Electron source requirements for laser-driven dielectric accelerators

Photocathode Physics for Photoinjectors
Jefferson Laboratory, Newport News, VA
October 19, 2016

R. Joel England

ACHIP

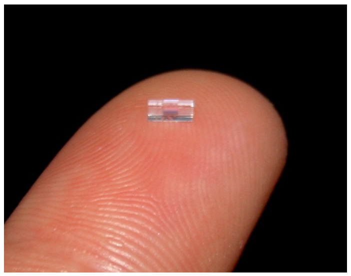
GORDON AND BETTY MOORE FOUNDATION

U.S. DEPARTMENT OF ENERGY
Office of Science

E163
DIELECTRIC LASER ACCELERATION

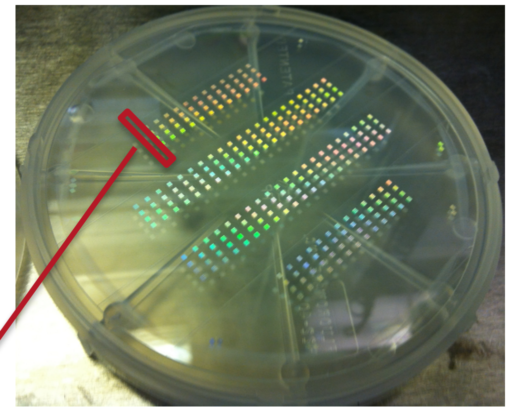
SLAC NATIONAL ACCELERATOR LABORATORY

Dielectric Laser Acceleration (DLA)



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

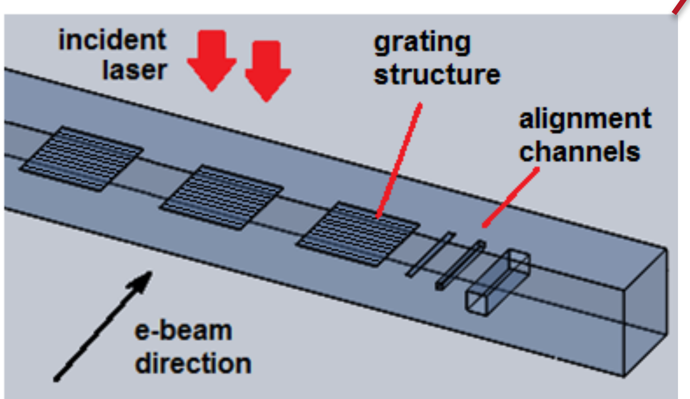
"Accelerator-on-a-chip"

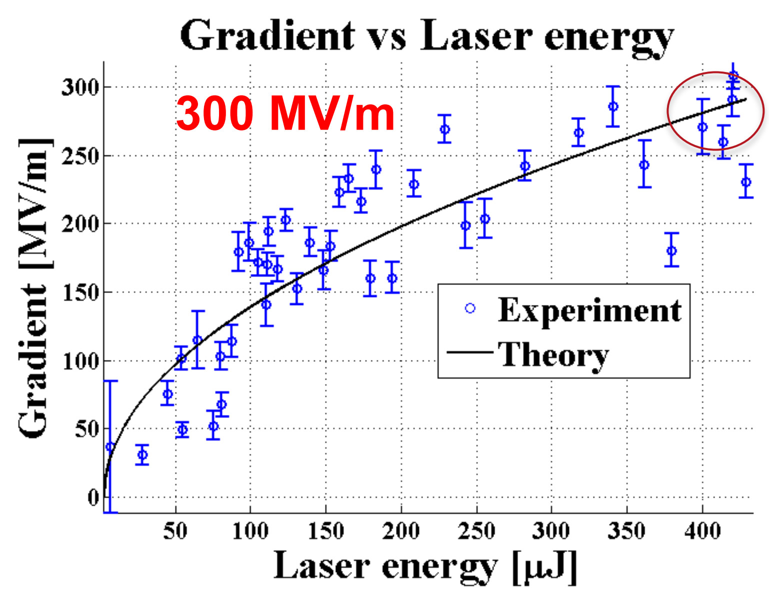


bonded silica phase reset accelerator prototypes fabricated at SLAC/ Stanford

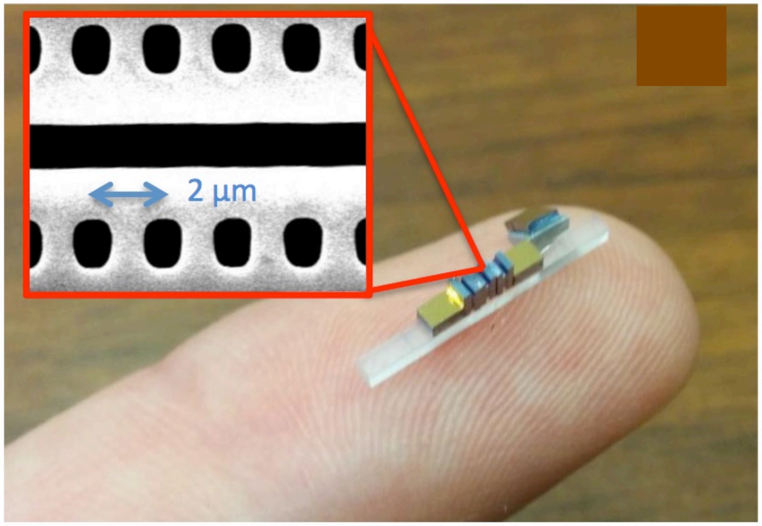
Goal: lower cost, more compact, energy efficient, higher gradient

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





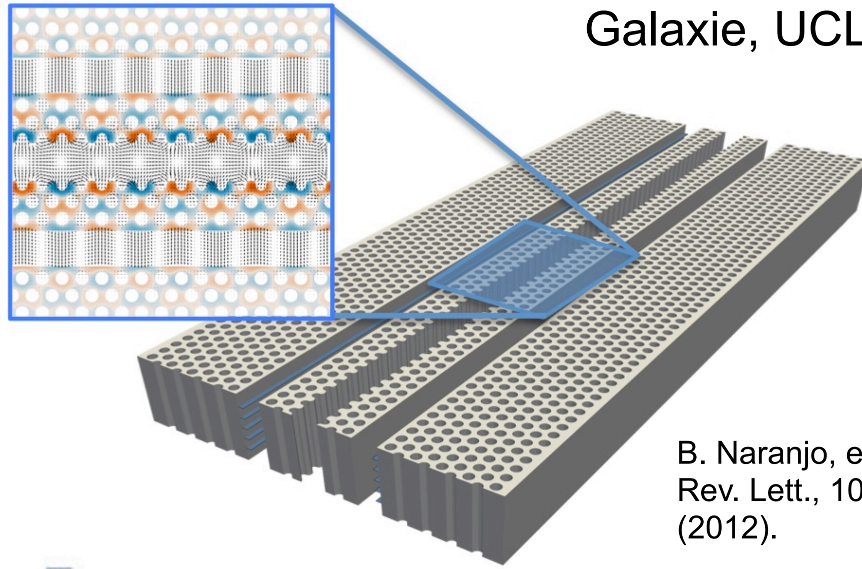
Various DLA Concepts Recently Proposed



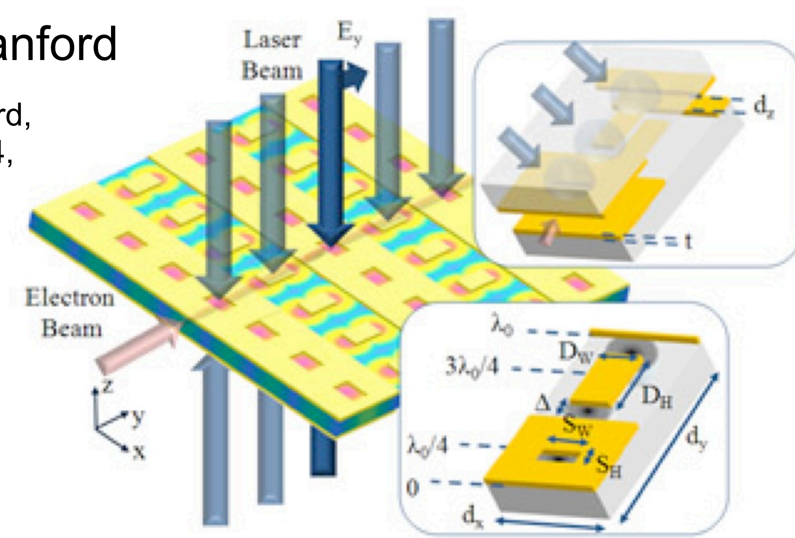
Buried Grating, Stanford

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

SLAC

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**

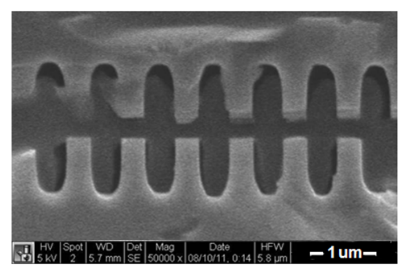
Solid-state laser

Available now
"off the shelf"

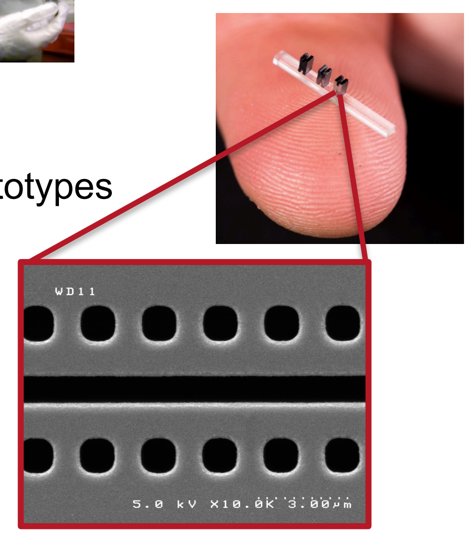
Fabricated using techniques of the integrated circuit industy.

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)

DLA is a promising new approach to particle acceleration with a range of potential applications

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.

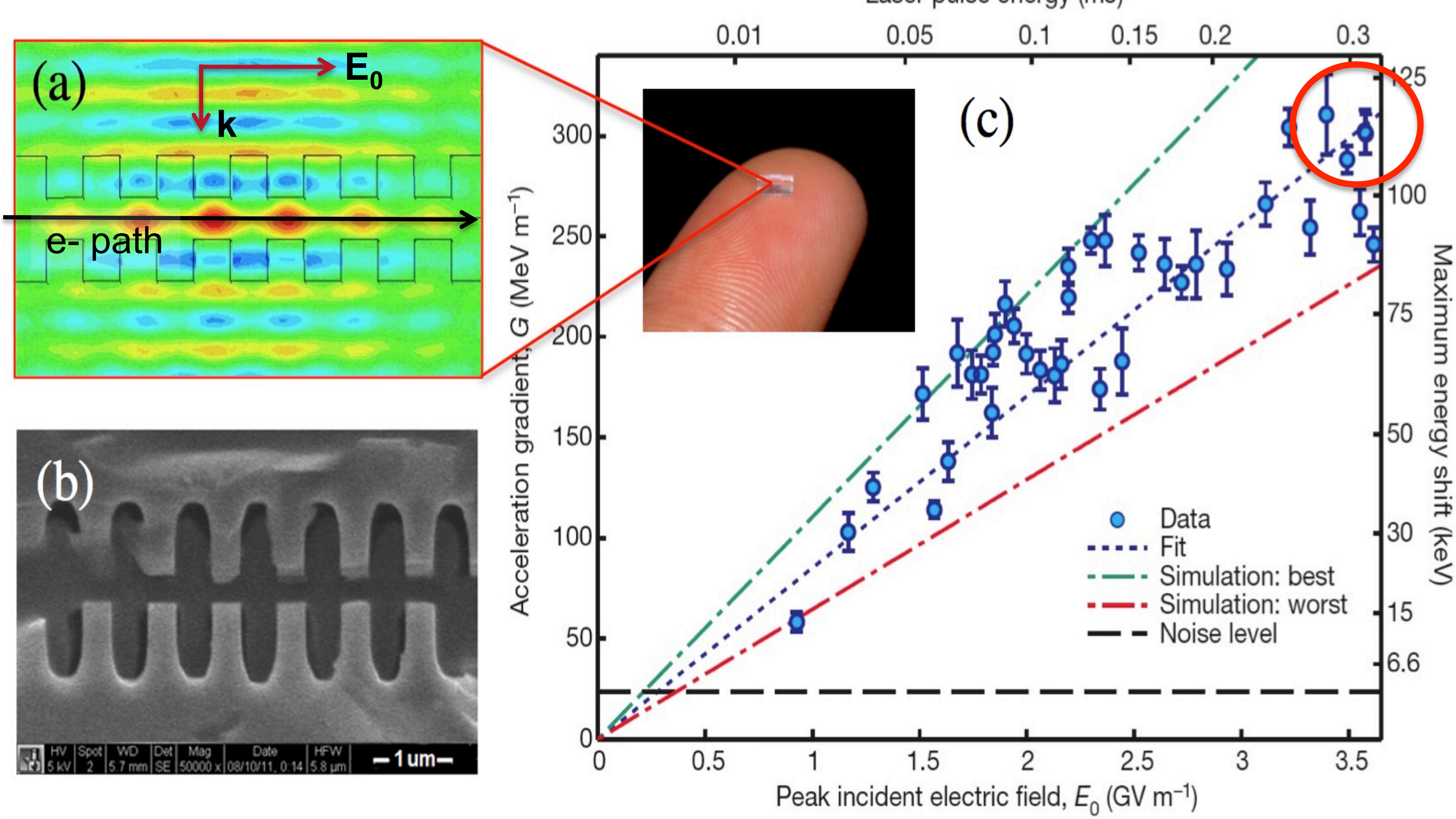
Sub-optical wavelength **(attosecond) temporal bunch structure** translated into sub-fs radiation pulses could enable ultrafast science (molecular movies, atomic physics).

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

The first experimental demonstration (2013) showed gradients 10 times higher than the main SLAC linac…

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

300 MV/m

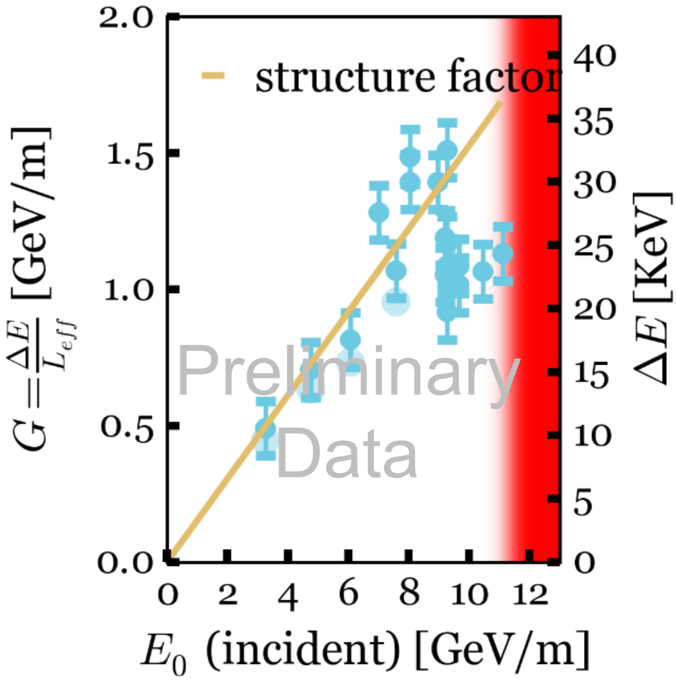


Subsequent short-pulse laser demonstrations at NLCTA and UCLA have exceeded the GeV/m threshold (2016).

SLAC

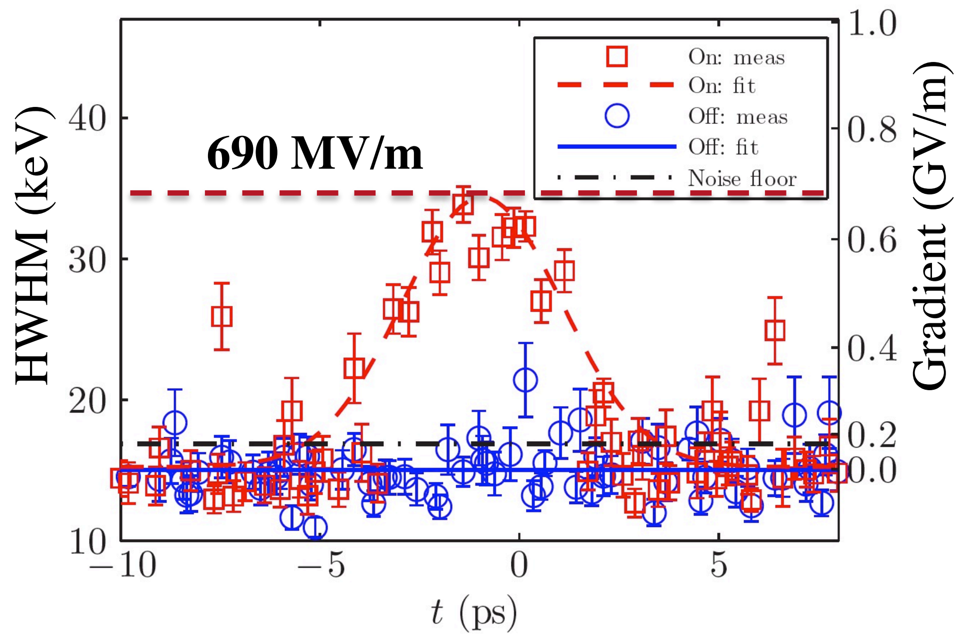
→ Record DLA gradients demonstrated at both NLCTA & UCLA facilities.
→ UCLA Pegasus now commissioned for **higher energy gain** experiments.

SLAC/UCLA: G_0 ~ 1.5 GeV/m*



* Preliminary data – in preparation

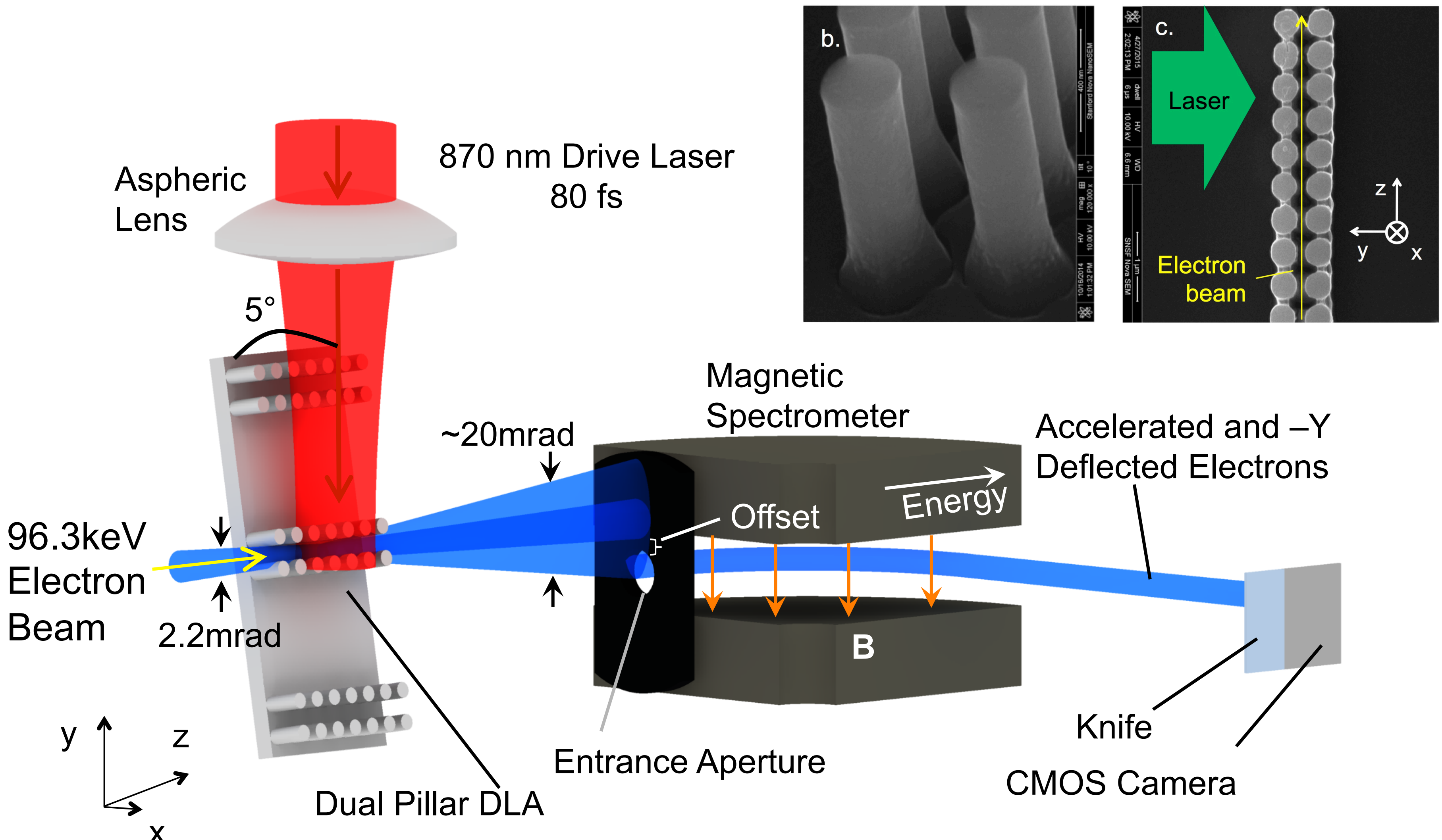
SLAC/NLCTA: G_0 = 690 MeV/m**



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

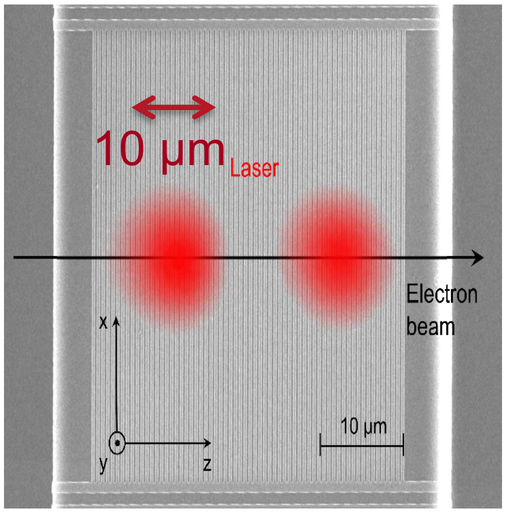
A recently demonstrated dual-pillar design allows higher gradient (370 MV/m) at sub-relativistic energies.

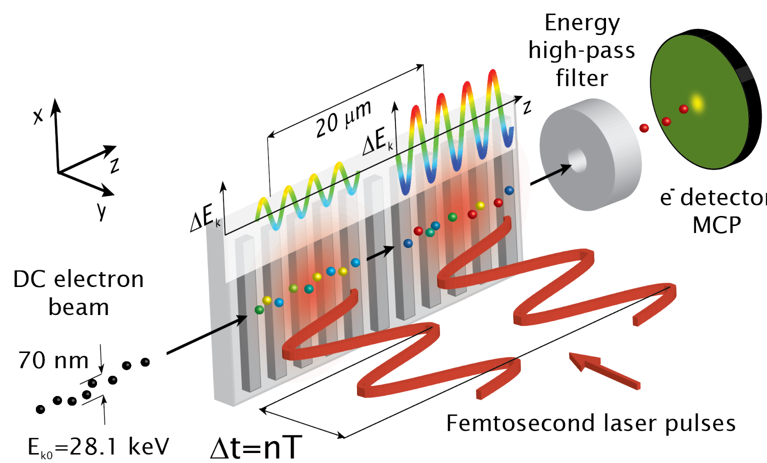
SLAC



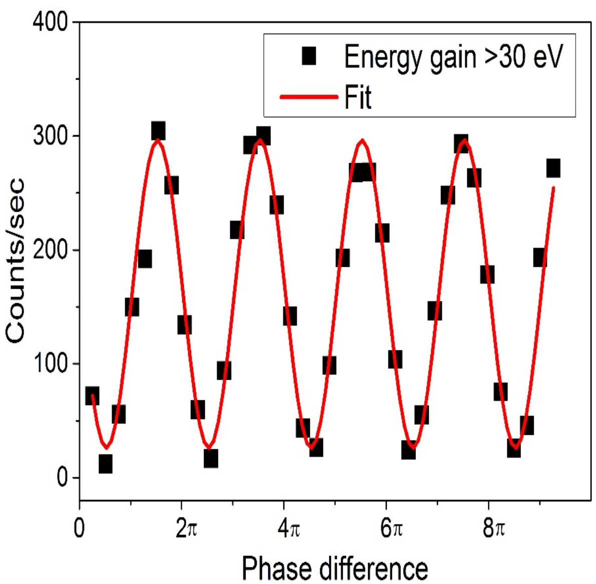
K. Leedle, et al. Opt. Lett. **40** (18) 4344 (2015)

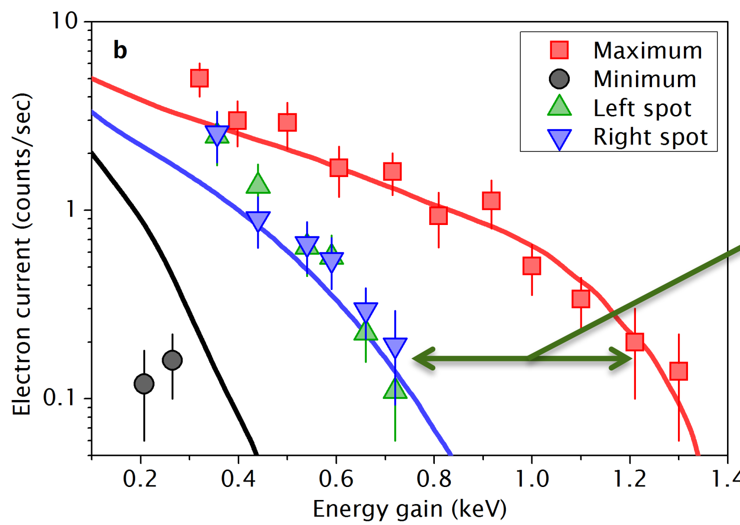
Hommelhoff Group has recently demonstrated phased 2-stage acceleration with 28 keV electrons





M. Kozák et al., arXiv:1512.04394v1





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

FRIEDRICH-ALEXANDER UNIVERSITÄT ERLANGEN-NÜRNBERG

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

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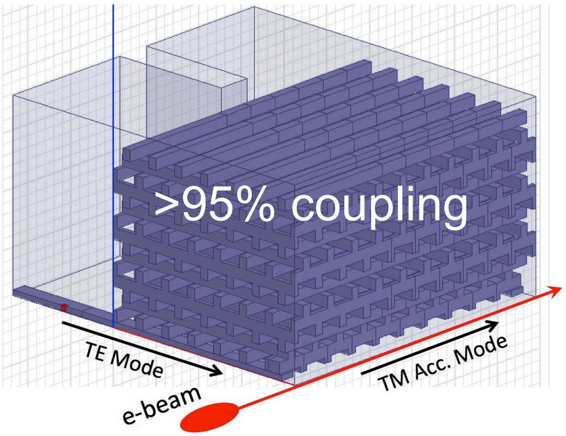
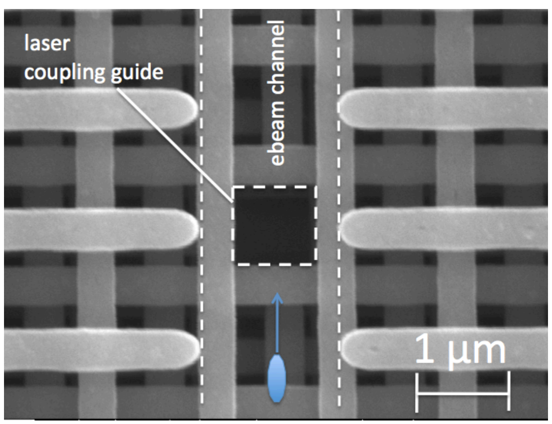
Efficient Coupler Designs

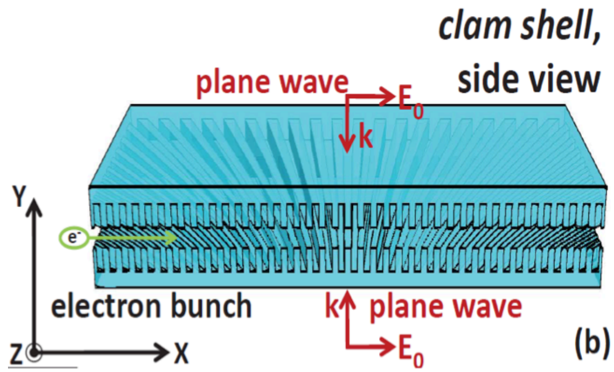




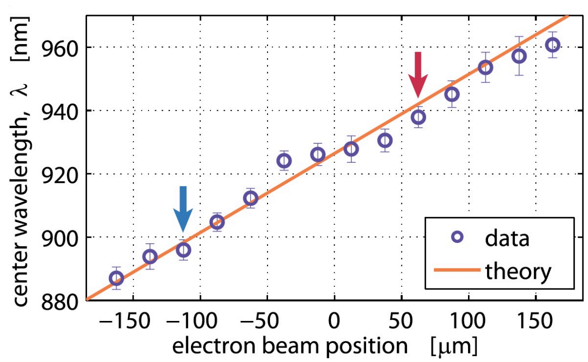
C. McGuinness, Z. Wu

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

Beam Position Monitor

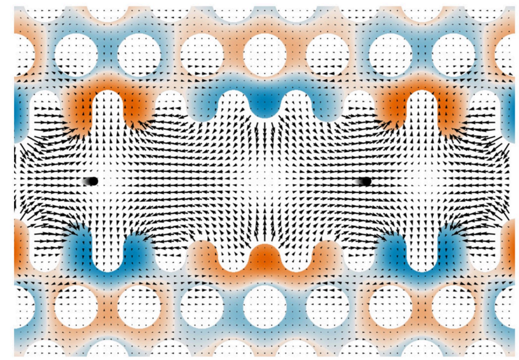


Opt. Lett., **37** (5) 975-977 (2012)

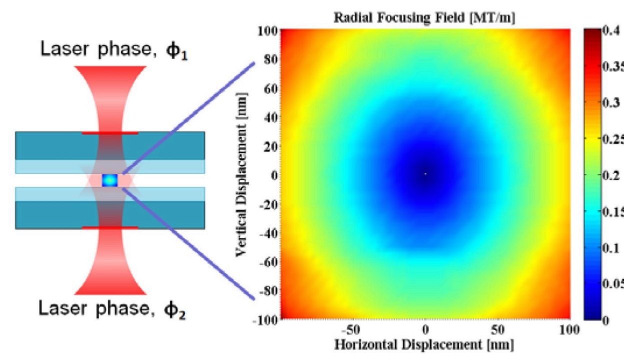


Opt. Lett., **39** (16) 4747 (2014)

Focusing Structures

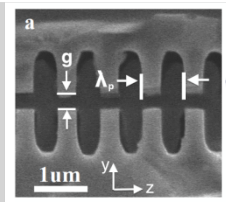
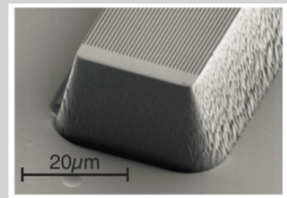
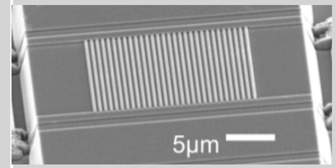
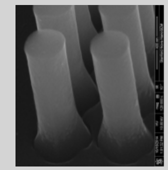


Naranjo, et al., PRL **109**, 164803 (2012).



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

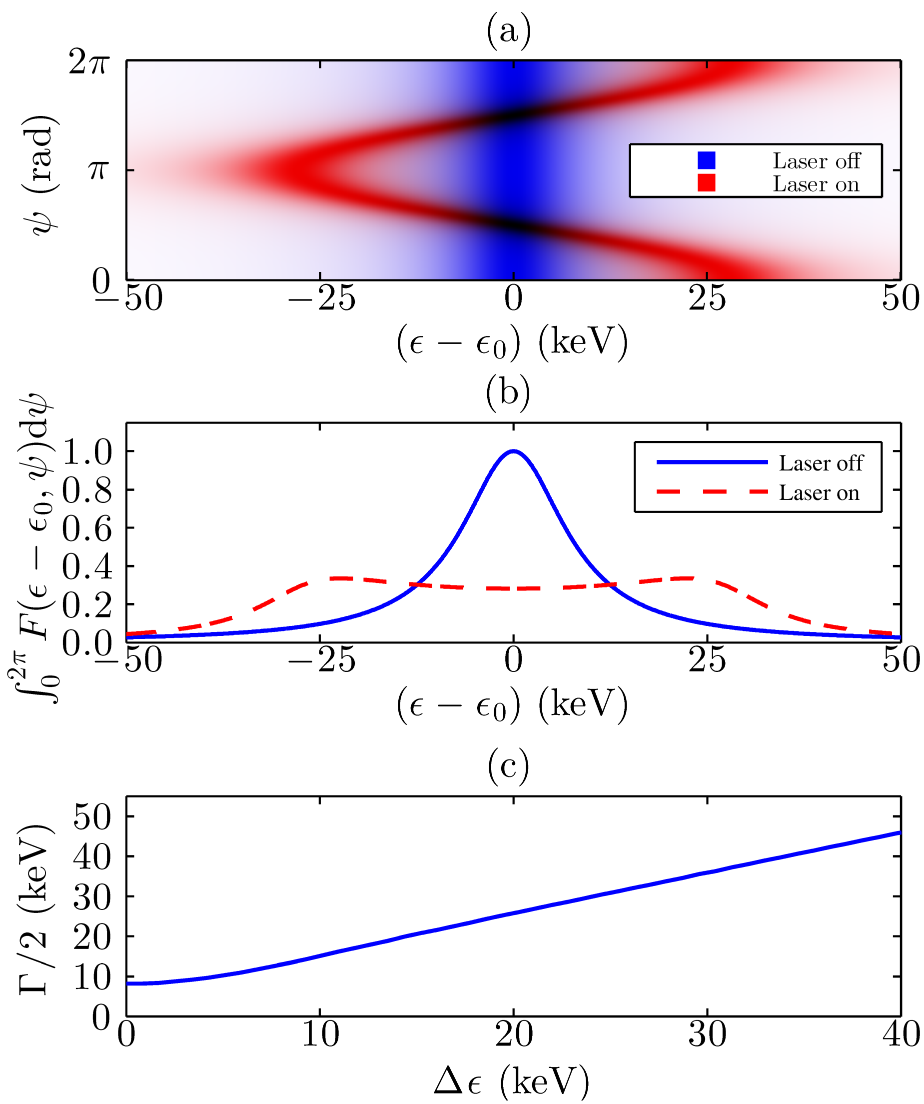
Comparison of Recent DLA Acceleration Experiments

	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	8 GV/m	2.85 GV/m	1.65 GV/m	~1.1 GV/m
Max Energy Gain	**30 keV**	**0.275 keV**	**1.22 keV**	**2.05 keV**
Max Acc Gradient	**~1.5 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

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

SLAC



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

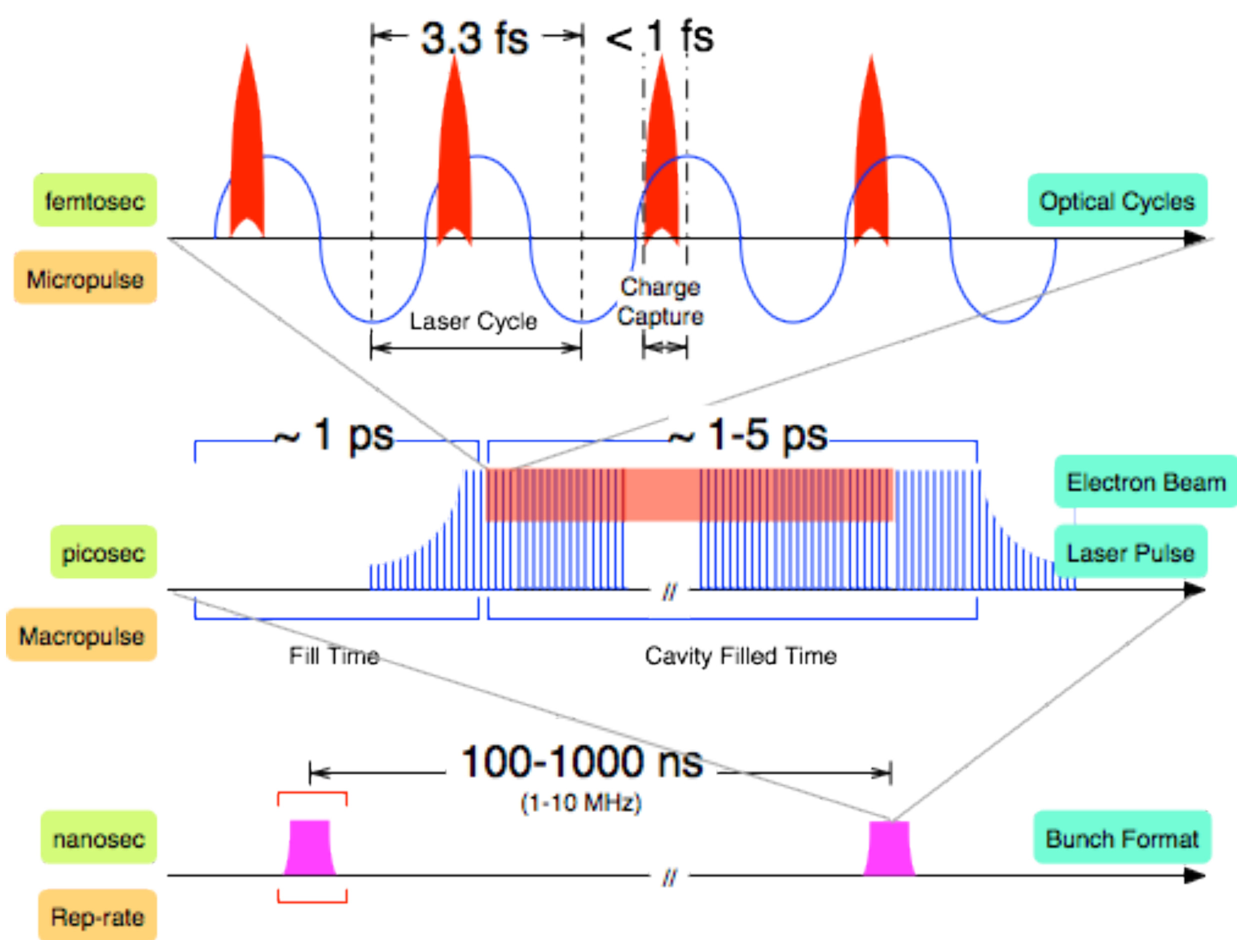
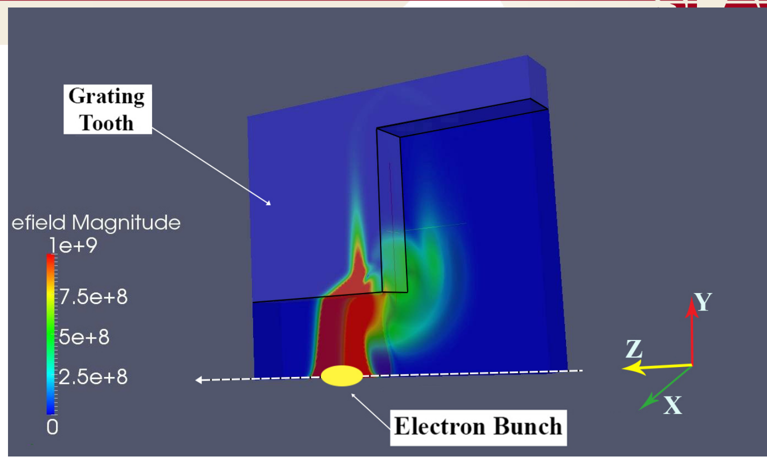
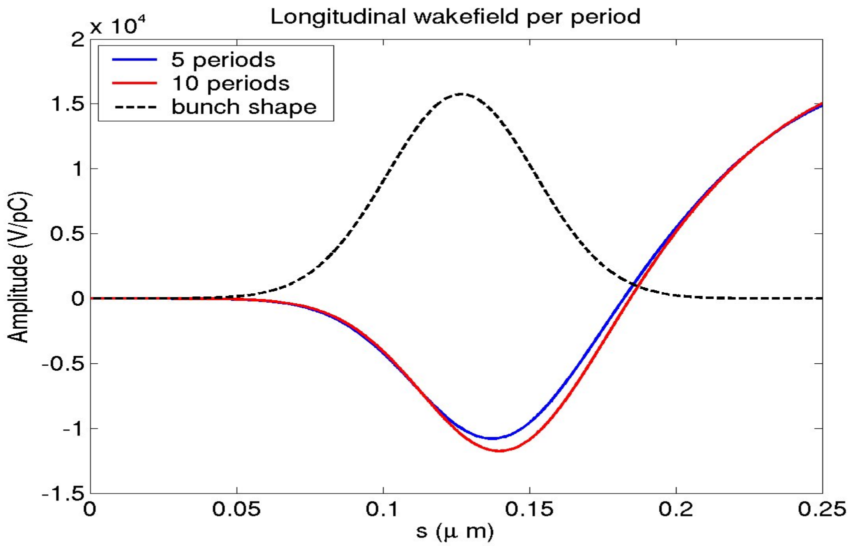


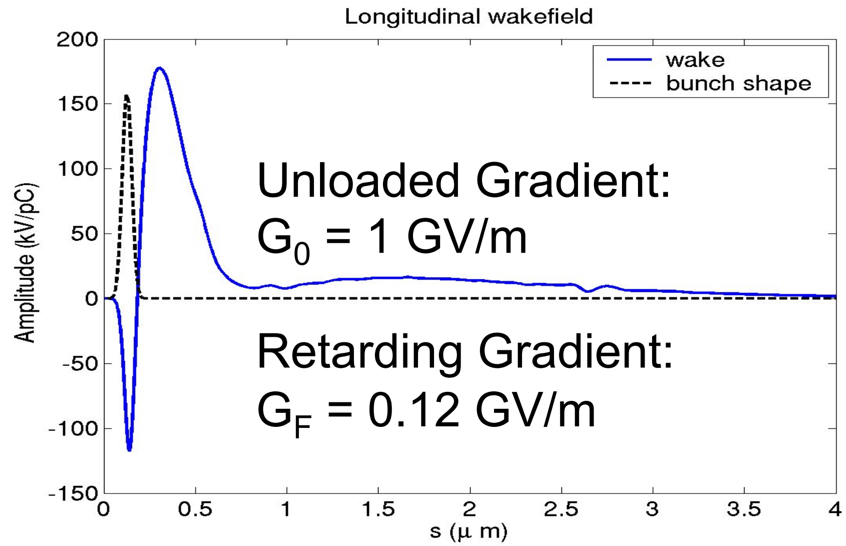
image courtesy of G. Travish

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

DLA Optimal Efficiency and Bunch Charge

unloaded gradient beam loading Cherenkov

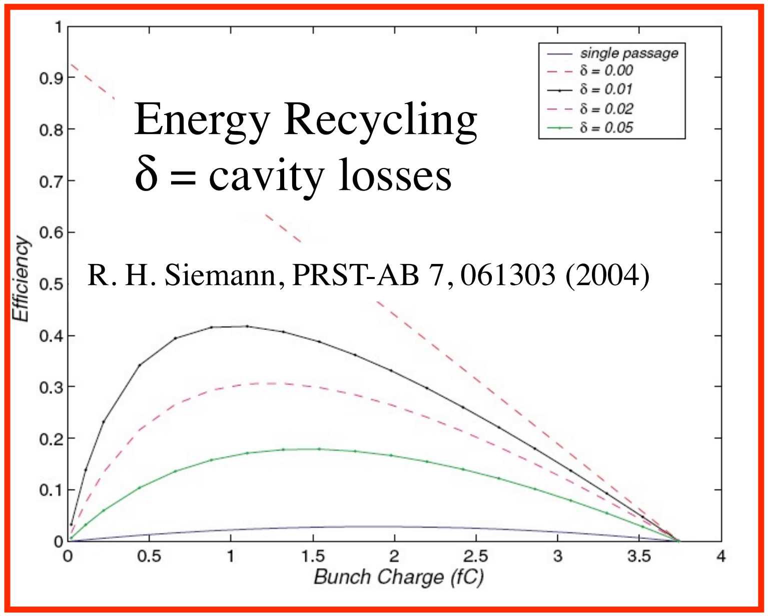
$$G_0 = \sqrt{\frac{Z_C P}{\lambda^2}} \; ; \; G_F = k\,q \; ; \; G_H = \frac{q\,c\,Z_H}{\lambda^2}$$

$$q_{\mathrm{opt}} = \frac{G_0}{2\left(c\,Z_H/\lambda^2 + k\right)} \qquad \eta_{\mathrm{opt}} = \frac{Z_C\,\beta_g}{4\,Z_H\left(1-\beta_g\right) + Z_C\,\beta_g}$$

Energy gain per unit length

$$\frac{dU_{\mathrm{beam}}}{dz} = q\,G = q\left(G_0 - G_F - G_H\right)$$

loaded gradient



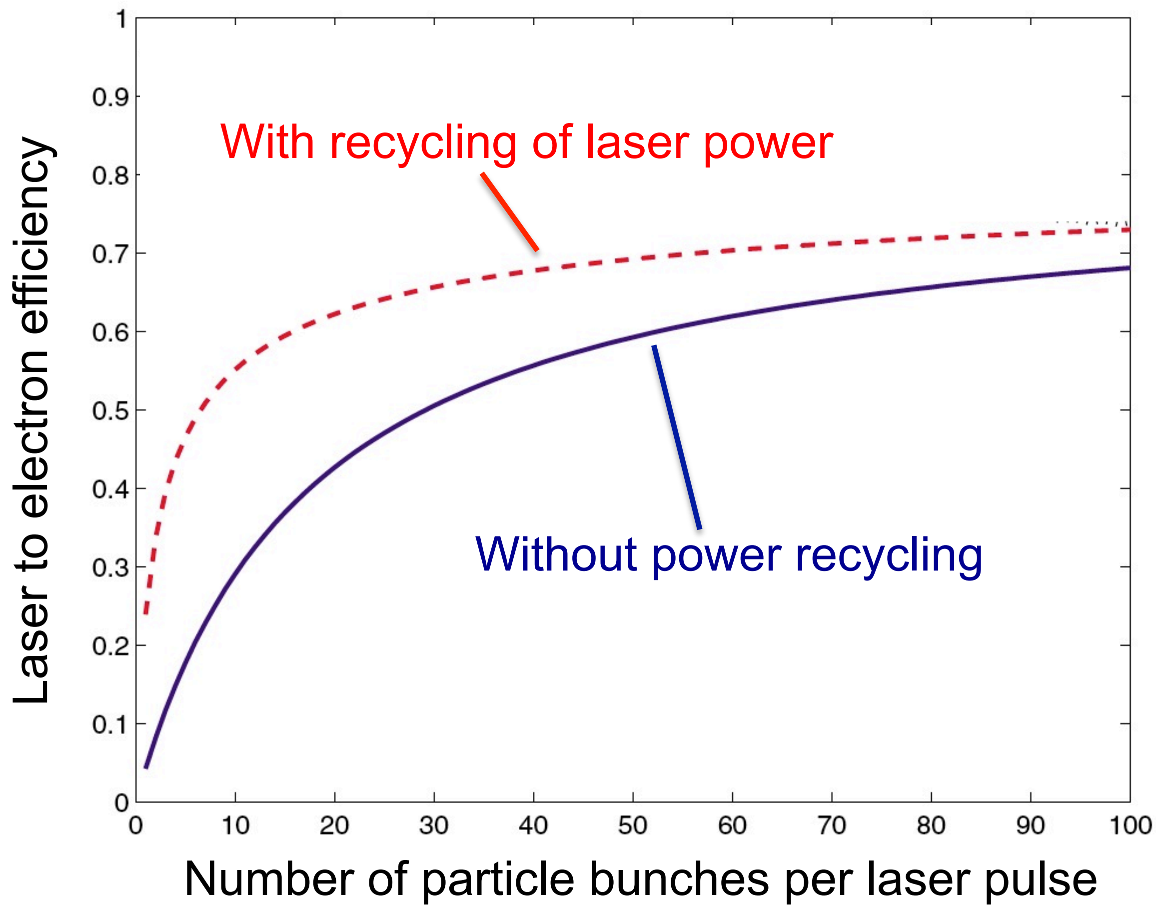
Example Parameters for DLA

Parameter	Symbol	Value	Units
Wavelength	λ	2	μm
Pulse Length	τ_{pulse}	100	fs
Characteristic Impedance	Z_C	19	Ω
Unloaded Gradient	G_0	1	GV/m
Loaded Gradient	G	0.5	GV/m
Optimal Charge	q_{opt}	27	fC
Optimal Single-bunch Efficiency	η_{opt}	2.3	%

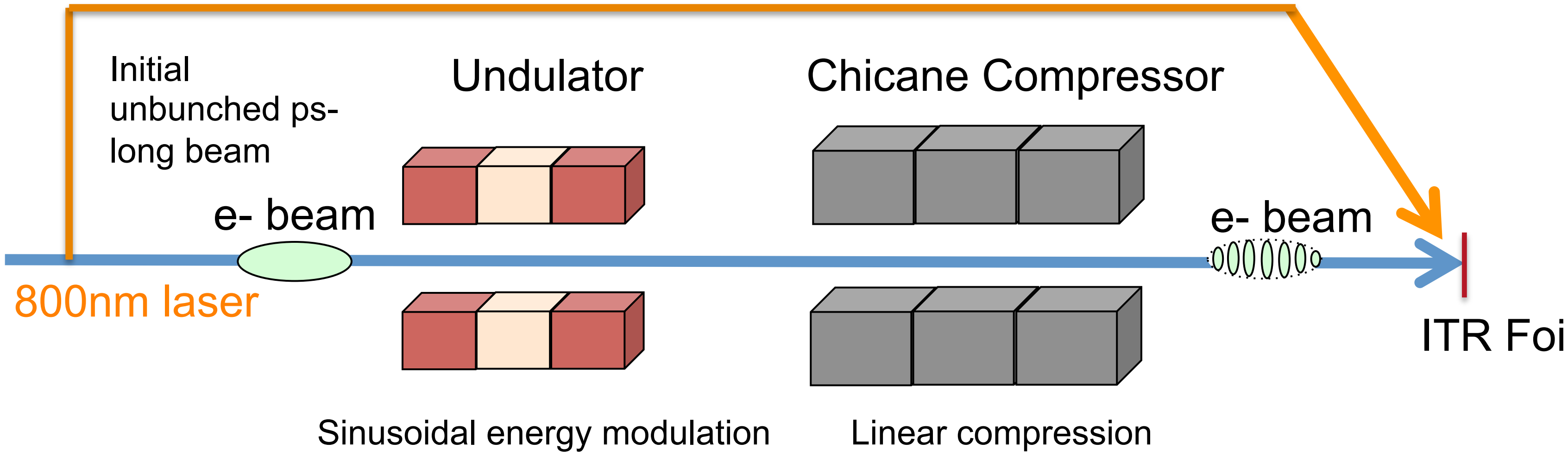
With particles in bunch trains, the field to electron power transfer efficiencies would approach 60%.

SLAC

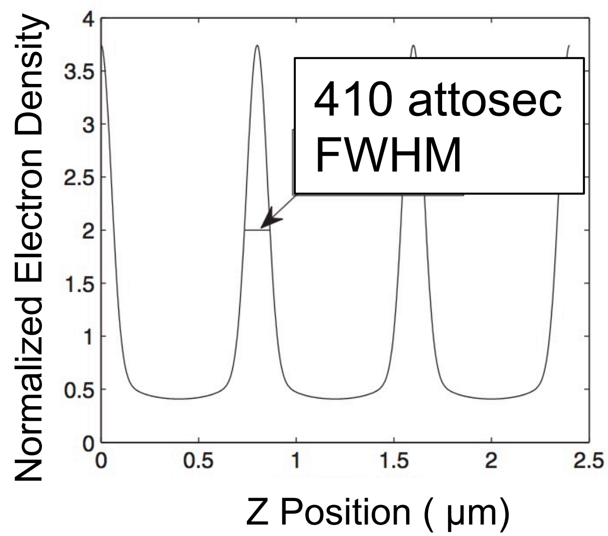
Na, Siemann, and Byer, PR-STAB **8**, 031301 (2005).

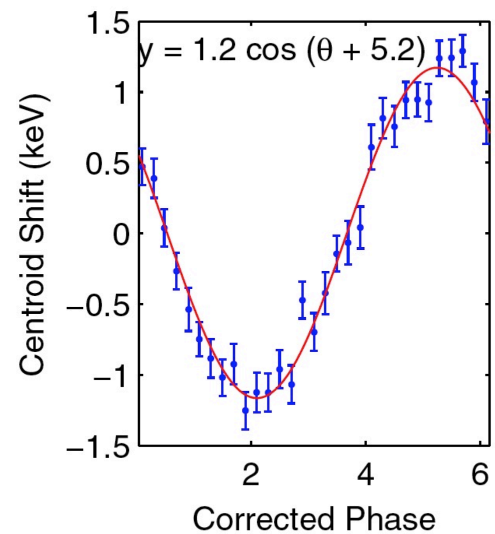


Microbunching and Net Acceleration: Prior Art



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

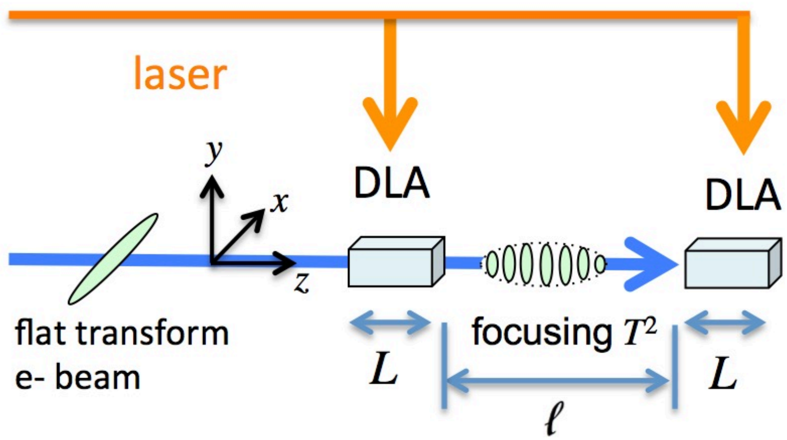




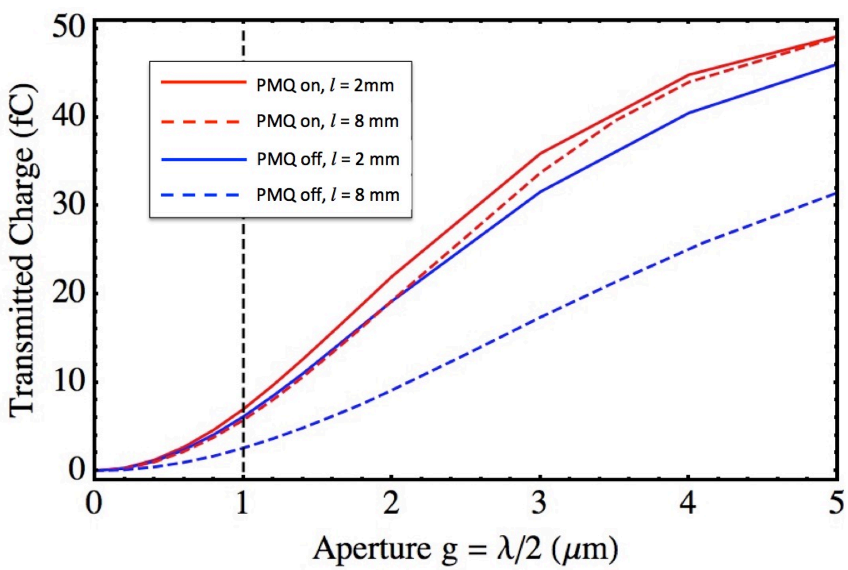
Sears, Colby, England, et al., PR-STAB **11**, 101301 (2008).

Microbunching and Net Acceleration: Future Experiments

SLAC



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
$\epsilon Nx,y$	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 → ϵ_{Ny} = 2 nm*
- PMQ focusing: (700 T/m) in drift l
- For bunching need l = 2mm @ 4 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).

Electron beam format for a DLA would be very different compared with RF accelerators

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	0.1 to 2 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

Confinement to the narrow channel of a DLA requires strong focusing

SLAC

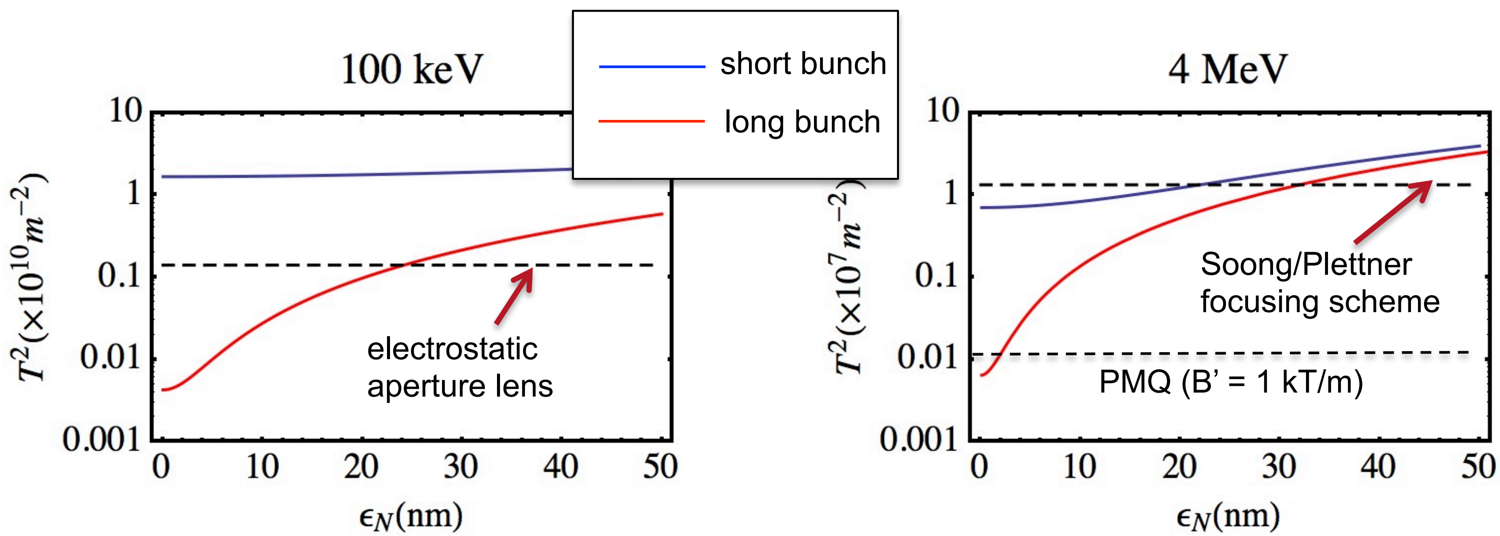
Parameter	Description	Units	Value
λ	wavelength	µm	2
σ	beam radius	µm	1
$T0$	initial kinetic energy	keV	100
Tf	final kinetic energy	MeV	4
Q	bunch charge	fC	4
τ	bunch duration	fs	0.1, 1000
ϵN	normalized emittance	nm rad	2
L	interaction distance	cm	2

Envelope equation

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

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 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

$13.5M / 5 years

Sub-Relativistic DLA experiments
Stanford: Harris, Solgaard
Erlangen: Hommelhoff

ACHIP

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

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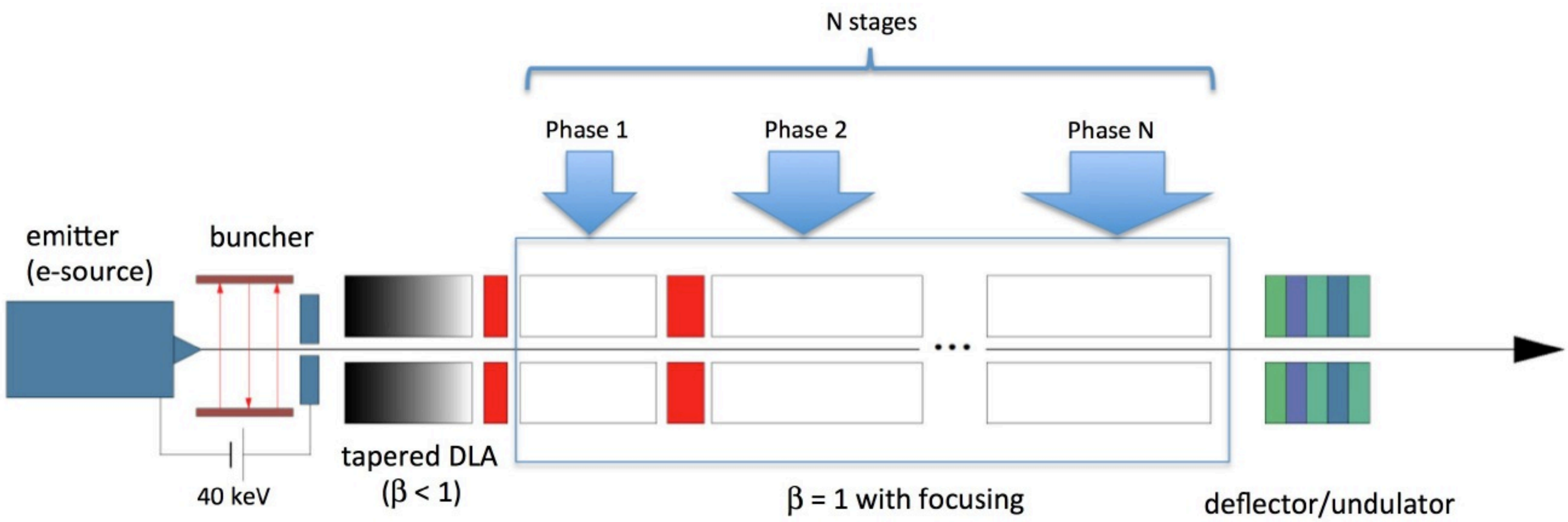
Components of a DLA Accelerator-on-a-Chip

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



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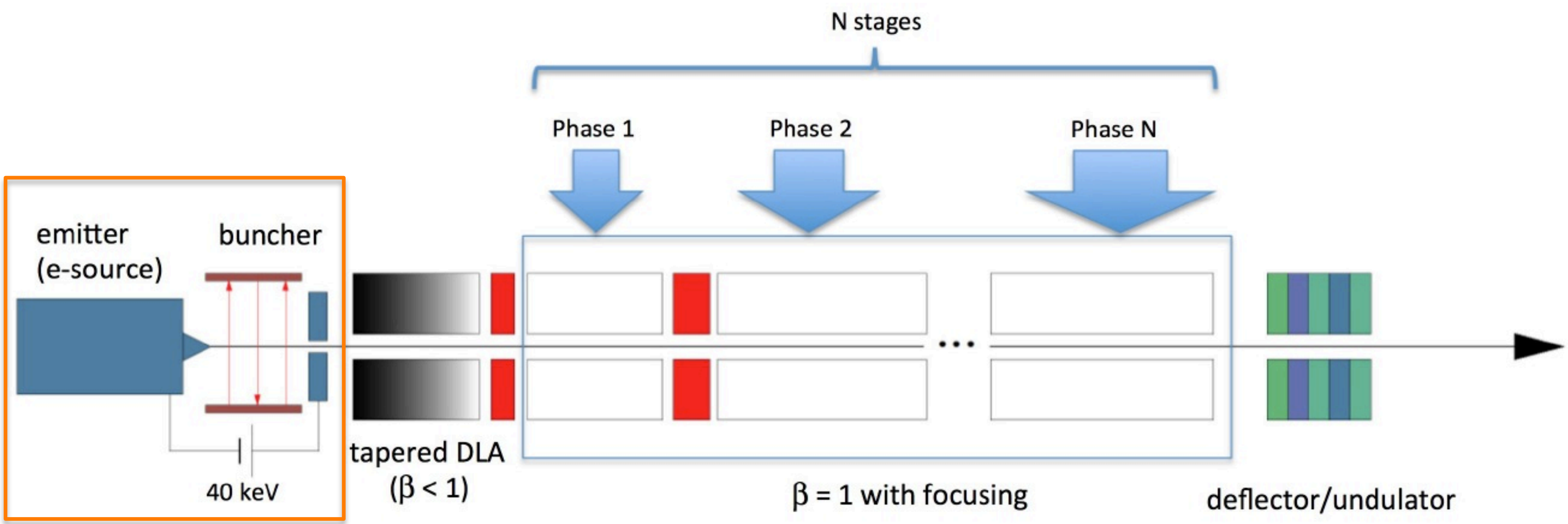
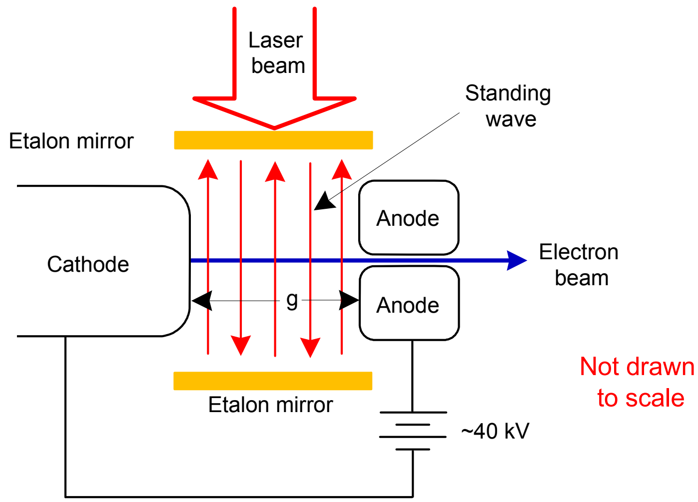
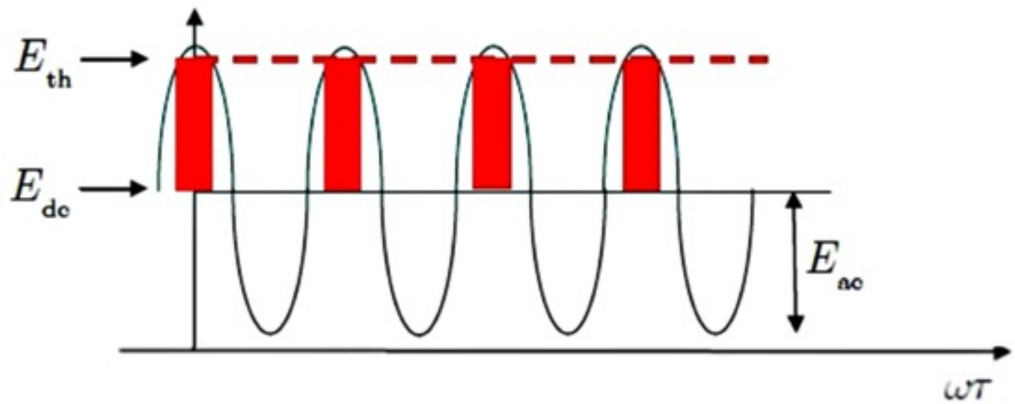


Concept for a laser-driven microbunched source



Sub-optical cycle bunched emission:



→ Laser beam travels through etalon with A-K gap located in center

- Polarization of laser beam is orthogonal to cathode surface
- Etalon creates standing-wave laser field distribution across cathode

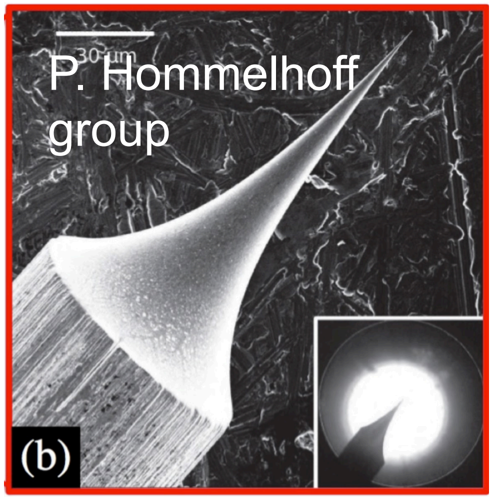
→ Laser field E_{AC} ~ 1/2 value needed for onset of field emission

- When laser field in same direction as DC field emission occurs
- When laser field in opposite direction as DC field emission suppressed

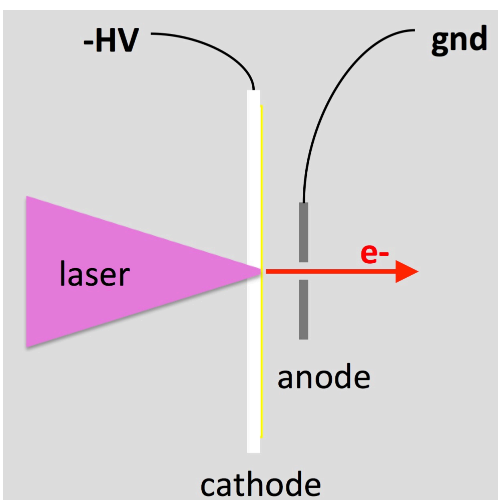
Schachter, Kimura, Ben-Zvi, “Ultrashort microbunch electron source,” AAC Proceedings (2014).

Flat Cathode and Tip Based Sources

Tip Source



Flat Cathode



Parameter	Units	Tip Source	Flat Cathode
Bunch Charge	fC	0.1	20
Min MacroBunch Duration	fs	100	100
Max Macrobunch Duration	fs	300	1000
Normalized Emittance	nm rad	0.1 nm rad	5 nm rad
Normalized Brightness*	A/(cm^2)	1e14	1.6e12
Virtual Source Size	nm	0.5	5000
Peak Current	nA	100	2e8

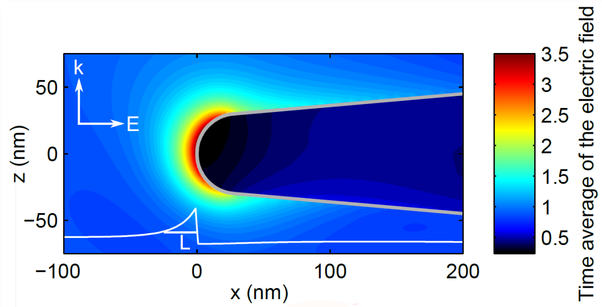
$$^{*}B_n = \frac{2I}{\epsilon_{x,n}\,\epsilon_{y,n}}$$

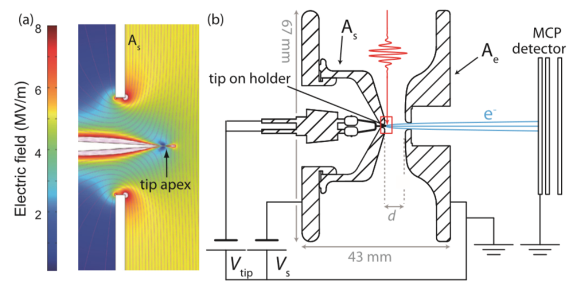
Note: work in progress; values in table not simultaneously achieved

Recent work at FAU Erlangen

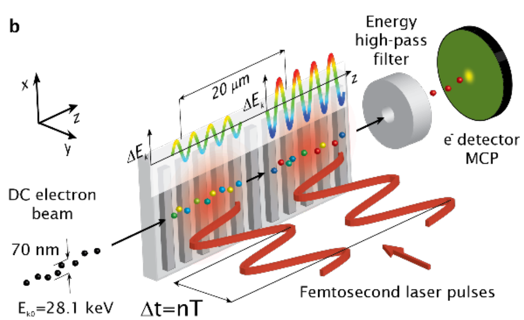
SLAC

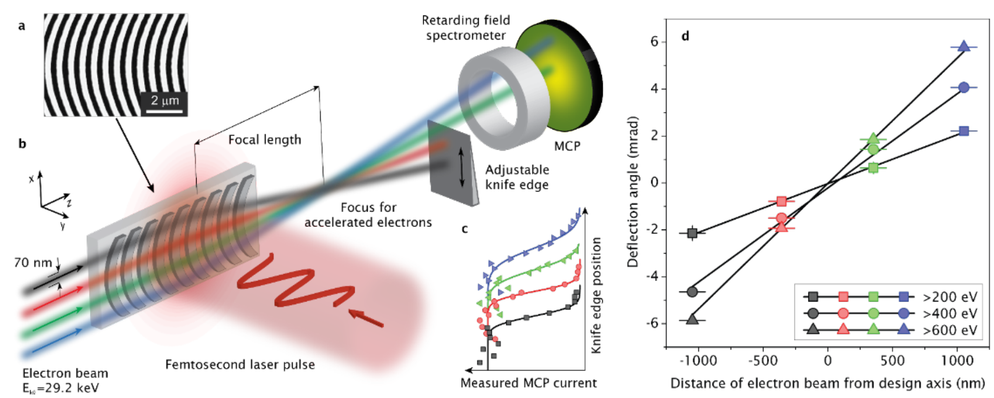
- Small virtual source radius, small emittance → **high brightness**
- Field enhancement on tip apex → **improvement of bunch dynamics**





- **Various DLA-related experiments**





J. McNeur et al., J. Phys. B 49, 034006 (2016).
M. Kozák et al., arXiv:1512.04394v1 (2015).
J. McNeur, et al., arXiv: 1604.07684 (2016).
M. Kozák et al., Opt. Lett. 41, 3435 (2016).

(for details see the next talk by M. Kozak)

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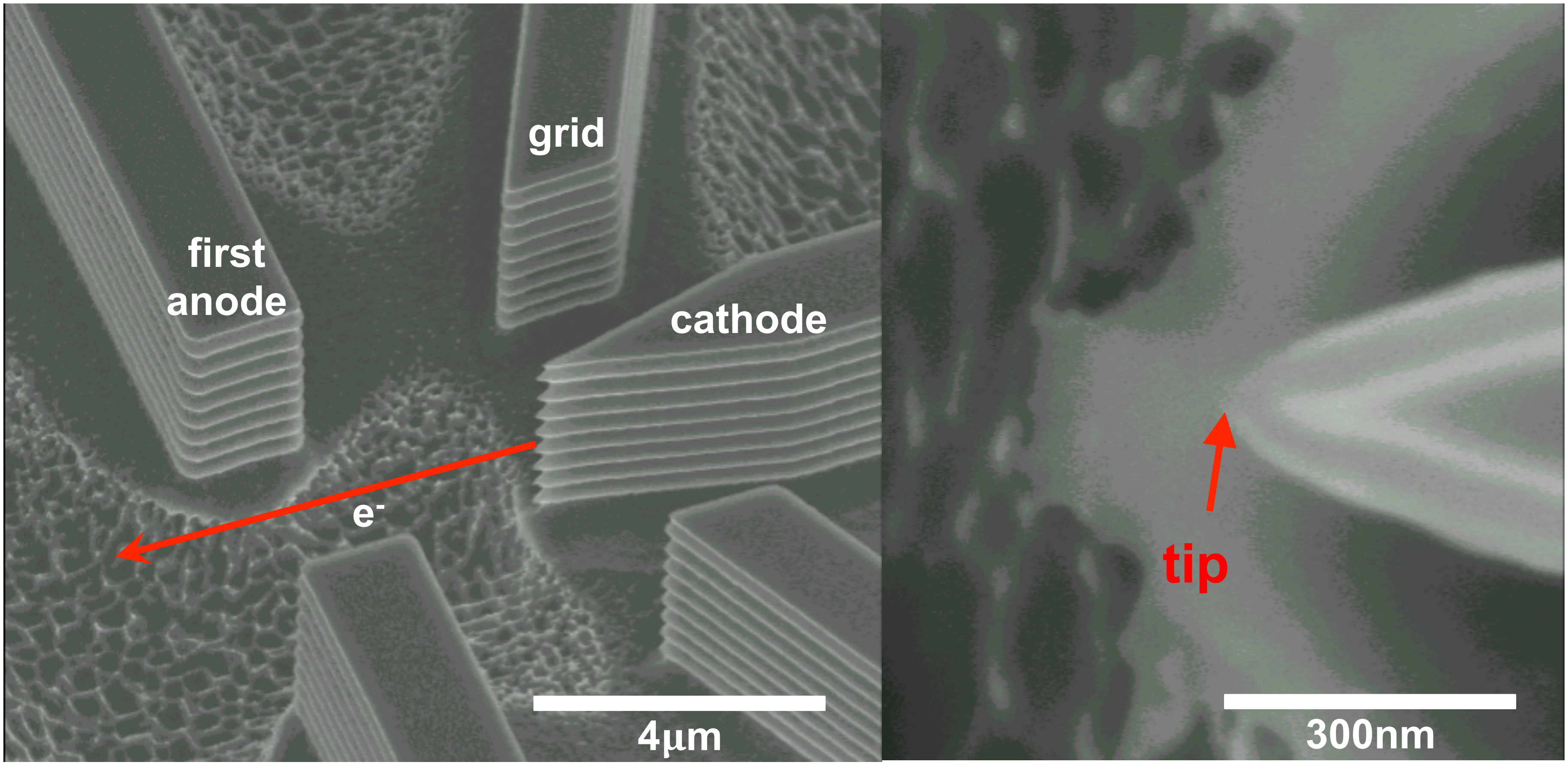
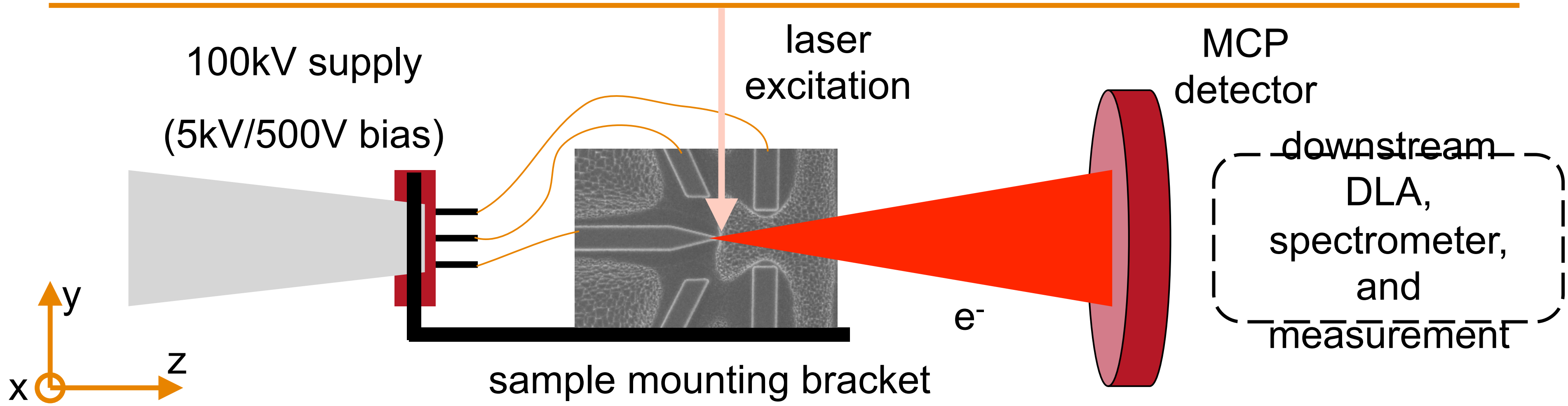
Lithographically-Defined Tip Array

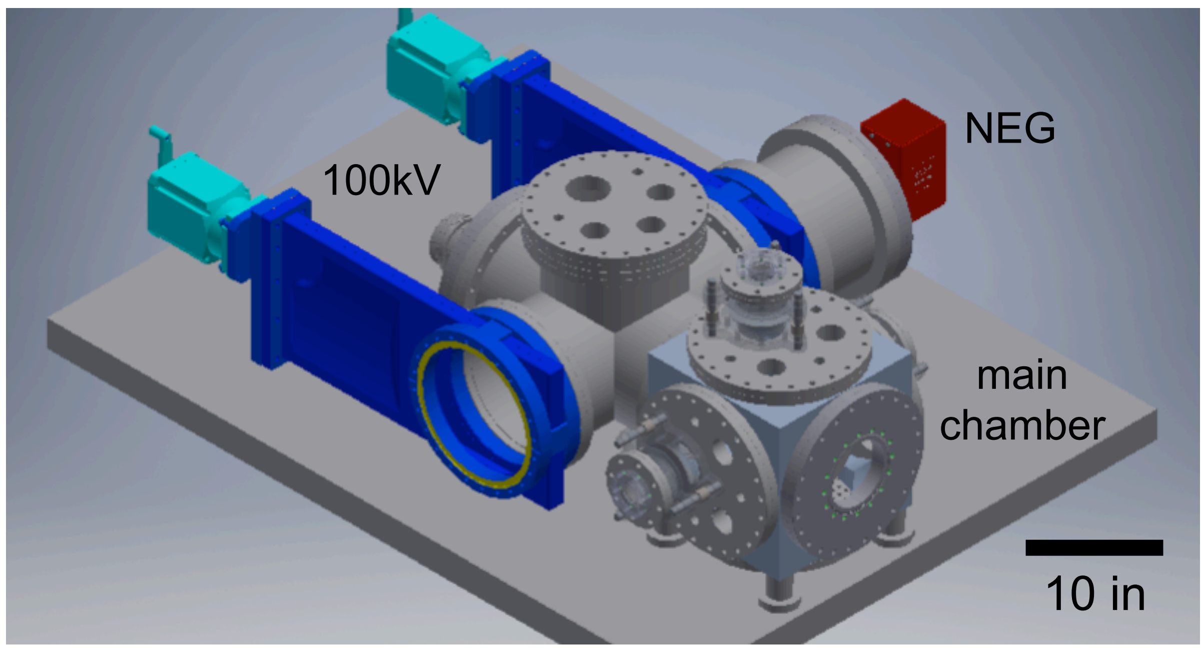


Si prototyping of line-emitter configuration (A. Ceballos, Stanford)

Integrated DLA Test Stand

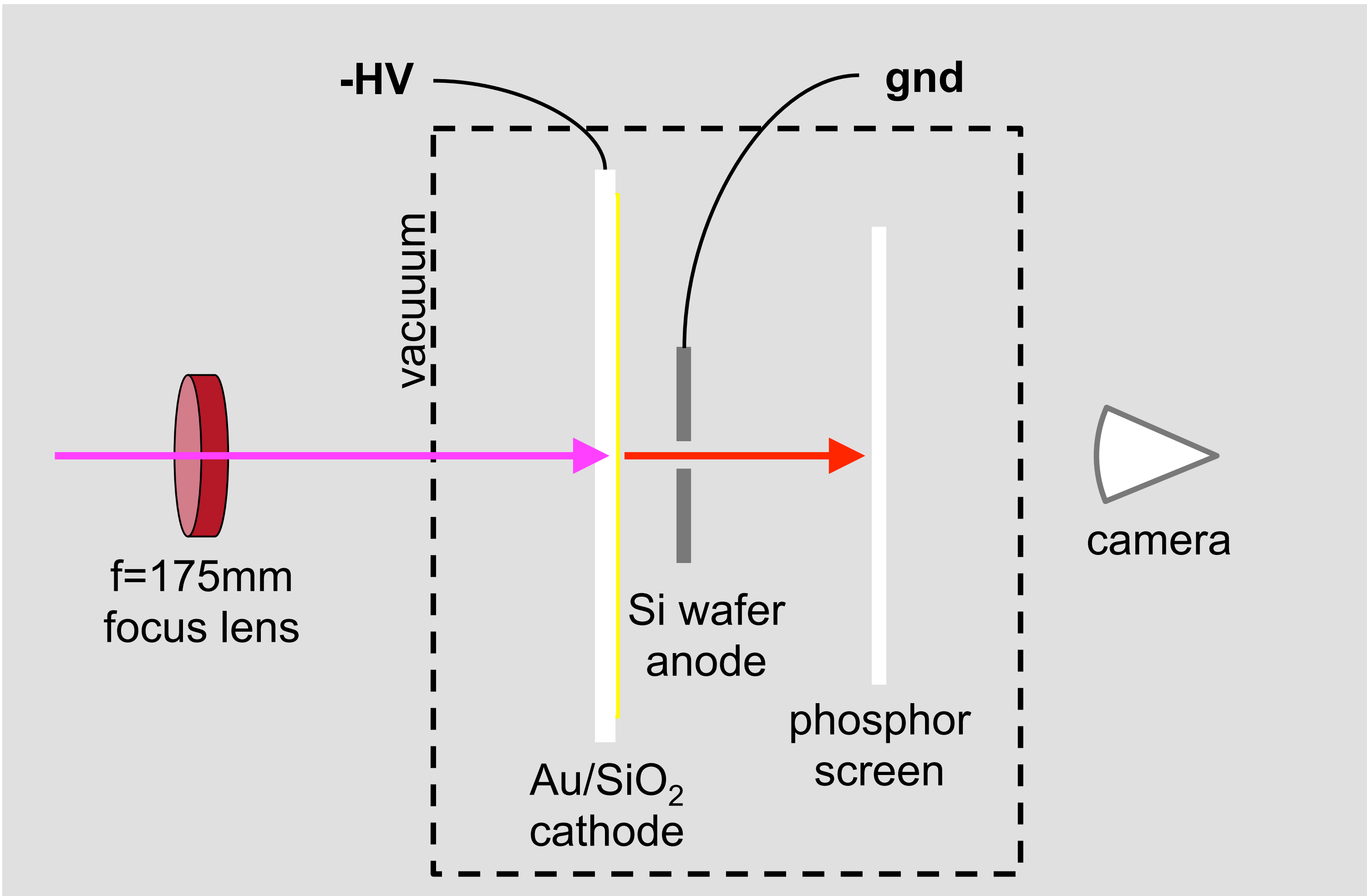


- new vacuum chamber for testing cathodes
- expandable for tip/DLA tests



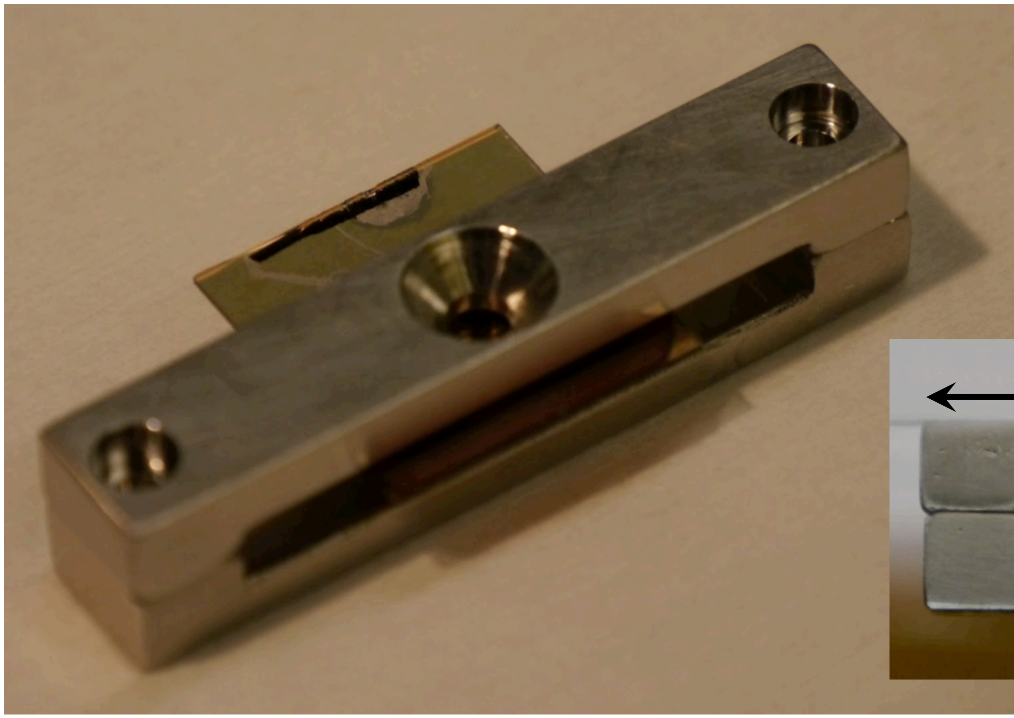
Solgaard group, Stanford U.

Flat Cathode Testing - Schematic



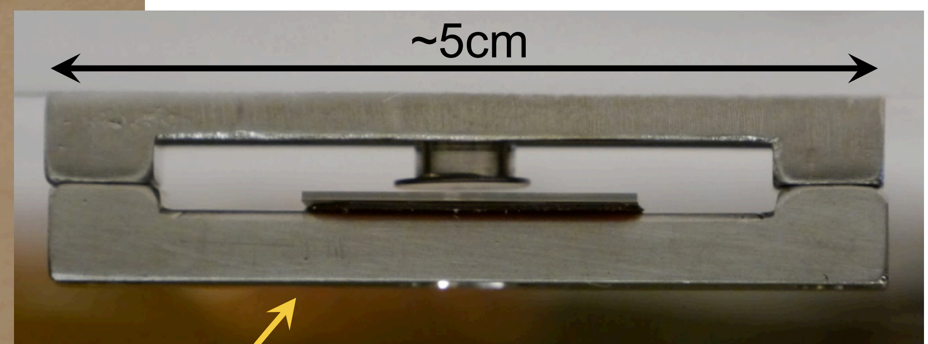
Solgaard group, Stanford U.

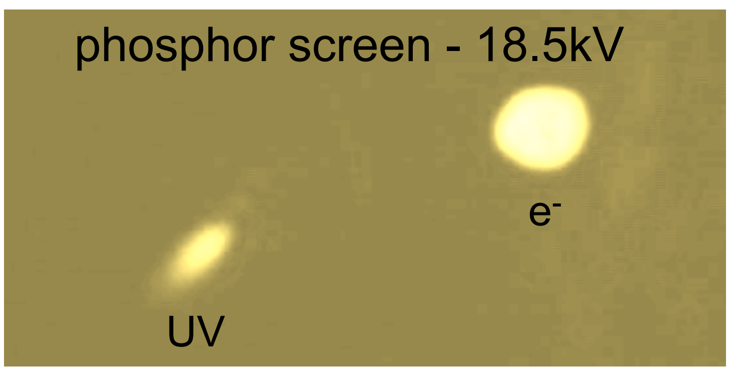
Flat Cathode Test Structures

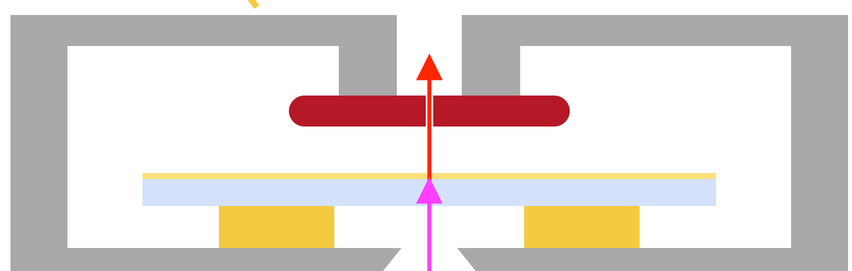


silicon
Au/F.S.
kapton
metal

Solgaard group, Stanford U.







Conclusions

SLAC

Significant progress in DLA in recent 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)

Compatible Electron Source Development

DLA requires low-charge (fC) bunches with nm-scale emittance
Optical microbunching needed for optimal efficiency
Wide aspect ratio of dual-grating type DLAs amenable to flat beam
Flat and tip-based field emission sources offer promise

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Thank You!

First ACHIP Collaboration Meeting, October 2015