Overview of dielectric laser accelerators (WG4)

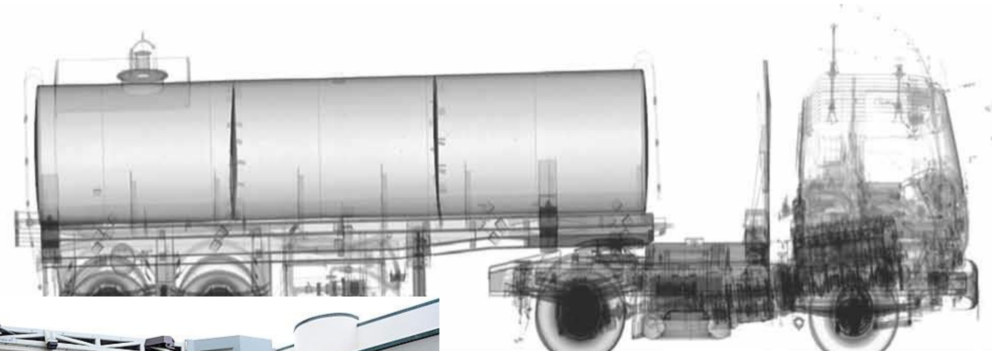
Evgenya Simakov

Los Alamos National Laboratory

April 25, 2017

Customers for compact accelerators

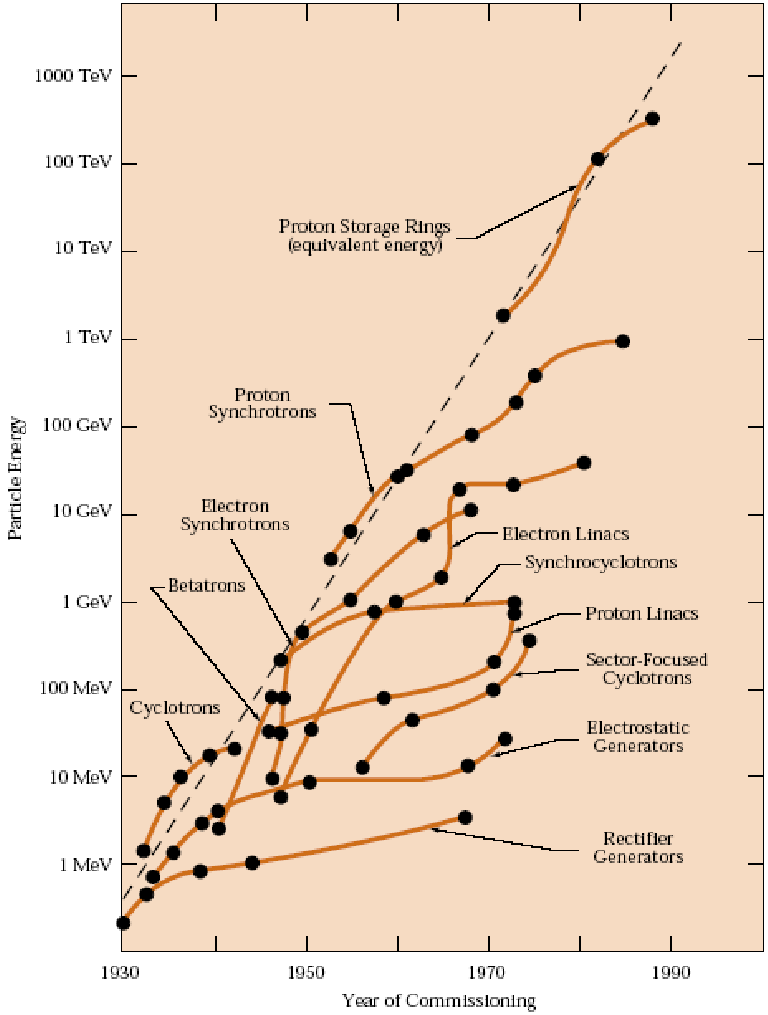
National Security: DARPA, DTRA, NA-22



Basic science:

Medicine:

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.

Big problem: accelerators today

Accelerator:

10-30 MV/m

Klystrons:

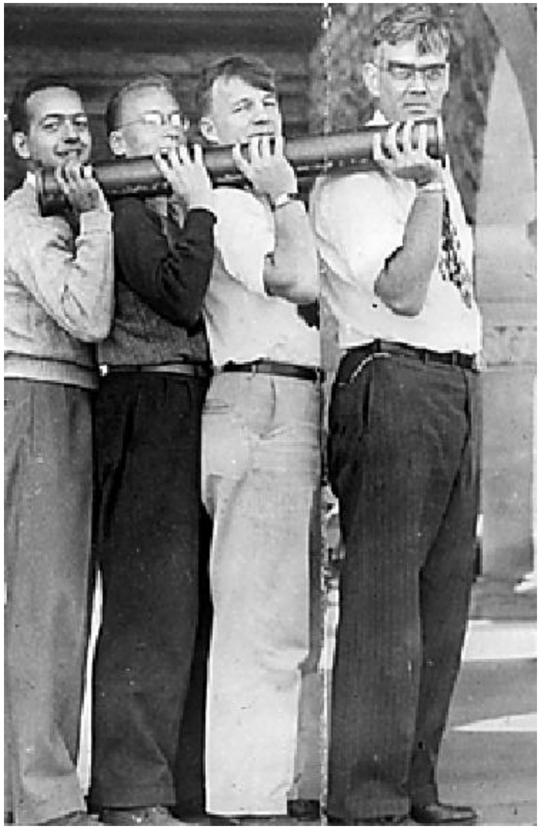
10 MW each

Shrinking the power source

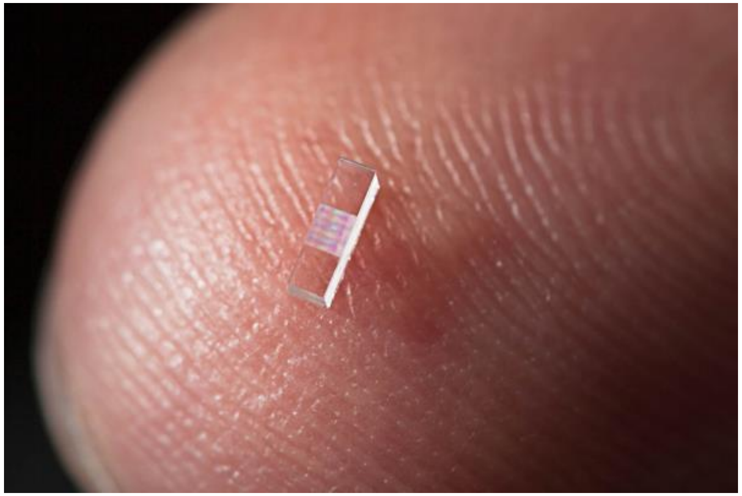
1 TW

10 MW

Shrinking the accelerating structure

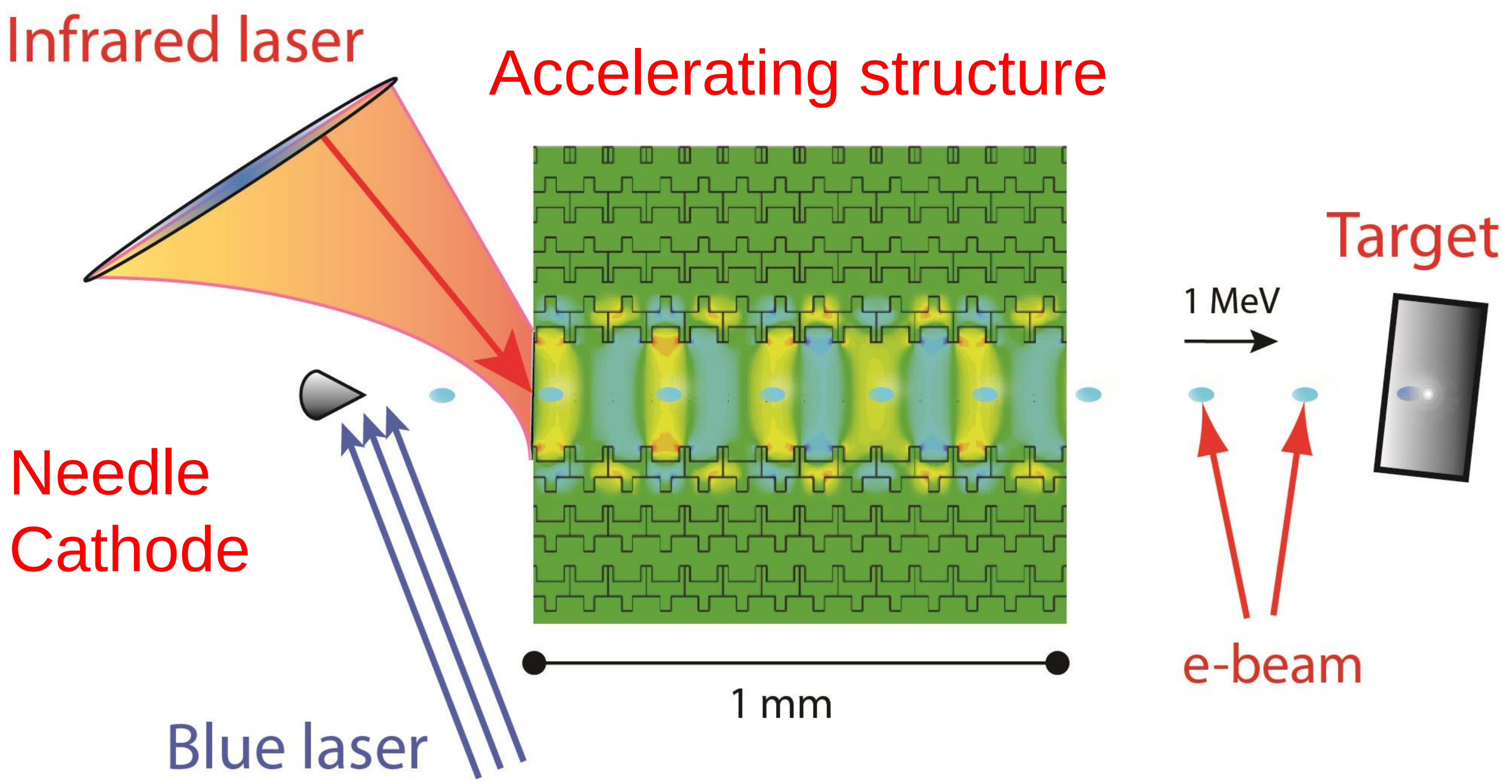


10 cm



10 microns

Dielectric laser accelerator (vision)



Projected Beam Parameter Comparison with Conventional RF Accelerators

Parameter	DLA	RF
Power Source	Commercial IR Laser	Microwave Klystron
Wavelength	1-10 µm	3-30 cm
Bunch Length	10-100 attosec	1-5ps
Bunch Charge	1-10 fC	0.1- 4 nC
Required Norm. Emittance	1-10 nm rad	0.1-1 µm rad
Rep Rate	10-100 MHz	1-1000 Hz
Confinement of Mode	Photonic Crystal (1D, 2D, 3D)	Metal Cavity
Material	Dielectric	Metal
Unloaded Gradient	1-10 GV/m	30-100 MV/m
Power Coupling Method	Free-space/Dielectric WG	Critically-coupled metal WG

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

R. L. Byer

+

R. H. Siemann

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)

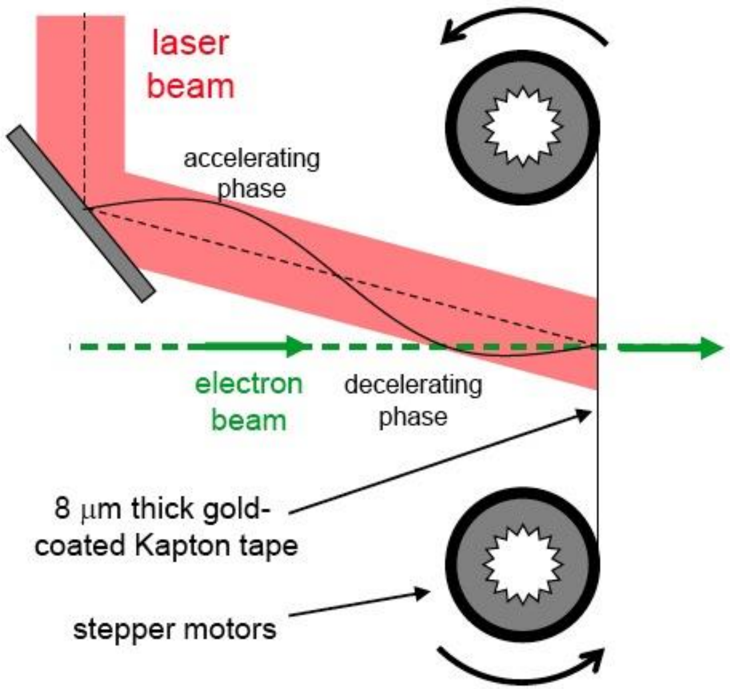
T. Plettner

E. Colby

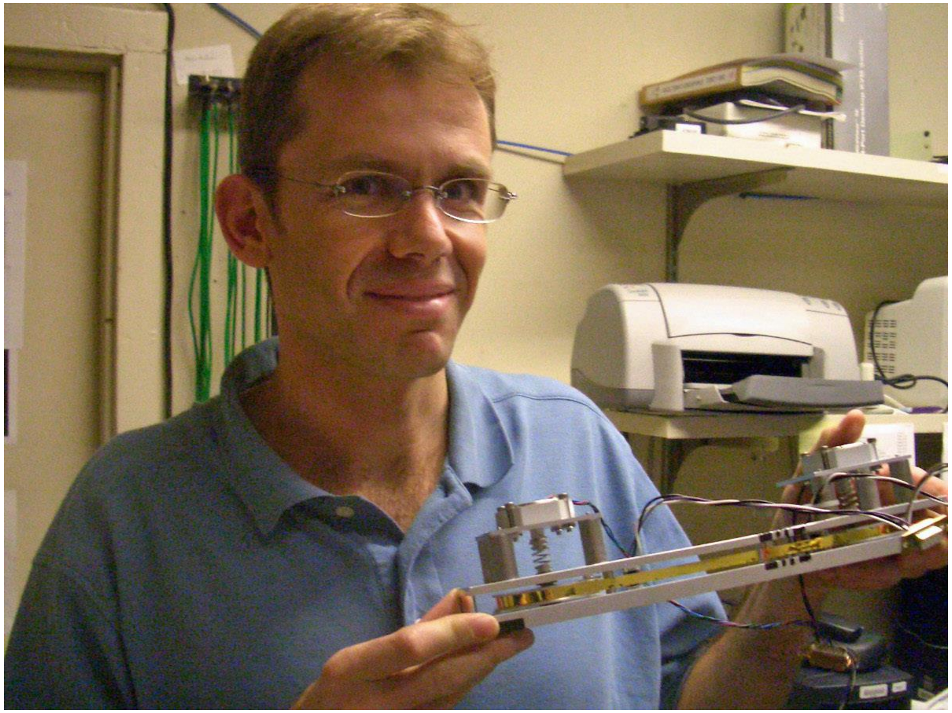
R. J. England

Postdocs and students (1996 – present)

One of the first demonstrations of laser acceleration with a structure: tape drive accelerator

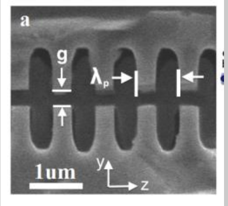
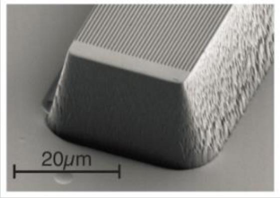
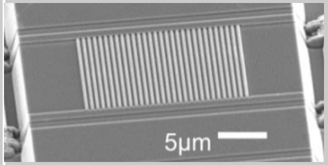
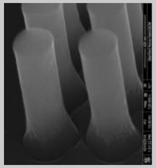


Plettner, Byer, Colby, et al., PRL **95**, 134801 (2005)
Sears, et al., PRL **95**, 194801 (2005).



Tomas Pletter with "tape drive" accelerator

Comparison of Recent DLA Acceleration Experiments

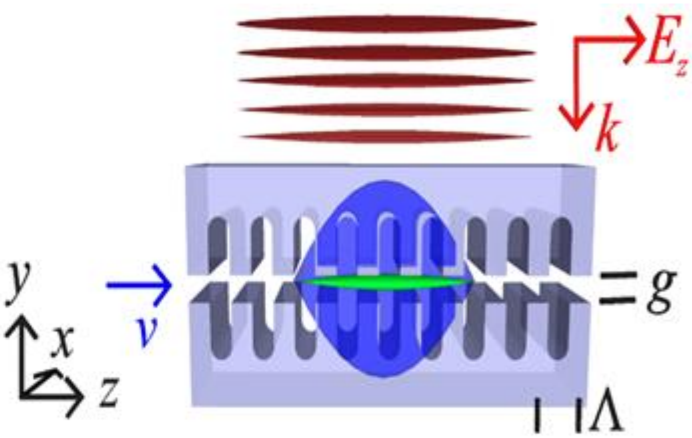
	SLAC & UCLA	Hommelhoff Erlangen	Stanford (Grating)	Stanford (Pillars)
				
Electron Energy	8 MeV	30 keV	96.3 keV	86.5keV
Relativistic β	0.998	0.33	0.54	0.52
Laser Energy	150 υJ	160 nJ	5.2 nJ	3.0 nJ
Pulse Length	40 fs	110 fs	130 fs	130 fs
Interaction Length	~20 um	11 um	5.6 um	5.6 um
Peak Laser Field	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

* Preliminary and subject to change

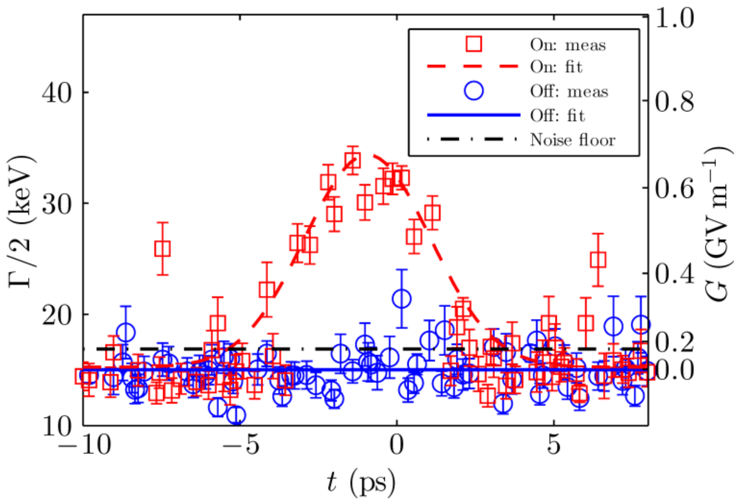
Recent demonstration of record high gradients in dielectric laser accelerating structures

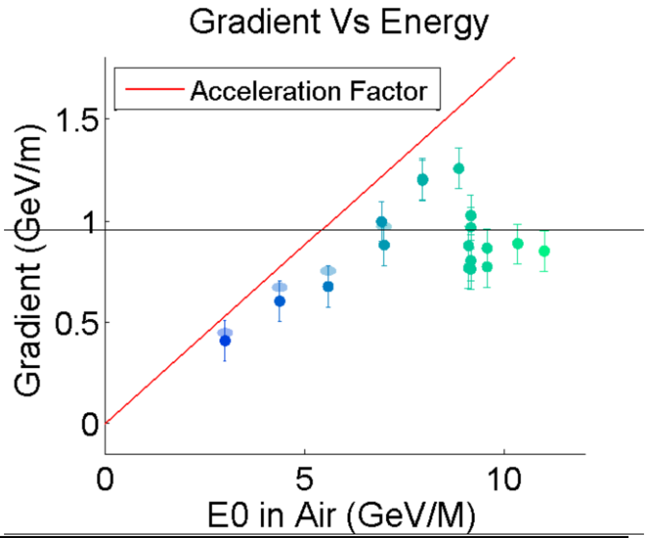
ACHIP

Demonstration of accelerating gradients close to 1 GV/m !



- Relativistic electron beam
- 800nm laser, 65 fs pulse duration
- SLAC (NLCTA): 690±100 MV/m
- UCLA (PEGASUS) 850 GV/m

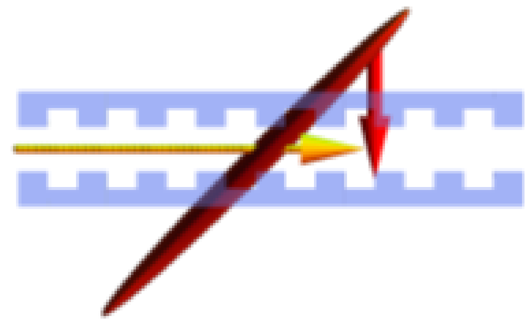


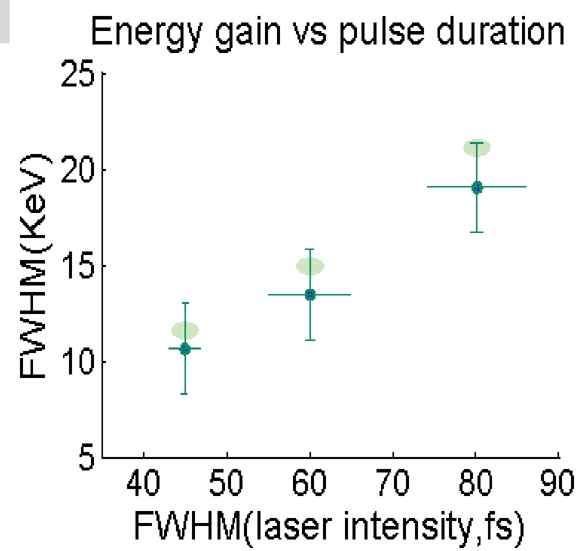


Increasing interaction length in a DLA

Energy	8 MeV
Charge	300fC→3fC
E spread	2 KeV
ϵ_n	40nm→0.4nm
Bunch length	0.5ps

λ	800 nm
Energy	<300μJ
Fluence	<0.75 J/cm^2
Size (w)	~50μm x 550μm
τ (I fwhm)	42fs





Co-propagating structures

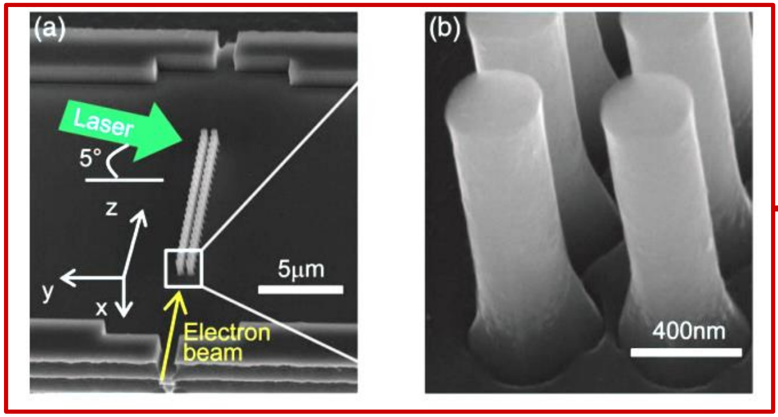
- Difficult to couple laser
- Accumulated nonlinear effect

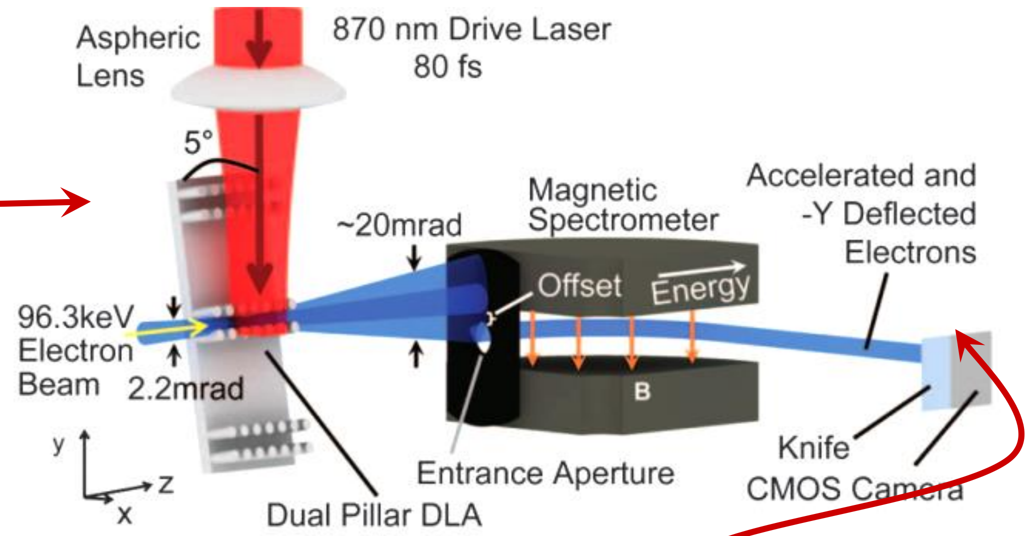
Pulse front tilt

- Requires a flat wavefront in the moving-frame

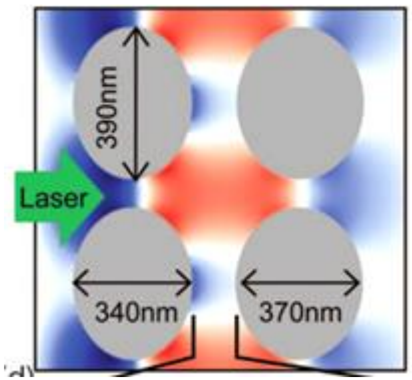
Silicon Dual Pillars laser accelerating structure

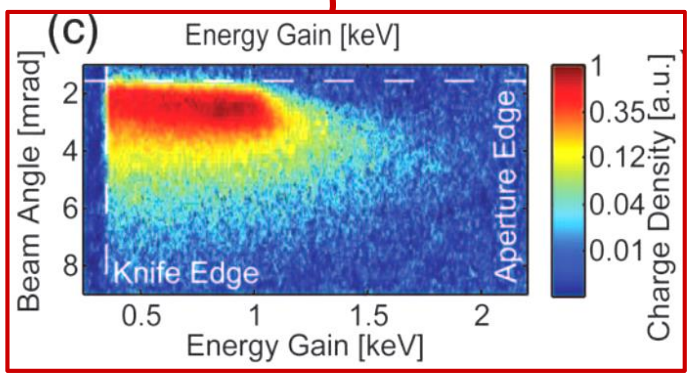
Stanford | ENGINEERING
Electrical Engineering





- 2D dual pillar DLA structures with improved accelerating field profiles.
- >370 MV/m for <100 keV (β~0.5).
- highest gradient DLA for subrelativistic beams.



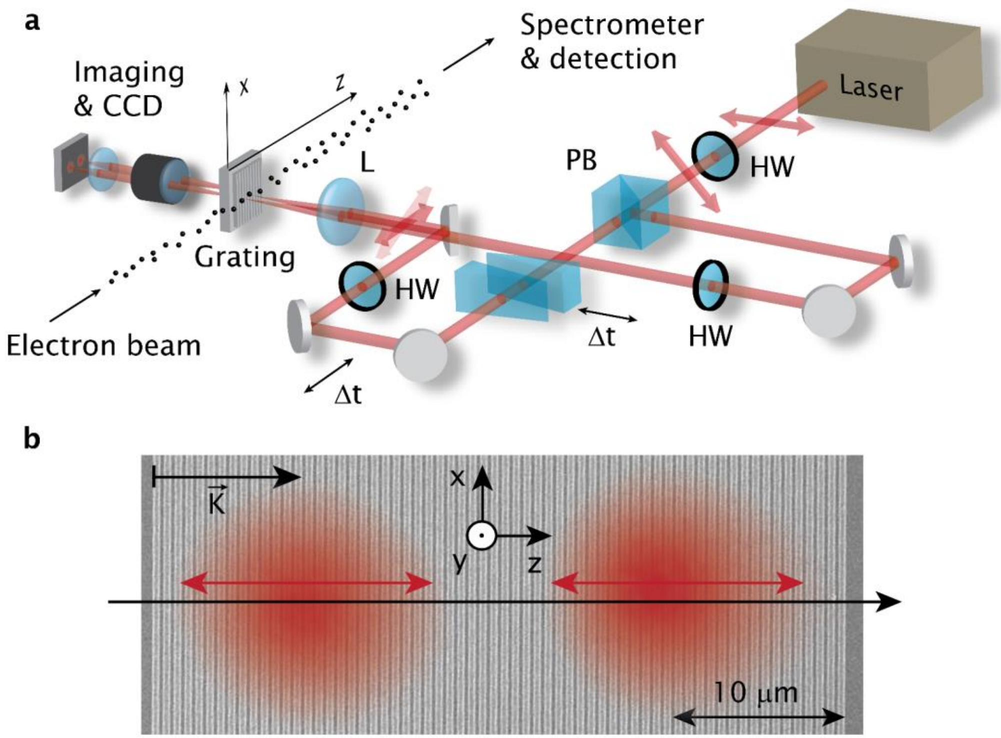


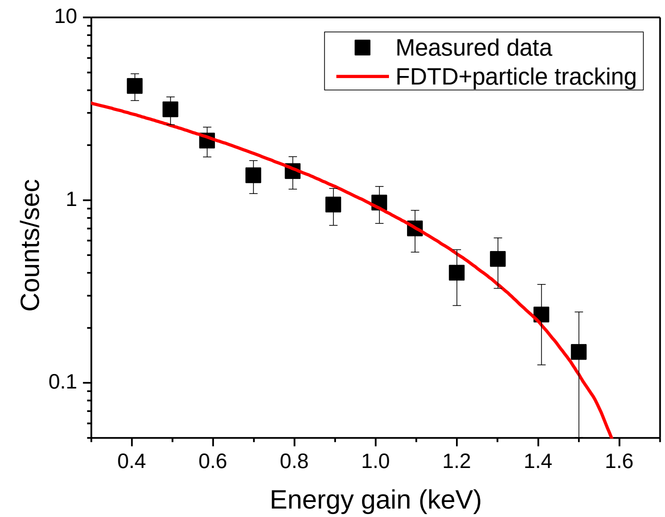
Leedle, Ceballos, et al., *Opt. Lett.* 40.18 (2015)

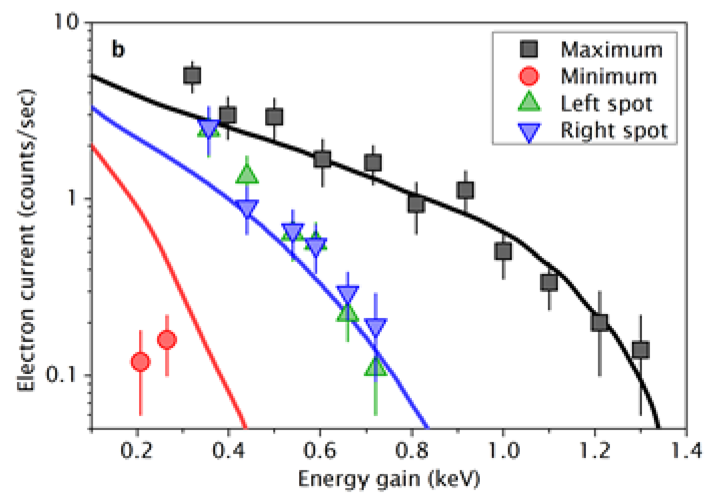
Staging for nonrelativistic beams in dielectric laser accelerators

FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

ACHIP





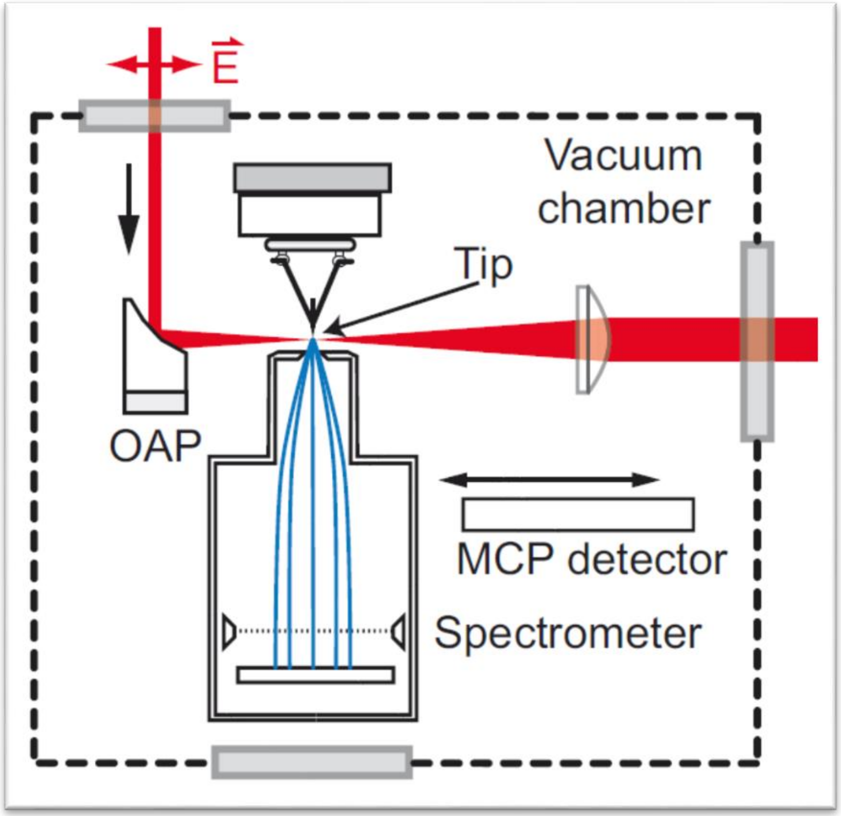


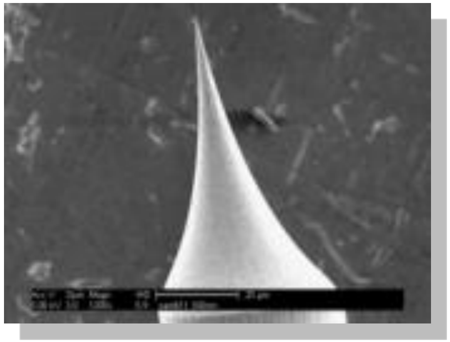
- Si grating instead of SiO_2
- 70 MV/m gradient for $\beta = 0.3$
- Staging with two laser pulses on a grating

Los Alamos NATIONAL LABORATORY EST.1943

NNSA

Tungsten tip cathodes





Tungsten tip
- etched from single crystal wire in W(310) orientation
- apex radius 5… 50nm
- clean surface by field evaporation

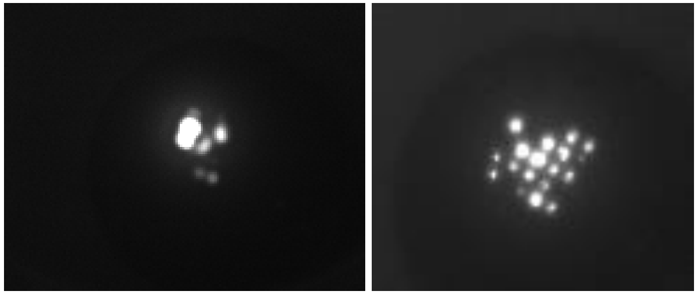
Focal parameters
- f = 15 mm; w_0=2.2µm
- max. intensity: 10^{12}W/cm^2

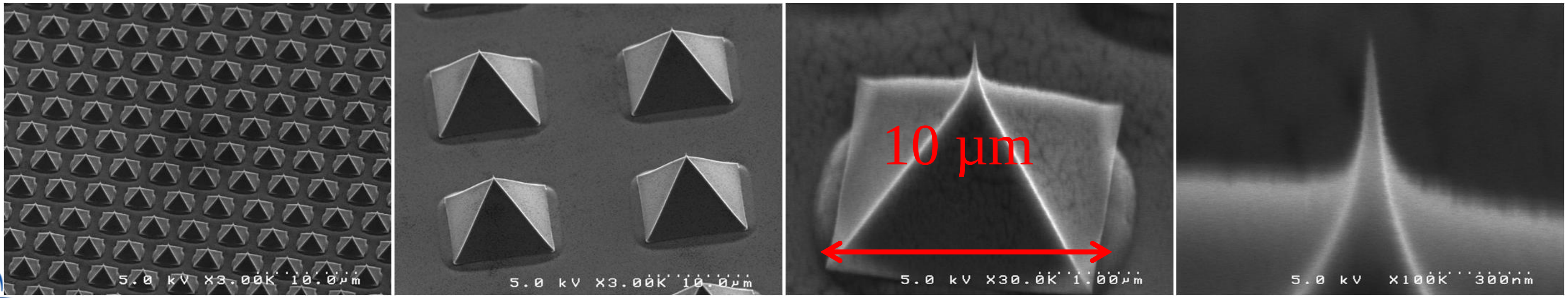
Diamond field emitter arrays

- Exquisitely sharp diamond pyramids.
- Current > 1 A/mm^2.
- Emittance < 1 mm*mrad.
- Photoemission never studied.

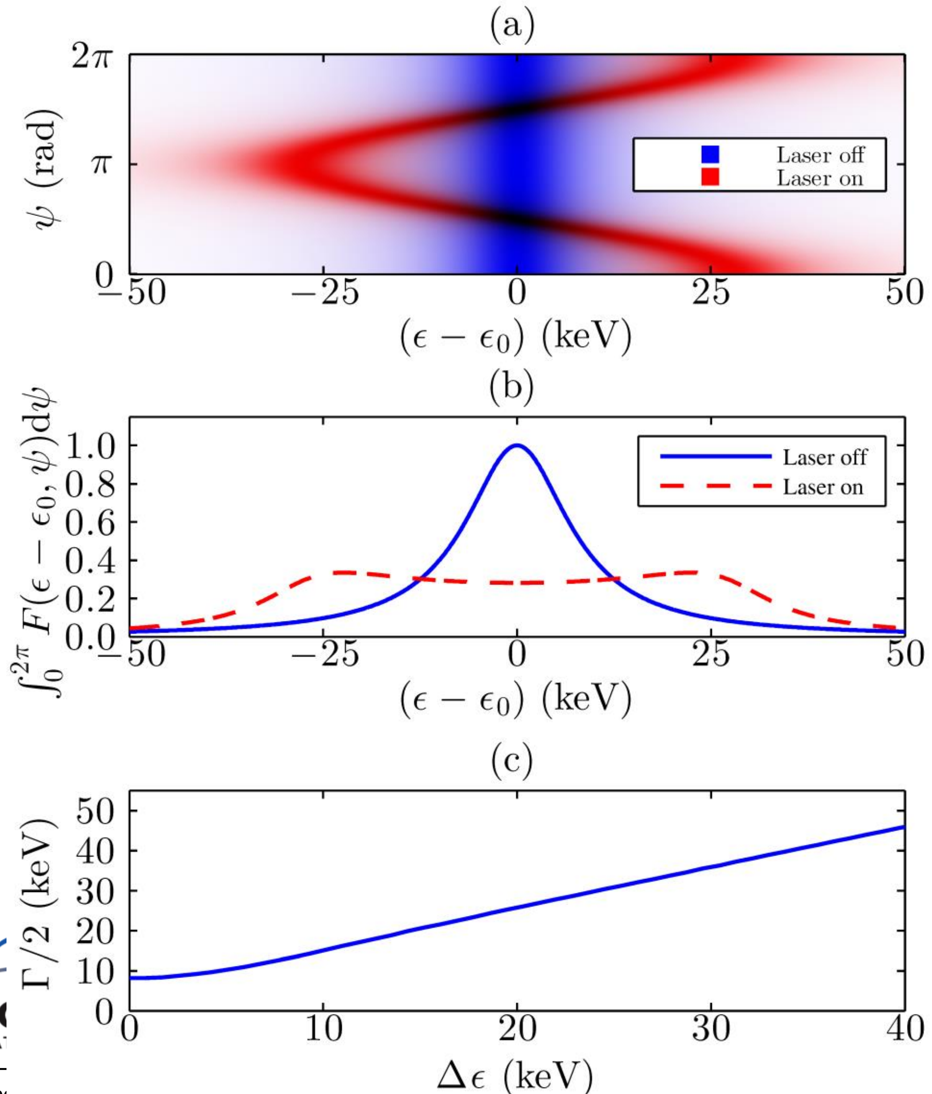
Can we observe enhanced photoemission from the tips?

We measured ~20 μA currents emitted by single diamond pyramids.





Electron bunches in recent DLA experiments to date are many laser wavelengths long.

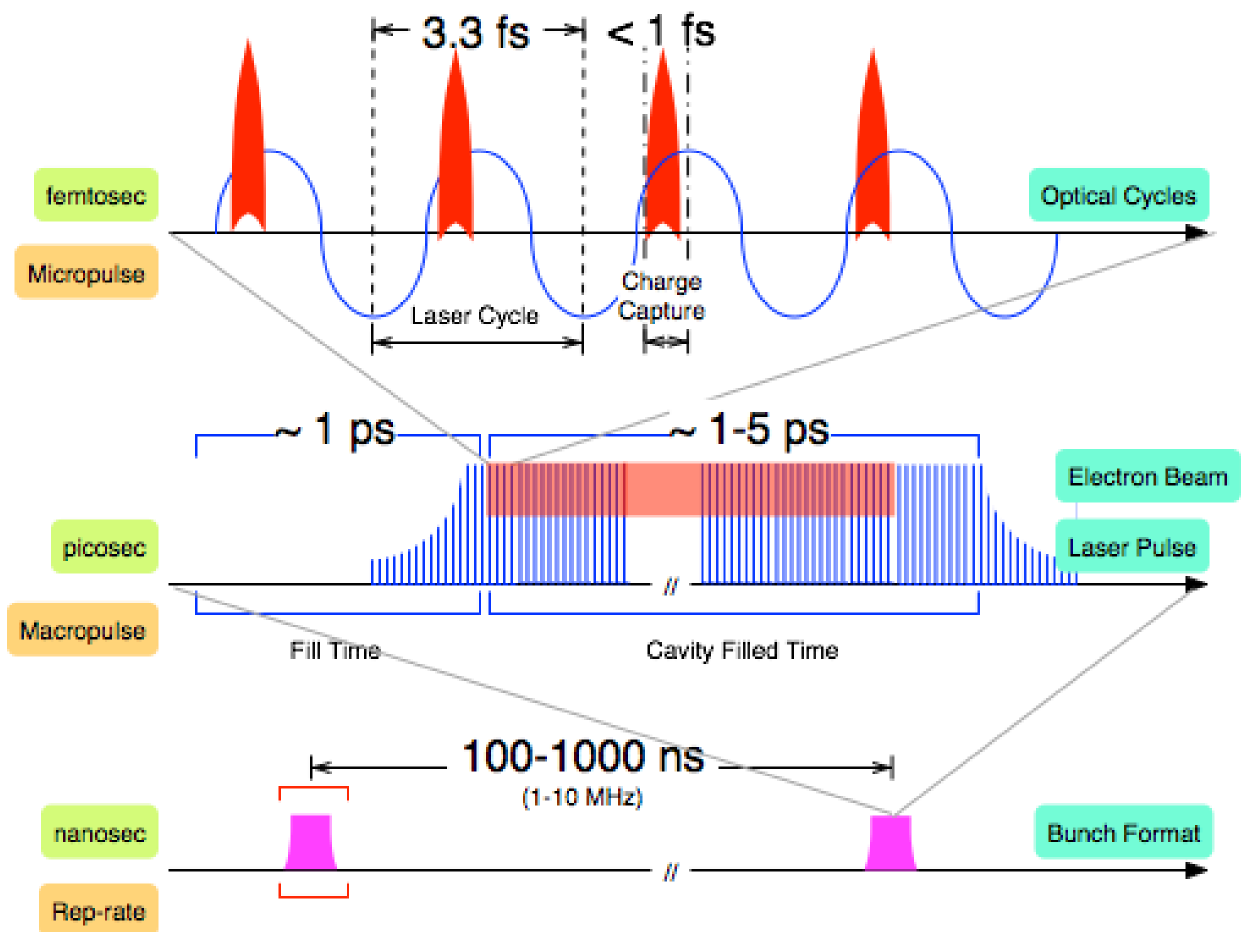


Sampling of all laser phases produces a sinusoidal energy modulation .

Projection onto the energy axis gives a 2-humped spectral distribution.

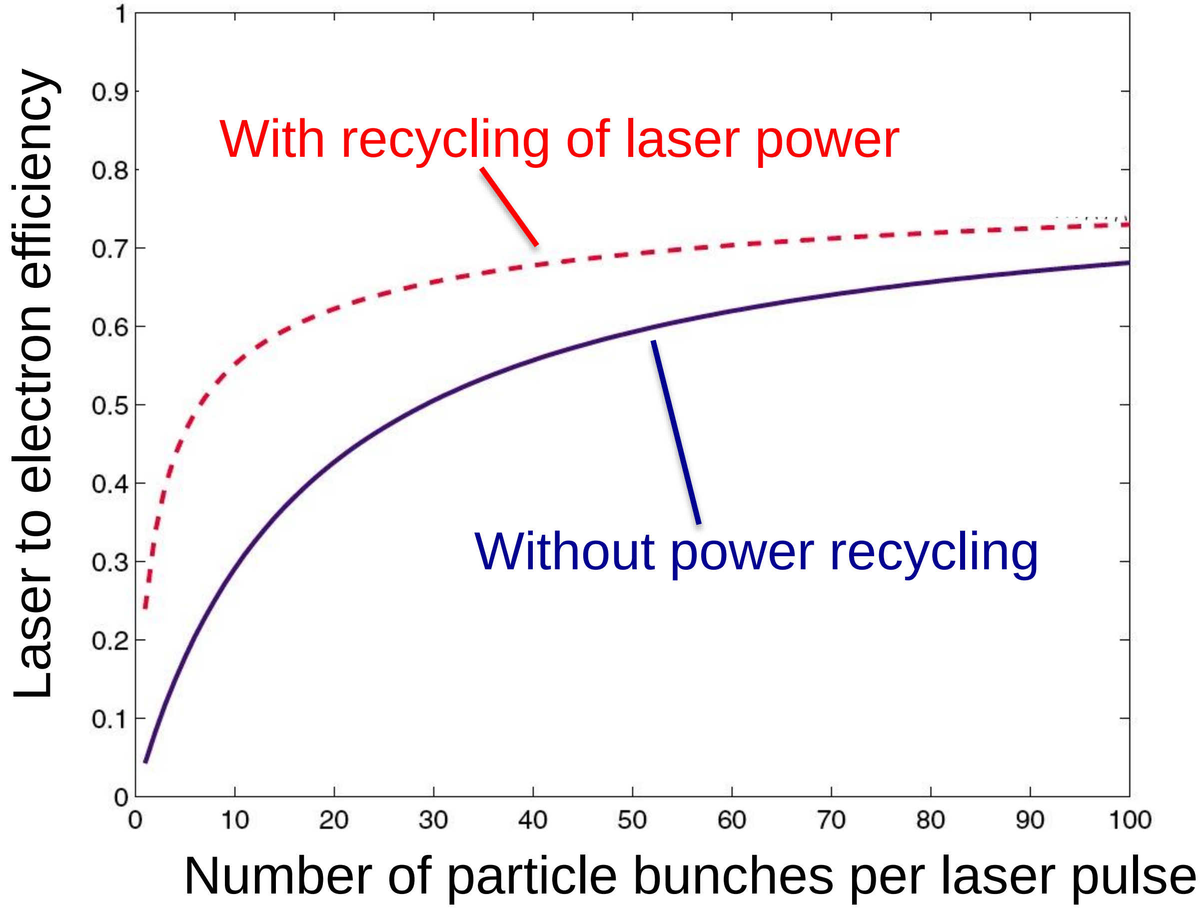
The energy gain and gradient are extrapolated from the HWHM of the spectrum.

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



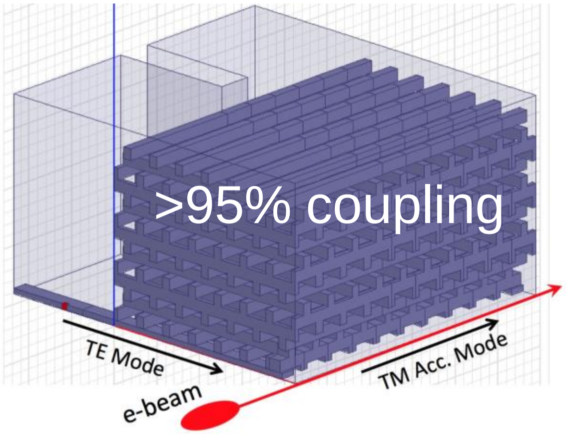
With particles optically bunched, the field to electron power transfer efficiencies could approach 60%.

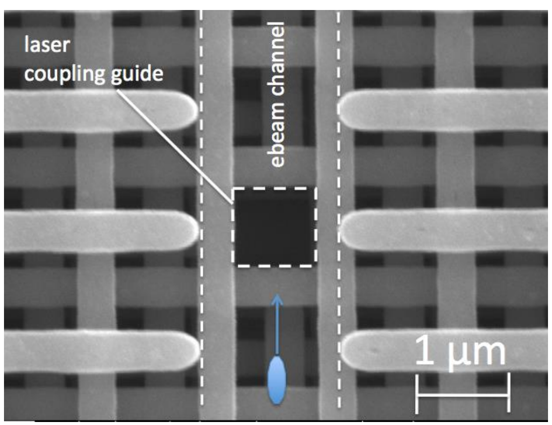
Na, Siemann, and Byer, PR-STAB **8**, 031301 (2005).



More on structures: gratings, PBGs and others

Efficient Coupler Designs

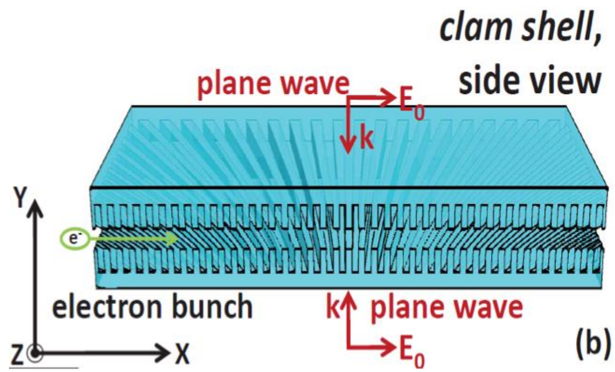




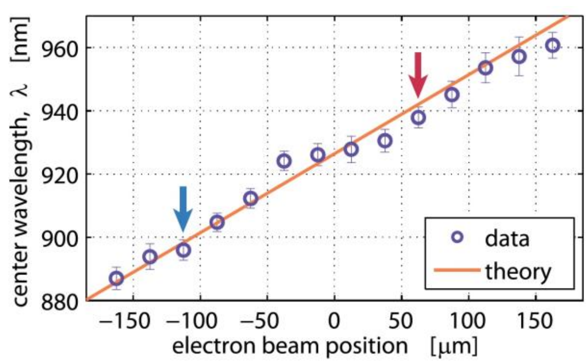
C. McGuinness, Z. Wu

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

Beam Position Monitor

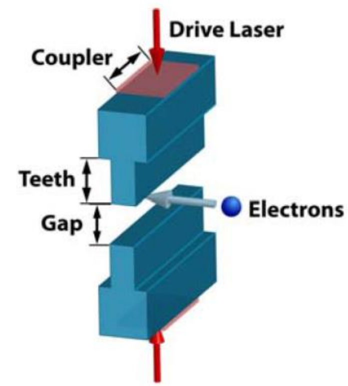


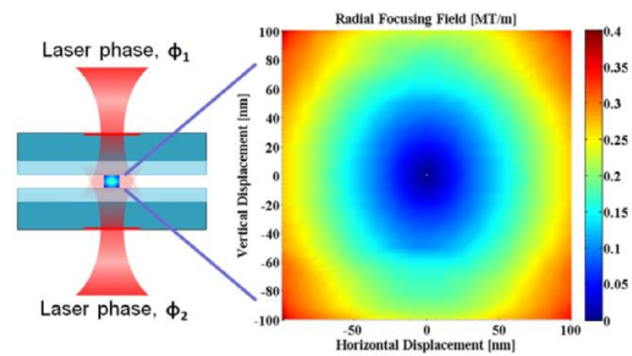
Opt. Lett., **37** (5) 975-977 (2012)



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

Focusing Structures

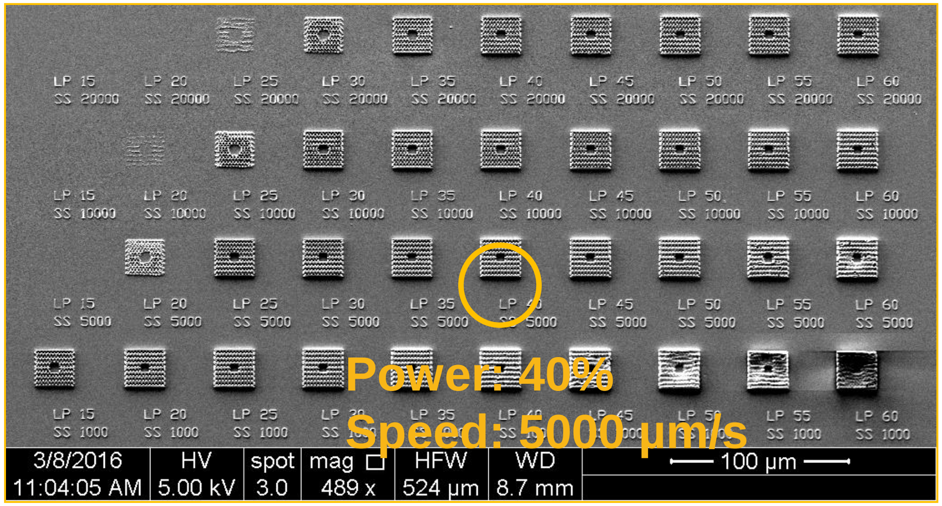




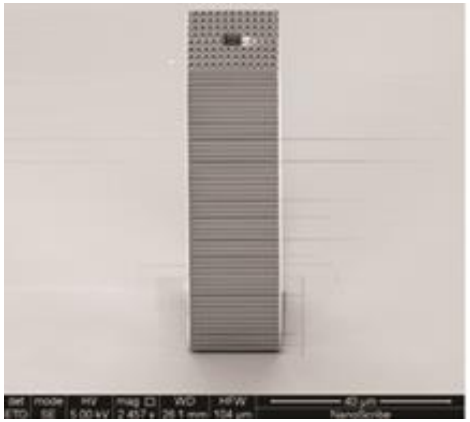
AIP Conf. Proc. **1507**, 516 (2012)
J. Mod. Opt. **58** (17), 1518-1528 (2011)

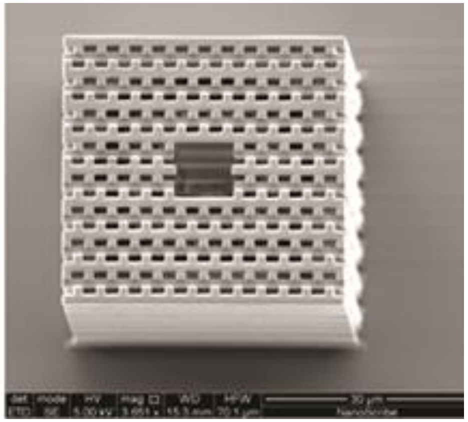
Additive manufacturing for woodpile structures

- Nanoscribe system is perfectly suited to print wood-pile structures on a micron scale.
- Resolution: ~100 nm (lateral) x 500 nm (vertical), smallest features below 1 μm.
- Possible use of new polymers

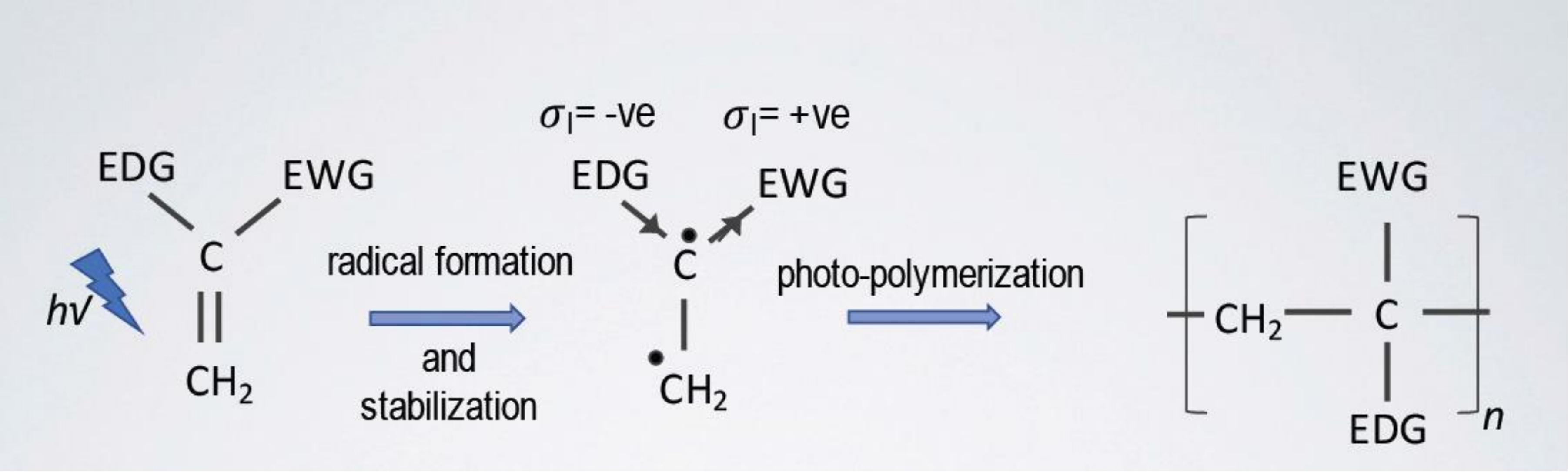


Bulk structures printed with IP-Dip

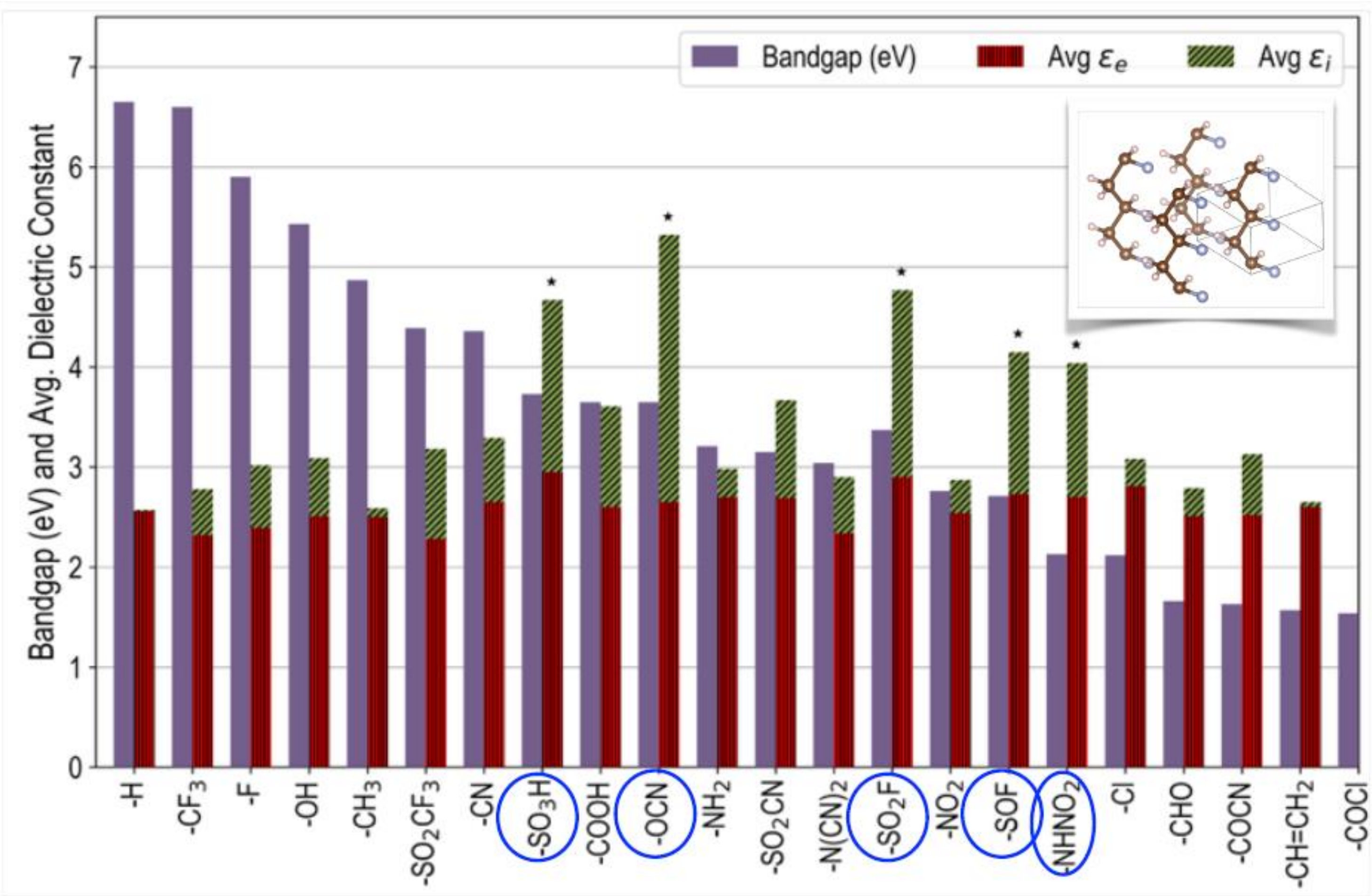




Synthesis of the new polymer materials

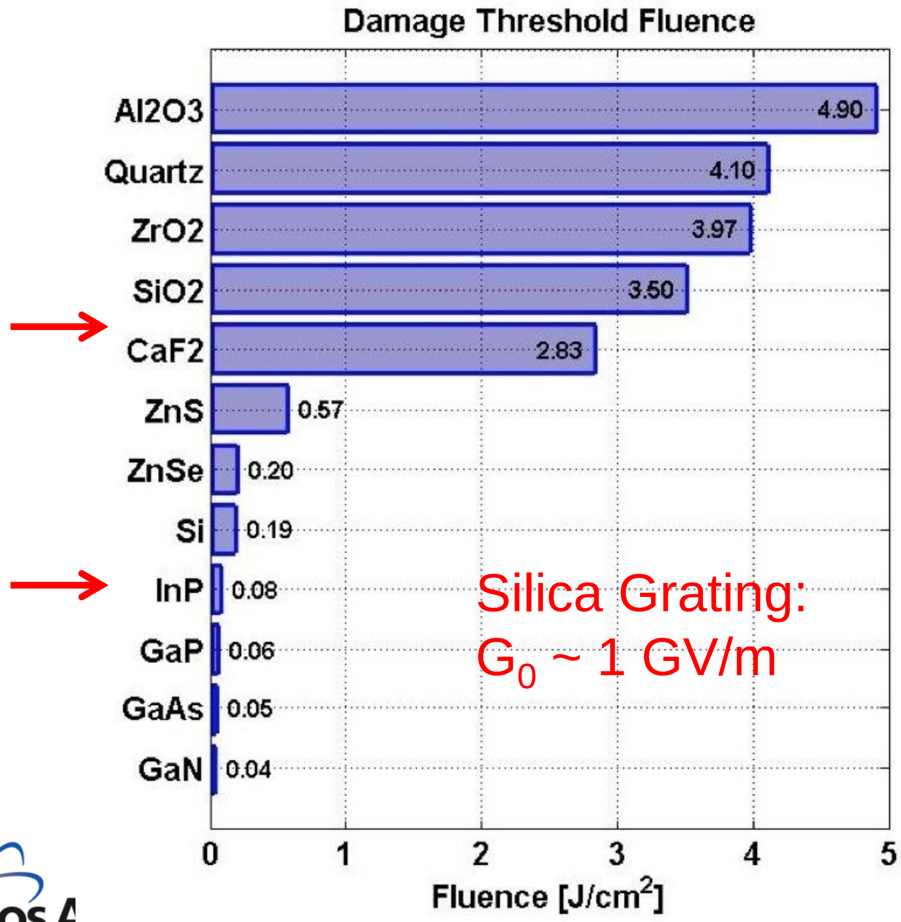


High dielectric constant polymers



Materials that can withstand intense laser fields.

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



Additive manufacturing compatible material: Ormocomp, ~0.3 J/cm^2.

DLA 2011 workshop

DLA 2011 ICFA workshop at SLAC: over 50 scientists from relevant fields (lasers, photonics, accelerators).

Conclusions:

No major roadblocks to scale DLA to higher energies using existing laser technology.

Compact footprint and reduced cost would give university labs and smaller facilities greater access.

Sub-optical wavelength **(attosecond) temporal bunch structure** translated into sub-fs radiation pulses could enable ultrafast science (molecular movies, atomic physics).

Compact **portable scanners and radiation sources** for medicine (e.g. direct e-beam oncology), security (Nuclear Fluorescence Imaging), phase contrast imaging, etc.

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

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
SLAC: Burt Richter
Stanford: Persis Drell

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 1 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 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.

Issues to be discussed in WG4

- Beam transport.
- New materials.
- Particle sources.
- Final focus.
- Efficiency, power, and cost