Recent Results in Dielectric Laser Acceleration of Electrons

Physics and Applications of High Brightness Beams
Havana, Cuba, March 28 – April 1, 2016

R. Joel England

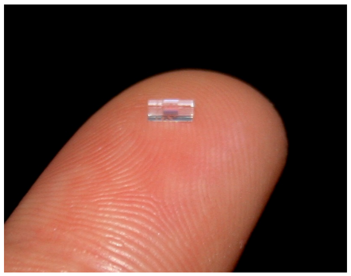
GORDON AND BETTY MOORE FOUNDATION

U.S. DEPARTMENT OF ENERGY Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

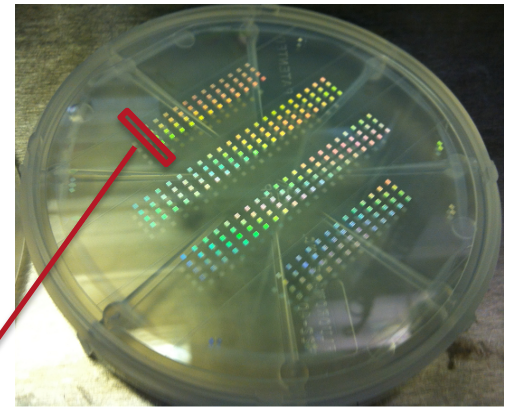
Dielectric Laser Acceleration (DLA)

SLAC



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

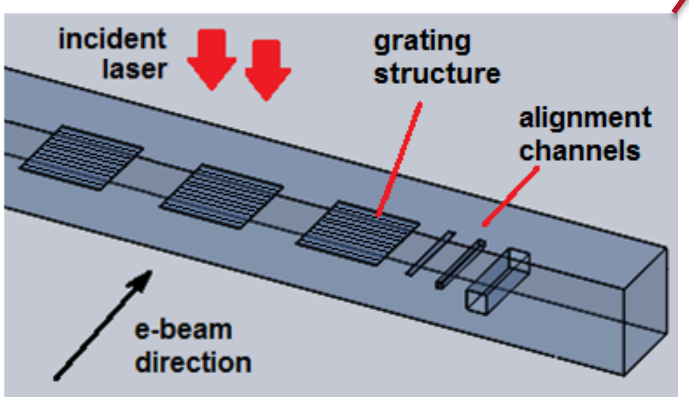
"Accelerator-on-a-chip"

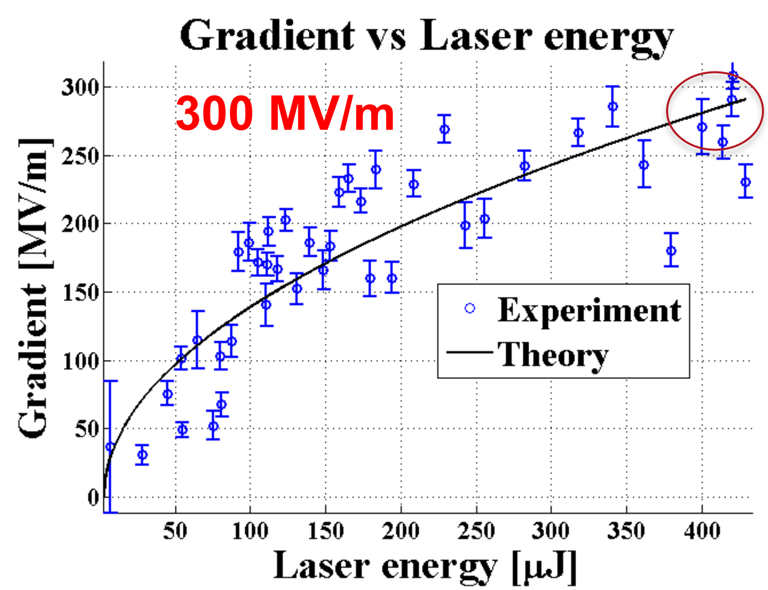


bonded silica phase reset accelerator prototypes fabricated at SLAC/ Stanford

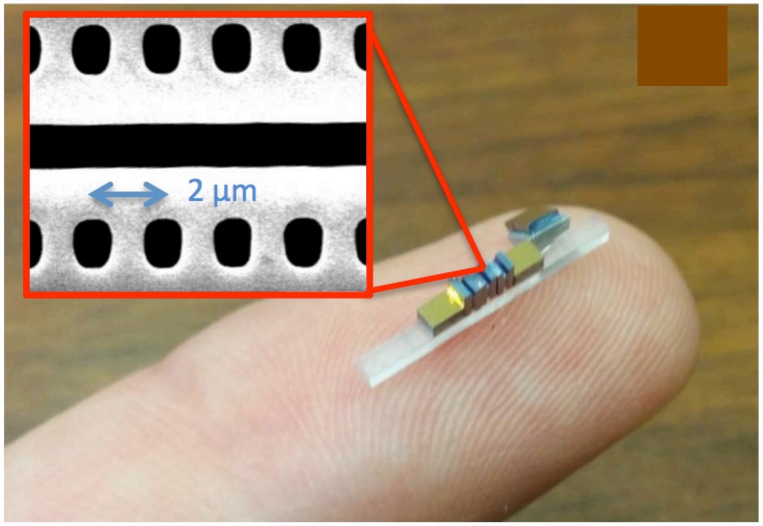
Goal: lower cost, more compact, energy efficient, higher gradient

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



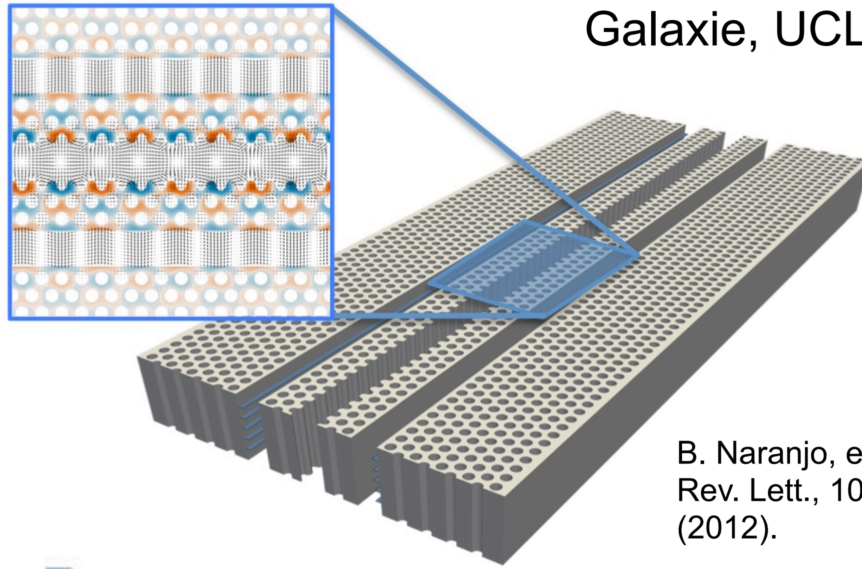


Various DLA Concepts Recently Proposed



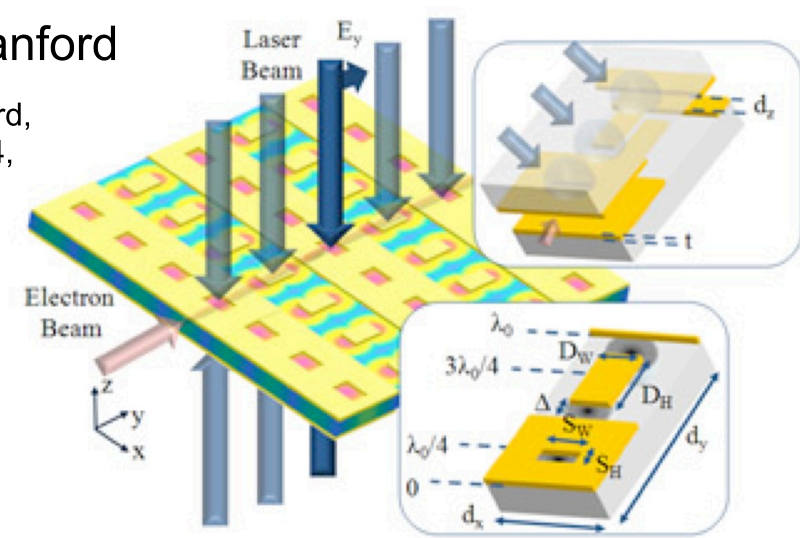
Buried Grating, Stanford

C. M. Chang and O. Solgaard, Applied Physics Letters, 104, 184102 (2014).



Galaxie, UCLA

B. Naranjo, et al., Phys. Rev. Lett., 109, 164803 (2012).



MLA, Tel-Aviv

D. Bar-Lev and J. Scheuer, Phys. Rev. ST Accel. Beams, 17, 121302 (2014)

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

Solid-state laser

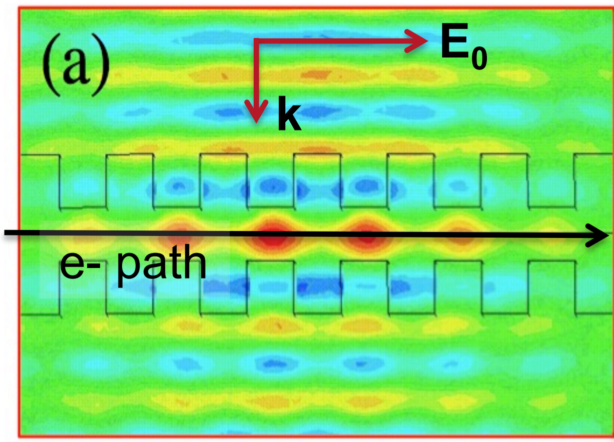
available now
"off-the-shelf"

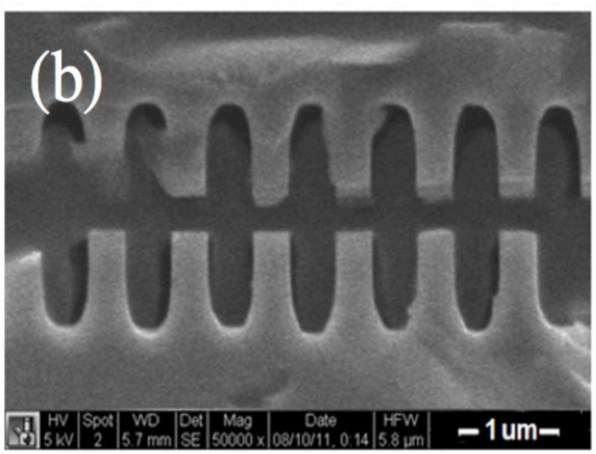
available in ~3 years

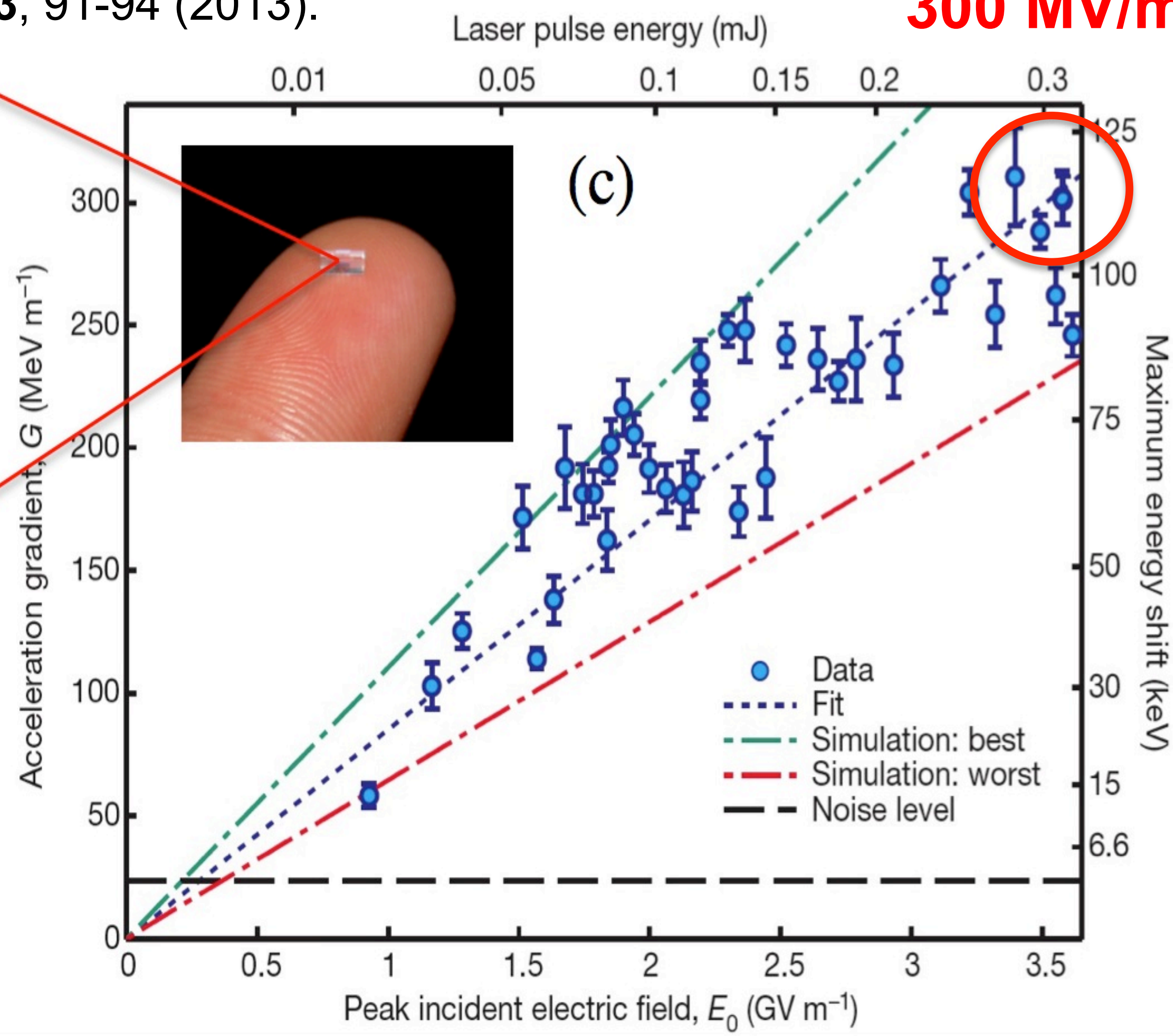
First gradients observed were 10 times higher than the main SLAC linac…

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

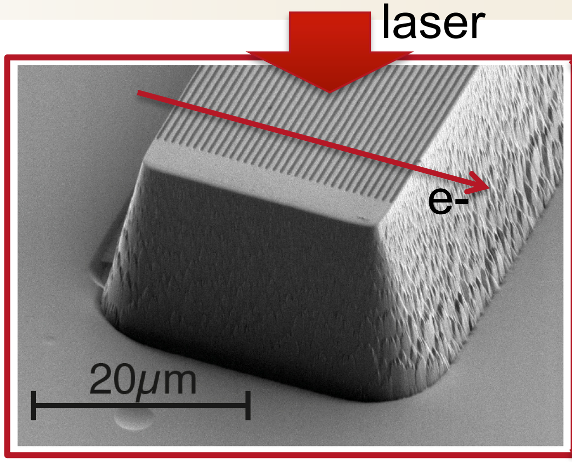
300 MV/m

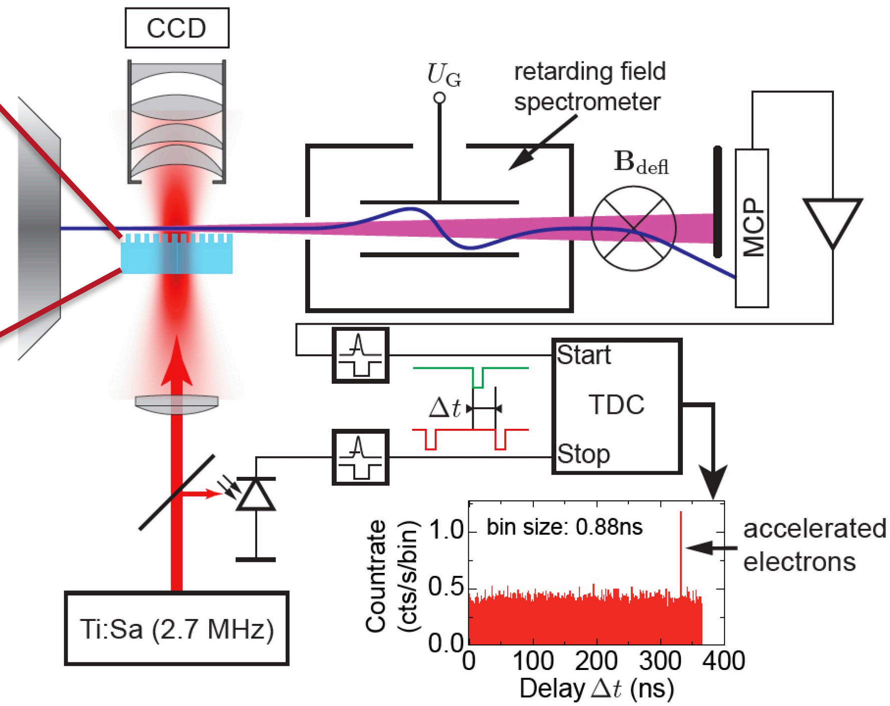


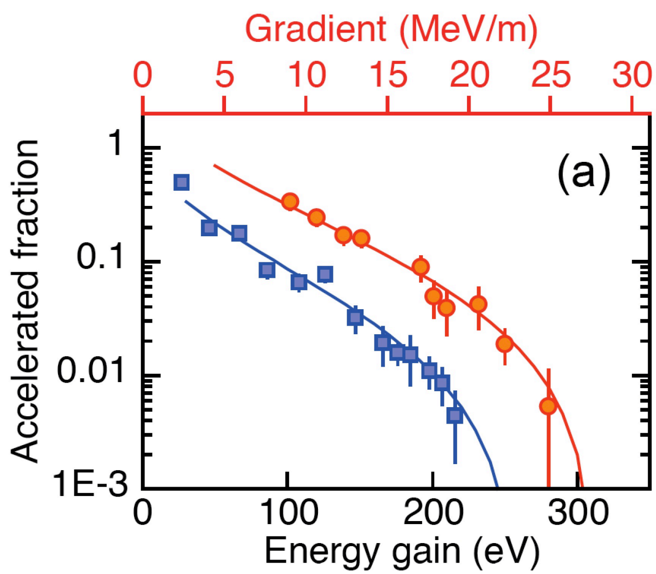




25 MV/m gradients were simultaneously demonstrated at 30 keV electron energy at U. Erlangen.

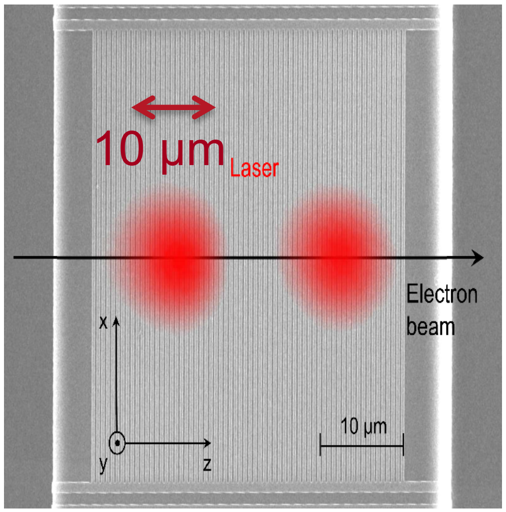


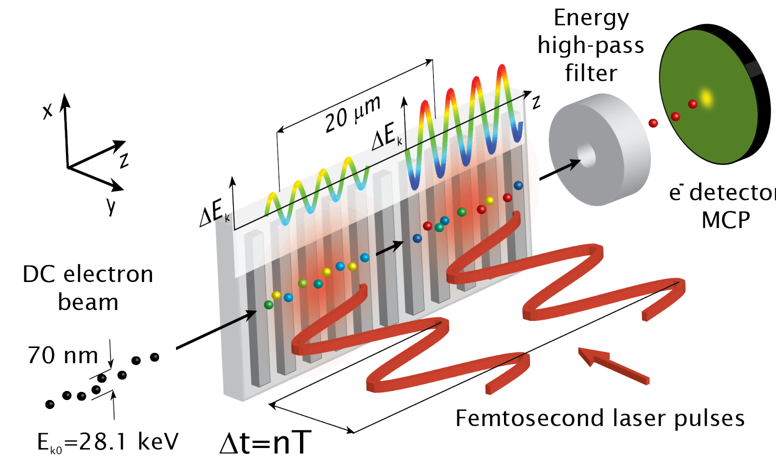




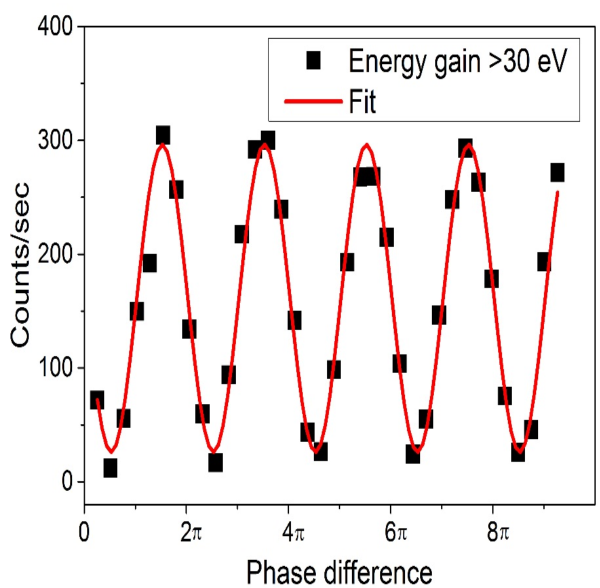
Breuer and Hommelhoff, Phys. Rev. Lett. **111**, 134803 (2013)

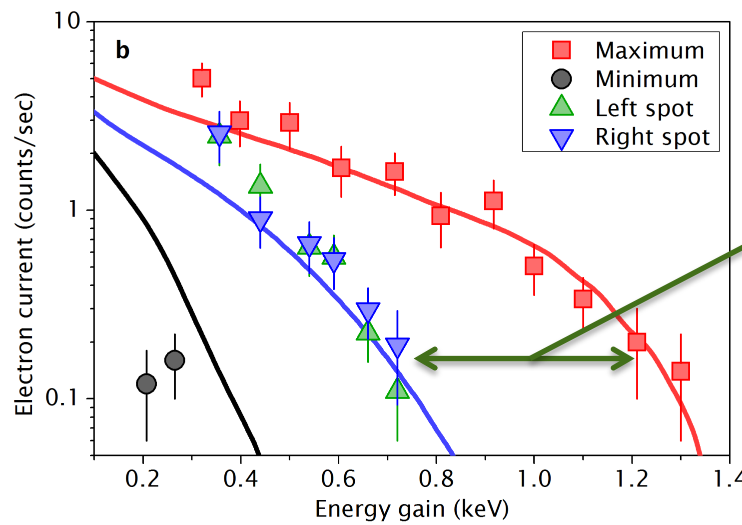
Hommelhoff Group has recently demonstrated phased 2-stage acceleration with 28 keV electrons





M. Kozák et al., arXiv:1512.04394v1





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

…as well as auxilliary sub-relativistic techniques for beam monitoring and control.

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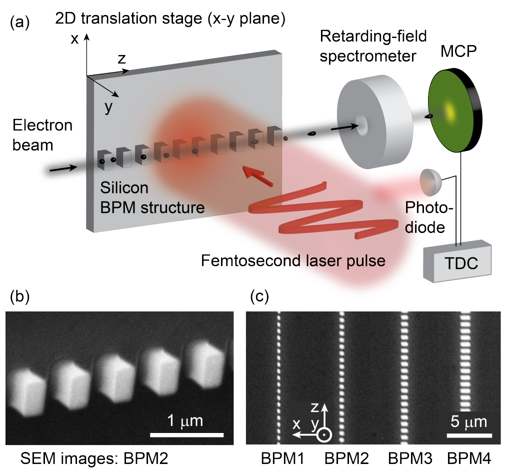
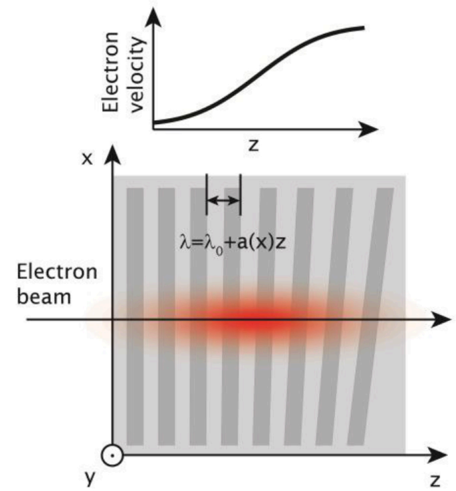
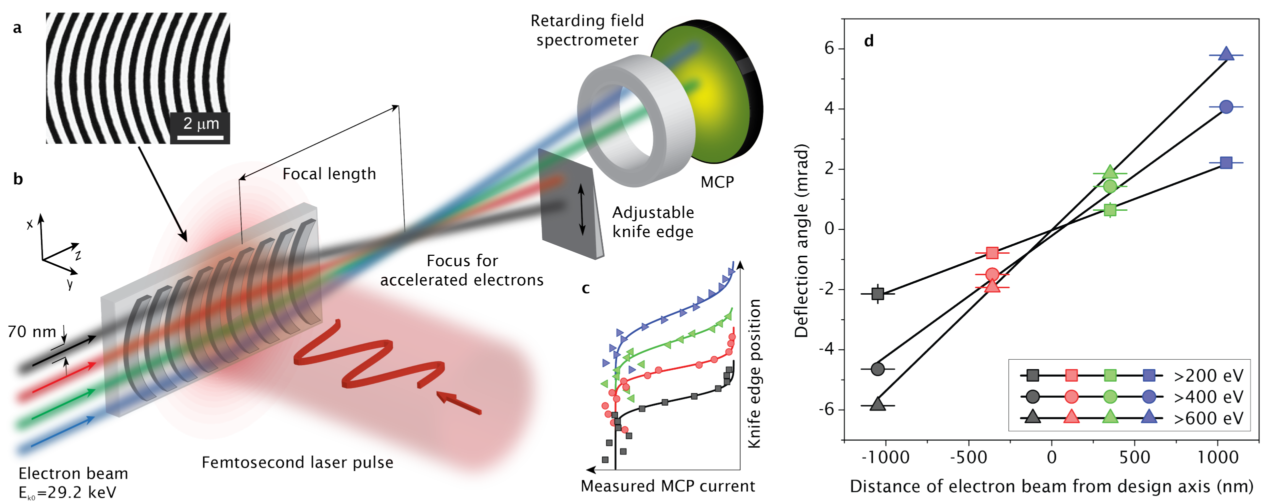


Beam Position Monitoring



Chirped Structures

Sub-relativistic Focusing

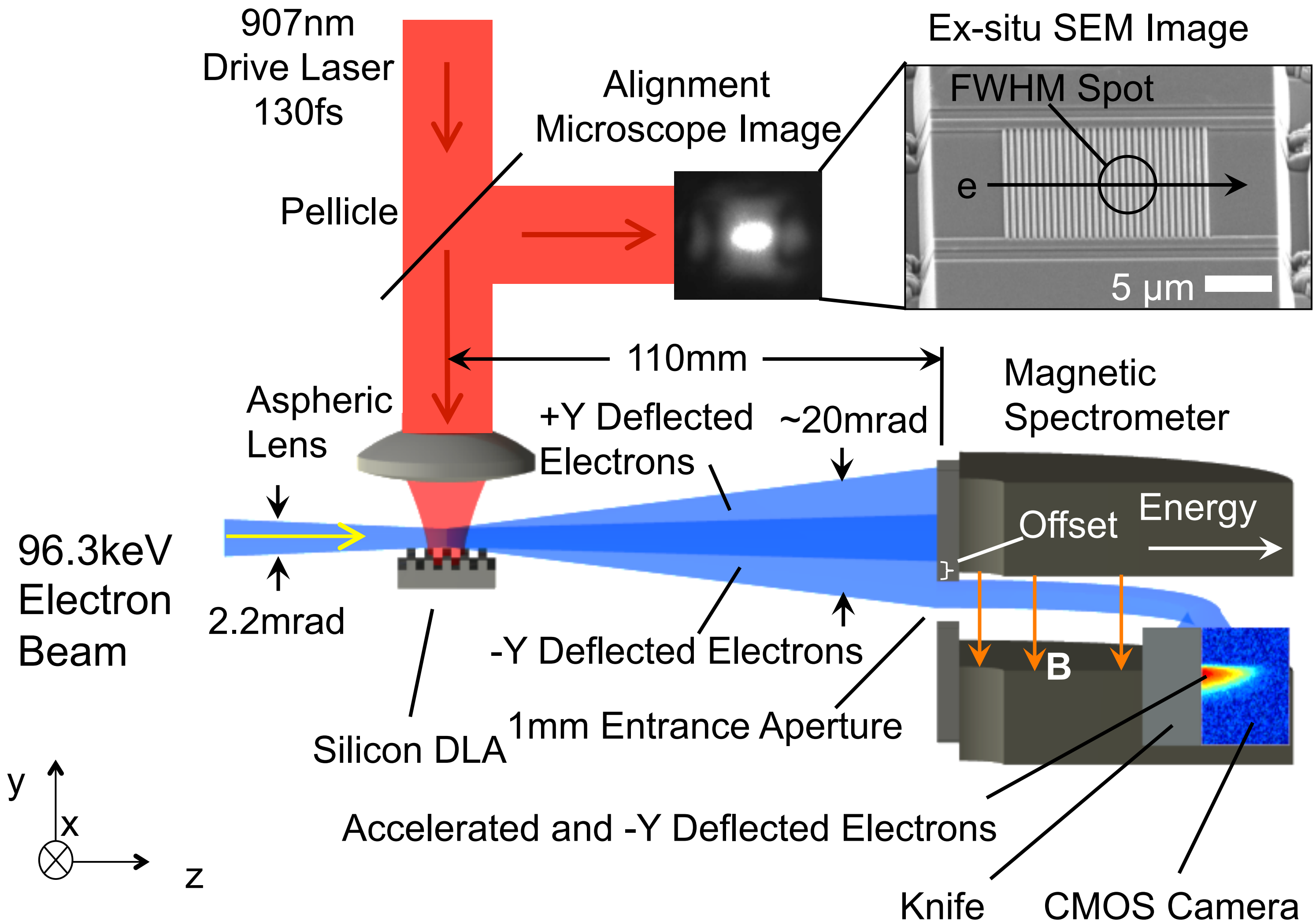


FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

See talk by M. Kozak

M. Kozák et al., arXiv:1512.04394v1

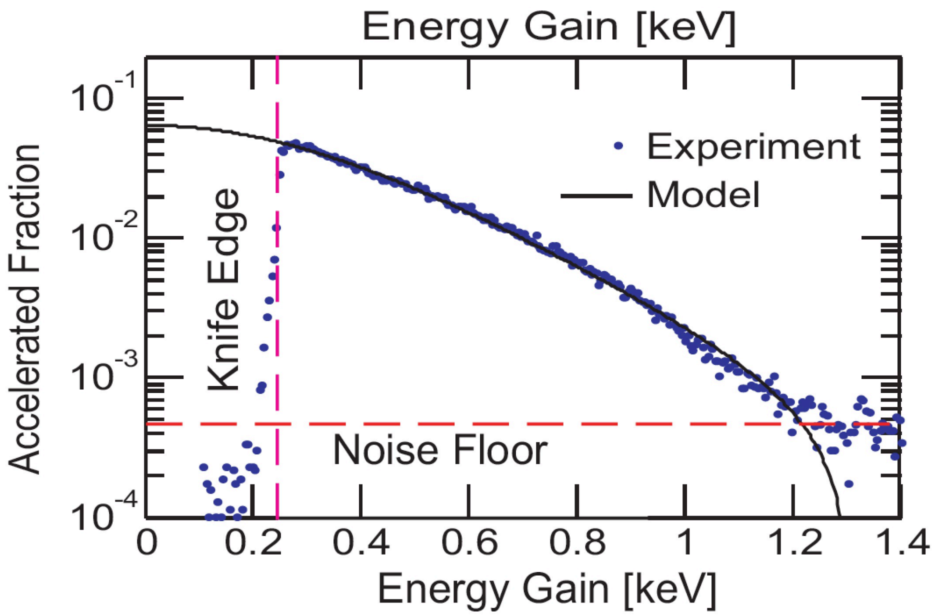
A SEM test stand for subrelativistic (100 keV) DLA demonstrations has been built at Stanford…

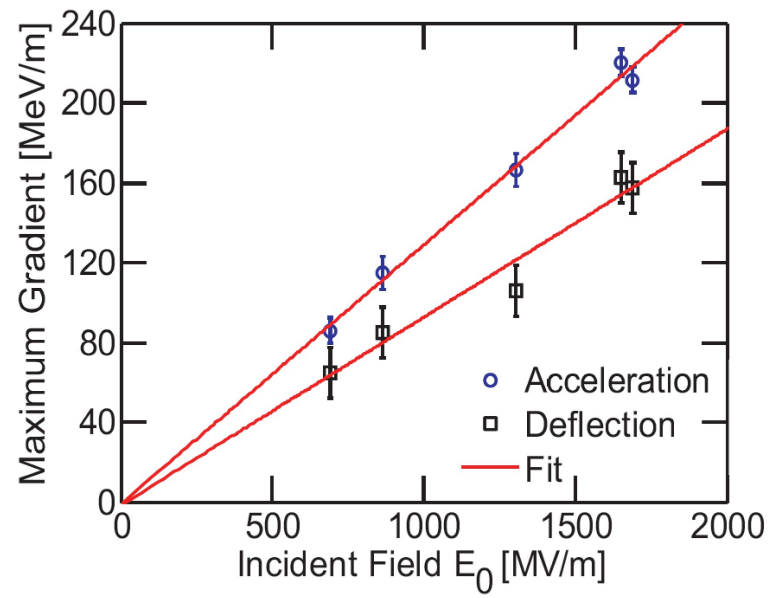


K. J. Leedle, R. F. Pease, R. L. Byer, and J. S. Harris, *Optica* (2014).

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

SLAC





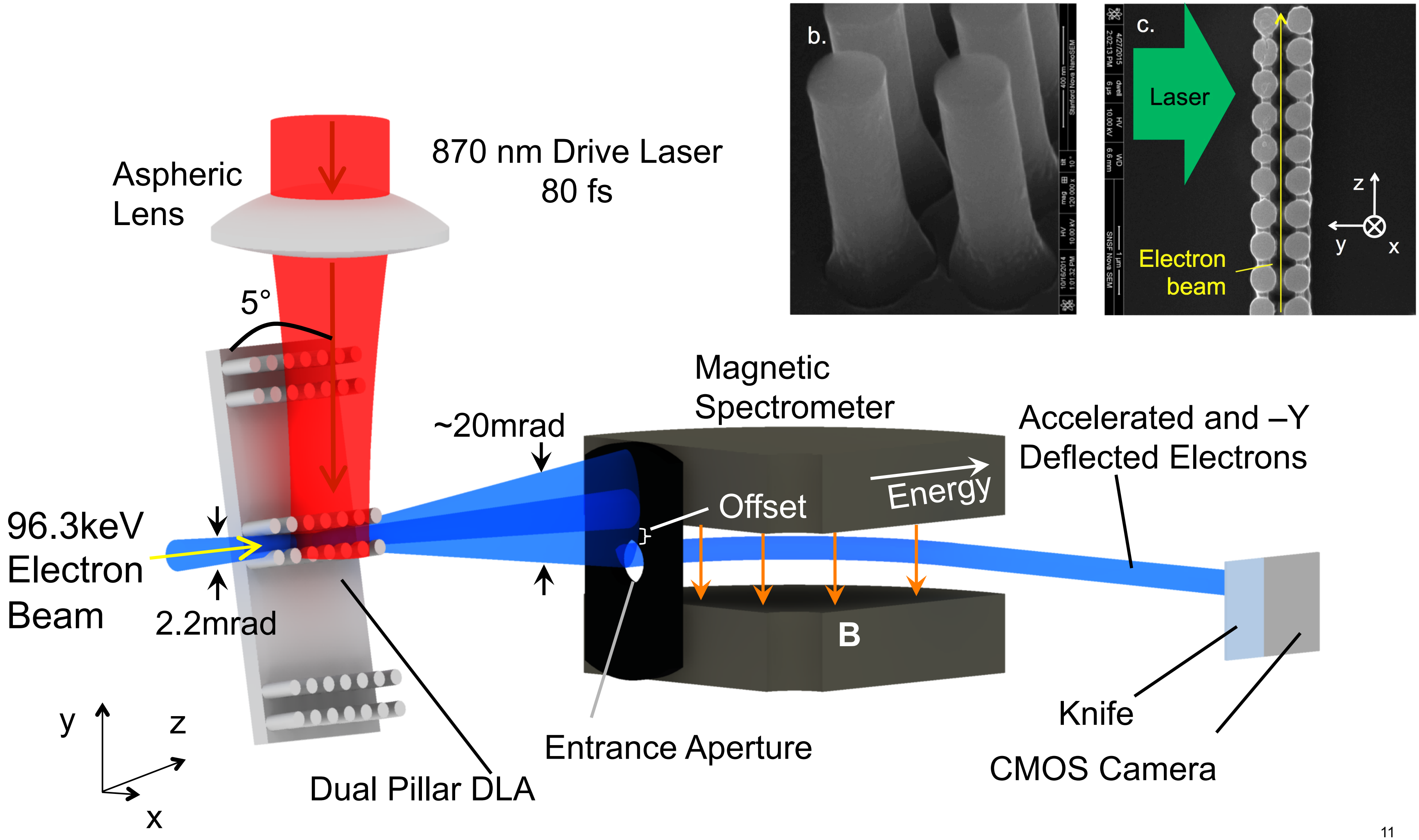
Letter

optica

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

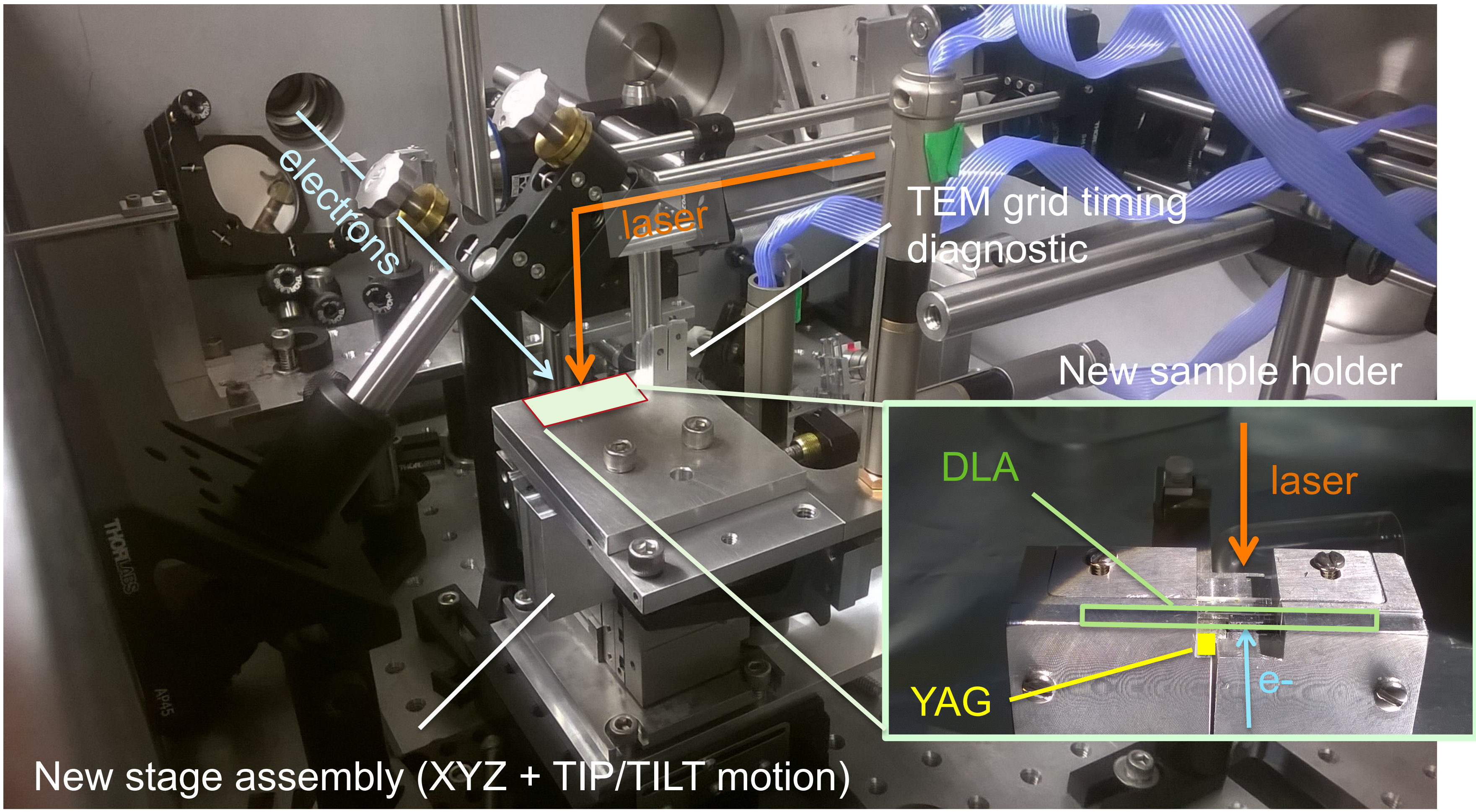
KENNETH J. LEEDLE,[1,*] R. FABIAN PEASE,[1] ROBERT L. BYER,[2] AND JAMES S. HARRIS[1,2]

A recently demonstrated dual-pillar design allows higher gradient (370 MV/m) at sub-relativistic energies.



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

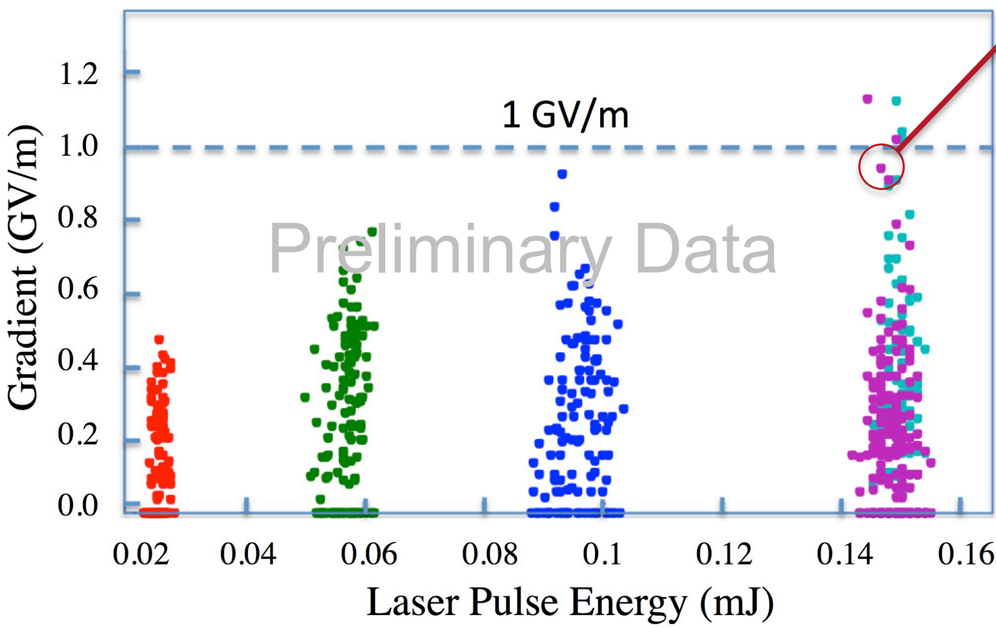
DLA Experiment Setup – UCLA Pegasus

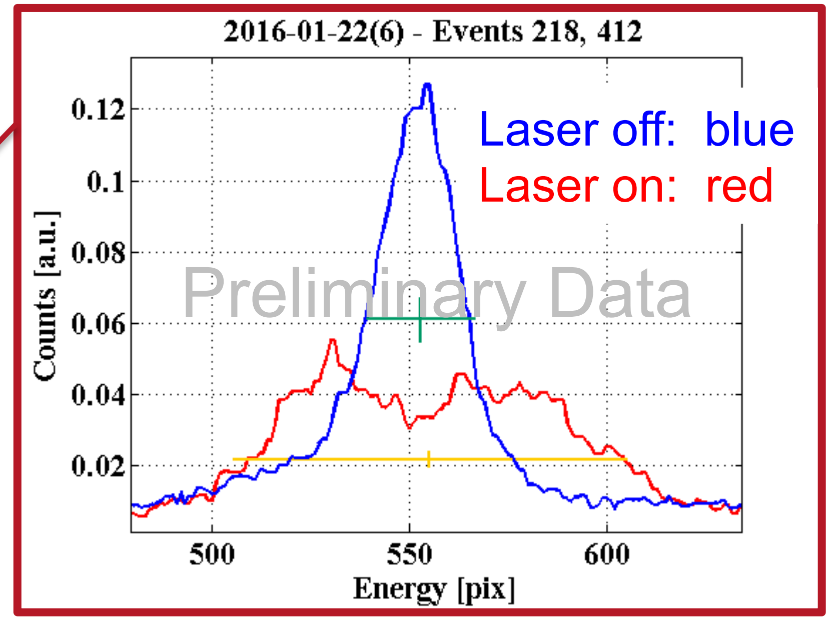


Recent joint SLAC/UCLA experiments have reached gradients up to 1 GV/m with 20 keV energy gain.

Example ~1 GV/m electron spectra

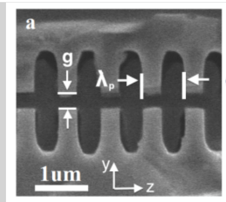
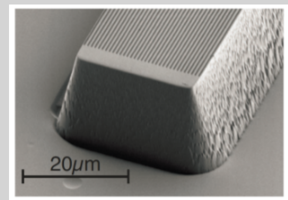
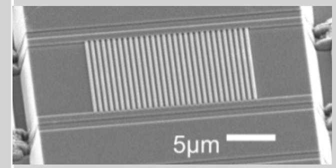
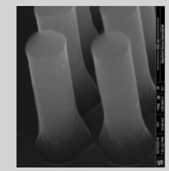
Extrapolated gradient vs. pulse energy





- Electron beam parameters: 8 MeV, 5 ps, 100 fC; Laser: TiSapph, 40 fs
- Vertical spread in data due to scanning laser delay in time.
- Maximal values represent optimal timing overlap of ebeam and laser.

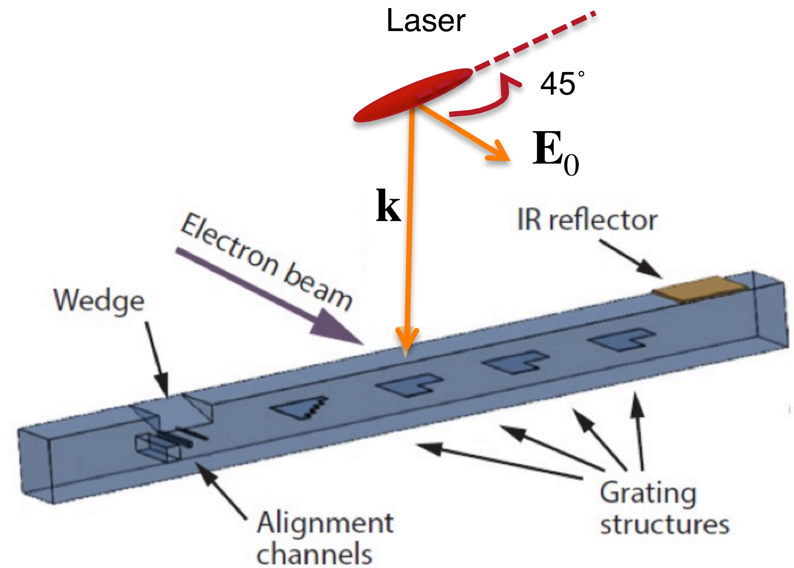
Comparison of Recent DLA Acceleration Experiments

	SLAC & UCLA	Hommelhoff Erlangen	Si Single Grating	Si Dual 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 uJ	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	1 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

Planned experiment to extend interaction length using pulse front tilted laser beam at UCLA Pegasus.

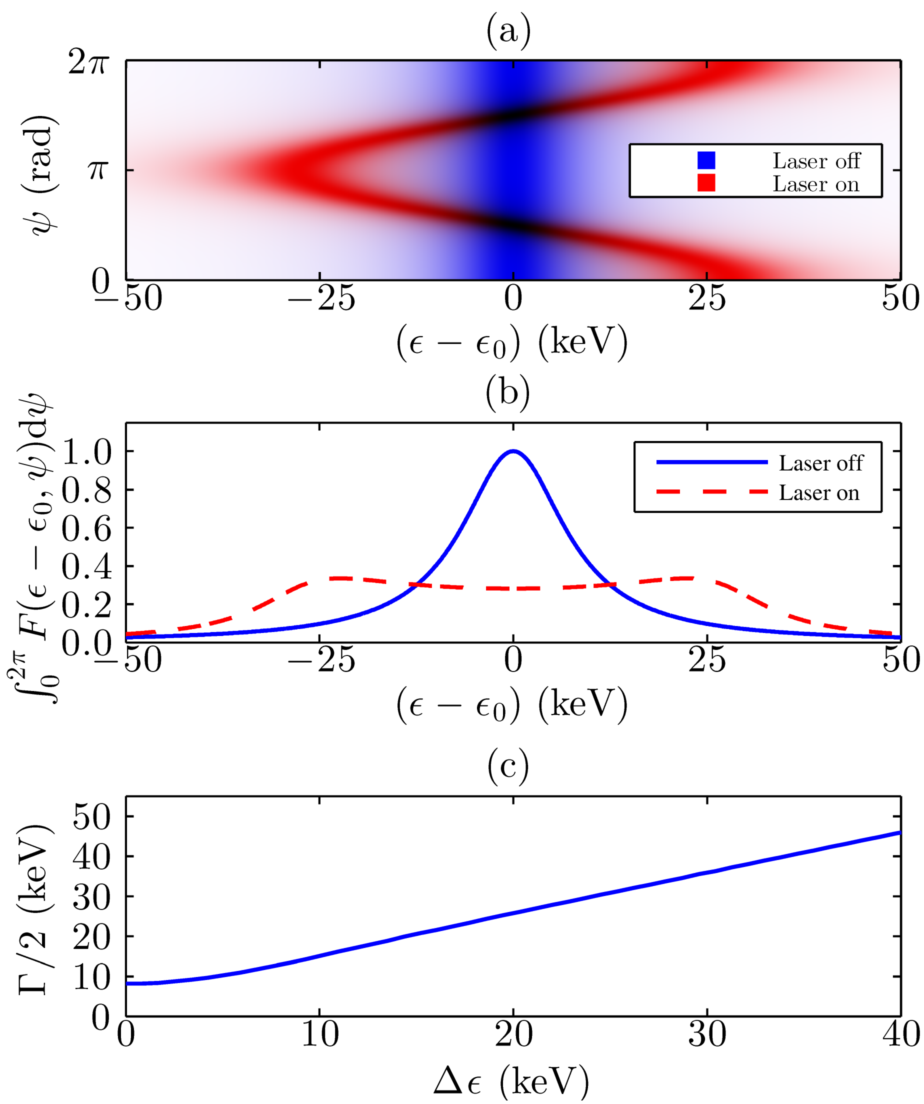
Parameter	Value
Beam Energy	8 MeV
Laser wavelength	Ti:Sapph (800nm)
Pulse duration	40 fs
DLA type	Silica dual-grating
Expected Gradient	> 1 GV/m
Total Energy Gain	1 MeV in 1 mm



Experiment Plan:
Step 1: Observe short-pulse acceleration with normal pulse front.
Step 2: Switch to 45° pulse front tilt to increase interaction length

Status:
→ DLA setup commissioned with ps timing diagnostic and multi-axis stage
→ Successful electron transmission on DLA (both 400nm and 800nm gaps)

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

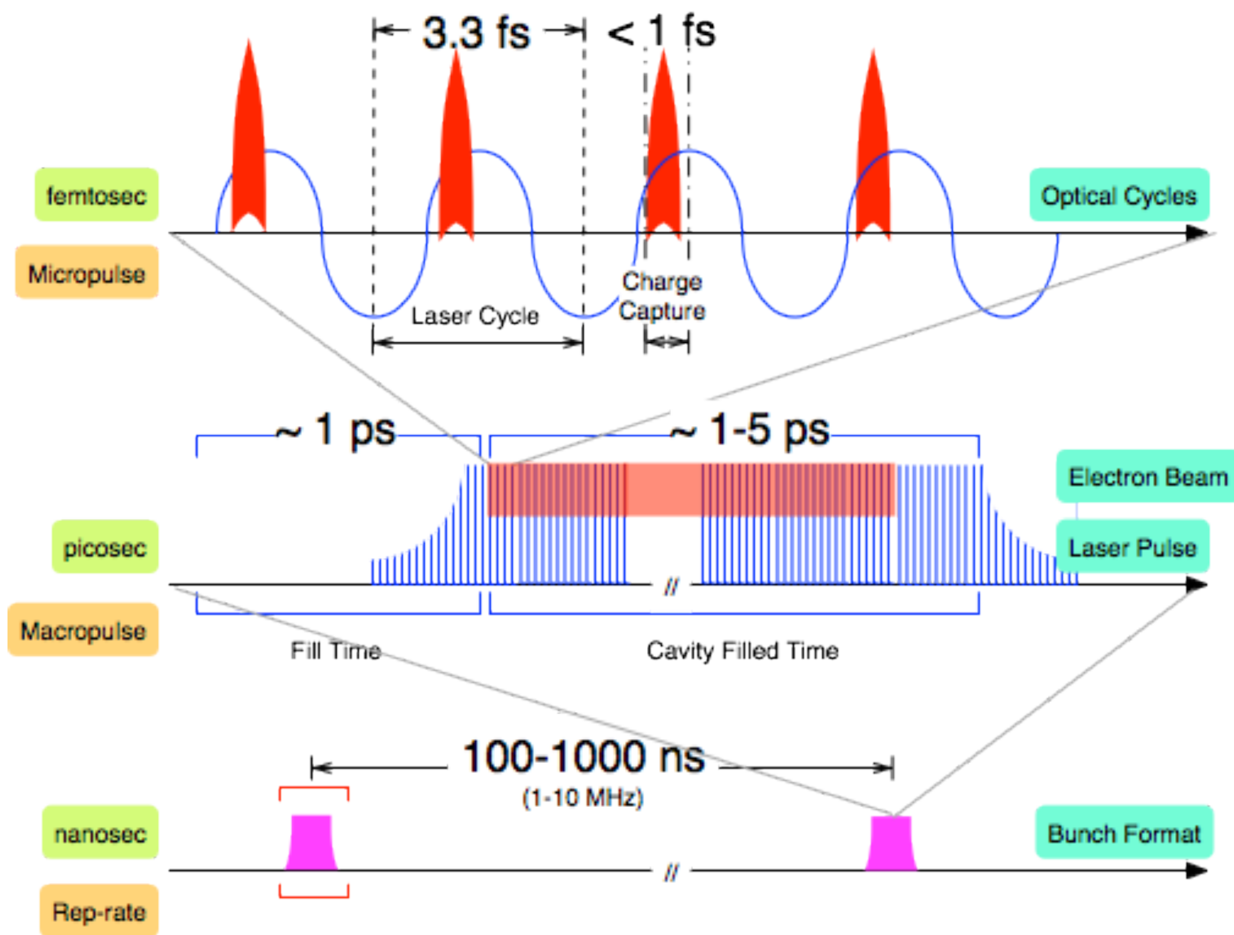


Sampling of all laser phases produces a sinusoidal energy modulation .

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

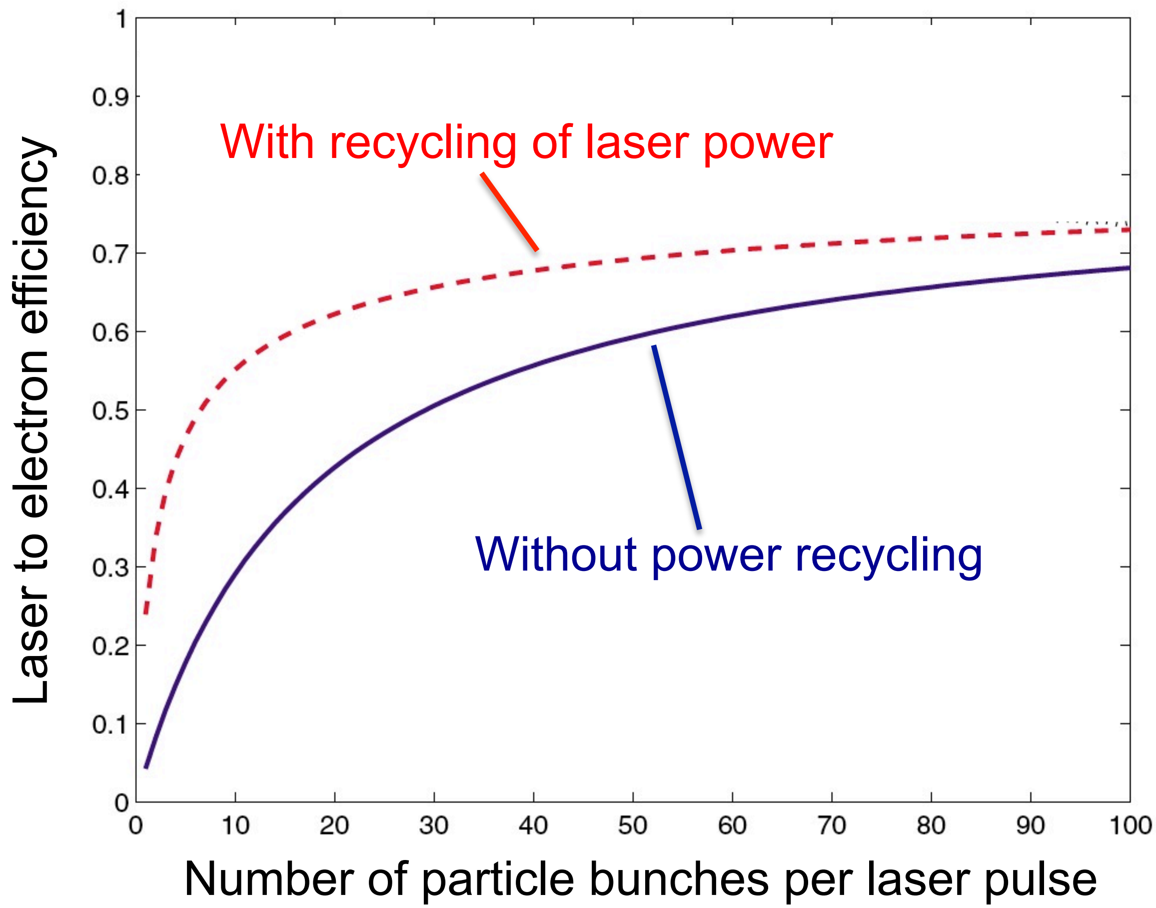
The energy gain and gradient are extrapolated from the HWHM of the spectrum.

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



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

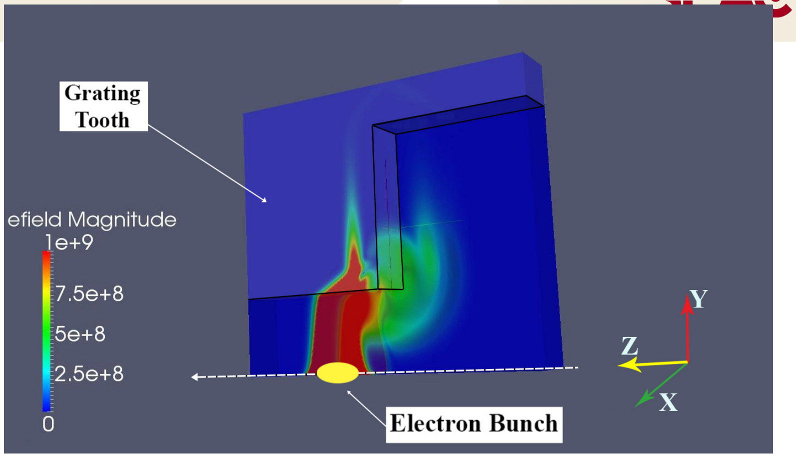
Na, Siemann, and Byer, PR-STAB **8**, 031301 (2005).

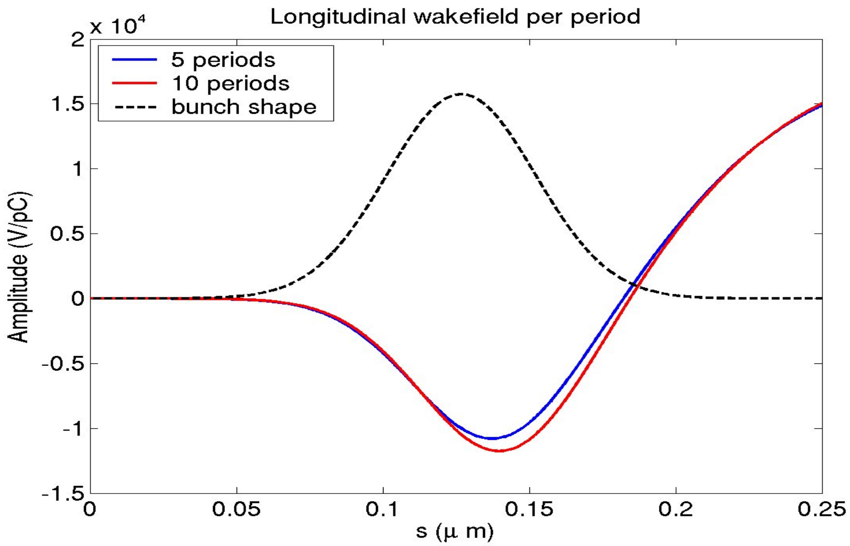


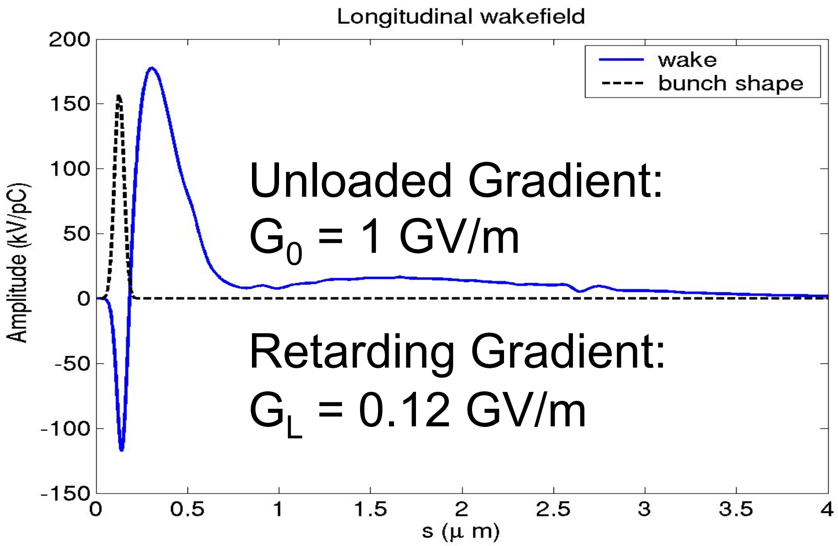
Longitudinal Wake Calculations in Fused Silica Grating Structure

SLAC

- Right picture shows ACE3P simulation of a bunch passing through the channel
- Plots below show the short and long range longitudinal wakes for a 10fC, 100as bunch. The loss factor is 0.12GV/m which is an order of magnitude less than expected gradient.

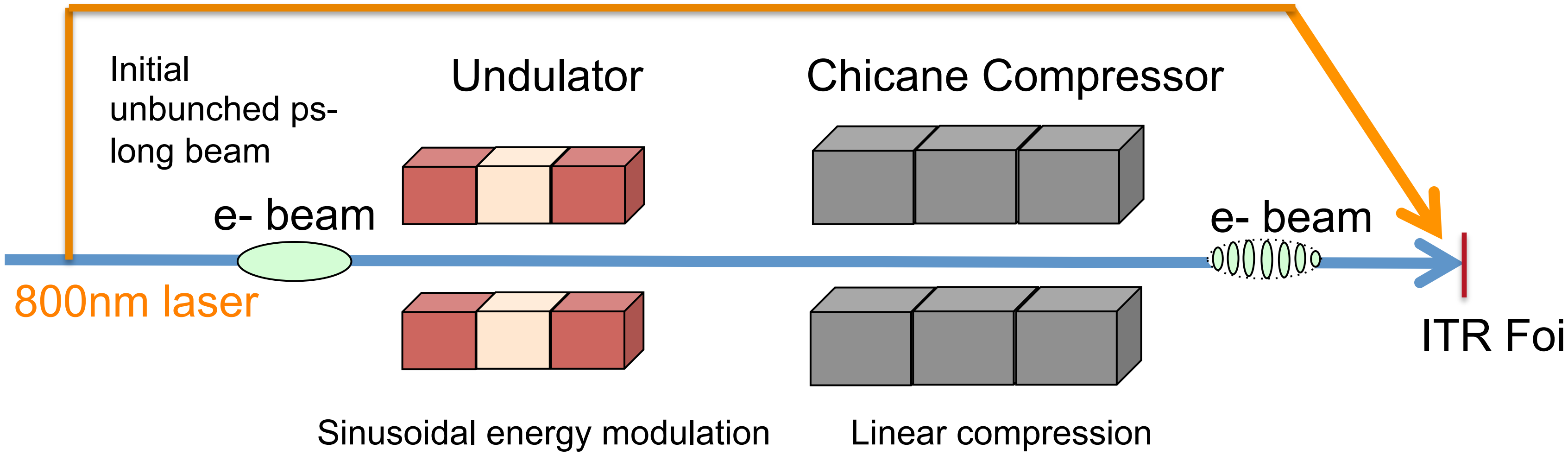




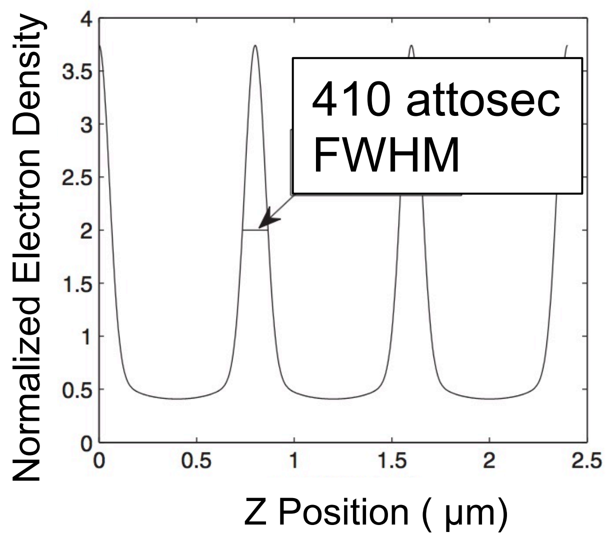


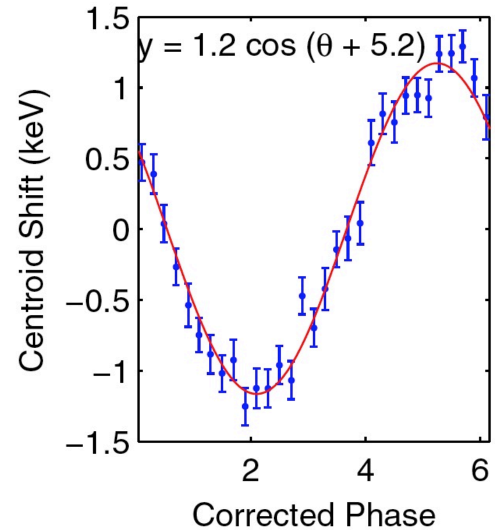
Simulations by B. Montazeri, C. Ng, K. Bane

Microbunching and Net Acceleration: Prior Art



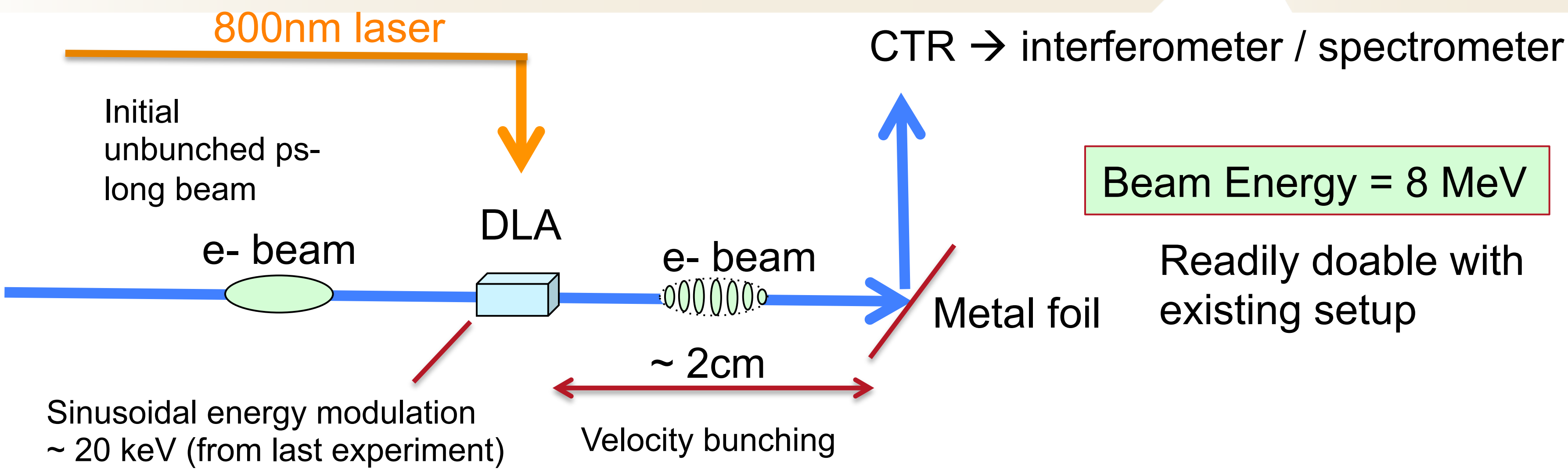
Parameter	Value	Units
λ_w	1.8	cm
λ_ℓ	800	nm
γ	117.4	–
K	0.636	–
FWHM	140	keV
σ_E	17	keV

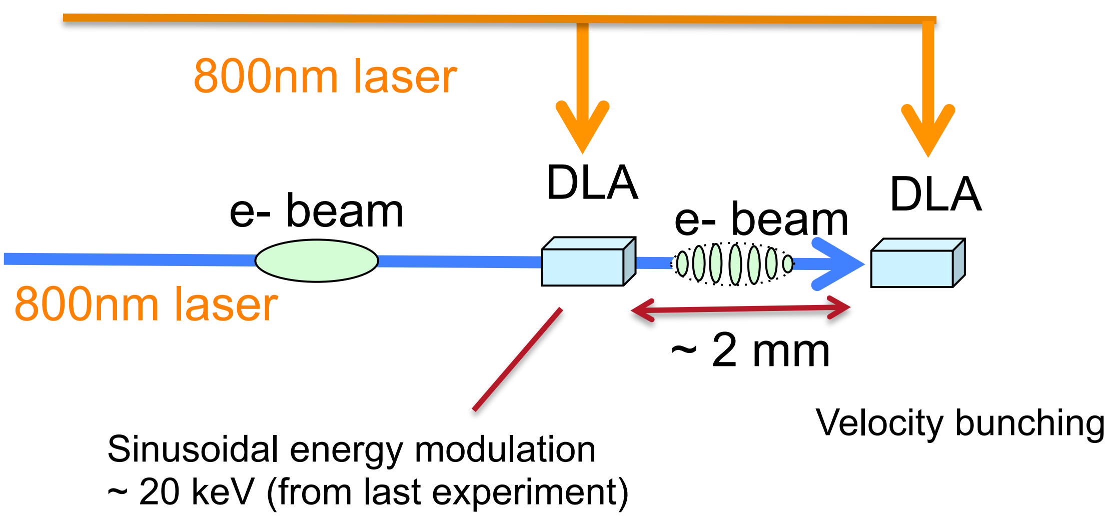




Sears, Colby, England, et al., PR-STAB **11**, 101301 (2008).

Microbunching and Net Acceleration: Future Experiments



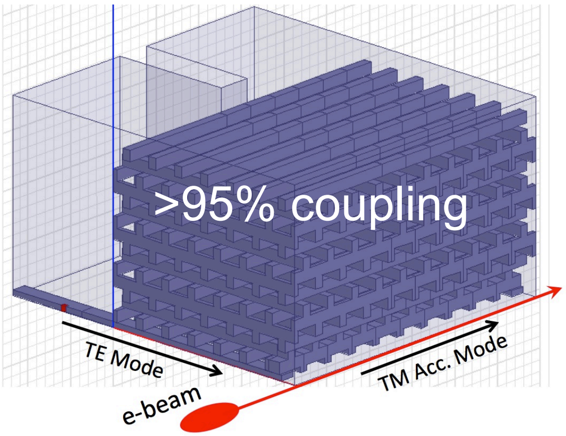


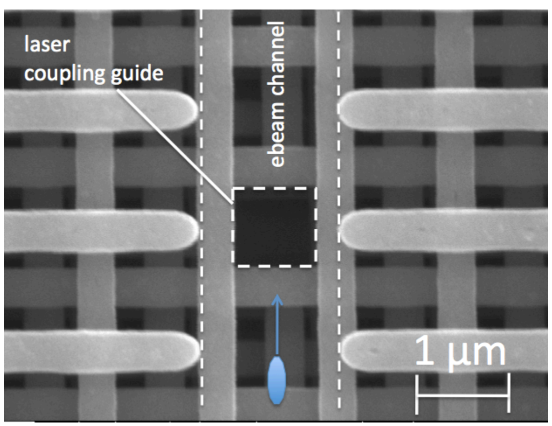
Beam Energy = 4 MeV

Needs transport simulations, possible intermediate focusing

Concepts for auxilliary beamline components have been developed for relativistic energies.

Efficient Coupler Designs

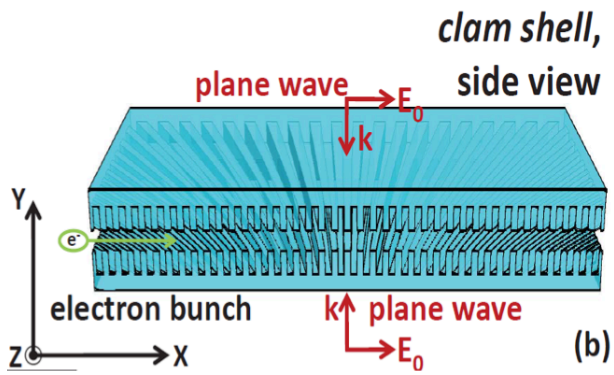




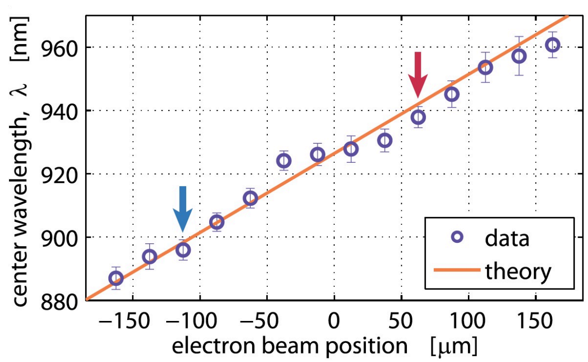
C. McGuinness, Z. Wu

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

Beam Position Monitor

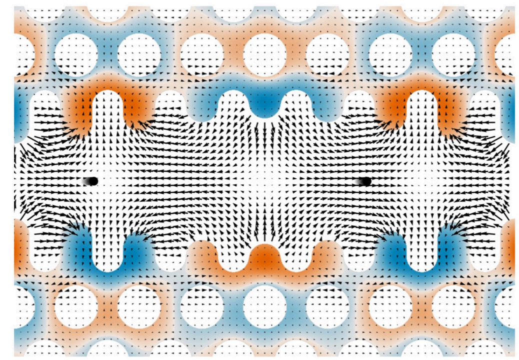


Opt. Lett., **37** (5) 975-977 (2012)

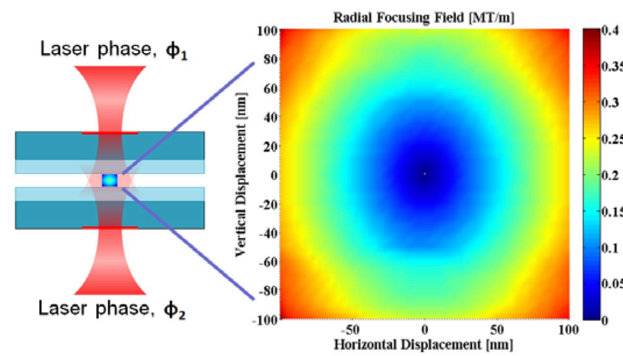


Opt. Lett., **39** (16) 4747 (2014)

Focusing Structures

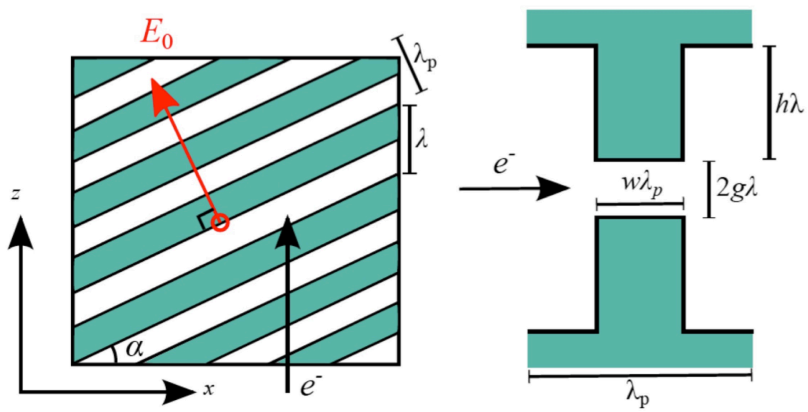


Naranjo, et al., PRL **109**, 164803 (2012).

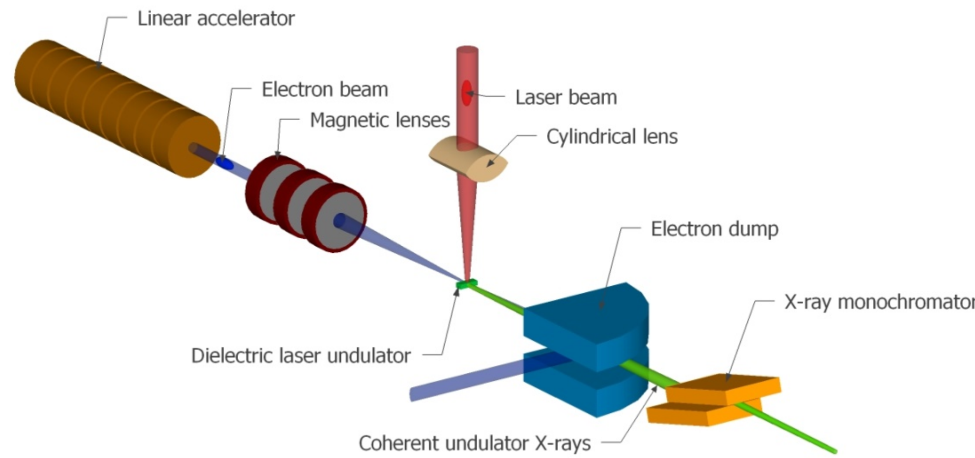


AIP Conf. Proc. **1507**, 516 (2012)
J. Mod. Opt. **58** (17), 1518-1528 (2011)

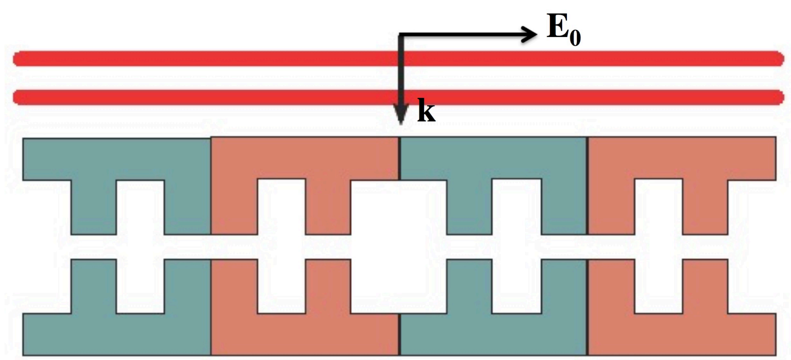
The same operating principles can be used to make deflectors and laser-driven undulators.



Single undulator "half-period" deflector



Schematic of proposed experimental setup



Multi-period undulator concept

K. Wootton, et al., IPAC 2015

Parameter	Value	Units
e- energy	60	MeV
Undulator period	100	μm
N periods	10	
Undulator Effective B	4	T
X-ray wavelength	3.6	nm
Photon Flux	1340	photons/sec

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

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ACHIP: Accelerator on a Chip International Program

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

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

Scientific Advisors
SLAC: Burt Richter
Stanford: Persis Drell

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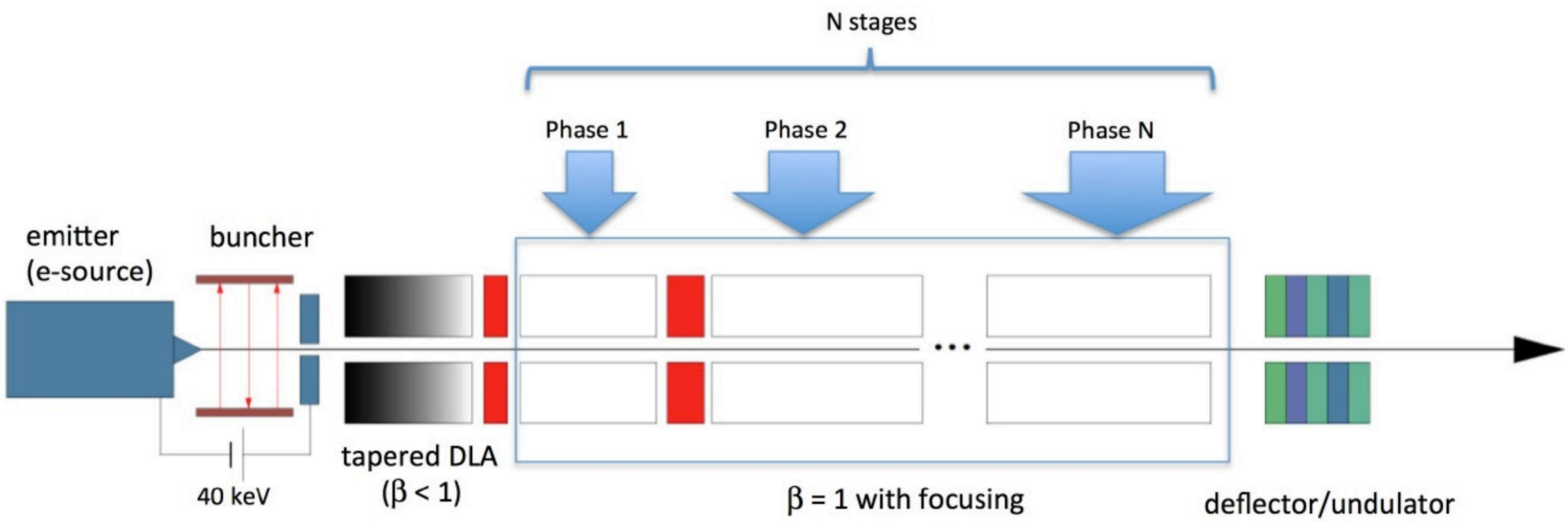
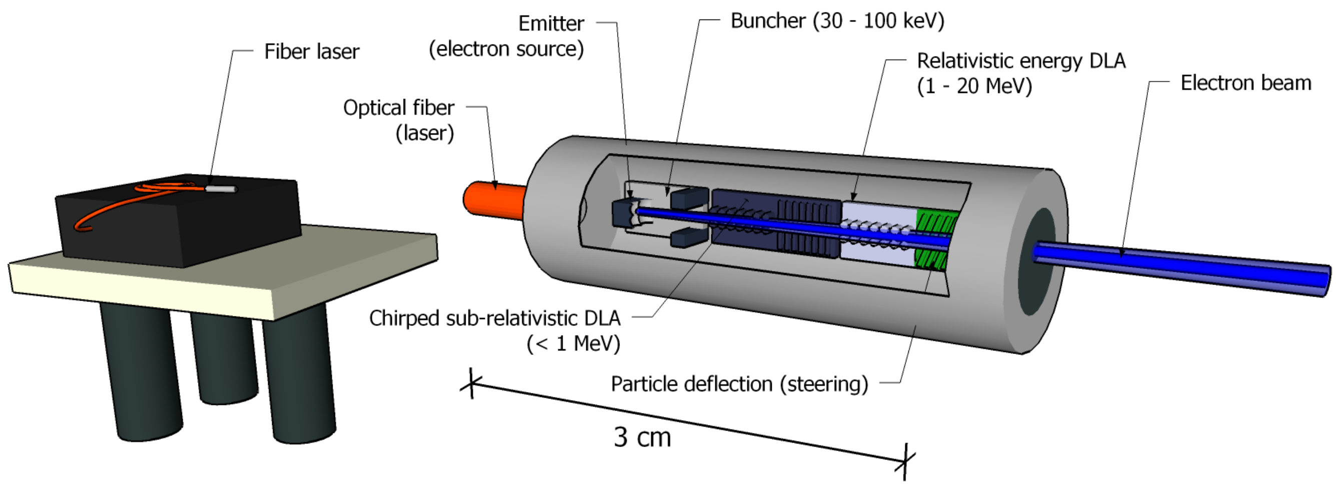
Components of a DLA Accelerator-on-a-Chip

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. Compact electron source
2. DLA structure development: (a) subrelativistic, (b) relativistic
3. Multi-staged acceleration
4. Coupling of laser to DLA
5. Laser-driven undulator/deflector



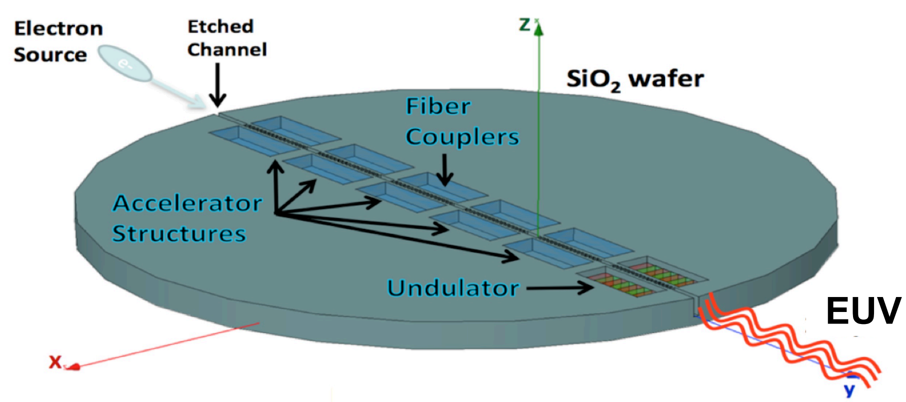
A Game-Changing Small Footprint Medical Accelerator Directly Maps to DLA's Unique Features

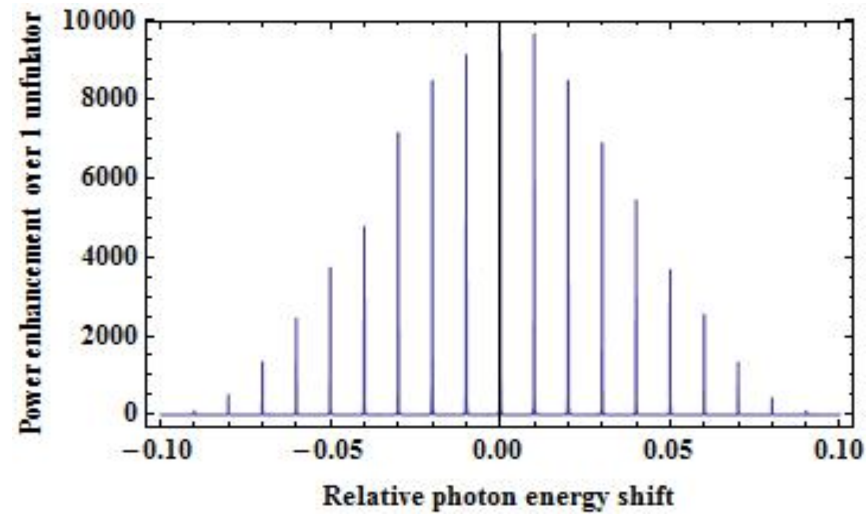


Parameter	Desired Capability	Unique DLA Features
Electron energy	10-20 MeV	Single-wafer design with 1 GV/m gradient
Useful dose	1 Gray/sec	2000 e- per bunch; 2 MHz rep rate
Treatment Volume	5-10 cm^3	Directed (vs omnidirectional) beam and on-chip deflection to scan tumor area
Small footprint	~ 1 cm x 10 cm	2um wavelength optical scale device with 2 cm active linac length
Wall Plug Power	< 100 Watt	Modest 2.9% wall-plug to electron efficiency

EUV Attosecond Frequency Comb

Modelocking scheme proposed could enable attosecond radiation pulses
(Z. Huang, talk at AAC14, proposal to NSF)





Parameter	Unit	Value
Beam Energy	MeV	40
Microbunch Charge	fC	10
Undulator Period	µm	250
Number of periods / Delay Modules	#	10 / 100
EUV Photon Energy	eV	50
Radiated Pulse Energy	nJ	100

DLA XFEL Strawman Parameter Table

Parameter	Units	Value
Ebeam Energy	GeV	1.056
Microbunch Charge	fC	0.5
Bunches per Train		150
Rep Rate	MHz	100
Normalized Emittance	nm	0.87
Laser Wavelength	μm	2
Laser Pulse Duration	ps	1
Undulator Period	mm	0.9
Equivalent Undulator B	T	1.6
Undulator K		0.14
Pierce Parameter		2.29E-04
Undulator Length	m	0.9
Photon Energy	keV	11.5
Gain Length	m	0.18
Photons per Bunch		6.6E+04
Photon Flux	photons/sec	9.9E+14
Brightness	SBU*	1.05E+21

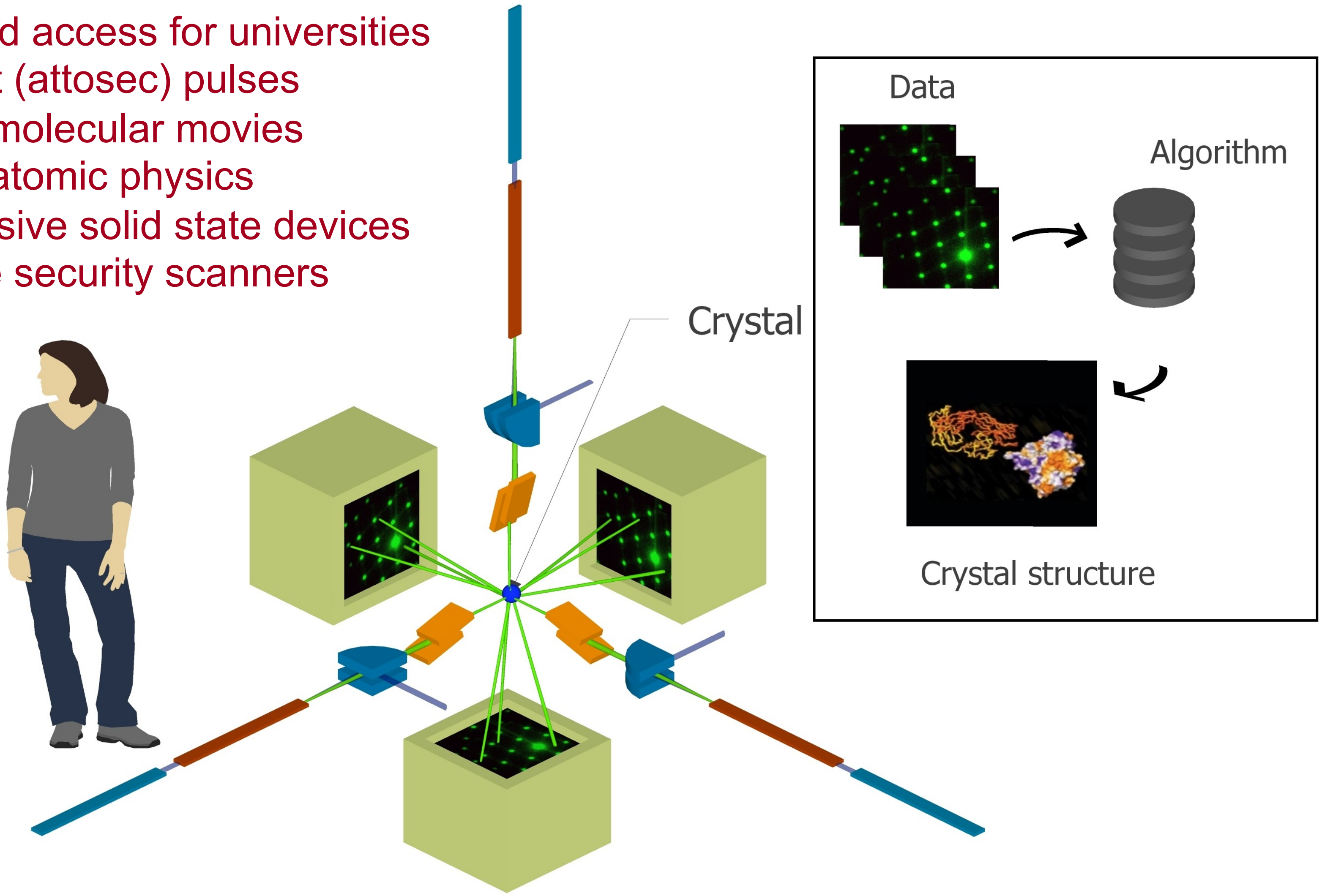
A DLA X-ray source would be in or near the Quantum FEL regime:

$$\frac{\hbar\omega}{\gamma m c^2} = 10^{-5}$$

* 1 "SBU" = ph/s/mm^2/$mrad^2$/0.1%BW

A DLA based attosecond light source could enable revolutionary new science capabilities.

- Improved access for universities
- Ultrafast (attosec) pulses
  - molecular movies
  - atomic physics
- Inexpensive solid state devices
- Portable security scanners



Concept for multi-axis ultrafast tomography with DLA based XFELs (K. Wootton)

Conclusions

SLAC

Significant progress in DLA over the last few years:

Demonstrations of various sub-relativistic structures
Gradients up to 1 GV/m recently demonstrated
Staging with co-phased laser pulses on a single grating
Sub-relativistic focusing, deflection, beam position monitor

ACHIP: Newly funded Moore Foundation program in this area

6 University partners + 3 national labs (SLAC, DESY, PSI)
1 Industry partner (Tech-X)

Future Plans

Pulse front tilt to demonstrate MeV energy gain (UCLA & SLAC)
Bunching and net acceleration experiments
Demonstration of laser undulators and relativistic energy deflection

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