Laser Acceleration on a Chip

Paul Scherrer Institut, Villigen Switzerland
Sept 22, 2015

R. Joel England

U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

Outline

Background: What is DLA?

Prior Art

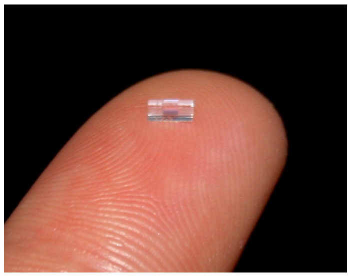
Recent Results

Experimental Challenges

Future Experiments

What is DLA?

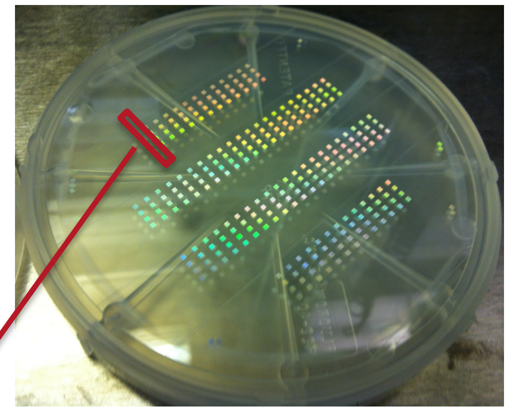
Dielectric Laser Acceleration (DLA) Concept



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

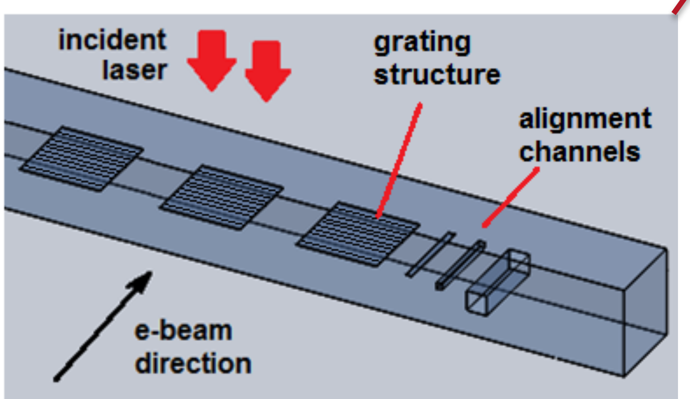
"Accelerator-on-a-chip"

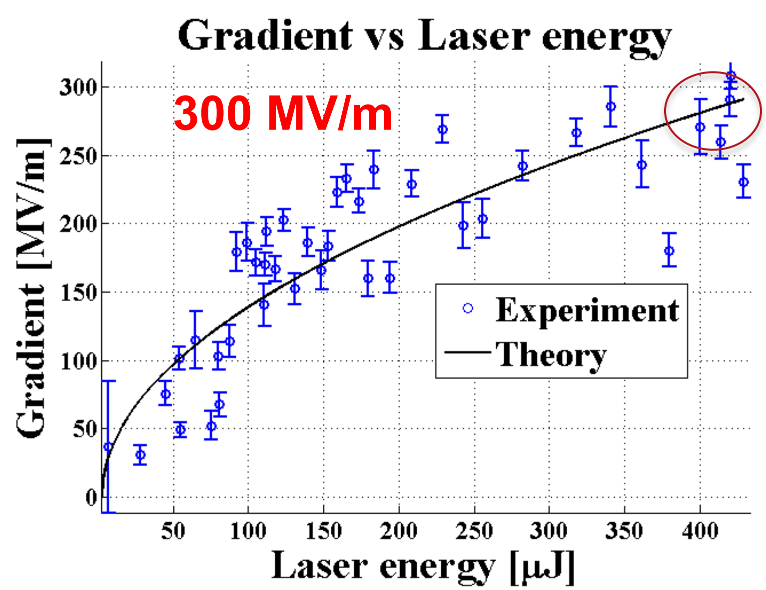


bonded silica phase reset accelerator prototypes fabricated at SLAC/ Stanford

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

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

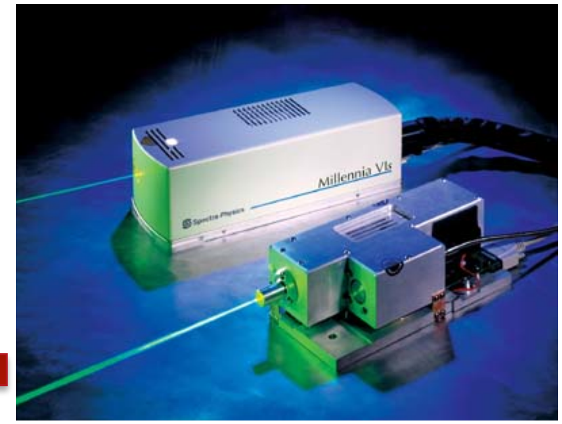




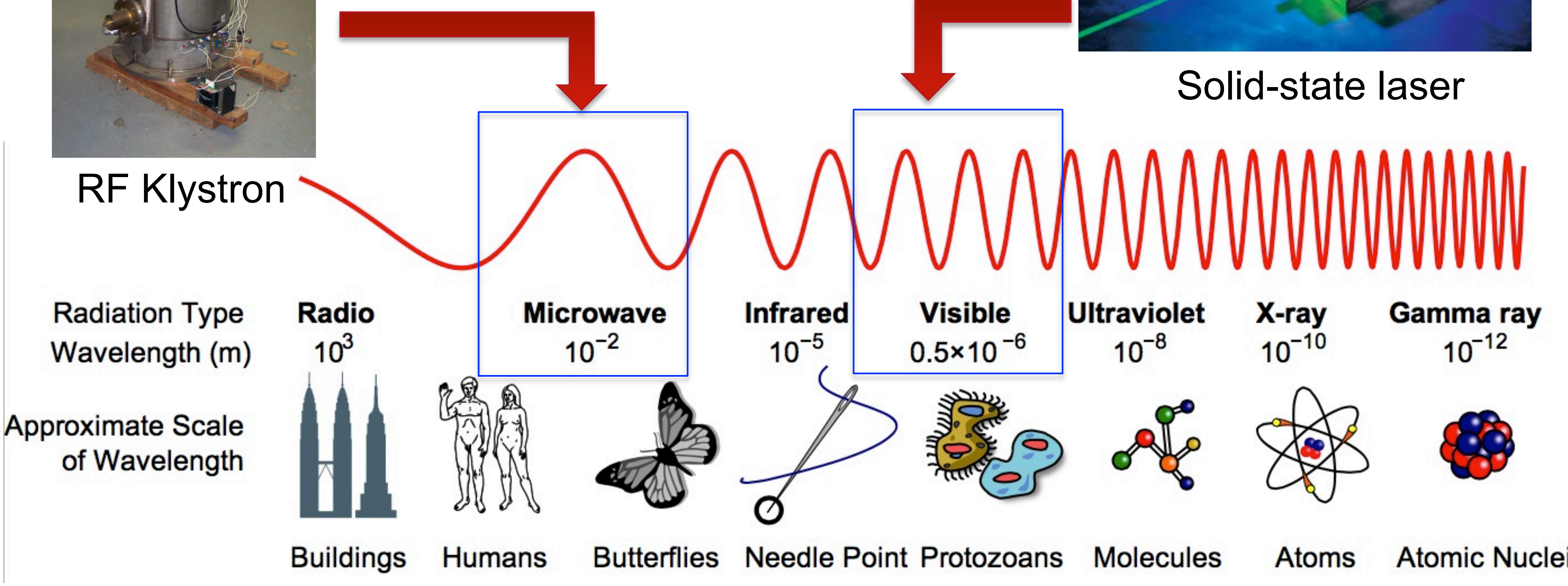
Lasers have followed a trajectory of exponential innovation.

RF Klystron

1. Smaller/less expensive than RF.
2. Energy efficient (near 50%).
3. High repetition rate (1 to 100 MHz).
4. Large electric fields (GV/m).

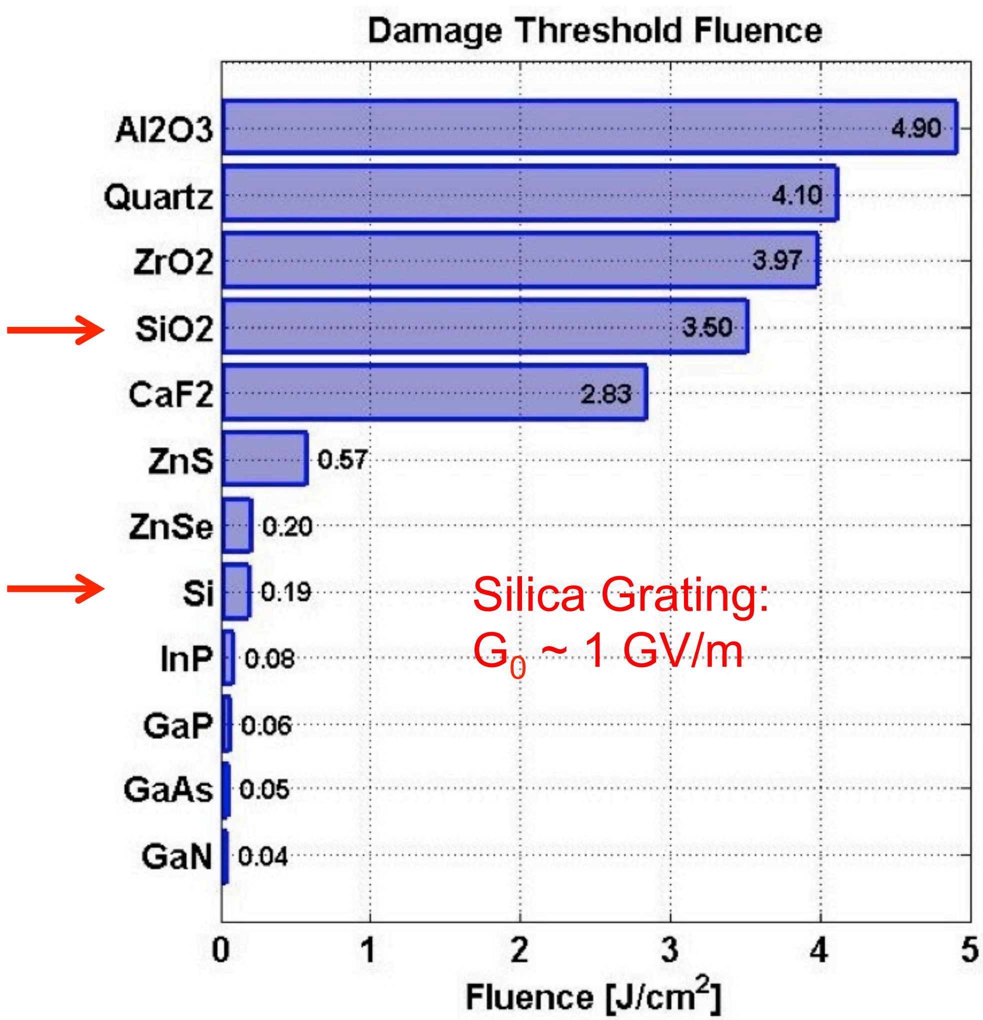


Solid-state laser



To obtain high gradients we need materials that can withstand intense laser fields.

“All accelerators operate at the damage limit” – Pief Panofsky



Ti:Sapph Laser wavelength: 800nm; Pulse length: 1ps; <u>Extensive data did not previously exist in this regime</u>.

Ken Soong

New technologies have made laser-driven micro-accelerators a possibility.

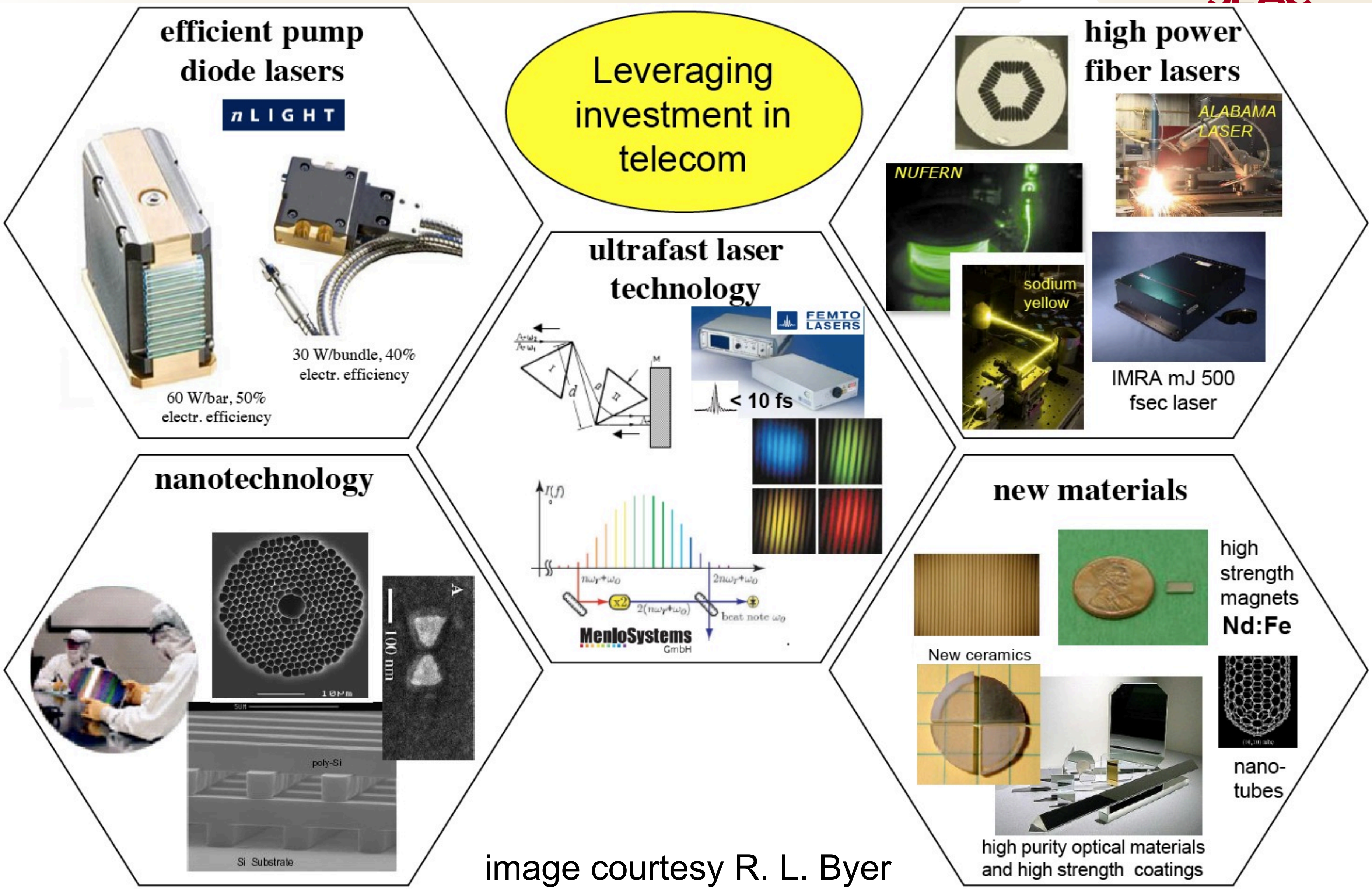
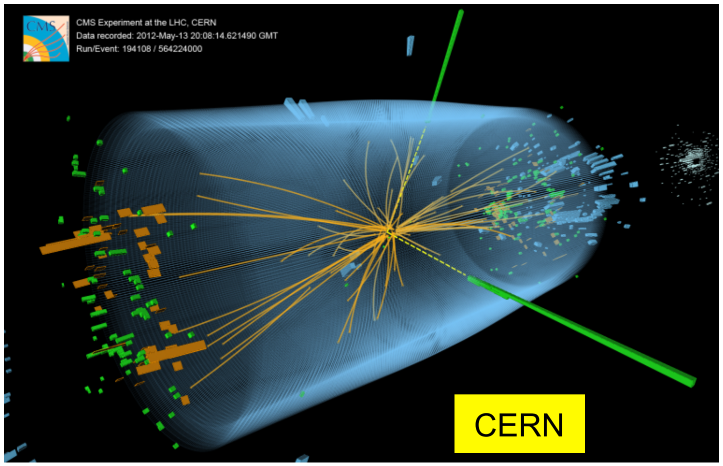


image courtesy R. L. Byer

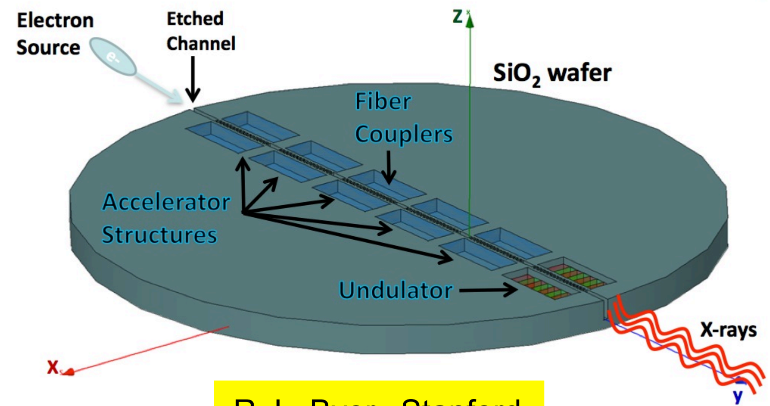
Such a system would have a variety of potential applications…

linear collider or Higgs factory



CERN

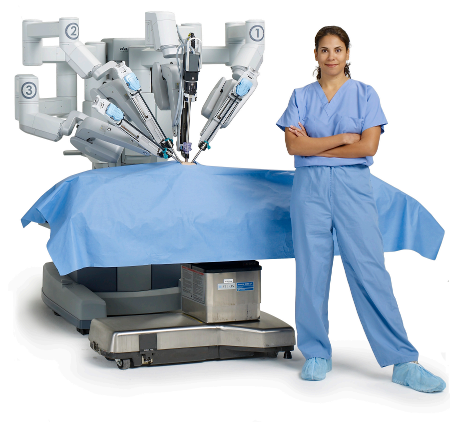
university-scale light source

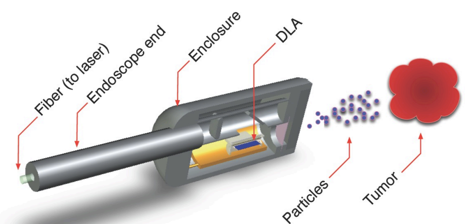


R. L. Byer, Stanford

SPRING8, UNE

medical imaging





Gil Travish, UCLA

portable cancer treatment

Various Nearer-Term Applications

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Medical: Brachytherapy

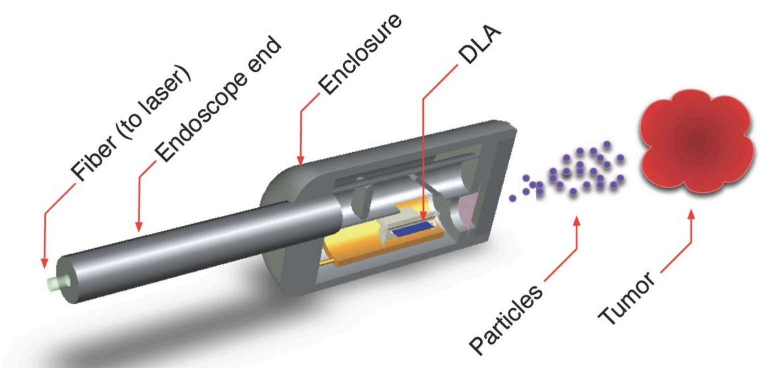
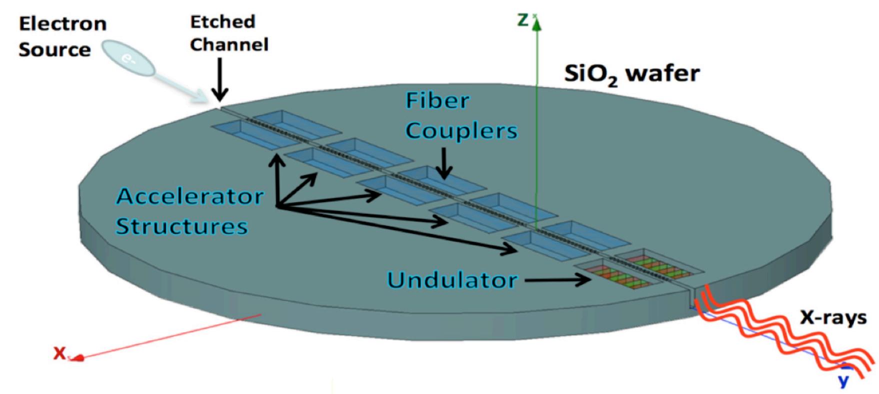


Image courtesy G. Travish (UCLA)

Direct ebeam tumor irradiation

- Improved targeting of tumor site
- Lower dose, less collateral damage
- Inexpensive devices → improved worldwide availability of treatment
- 20 MeV beam with 2000 e- bunches at 50 MHz → ~ 1 Gray/s

XUV Light Source



Wafer-scale XUV source w/ optical unduator

- Same operating principles can be used to make deflectors/undulators.
- Modelocking scheme proposed could enable attosecond radiation pulses (see Z. Huang, AAC14)
- 40 MeV beam, 10 fC, 250 um undulator period → 660 attosec XUV (50 eV) pulse train with 100 nJ/pulse

DLA Applications: Linear Collider

P. Bermel, et al, "Summary of the Dielectric Laser Accelerator Workshop," **NIM-A** 734, 51-59 (2014).

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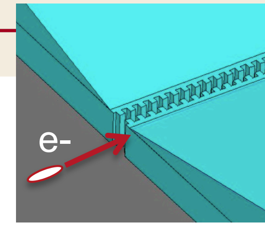
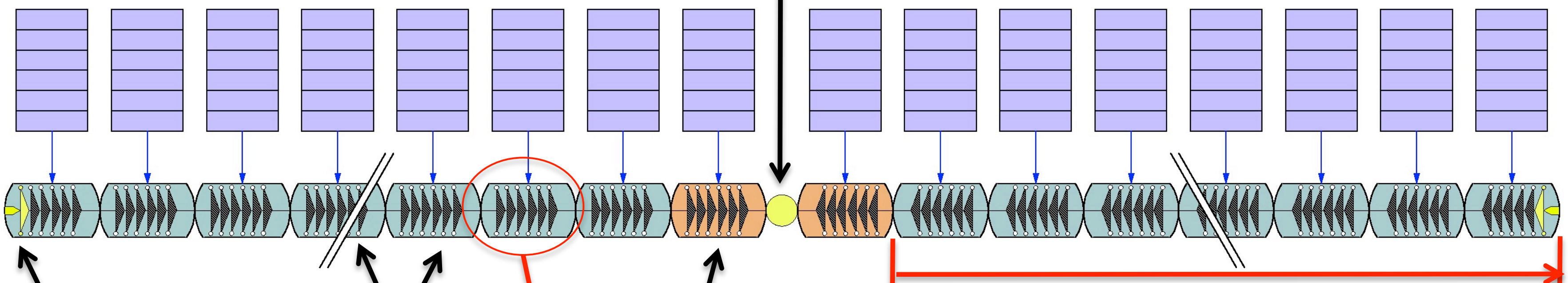
6 fiber lasers per
6" wafer module
2 kW per laser

Thulium fiber laser λ=2 μm

Interaction Point



concept for 1 DLA accelerator structure (E. Peralta)



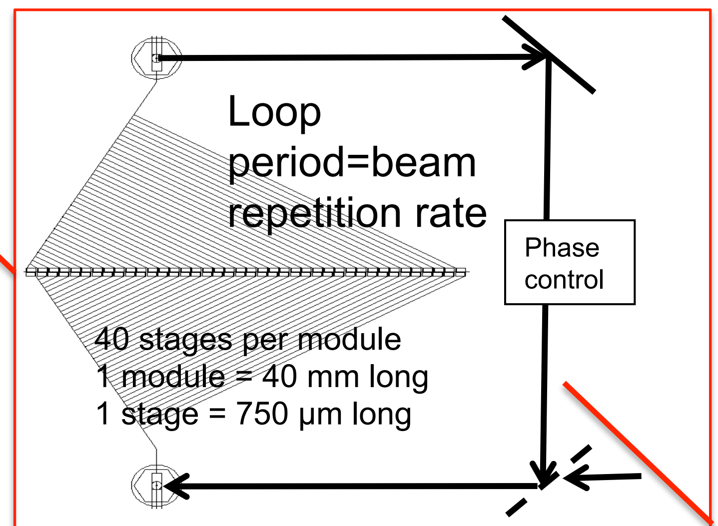
0.5 TeV ⇔ 500 m ⇔ 15,700 lasers

needle emitter and injector module

accelerator wafers

final focus and steering wafers

Parameter	Units	CLIC 3 TeV	DLA 3TeV	DLA 250 GeV
Bunch Charge	e	3.7e9	3.0e5	3.8e5
Rep Rate	MHz	5e-5	20	60
Beamstrahlung E-loss	%	**28.1**	**1.0**	**0.6**
Enhanced Luminosity / top 1%	cm-2/s	2.0e34	3.2e34	1.3e34
Wallplug Power	MW	582	374	152



Prior Art

Shortly after lasers were invented it was suggested to use them to accelerate particles.

Koichi Shimoda, Applied Optics 1 (1), 33 (1961)

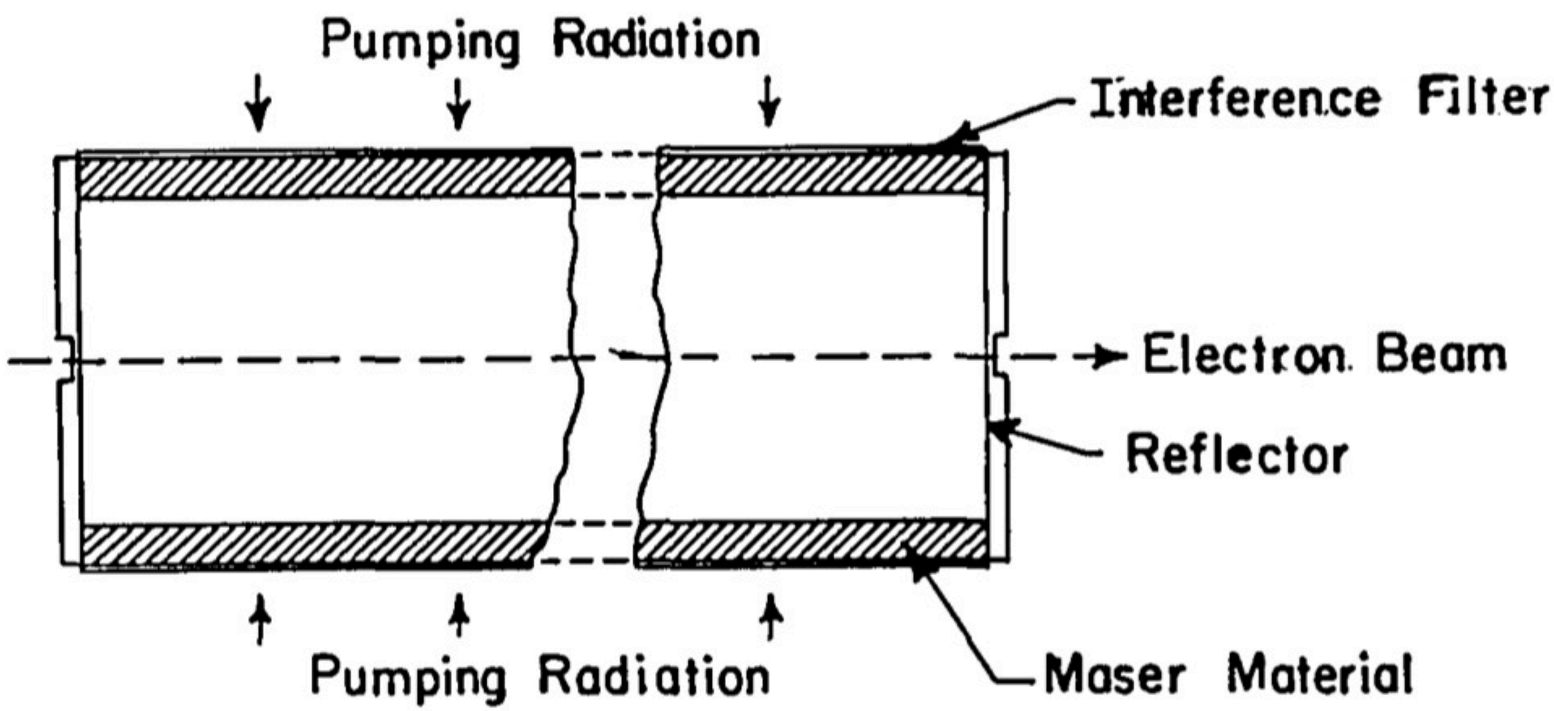


Fig. 1. Schematic diagram of an electron linear accelerator by optical maser.

A variety of micro-accelerator concepts have been proposed…

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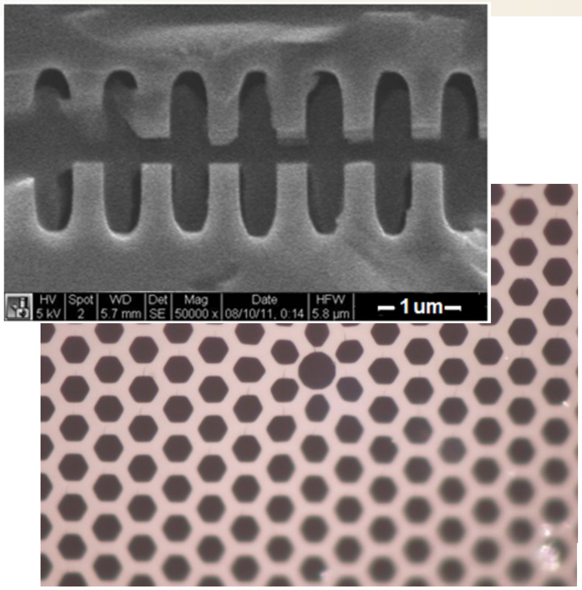

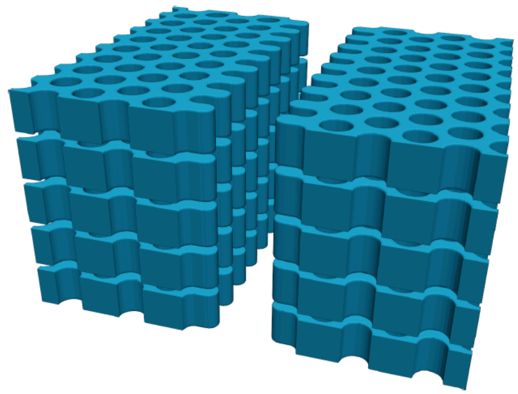

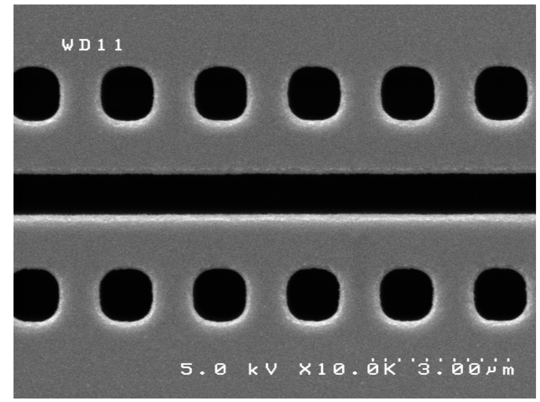

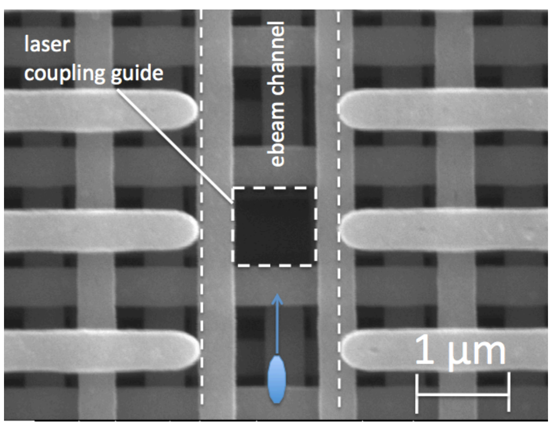

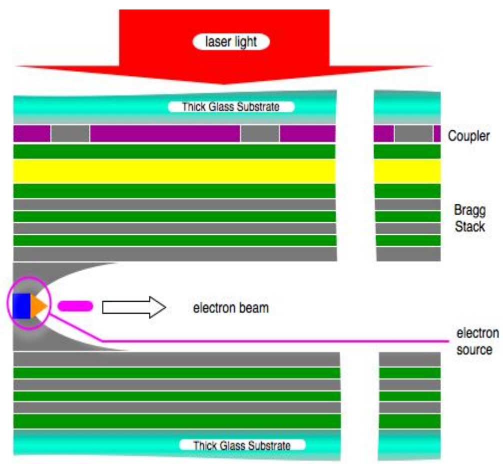

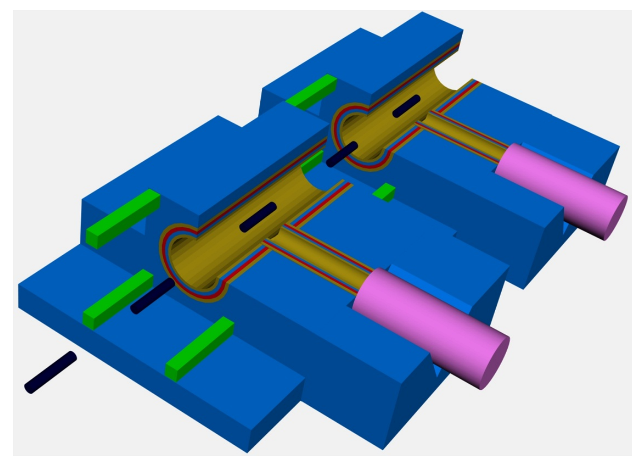

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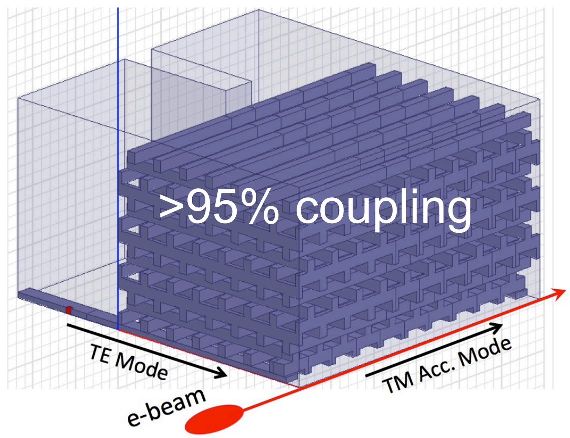
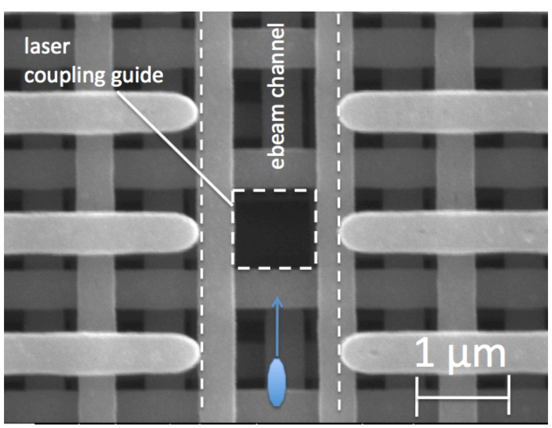
… as well as compatible accelerator subcomponents

Efficient Coupler Designs

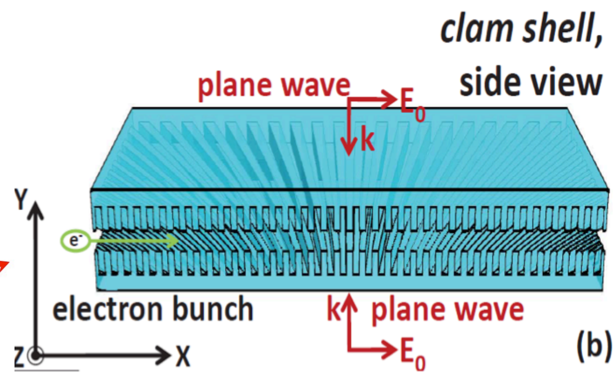




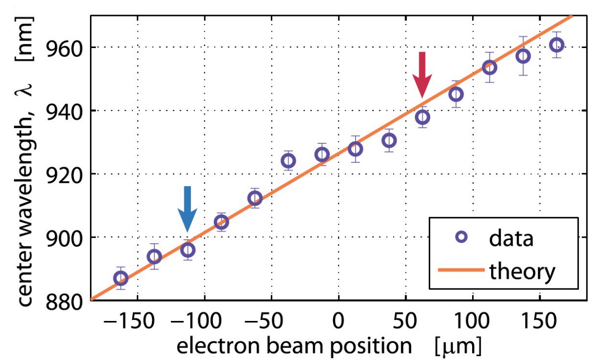
C. McGuinness, Z. Wu

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

Beam Position Monitor

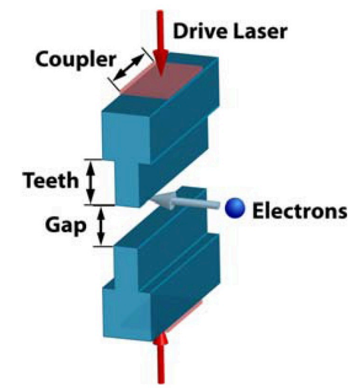


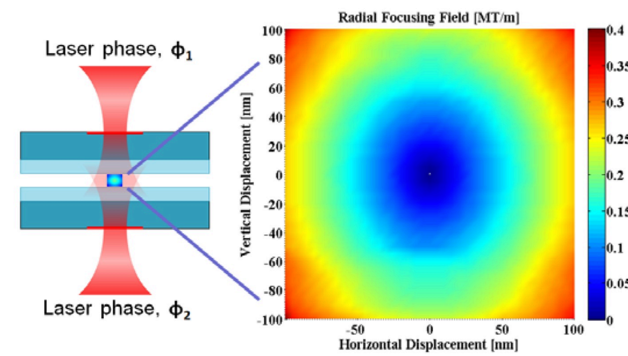
Opt. Lett., **37** (5) 975-977 (2012)



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

Focusing Structures



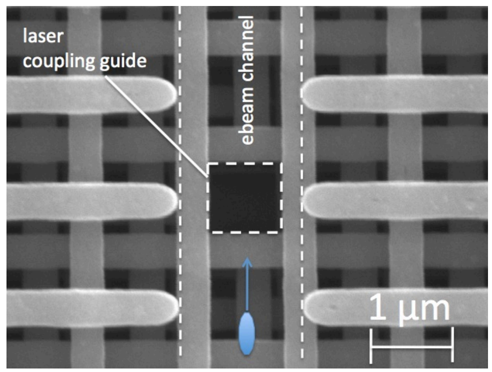


AIP Conf. Proc. **1507**, 516 (2012)
J. Mod. Opt. **58** (17), 1518-1528 (2011)

A variety of early 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).

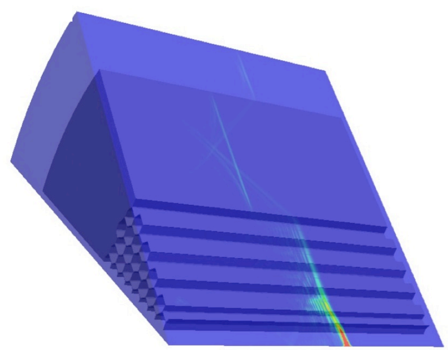


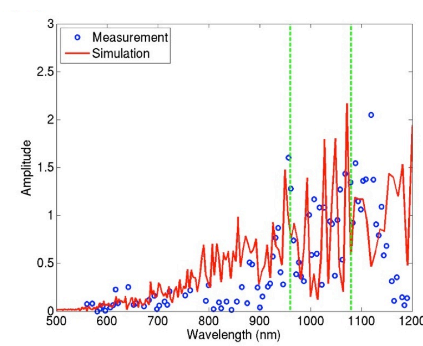
3D Photonic crystal fabrication with complex multi-layer designs suitable for efficient power coupling

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

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

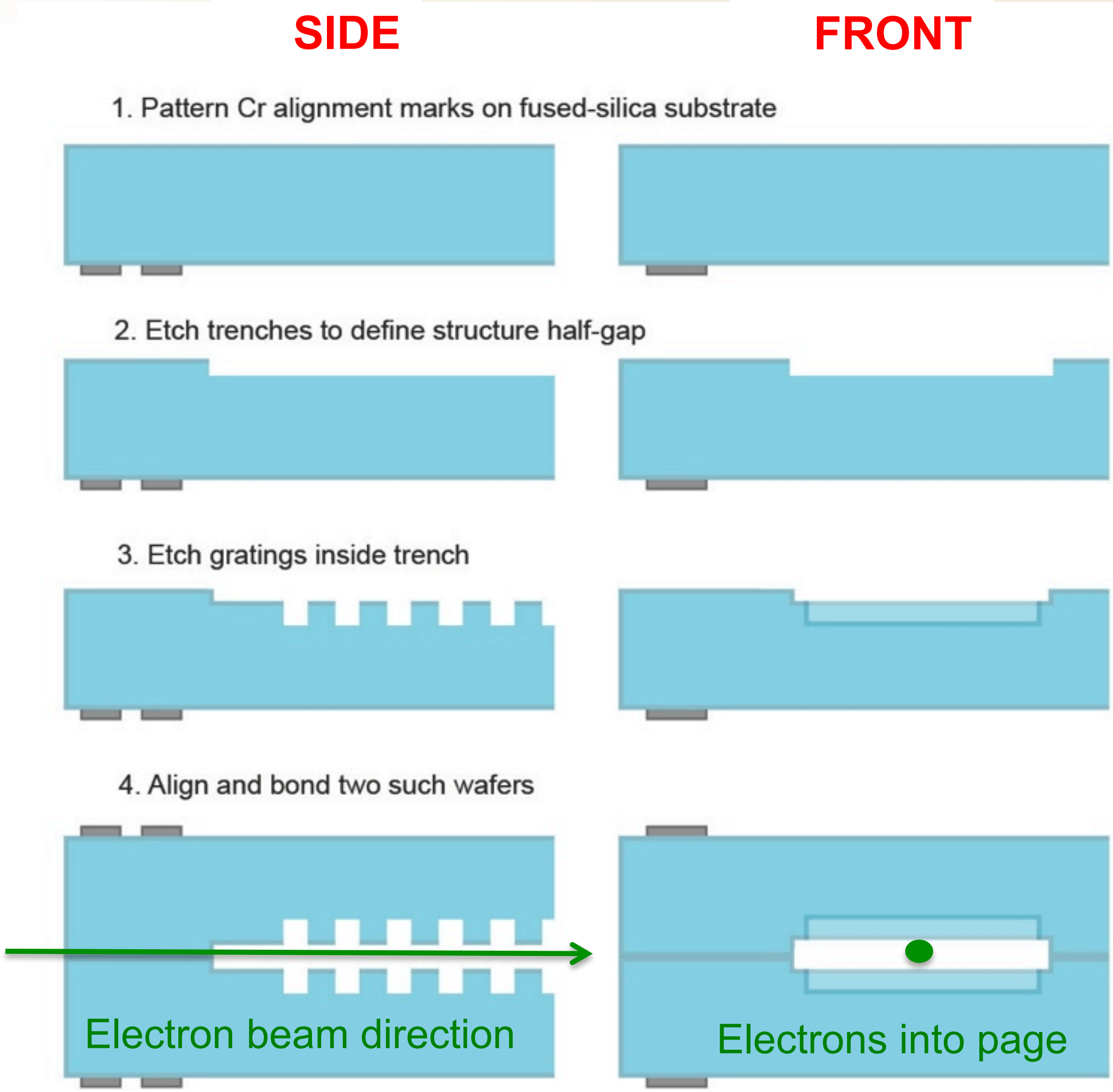
C-K. Ng, et al. PR-STAB **13**, 121301 (2010)
R. J. England, et al. AIP Conf. Proc. 1086, 550 (2009)

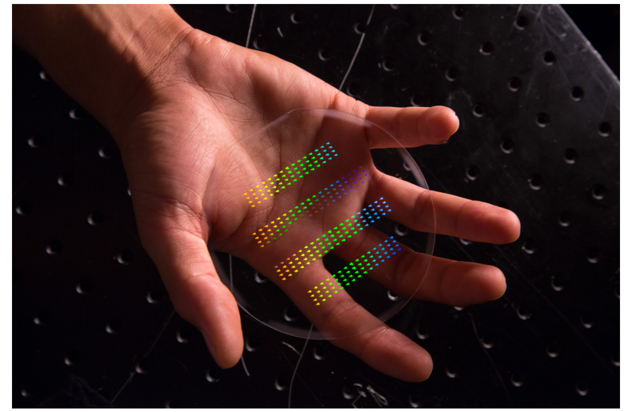


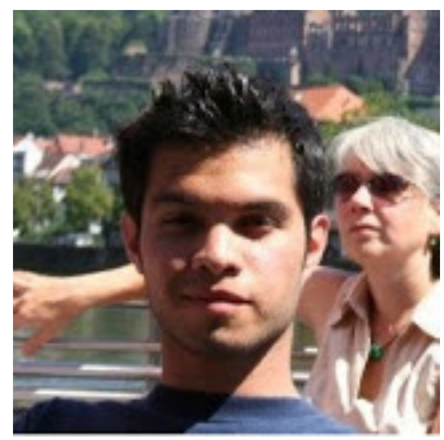


Recent Results

First prototype structures were made of fused silica glass at Stanford Nanofabrication Facility

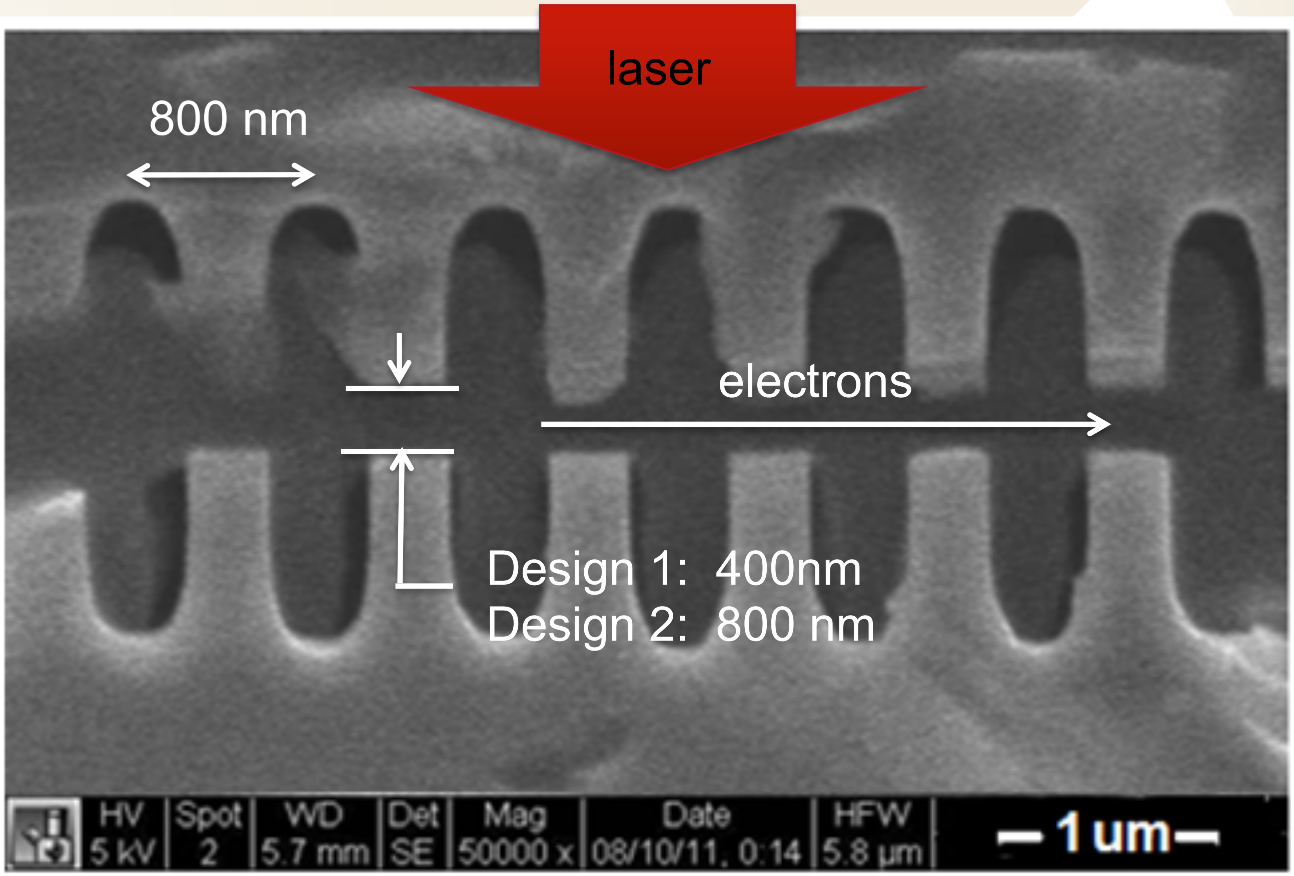






Edgar Peralta

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.

We conduct demonstrations using a pre-accelerated test electron beam and infrared laser.

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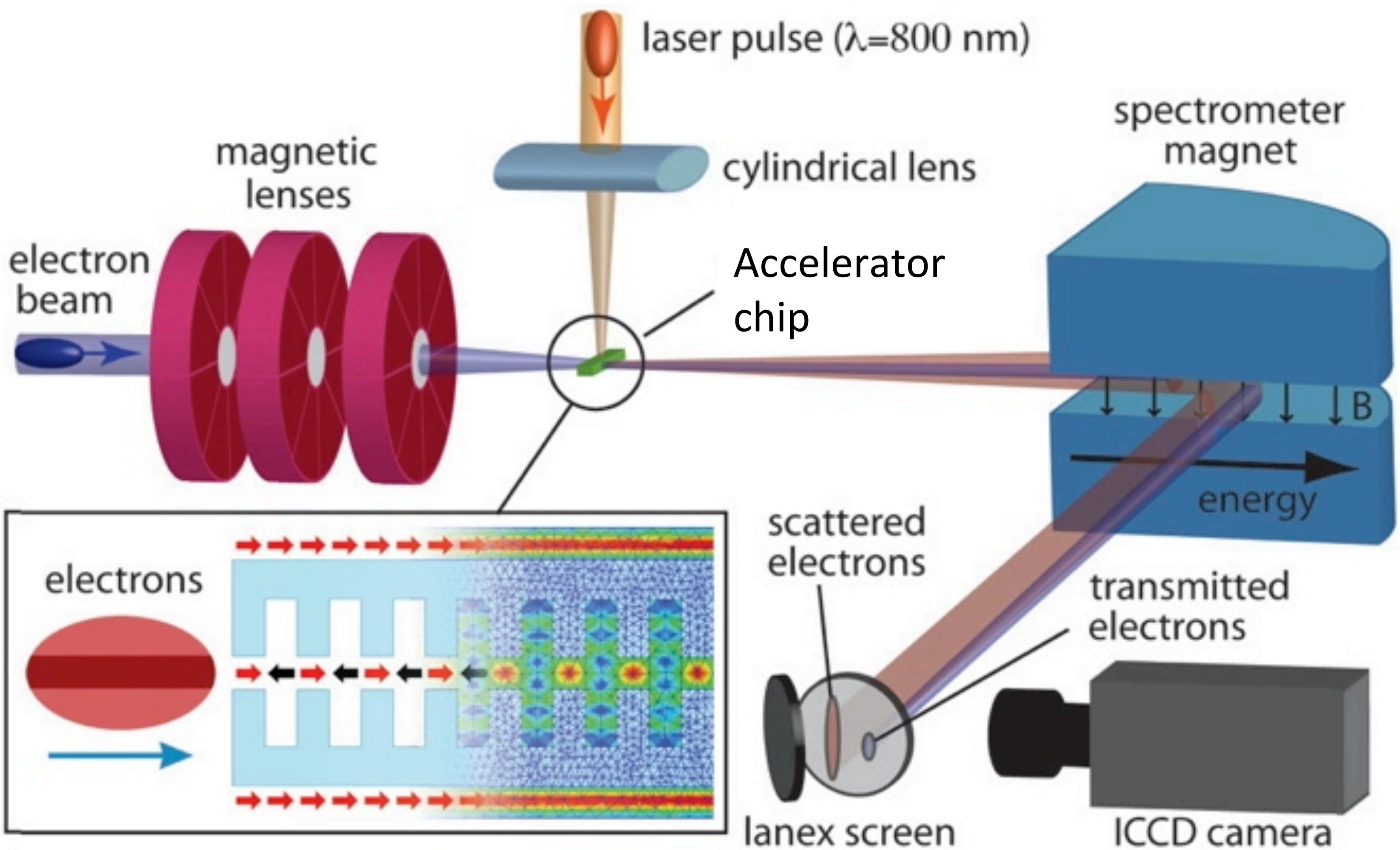
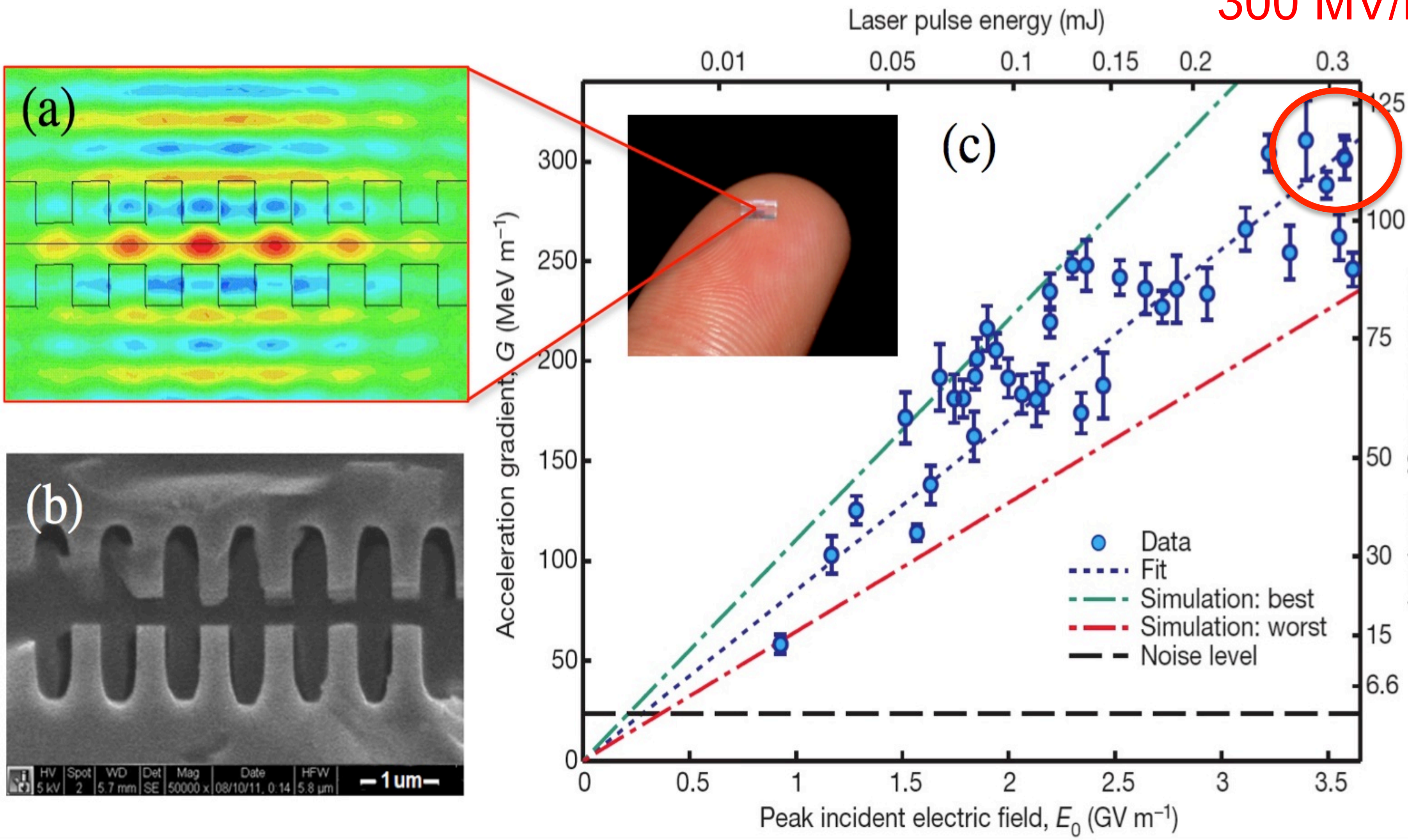


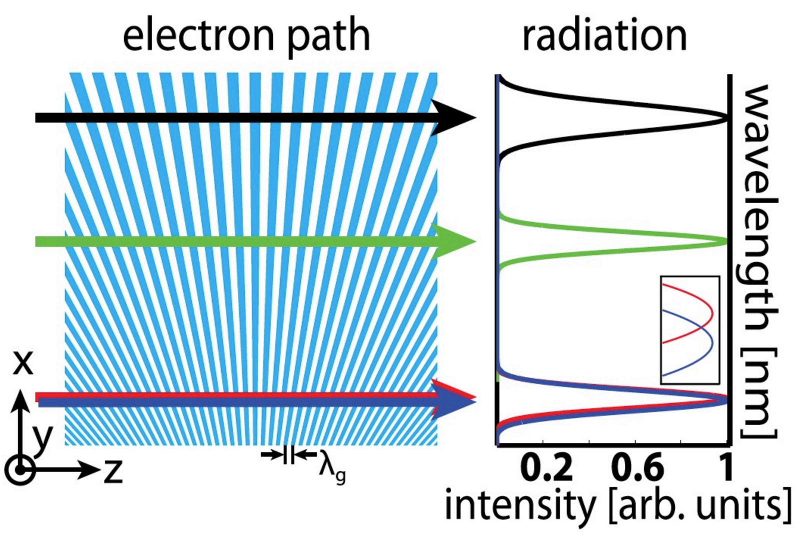
Gradients have been observed that are 10 times higher than the main SLAC linac…

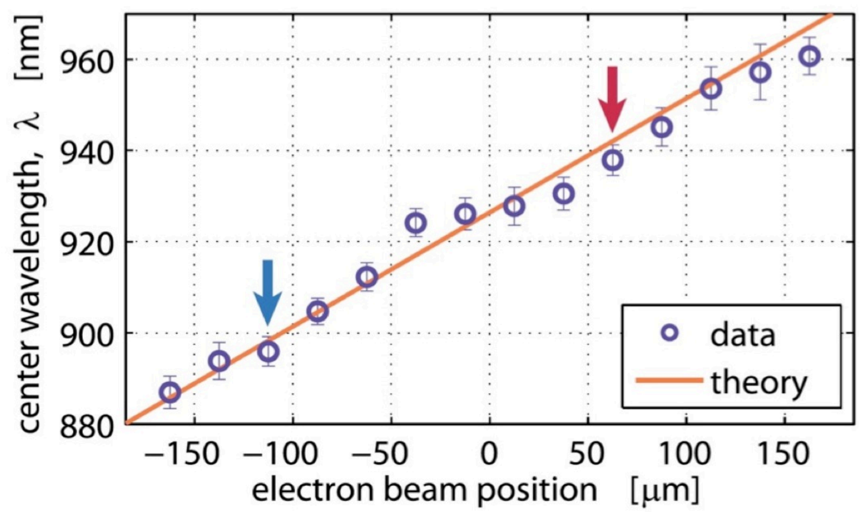
300 MV/m



The "reverse" process has been shown as a way to precisely measure particle position.

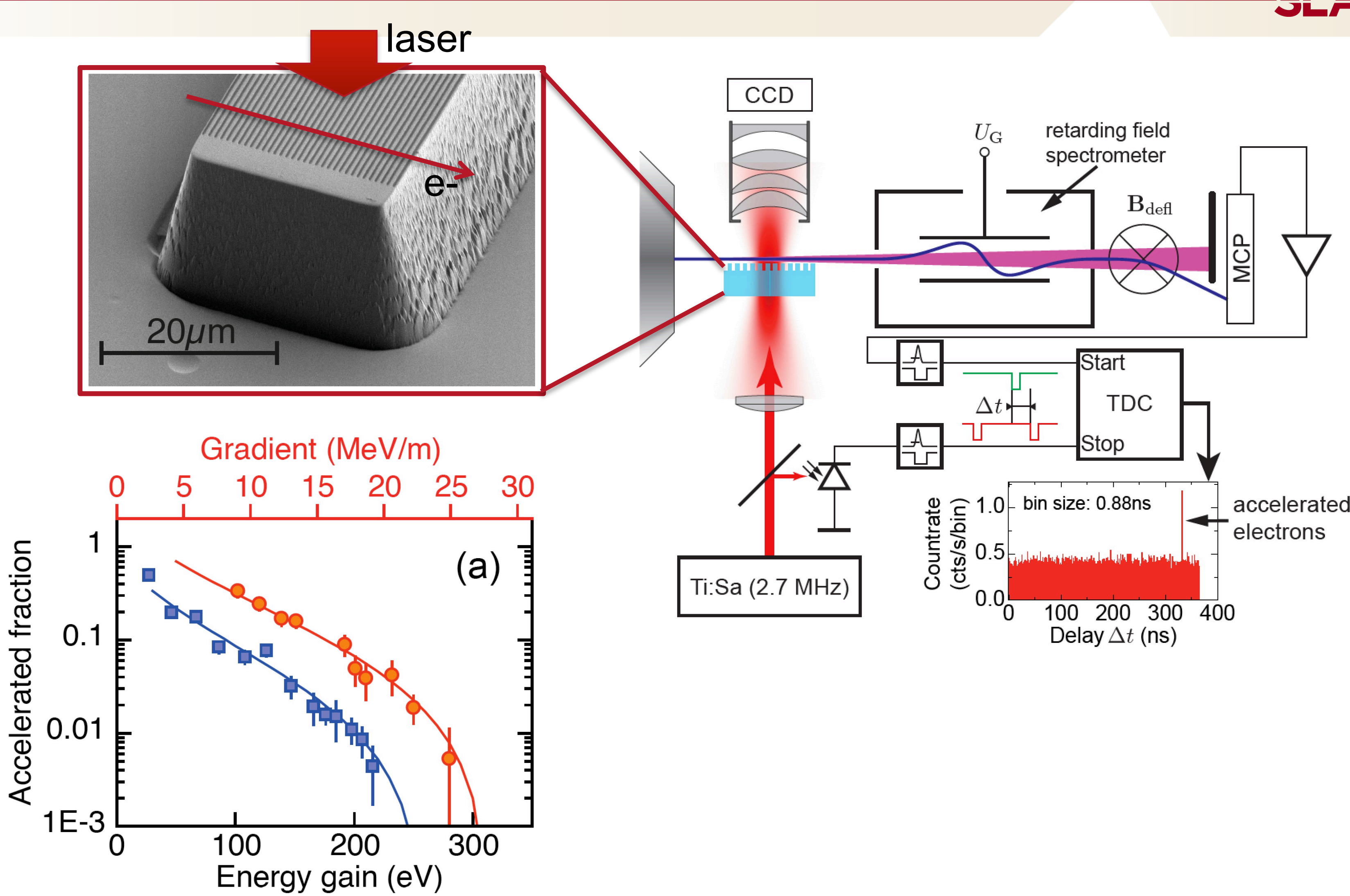
"To be efficient, the accelerator must operate in reverse."
- Ron Ruth, SLAC





K. Soong, et al., Opt. Lett. **39** (16), 4747 (2014)

25 MV/m gradients were simultaneously demonstrated at 30 keV electron energy at U. Erlangen.



Breuer and Hommelhoff, Phys. Rev. Lett. **111**, 134803 (2013)

A SEM test stand for more extensive subrelativistic DLA demonstrations has been built at Stanford.

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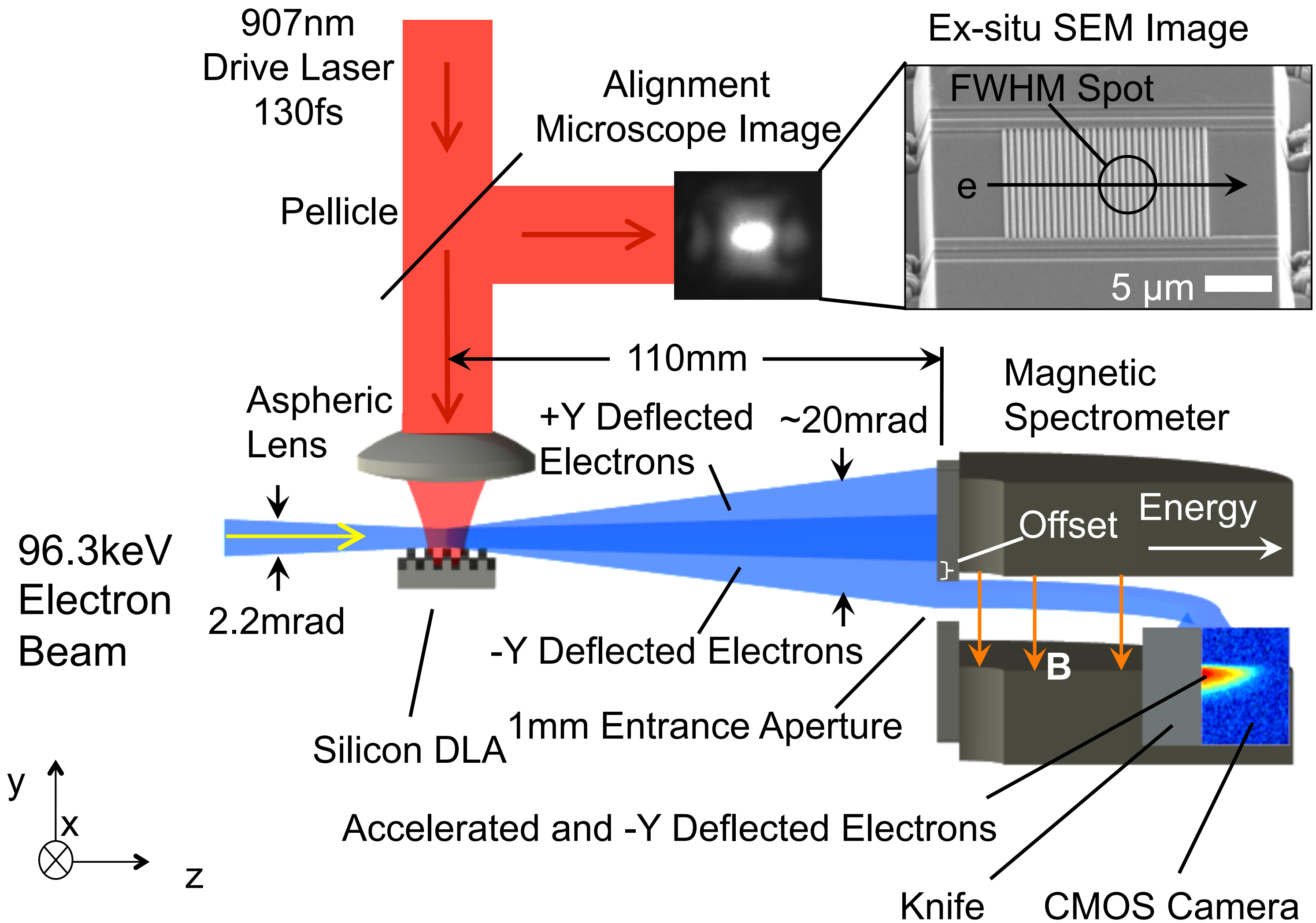
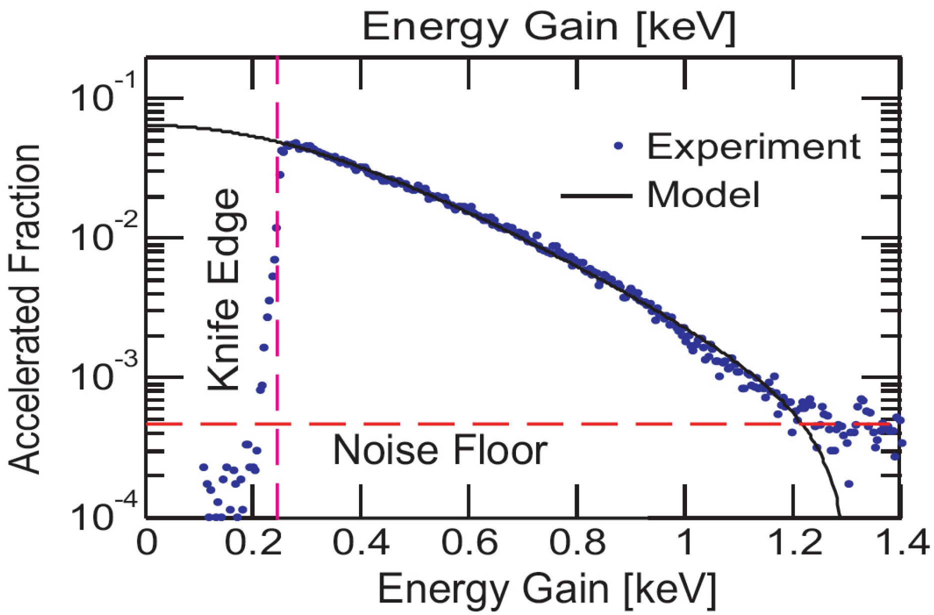
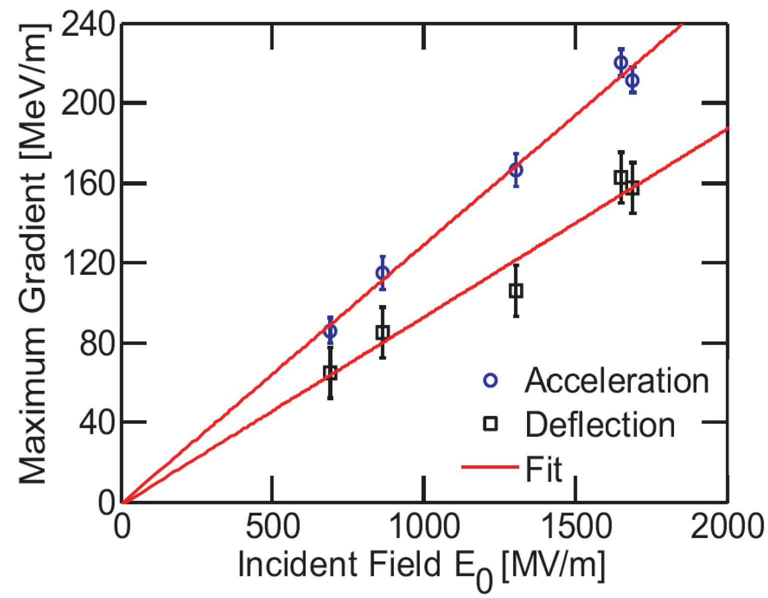
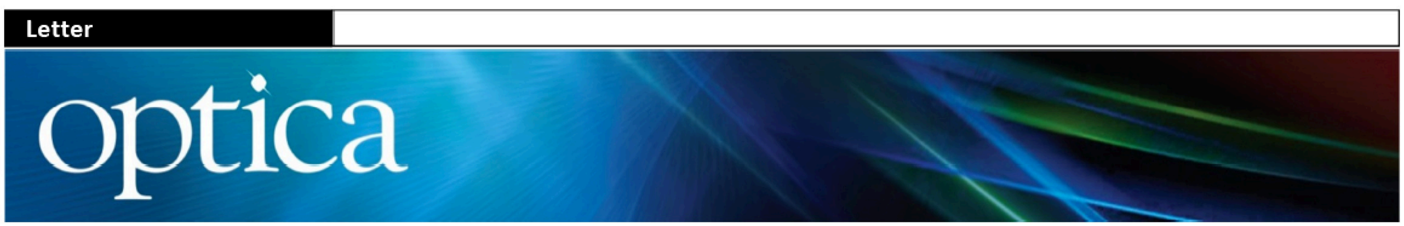


K. J. Leedle, R. F. Pease, R. L. Byer, and J. S. Harris, *in preparation* (2014).

… and has been used to demonstrate 240 MV/m gradients using 96 keV electrons.







Laser Acceleration and Deflection of 96.3 keV Electrons with a Silicon Dielectric Structure

KENNETH J. LEEDLE,[1,*] R. FABIAN PEASE,[1] ROBERT L. BYER,[2] AND JAMES S. HARRIS[1,2]

A recently demonstrated alternative dual-pillar design allows higher gradient and field enhancement.

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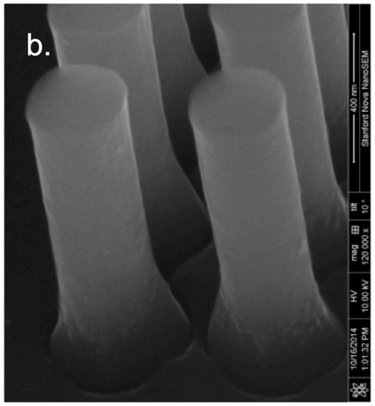
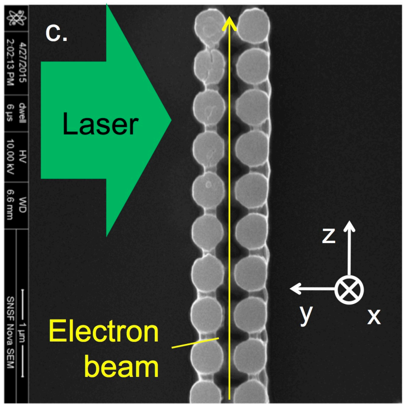
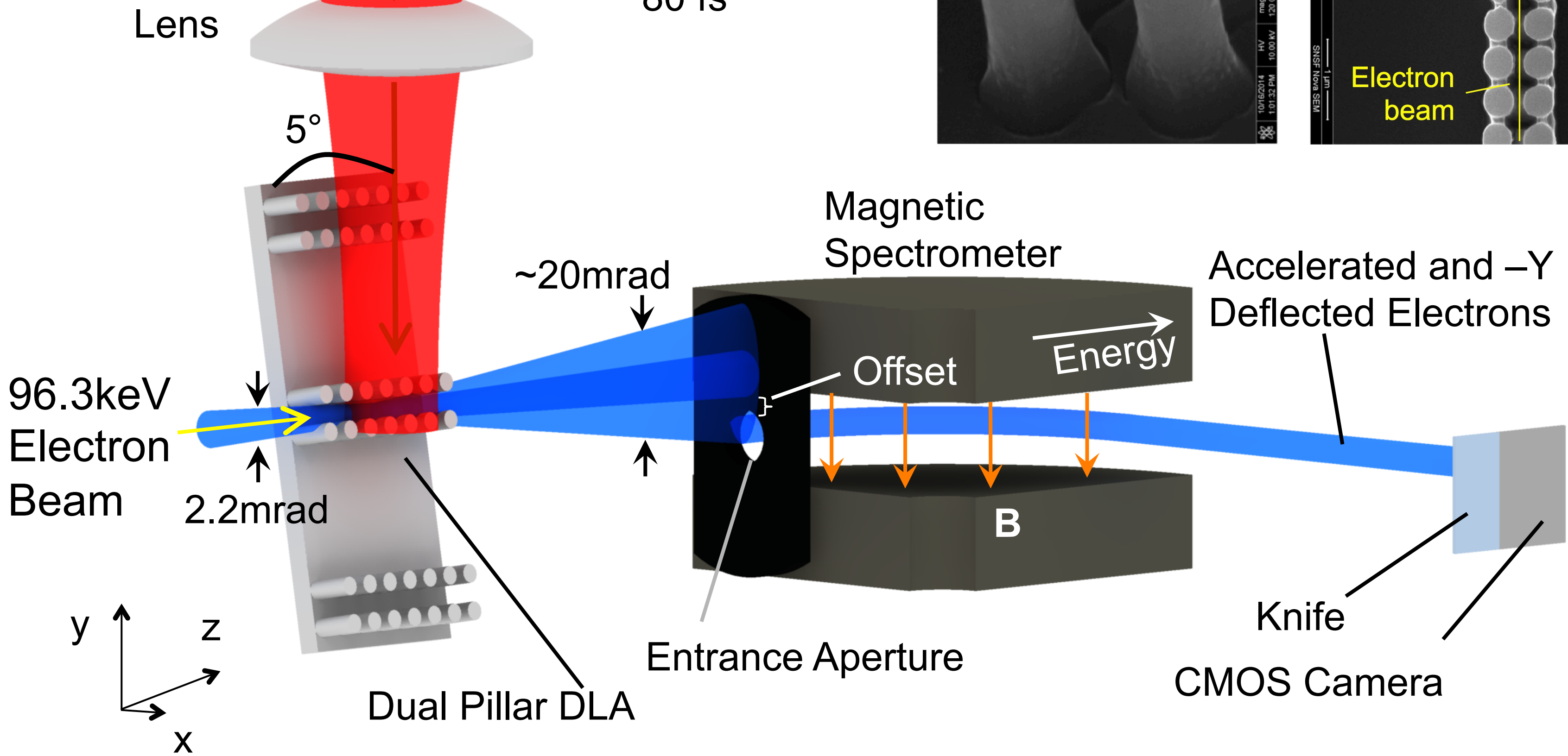


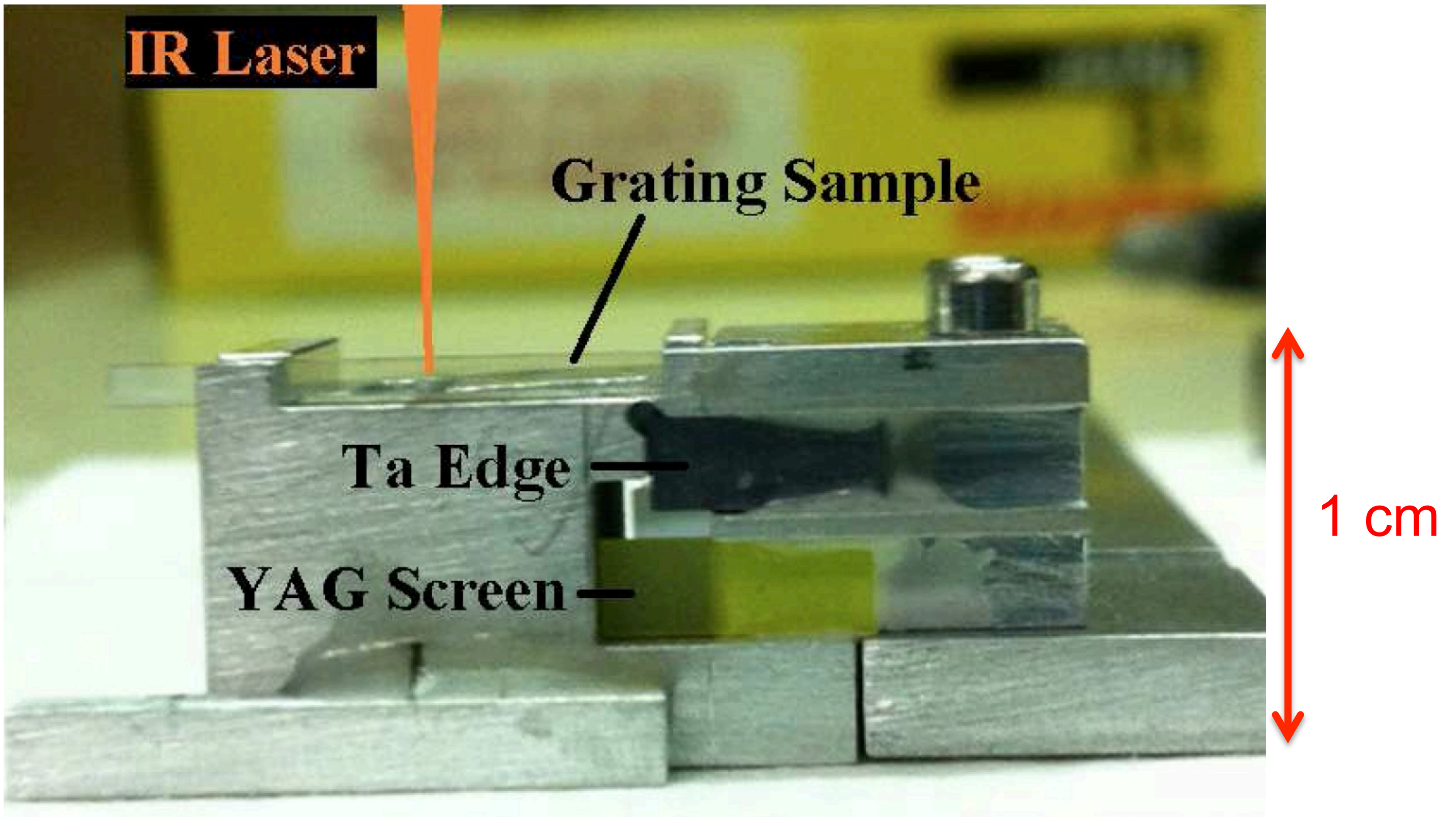




K. Leedle, et al. Opt. Lett. **40** (18) 4344 (2015)

Experimental Challenges

These are tiny structures! The accelerating channels are not visible without magnification.



For typical beam sizes, only a small fraction of the particles make it through the accelerating channel.

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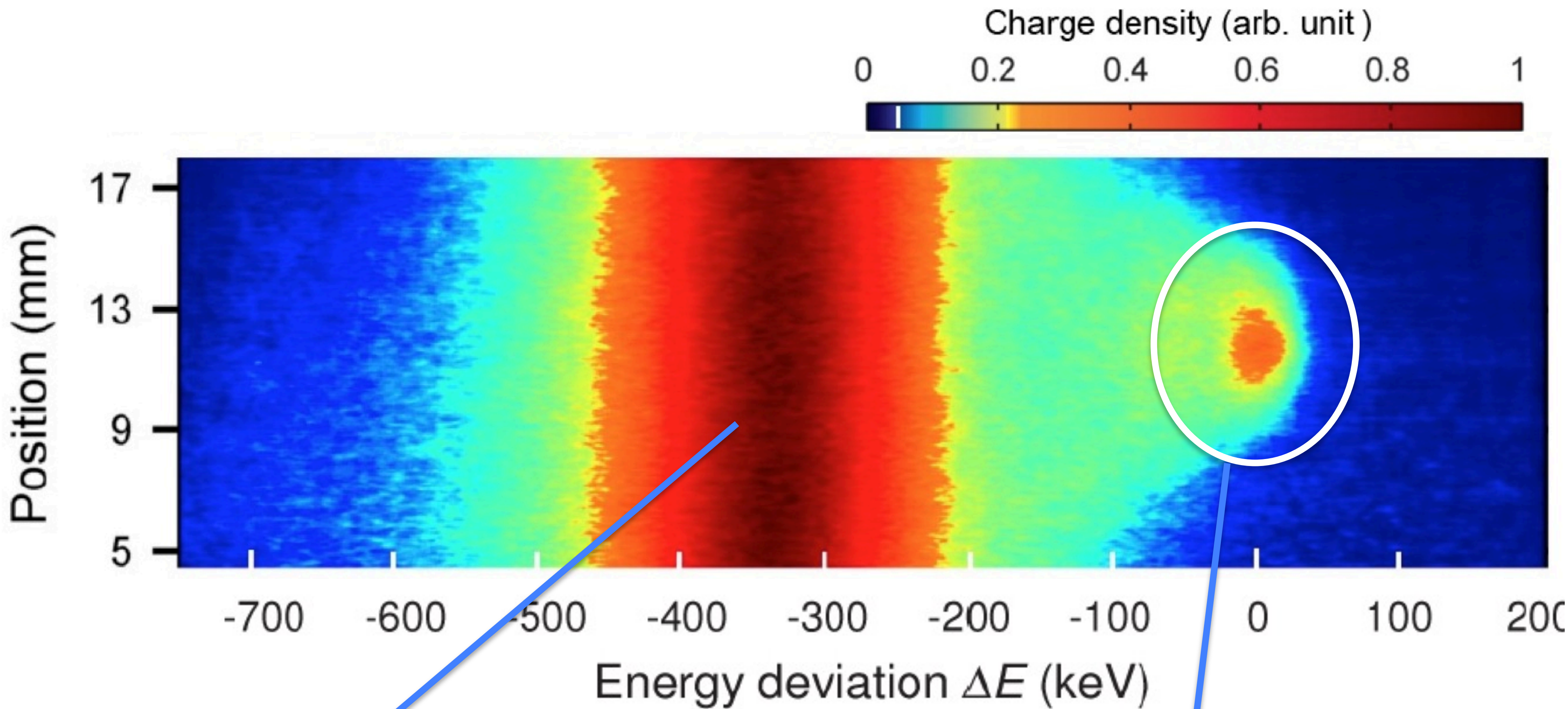

Particles that hit the glass substrate (98%)

Particles transmitted through the accelerating channel (<2%)

In experiments to date, electron pulse is also longer than the wavelength of the laser.

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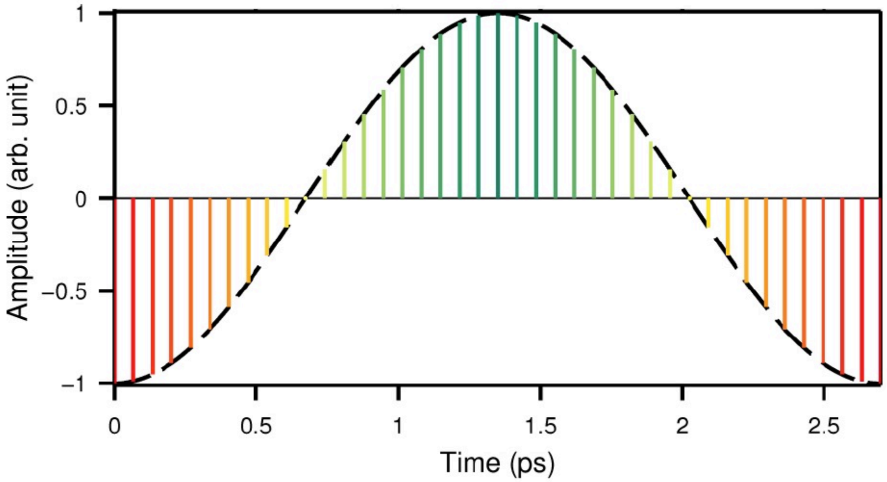
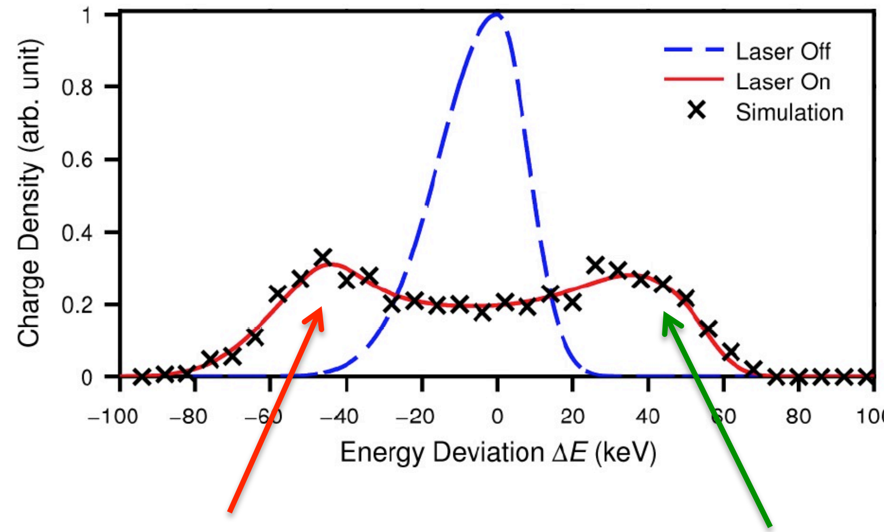
Accelerating wave



Green: energy gain
Red: energy loss

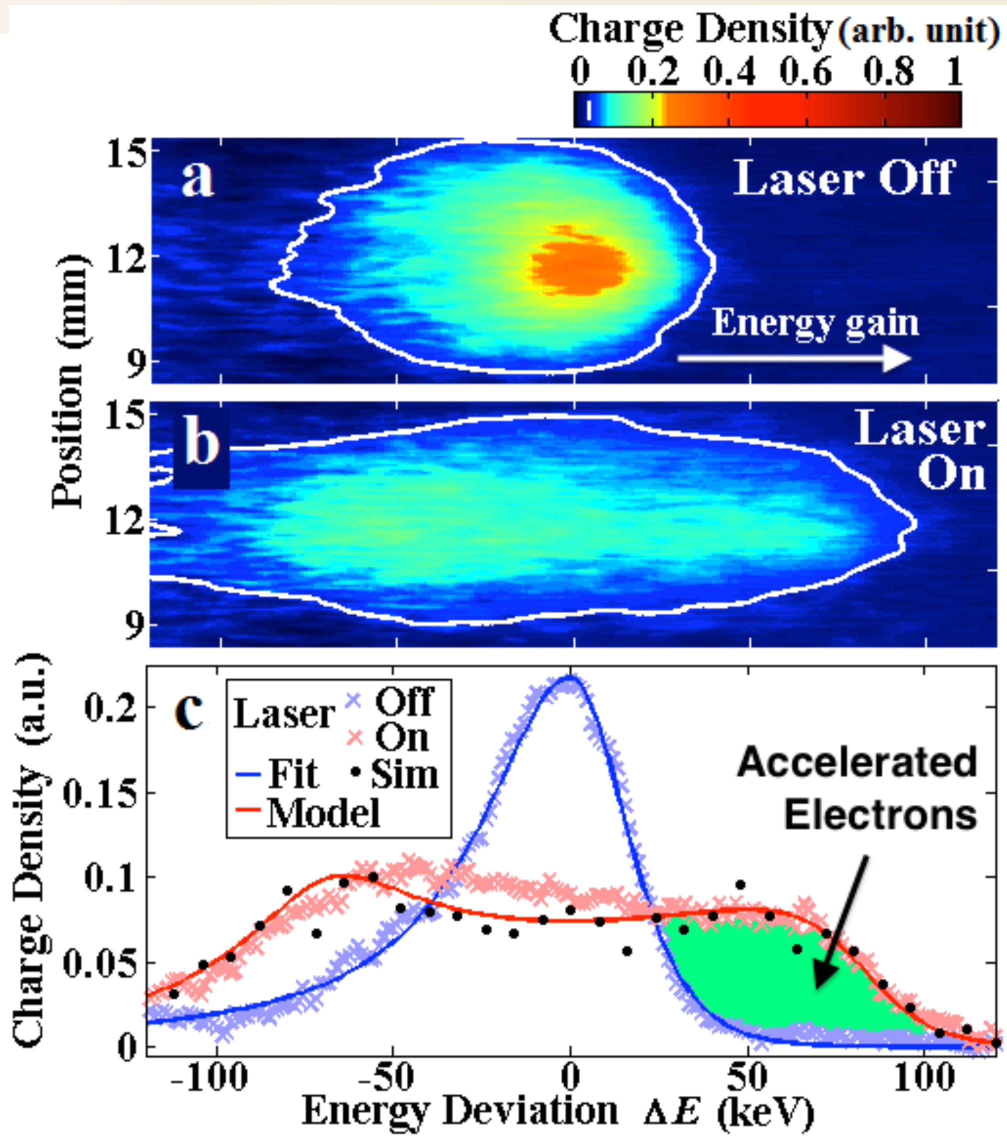
Particle Energy Distribution



Decelerated particles

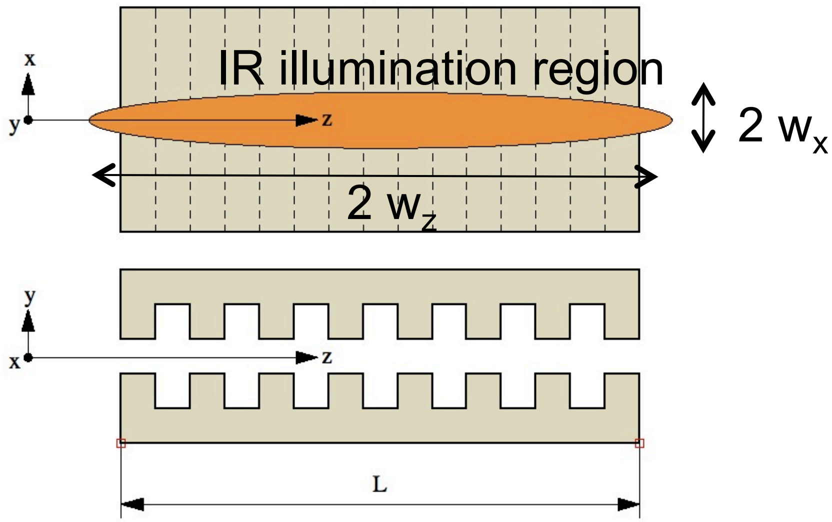
Accelerated particles

So gradient is measured by observing the resultant energy modulation.

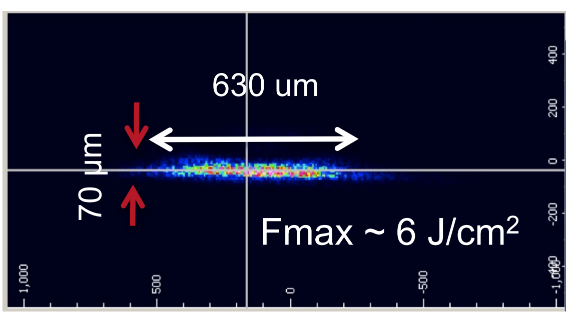


Dephasing places additional constraints on structure length and angular laser alignment.

Reduced Interaction Length



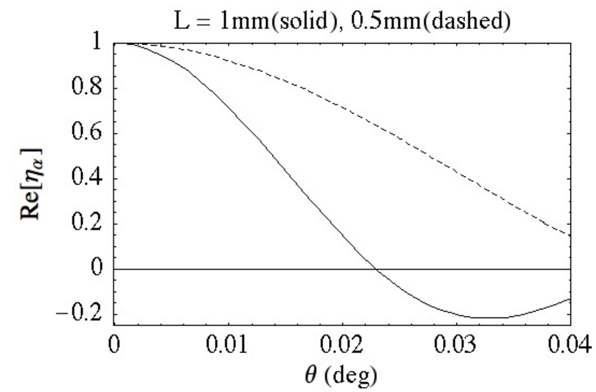
Reduced IP Spot Size

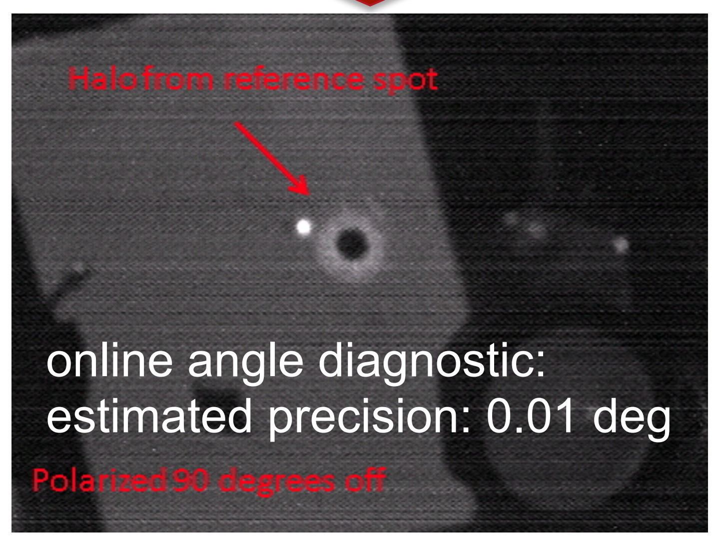


$L \sim w_z \sim \Delta t$

Laser pulse length reduced from 3.3 to 1.5ps

Angular Dephasing





Precise timing, mode profile, spatial overlap, and electron beam stability are therefore needed.

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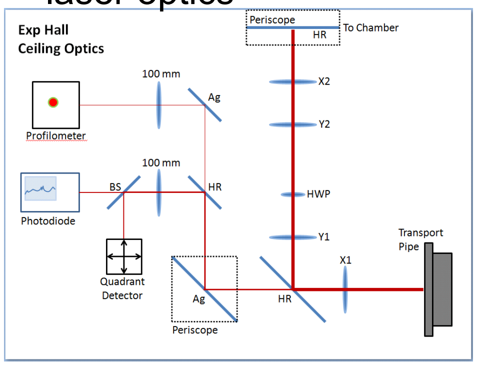
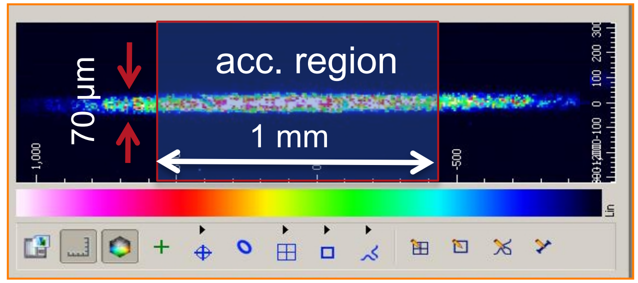
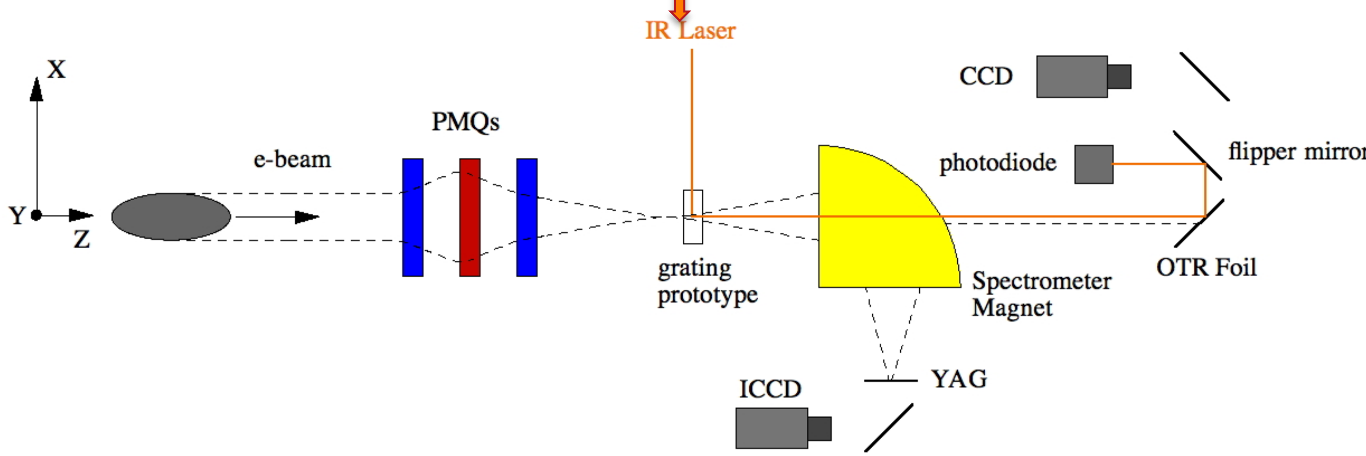
laser optics



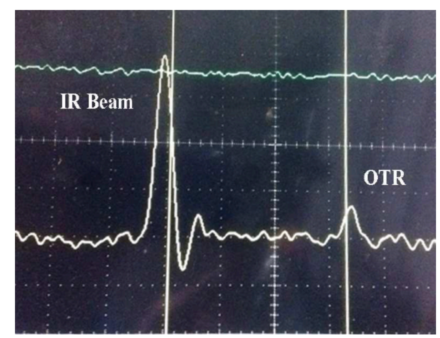
CCD image of tailored IR laser profile



IR



<u>Laser Parameters</u>:
Ti:Sapph 800nm,
3ps, 600 Hz rep rate
1 mJ per pulse
IP Fluence: 0.2 J/cm^2



Optical Transition Radiation (OTR) timing diagnostic for overlap of IR and ebeam with 50ps photodiode

Desired Experimental Parameters

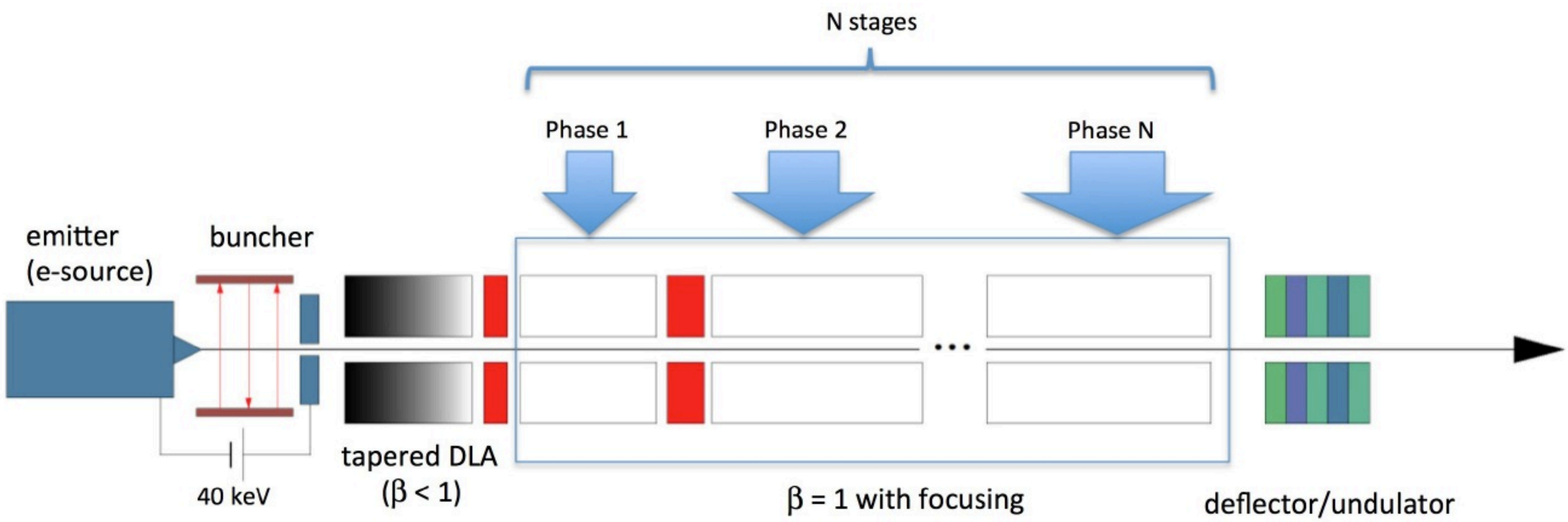
Parameter	Demonstration	Ideal
Bunch Charge	≤ 1 pC	1-5 fC
Normalized Emittance	≤ 1 μm	1-5 nm
RMS Spot Size	≤ 10 x 10 μm	100 x 100 nm
Laser Wavelength	1-10 μm	1-2 μm
Laser Pulse Length	10-1000 fs	10-1000 fs
Laser Pulse Energy	10-1000 μJ	1-10 μJ
Rep Rate	1-100 Hz	10-100 MHz
Energy Spread	2.6e-4	2.6e-4

Future Experiments

Breakdown by Components; Time Scale ~ 5 Years

Overall goal: The demonstration of an integrated multi-stage particle "accelerator on a chip" will validate the potential to scale to energy levels of interest for "real-world" applications.

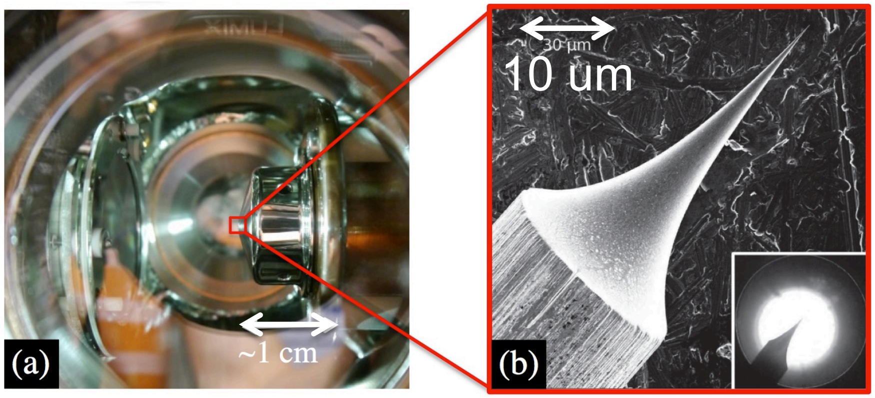
1. On-chip electron source
2. DLA structure development: (a) subrelativistic, (b) relativistic
3. Multi-staged acceleration
4. Coupling of laser to DLA
5. Laser-driven deflectors and undulators



1. On-Chip Electron Source

SLAC

What is the current state of the art?
laser-triggered nanotip field emitters
30 keV energy, 10 nm emittance
2000 e- per pulse; 1cm footprint



P. Hommelhoff, Erlangen Univ.

Lead institutions:
Erlangen U., Germany (Hommelhoff)

Where do we need to go?
high brightness (1 fC @ 1 MHz or 1 nA)
integrated on-chip with DLA

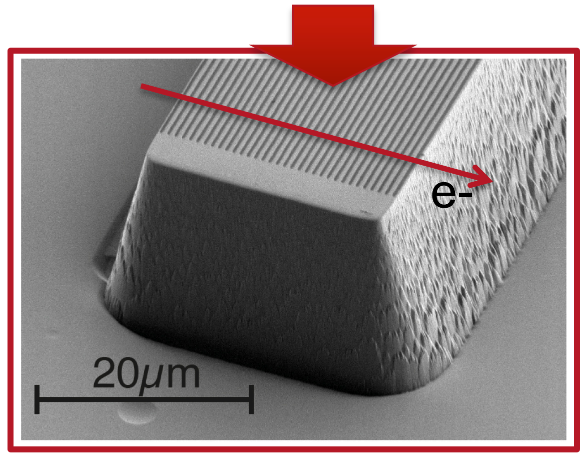
Risks and mitigations?
Lifetime (metal tips damage at high rep rate) → alternative materials (e.g. diamond)

Nanotip sources developed by university collaborators offer a path to on-chip electron sources.

2a. DLA Structure Development (Sub-relativistic Energy)

SLAC

What is the current state of the art?
25 MV/m (30 keV beam energy)
220 MV/m (100 keV beam energy)



P. Hommelhoff, Erlangen Univ.

Lead institutions:
Erlangen U., Germany (Hommelhoff),
Stanford U. (Harris)

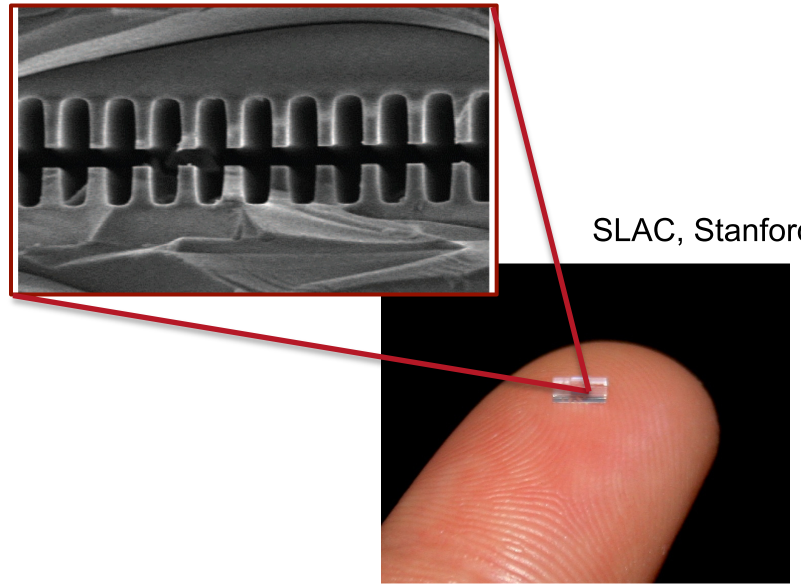
Where do we need to go?
Tapered DLAs for changing e- velocity
Optical microbunching in the DLA structure.

Risks and mitigations?
Beam containment with small apertures → need strong focusing elements built in

University experiments in last 2 years at low energy (30keV to 100 keV) are making progress toward compatible on-chip injectors.

2b. DLA Structure Development (Relativistic Energy)

What is the current state of the art?
long-pulse (1.3ps FWHM): **300 MV/m**
short-pulse (70 fs FWHM): **700 MV/m**



SLAC, Stanford

Lead institutions:
SLAC (England), Stanford U. (Byer), UCLA (Rosenzweig, Musumeci)

Where do we need to go?
1 MeV energy gain per stage
Net acceleration with microbunched electrons

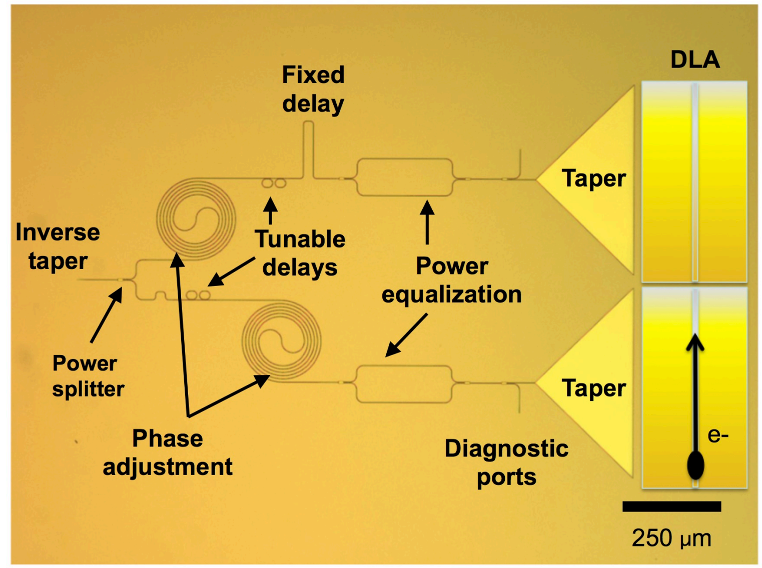
Risks and mitigations?
Extending the interaction length → use pulse front tilted laser beams

National lab experiments have shown high-gradient operation and set the stage for scaling DLA to multi MeV energies.

3. Multi-staged Acceleration

What is the current state of the art?
STELLA @ BNL using IFEL (2004)
LEAP @ SLAC using ITR at a metal foil (2008)

Lead institutions:
Stanford U. (Byer, Harris, Solgaard),
SLAC (England), Purdue U. (M. Qi),
Erlangen U., Germany (Hommelhoff)



M. Qi, Purdue Univ.

Where do we need to go?
2 to 8 stages @1 MeV/stage
Start with free space coupling, proceed to optical waveguides

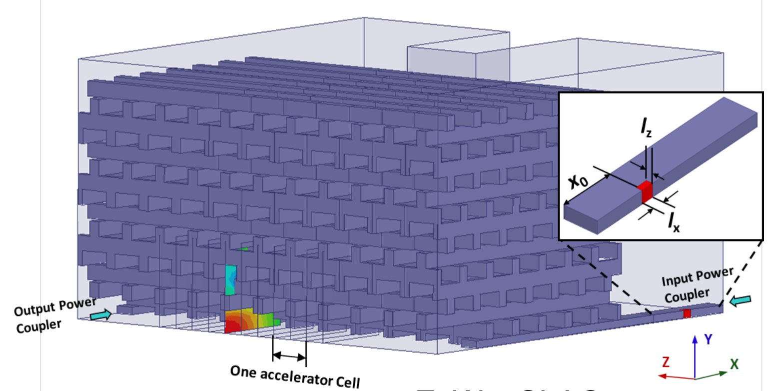
Risks and mitigations?
Timing & phase control → on-chip resonators to thermally control phase

Nanofabricated photonic structures enable staging of many DLAs to reach particle energies of interest for real-world applications.

4. Coupling to DLA Structure

What is the current state of the art?
Near 100% power efficiency shown <u>in simulation</u>

Lead institutions:
SLAC (England, Ng), Purdue (M. Qi)
Stanford U. (Vuckovic, Fan),



Z. Wu, SLAC

Where do we need to go?
Fabricate and demonstrate efficient designs.
Combine them to make laser distribution networks.

Risks and mitigations?
Dispersion control (for sub-ps pulses) → hollow-core photonic xtal designs

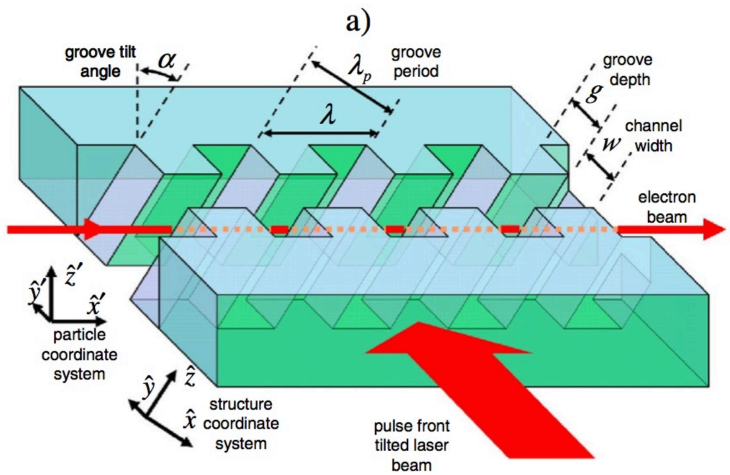
Work to date has been largely simulation: need to fabricate and demonstrate these designs.

5. Laser-Driven Deflectors and Undulators

What is the current state of the art?
Simulational designs published/patented

Lead institutions:
Stanford U. (Byer), SLAC (England, Tantawi),

Where do we need to go?
Measure single and multi-period deflection
Produce undulator radiation in X-ray and XUV



T. Plettner, Stanford (2008)

Risks and mitigations?
Background discrimination (brehmsstrahlung) → develop designs for K > 0.1

Development of DLA-based laser deflectors would enable on-chip beam steering and radiation production for a compact medical device.

Milestones toward a real-world DLA device.

SLAC

✔ Optical microbunching. (SLAC, Sears 2008)

✔ Single-staged DLA with high gradient. (Peralta, Breuer, Leedle 2013-2015)

→ Net acceleration, 2-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 on one wafer.

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

SLAC

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
SLAC: Burt Richter
Stanford: Persis Drell

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

Summary

• Dielectric Laser Acceleration (DLA) offers a compact and lower cost alternative to future RF based accelerators with potential gradients in the 1 to 10 GV/m range.

• Recent progress in DLA has demonstrated the basic viability of the concept at both relativistic and sub-relativistic energies, with promising intial gradients (> 300 MV/m).

• Experimental parameters are stringent but achievable.

• Future experiments require suitable test facilities and electron sources with low-charge (<pC) low-emittance (<μm) beams and compatible laser systems.

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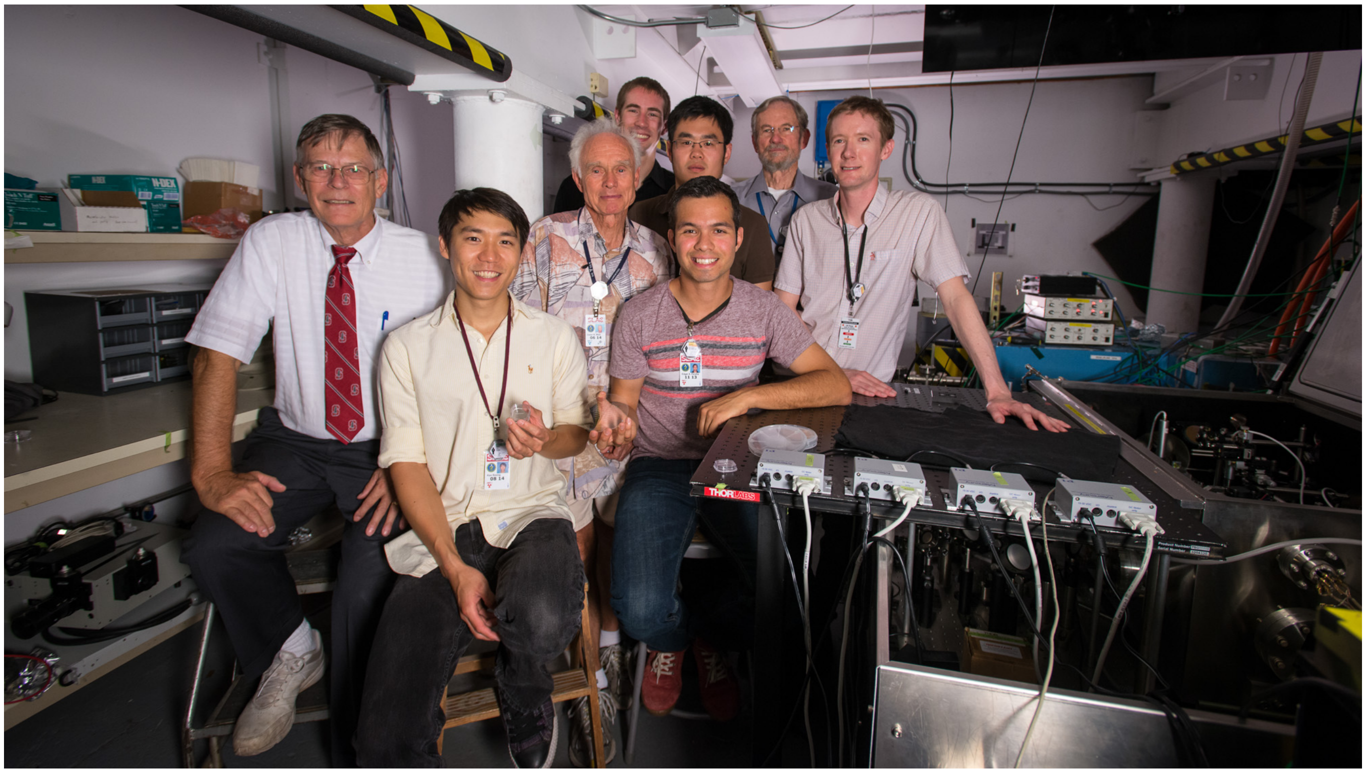
Thank you!



contact: england@slac.stanford.edu

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