GORDON AND BETTY MOORE FOUNDATION
ACHIP Accelerator on a Chip International Program
DFG
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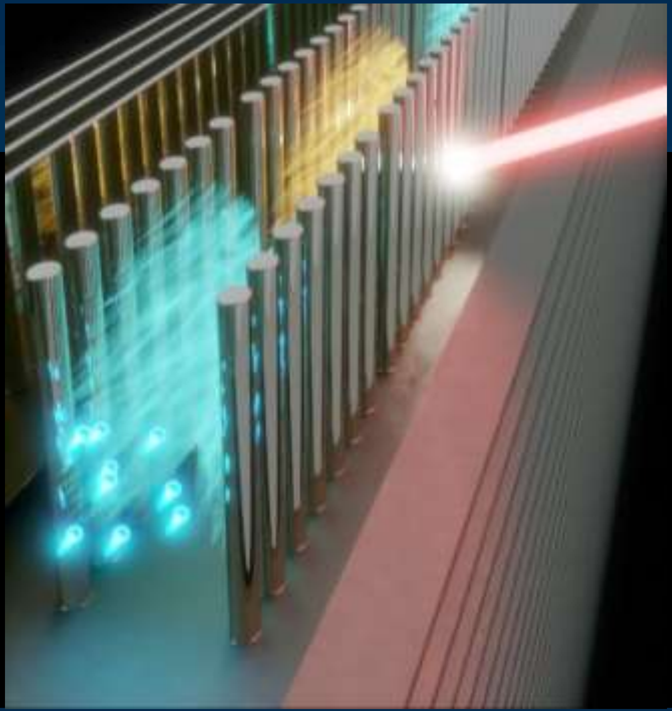
erc
MAX PLANCK INSTITUTE FOR THE SCIENCE OF LIGHT
EUROPEAN NETWORK FOR NOVEL ACCELERATORS EuroNNAc4 NPACT supported by EU via I-FAST
TECHNISCHE UNIVERSITÄT DARMSTADT

Free electron net energy gain and phase space control in photonic chip based accelerators



<u>S. Kraus</u>, R. Shiloh, T. Chlouba, J. Illmer, L. Brückner, J. Litzel, P. Hommelhoff

Friedrich-Alexander-Universität Erlangen-Nürnberg (FAU)

Steffi.Kraus@fau.de

Particle accelerators

16:30 – 16:50: sub-relativistic electrons (- keV)
16:50 – 17:10: relativistic electrons (- GeV)

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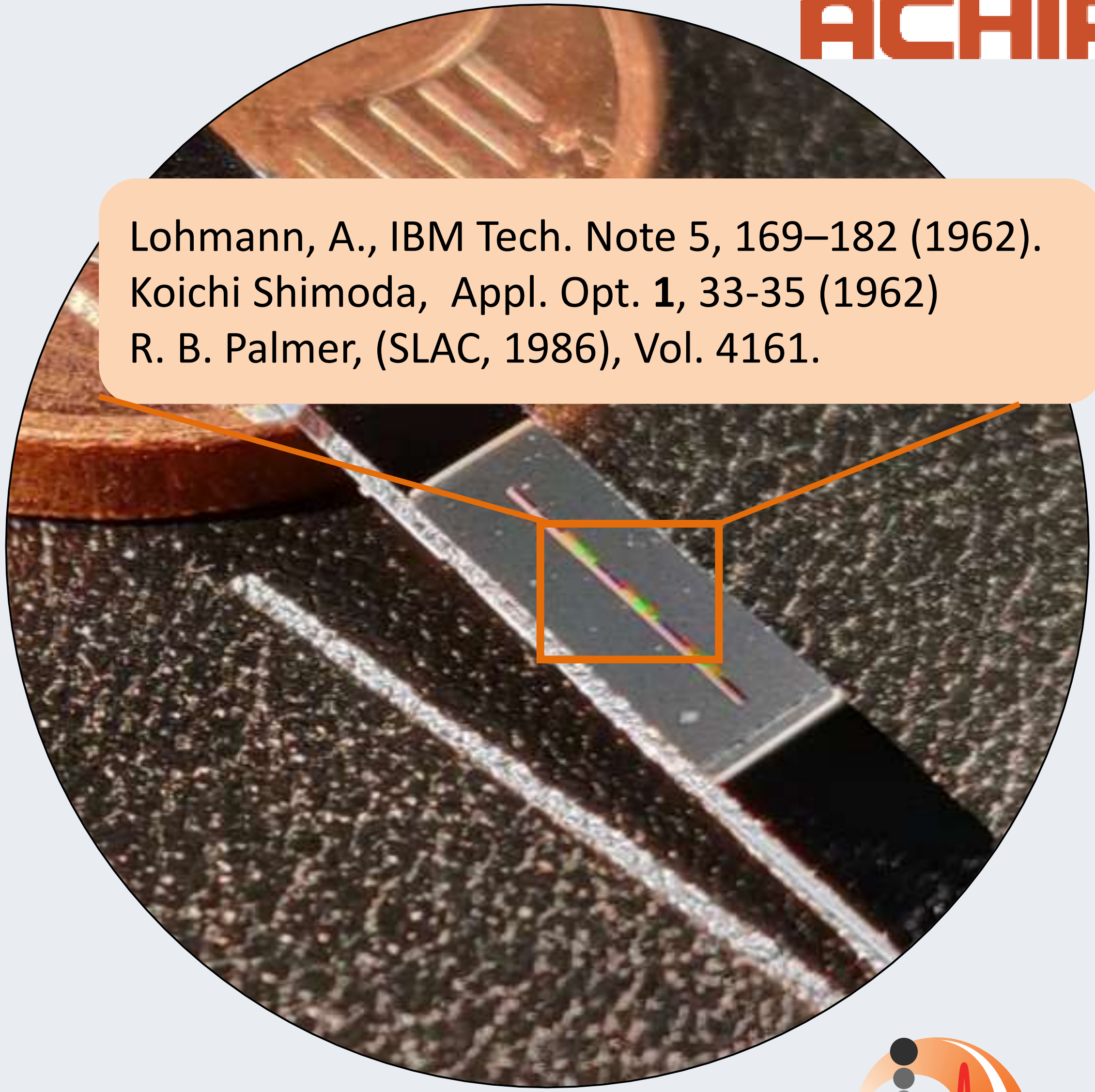
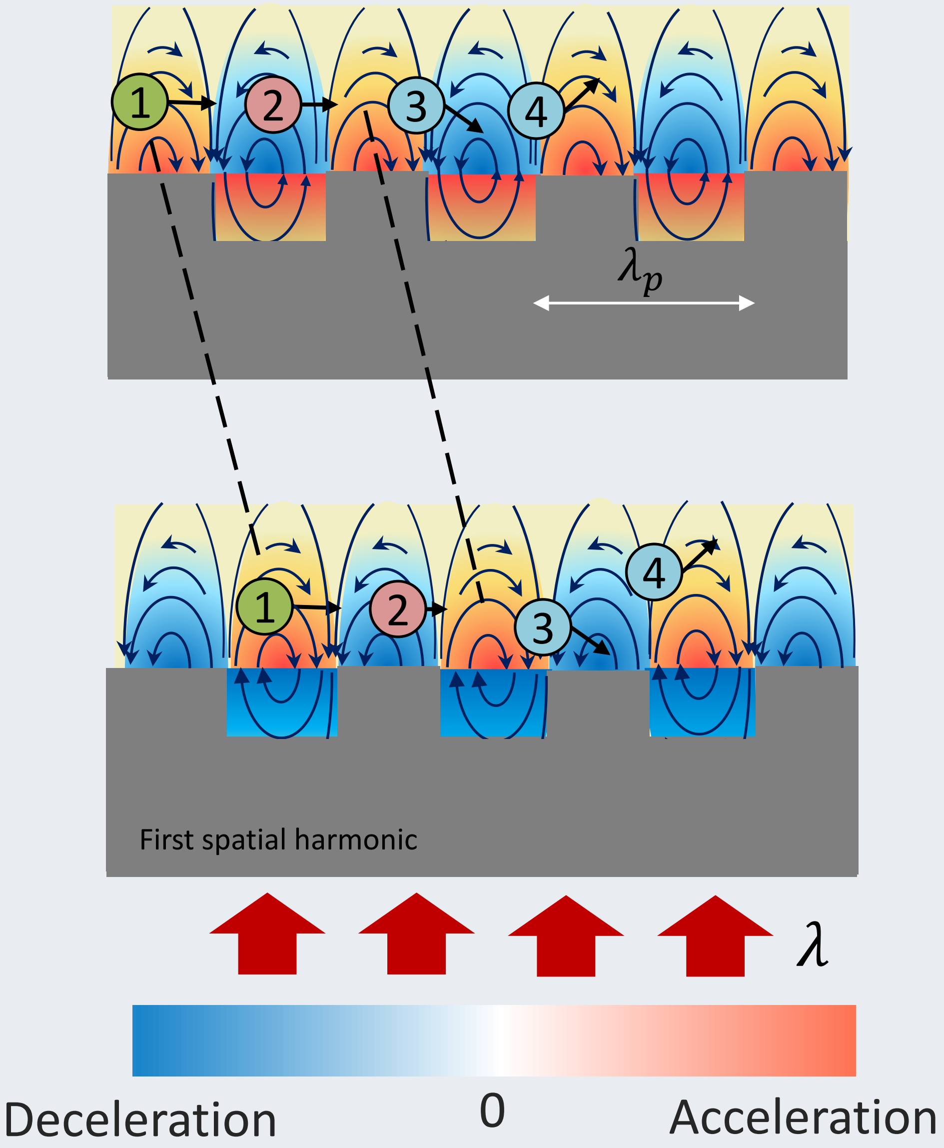
ACHIP



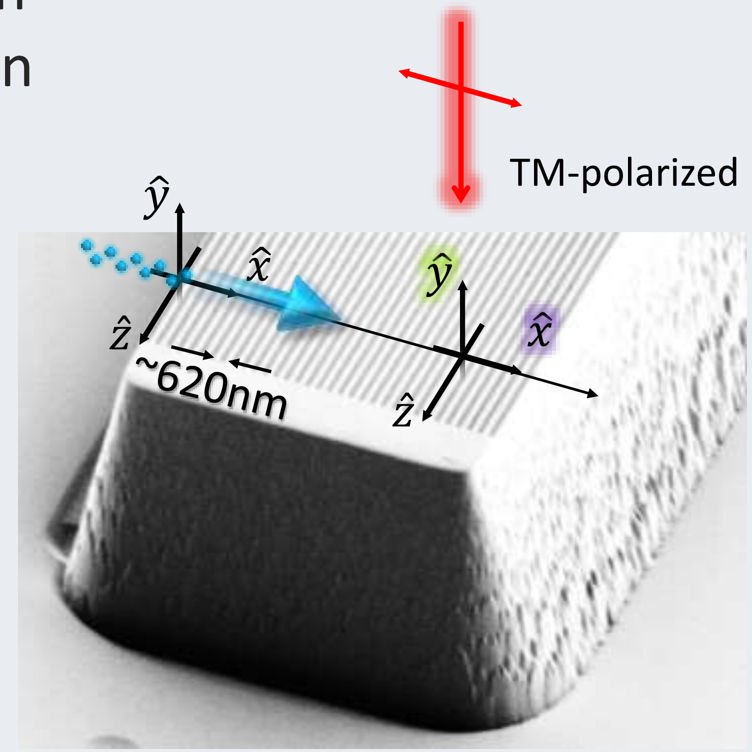
Lohmann, A., IBM Tech. Note 5, 169–182 (1962).
Koichi Shimoda, Appl. Opt. **1**, 33-35 (1962)
R. B. Palmer, (SLAC, 1986), Vol. 4161.

Operation principle



Depending on particles position:

- ① Acceleration
- ② Deceleration
- ③ ④ Deflection



$$\beta = \lambda_p / m\lambda$$

m: order number

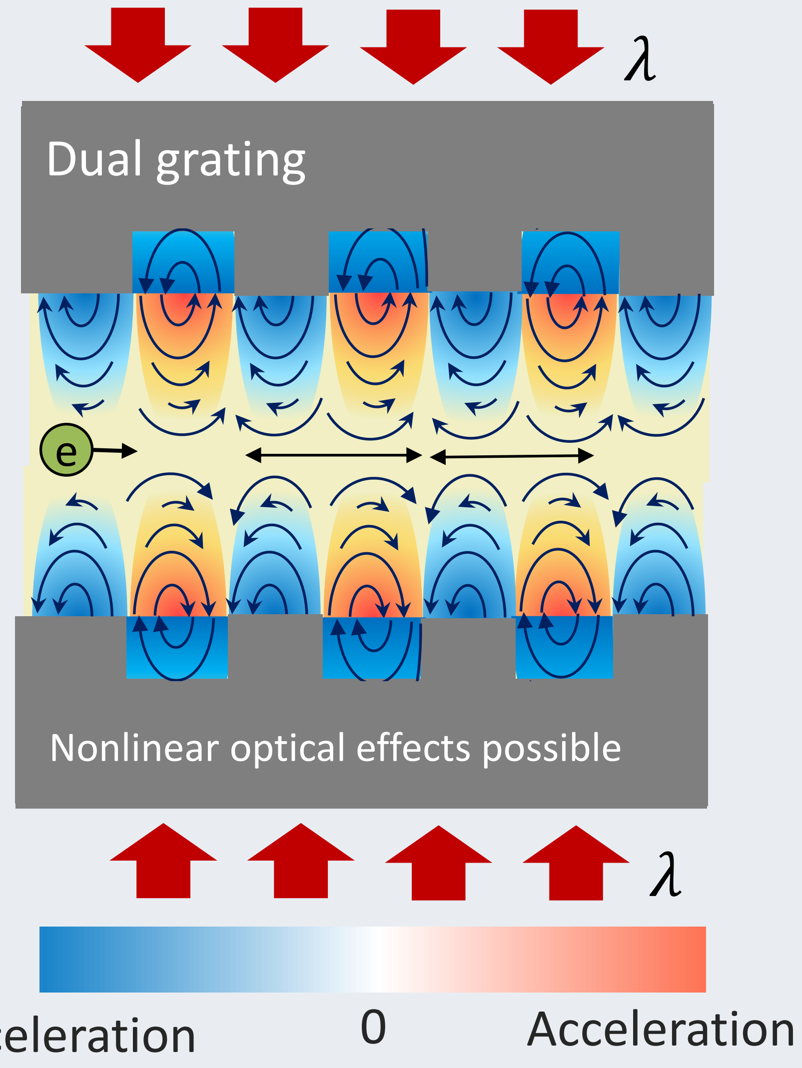
Proof of concept:

$\beta = 0.3$: **25 MeV/m:** J. Breuer, P. Hommelhoff, PRL 111, 134803 (2013)

$\beta = 0.7$: **250MeV/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.

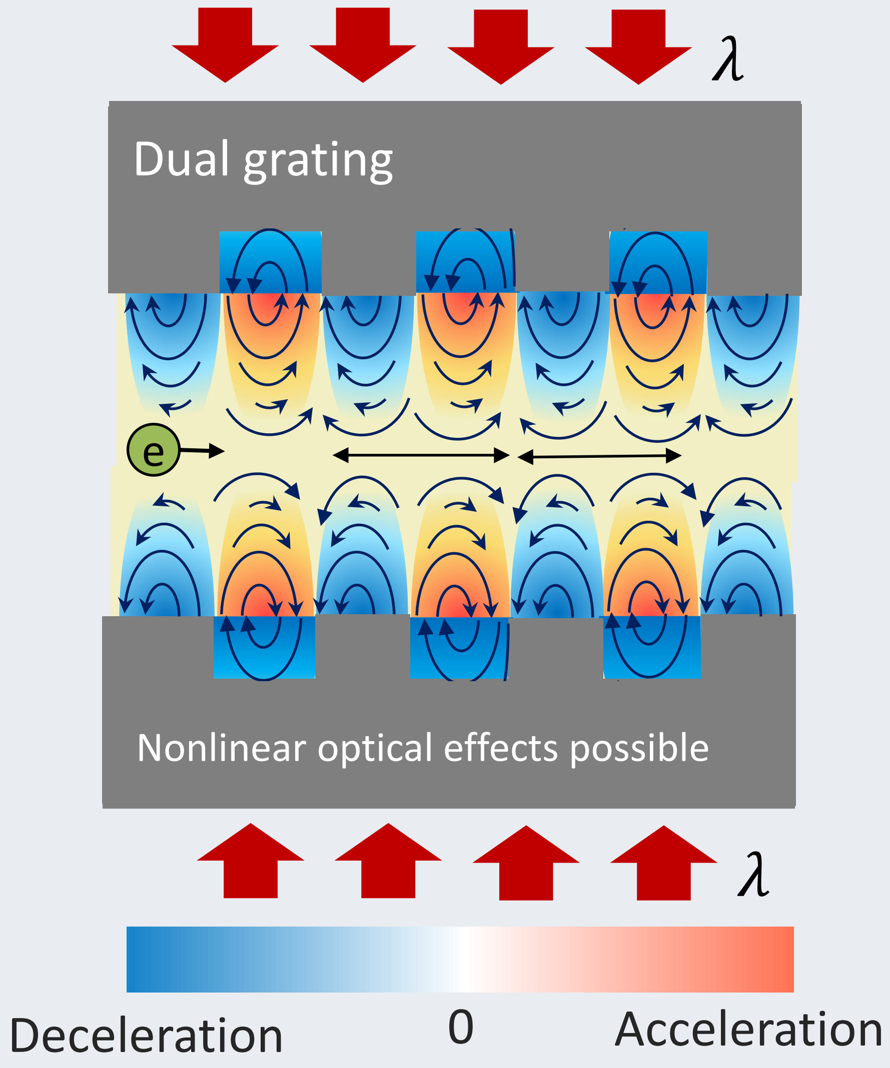
Operation principle

First spatial harmonic



Operation principle

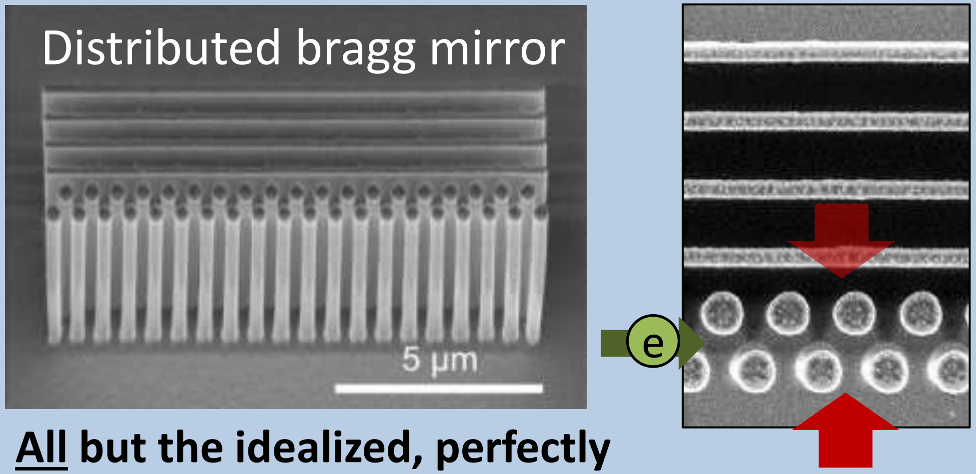
First spatial harmonic



Dual-pillar grating (2015) (1986)

- Driving laser interacts with little material
- Fabrication recipe relatively simple
- Special alignment not required
- Symmetric field profile

Peyman, Y., [Doctoral dissertation, FAU, Erlangen]

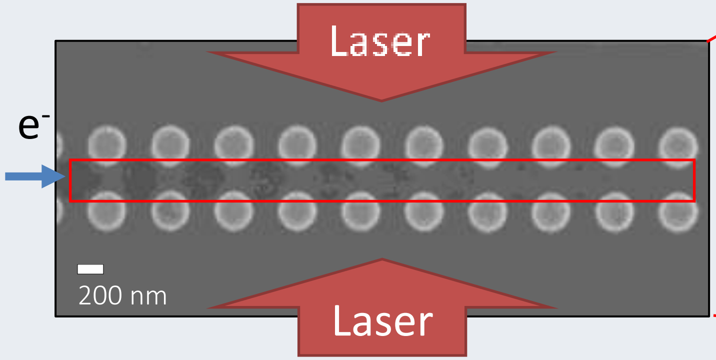


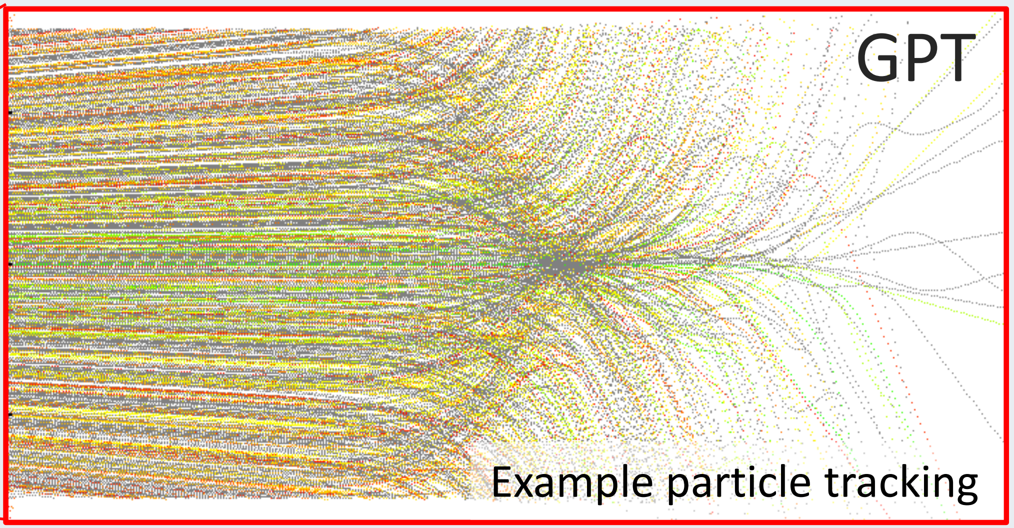
All but the idealized, perfectly on-axis electrons, are lost

R. B. Palmer, (SLAC, 1986), Vol. 4161., Leedle et al., Opt. Lett. 40, 18 (2015)
Leedle et al., Opt. Lett. 43, 9 (2018), Yousefi et al., Opt. Lett. 44, 6 (2019)

Dual pillar structures – Sub relativistic electron sources (30keV)

1. The forces depend on the injection phase
2. Result: at least half the electrons crash into the structure first, then the other half





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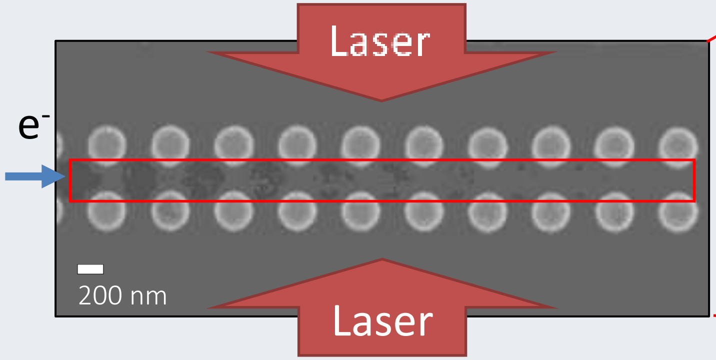

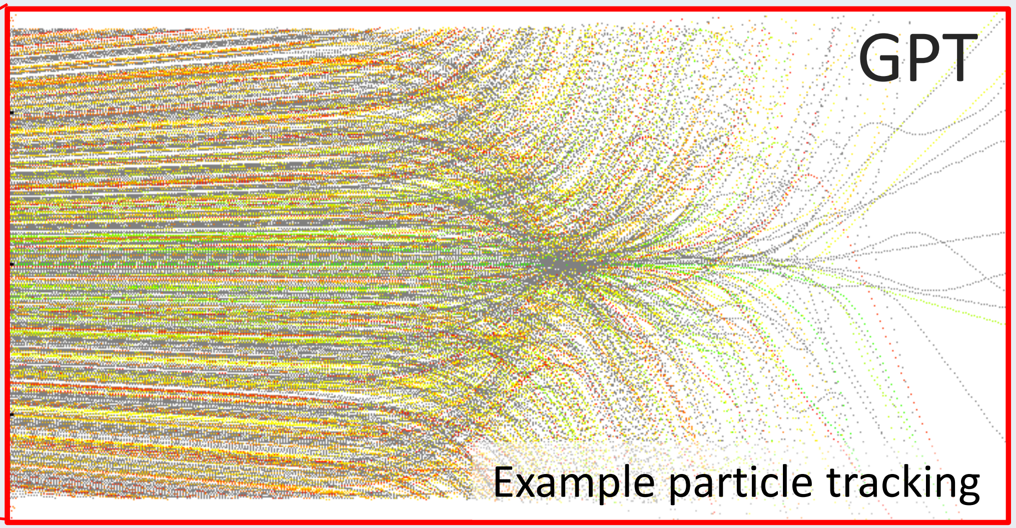

- ➢Recall: optical field strengths ~ 1GV/m
- ➢Conventional elements (quadrupoles, solenoids, etc.) cannot compensate the optical defocusing forces

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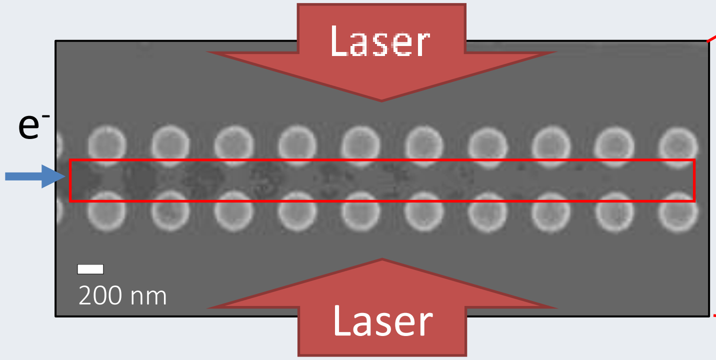
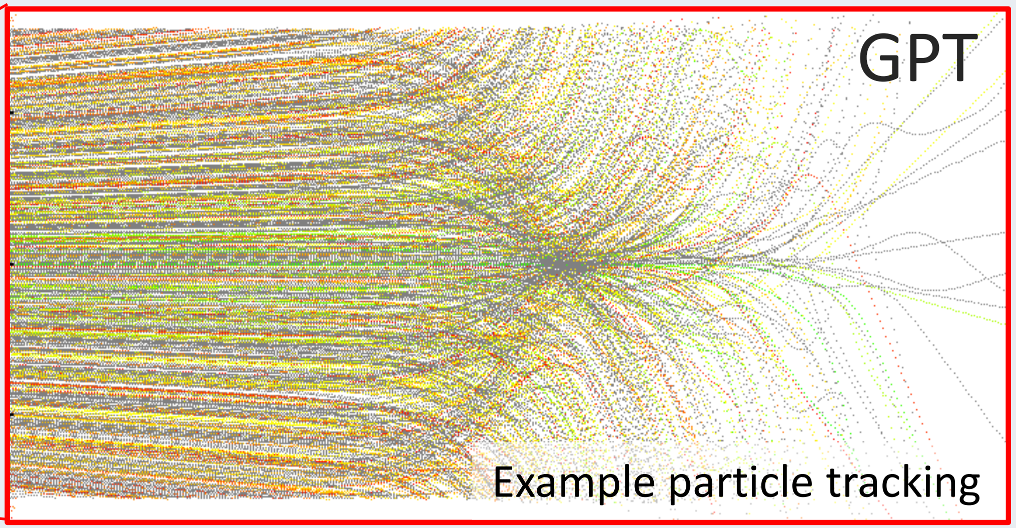




- ➢Recall: optical field strengths ~ 1GV/m
- ➢Conventional elements (quadrupoles, solenoids, etc.) cannot compensate the optical defocusing forces

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

Niedermayer, U., Egenolf, T., & Boine-Frankenheim, O. (2020). *PRL*, *125*(16), 164801.
Niedermayer, U., Egenolf, T., Boine-Frankenheim, O., & Hommelhoff, P. (2018). *PRL*, *121*(21), 214801.

ALTERNATING PHASE FOCUSING

Ja. B. FAINBERG 1956

Ukrainian Academy of Sciences, Kharkov

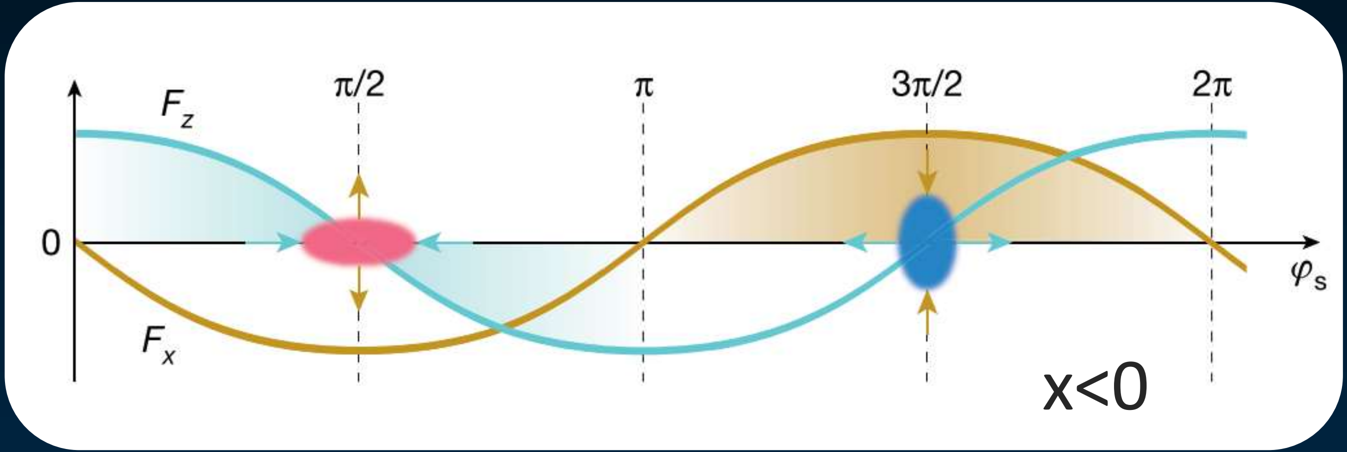
Guiding with Alternating Phase Focusing

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 the fundamental wave number of structure
φ_s the synchronous phase

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

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



Niedermayer, U., Egenolf, T., Boine-Frankenheim, O., Hommelhoff P., *Physical review letters* 121.21 (2018): 214801.
Shiloh, R., Illmer, J., Chlouba, T., Yousefi, P., Schönenberger, N., Niedermayer, U., Mittelbach, A., & Hommelhoff, P. (2021). *Nature*, *597*(7877), 498-502.

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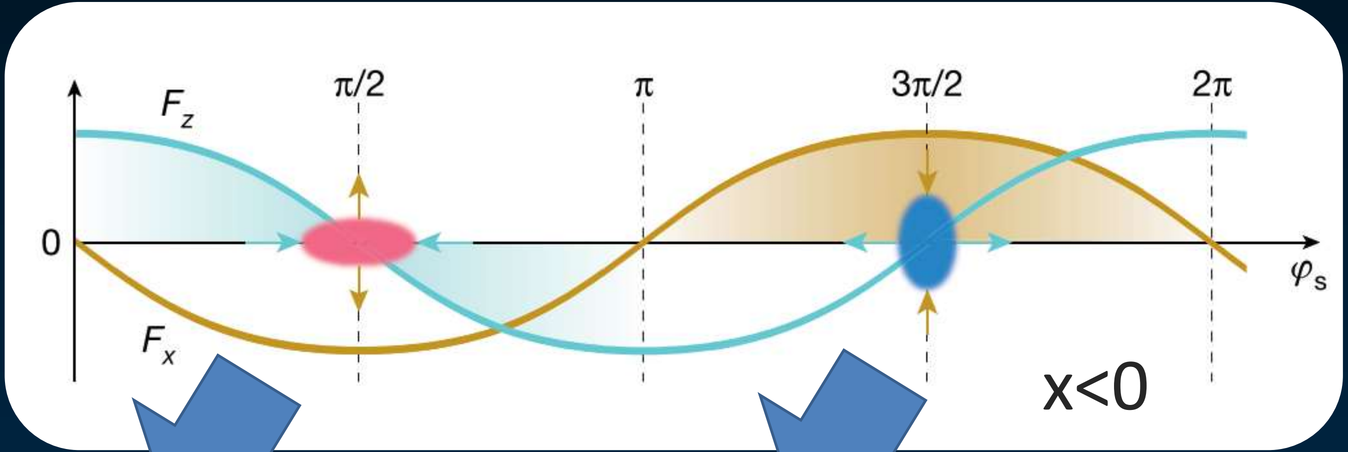

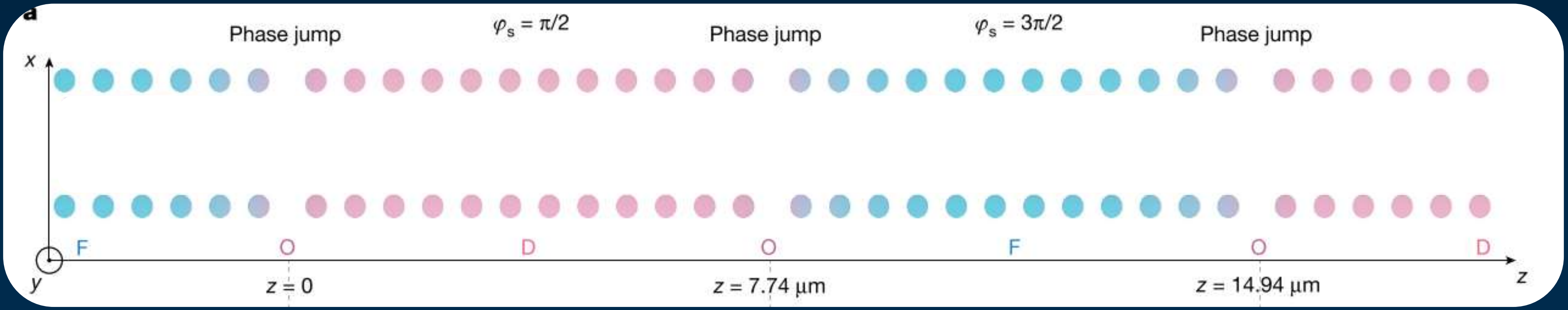

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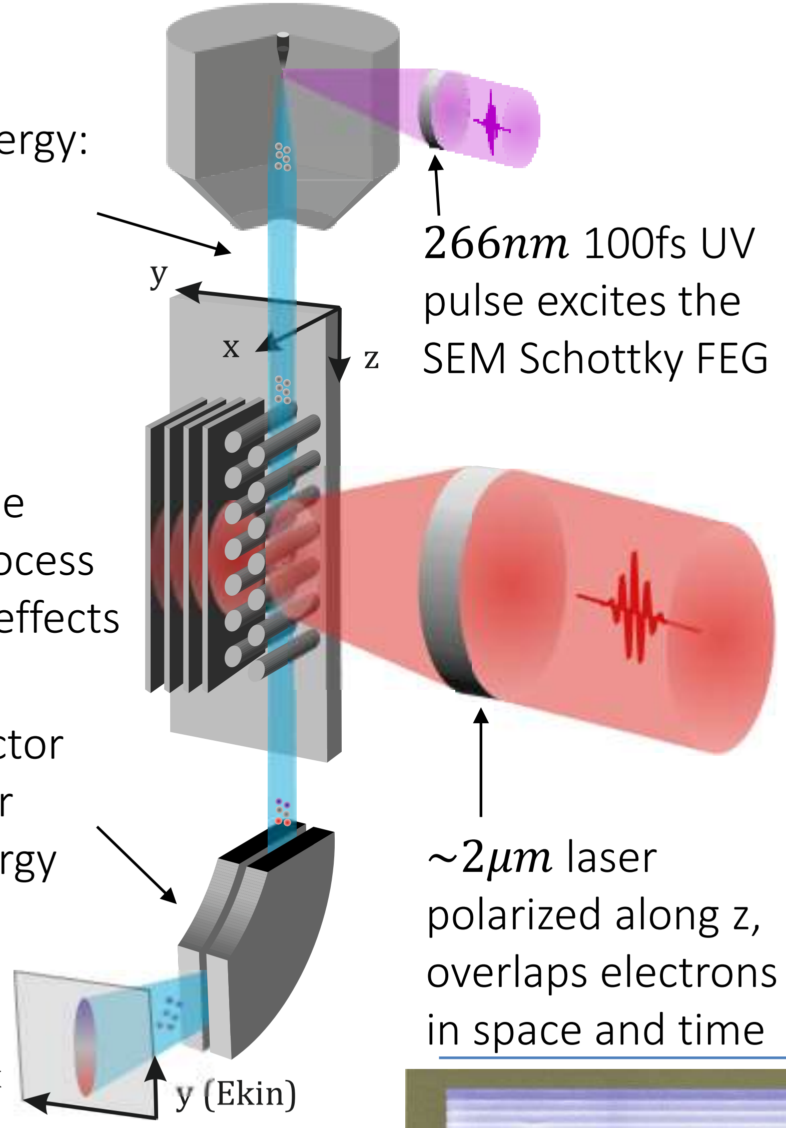
Experimental setup

Kozák, M., McNeur, J., Schönenberger, N., Illmer, J., Li, A., Tafel, A., ... & Hommelhoff, P. (2018). *Journal of Applied Physics*, *124*(2), 023104.

Electron energy:
~$30 keV$



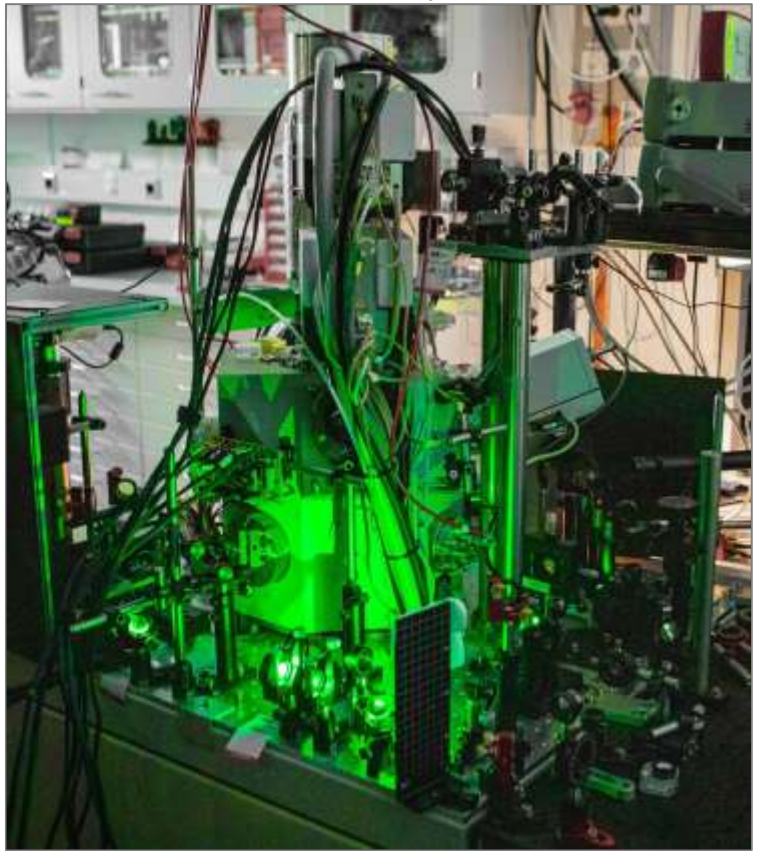
$266nm$ 100fs UV pulse excites the SEM Schottky FEG

„Dual pillar“ structure:
- ✓ Symmetric field profile
- ✓ Simple fabrication process
- ✓ No nonlinear optical effects

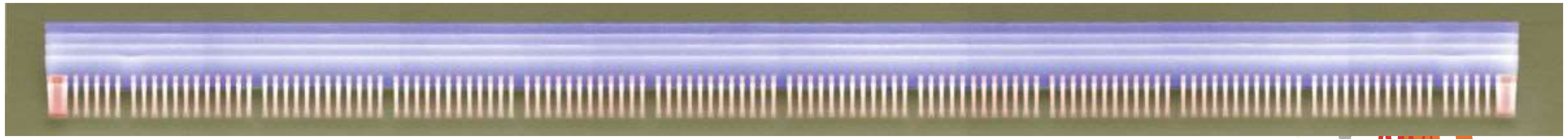
Magnetic sector spectrometer analyzes energy spectra

$\sim 2\mu m$ laser polarized along z, overlaps electrons in space and time

Ultrafast scanning electron microscope

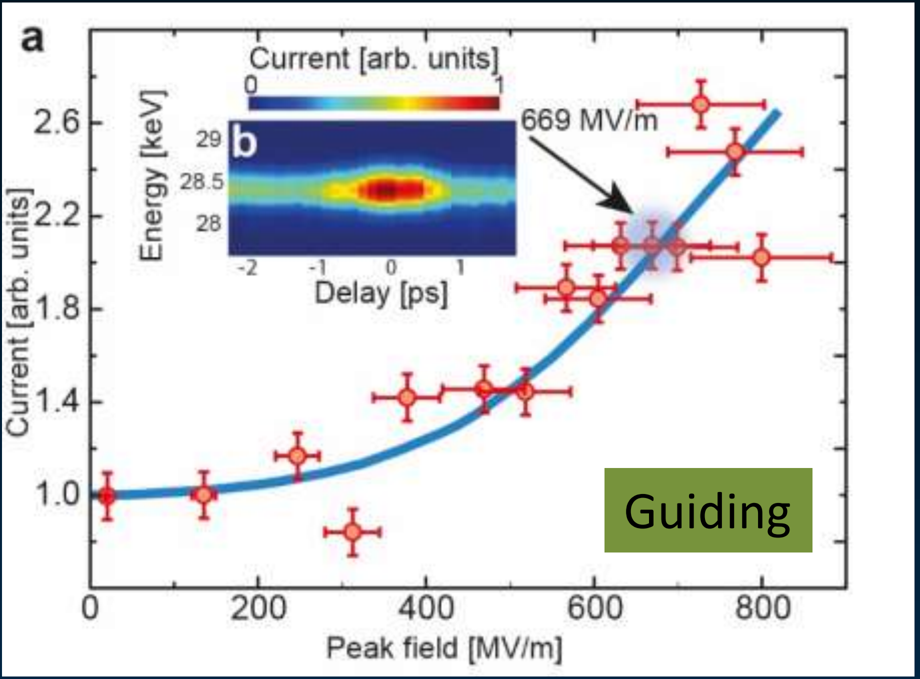


$77\mu m$

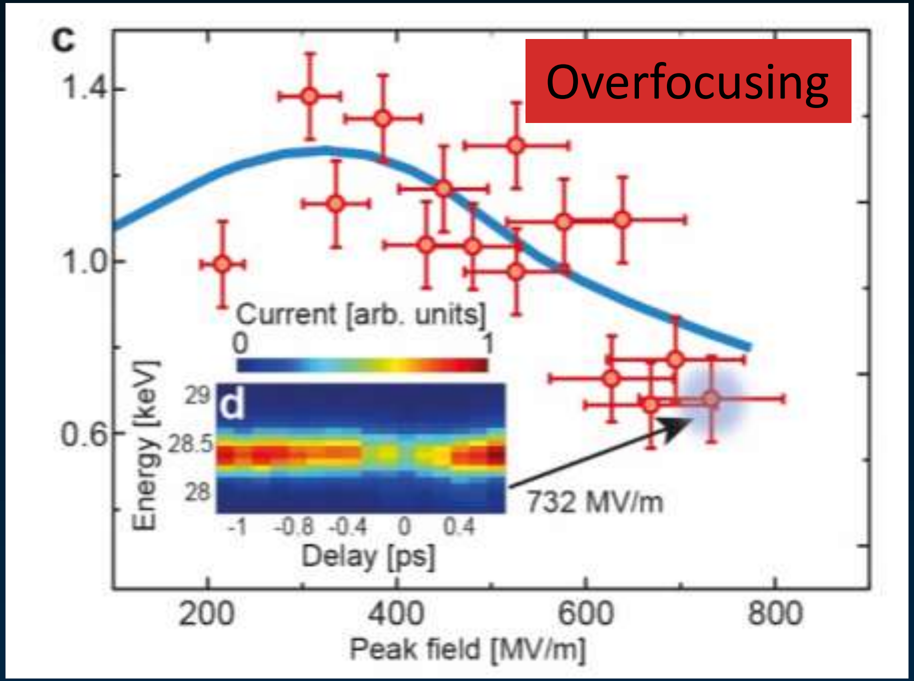


Yousefi et al., Opt. Lett. 44, 6 (2019)

Alternating phase focusing effect: proof of principle

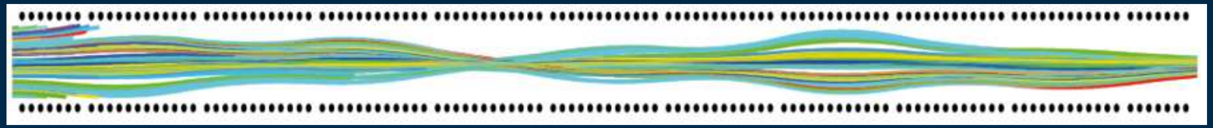


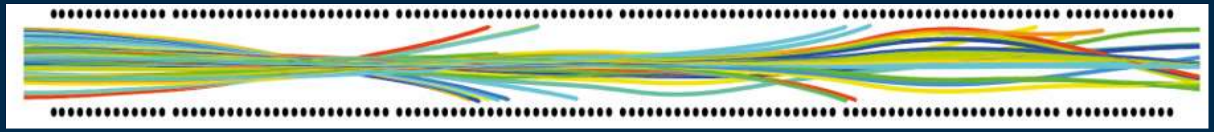
2.7 larger electron current at optimal transport field strength (~700 MV/m)



Overfocusing effect (>400 MV/m)

Different structure geometry with larger macrocells here



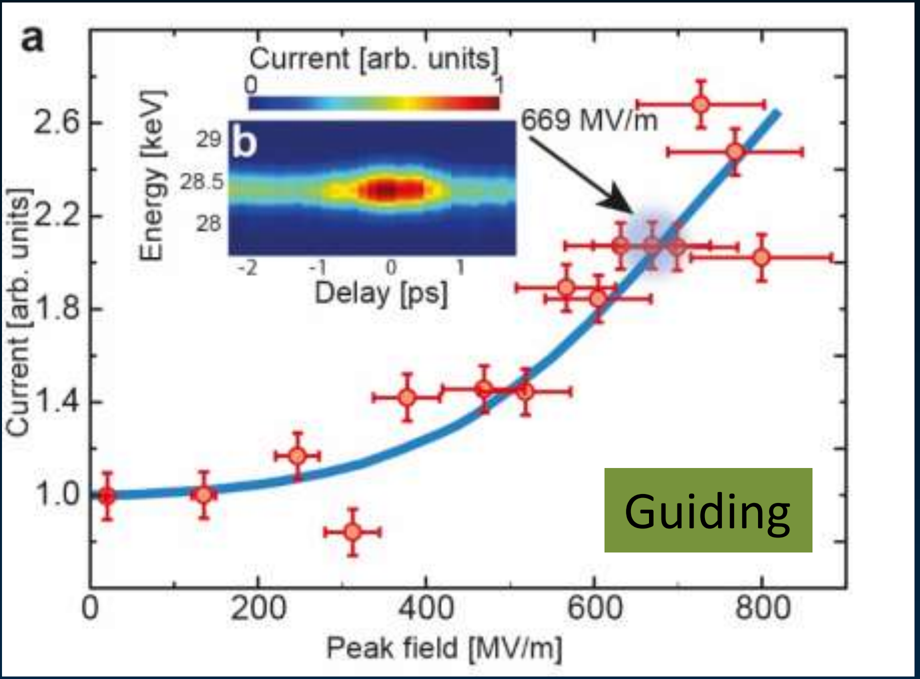


R. Shiloh, J. Illmer, T. Chlouba, P. Yousefi, N. Schönenberger, U. Niedermayer, A. Mittelbach, P. Hommelhoff, Nature 597, 498 (2021)

Niedermayer, U., Egenolf, T., Boine-Frankenheim, O., Hommelhoff P., *Physical review letters* 121.21 (2018): 214801.

Next step: Acceleration AND guiding

Guiding and acceleration ?



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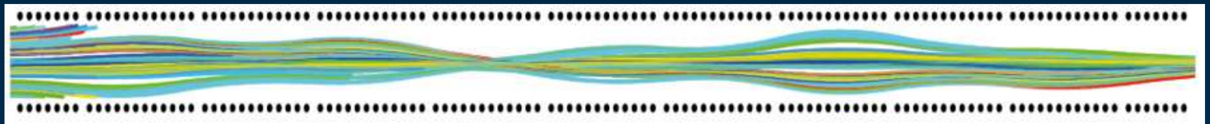
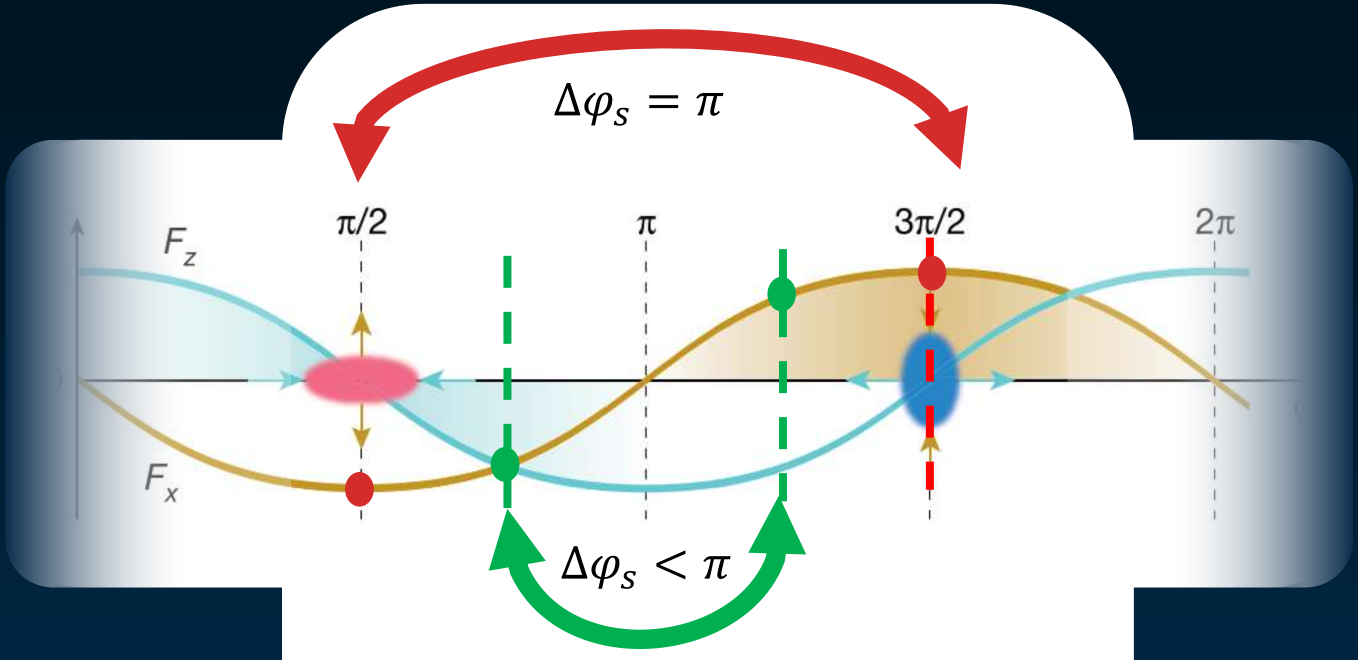




Optimized guiding: $\Delta\varphi_s = \pi$

$F_z = 0$

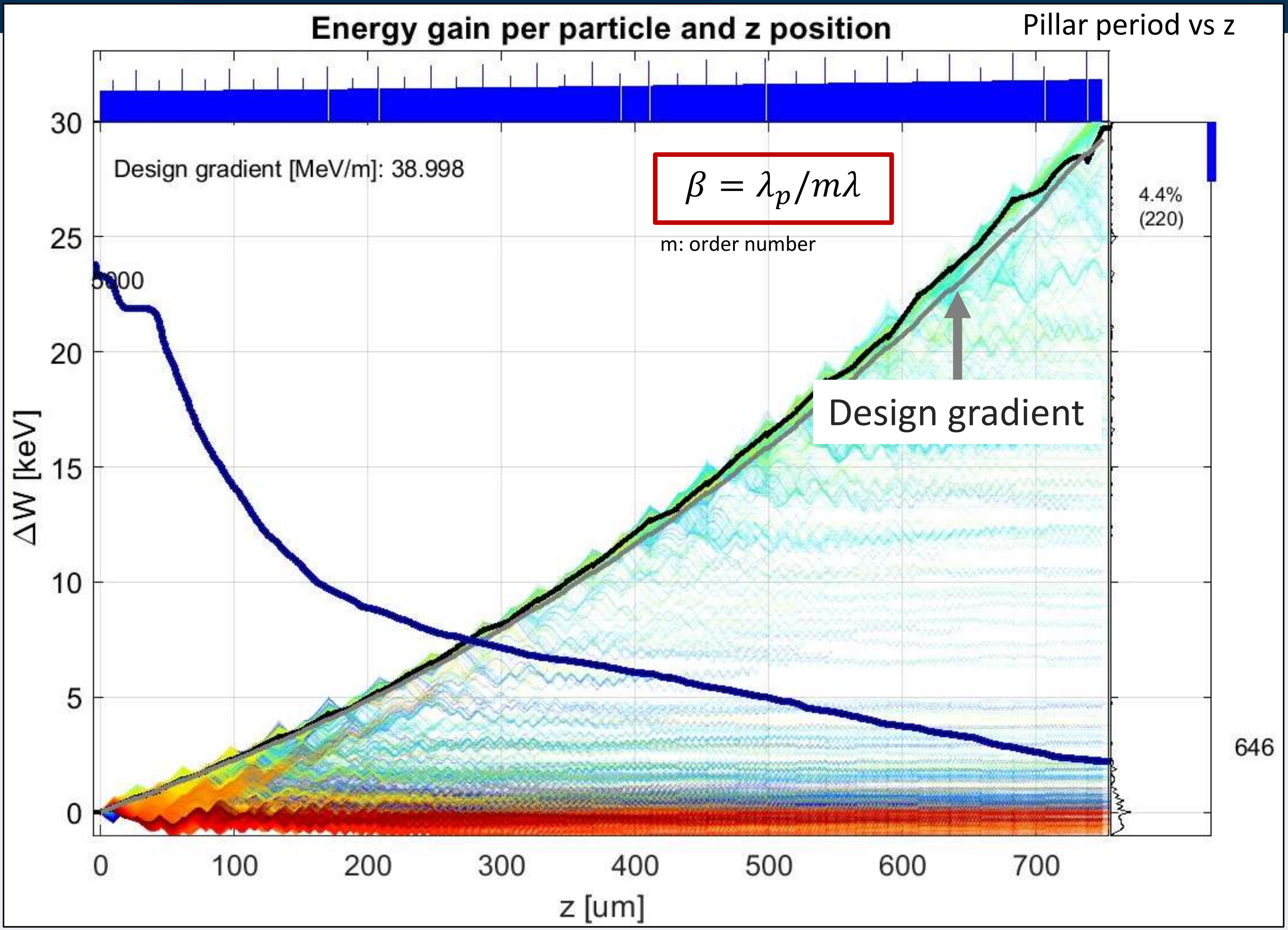
Guiding + de-/acceleration: $\Delta\varphi_s < \pi$

$F_z \neq 0$

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

Niedermayer, U., Egenolf, T., Boine-Frankenheim, O., Hommelhoff P., *Physical review letters* 121.21 (2018): 214801.

Towards significant acceleration – APF + Tapering



Electron guiding and acceleration

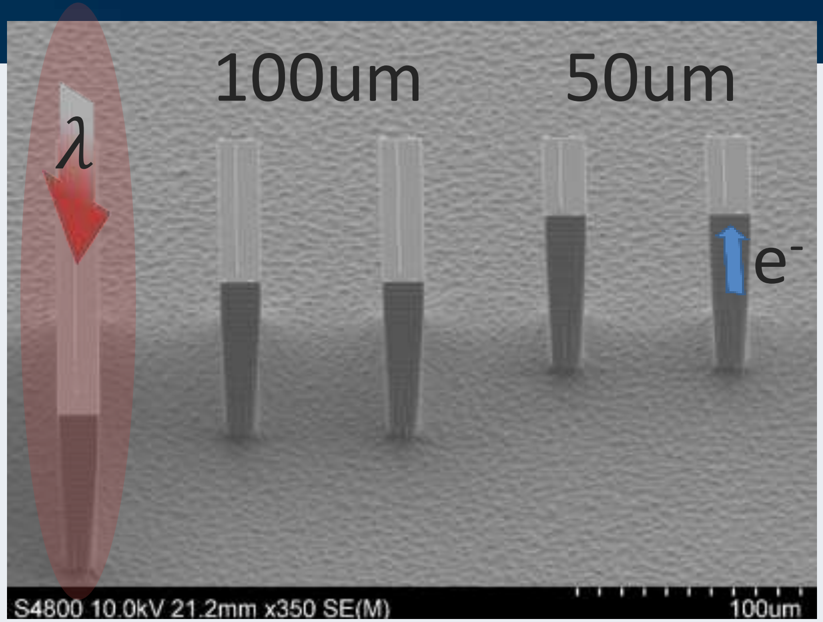
Features included:

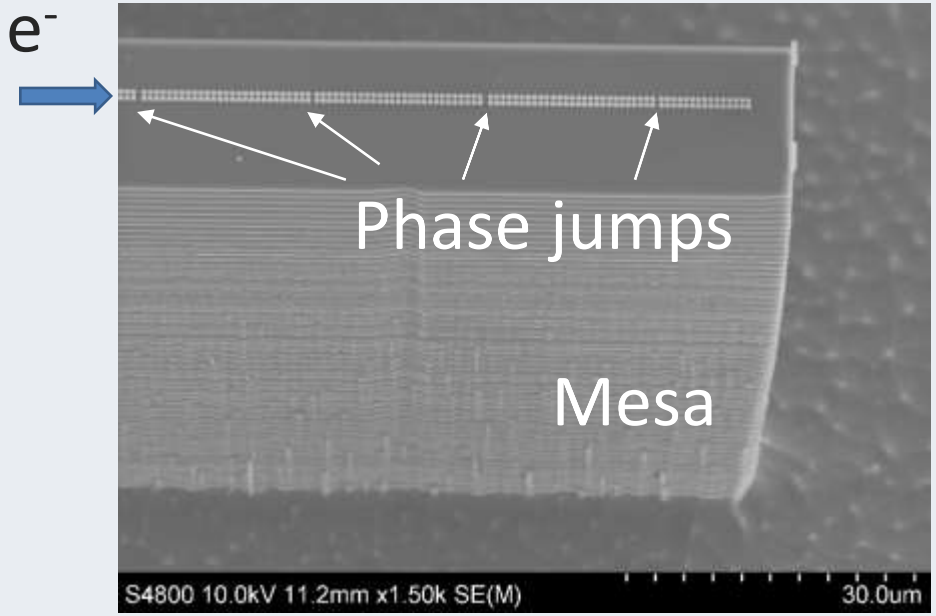
- APF effect
- Tapered
- Numerically optimized
- Longer interaction with tilted laser pulse front (PFT)

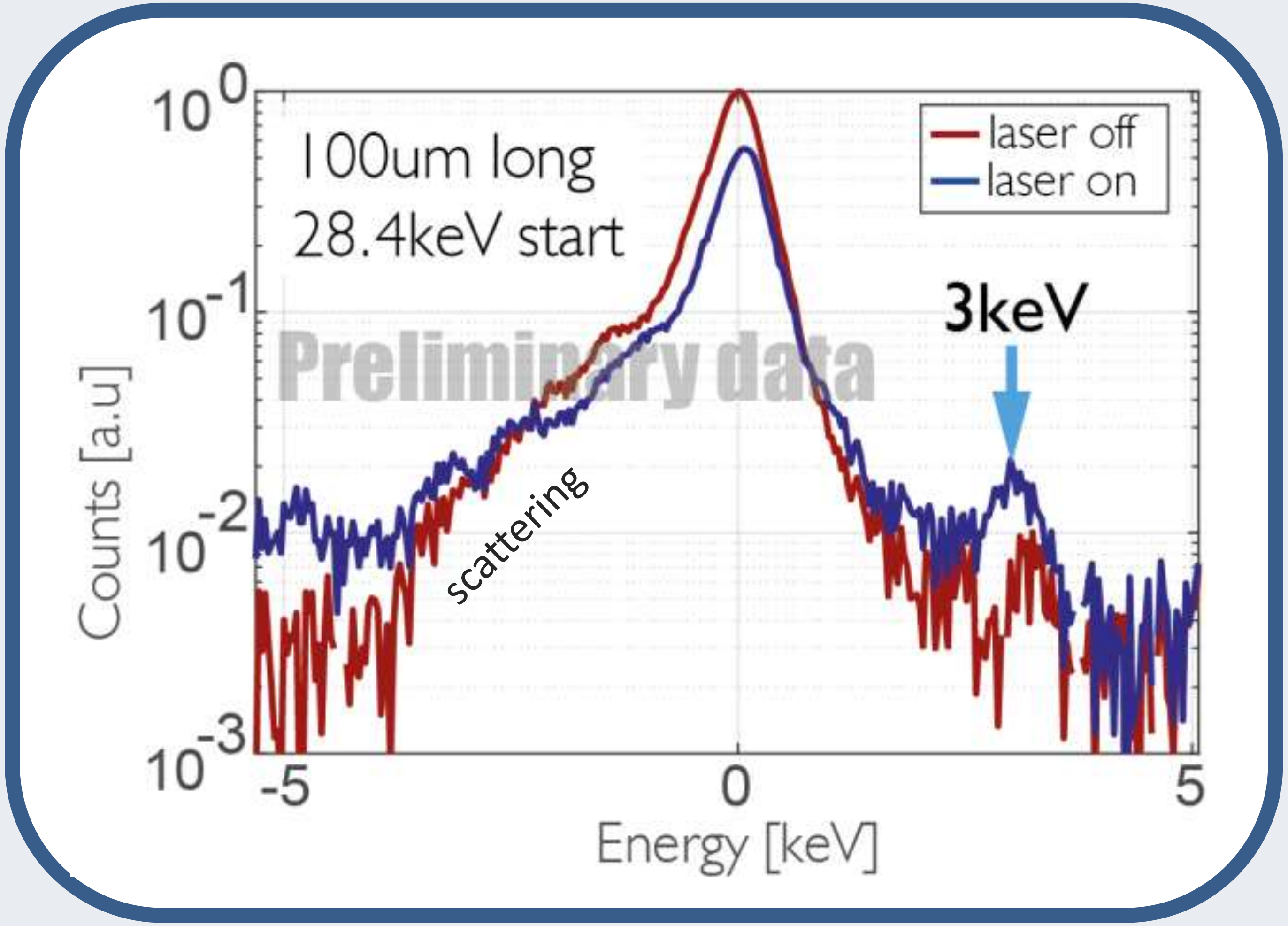
With a 800um long structure we expect an energy gain of approx. 30keV for 4.4% of the electrons

Energy doubler

First net energy gain in 100μm long structure

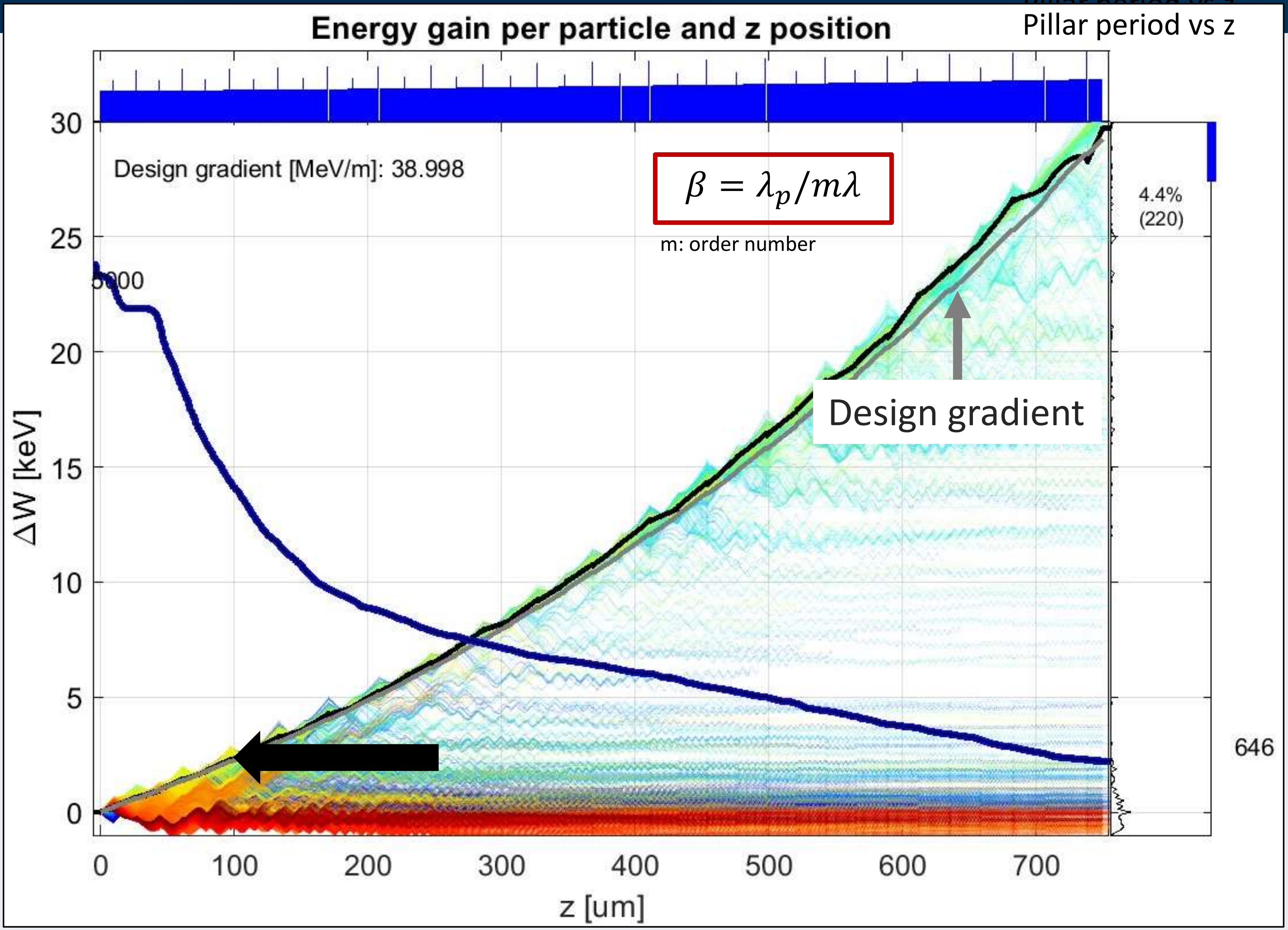






E_{Peak} = 600MV/m - 700MV/m
Expected gradient: 30MeV/m

Towards significant acceleration – APF + Tapering



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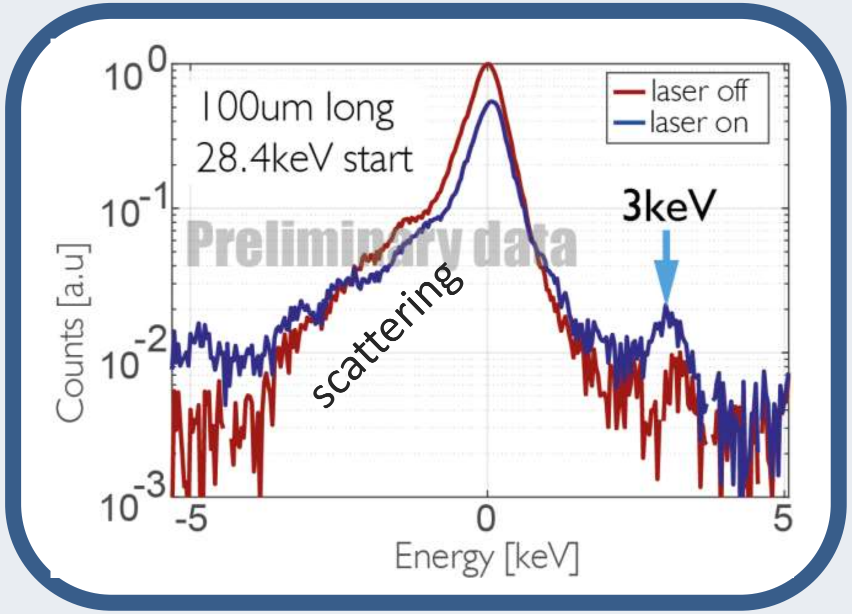
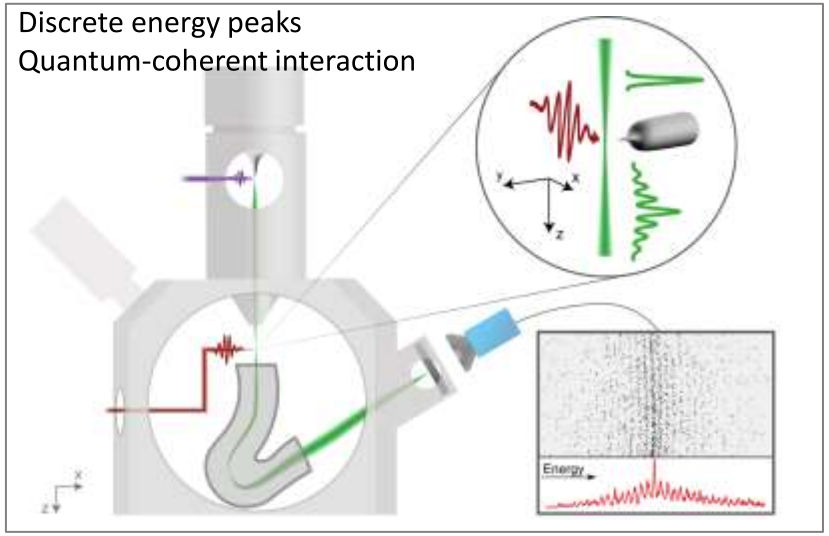
Energy doubler

Conclusion and outlook

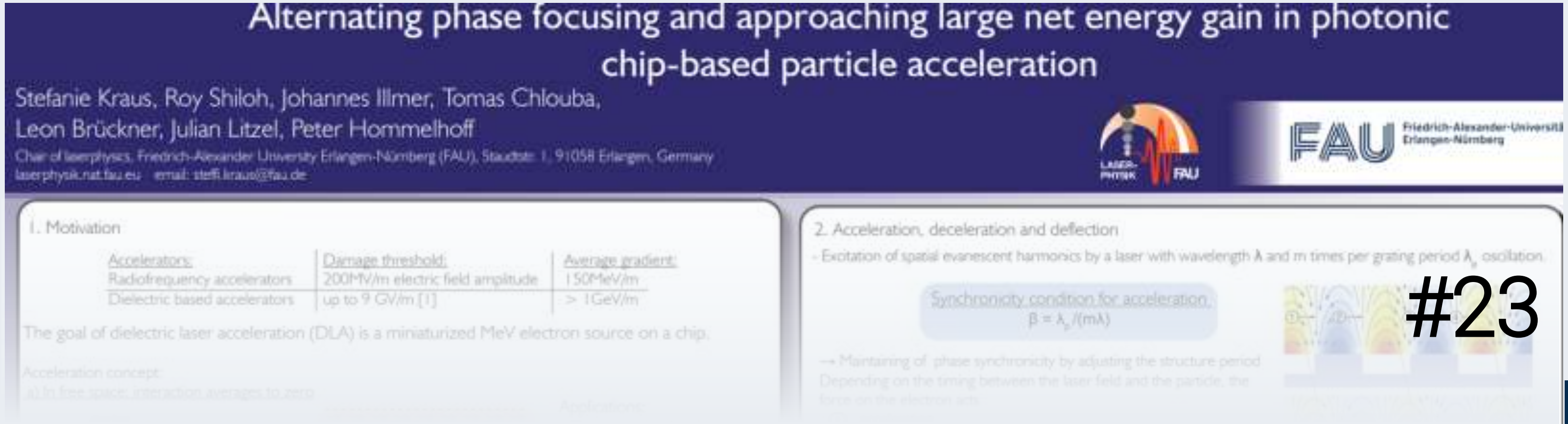


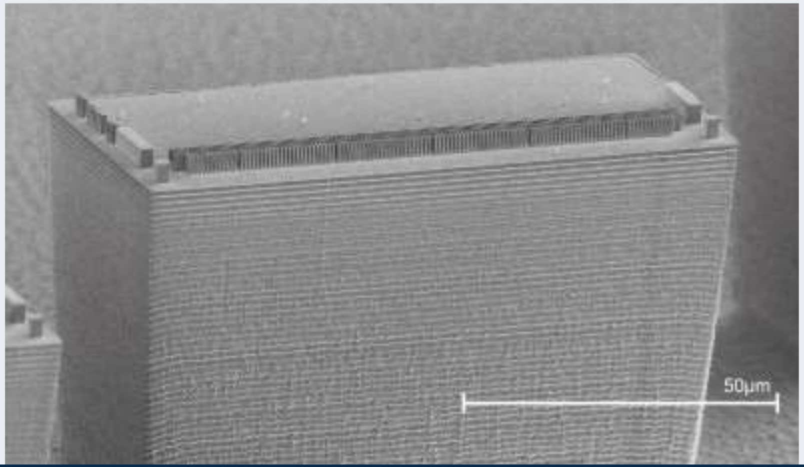
Nanophotonic-based particle acceleration

- Complex electron phase space control demonstrated over 77μm long structure: alternating phase focusing
- **First 3keV (10%) energy gain**



Shiloh, R., Chlouba, T., & Hommelhoff, P. (2022). PRL, *128*(23), 235301.

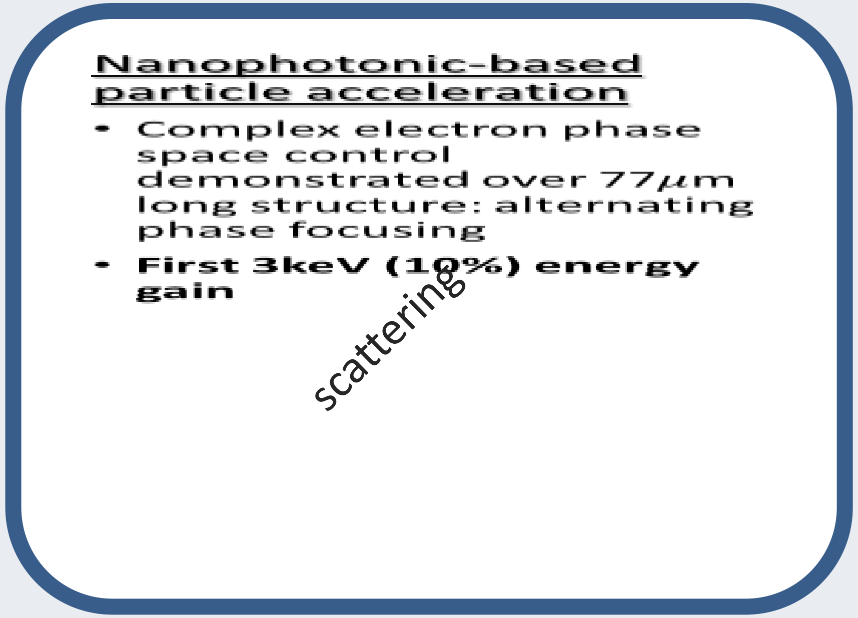




R. Shiloh, J. Illmer, T. Chlouba, P. Yousefi, N. Schönenberger, U. Niedermayer, A. Mittelbach, P. Hommelhoff, Nature 597, 498 (2021)

Thank you for your attention!

Conclusion and outlook



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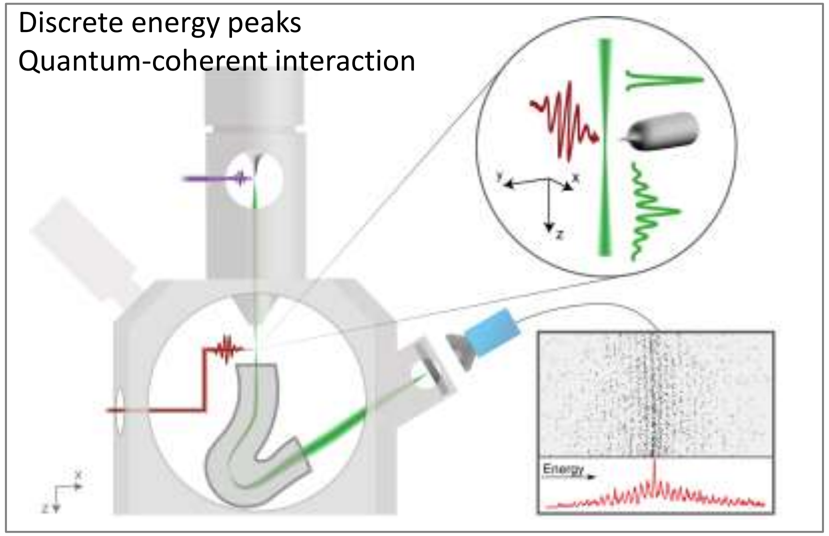
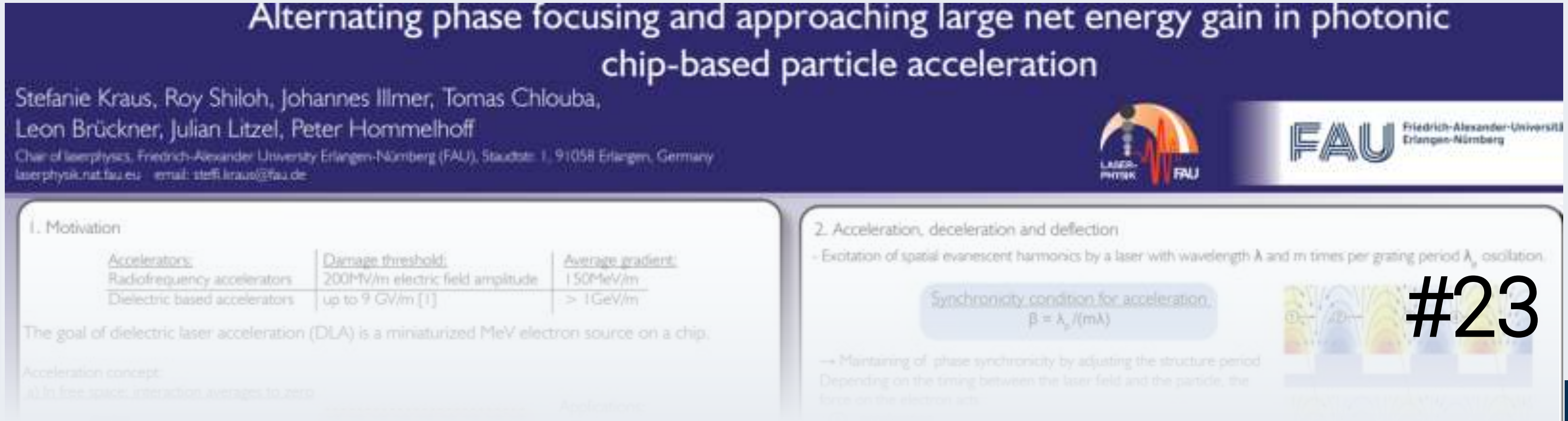
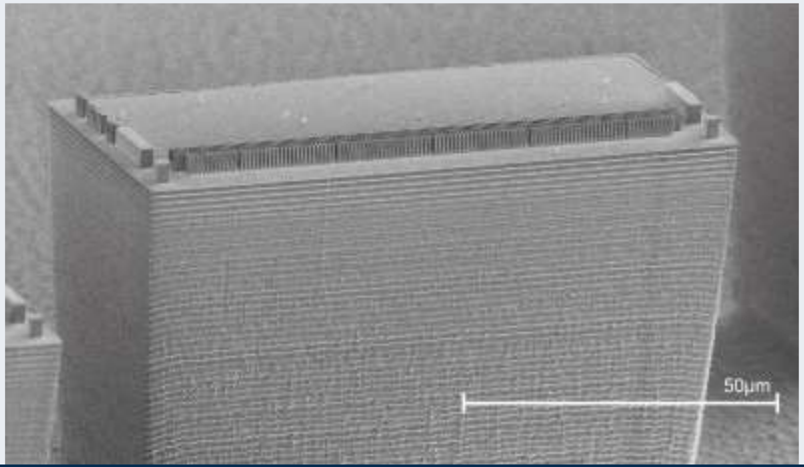


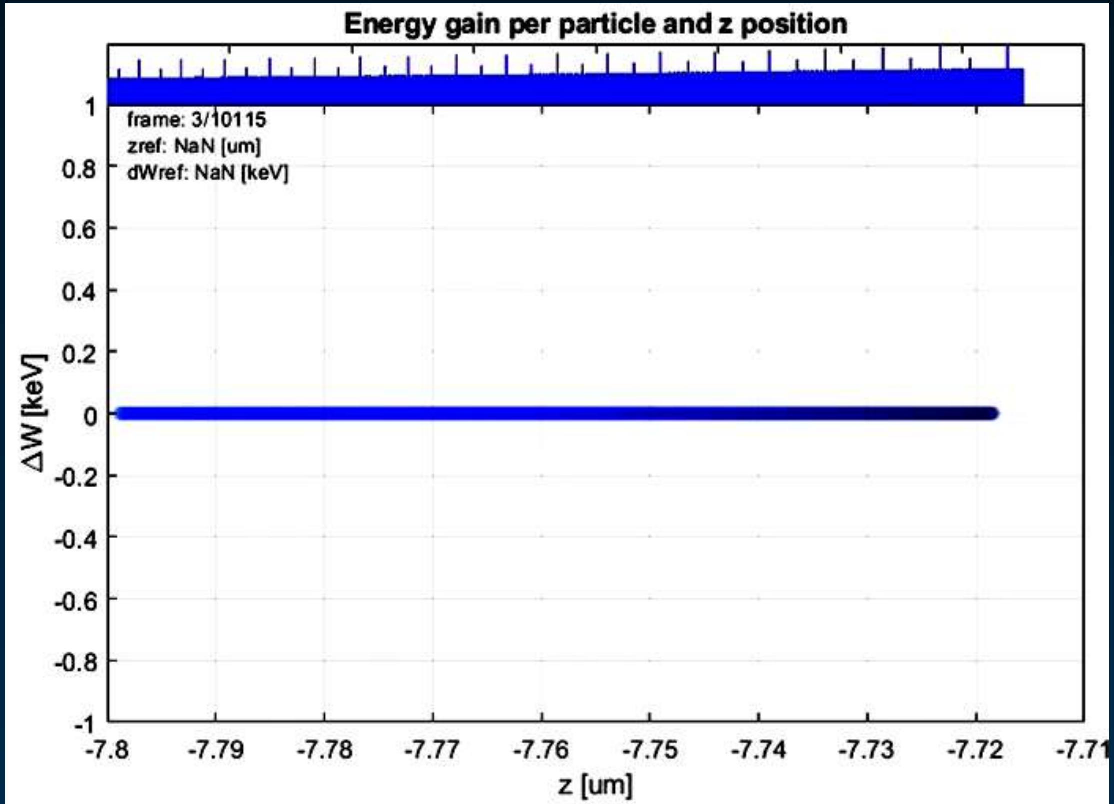
Shiloh, R., Chlouba, T., & Hommelhoff, P. (2022). PRL, *128*(23), 235301.

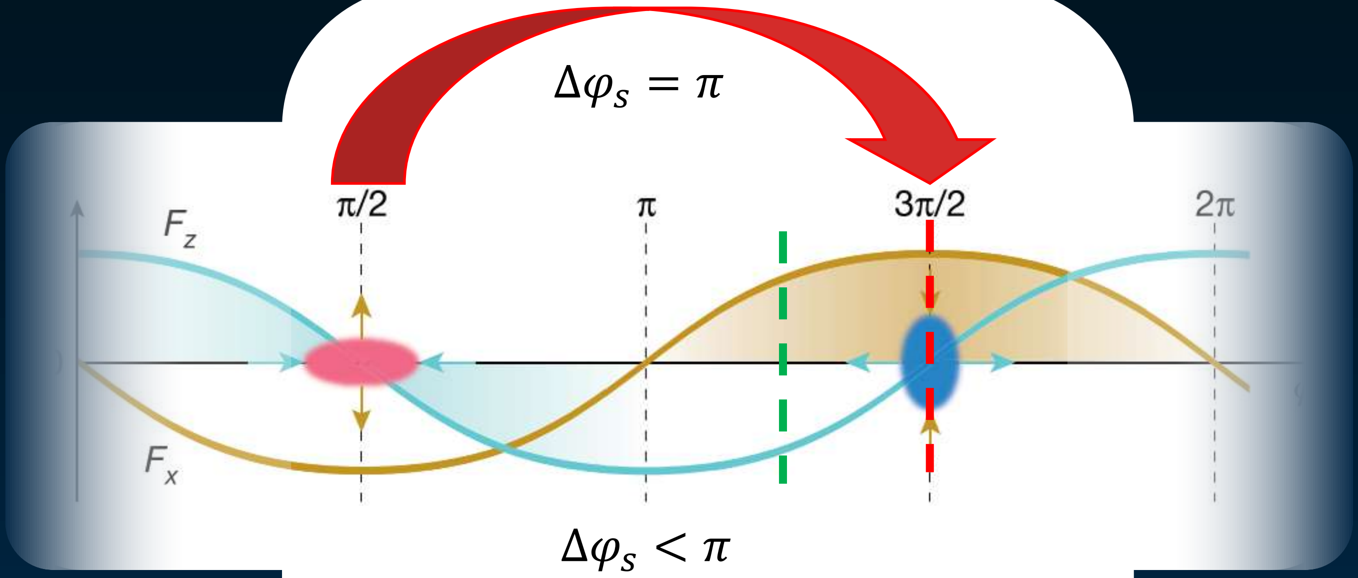




R. Shiloh, J. Illmer, T. Chlouba, P. Yousefi, N. Schönenberger, U. Niedermayer, A. Mittelbach, P. Hommelhoff, Nature 597, 498 (2021)

Guiding and acceleration ?





Optimized guiding: $\Delta\varphi_s = \pi$

$F_{z_{avg}} = 0$

Guiding + de-/acceleration: $\Delta\varphi_s < \pi$

$F_{z_{avg}} \neq 0$

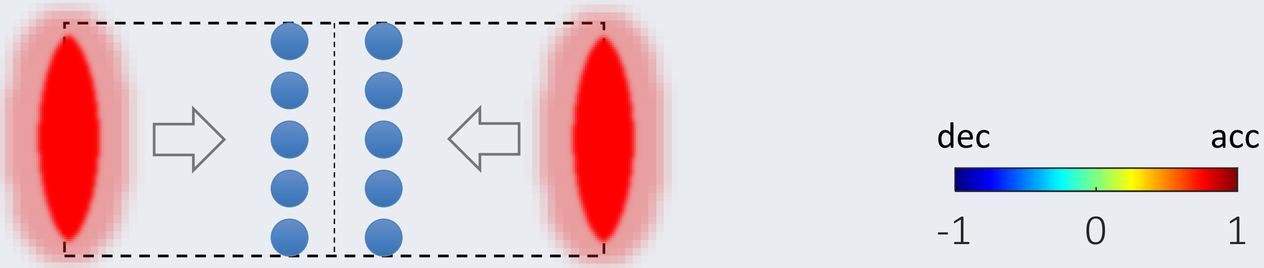
Particle is copropagating with the optical nearfield mode

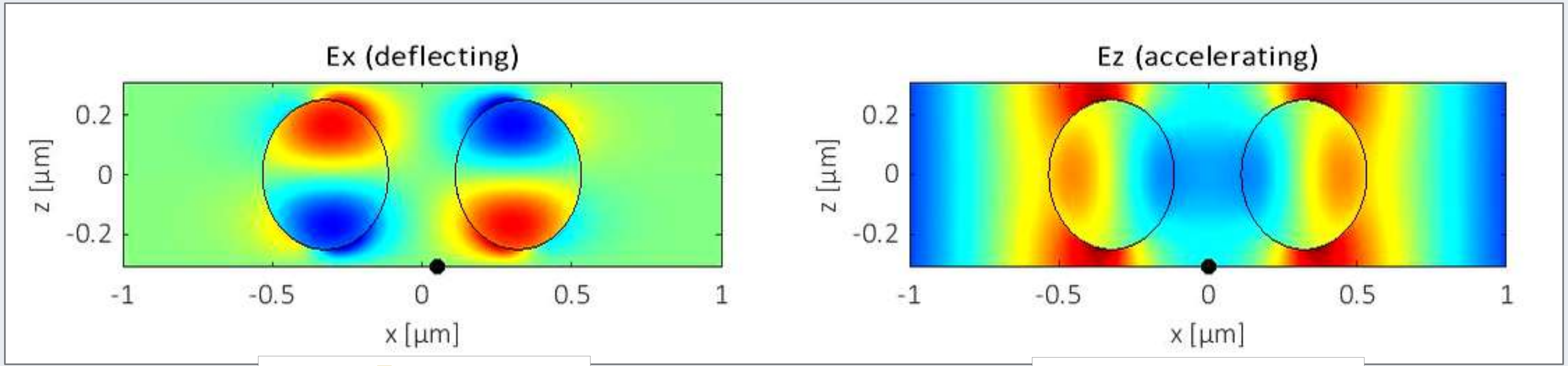
φ_s particle's position inside of the mode

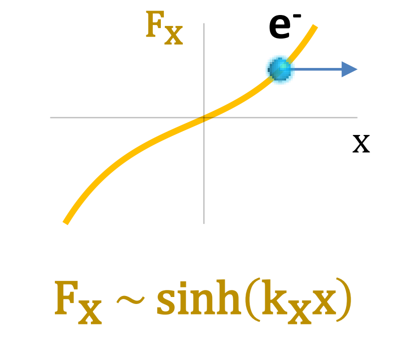
* Fx,Fz for sync. e⁻

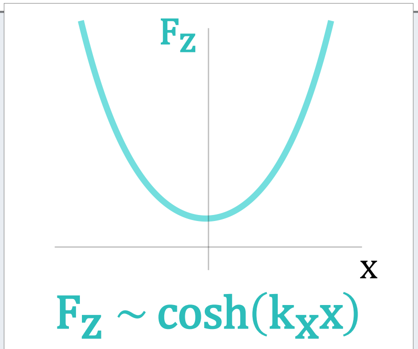
Full fields of a dual-pillar structure

- Particle experiences on average only an accelerating field









Write the electric field as a Fourier series w.r.t. to the grating (period Λ):

$$E_z(x,y,z) = \sum_{m=-\infty}^{\infty} \mathrm{e}_m(x,y) e^{-im2\pi z/\Lambda}$$

For our structures:
$|\mathrm{e}_1|/E_{incident} \approx 0.1$

The energy gain ΔW of an electron in such a field, assuming only one dominant Fourier order m with amplitude $|\mathrm{e_m}|$ and phase φ_m is,

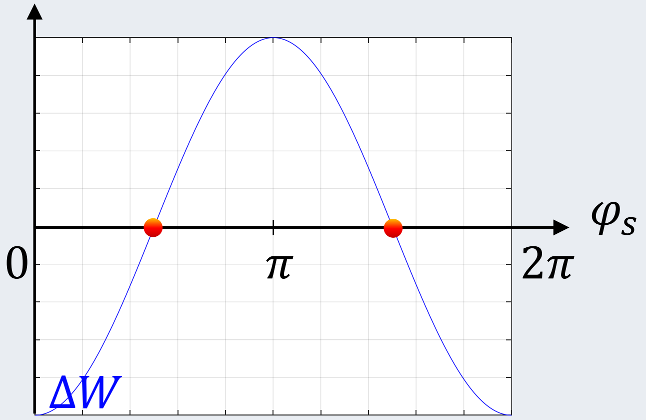
$$\Delta W = q\Lambda|\mathrm{e_m}|\cos(\varphi_s), \quad \varphi_s = 2\pi s/\beta\lambda + \varphi_m$$

Where s is the distance of this particle from some arbitrarily-defined reference particle moving at constant velocity, $z = vt$.

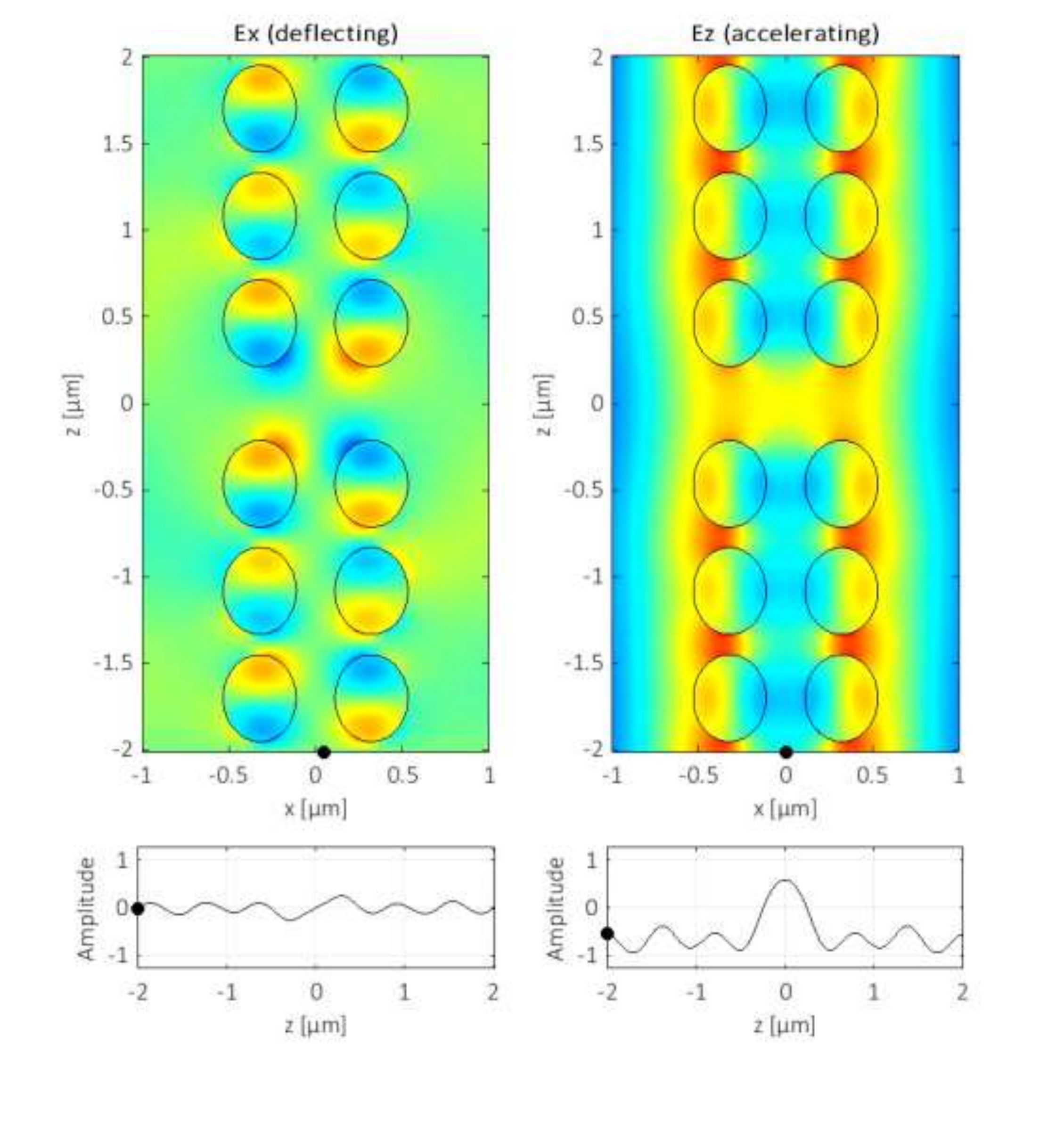
Designing energy gain per cell

$$\Delta z^{(n+1)} = q|\mathrm{e}_1|\lambda^2 \cos\left(\varphi_s^{(n)}\right)/{\gamma^{(n)}}^3 m_e c^2$$

$$\beta^{(n+1)} = \beta^{(n)} + \Delta z^{(n+1)}/\lambda$$

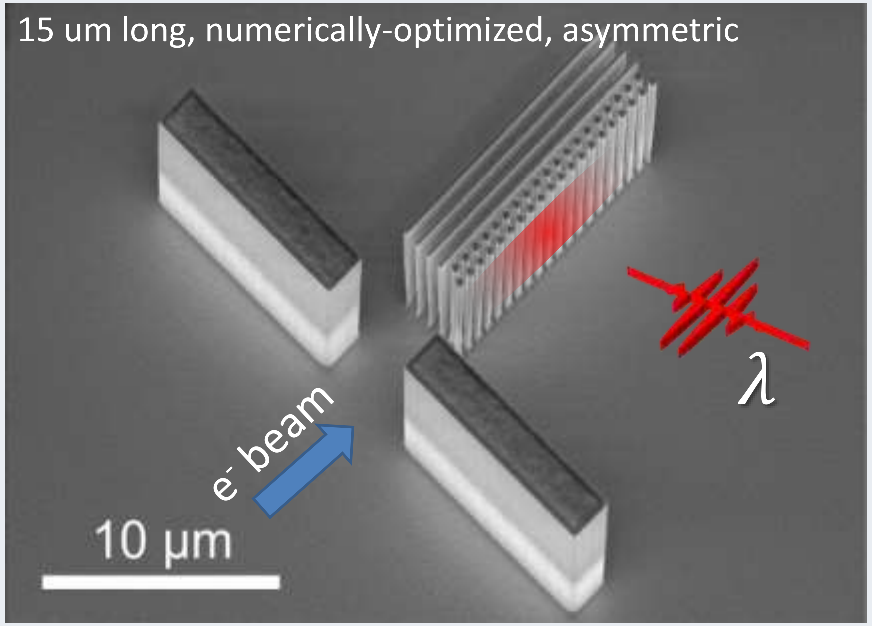


Full fields – APF



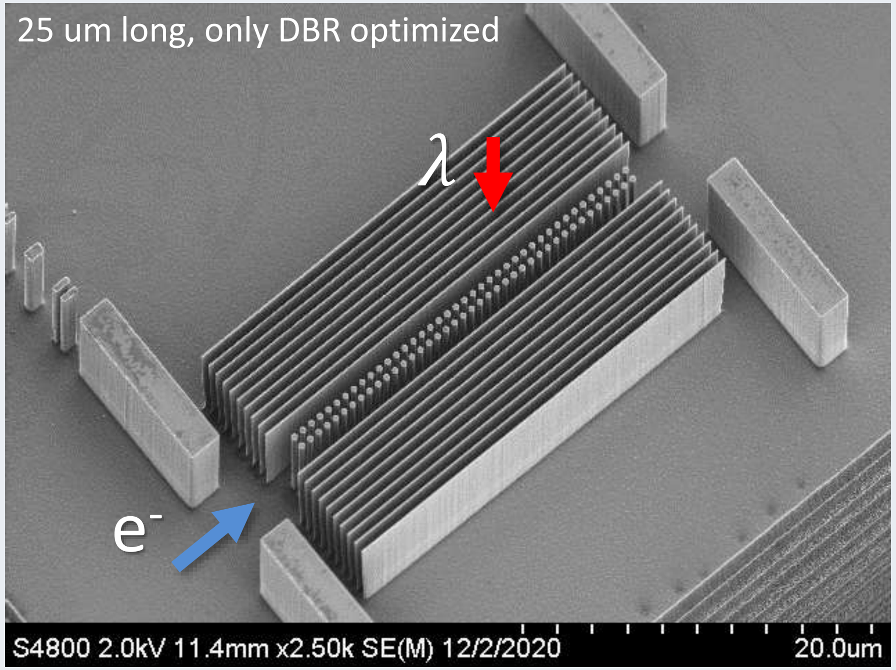
Top illumination

Side illumination



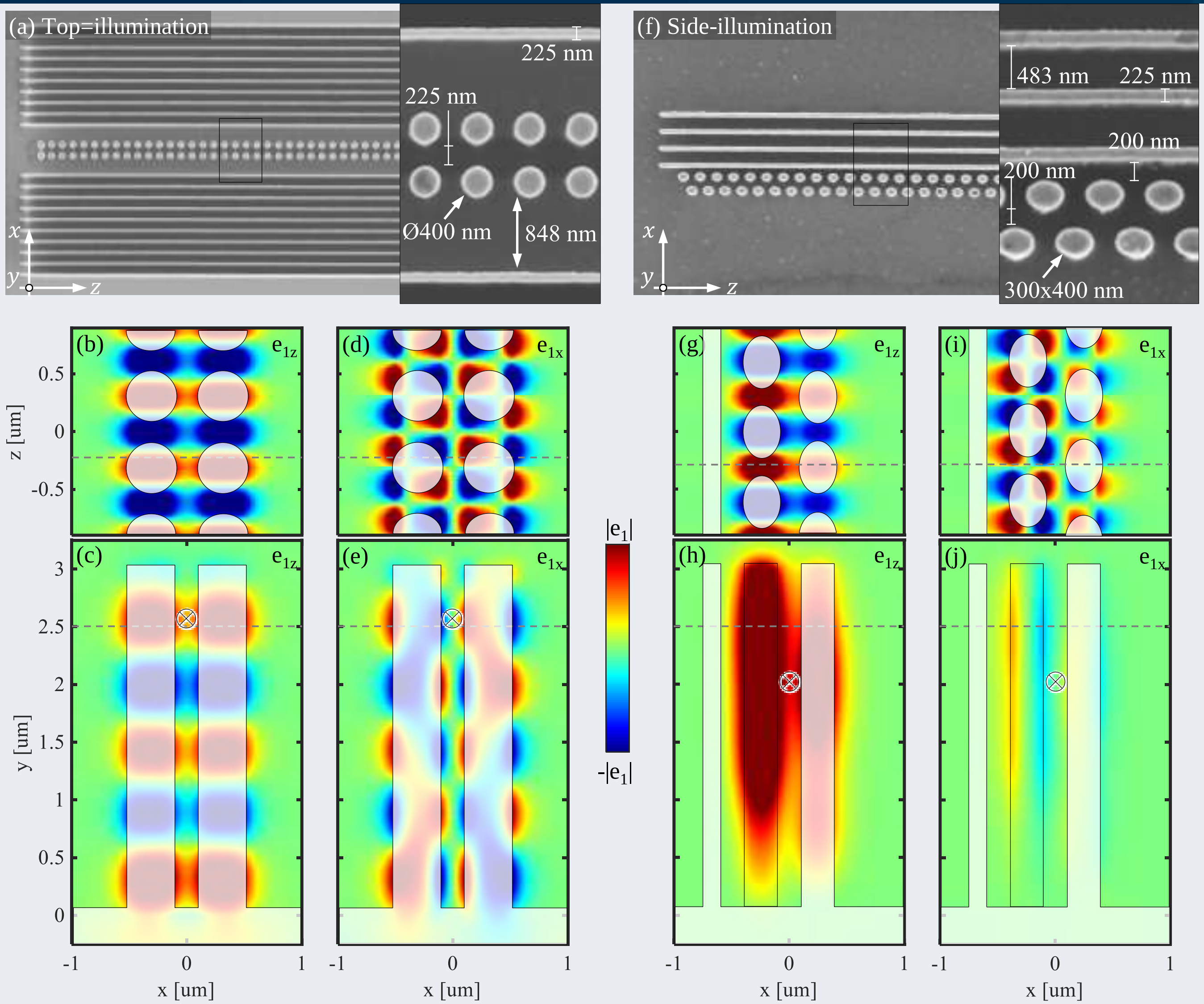
- DBR only mimics two-sided illumination
- Experimentally, can only work with point-reflection from sample

Top illumination



- Transverse symmetry guaranteed
- Experimentally, structure shadow easily seen from reflection
- Additional effect in the vertical direction?

Top illumination

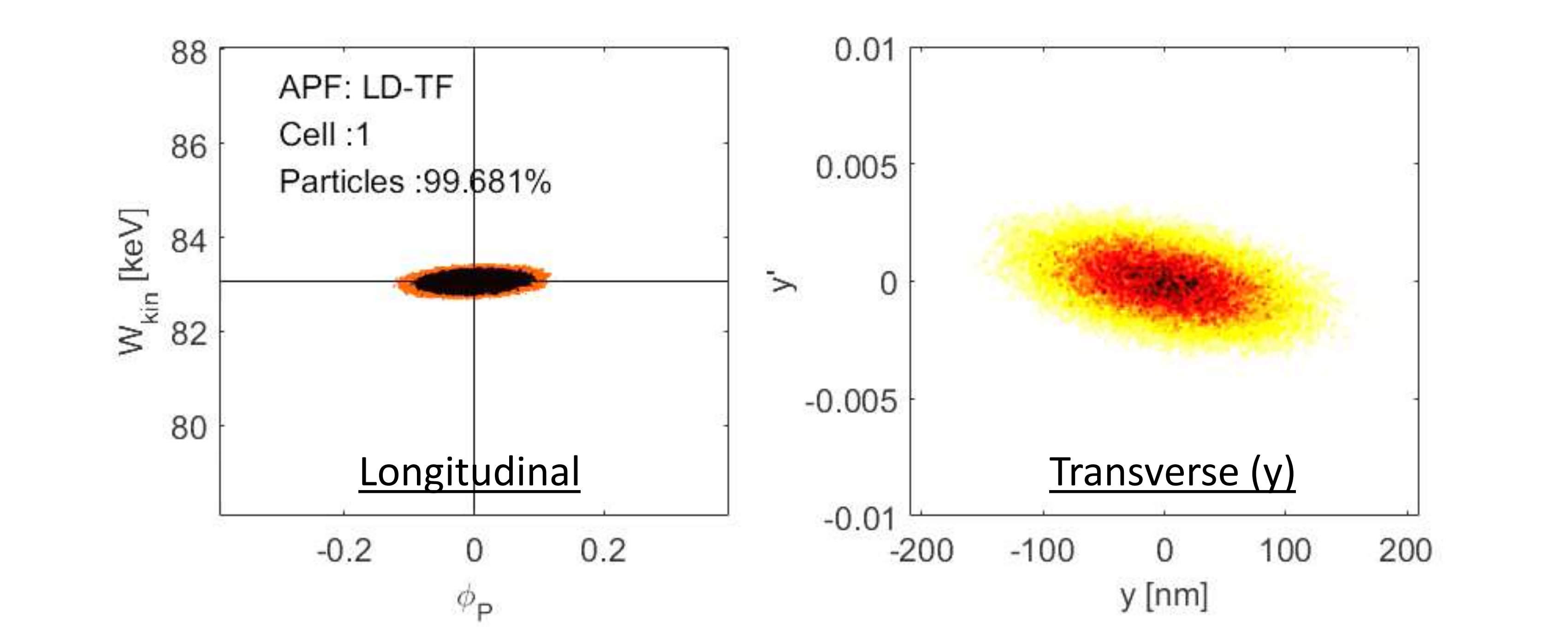


Shiloh, R., Chlouba, T., Yousefi, P., & Hommelhoff, P. (2021,*Optics Express*, *29*(10), 14403-14411.

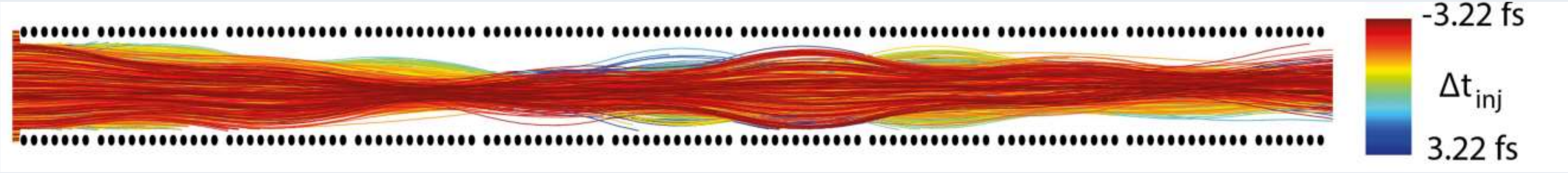
Alternating phase focusing

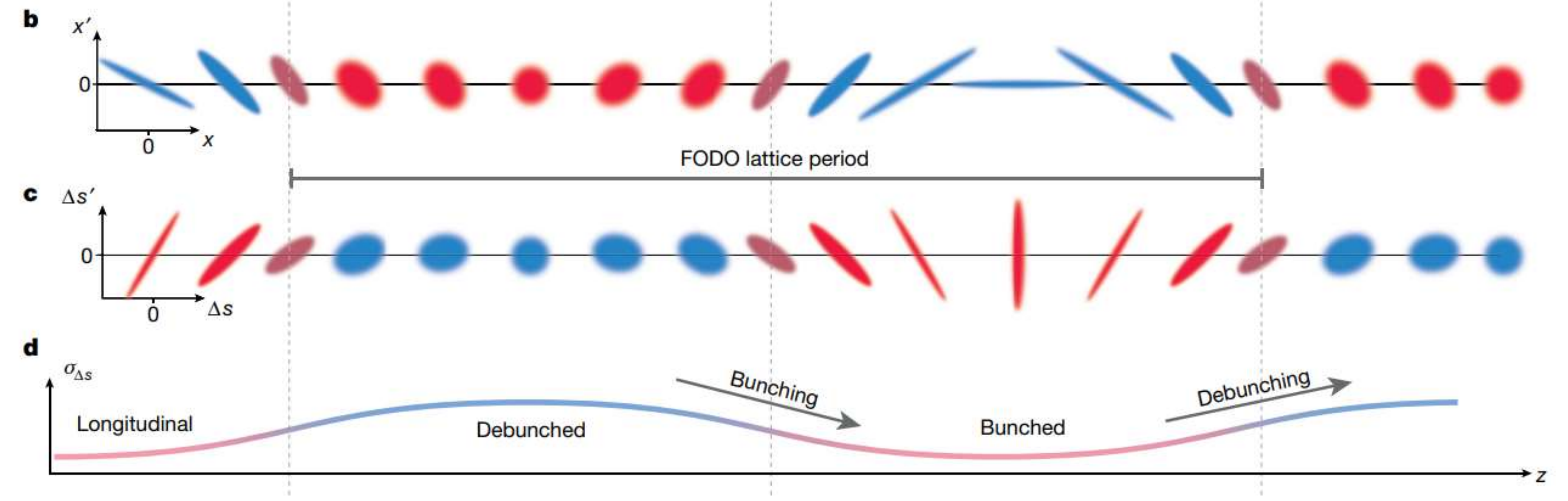
Alternate the transverse and longitudinal directions

Net focusing in both dimensions!

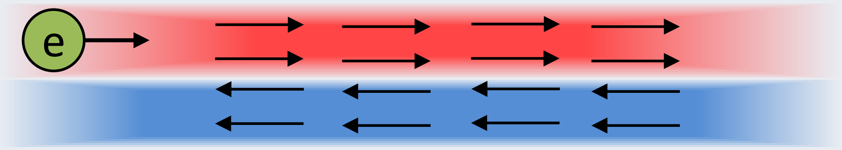


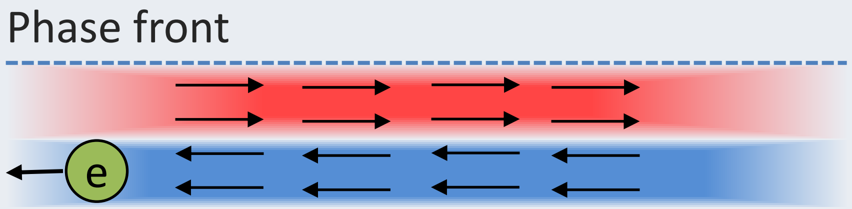
First structure design that allows building the accelerator on a chip with initial energy **83 keV** to more than **1 MeV**:
56% transmission for 100pm rad,
93% for 25pm rad emittance


-3.22 fs
Δt_{inj}
3.22 fs


b
x′
0
0
x
FODO lattice period
c
Δs′
0
0
Δs
d
$\sigma_{\Delta s}$
Longitudinal
Debunched
Bunching
Bunched
Debunching
z

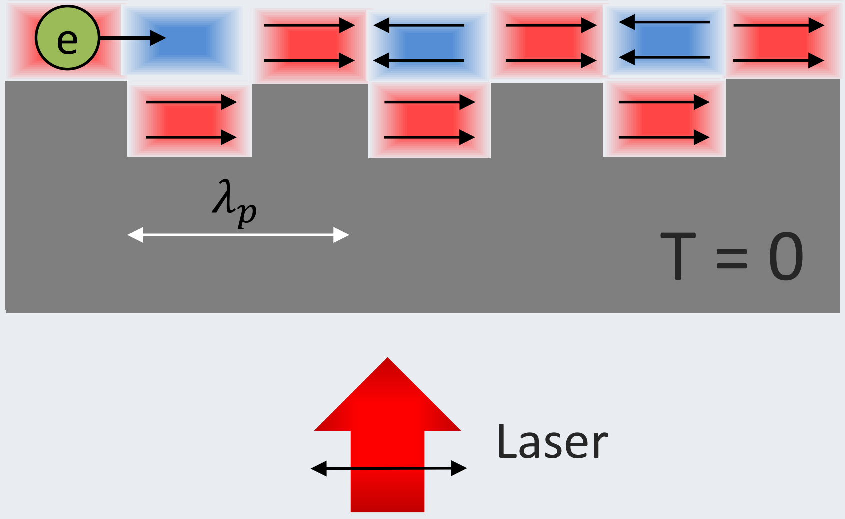
In free space: Interaction averages to zero

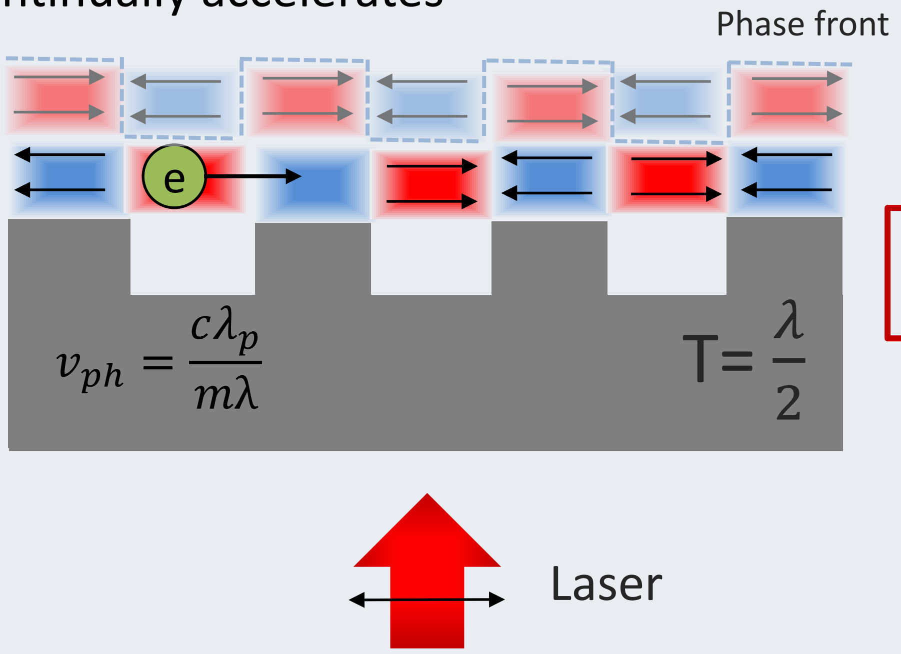




Dielectric structure necessary
to reach synchronicity condition

With dielectric structure: synchronized electron continually accelerates

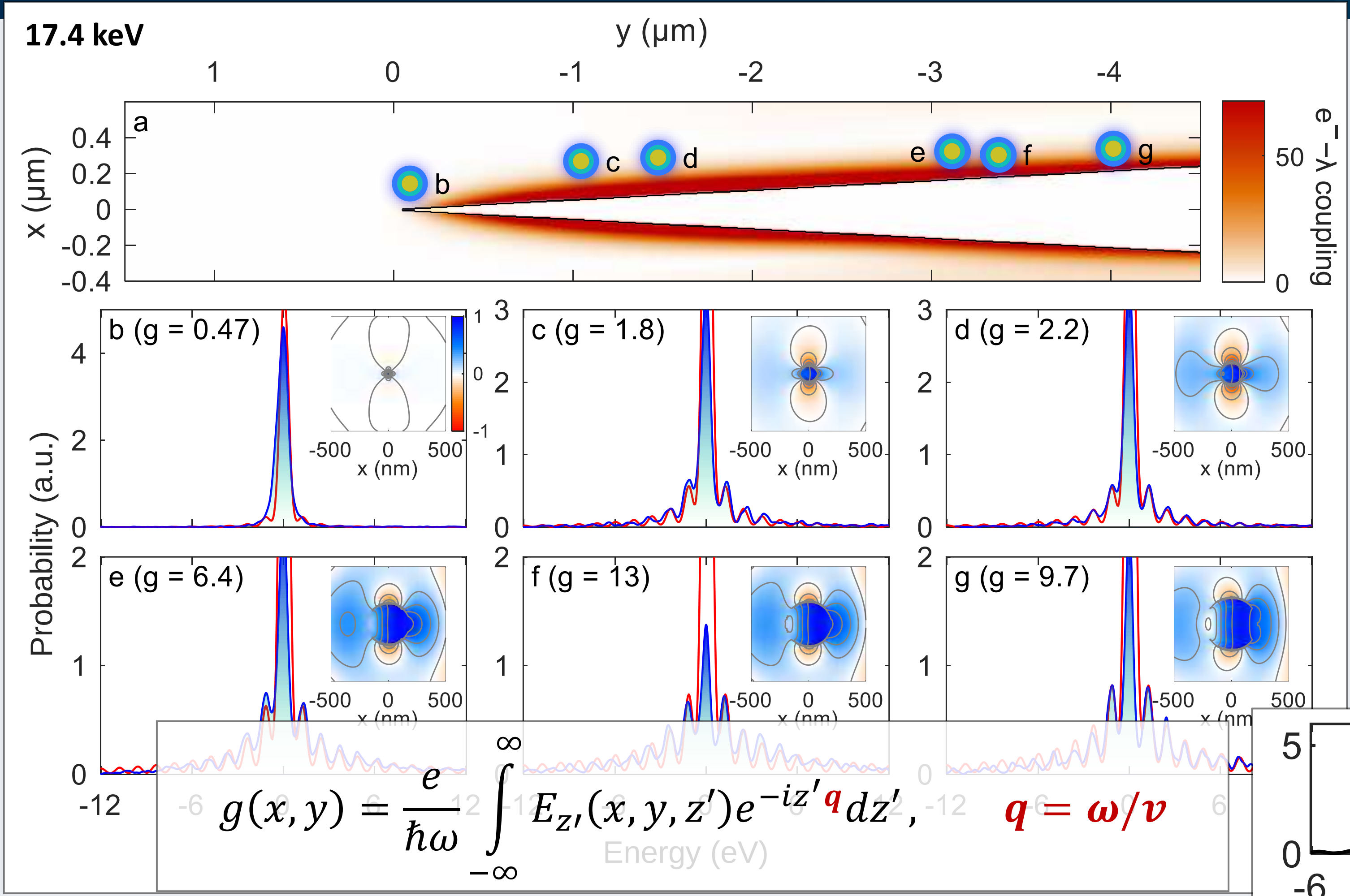




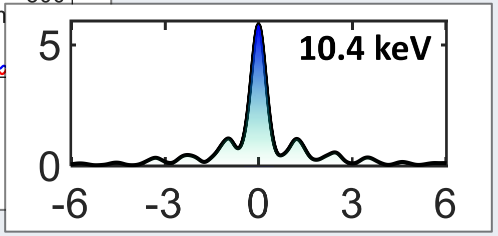
$$\beta = \lambda_p / m\lambda$$

m: order number

PINEM in an SEM



$$g(x,y) = \frac{e}{\hbar\omega}\int_{-\infty}^{\infty} E_{z'}(x,y,z')e^{-iz'q}dz', \quad q = \omega/v$$



Shiloh, R., Chlouba, T., & Hommelhoff, P. (2022). PRL, *128*(23), 235301.