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Beam Shaping with Dielectric Structures

5th European Advanced Accelerator Concepts Workshop, EAAC :: September 20, 2021

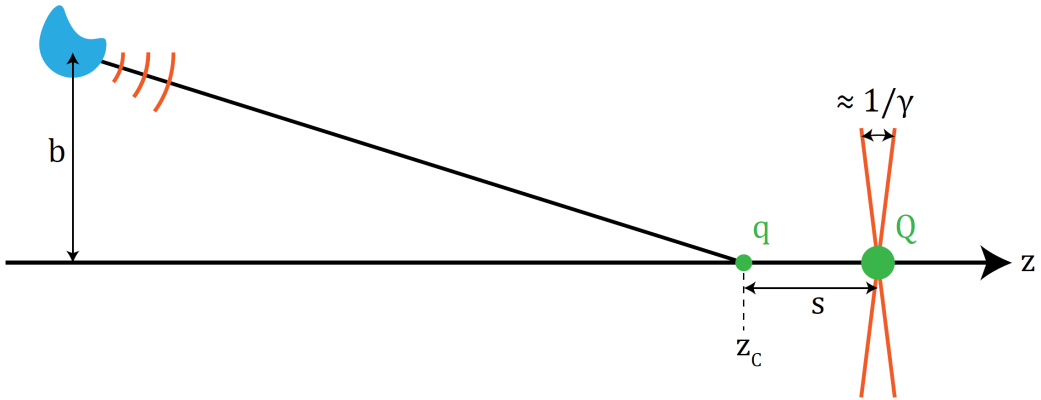
ACHIP

GORDON AND BETTY MOORE FOUNDATION

Outline

- Idea
  - Dielectric grating wakefields for beam shaping
- Simulations
- Experiments at SwissFEL, PSI
- Outlook
  - DLA for ESASE at FELs
    (Enhanced Self-Amplified Spontaneous Emission)

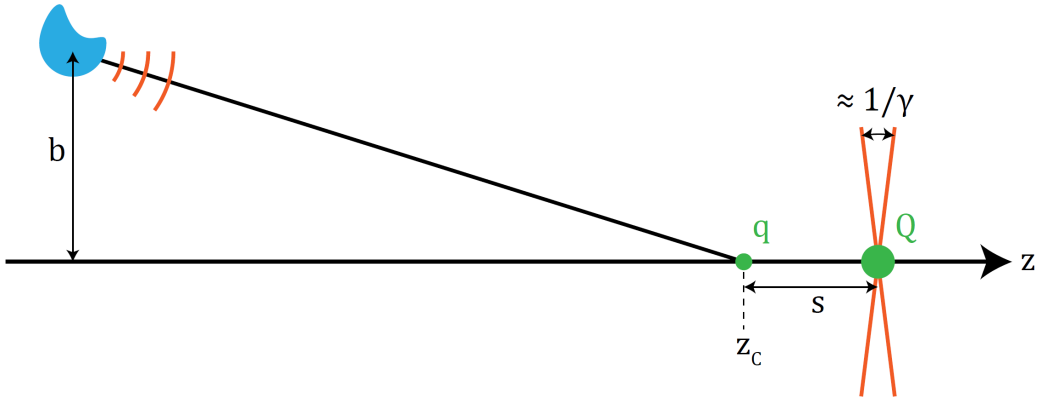
Dielectric Wake Field



$$W_z(s) = -\frac{1}{Q}\int \mathrm{d}z\,[E_z(z,t)]_{t=(z+s)/c}$$

$$z_c \approx \frac{b^2 - s^2}{2s} \quad \text{(catch up distance)}$$

Dielectric Wake Field Concept



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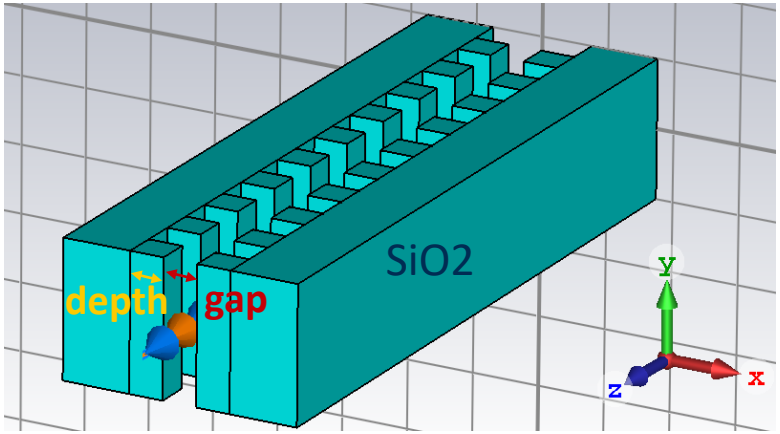
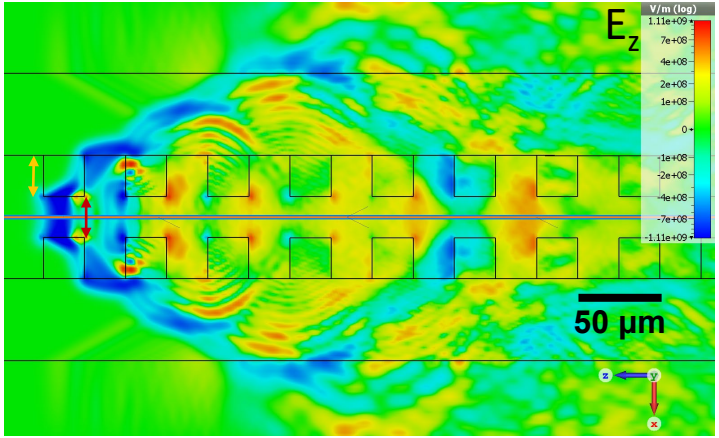
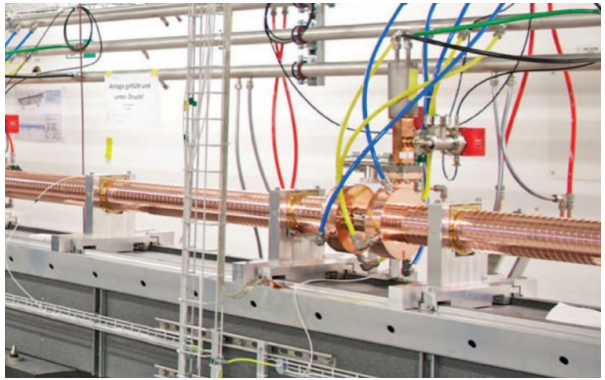




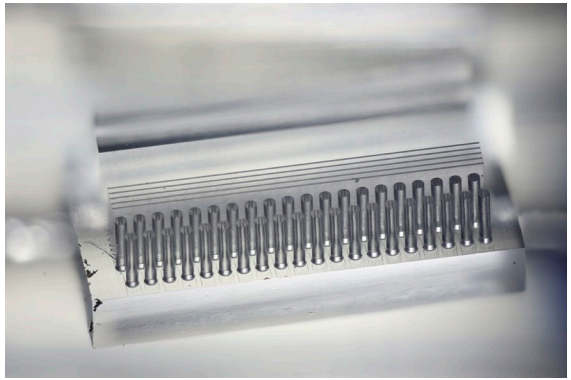
CST Studio

Metal vs. Dielectric Grating Wakefield

	Metallic	Dielectric
Field Threshold	100 GV/m	10 GV/m
Frequency	10 GHz	10 THz
Beam shaping	Passive, no temporal jitter	

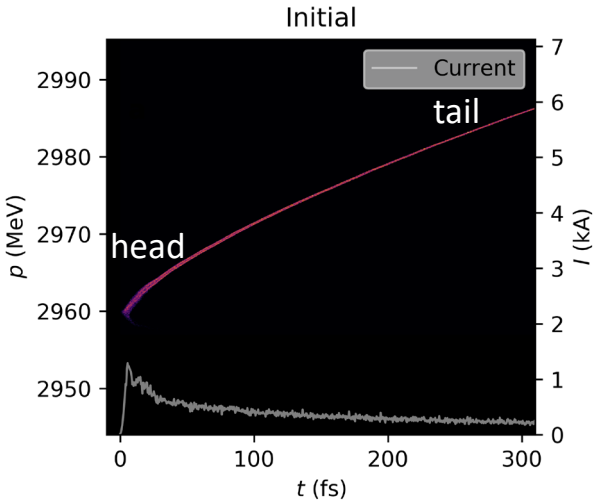


P. Craievich, 2018, doi:10.18429/JACoW-LINAC2018-WE1A05



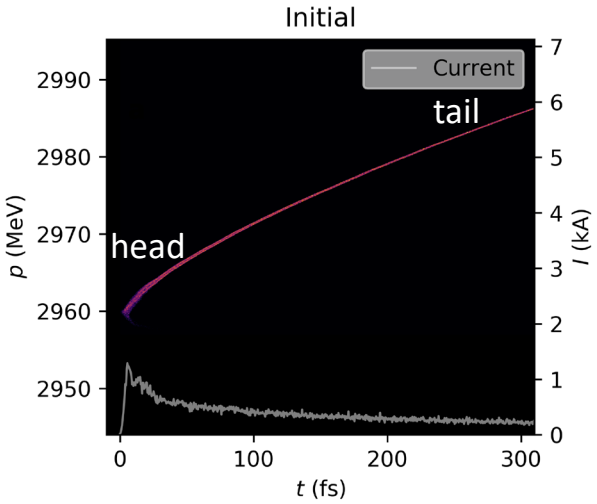
Courtesy of R. Ischebeck

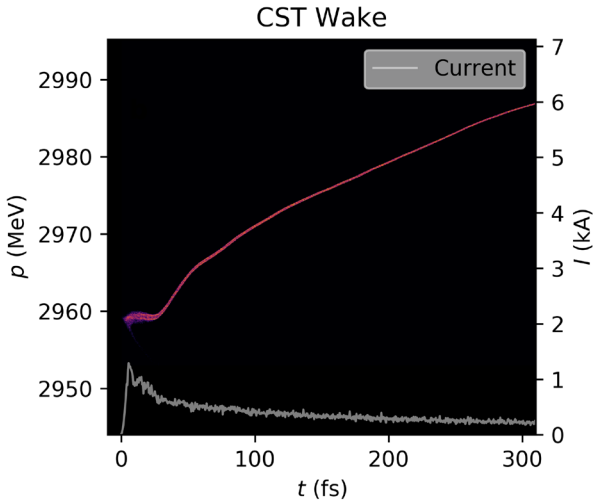
Short Pulse Generation (Simulation, Athos SwissFEL)



Q = 200 pC
non-linear compression

Short Pulse Generation (Simulation, Athos SwissFEL)

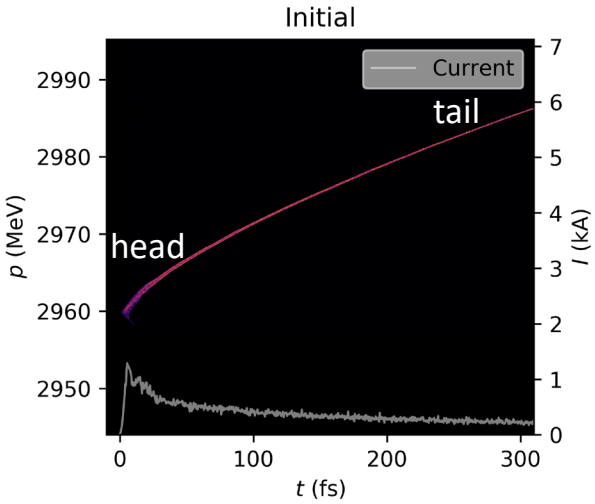


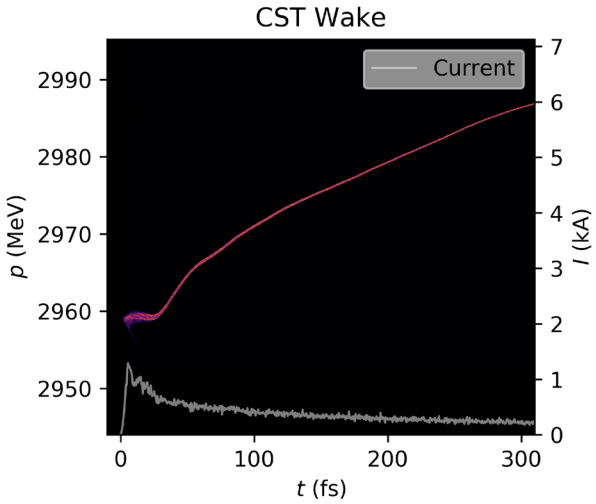


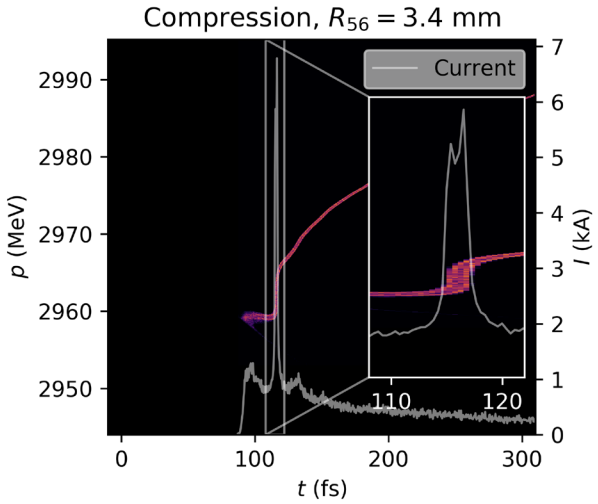
Q = 200 pC
non-linear compression

Wakefield Source:
Double grating, fused silica
Periodicity = 50 μm
Length = 5 mm

Short Pulse Generation (Simulation, Athos SwissFEL)





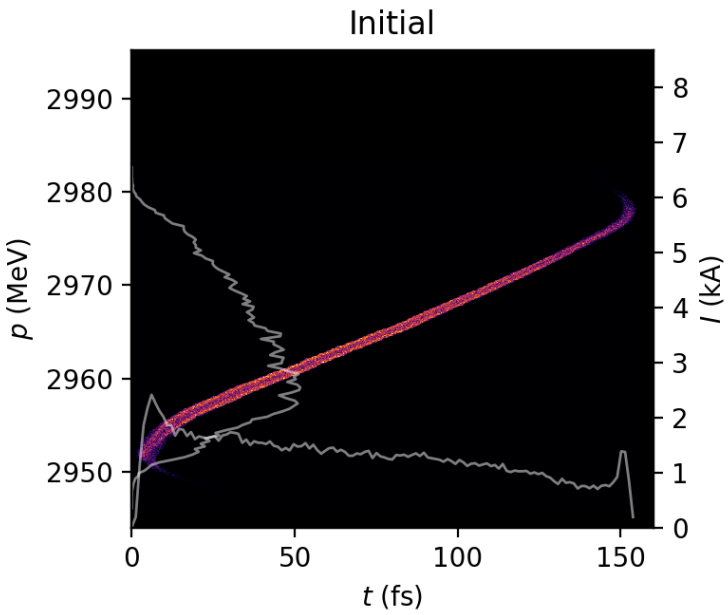


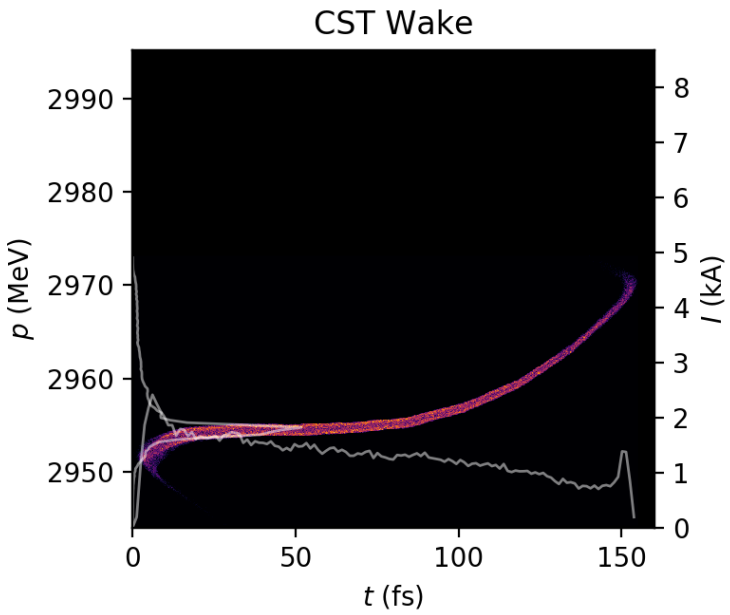
Q = 200 pC
non-linear compression

Wakefield Source:
Double grating, fused silica
Periodicity = 50 μm
Length = 5 mm

Compression with magnetic chicane →
6-7 kA peak current
~1 fs rms spike length

Dechirping for Nominal Beam at SwissFEL (Simulation, Athos)





Nominal Athos beam parameters

Q = 200 pC

Remaining chirp after Linac 2

Wakefield Source:

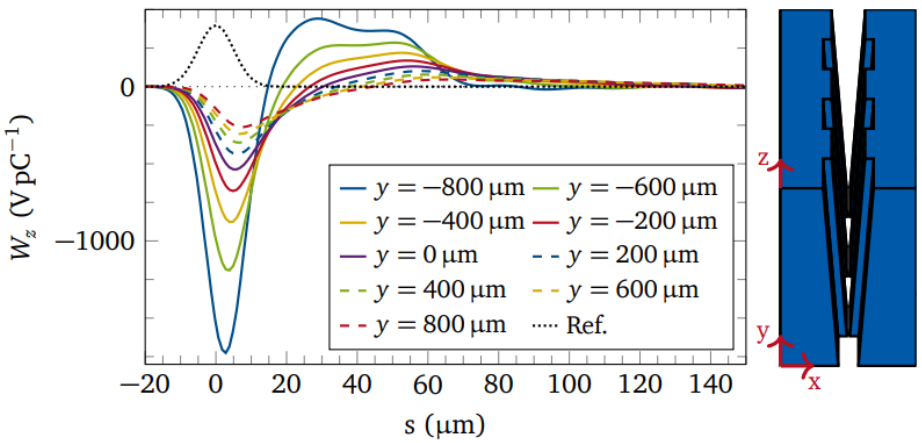
Double grating, fused silca

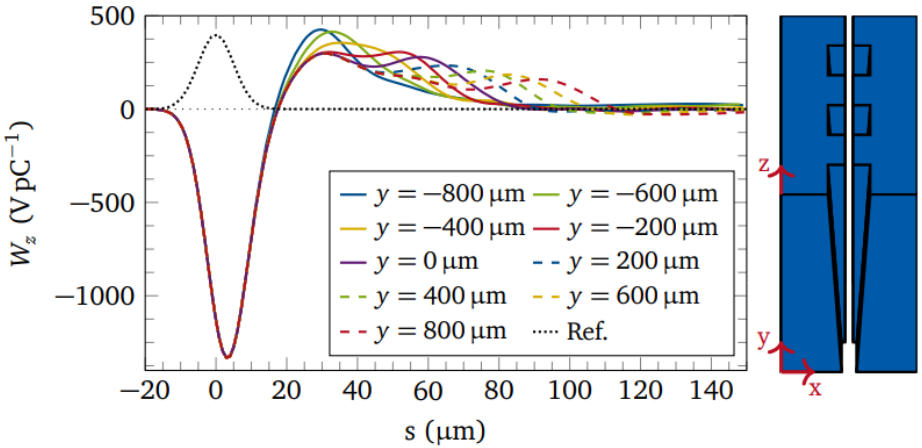
Periodicity = 300 µm, Aperture = 150 µm

Length = 33 mm

Tunable Wakefield Structures for Beam Shaping

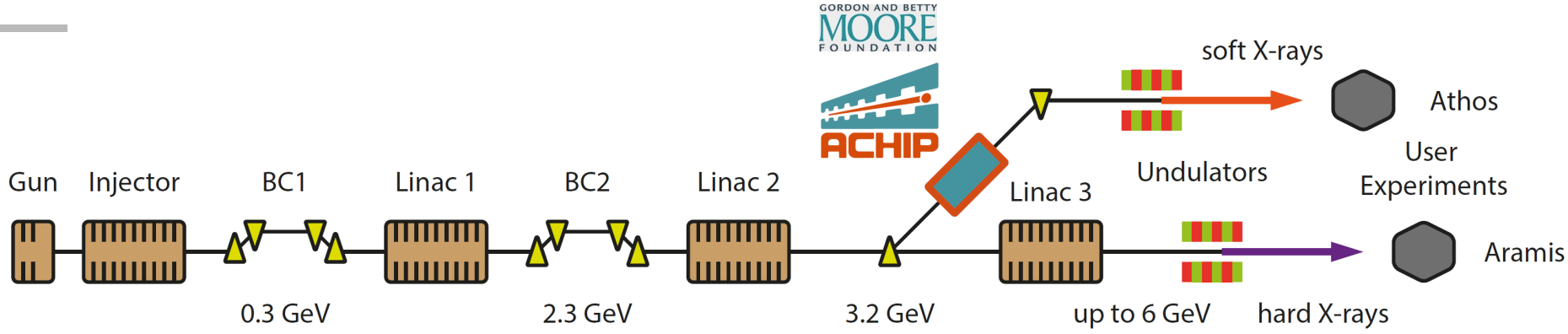
Vary grating parameters (gap, pitch) along “invariant” direction of grating



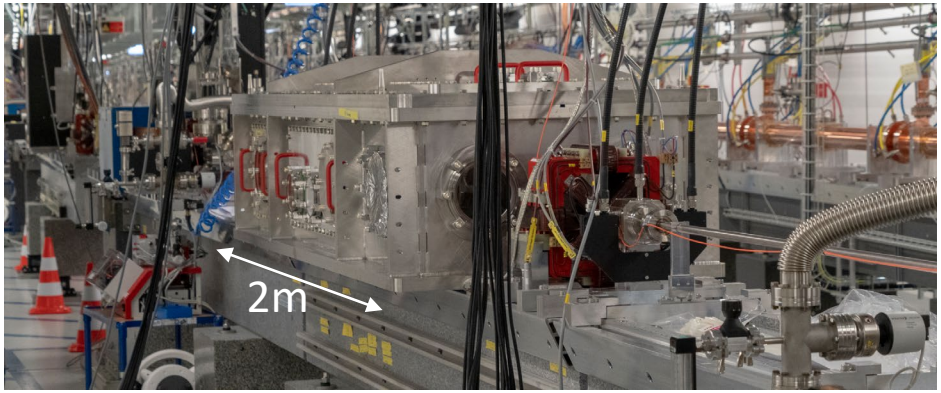


T. Egenolf, 2020, 10.25534/tuprints-00014139

Experimental Setup: ACHIP Chamber at SwissFEL



B. Hermann, et al., 2021,
DOI: 10.1103/PhysRevAccelBeams.24.022802



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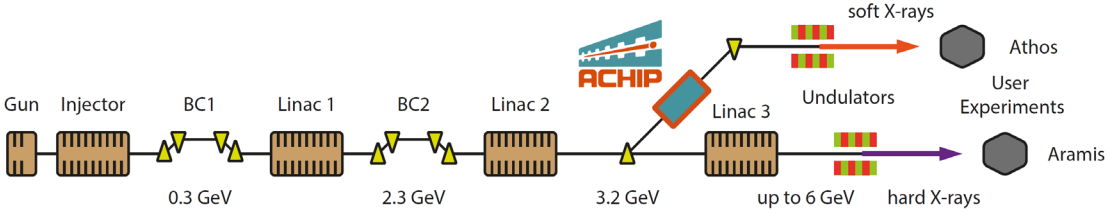
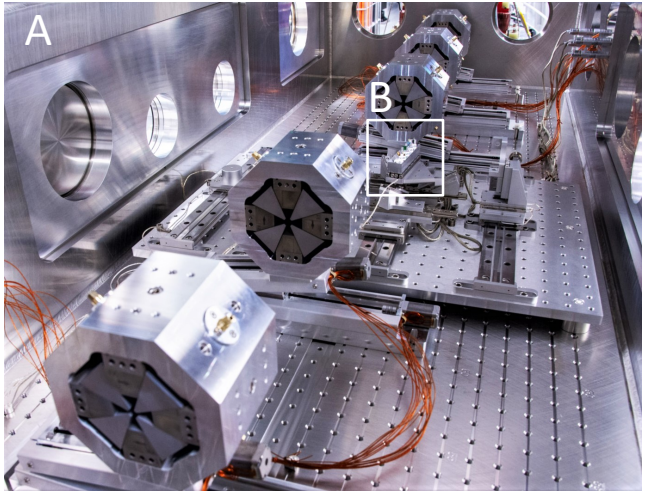
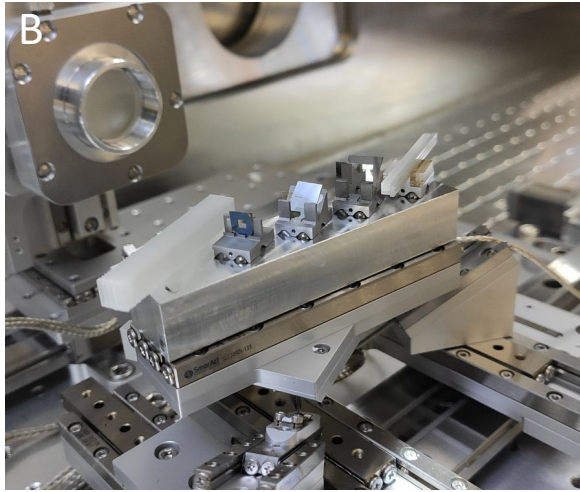


- Beam Focusing:
  in-vacuum permanent magnet quadrupole triplet (A)

- Sample positioning: hexapod (B)
  - **Beam diagnostics**
    - **Wire scanners**
    - Scintillators , OTR
  - **Dielectric wake field structures**
  - Smith-Purcell THz generation





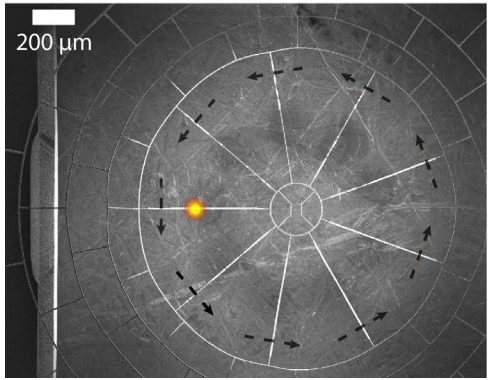
Beam Profile Characterization

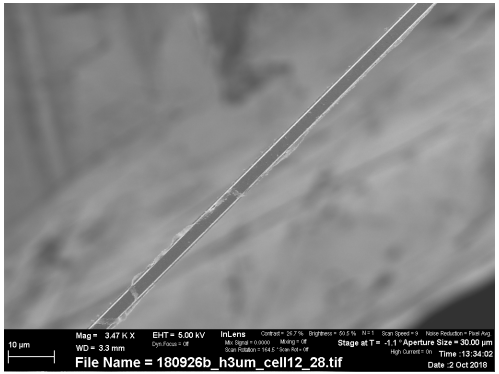
YAG screen resolution limited

→Wire scan tomography

- Nano-fabricated Au wires (1 µm)
- Sub-µm resolution

S. Borrelli, et al., 2018,
DOI: 10.1038/s42005-018-0048-x





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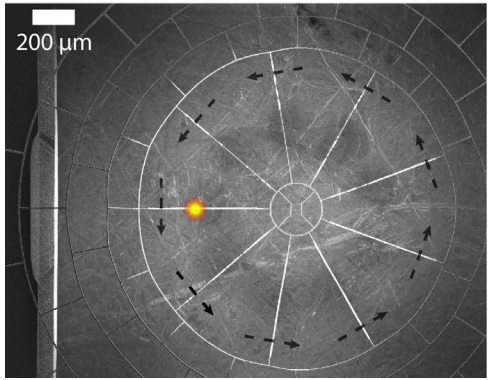

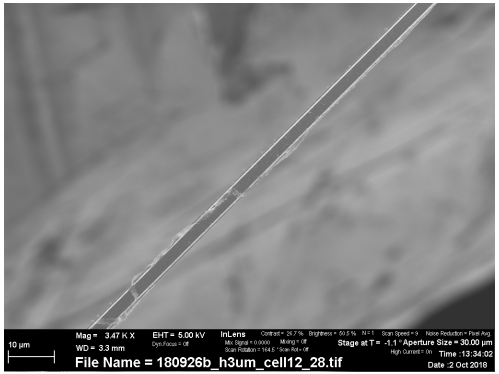

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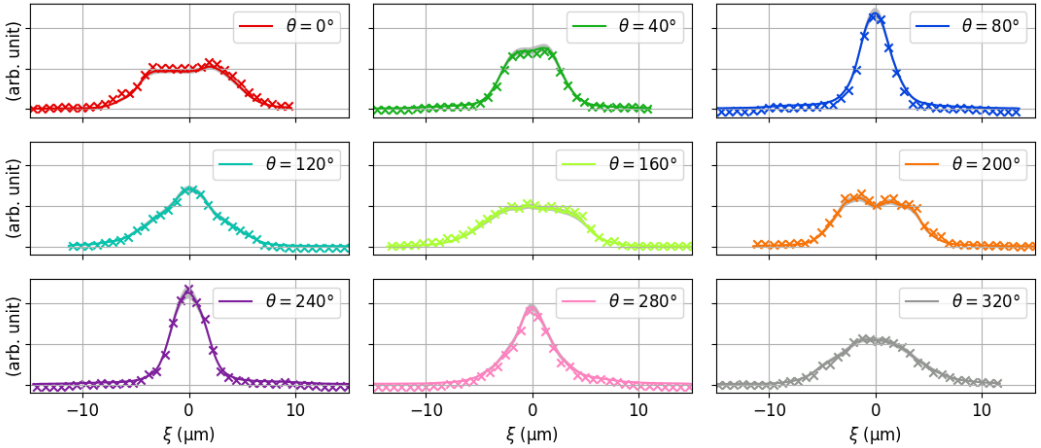

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  G. L. Orlandi, et al., 2020,
  https://doi.org/10.1103/PhysRevAccelBeams.23.042802

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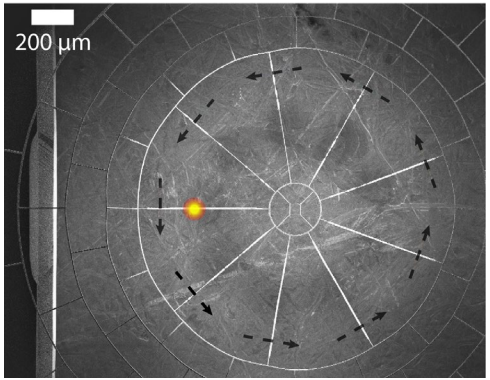

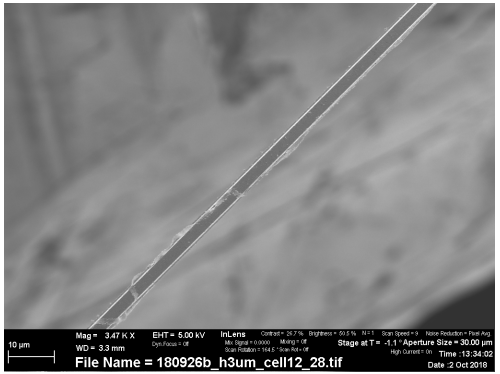

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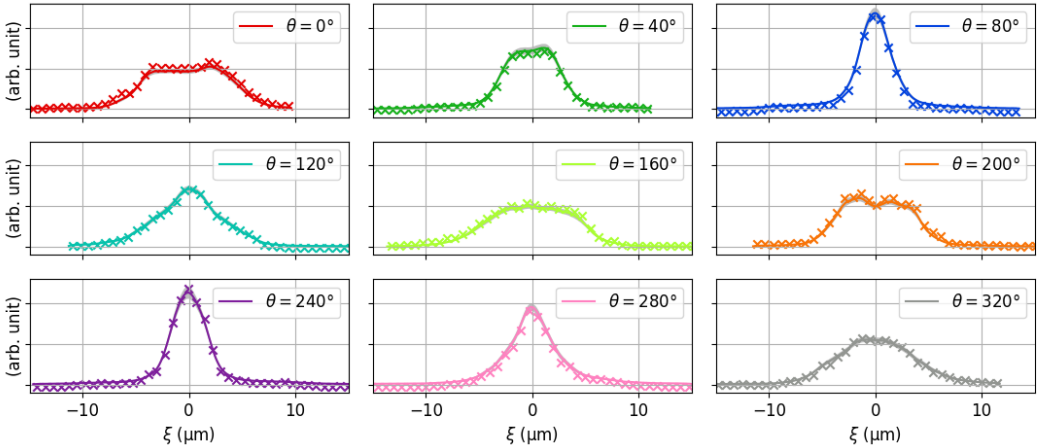
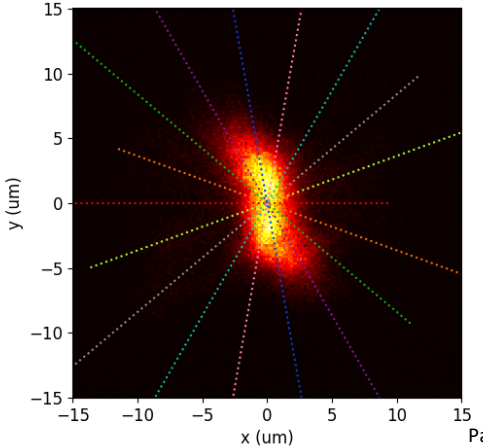
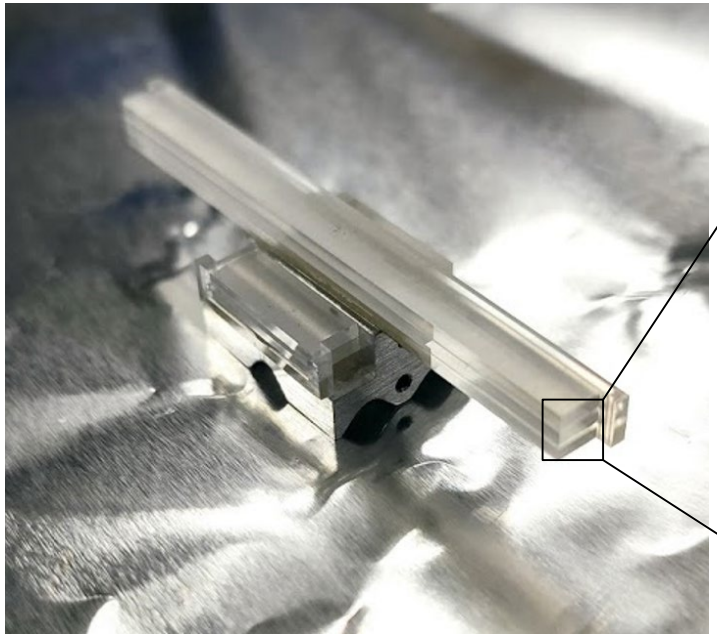
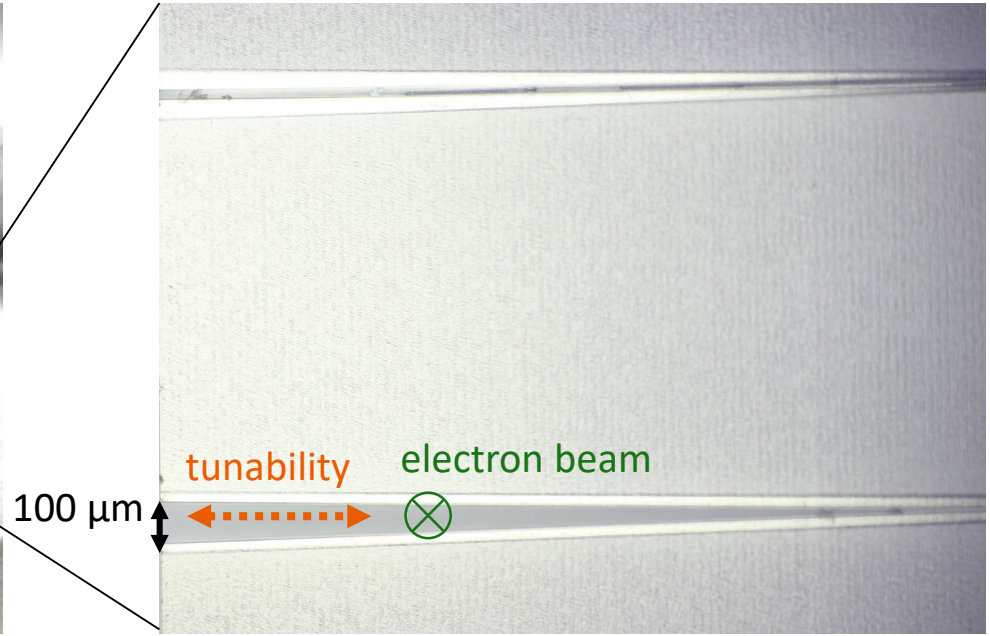




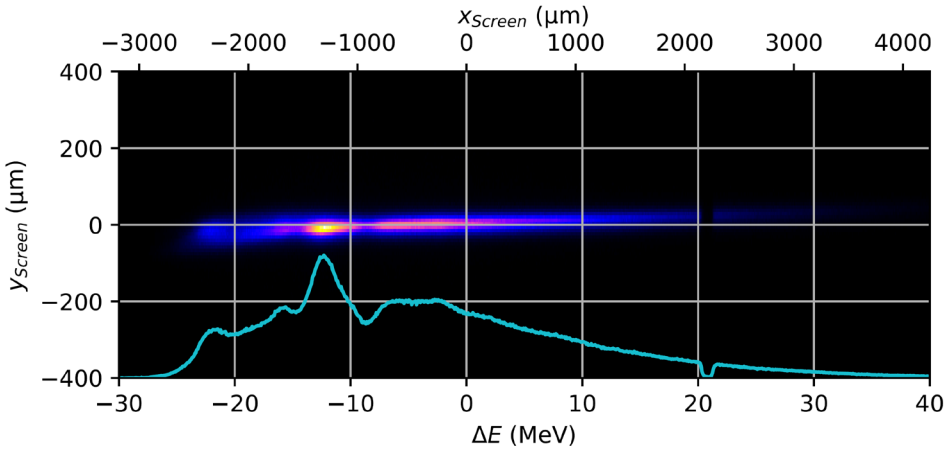
Wakefield Structure Design and Fabrication

- Fabricated by FEMTOprint SA, SiO2 fused silica, 50 µm period
- Tunable gratings (gap 10 – 100 µm) for adaptive beam shaping
- Length: 10 mm – 40 mm

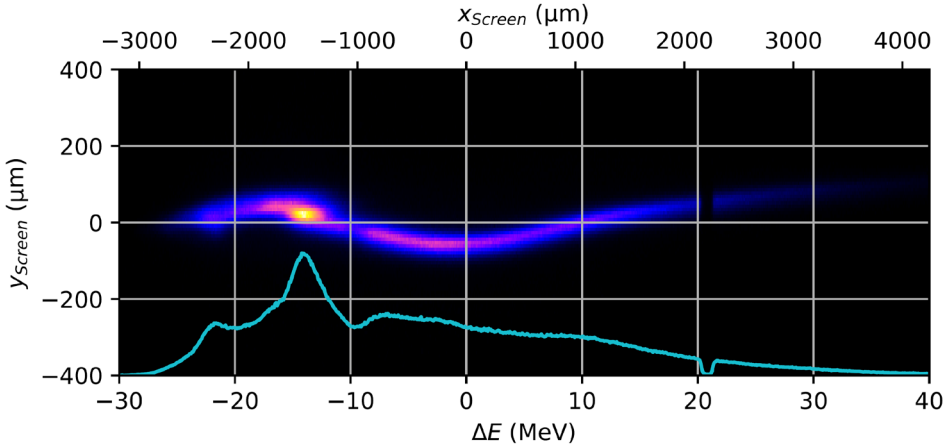




Wakefield Measurment with Spectrometer

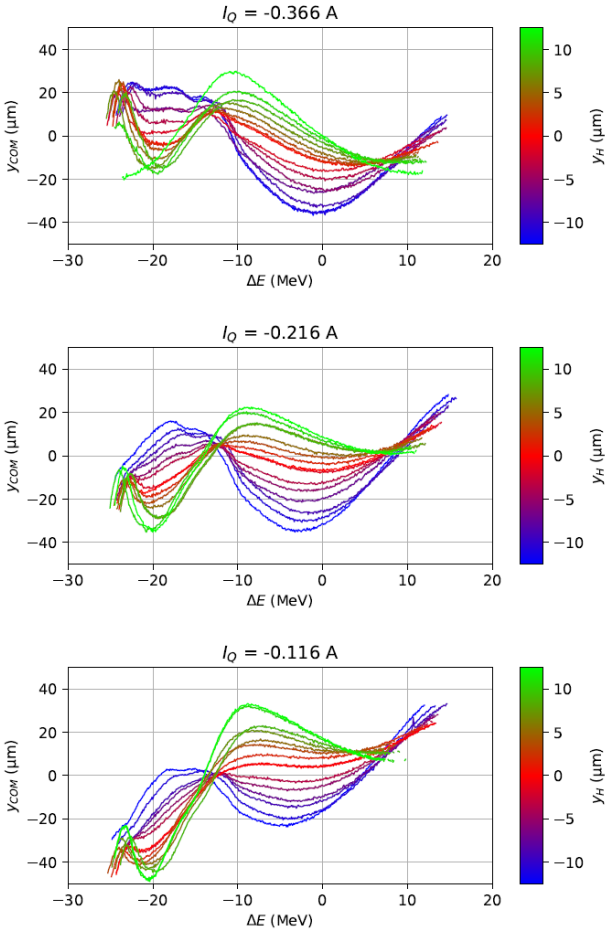


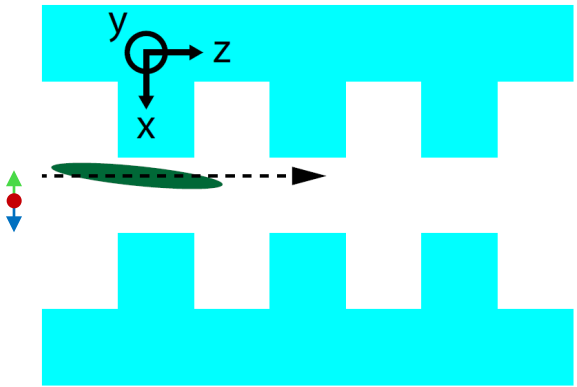
Without structure



With structure
off-centered

Effect of Beam Tilts on Transverse Wakefields



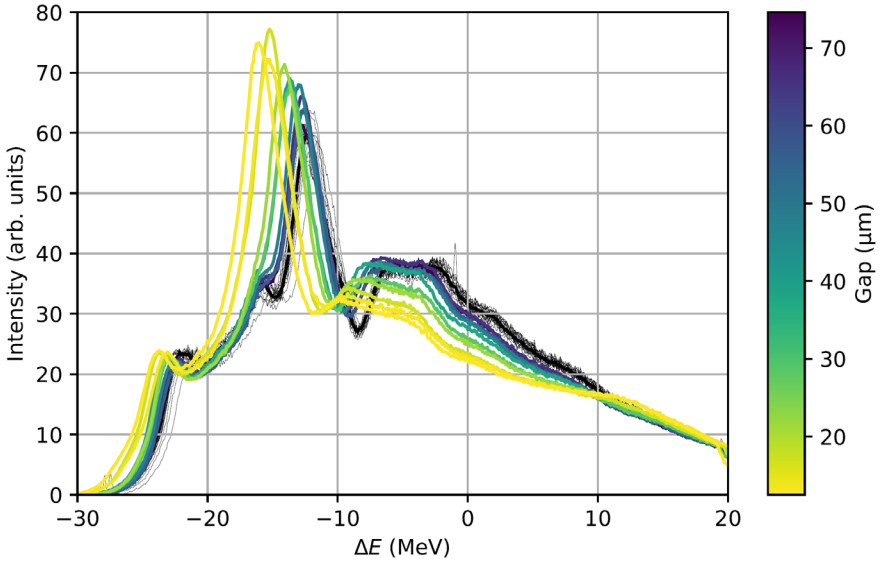


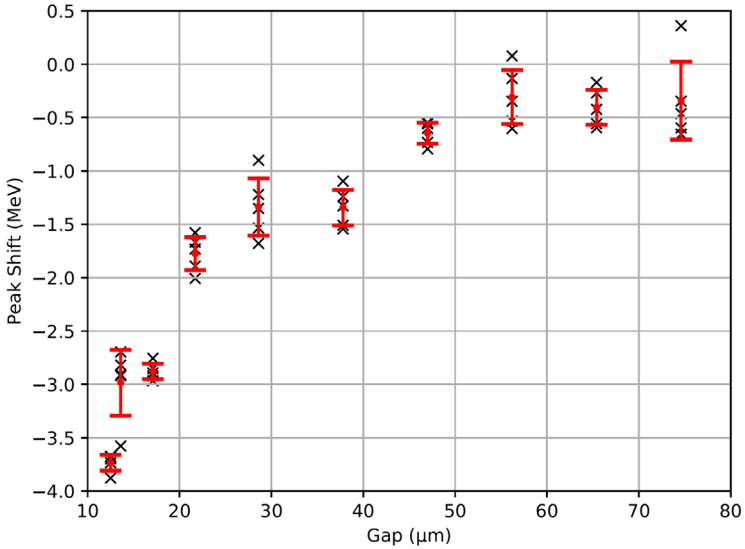
Beam tilts break symmetry

→ Asymmetric streaking for offsets $\pm x$

→ Reduce tilt with skew quad currents I_Q

Spectrum for Different Gap Sizes
Non-linear Compression (Current 10 fs FWHM)





Smaller gap → larger energy loss

Net field gradients > 100 MV/m

Intensity Limits for DLAs

SwissFEL Experiment

- $\lambda = 50\ \mu\text{m}, \text{Q} = 10\ \text{pC}, \sigma_\text{z} \approx 10\ \text{fs}$
- Loss due to wakefields ≈ 0.1 GV/m

Relativistic DLA ($\gamma \gg 1$)

- Realistic acceleration gradient ≈ 1 GV/m
- $\lambda = 2\ \mu\text{m}$
- Keeping $\frac{\sigma_{x,y,z}}{\lambda}$ (relative size of bunch) constant
- $\sigma_\text{z} \approx 10\ \text{fs}/25 = 400\ \text{as}$
- **wake loss = acc. gradient**

→ $Q_{max} = 10 * \left(\frac{2}{50}\right)^3 * 10\ pC = 6.4\ fC \approx \mathbf{40\ 000\ e^-}$ (per micro-bunch)

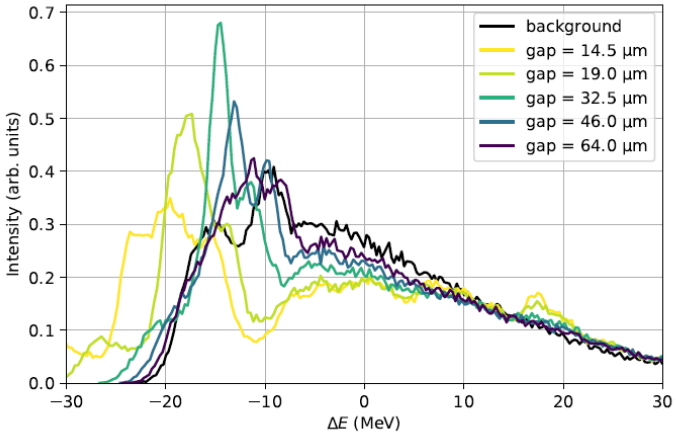
Simulation of Wakefield Experiment

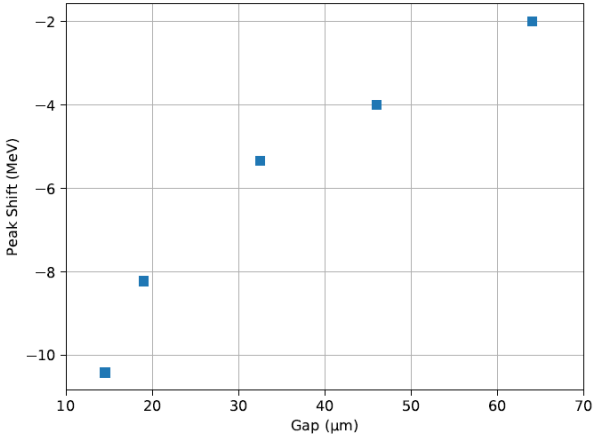
Longitudinal phase space (LPS) measurement in injector

→ Elegant tracking to wakefield experiment

→ CST wakefield solver

→ Elegant tracking to spectrometer





Simulated effects around three times stronger than in experiment

→ More accurate LPS required, future PolariX TDC in Athos very benefitial

P. Craievich, et al., 2020, 10.1103/PhysRevAccelBeams.23.112001

Outlook: DLA for ESASE
Enhanced Self-Amplified Spontaneous Emission

Generation of atto-second pulse trains at FELs obtained by laser modulation

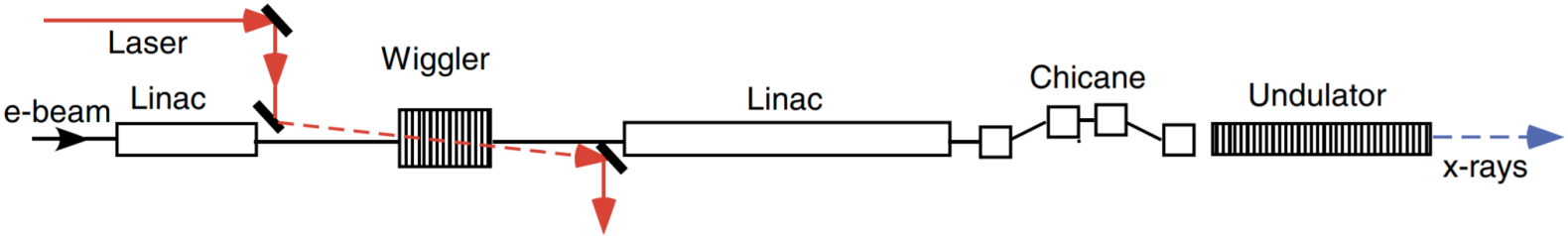


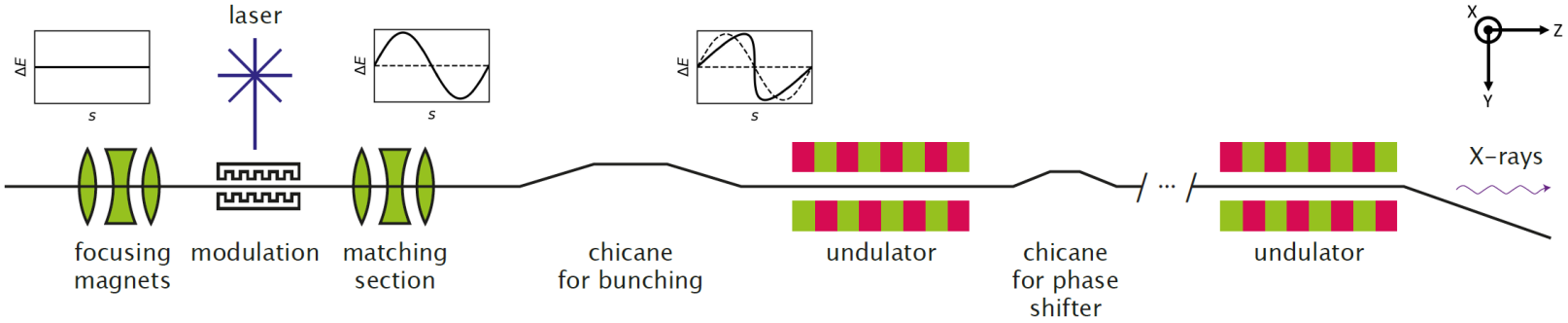
FIG. 1. (Color) A schematic of ESASE x-ray FEL.

A. A. Zholents, 2005, https://doi.org/10.1103/PhysRevSTAB.8.040701

ESASE successfully demonstrated at SLAC:

J. P. Duris, et al., 2021, https://doi.org/10.1103/PhysRevLett.126.104802

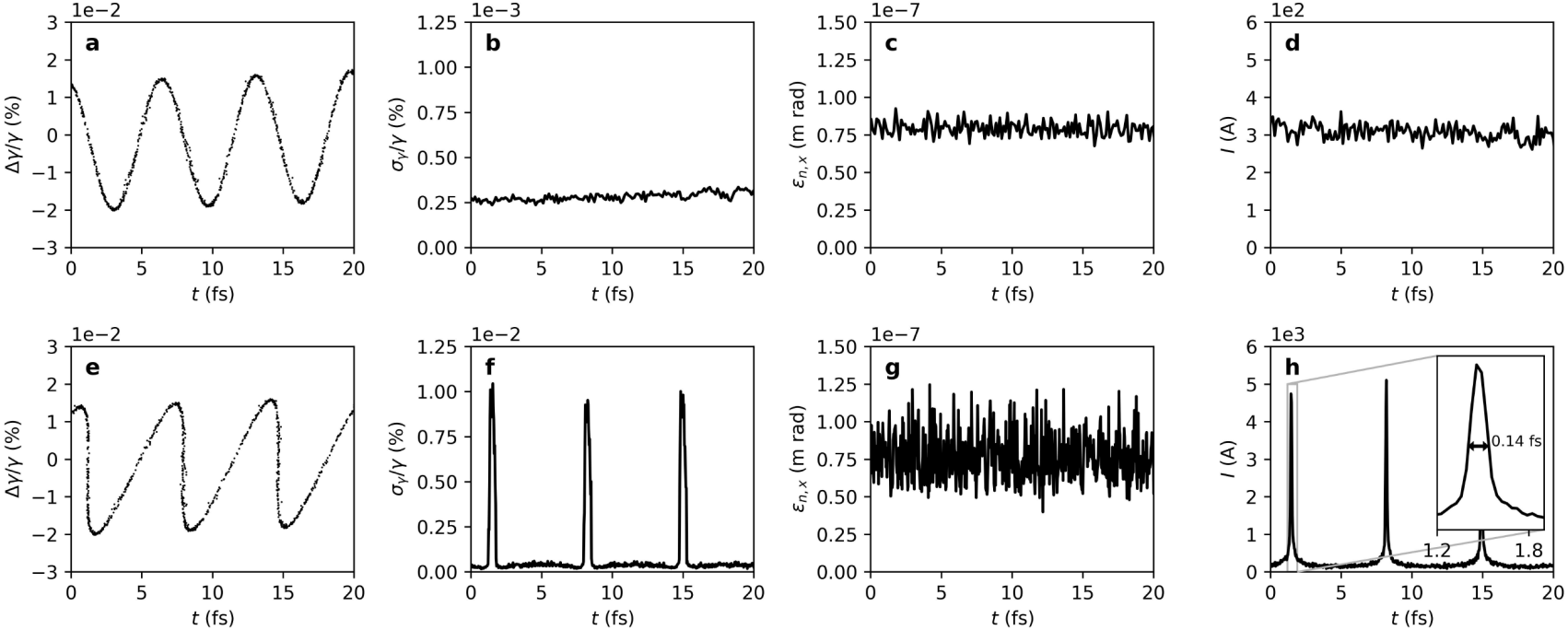
Outlook: DLA for ESASE



B. Hermann, et al., 2019, https://doi.org/10.1038/s41598-019-56201-8

Dielectric microstructure (DLA) instead of magnetic wiggler (conventional ESASE) to transfer energy from laser to electron beam resonantly

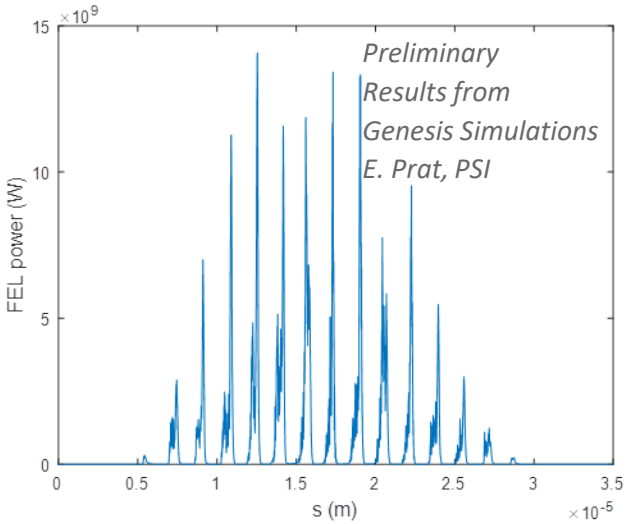
Outlook: DLA for eSASE

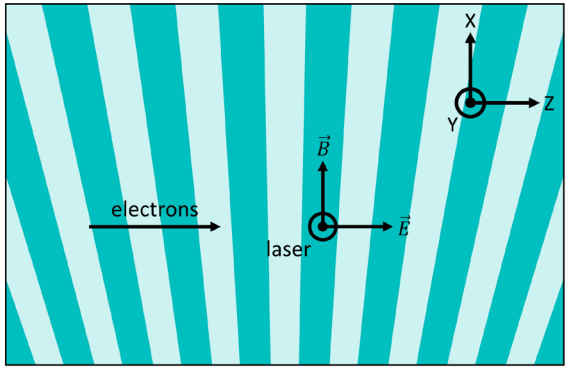


Q = 30 pC, limited by aperture and emittance

B. Hermann et al., 2019,
https://doi.org/10.1038/s41598-019-56201-8

Outlook: DLA for eSASE





- Synchronization of laser (timing jitter, same for ESASE)

- Small aperture of dielectric structure (few µm), strong focusing, charge limitation

+ Efficient laser modulation of longitudinal phase space with DLA
(~10x less laser power than for wiggler modulation)

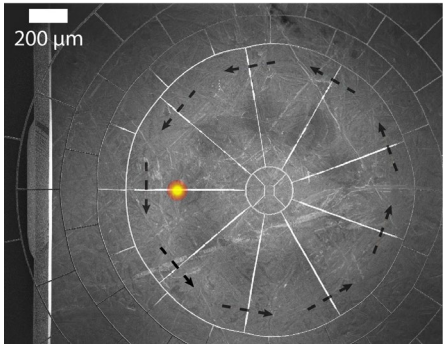
+ Tunability of amplitude and wavelength:

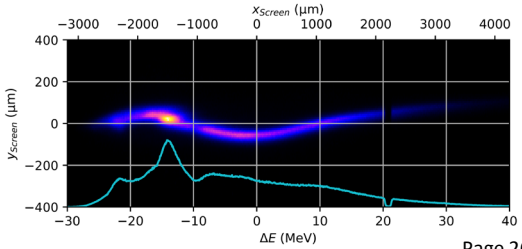
Summary

- Beam shaping possibilities with dielectric grating wake fields
  - Short pulse generation
  - De-chirping
  - Stability (Passive → no temporal jitter)
  - Tunability (Varying grating parameters)
  - Experiments at SwissFEL (ACHIP chamber)
    - Wire scanner tomography
    - Tunable wakefield structures

- DLA for ESASE

→ Dielectric structures, laser- or wakefield-driven, provide compact and cost-efficient alternatives to conventional beam shaping techniques





Acknowledgments

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Beam Shaping with Dielectric Structures

5th European Advanced Accelerator Concepts Workshop, EAAC :: September 20, 2021

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