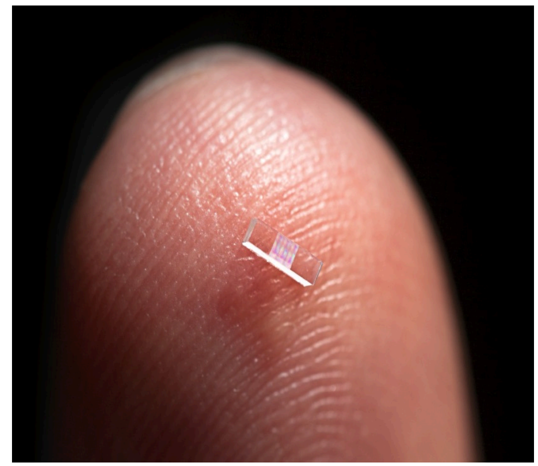
Dielectric Laser Acceleration: Results and Perspective

2015 European Advanced Accelerator Concepts Workshop

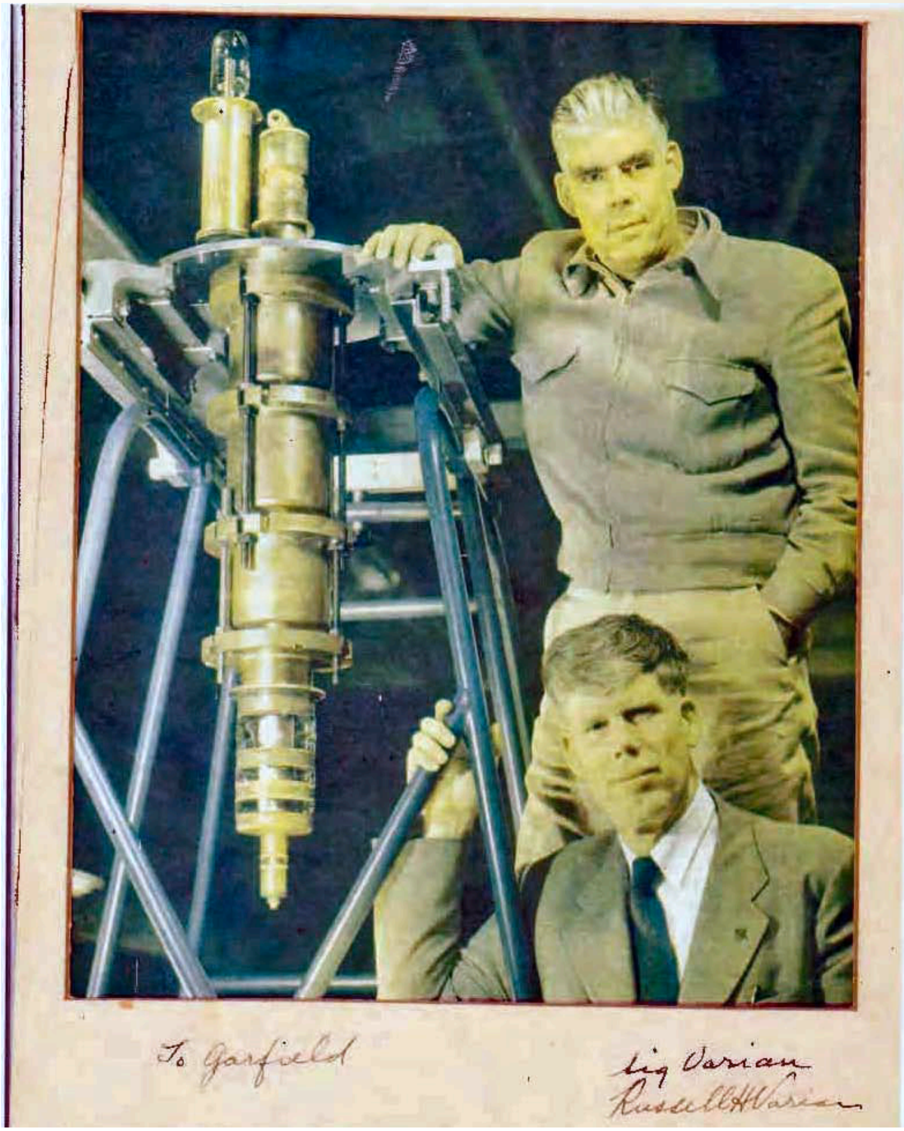
R. Joel England



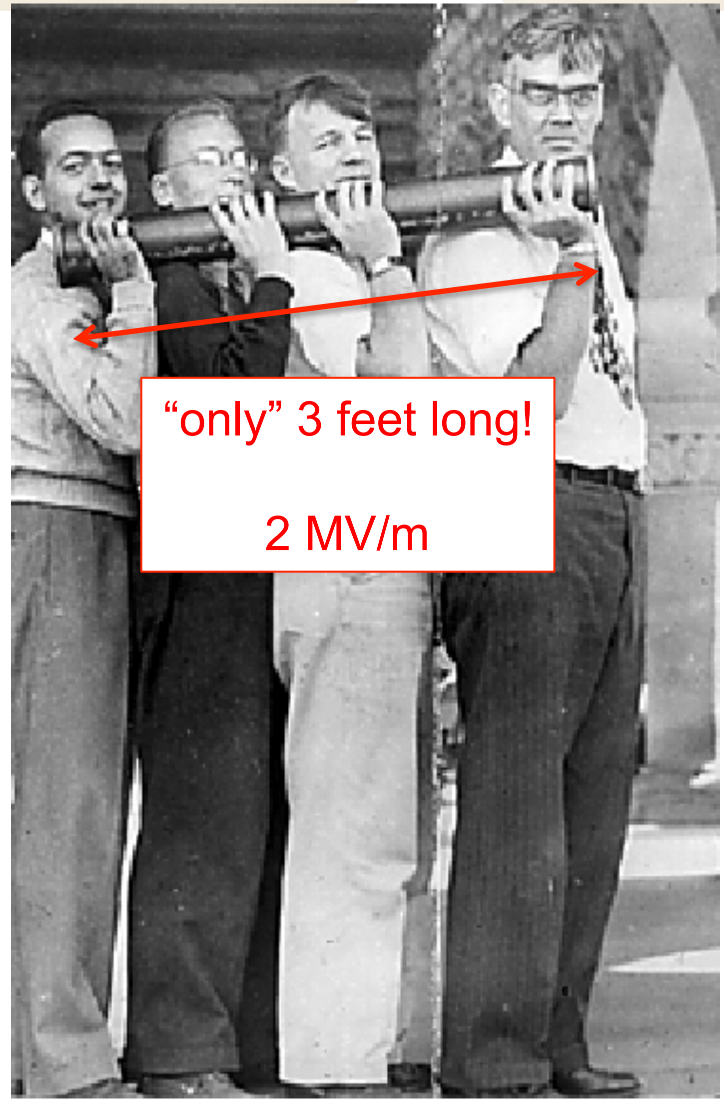
U.S. DEPARTMENT OF ENERGY
Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

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

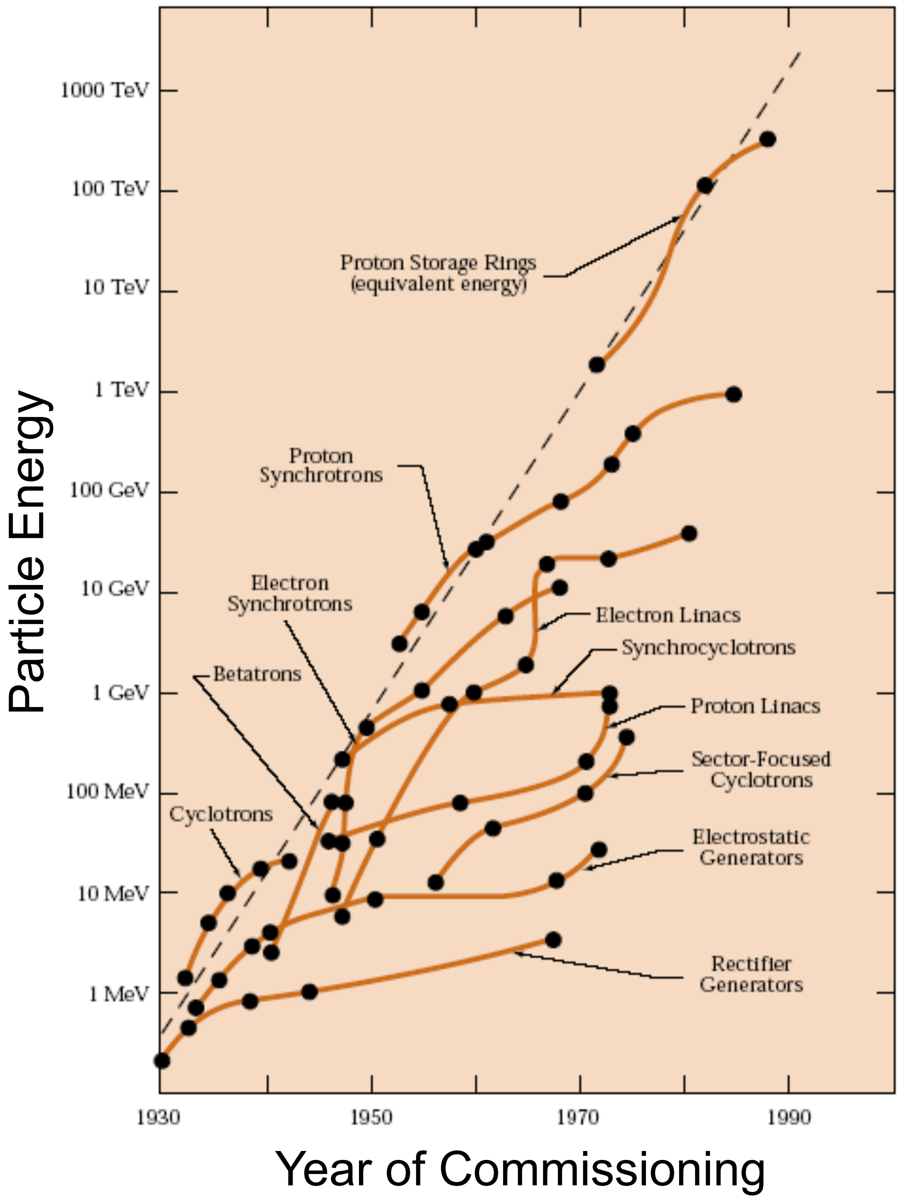


Klystron invented 1937



Microwave linac invented 1948

Innovation leads to exponential progress



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

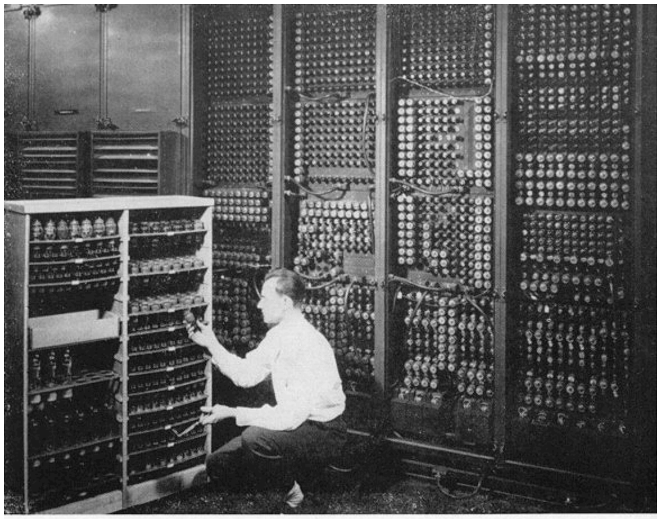
Progress is marked by the saturation of the current technology followed by the adoption of **innovative new approaches** to particle acceleration led by scientists with a **vision** for the future and the **passion** to make it happen.

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

Can we do for particle accelerators what the microchip industry did for computers?

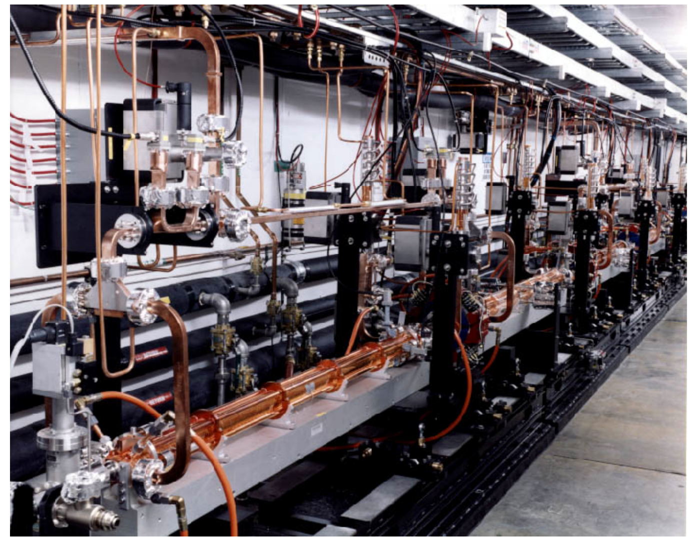
SLAC

ENIAC, early computer



Replacing a bad tube meant checking among ENIAC's 19,000 possibilities.

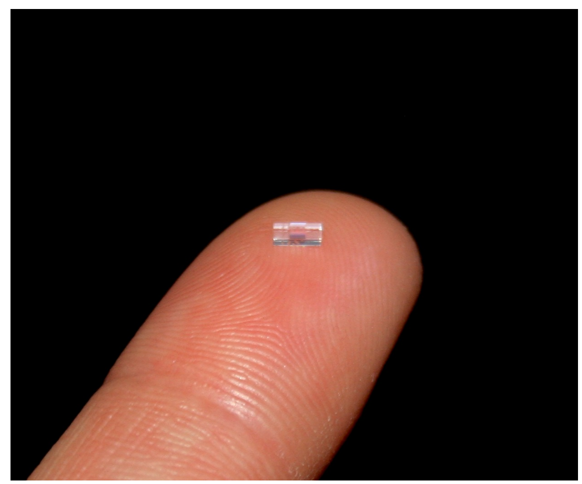
NLCTA accelerator at SLAC



smaller, affordable, faster, better

integrated circuit CPU

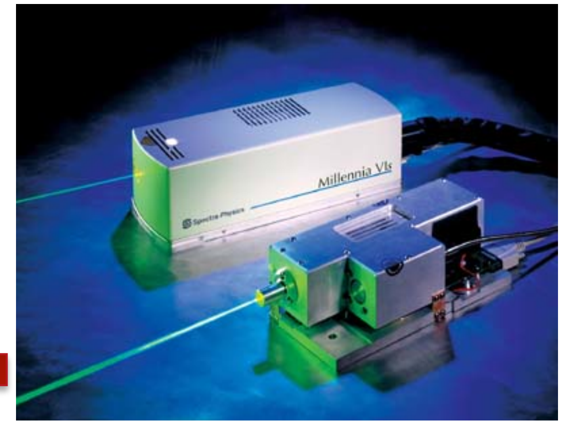
Micro-accelerator fabricated at Stanford



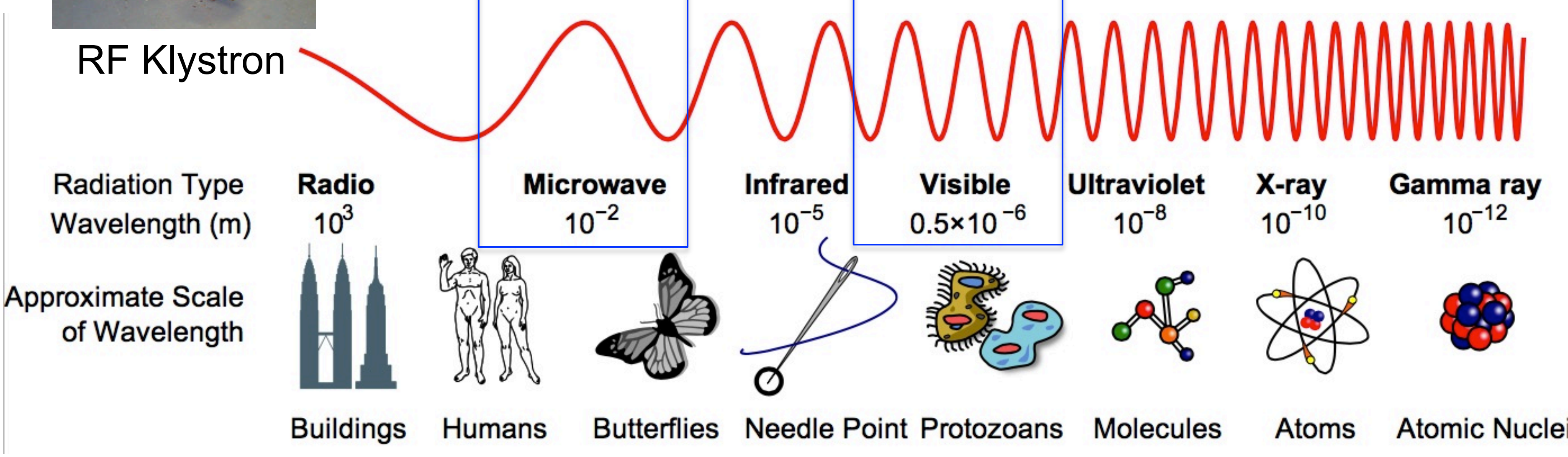
Lasers have followed a similar trajectory in exponential innovation.

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



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

SLAC

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

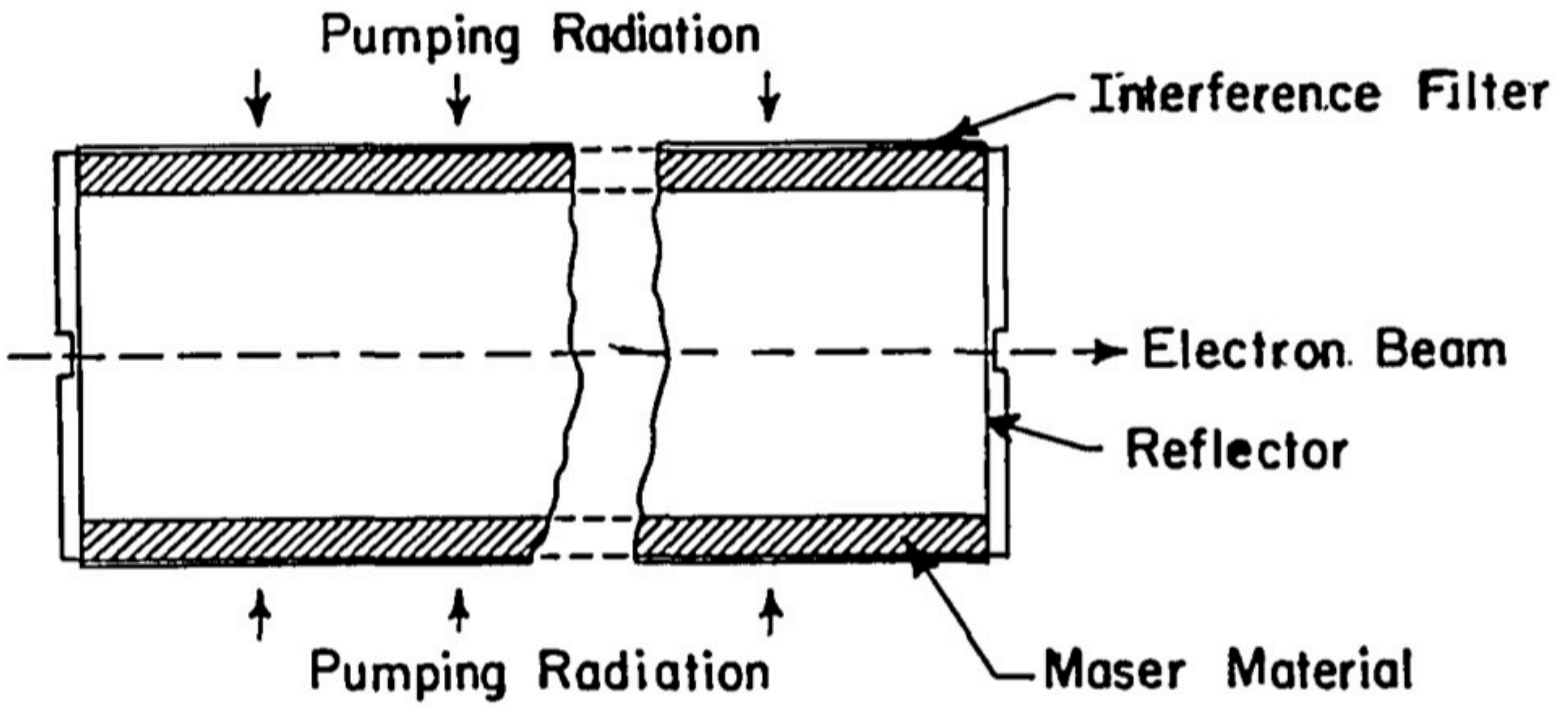


Fig. 1. Schematic diagram of an electron linear accelerator by optical maser.

In the intervening years, new technologies have made laser-driven micro-accelerators a possibility.

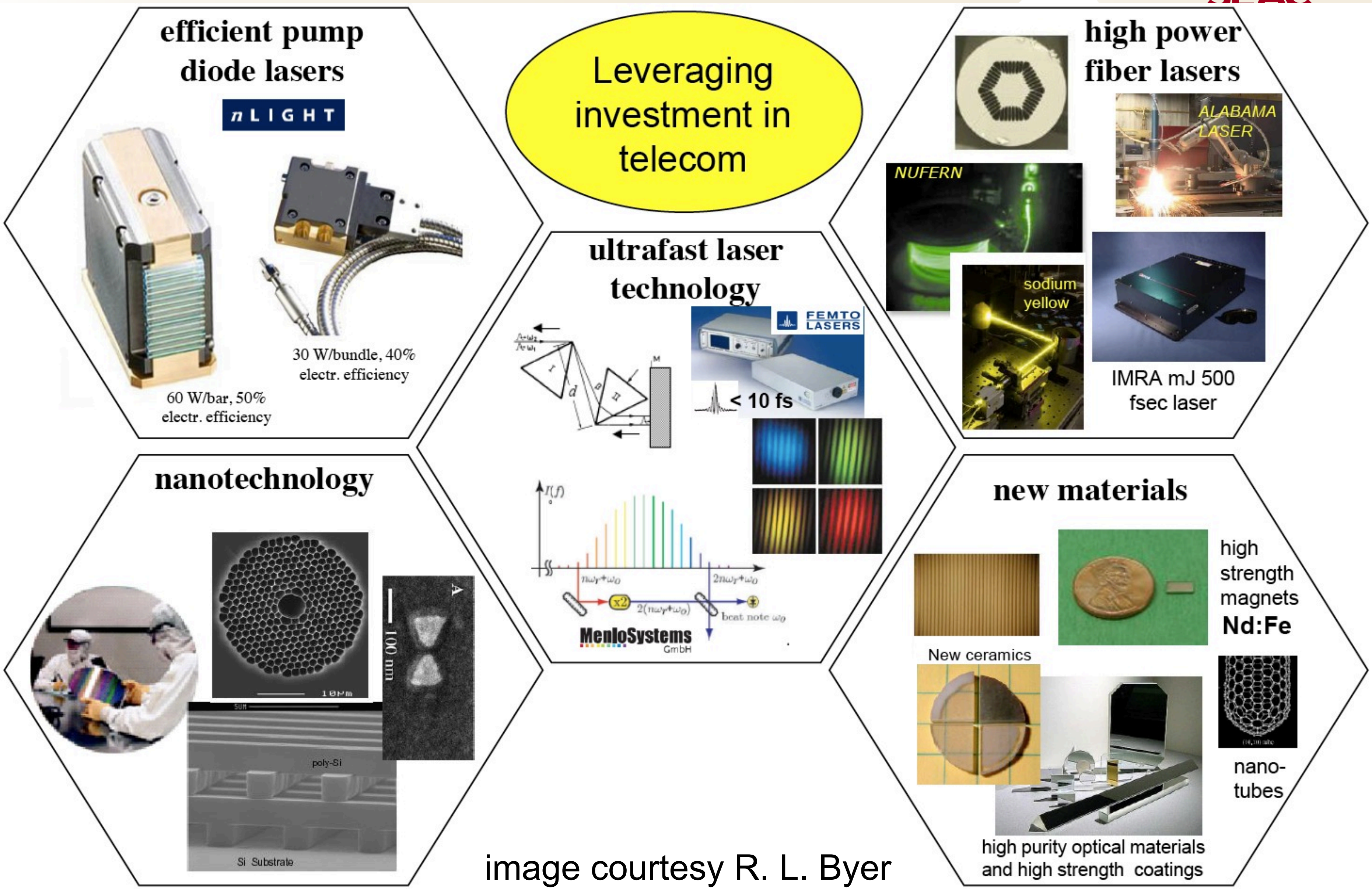
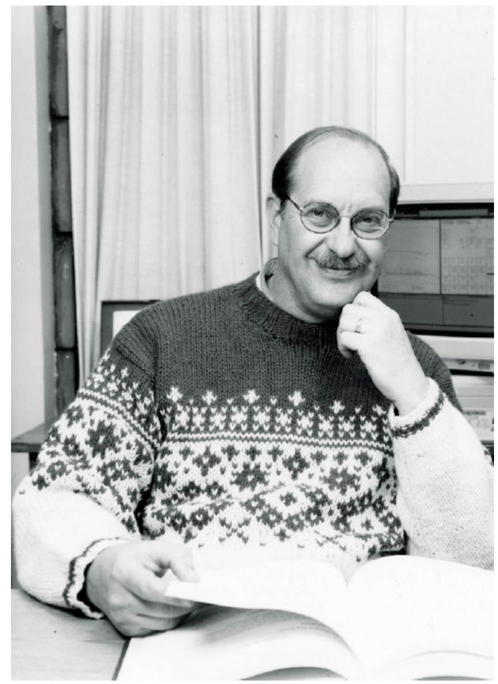


image courtesy R. L. Byer

An initiative to accomplish this was started by Bob Byer and Bob Siemann in 1996

lasers

+



accelerators

This led to a joint SLAC/Stanford program to explore laser-driven particle accelerators.

LEAP: Laser Electron Acceleration Program (1997-2004)

E. Colby

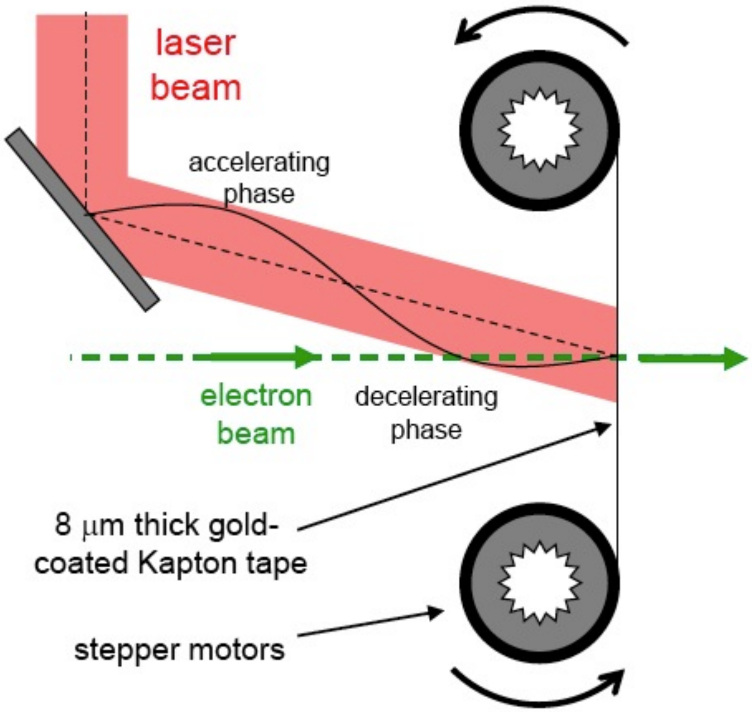
T. Plettner



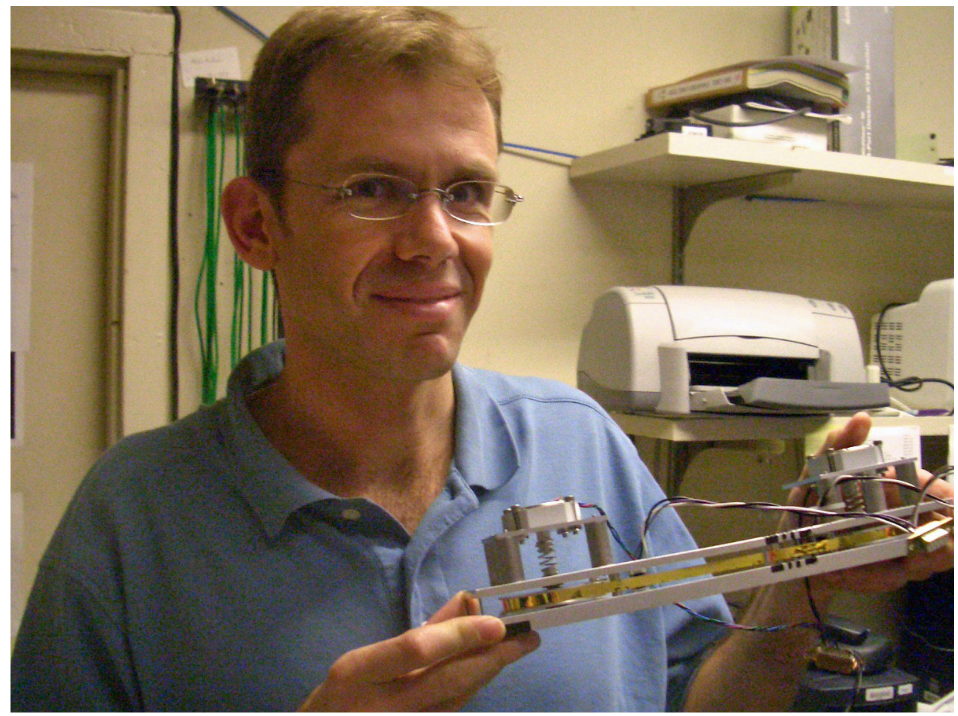





This led to one of the first demonstrations of laser acceleration with a structure.



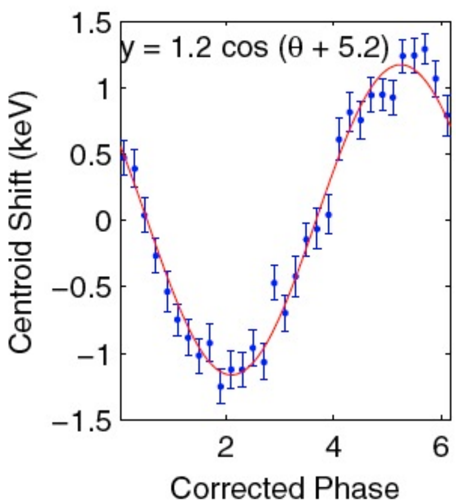
Plettner, Byer, Colby, et al., PRL **95**, 134801 (2005)
Sears, et al., PRL **95**, 194801 (2005).



Tomas Pletter with "tape drive" accelerator

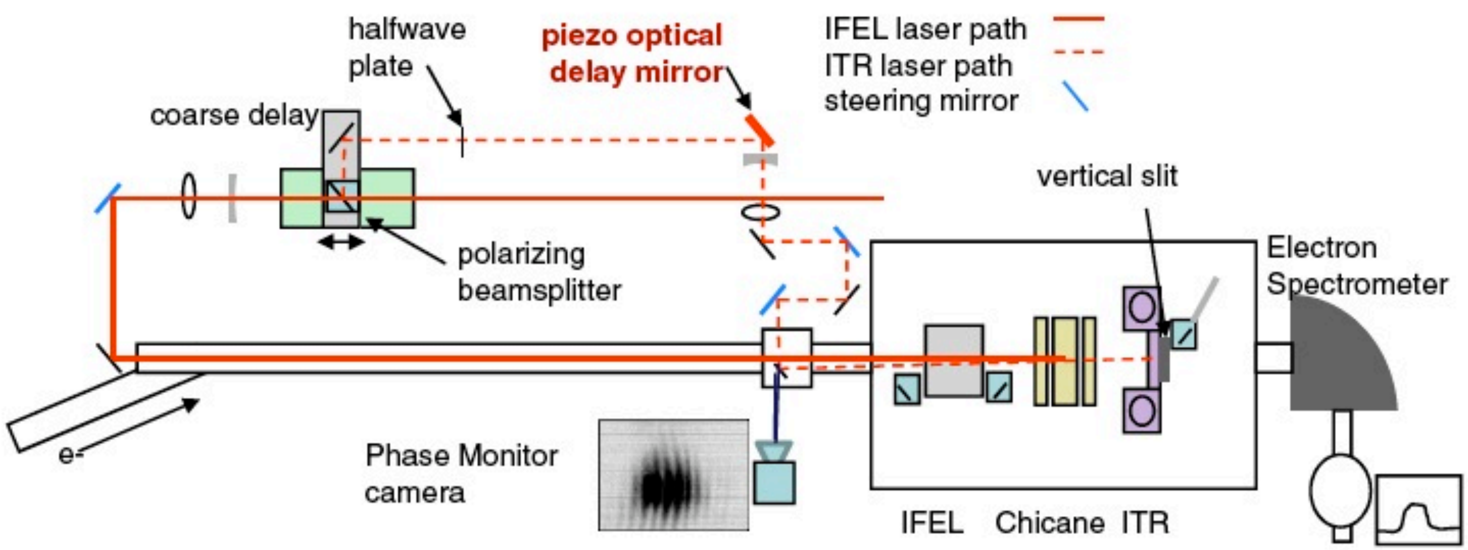
Important result: showed that laser-driven structures can accelerate particles, but we need to develop ways of doing this that don't destroy the accelerator!

Early experiments demonstrated optical microbunching and acceleration using lasers.



STELLA
W. D. Kimura, et al. "Demonstration of High Trapping Efficiency and Narrow Energy Spread in a Laser Driven Accelerator," PRL 92, 054801 (2004).
SLAC E163/LEAP Program
C.M.S. Sears, et al. "Phase stable net acceleration of electrons from a two-stage optical accelerator." PRST-AB **11**, 101301 (2008).

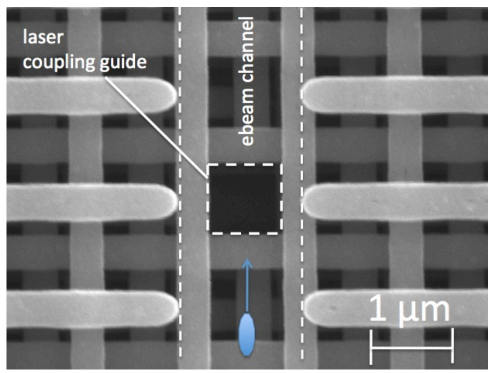
Net laser acceleration of 1.2 keV demonstrated for **400 attosec microbunches** using inverse transition radiation (ITR) at a metal foil.



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).

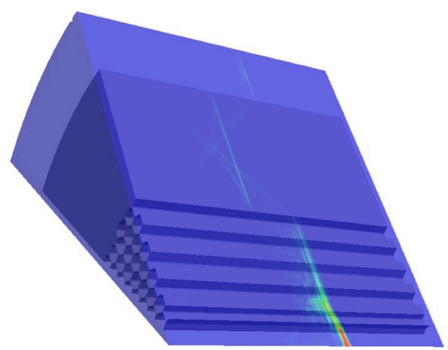


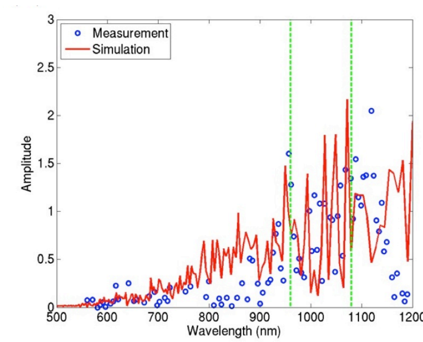
3D Photonic crystal fabrication with complex multi-layer designs suitable for efficient power coupling

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

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

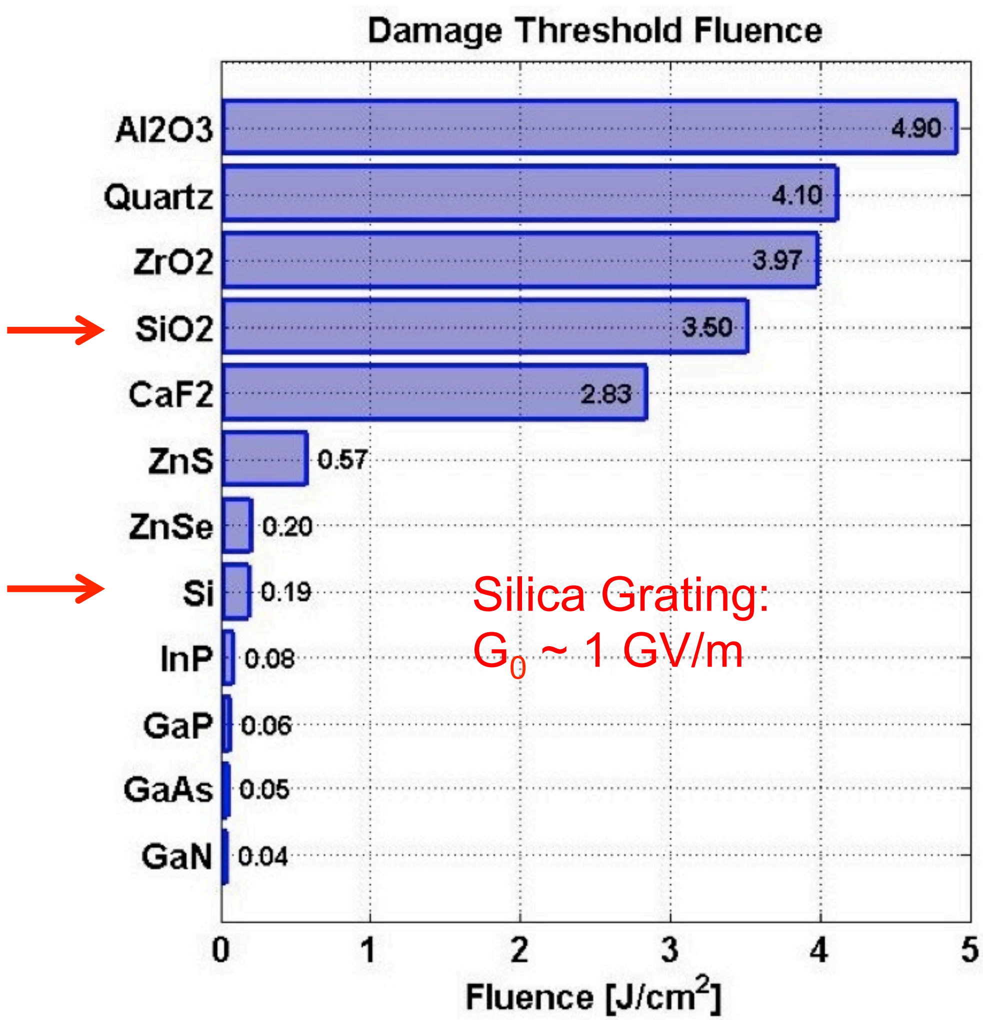
C-K. Ng, et al. PR-STAB **13**, 121301 (2010)
R. J. England, et al. AIP Conf. Proc. 1086, 550 (2009)





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

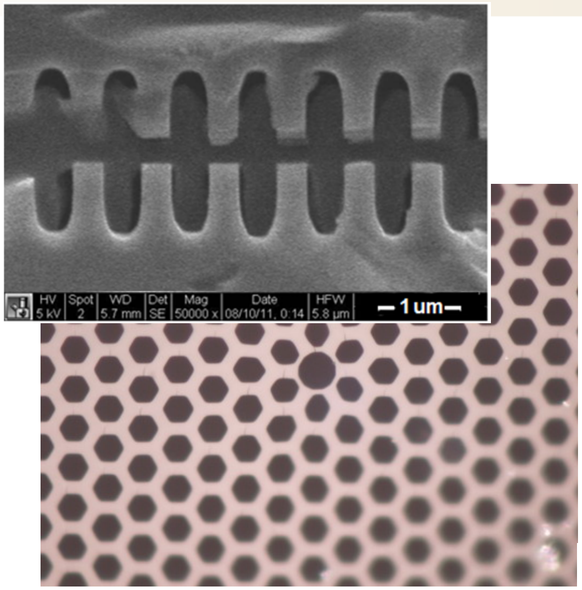
"All accelerators operate at the damage limit" – Pief Panofsky

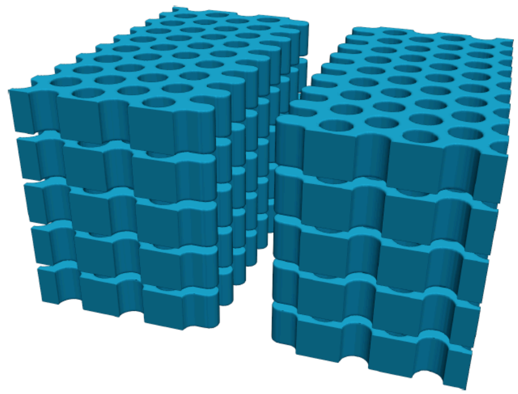


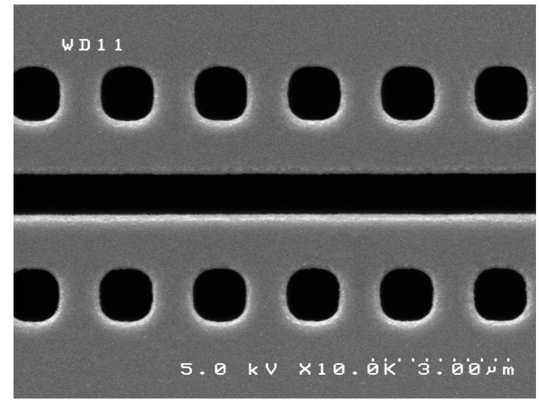
Ti:Sapph Laser wavelength: 800nm; Pulse length: 1ps; <u>Extensive data did not previously exist in this regime</u>.

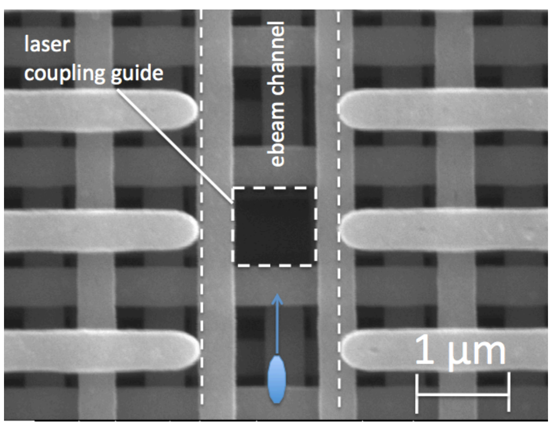
Ken Soong

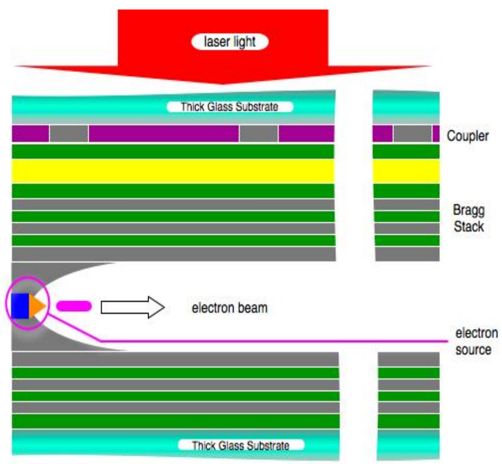
A variety of “dielectric laser-driven accelerators” (DLA) have been proposed…

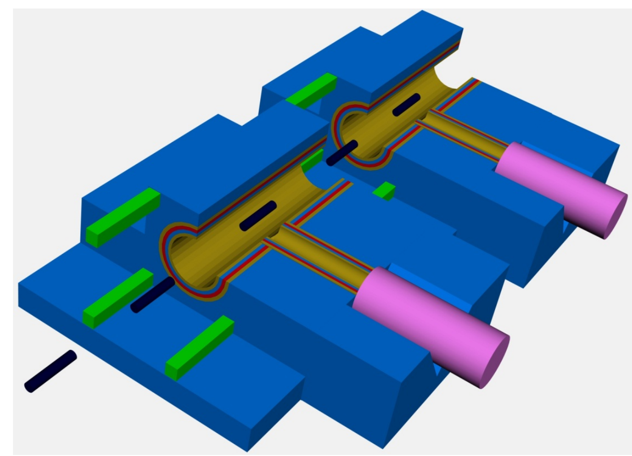








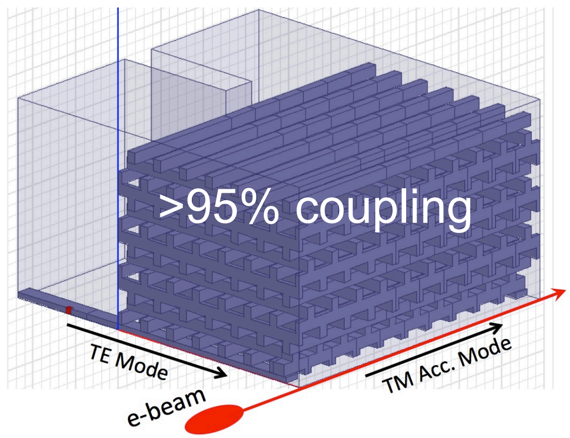


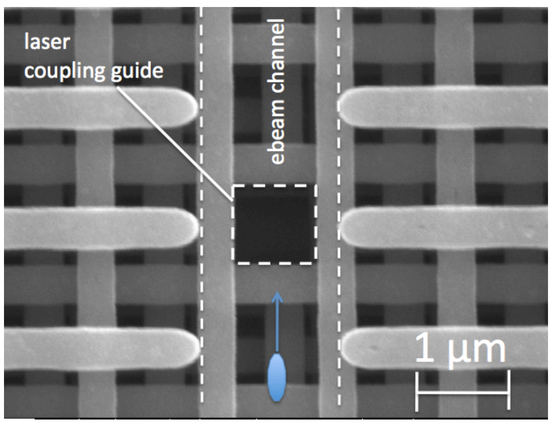


… as well as compatible accelerator subcomponents.

SLAC

Efficient Coupler Designs

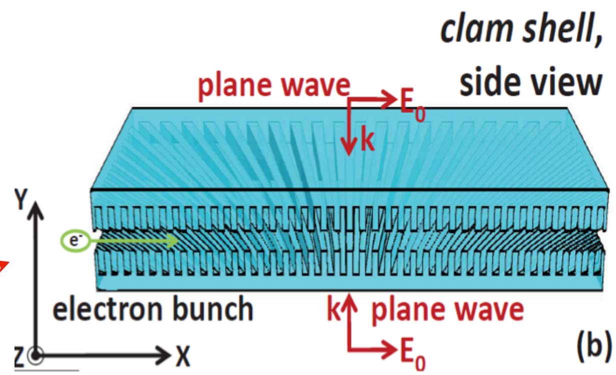




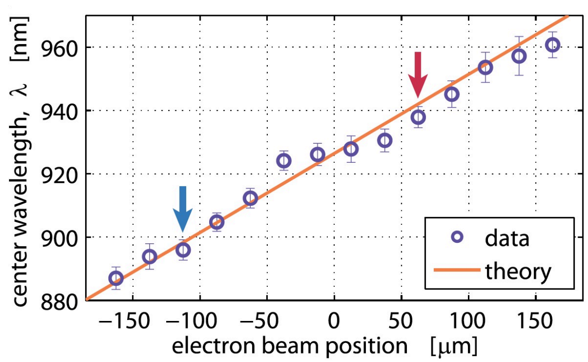
C. McGuinness, Z. Wu

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

Beam Position Monitor

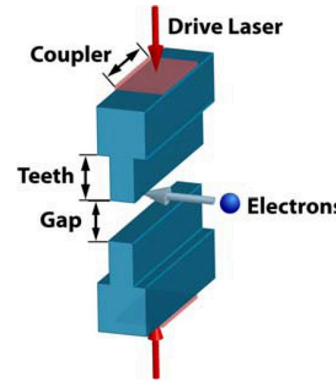


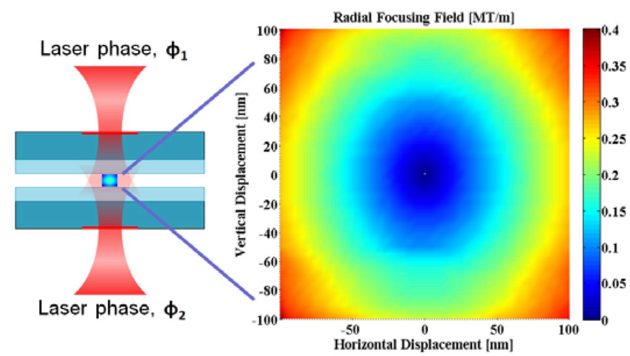
Opt. Lett., **37** (5) 975-977 (2012)



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

Focusing Structures





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

DLA operates with available microJoule lasers.

High average power, not high peak power lasers!

Parameter	Medical (5 yrs)	HEP (20 yrs)
Wavelength	**1 to 2 μm**	1 to 2 μm
Pulse Duration	**1.6 ps**	1 ps
Pulse Energy	**150 nJ**	64 μJ
Laser Power	**300 mW**	1.3 kW
Rep Rate	**2 MHz**	20 MHz
Laser Efficiency	**30%**	40-50%
Cost/laser	**$150k**	< $100k

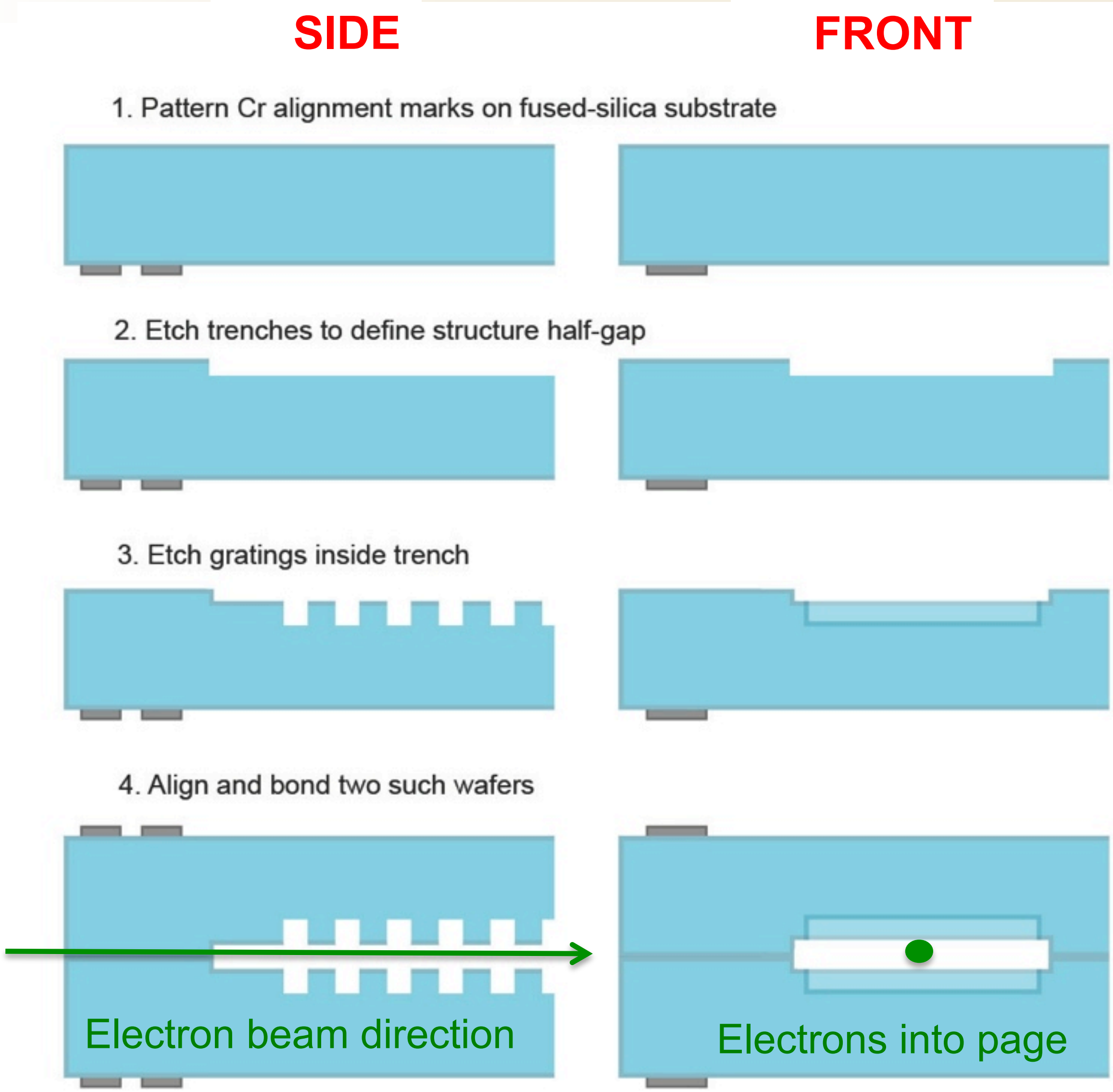
available now “off-the-shelf”

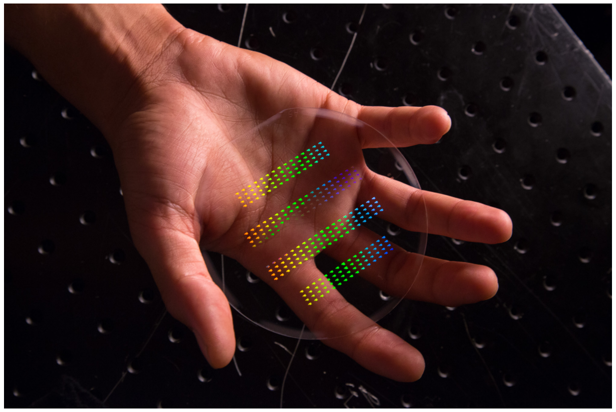
available in ~3 years

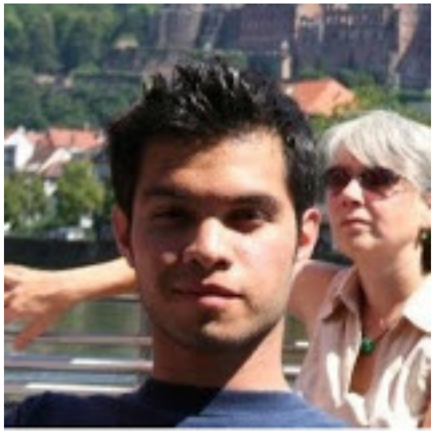
Solid-state laser

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

SLAC

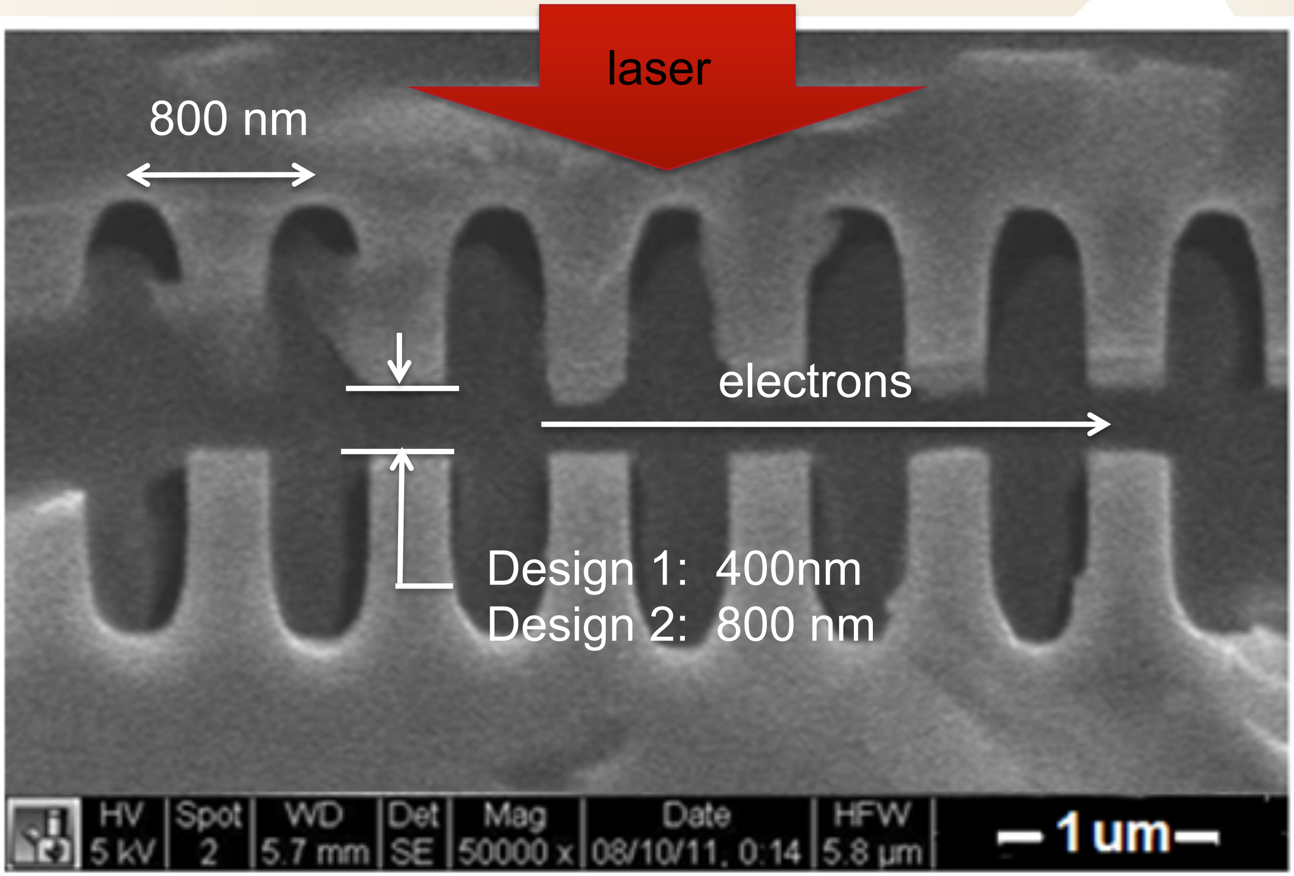






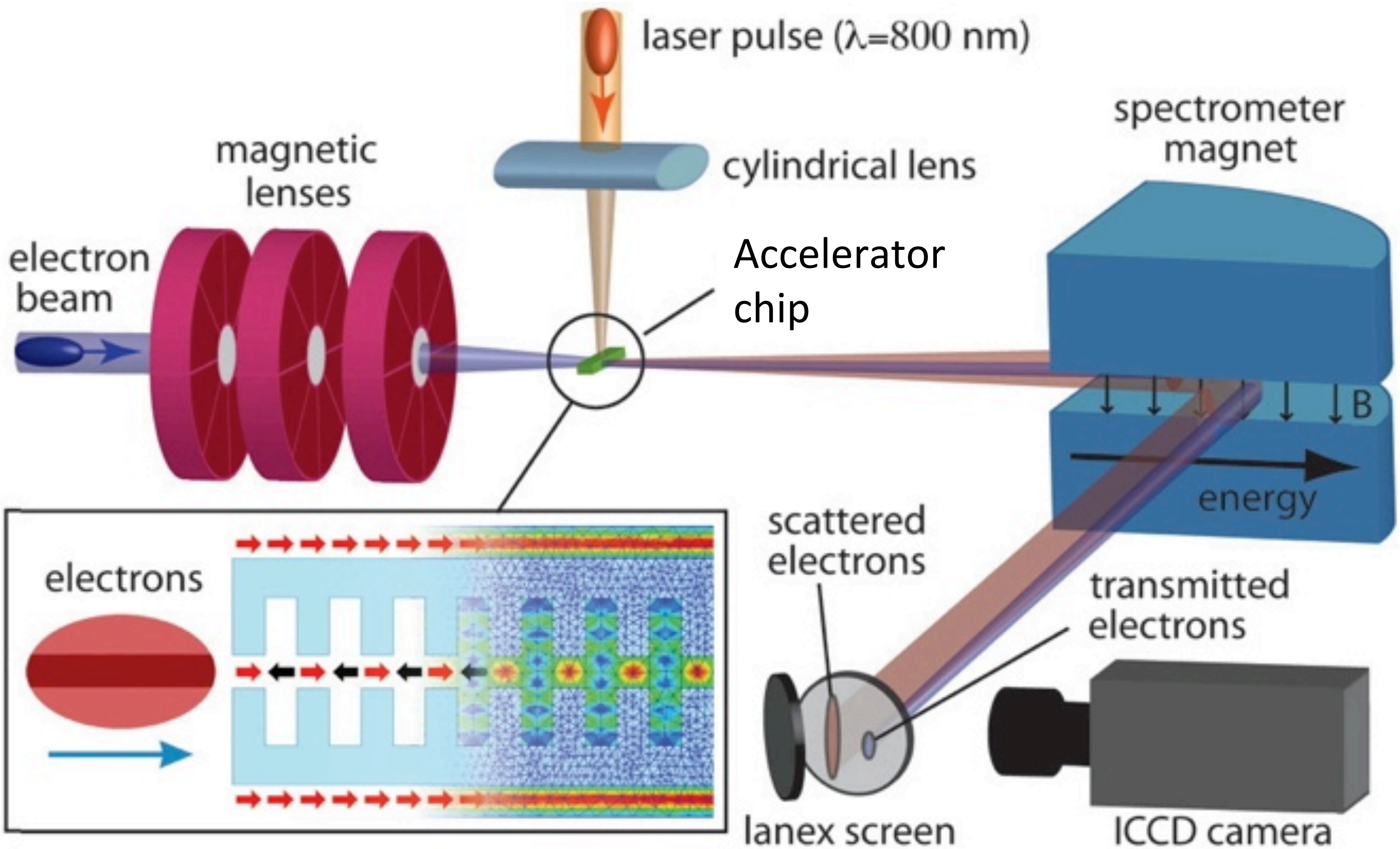
Edgar Peralta

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.

Demonstrations conducted at SLAC used a pre-accelerated (60 MeV) electron beam and Ti:Sapph laser.

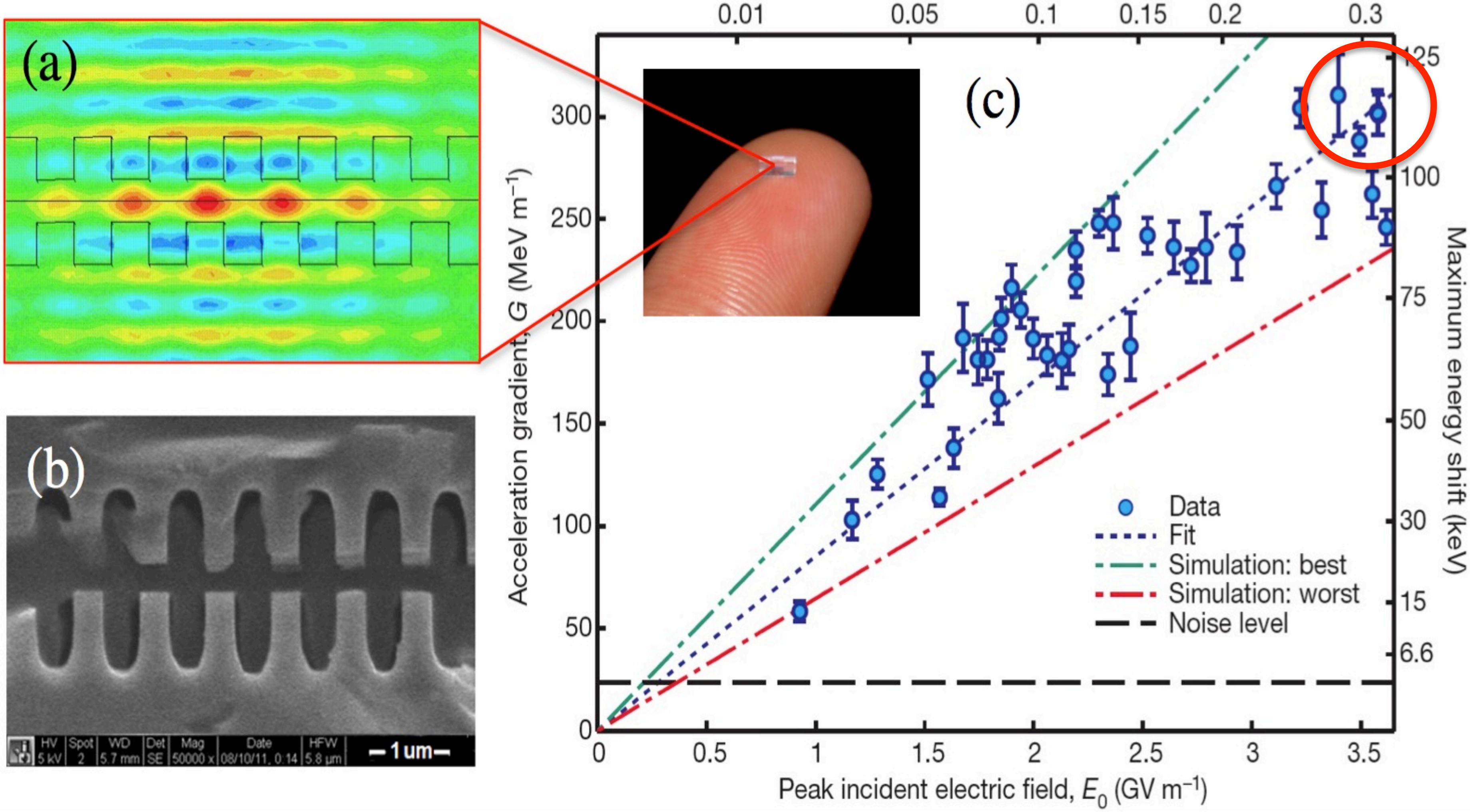


SLAC Next Linear Collider Test Accelerator (NLCTA) Setup for DLA Testing

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

Nature **503**, 91-94 (2013).

300 MV/m



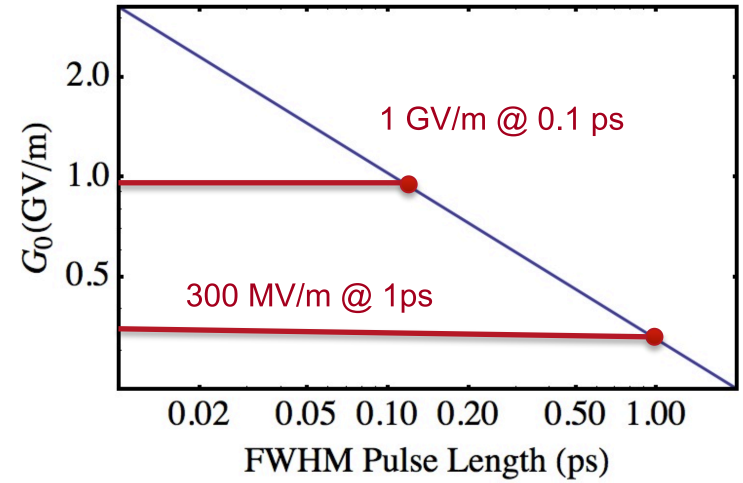
… and have recently (last month) been extended to higher gradients using shorter laser pulses.

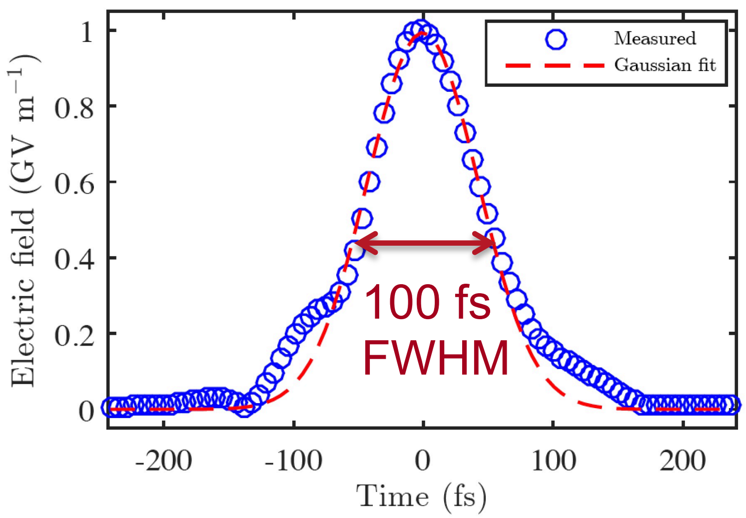
SLAC

E_{inc} increased from 3.5 GeV/m to > 7 GeV/m

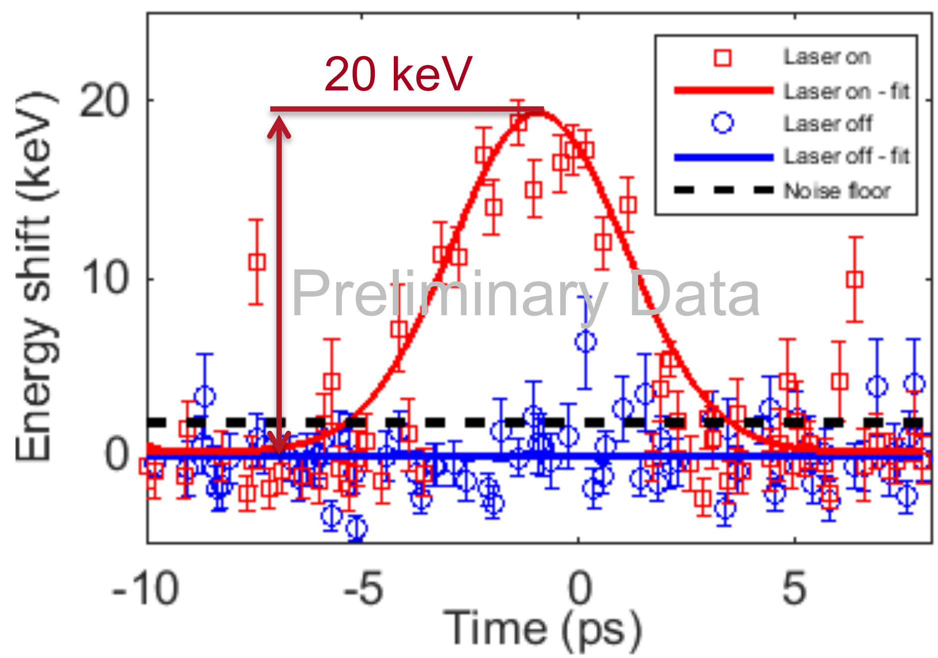
Incident fluence: 0.7 J/cm^2

~700MeV/m gradient





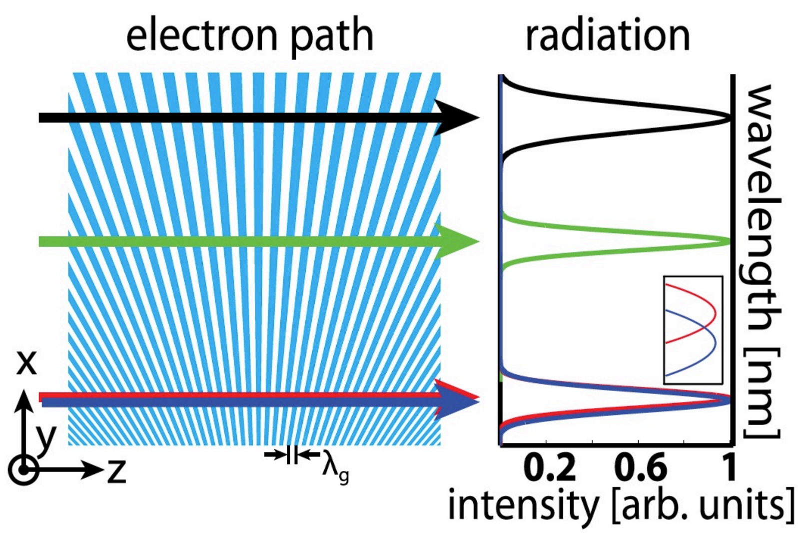
*in prep for publication (2015)

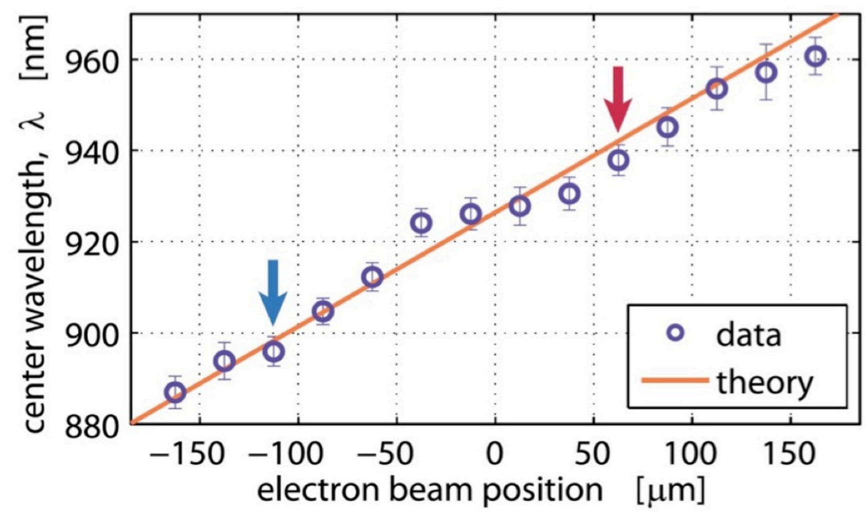


The "reverse" process has been shown as a way to precisely measure particle position.

SLAC

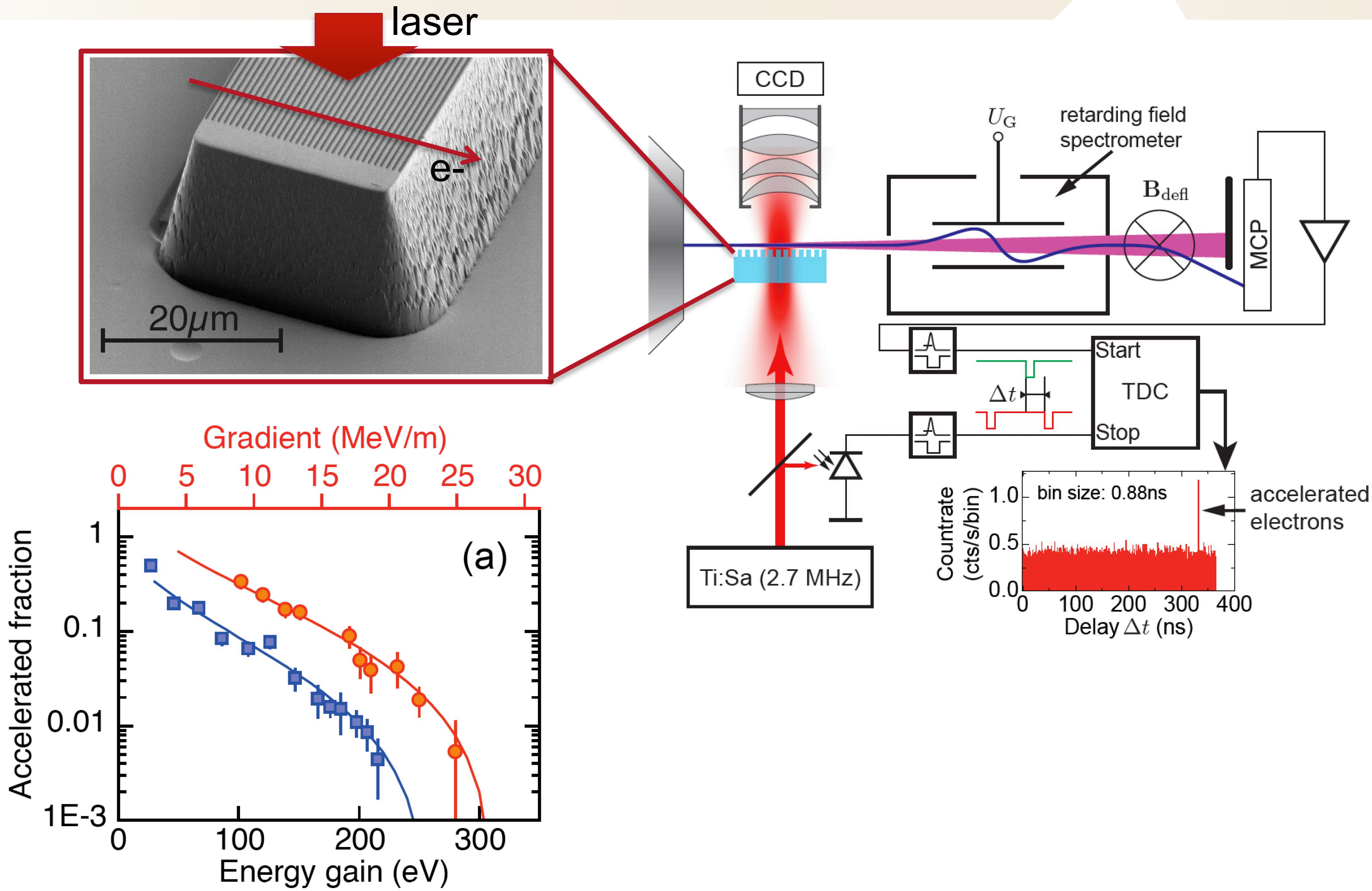
"To be efficient, the accelerator must operate in reverse."
- Ron Ruth, SLAC





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

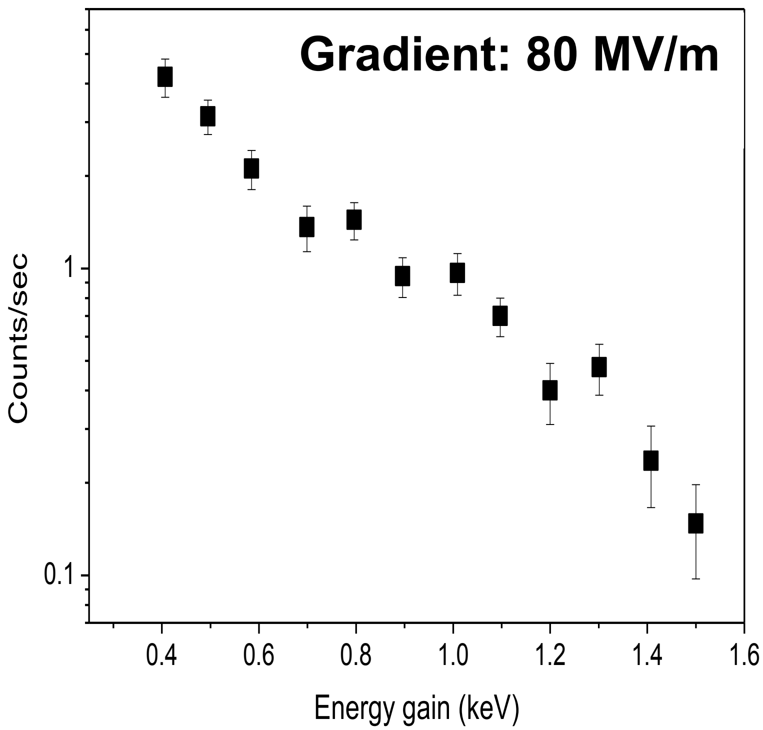
25 MV/m gradients were simultaneously demonstrated at 30 keV electron energy at U. Erlangen.



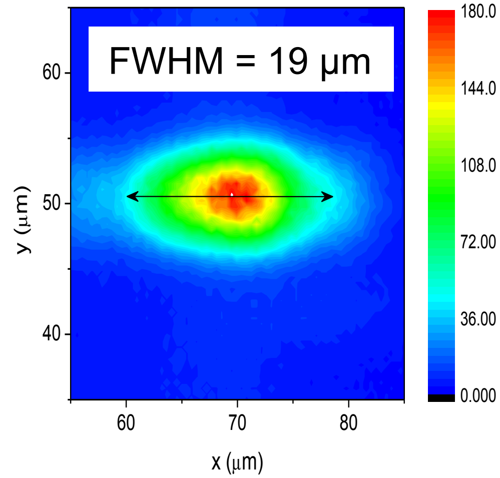
Breuer and Hommelhoff, Phys. Rev. Lett. **111**, 134803 (2013)

This technique has recently been extended for the first time from 800nm to 2μm optical wavelength...

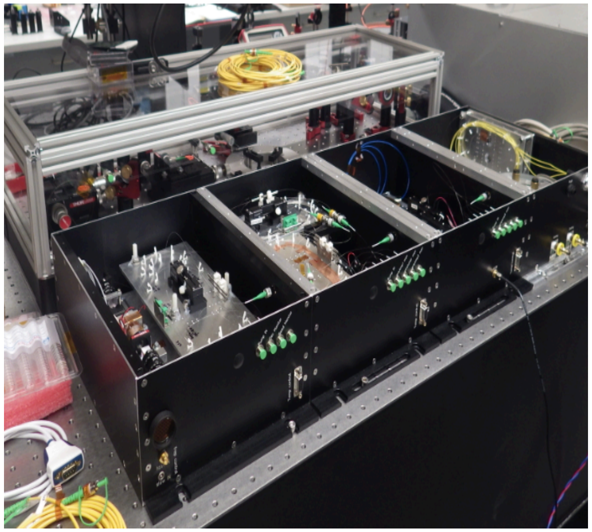
Energy gain and acceleration gradient much higher than for 787 nm (previous work) excitation and fused silica grating; agrees with numerical and theoretical analysis



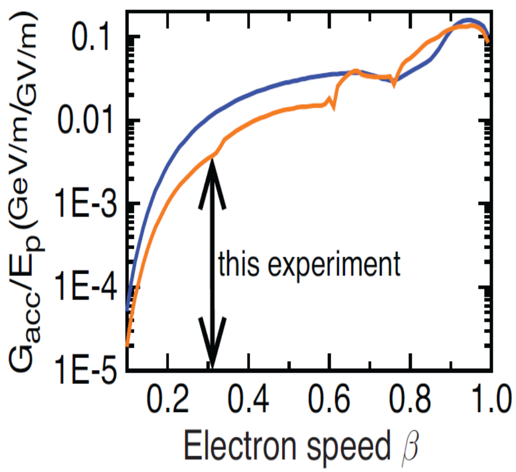
Dependence of accelerated electrons count rate (over threshold given by retarding field spectrometer) on accumulated energy gain.



Laser profile at IP

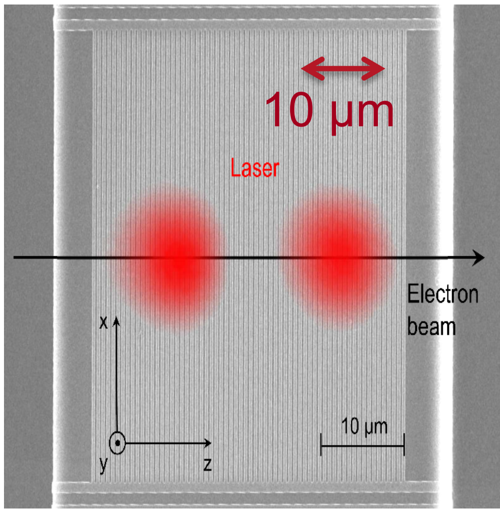


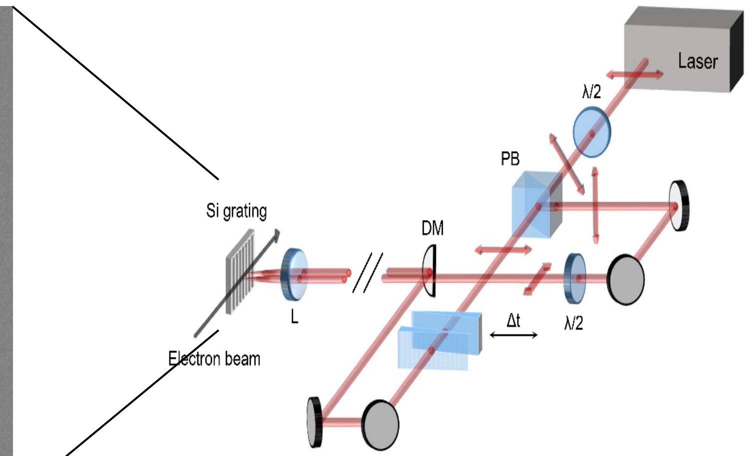
IMRA Thulium Fiber Laser



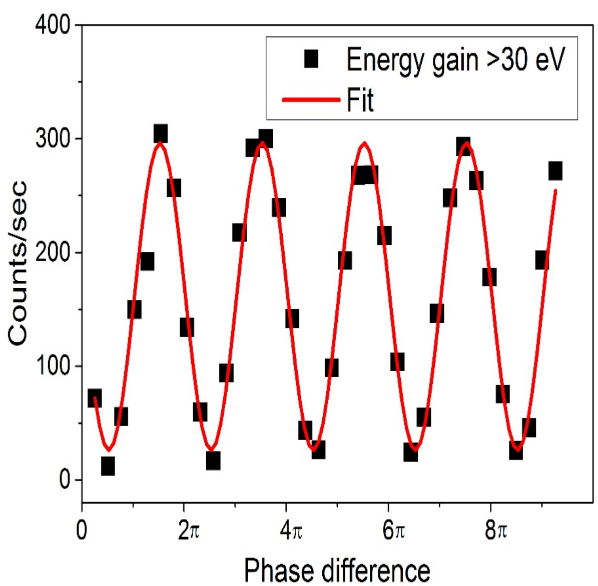
Increasing electron velocity to ß=0.95 increases coupling efficiency by more than 10. GeV/m gradient achievable!

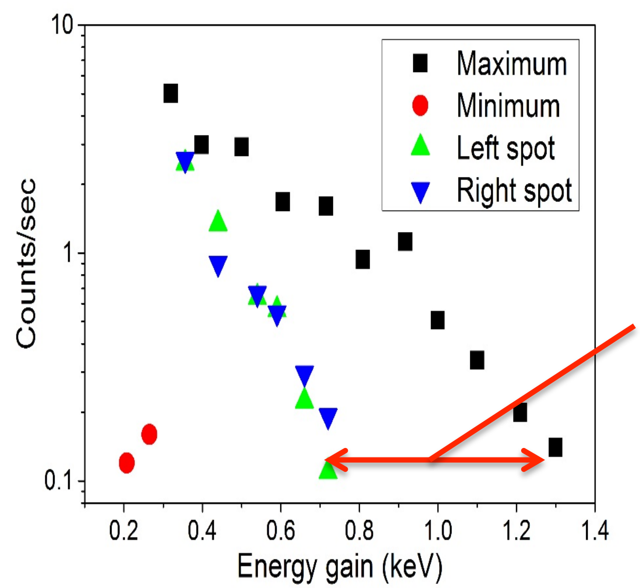
... leading to first successful demonstration of 2-stage phase controlled DLA acceleration.





J. McNeur, P. Hommelhoff (2015)

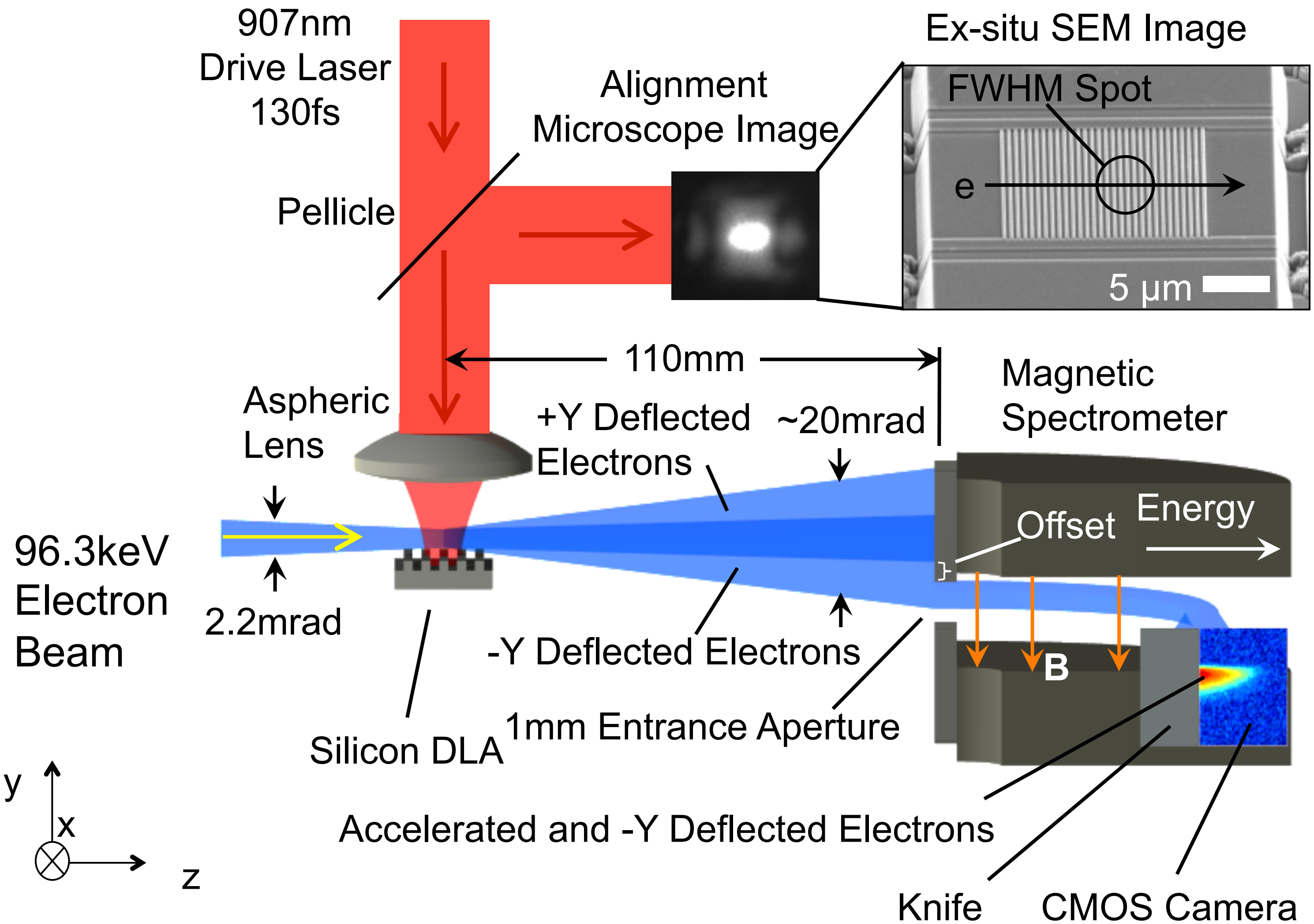




Factor x2 increase for 2 stage vs. 1 stage (linear scaling)

A SEM test stand for subrelativistic (100 keV) DLA demonstrations has been built at Stanford…

SLAC

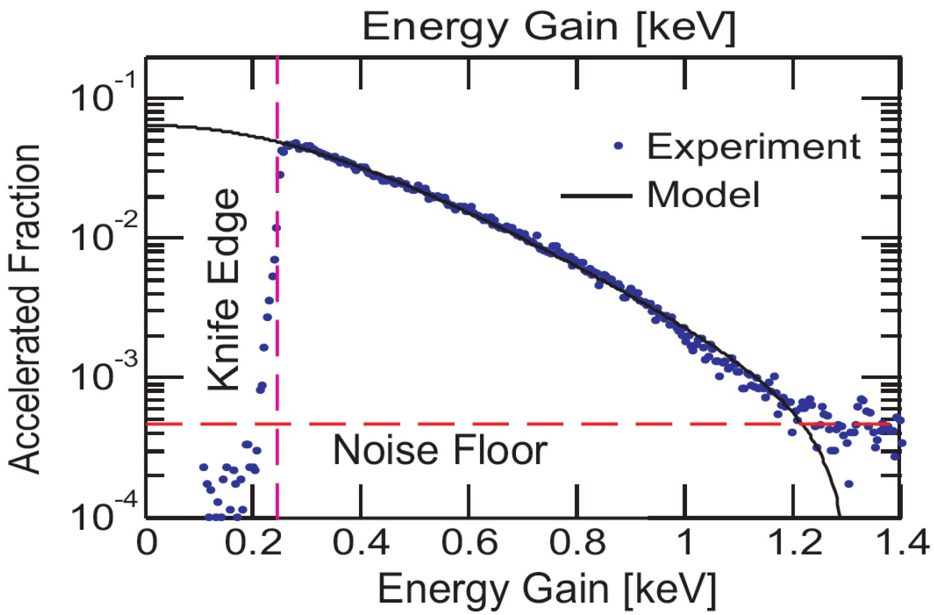


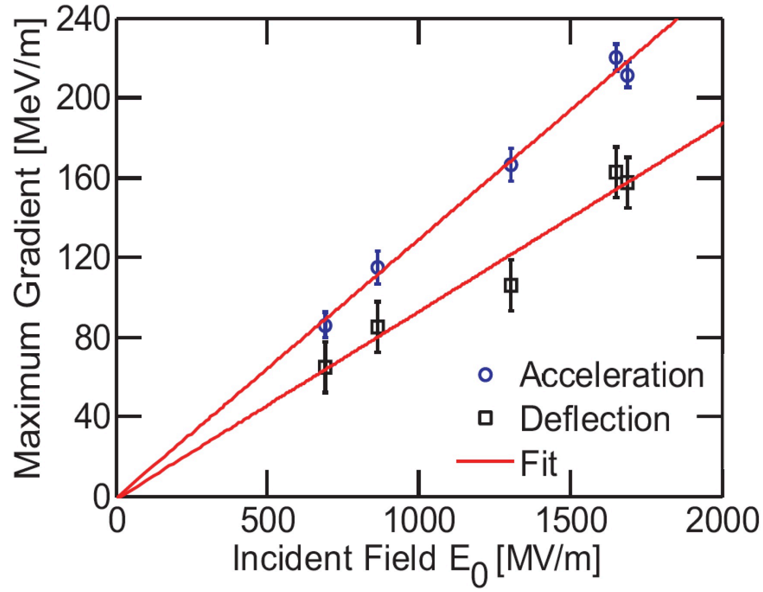
K. J. Leedle, R. F. Pease, R. L. Byer, and J. S. Harris, *Optica* (2014).

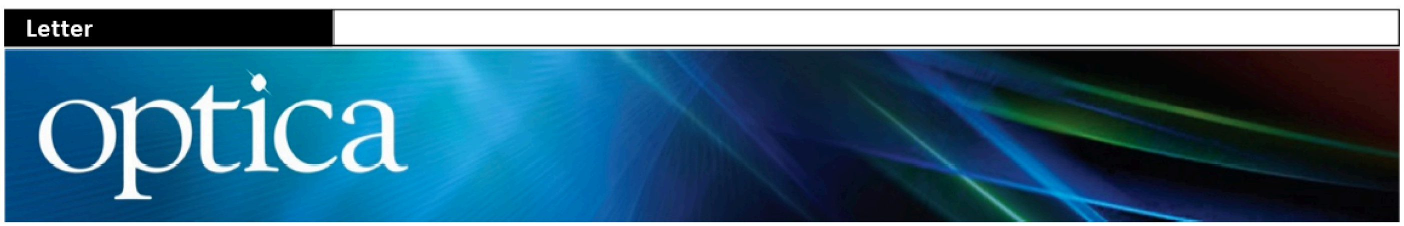
Ken Leedle 11/5/2014

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

SLAC





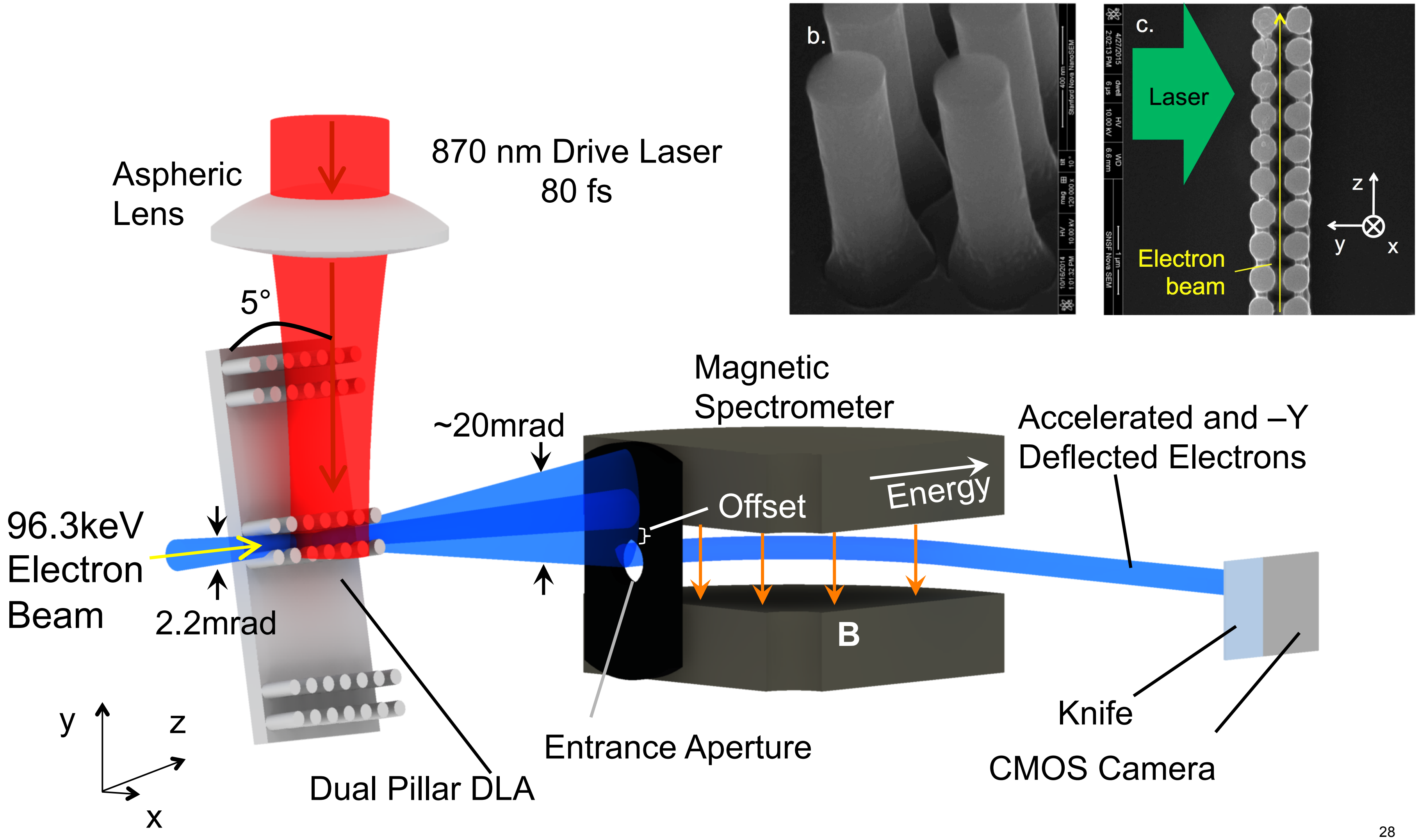


Laser Acceleration and Deflection of 96.3 keV Electrons with a Silicon Dielectric Structure

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

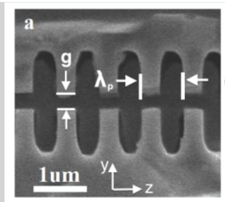
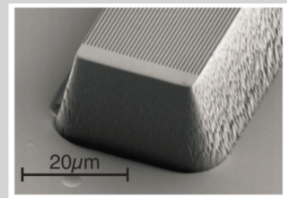
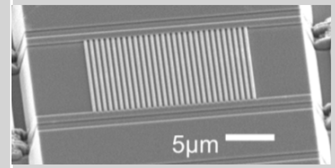
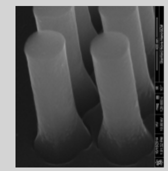
A recently demonstrated alternative dual-pillar design allows higher gradient and field enhancement.

SLAC



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

DLA Experiment Comparison

	SLAC (SiO_2)	Hommelhoff (SiO_2)	Si Single Grating	Si Dual Pillars
				
Electron Energy	60 MeV	30 keV	96.3 keV	86.5keV
Relativistic β	0.9996	0.33	0.54	0.52
Laser Energy	330 mJ	160 nJ	5.2 nJ	3.0 nJ
Pulse Length	60 fs	110 fs	130 fs	130 fs
Interaction Length	~36 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	700 MeV/m*	25 MeV/m	220 MeV/m	370 MeV/m
G_{max}/E_p	~0.1	~0.01	~0.13	~0.4

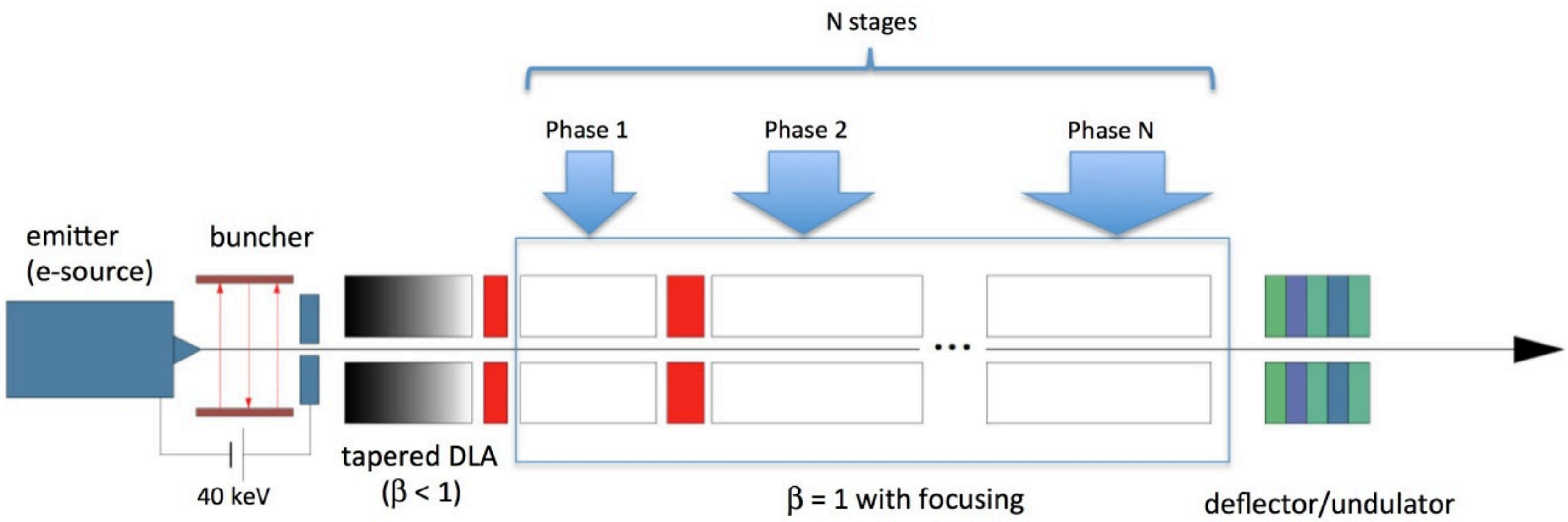
*Preliminary and subject to change

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.

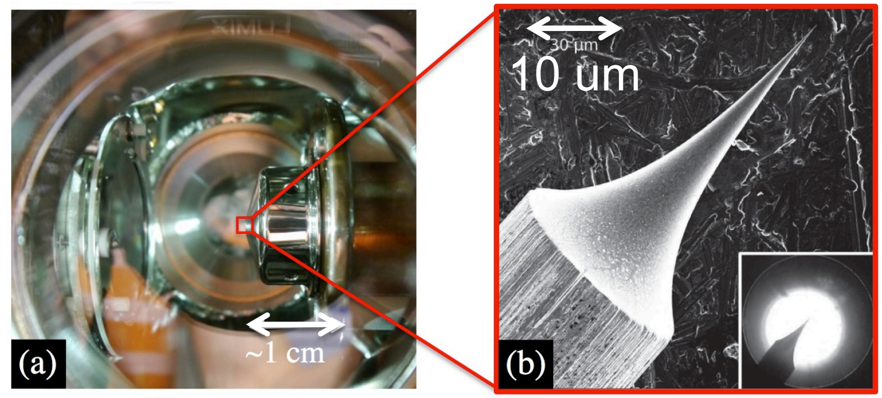
1. On-chip electron source
2. DLA structure development: (a) subrelativistic, (b) relativistic
3. Multi-staged acceleration
4. Coupling of laser to DLA
5. Laser-driven deflectors and undulators



1. On-Chip Electron Source

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

Lead institutions:
Erlangen U., Germany (Hommelhoff)



P. Hommelhoff, Erlangen Univ.

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)

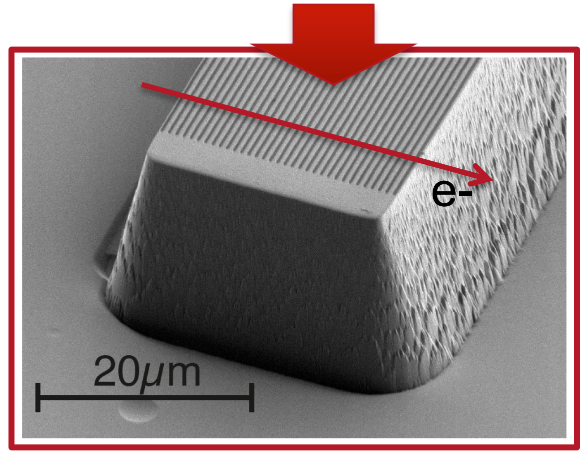
Nanotip sources developed by university collaborators offer a path to on-chip electron sources.

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

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

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.

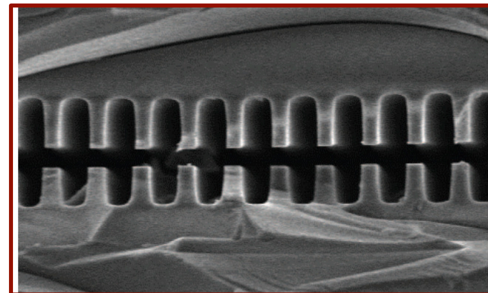


P. Hommelhoff, Erlangen Univ.

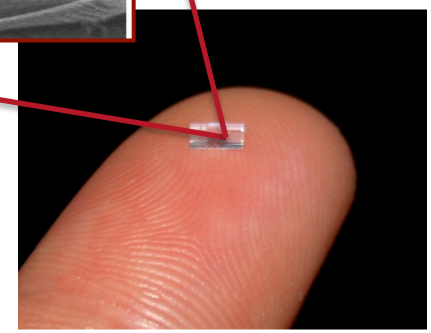
Risks and mitigations?
Beam containment with small apertures → need strong focusing elements built in

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)



SLAC, Stanford



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

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

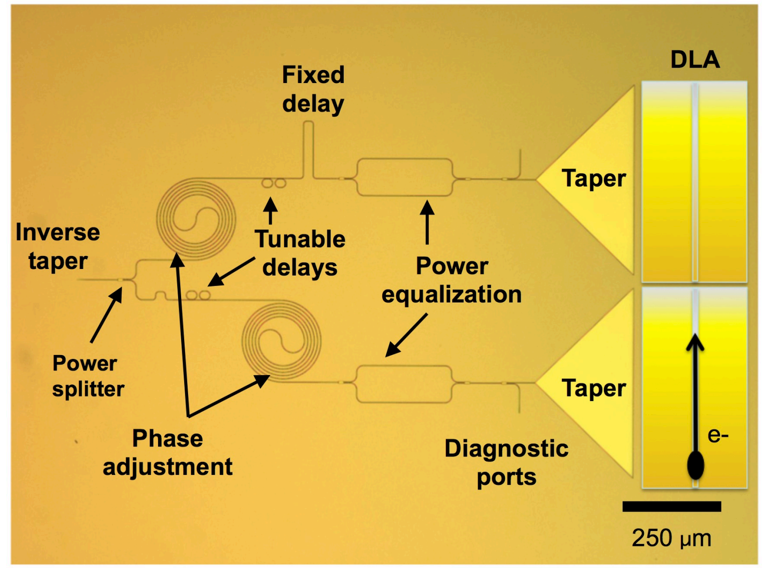
National lab experiments have shown high-gradient operation and set the stage for scaling DLA to multi MeV energies.

3. Multi-staged Acceleration

SLAC

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.

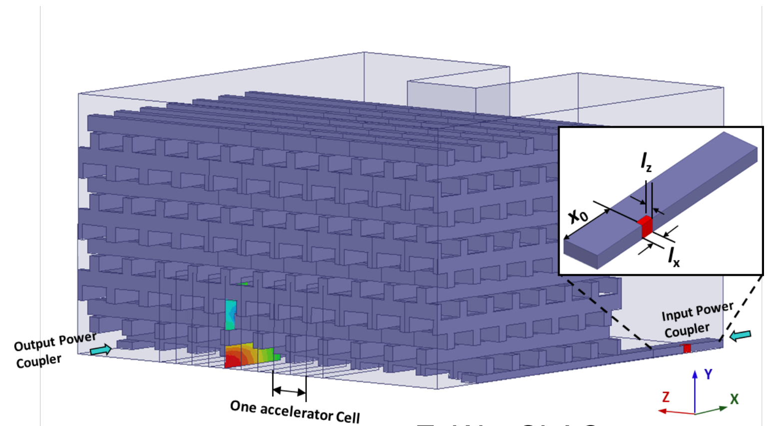
Where do we need to go?
2 to 8 stages @1 MeV/stage
Start with free space coupling, proceed to optical waveguides

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 in simulation



Z. Wu, SLAC

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

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

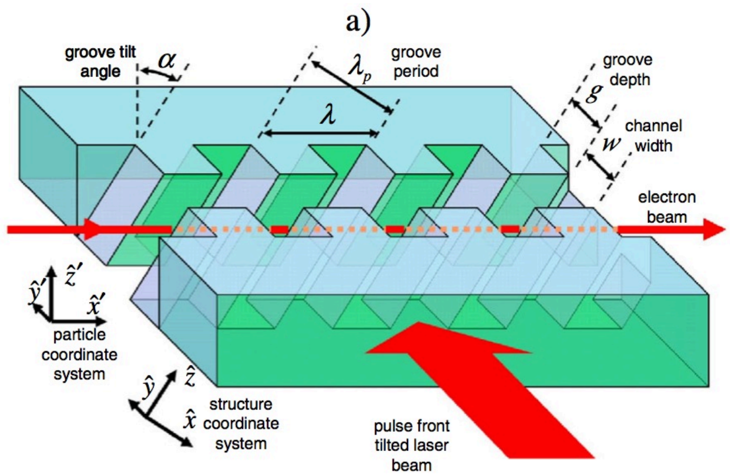
Work to date has been largely simulation: need to fabricate and demonstrate these designs.

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.

A new 5-Year initiative in DLA has been approved by the 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
SLAC: Burt Richter
Stanford: Persis Drell

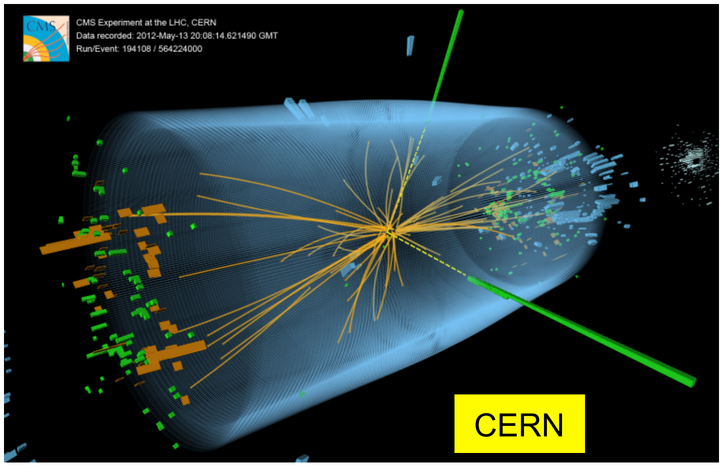
Relativistic DLA experiments
SLAC: England, Tantawi
DESY/UnivHH: Assmann, Kaertner, Hartl
PSI/EPFL: Ischebeck, Frei

Milestones toward a real-world DLA device.

- ✔ 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.

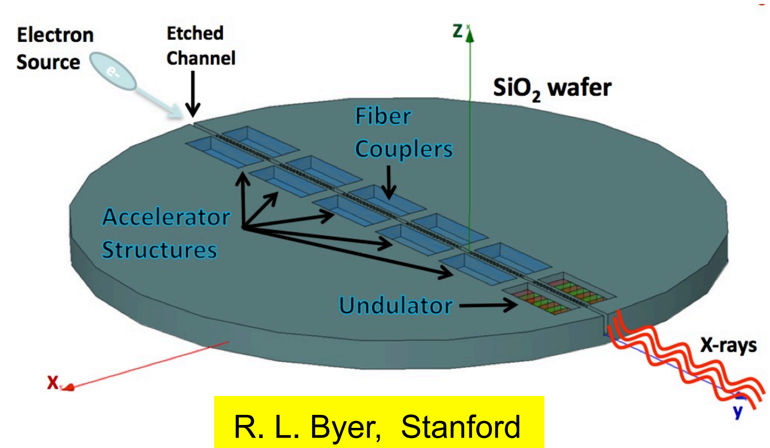
Such a system would have a variety of potential applications…

linear collider or Higgs factory



CERN

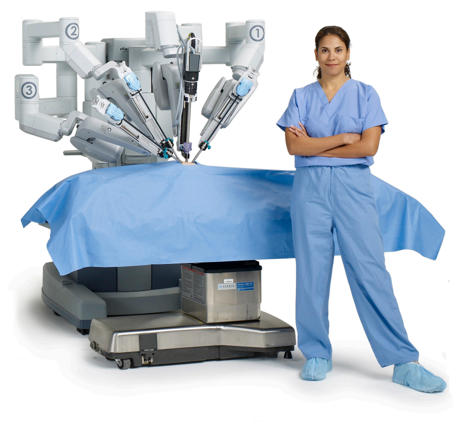
university-scale light source

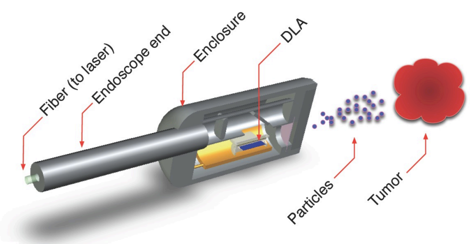


R. L. Byer, Stanford

SPRING8, UNE

medical imaging





Gil Travish, UCLA

portable cancer treatment

Various Nearer-Term Applications

Medical: Brachytherapy

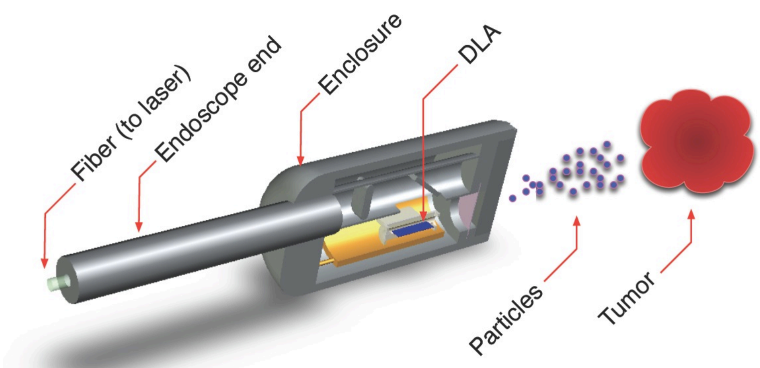
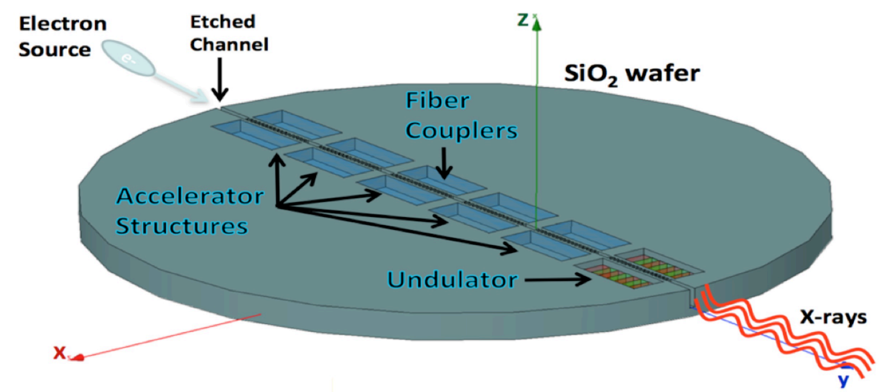


Image courtesy G. Travish (UCLA)

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

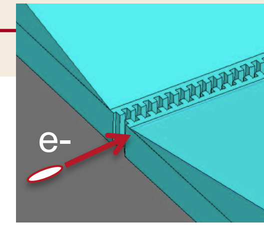
P. Bermel, et al, "Summary of the Dielectric Laser Accelerator Workshop," **NIM-A** 734, 51-59 (2014).

SLAC

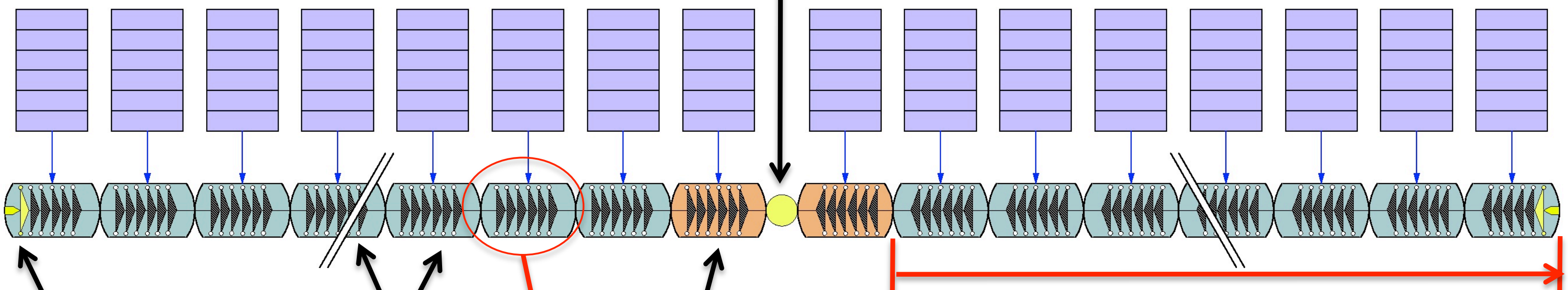
6 fiber lasers per
6" wafer module
2 kW per laser

Thulium fiber laser $\lambda=2\,\mu m$

Interaction Point



concept for 1 DLA accelerator structure (E. Peralta)



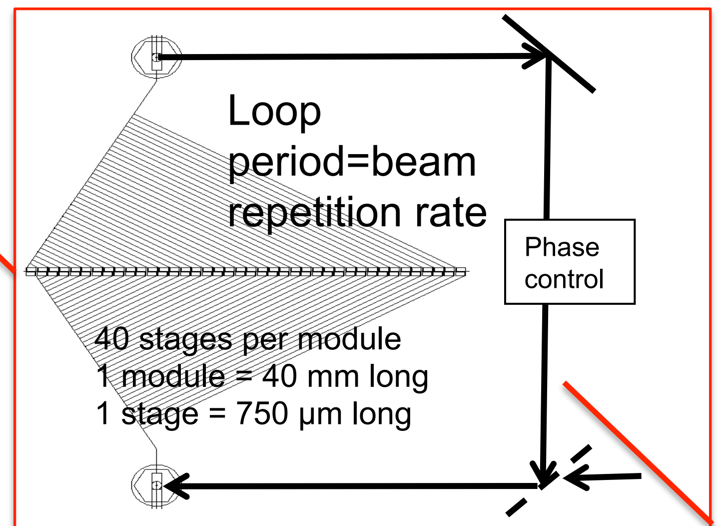
needle emitter and injector module

accelerator wafers

final focus and steering wafers

0.5 TeV ⇔ 500 m ⇔ 15,700 lasers

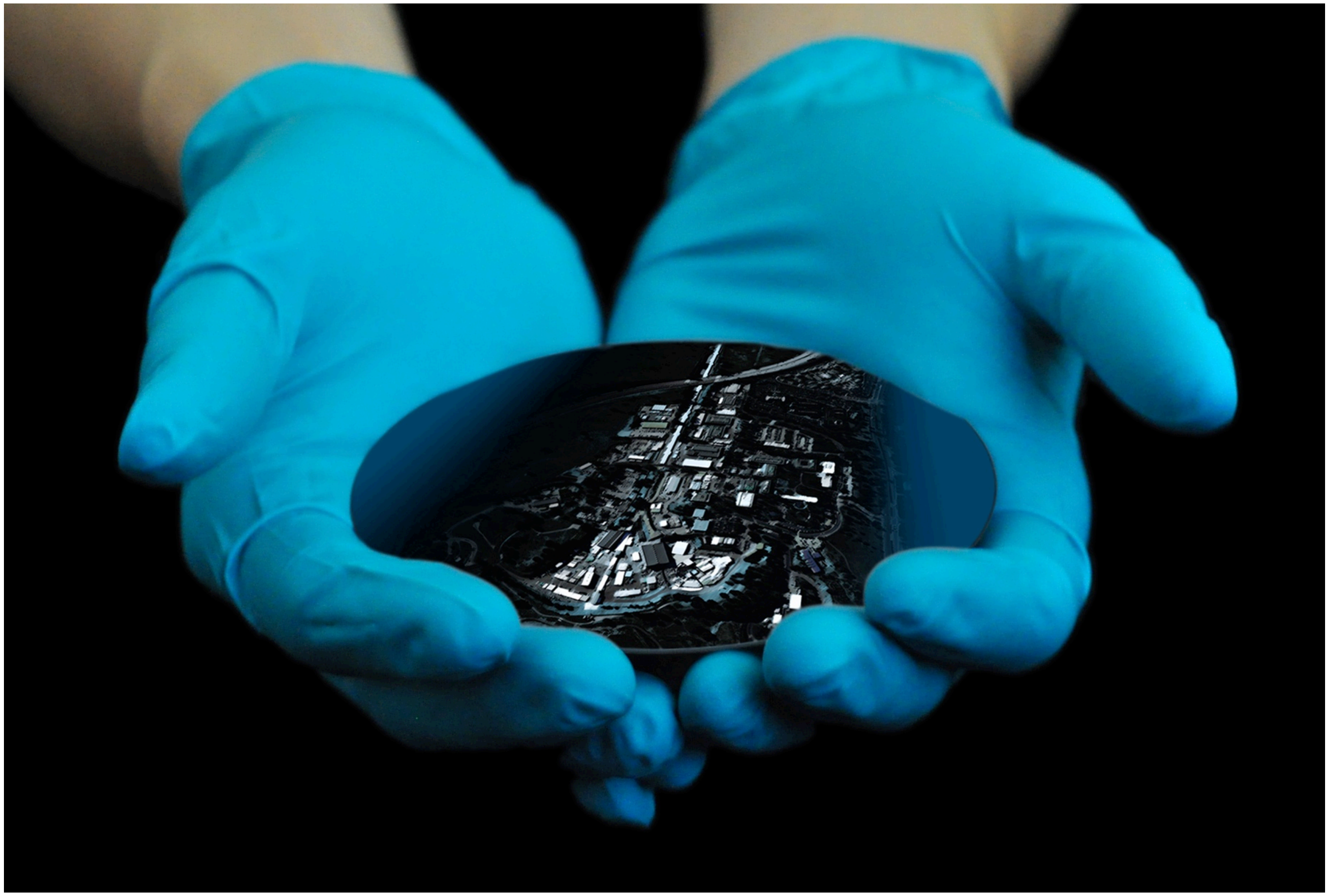
Parameter	Units	CLIC 3 TeV	DLA 3TeV	DLA 250 GeV
Bunch Charge	e	3.7e9	3.0e5	3.8e5
Rep Rate	MHz	5e-5	20	60
Beamstrahlung E-loss	%	**28.1**	**1.0**	**0.6**
Enhanced Luminosity / top 1%	cm-2/s	2.0e34	3.2e34	1.3e34
Wallplug Power	MW	582	374	152



And perhaps someday…

Laser?

Stanford ~~Linear~~ Accelerator Center



photoshop rendering of SLAC on a wafer by K. Soong

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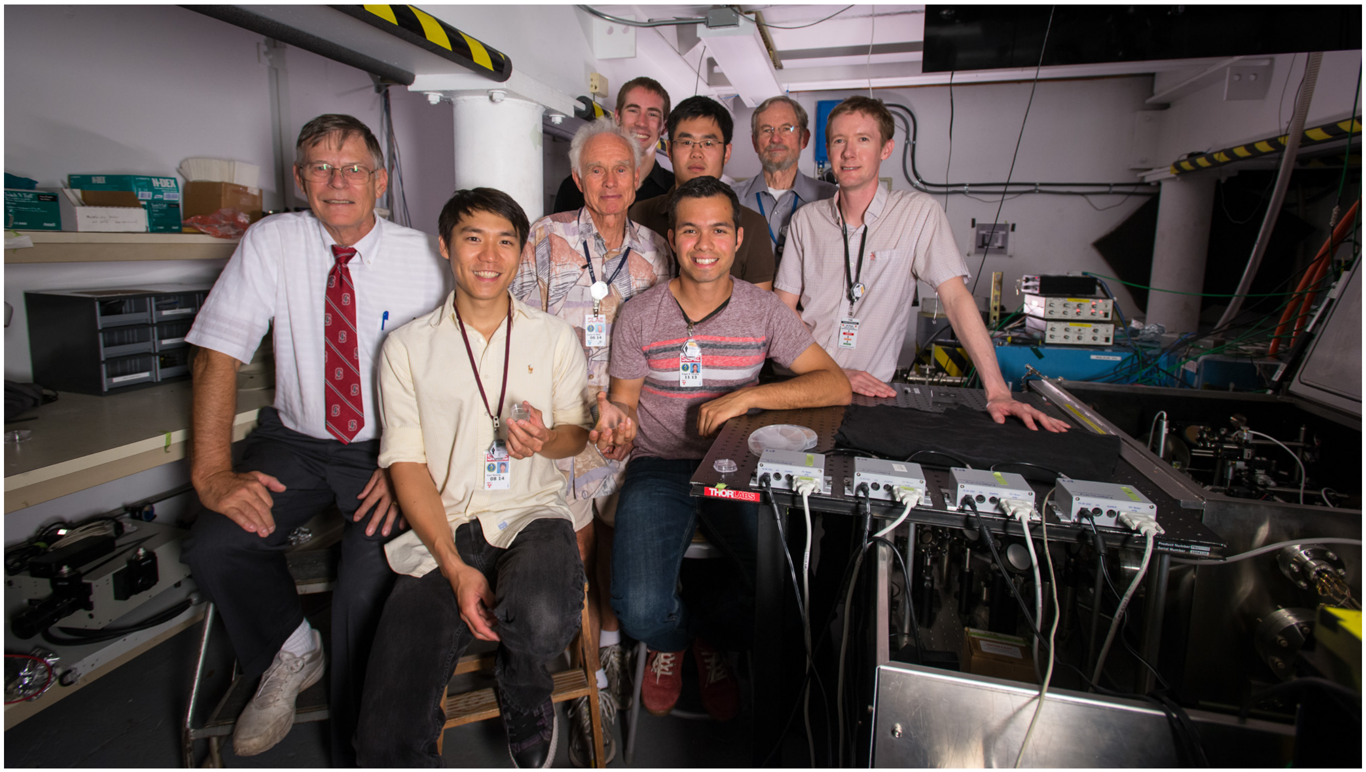
Thank you!



contact: england@slac.stanford.edu

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