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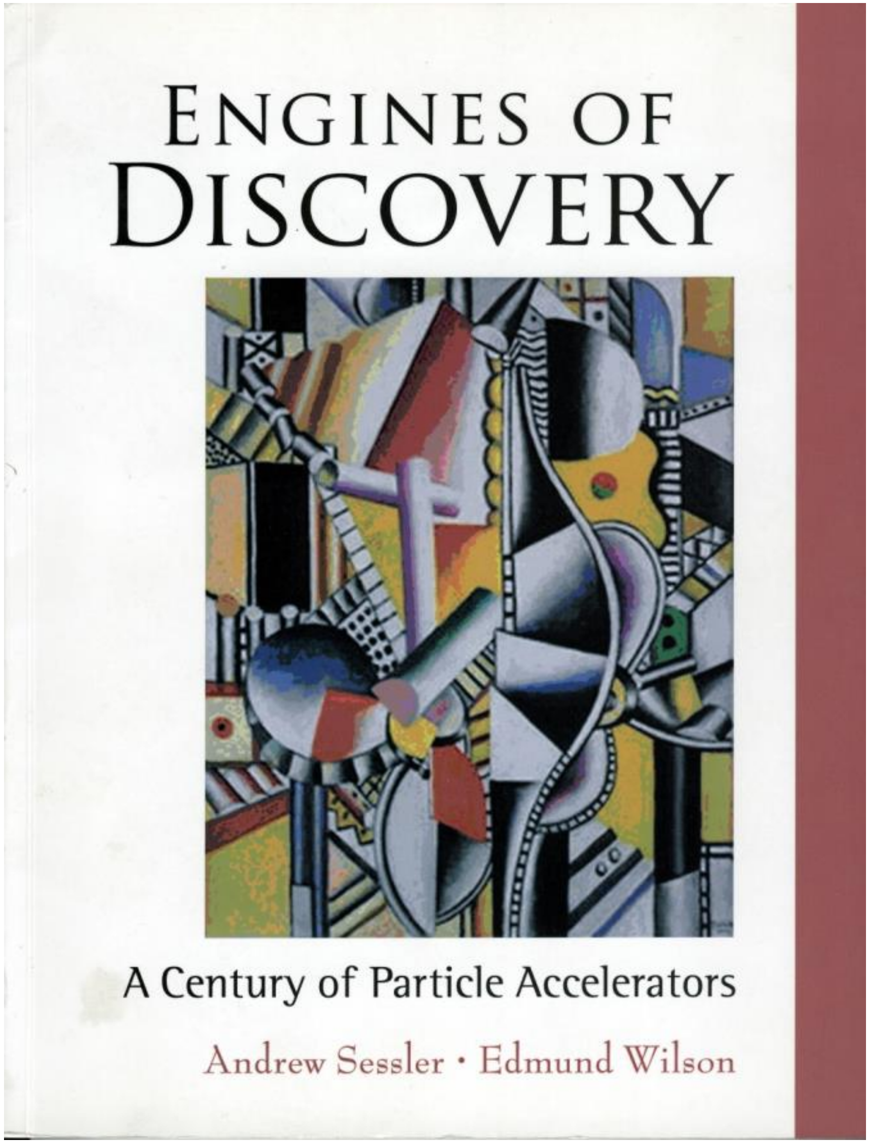
Stanford University
rlbyer@stanford.edu

Abstract

In 2015 the Moore Foundation accepted a proposal to fund an accelerator science program with the goal of demonstrating a laser driven accelerator on a chip. To date the international collaboration has demonstrated greater than 800MeV/meter gradient in a fused silica grating structure and has demonstrated the first accelerators based on silicon. The ACHIP collaboration is making progress toward a 100MHz repetition rate accelerator with attosecond electron bunches to enable applications to science and to medicine.

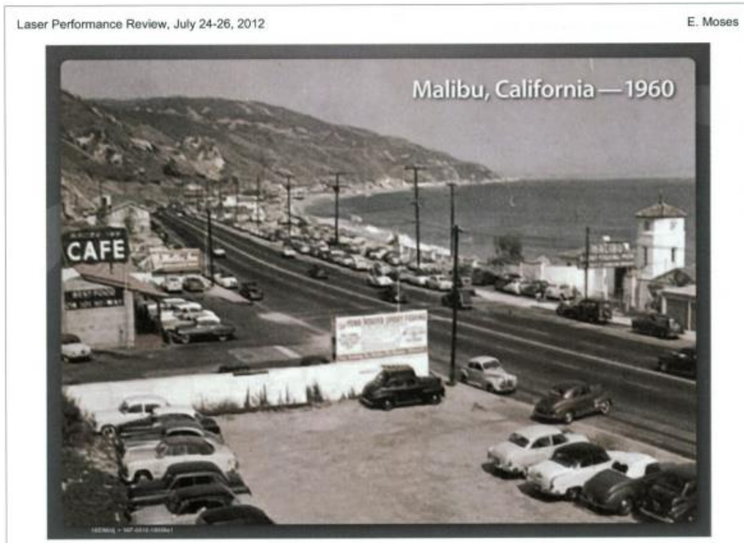
Symposium in Honor of
Toshiki Tajima
UC Irvine
January 25-26, 2018

A Century of Particle Accelerators



First came accelerators

Fifty + years of Lasers



Malibu Beach, CA 1960

Ted Maiman and the Ruby Laser

then came Lasers

Laser Acceleration

T. Tajima[1*], K. Nakajima[2], and G. Mourou[3]

[1]Department of Physics and Astronomy, University of California, Irvine, CA 92610, USA

[2]Center for Relativistic Laser Science, Institute for Basic Science (IBS), Gwangju 61005, Korea

[3]IZEST, Ecole Polytechnique, 91128 , Palaiseau, France

[*]2015 recipient of the Enrico Fermi Prize

I. Introduction
II. Laser compression
III. LWFA scaling
IV. Toward high energy acceleration with nonluminosity paradigms
V. Ion acceleration
VI. Zeptosecond science
VII. Ultrahigh energy cosmic ray acceleration
VIII. Application of LWFA to X-rays and gamma-ray sources
IX. Application to medicine
X. Conclusions

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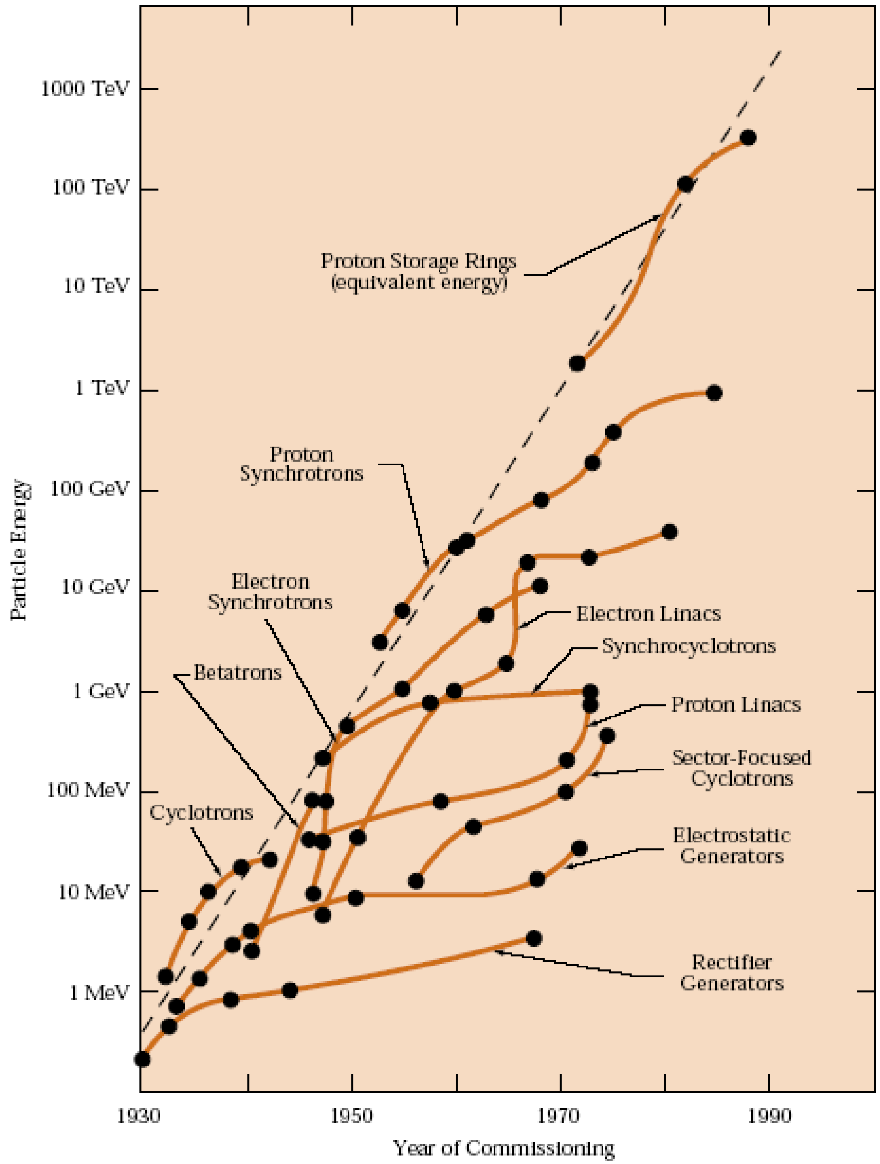
The Livingston plot – 1954
Innovation leads to exponential progress



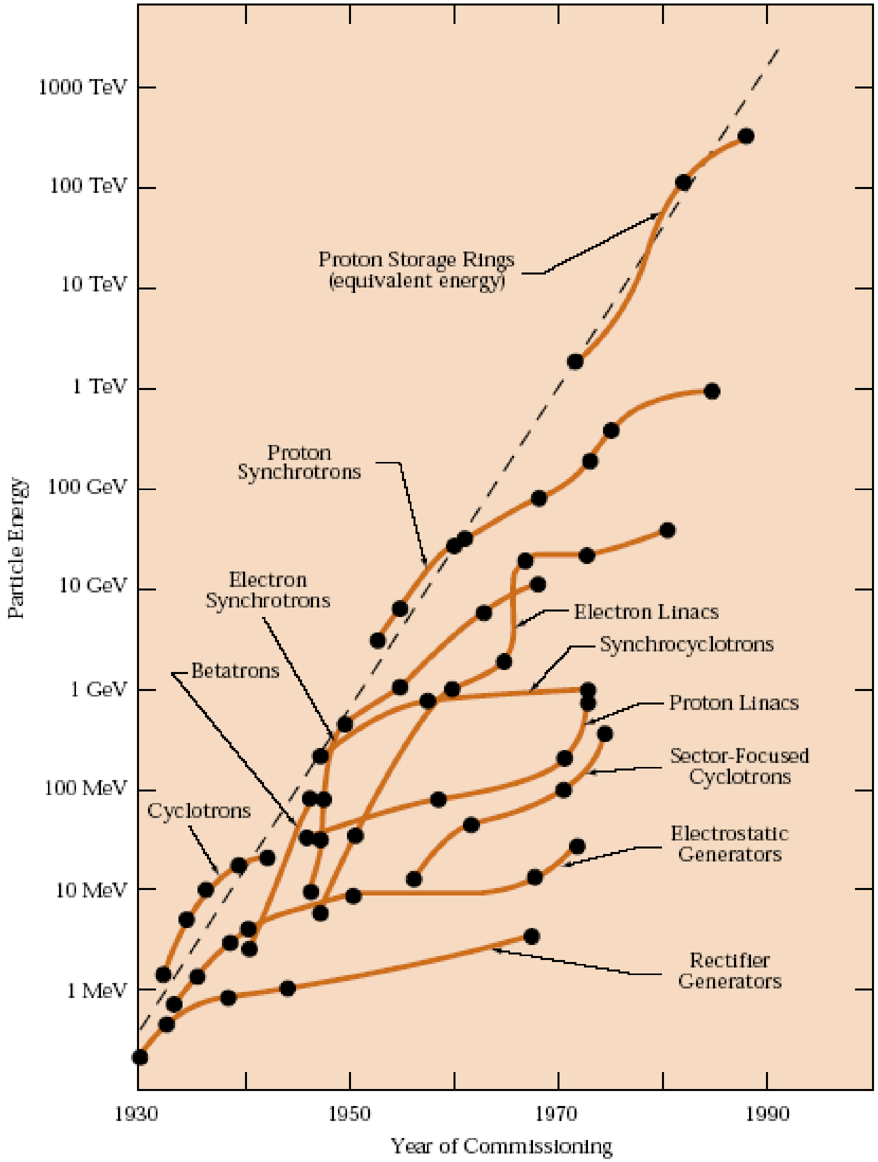
In 1954 Livingston noted that progress in high energy accelerators was exponential with time.

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 2015 see a commitment to explore innovative new approaches to laser driven linear accelerators?

The Livingston plot – 1954
Innovation leads to exponential progress



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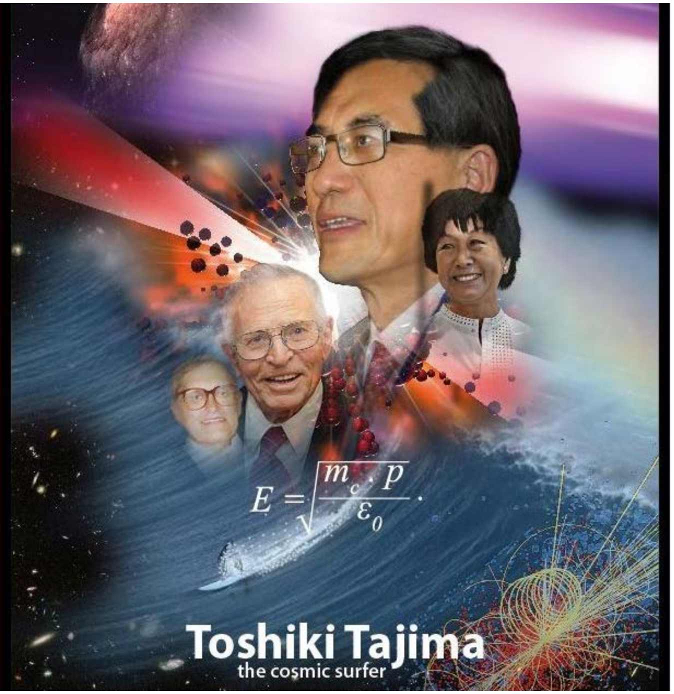
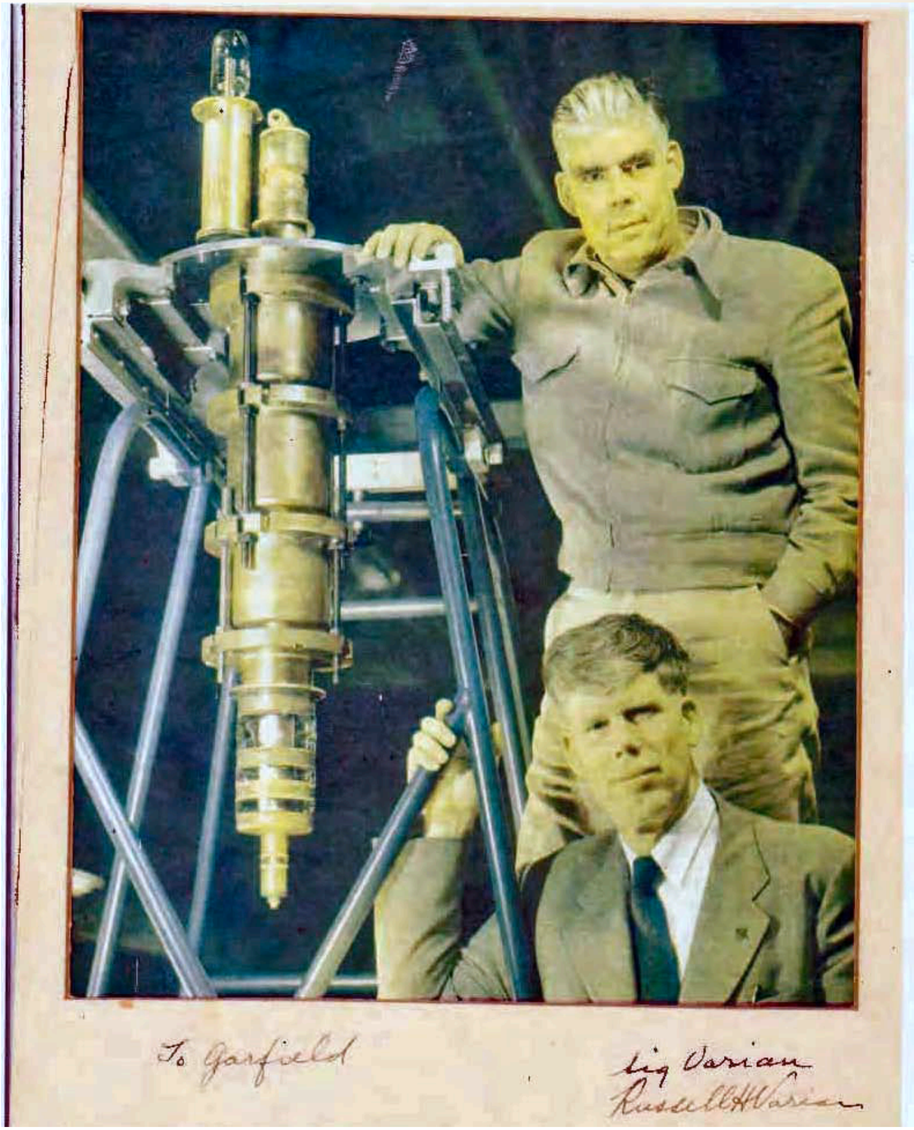
YES! Moore Foundation

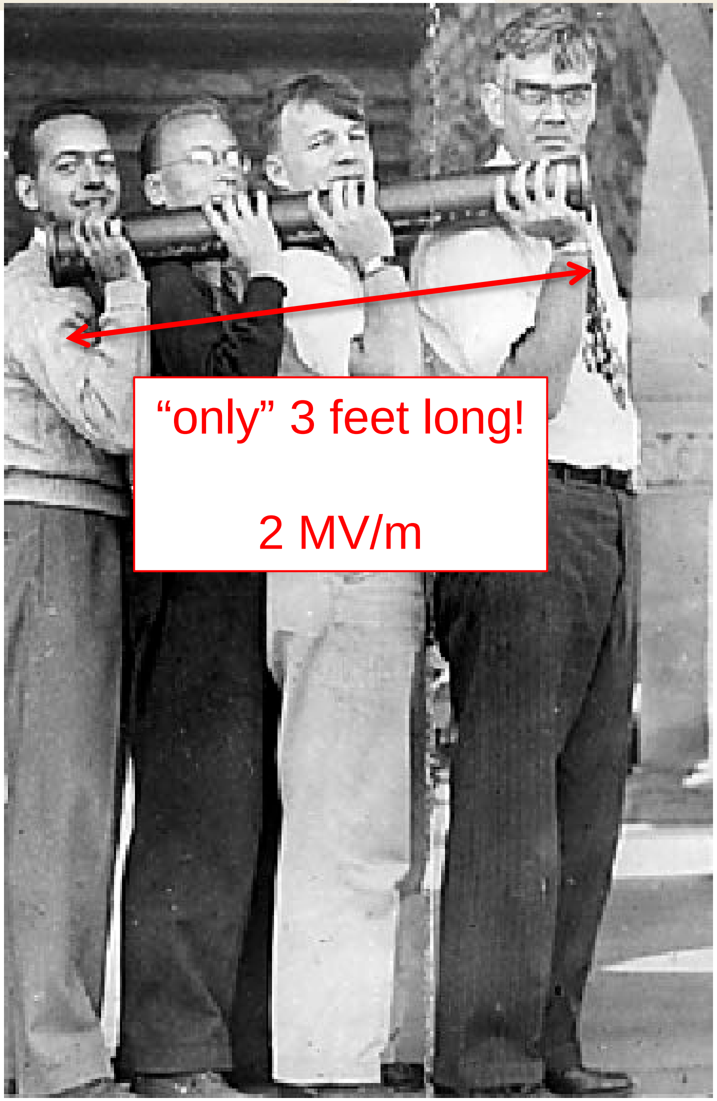


Introduction	*Early Progress in Laser Accelerators*
Success!	*Laser Acceleration in Dielectric Structures*
Current Activity	*Laser Acceleration on a chip: ACHIP*

When the SLAC linac and microwave klystron were invented they were revolutionary developments



Klystron invented 1937



Microwave linac invented 1948

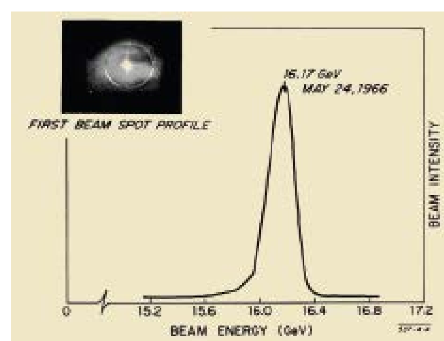
"Project M"

1955 first brainstorming and informal discussions

SLAC CHRONOLOGY

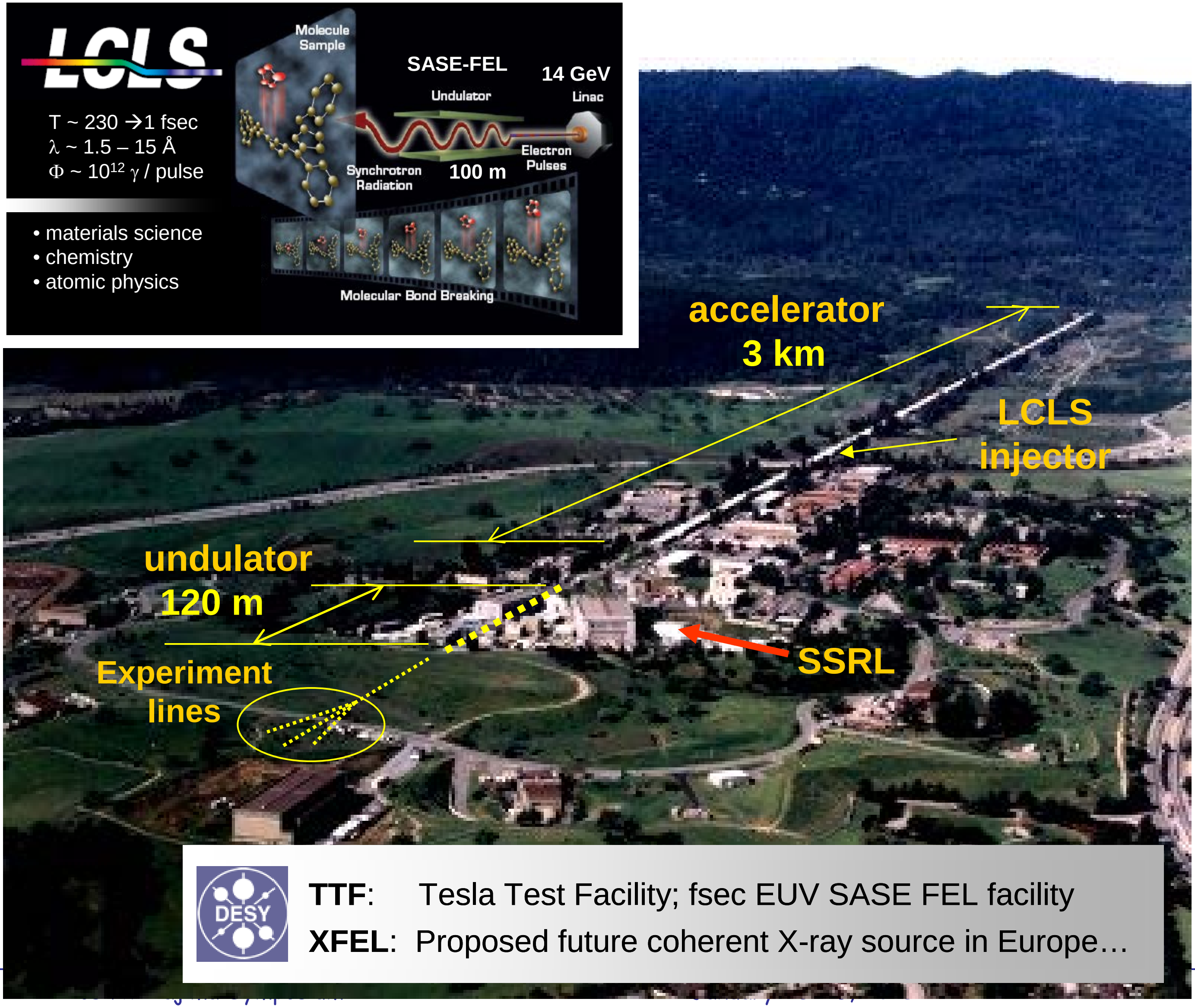
April 1957	Proposal for two-mile accelerator submitted by Stanford University to Federal Government
September 1961	Project authorized by U. S. Congress
April 1962	Contract signed by U. S. Atomic Energy Commission and Stanford University
July 1962	Ground breaking; construction begins
July 1964	Start of accelerator installation
October 1, 1965	First "Users Conference," attended by 150 people from laboratories all over the world, to be made acquainted with SLAC.
December 1965	Installation of accelerator complete
February 12, 1966	Program Advisory Committee met, and approved and scheduled the first experiments to be performed with the two-mile beam
May 21, 1966	First beam transmitted over entire two-mile length of the accelerator
June 2, 1966	18.4 GeV of beam energy achieved
June 22, 1966	Second "Users Conference" held at SLAC
July 13, 1966	Positrons accelerated
October 17, 1966	First interlaced multiple beams of different energies and intensities accelerated
November 1966	Experiments begin with the beam in the end stations
January 10, 1967	20.16 GeV of beam energy achieved

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



First beam at SLAC, 1966

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…

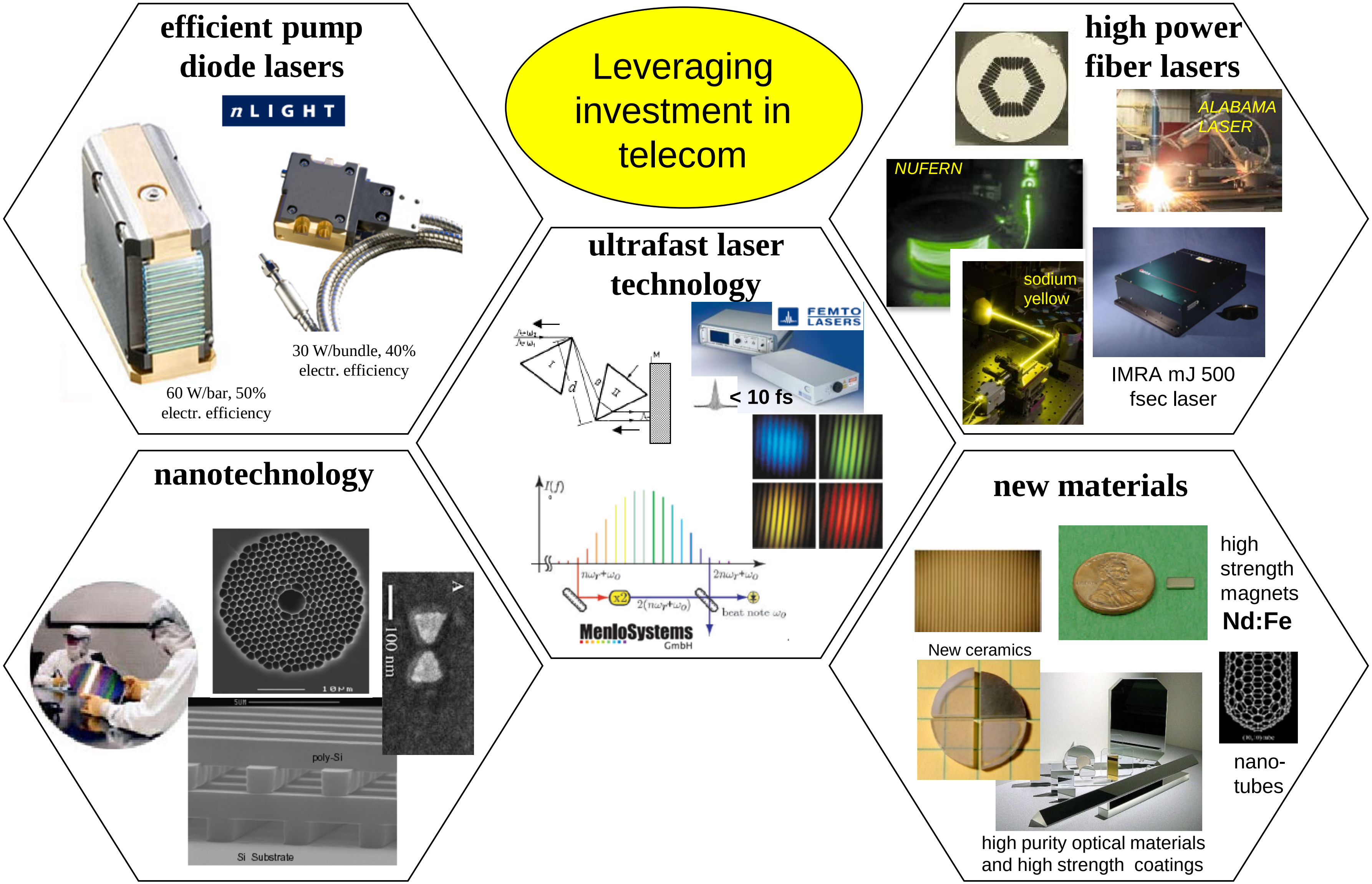
LCLS properties

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

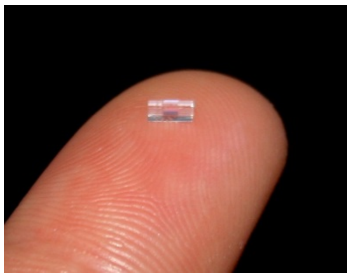
- 120 m undulator
- 23 cm period
- 15-1.5 A radiation
- 0.8-8 keV photons
- 10^{14} photons/sec
- ~77 fsec

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

Emergence of new technologies make Laser Acceleration Possible



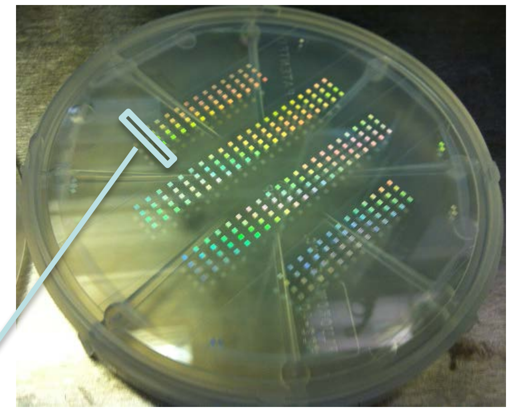
Dielectric Laser Acceleration (DLA)



laser-driven microstructures

- **lasers:** high rep rates, strong field gradients, commercial support
- **dielectrics**: higher breakdown threshold → higher gradients (1-10 GV/m), leverage industrial fabrication processes

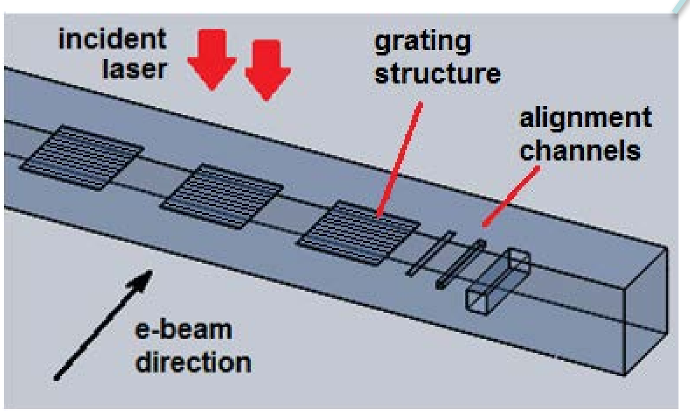
"Accelerator-on-a-chip"

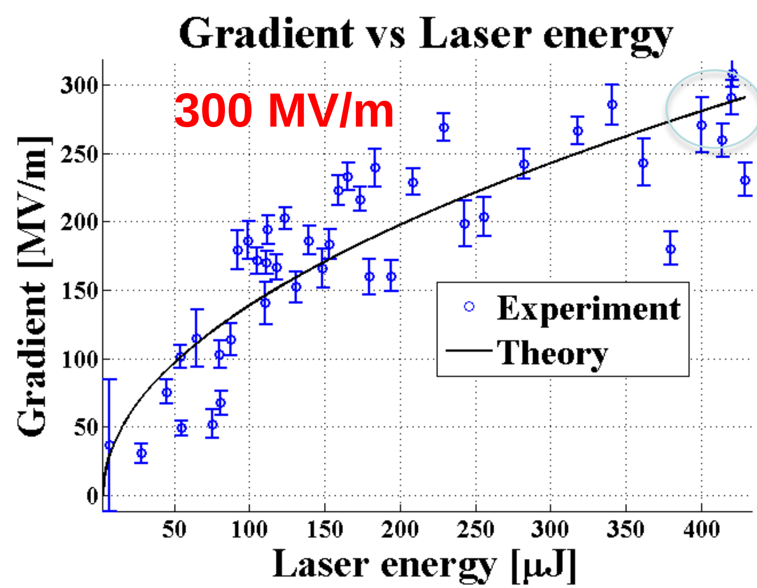


bonded silica phase reset accelerator prototypes fabricated at SLAC/Stanford

Goal: lower cost, more compact, energy efficient, higher gradient

Wafer is diced into individual samples for e-beam tests.





DLA leverages advances in two major industries: solid state lasers + semiconductor fabrication

SLAC

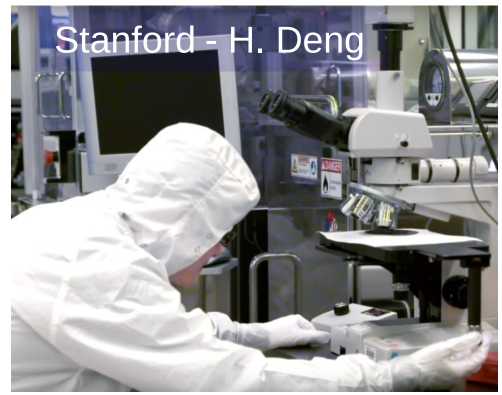
High average power,
not high peak power lasers!

Parameter	DLA Value
Wavelength	**2 µm**
Pulse Duration	**100 fs**
Pulse Energy	**1 µJ**
Laser Power	**100 W**
Rep Rate	**100 MHz**
Laser Efficiency	**30%**
Cost/laser	**$300k**

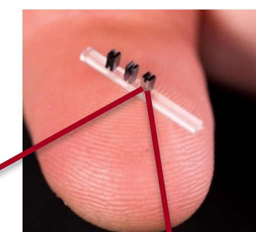
Solid-state laser

Available now “off the shelf”

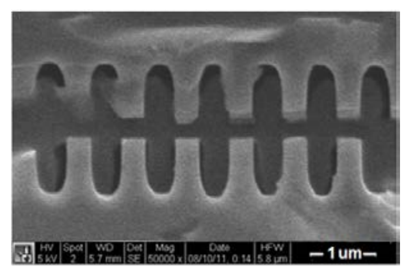
Fabricated using techniques of the integrated circuit industy.



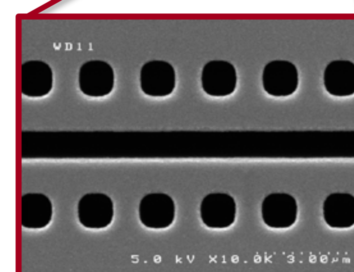
DLA structures are made by students in the Nanofabrication Facilities at partner universities.



SEM images of DLA prototypes tested at NLCTA



fused silica
(UV photolithography)

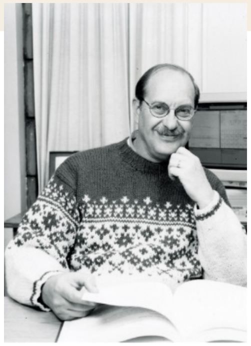


silicon
(DRIE)

An initiative in particle acceleration using lasers was started by Bob Byer and Bob Siemann (1996)

R. L. Byer

+



R. H. Siemann

T. Plettner

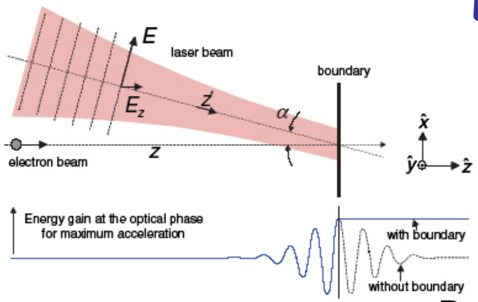
E. Colby

R. J. England

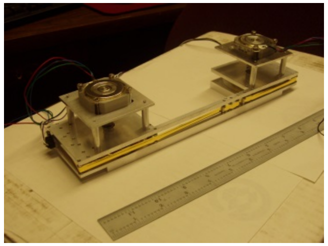
Stanford & SLAC Programs in laser-driven acceleration:

LEAP (1996-2015)
E-163 (2005-present)
DARPA AXiS (2011-2013)
ACHIP (2016-2020)
NSF-BSF (2016-2018)

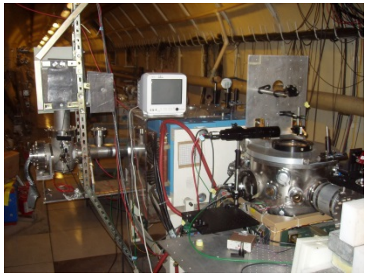
Postdocs and students (1996 – present)



Laser driven particle acceleration 1996 - 2004



collaborators



ARDB, SLAC

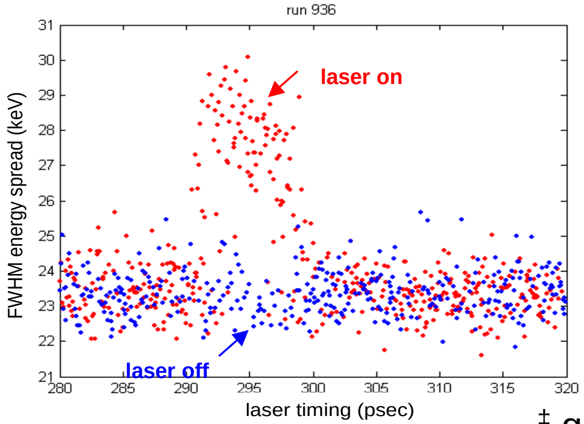
Bob Siemann*, Bob Noble†, Eric Colby†, Jim Spencer†, Rasmus Ischebeck†, Melissa Lincoln‡, Ben Cowan‡, Chris Sears‡, D. Walz†, D.T. Palmer†, Neil Na‡, C.D Barnes‡, M Javanmarad‡, X.E. Lin†

Stanford University

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

ARDA, SLAC

Zhiu Zhang†, Sami Tantawi†

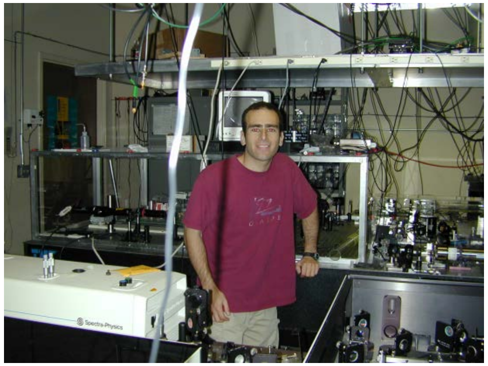


Techion Israeli Institute of Technology

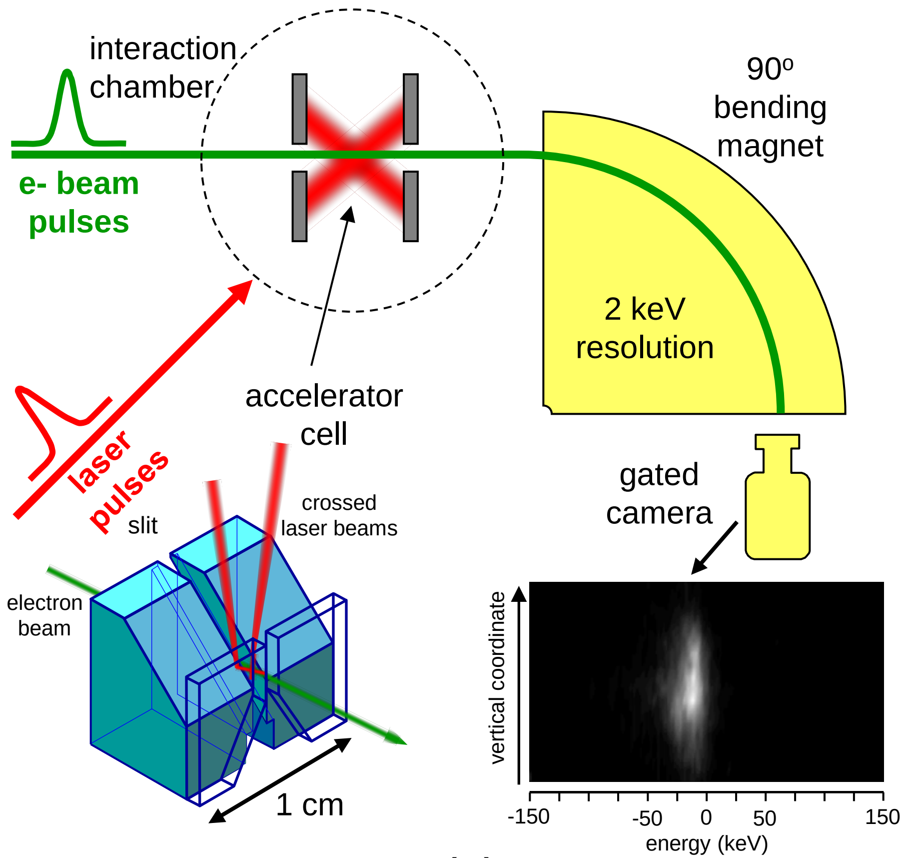
Levi Schächter*

UCLA

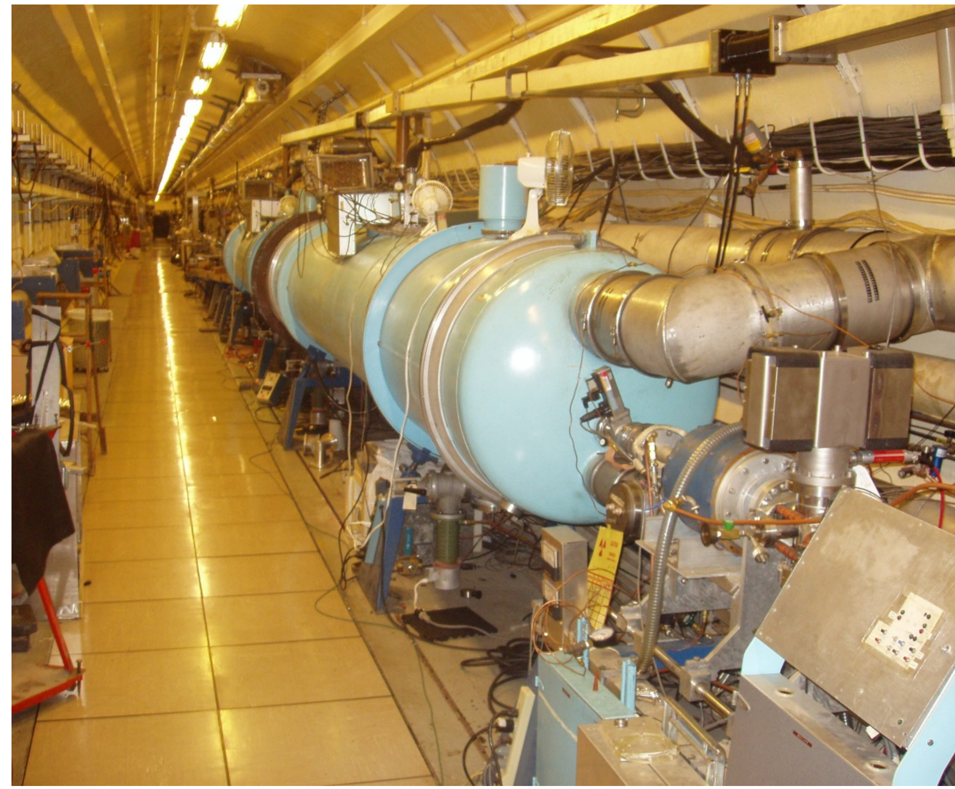
J. Rosenzweig*



‡ grad students † postdocs and staff * faculty



(a)



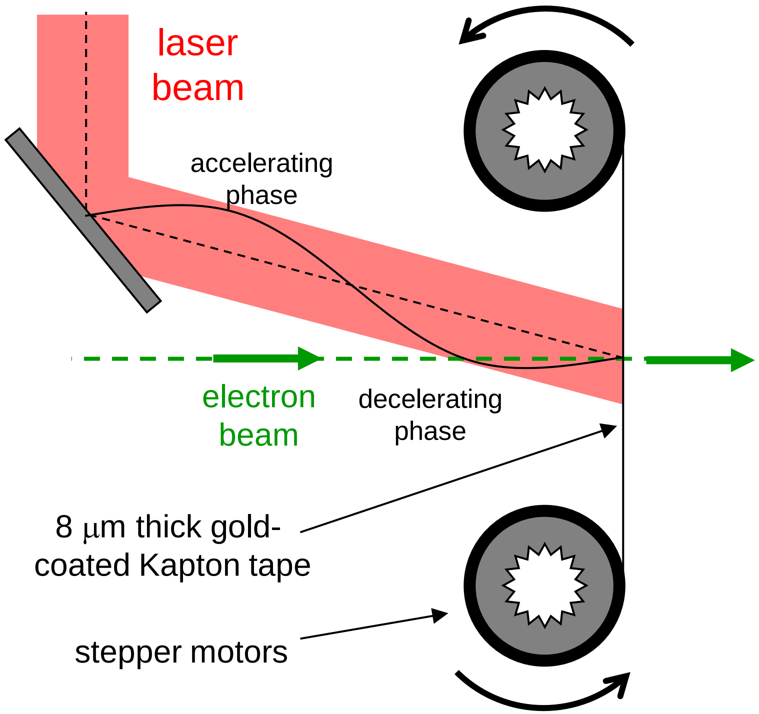
(b)

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

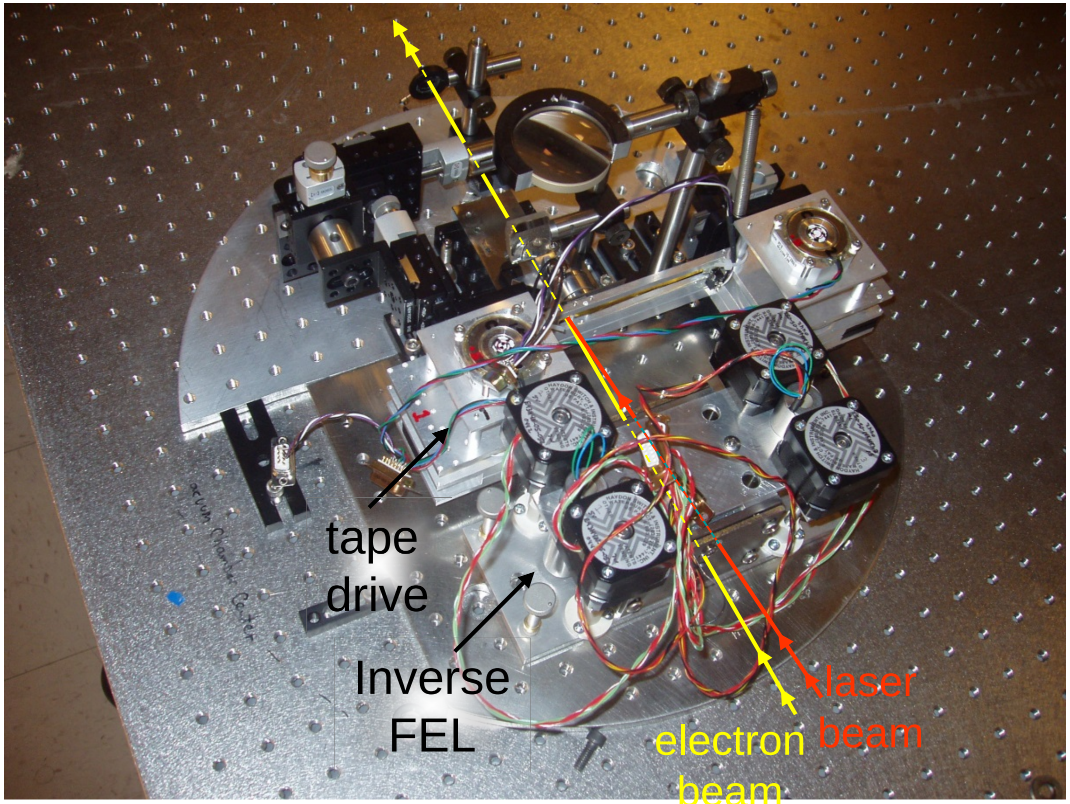
The view of the 30 MeV super-conducting linear accelerator in the underground tunnel on campus in the HEPL lab.

LEAP Experimental Success- November 2004

We have accelerated electrons with visible light!

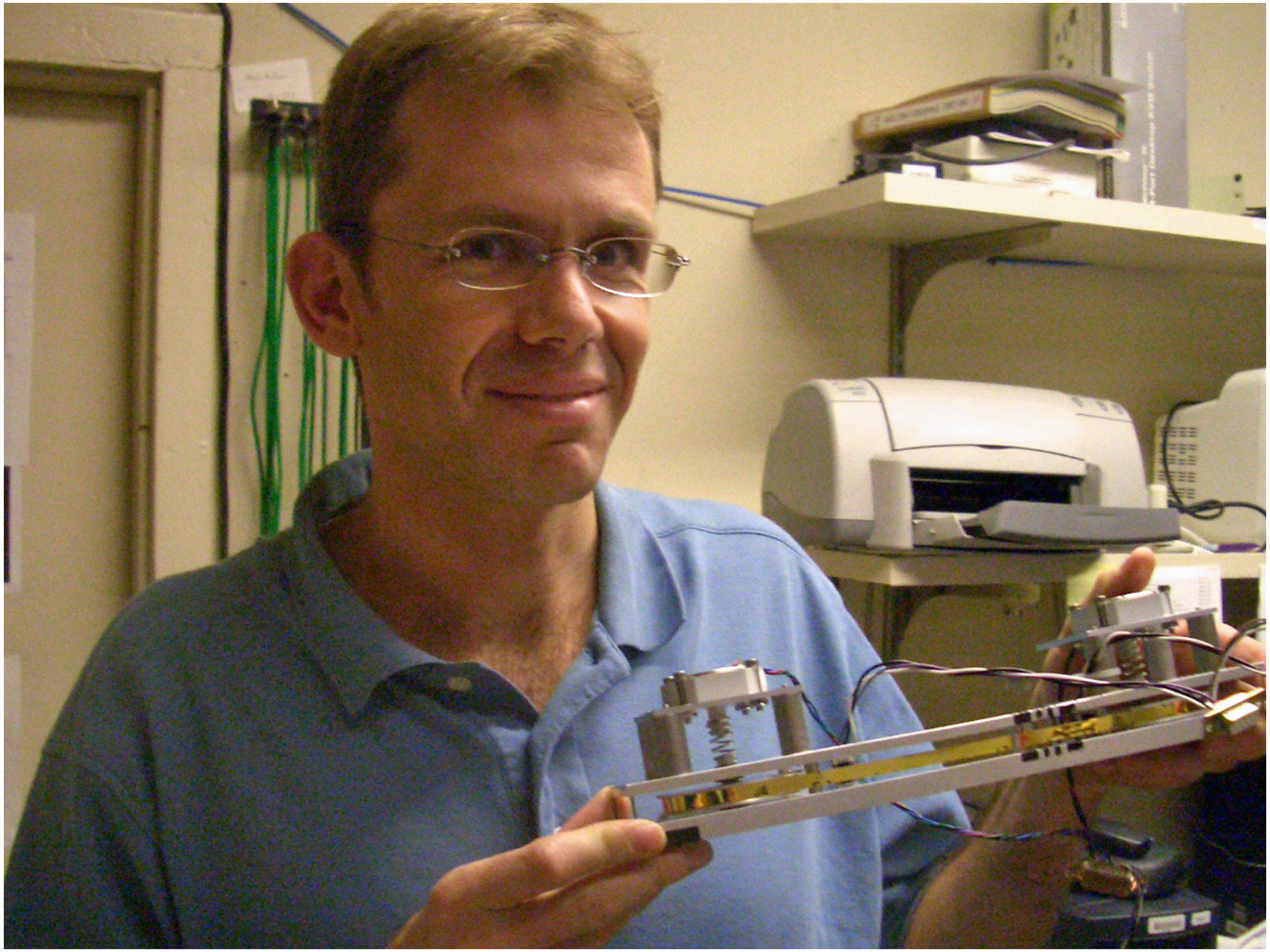


<u>Simplified</u> single-stage Accelerator Cell - Gold coated Kapton tape to terminate the Electric field.



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

Tomas Plettner and LEAP Accelerator Cell



The key was to operate the cell above 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

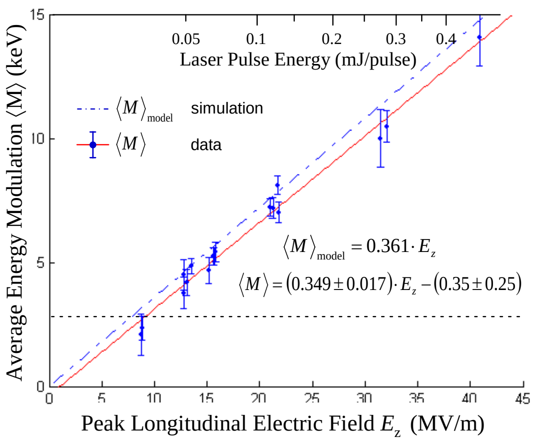
PRL **95,** 134801 (2005) PHYSICAL REVIEW LETTERS week ending 23 SEPTEMBER 2005

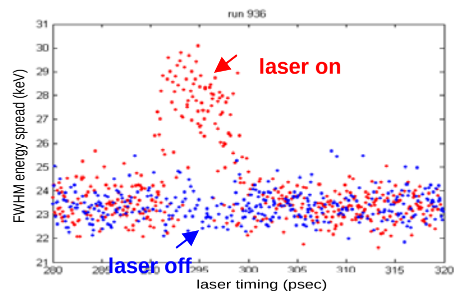
Visible-Laser Acceleration of Relativistic Electrons in a Semi-Infinite Vacuum

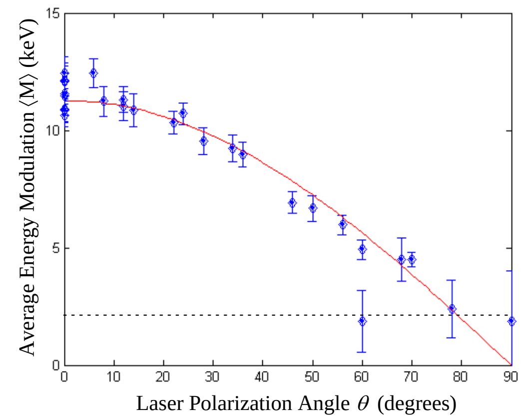
T. Plettner and R. L. Byer
Stanford University, Stanford, California 94305, USA

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 endi… 4 NOVEMBE… …005

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

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

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

Cross-correlation in time

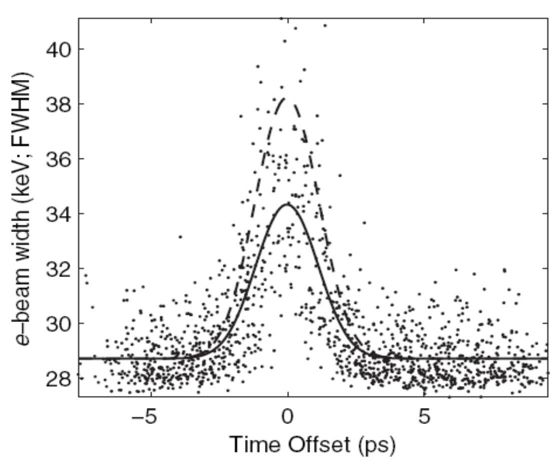


FIG. 2. Example data run with 1500 laser on events. The solid curve is the least squares fit to all data points and gives the mean interaction of 18 keV. The dashed curve is the maximum estimate and gives the peak interaction of 25 keV. The width of cross correlation is 2.2 ps rms.

Observation of harmonic interaction

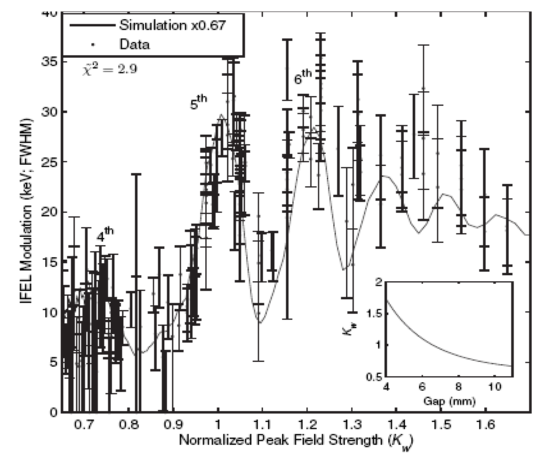
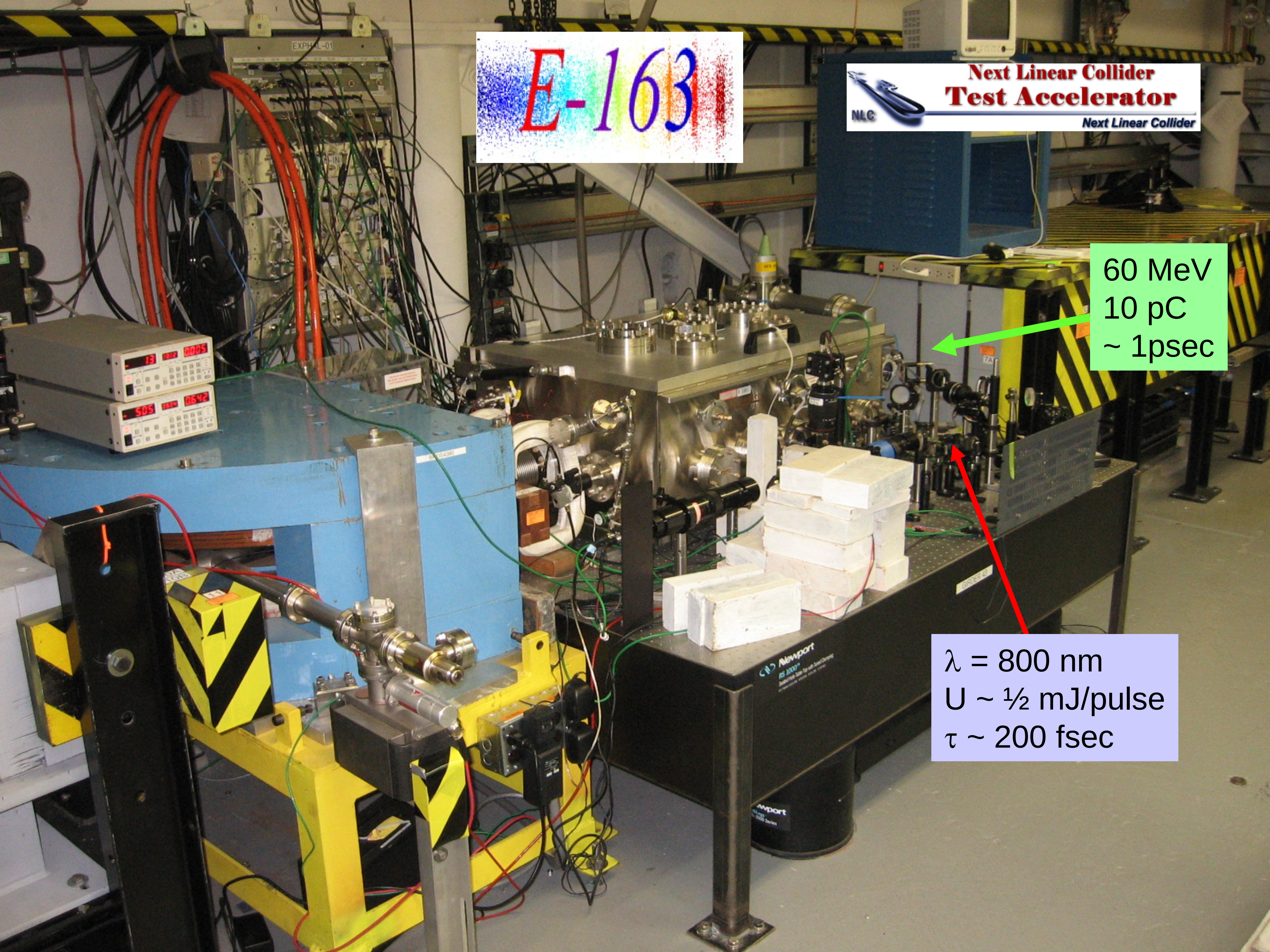
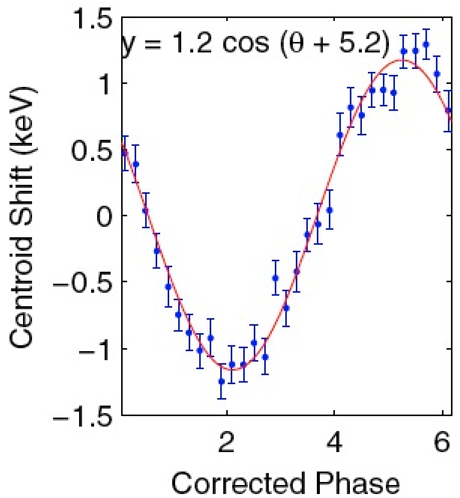


FIG. 4. IFEL gap scan data, with 164 runs total. Comparison to simulation (solid line) shows very good agreement to the shape and spacing of resonance peaks. The harmonic numbers are given next to each peak. Simulation has been rescaled vertically by 0.67 to better visualize overlap.

* graduate student C.M. Sears


E-163
Next Linear Collider
Test Accelerator
Next Linear Collider
60 MeV
10 pC
~ 1psec
λ = 800 nm
U ~ ½ mJ/pulse
τ ~ 200 fsec

3rd Success: Bunching and Net Acceleration

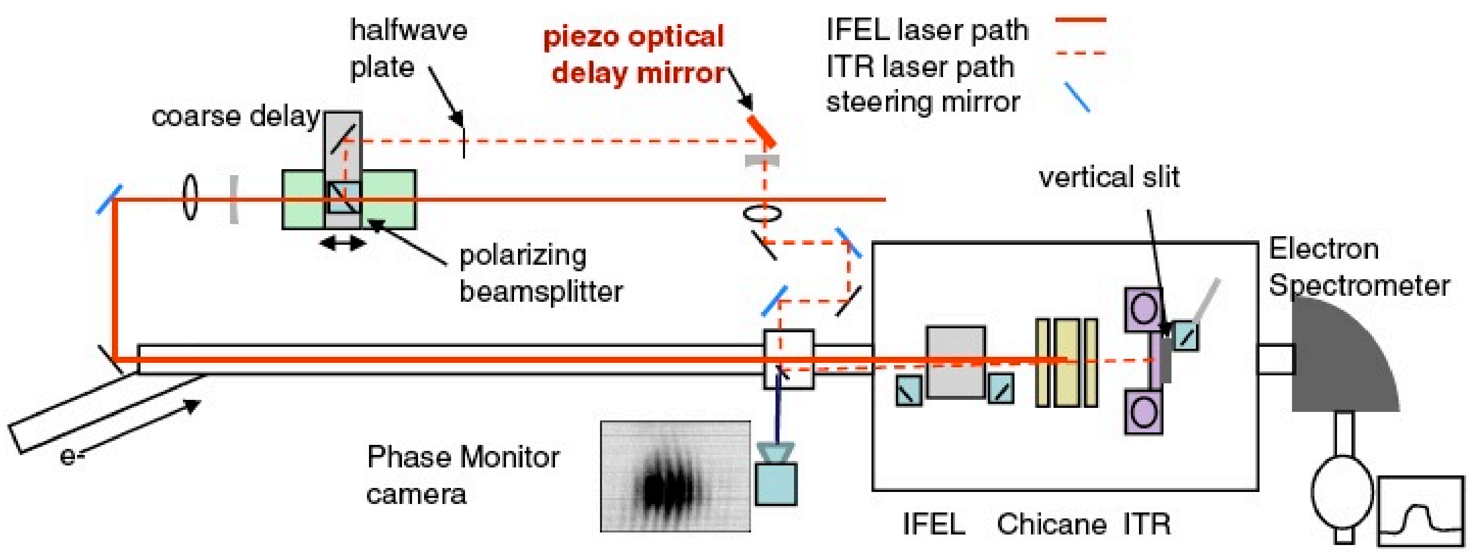


Net laser acceleration of 1.2 keV

demonstrated **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)].

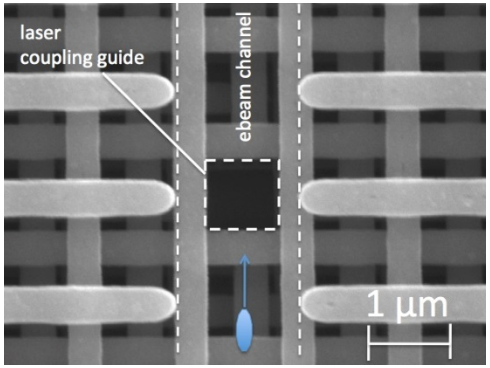
C.M.S. Sears, et al. “Phase stable net acceleration of electrons from a two-stage optical accelerator.” PRST-AB **11**, 101301 (2008).



Since then a variety of successful demonstrations set the stage…

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. PRST-AB **11**, 101301 (2008).

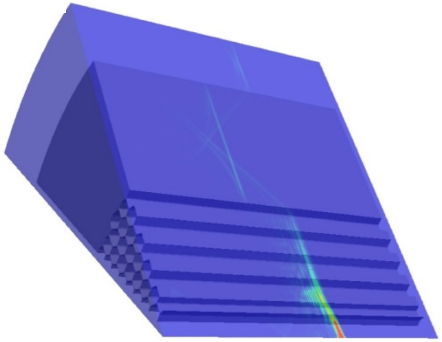


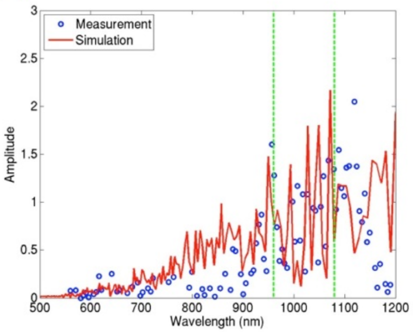
3D Photonic crystal fabrication with complex multi-layer designs suitable for efficient power coupling

Staude, McGuinness, et al. Opt. Exp. **20**, 5607 (2012)

Excitation of TM modes
In photonic crystal fibers via wakefield stimulation with 60 MeV electrons

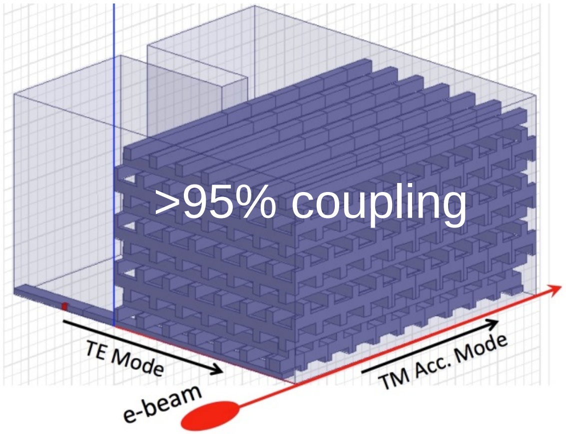
C-K. Ng, et al. PR-STAB **13**, 121301 (2010)
R. J. England, et al. AIP Conf. Proc. 1086, 550 (2009)

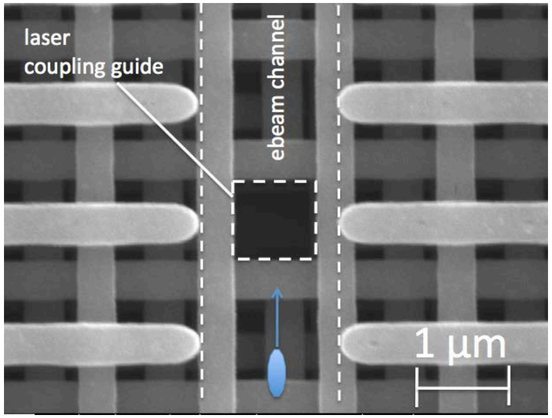




… including development of concepts for compatible accelerator subcomponents.

Efficient Coupler Designs

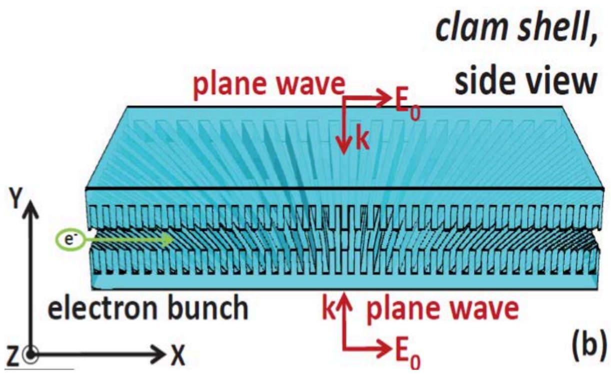




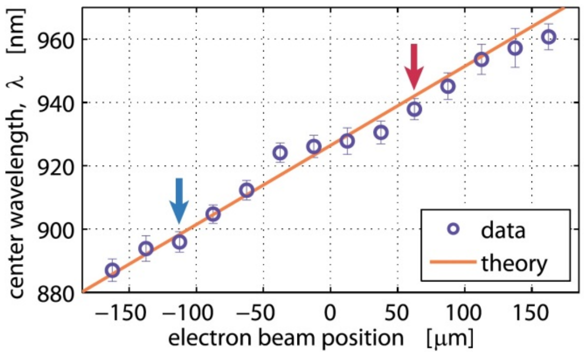
C. McGuinness, Z. Wu

Phys. Rev. ST-AB, **17,** 081301 (2014)

Beam Position Monitor

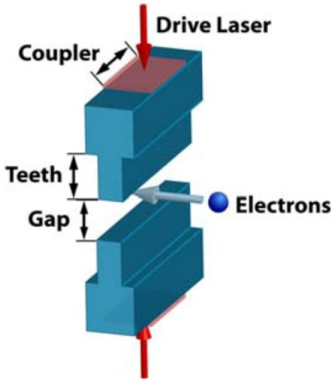


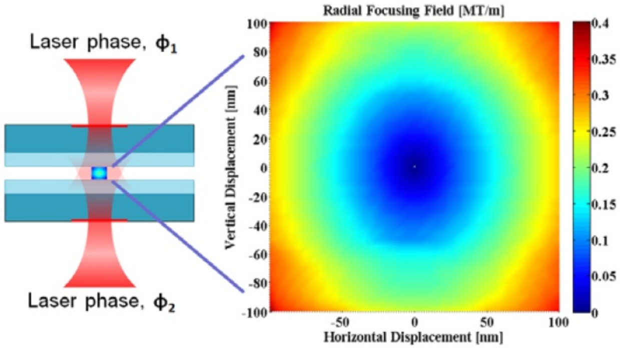
Opt. Lett., **37** (5) 975-977 (2012)



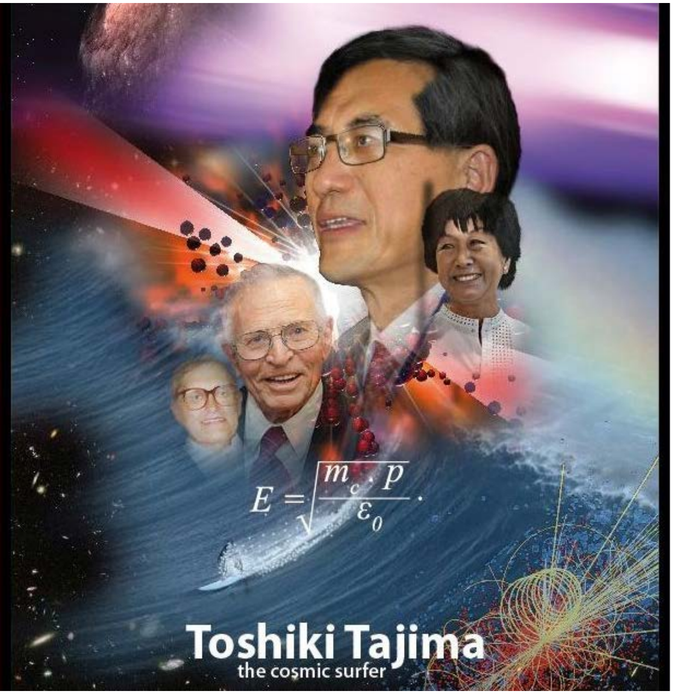
Opt. Lett., **39** (16) 4747 (2014)

Focusing Structures





AIP Conf. Proc. **1507**, 516 (2012)
J. Mod. Opt. **58** (17), 1518-1528 (2011)



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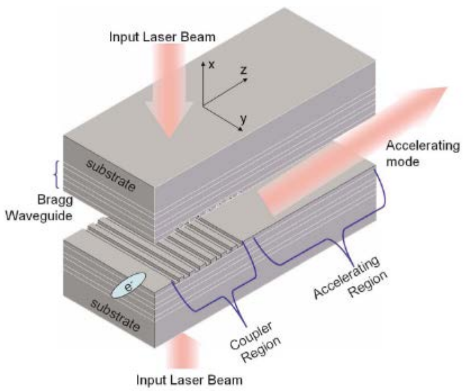
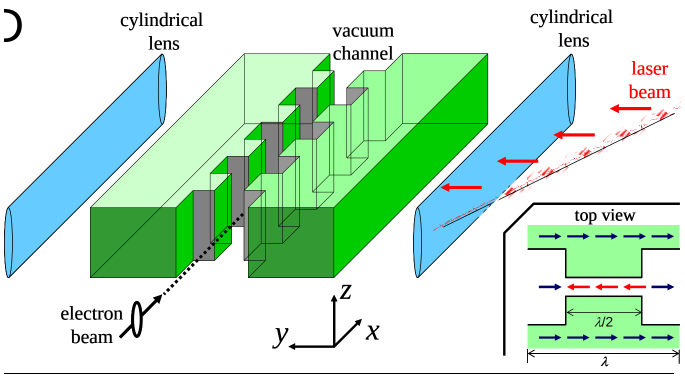
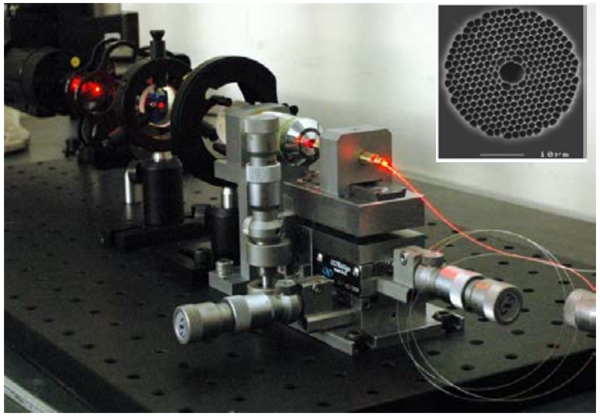
Success!	*Laser Acceleration in Dielectric Structures*
Current Activity	*Laser acceleration on a chip: ACHIP*



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

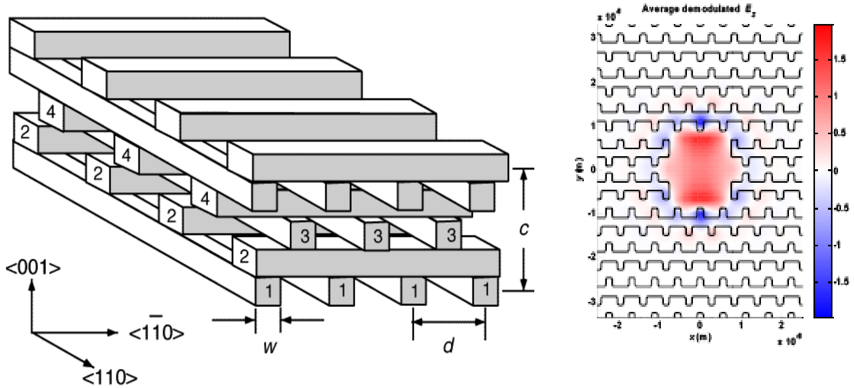


Hollow core PBG fibers



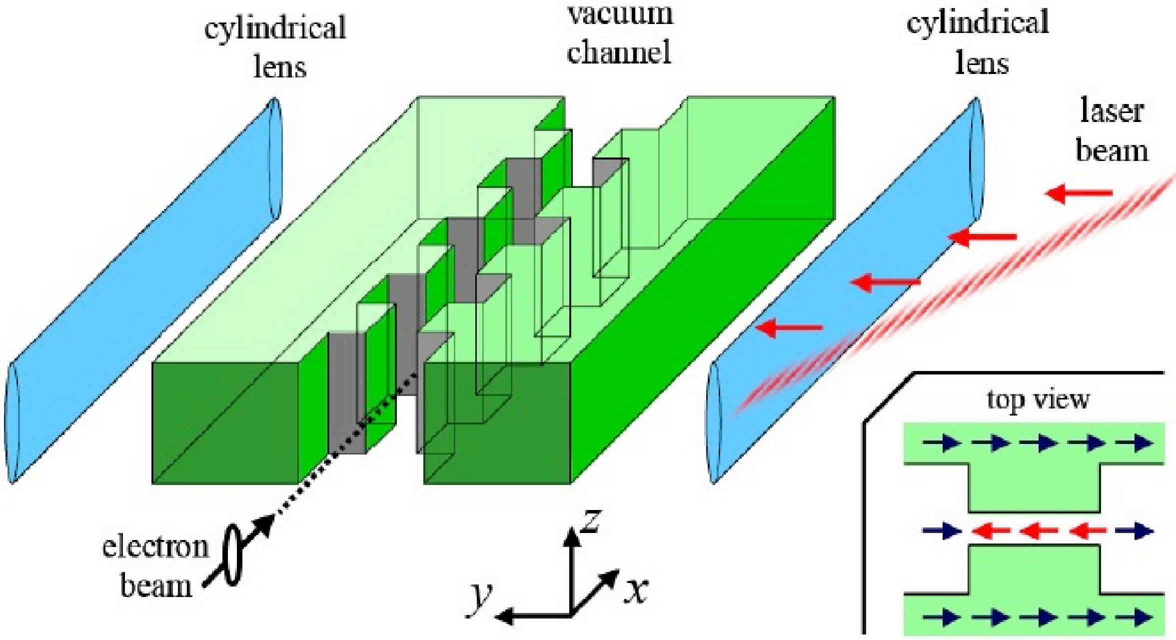
X.E. Lin, Phys. Rev. ST Accel. Beams 4, 051301 (2001)

3-D photonic bandgap structures



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

but I will focus mainly on this approach.



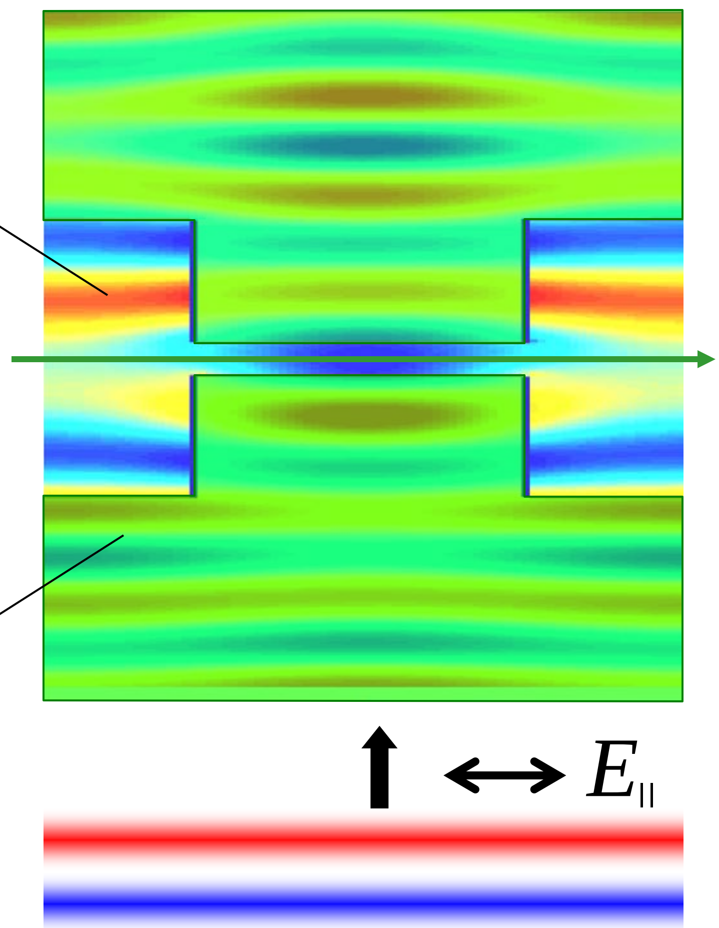
T. Plettner, et al. PRST-AB **9**, 111301 (2006).

... for several reasons:

1. It would take too long to describe all of them.
2. We have working prototypes built at Stanford.
3. They have been experimentally tested.
4. It illustrates some of the basic operating principles.

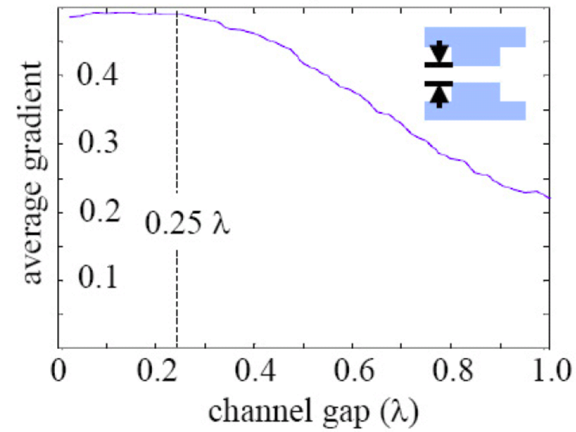
Transverse pumped phase-reset grating structure

EM field map in one unit



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

vacuum channel width < λ



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

1 J/cm² fluence

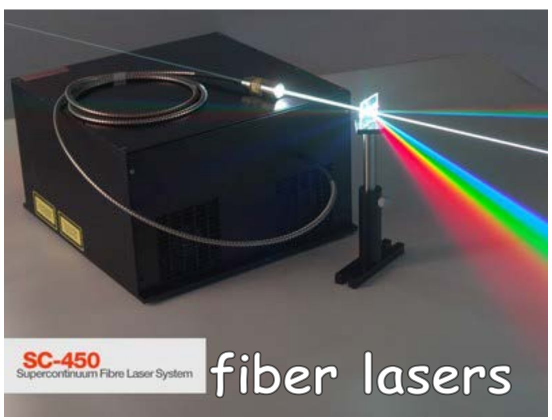
~10 fsec pulses

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

G_{loaded} ~ 2 GeV/m

Laser-Powered

Relatively inexpensive and commercially developed!

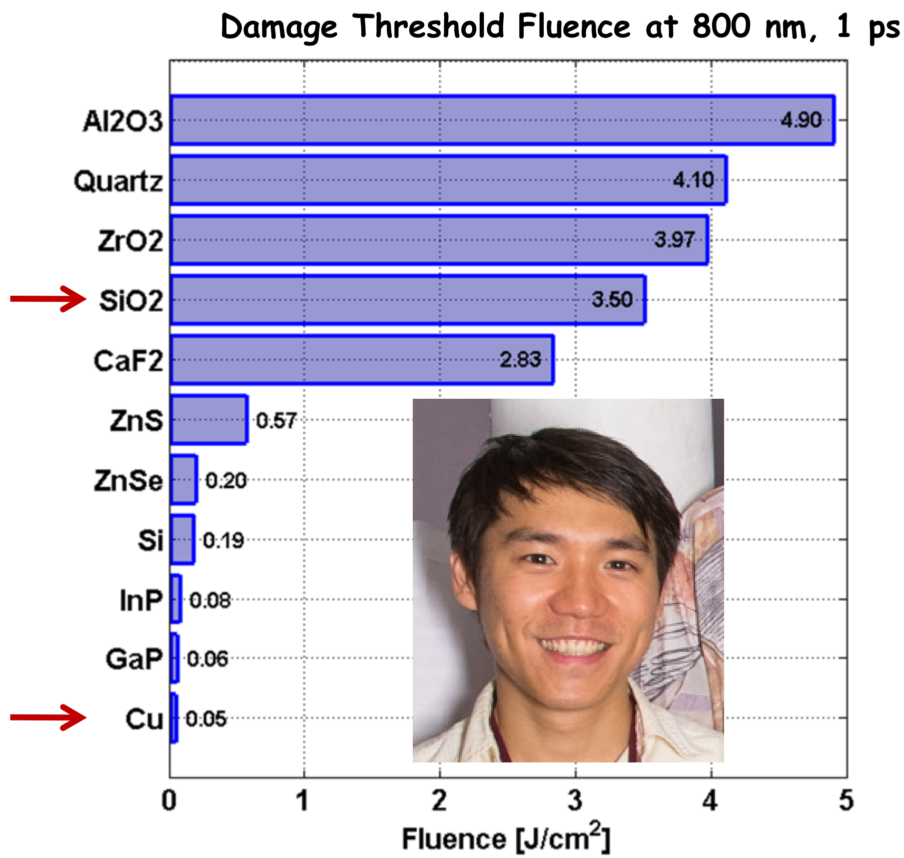


Dielectrics are highly resilient to damage

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

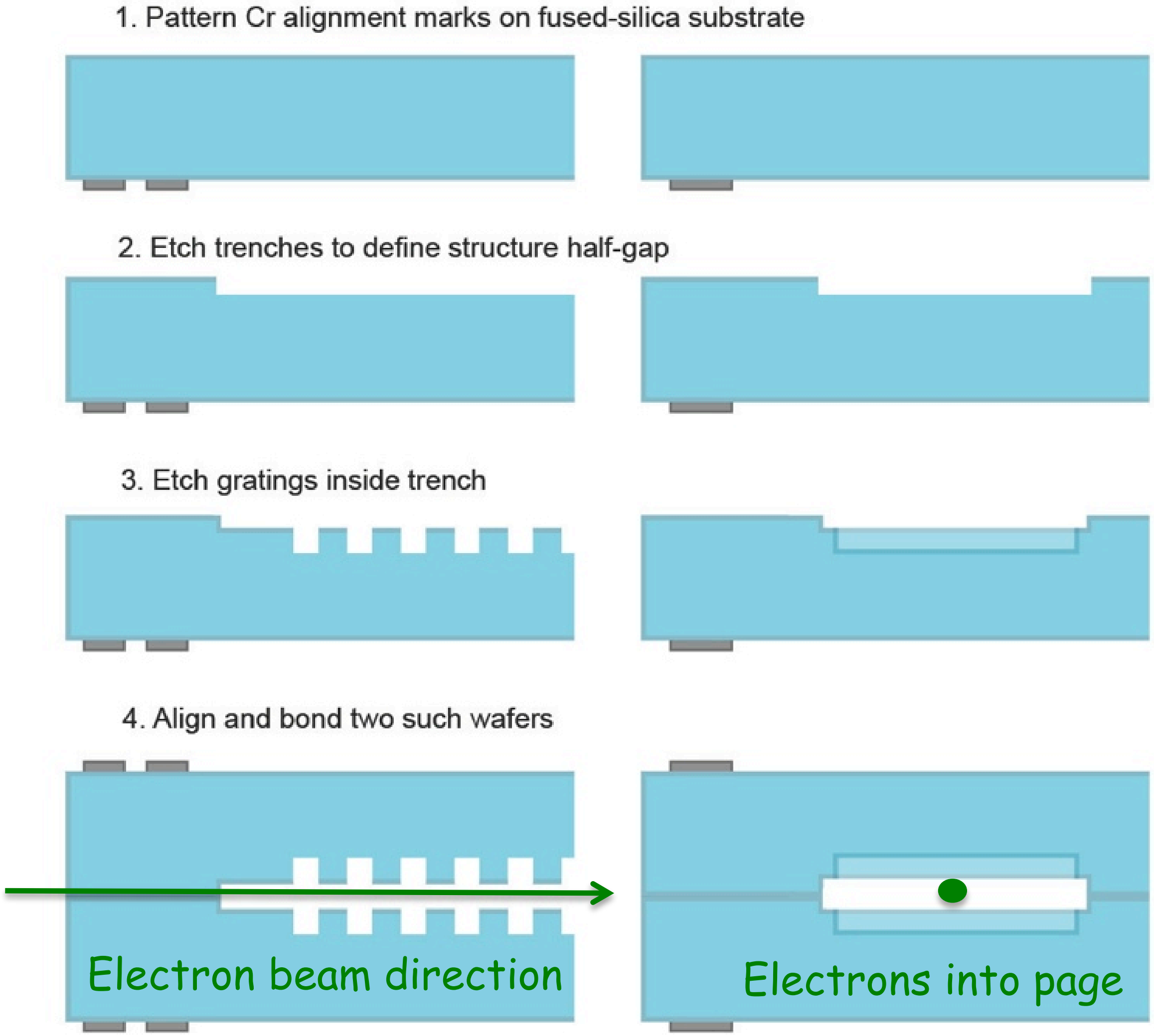
EXPERIMENTAL DETERMINATION OF DAMAGE THRESHOLD CHARACTERISTICS OF IR COMPATIBLE OPTICAL MATERIALS*

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

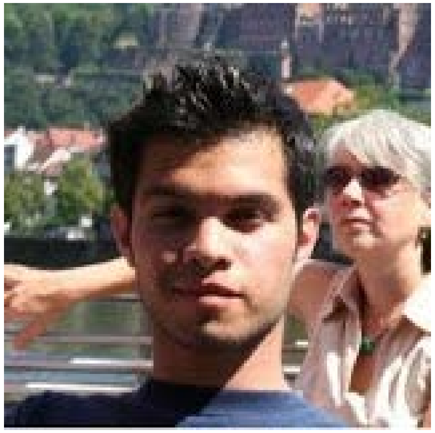


First prototype Fused Silica structures have been made at Stanford Nanofabrication Facility

SIDE **FRONT**



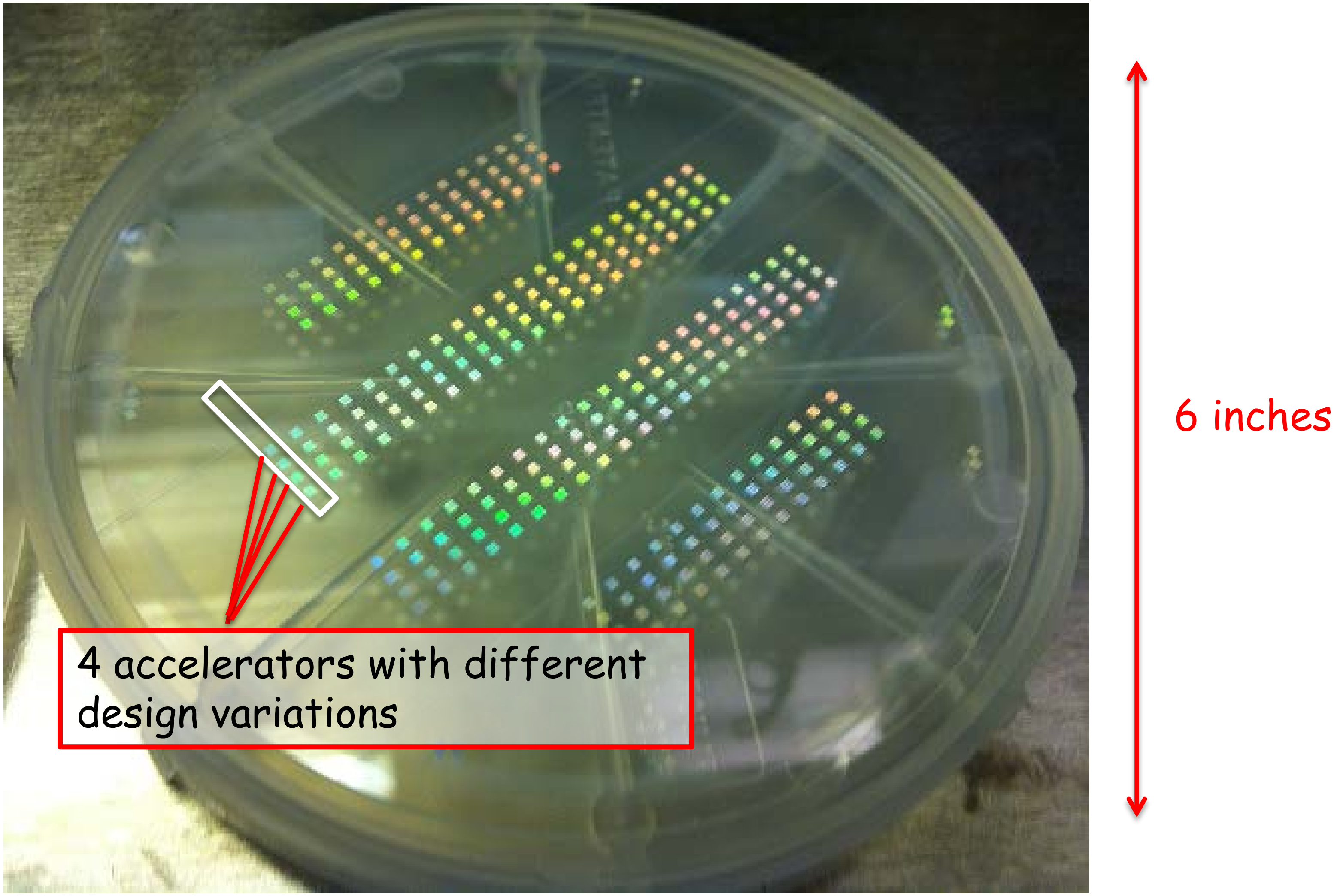
Stanford Nanofabrication Facility



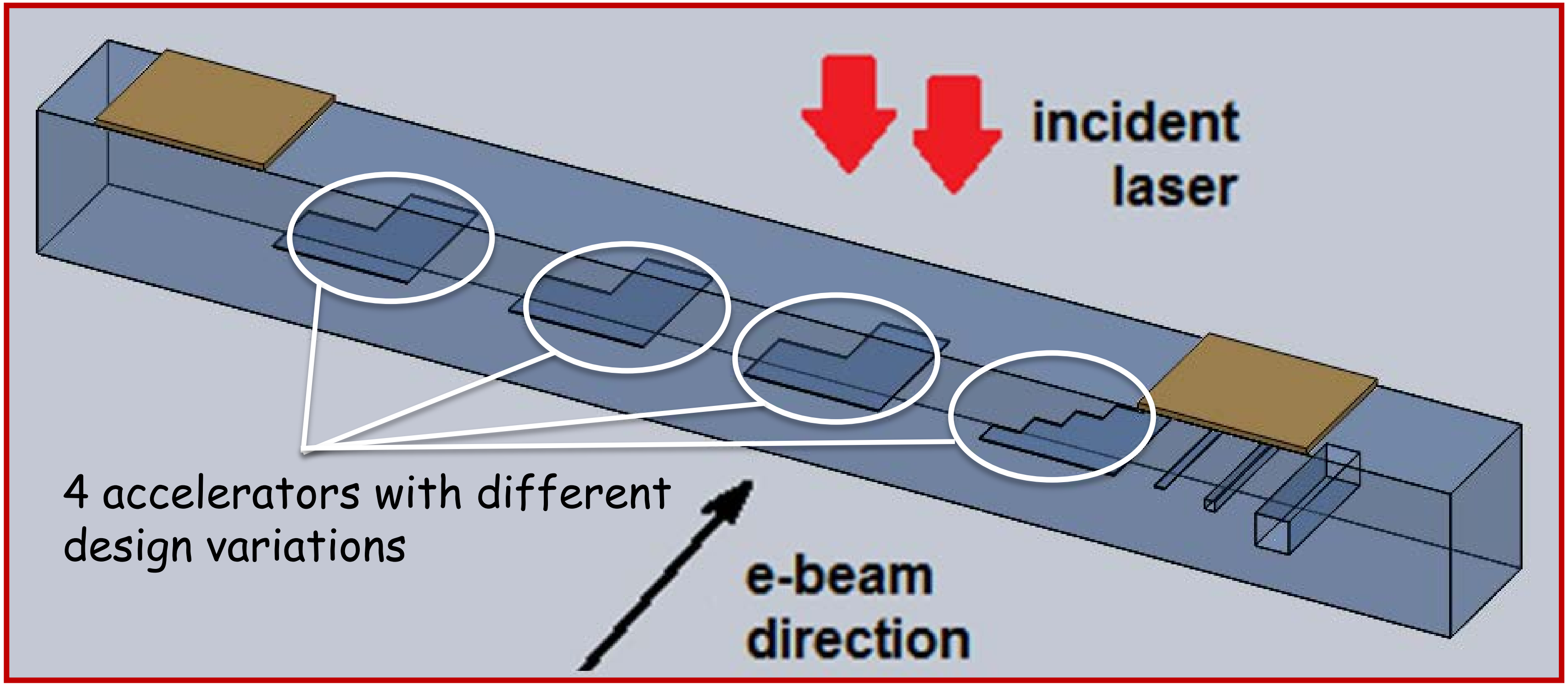
Edgar Peralta


Re: The best 30seconds of my last ~ 5 years!
SLAC - NLCTA Accelerator
4:05 AM
February 23, 2013
Ken Soong
Edgar Peralta

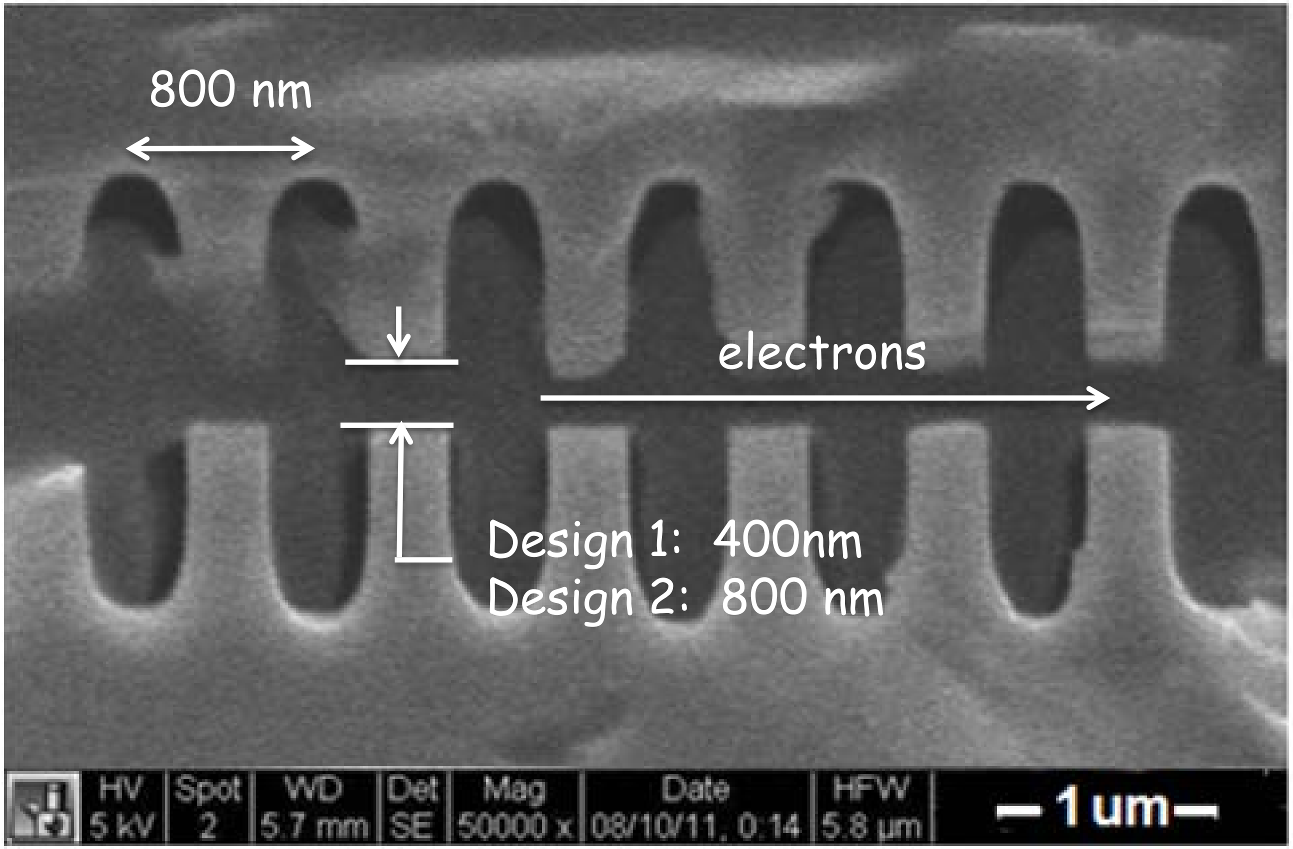
A single bonded wafer pair contains over 200 individual accelerator structures



Rows of these are diced into test samples.

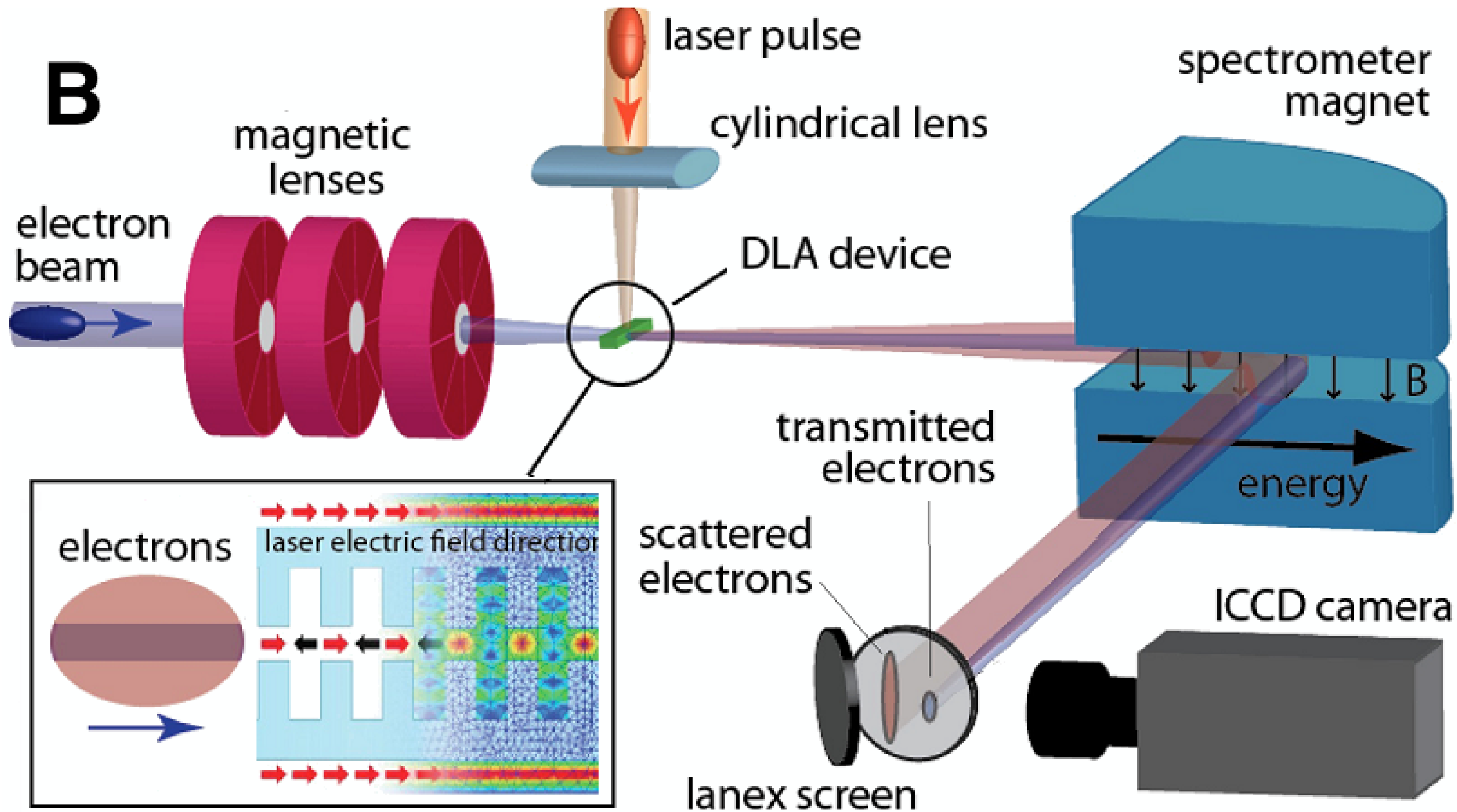


The final result looks like this…



Electron microscope image of the bonded structure.
Rough edges are due to damage from sawing the structure in half in order to image the interior.

Experiment Schematic



Experimental Challenges
Timing and alignment

Getting the 60MeV e-beam through the structure

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

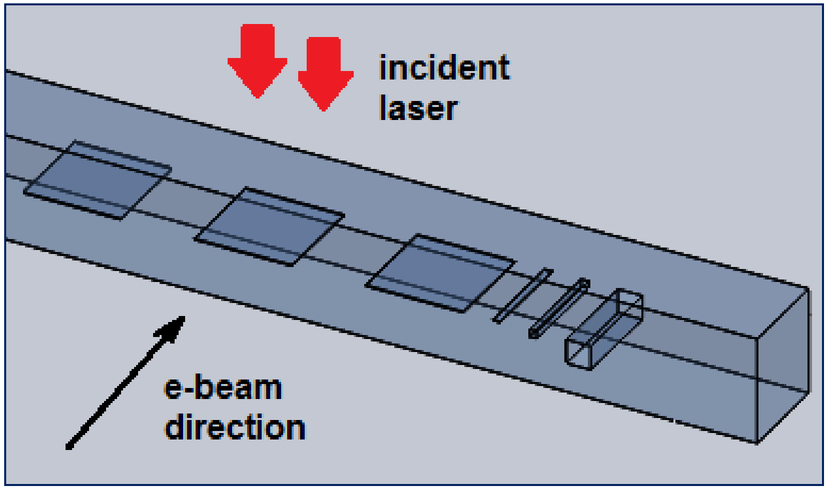
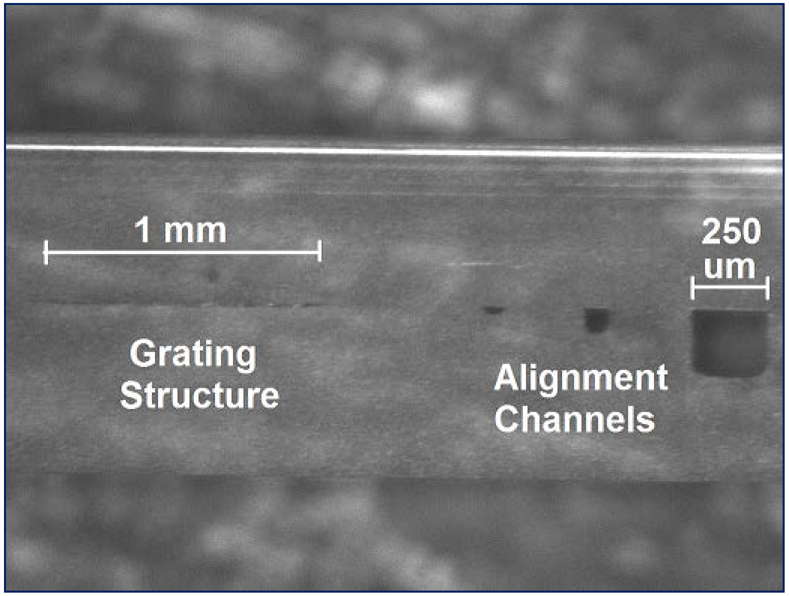


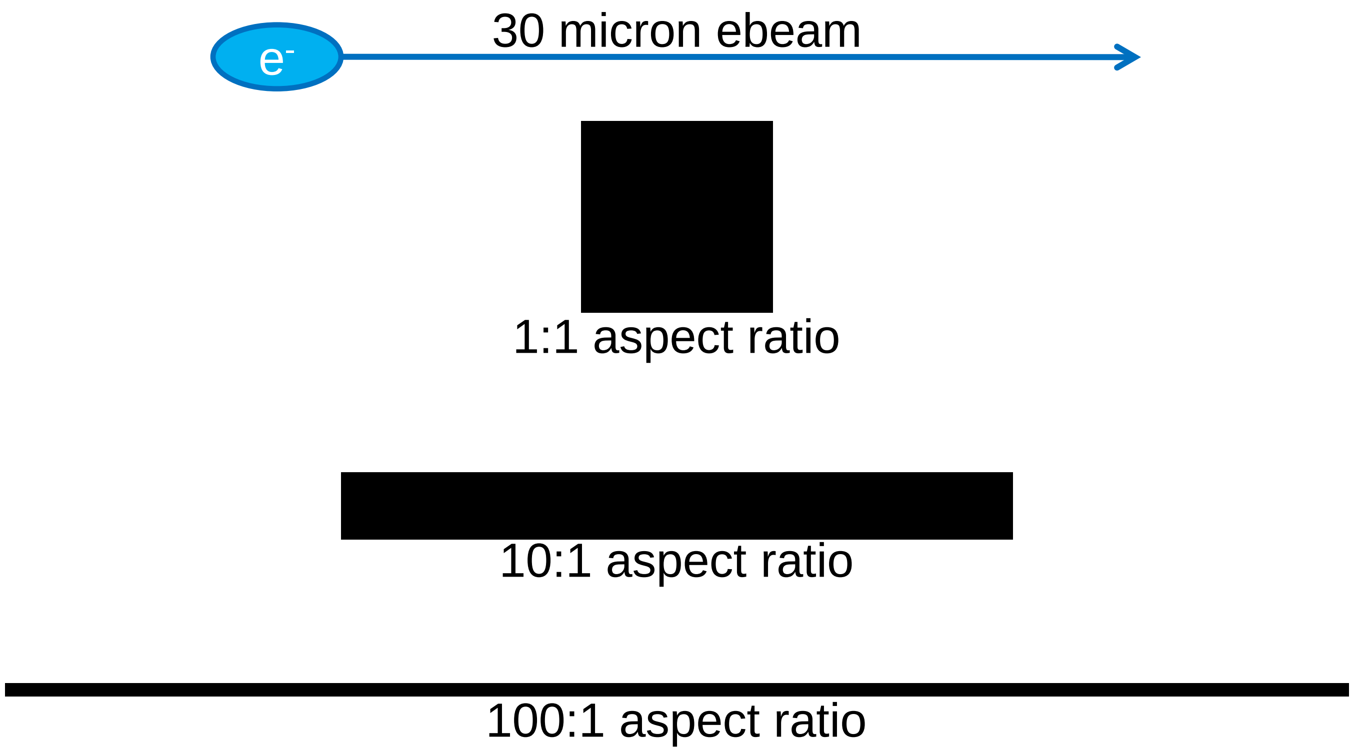
Diagram of test sample



Microscope image of test sample

Experimental Challenge

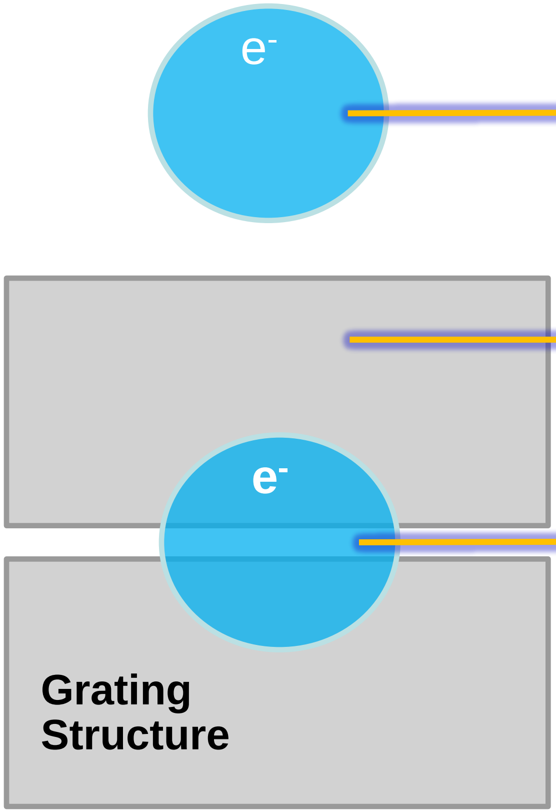
How hard is it to transmit through a 1000:1 aspect ratio channel?
The following gives a sense of scale.

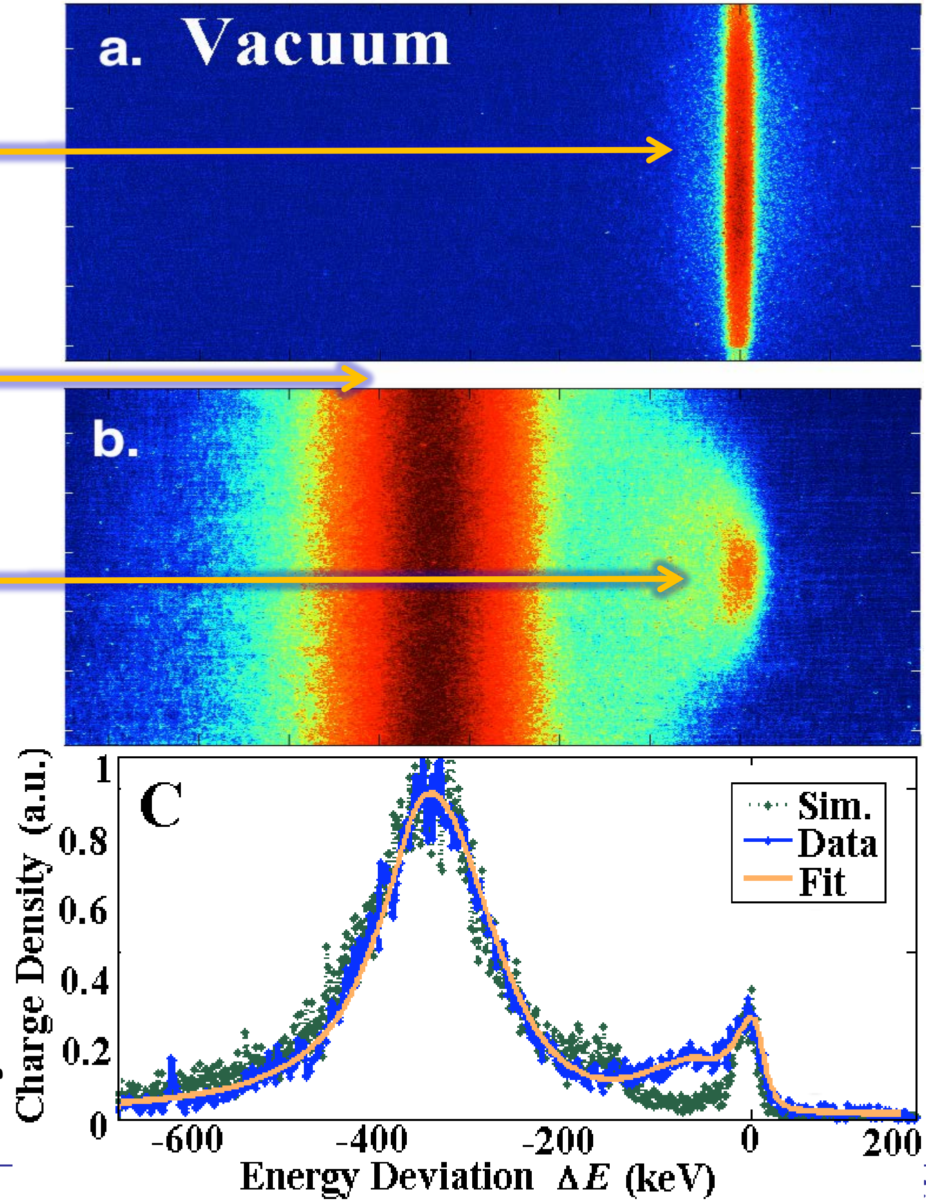


1000:1 aspect ratio – 540 optical periods long
(our structures)

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

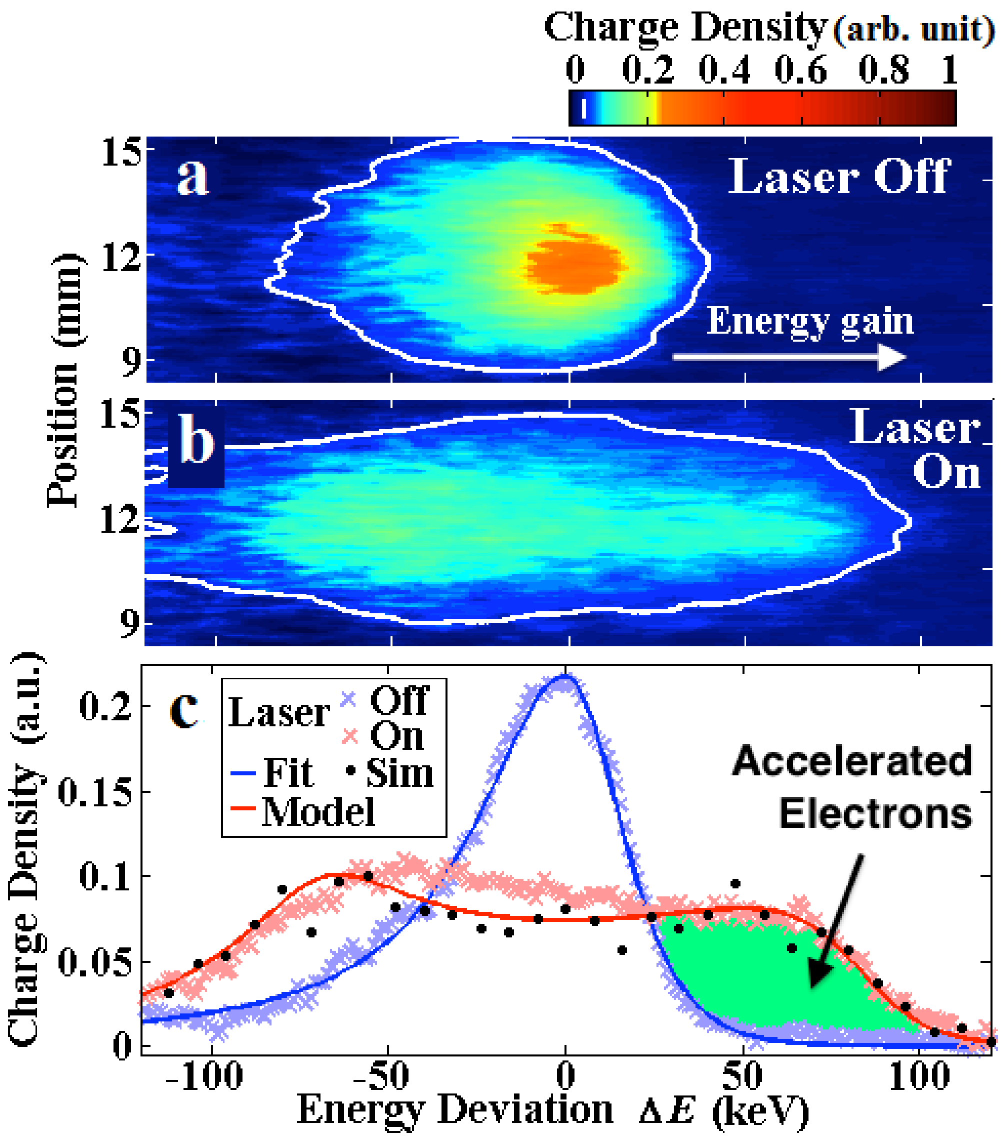
Byer Group





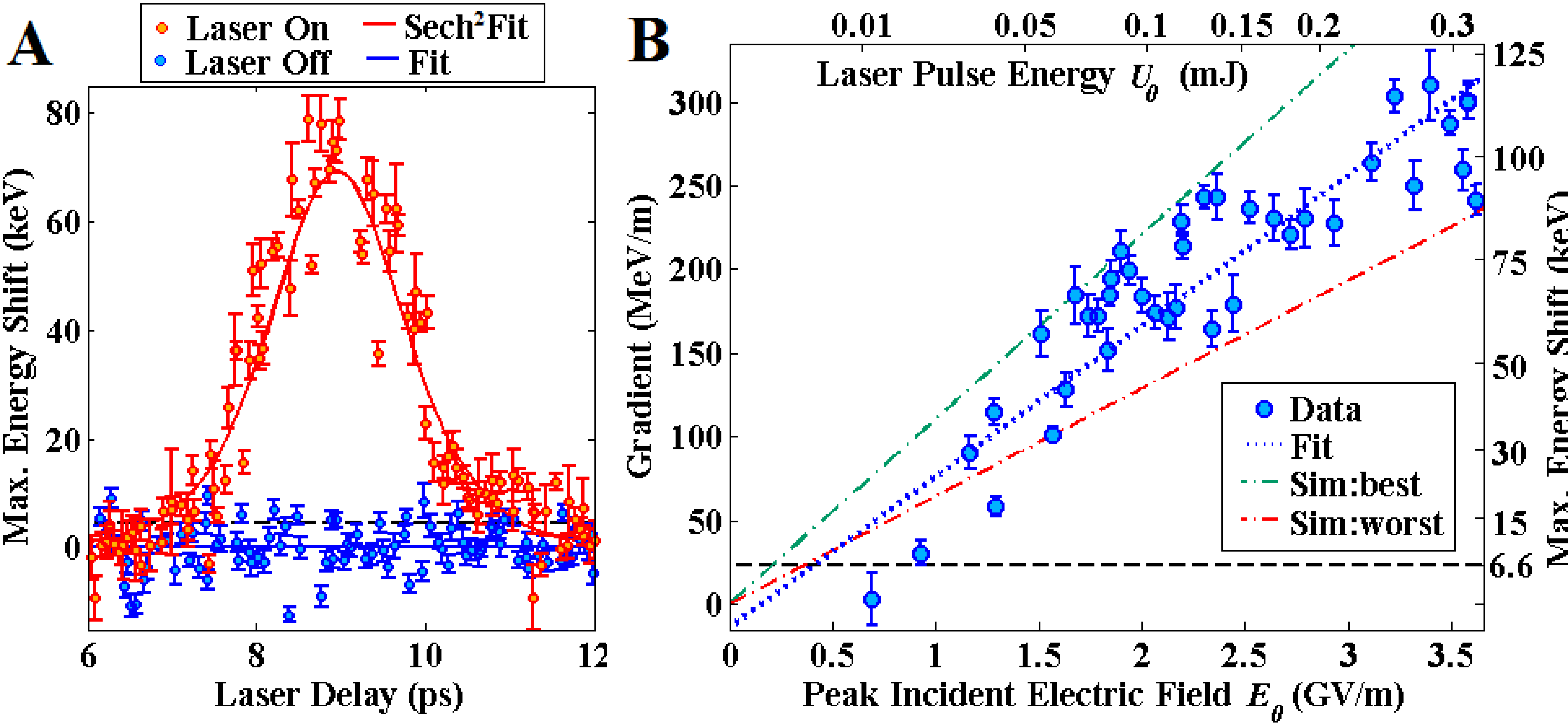
Prompt vs Straggled
Electron Energy beamsplitter

We measure the gradient by observing the resultant energy broadening.



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

Measured: 300MeV/m gradient in fused silica structure



TIMING GRADIENT

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

E. A. Peralta, K. Soong et al - Sept 27, 2013
'Accelerator on a Chip'

nature International weekly journal of science

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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

Nature (2013) | doi:10.1038/nature12664
Received 28 June 2013 | Accepted 16 September 2013 | Published online 27 September 2013

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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

Science jobs | Science events

natureevents directory

NGS Data Analysis
15 October 2013 — 17 October 2013
501 Geary Street, San Francisco, United States

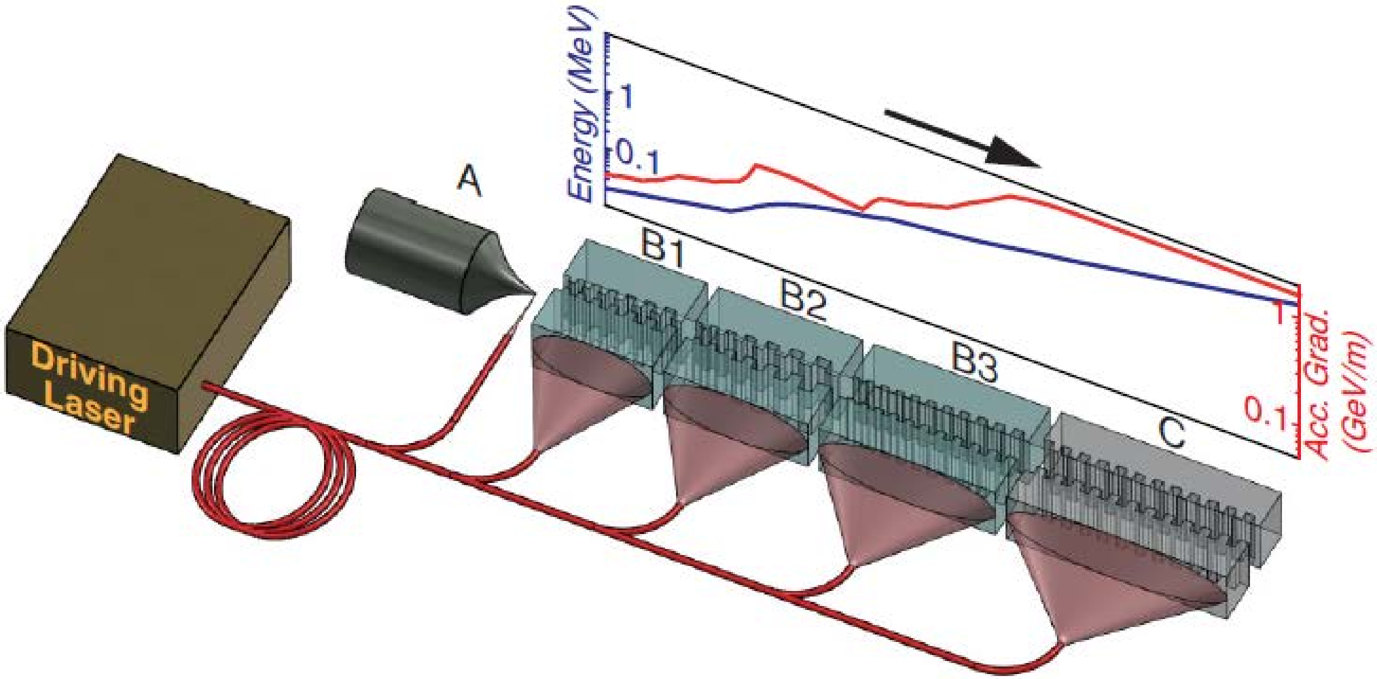
Low-Beta Accelerator

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)



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Accelerator on a chip

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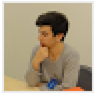

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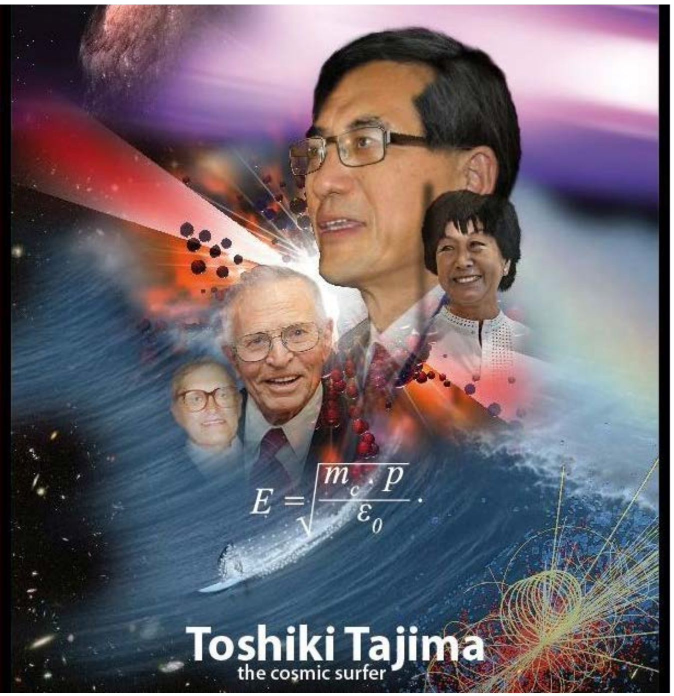
NATURE WORLD NEWS

Party on Friday March 1, 2013 – Celebrating success!

So we've demonstrated acceleration on a chip. What's next?



Introduction — *Early Progress in Laser Accelerators*

Success! — *Laser Acceleration in Dielectric Structures*

Moore Foundation — Recent Progress in the *Accelerator on a Chip Program*

Moore Foundation Awards $13.5m for accelerator science

DRAFT press release for accelerator grant announcement
October 22, 2015

$13.5M Awarded to Stanford University from the Gordon and Betty Moore Foundation to Advance the Technology of Particle Accelerators

International effort aims to demonstrate working prototype of "accelerator-on-a-chip"

PALO ALTO, Calif. November XX, 2015 — The Gordon and Betty Moore Foundation awarded $13.5 million to Stanford University and its international partners to take an innovative particle accelerator design dubbed the "accelerator-on-a-chip" and make it into a fully functional and scalable working prototype. This laser-driven particle accelerator could have a major impact on the physics community and on science in general by providing new particle and photon sources that are less expensive to build, addresses current infrastructure challenges and provides broader access to the scientific community.

The international effort to demonstrate a working prototype of an accelerator is based on experiments published in 2013 by the project's two principal investigators, Dr. Robert Byer of Stanford University in *Nature* and Dr. Peter Hommelhoff of Friedrich-Alexander University Erlangen-Nuremberg in *Physical Review Letters*.

Dr. Byer's team showed that after firing high-energy relativistic electrons into a tiny device made from silica glass, a pulse of laser light fired at gratings in the device could cause the electrons to accelerate at a rate 10 times higher than that achieved in today's conventional accelerators. Dr. Hommelhoff's team, in a parallel approach, demonstrated that a laser could also be used to accelerate lower-energy, non-relativistic electrons. Both results taken together open the door to a compact particle accelerator. See how accelerator-on-a-chip works in this brief video.

Peter and Bob – Co-Directors
Moore Foundation ACHIP program

Byer
Group

A new 5-Year initiative in DLA has been approved by the Gordon and Betty Moore Foundation.

SLAC

ACHIP: Accelerator on a Chip International Program

ACHIP

$13.5M / 5 years

GORDON AND BETTY MOORE FOUNDATION

Sub-Relativistic DLA experiments
Stanford: Harris, Solgaard
Erlangen: Hommelhoff

Structure Design & Fabrication
Stanford: Byer, Harris, Solgaard
Erlangen: Hommelhoff

Systems Integration (Core DLA Groups)
Stanford: Byer, Harris, Solgaard
Erlangen: Hommelhoff

Electron source
UCLA: Musumeci
Erlangen: Hommelhoff
Stanford: Harris, Solgaard

Simulations
Tech-X: Cowan
U Darmstadt: Boine-Frankenheim

Light Coupling
Stanford: Fan, Vuckovic
Purdue: Qi

Scientific Advisors
UCLA Chan Joshi
SLAC: Lia Merminga
DESY: R. Brinkman

Relativistic DLA experiments
SLAC: England, Tantawi
DESY/UnivHH: Assmann, Kaertner, Hartl
PSI/EPFL: Ischebeck, Frei

Milestones for the ACHIP Moore Foundation Program

✔ Optical microbunching. (SLAC, Sears 2008)

✔ Demonstrate position monitoring. (SLAC, Soong 2014)

✔ Single-staged DLA with ~0.8 GV/m gradient. (SLAC/UCLA 2016)

→ Net acceleration, multi-stage operation, and MeV-level energy gains.

→ Demonstrate elements for focusing, deflection, and undulator radiation.

→ Develop a suitable laser-triggered field emission source.*

→ Develop DLA structures for sub-relativistic bunching & acceleration to ~ 1 MeV.*

→ Develop high-efficiency optical guide networks to enable up to 8 stages.

→ Integrate electron source/injector, couplers, and DLA accelerator.

* Asterisked items conducted primarily through university collaboration.

What are the biggest challenges going forward?

particle source
(Demonstrated at MPQ)

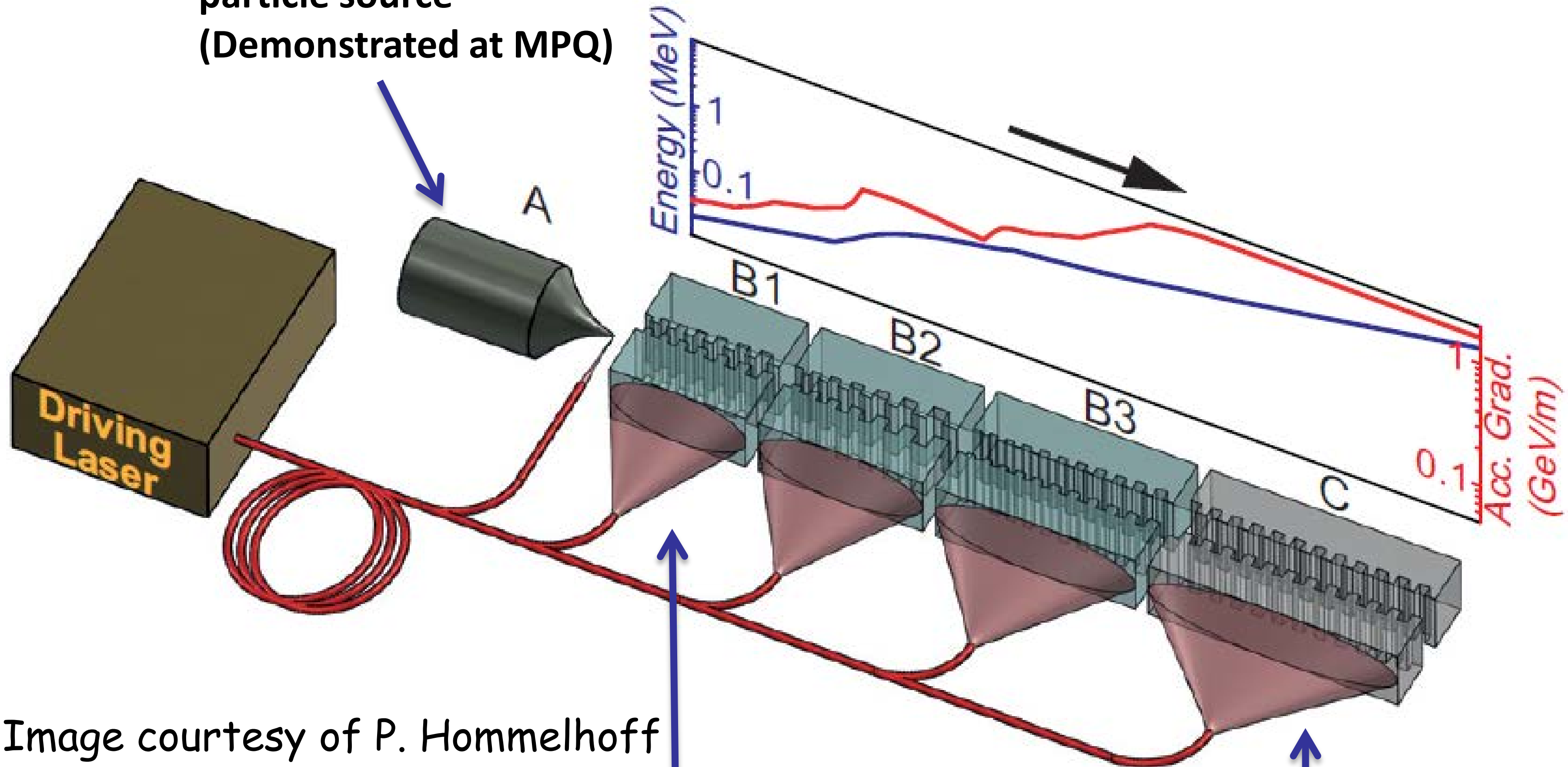
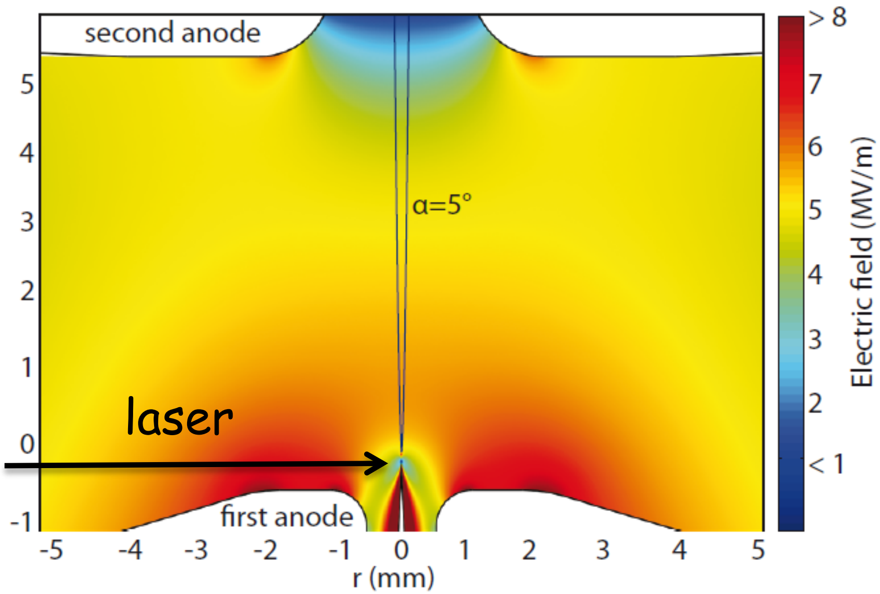


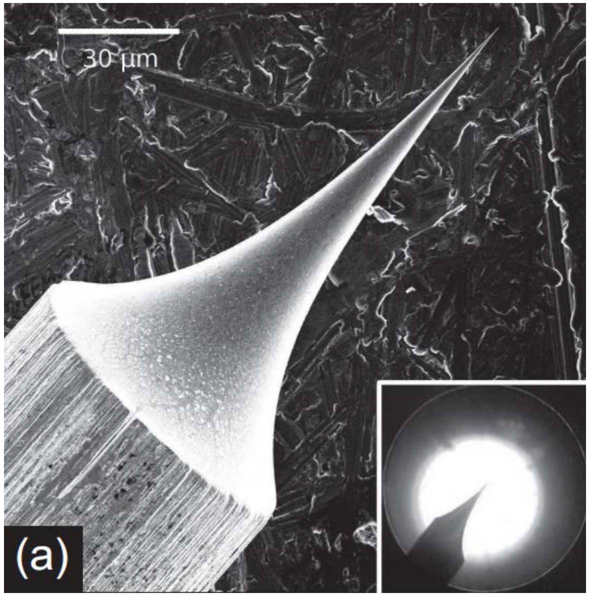
Image courtesy of P. Hommelhoff

injector
(Demonstrated at MPQ)

speed of light accelerator
(Demonstrated at SLAC)

Dr. Peter Hommelhoff, Johannes Hoffrogge, (Erlangen)

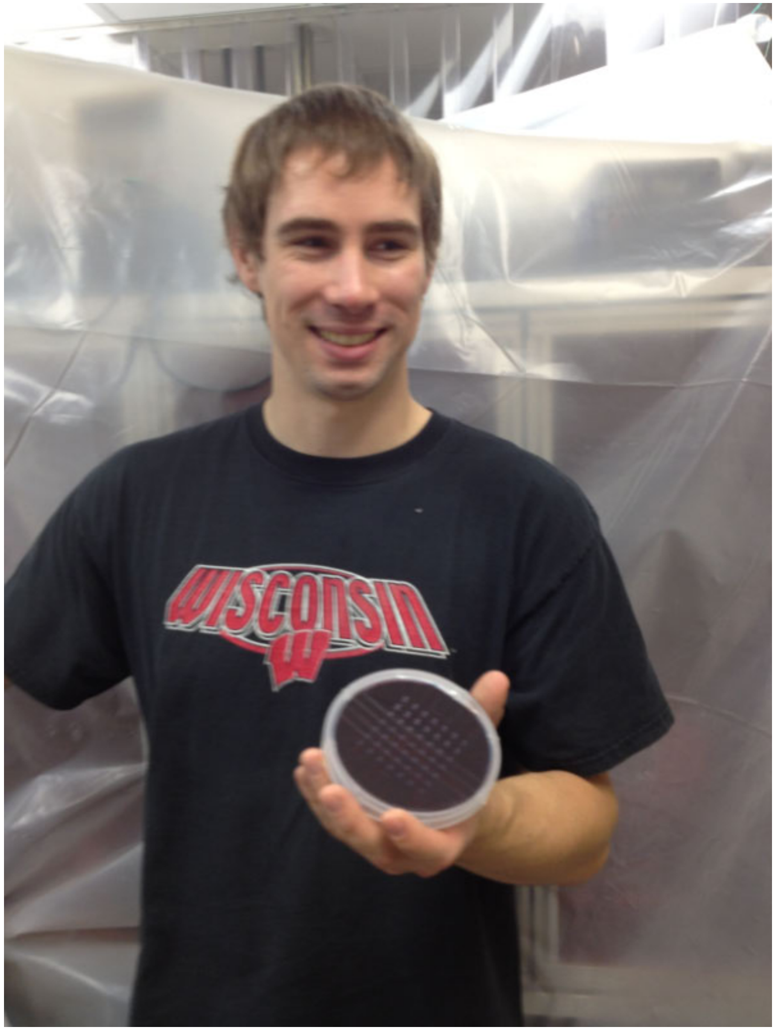




30 keV electron pulses triggered by a 10 femtosecond 800nm Ti:Sapphire laser with up to 2000 electrons per pulse.

J. Hoffrogge et. al, "A tip-based source of femtosecond electron pulses at 30keV". arXiv:1303.2383 (2013).

Ken Leedle holding first Silicon Accelerator wafer



370MeV/m acceleration in Silicon Dual Pillar Structure

4344 Vol. 40, No. 18 / September 15 2015 / *Optics Letters* Letter

Optics Letters

Dielectric laser acceleration of sub-100 keV electrons with silicon dual-pillar grating structures

KENNETH J. LEEDLE,[1,*] ANDREW CEBALLOS,[1] HUIYANG DENG,[1] OLAV SOLGAARD,[1] R. FABIAN PEASE,[1] ROBERT L. BYER,[2] AND JAMES S. HARRIS[1,2]

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[2]*Department of Applied Physics, Stanford University, Stanford, California 94305, USA*
*Corresponding author: kleedle@stanford.edu

Received 15 July 2015; revised 11 August 2015; accepted 12 August 2015; posted 17 August 2015 (Doc. ID 246065); published 14 September 2015

We present the demonstration of high-gradient laser acceleration and deflection of electrons with silicon dual-pillar grating structures using both evanescent inverse Smith–Purcell modes and coupled modes. Our devices accelerate subrelativistic 86.5 and 96.3 keV electrons by 2.05 keV over 5.6 μm distance for accelerating gradients of 370 MeV/m with a 3 nJ mode-locked Ti:sapphire laser. We also show that dual pillars can produce uniform accelerating gradients with a coupled-mode field profile. These results represent a significant step toward making practical dielectric laser accelerators for ultrafast, medical, and high-energy applications.

OCIS codes: (320.0320) Ultrafast optics; (230.3990) Micro-optical devices; (050.2770) Gratings.

http://dx.doi.org/10.1364/OL.40.004344

accelerating mode at subrelativistic energies. Previous demonstrations at subrelativistic energies were based on single gratings similar to [4] that produce a skewed acceleration profile.

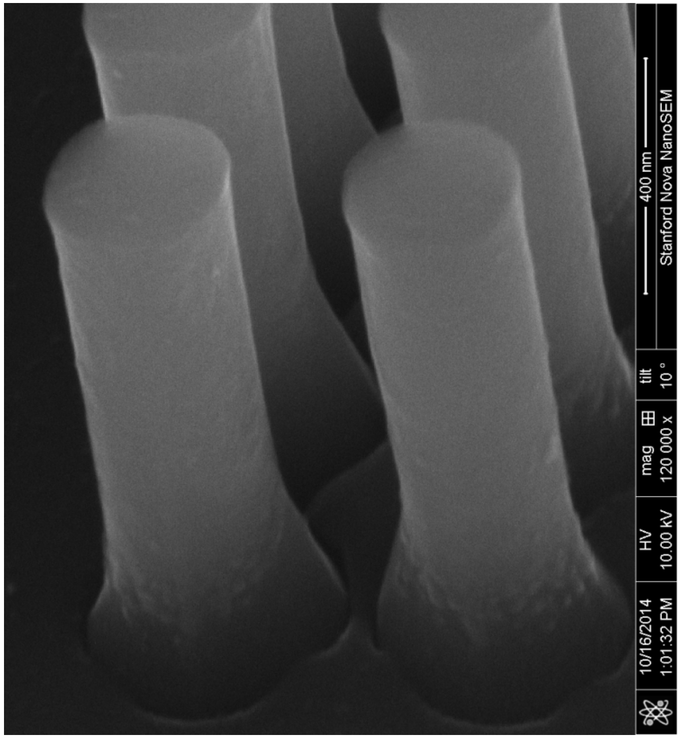
A scalable, dielectric laser-accelerator architecture should be capable of monolithically integrating the accelerator structures and the optical power-distribution system fed by fiber or other laser systems [5]. A variety of different silicon-accelerator structures have been proposed, including woodpile structures, photonic crystal slabs, and buried-grating structures [6–8]. These structures have the potential to demonstrate GeV/m accelerating gradients with relativistic electrons and sub-100-fs drive laser pulses.

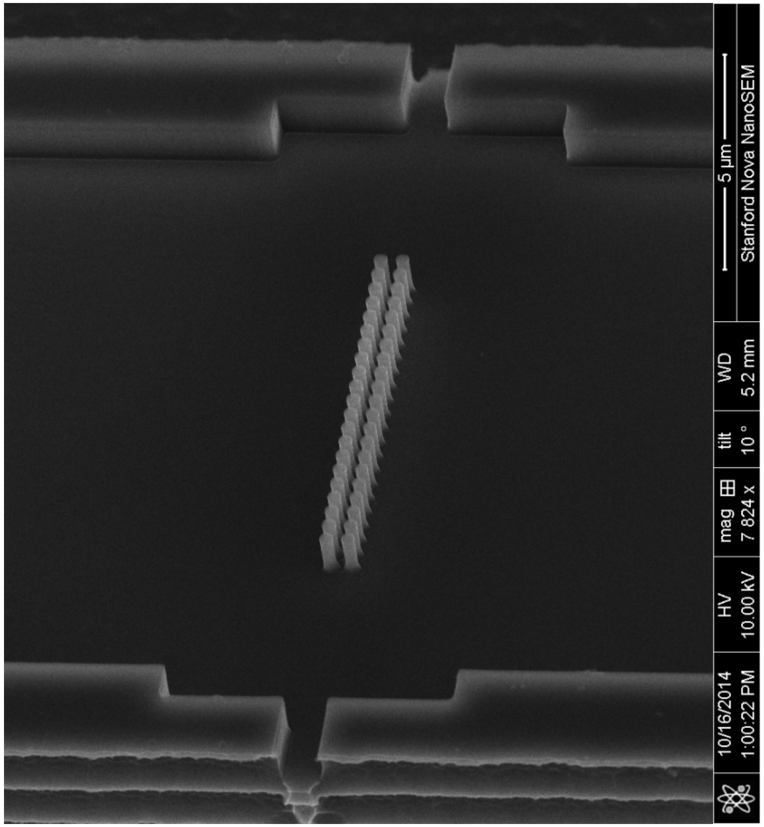
We opt instead for a minimalist geometry based on two rows of pillars, first proposed for the RF regime [9]. Using the dual-pillar geometry forgoes the need for any macroscopic assembly or complex fabrication procedures by etching the gratings directly out of a monolithic single-crystal silicon slab.

Silicon Dual Pillar Accelerators

Elegant and simple but very effective structure

- Simple geometry; ok thermal characteristics
- Good field ratios: $G_0 > 0.4\ E_0$ possible
- Driven at glancing angle: 4.5º the half angle of drive beam





Silicon Dual Pillar structure pumped by Ti:sapphire laser

Byer Group

Letter Vol. 40, No. 18 / September 15 2015 / *Optics Letters* 4345

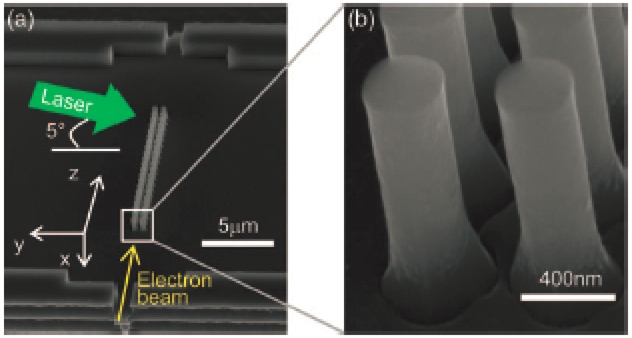


Fig. 1. Scanning electron micrographs of the dual-pillar accelerator structures. (a) Mesa layout with a 10.5 μm long grating on the 25 μm wide mesa. A wall on either side of the mesa helps block stray electrons from upstream in the electron-beam column. The electron-beam trajectory and laser trajectory are superimposed. (b) Detailed inset of the evanescent-mode pillar structure.

Figure 1 shows the silicon dual-pillar grating structures used in this experiment. The pillars are fabricated from 5 to 10 ohm–cm phosphorus-doped silicon. The pillars are slightly elliptical in shape, written via electron-beam lithography using a JEOL EBX-6300, and etched to 1.2 μm tall using reactive ion etching. The inverse Smith–Purcell evanescent-mode grating had pillar width of 320 nm in the z dimension, 310 nm thickness in the y dimension, and electron-channel gap of 205 nm. Our coupled-mode grating was asymmetrical across the electron-beam channel. It had pillar width of 390 nm (z dimension), the illumination side had y-dimension thickness of 340 nm, the far grating pillars had y-dimension thickness of

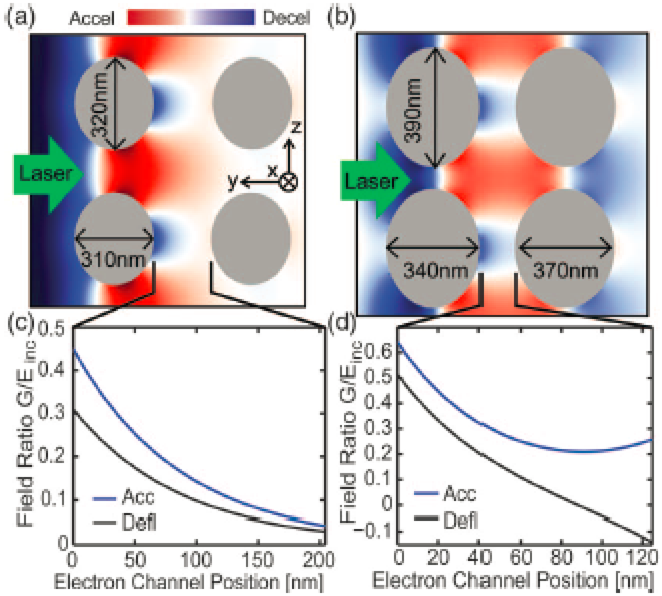


Fig. 2. (a) Inverse Smith–Purcell dual-pillar E_z electric-field profile. (b) Off-center cosh-mode E_z electric-field profile that exhibits even acceleration gradient and minimal deflection near the far side of the channel. (c) Model's maximum acceleration and deflection-gradient field ratio G/E_{inc} of the inverse Smith–Purcell mode versus position in the channel. (d) Model's maximum acceleration and deflection field ratio versus position in the channel for the cosh mode.

$$F_{\text{acc}} = \frac{qc}{\beta\gamma}\begin{bmatrix} 0 \\ \frac{1}{\gamma}(C_S \cosh(k_y y) + C_C \sinh(k_y y))\cos(\varphi) \\ (C_S \sinh(k_y y) + C_C \cosh(k_y y))\sin(\varphi) \end{bmatrix}. \quad (3)$$

690Mev/m Fused Silica Structure – goal >1000MeV/m

Dielectric laser acceleration of electrons with 0.69 GV m^{-1} accelerating gradient

K. P. Wootton,[1,*] Z. Wu,[1,†] B. M. Cowan,[2] I. Makasyuk,[1] E. A. Peralta,[3] K. Soong,[3] R. J. England,[1] and R. L. Byer[3]
[1] *SLAC National Accelerator Laboratory, 2575 Sand Hill Road, Menlo Park, California 94025, USA*
[2] *Tech-X Corporation, 5621 Arapahoe Ave, Boulder, Colorado 80303, USA*
[3] *Stanford University, Stanford, California 94305, USA*

(Dated: August 12, 2015)

Dielectric laser acceleration of electrons is a promising technology for the miniaturization of particle accelerators. In this work, experimental results are presented of 0.69 GV m^{-1} accelerating gradient of relativistic electrons. This is a record-high accelerating gradient for dielectric laser accelerator technology, more than doubling the previous record gradient [E. A. Peralta *et al.*, *Nature (London)* **503**, 91 (2013)]. The present experiment employs of 70 fs duration laser pulses in order to reach higher acceleration gradients.

PACS numbers: 29.27.-a, 41.75.Jv, 87.85.Rs, 42.62.-b

Introduction
Dielectric laser accelerator concept [1]. Dielectric laser accelerator theory [2, 3]. Recent experimental results [4–6].

Dielectric accelerator structure – design and fabrication

Accelerator arrangement
The experiment was performed using the NLCTA linear accelerator at SLAC. The experimental arrangement is illustrated in Fig. 1.

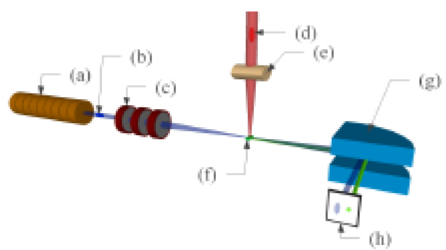


FIG. 1. Schematic of experimental setup at NLCTA. (a) Linear accelerator. (b) Electron beam. (c) Magnetic lens. (d) Laser pulse. (e) Cylindrical lens. (f) Dielectric laser accelerator. (g) Spectrometer. (h) Detector, indicating the straggled and transmitted (accelerated) electron beam populations.

Laser arrangement
The temporal profile of the laser pulse was measured using a GRENOUILLE apparatus employing the Frequency-Resolved Optical Gating (FROG) technique [7, 8].

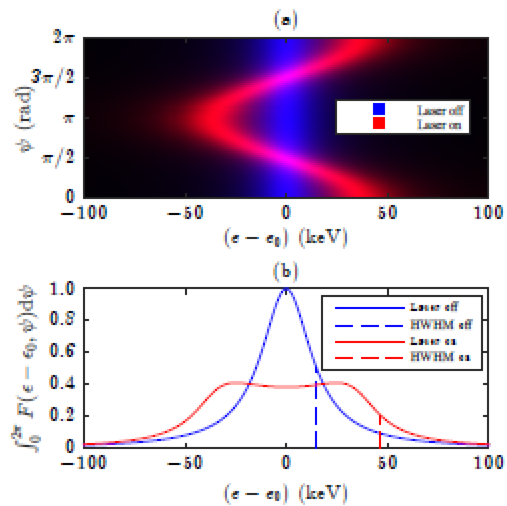
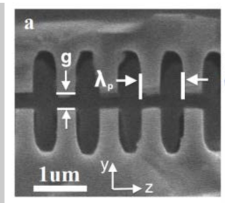
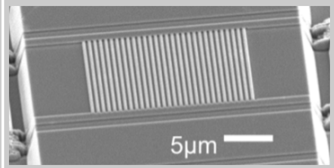
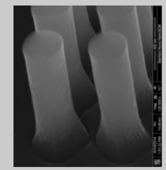
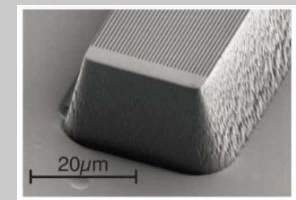


FIG. 2. Numerical model of electron beam energy response to laser-driven microstructure. (a) For an electron beam longer than a laser optical cycle, the transmitted population energy distribution is constant in time with the laser off, and modulated sinusoidally in time with the laser on. (b) Integration of (a) over ψ, illustrating the change in the transmitted population energy distribution with the laser on and off. The half-width at half-maximum (HWHM) of the transmitted population is evaluated as a figure of merit.

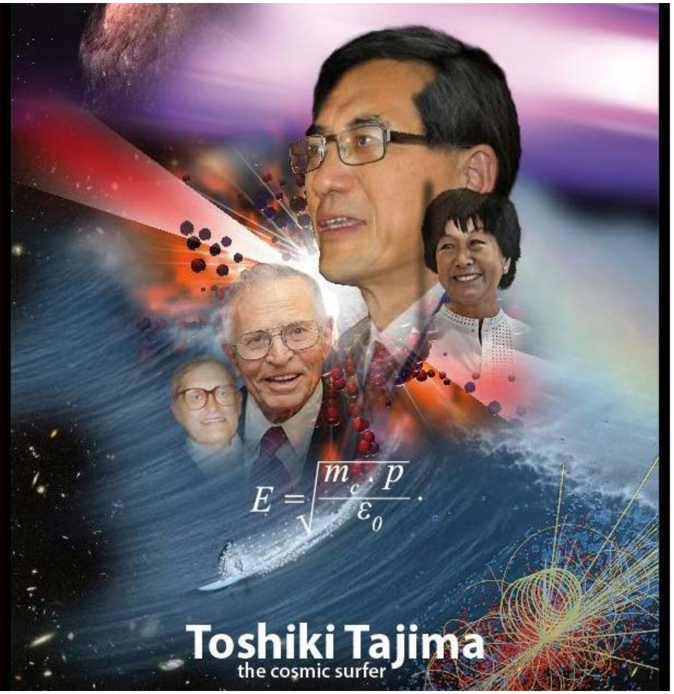
DLA Experiment Comparison

	SLAC (SiO_2)	Single Grating	Dual Pillars	Hommelhoff(SiO_2)
				
E_0	60 MeV	96.3 keV	86.5keV	30 keV
β	0.9996	0.54	0.52	0.33
E_{pulse}	330 μJ	5.2 nJ	3.0 nJ	160 nJ
t_p	1.1 ps	130 fs	130 fs	110 fs
L_{int}	~360 um	5.6 um	5.6 um	11 um
Pk Field	3.5 GV/m	1.65 GV/m	~1.8 GV/m*	2.85 GV/m
Max ΔE	100 keV	1.22 keV	2.1 keV	0.275 keV
G_{max}	690 MeV/m	220 MeV/m	375 MeV/m*	25 MeV/m
G_{max}/E_p	~0.1	~0.13	~0.2*	~0.01

*Preliminary and subject to change

Moore Foundation Collaboration meeting at UCLA Feb 29, 201

Byer Group



Introduction *Early Progress in Laser Accelerators*

Success! *Laser Acceleration in Dielectric Structures*

Moore Foundation: *Laser acceleration on a chip: ACHIP*

Accelerator on a Chip Program

Dr. Kenneth J. Leedle on behalf of
Prof. Robert L. Byer and the ACHIP Collaboration

GORDON AND BETTY MOORE FOUNDATION

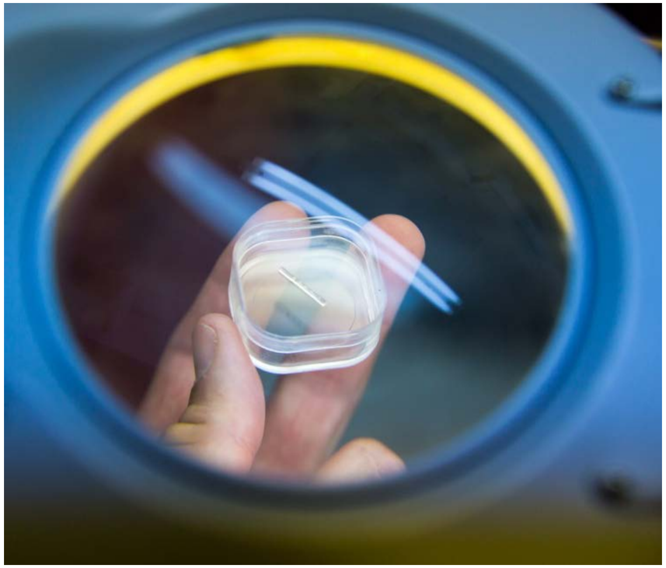
ACHIP

FAU UCLA TECHNISCHE UNIVERSITÄT DARMSTADT

SLAC NATIONAL ACCELERATOR LABORATORY

PAUL SCHERRER INSTITUT PSI

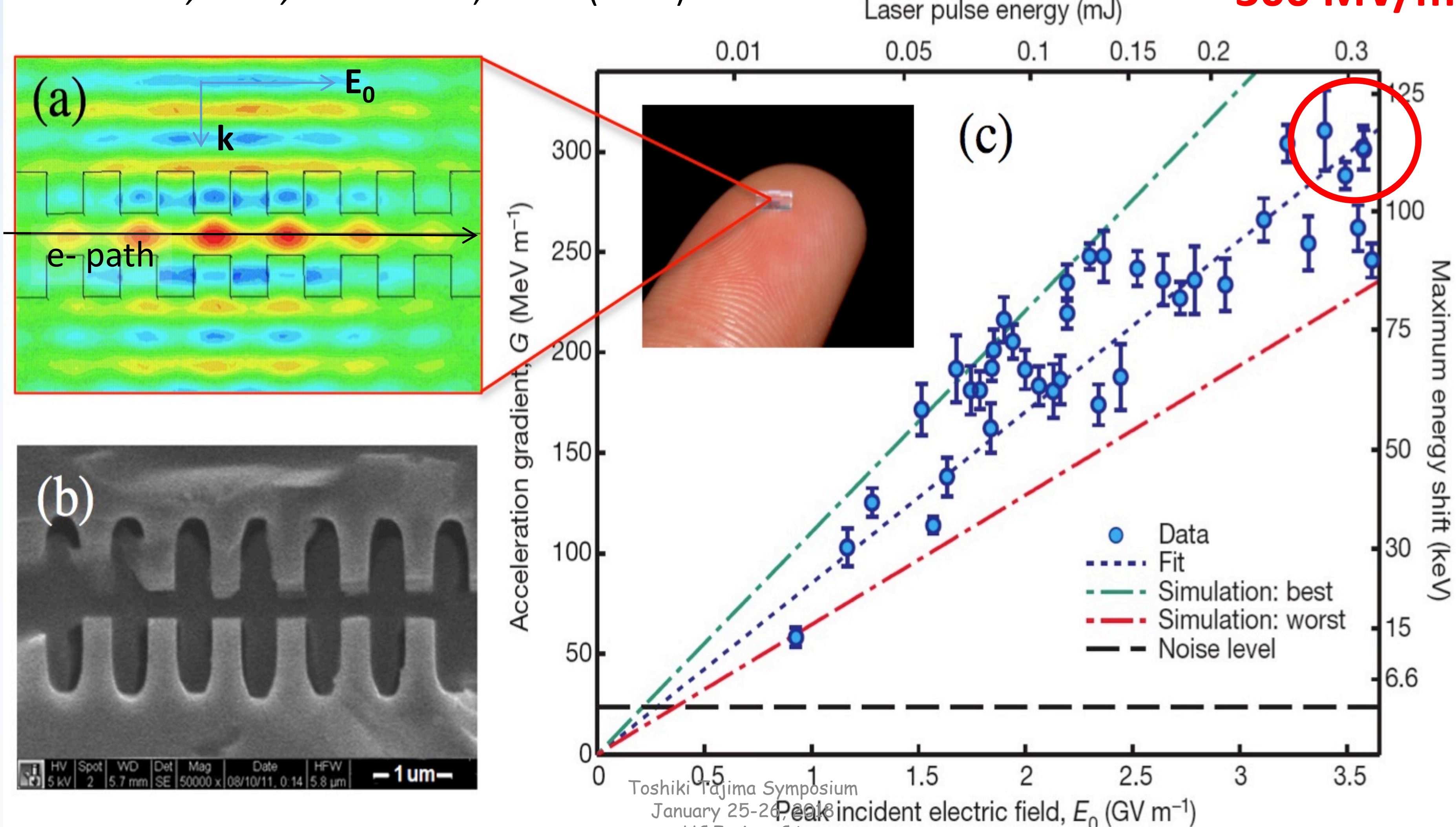
DESY



First gradients observed were 10 times higher than the main SLAC linac…

Peralta, et al., Nature **503**, 91-94 (2013).

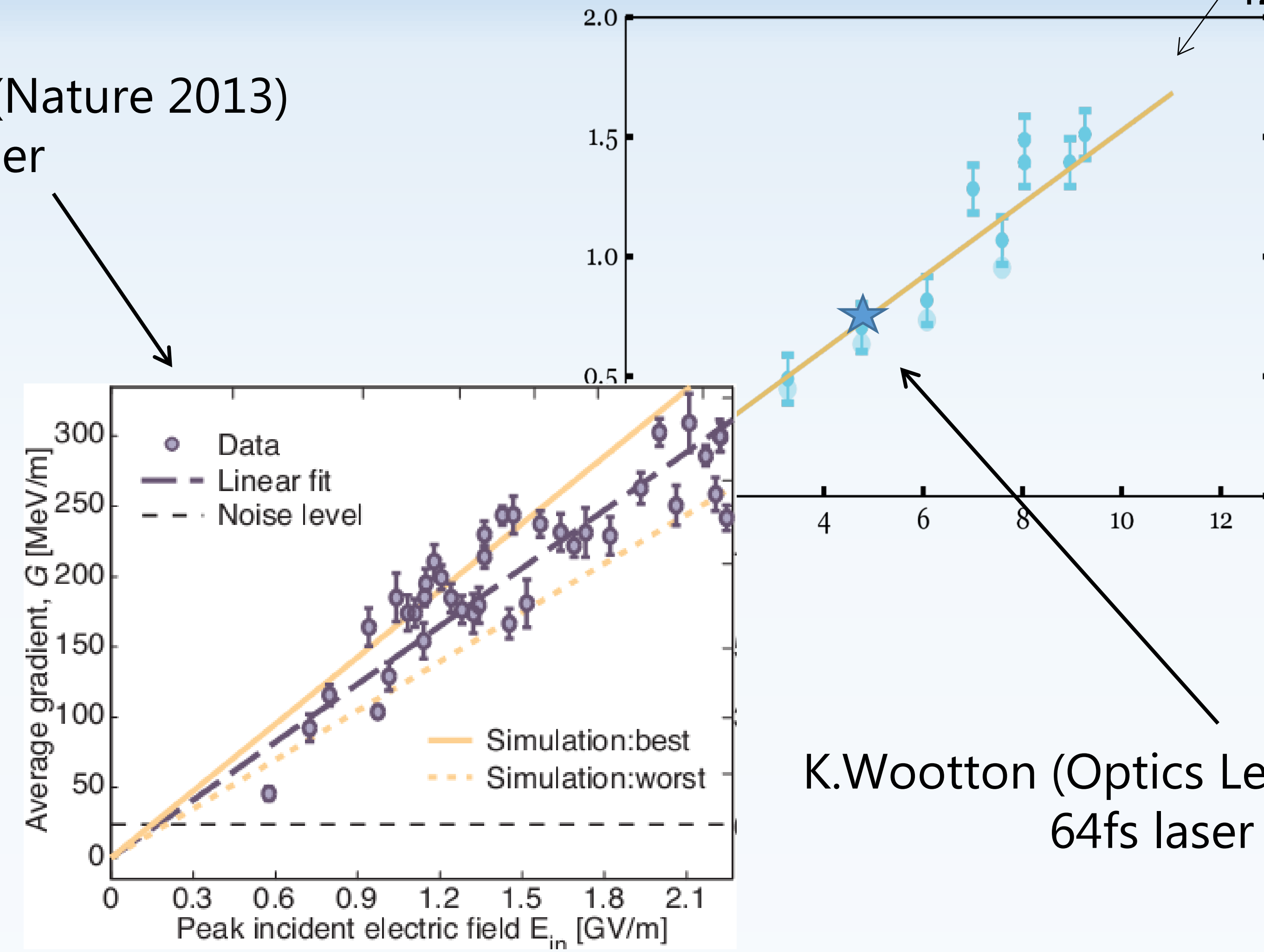
300 MV/m



GeV/m gradients measured with standard femtosecond lasers

UCLA (in prep)
42fs laser

E.Peralta (Nature 2013)
1.24ps laser

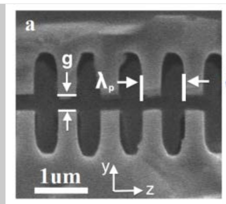
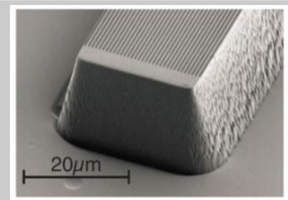
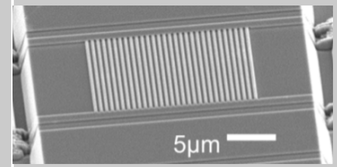
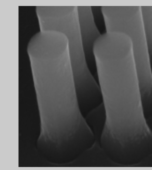


K.Wootton (Optics Letters 2016)
64fs laser

Next: Pulse front tilted drive for 1mm interaction length – 1 MeV energy gain

Comparison of Recent DLA Acceleration Experiments

SLAC

	SLAC & UCLA	Hommelhoff Erlangen	Stanford (Grating)	Stanford (Pillars)
				
Electron Energy	8 MeV	30 keV	96.3 keV	86.5keV
Relativistic β	0.998	0.33	0.54	0.52
Laser Energy	150 υJ	160 nJ	5.2 nJ	3.0 nJ
Pulse Length	40 fs	110 fs	130 fs	130 fs
Interaction Length	~20 um	11 um	5.6 um	5.6 um
Peak Laser Field	3.5 GV/m	2.85 GV/m	1.65 GV/m	~1.1 GV/m
Max Energy Gain	20 keV	0.275 keV	1.22 keV	2.05 keV
Max Acc Gradient	**0.85 GV/m***	25 MeV/m	220 MeV/m	**370 MeV/m**
G_{max}/E_p	~0.18	~0.01	~0.13	~0.4

Josh McNuer .... Peter Hommelhoff

SLAC

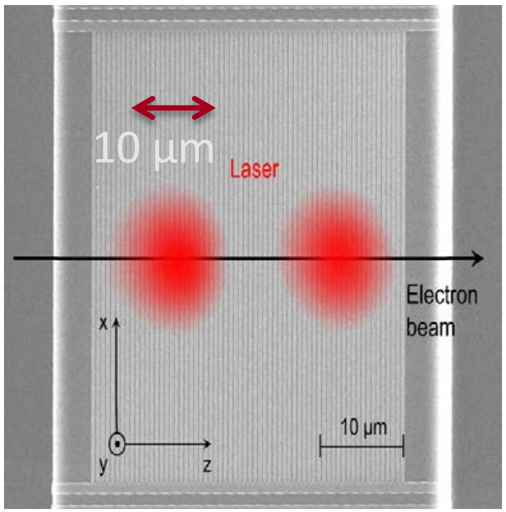
Elements of a dielectric laser accelerator

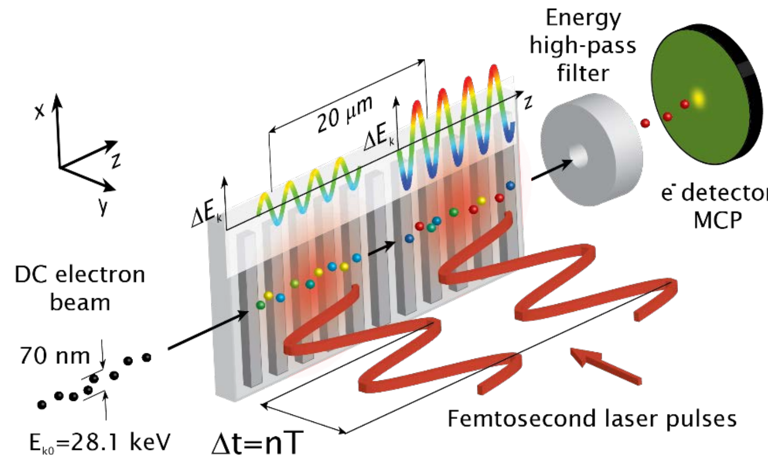
J. McNeur[1,*], M. Kozák[1], N. Schönenberger[1], K. J. Leedle[2], H. Deng[2], A. Ceballos[2], H. Hoogland[3], A. Ruehl[4], I. Hartl[4], R. Holzwarth[3], O. Solgaard[2], J.S. Harris[2,5], R.L. Byer[5], P. Hommelhoff[1]

[1] Department of Physics, Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU), Staudtstrasse 1, 91058 Erlangen, Germany, EU
[2] Department of Electrical Engineering, Stanford University, Stanford, California 94305, USA
[3] Menlo Systems GmbH, Am Klopferspitz 19a, 82152 Martinsried, Germany, EU
[4] Deutsches Elektronen-Synchrotron DESY, D-22607 Hamburg, Germany, EU
[5] Department of Applied Physics, Stanford University, Stanford, California 94305, USA
[*] e-mail: joshua.mcneur@fau.de

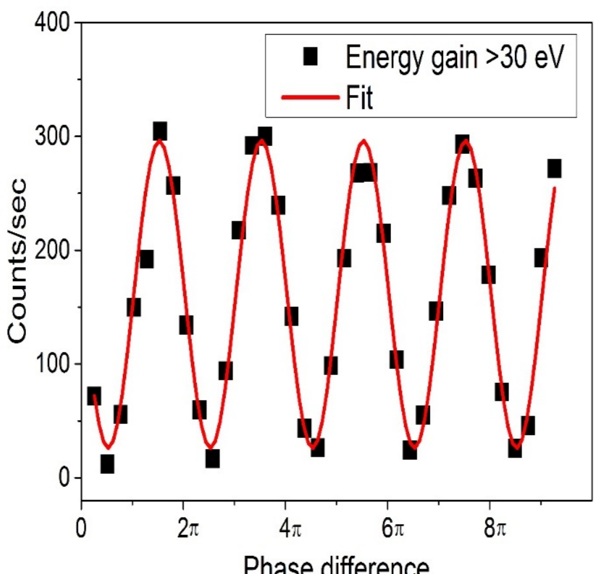
The widespread use of high energy particle beams in basic research[1-3], medicine[4,5] and coherent X-ray generation[6] coupled with the large size of modern radio frequency (RF) accelerator devices and facilities has motivated a strong need for alternative accelerators operating in regimes outside of RF. Working at optical frequencies, dielectric laser accelerators (DLAs) – transparent laser-driven nanoscale dielectric structures whose near fields can synchronously accelerate charged particles – have demonstrated high-gradient acceleration with a variety of laser wavelengths, materials, and electron beam parameters[7-11], potentially enabling miniaturized accelerators and table-top coherent x-ray sources[9,12]. To realize a useful (i.e. scalable) DLA, crucial developments have remained: concatenation of components including sustained phase synchronicity to reach arbitrary final energies as well as deflection and focusing elements to keep the beam well collimated along the design axis. Here, all of these elements are demonstrated with a subrelativistic electron beam. In particular, by creating two interaction regions via illumination of a nanograting with two spatio-temporally separated pulsed laser beams, we demonstrate a phase-controlled doubling of electron energy gain from 0.7 to 1.4 keV (2.5% to 5% of the initial beam energy) and through use of a chirped grating geometry, we overcome the dephasing limit of 25 keV electrons, increasing their energy gains to a

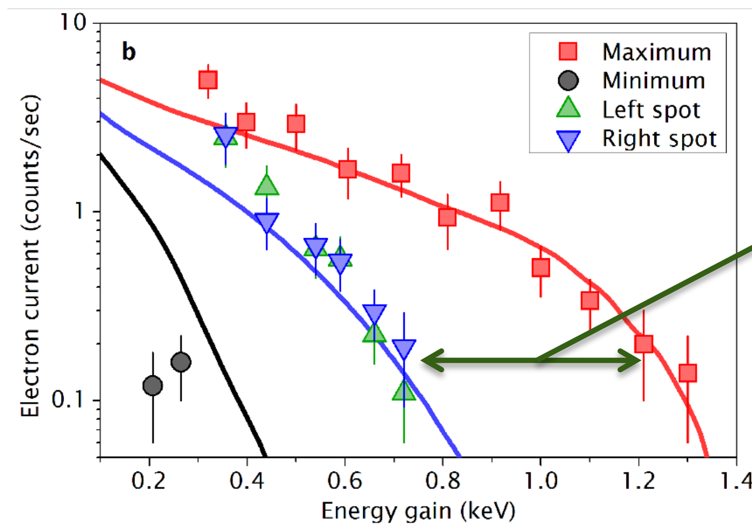
Hommelhoff Group has recently demonstrated phased 2-stage acceleration with 28 keV electrons





M. Kozák et al., arXiv:1512.04394v1





Factor x2 increase for 2 stage vs. 1 stage (linear scaling)

Focusing Structure

SLAC

BA(

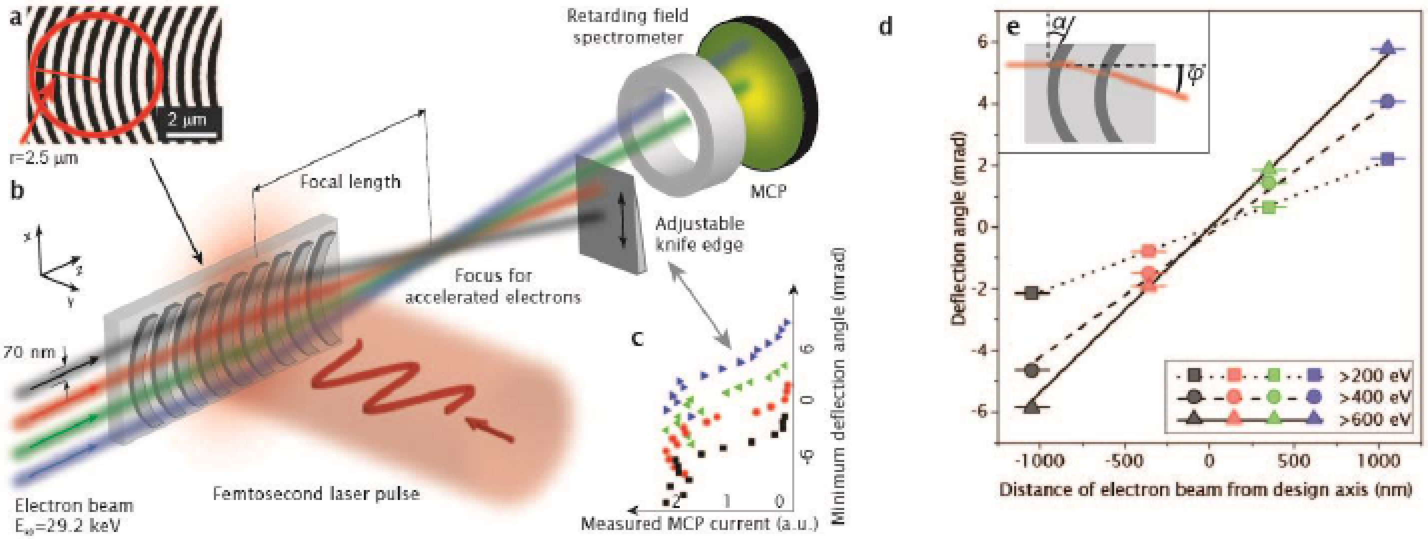
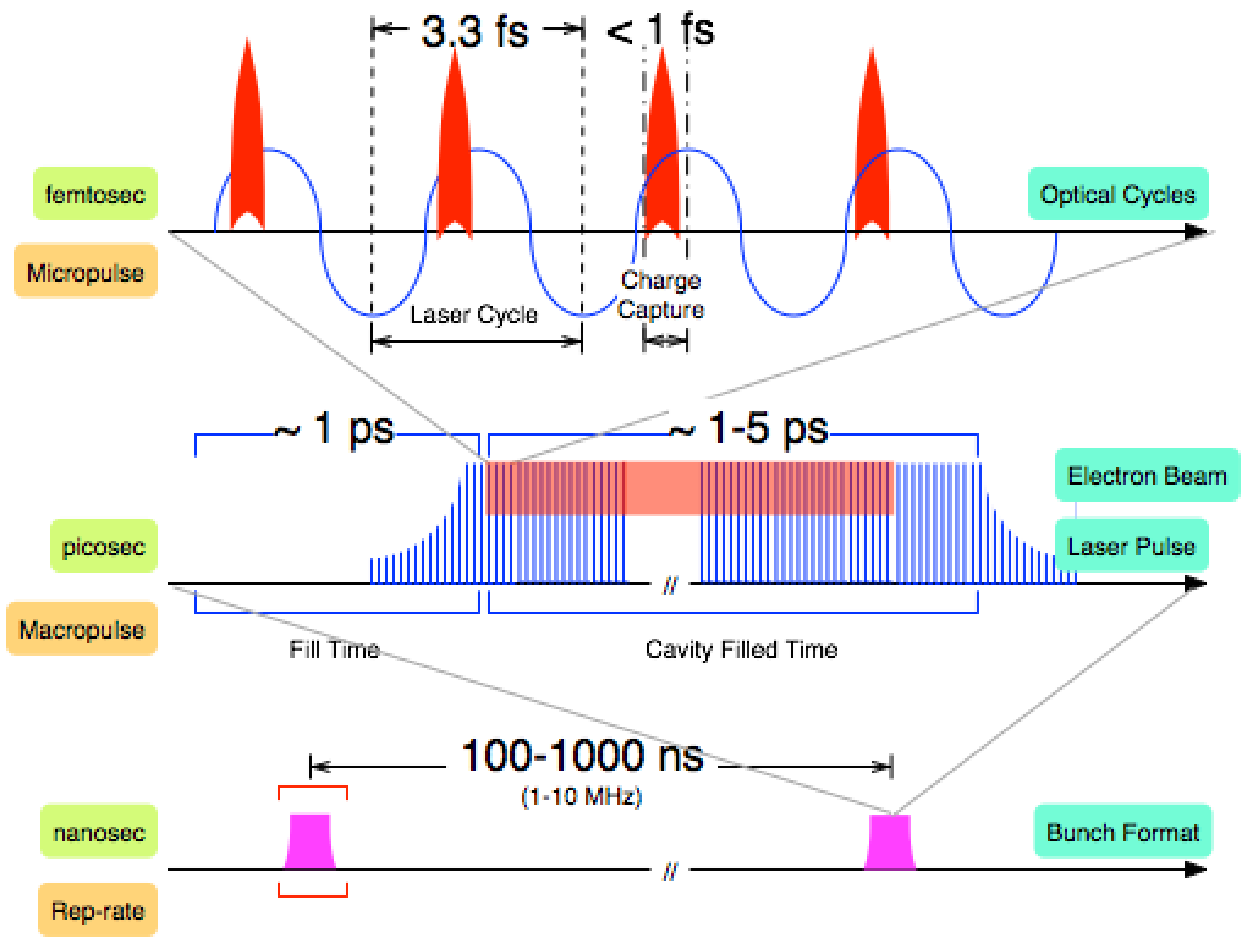
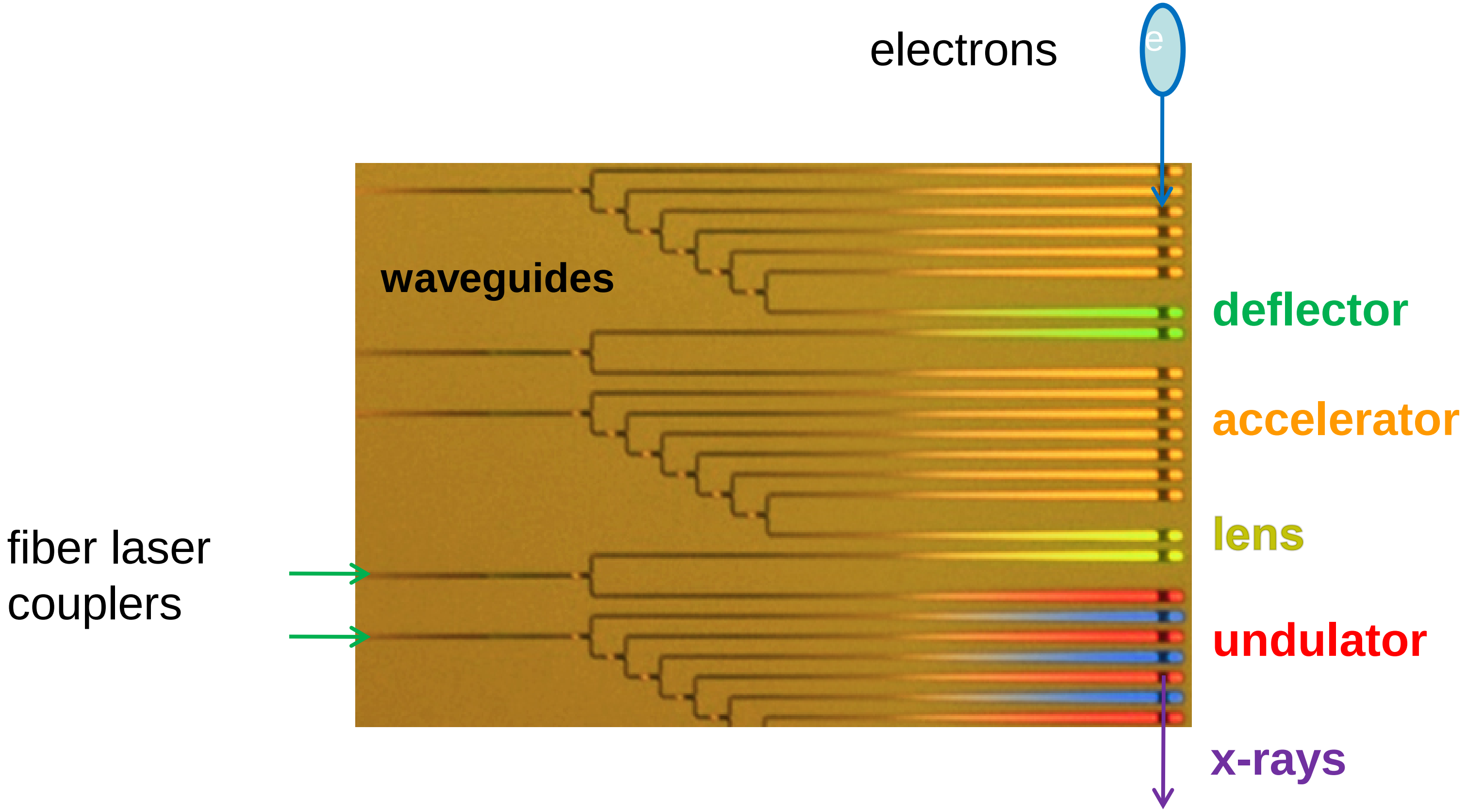


Figure 4. Demonstration of a dielectric laser focusing structure. a. A scanning electron microscope image of the dielectric laser focusing element, with parabolic grating teeth fabricated from Si. The radius of curvature at the vertex of the parabola, 2.5μm, is indicated. **b.** The characterization of focusing performance: accelerated electrons that traverse the lens above the parabolic vertex are deflected downwards and those that traverse below the vertex are deflected upwards. The grating curvature angle α and electron beam deflection angle φ are shown in inset **e**. The spatial profile of the accelerated electrons as a function of x is measured with a knife edge scan, sample results of which are shown in **c**. **d.** The position of the centroid of the accelerated spatial distribution at the location of the knife edge as a function of x, with linear fits for each energy setting. Due to the chromaticity of the lens, electrons that are accelerated strongly are also focused strongly, and thus the measured focal distance depends on the electron energy gain.

Optical structures naturally have **attosec** time scales and favor **high-repetition** rate operation

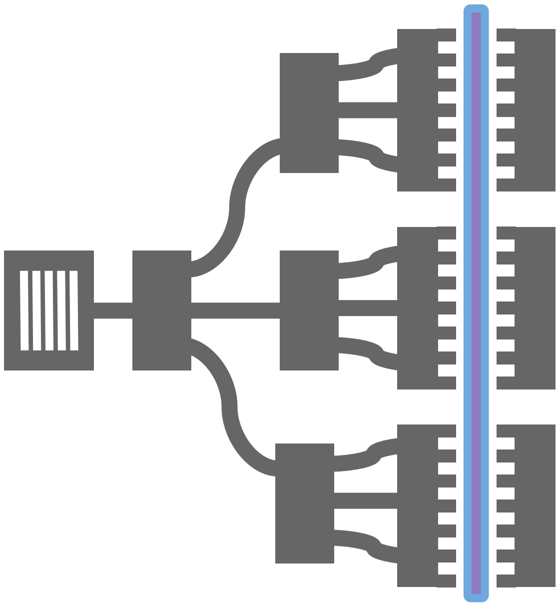


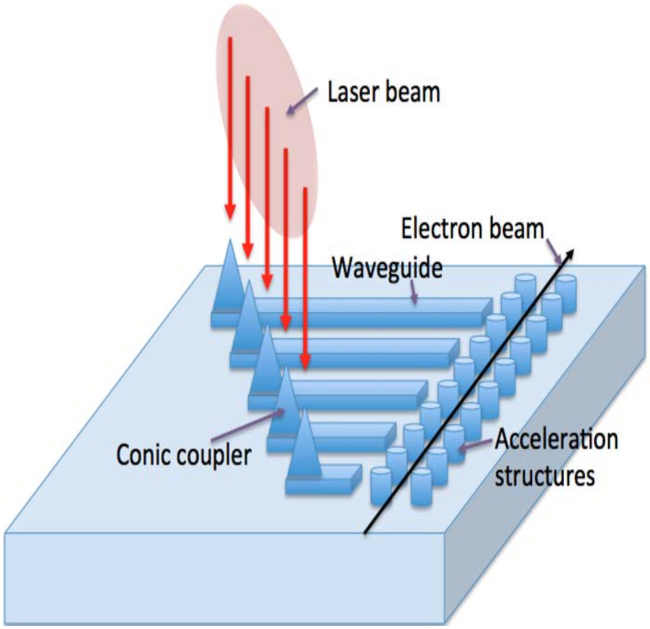
Accelerator on a Chip

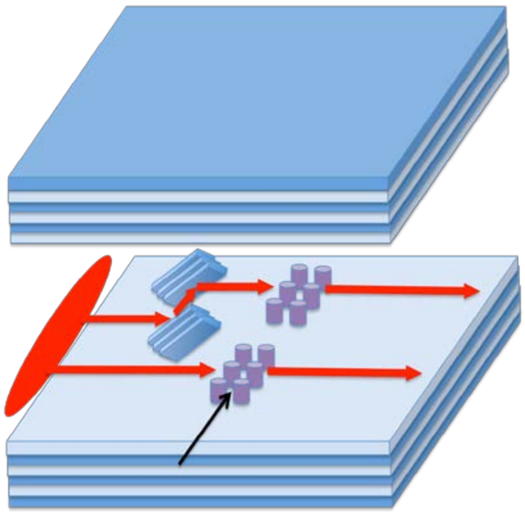


Goal: all components necessary for building an accelerator are compatible with planar lithographic processing!

Design Prototypes: How to get laser power onto the chip with proper phase and timing?

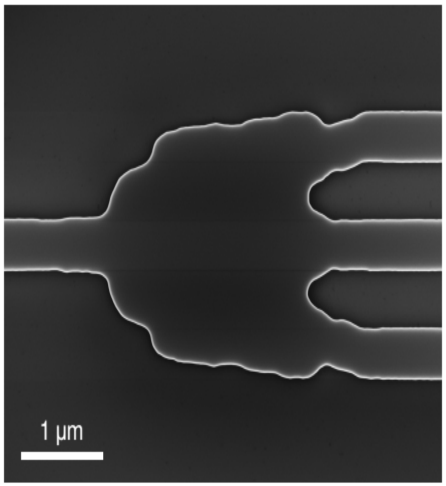


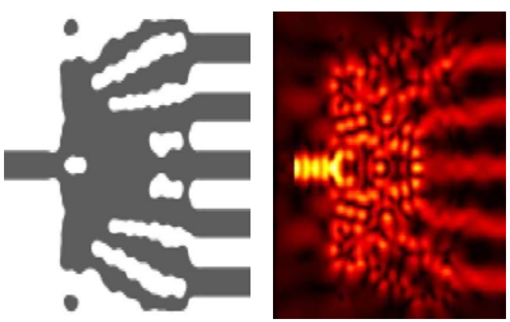


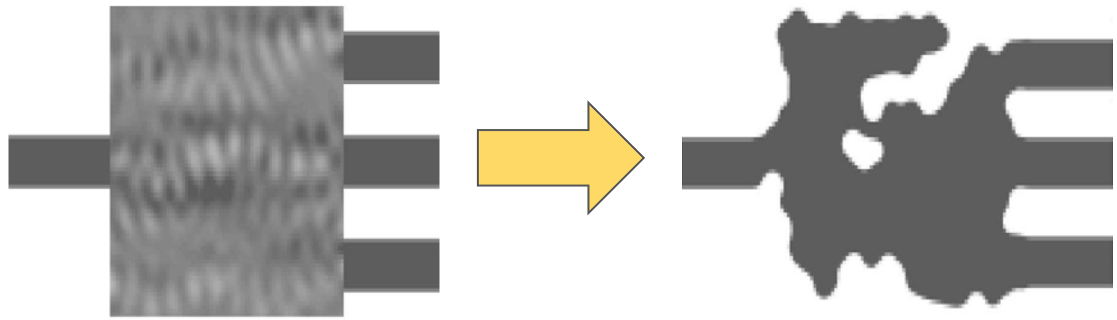


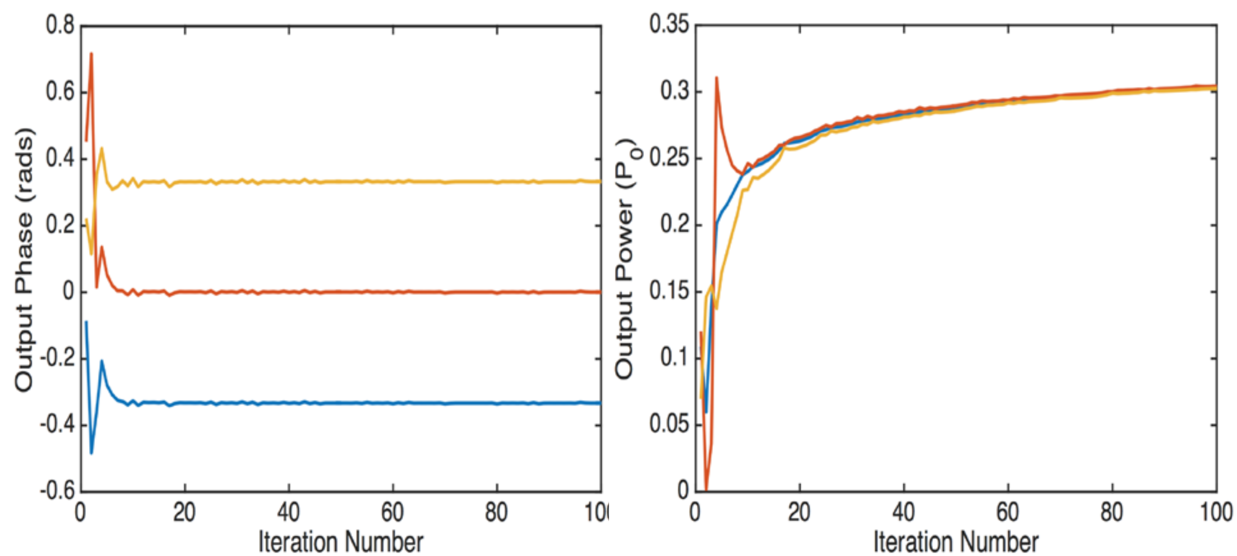
Use “Inverse design” or “Adjoint Design” to invent new structures that meet all of the requirements

Splitters (multi-port and phase control)

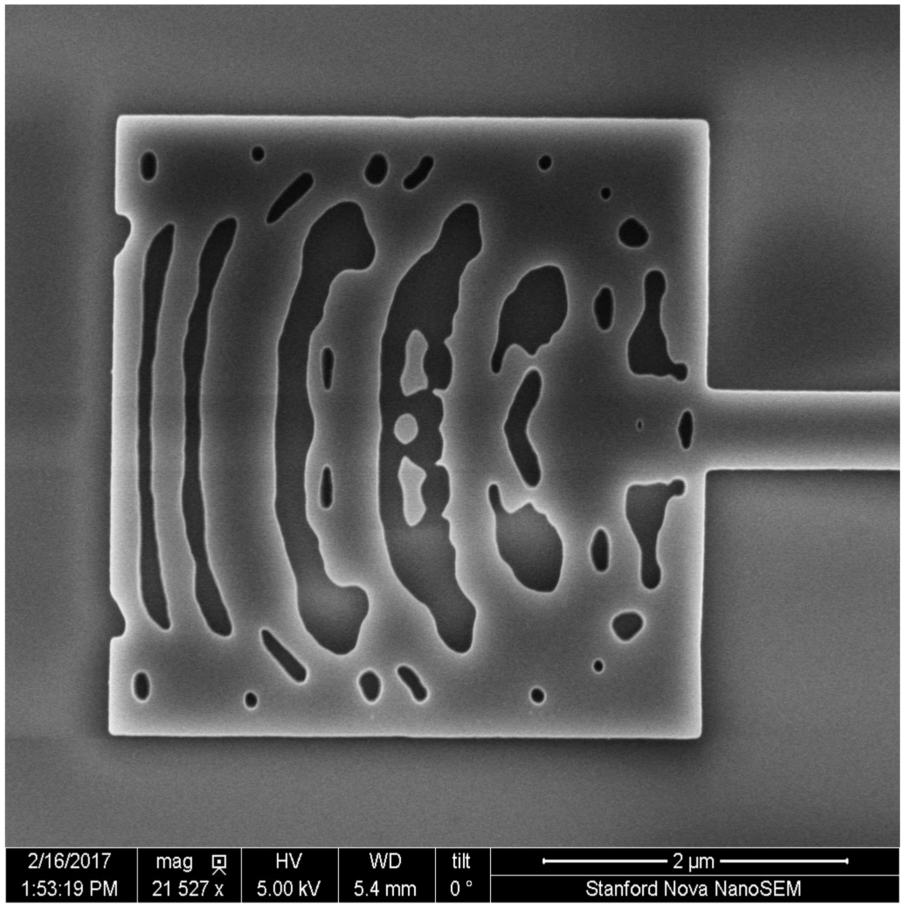








Grating Coupler (Fabrication)



Fabrication of grating couplers using e-beam lithography and plasma etcher

On-Chip Laser Power Delivery System for Dielectric Laser Accelerators

Tyler W. Hughes,* Si Tan,† Zhexin Zhao, Neil Sapra, Kenneth J. Leedle, Huiyang Deng, Yu Miao, Dylan S. Black, Olav Solgaard, James S. Harris, Jelena Vuckovic, Robert L. Byer, and Shanhui Fan
Stanford University, Stanford, CA 94305

Yun Jo Lee and Minghao Qi
Purdue University, West Lafayette, IN 47907

(ACHIP Collaboration)

(Dated: September 11, 2017)

We propose an on-chip optical power delivery system for dielectric laser accelerators based on a fractal 'tree-branch' dielectric waveguide network. This system replaces experimentally demanding free-space manipulations of the driving laser beam with chip-integrated techniques based on precise nano-fabrication, enabling access to orders of magnitude increases in the interaction length and total energy gain for these miniature accelerators. Based on computational modeling, our laser delivery system is estimated to provide 21 keV of energy gain over an acceleration length of 192 μm with a single laser input, corresponding to a 108 MV/m acceleration gradient. The system may may achieve 1 MeV of energy gain over a distance less than 1 cm by sequentially illuminating 49 identical structures. These findings are verified by detailed numerical simulation and modeling of the subcomponents and we provide a discussion of the main constraints, challenges, and relevant parameters in regards to on-chip laser coupling for dielectric laser accelerators.

I. INTRODUCTION

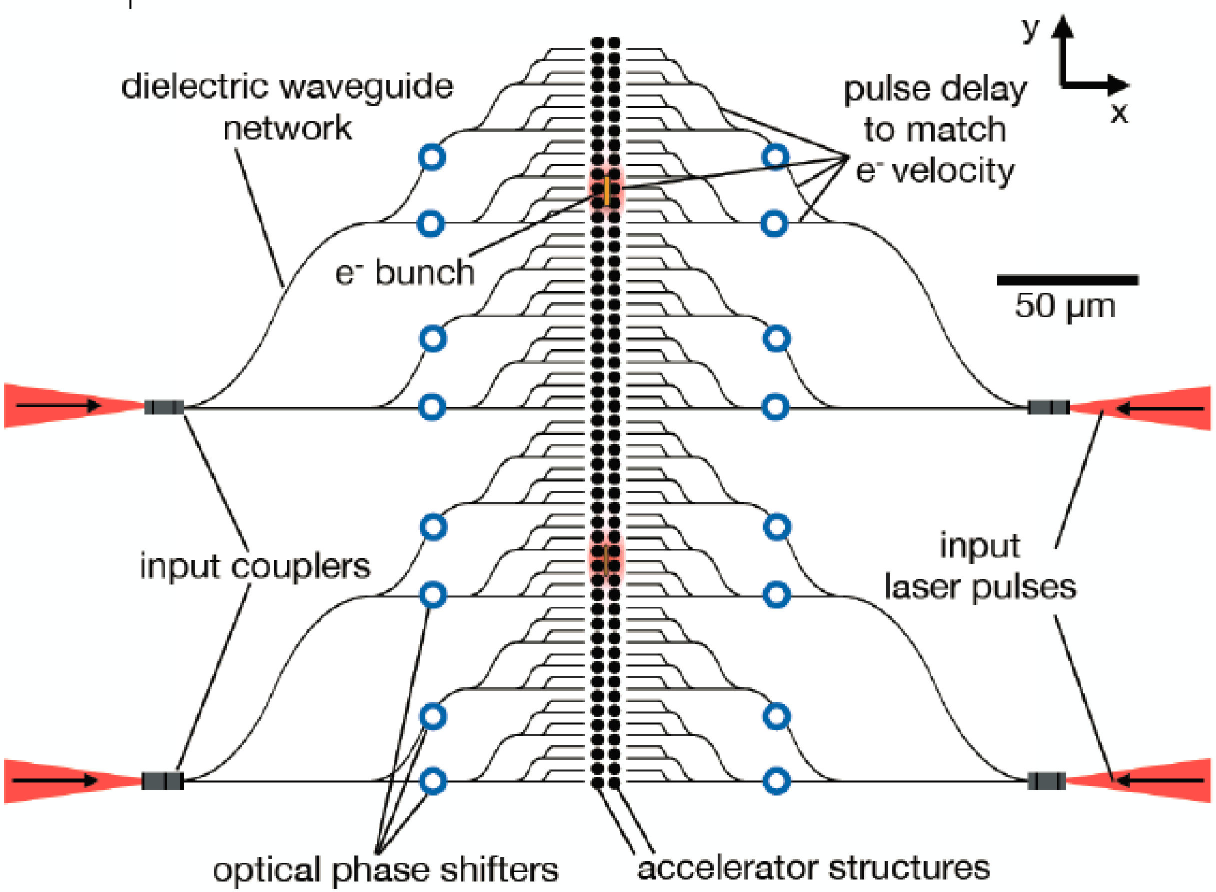
In recent years, dielectric laser accelerators (DLAs) have demonstrated acceleration gradients (energy gain per unit length) approaching 1 GV/m [1–7], several orders of magnitude higher than those attainable by conventional linear accelerator systems based on microwave-driven metal waveguide structures [8]. This breakthrough is made possible by the advent of advanced nano-fabrication techniques [9–13] combined with the fact that dielectric materials may sustain electric fields close to 10 GV/m when illuminated by ultra-fast NIR laser pulses [14–16]. High acceleration gradients may allow DLAs to accomplish significant energy gains in very short lengths, which would enable numerous opportunities in fields where compact and low-cost accelerators would be useful, such as medical imaging, radiation therapy, and industrial applications [17–19].

Since DLA structures are already driven at their dam-

delivery system would allow for orders of magnitude increases in the interaction lengths and energy gains achievable from DLA by replacing free-space manipulation with precise nano-fabrication techniques.

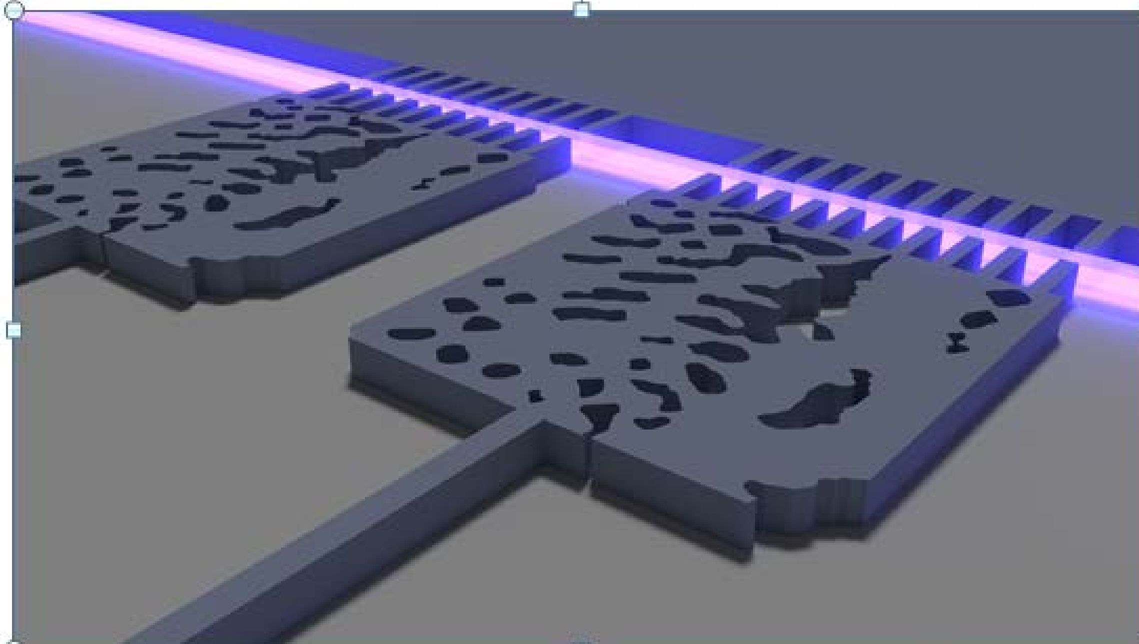
In designing any laser power delivery system for DLA, there are a few major requirements to consider. (1) The optical power spatial profile must have good overlap with the electron beam side profile. (2) The laser pulses must be appropriately delayed along the length of the accelerator to arrive at the same time as the moving electron bunches. (3) The optical fields along each section of the accelerator must be of the correct phase to avoid dephasing between the electrons and incoming laser fields. To accomplish all three of these requirements, we introduce a method for on-chip power delivery, which is based on a fractal 'tree-branch' geometry introduced in Fig. 1. In this paper, we provide a systematic study of the structure, operating principles, the optimal range of operat-

Tree-Branch Structure



ACHIP Collaboration #5

ACHIP Collaboration Meeting V



LASER COUPLING – VUCKOVIC LAB

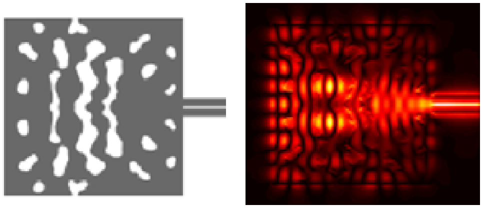
14 September 2017

Using Inverse Design to Engineer Solutions

Laser delivery and phase control

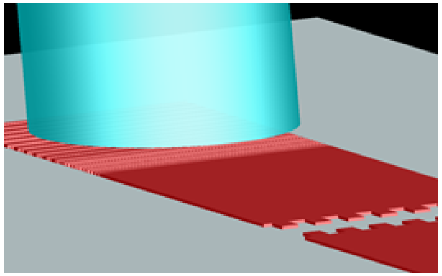
Additional development in inverse design software has allowed for integration of more advanced optimization algorithms and features to enable design of phase-controlled power splitters in 3D simulations.

Avoiding nonlinear effects



Coupling to slot-waveguides may provide advantages in avoiding nonlinear effects and power-handling increases are being investigated

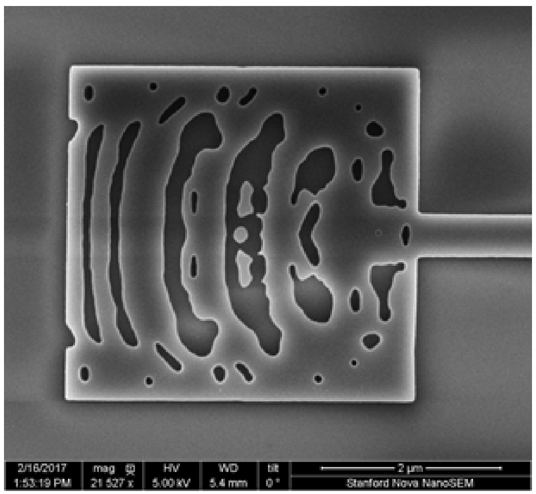
Fiber-coupled accelerators with hollow-core fibers

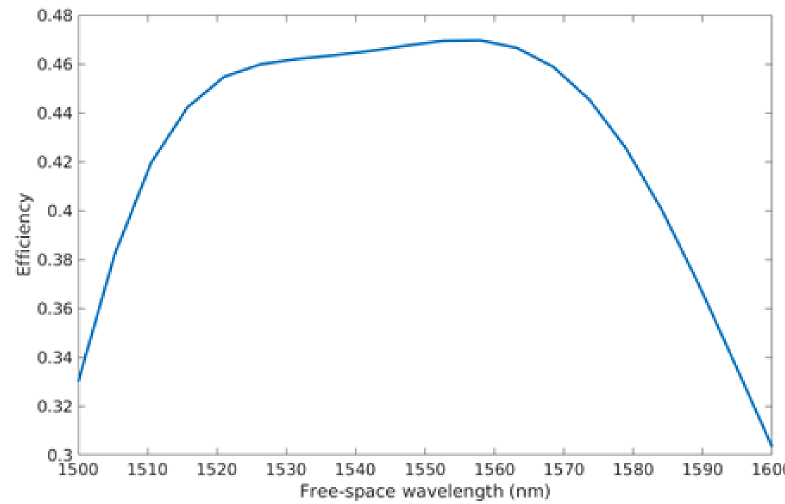


New efficient and broadband grating couplers designed to interface with commercial hollow-core fibers have opened up the possibility for an easily integrated fiber-coupled accelerator to be tested.

Stanford University

Free-space broadband vertical couplers



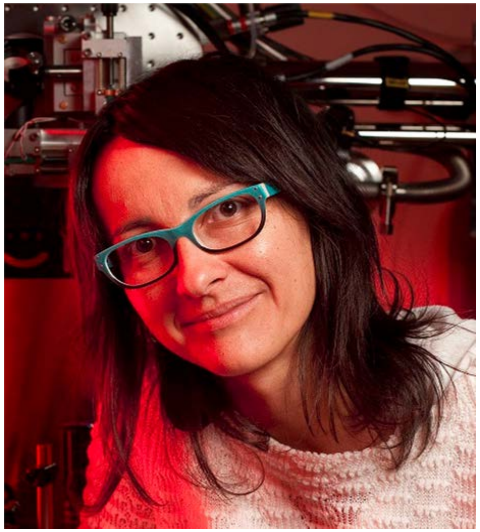


Previously shown, we use inverse design to design ultra-compact and broadband vertical couplers. Design scalable to 2µm wavelength.

Stanford University

Acknowledgements

Professor
Fan



Professor
Vuckovic

Professor
Qi

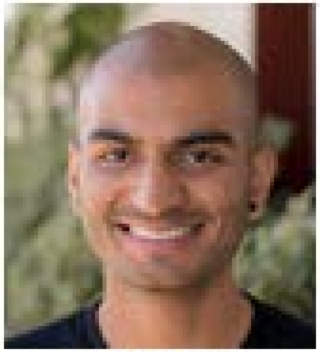
ACHIP

GORDON AND BETTY
MOORE
FOUNDATION

ACHIP Students at Stanford

Acknowledgements

Tyler Hughes



Neil Sapra

Zhexin Zhao

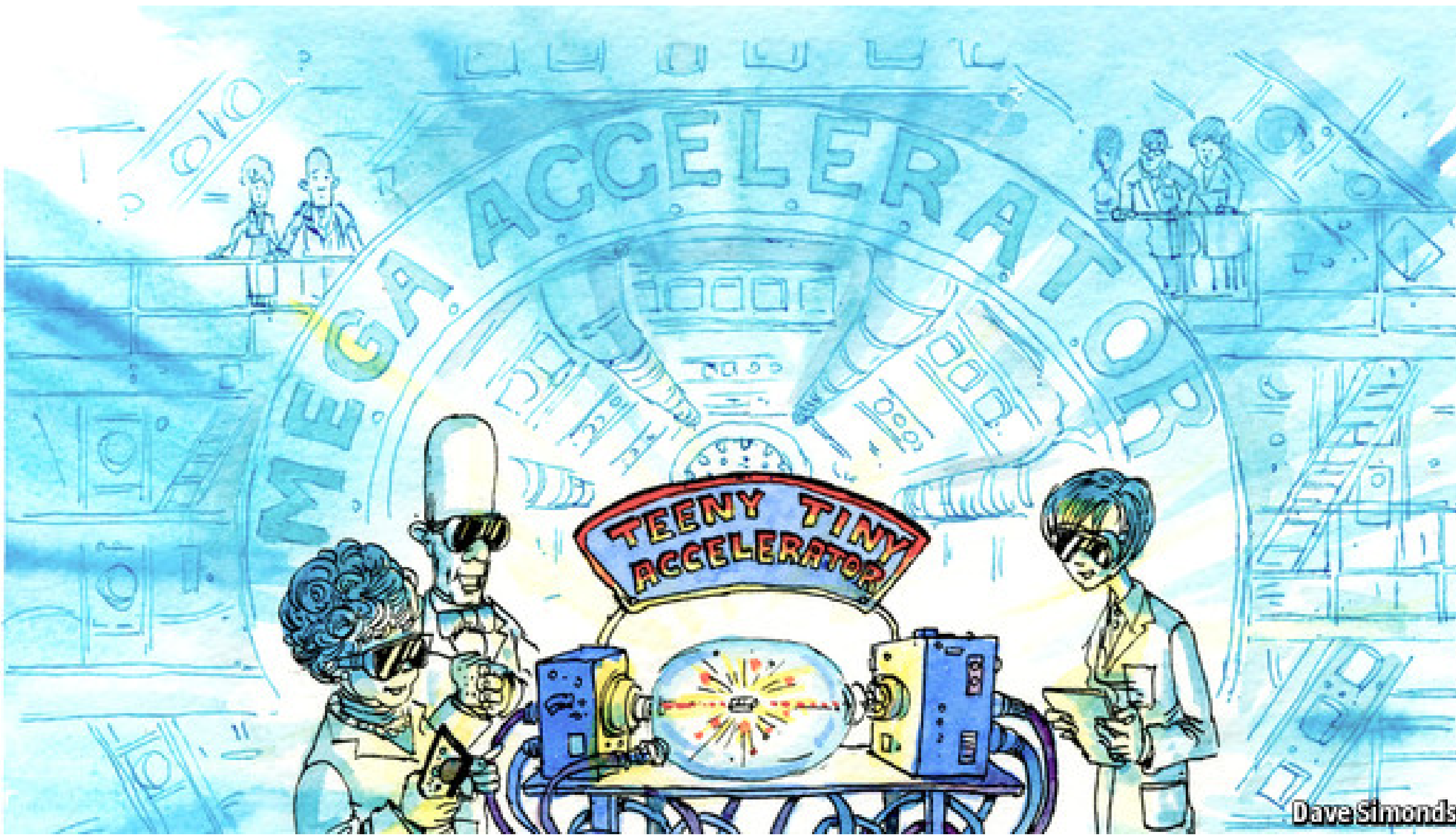
Si Tan

Yunjo Lee

What We Do

Byer Group

Dielectric Laser-driven Accelerators (DLA)



*The Economist, Oct 19th 2013

55 Scientists attend ACHIP meeting in Erlangen (September 2016)

Advisory Board members: Lia Merminga, Chan Joshi, Reinhard Brinkman

On behalf of

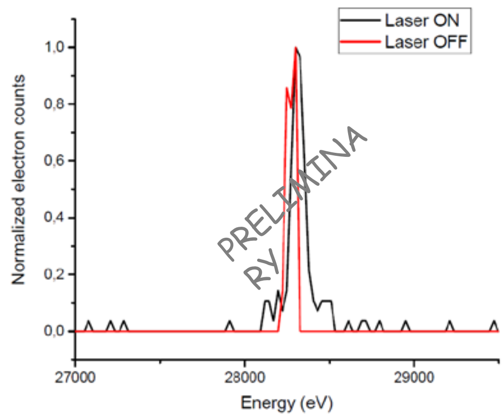
- R. L. Byer, J. S. Harris, O. Solgaard groups at Stanford
- P. Hommelhoff group at FAU Erlangen
- F. X. Kaertner THz group at DESY

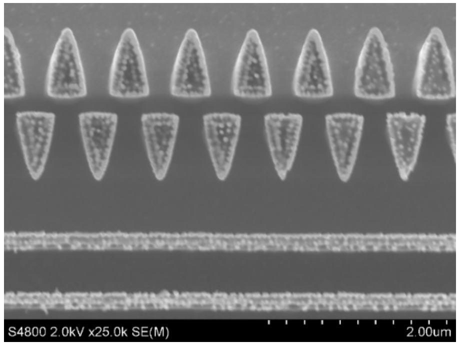
Outline:

- Stanford Update
- DESY THz Update
- FAU Update
- Research Plans for Year 3
- Shoebox Test Platform Overview

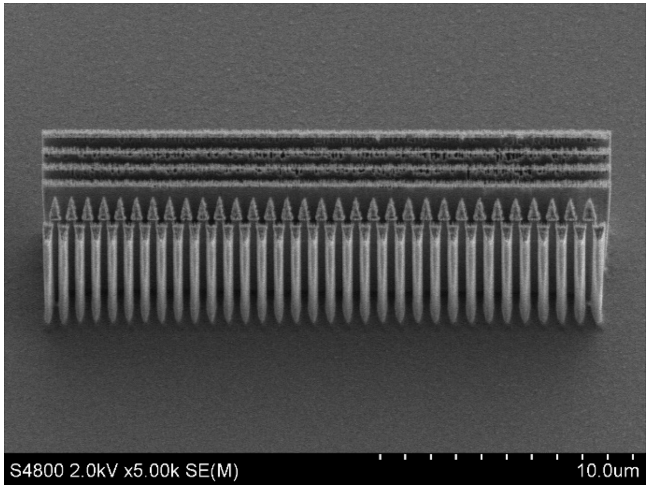
Sine-pillar Stucture Testing

Simulations indicated 700 MeV/m gradient possible, but only <100 MeV/m measured, likely due to gap size smaller than design

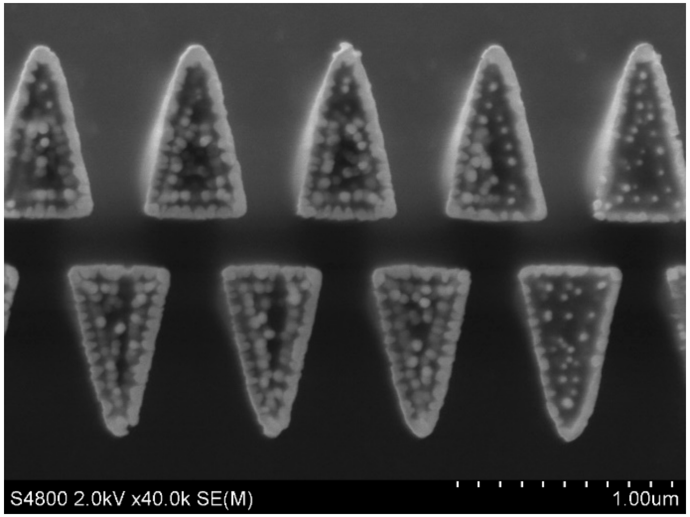




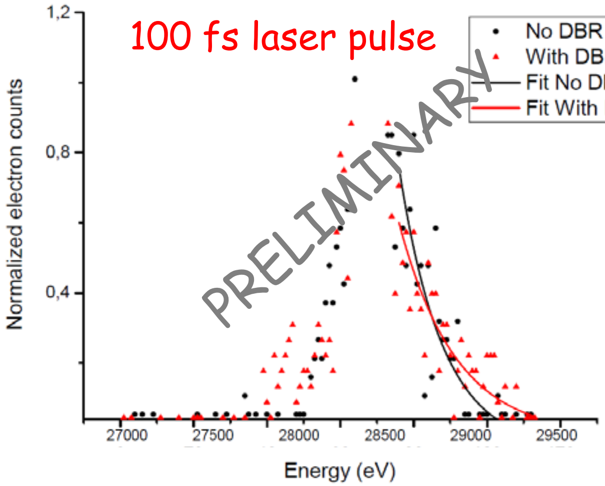
Old structure with too small gap – the chirp design reduces the tolerance since desired gradient must be reached to match chirp

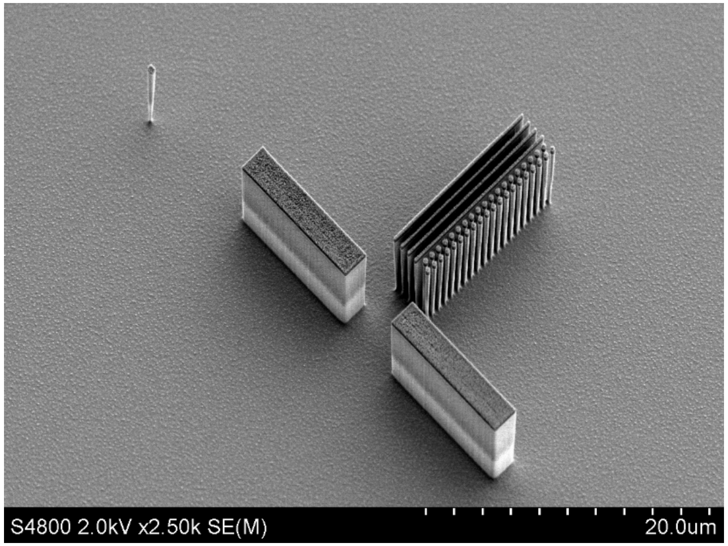


New structures fabricated with refined oxygen plasma cleaning process after lithography, correct gap size achieved



Dual Pillar with and without DBR Comparison

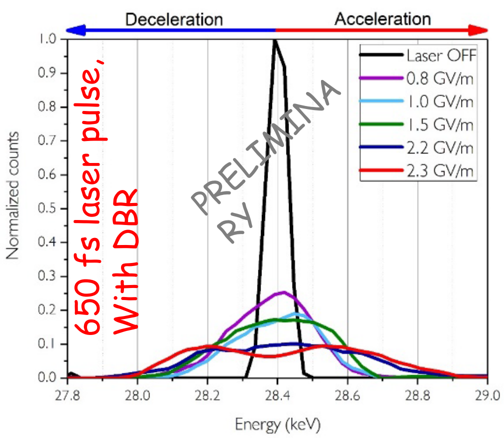


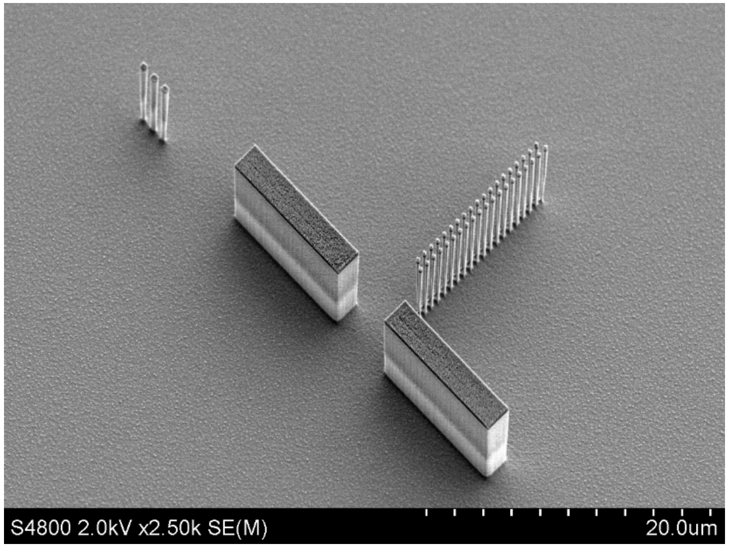


1.2 keV (~100 MeV/m) energy gain with DBR, 0.8 keV (~66 MeV/m) without

Better statistics needed for comparison to simulations - ongoing

With a stretched pulse (650 fs), more electrons interact with laser pulse (necessary for upcoming bunching experiments) ----
------------>

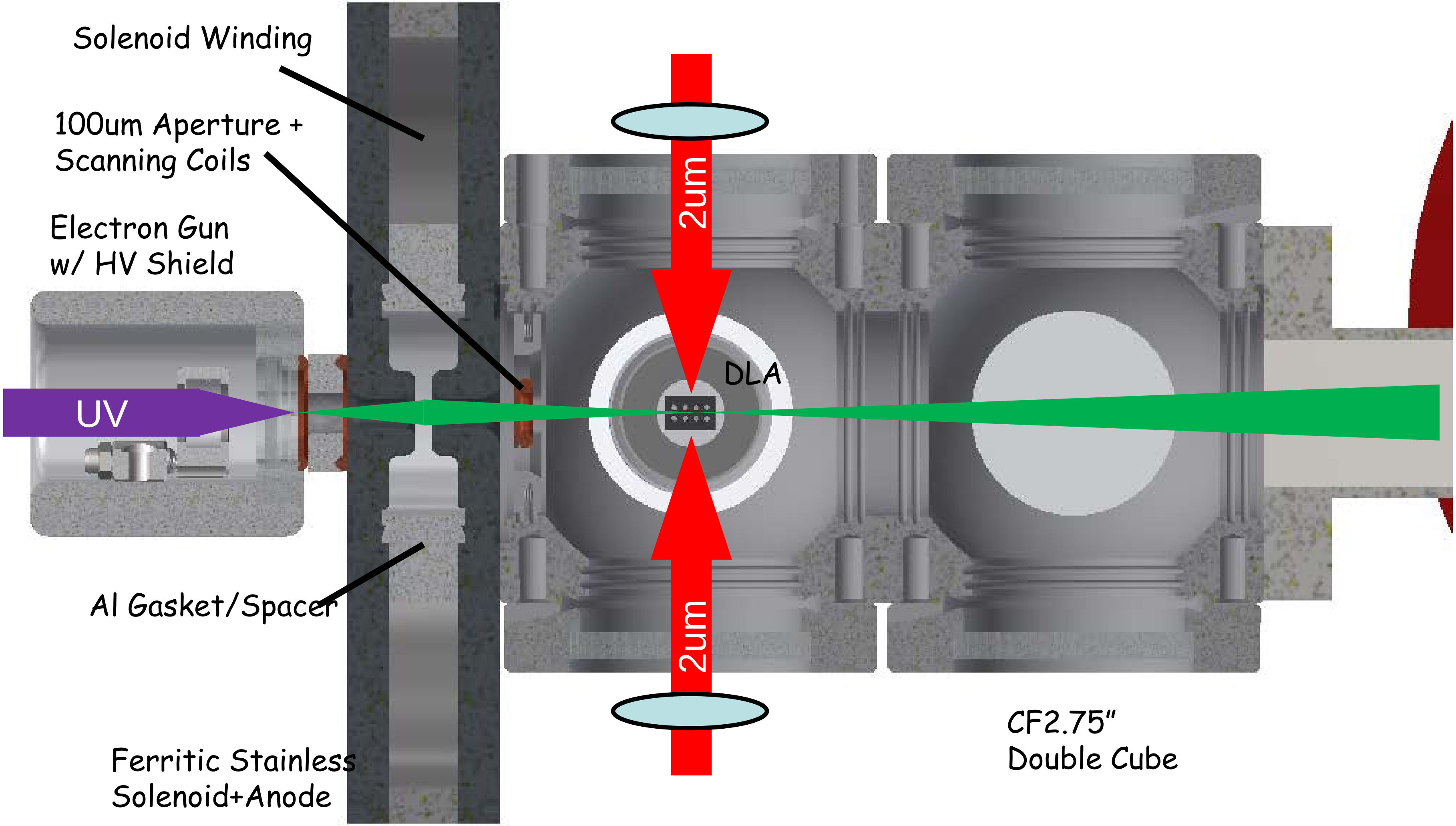




Shoebox Platform Design

- Goal: A modular test platform for ACHIP Shoebox Demonstration
- Platform Provides:
  - All necessary electron optics for any electron gun on a CF2.75(CF40) flange
    - Focusing, imaging, spectrometer, divergence setting
    - Provide maximum flexibility as electron gun performance improves
    - Electron guns will be interchangeable without changing any other part of the system
    - Solenoid lens works up to over 100keV
      - Uses interchangeable pole pieces for different configurations
    - Spectrometer works from 15keV to 10MeV
    - Scanning transmission electron imaging for maximum contrast, speed, flexibility
      - Uses existing STEM controls and interface
  - DLA Hexapod platform
    - Interchangeable samples on standard SEM mounts
    - 6-axis nanometer-scale positioning
  - Free space optics will be located outside vacuum chamber
  - Waveguide optics will be located inside chamber with external alignment
  - Vibration-free UHV system
  - Entire system will fit on optics table

Shoebox Testing Chamber 30cm length
Electron Source Concept, Solenoid, Main Chamber



DLA is a promising new approach to particle acceleration

ACHIP Collaboration Meeting 6

TECHNISCHE UNIVERSITÄT DARMSTADT

14-16 March 2018 *TU Darmstadt*
America/Los_Angeles timezone

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The Accelerator-on-a-Chip International Program (https://achip.stanford.edu) is a consortium of seven universities, three national research laboratories and one company, that has been formed with the goal to develop a micrometer-scale accelerator which is driven by the electromagnetic fields of a laser.

We are pleased to announce the biannual collaboration meeting in March 14–16, 2018, which will be organized by the DLA group of Technical University Darmstadt, and which will be held at the old university main building. This meeting is intended to share progress at the different partners, and to discuss collaboration efforts.

The workshop will start with the working groups on March 14. The plenary sessions will start on March 15.

Registration for this workshop is free of charge, but participation is subject to invitation.

Dates: from 14 March 2018 05:00 to 16 March 2018 09:30
Timezone: America/Los_Angeles
Location: *TU Darmstadt*
Altes Hauptgebäude
Hochschulstraße 1
64289 Darmstadt
Room: S1|03 175

Integration Group Report

Quarterly Reports Teleconference: Nov 15, 2017

Accelerator on a Chip International Program (ACHIP)
Gordon and Betty Moore Foundation

**Co-leads: R. Joel England, P. Musumeci,
P. Hommelhoff**

ACHIP
Accelerator on a Chip International Program

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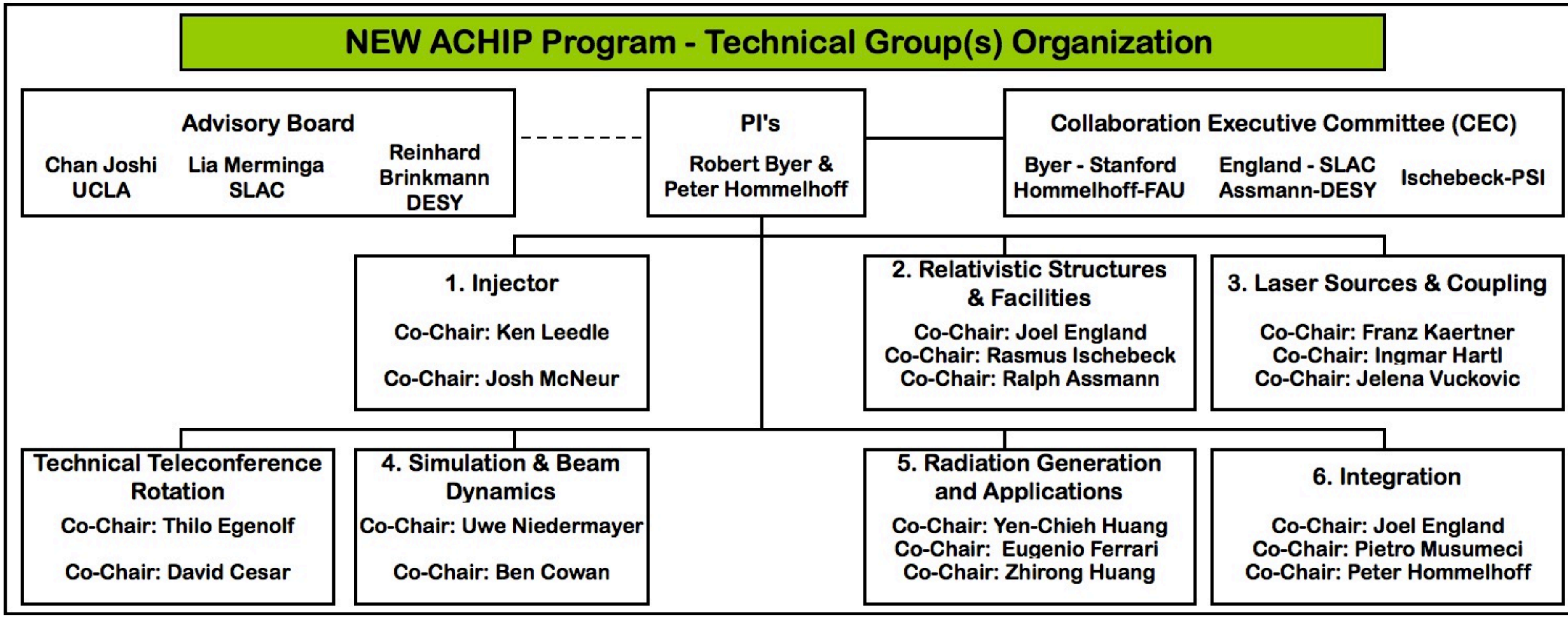
Org Chart Year 3 – New Group Structure



Co-leads for all technical groups have now been finalized.

Stretch Goals

The stretch goals of the program, as stated on Page 2 of the ACHIP proposal:

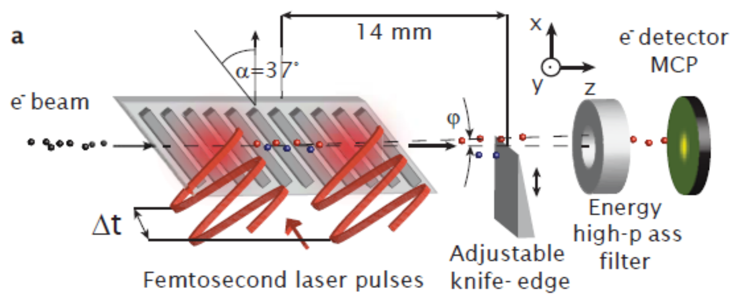
Goal 1: Demonstrate acceleration with an integrated multi-stage DLA with GV/m peak gradients and energy gain ≥ 1 MeV for sub-relativistic and relativistic electrons.

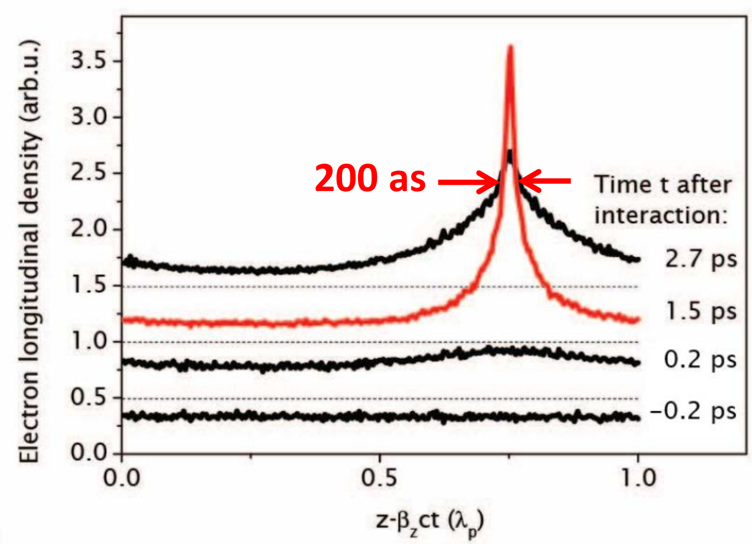
Goal 2: Exploration of capabilities enabled by the transverse fields in DLA structures, including X-Ray and EUV production, focusing, and sub-fs-level diagnostics.

We note that Goal 1 is most strongly tied to the activities of the Integration Group (Group 6, and by extension to groups 1-4), while Goal 2 is most closely aligned with the Radiation Generation and Applications group (Group 5). We also note that pursuant to prior discussion, focusing was deemed to be such an intrinsically critical need that it spans all technical groups and is not limited to any particular one.

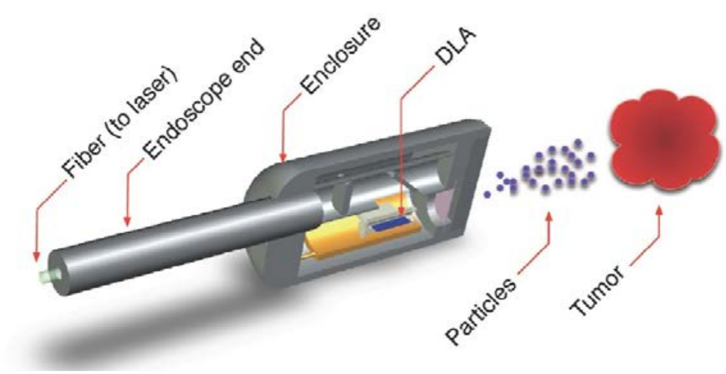
Some Potential Applications

Attosecond Streak Camera

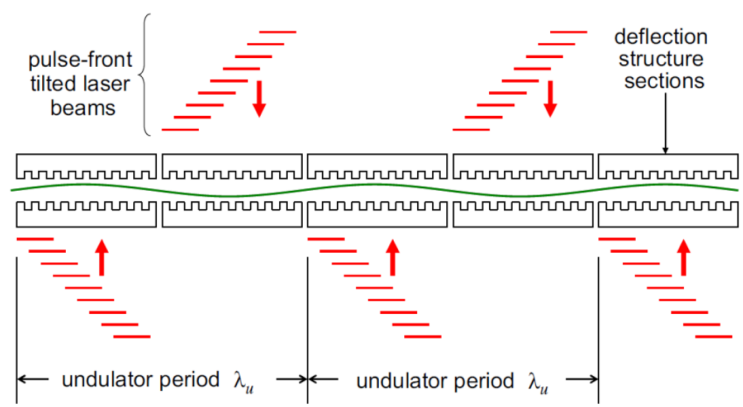




Medical Radiation Therapy Devices



FEL on a Chip



K. Wooton, J. McNeur, & K. J. Leedle, *submitted to RAST;* slac-pub-16810 (2016)

10 TeV Collider Parameters

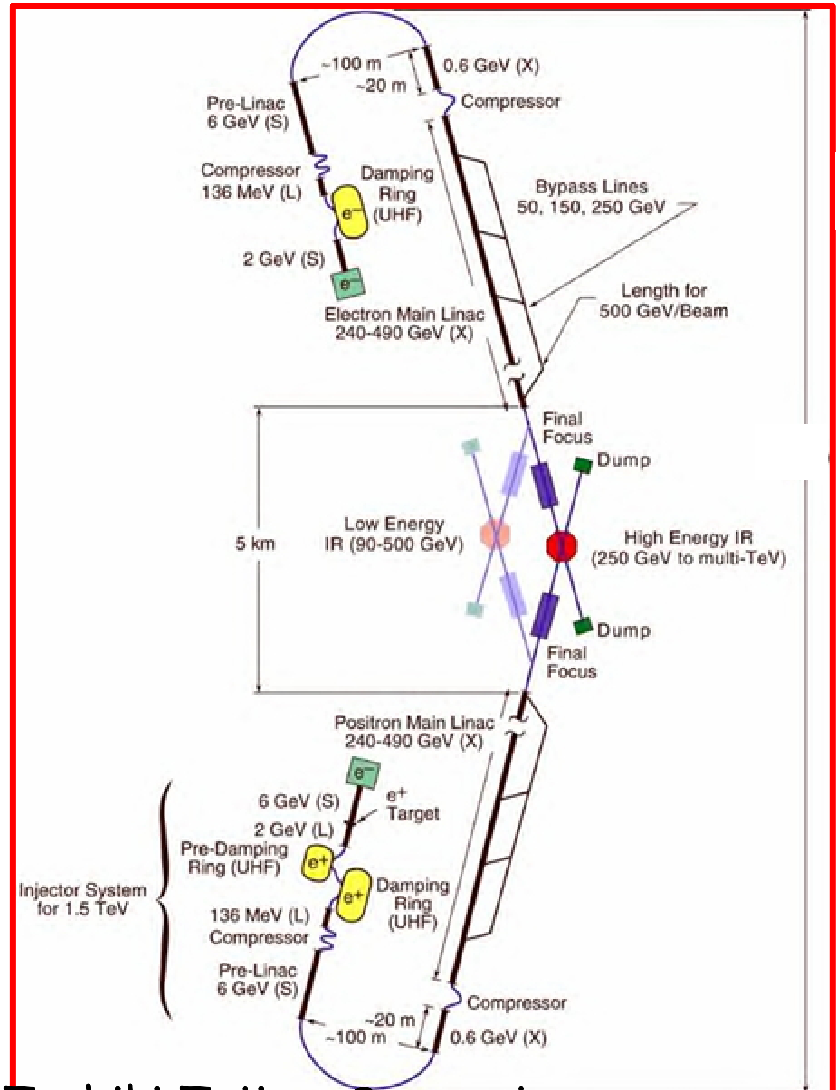
SLAC

	Traditional RF	DLA
Source	Klystron (Microwaves)	Commercial μJ Class IR Laser
Wavelength	2-10 cm	1-10 μm
Bunch Length	1-5 ps	1-100 attosec
Bunch Charge	1-4 nC	1-10 fC
Required Emittance	0.1-1 μm	1-10 nm
Rep Rate	1-1000 Hz	1-10 MHz
Confinement of Mode	Metal Boundaries	Photonic Crystal (1D, 2D, 3D)
Material	Metal	Dielectric
Max Unloaded Gradient	30-100 MV/m	0.5-2 GV/m
Power Coupling Method	Critically-coupled Metal WG	Free-space /Silicon WG
Luminosity (cm^-2/s) *	1.70E+35	1.05E+36
Beamstrahlung E-loss (%) *	**53**	**4.4**
Wall Plug Power (MW) *	540	390

* For 10TeV c-o-m collider scenario, based on numbers from Report of ICFA-ICUIL 2010 Joint Task Force on Ultra-High Intensity Lasers, Ch. 1. RF numbers extrapolated from ILC parameters scaled to higher luminosity.

Future high energy physics facilities could be smaller and more affordable.

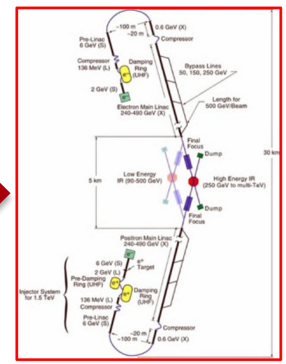
International Linear Collider



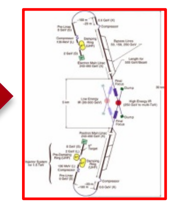
Active Linac Length

12.5 km

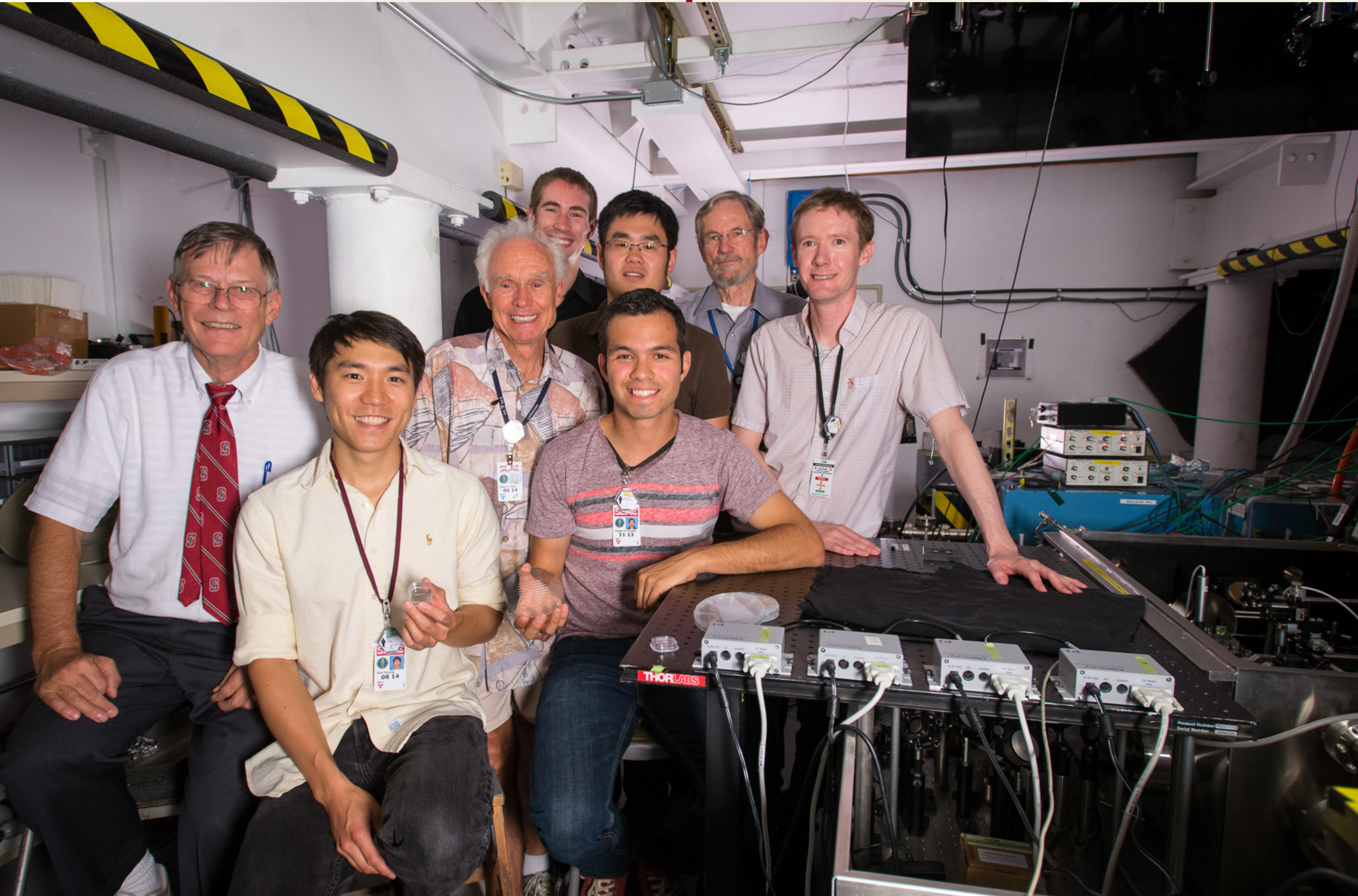
1.6 km



168 m



Accelerator Team at E163 Experimental Hall



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Dr. Bob Noble
Dr. Ziran Wu
Prof. Minghao Qi (visiting scientist)
Chunghun Lee (visiting student)

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Dr. Ben Cowan
Dr. Brian Schwartz
Dr. Dan Abell
Dr. Estelle Cormier

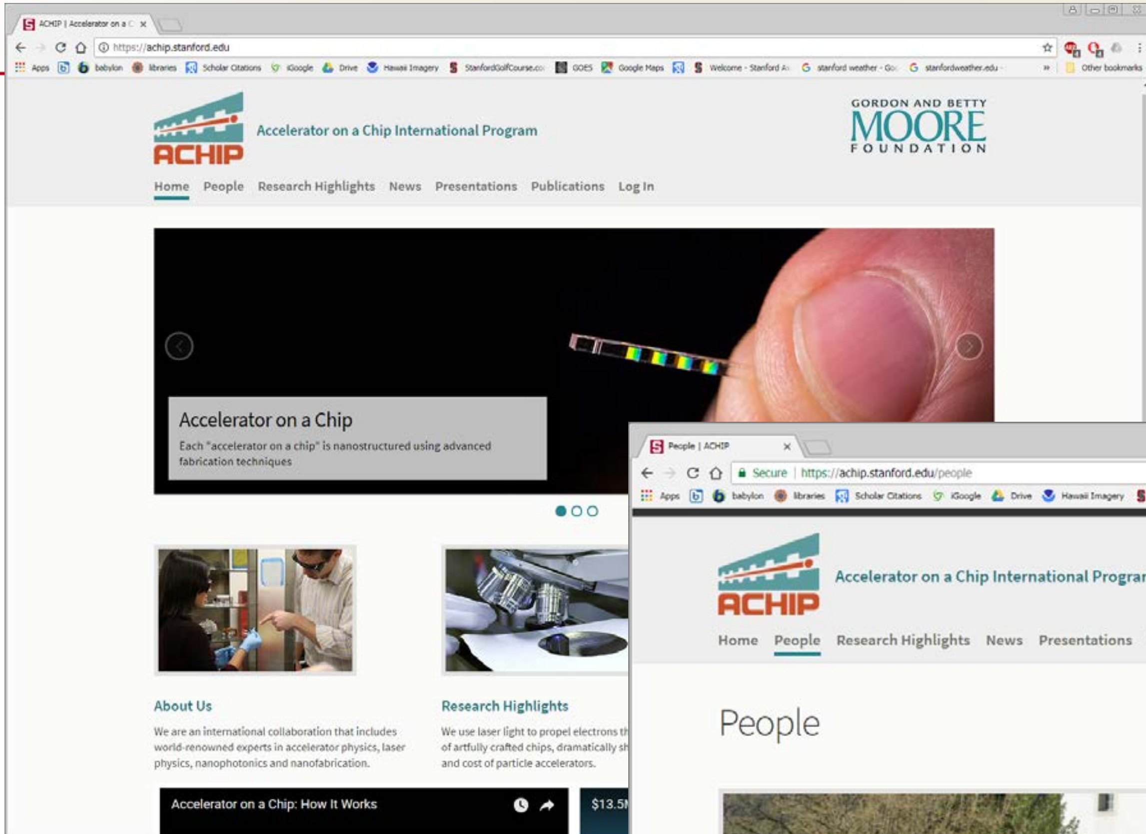
UCLA
Dr. Gil Travish
Dr. Esin Sozer
Josh McNeur

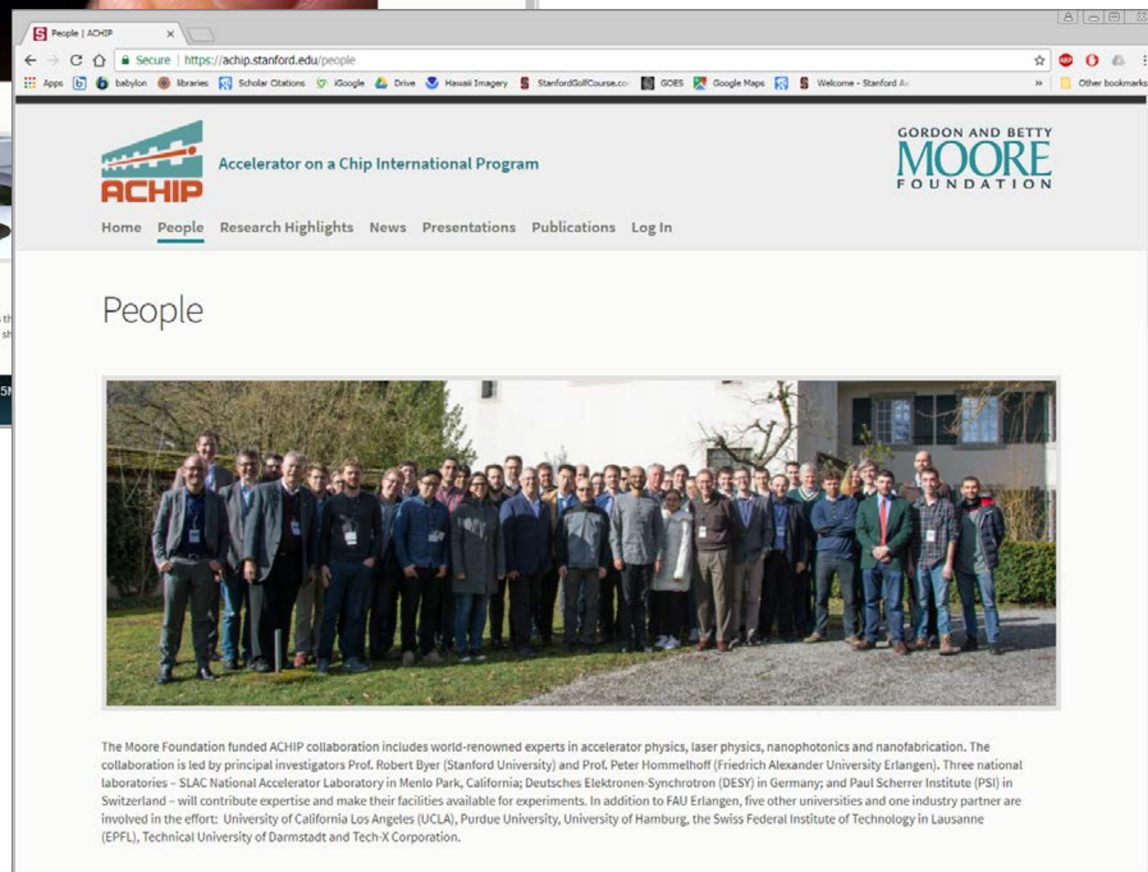
Stanford Laser Accelerator Laboratory

SLAC - Stanford Laser Accelerator Laboratory

On a WAFER !

ACHIP.stanford.edu - Web Site





ACHIP Publications

SLAC

Publications | ACHIP

https://achip.stanford.edu/publications

ACHIP — Accelerator on a Chip International Program

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Publications

A selection of relevant papers published prior to the start of the ACHIP Collaboration:

- E. Prat, et al., "Outline of a dielectric laser acceleration experiment at SwissFEL," Nuclear Instruments and Measurements A, in press.
- T. Hughes, G. Veronis, K. P. Wootton, R. J. England, S. Fan, "Method for computationally efficient design of delectric laser accelerator structures," Optics Express 25 (13), 15414-15427 (2017).
- K. P. Wootton, et al., "Towards a Fully Integrated Accelerator on a Chip: Dielectric Laser Acceleration (DLA) From the Source to Relativistic Electrons," JACoW, IPAC (2017).
- K. J. Leedle, R. F. Pease, R. L. Byer,and J. S. Harris, “Laser acceleration and deflection of 96.3 keV electrons with a silicon dielectric structure,” *Optica* 2, 158–161 (2015).
- K. J. Leedle, A. Ceballos, et al., “Dielectric laser acceleration of sub-100 keV electrons with silicon dual-pillar grating structures,” *Optics Letters* 40 (18), 4344 (2015).
- R. J. England, R. J. Noble, eds., "Dielectric laser accelerators," Reviews of Modern Physics 86, 1337 (2014).
- K. Soong, E. Peralta, et al., "Electron beam position monitor for a dielectric microaccelerator," Optics Letters 39 (16), 4747-4750 (2014).
- J. Hoffrogge, et al., "Tip-based source of femtosecond electron pulses at 30 keV," J. Appl. Phys. 115 (9), 094506 (2014).
- E. A. Peralta, K. Soong, et al., "Demonstration of Electron Acceleration in a Laser-Driven Micro-Structure," Nature 503, 91-94 (2013).
- J. Breuer and P. Hommelhoff, "Laser-Based Acceleration of Nonrelativistic Electrons at a Dielectric Structure," Phys. Rev. Lett. 111, 134803 (2013).
- T. Plettner, R. L. Byer, B. Montazeri, "Electromagnetic forces in the vacuum region of laser-driven layered grating structures," *J. Mod. Opt.* 58, 1518 (2011).
- C. M. S. Sears, et al., "Phase stable net acceleration of electrons from a two-stage optical accelerator," Phys. Rev. ST-AB 11, 101301 (2008).