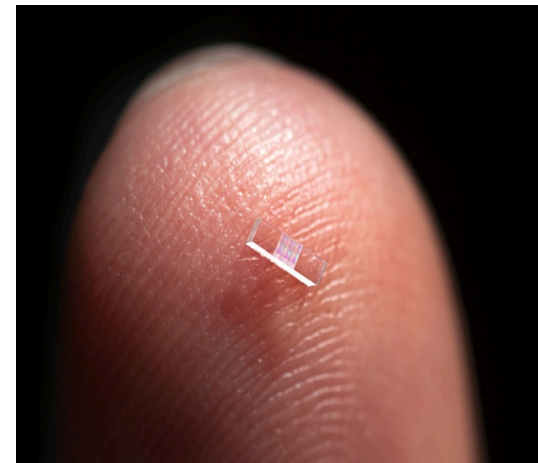


Dielectric Laser Acceleration: Accelerator on a Chip

LINAC 2016

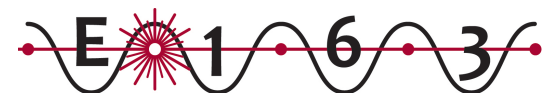
East Lansing, MI

R. Joel England



U.S. DEPARTMENT OF
ENERGY

Office of Science



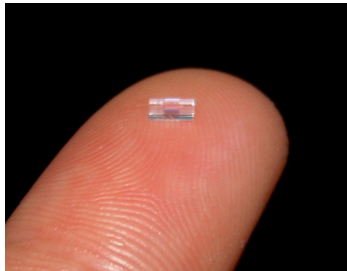
DIELECTRIC LASER ACCELERATION

SLAC

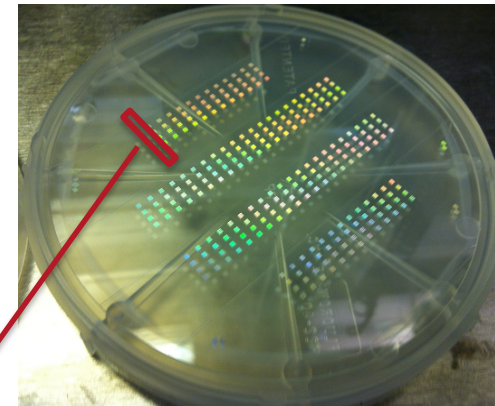
NATIONAL
ACCELERATOR
LABORATORY

Dielectric Laser Acceleration (DLA)

"Accelerator-on-a-chip"



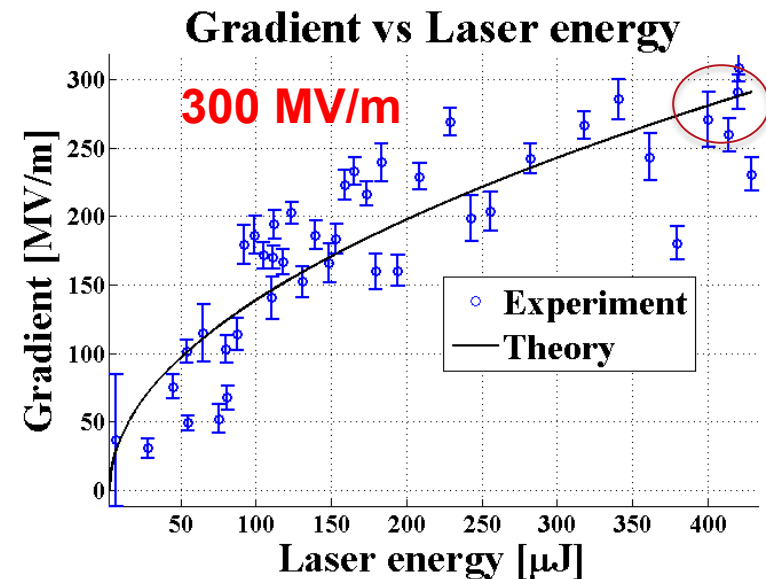
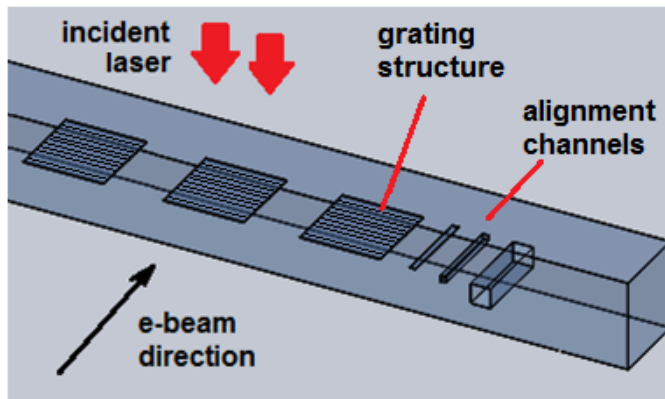
- laser-driven microstructures
- **lasers:** high rep rates, strong field gradients, commercial support
 - **dielectrics:** higher breakdown threshold \rightarrow higher gradients (1-10 GeV/m), leverage industrial fabrication processes



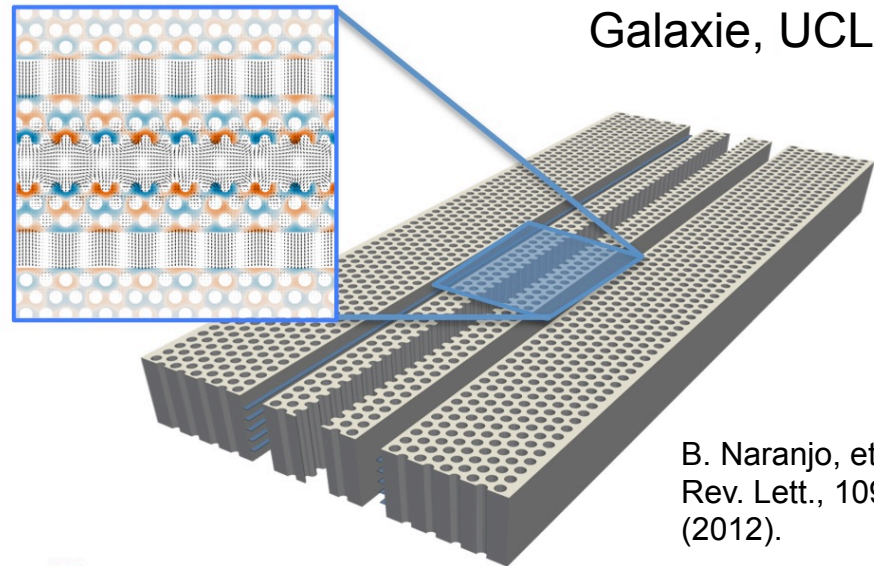
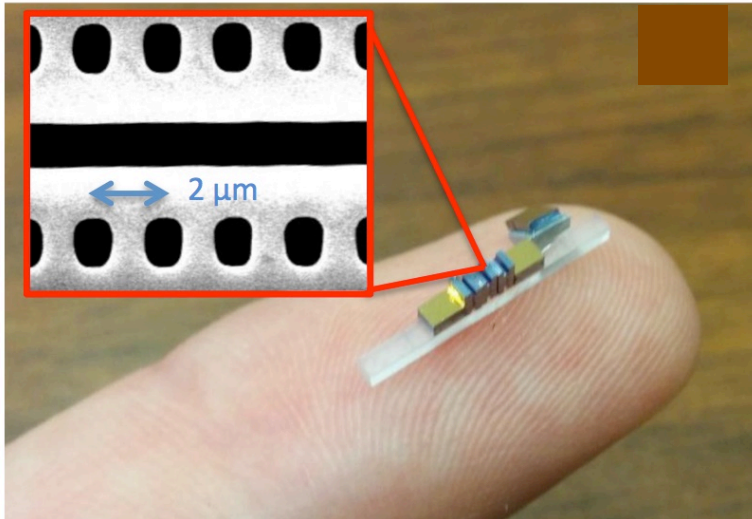
bonded silica phase reset accelerator prototypes fabricated at SLAC/Stanford

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

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



Various DLA Concepts Recently Proposed

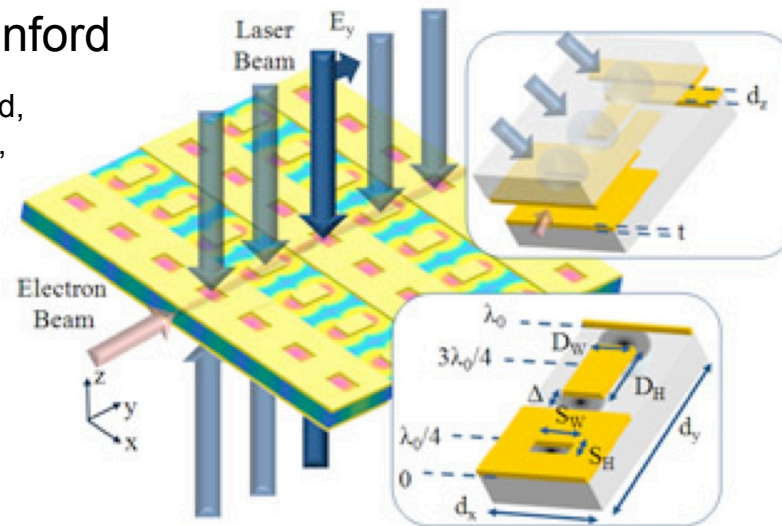


Galaxie, UCLA

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

Buried Grating, Stanford

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

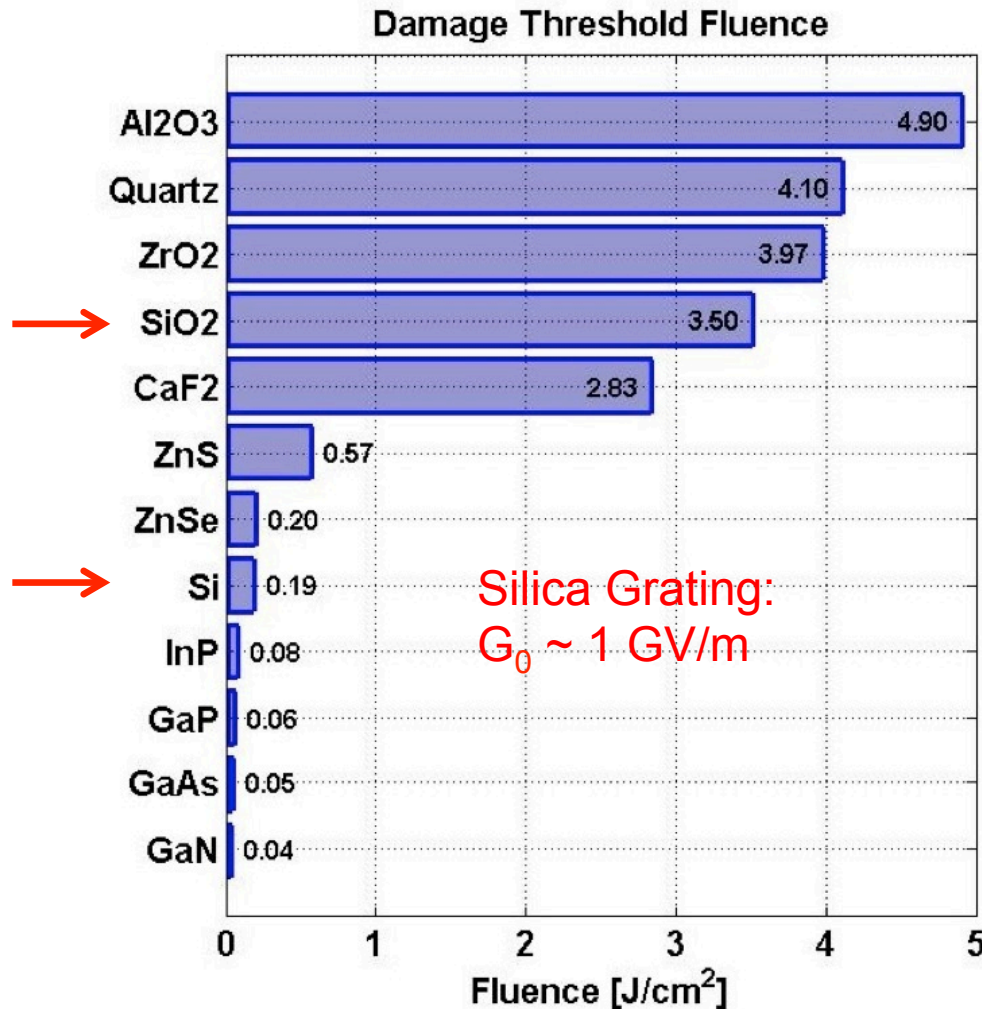


MLA, Tel-Aviv

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

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;
Extensive data did not
previously exist in this regime.



Ken Soong

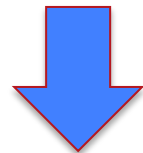
DLA leverages advances in two major industries: solid state lasers + semiconductor fabrication

High average power,
not high peak power lasers!

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



Solid-state laser



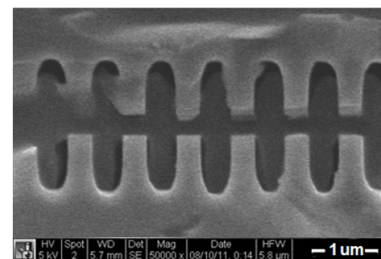
Available now
“off the shelf”

Fabricated using techniques of
the integrated circuit industry.

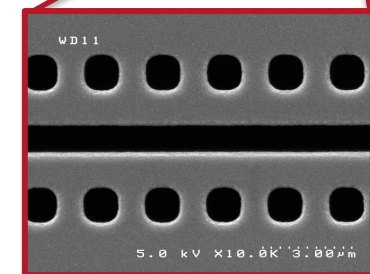
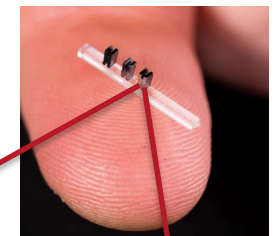


DLA structures are made by students in the Nanofabrication Facilities at partner universities.

SEM images of DLA prototypes tested at NLCTA



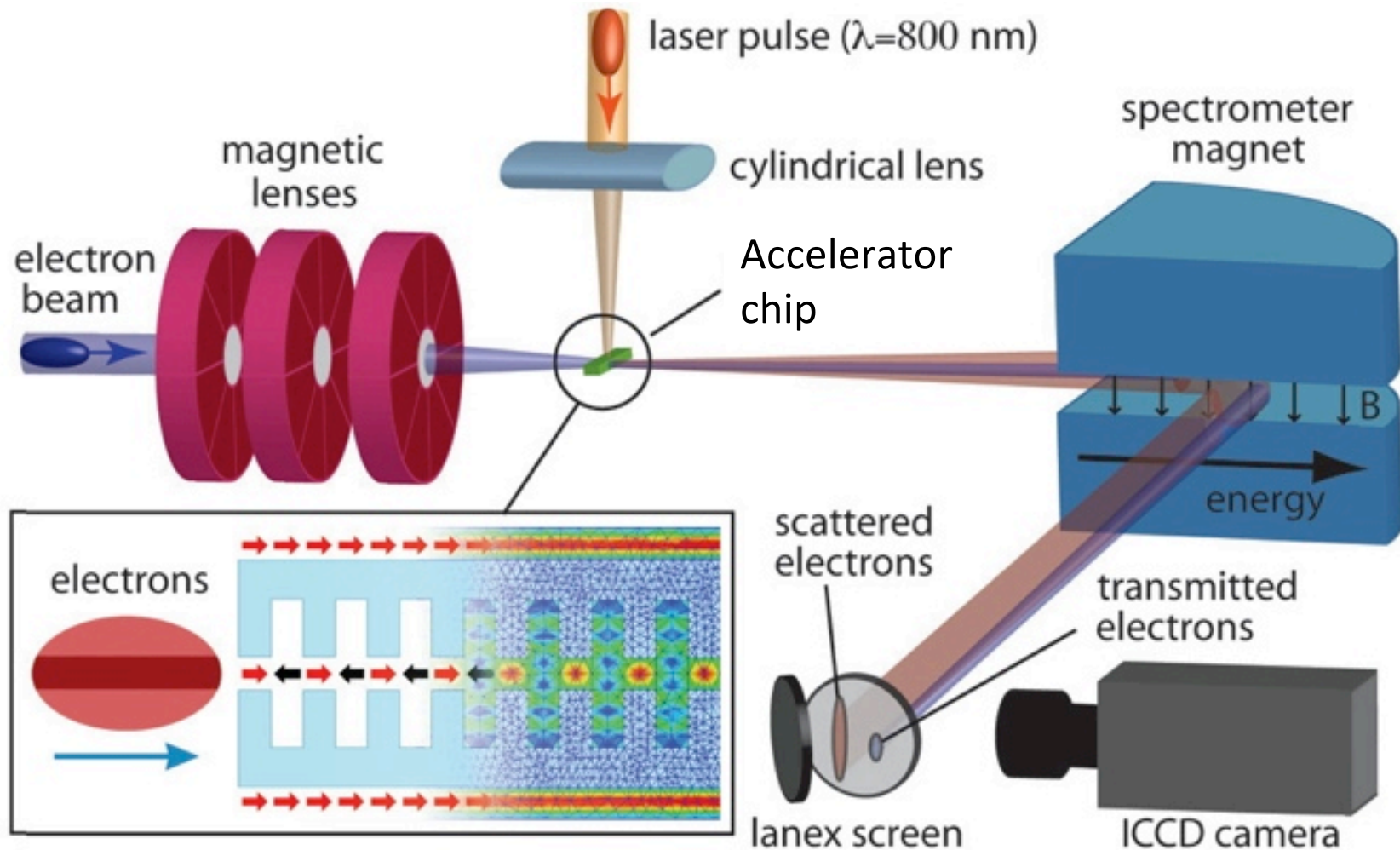
fused silica
(UV photolithography)



silicon
(DRIE)

First demonstrations conducted at SLAC used a pre-accelerated (60 MeV) electron beam (2013).

SLAC



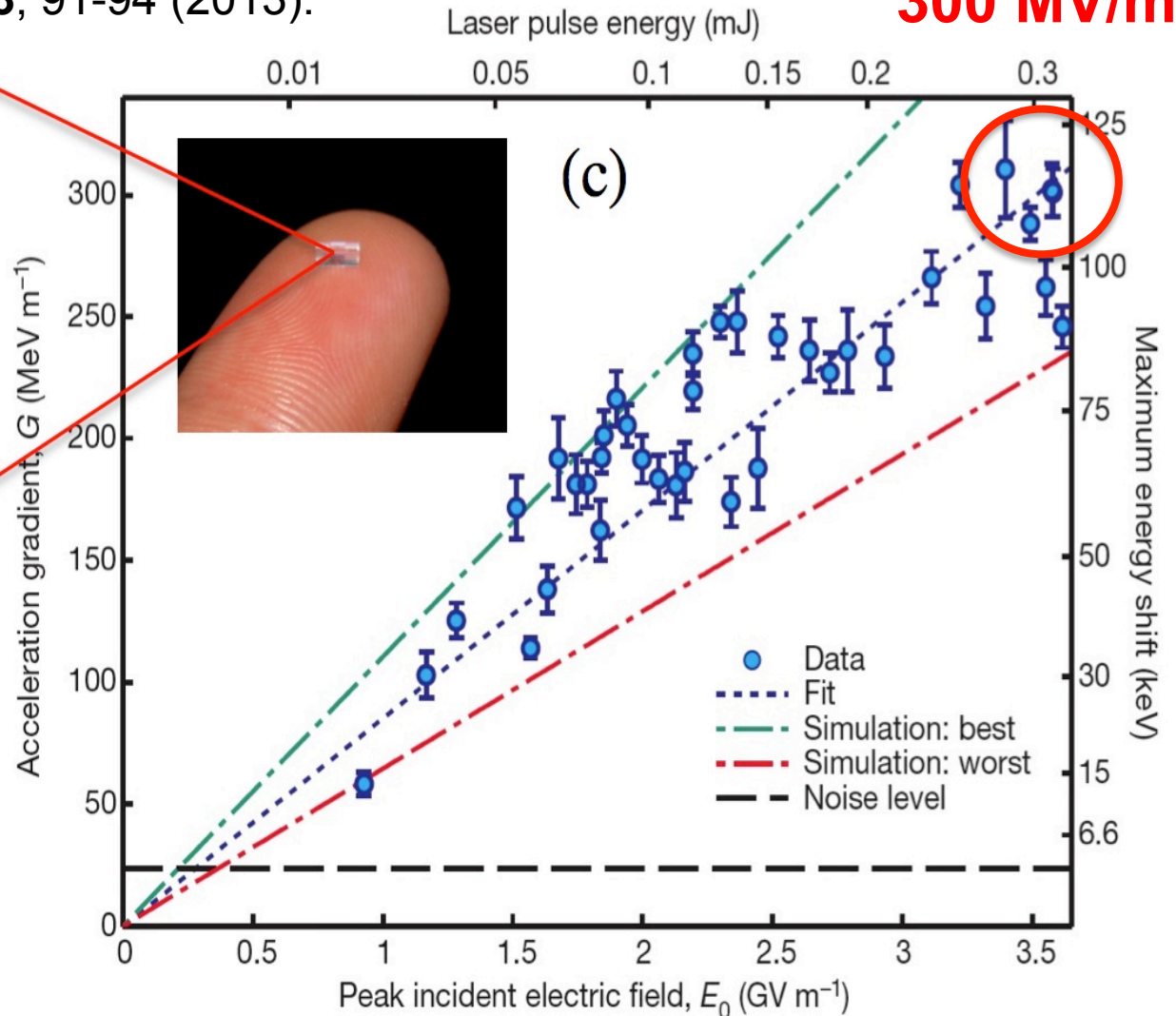
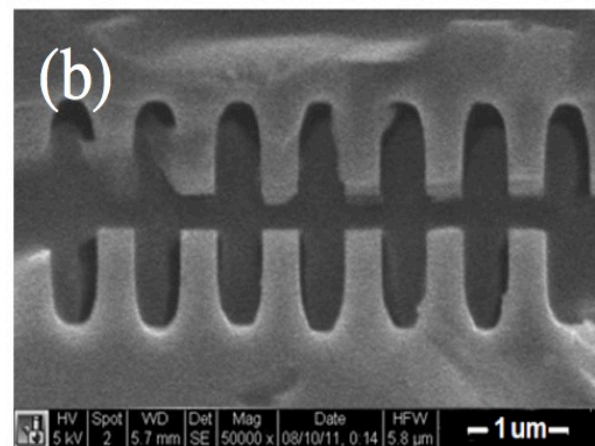
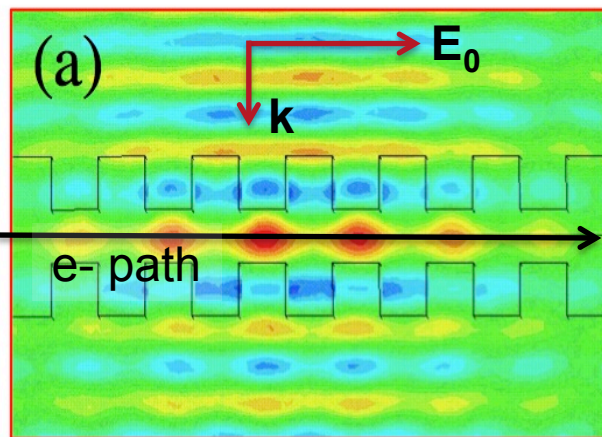
SLAC Next Linear Collider Test Accelerator (NLCTA) Setup for DLA Testing

Accelerating gradients observed were 10 times higher than the main SLAC linac...

SLAC

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

300 MV/m

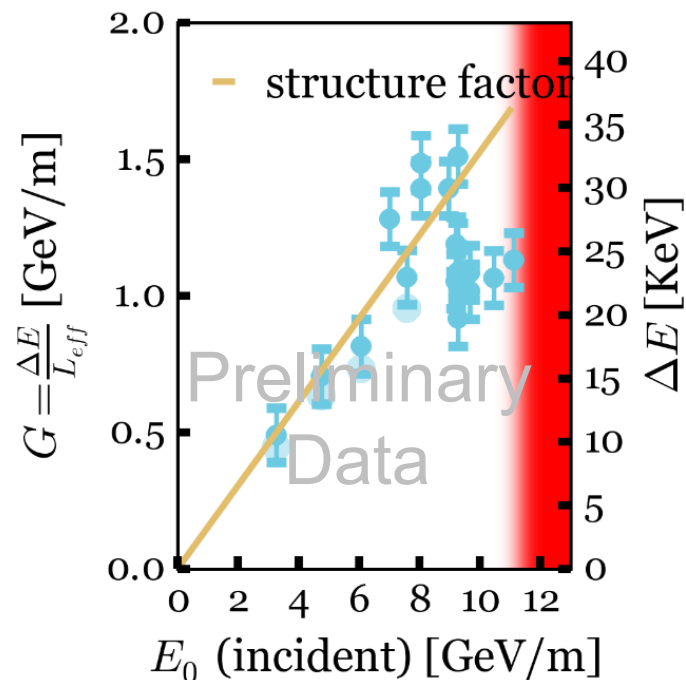


Subsequent short-pulse laser demonstrations at NLCTA and UCLA have exceeded the GeV/m threshold (2016).



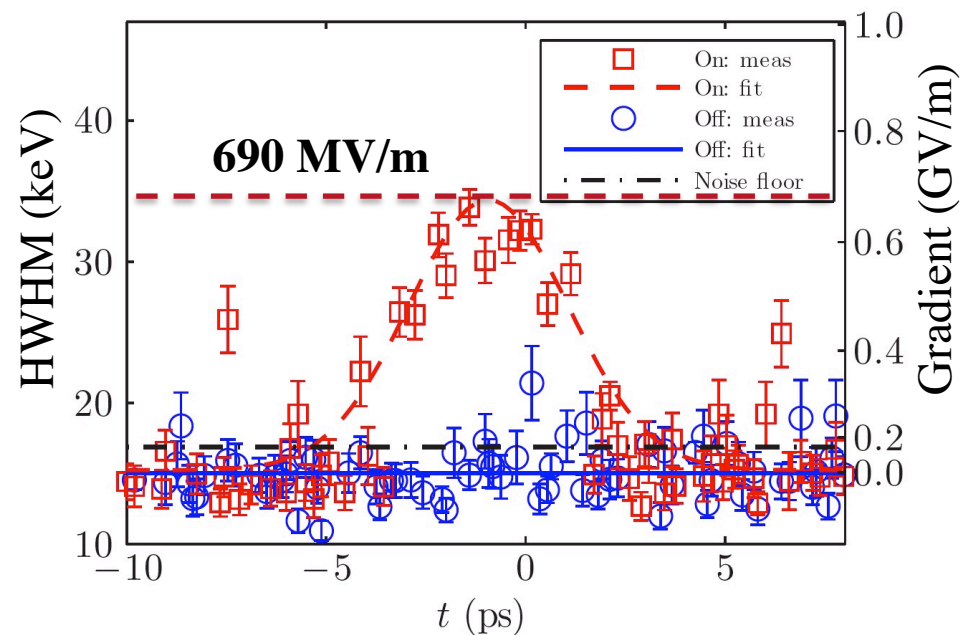
- Record DLA gradients demonstrated at both NLCTA & UCLA facilities.
- UCLA Pegasus now commissioned for **higher energy gain** experiments.

SLAC/UCLA: $G_0 \sim 1.5 \text{ GeV/m}^*$



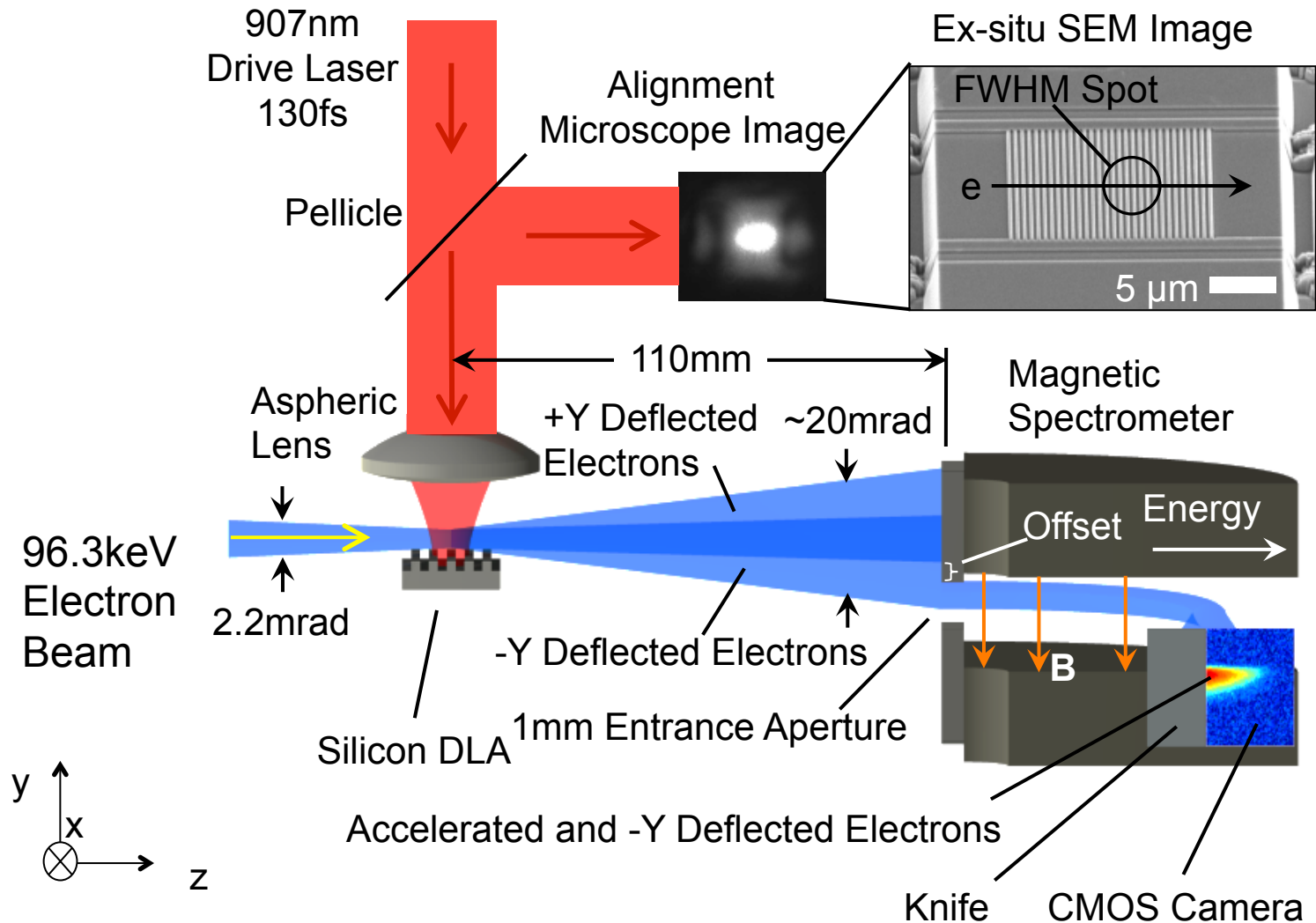
* Preliminary data – in preparation

SLAC/NLCTA: $G_0 = 690 \text{ MeV/m}^{**}$



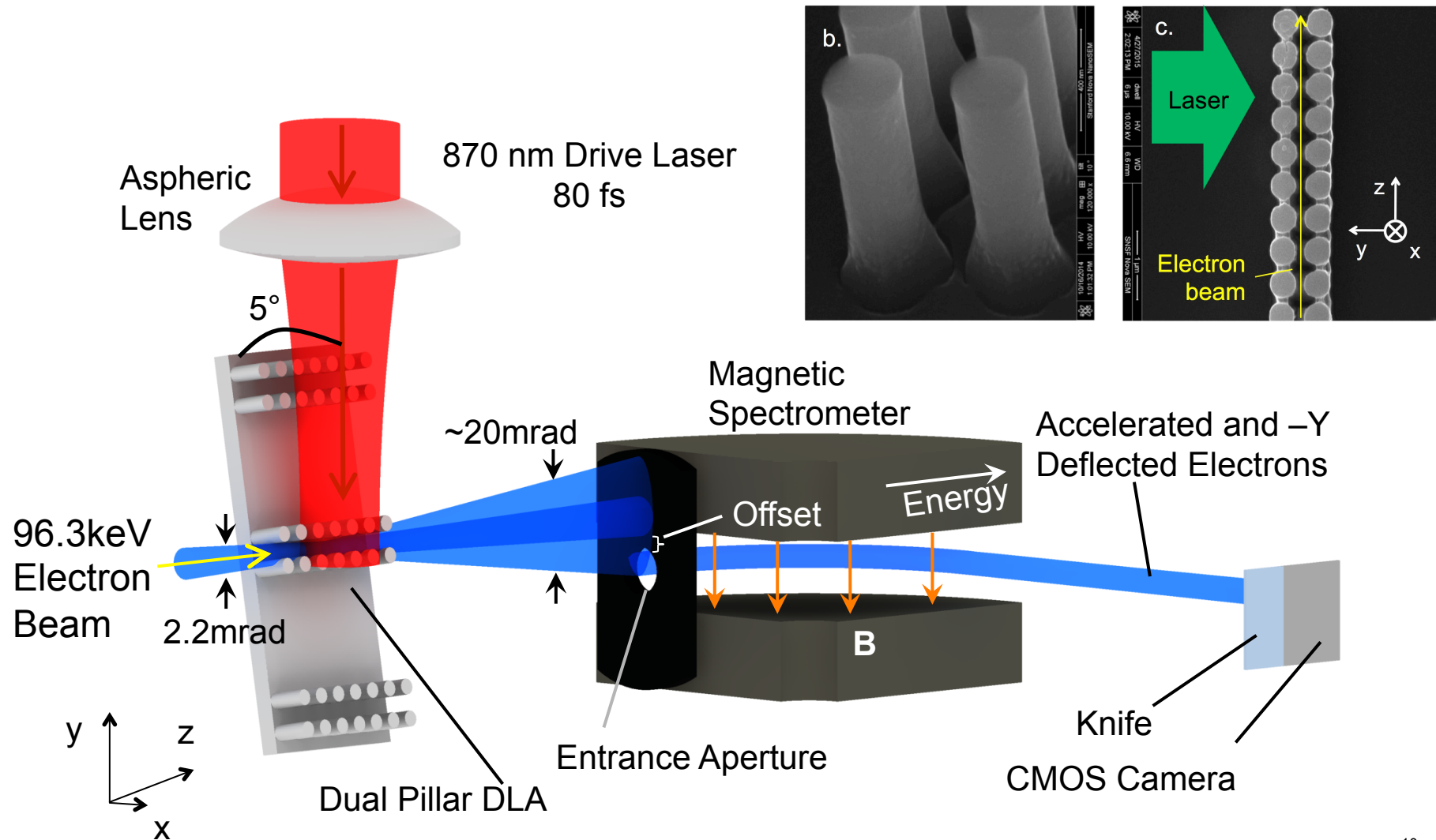
Wootton, et al. Optics Letters **41, 2672 (2016).

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



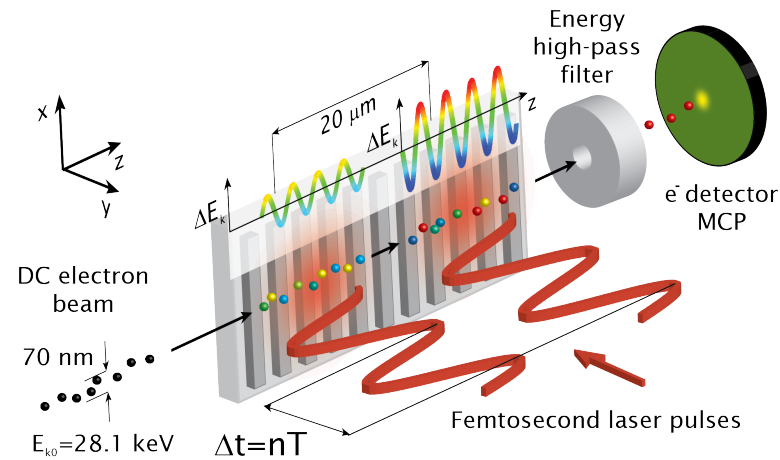
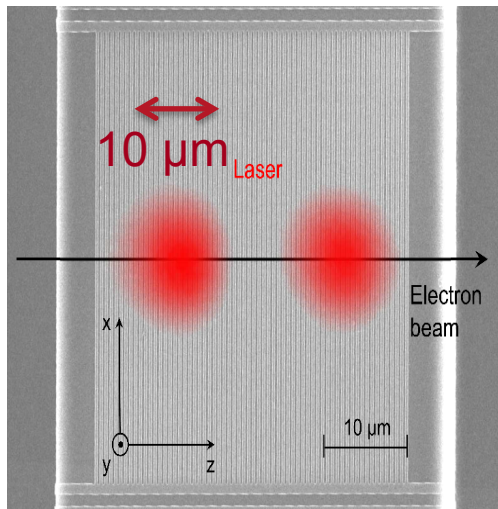
A recently demonstrated dual-pillar design allows higher gradient (370 MV/m) at sub-relativistic energies.

SLAC

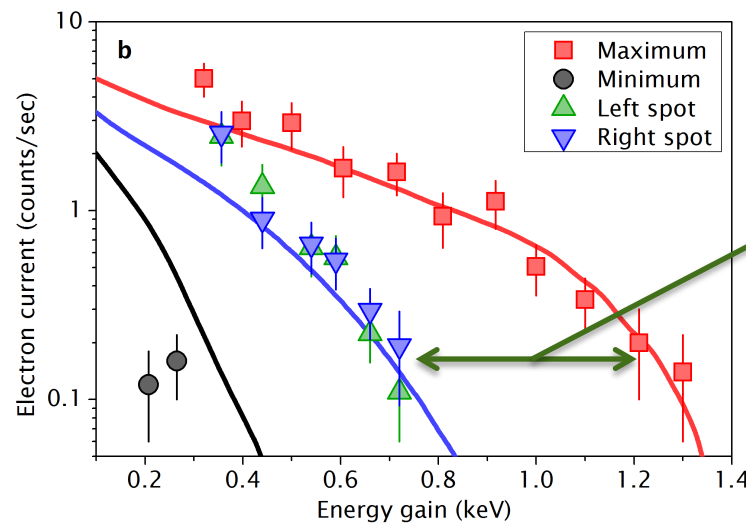
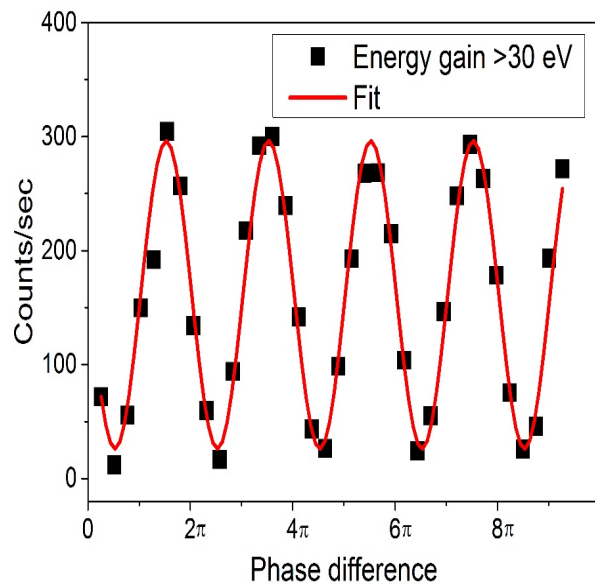


K. Leedle, et al. Opt. Lett. **40** (18) 4344 (2015)

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

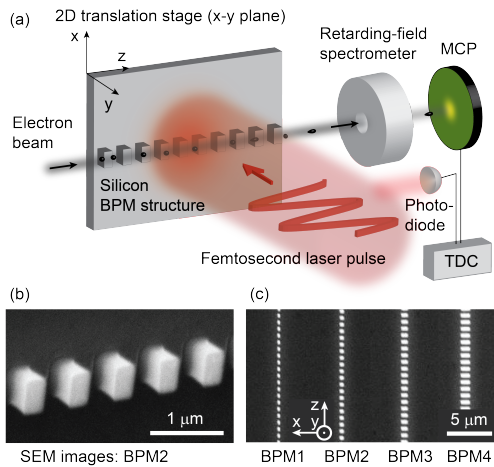


M. Kozák et al., arXiv:1512.04394v1

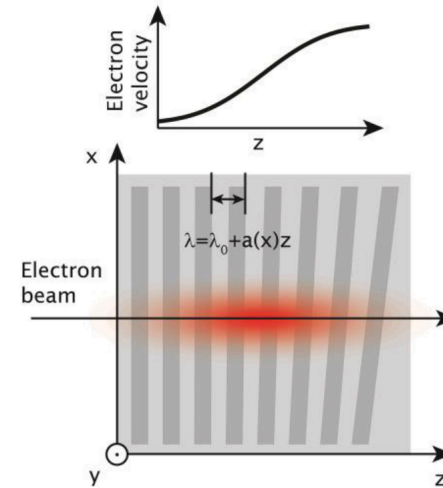


Factor x2 increase for 2 stage vs. 1 stage (linear scaling)

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

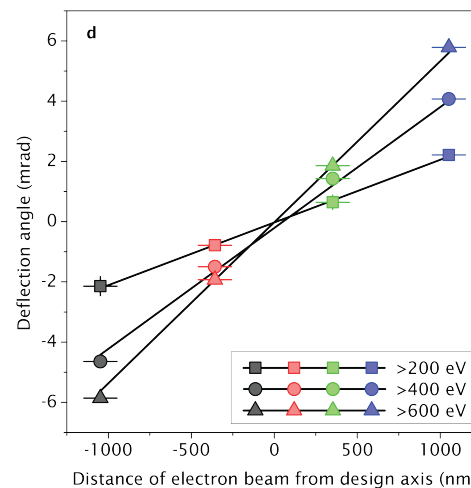
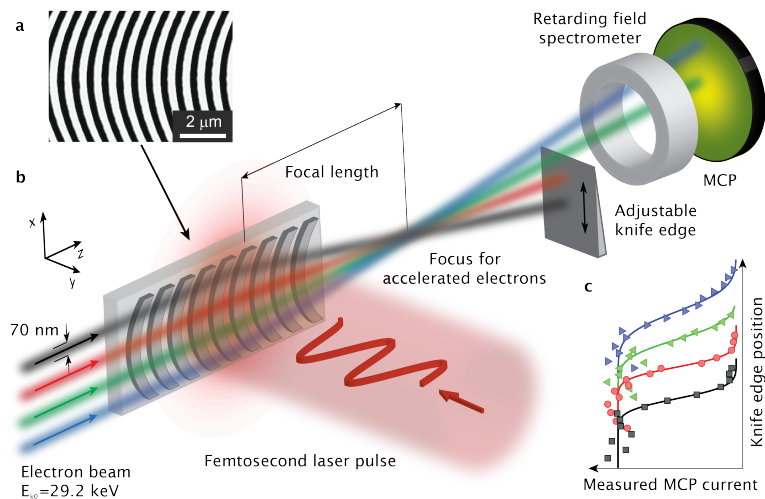


Beam Position Monitoring



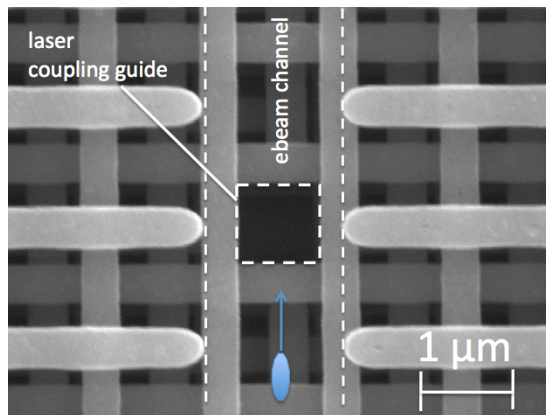
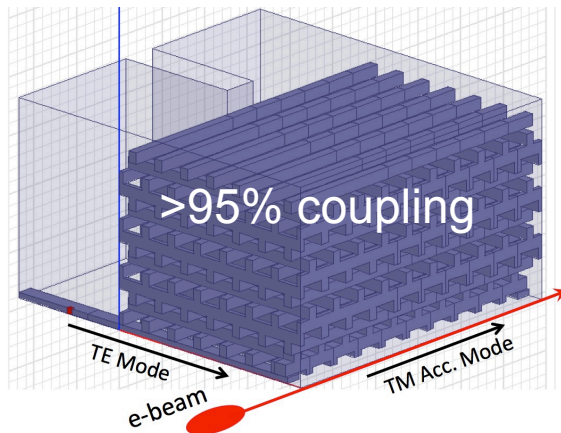
Chirped Structures

Sub-relativistic Focusing



Similar concepts for auxiliary beamline components have been developed for relativistic energies.

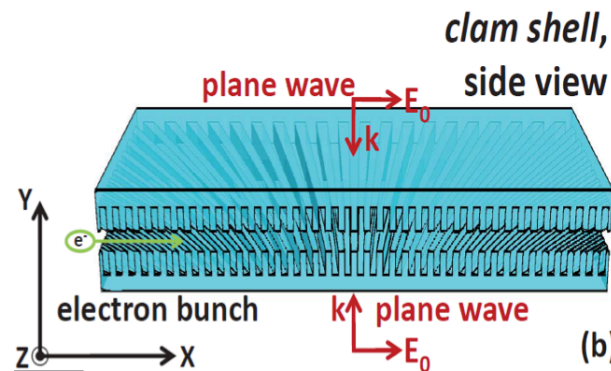
Efficient Coupler Designs



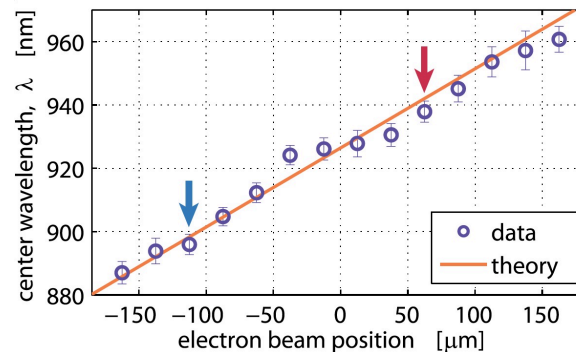
C. McGuinness, Z. Wu

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

Beam Position Monitor

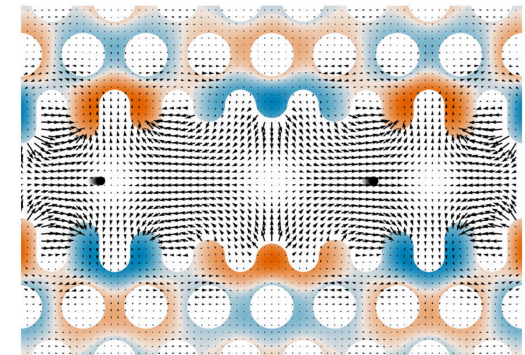


Opt. Lett., **37** (5) 975-977 (2012)

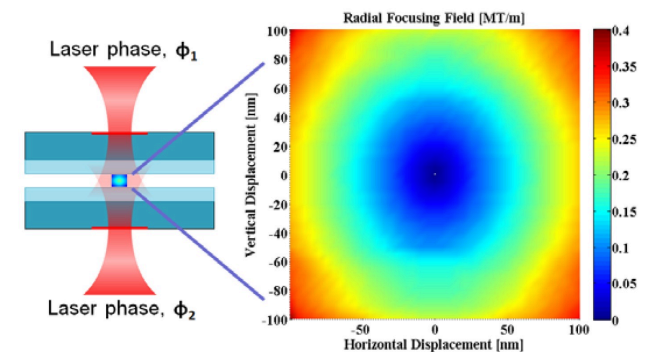


Opt. Lett., **39** (16) 4747 (2014)

Focusing Structures



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



AIP Conf. Proc. **1507**, 516 (2012)

J. Mod. Opt. **58** (17), 1518-1528 (2011)

Focusing in micron scale apertures requires high-gradient focusing schemes.

Example DLA parameters

Parameter	Description	Units	Value
λ	wavelength	μm	2
σ	beam radius	μm	1
$T0$	initial kinetic energy	keV	100
Tf	final kinetic energy	MeV	4
Q	bunch charge	fC	4
τ	bunch duration	fs	0.1, 1000
ϵN	normalized emittance	nm rad	2
L	interaction distance	cm	2

PMQs may be a viable interim solution if emittance can be reduced to ~ 2 nm.

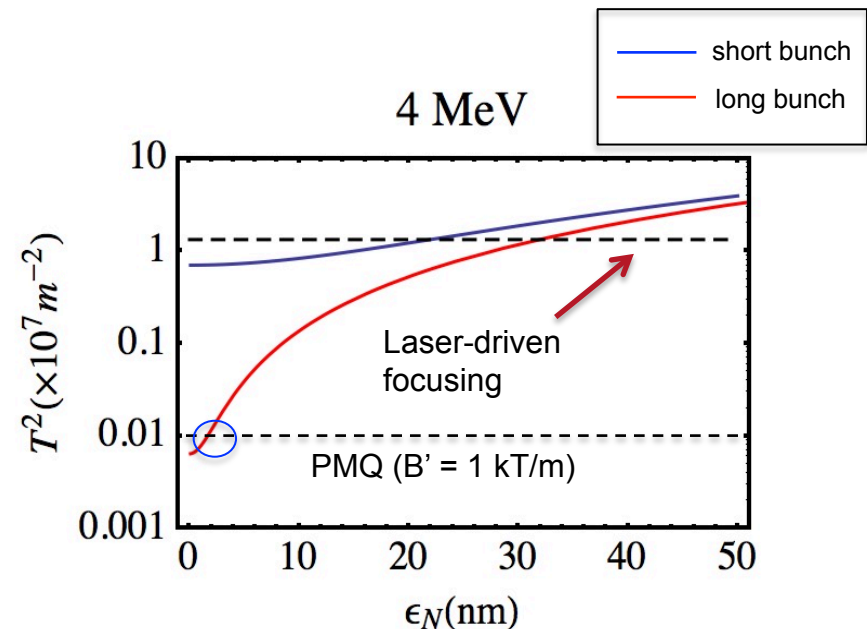
2nm emittance appears achievable in UCLA setup using **flat beam transform to reduce vertical emittance.**

Envelope equation

$$\sigma'' + \frac{\gamma'}{(\beta\gamma)^2} \sigma' - \left[\left(\frac{\gamma'}{\beta\gamma} \right)^2 - T^2 \right] \sigma - \frac{\epsilon_n^2}{(\beta\gamma)^2 \sigma^3} - \frac{K}{\sigma} = 0$$

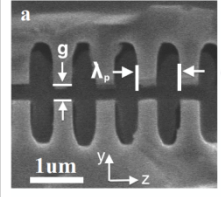
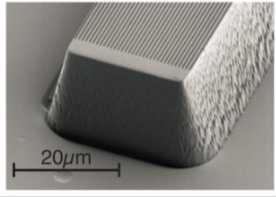
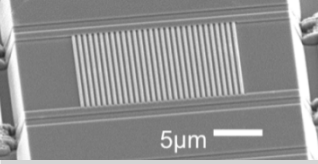
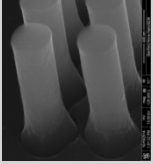
space charge term: $K = \frac{2}{(\beta\gamma)^3} \frac{I}{I_A}$

external focusing: $T^2(z) = \frac{\epsilon_n^2 / \sigma^4 + \alpha^2}{\gamma(z)^2 - 1} + \frac{K(z)}{\sigma^2}$



*A. Ody, et al., High Brightness Beams Workshop, Havana Cuba (2016).

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 μ J	160 nJ	5.2 nJ	3.0 nJ
Pulse Length	40 fs	110 fs	130 fs	130 fs
Interaction Length	\sim 20 μ m	11 μ m	5.6 μ m	5.6 μ m
Peak Laser Field	8 GV/m	2.85 GV/m	1.65 GV/m	\sim 1.1 GV/m
Max Energy Gain	30 keV	0.275 keV	1.22 keV	2.05 keV
Max Acc Gradient	\sim1.5 GV/m*	25 MeV/m	220 MeV/m	370 MeV/m
G_{\max}/E_p	\sim 0.18	\sim 0.01	\sim 0.13	\sim 0.4

* Preliminary and subject to change

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

SLAC

ACHIP: Accelerator on a Chip International Program

\$13.5M / 5 years

Structure Design & Fabrication

Stanford: Byer, Harris, Solgaard
Erlangen: Hommelhoff

Simulations

Tech-X: Cowan
U Darmstadt: Boine-Frankenheim

Scientific Advisors

SLAC: Burt Richter
Stanford: Persis Drell

Sub-Relativistic DLA experiments

Stanford: Harris, Solgaard
Erlangen: Hommelhoff

Systems Integration (Core DLA Groups)

Stanford: Byer, Harris, Solgaard
Erlangen: Hommelhoff

Relativistic DLA experiments

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



Electron source

UCLA: Musumeci
Erlangen: Hommelhoff
Stanford: Harris, Solgaard

Light Coupling

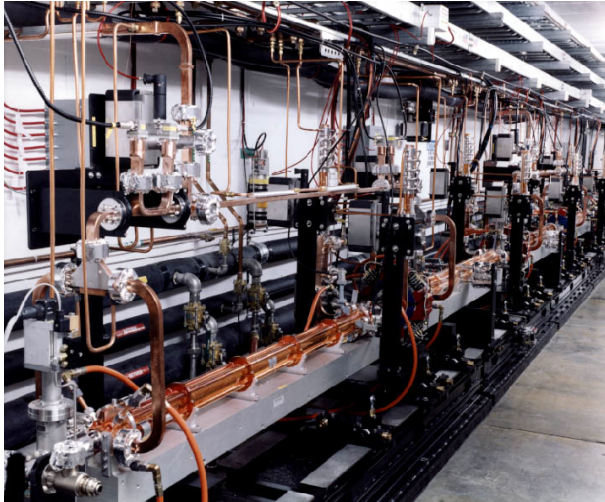
Stanford: Fan, Vuckovic
Purdue: Qi

GORDON AND BETTY
MOORE
FOUNDATION

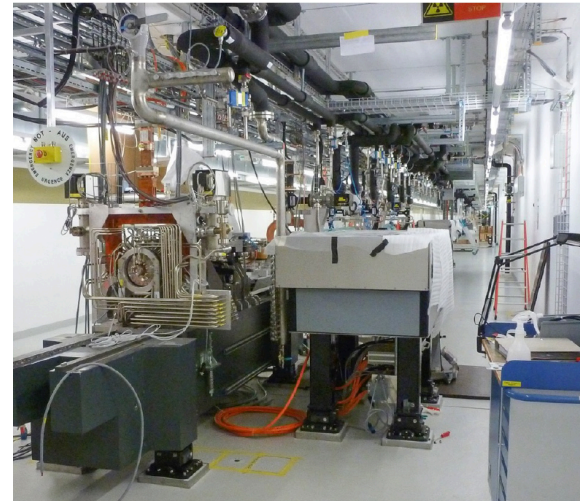
As in-kind supporters of this project, SLAC, DESY, and PSI have pledged access to facilities and resources.

SLAC

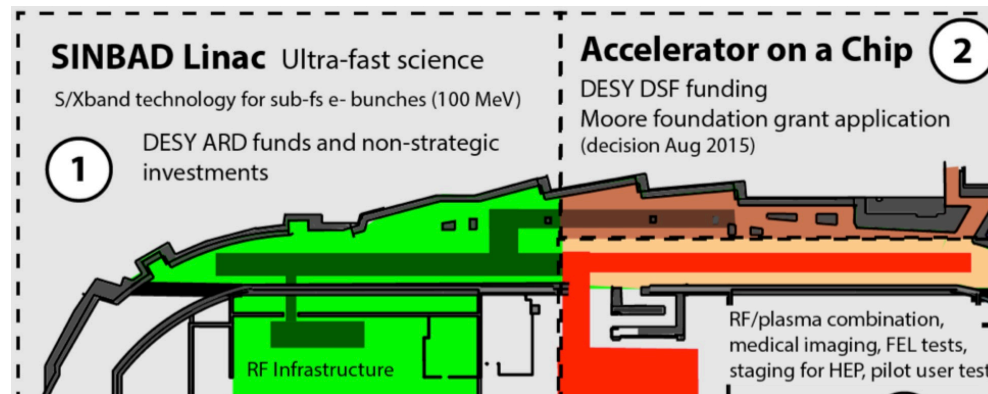
SLAC NLCTA



PSI SwissFEL



DESY SINBAD/ATHENAe



Milestones for the ACHIP Moore Foundation Program

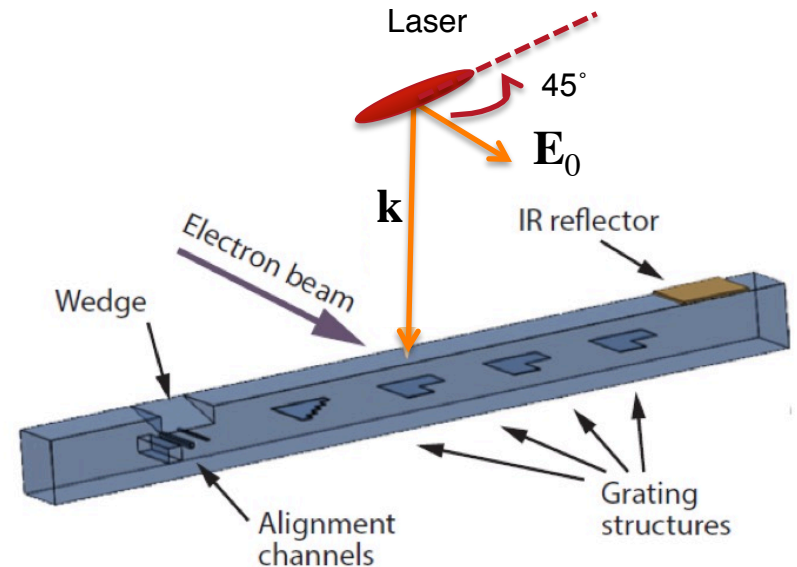
SLAC

- ✓ 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 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.

* Asterisked items conducted primarily through university collaboration.

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.

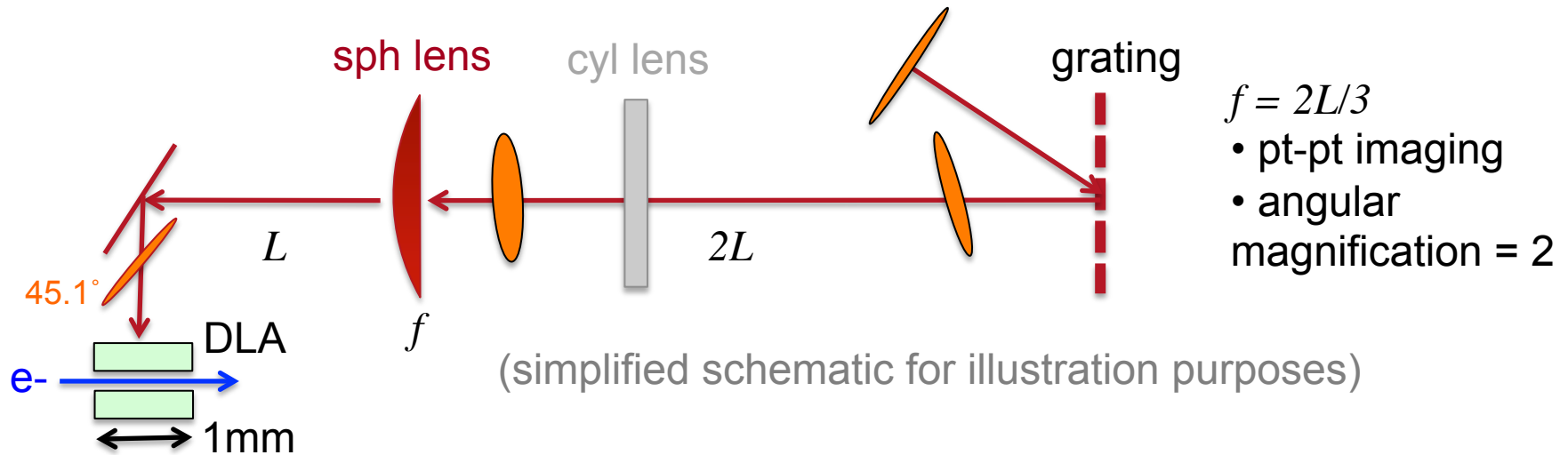
Step 2: Switch to 45° pulse front tilt to increase interaction length

Status:

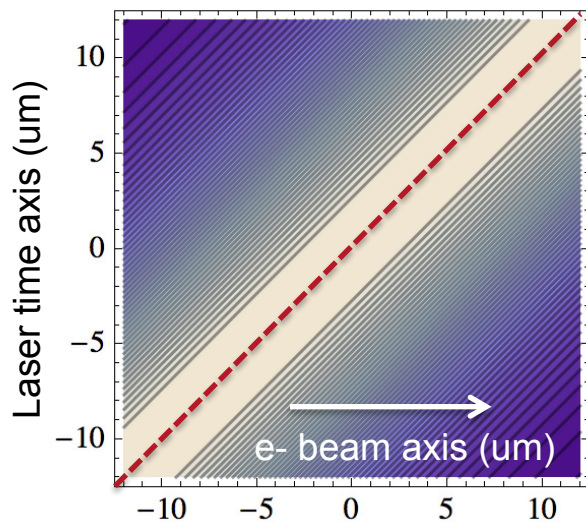
→ DLA setup commissioned with ps timing diagnostic and multi-axis stage

→ Successful electron transmission on DLA (both 400nm and 800nm gaps)

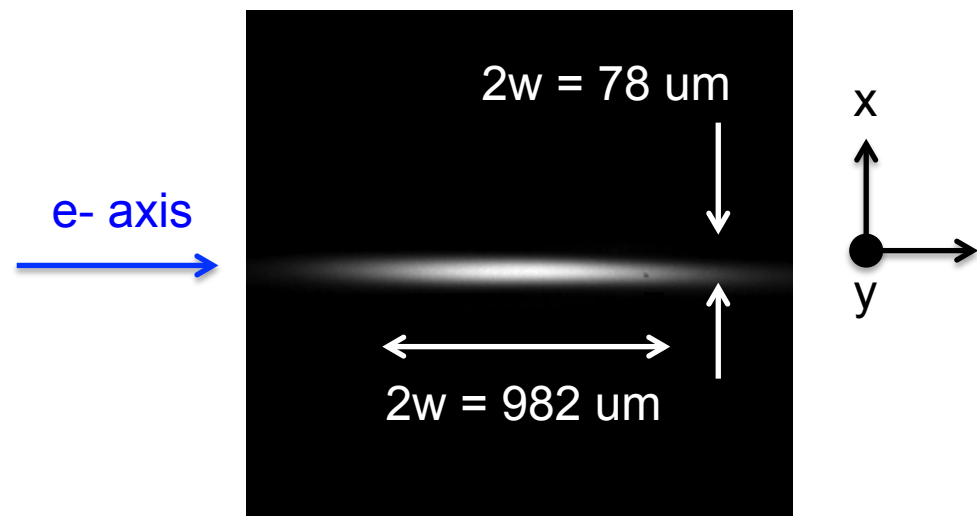
Optics Setup for Pulse Front Tilt at UCLA



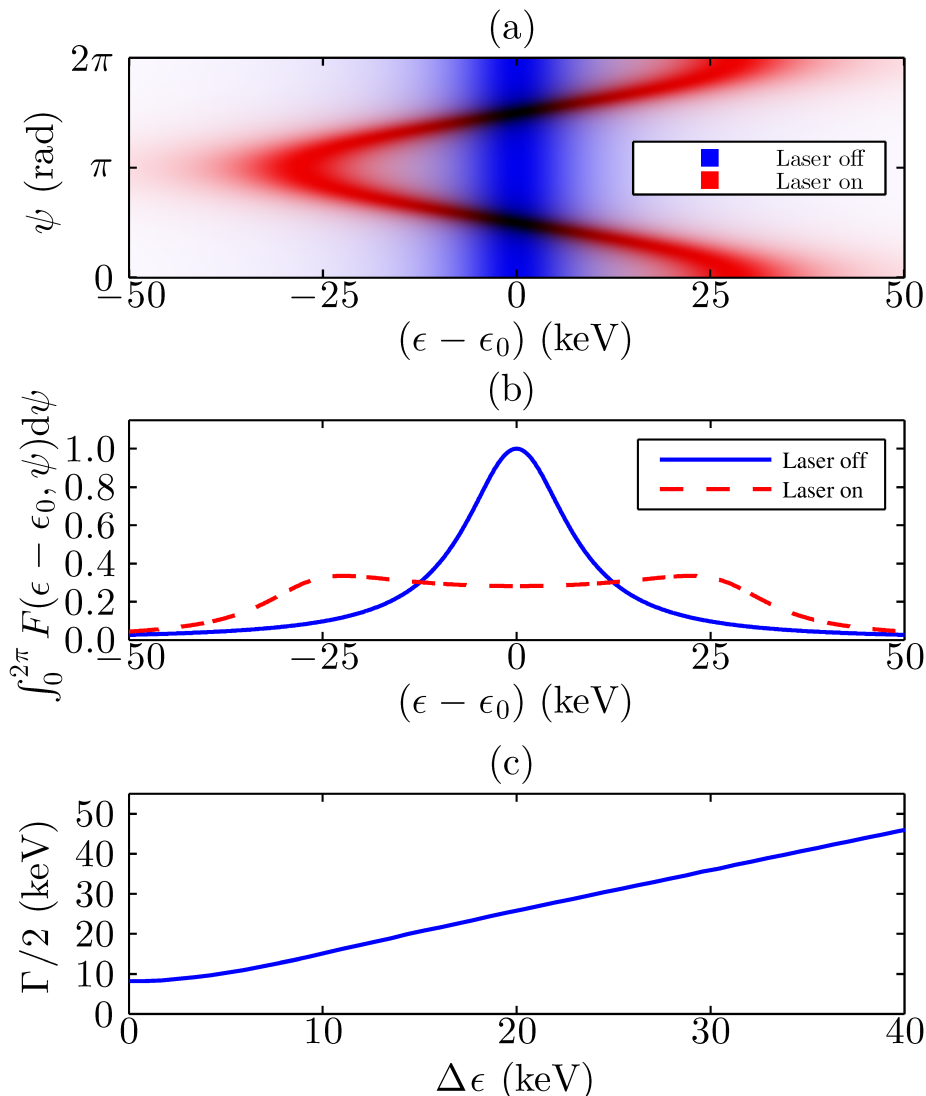
Simulated pulse front tilt (45.1°)



Measured IP laser spatial profile



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

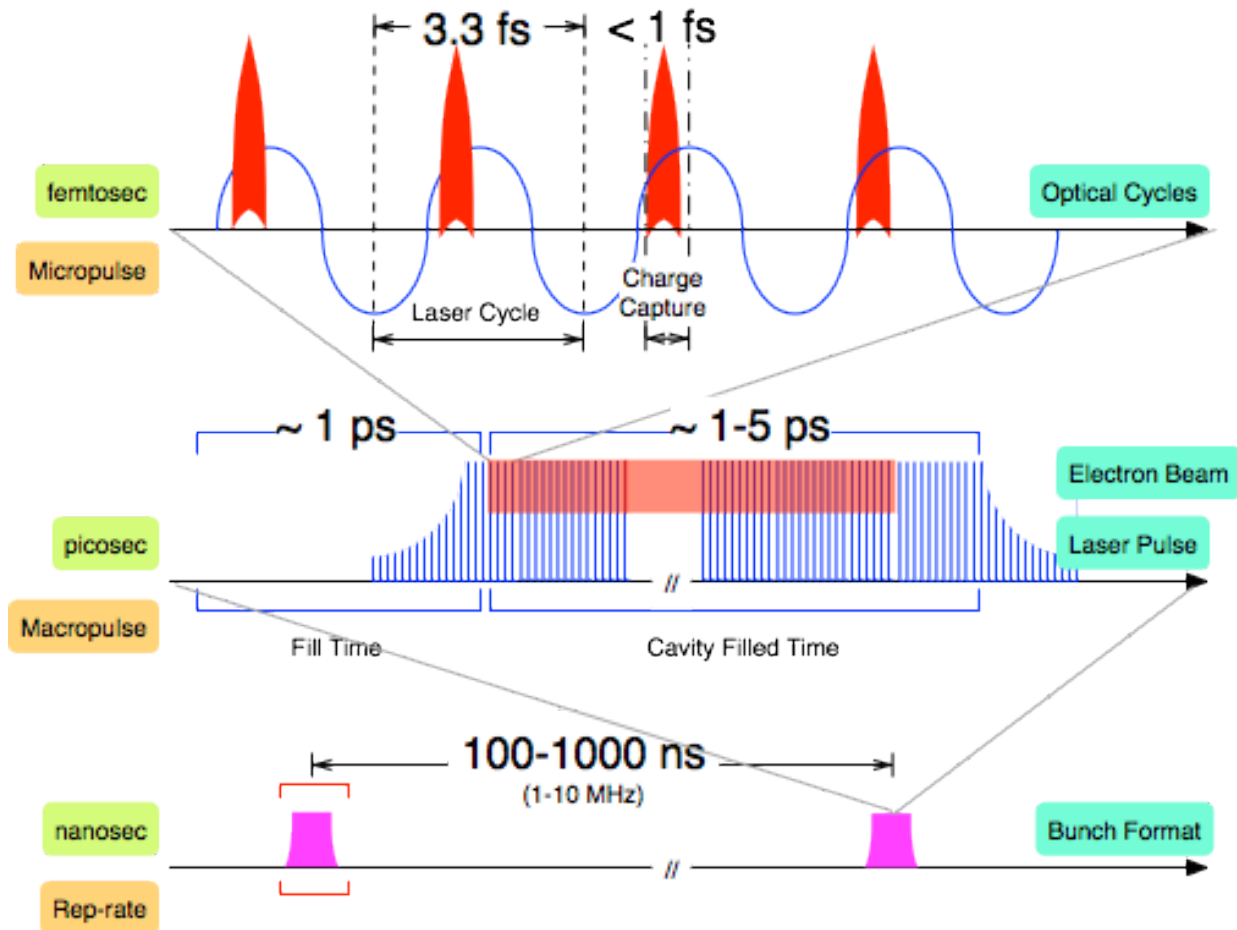


Sampling of all laser phases produces a sinusoidal energy modulation .

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

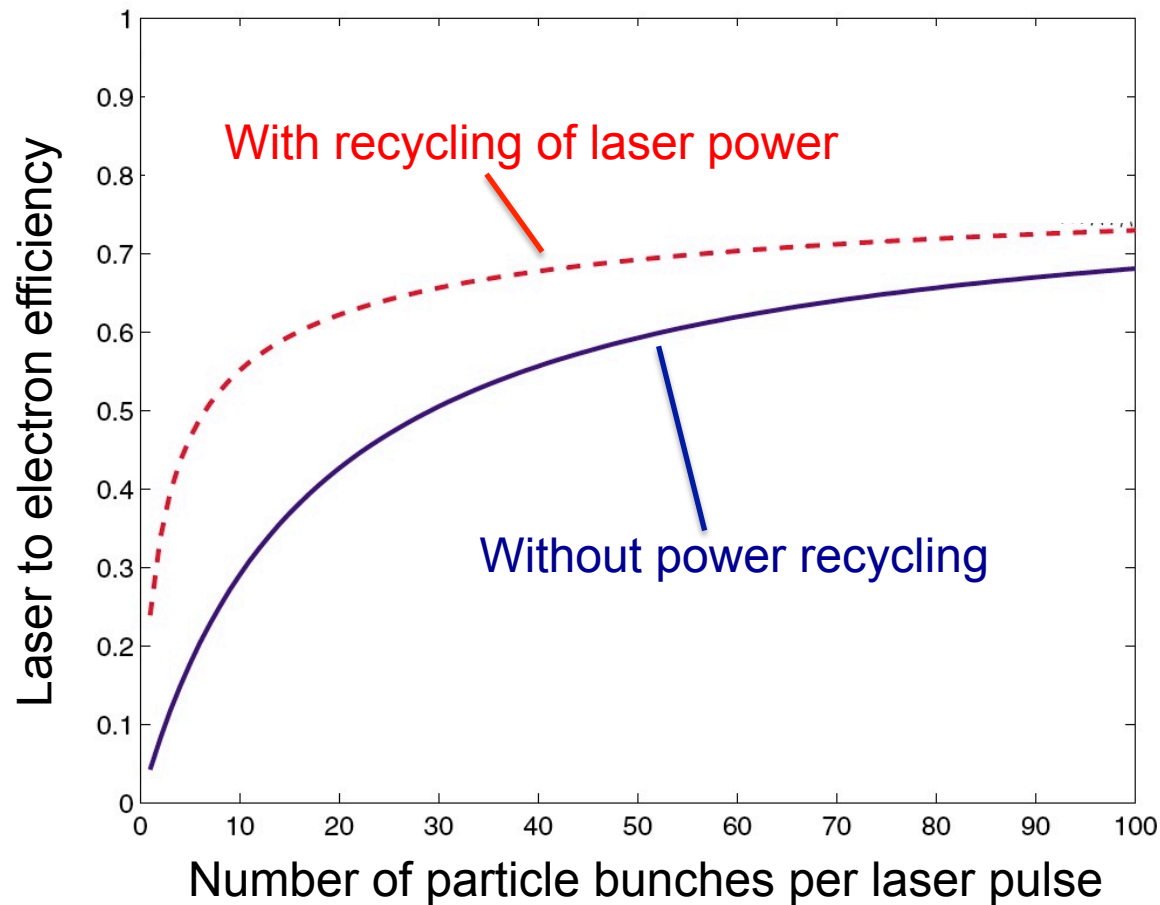
The energy gain and gradient are extrapolated from the HWHM of the spectrum.

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



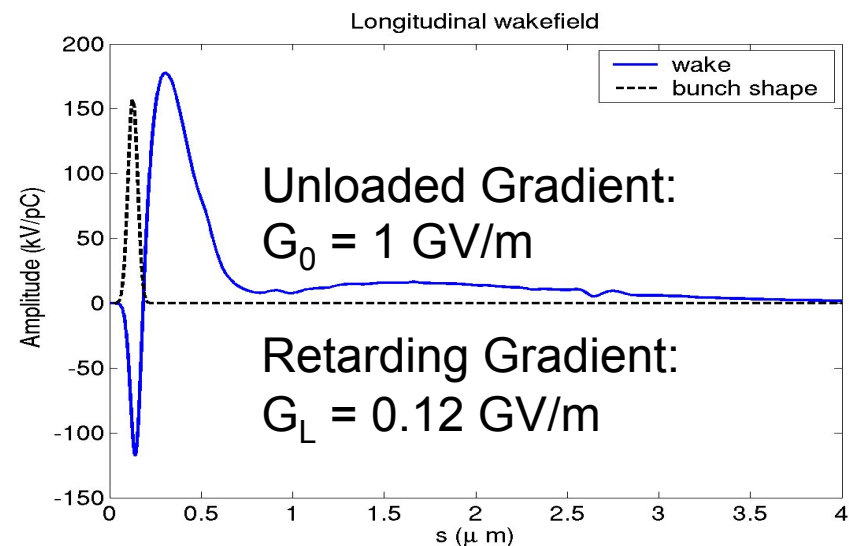
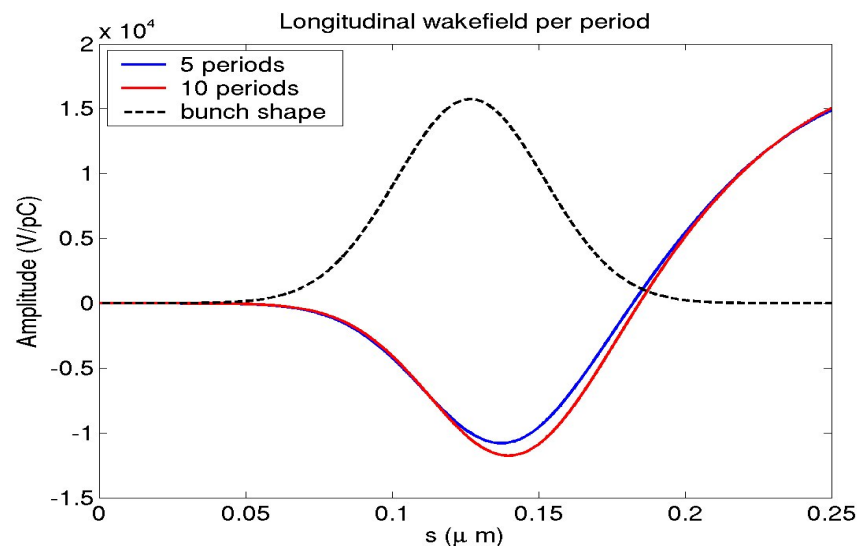
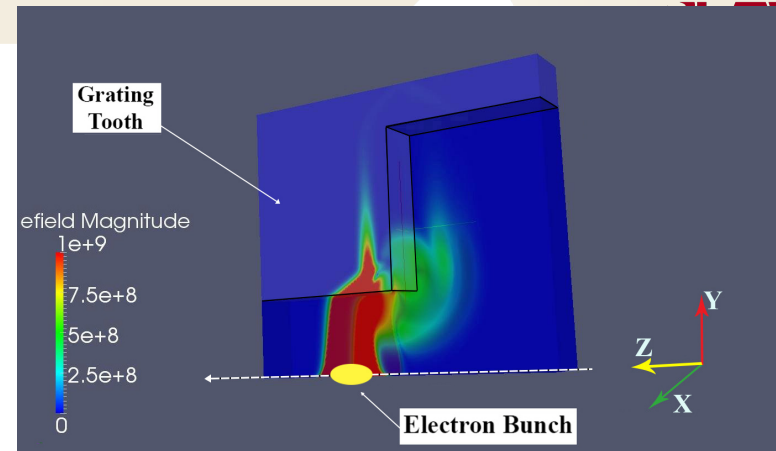
With particles optically bunched, the field to electron power transfer efficiencies would approach 60%.

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



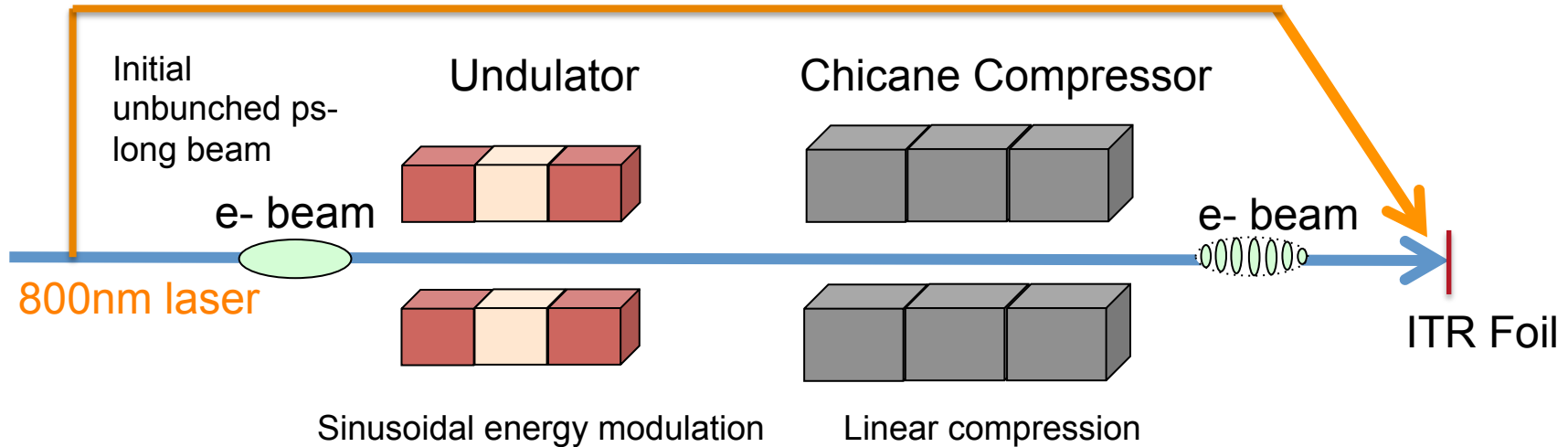
Longitudinal Wake Calculations in Fused Silica Grating Structure

- 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.

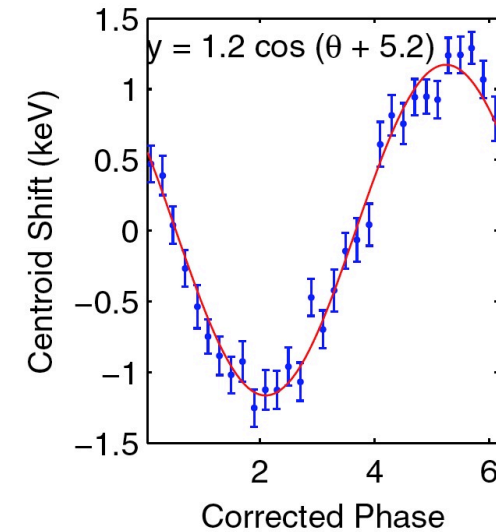
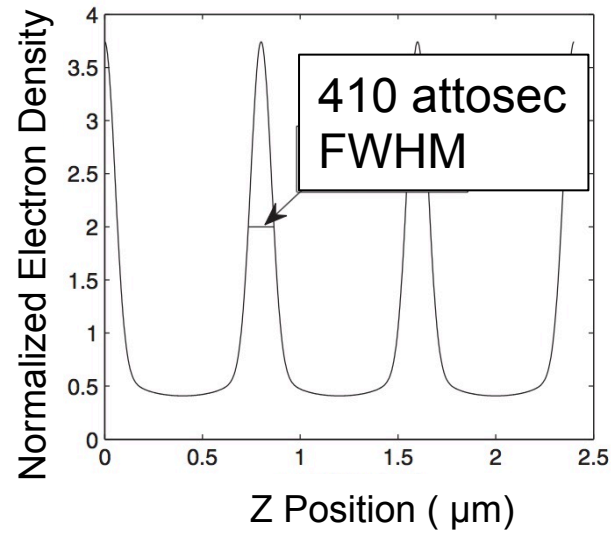


Simulations by B. Montazeri, C. Ng, K. Bane

Microbunching and Net Acceleration: Prior Art

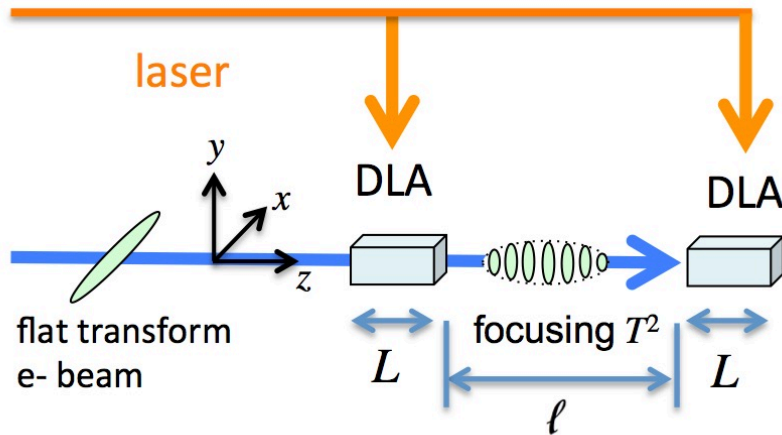


Parameter	Value	Units
λ_w	1.8	cm
λ_ℓ	800	nm
γ	117.4	-
K	0.636	-
FWHM	140	keV
σ_E	17	keV

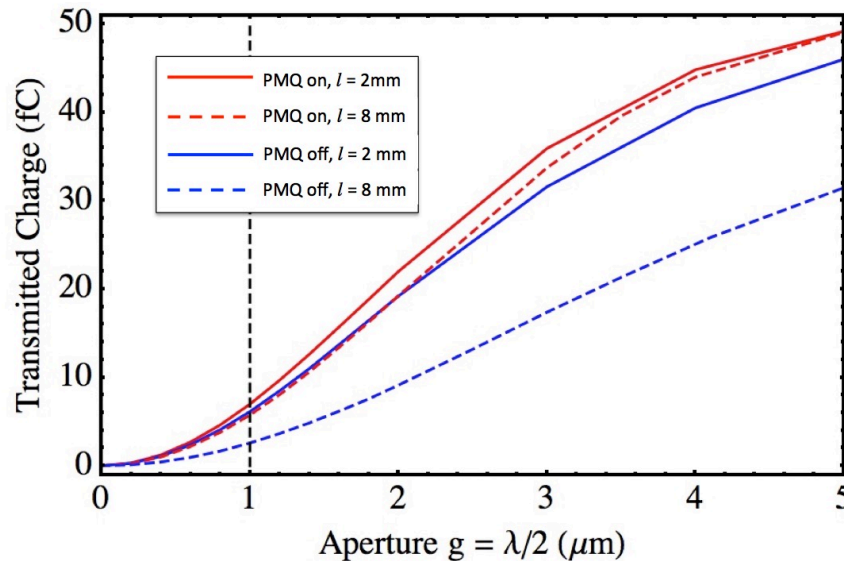


Sears, Colby, England, et al., PR-STAB **11**, 101301 (2008).

Microbunching and Net Acceleration: Future Experiments



Parameter	Description	Units	Value
λ	wavelength	μm	2
g	beam aperture	μm	1
$U0$	beam energy	MeV	4
Q	bunch charge	fC	50
τ	RMS bunch duration	fs	160
$\epsilon N_{x,y}$	normalized emittance	nm rad	200, 2
$\sigma_{x,y}$	RMS spot size	μm	200, 1
L	DLA interaction length	mm	1
l	bunching drift	mm	2, 8
δU	Energy spread	keV	7

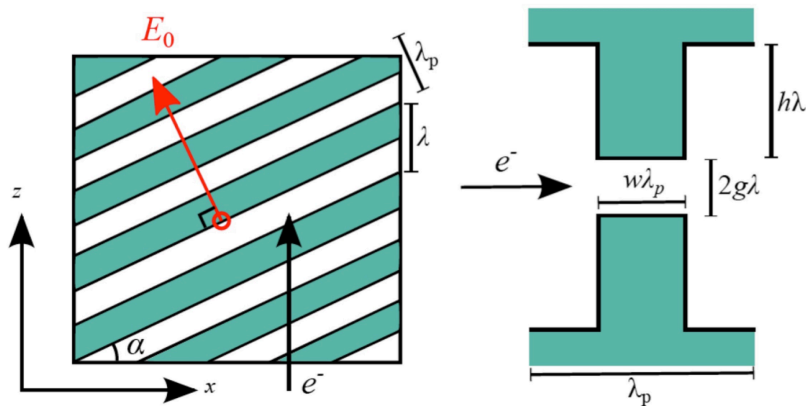


- Flat beam transform $\rightarrow \epsilon_{Ny} = 2 \text{ nm}^*$
- PMQ focusing: (700 T/m) in drift l
- For bunching need $l = 2\text{mm} @ 4 \text{ MeV}$

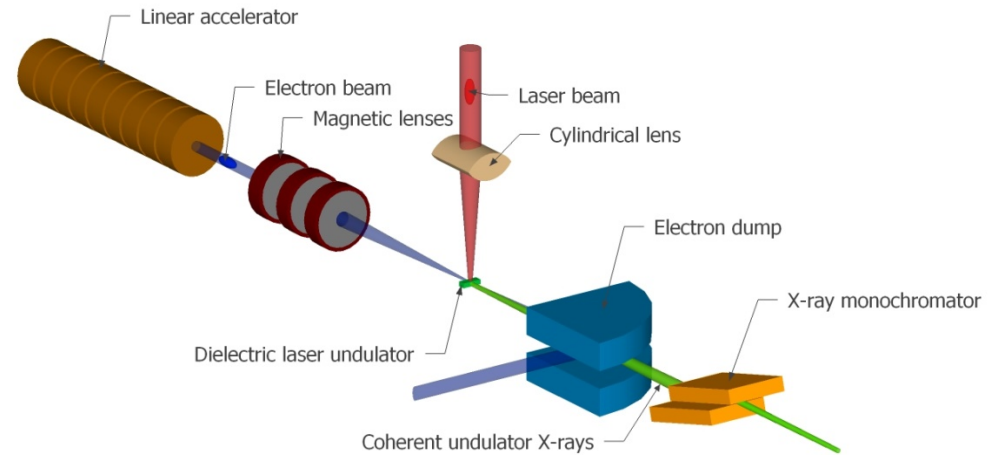
Simple particle transmission study suggests that for shorter distances, external focusing may not be needed.

*A. Ody, et al., High Brightness Beams Workshop, Havana Cuba (2016).

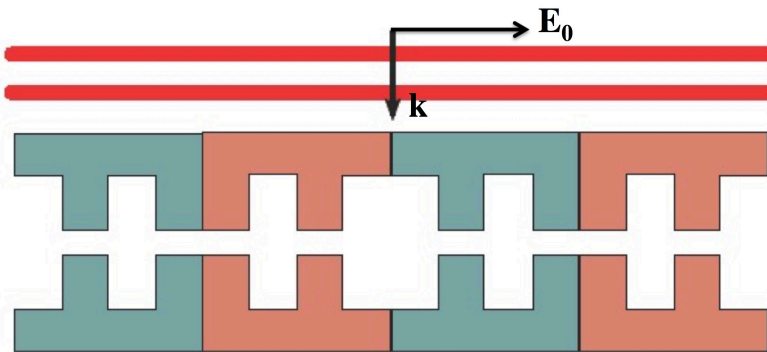
The same operating principles can be used to make deflectors and laser-driven undulators.



Single undulator “half-period” deflector



Schematic of proposed experimental setup



Multi-period undulator concept

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

Development of Compatible Electron Sources

What is the current state of the art?

laser-triggered nanotip field emitters

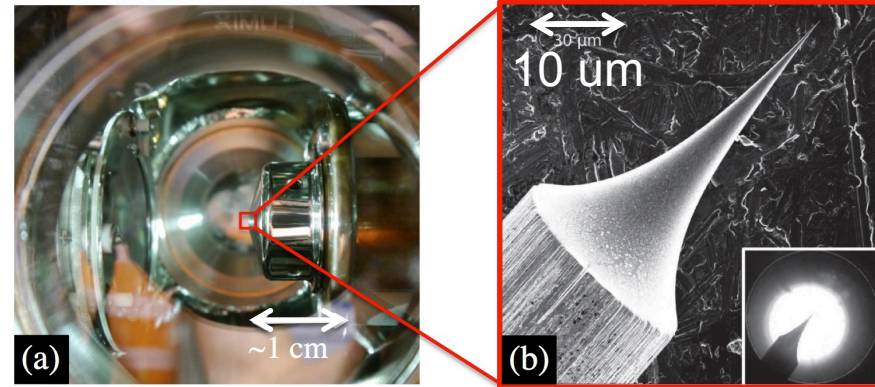
30 keV energy, <10 nm emittance

2000 e⁻ per pulse; 1cm footprint

Lead institutions:

Stanford U., USA (Solgaard)

Erlangen U., Germany (Hommelhoff)



P. Hommelhoff, Erlangen Univ.

Where do we need to go?

reliable high-rep (MHz) operation;

integrated on-chip with DLA

Risks and mitigations?

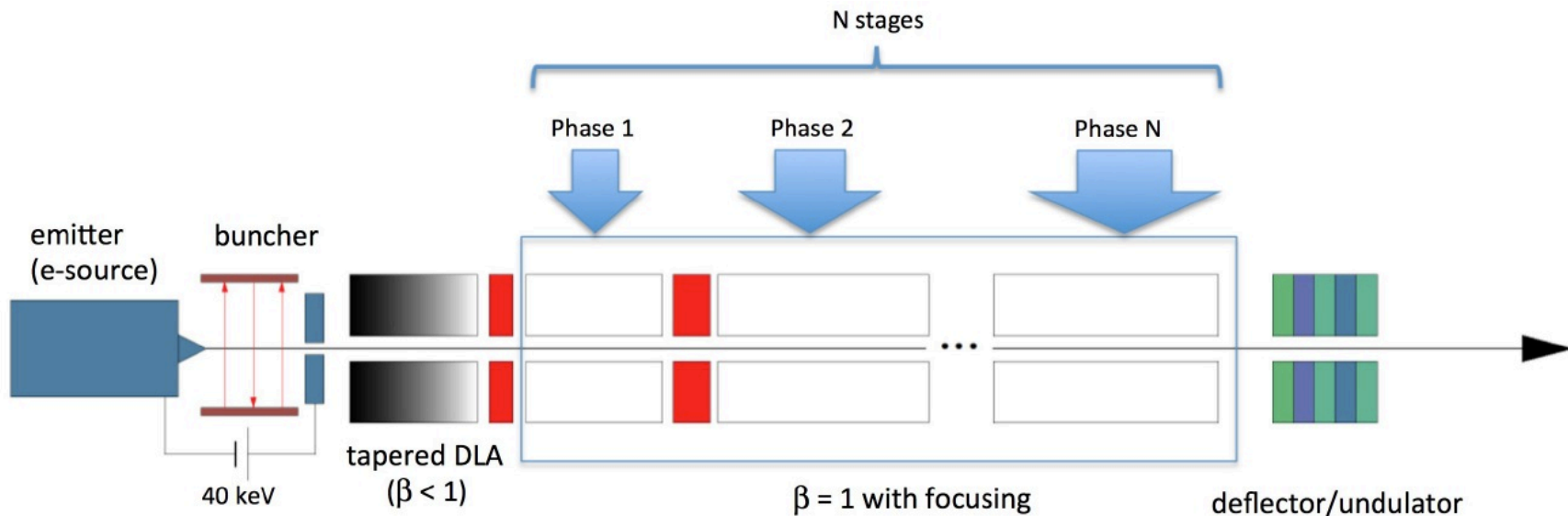
Lifetime (metal tips damage at high rep rate) → alternative materials (e.g. diamond)

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

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.

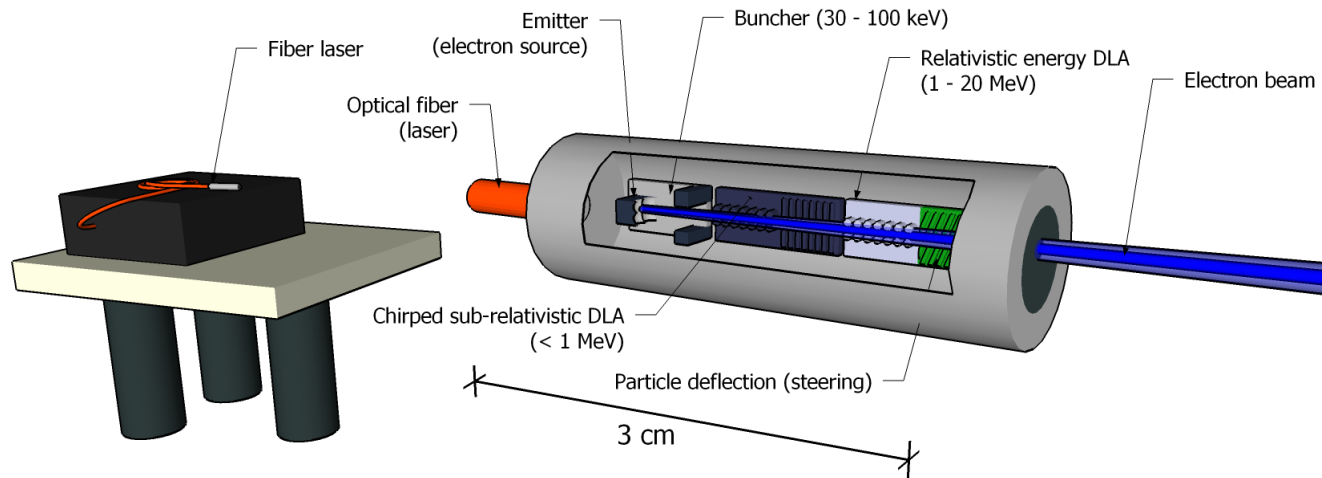
1. Compact electron source
2. DLA structure development: (a) subrelativistic, (b) relativistic
3. Multi-staged acceleration
4. Coupling of laser to DLA
5. Laser-driven undulator/deflector



A future DLA accelerator would operate in a very different parameter regime compared with RF

Parameter	DLA	RF
Power Source	Commercial IR Laser	Microwave Klystron
Wavelength	1-10 μm	2-10 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/ Silicon WG	Critically-coupled metal WG

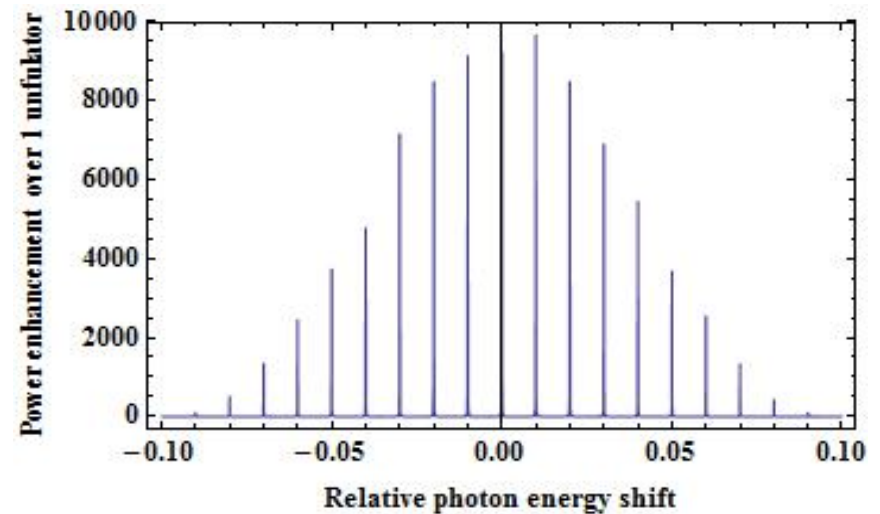
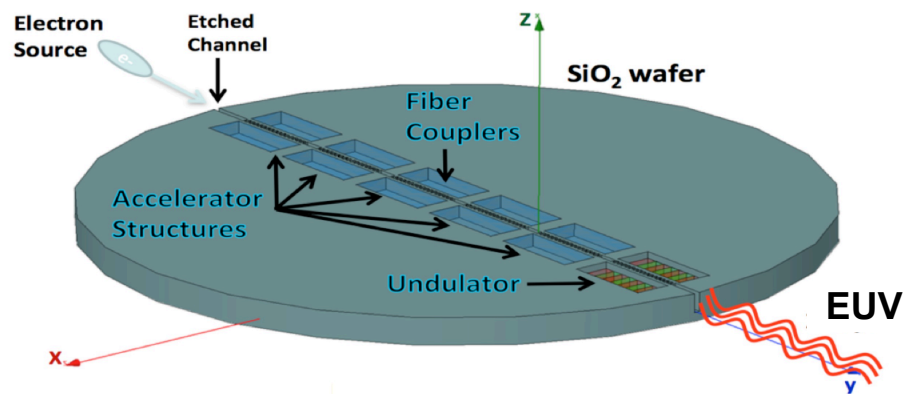
A Game-Changing Small Footprint Medical Accelerator Directly Maps to DLA's Unique Features



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:

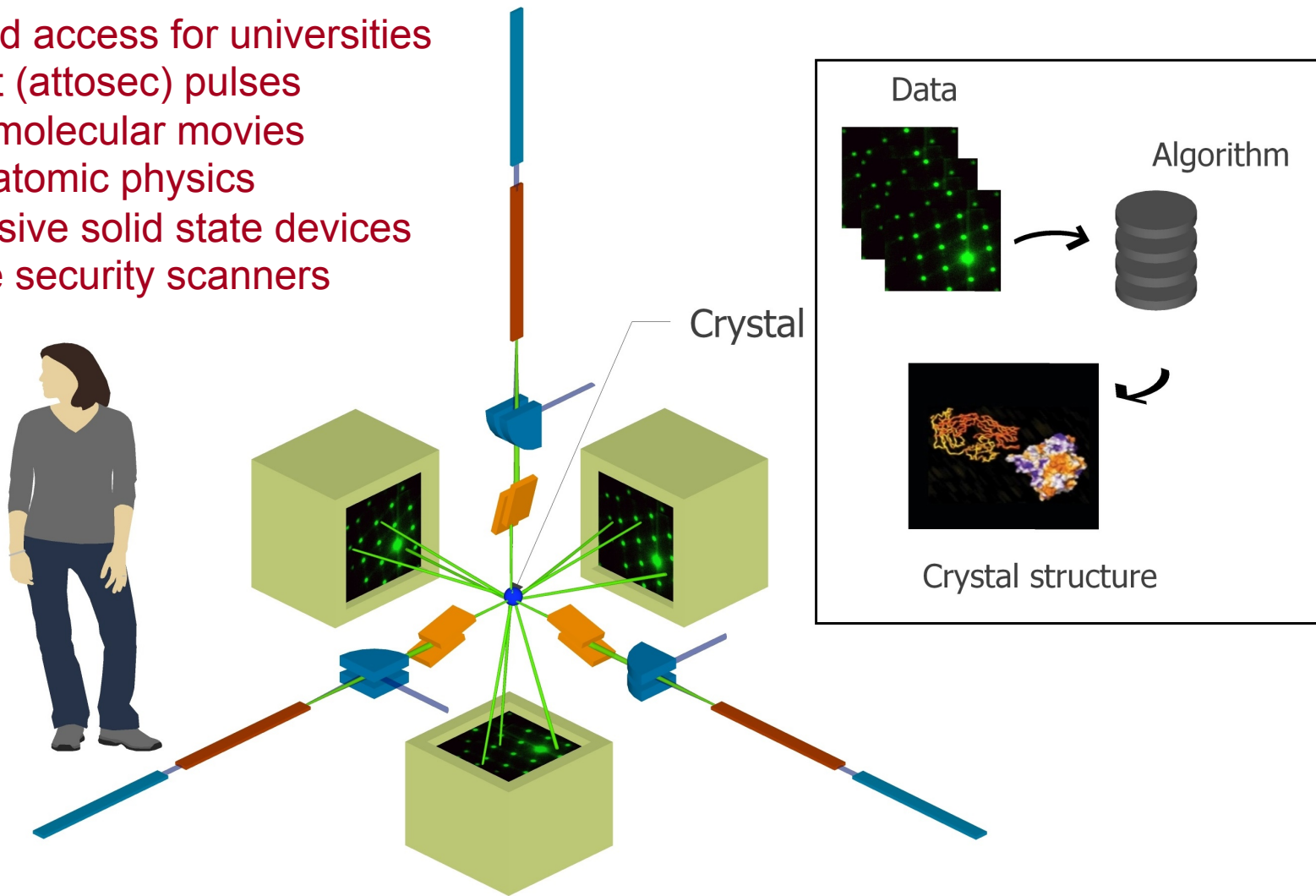
$$\leftarrow \frac{\hbar\omega}{\gamma m c^2} = 10^{-5}$$

* 1 "SBU" = ph/s/mm²/mrad²/0.1%BW

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

SLAC

- 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

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 monitoring

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
- Development and testing of focusing structures
- Demonstration of laser undulators and relativistic energy deflection

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