Towards a Fully Integrated Accelerator on a Chip: Dielectric Laser Acceleration (DLA)

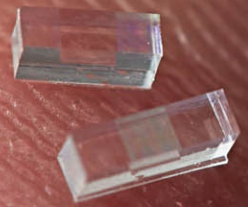
From the Source to Relativistic Electrons

Kent P. Wootton – SLAC National Accelerator Laboratory

8th International Particle Accelerator Conference

17th May 2017

Copenhagen, Denmark



Work supported by the U.S. Department of Energy under Contract no. DE-AC02-76SF00515, and the Gordon and Betty Moore Foundation under grant GBMF4744.

Accelerator on a Chip International Program (ACHIP)

GORDON AND BETTY MOORE FOUNDATION

PIs: R. L. Byer *(Stanford)*

& P. Hommelhoff *(FAU Erlangen)*

5 year programme (2015-2020)

- Stanford
- FAU Erlangen
- Purdue
- UCLA
- EPFL
- TU Darmstadt
- Hamburg
- Tech-X

In-kind contributions:

- SLAC
- DESY
- PSI

https://sites.stanford.edu/achip/

Motivating compact electron accelerators

- High gradients enable compact linear accelerators

1947

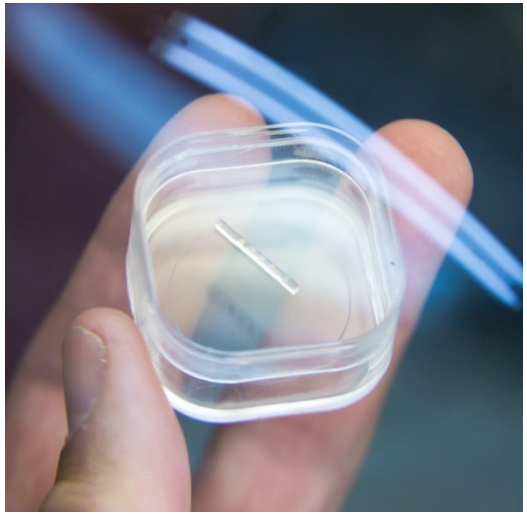
~MeV m^{-1}

SLAC Archives, ARC127

Applications:

- Radiotherapy
- Industrial/security
- Attosecond science

2013



~GeV m^{-1}

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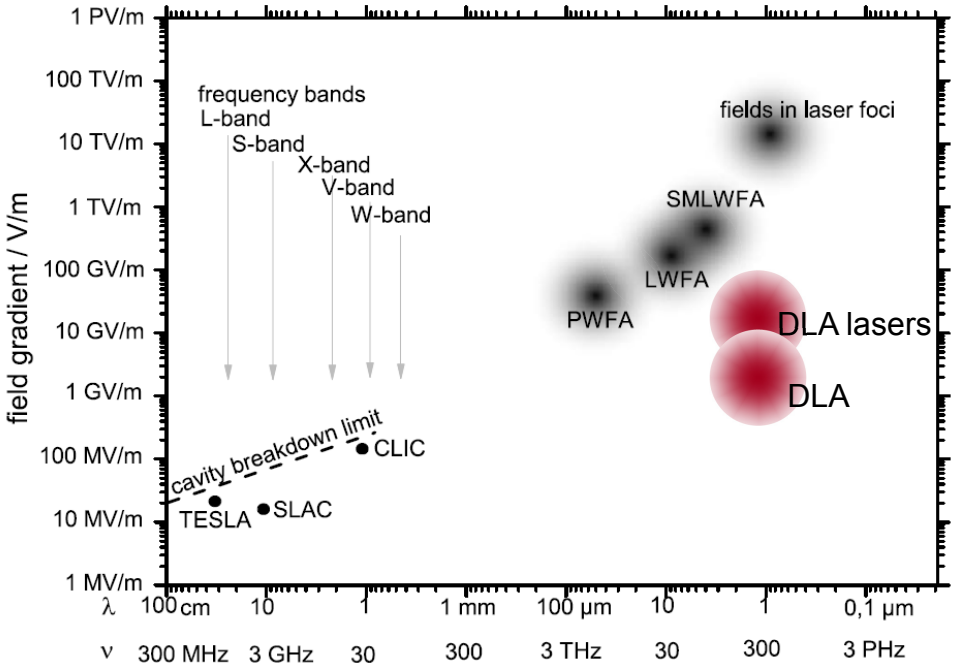
Laser driven accelerators

"Is there any point in considering the far infrared …?

Only if the breakdown conditions there are different, yielding spectacular values of E_0."

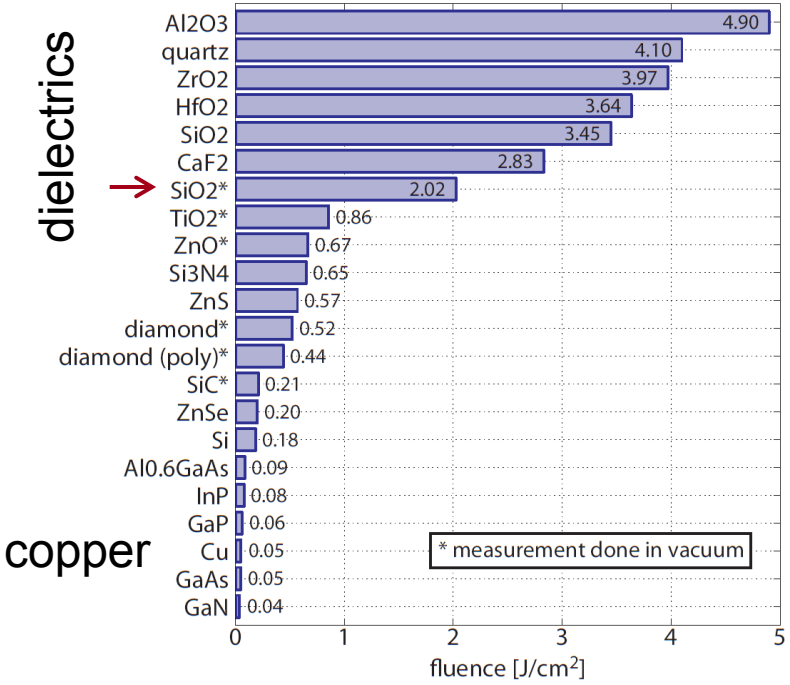
J. D. Lawson, *Laser Accelerators?*, Tech. Rep. RL-75-043, Rutherford Laboratory (Chilton, Oxon, UK, 1975).



B. Hidding, et al., *Phys. Plasmas*, 16, 043105 (2009).

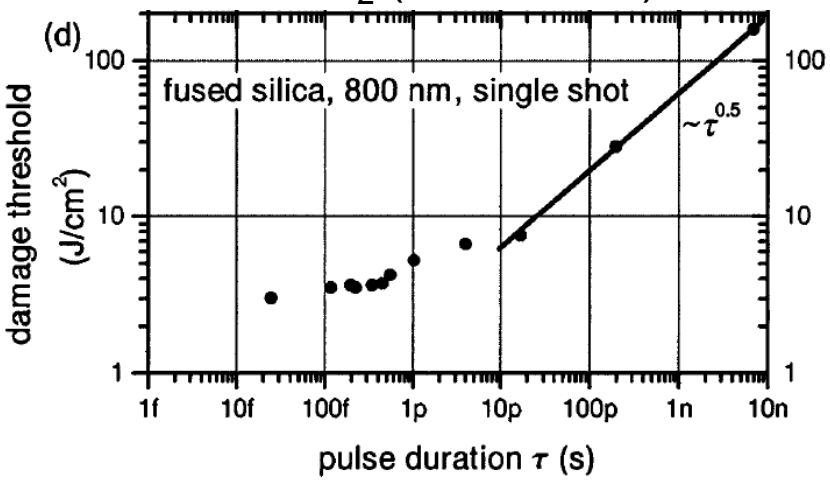
Material damage fluence and accelerating gradient

Damage threshold



K. Soong, et al., AIP Conf. Proc., 1507, p. 511 (2012)

SiO_2 (fused silica)

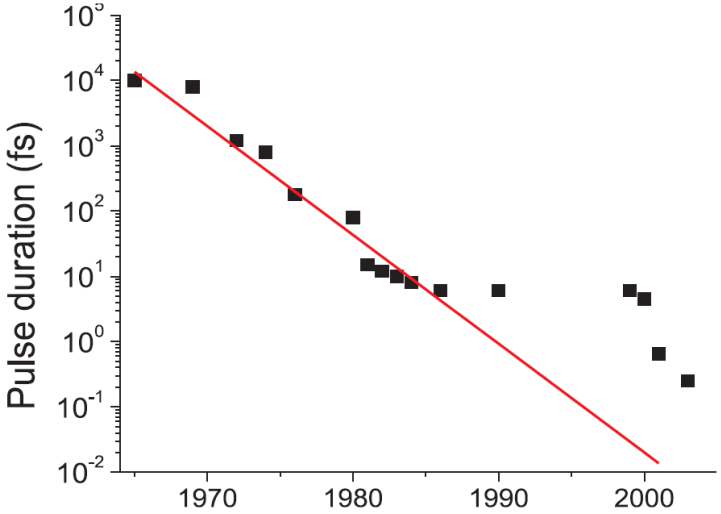


A.-C. Tien, et al., Phys. Rev. Lett., 82, p. 3883 (1999)

$$E = \sqrt{\frac{2FZ_0}{\tau}} \qquad F = 2\ \mathrm{J\ cm^{-2}},\ \tau = 100\ \mathrm{fs},\quad E = 12\ \mathrm{GV\ m^{-1}}$$

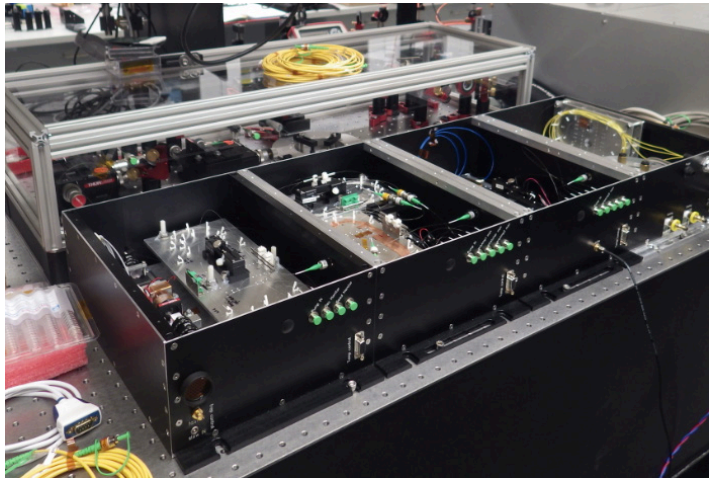
Lasers for accelerators

- fs-duration lasers commercially available



J. Levesque and P. B. Corkum, Can. J. Phys., 84, 1-18 (2006).

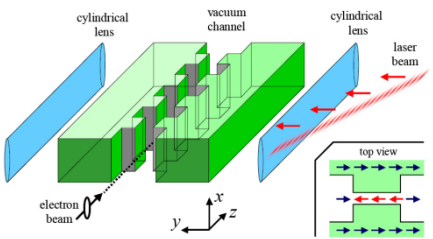
- Tabletop-scale fibre, regenerative amplifiers
- Pulse energy 0.1–5 mJ



Dielectric laser accelerator structures

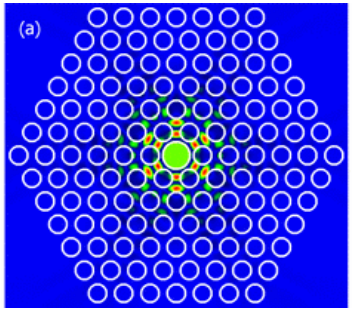
- Dielectric-vacuum structures
- UV and electron beam lithography

1-D



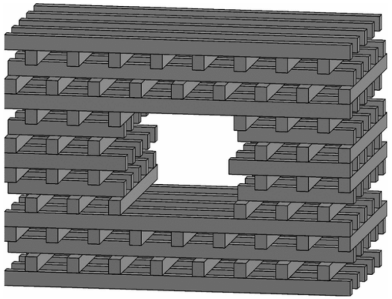
Plettner, et al., *PRSTAB*, 9, 111301 (2006)

2-D

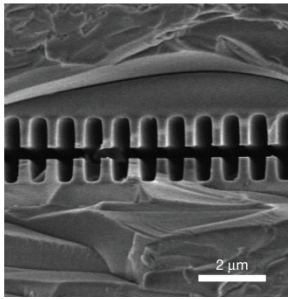


Noble, et al., *PRSTAB*, 14, 121303 (2011)

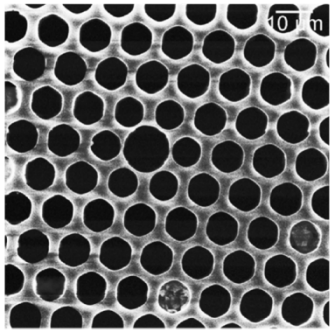
3-D



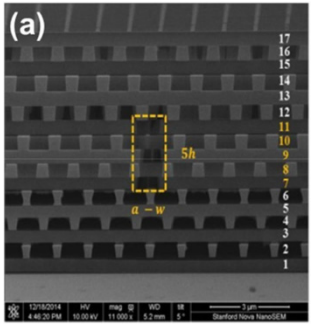
Cowan, *PRSTAB*, 11, 011301 (2008)



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

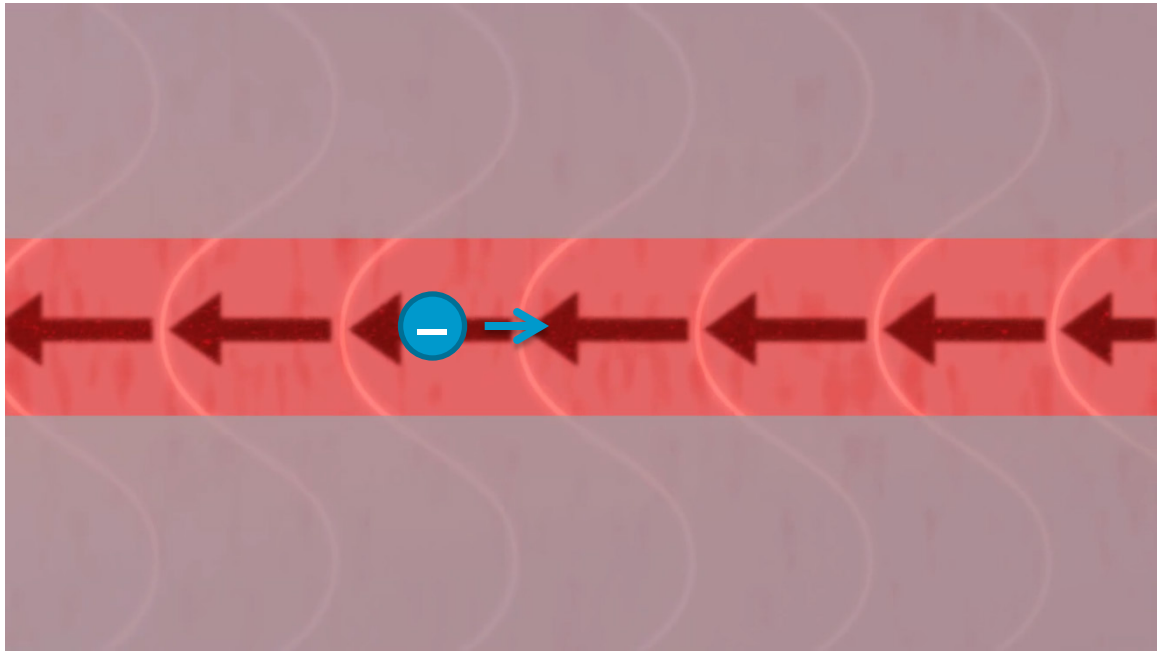


Noble, et al., *PRSTAB*, 14, 121303 (2011)

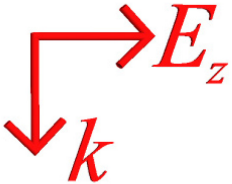


Wu, et al., *IEEE JSTQE*, 22, 4400909 (2016)

DLA – Acceleration

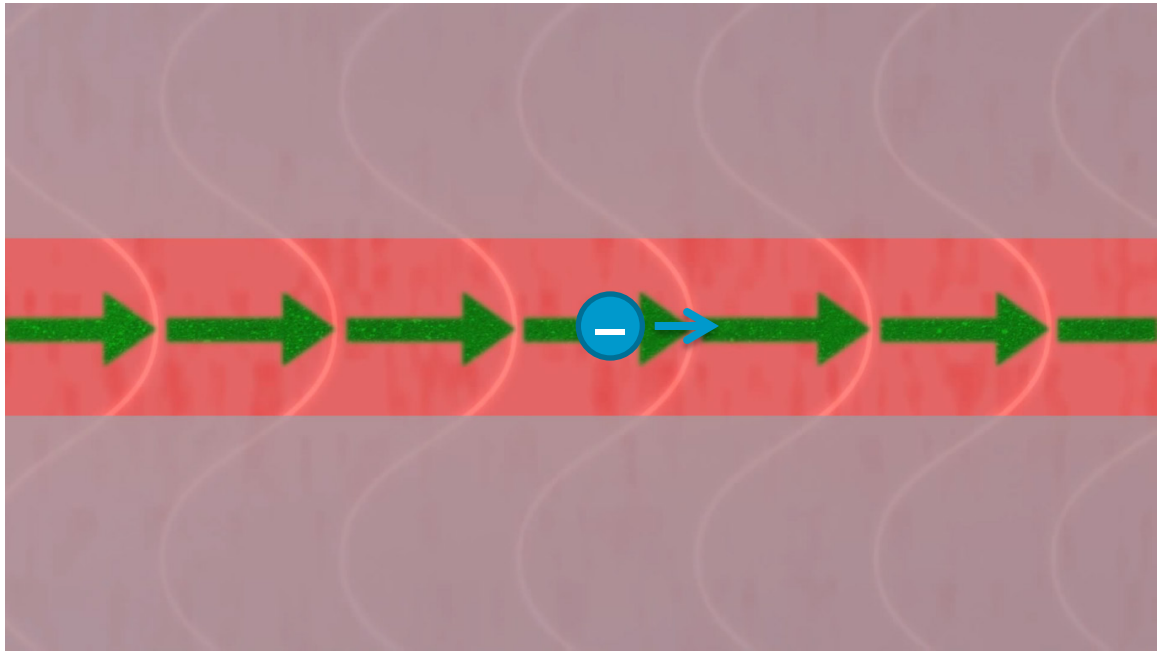


SLAC National Accelerator Laboratory https://youtu.be/V89qvy8whxY

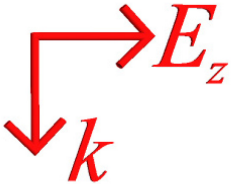


- Plane wave
- No acceleration

DLA – Acceleration



SLAC National Accelerator Laboratory https://youtu.be/V89qvy8whxY



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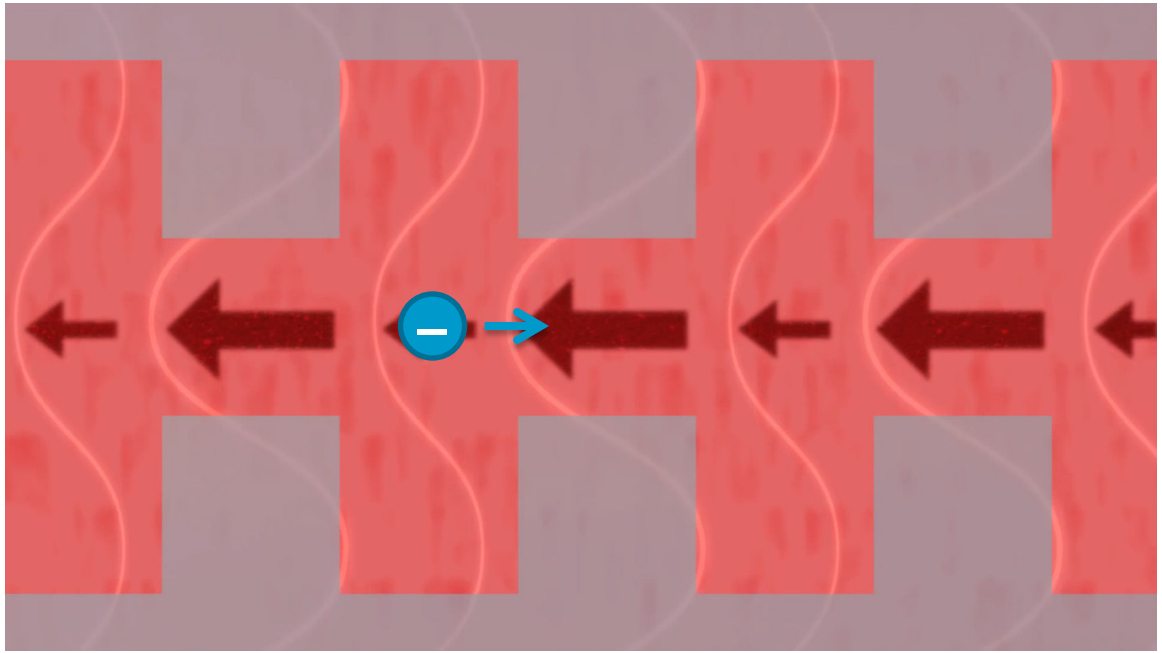
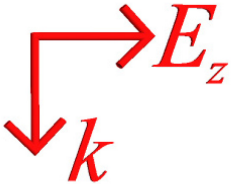
DLA – Acceleration

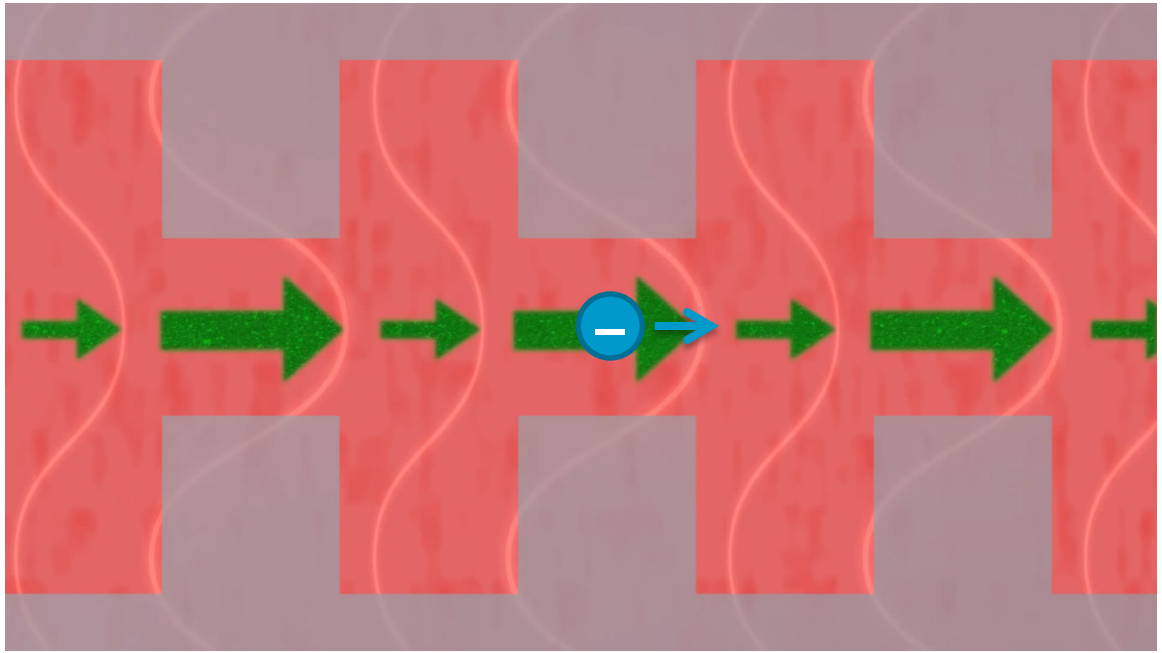


SLAC National Accelerator Laboratory https://youtu.be/V89qvy8whxY

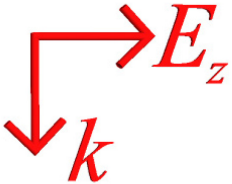


- Plane wave
- No acceleration
- Refractive index modifies phase
- Acceleration

DLA – Acceleration

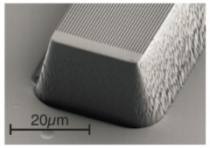
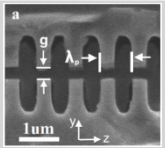
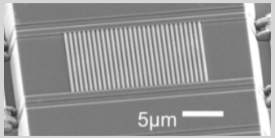
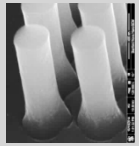


SLAC National Accelerator Laboratory https://youtu.be/V89qvy8whxY



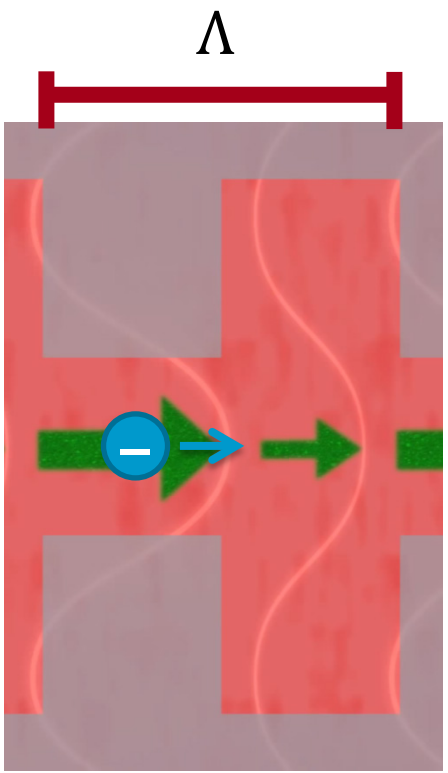
- Plane wave
- No acceleration
- Refractive index modifies phase
- Acceleration

Recent DLA Acceleration Experiments

	SiO_2 Single grating	SiO_2 Dual grating	Si Single Grating	Si Dual Pillars
				
Electron Energy	30 keV	8 MeV	96.3 keV	86.5keV
Relativistic β	0.33	0.998	0.54	0.52
Laser Energy	160 nJ	150 μJ	5.2 nJ	3.0 nJ
Pulse Length	110 fs	40 fs	130 fs	130 fs
Interaction Length	11 um	~20 um	5.6 um	5.6 um
Peak Laser Field	2.85 GV/m	3.5 GV/m	1.65 GV/m	~1.1 GV/m
Max Energy Gain	0.275 keV	20 keV	1.22 keV	2.05 keV
Max Acc Gradient	25 MeV/m	0.85 GV/m *	220 MeV/m	370 MeV/m
G_{max}/E_p	~0.01	~0.18	~0.13	~0.4

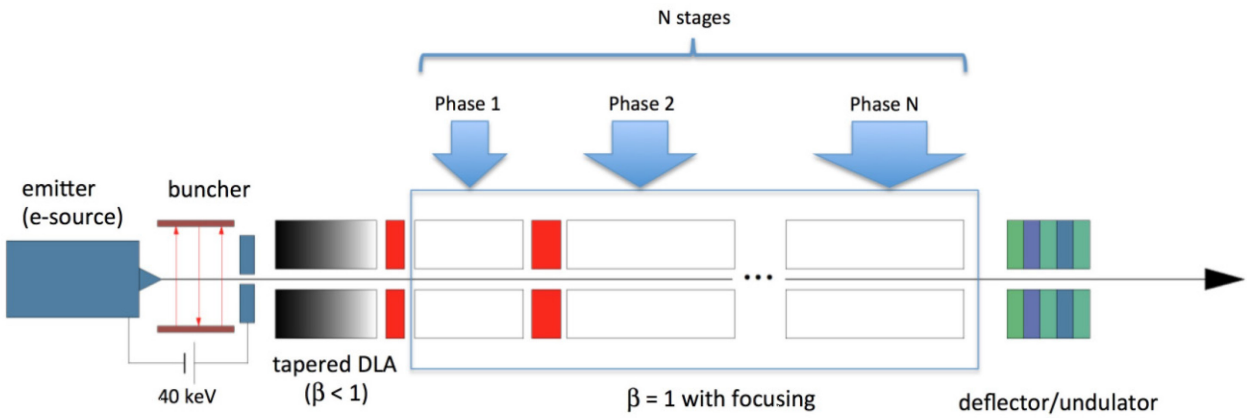
* Preliminary

Fundamental accelerator properties



- Structure period $\Lambda = h\beta\lambda,\ \beta = \frac{v}{c},\ h = 1, 2, 3, \ldots$
- $\lambda = 800\ \mathrm{nm}$, optical cycle → 2.7 fs
- $\lambda = 2\ \mu\mathrm{m}$, optical cycle → 6.7 fs
- Bunches occupying a few degrees of laser phase would be sub-femtosecond duration
- *What is needed for a tabletop source of relativistic (~1 MeV) attosecond bunches?*

Accelerator 'in-a-shoebox'

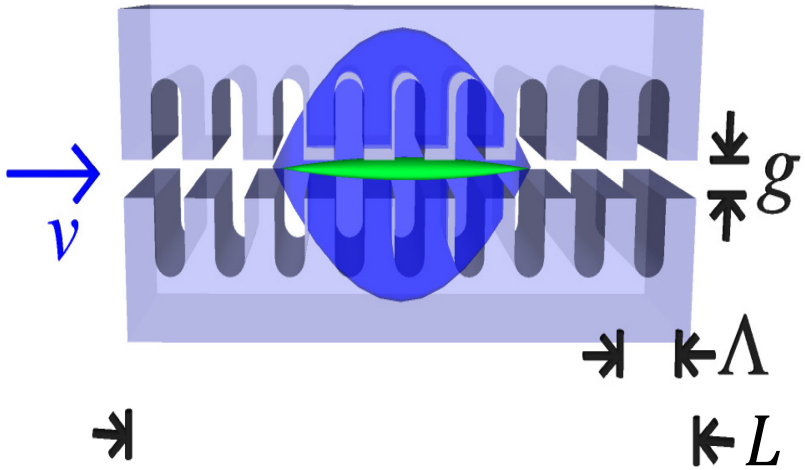


R.J. England, et al., AIP Conf. Proc. 1777, 060002 (2016).

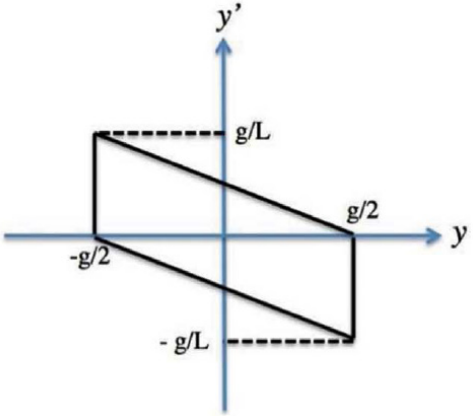
- Electron source
- Buncher
- Transverse focussing
- Accelerating structures
- Laser delivery
- Diagnostics/control

Electron source emittance requirements

- Admittance of structure between two focussing elements
- Assuming $\lambda = 2\ \mu\mathrm{m}$
  - Gap $g \approx \lambda/2$



Wootton, et al., Opt. Lett., 41, p. 2696 (2016)

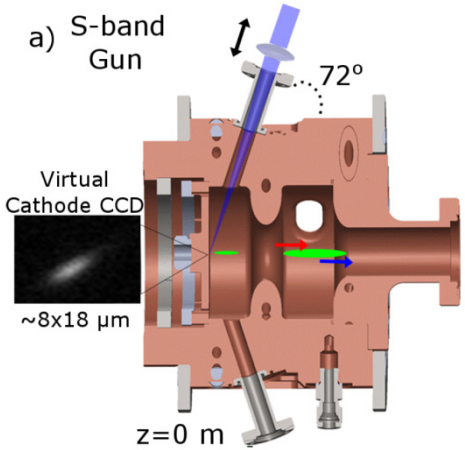


A. Ody, et al., NIMA, (2016, in press)

Parameter	Value
L	$1\ \mathrm{mm}$
g	$1\ \mu\mathrm{m}$
Admittance	$1\ \mathrm{nm\ rad}$

Low emittance electron sources

Flat RF photocathode

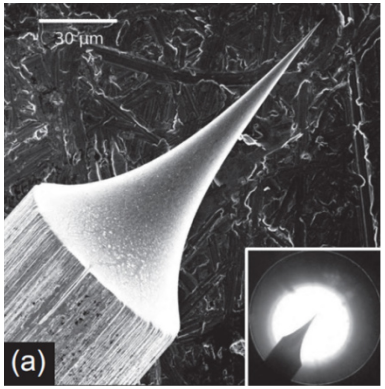


$\varepsilon_n = 5$ nm rad

$\varepsilon = 0.3$ nm rad

J. Maxson, et al., Phys. Rev. Lett., 118, p. 154802 (2017)

Tungsten nanotip



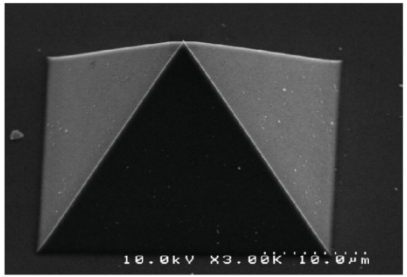
M. Krüger, PhD thesis, LMU-München (2013)

$\varepsilon_n = 1$ nm rad

$\varepsilon = 0.08$ nm rad

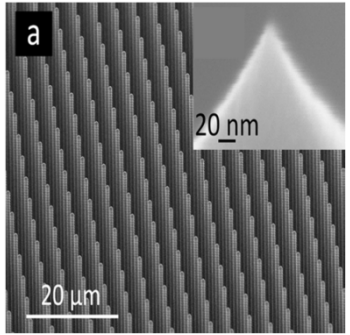
J. McNeur, et al., J. Phys. B: At. Mol. Opt. Phys., 49, 034006 (2016)

Diamond nanotip

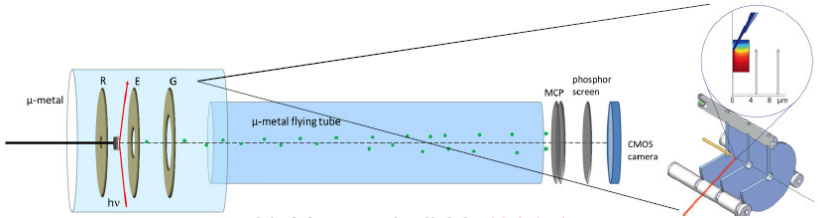


E. Simakov, et al., AIP Conf. Proc., 1812, 060010 (2017)

Silicon nanotip



H. Ye, et al., Ultrafast Phenomena, 09.Wed.P3.37 (2014)

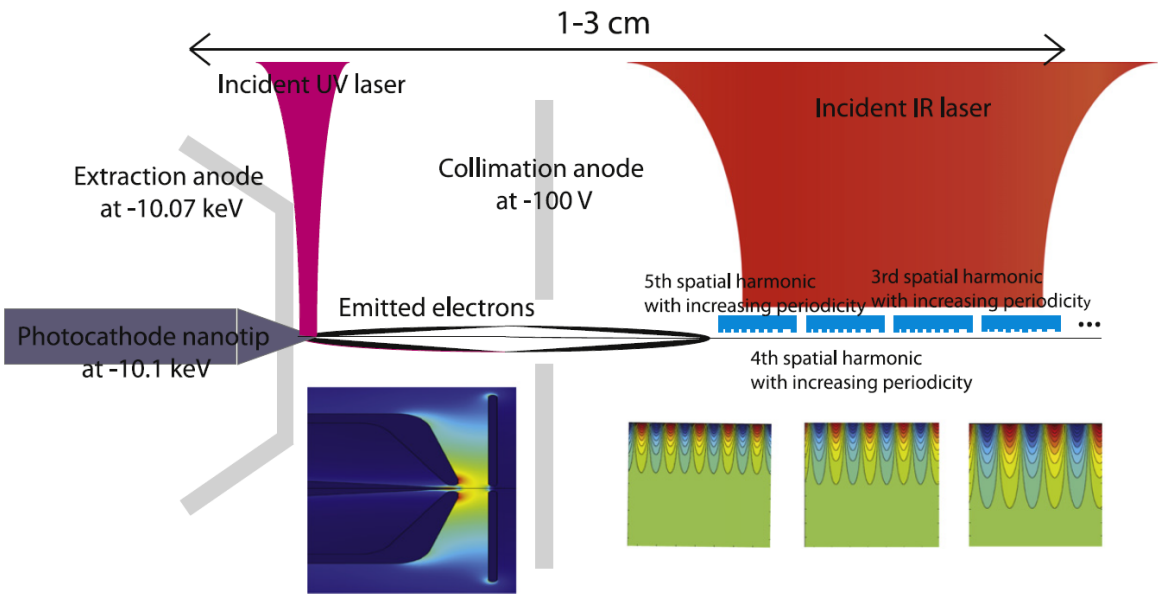


H. Ye, et al., ibid, (2014)

DC photocathode electron gun

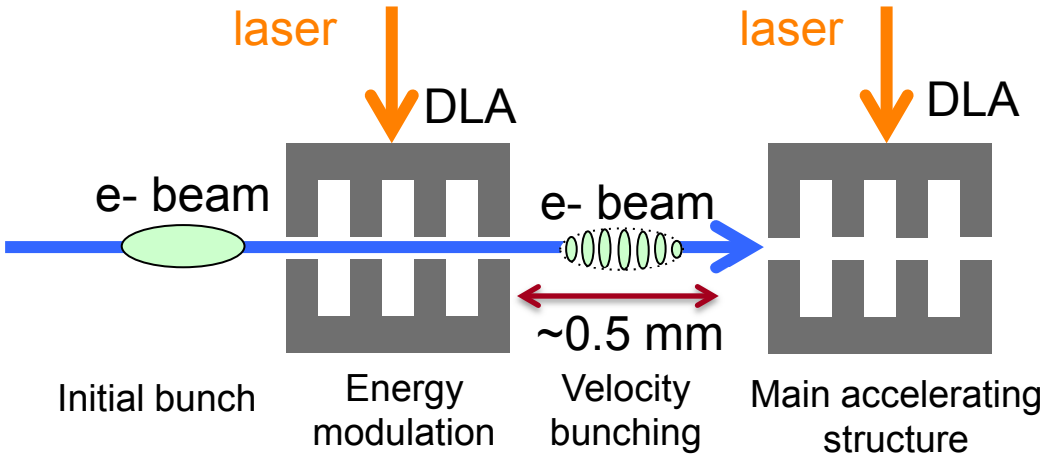
- Photo-assisted field-emission source
- Cathode geometry may be flat or nanotip
- UV and IR laser pulses produced from same source
- Few nm rad transverse emittance
- Electron bunch length

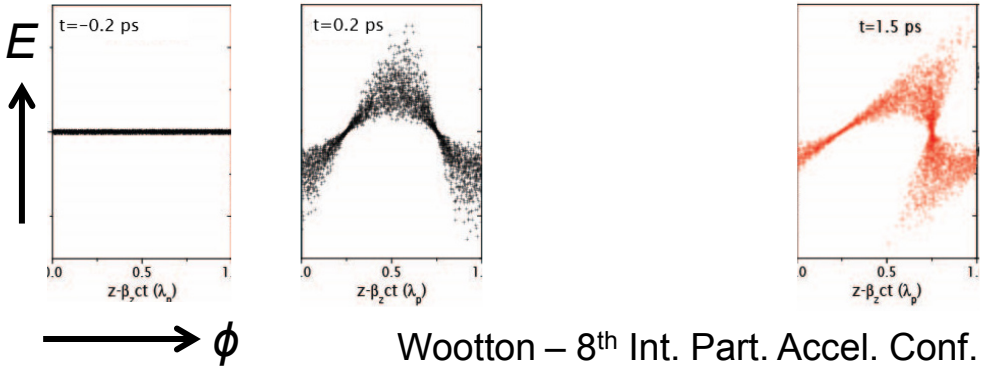
  $\tau \approx 100 - 300$ fs
  - Needs microbunching

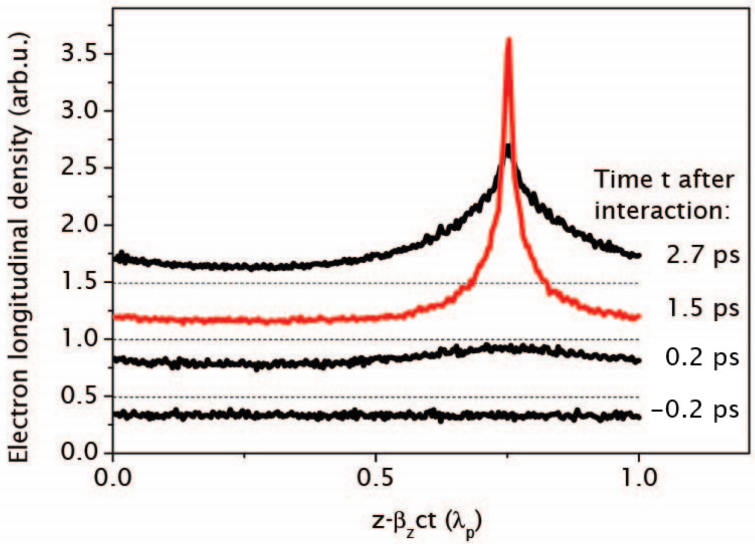


J. McNeur, et al., J. Phys. B: At. Mol. Opt. Phys., 49, 034006 (2016)

Buncher – Velocity microbunching



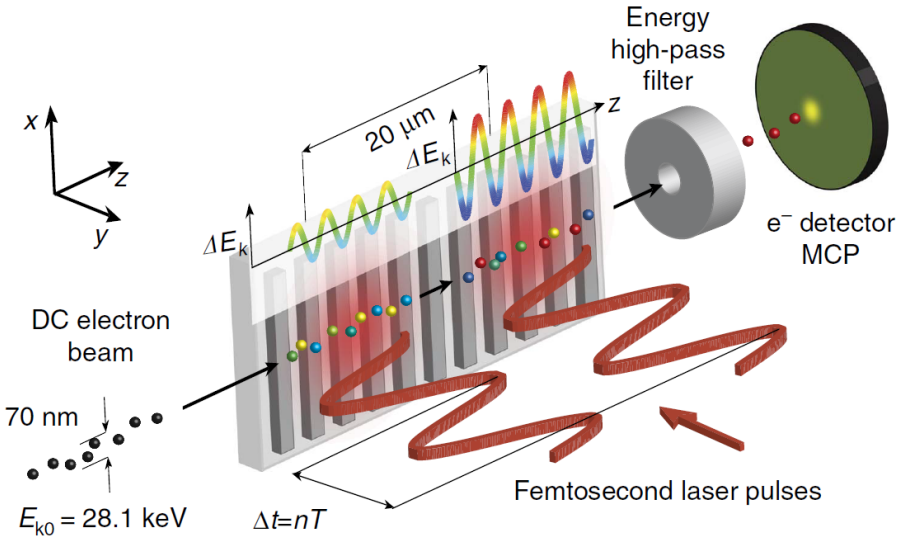


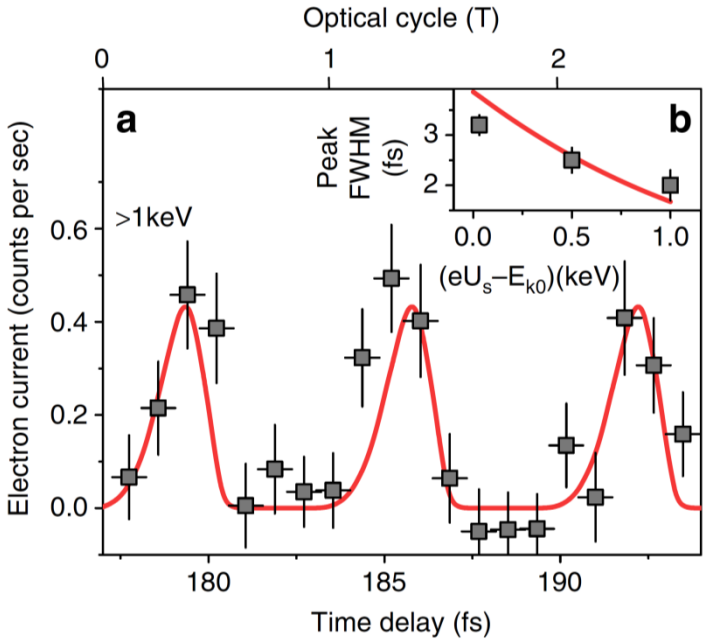


Wootton, McNeur, Leedle, Rev. Accel. Sci. Technol., 9, p. 105 (2016)

A. Ody, et al., NIMA, (2016, in press)

Buncher – optical phase-controlled acceleration





M. Kozák, et al., Nat. Commun., 8, 14342 (2017)

Acceleration – sub-relativistic structures

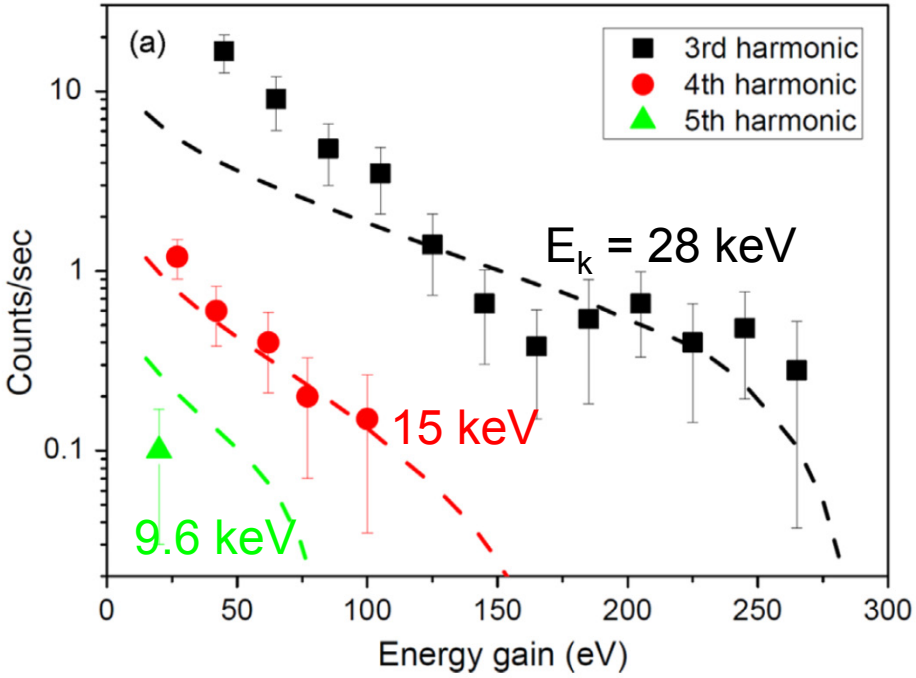
- Synchronicity condition between electron and accelerating mode

$$\Lambda = h\beta\lambda$$

$$\beta \ll 1?$$

- Accelerate low energy electrons using high-order mode $h = 3, 4, 5, \ldots$

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



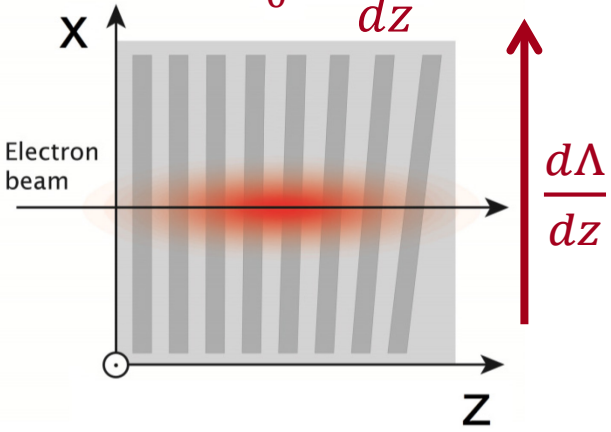
J. McNeur, et al., NIMA, 829, 50 (2016)

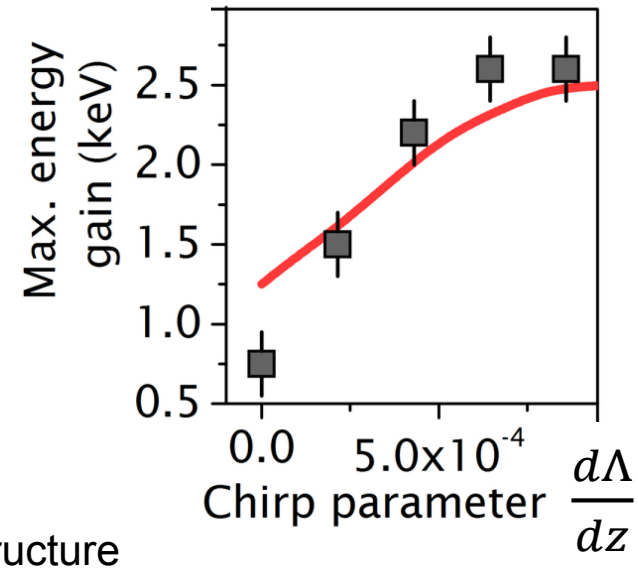
Sub-relativistic structures

Increasing chirp to velocity match accelerating electrons

J. McNeur, et al., arXiv: 1604.07684 (2016).

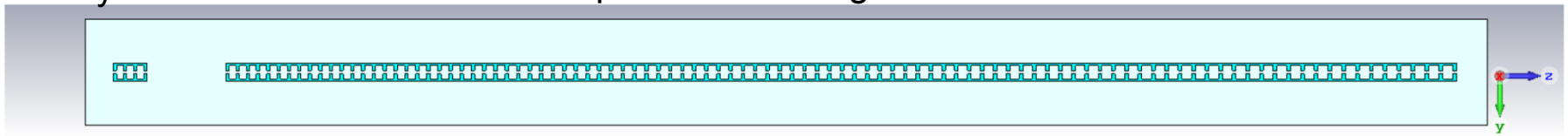
$$\Lambda = \Lambda_0 + \frac{d\Lambda}{dz} z$$





Velocity buncher

Chirped accelerating structure

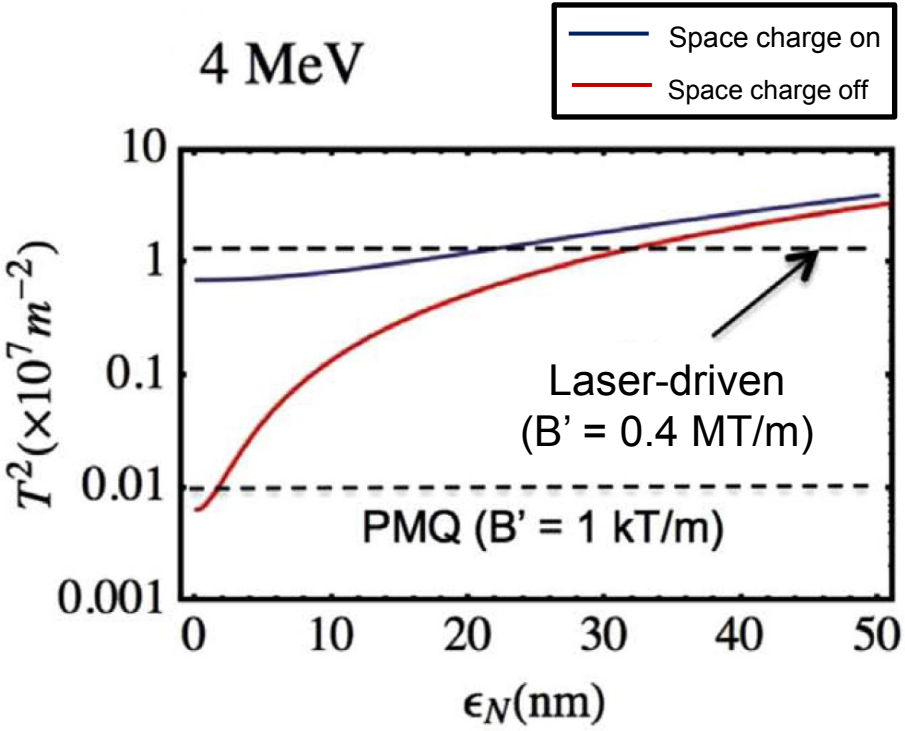


U. Niedermayer, WEPVA003 (this afternoon)

Focussing requirements for demonstration

$$B' = T^2 \frac{\beta\gamma m_e c}{q_e}$$

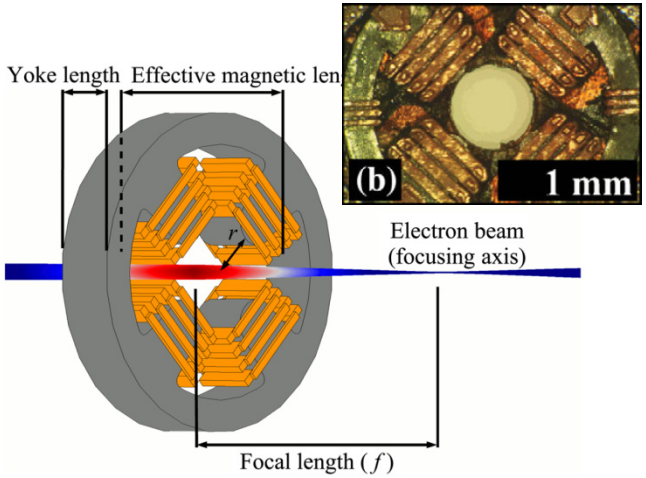
- PMQs may be viable for low emittance beams without space charge
- Long term, require MT m^{-1} transverse gradients for transport of high peak charge microbunches
  - Laser driven focussing structures



A. Ody, et al., NIMA, (2016, in press)

Focussing structures – magnetic

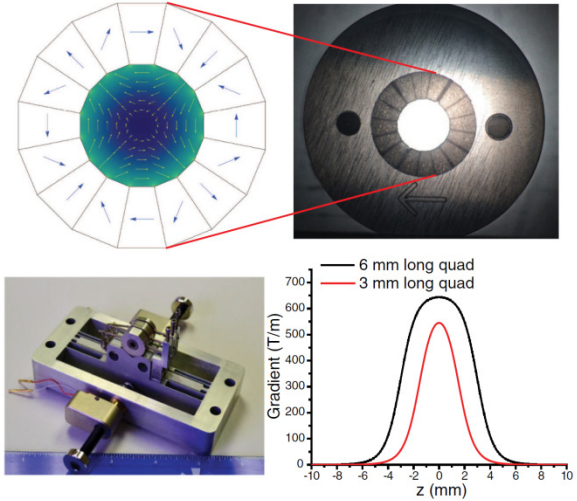
Micro electromagnetic quads



J. Harrison, et al., Phys. Rev. ST Accel Beams, 18, 023501 (2015)

200 T m^{-1}

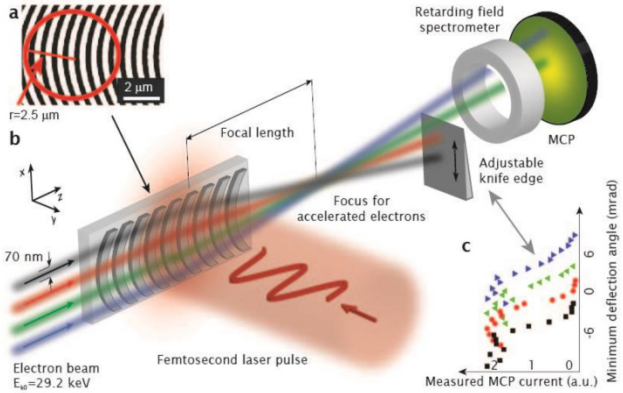
Permanent magnet quads (PMQ)

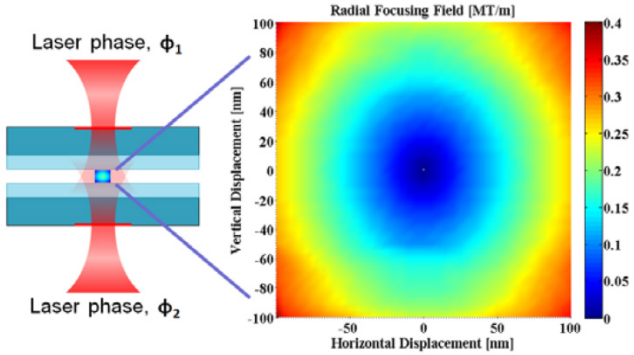


D. Cesar, et al., Phys. Rev. Lett., 117, 024801 (2016)

700 T m^{-1}

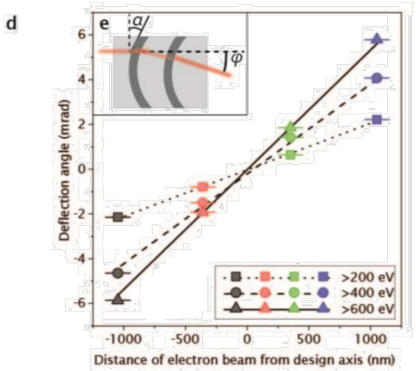
Focussing structures – laser-driven



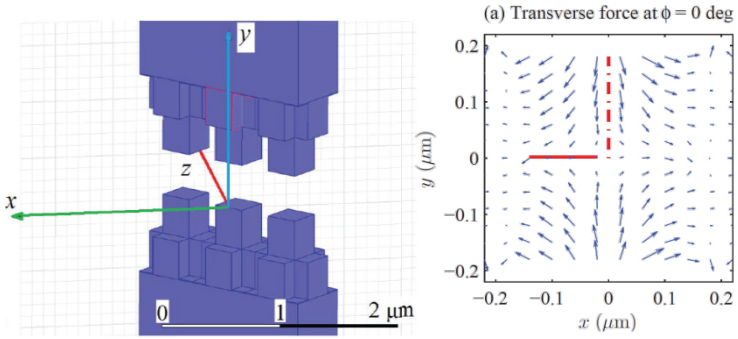


T. Plettner, et al., J. Mod. Opt., 58, p. 1518 (2011).
K. Soong, et al., AIP Conf. Proc. 1507, p. 516 (2012).

0.4 MT m^{-1}



J. McNeur, et al., arXiv: 1604.07684 [physics.acc-ph] (2016).



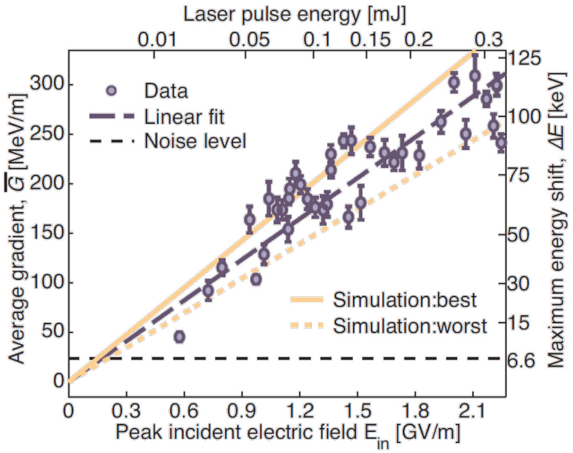
K.P. Wootton, et al., AIP Conf. Proc. 1812, 060001 (2017).

2 MT m^{-1}

High-gradient structures – previous experiments

SLAC, 2013 ($\beta \approx 1$)

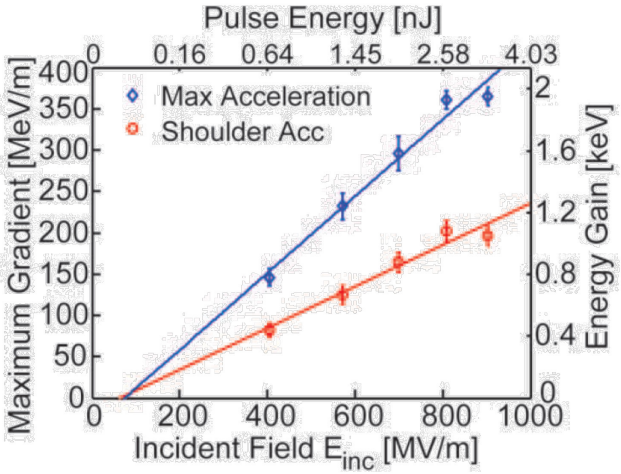
$310 \pm 21\ \mathrm{MV\ m^{-1}}$



Peralta, et al., Nature, 503, p. 91 (2013)

Stanford ($\beta \approx 0.5$)

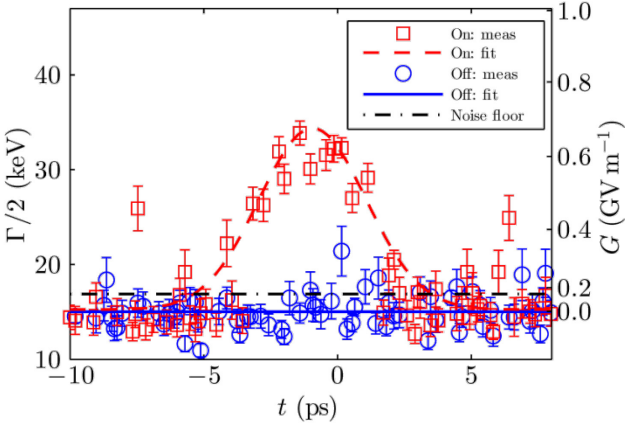
$376 \pm 40\ \mathrm{MV\ m^{-1}}$



Leedle, et al., Opt. Lett., 40, p. 4344 (2015)

SLAC ($\beta \approx 1$)

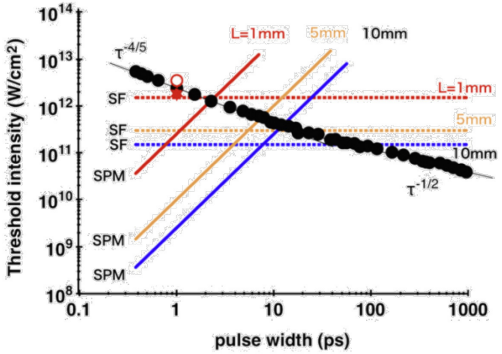
$690 \pm 100\ \mathrm{MV\ m^{-1}}$



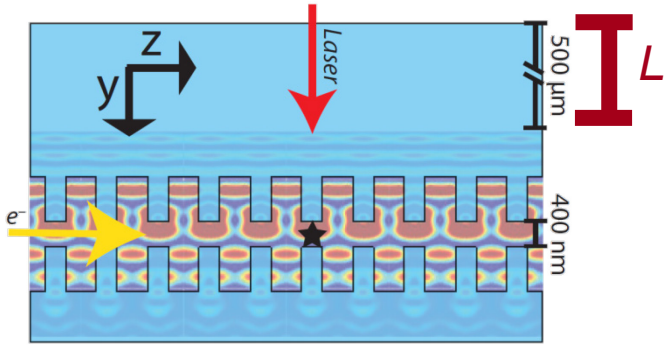
Wootton, et al., Opt. Lett., 41, p. 2696 (2016)

High-gradient structures – Nonlinear effects

At high fields, self focussing and self-phase modulation distort phase

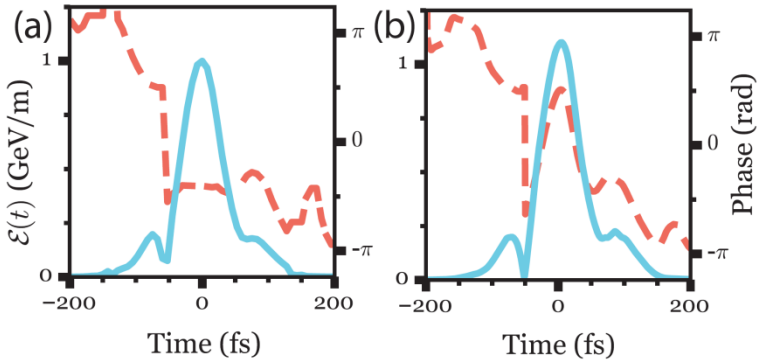


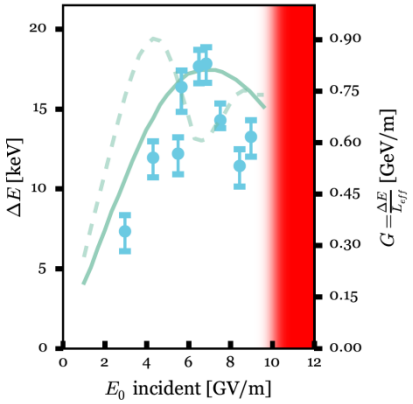
Koyama, et al., J. Phys. B: At. Mol. Opt. Phys., 47, 234005 (2014)



Laser pulse before structure

Laser pulse after 500 µm SiO_2



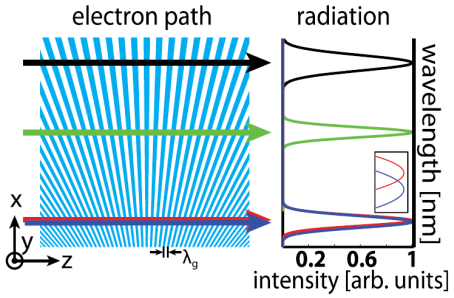


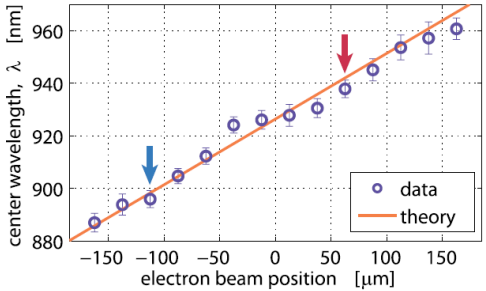
Results in saturation of energy gain

D. Cesar, et al., (in preparation)

Diagnostics/control

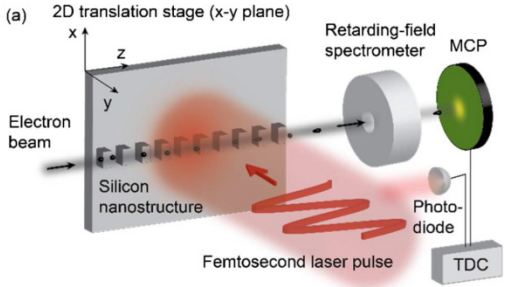
Beam transverse position

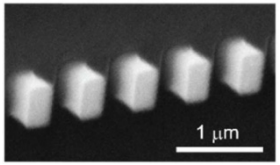




K. Soong, et al., Opt. Lett., 39, 4747 (2014)

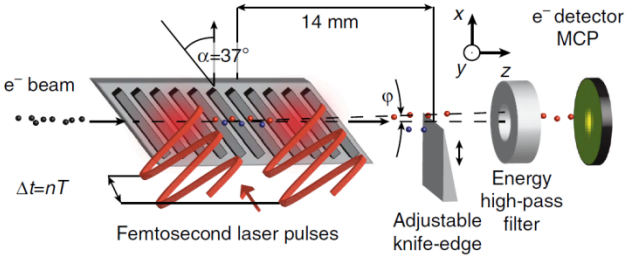
Temporal + spatial

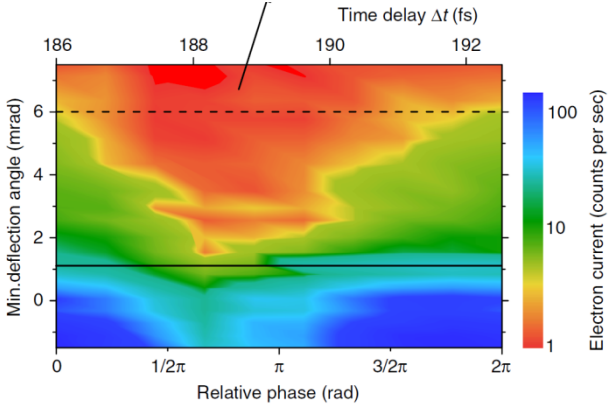




M. Kozák, et al., Opt. Lett., 41, 3435 (2016)

Electron steering

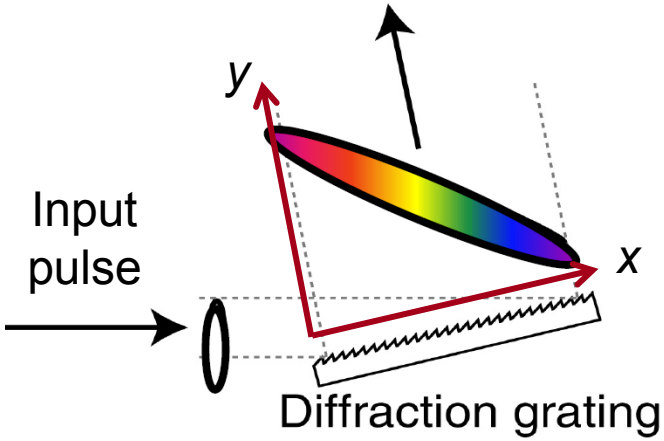




M. Kozák, et al., Nat. Commun., 8, 14342 (2017)

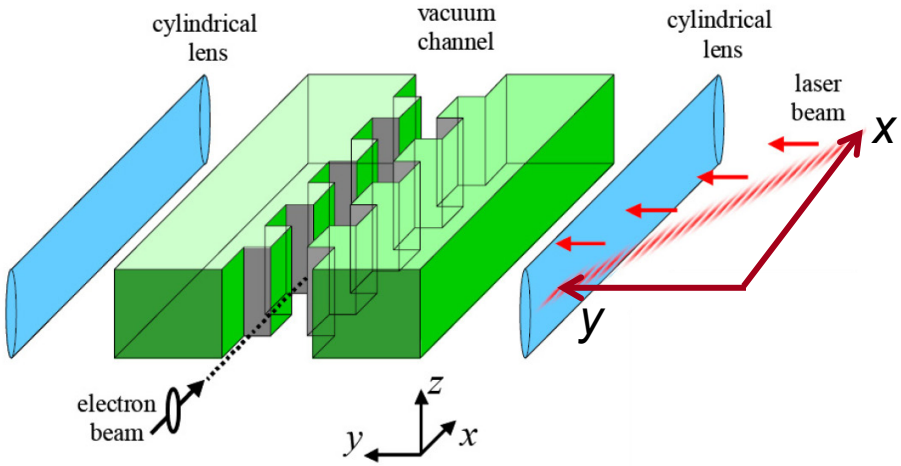
Pulse-front tilt

- Dispersive elements produce pulse-front tilt



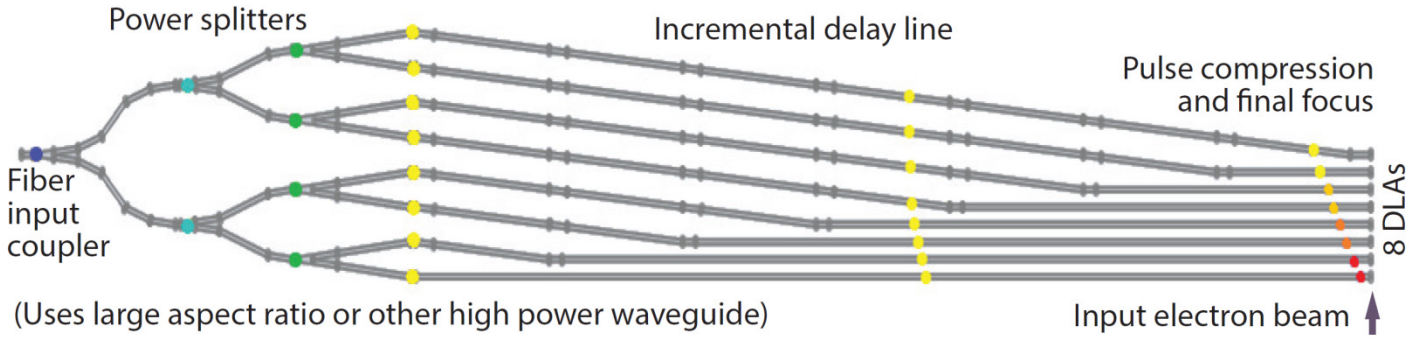
S. Akturk, et al., Opt. Express, 11, 491 (2003)

- High field <100 fs laser pulse
- Extended interaction distance



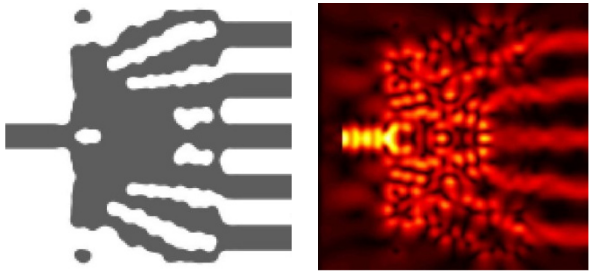
T. Plettner, et al., PRSTAB, 9, 111301 (2006)

On-chip laser management

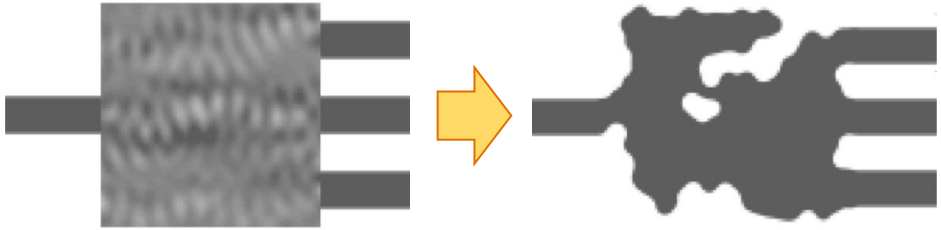


E. Peralta, et al., AIP Conf. Proc., 1507, 169 (2012)

Inverse design 1→5 coupler



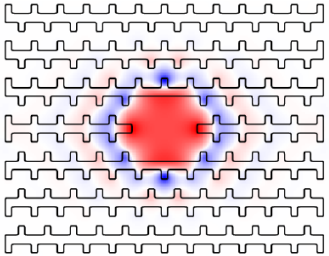
1→3, 0.3 rad phase advance per arm

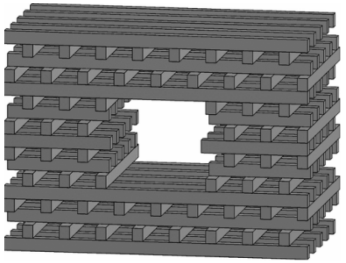


A. Piggott, et al., Nat. Photonics, 9, p. 374 (2015)

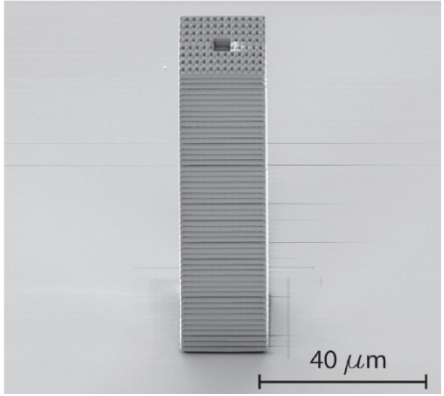
Future – 3D printed DLAs

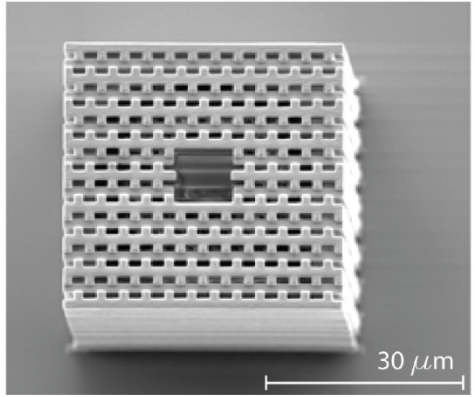
- Nanoscribe feature size <100 nm
- Enable fabrication of exotic structures, waveguides
- Material damage tests underway





Cowan, Phys. Rev. ST Accel. Beams, 11, 011301 (2008)





E. Simakov, et al., AIP Conf. Proc., 1812, 060010 (2017)

Summary

Tabletop demonstration

- DC photocathodes produce few nm emittance required
- Phase-controlled acceleration suggests velocity bunching feasible
- Integrate with chirped structures, demonstrated
- PMQs may provide necessary focussing for tabletop demonstration

Longer-term integrated accelerator

- Laser-driven focussing structures
- Laser delivery and control on-chip
- 3D printing of photonic crystal structures

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blue = students

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LLNL
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Mike Messerly

DLA posters at IPAC'17

Monday, ABISKO

MOPVA012 U. Dorda, et al., The Dedicated Accelerator R&D Facility "Sinbad" at DESY

Tuesday, ABISKO

TUPAB040 B. Marchetti, et al., Status Update of the SINBAD-ARES Linac Under Construction at DESY

Wednesday, VALHALL

WEPVA002 T. Egenolf, et al., Simulations of DLA Grating Structures in the Frequency Domain

WEPVA003 U. Niedermayer, et al., Designing a Dielectric Laser Accelerator on a Chip

WEPVA005 W. Kuropka, et al., Simulation of Many Period Grating-Based Dielectric Laser Accelerators for Electrons

WEPVA006 F. Mayet, et al., A Concept for Phase-Synchronous Acceleration of Microbunch Trains in DLA …

WEPVA007 F. Mayet, et al., Simulations and Plans for a Dielectric Laser Acceleration Experiment at SINBAD

WEPVA011 K. Koyama, et al., Development of a Laser Driven Dielectric Accelerator for Radiobiology Research

WEPVA016 J. Oegren, et al., Dielectric Laser Accelerator Investigation, Setup Substrate Manufacturing …

WEPVA020 Y. Wei, et al., Dielectric Accelerators Driven by Pulse-Front-Tilted Lasers

Thursday, ABISKO

THPAB013 F. Mayet, et al., A Fast Particle Tracking Tool for the Simulation of Dielectric Laser Accelerators