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.

U.S. DEPARTMENT OF ENERGY

Office of Science

SLAC NATIONAL ACCELERATOR LABORATORY

ACHIP

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

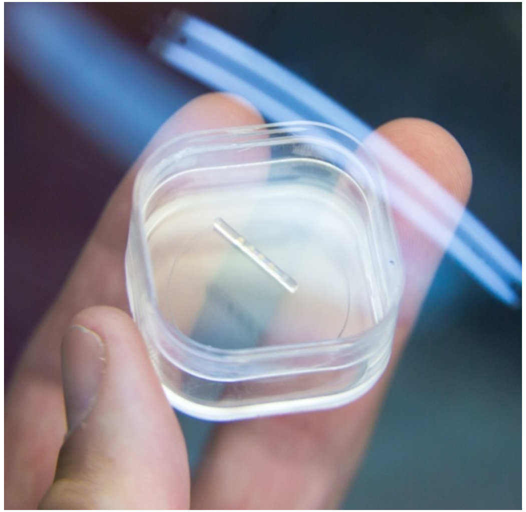
~MeV m^{-1}

SLAC Archives, ARC127

Applications:

- Radiotherapy
- Industrial/security
- Attosecond science

2013



~GeV m^{-1}

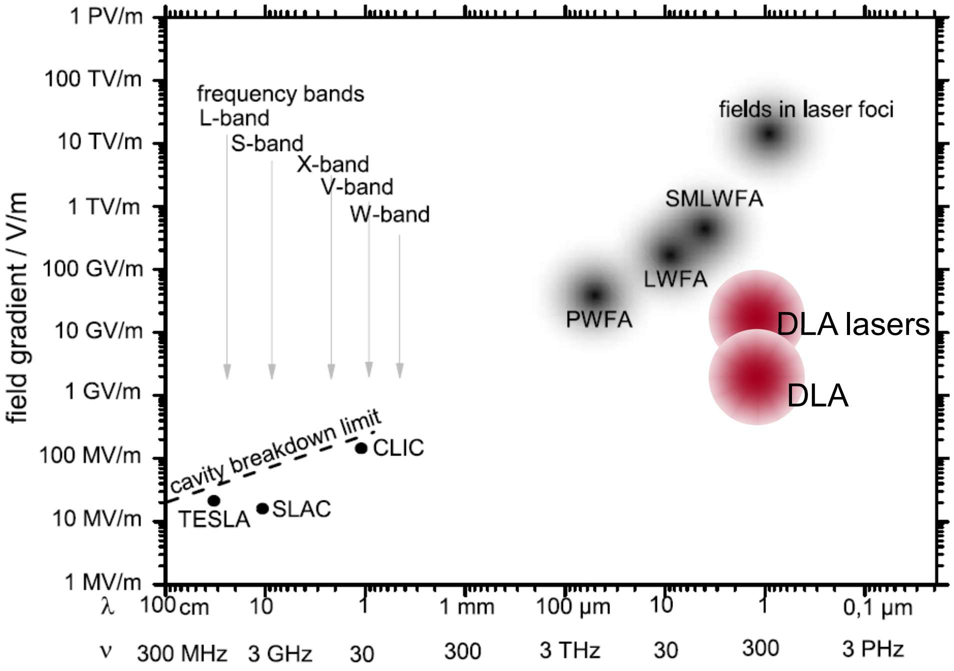
SLAC National Accelerator Laboratory

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)*.



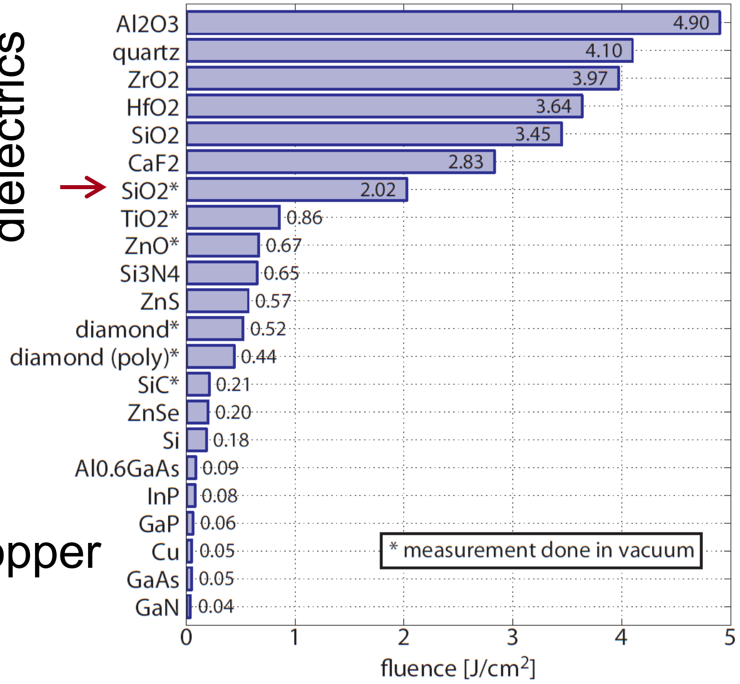
B. Hidding, et al., *Phys. Plasmas, 16, 043105 (2009)*.

Material damage fluence and accelerating gradient

Damage threshold

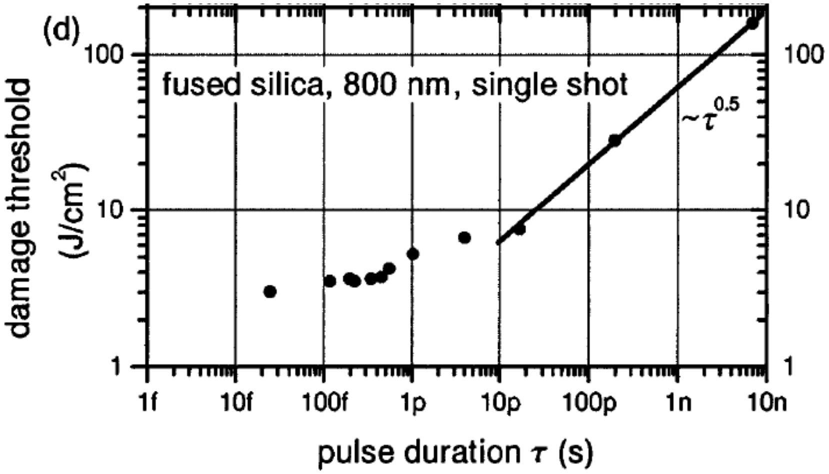
dielectrics

copper



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

SiO_2 (fused silica)

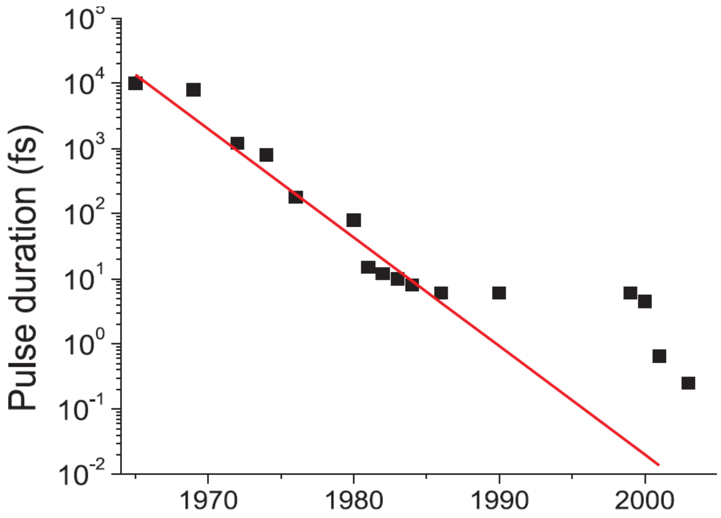


A.-C. Tien, et al., Phys. Rev. Lett., 82, p. 3883 (1999)

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

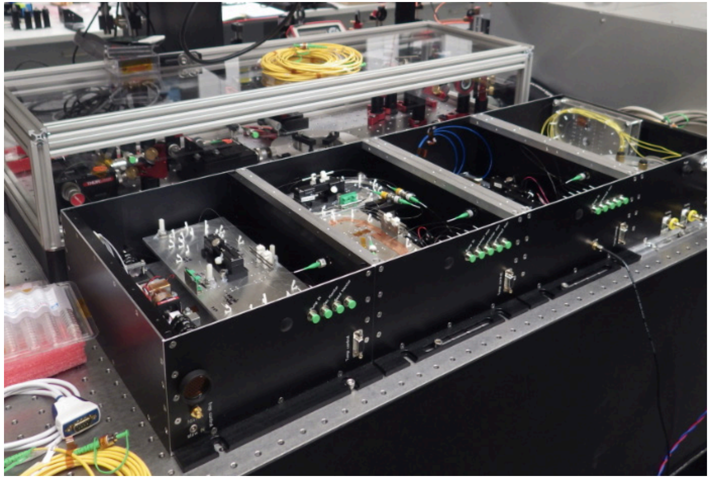
Lasers for accelerators

- fs-duration lasers commercially available



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

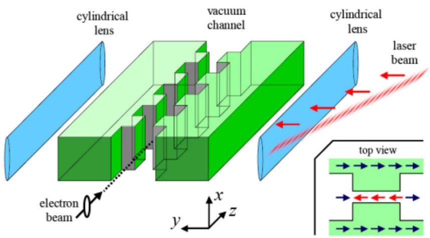
- Tabletop-scale fibre, regenerative amplifiers
- Pulse energy 0.1–5 mJ



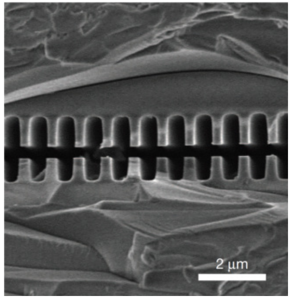
Dielectric laser accelerator structures

- Dielectric-vacuum structures
- UV and electron beam lithography

1-D

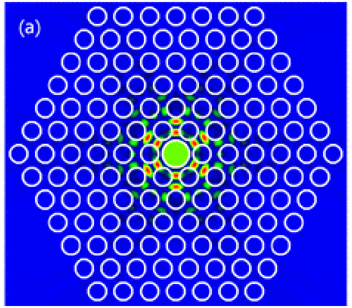


Plettner, et al., PRSTAB, 9, 111301 (2006)

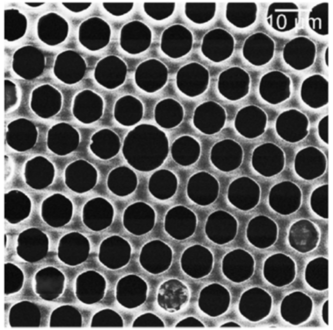


Peralta, et al., Nature, 503, p. 91 (2013)

2-D

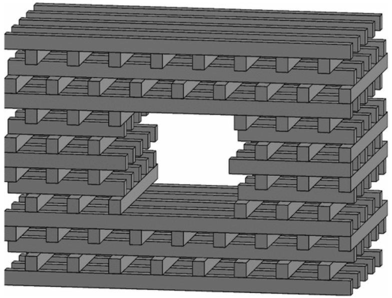


Noble, et al., PRSTAB, 14, 121303 (2011)

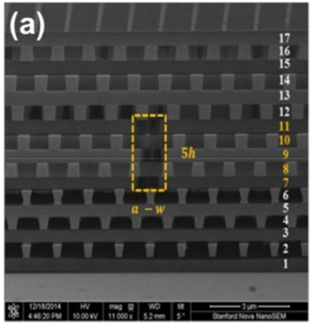


Noble, et al., PRSTAB, 14, 121303 (2011)

3-D

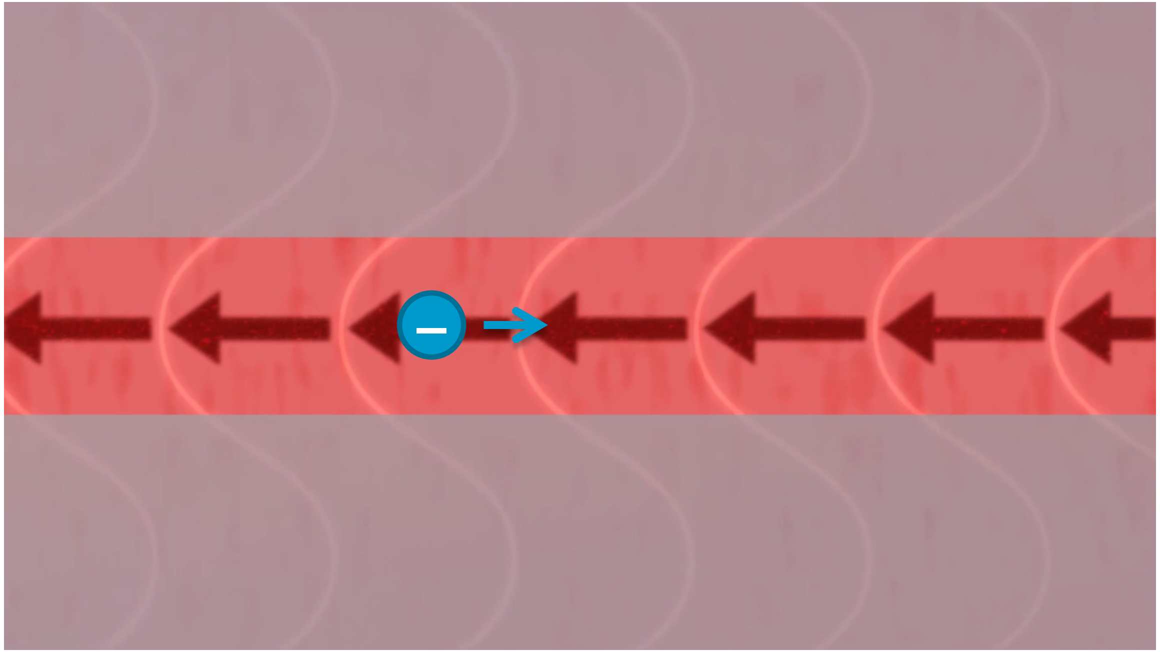


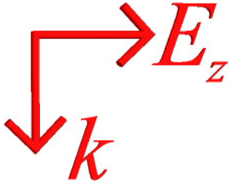
Cowan, PRSTAB, 11, 011301 (2008)



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

DLA – Acceleration

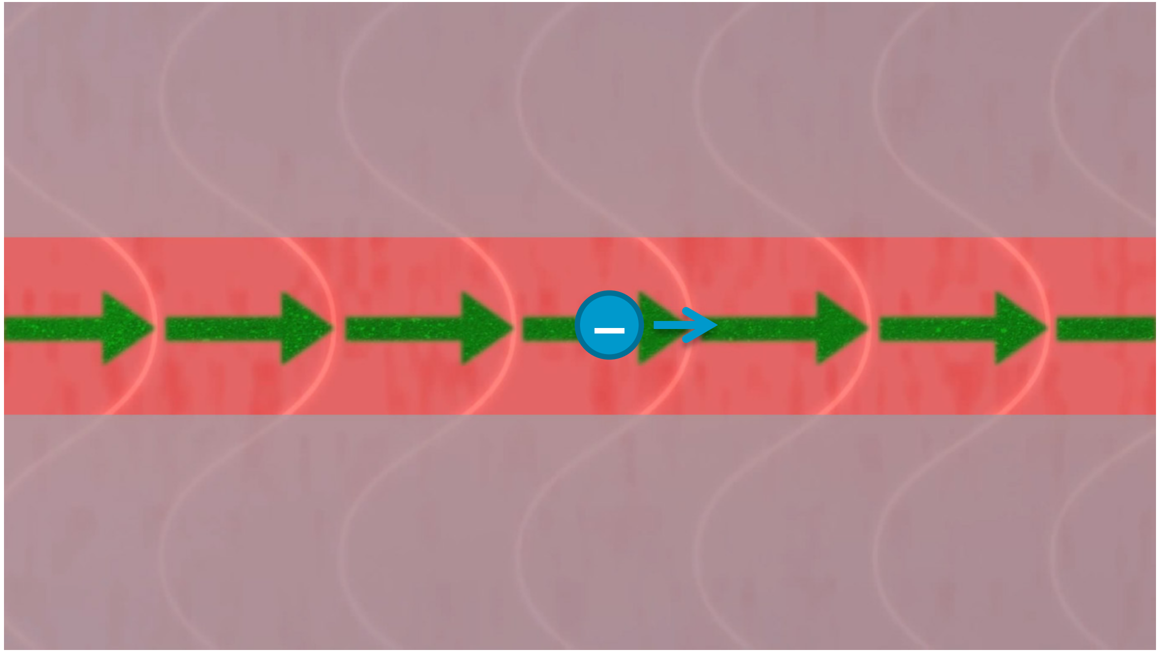




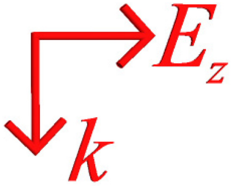
- Plane wave
- No acceleration

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

DLA – Acceleration



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



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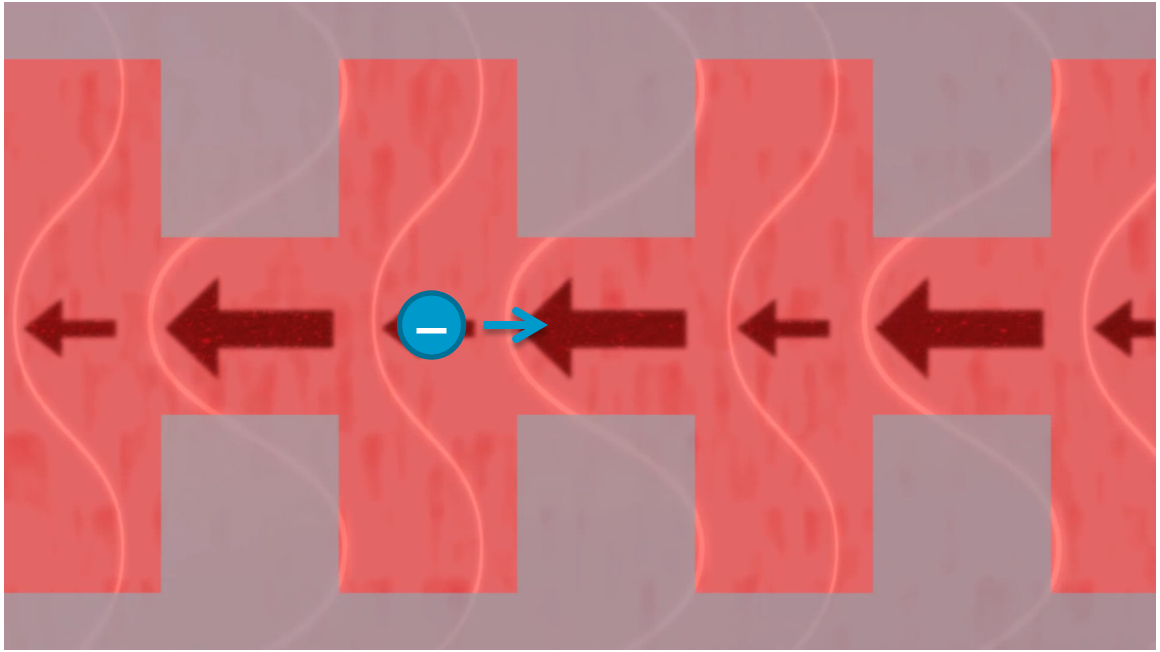
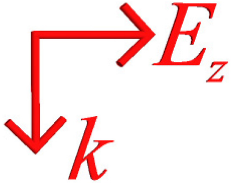
DLA – Acceleration

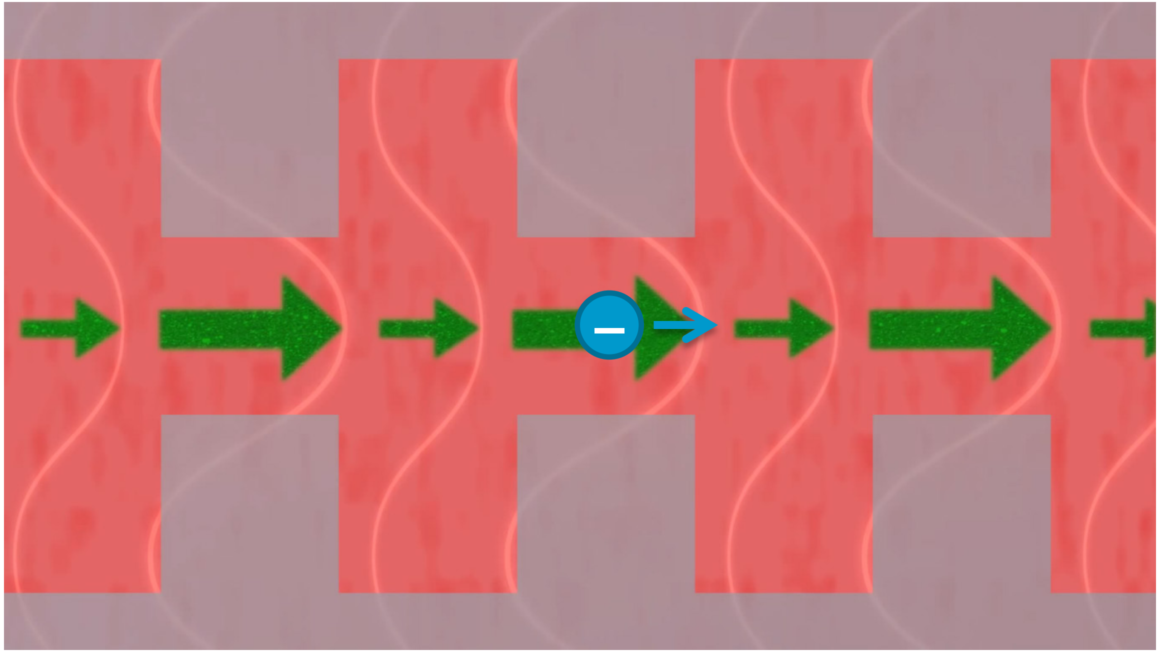


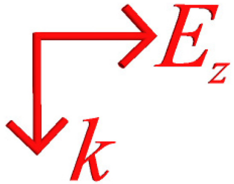


- Plane wave
- No acceleration
- Refractive index modifies phase
- Acceleration

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

DLA – Acceleration

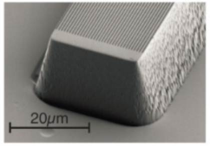
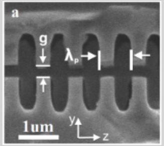
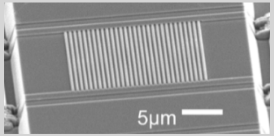
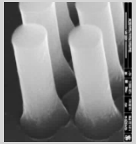




- Plane wave
- No acceleration
- Refractive index modifies phase
- Acceleration

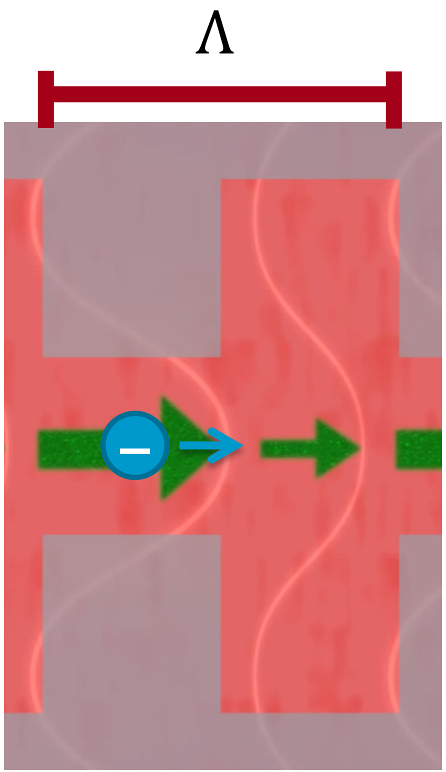
SLAC National Accelerator Laboratory https://youtu.be/V89qvy8whxY

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

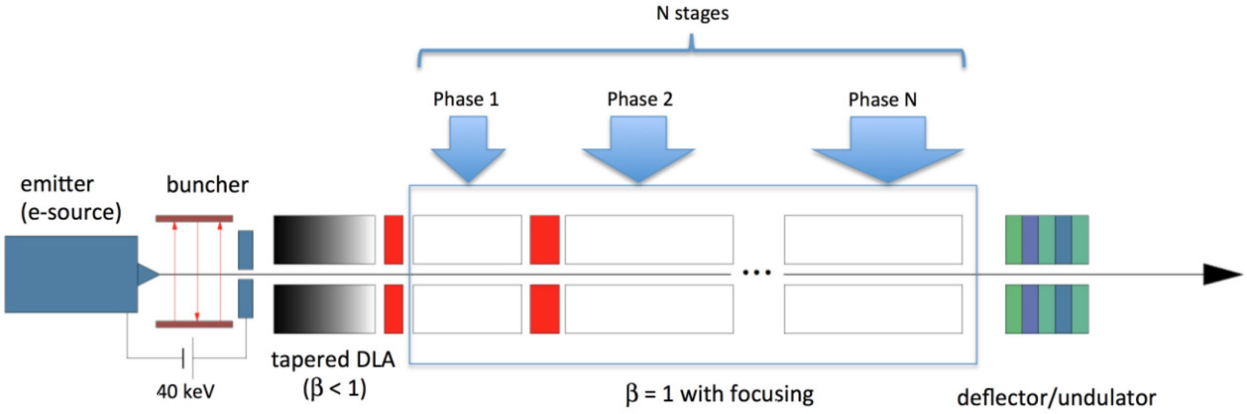
Fundamental accelerator properties



- 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'

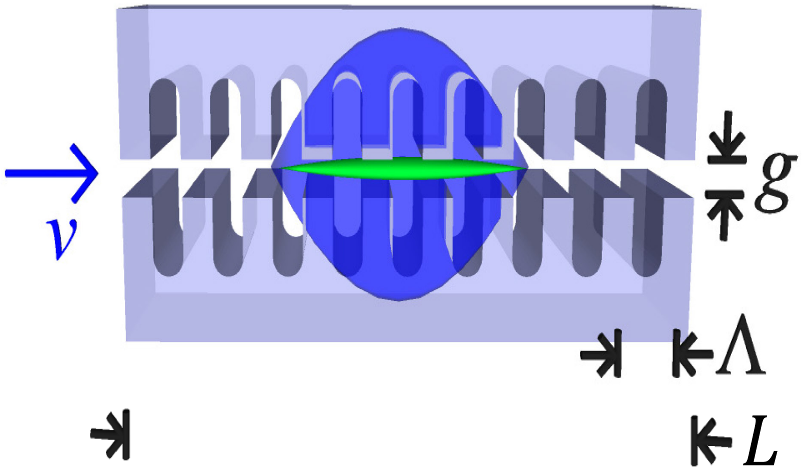


R.J. England, et al., AIP Conf. Proc. 1777, 060002 (2016).

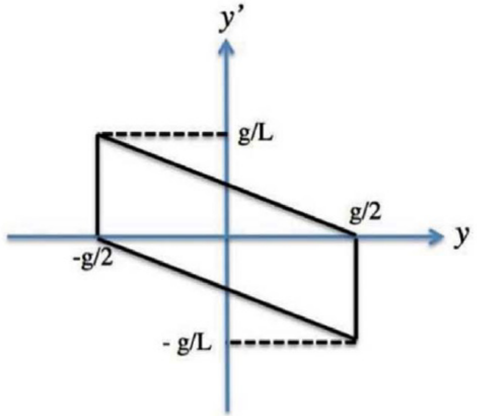
- Electron source
- Buncher
- Transverse focussing
- Accelerating structures
- Laser delivery
- Diagnostics/control

Electron source emittance requirements

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



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

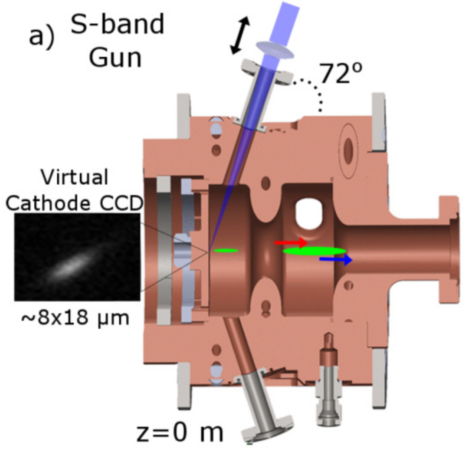


A. Ody, et al., NIMA, (2016, in press)

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

Low emittance electron sources

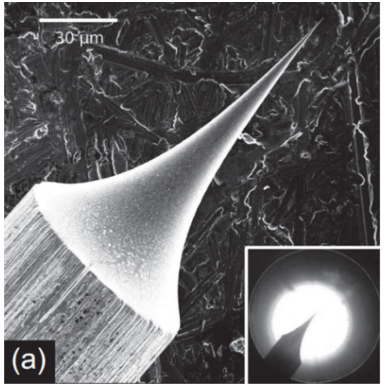
Flat RF photocathode



$$\varepsilon_n = 5 \text{ nm rad}$$
$$\varepsilon = 0.3 \text{ nm rad}$$

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

Tungsten nanotip

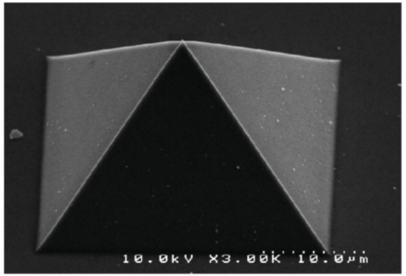


M. Krüger, PhD thesis, LMU-München (2013)

$$\varepsilon_n = 1 \text{ nm rad}$$
$$\varepsilon = 0.08 \text{ nm rad}$$

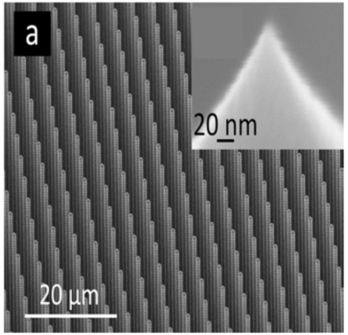
J. McNeur, et al., J. Phys. B: At. Mol. Opt. Phys., 49, 034006 (2016)

Diamond nanotip

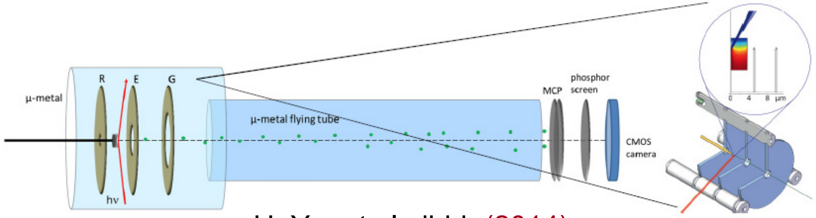


E. Simakov, et al., AIP Conf. Proc., 1812, 060010 (2017)

Silicon nanotip



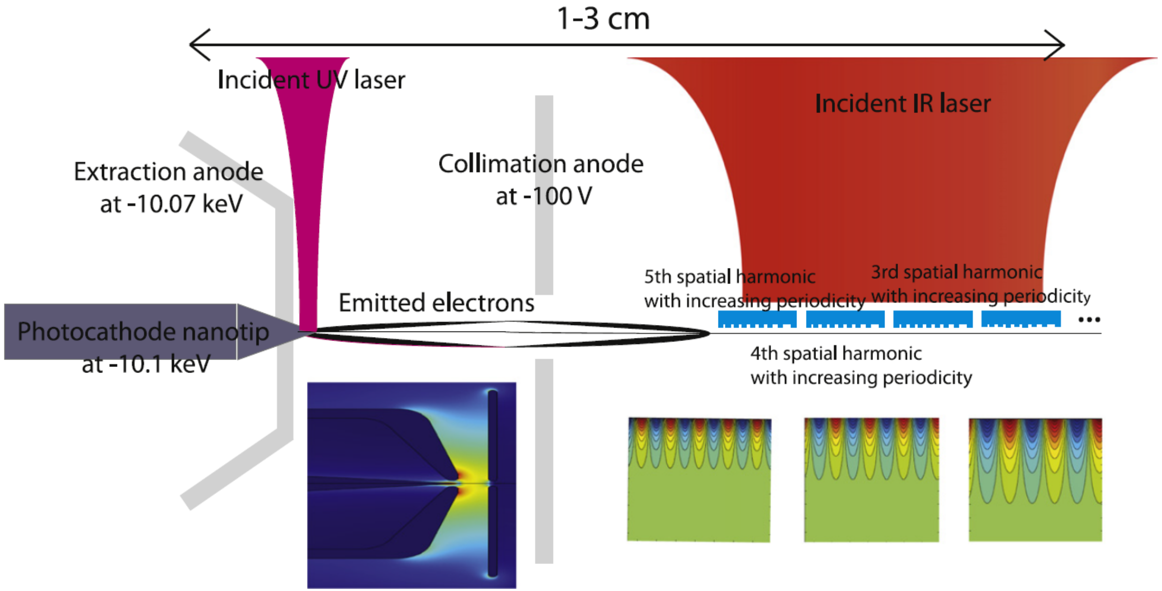
H. Ye, et al., Ultrafast Phenomena, 09.Wed.P3.37 (2014)



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

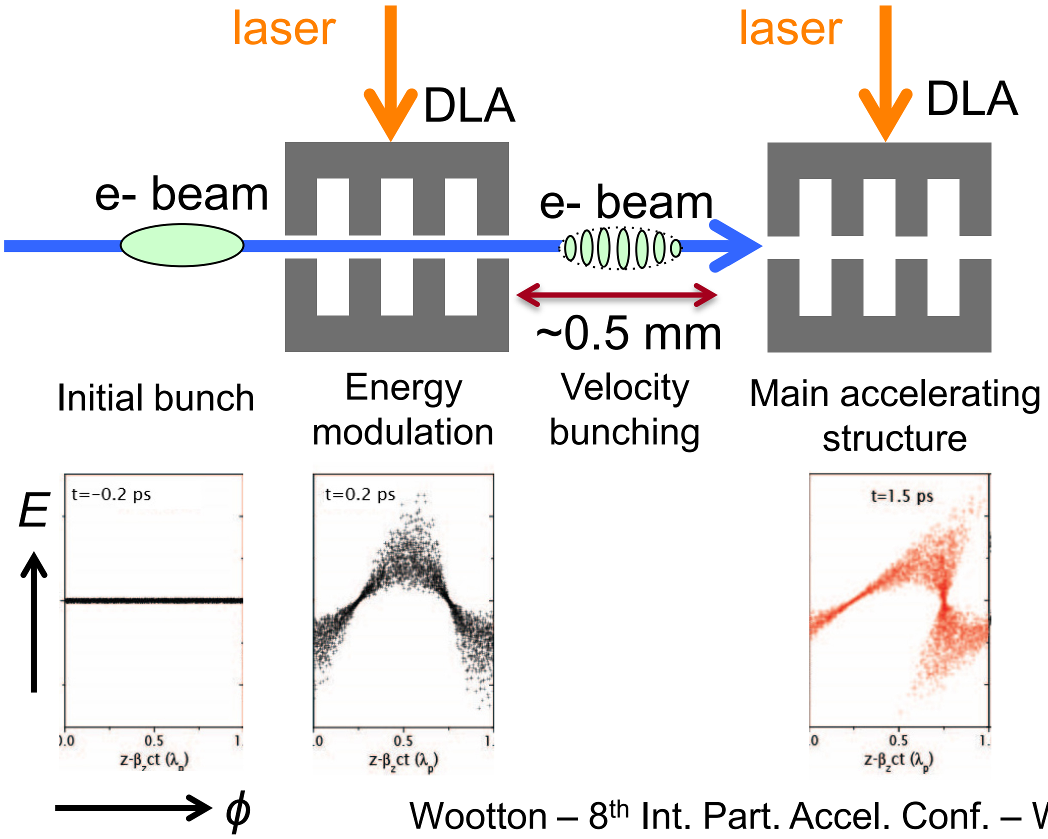
DC photocathode electron gun

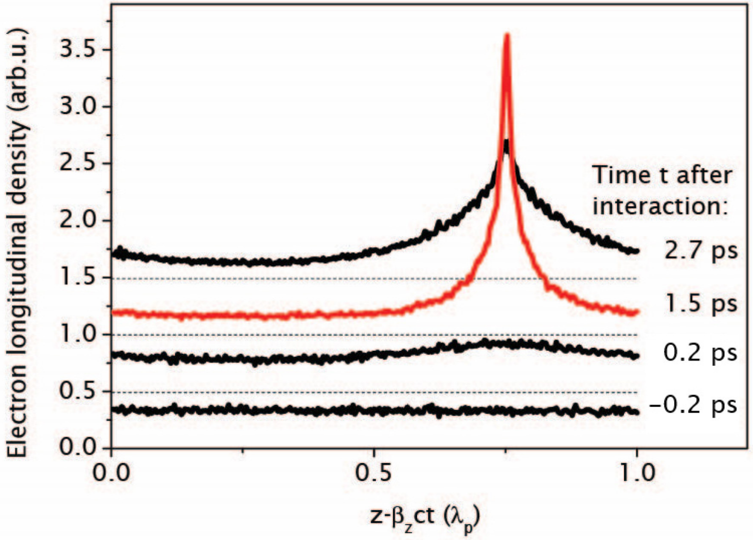
- Photo-assisted field-emission source
- Cathode geometry may be flat or nanotip
- UV and IR laser pulses produced from same source
- Few nm rad transverse emittance
- Electron bunch length $\tau \approx 100 - 300 \text{ fs}$
  - Needs microbunching



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

Buncher – Velocity microbunching

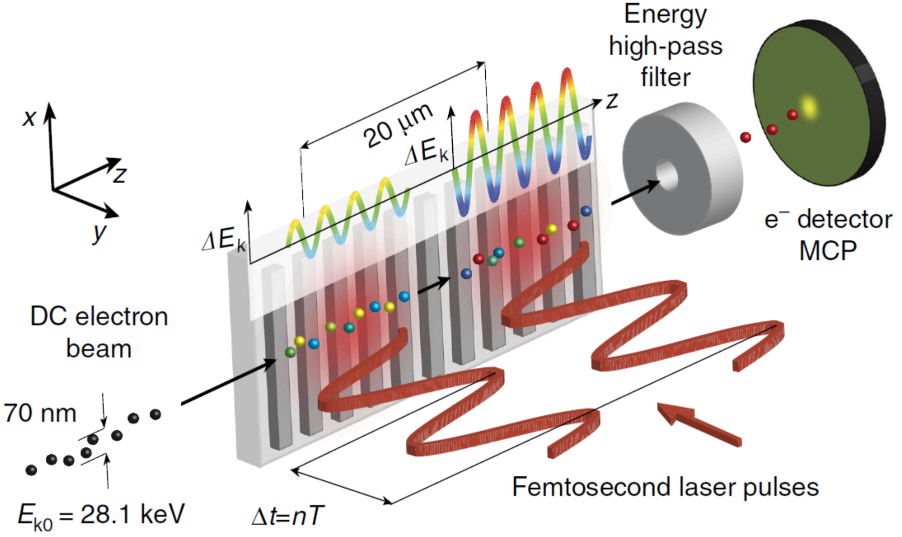


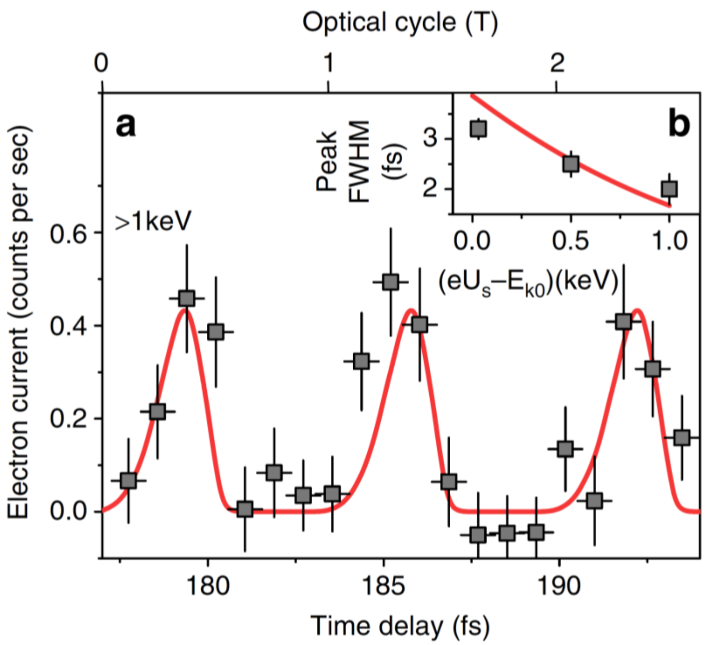


Wootton, McNeur, Leedle, Rev. Accel. Sci. Technol., 9, p. 105 (2016)

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

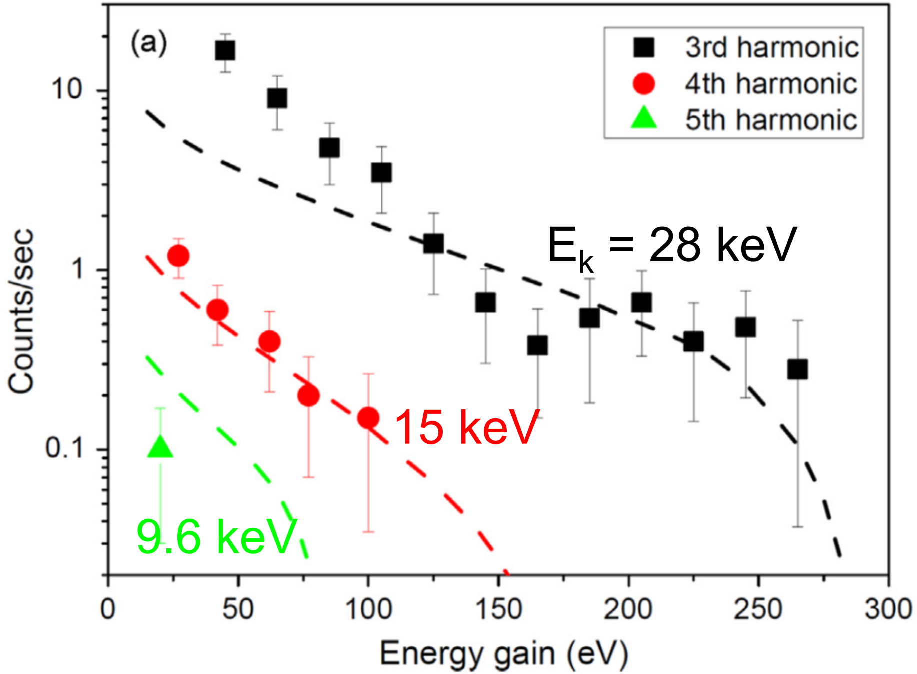
- Synchronicity condition between electron and accelerating mode

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

$$\beta \ll 1?$$

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

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



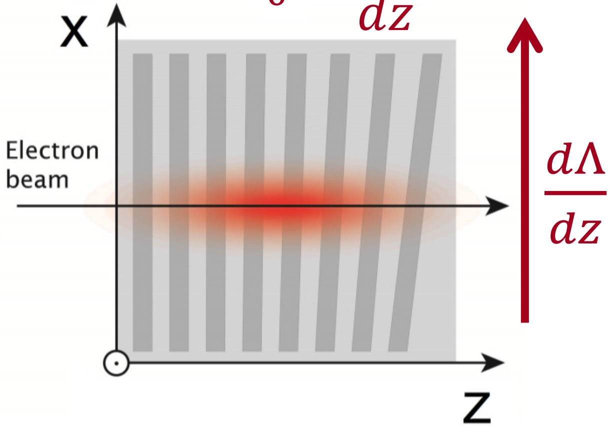
J. McNeur, et al., NIMA, 829, 50 (2016)

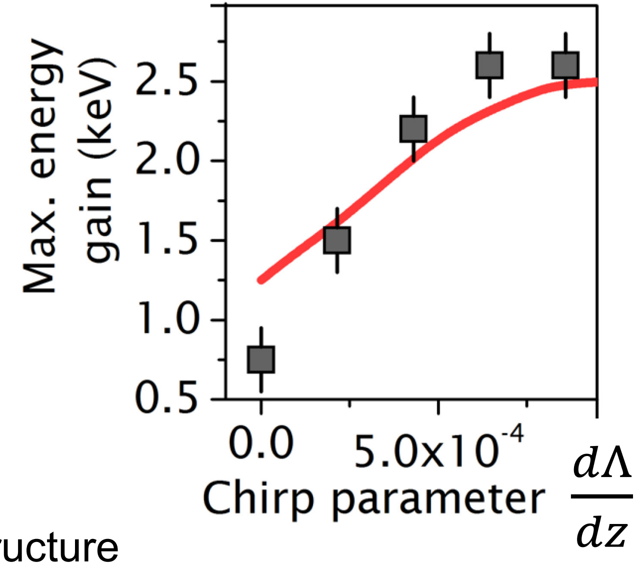
Sub-relativistic structures

Increasing chirp to velocity match accelerating electrons

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

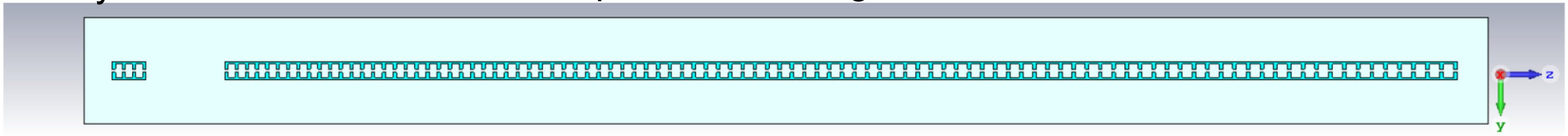
$$\Lambda = \Lambda_0 + \frac{d\Lambda}{dz} z$$





Velocity buncher

Chirped accelerating structure

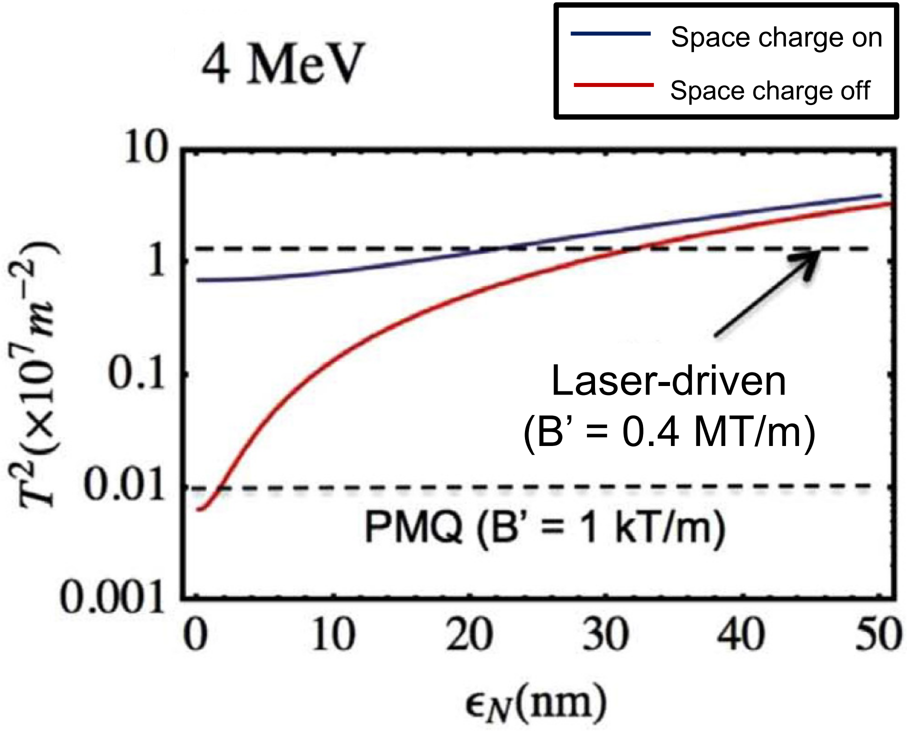


U. Niedermayer, WEPVA003 (this afternoon)

Focussing requirements for demonstration

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

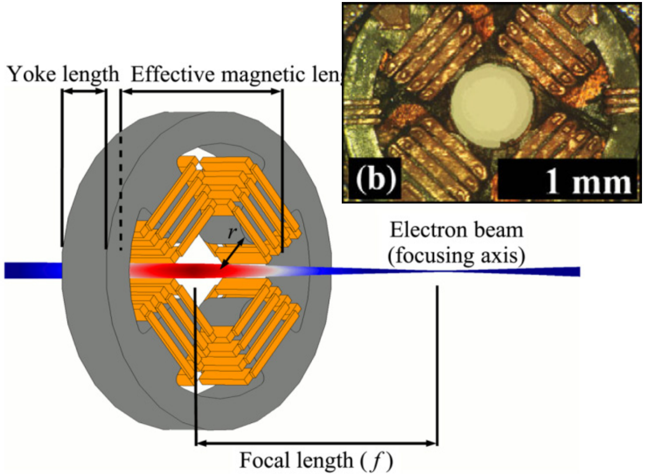
- PMQs may be viable for low emittance beams without space charge
- Long term, require MT m^{-1} transverse gradients for transport of high peak charge microbunches
  - Laser driven focussing structures



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

Focussing structures – magnetic

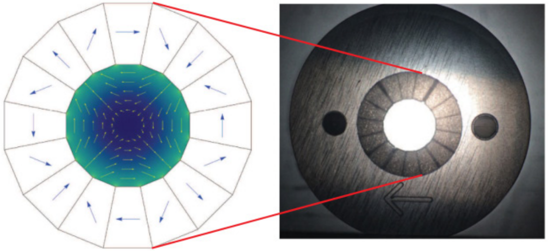
Micro electromagnetic quads

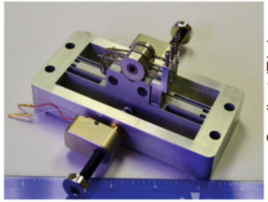


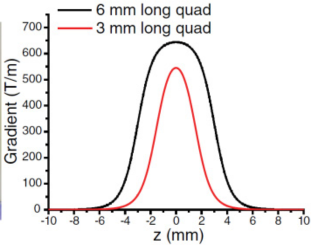
J. Harrison, et al., Phys. Rev. ST Accel Beams, 18, 023501 (2015)

$200\ \mathrm{T\ m^{-1}}$

Permanent magnet quads (PMQ)



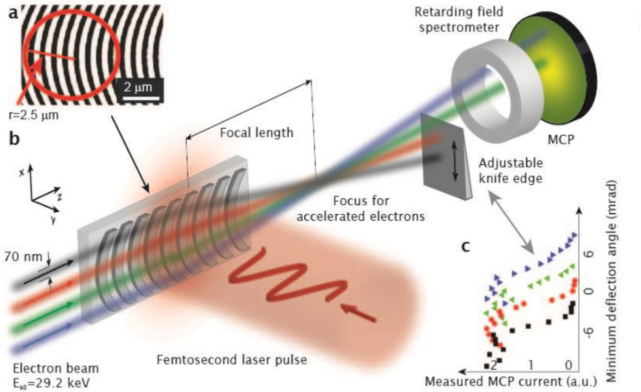


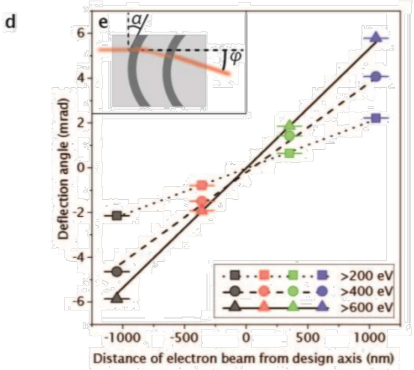


D. Cesar, et al., Phys. Rev. Lett., 117, 024801 (2016)

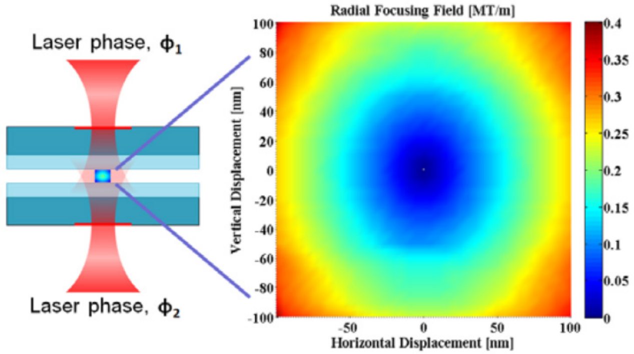
$700\ \mathrm{T\ m^{-1}}$

Focussing structures – laser-driven



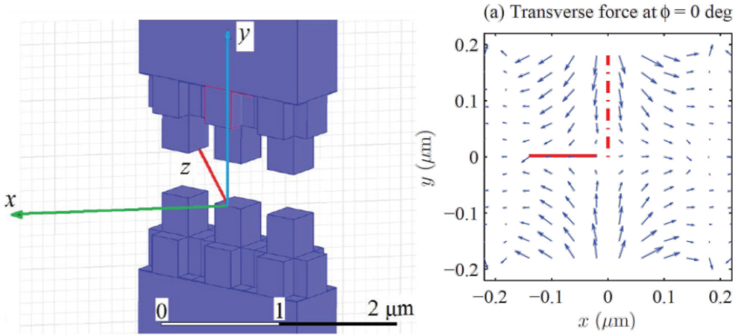


J. McNeur, et al., arXiv: 1604.07684 [physics.acc-ph] (2016).



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}



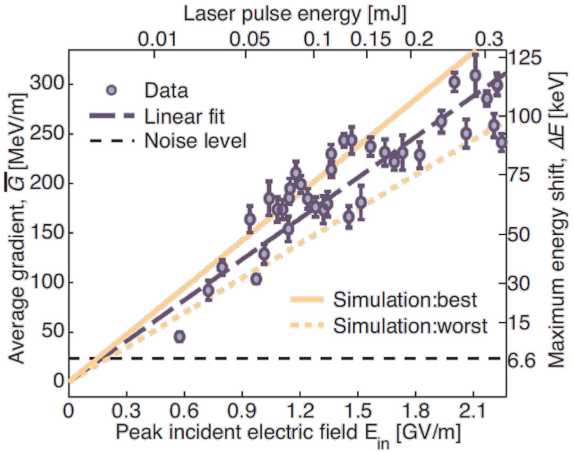
K.P. Wootton, et al., AIP Conf. Proc. 1812, 060001 (2017).

2 MT m^{-1}

High-gradient structures – previous experiments

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

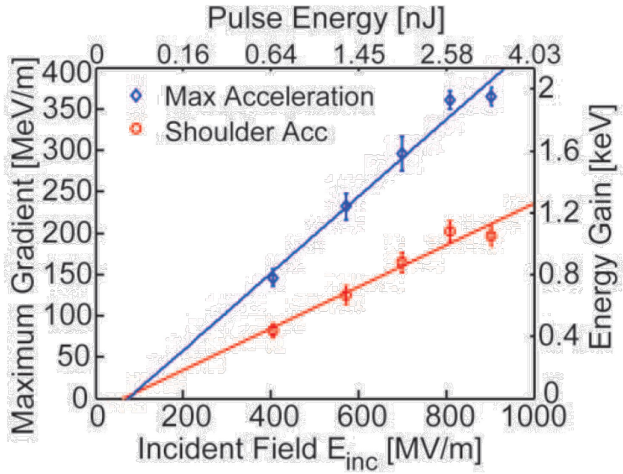
$310 \pm 21\ \mathrm{MV\ m^{-1}}$



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

Stanford ($\beta \approx 0.5$)

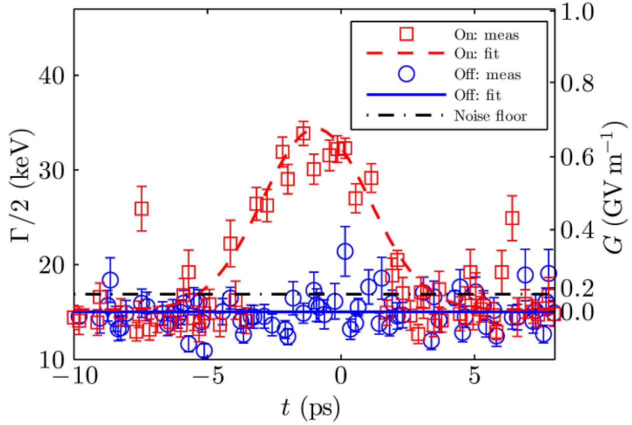
$376 \pm 40\ \mathrm{MV\ m^{-1}}$



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

SLAC ($\beta \approx 1$)

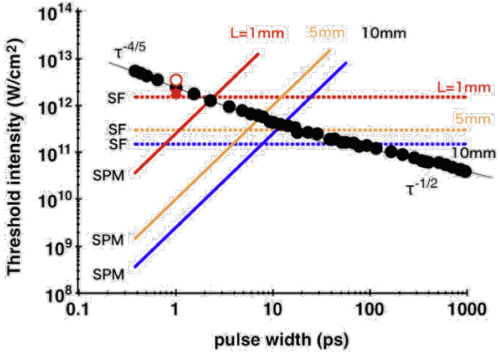
$690 \pm 100\ \mathrm{MV\ m^{-1}}$



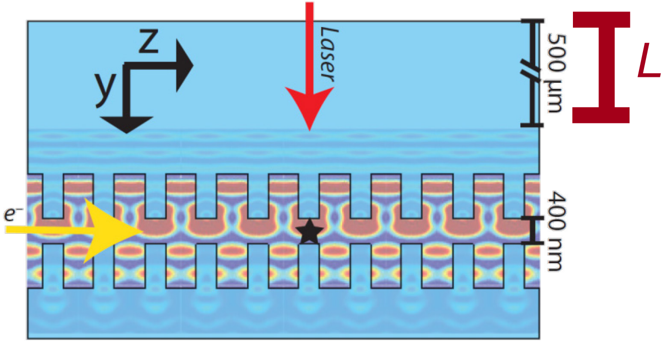
Wootton, et al., Opt. Lett., 41, p. 2696 (2016)

High-gradient structures – Nonlinear effects

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

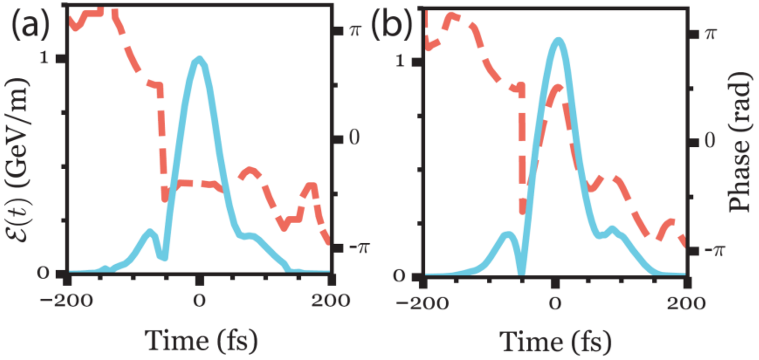


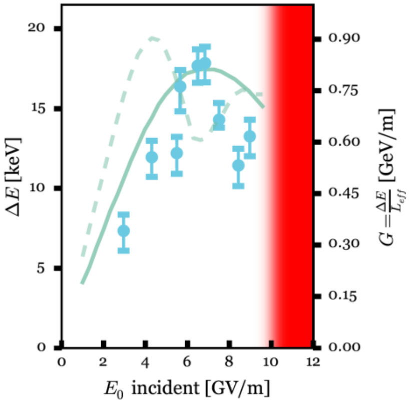
Koyama, et al., J. Phys. B: At. Mol. Opt. Phys., 47, 234005 (2014)



Laser pulse before structure

Laser pulse after 500 μm SiO_2



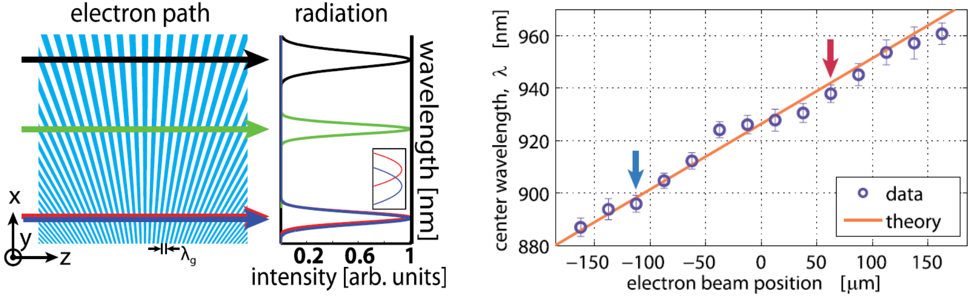


Results in saturation of energy gain

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

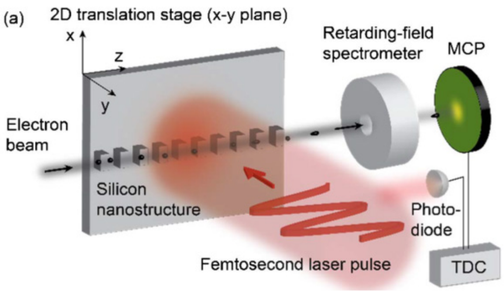
Diagnostics/control

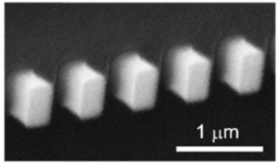
Beam transverse position



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

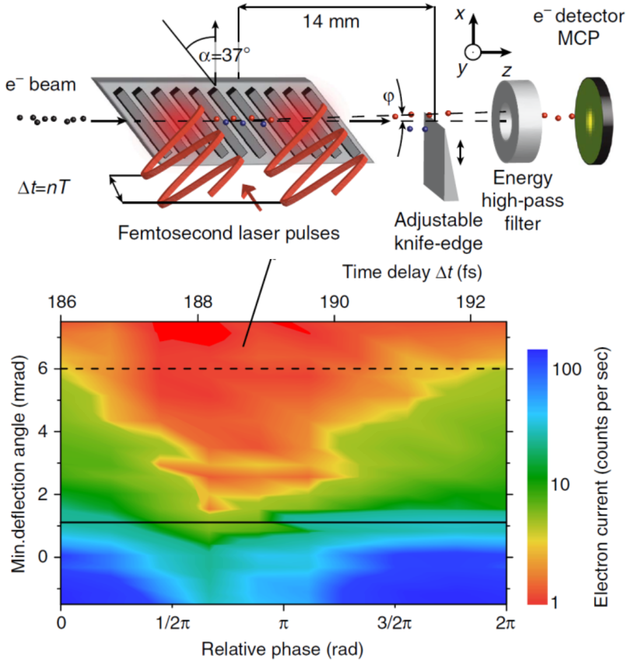
Temporal + spatial





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

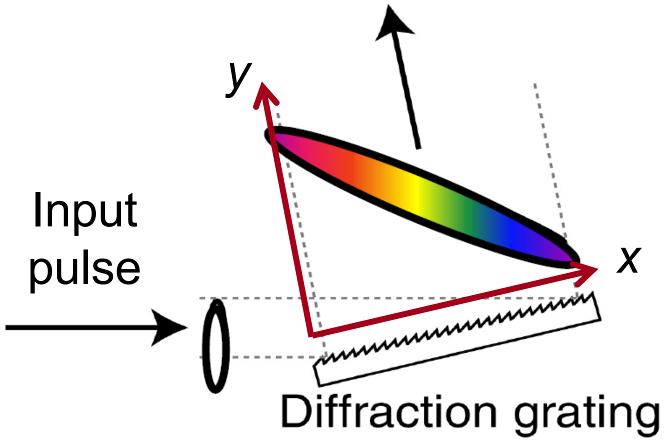
Electron steering



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

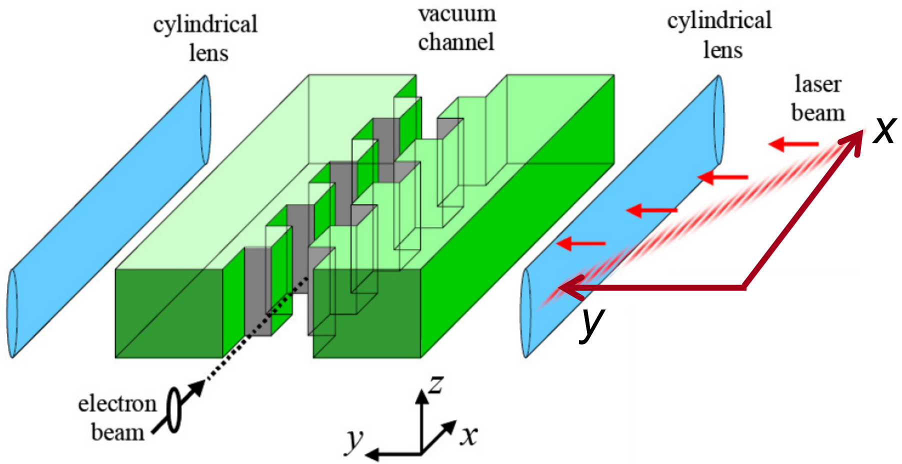
Pulse-front tilt

- Dispersive elements produce pulse-front tilt



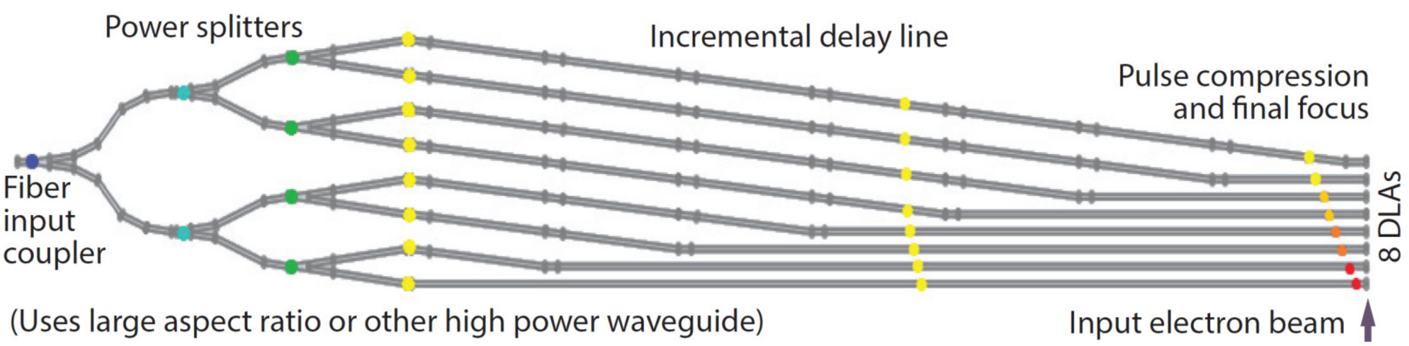
S. Akturk, et al., Opt. Express, 11, 491 (2003)

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



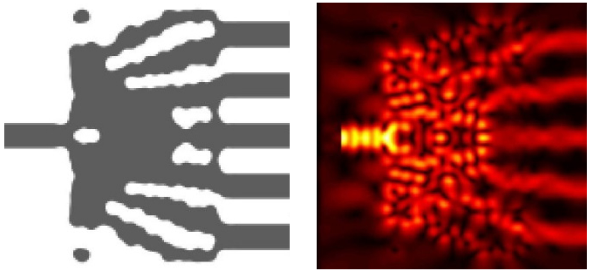
T. Plettner, et al., PRSTAB, 9, 111301 (2006)

On-chip laser management

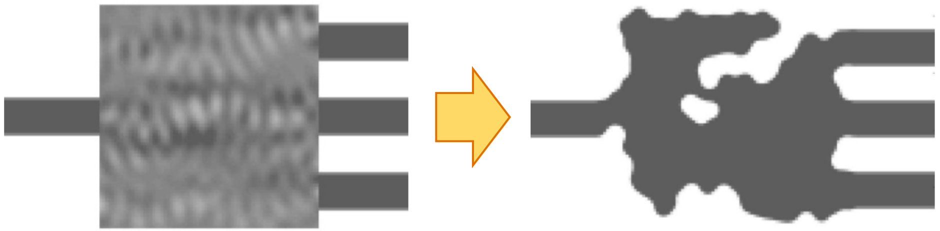


E. Peralta, et al., AIP Conf. Proc., 1507, 169 (2012)

Inverse design 1→5 coupler



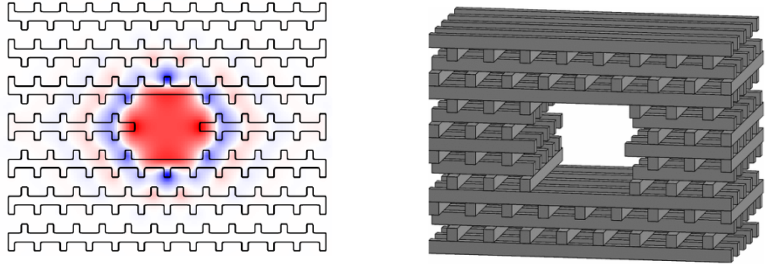
1→3, 0.3 rad phase advance per arm



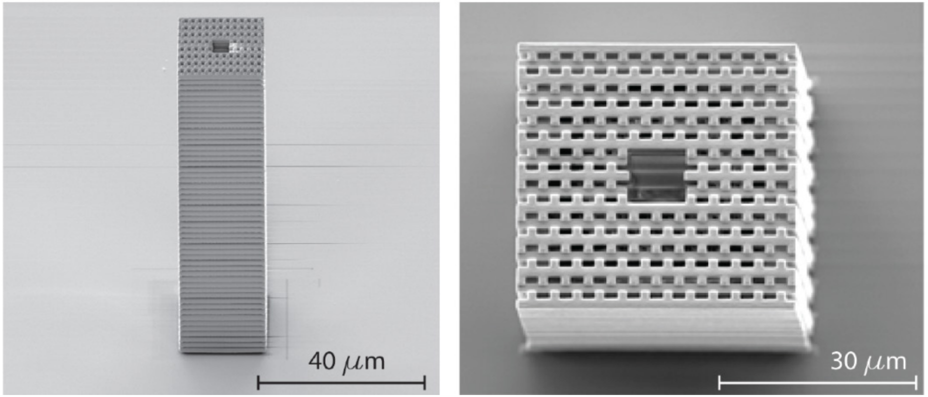
A. Piggott, et al., Nat. Photonics, 9, p. 374 (2015)

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

Acknowledgments

Stanford Univ.
Bob Byer
James Harris
Olav Solgaard
Shanhui Fan
Jelena Vuckovik
Ken Leedle
Andrew Ceballos
Huiyang Deng
Stephen Wolf
Si Tan
Yu Miao
Dylan Black
Peyton Broaddus
Logan Su
Alex Piggott
Jiahui Wang
Tyler Hughes

Stanford (contd.)
Zhexin Zhao
Neil Sapra
Levi Ofer
Mike Hennessy
Jim Perales

FAU Erlangen
Peter Hommelhoff
Josh McNeur
Martin Kozák
Ang Li
Johannes Illmer
Alexander Tafel
Peyman Yousefi
Norbert Schonenberger
Anna Mittelbach

Univ. Hamburg
Franz Kärtner

TU Darmstadt
Oliver Boine-Frankenheim
Uwe Niedermayer
Thilo Egenholf

Tel-Aviv Univ.
Jacob Scheuer
Doron Bar-Lev
Avi Gover

Purdue Univ.
Minghao Qi
Yun Jo Lee

Technion
Levi Schachter
Adi Hanuka

Tech-X Corp.
Ben Cowan

UCLA
Pietro Musumeci
James Rosenzweig
David Cesar
Jared Maxson
Xinglai Shen
Alexander Ody

Paul Scherrer Inst.
Rasmus Ischebeck
Franziska Frei
Eduard Prat
Marco Calvi
Dominique Zehnder
Simona Bettoni
Nicole Hiller
Micha Dehler

SLAC
Joel England
Kent Wootton

DESY
Ralph Assmann
Ingmar Hartl
Axel Ruehl
Willi Kuropka
Frank Mayet

LANL
Evgenya Simakov
Dmitry Shchegolkov

LLNL
Paul Pax
Mike Messerly

blue = students

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