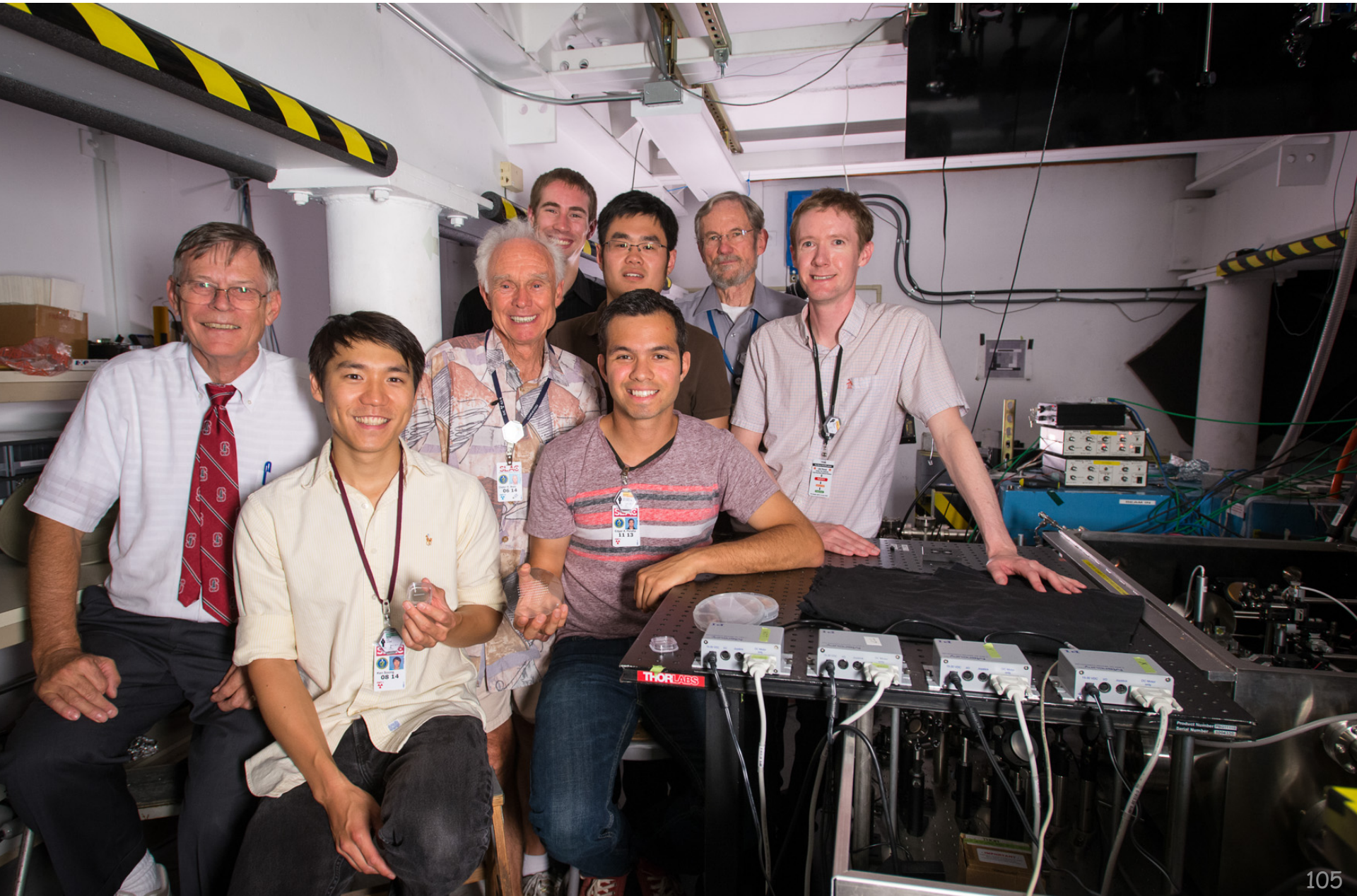

Accelerator Laboratory on a Wafer

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BACK UP SLIDES

Energy Doubling of 42 GeV incident Electrons – Feb 2007

Byer Group

Vol 445|15 February 2007|doi:10.1038/nature05538 nature

LETTERS

Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator

Ian Blumenfeld[1], Christopher E. Clayton[2], Franz-Josef Decker[1], Mark J. Hogan[1], Chengkun Huang[2], Rasmus Ischebeck[1], Richard Iverson[1], Chandrashekhar Joshi[2], Thomas Katsouleas[3], Neil Kirby[1], Wei Lu[2], Kenneth A. Marsh[2], Warren B. Mori[2], Patric Muggli[3], Erdem Oz[3], Robert H. Siemann[1], Dieter Walz[1] & Miaomiao Zhou[2]

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Recent plasma wakefield accelerator experiments have shown high-gradient acceleration of electrons using a 10-cm-long plasma[11]. To obtain energy gains of interest to high-energy physics, these high gradients must be extended over metre-scale plasmas. Such an extension transitions the plasma wakefield accelerator from a regime in which the drive beam has no time to distort, deplete or go unstable, to a regime in which it is significantly depleted in energy, deformed owing to combined effects of diffraction and multiple transverse oscillations, and possibly goes unstable because of the electron-hose instability[16]. This work is in this latter regime.

A schematic of the experimental set-up is shown in Fig. 1. In the present work carried out at the Final Focus Test Beam facility at SLAC, the nominally 50-femtosecond-long electron beam containing 1.8×10^{10} particles is focused to a spot size of ~10 μm at the entrance of an 85-cm-long column of lithium vapour with a density n_e of 2.7×10^{17} cm^{-3}. The nominally 42 GeV beam has a correlated energy spread of approximately 1.5 GeV, with electrons in the front of the beam at higher energies than those at the back. The beam exiting the plasma traverses a metre-long dipole magnet, which disperses the beam electrons according to their energy. The transverse distribution of the dispersed electrons is measured at two distances (planes 1 and 2 in Fig. 1) downstream of the dipole magnet to distinguish the energy changes of the electrons from their possible transverse deflection due to the plasma.

Images of the dispersed electrons are recorded along with the relevant beam parameters on a shot-to-shot basis. The energy gain achieved for each shot is determined as described in the Methods section. Figure 2 shows one example of the electron energy

Plasma-Wake Field Afterburner for SLAC

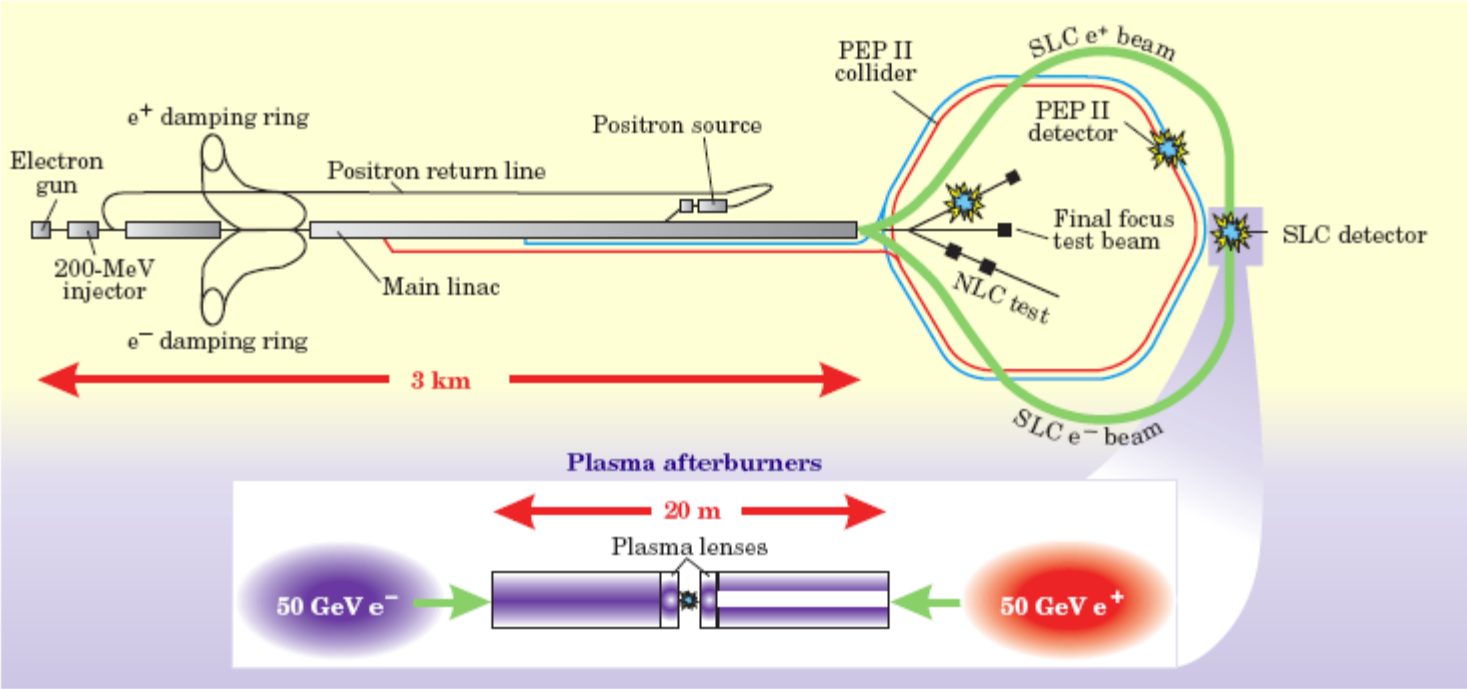

Figure 6. To test the feasibility of plasma-wakefield afterburners added to a high-energy radio-frequency linear collider as an energy doubler, we propose the installation of two 10-m-long plasma afterburners at the ends of the 50-GeV electron and positron beams of the Stanford Linear Collider (SLC), just before the point where the beams are focused to collide with each other (see inset). That would double the collider's e^+e^- collision energy to 200 GeV. Unlike the plasma filling the electron afterburner, the positron afterburner's plasma would have a hollow axial channel. The SLC shares the downstream end of the 3-km-long Stanford Linear Accelerator with the PEP II asymmetric B-meson factory and other facilities.

Plasma and Fusion Research: Review Articles Volume 4, 045 (2009)

Surfing Plasma Waves: A New Paradigm for Particle Accelerators*)

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(Received 26 August 2008 / Accepted 6 February 2009)

Accelerator-based experiments have produced key breakthroughs in our understanding of the physical world. New accelerators, to explore the frontiers of Tera-scale Physics, appear possible, based on concepts developed over the last three decades in multi-disciplinary endeavors. The Plasma-Based Particle Accelerator is one concept that has made spectacular advances in the last few years. In this scheme, electrons or positrons gain energy by surfing the electric field of a plasma wave that is produced by the passage of an intense laser pulse or an electron beam through the plasma. This talk reviews the principles of this new technique and prognosticates how it is likely to impact science and technology in the future.

© 2009 The Japan Society of Plasma Science and Nuclear Fusion Research

Keywords: plasma wakefield accelerator, laser, relativistic electron beam, tera-scale physics

DOI: 10.1585/pfr.4.045

1. Introduction

More than a decade before Moore's law, depicting the number of transistors on an integrated circuit versus time was postulated, Livingston had graphed a similar relationship for maximum energies produced by high-energy particle accelerators. The updated version of the plot depicted in Fig. 1 came to be known as the Livingston curve. Since its first appearance in 1954, the Livingston curve has been the barometer of the future vitality of the field of high-energy physics much in the same way as Moore's law has been for the semiconductor industry. As did Moore's law, the Livingston curve showed that between 1930 and 1980 the maximum energy of electron accelerators roughly increased by a factor 10 per decade while the cost of increasing the energy dramatically went down roughly the same factor. The exponential increase depicted by the Livingston curve was possible because of continuous technological innovations for acceleration and focusing of charged particles as the existing technologies

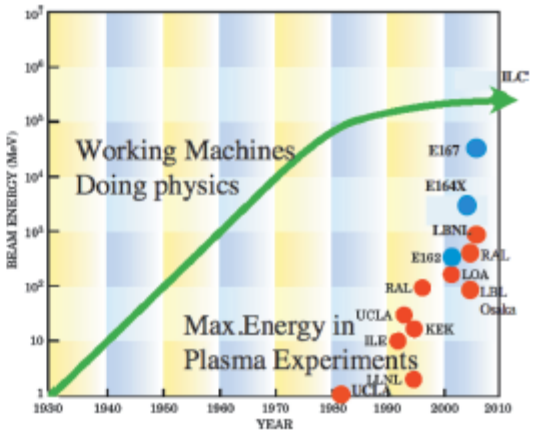

Fig. 1 Accelerator Moore's law. The exponential growth of electron beam energy, first noted by Livingston (green curve), began tapering off around 1980 as conventional

Surfing Plasma Waves

Experiments using lasers to excite the plasma wakefields have produced very impressive results. These have shown that electron beams with low divergence angles and narrow energy spreads can be generated with energies in the 1 GeV [9–11] range from plasma in a distance of about one centimeter. The titanium-sapphire lasers needed to produce such beams have tens of terawatts of power but the accelerator itself is extremely compact. The beam parameters are well suited for many applications that require "table-top" accelerators including in nuclear medicine, cancer therapy, structural biology and material science [12].

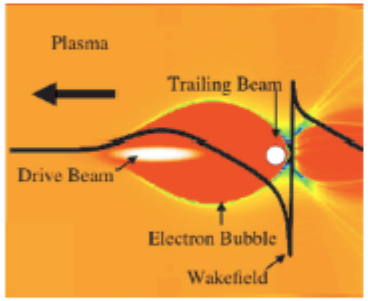

Fig. 3 Three dimensional computer simulation of an extremely nonlinear wakefield (black curve) excited in plasma by either an electron or a photon drive beam. The plasma electrons have been completely blown out of the red region by the drive beam. A second distinct trailing beam is placed where the wakefield is negative and is accelerated by it. The arrow shows the direction of the drive beam.

is no relative motion between the accelerating beam electrons (their mass is increased) and those that loose energy (their mass is reduced).

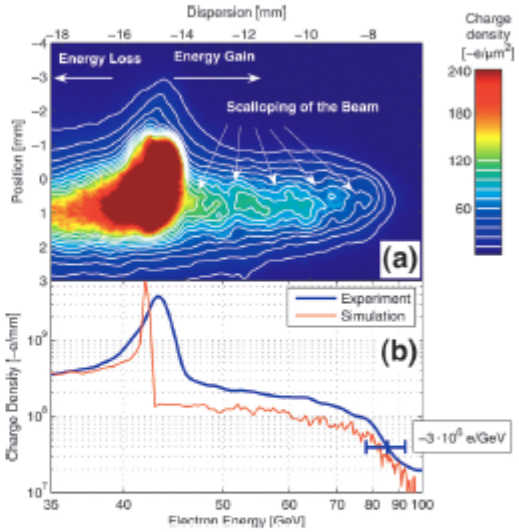

Fig. 4 (a) The energy spectrum of the initially 42 GeV electrons after passing through an approximately one meter long plasma observed in recent experiments at SLAC (b) A comparison between the measured spectrum and the simulated spectrum showing that some electrons are accelerated out to 85 GeV energy. (Blumenfeld *et al.*, Nature vol.445, p.741, 2007)

045-3

Realization

Byer Group

LETTER

Out in print November 7, 2013

doi:10.1038/nature12664

Demonstration of electron acceleration in a laser-driven dielectric microstructure

E. A. Peralta[1], K. Soong[1], R. J. England[2], E. R. Colby[2], Z. Wu[2], B. Montazeri[3], C. McGuinness[1], J. McNeur[4], K. J. Leedle[3], D. Walz[2], E. B. Sozer[4], B. Cowan[5], B. Schwartz[5], G. Travish[4] & R. L. Byer[1]

2006 ← → 2013

October 2006
Grating accelerator structure proposed.

August 2011
Experiment started.

December 2012
First indication of success.

February 2013
Experimental success!

Popular Science!

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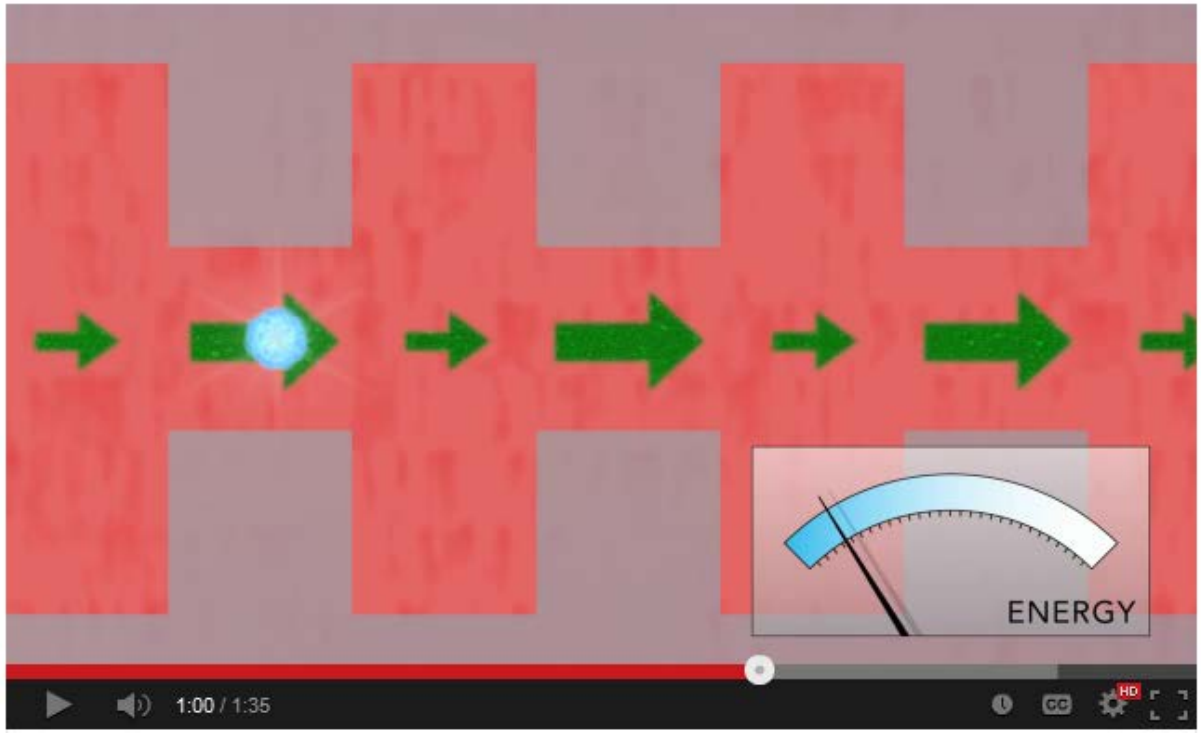

Accelerator on a Chip: How It Works

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In an advance that could dramatically shrink particle accelerators for science and medicine, researchers used a laser to accelerate electrons at a rate 10 times higher than conventional technology in

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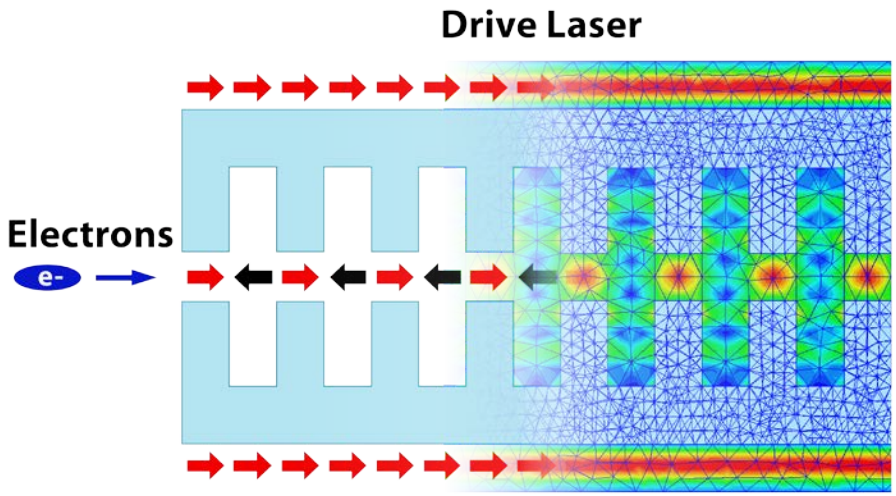
How it Works?



Basic Principle:

The grating teeth periodically modulates the phase of the laser fields, imparting a
π- phase shift to the electric field between pillars.

→ " Laser field rectifier "

Virtual Tour: Test Sample

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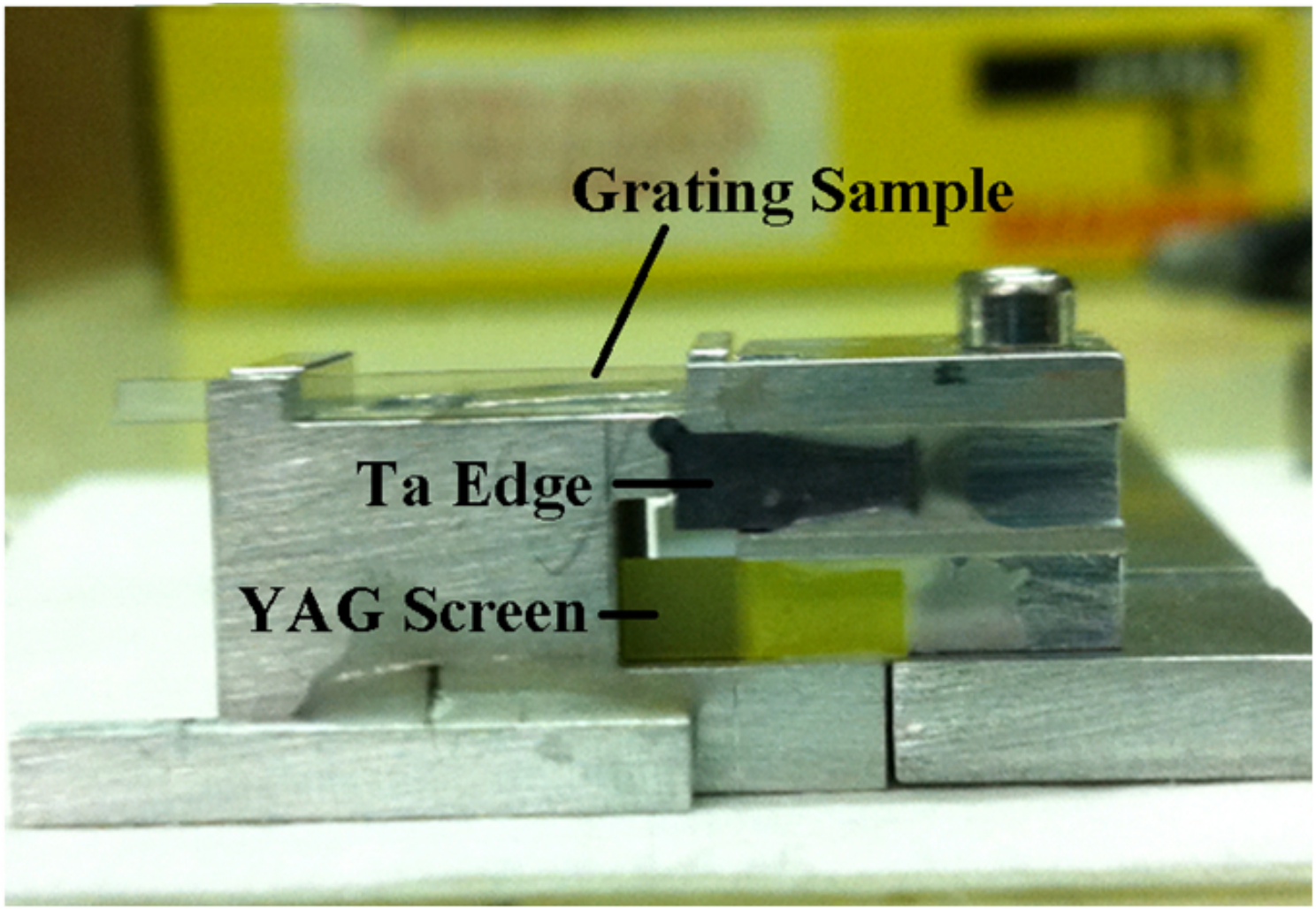
Sample holder

~1 cm



Preliminary Results

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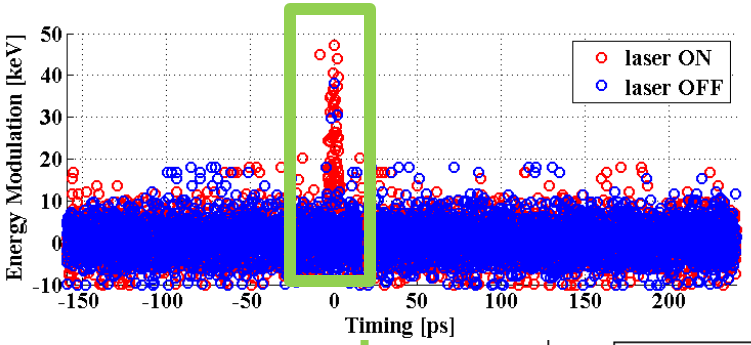
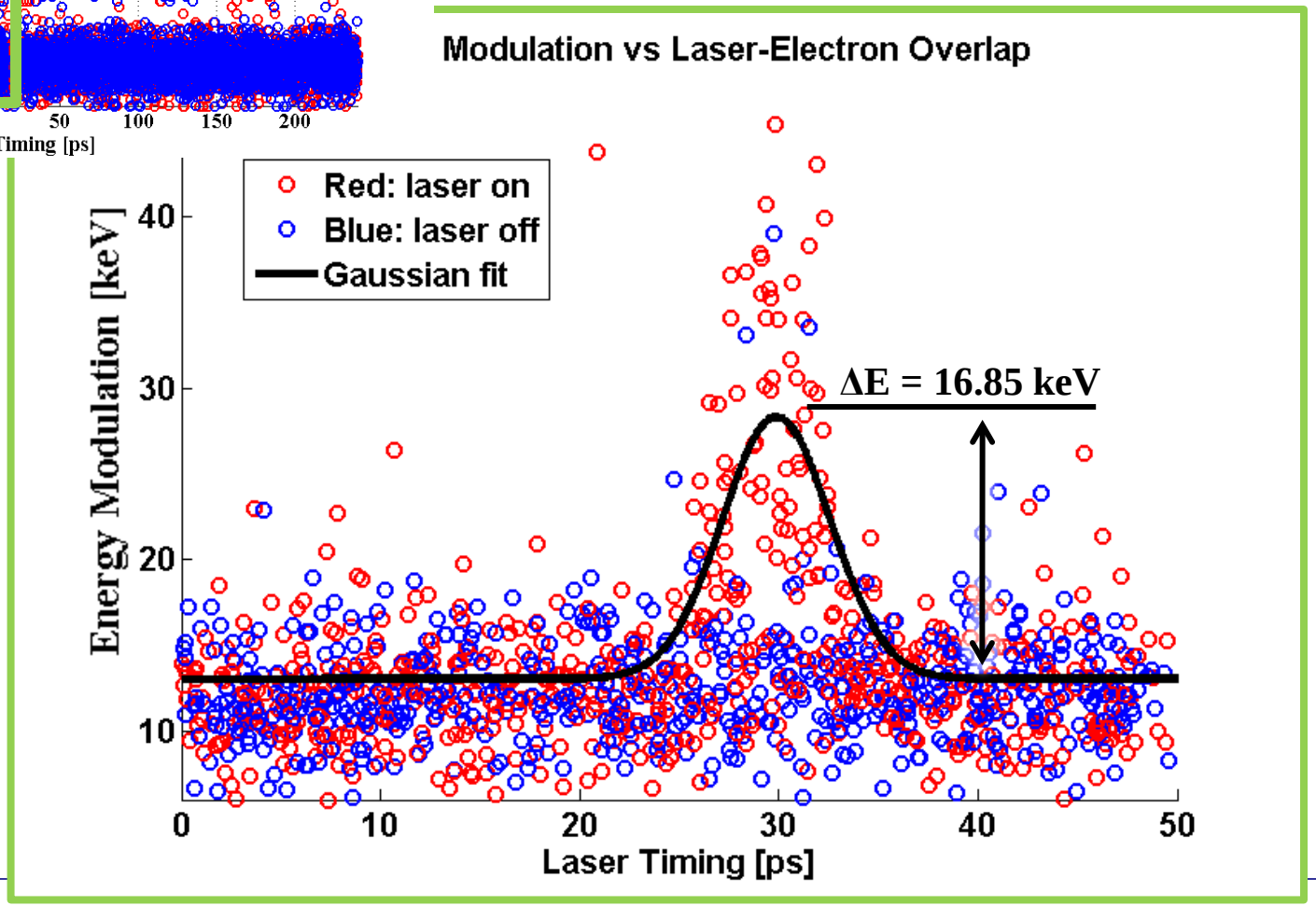
December 2012: We saw the first indication of acceleration at 33 MeV/m





Accelerator and X-ray Laser on a Chip

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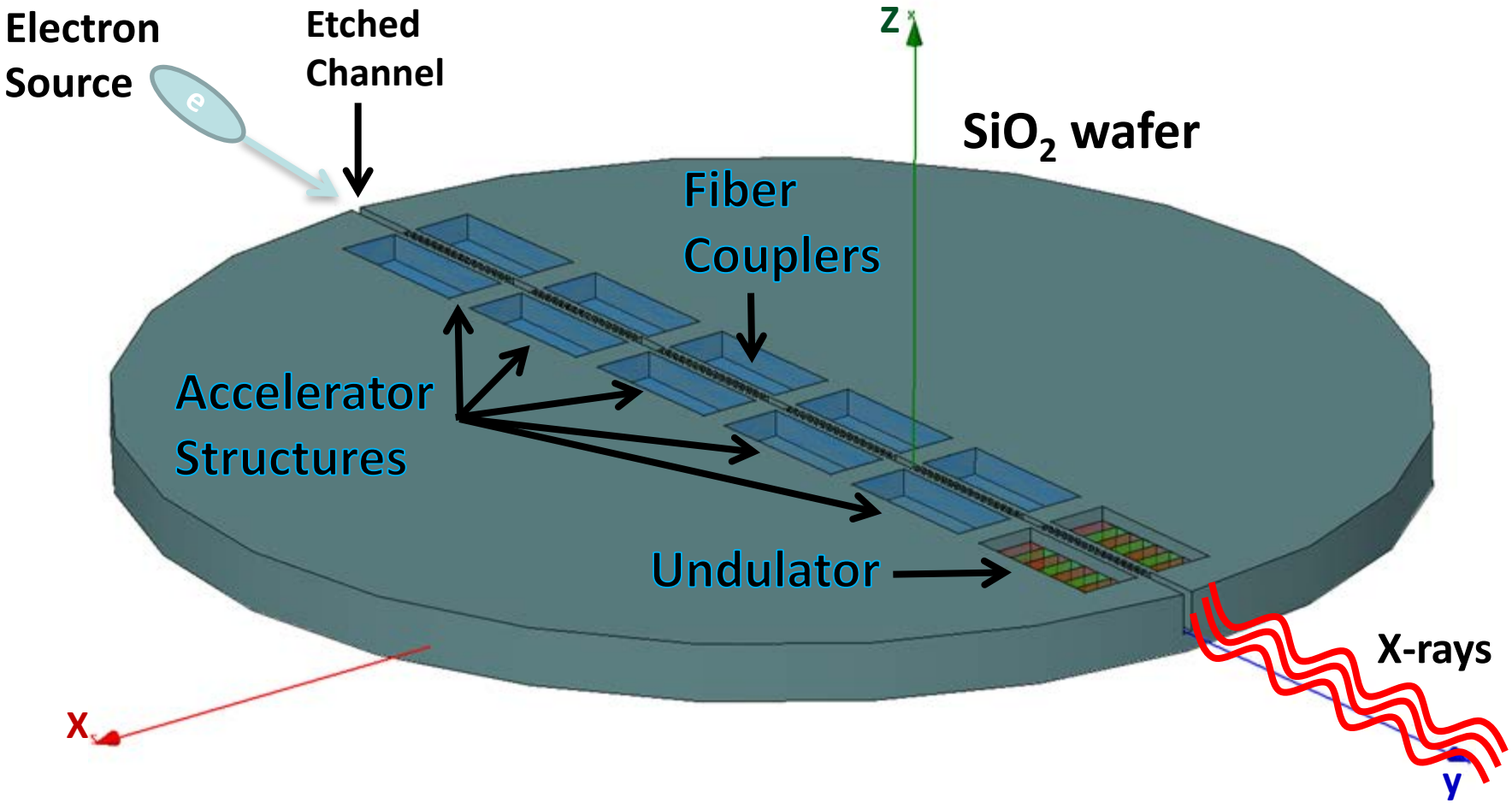

Increasing Gradient

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VOLUME 74, NUMBER 12 PHYSICAL REVIEW LETTERS 20 MARCH 1995

Laser-Induced Damage in Dielectrics with Nanosecond to Subpicosecond Pulses

B. C. Stuart, M. D. Feit, A. M. Rubenchik, B. W. Shore, and M. D. Perry
Lawrence Livermore National Laboratory, P.O. Box 808, L-443, Livermore, California 94550
(Received 24 August 1994)

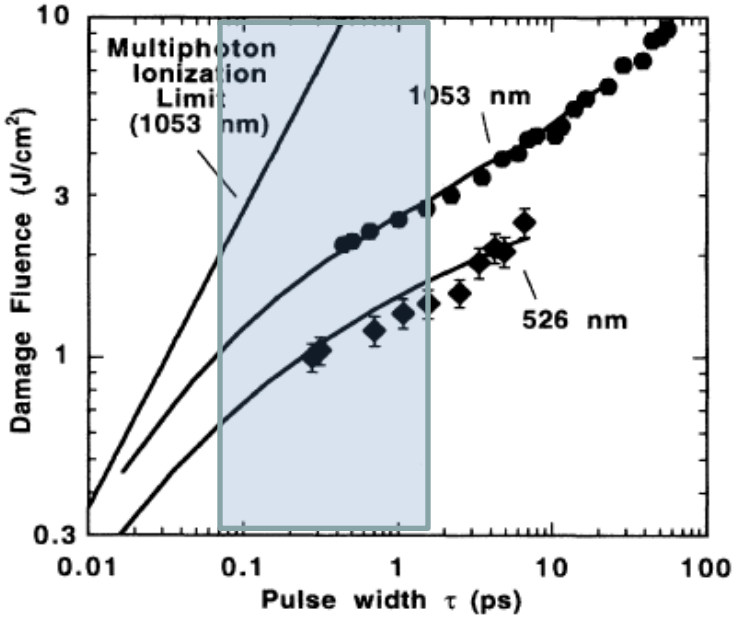

FIG. 4. Experimental and theoretical damage thresholds for fused silica at 1053 nm (●) and 526 nm (◆). The theoretical damage thresholds (solid curves) correspond to the formation of a critical density plasma ($\approx 10^{21}$ cm^{-3}), as discussed in the text. Relative errors in the experimental data are shown, estimated absolute error is ±15%.

$$G \propto \eta \sqrt{\frac{F(\tau)}{\tau^{\frac{1}{2}}}}$$

Compressing the IR pulse from 2 ps to 20 fs can give us a **factor of 3 larger gradients.**

Low-Beta Accelerator

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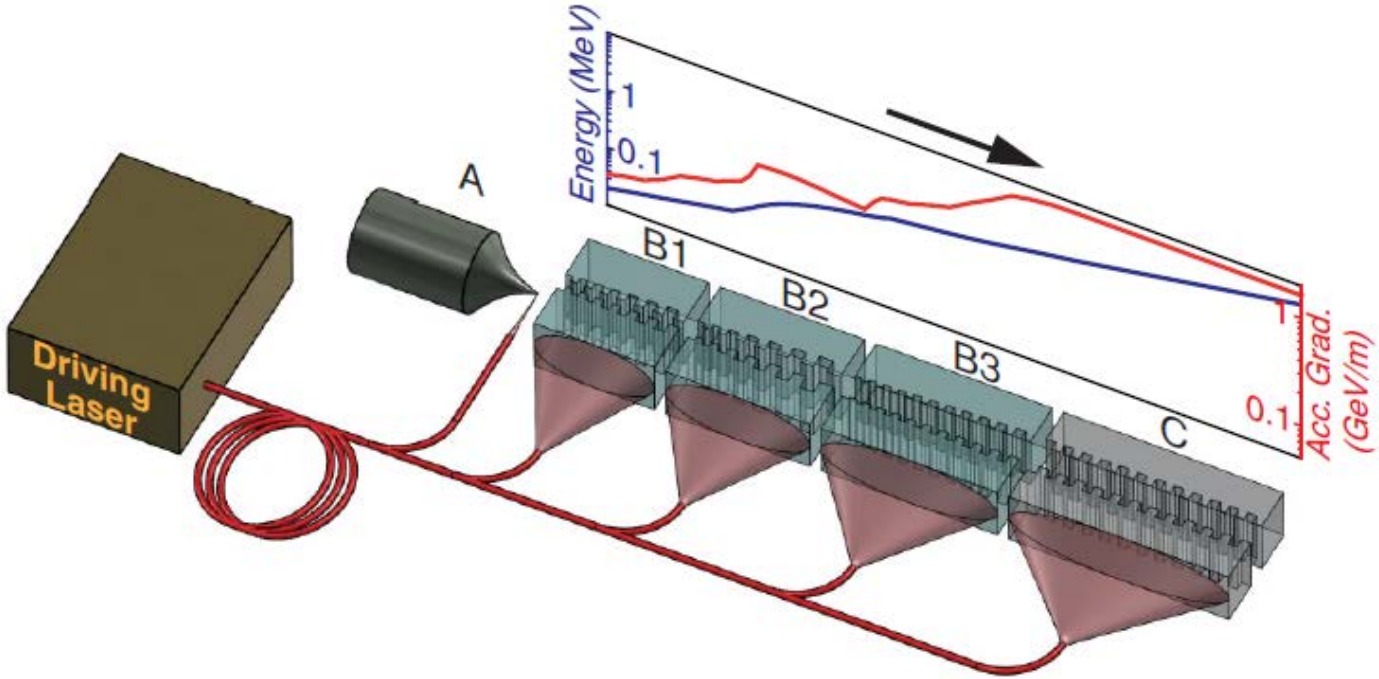
PRL **111,** 134803 (2013) PHYSICAL REVIEW LETTERS week ending 27 SEPTEMBER 2013

Laser-Based Acceleration of Nonrelativistic Electrons at a Dielectric Structure

John Breuer
Max Planck Institute of Quantum Optics, Hans-Kopfermann-Strasse 1, 85748 Garching, Germany

Peter Hommelhoff*
Department of Physics, Friedrich Alexander University Erlangen-Nuremberg, Staudtstrasse 1, 91058 Erlangen, Germany and Max Planck Institute of Quantum Optics, Hans-Kopfermann-Strasse 1, 85748 Garching, Germany
(Received 15 July 2013; published 27 September 2013)



DLA Beam Position Monitor

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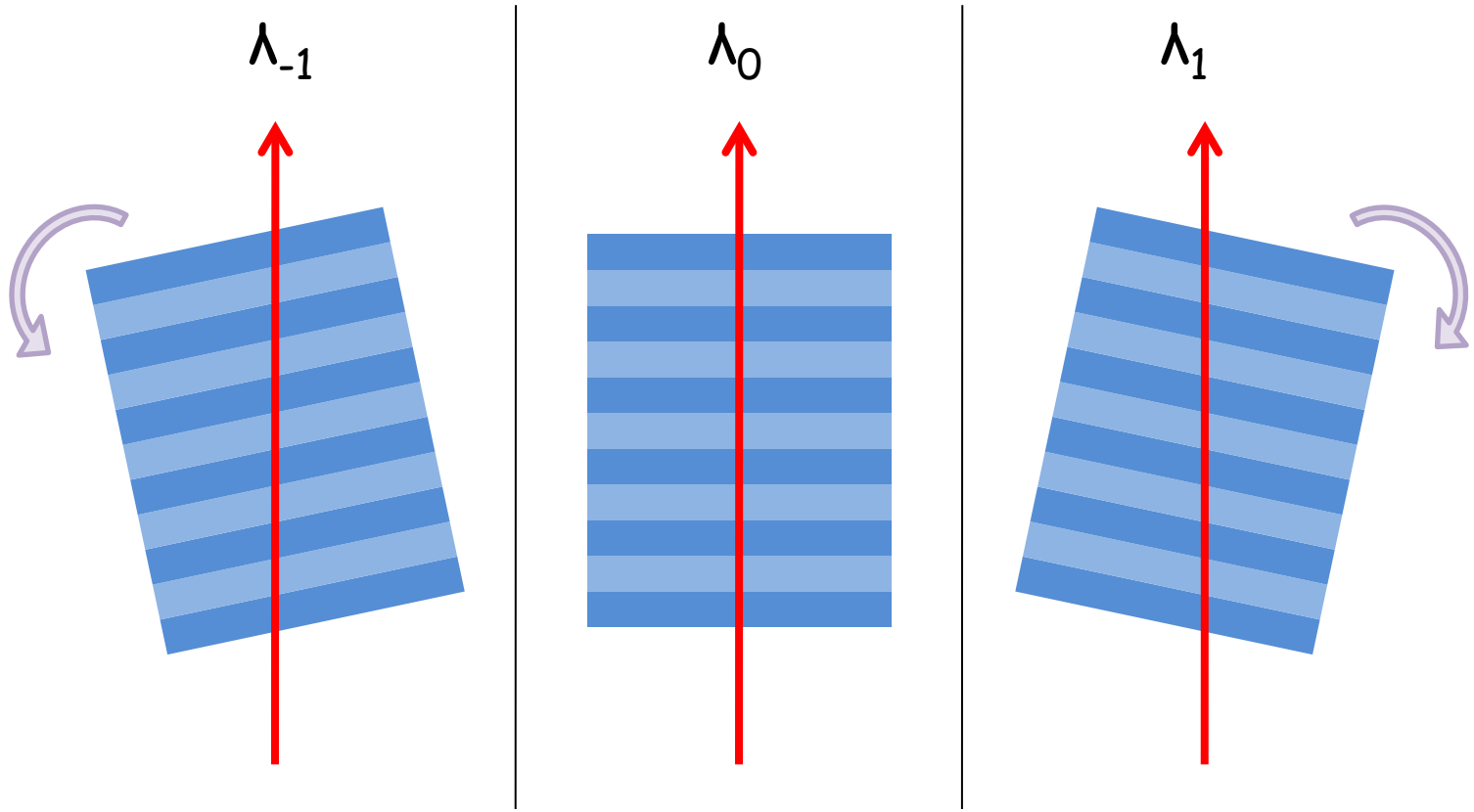
Verification of the grating-BPM concept: *geometry dependent radiation.*



By rotating a fixed period grating structure,
we should be able to vary the radiation as:

$$\lambda = \frac{\lambda_0}{\cos\theta}$$

DLA Beam Position Monitor

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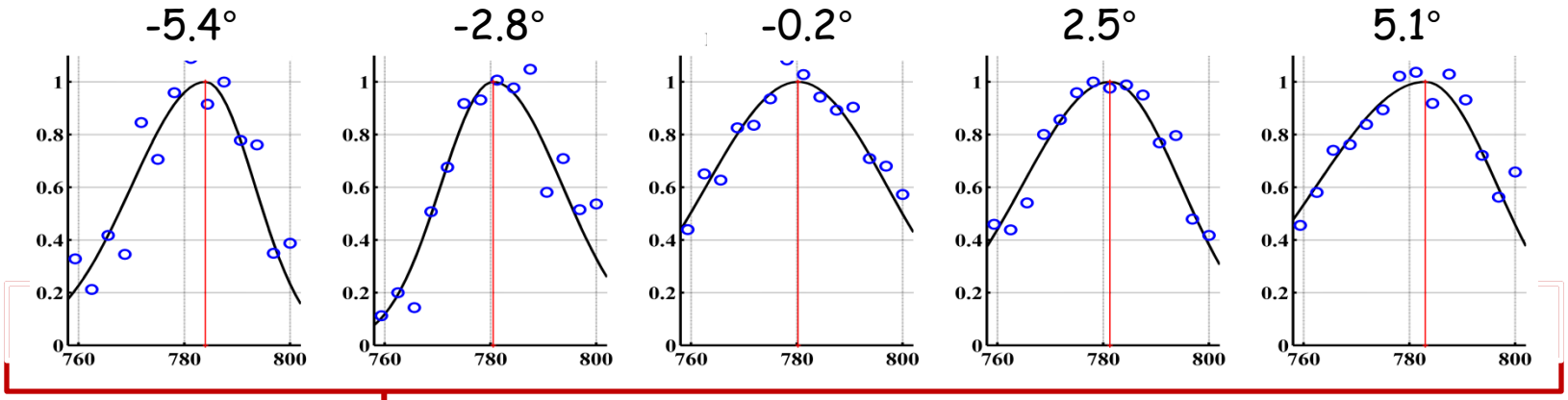
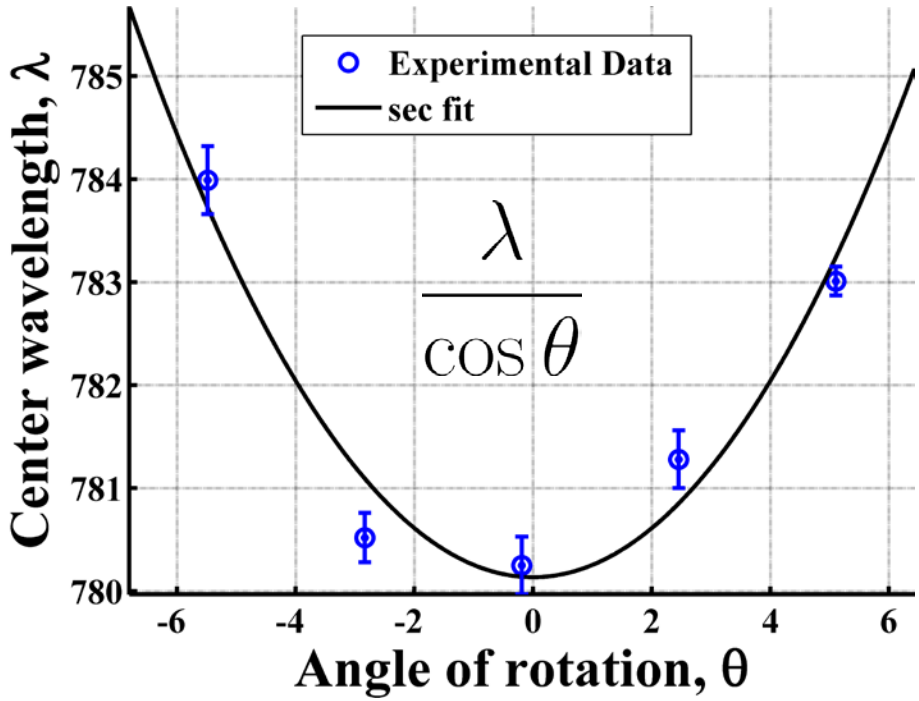
Spectrum vs. Rotation θ





Preliminary results verify a geometry dependent wakefield wavelength!

Robert L. Byer
William R. Kenan, Jr. Professor in the School of Humanities and Sciences
Department of Applied Physics
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e-mail: rlbyer@Stanford.edu

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Keep it simple, straightforward and elegant

Robert L. Byer - Professor of Applied Physics
Roger Route - Senior Research Associate
Vivian Drew - Administrator

Diode Pumped Solid State Lasers

Alireza Marandi (PhD)	Ising spin model sync pumped OPO for Computation
Kirk Ingold	Sync pumped OPOs for IR spectroscopy
Charles Rudy (Phd)	Ultrafast Two micron Tm Fiber oscillator/amplifier
Karel Urbanek	Solid state and fiber lasers
Stephen Wolf	Ultrafast 2micron Tm:fiber source for laser acceleration

Laser Accelerators and attosecond Coherent X-rays

Chris McGuinness (PhD)	Silicon photonic structures for laser electron accelerators
Edgar Peralta	Grating structures for laser electron acceleration
Ken Soong	Dielectric structures for laser electron steering, focusing
Prof. Peter Hommelhoff (Erlangen)	Electron point source for laser acceleration

Laser Interferometry for Gravitational Wave detection - LIGO

Grant Cutler	Advanced LIGO isolation platforms
Brian Lantz	Senior Scientist – Advanced LIGO
Ashot Markosyan	Optical properties of LIGO mirrors and coatings
Roger Route	Materials studies for Advanced LIGO

Laser in Space Antenna research – lower cost LISA options

Sasha Buchman	gLISA – earth orbiting lower cost LISA mission
John Conklin (Univ Florida)	Spherical mass for the Gravitational Reference Sensor
Shailendhar Saraf	Optical clocks and phase meter for eLISA

Scientific Staff

Dr. Saps Buchman	LISA Program Manager
Dr. Brian Lantz	LIGO isolation and control
Dr. Igor Makasyuk	SLAC – Laser Acceleration program technical support
Dr. Ashot Markosyan	LIGO – low optical loss mirrors and coatings
Dr. Roger Route	Advanced Materials and Research support
Dr. Shailendhar Saraf	Laser Optical Clocks for space applications
Prof. Konstantin Vodopyanov (Univ Central Florida)	Sync Pumped OPOs - Precision IR Spectroscopy

NRC Study

An Assessment of the Prospects for Inertial Fusion Energy – Feb 2013

RONALD C. DAVIDSON, Princeton University, *Co-Chair*
GERALD L. KULCINSKI, University of Wisconsin-Madison, *Co-Chair*

Livingston plot for Beam Energy of Plasma Accelerators

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Figure 1. Exponential growth of accelerator beam energy, traditionally depicted by the Livingston curve (green), began tapering off around 1980 as conventional radio-frequency technology approached its limits. The extrapolation to 2010 ends with the 250-GeV electron and positron beams of the 30-km-long Next Linear Collider (NLC), which particle physicists are proposing to build with state-of-the-art rf technology. Progress toward a more radical solution that might eventually reach the high-energy frontier with much shorter linear accelerators is indicated by the red dots, which mark energies already obtained in some of the plasma-acceleration experiments in the US, Japan, and Europe. (Institutional abbreviations are spelled out in the text.) The blue dot marks the record electron energy anticipated from a plasma experiment now in progress at SLAC. (E162 point courtesy of P. Muggli, UCLA.)

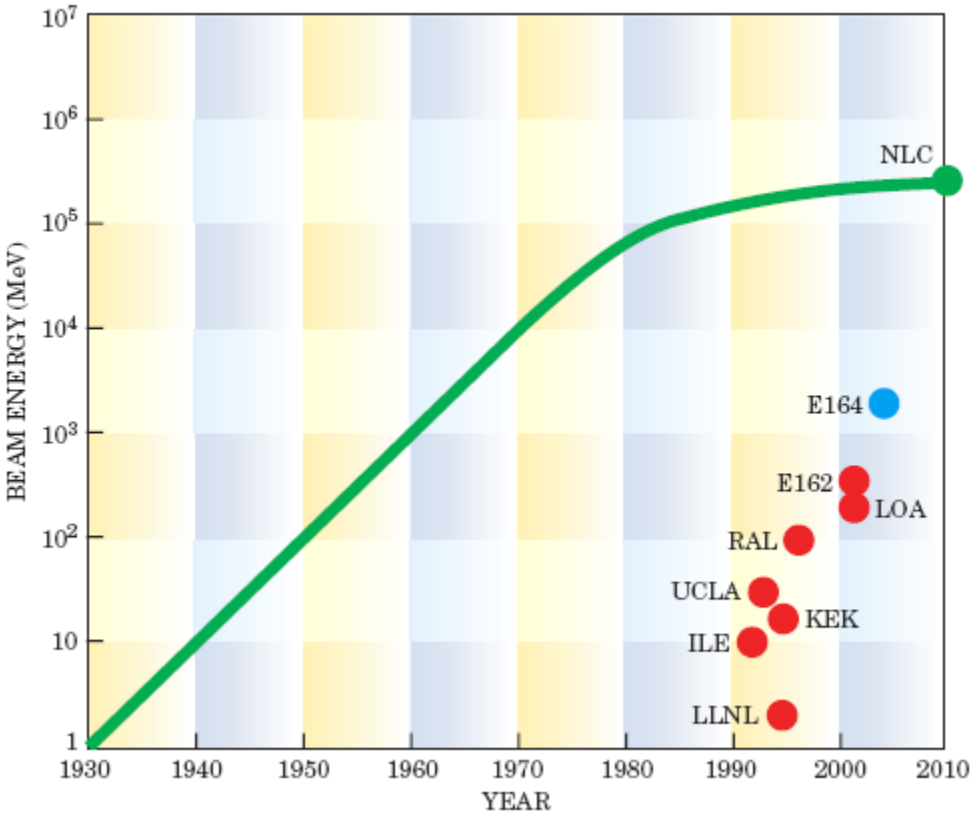

Image of simulated Electric Field and Structure, Acceleration Gradient vs Laser input energy and field

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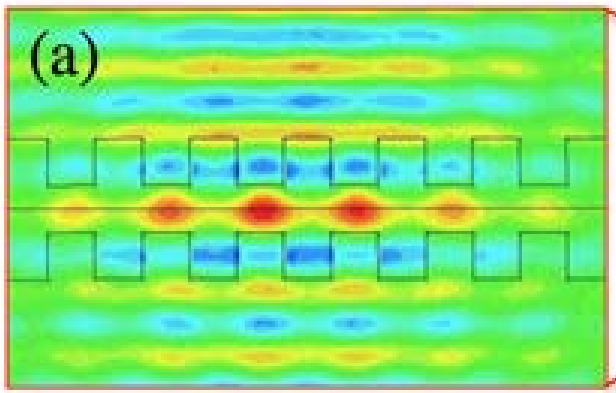

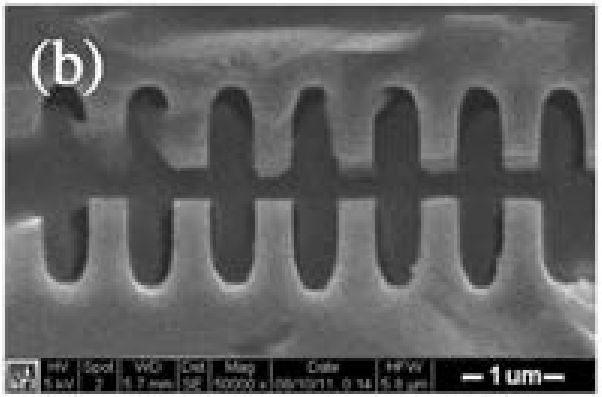

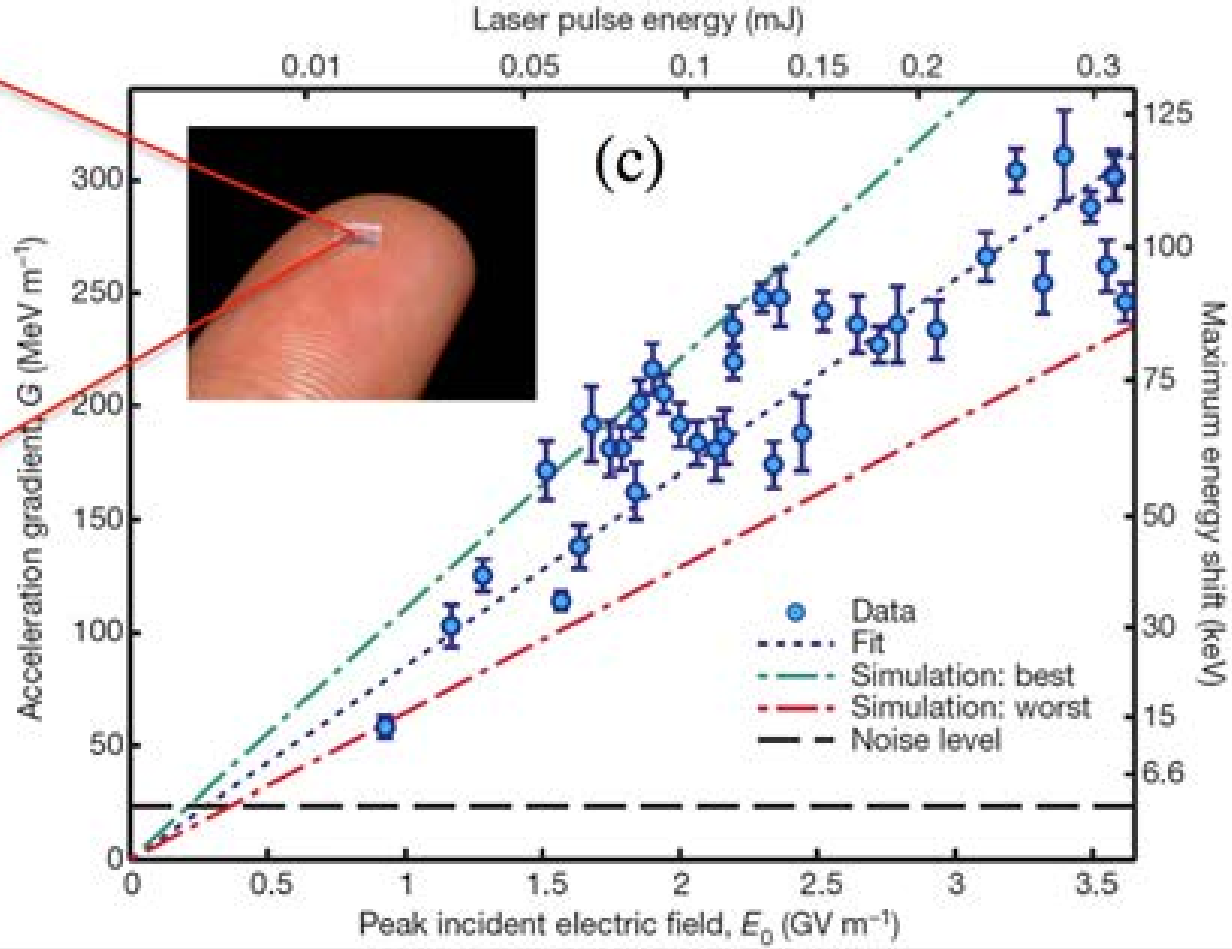

View of Silicon Accelerator Structure

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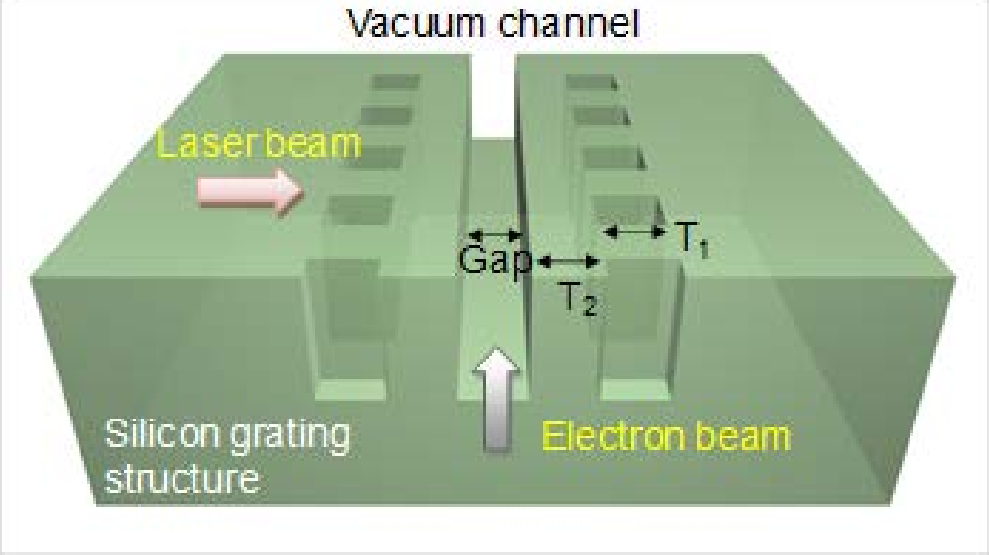

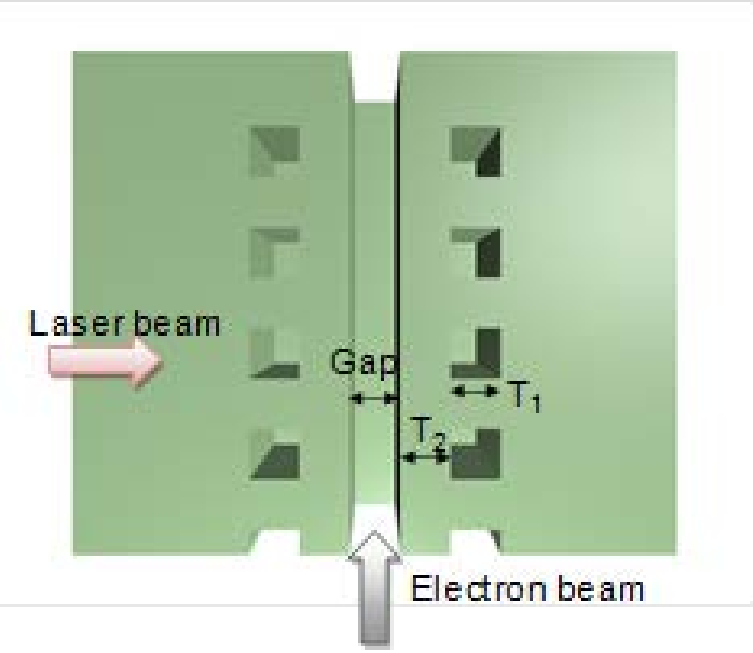

Schematic of On-chip laser guiding to Accelerator Structure

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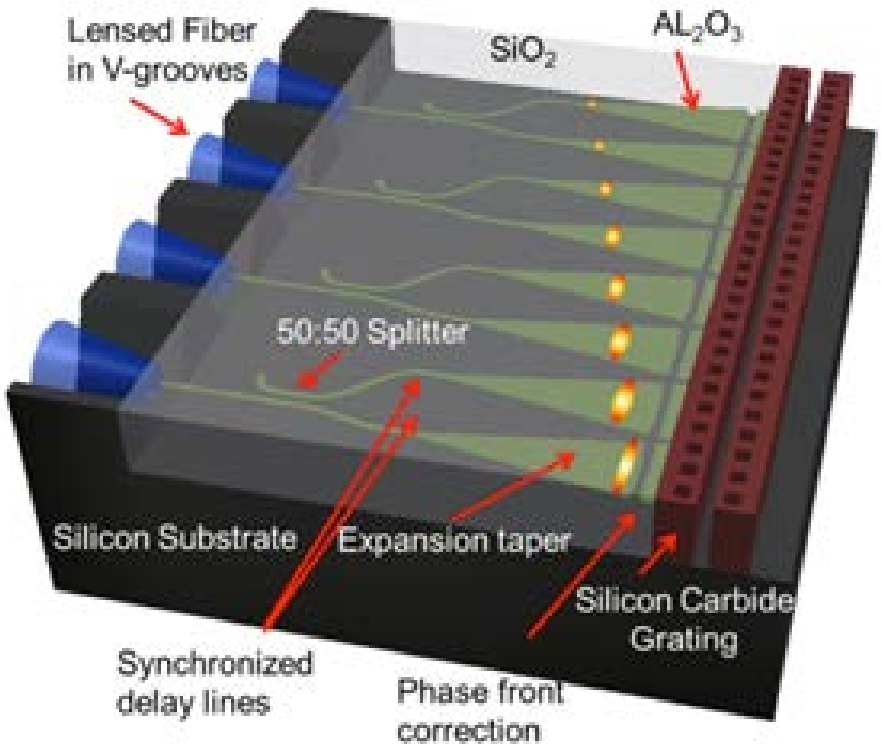

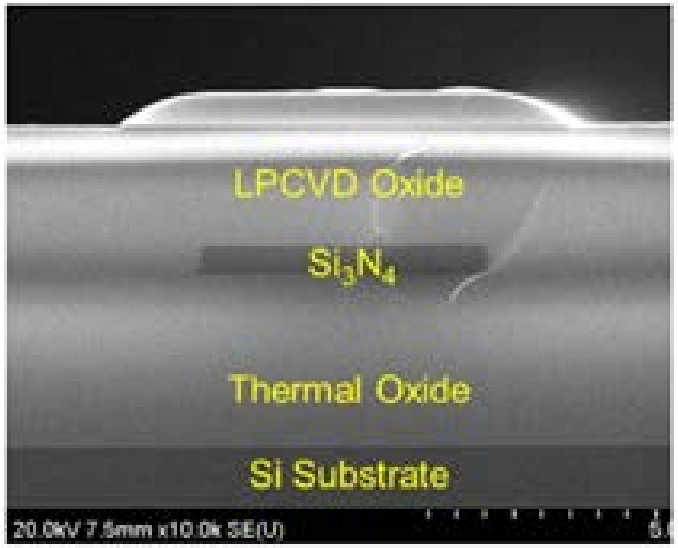

On chip Silicon-Nitride waveguide

(a)Tungsten supertip electron source, (b) Mounted tip illuminated by a ultrafast laser

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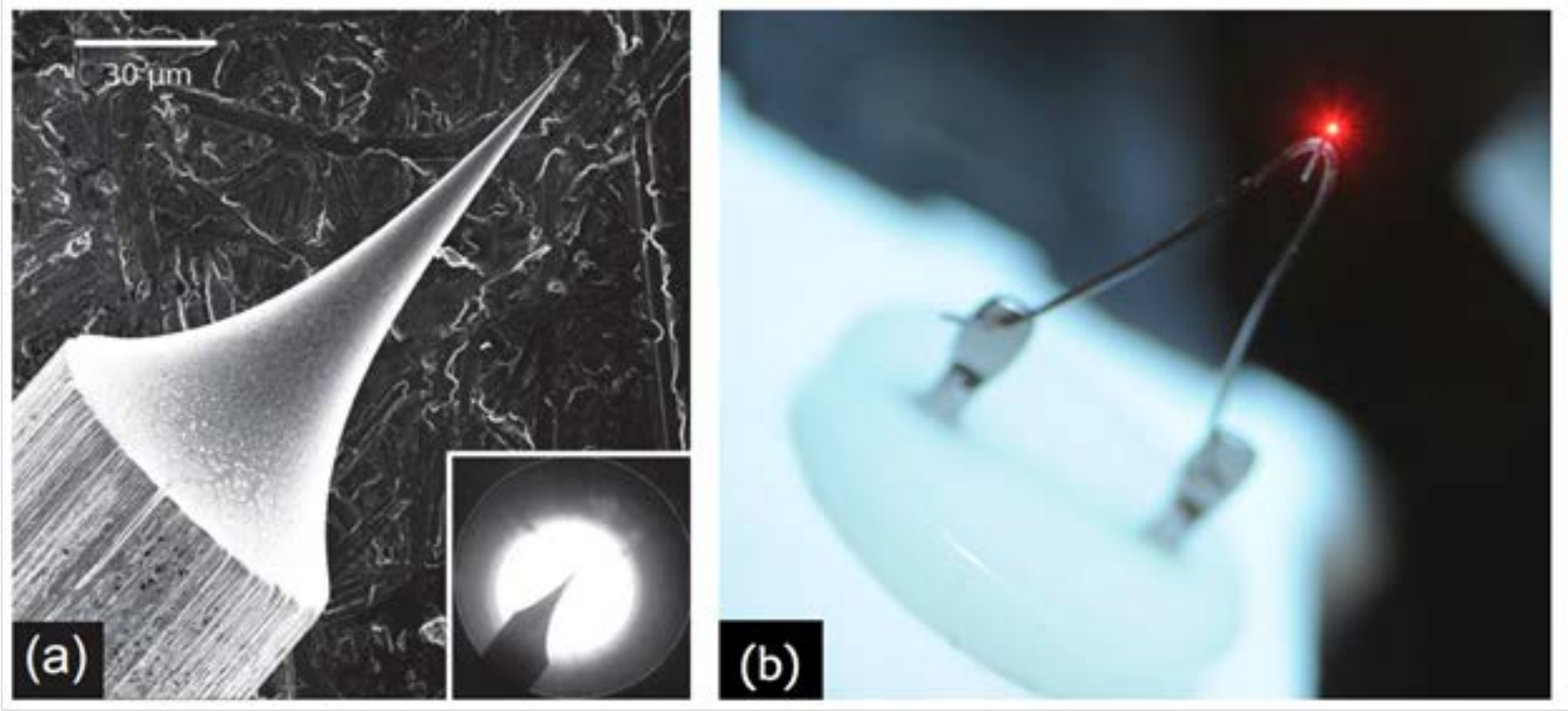

Courtesy P. Hommelhoff

Schematic of Laser driven Injector and Pre-accelerator Concept (Hommelhoff)

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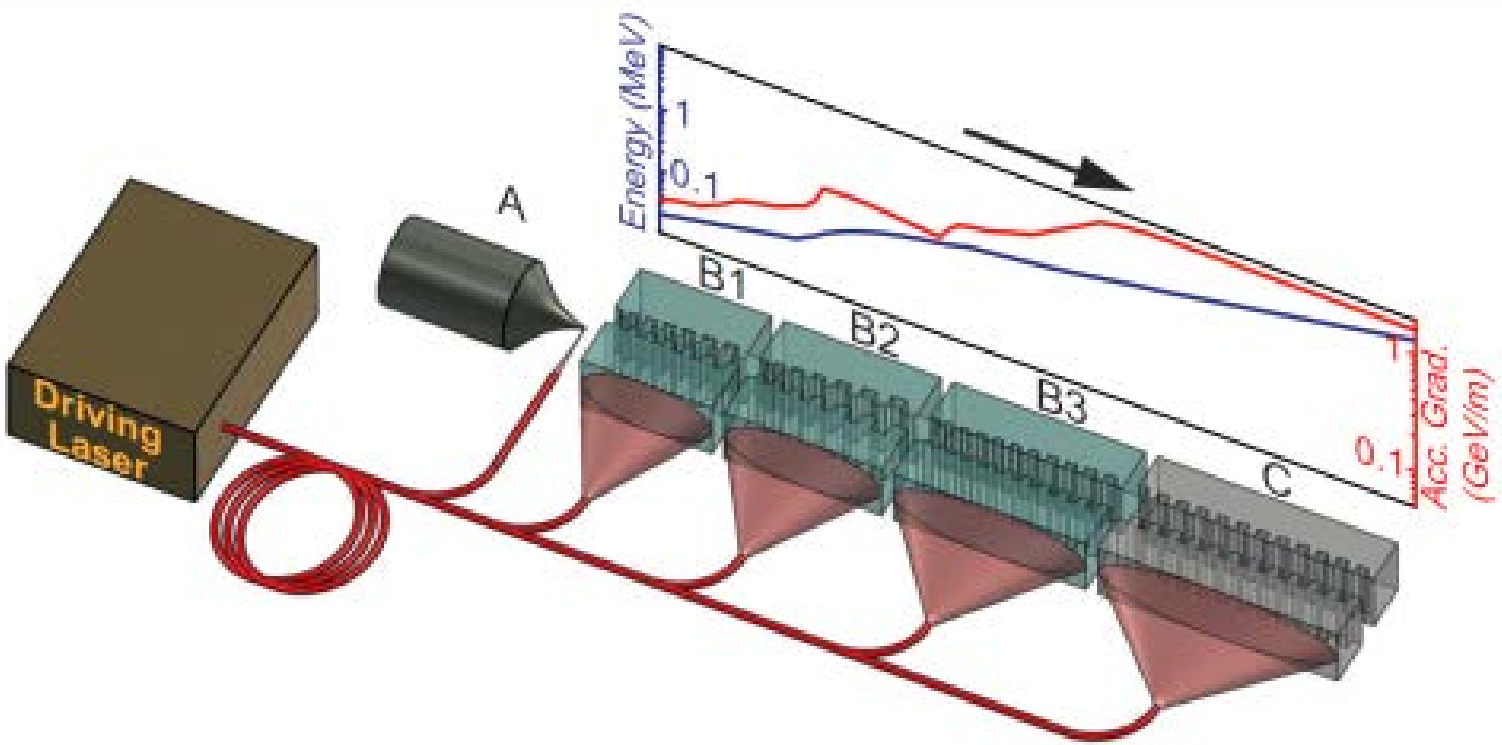
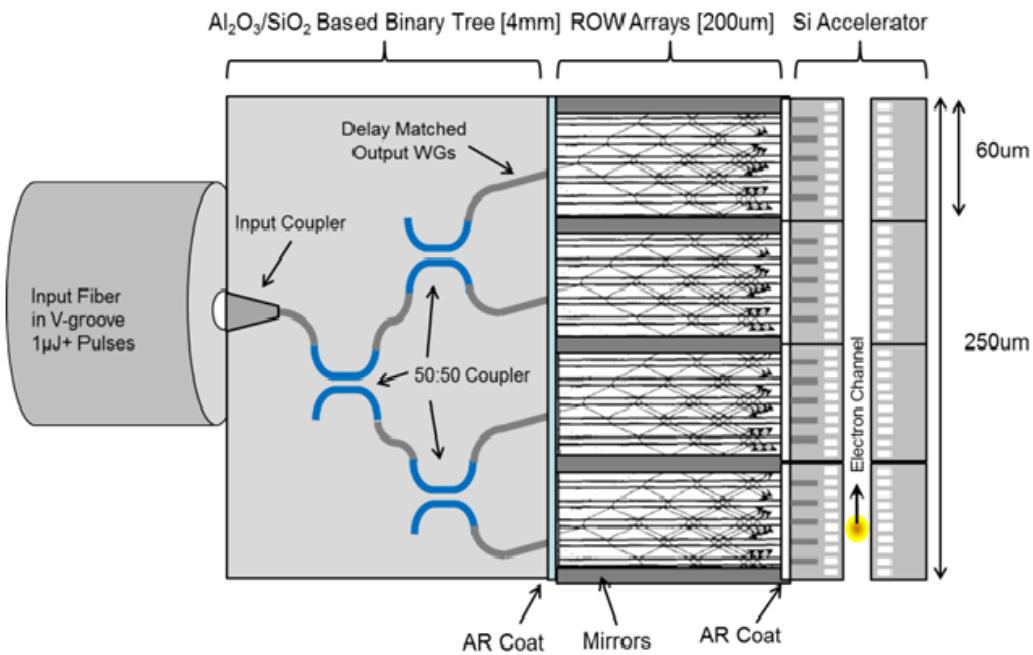


Schematic of waveguide delivery structure
Ken Leedle & Jim Harris

Byer Group



SiO_2 Al_2O_3 SiO_2 Waveguide Mode

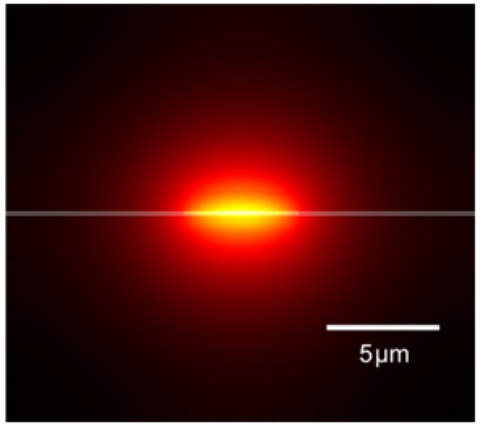


Fig. 7. (a) Proposed monolithic integrated waveguide accelerator structure; (b) TE-mode intensity profile of Al_2O_3 wide-aspect ratio waveguide in SiO_2 for delay matching stage.

Develop Waveguide concept for delivery of high peak power 150fsec pulsed to accelerator structure

Accelerator and X-ray Laser on a Chip

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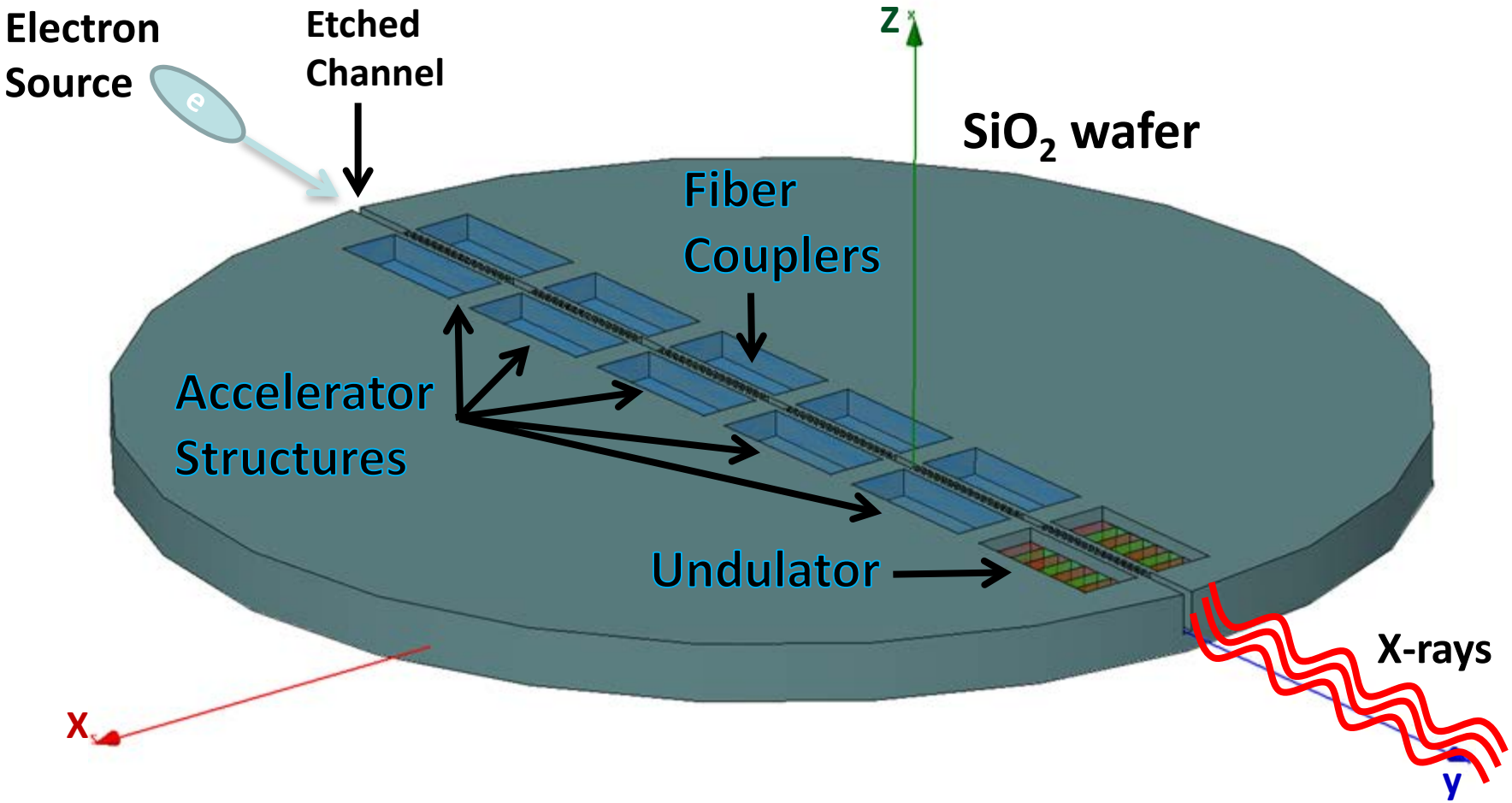

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