Alternating phase focusing and approaching large net energy gain in photonic chip-based particle acceleration

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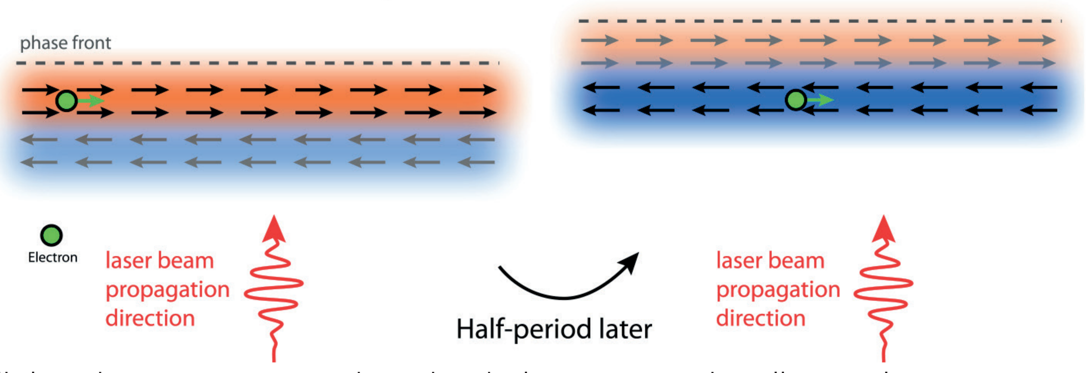
1. Motivation

Accelerators:	Damage threshold:	Average gradient:
Radiofrequency accelerators	200MV/m electric field amplitude	150MeV/m
Dielectric based accelerators	up to 9 GV/m [1]	> 1GeV/m

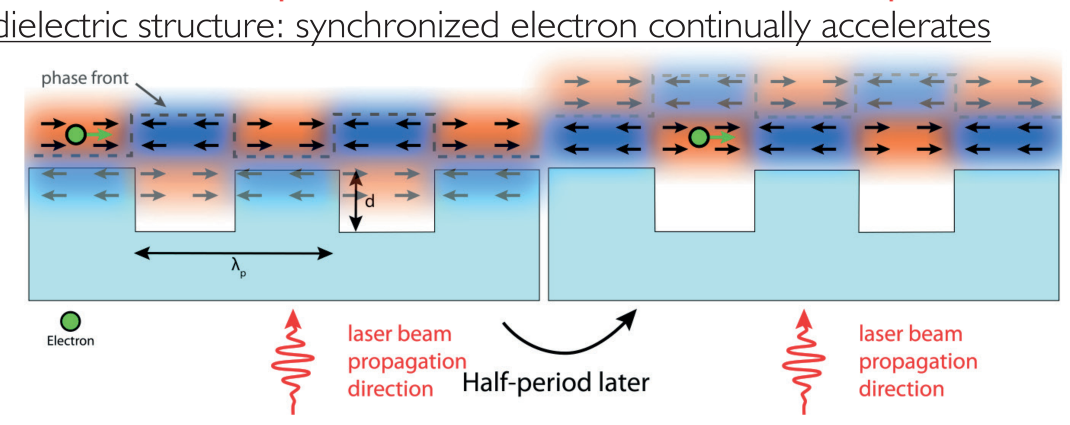
The goal of dielectric laser acceleration (DLA) is a miniaturized MeV electron source on a chip.

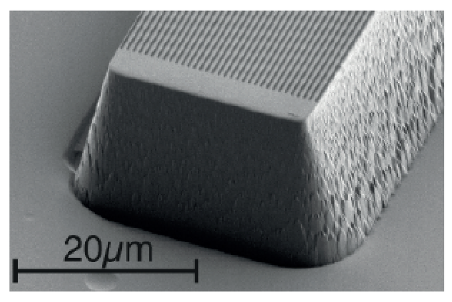
Acceleration concept:
a) In free space: interaction averages to zero



Applications:
- Table top accelerator
- Minimally invasive beam irradiation tools

b) With dielectric structure: synchronized electron continually accelerates





SEM picture of the single-sided silica structure with which a gradient of 25MeV/m could be achieved.

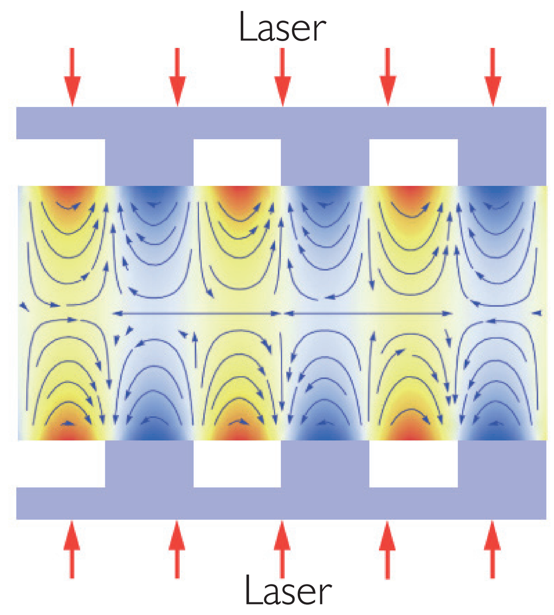
2. Acceleration, deceleration and deflection

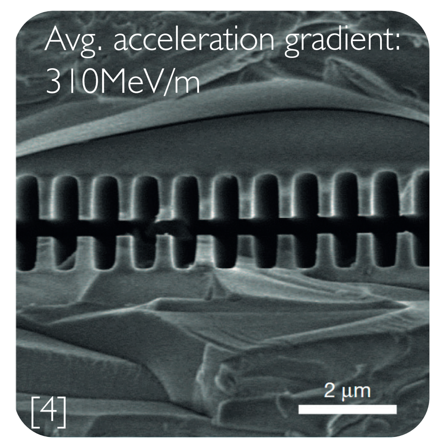
- Excitation of spatial evanescent harmonics by a laser with wavelength λ and m times per grating period λ_p oscillation.

Synchronicity condition for acceleration
$\beta = \lambda_p/(m\lambda)$

→ Maintaining of phase synchronicity by adjusting the structure period
Depending on the timing between the laser field and the particle, the force on the electron acts
1. accelerating
2. decelerating
3,4. and/or deflecting

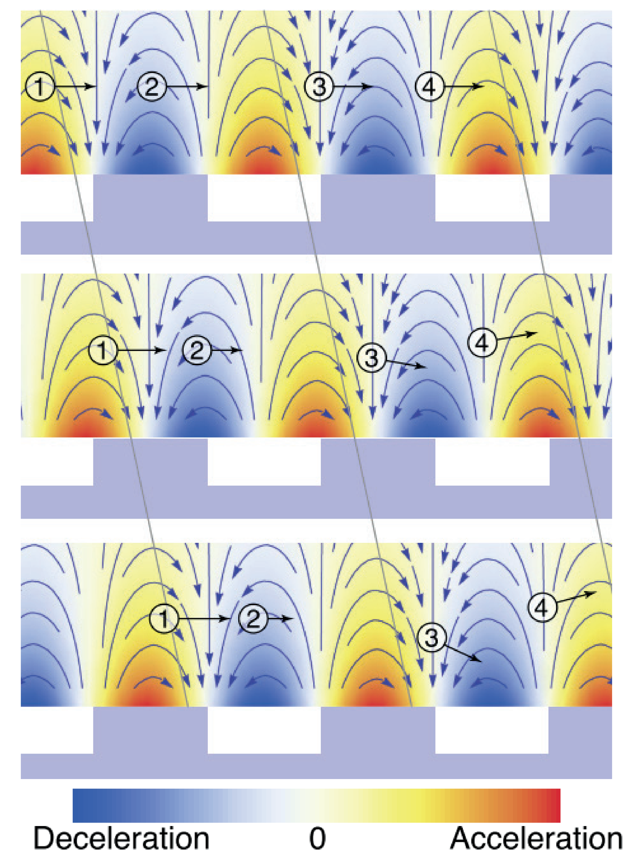
→ Symmetric field pattern achieved by introducing a second structure on top with illumination from two sides.



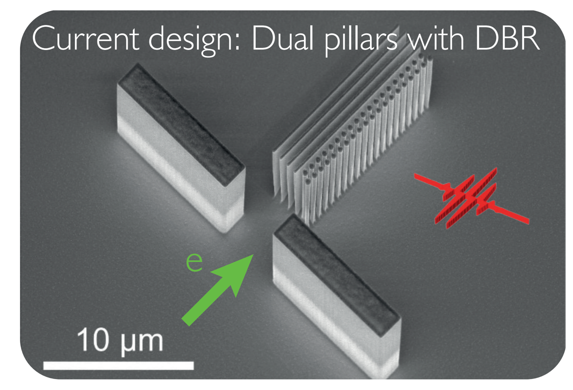


SEM picture of the dual-driven structure

→ Sub-100nm alignment precision of the gratings in x,y,z, and two angles by trial and error
→ Instead, one-step fabricated dual pillar structure with distributed bragg reflector

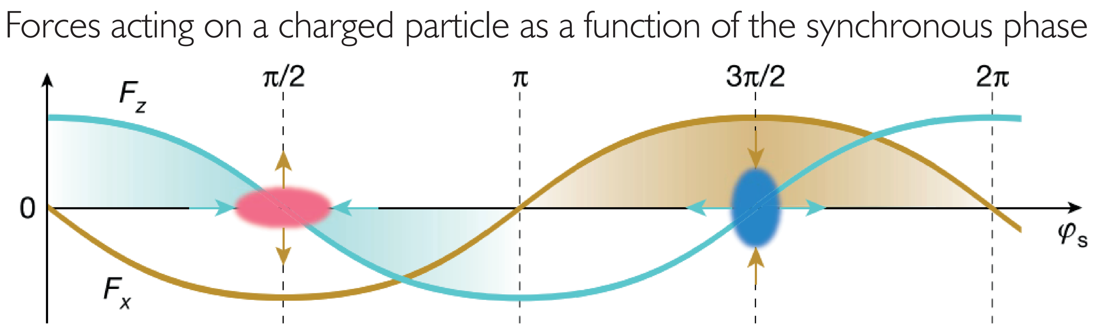


Optical evanescent nearfields of 1st spatial harmonic (m = 1) [3].



3. Acceleration and confinement

Forces acting on a charged particle as a function of the synchronous phase

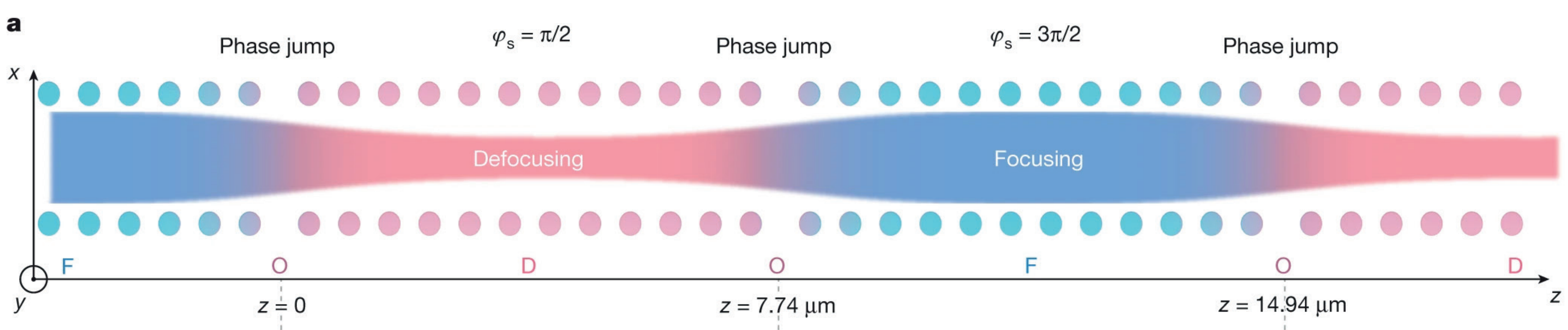


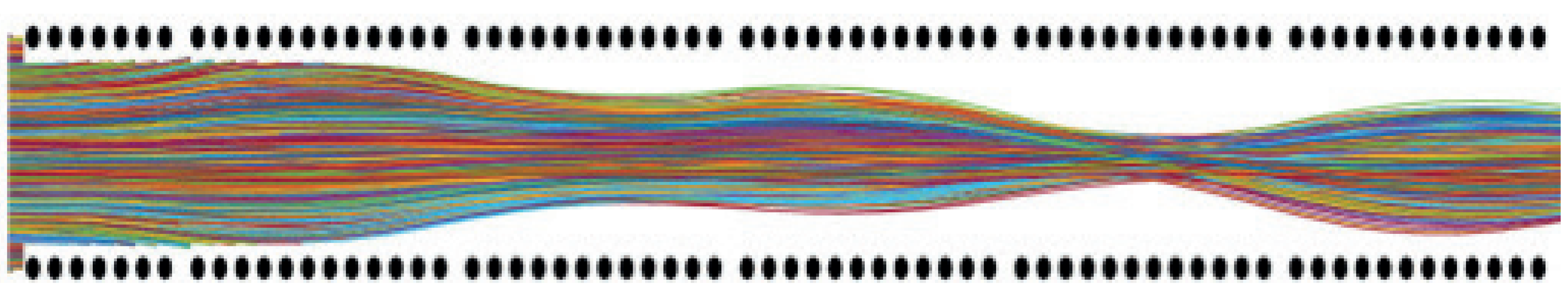
→ Repeated alternation between focusing and defocusing forces in the transverse and the longitudinal directions

→ Acceleration and guiding over long structures possible [2,5]

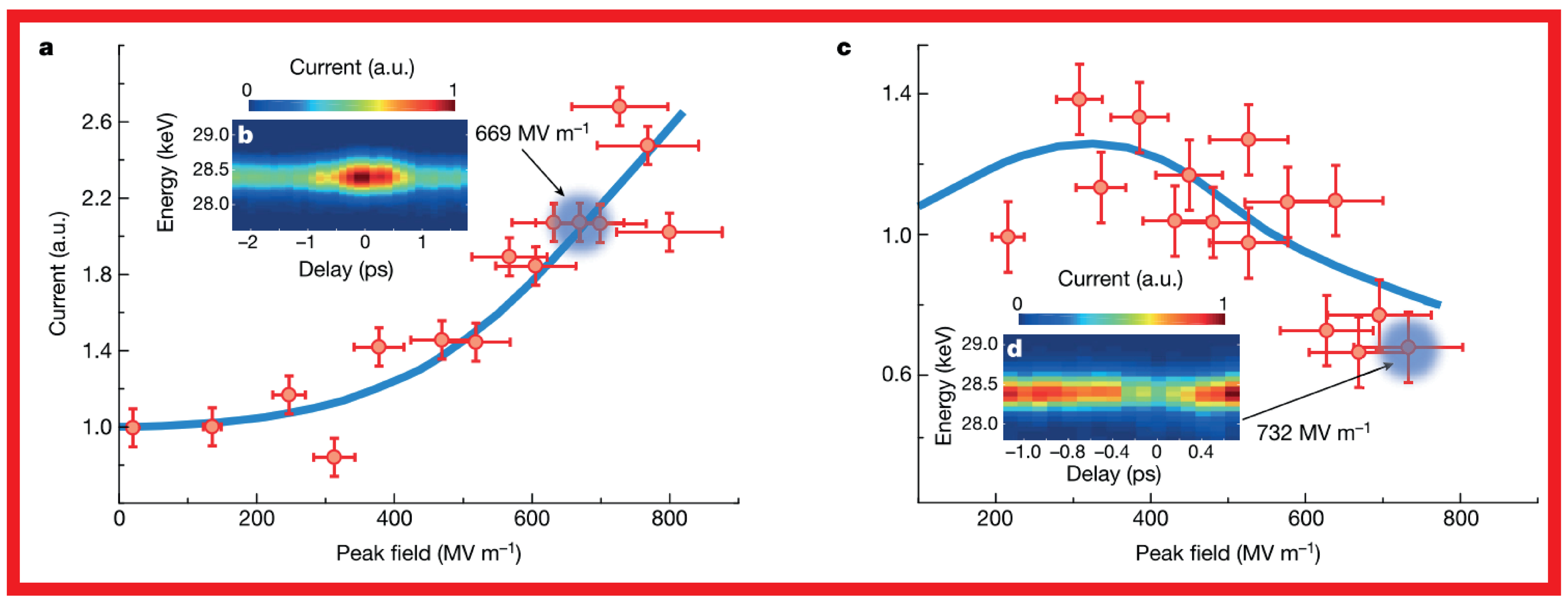
φ_s : Synchronous phase between electrons and optical nearfield for x<0

Gaps in the periodic structure for jumps in the synchronous phase





Particle tracking simulation of different particles (colours) showing the breathing of the envelope of the trajectories.



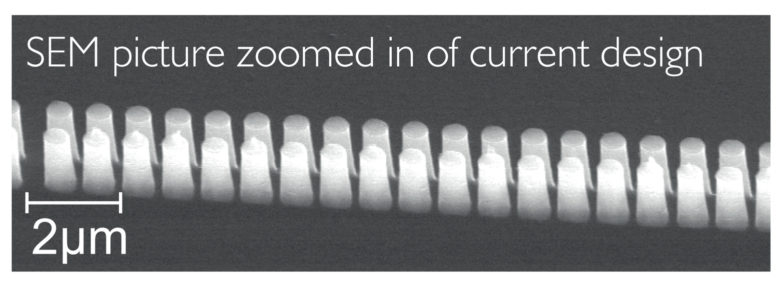
Experimental verification of electron guiding using APF: Current measured through the structure as a function of the peak field. Red: Experimental data, Blue: Simulation results. a) Guiding of the electrons through the structure. c) At too high fields overfocusing effect which leads to an electron loss. The insets b and d show the spectrally resolved current time delay [2].

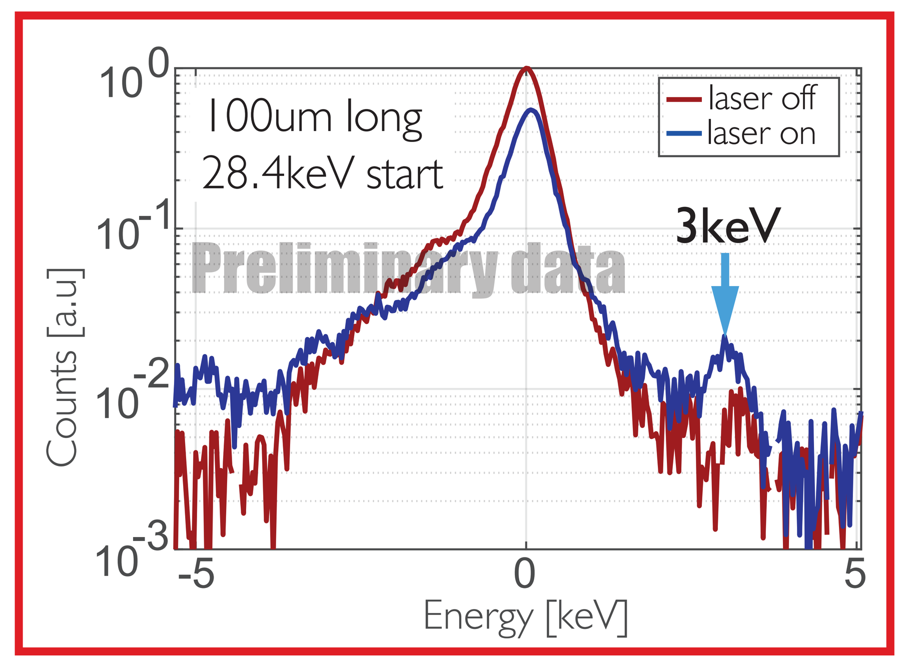
Shiloh, R., Illmer, J., Chlouba, T., Yousefi, P., Schönenberger, N., et al., Nature 597, 498–502 (2021).

4. Energy doubler design - **FIRST PRELIMINARY DATA**

New accelerating structures:
- APF confinement
- Top illuminated
- **→ Confinement of accelerated electrons**
- Linear pulse front tilt (see 5.)

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

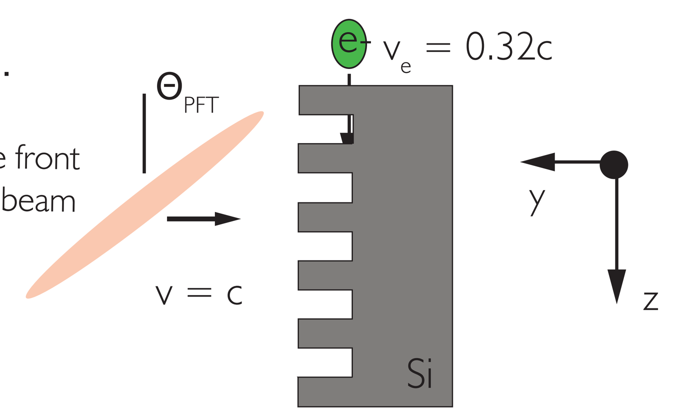




5. Pulse front tilt for micro-meter long structures

- Temporal and spatial overlap of the laser intensity front and the electron beam continuously along the structure by introducing a linear pulse front tilt definded by

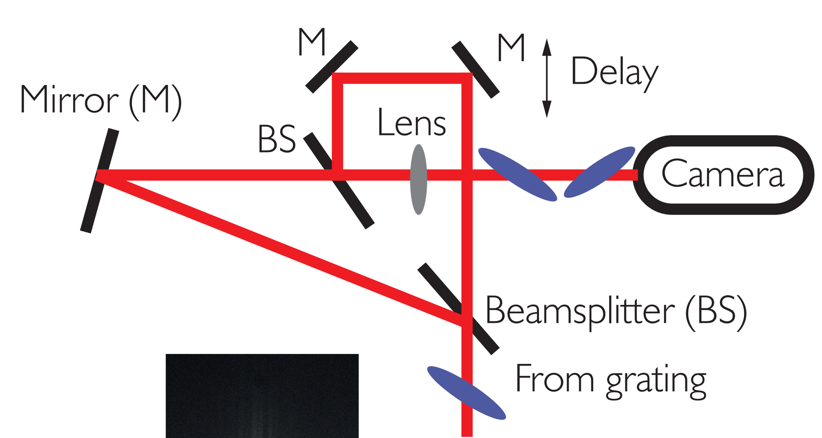
$\tan(\Theta_{PFT}) = 1/\beta$.

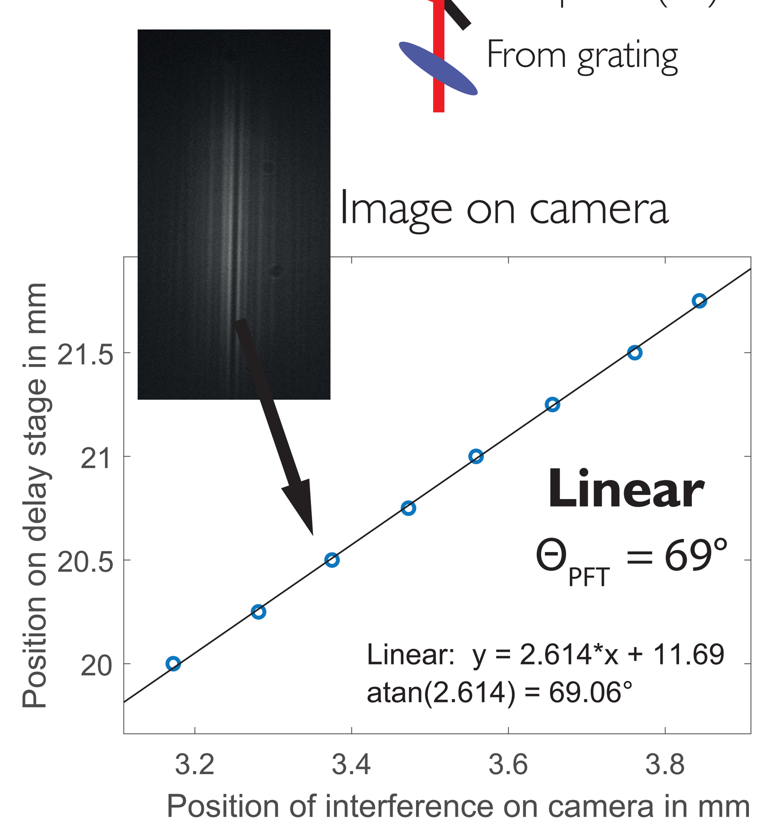


- Shorter structures with acceleration and a linear gradient curve
→ Linear PFT with $\tan(\Theta_{PFT}) = 1/\beta$ = const.

Diffraction grating

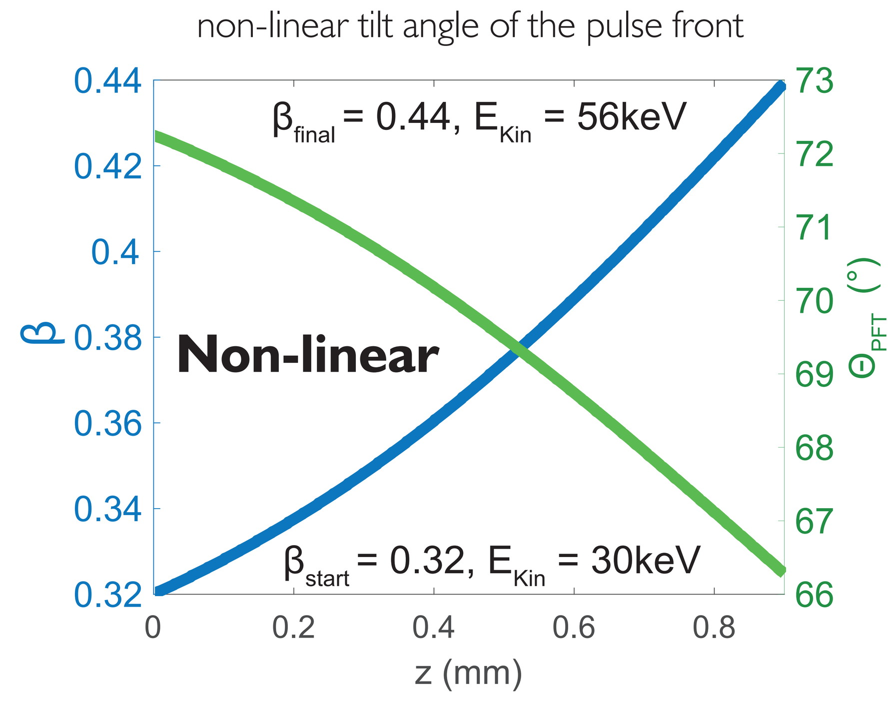
Measurement of PFT angle with inverted field interferometer [7]: Linear pulse front tilt for shorter structures





- Longer structures with higher acceleration and a non-linear gradient curve
→ Non-linear PFT with $\tan(\Theta_{PFT}) = 1/\beta(z)$

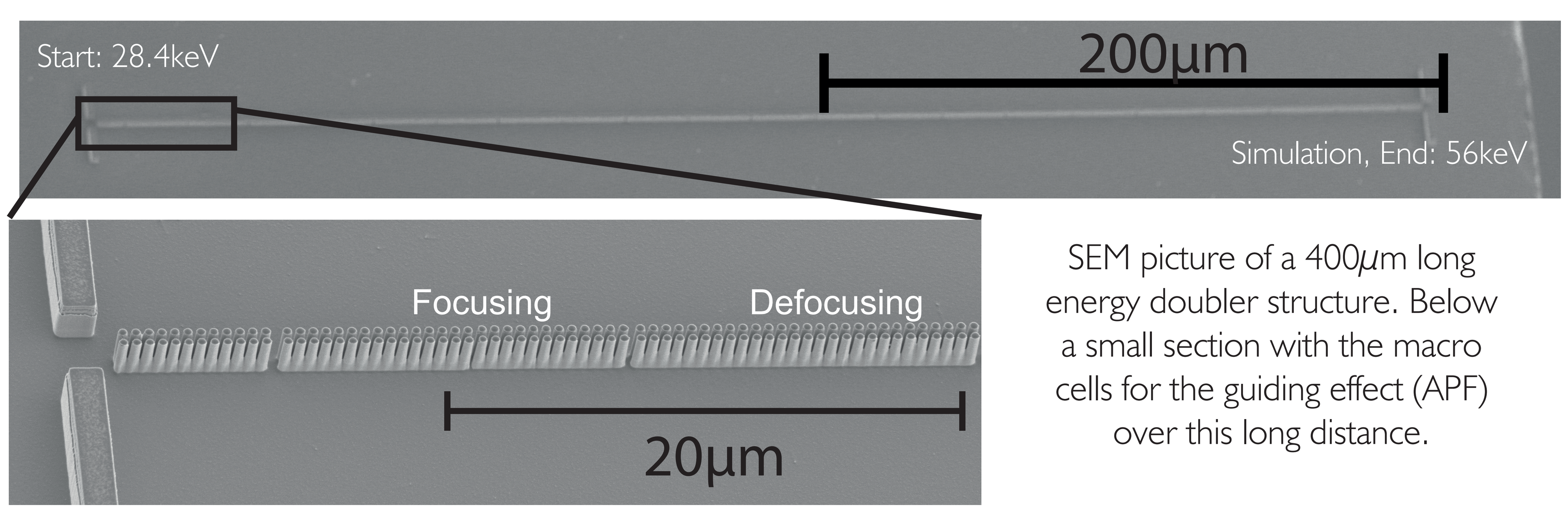
Simulation: Non-linear acceleration leads to a non-linear tilt angle of the pulse front



Options to obtain a non-linear pulse front tilt:
- Stairstep echelon [6]
- Deformable mirrors

6. Outlook - Going from 30keV to 1MeV

- For the current energy doubler design: average gradient of approximately 30MeV/m over a 1mm long structure
The goal in the future is an energy gain of 1MeV over a several millimeter long structure.
→ Pre-buncher to increase the current throughput through the small channel [8].



SEM picture of a 400μm long energy doubler structure. Below a small section with the macro cells for the guiding effect (APF) over this long distance.

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[2] Shiloh, R., Illmer, J., Chlouba, T., Yousefi, P., Schönenberger, N., et al., Nature 597, 498–502 (2021).
[3] Breuer, J., and Hommelhoff, P. Phys. Rev. Lett. 111, 134803 (2013).
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[6] Ofori-Okai, B. K., Sivarajah, P., Huang, W. R., and Nelson, K. A. , Optics express 24.5, 5057-5068 (2016).
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