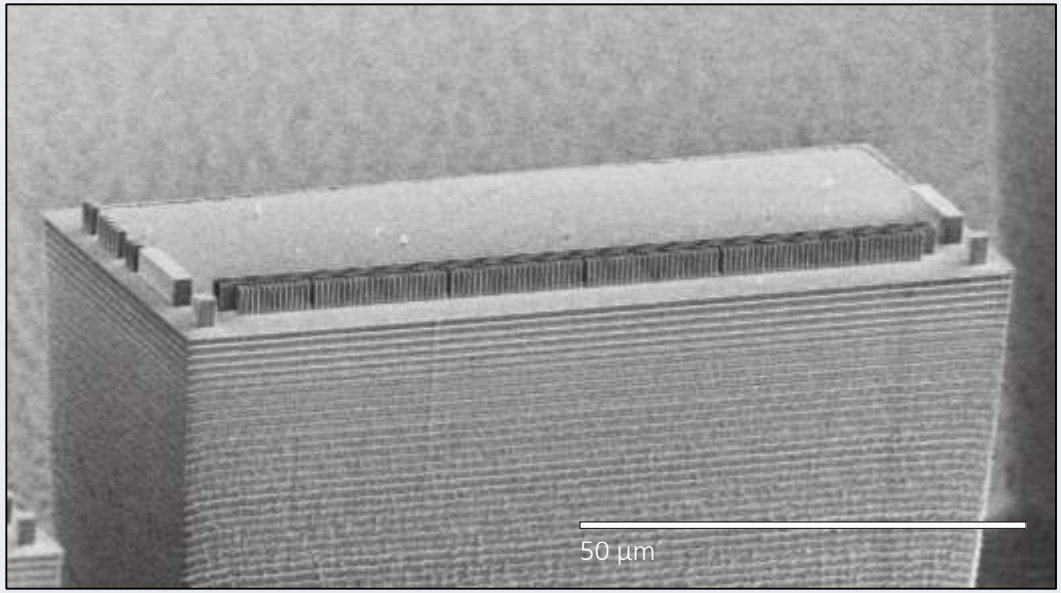
Beam transport on a chip: Alternating phase focusing

R. Shiloh[1†], J. Illmer[1†], T. Chlouba[1†], P. Yousefi[1], N. Schönenberger[1,2], U. Niedermayer[3], A. Mittelbach[1], and P. Hommelhoff[1,2]



5th European Advanced Accelerator Concepts Workshop

INFN-LNF (online)

20th-23rd September, 2021

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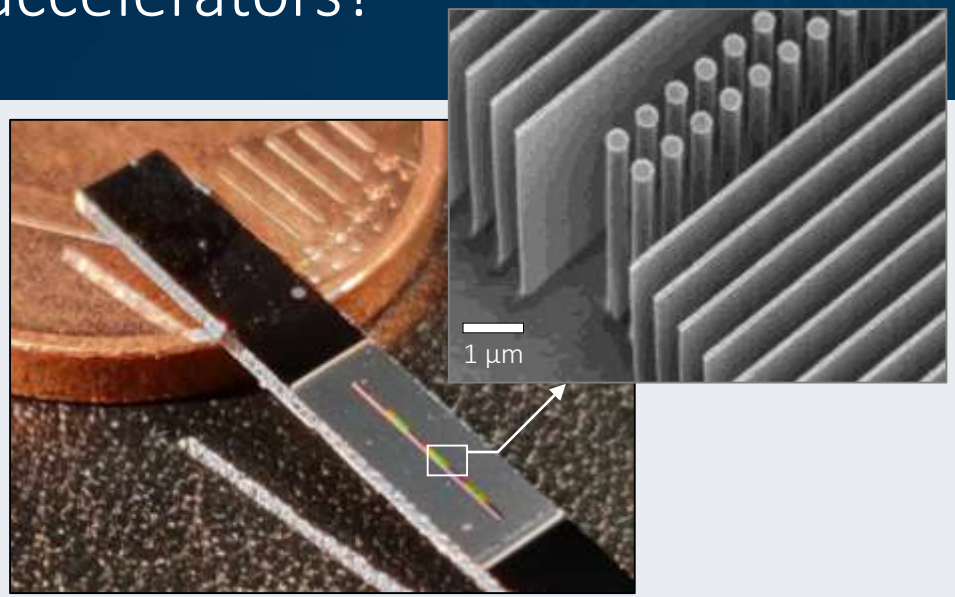
[2] *Max Planck Institute for the Science of Light, Erlangen, Germany*

[3] *Technische Universität Darmstadt, Institute for Accelerator Science and Electromagnetic Fields, Darmstadt, Germany*

Particle accelerators

Why dielectric-based laser accelerators?



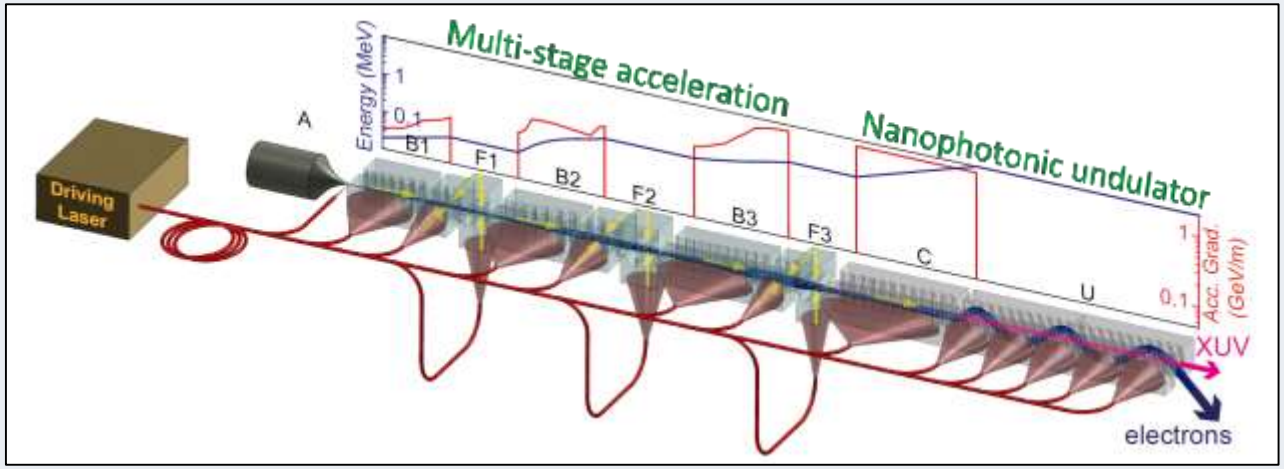
	Dielectric materials and optical frequencies	Higher damage threshold than metallic cavities	Higher gradients and smaller, minituarized structures	Much stricter requirements on beam properties	Lower *average* current
DLA	f=150 THz (λ=2 µm) τ=6.6 fs RR ~ kHz-MHz	>3 GV/m fields	Gradient >1 GeV/m Physical aperture: ~200 nm	Emittance <100 pm rad (norm)	fA-pA
RF	f=3 GHz τ=333 ps RR ~ Hz-kHz	<200 MV/m	25-50 MeV/m ~1cm	1 µm ~ 1 mm rad	nA-µA and larger

Electron pulse and structure excitation naturally phase-locked (same laser!)

Why dielectric-based laser accelerators?

Our laser parameters for DLA:

Wavelength	1.93 μm
Pulse duration	250 fs
Laser power	10 W
Repetition rate	167 kHz
Pulse energy	60 μJ
Wall-plug efficiency	>30%



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

Main components:

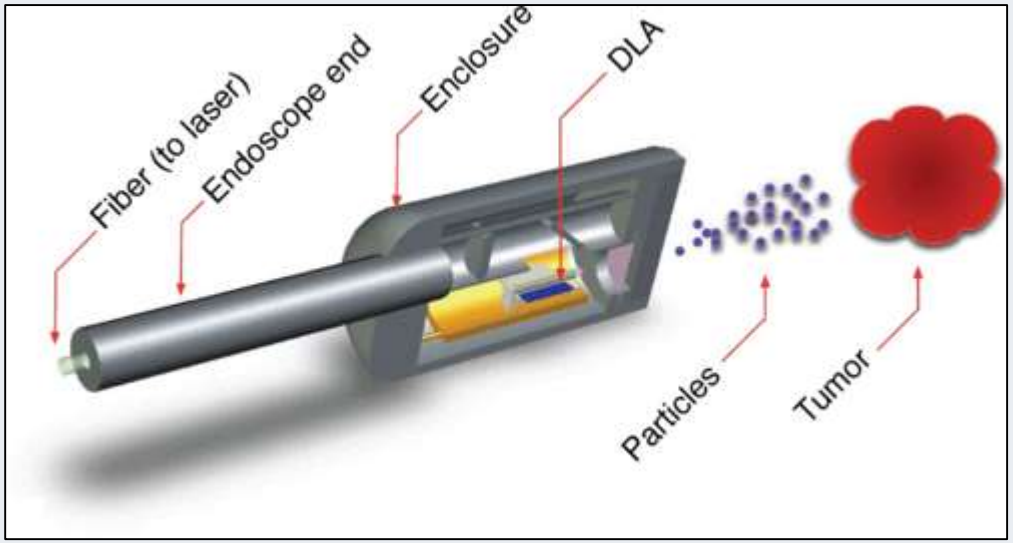
- Electron sources: ultrafast SEMs / TEMs / custom
- Structure fabrication: nano-lithography silicon / fused silica / other materials
- *In the future:* **laser-driven undulator**?

Opportunities:

- Compact, low-cost light sources (FELs in every institute?)
- Laser period (~6 fs) → attosecond bunching → sub-fs radiation pulses?
- *In the future:* ultrafast electron diffraction/microscopy applications? Low-power EUV for inspection? **Medical treatment**?

Particle accelerators for medicine?

- Short term: compact incoherent x ray source (bremsstrahlung)
- Very long term: optical lab sized coherent x ray source
- Intermediate term: medical irradiation source:



England et al., "Dielectric laser accelerators," Rev. Mod. Phys. **86**, 1337 (2014)

- Intraoperative electron beam radiation therapy (IOERT)
- Proximity radiation of tissue (minimally invasive "electron beam scalpel"?)
- Neuronal endplate treatment (Prof. Warren Grundfest, UCLA)
- New high dose rate radiation effects to be expected?

Electron accelerators with lasers - 1962

Proposal for an Electron Accelerator Using an Optical Maser

Koichi Shimoda

January 1962 / Vol. 1, No. 1 / APPLIED OPTICS 33

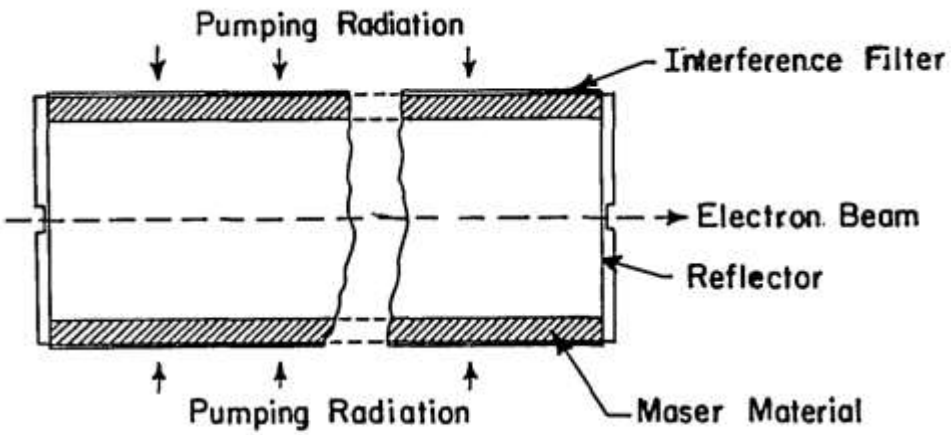


Fig. 1. Schematic diagram of an electron linear accelerator by optical maser.

IBM TN-5

Electron Acceleration by Light Waves

A. Lohmann*

October 3, 1962

Summary

Light, particularly in the form of evanescent waves, can be employed to accelerate charged particles. Since the field strength in LASER radiation is expected to be of the order of 10^9 V/m, an accelerator of significantly reduced dimensions based upon this concept appears feasible. The proposed accelerator works on what may be defined as the time-reversed Smith-Purcell effect.

First patent filed in 1963

3,267,383
PARTICLE ACCELERATOR UTILIZING COHERENT LIGHT
Adolf W. Lohmann, San Jose, Calif., assignor to International Business Machines Corporation, New York, N.Y., a corporation of New York
Filed May 27, 1963, Ser. No. 283,475
9 Claims. (Cl. 328—33)

The present invention relates to particle accelerators and more particularly to a particle accelerator wherein energy is transferred to particles by means of visible or infrared light waves.

Aug. 16, 1966 A. W. LOHMANN 3,267,383
PARTICLE ACCELERATOR UTILIZING COHERENT LIGHT
Filed May 27, 1963 2 Sheets-Sheet 2

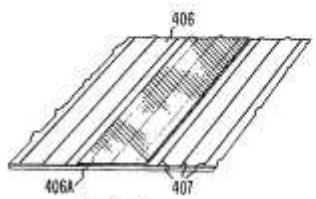


FIG.4

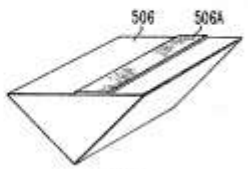


FIG.5

Aug. 16, 1966 A. W. LOHMANN 3,267,383
PARTICLE ACCELERATOR UTILIZING COHERENT LIGHT
Filed May 27, 1963 2 Sheets-Sheet 1

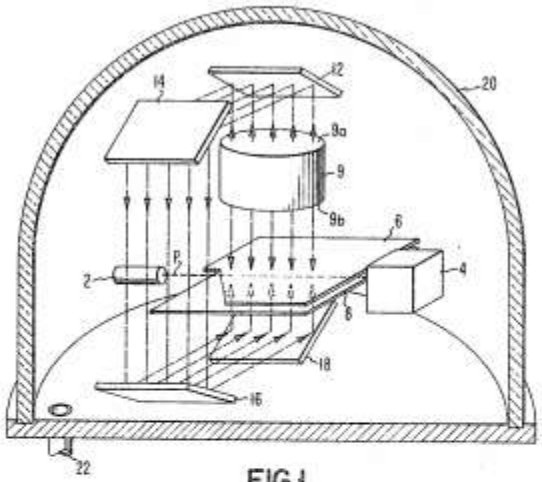


FIG.1

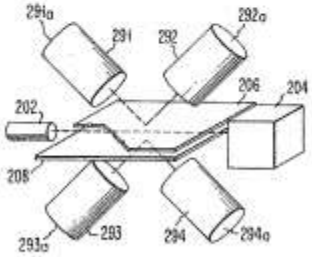


FIG.2

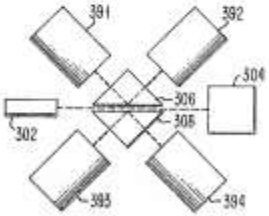
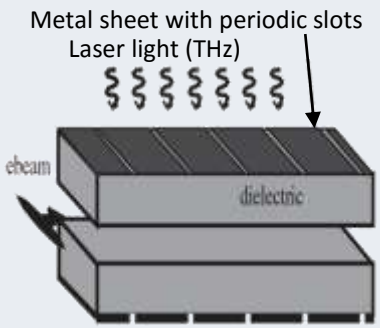


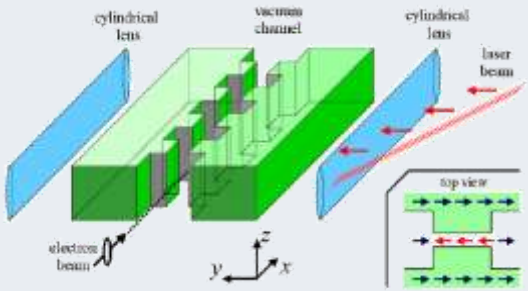
FIG.3

INVENTOR
ADOLF W. LOHMANN
BY

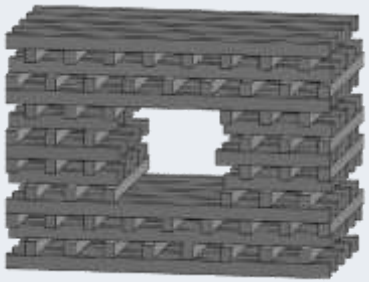
A family of nanophotonic structures



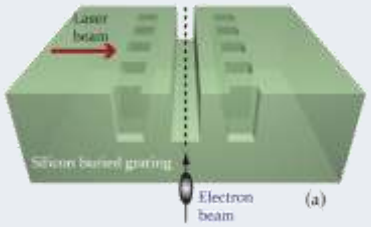
Yoder and Rosenzweig, Phys. Rev. ST AB **8**, 111301 (2005)



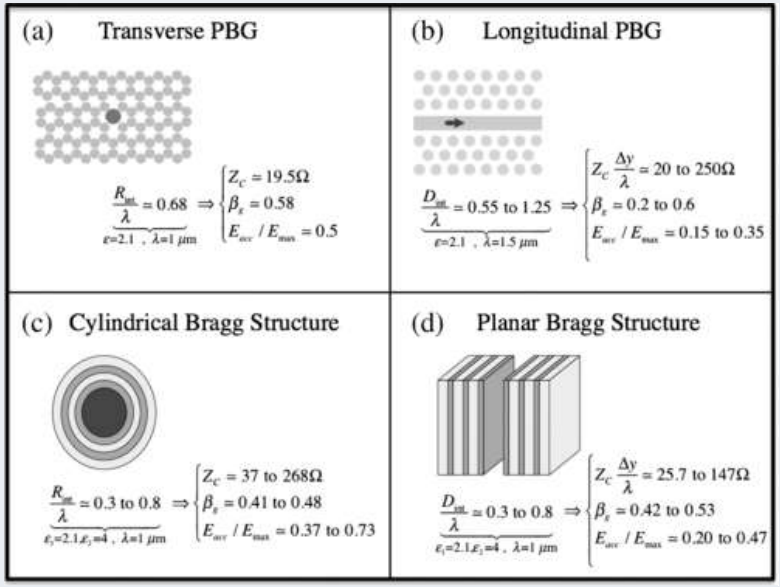
Plettner, Lu, Byer, Phys. Rev. ST AB **9**, 111301 (2006)



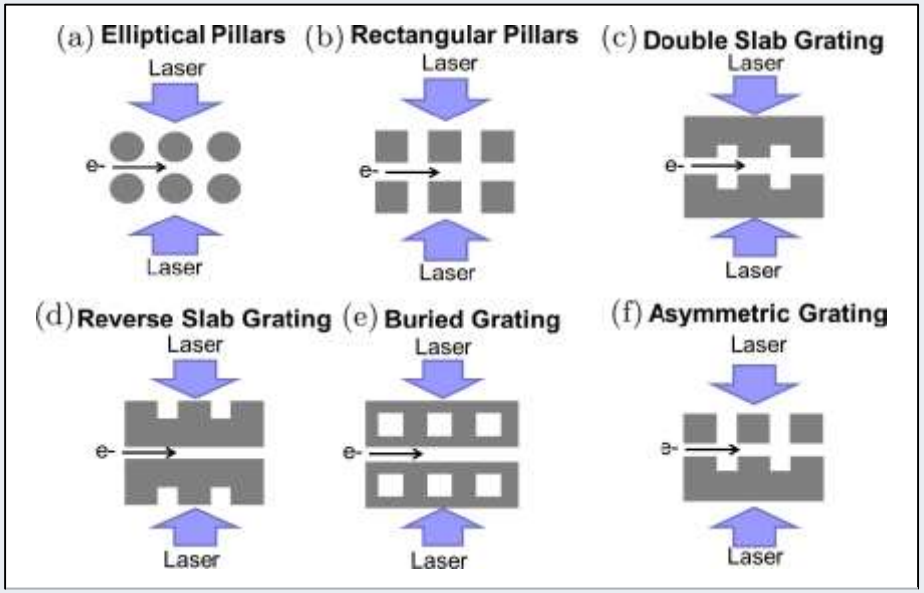
Cowan, Phys. Rev. ST AB **11**, 011301 (2008)



Chang, Solgaard, APL **104**, 184102 (2014)



REVIEW: England et al., "Dielectric laser accelerators," Rev. Mod. Phys. **86**, 1337 (2014)



REVIEW: Wootton, McNeur, Leedle, "Dielectric Laser Accelerators: Designs, Experiments, and Applications," Rev. of Accel. Sci. and Tech. **9**, 105-126 (2016)

ACHIP: Accelerator on a Chip International Program

Goals: demonstrate (1) a shoebox-sized 1 MeV accelerator & (2) photon generation

Organizational chart

PIs: R. L. Byer, Stanford, P. Hommelhoff, FAU Erlangen

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

Structures
Stanford: Harris, Solgaard, Byer
Erlangen: Hommelhoff

Electron source
UCLA: Musumeci
Erlangen: Hommelhoff
Stanford: Harris, Solgaard

System integration (Core DLA groups)
Stanford: Byer, Harris, Solgaard
Erlangen: Hommelhoff

Simulations
Tech-X: Cowan
U Darmstadt: Boine-Frankenheim

Light Coupling
Stanford: Fan, Vučković

Associated Scientific Collaborators
Yenchieh Huang (Tsinghua)
Zhirong Huang (SLAC)
Kazu Koyama (Tokyo U)
Ido Kaminer (Technion)
James Rosenzweig (UCLA)
Evgenya Simakov (Los Alamos)

Relativistic DLA experiments
SLAC: England, Tantawi
DESY/UnivHH: Aßmann, Kärtner, Hartl
PSI/EPFL: Ischebeck, Rivkin

Industrial affiliate
HAMAMATSU
PHOTON IS OUR BUSINESS
(joined June 2017)

Sept. 2015 – Sept. 2022

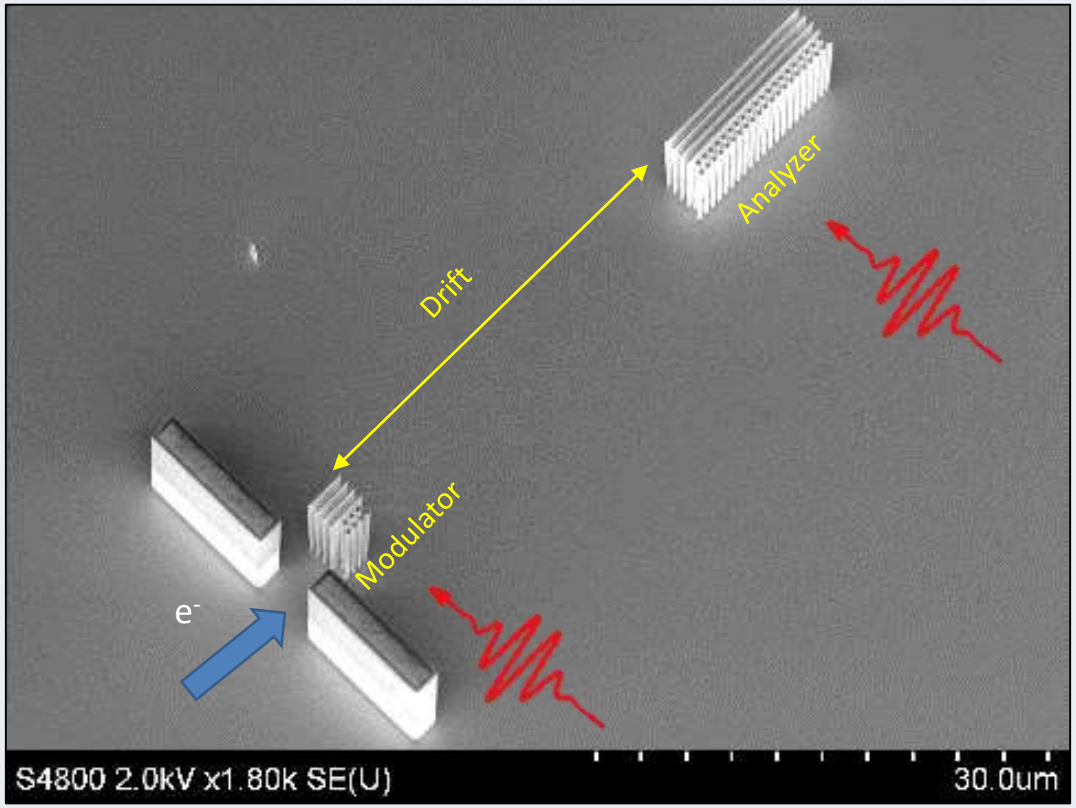
ACHIP Scientific Advisory Board:
Chan Joshi, UCLA, Reinhard Brinkmann, DESY, Tor Raubenheimer, SLAC

ACHIP: Accelerator on a Chip International Program

Goals: demonstrate (1) a shoebox-sized 1 MeV accelerator & (2) photon generation

ACHIP: Accelerator on a Chip International Program

Ballistic buncher: down to 270±80 attoseconds (FWHM)



Schönenberger et al., Phys. Rev. Lett. **123**, 264803 (2019)
Black et al., Phys. Rev. Lett. **123**, 264802 (2019)

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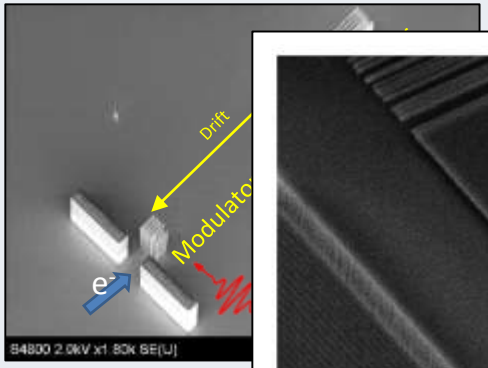
Inverse design of an optimized electron accelerator on a chip



Schönenberger et al., Phys. Re
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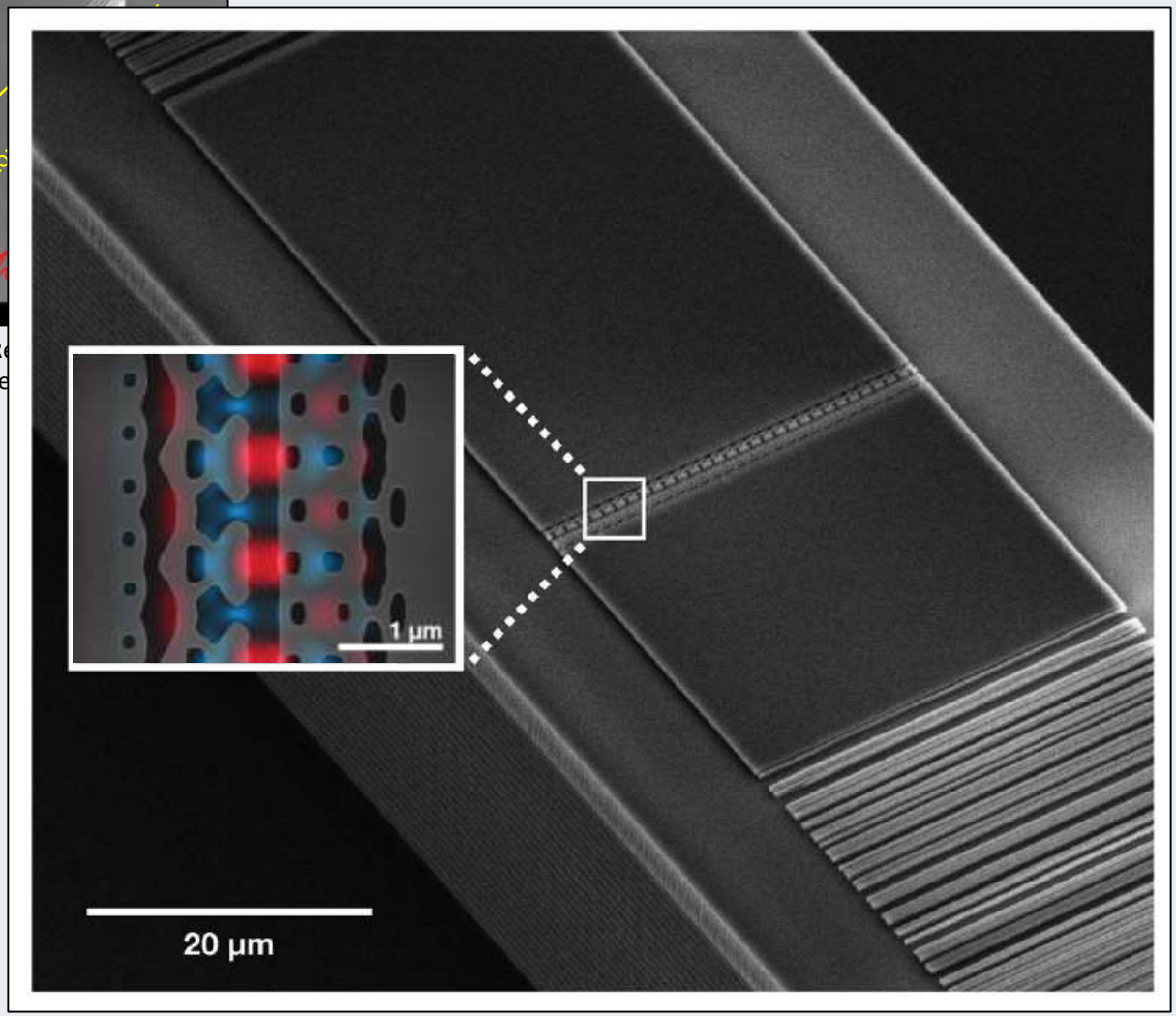
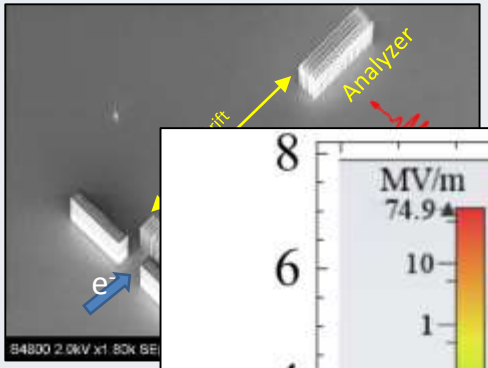
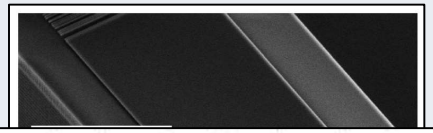


Sapra et al., Science, **367**, 79-83 (2020)

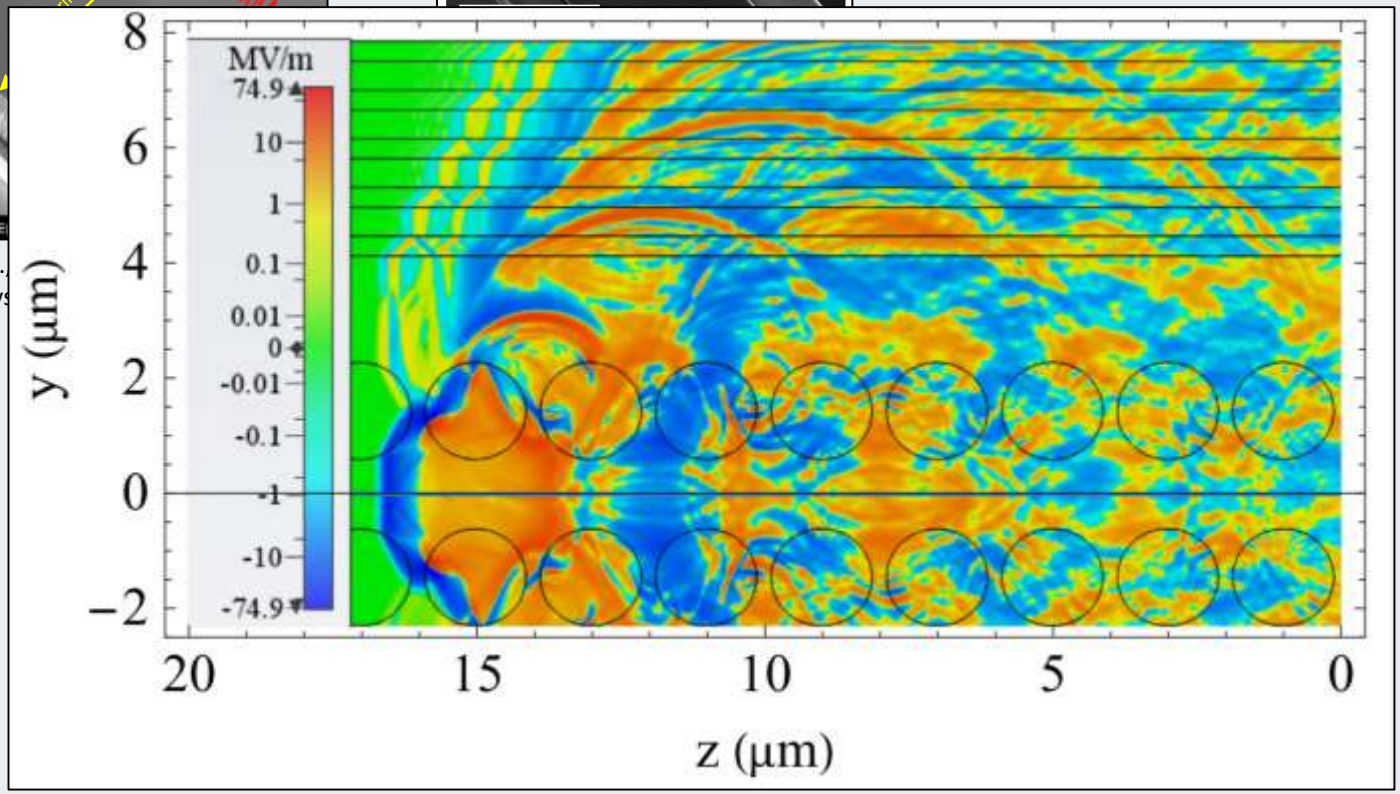
ACHIP: Accelerator on a Chip International Program

Wakefield calculations in DLA structures





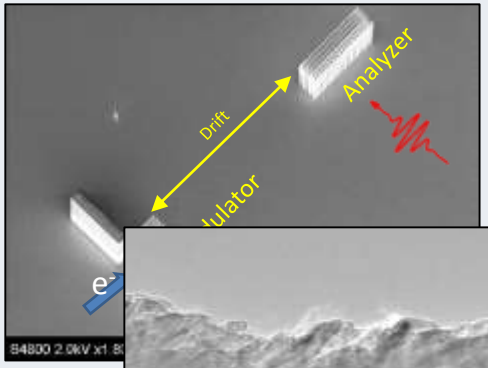
Schönenberger et al.,
Black et al., Phys



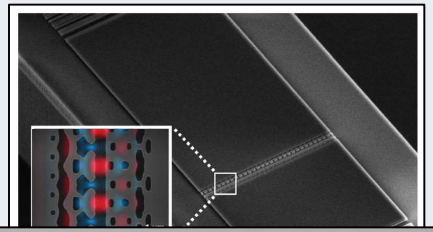
Egenolf et al., Phys. Rev. Accel. Beams **23**, 054402 (2020)

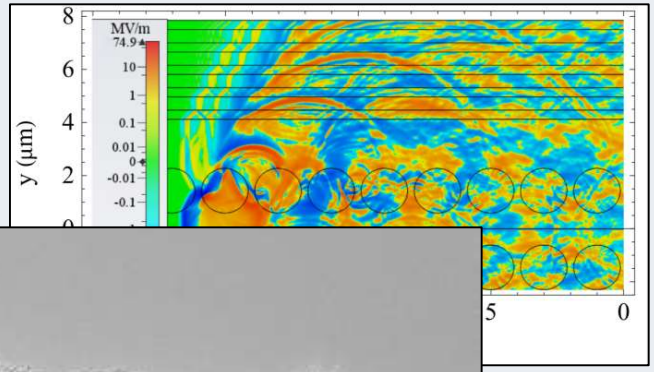
ACHIP: Accelerator on a Chip International Program

Diamond-coated needle-tips as high brightness sources

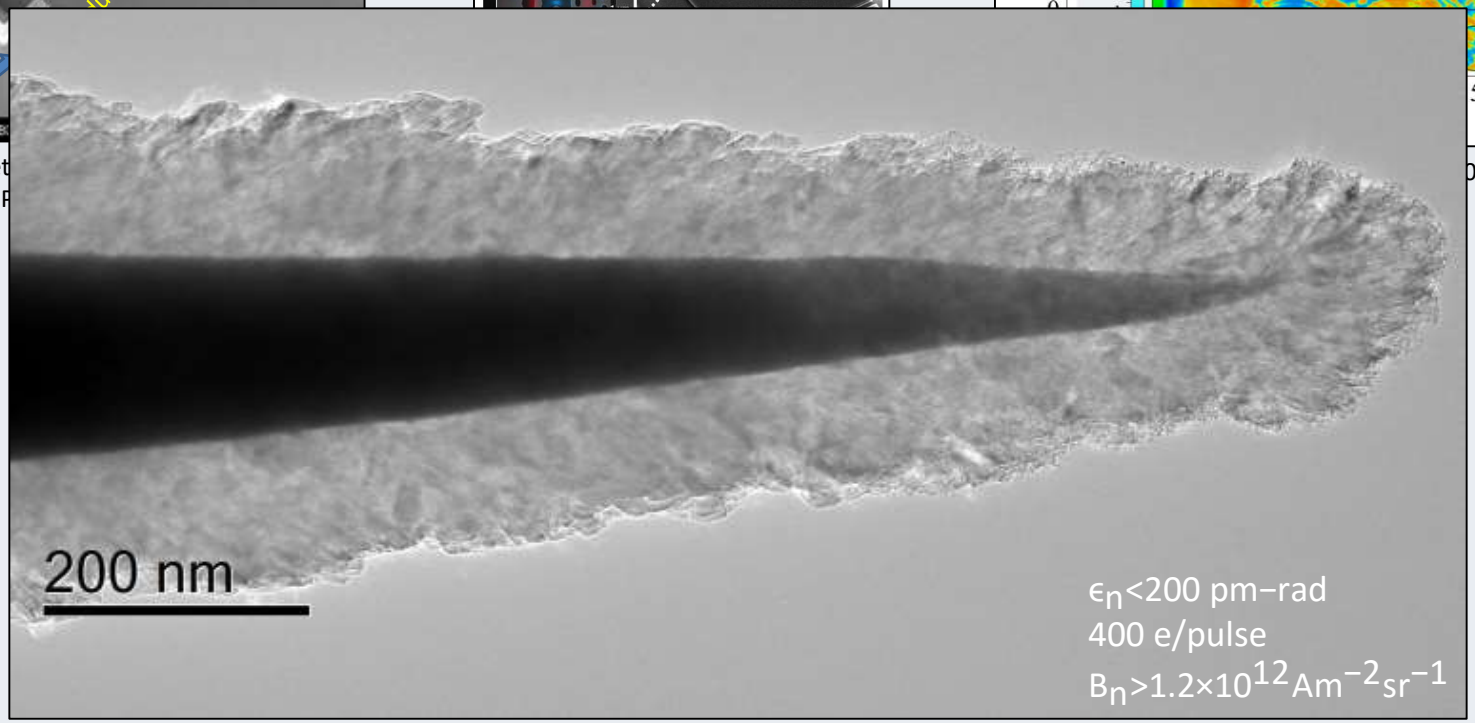


Schönenberger et
Black et al., P





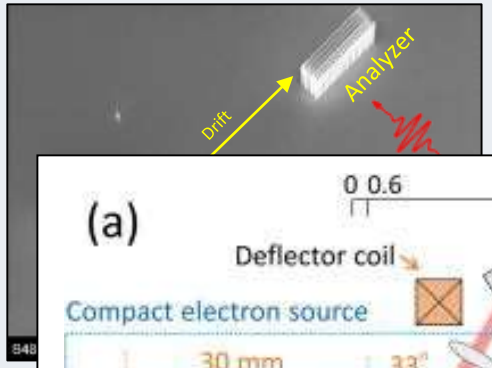
054402 (2020)

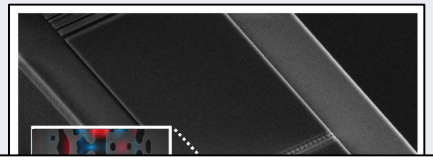


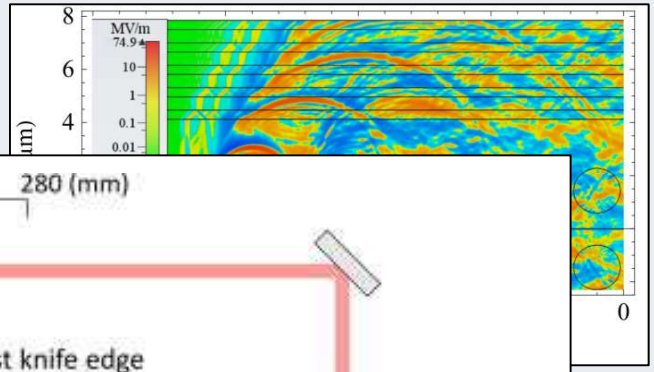
Tafel et al., Phys. Rev. Lett. **123**, 146802 (2019)

ACHIP: Accelerator on a Chip International Program

Compact 30kV electron source







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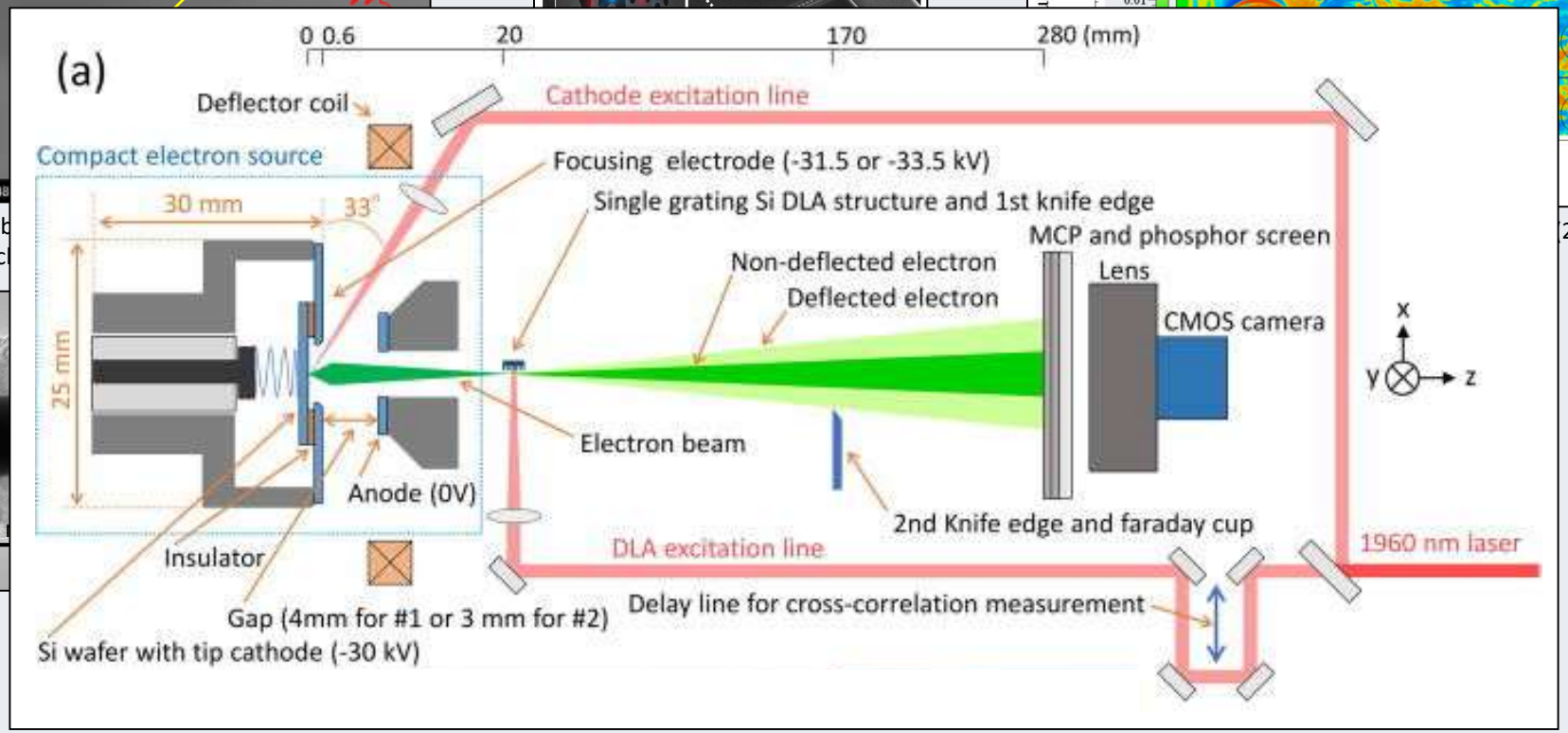
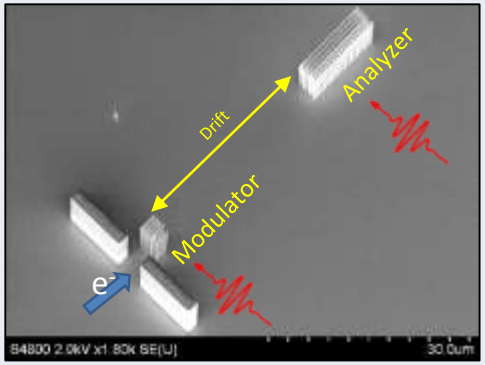


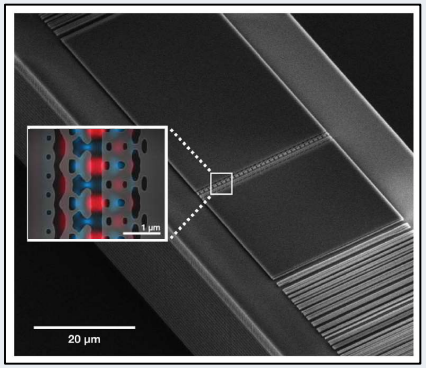
Hirano et al., Appl. Phys. Lett. **116**, 161106 (2020)

ACHIP: Accelerator on a Chip International Program

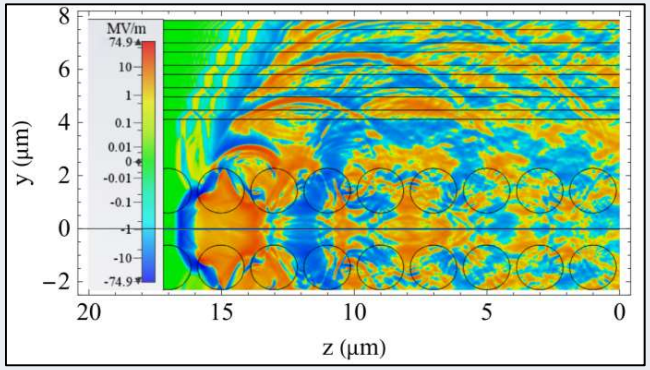
Laser-modulated 3 GeV electron beam in DLA



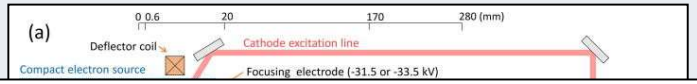
Schönenberger et al., Phys. Rev. Lett. **123**, 264803 (2019)
Black et al., Phys. Rev. Lett. **123**, 264802 (2019)

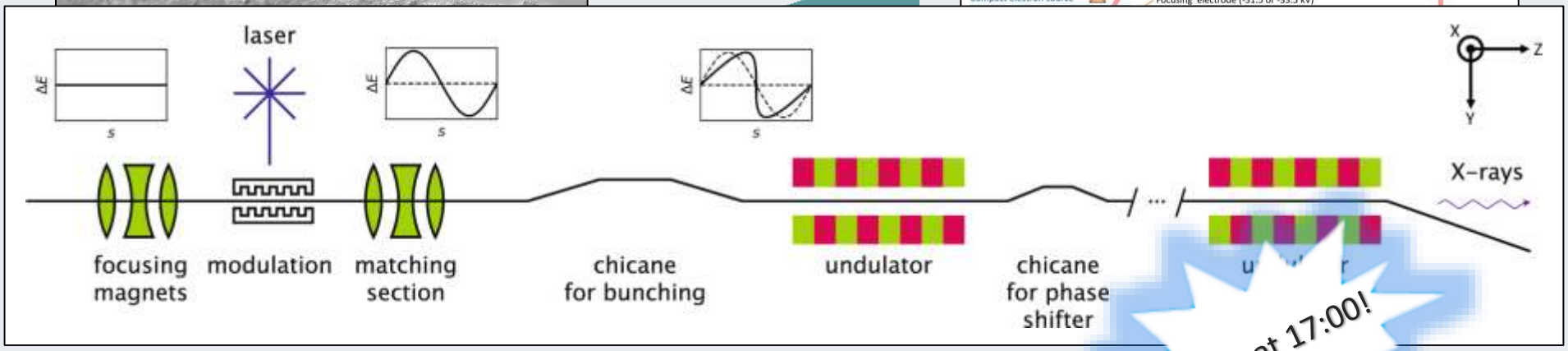


Sapra et al., Science, **367**, 79-83 (2020)



Egenolf et al., Phys. Rev. Accel. Beams **23**, 054402 (2020)



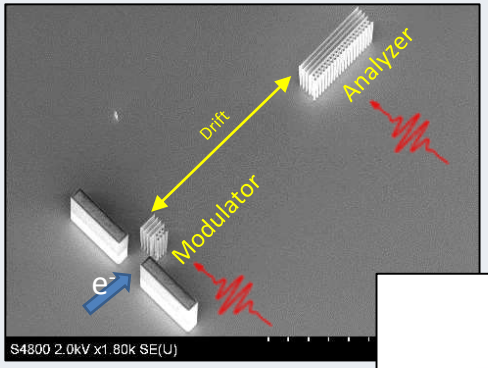


Hermann et al., Sci. Rep., **9**,19773 (2019)

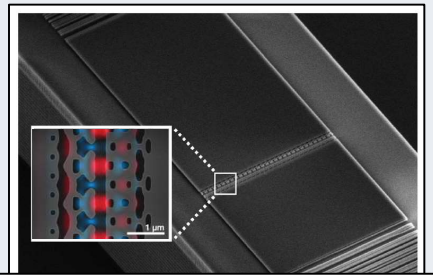
Today at 17:00!

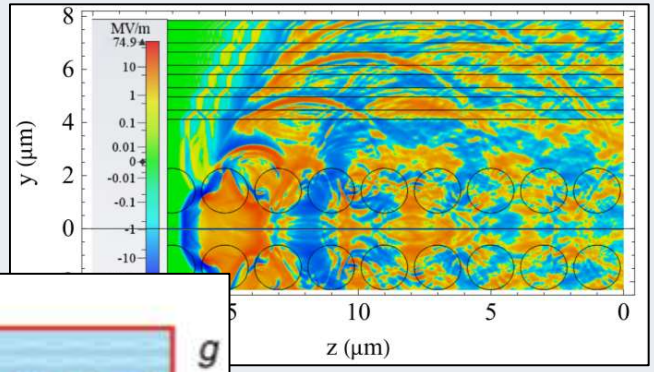
ACHIP: Accelerator on a Chip International Program

850 MeV/m average gradient at UCLA Pegasus

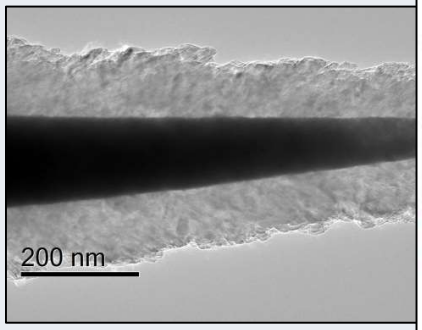


Schönenberger et al., Phys. Rev. Lett. **123**
Black et al., Phys. Rev. Lett. **123**, 264

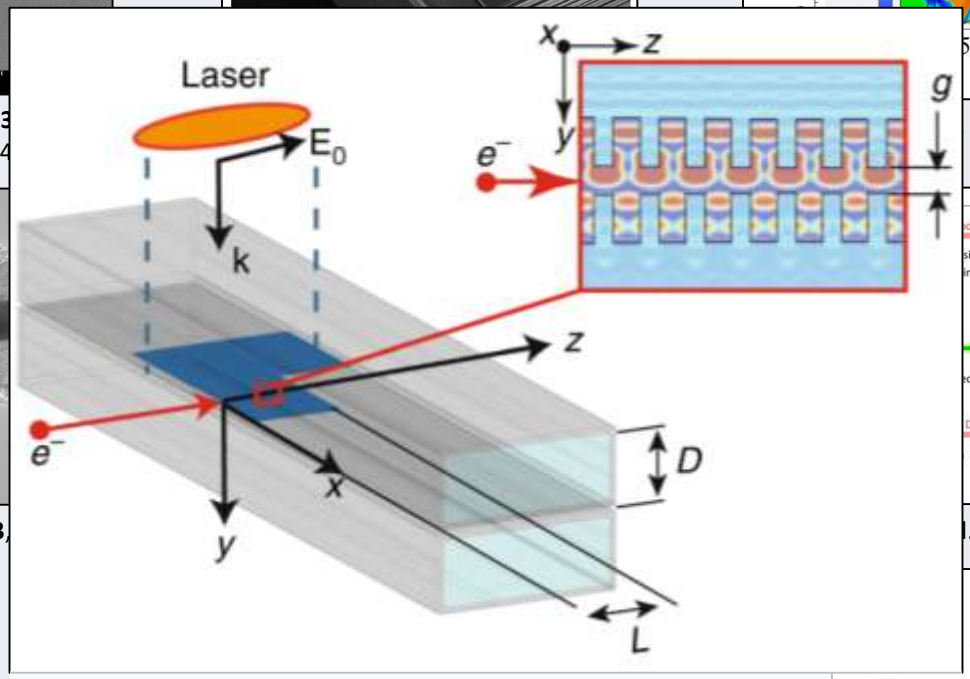




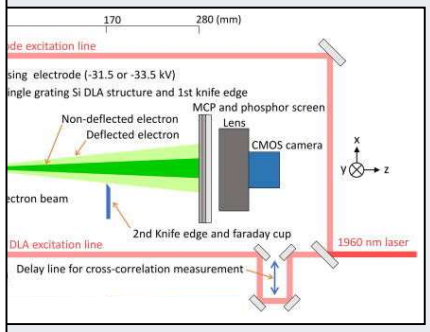
Rev. Accel. Beams **23**, 054402 (2020)



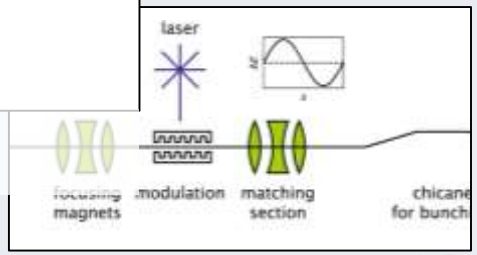
Tafel et al., Phys. Rev. Lett. **123**,



Cesar et al., Comm. Phys., **1**, 46 (2018)

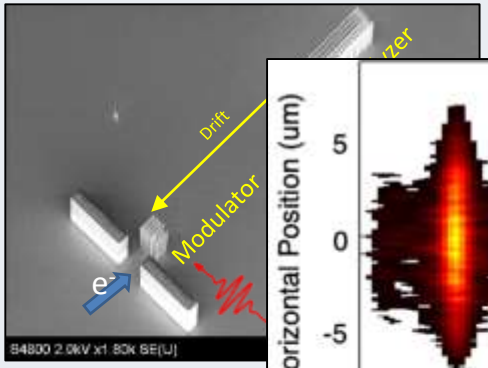


. Phys. Lett. **116**, 161106 (2020)

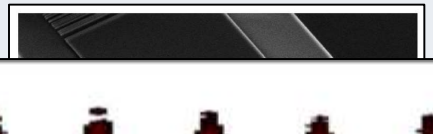


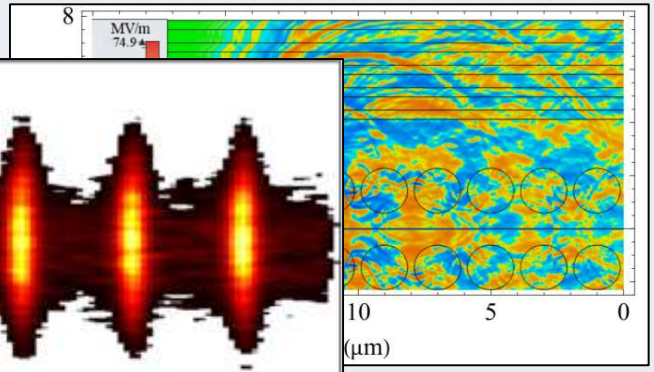
Hermann et al., Sci. Rep., **9**,19773 (2019)

ACHIP: Accelerator on a Chip International Program
DSEY/SINABD: planned acceleration experiments

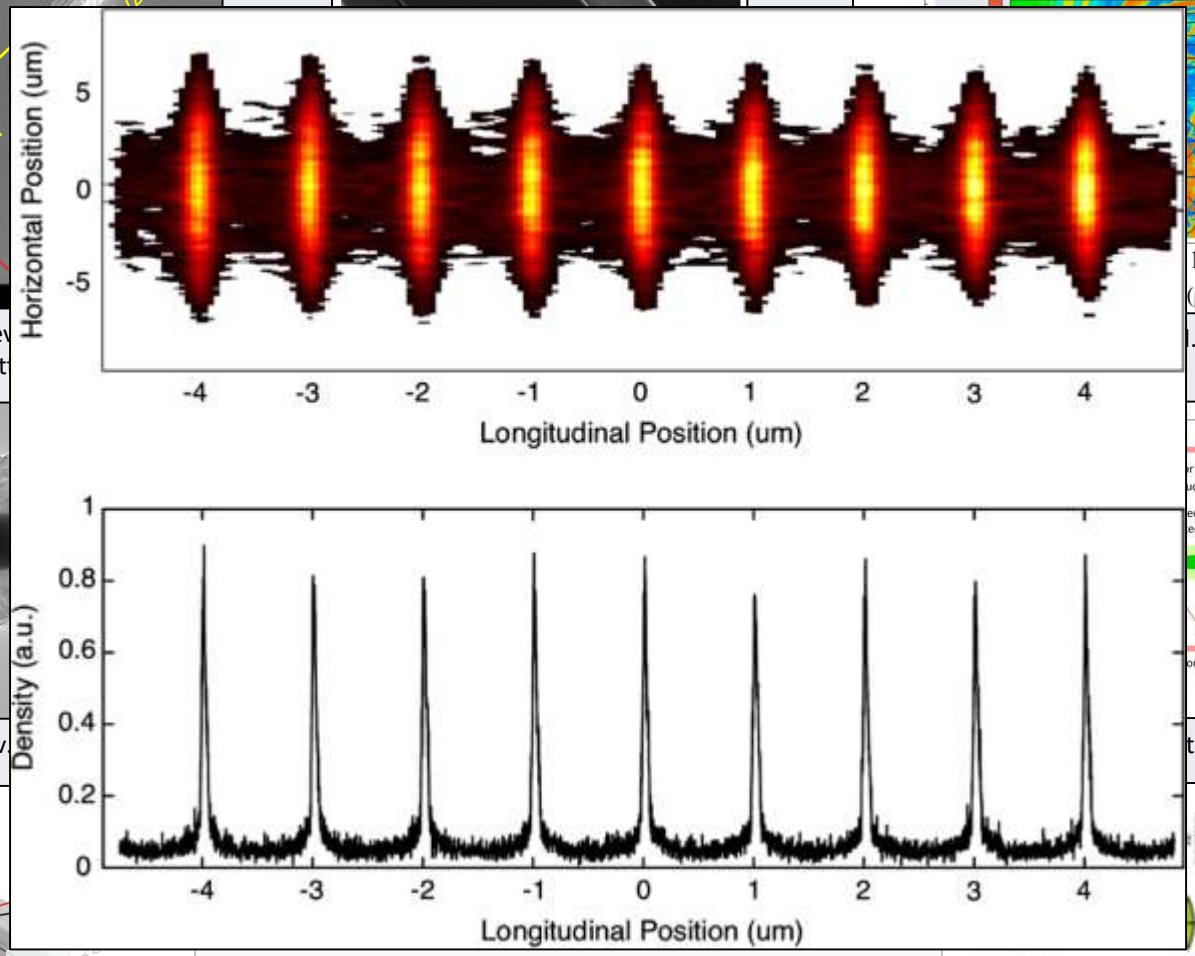


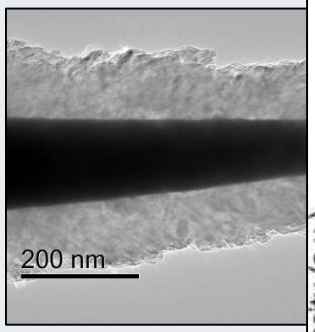
Schönenberger et al., Phys. Rev
Black et al., Phys. Rev. Let



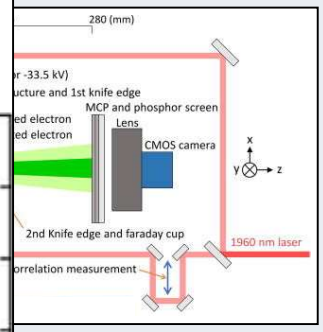


. Beams **23**, 054402 (2020)

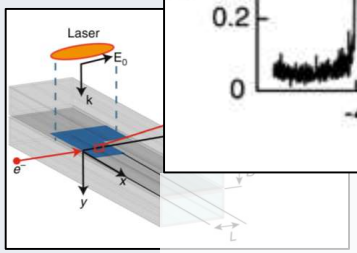




Tafel et al., Phys. Rev.

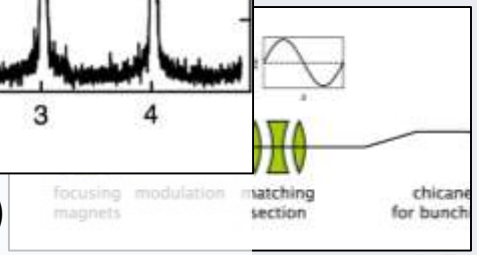


t. **116**, 161106 (2020)



Cesar et al., Comm. Phys., **1**, 46 (2018)

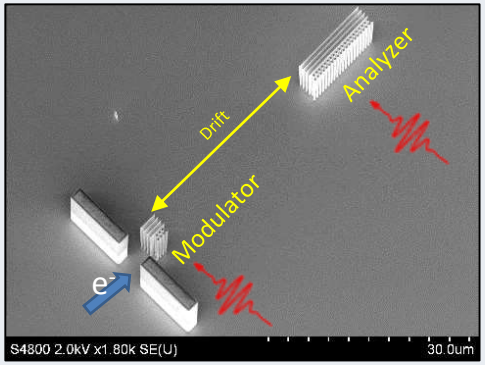
Mayet et al., NIMA **909**, 213-216 (2018)



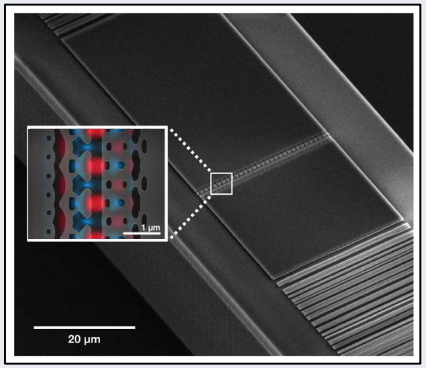
Hermann et al., Sci. Rep., **9**,19773 (2019)

ACHIP: Accelerator on a Chip International Program

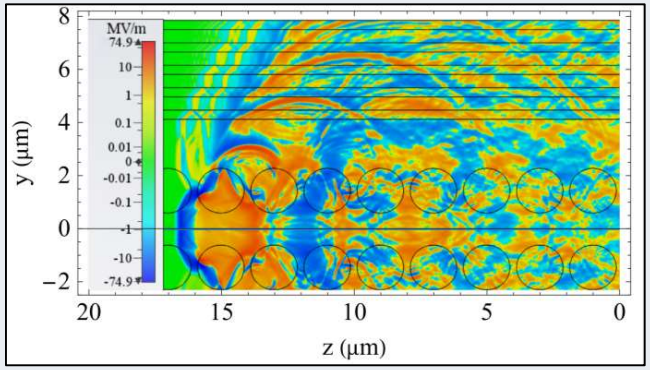
…and more!



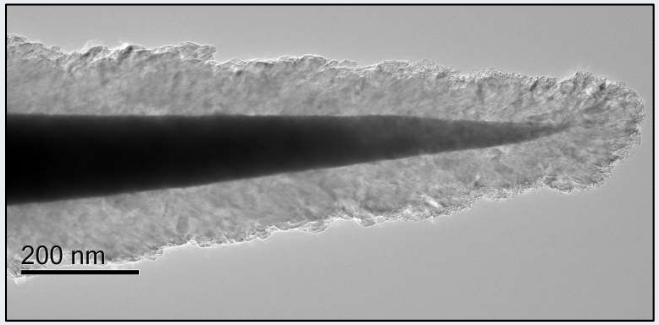
Schönenberger et al., Phys. Rev. Lett. **123**, 264803 (2019)
Black et al., Phys. Rev. Lett. **123**, 264802 (2019)



Sapra et al., Science, **367**, 79-83 (2020)

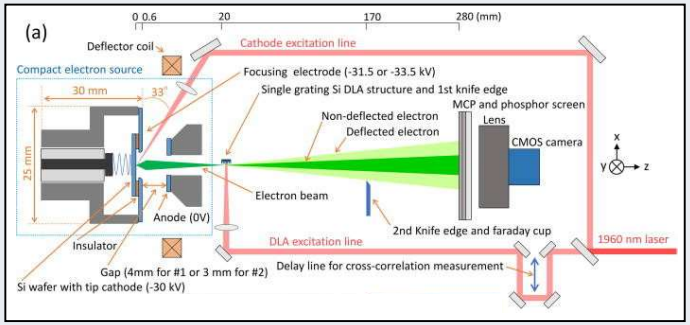


Egenolf et al., Phys. Rev. Accel. Beams **23**, 054402 (2020)

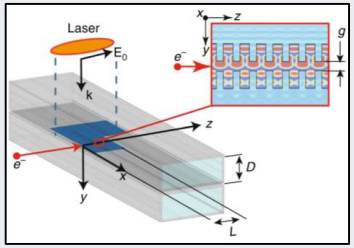


Tafel et al., Phys. Rev. Lett. **123**, 146802 (2019)

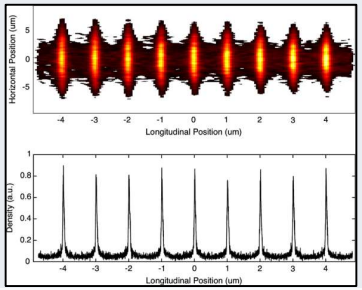
ACHIP



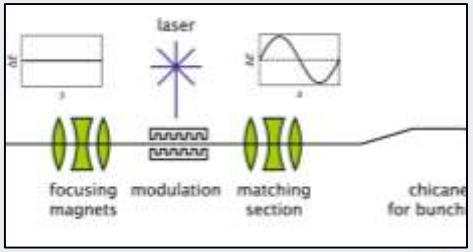
Hirano et al., Appl. Phys. Lett. **116**, 161106 (2020)



Cesar et al., Comm. Phys., **1**, 46 (2018)



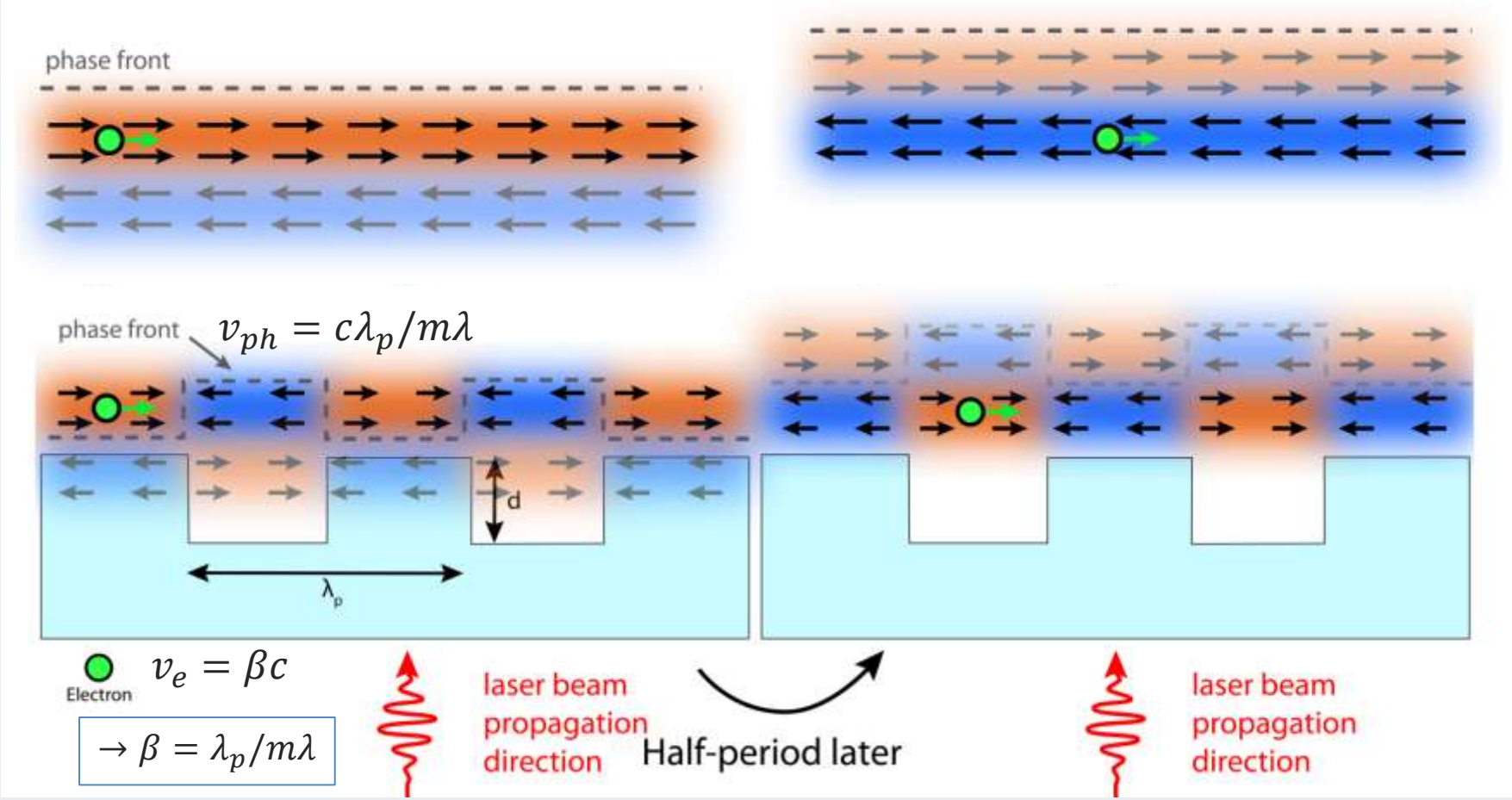
Mayet et al., NIMA **909**, 213-216 (2018)



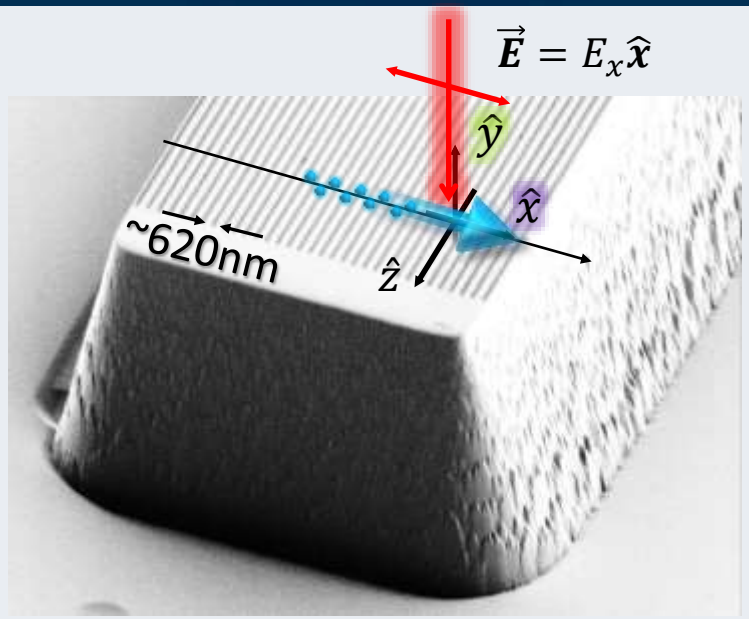
Hermann et al., Sci. Rep., **9**,19773 (2019)

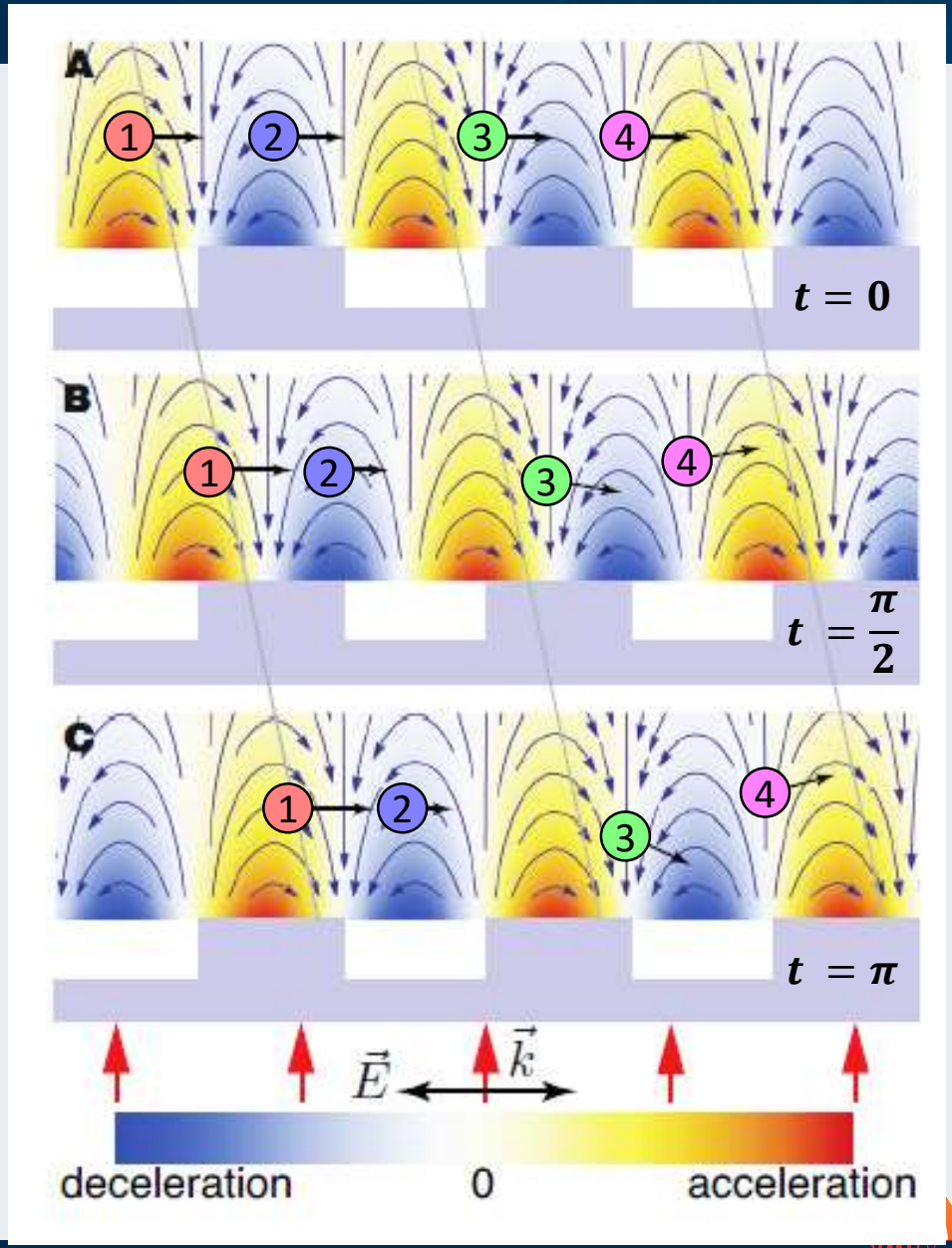
Phase-synchronous acceleration

(here with optical drive fields):



Phase-synchronous acceleration





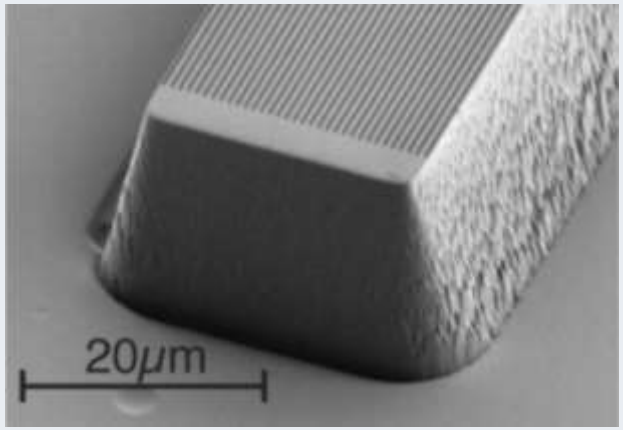
1 Acceleration

2 Deceleration

3 Deflection ("focusing")

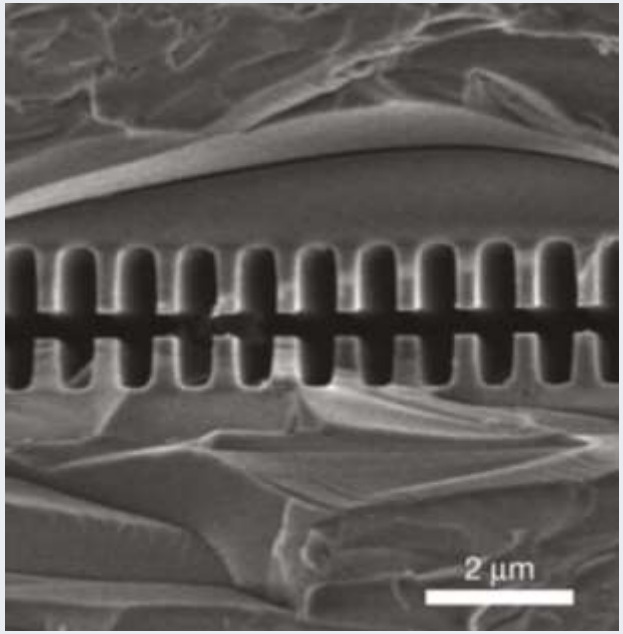
4 Deflection ("defocusing")

Structure evolution



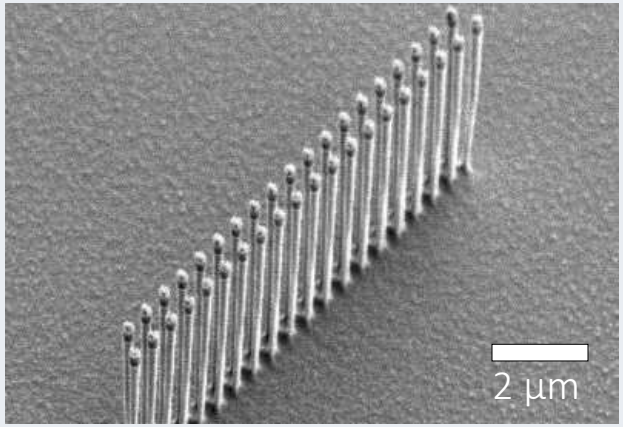
Breuer and Hommelhoff, PRL **111**, 134803 (2013)

- ✓ Simple fabrication
- ✗ Asymmetric field deflects electrons vertically



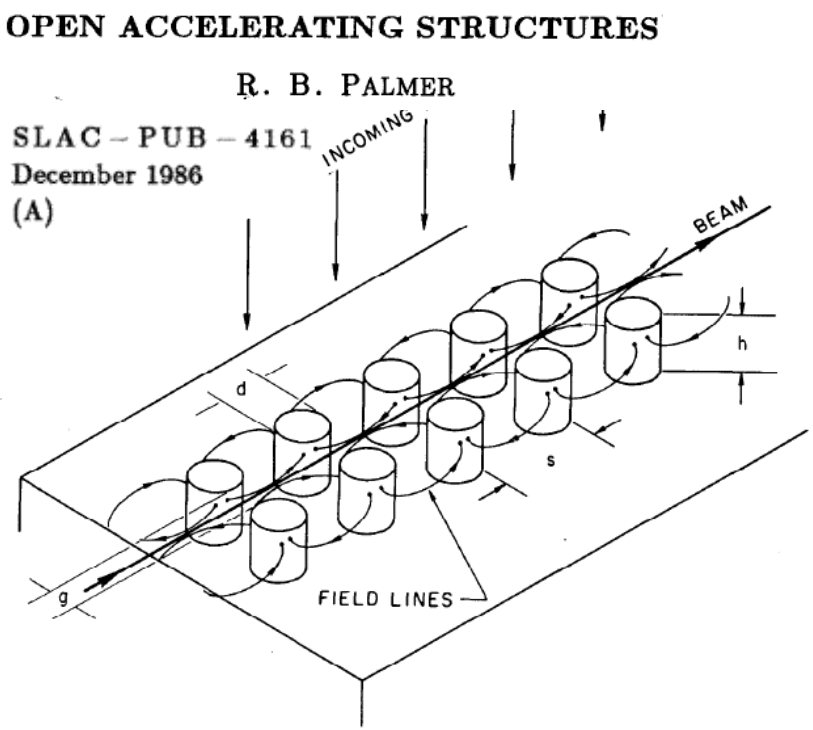
Peralta, et al. Nature **503**, 91-94 (2013)

- ✓ Symmetric field profile in the channel
- ✗ Fabrication (and alignment of wafers) difficult
- ✗ Laser must travel through bulk material

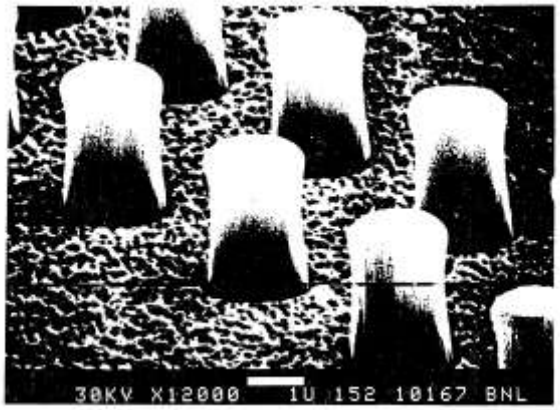


Leedle et al., Opt. Lett. 40, **18** (2015)
Yousefi et al., NIMA 909, **221** (2018)

Structure evolution



Palmer (1986)
SLAC-PUB-4161



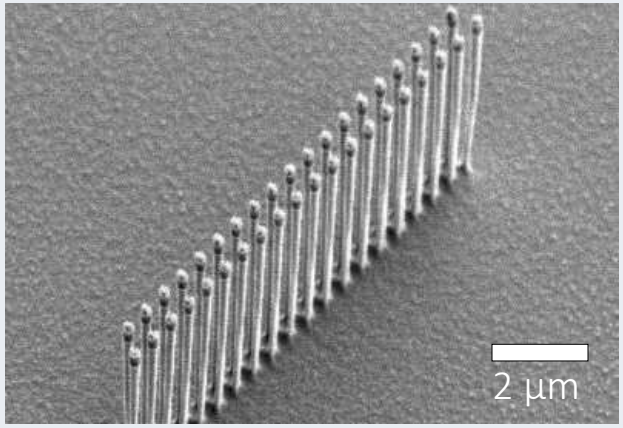
Chen… Palmer et. al. (1989)
BNL—43465 DE90 003699

Leedle et al., Opt. Lett. 40, **18** (2015)
Yousefi et al., NIMA 909, **221** (2018)

Structure evolution

„Dual pillar“ structure:

- ✓ Symmetric field profile in the channel
- ✓ Simple fabrication process (e-beam lithography + etching)
- ✓ No nonlinear optical effects (laser doesn‘t traverse the bulk)

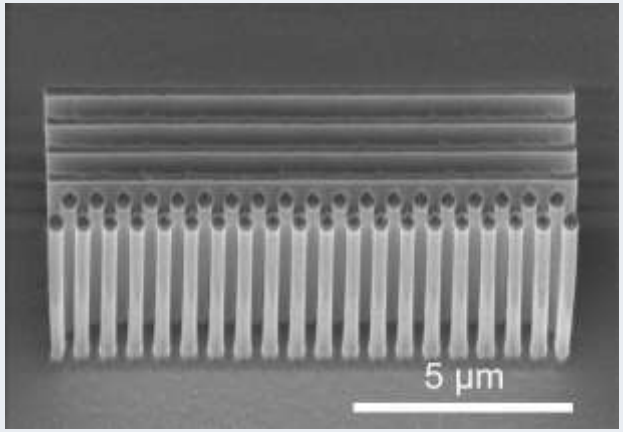


Palmer, SLAC-PUB-4161 (1986)
Leedle et al., Opt. Lett. 40, **18** (2015)
Yousefi et al., NIMA 909, **221** (2018)

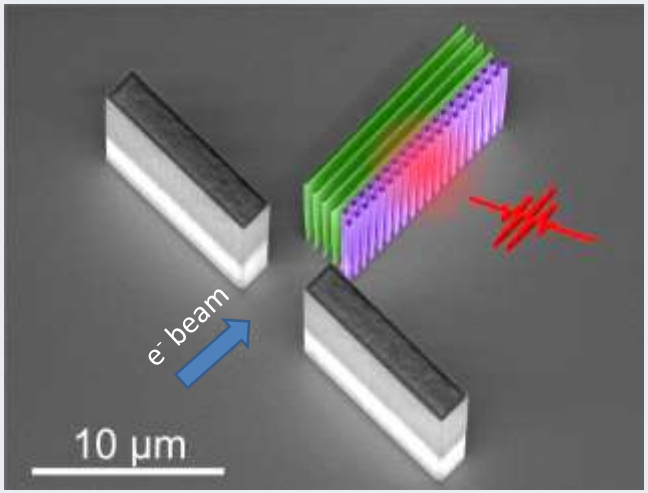
Dual pillar with a distributed Bragg reflector

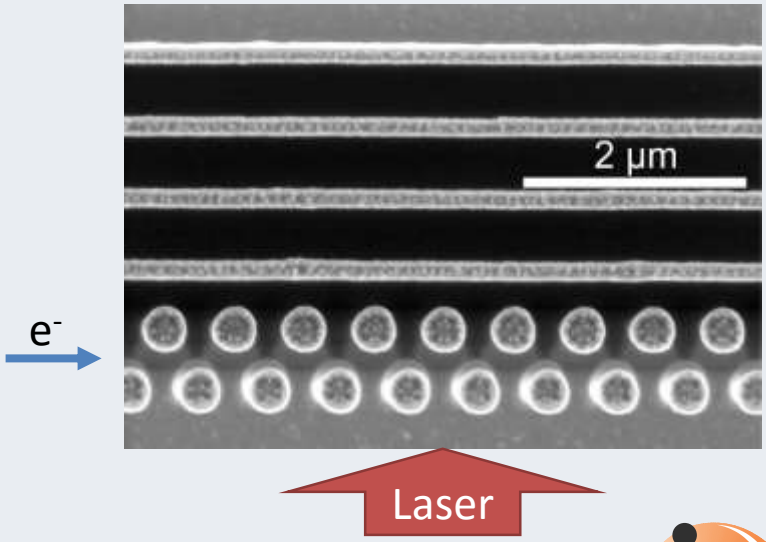
(For subrelativisic electrons, ~30keV)

Parameter	Size (nm)
Pillar period	660
Mirror spacing	500
Mirror plate thickness	144
Aperture width	225
Height	3000



Yousefi et al., NIMA **909**, 221 (2018)





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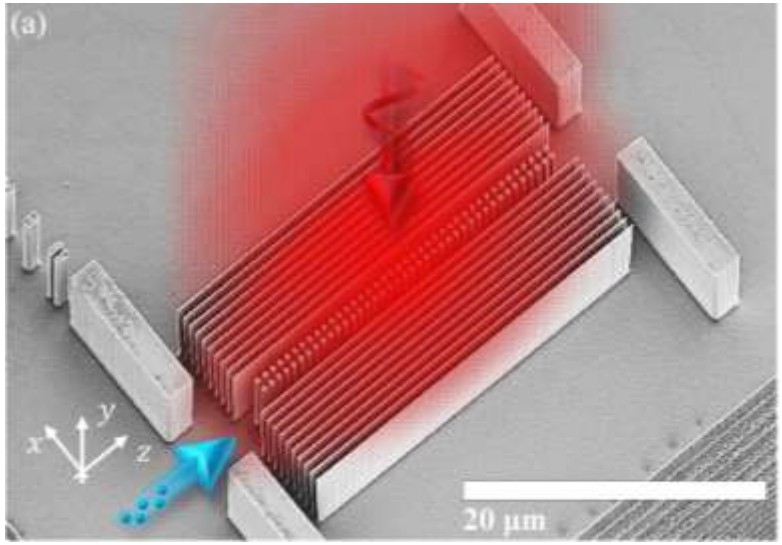
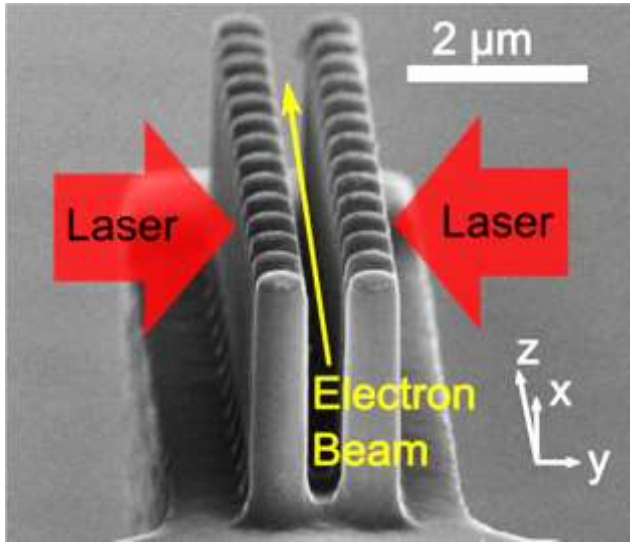


Shiloh, Chlouba, Yousefi, Hommelhoff
Opt. Exp. **29**, 14403 (2021)



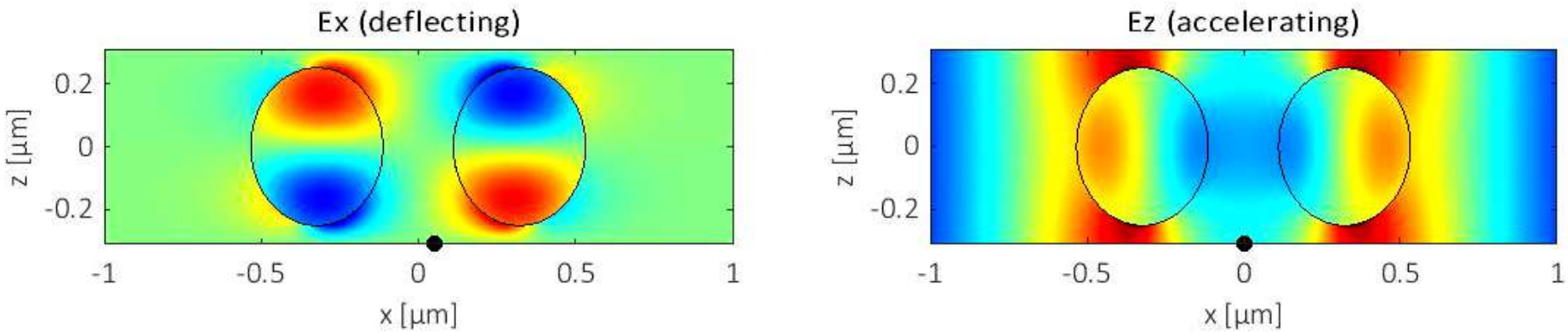
Leedle, Ceballos, Deng, Solgaard, Fabian-Pease,
Byer, Harris, Opt. Lett. **43**, 2181 (2018)

Yousefi et al., NIMA **909**, 221 (2018)

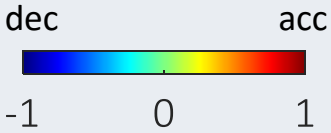
Laser

Full fields of a dual-pillar structure

- "Synchronous particle" experiences only an accelerating field



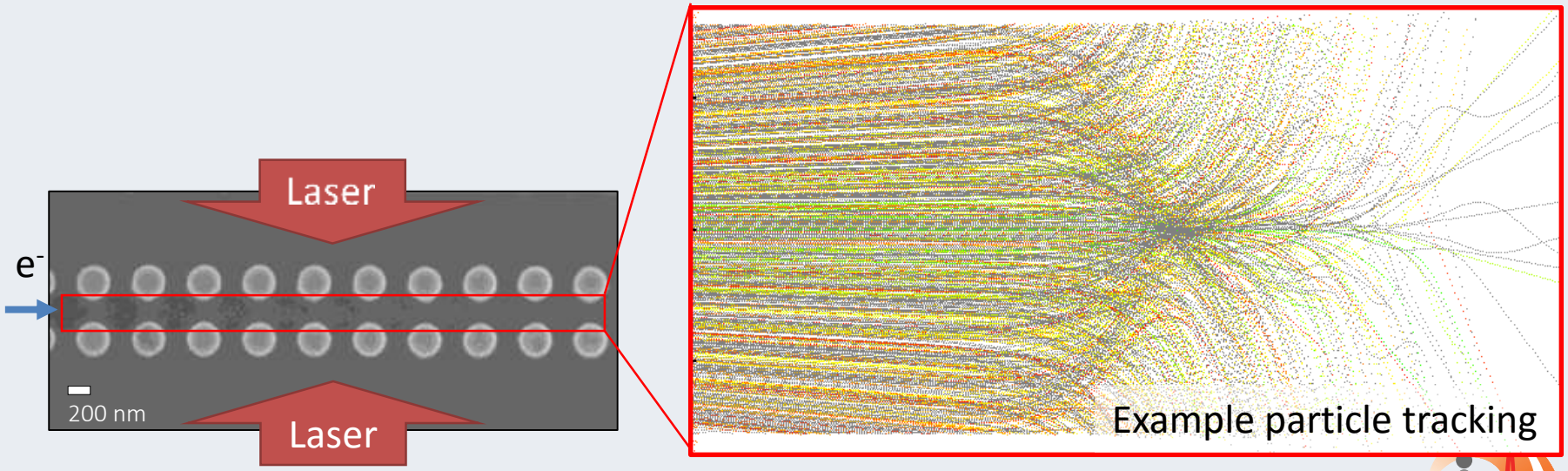
- Laser illumination: symmetric from both sides ($+\hat{\mathbf{x}}$ and $-\hat{\mathbf{x}}$)



Full fields of a dual-pillar structure

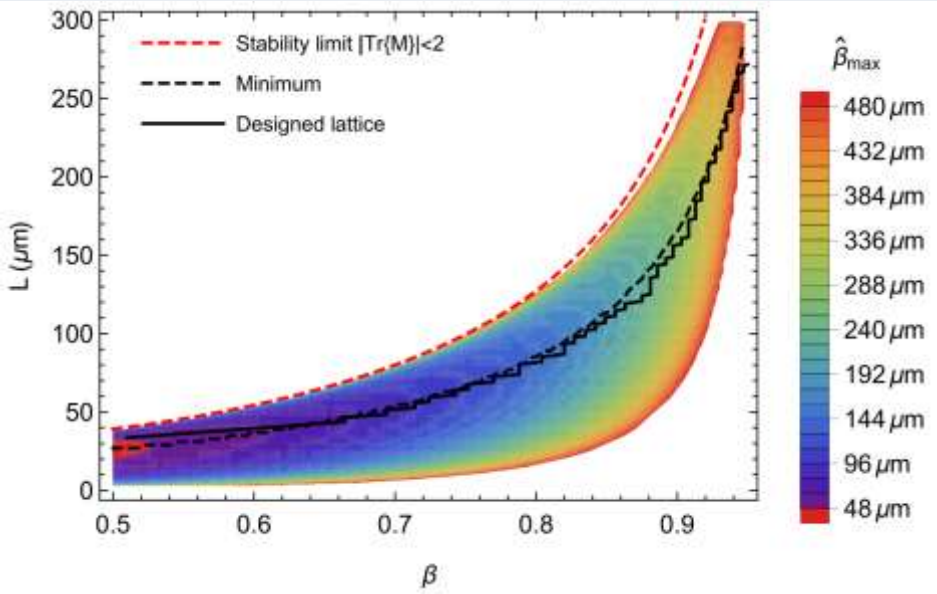
- "Synchronous particle" experiences only an accelerating field
- Deviation from synchronicity = transverse deflection (beam defocus)
- We're using near-field optical forces (recall: field strengths ~ 1GV/m)
- Conventional elements (quadrupoles, solenoids, einzel lenses, etc..) cannot compensate the optical defocusing forces

➢ A solution: **use engineered dielectric structures!**



Guiding with Alternating Phase Focusing

- Adapted (Fainberg 1956) to dielectric laser acceleration under ACHIP
- In a nutshell: once the electron beam begins to defocus, flip the laser's phase, so **alternate between focusing forces and defocusing forces**
- In practice: gaps are introduced periodically along the structure
- Much like designing a FODO lattice, except alternate between *longitudinal* and one transverse directions (z−x here)
- The APF lattice period adjusted to beam energy + maximum beam envelope fits in the channel.



Niedermayer, Egenolf, Boine-Frankenheim, Hommelhoff, Phys. Rev. Lett. **121**, 214801 (2018)

Guiding with Alternating Phase Focusing

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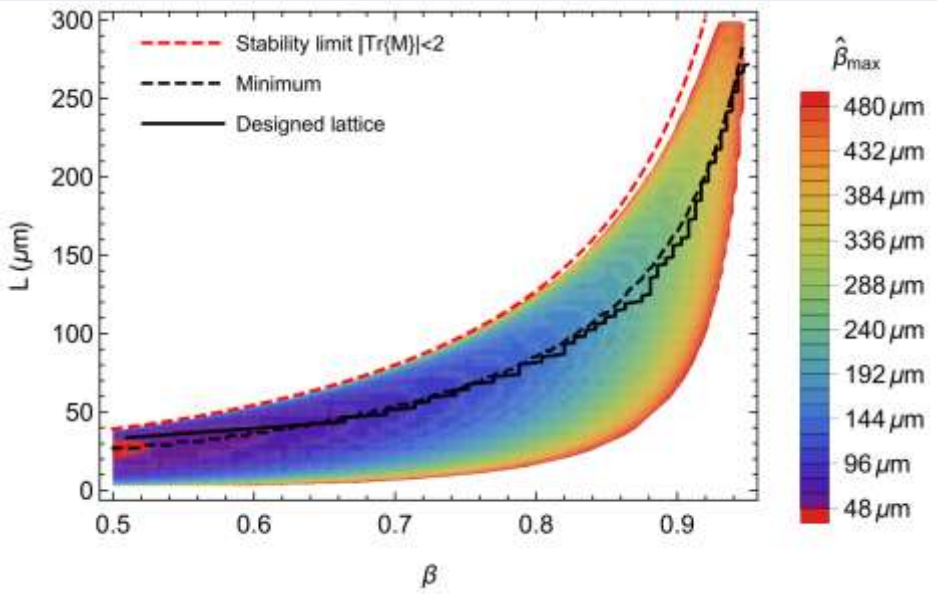


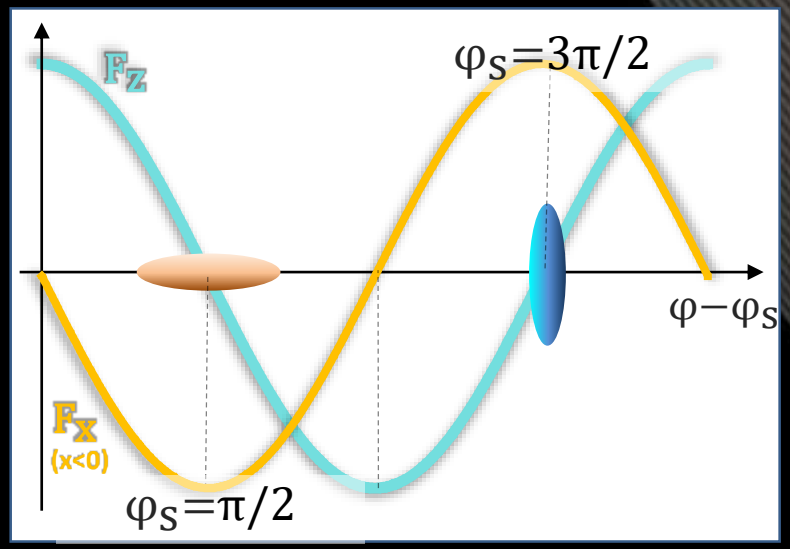
➢ ***NEXT*: beam transport with APF (no acceleration)**

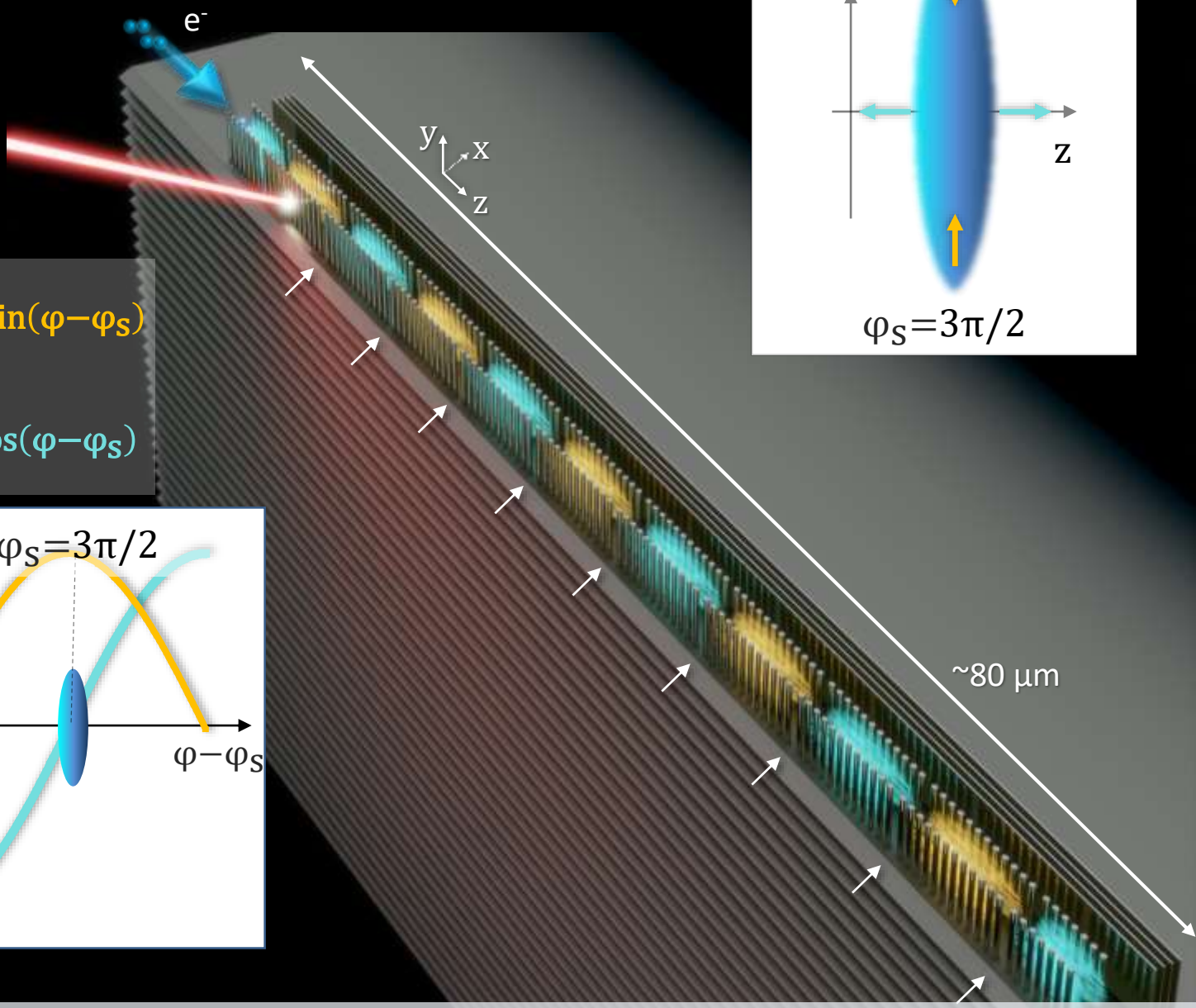
Niedermayer, Egenolf, Boine-Frankenheim, Hommelhoff, Phys. Rev. Lett. **121**, 214801 (2018)

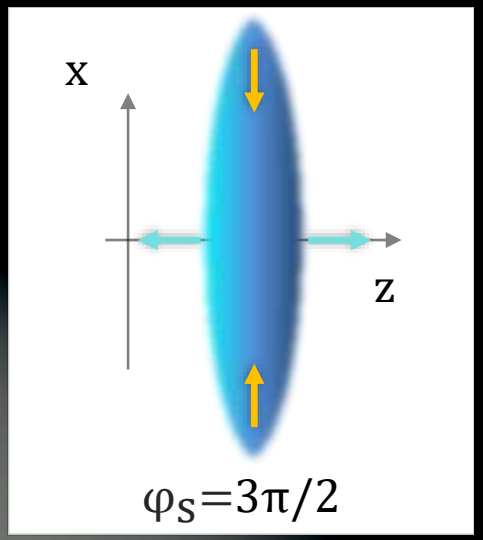
Guiding with Alternating Phase Focusing

$$F_x = \frac{qc}{\beta\gamma} C_C \frac{1}{\gamma} \sinh(k_x x) \sin(\varphi - \varphi_s)$$

$$F_z = \frac{qc}{\beta\gamma} C_C \cosh(k_x x) \cos(\varphi - \varphi_s)$$

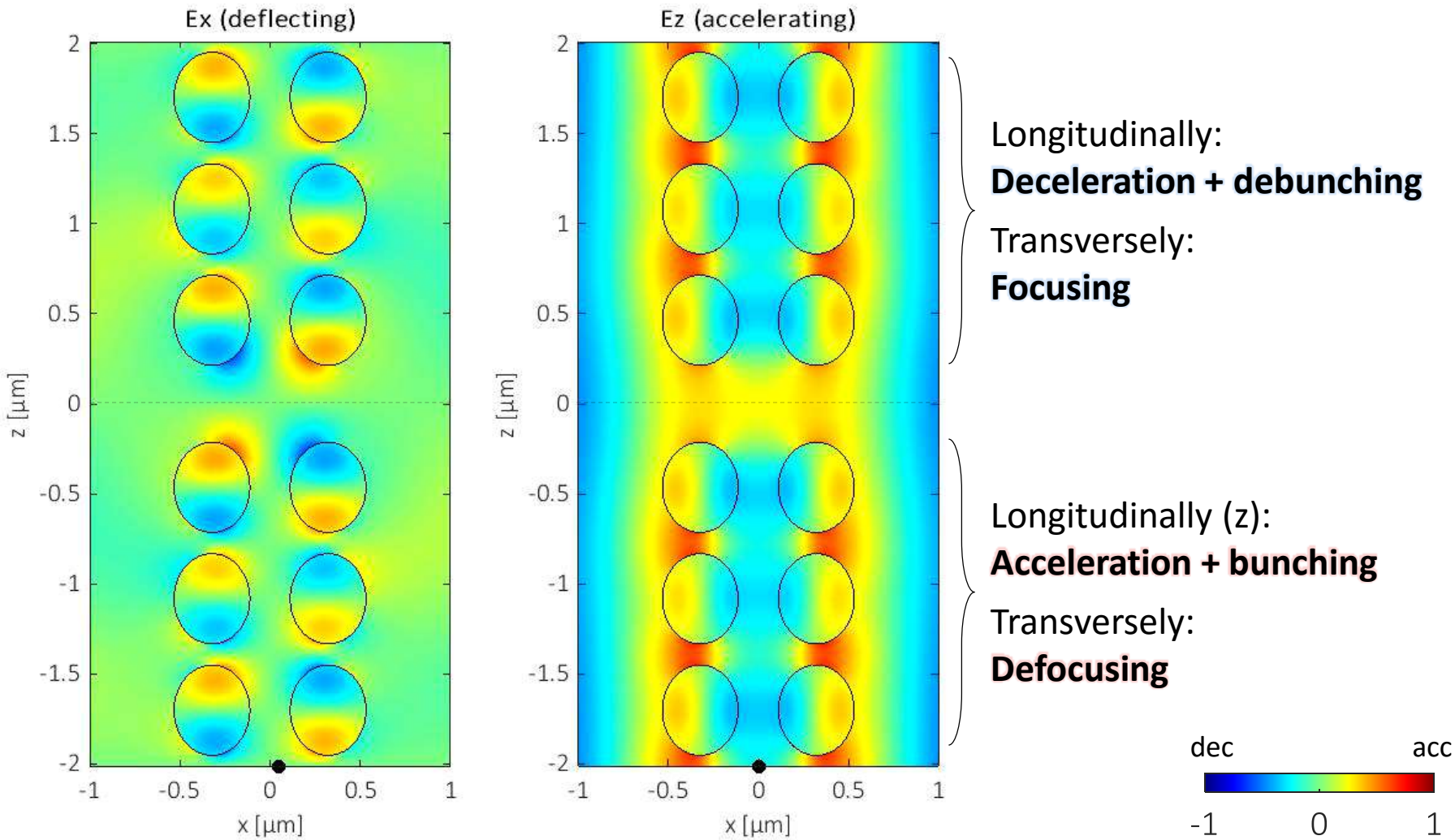






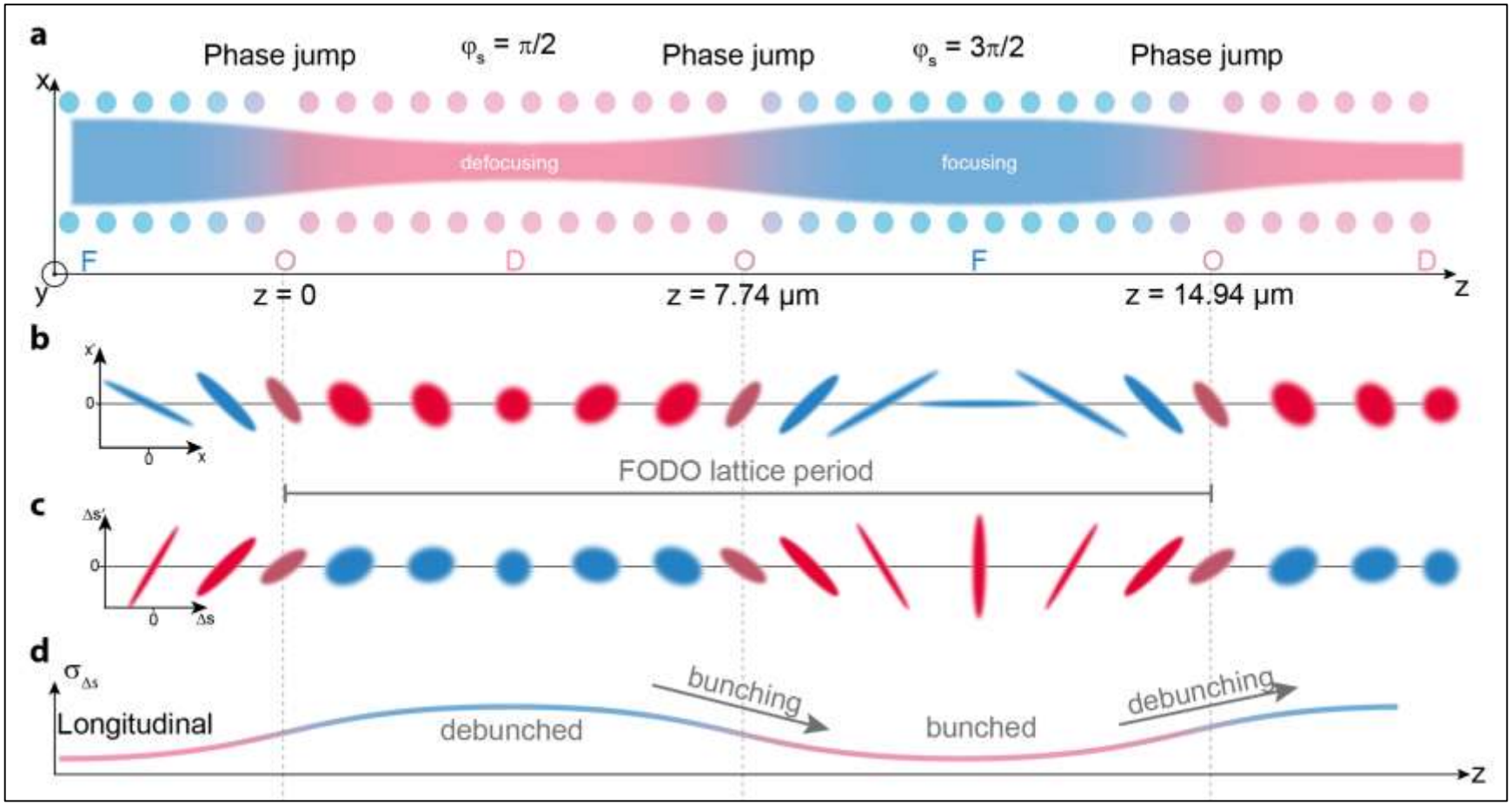
Artwork: Johannes Illmer

Guiding with Alternating Phase Focusing



Shiloh†, Illmer†, Chlouba†, Yousefi, Schönenberger, Niedermayer, Mittelbach, Hommelhoff, Nature, in press

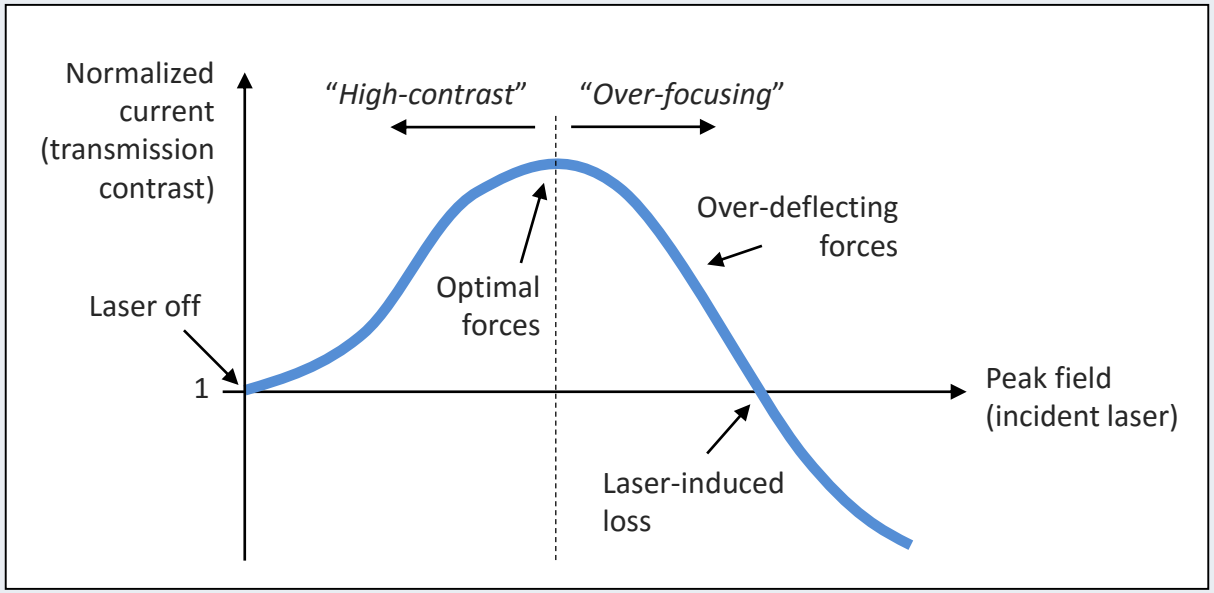
Guiding with Alternating Phase Focusing



Shiloh†, Illmer†, Chlouba†, Yousefi, Schönenberger, Niedermayer, Mittelbach, Hommelhoff, Nature, in press

Guiding with Alternating Phase Focusing - experiment

- What do we expect from an experiment?

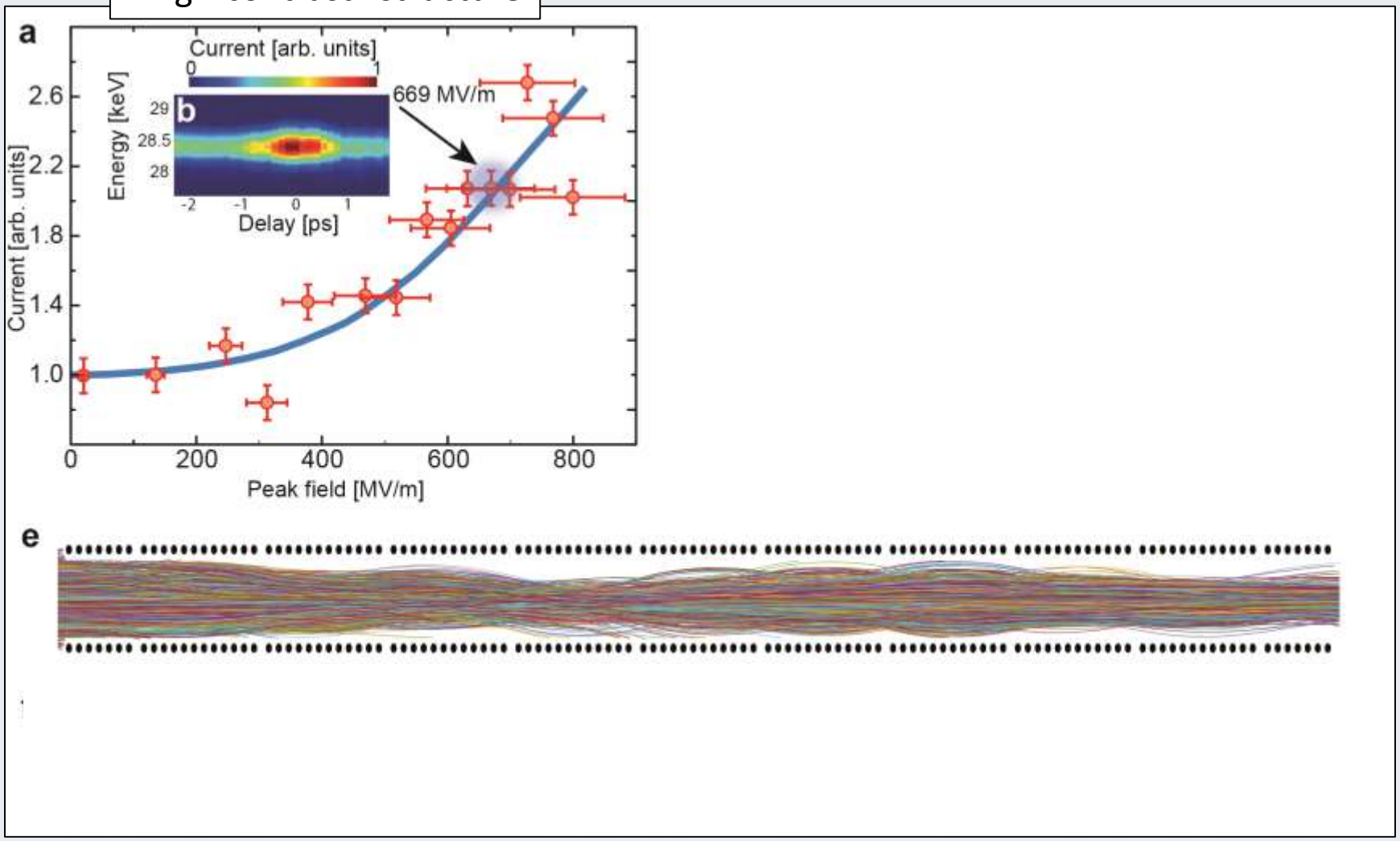


- Low incident peak fields: electron transmission grows
- Medium incident peak fields: transmission peaks
- High incident peak fields: transmission deteriorates

Shiloh†, Illmer†, Chlouba†, Yousefi, Schönenberger, Niedermayer, Mittelbach, Hommelhoff, Nature, in press

Guiding with Alternating Phase Focusing - experiment

"High-contrast" structure

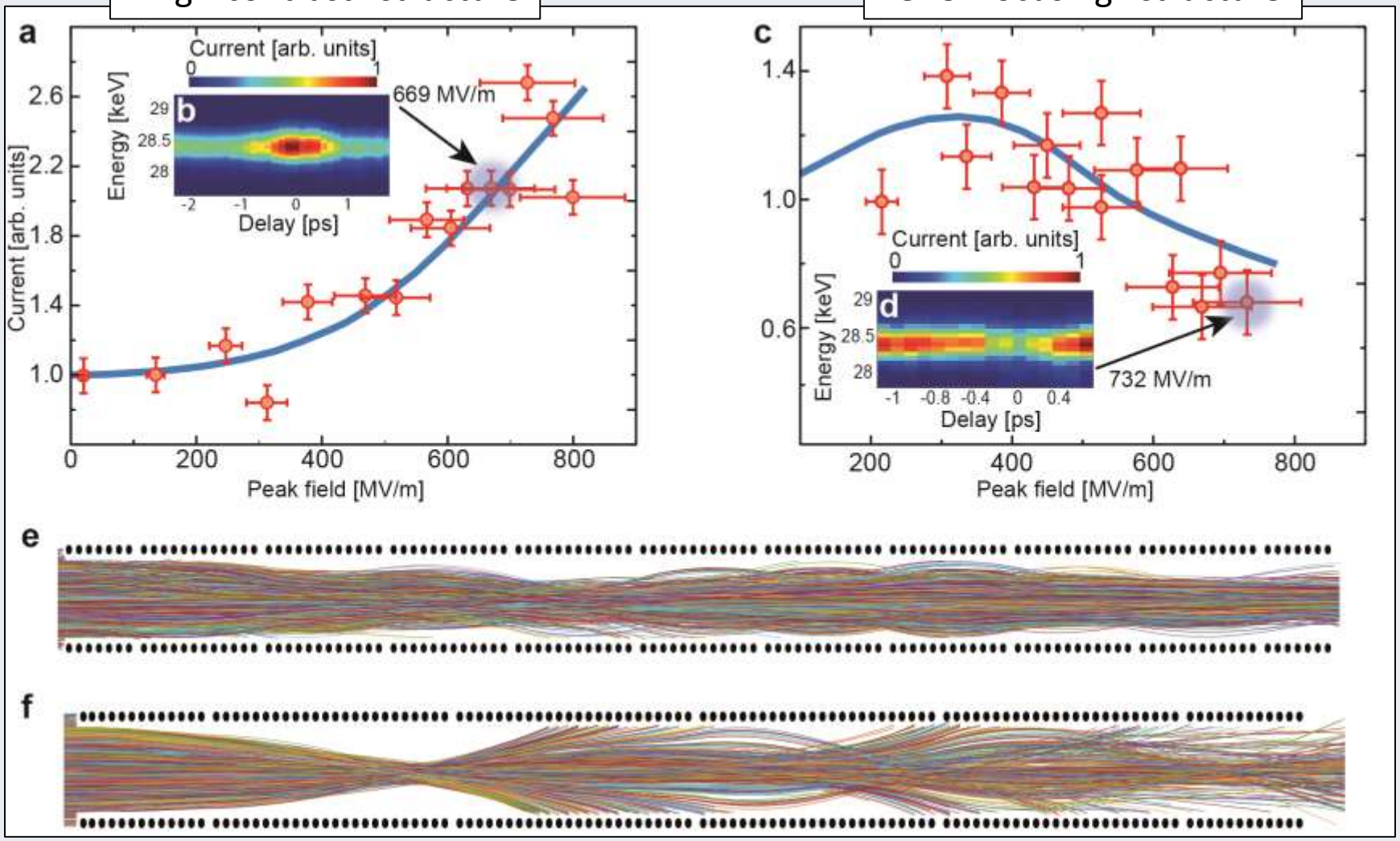


Shiloh†, Illmer†, Chlouba†, Yousefi, Schönenberger, Niedermayer, Mittelbach, Hommelhoff, Nature, in press

Guiding with Alternating Phase Focusing - experiment

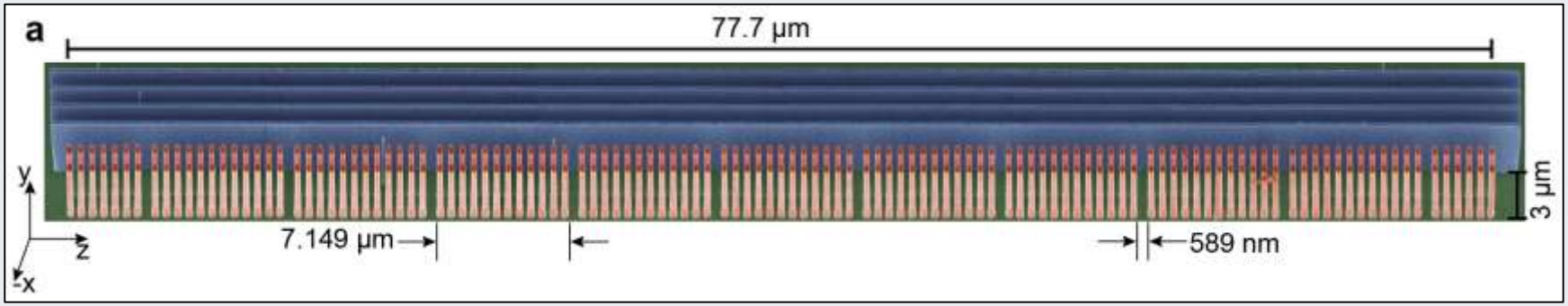
"High-contrast" structure

"Over-focusing" structure



Shiloh†, Illmer†, Chlouba†, Yousefi, Schönenberger, Niedermayer, Mittelbach, Hommelhoff, Nature, in press

Guiding with Alternating Phase Focusing - experiment



<u>Structure parameters</u>

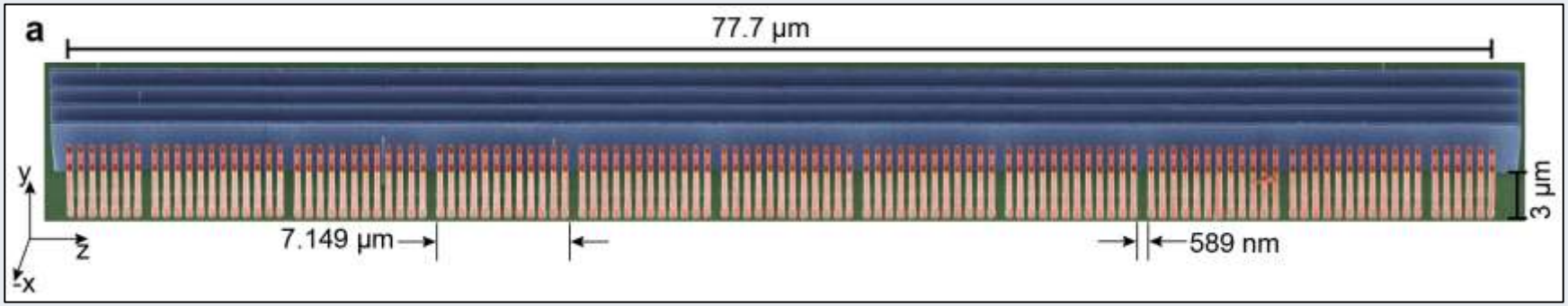
Channel width x length:	225 nm x ~77 µm
FODO periods:	5 (high-contrast) / 2.5 (over-focusing)
Phase jumps:	10 (high-contrast) / 5 (over-focusing)

<u>Electron beam properties</u>

Mean electron energy:	28.4 keV
Normalized emittance:	100 pm-rad
Electron pulses:	400-600 fs (FWHM)
Repetition rate:	167 kHz

Shiloh†, Illmer†, Chlouba†, Yousefi, Schönenberger, Niedermayer, Mittelbach, Hommelhoff, Nature, in press

Guiding with Alternating Phase Focusing - experiment



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Electron pulses:	400-600 fs (FWHM)
Repetition rate:	167 kHz
Beam current:	0.133 fA or 0.005 electron per pulse throughput
	(NOT indicative of future prospects)

Shiloh†, Illmer†, Chlouba†, Yousefi, Schönenberger, Niedermayer, Mittelbach, Hommelhoff, Nature, in press

Average beam current in DLAs

Starting from the source:

- Simply increase the laser RR (167 kHz -> 1 MHz or even 100 MHz)
- Previously in our SEM: up to 1000 e/pulse at the tip emitter -> ~1-10 e/pulse at the sample [*Kozák et al., J. of App. Phys.* ***124****, 023104 (2018)*]
- Dedicated compact 30 kV source for DLA: 28 e/pulse [*Hirano et al., Appl. Phys. Lett.* ***116****, 161106 (2020)*]
- High-brightness needle sources – Tungsten+diamond, LaB_6 nanowire, diamond pyramids, Silicon nanotips offer up to 12000 e/pulse with different parameters [*A. Ceballos, DLA Applications Workshop, March 26 (2019)]*
- Schemes for parallelization of DLA structures: x10, x100, x1000 channels… [*Zhao et al., Photonics Research* ***8*** *10, 1586-1598 (2020)*]

More points:

- Though the average current is low, with attosecond bunching abilities we can reach high peak currents – potentially even up to kA
- Recall that DLAs don't have to be a stand-alone solution, and can be integrated into small or large facilities (less worries about the source)

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Open positions! Pls. get in touch.

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Conclusion and outlook

Nanophotonics-based particle acceleration

- All individual elements for an accelerator demonstrated
- Peak gradient of close to 1 GeV/m demonstrated
- Waveguide-integrated feeding demonstrated
- Inverse photonics structure design demonstrated
- Net energy gain demonstrated
- Attosecond bunch train generation demonstrated
- Complex electron phase space control demonstrated: alternating phase focusing
- Design proposal of an on-chip accelerator: Niedermayer et al., Phys. Rev. App. 16, 024022 (2021)

❖ Soon: 1 MeV accelerator on a chip?
❖ New light sources, new medical devices?
❖ Attosecond / zeptosecond pulses feasible: e- based imaging
❖ Soon: more experiments at 100 MeV (at DESY) and 3 GeV (at PSI)