Coherent nanophotonic electron accelerator

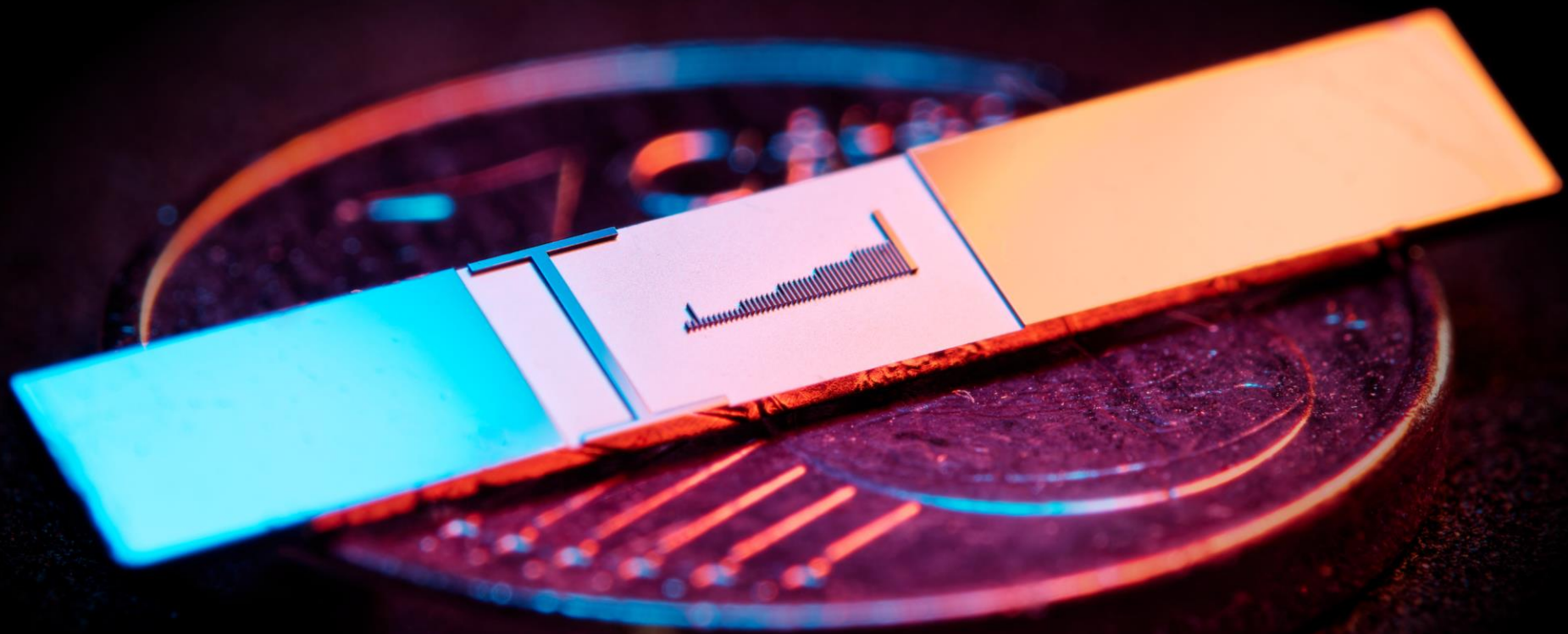


Image credits: J.Litzel, S.Kraus

J. Litzel, L. Brückner, T. Chlouba, J. Freier, M. Konrad, S. Kraus, I. Probst , T. Shibuya, R. Shiloh and P. Hommelhoff

Friedrich-Alexander-University Erlangen-Nürnberg (FAU)

MAX PLANCK INSTITUTE
FOR THE SCIENCE OF LIGHT

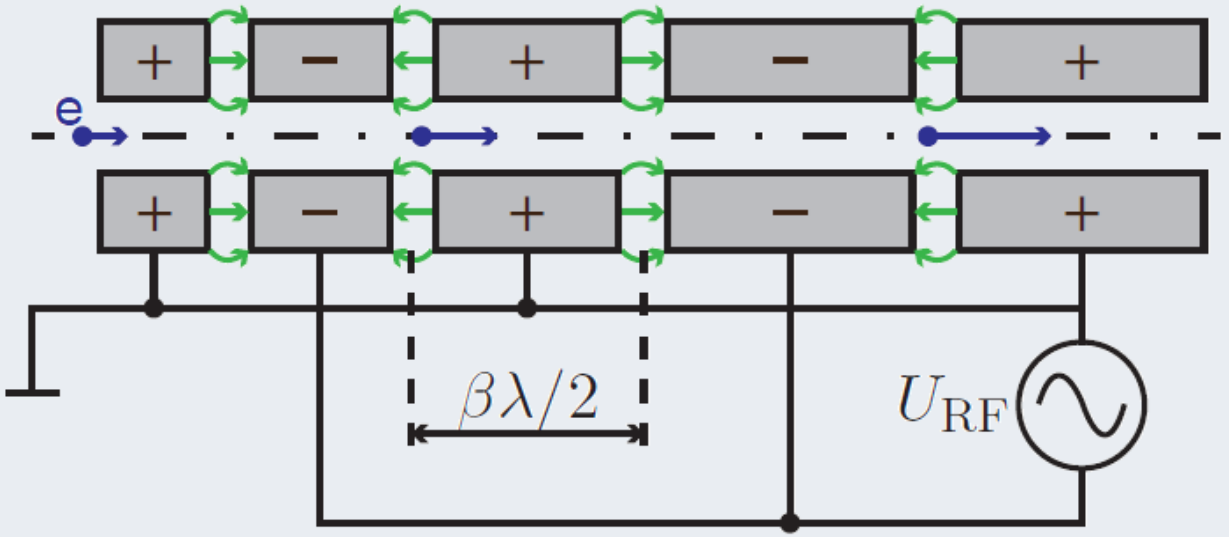
FAU Friedrich-Alexander-Universität
Faculty of Sciences

LINAC 2024 CHICAGO

Widerøe linac – realized with laser fields

Proposals to employ lasers in similar (structure-based) schemes:
Shimoda, Applied Optics 1962
Lohmann, IBM Technical Note, 1962
Lohmann, Patent 1966
Takeda, Matsui, NIMB 1968

First experimental demonstration with mm wave and metal structure (keV/m):
Mizuno et al., Nature 1987
Propsoal dielectrics: Rosenzweig et al., PRL 1995
Huang et al. (Byer group), APL 1996
Optical field-based exp. at vacuum boundary: Plettner, Byer, PRL 2005



Gustav Ising, 1924
Rolf Widerøe, 1928

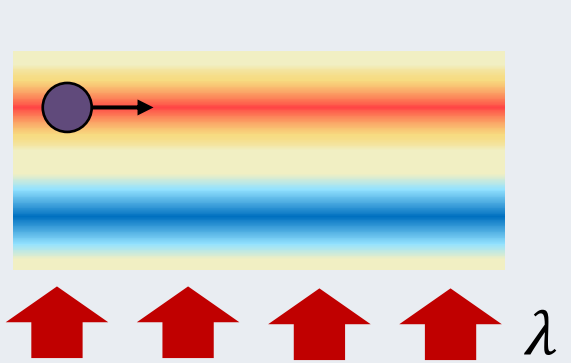
taken from J. Breuer's thesis

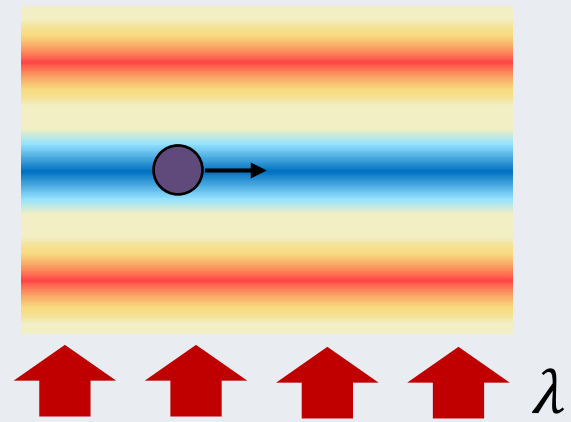
Switch fields *synchronously* with the particle's position/velocity

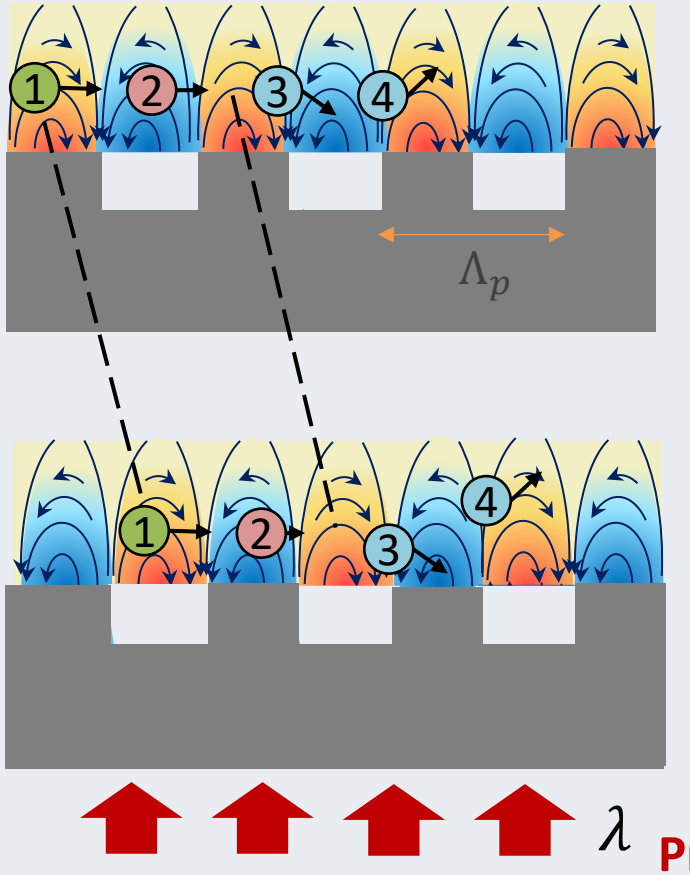
Operation principle

Synchronicity condition:

$$\beta = \Lambda_p/(\lambda m)$$

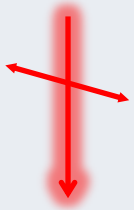




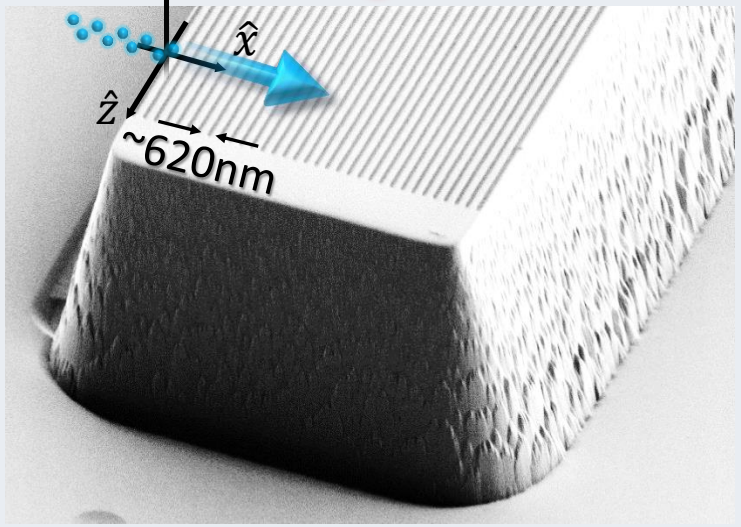


Depending on particles position:

1. Acceleration
2. Deceleration
3 4. Deflection



TM-polarized





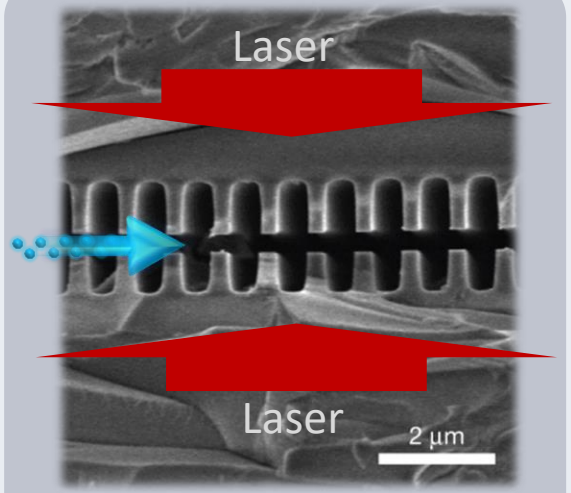
Proof of concept:

25 keV: **25 MeV/m:** J. Breuer, P. Hommelhoff, PRL 111, 134803 (2013)

60 MeV: 250 MeV/m: Peralta, E. A., Soong, K., England, R. J., Colby, E. R., Wu, Z., Montazeri, B., ... & Byer, R. L. (2013). *Nature*, *503*(7474), 91-94.

2013

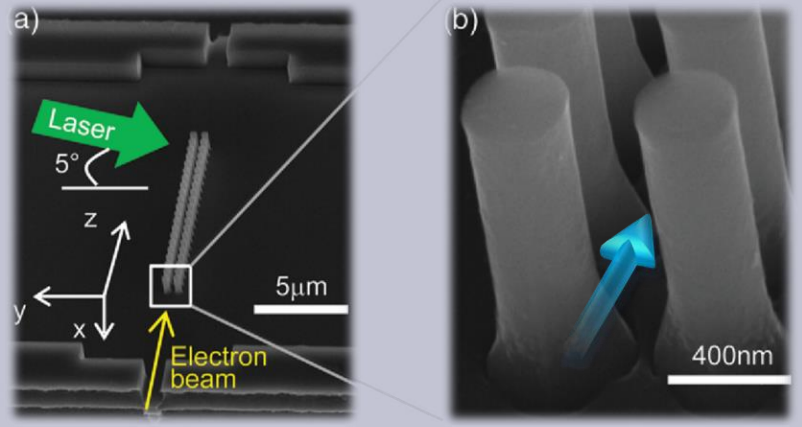
Bonded silica gratings



Peralta et al. Nature 503, 91–94 (2013)
Koyama, K., et al. IPAC (2014)
Wie et al., Physics of Plasmas 24.7 (2017)
Cesar et al., NIMA 909, 252-256 (2018)
Cesar et al., Optics Expr., 26(22), (2018)
Crisp et al., PRAB, 27(5), (2024)

2015

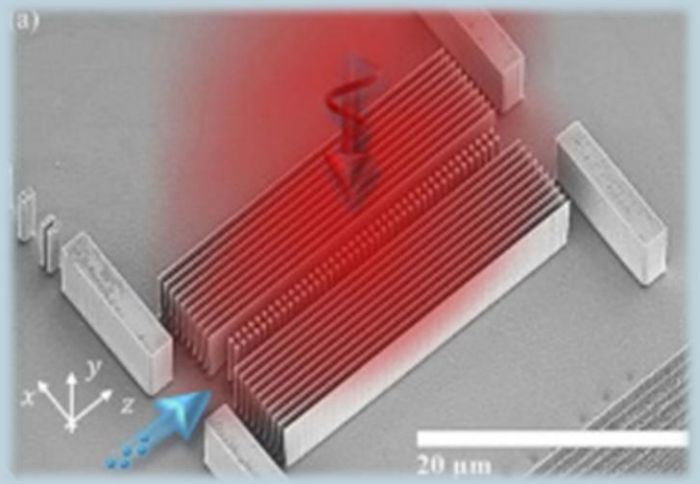
Silicon pillar structures



Leedle, et al. CLEO, pp. FM3M-7 (2018)
Leedle, et al. Opt. Lett. 40, 4344-4347 (2018)
Yousefi et al., Opt. Lett. 44, 1520-1523 (2019)
Black et al., PRAB 23, 114001 (2020)
Fishman et al., Nature Comm 14, 3687 (2023)

2021

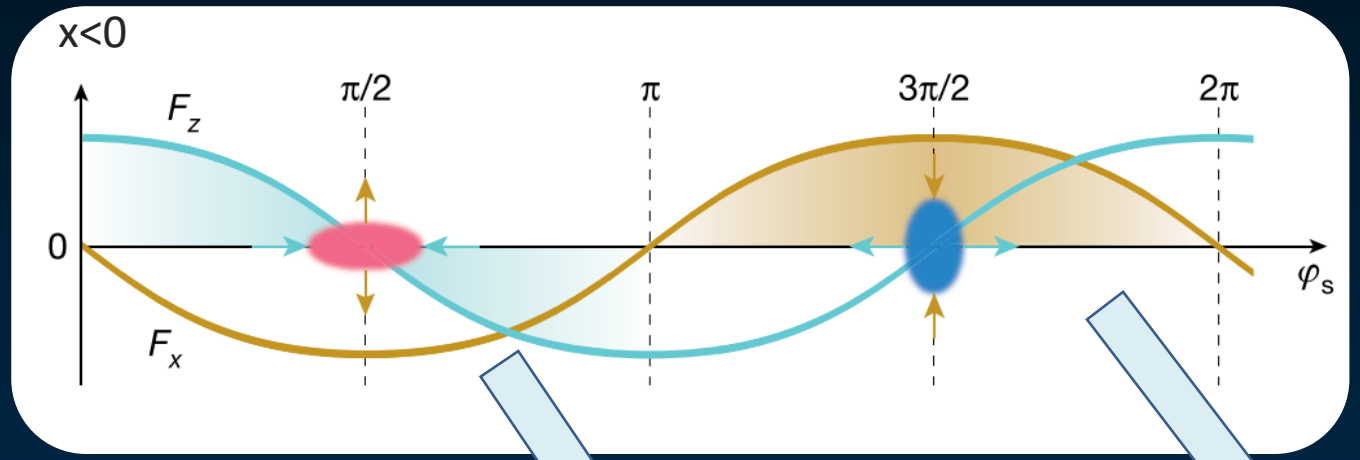
Top illumination

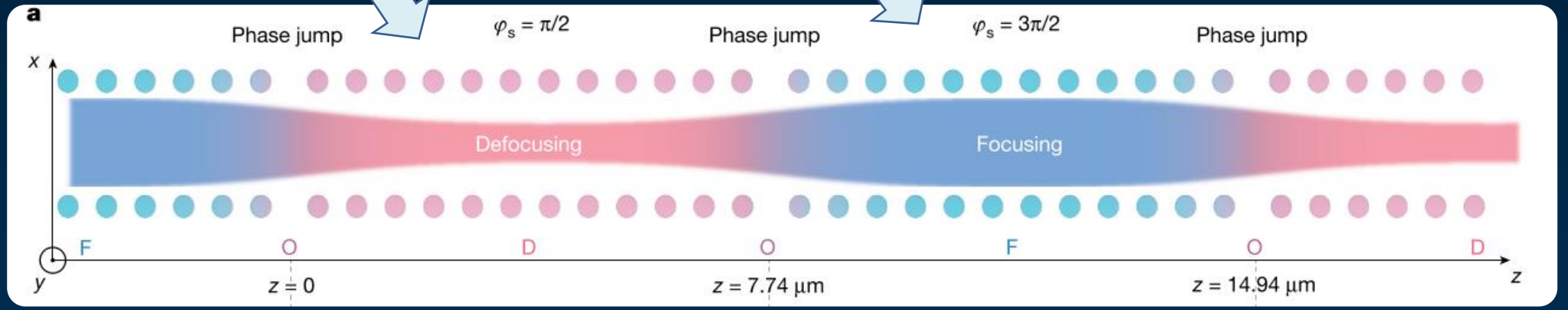


Chen et al., Proposal (1989)
Shiloh, et al., Opt. Express 29, 14403-14411 (2021)

Guiding with Alternating Phase Focusing

In a nutshell: once the electron beam begins to defocus, flip the laser's phase, so **alternate between focusing forces and defocusing forces**





C_c: excitation coefficient
k_x: fundamental wave number of structure
φ_s: synchronous phase
z: longitudinal direction
x: transversal direction
β: relative electron velocity
γ: Lorentz factor

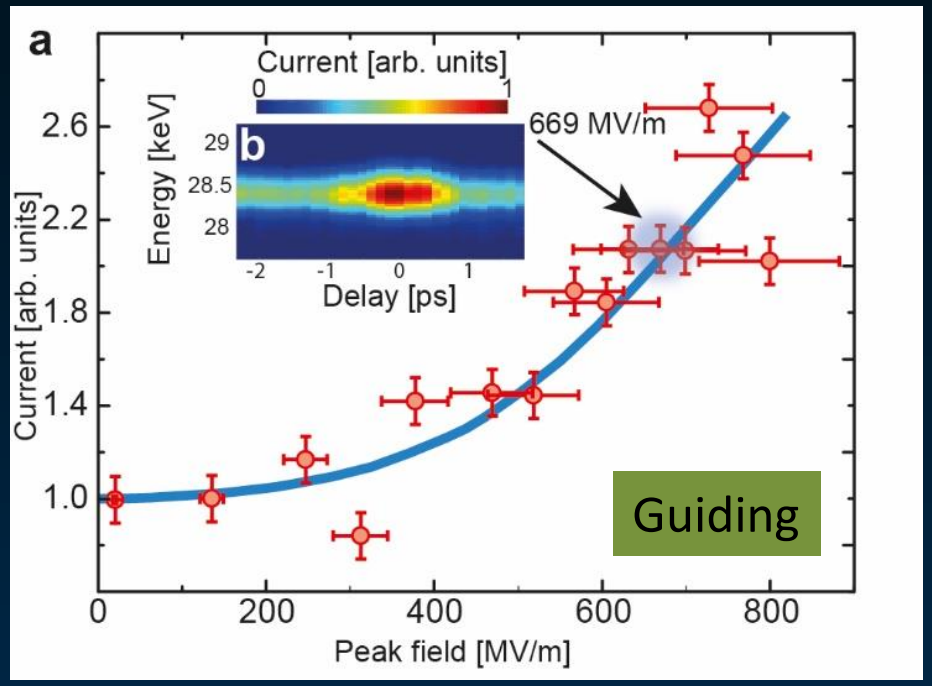
$$F_x = \frac{qc}{\beta\gamma^2} C_C \sinh(k_x x) \sin(\varphi_s)$$

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

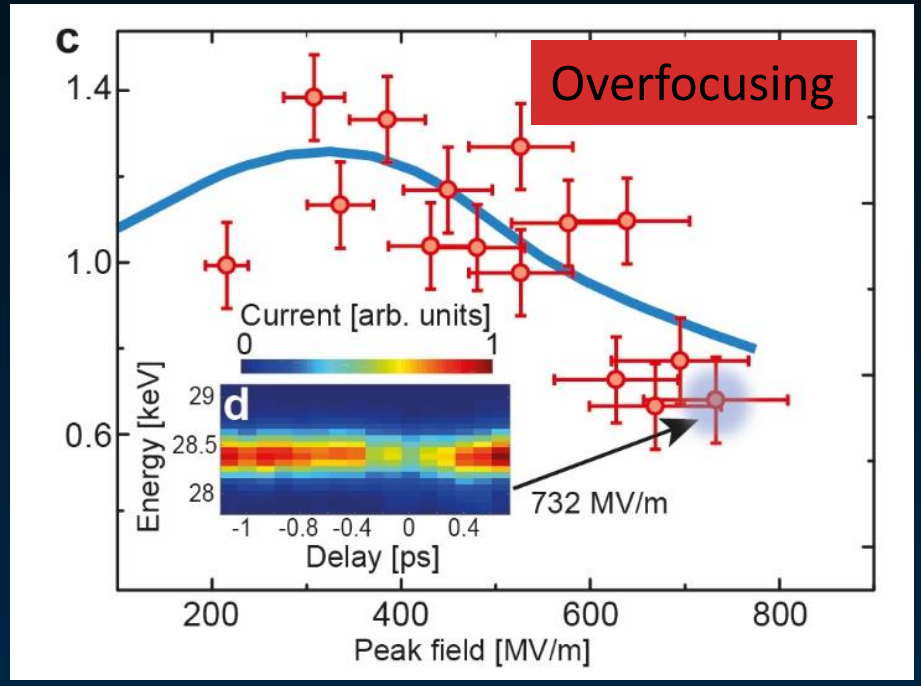
Niedermayer, U., Egenolf, T., Boine-Frankenheim, O., Hommelhoff P., *Phys. Rev. Lett.* 121, 214801 (2018)

Shiloh, R., Illmer, J., Chlouba, T., Yousefi, P., Schönenberger, N., Niedermayer, U., Mittelbach, A., & Hommelhoff, P. *Nature* 597, 498 (2021)

Alternating phase focusing effect: proof of principle

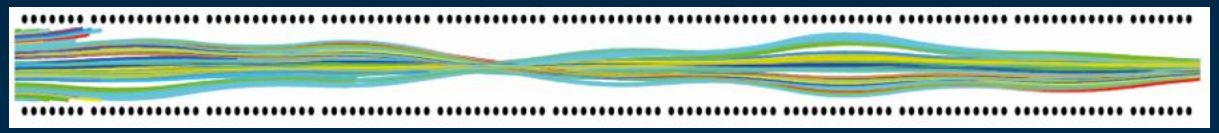


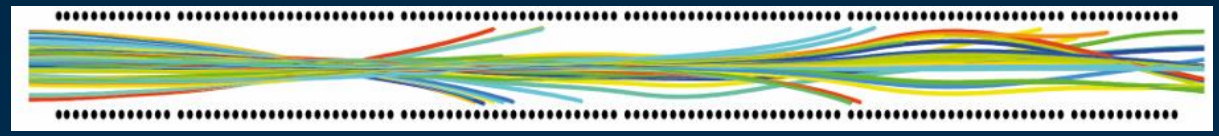
2.7 larger electron current at optimal transport field strength (~700 MV/m)



Overfocusing effect (>400 MV/m)

Different structure geometry with larger macrocells here





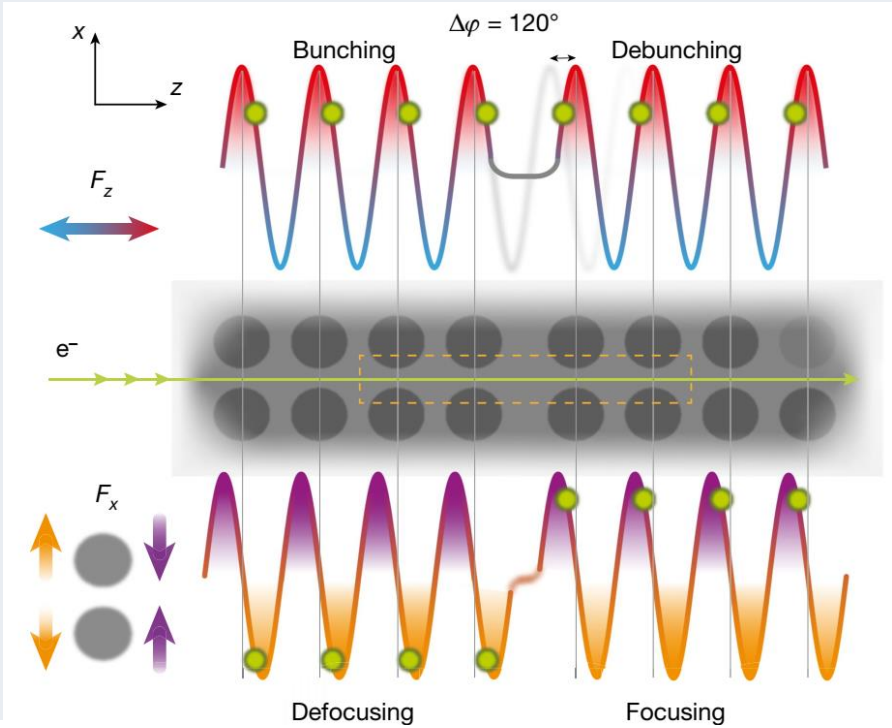
Next step: Acceleration AND guiding

R. Shiloh, J. Illmer, T. Chlouba, P. Yousefi, N. Schönenberger, U. Niedermayer, A. Mittelbach, P. Hommelhoff, Nature 597, 498 (2021)

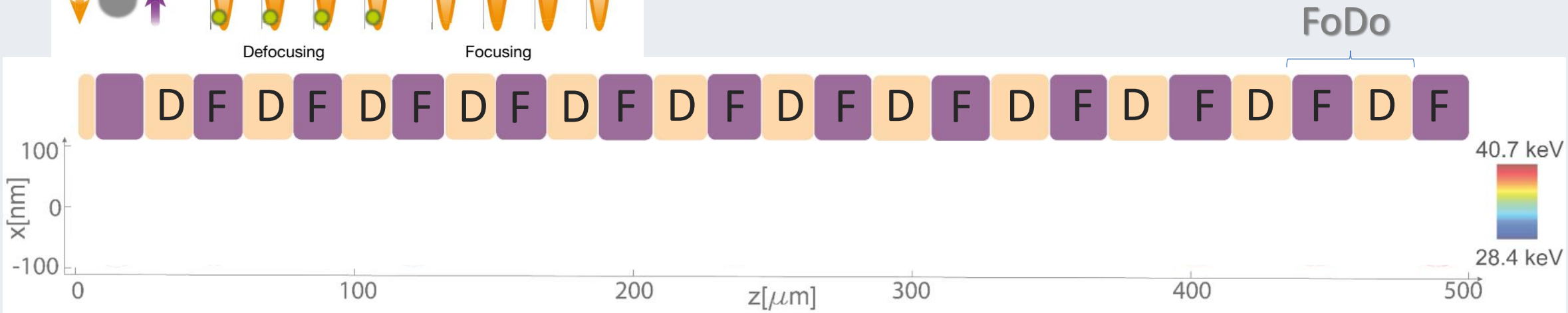
Coherent laser **acceleration** of electrons

Synchronicity condition:

$$\beta = \Lambda_p/(\lambda m)$$



Phase jumps + Tapering
=
Guiding + Acceleration



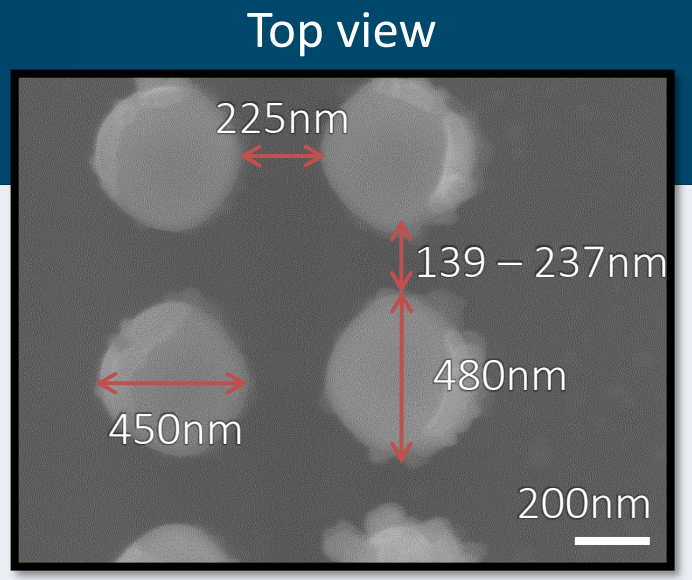
T. Chlouba, R. Shiloh, S. Kraus, L. Brückner, J. Litzel, P. Hommelhoff, Nature, 622, 476 (2023)

The experiment

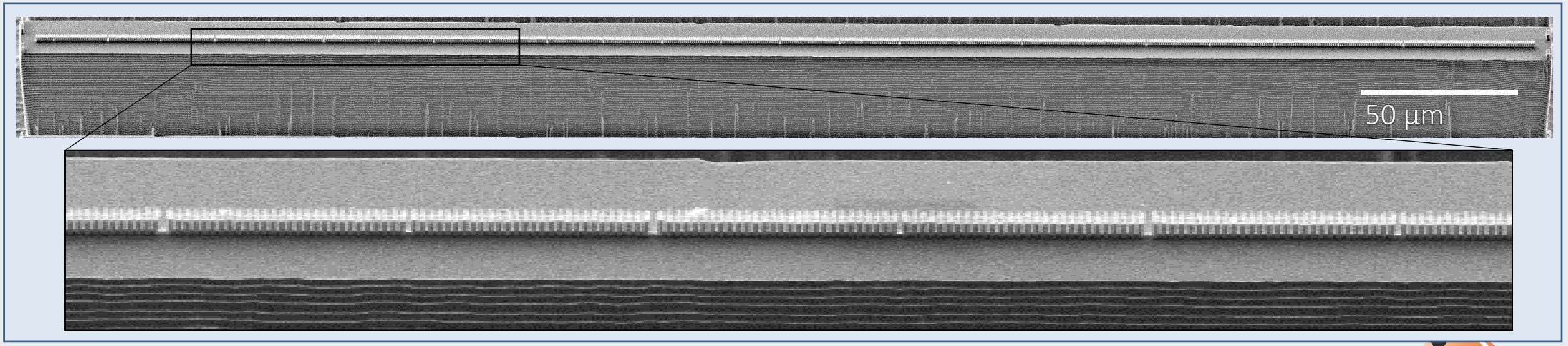


Acceleration structures

- 500 µm long, made of **733 pillar pairs**
- Tapered periodicity: from 619 nm to 717 nm
- Pillar radii: 240nm x 225nm, 225nm wide channel
- Macro-cells: from 5 µm to 22.5 µm (total of 26 segments)
- Average design gradient: 22.7 MeV/m
- Peak electric optical field: 600 MV/m (2.2 µJ pulse energy and 360 mW average power)
- Laser pulse front tilting required in experiment

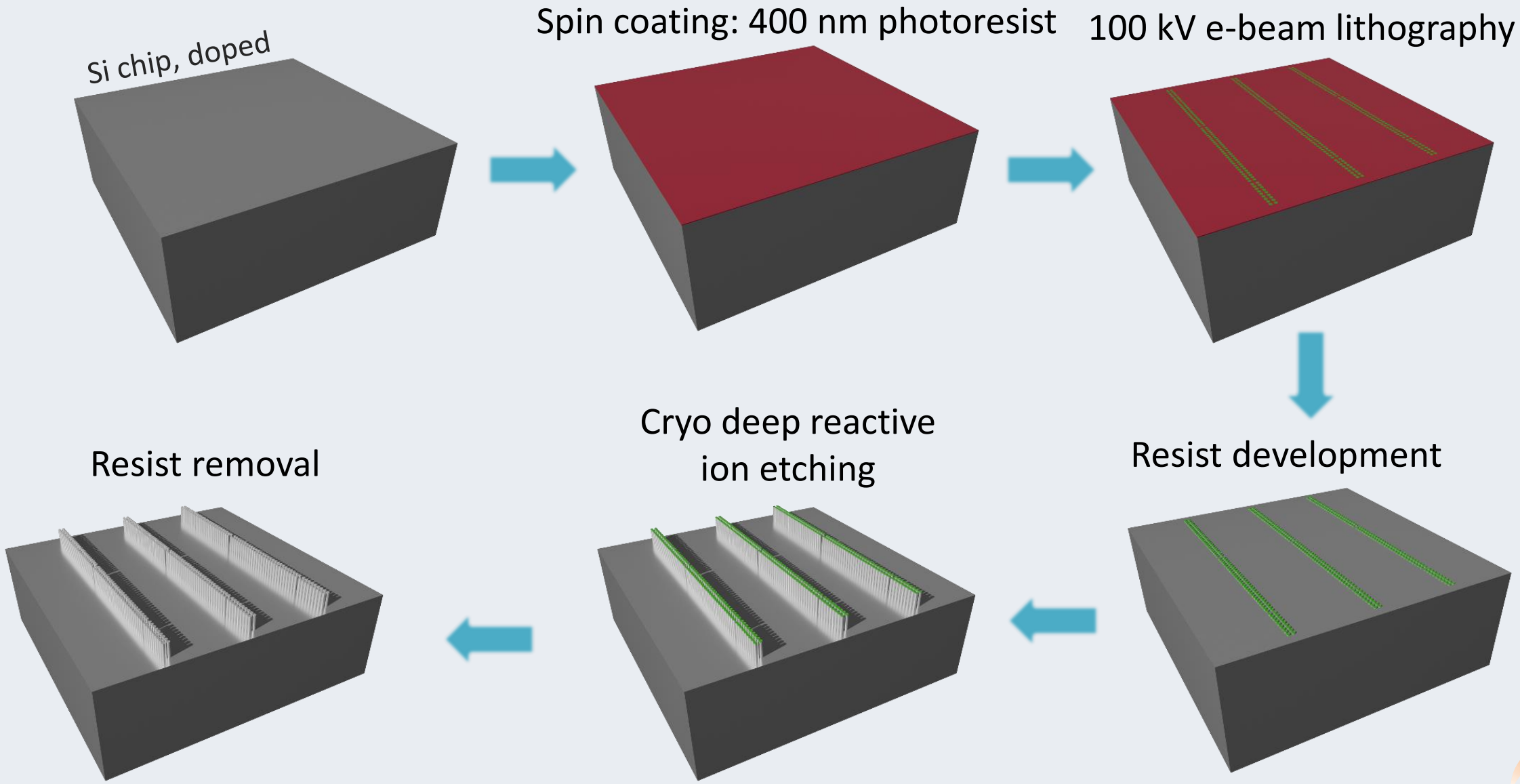


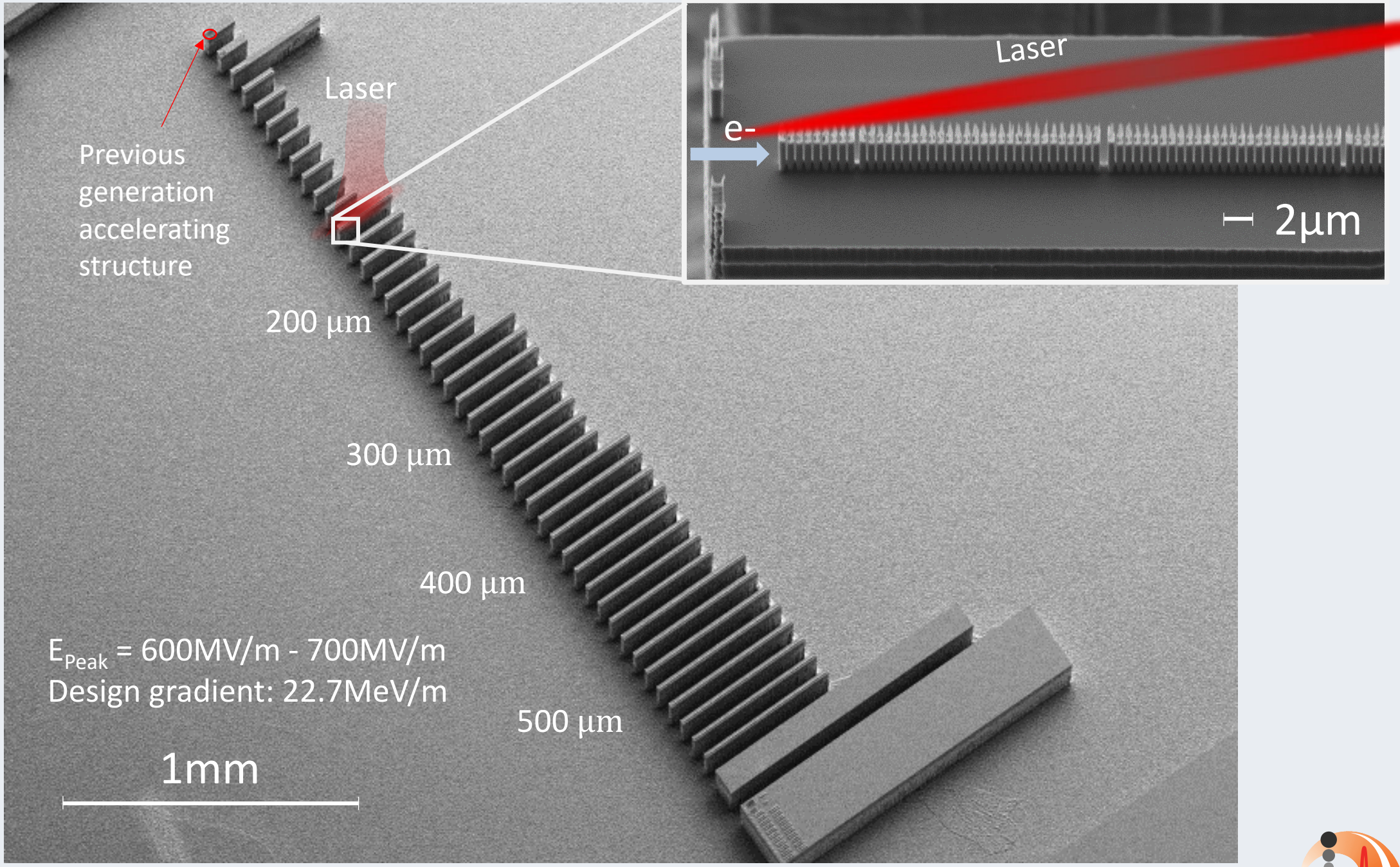
$2\mu m$ pillar height

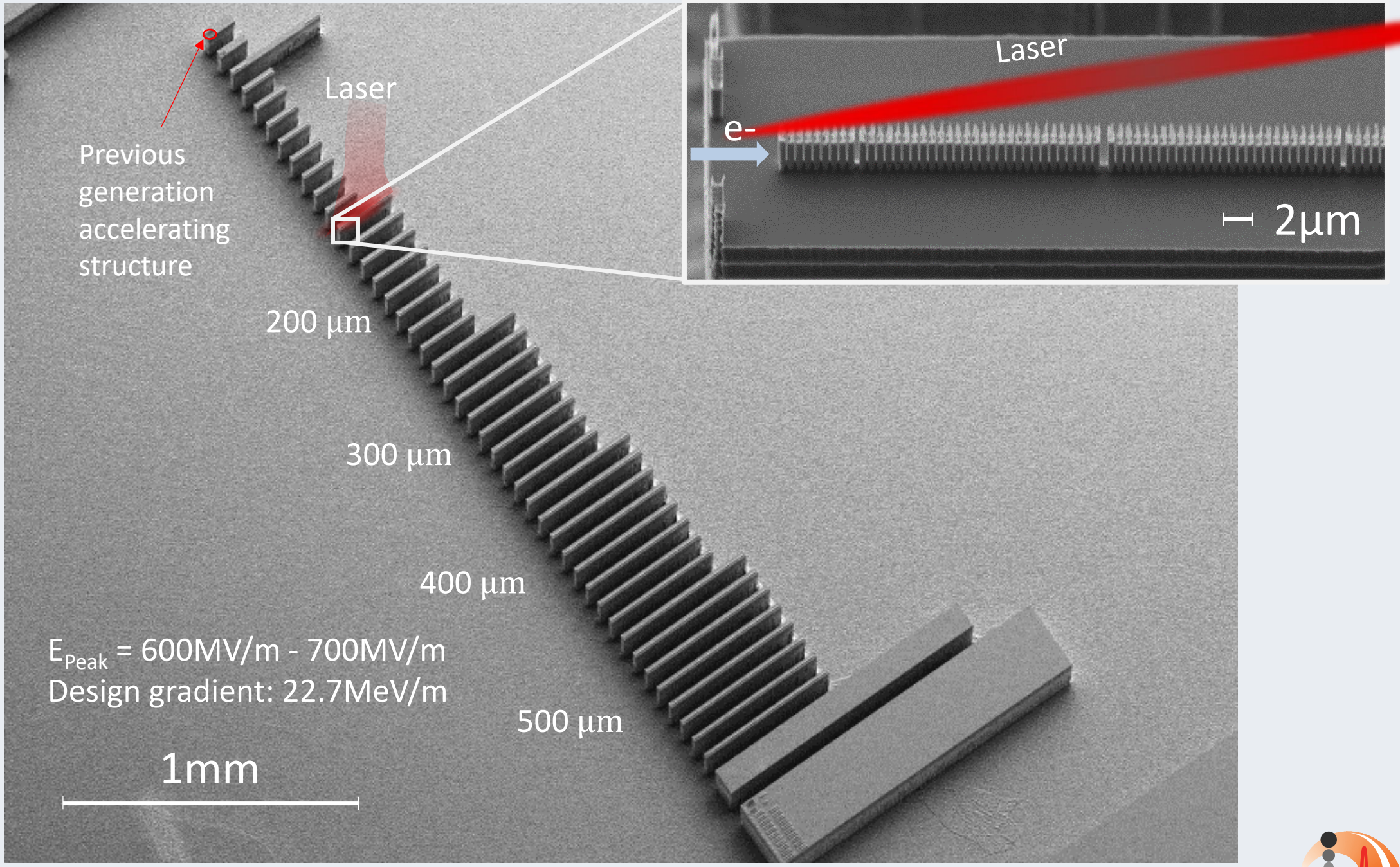


T. Chlouba, R. Shiloh, S. Kraus, L. Brückner, J. Litzel, P. Hommelhoff, Nature, 622, 476 (2023)

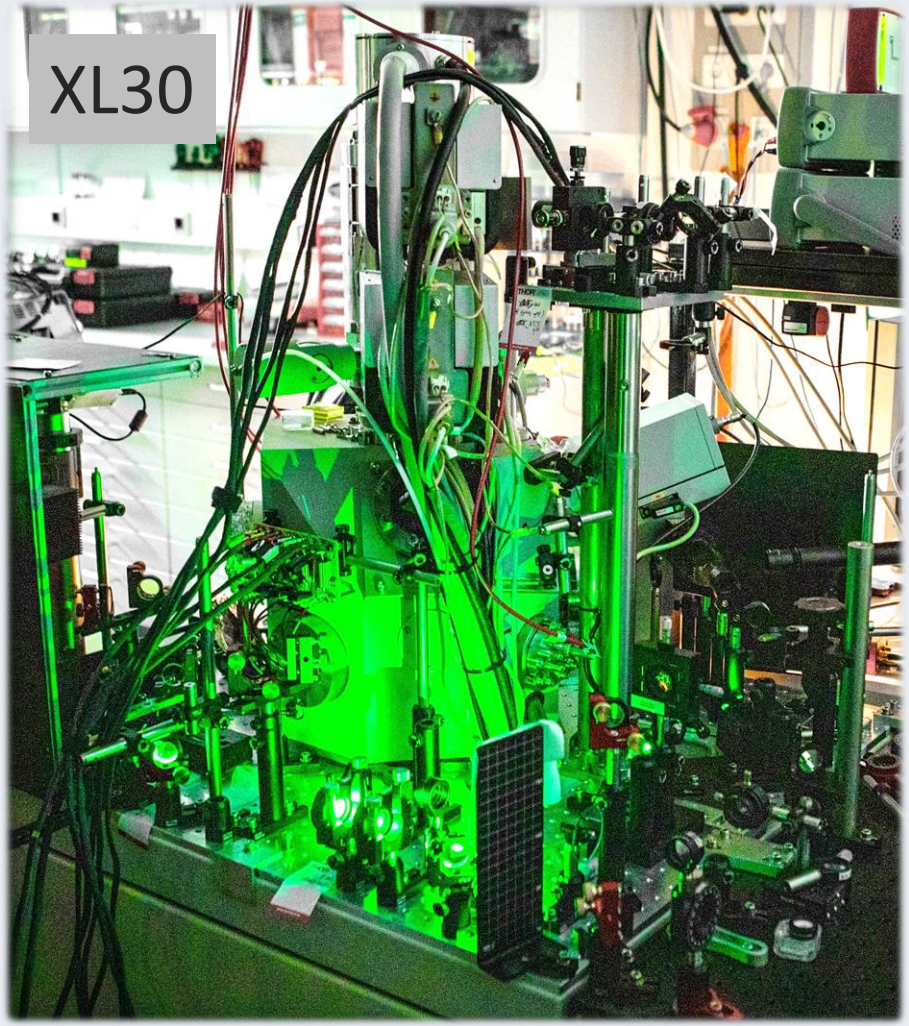
Structure fabrication

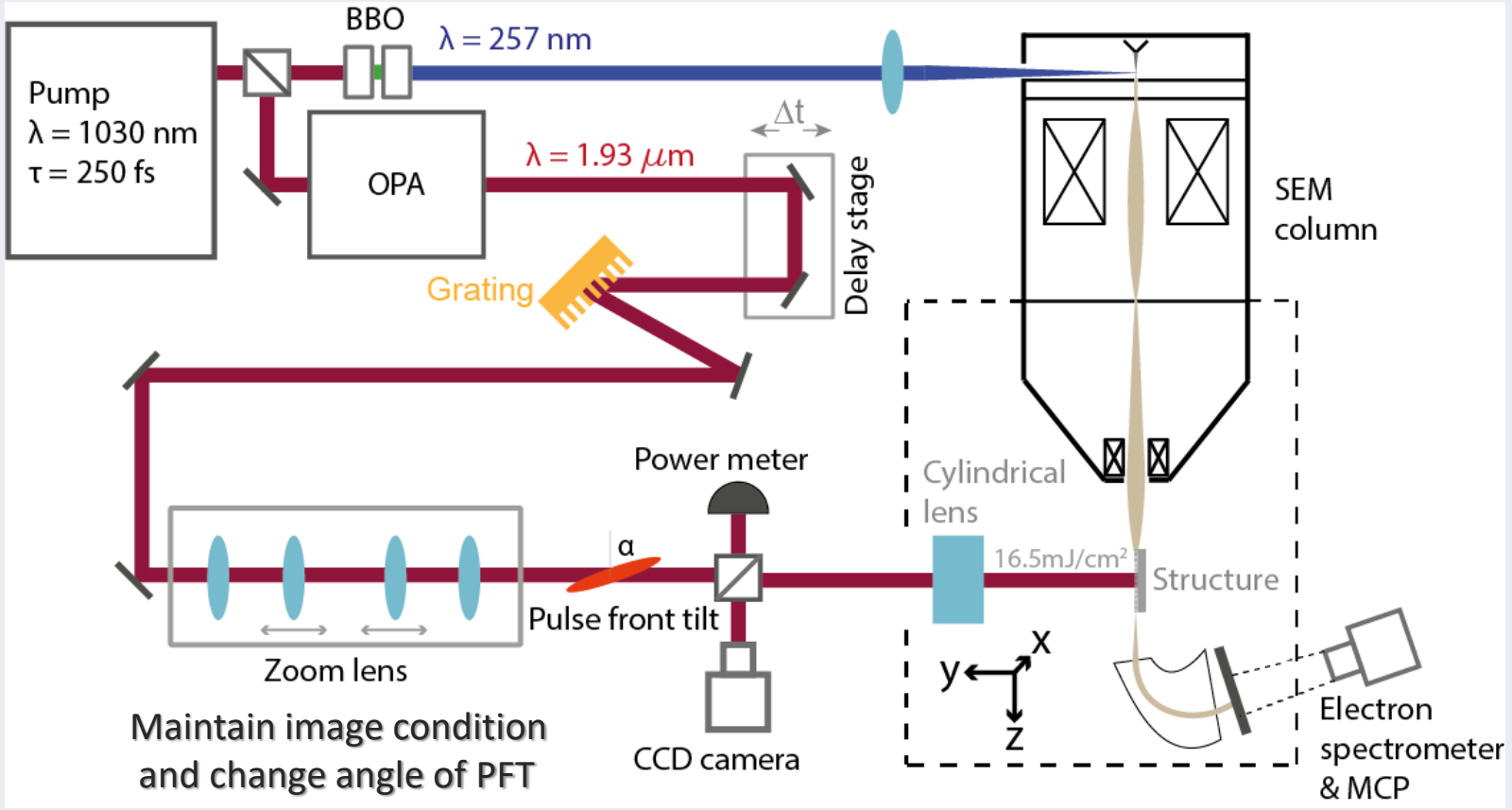



Laser
Previous generation accelerating structure
200 µm
300 µm
400 µm
500 µm
E_{Peak} = 600MV/m - 700MV/m
Design gradient: 22.7MeV/m
1mm
Laser
e-
2µm


Laser
Previous generation accelerating structure
200 µm
300 µm
400 µm
500 µm
E_{Peak} = 600MV/m - 700MV/m
Design gradient: 22.7MeV/m
1mm
Laser
e-
2µm

Experimental setup at FAU



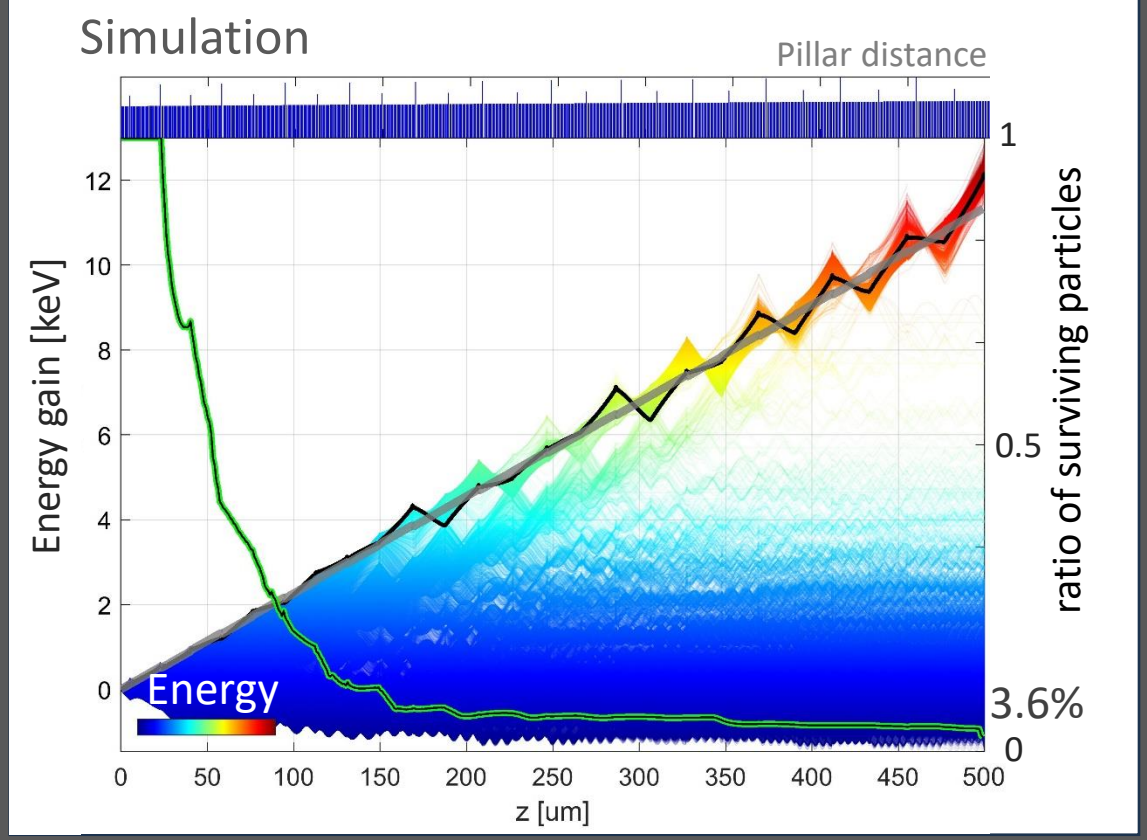


$FWHM_{Electrons}$ = 700fs
$FWHM_{Laser}$ = 250fs

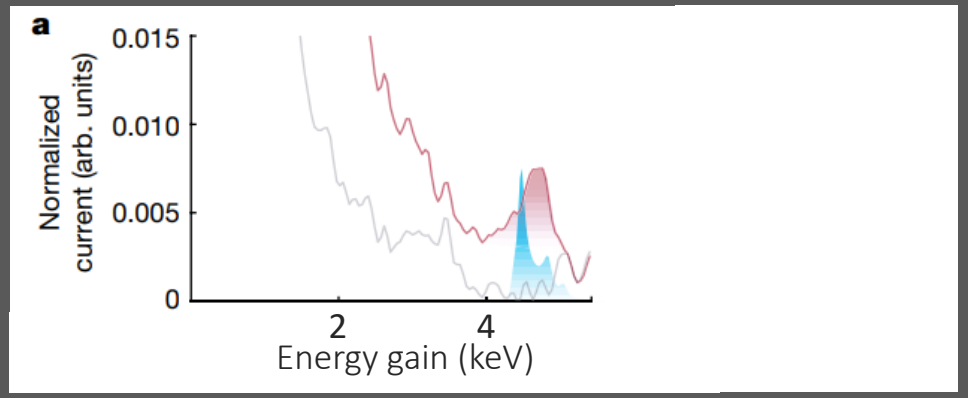
The results

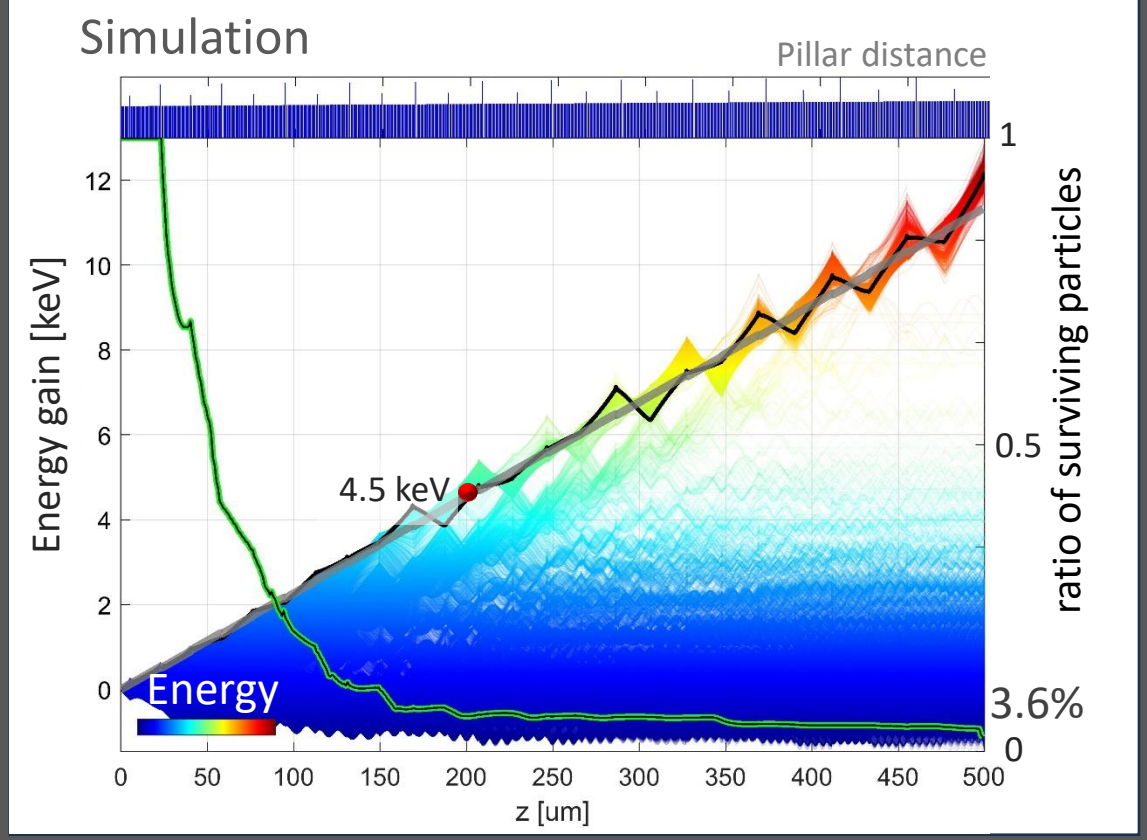


The design curve



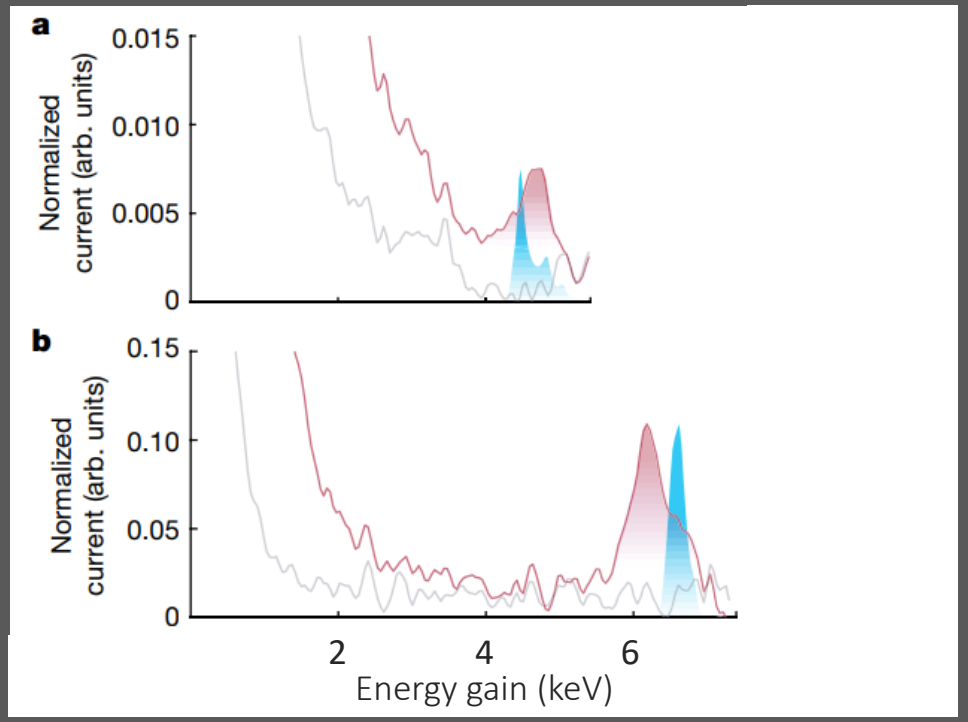
200μm


a
0.015
0.010
0.005
0
Normalized current (arb. units)
2
4
Energy gain (keV)

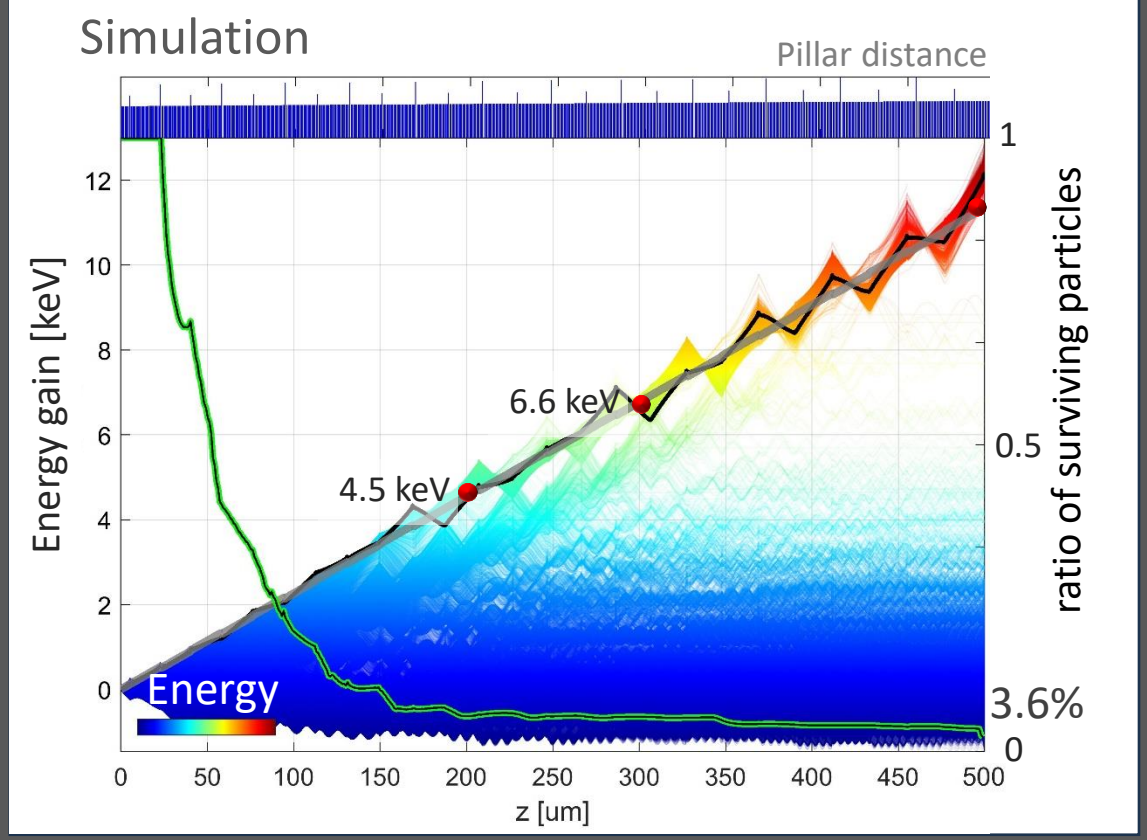

Simulation
Pillar distance
Energy gain [keV]
12
10
8
6
4
2
0
4.5 keV
Energy
0
50
100
150
200
250
300
350
400
450
500
z [um]
1
0.5
3.6%
0
ratio of surviving particles

200μm

300μm



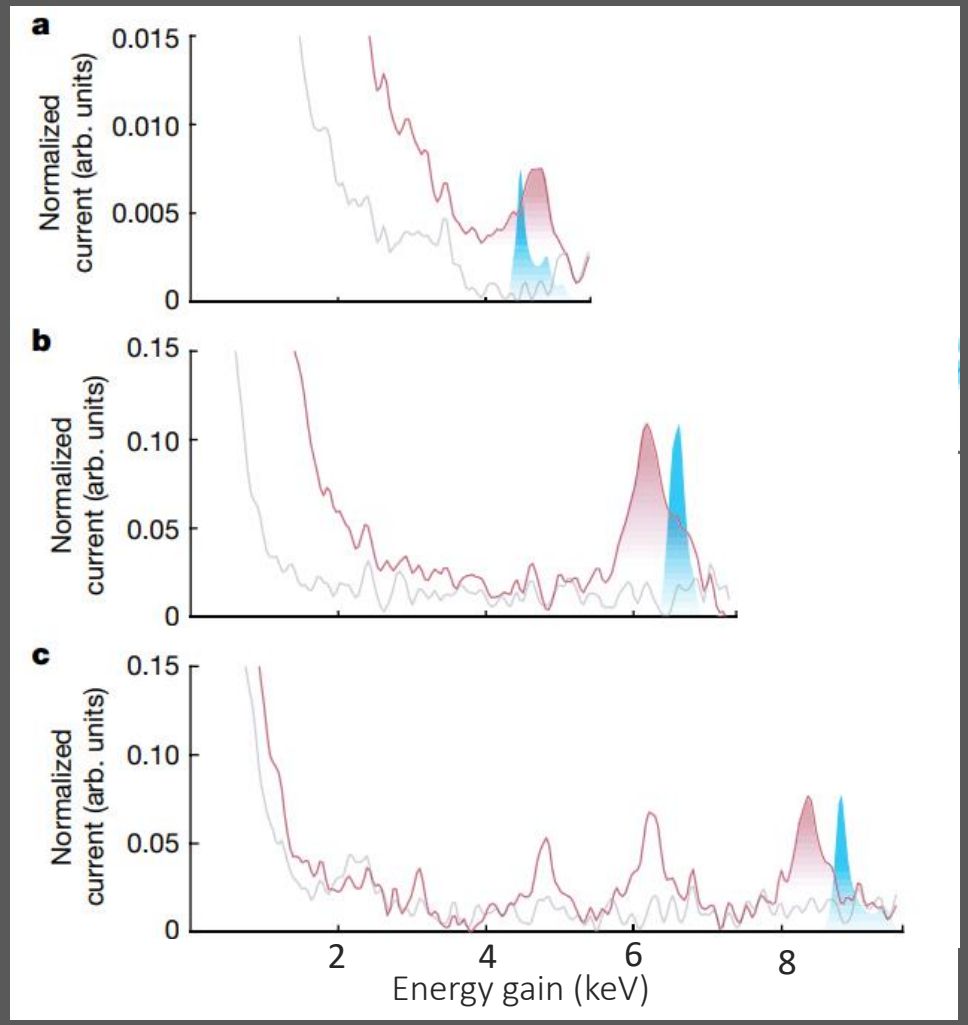
Simulation

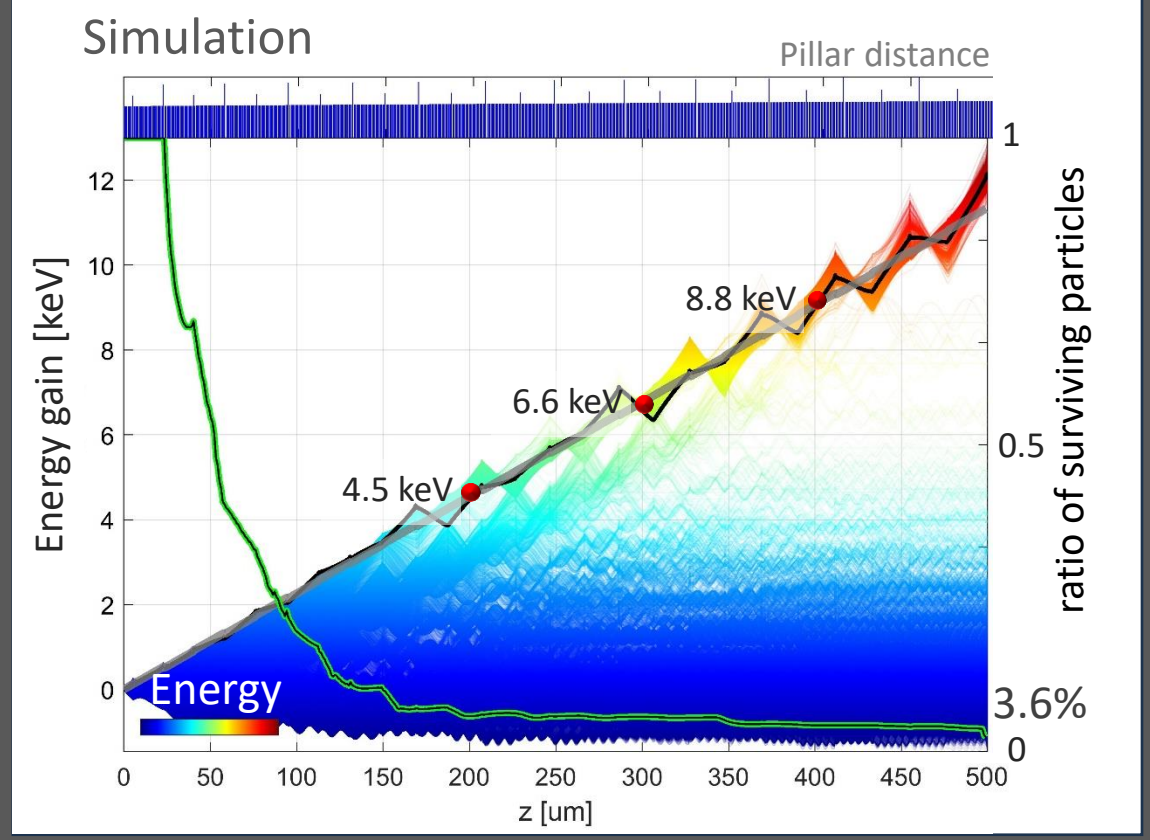


200μm

300μm

400μm



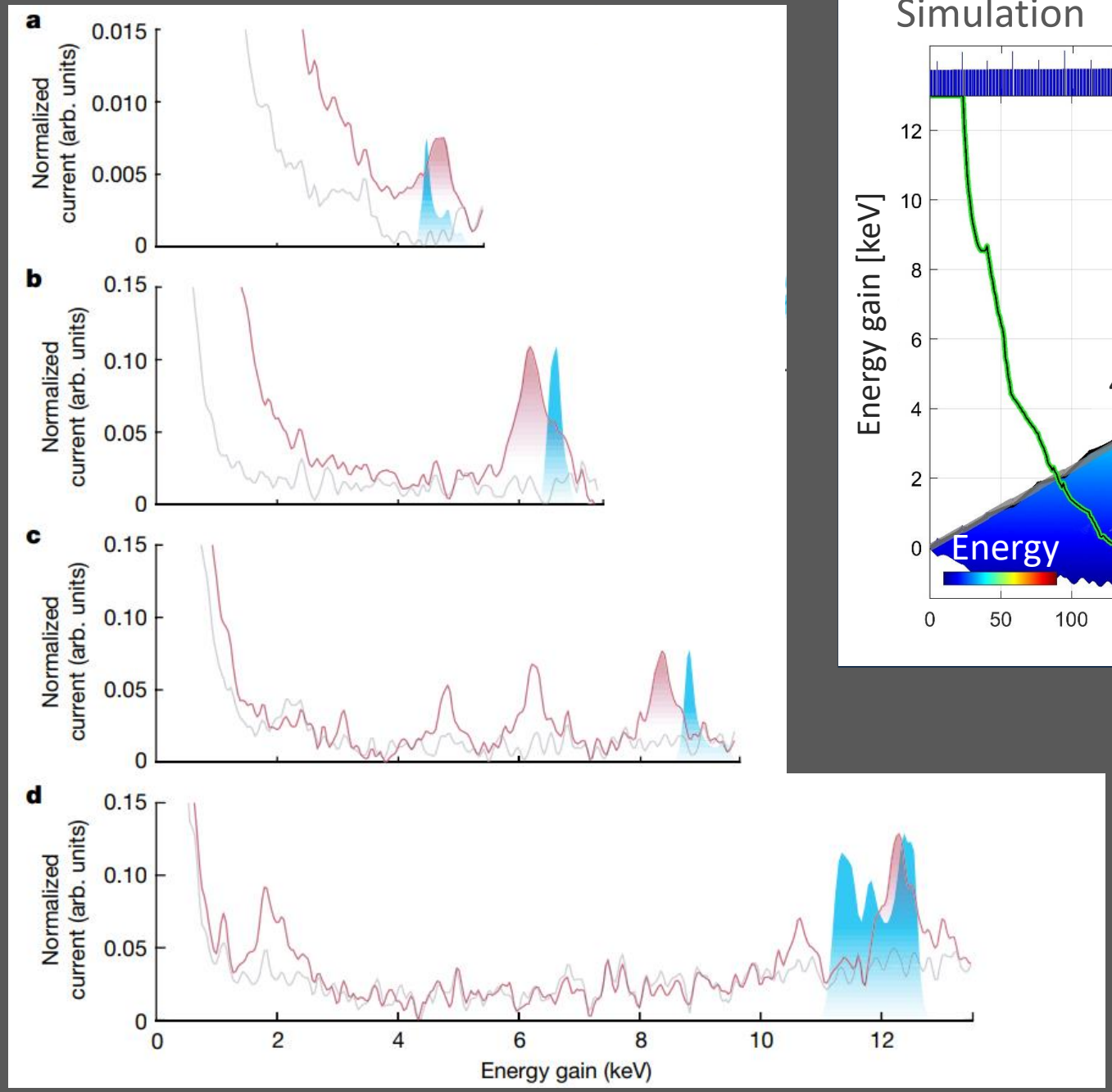


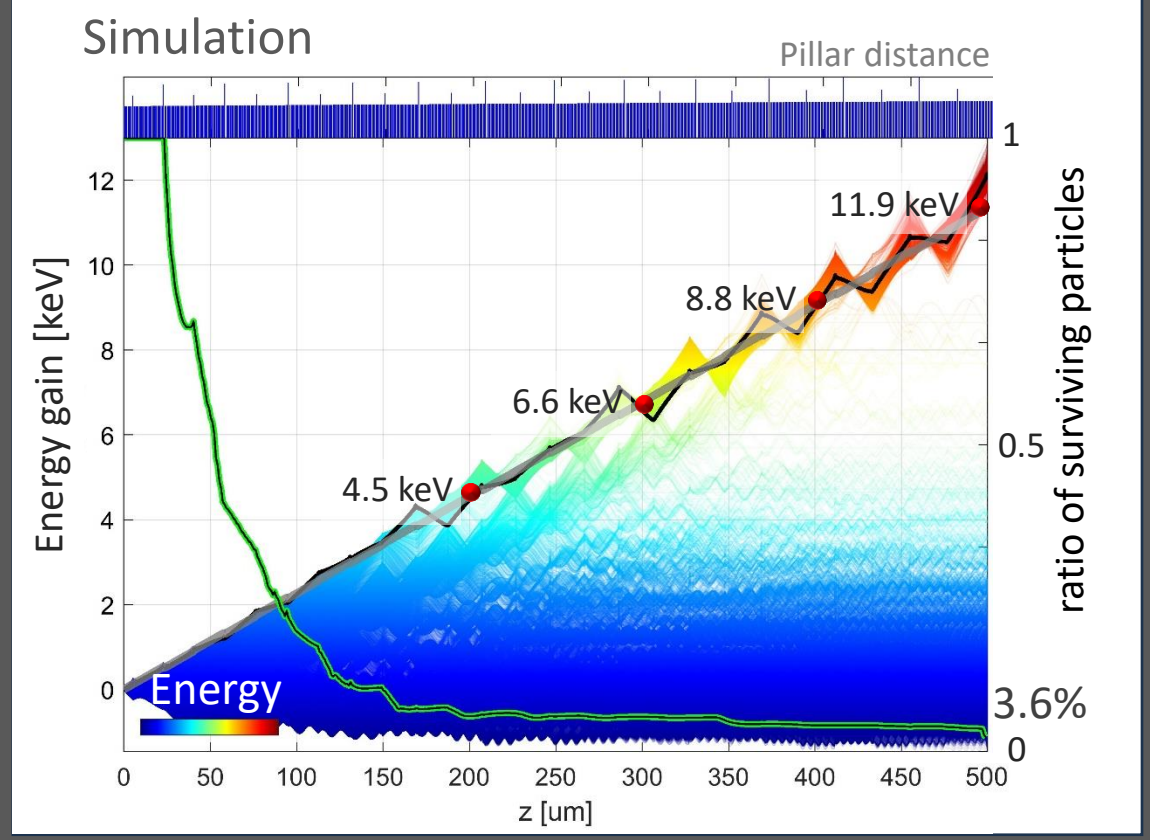
200μm

300μm

400μm

500μm



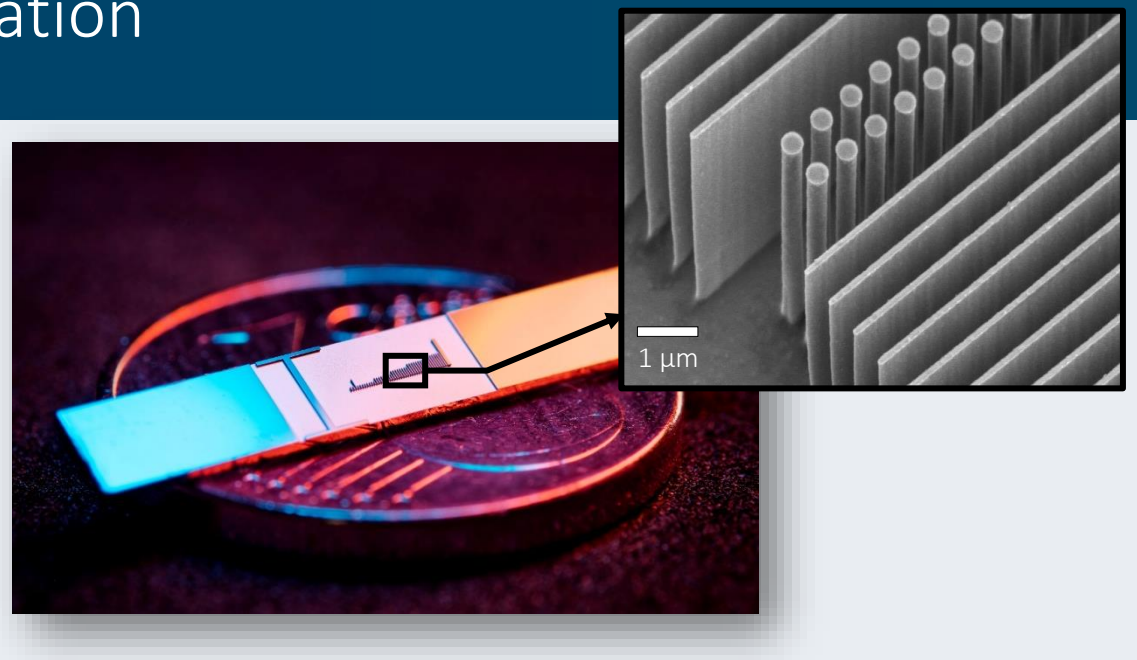


Maximum energy gain
12.3 keV
Total energy of 40.7 keV
43% energy gain

Similar results from Stanford/Darmstadt team:
Broaddus, Egenolf, …, Byer, Leedle, Solgaard,
Phys. Rev. Lett. 132, 085001 (2024)

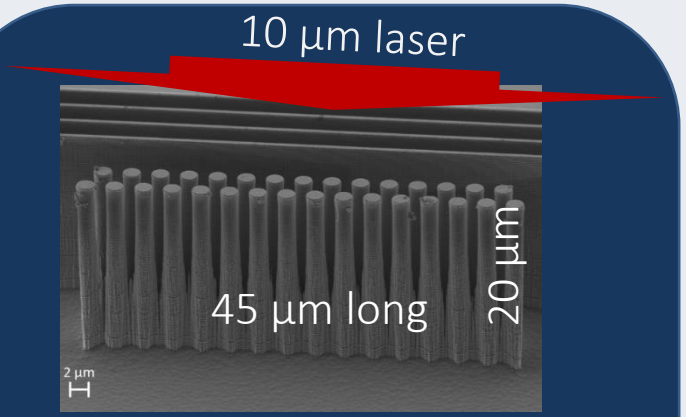
Pros and Cons of dielectric laser acceleration





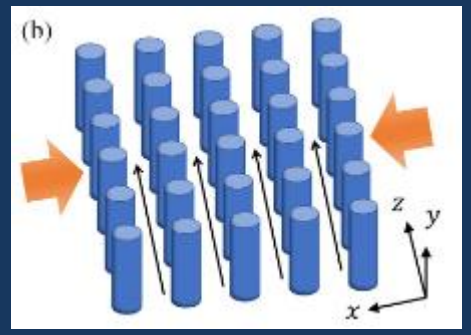
	Dielectric materials and optical frequencies	Higher damage threshold than metallic cavities	Higher gradients and smaller, minituarized structures	Much stricter requirements on beam properties	Lower current per channel
DLA	f=150 THz (λ=2 µm) τ=6.6 fs RR ~ kHz-MHz	>3 GV/m fields	Gradient >1 GeV/m Physical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

What‘s next for DLA?



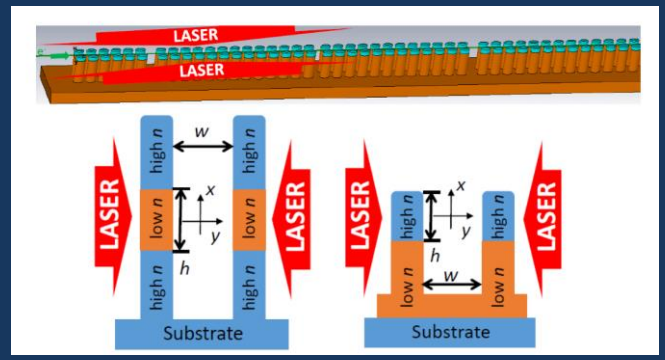
L. Brückner, T. Chlouba, Y. Morimoto, N. Schönenberger, T. Shibuya, T. Siefke, U. Zeitner, and P. Hommelhoff, Opt. Express 32, 28348-28355 (2024)

New wavelengths (10 µm)
New materials (SiC)
→ High gradient



*Z. Zhao et al., Photonics Research **8** 10, 1586-1598 (2020)*

Multichannel DLA
→ High current



U. Niedermayer, T. Egenolf, and O. Boine-Frankenheim Phys. Rev. Lett. 125, 164801 (2020)

Vertical confinement
→ High transmission

Novel fabrication
Novel laser source

Electron injection

Structure fabrication


S. Kraus
L. Brückner
T. Shibuya
P. Hommelhoff
M. Konrad
J. Litzel
T. Chlouba
Z. Zhao
R. Shiloh
GORDON AND BETTY
MOORE
FOUNDATION
ACHIP