Feb 27, 2020 :: JUAS Visit at PSI :: Benedikt Hermann

Dielectric Laser Acceleration

ACHIP – Acceleration on a Chip International Program

Overview

1. **Particle acceleration with waves**

2. **Dielectric laser acceleration (DLA)**
   - Accelerator on a Chip International Program (ACHIP)
   - Recent experiments

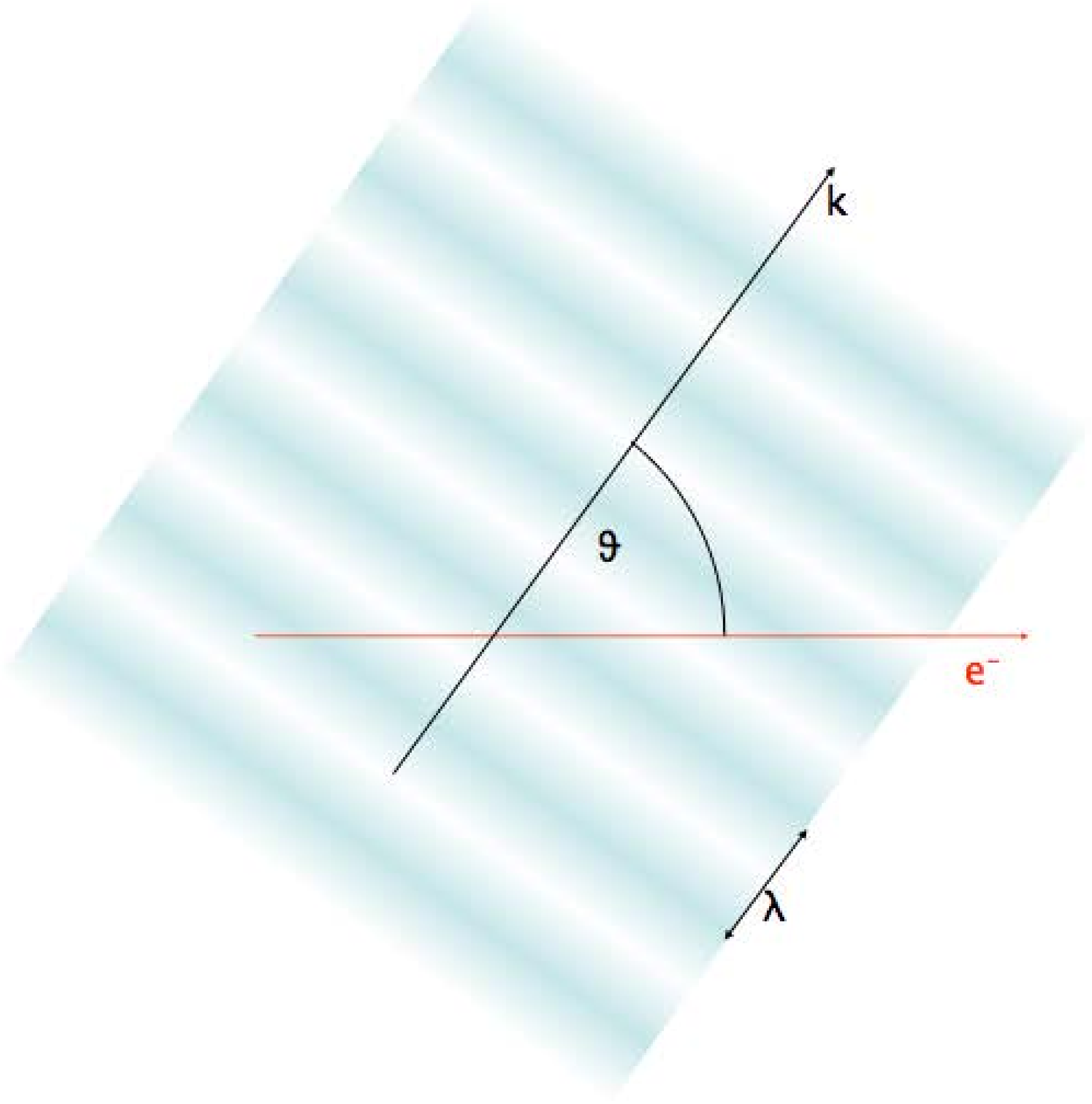
3. **ACHIP interaction chamber at SwissFEL, PSI**
   - Diagnostics for sub-um beams
   - Wake field studies

4. **Outlook**

How to Accelerate Charged Particles

Assume:

- an ultrarelativistic particle of charge e
- moving along the z axis
- accelerated by a plane electromagnetic wave that propagates at an angle ϑ to the z axis

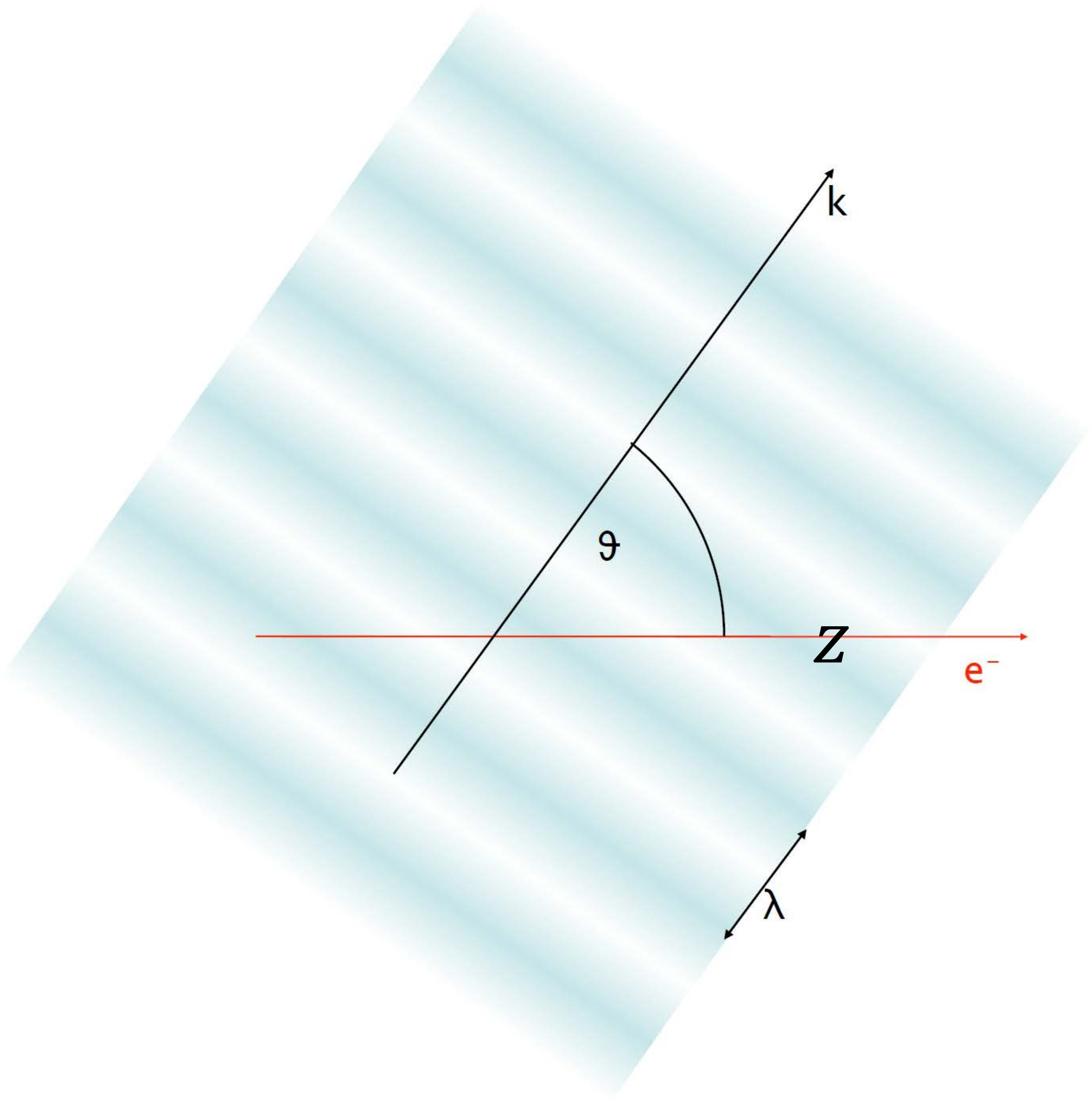


Introduction: Electron Acceleration with Waves

Interaction of ultra-relativistic electrons with plane waves

Electric field:

$$E_{||} = \sin\vartheta\cos(\omega t - \frac{2\pi}{\lambda\cos\vartheta}\ z)$$



Energy gradient:

$$\frac{\Delta W}{L} = \int_0^L \frac{eE_{||}\mathrm{d}z}{L} = \frac{\mathcal{O}(L^0)}{L} \rightarrow 0\ \ (L \rightarrow\ \infty)$$

Lawson-Woodward Theorem

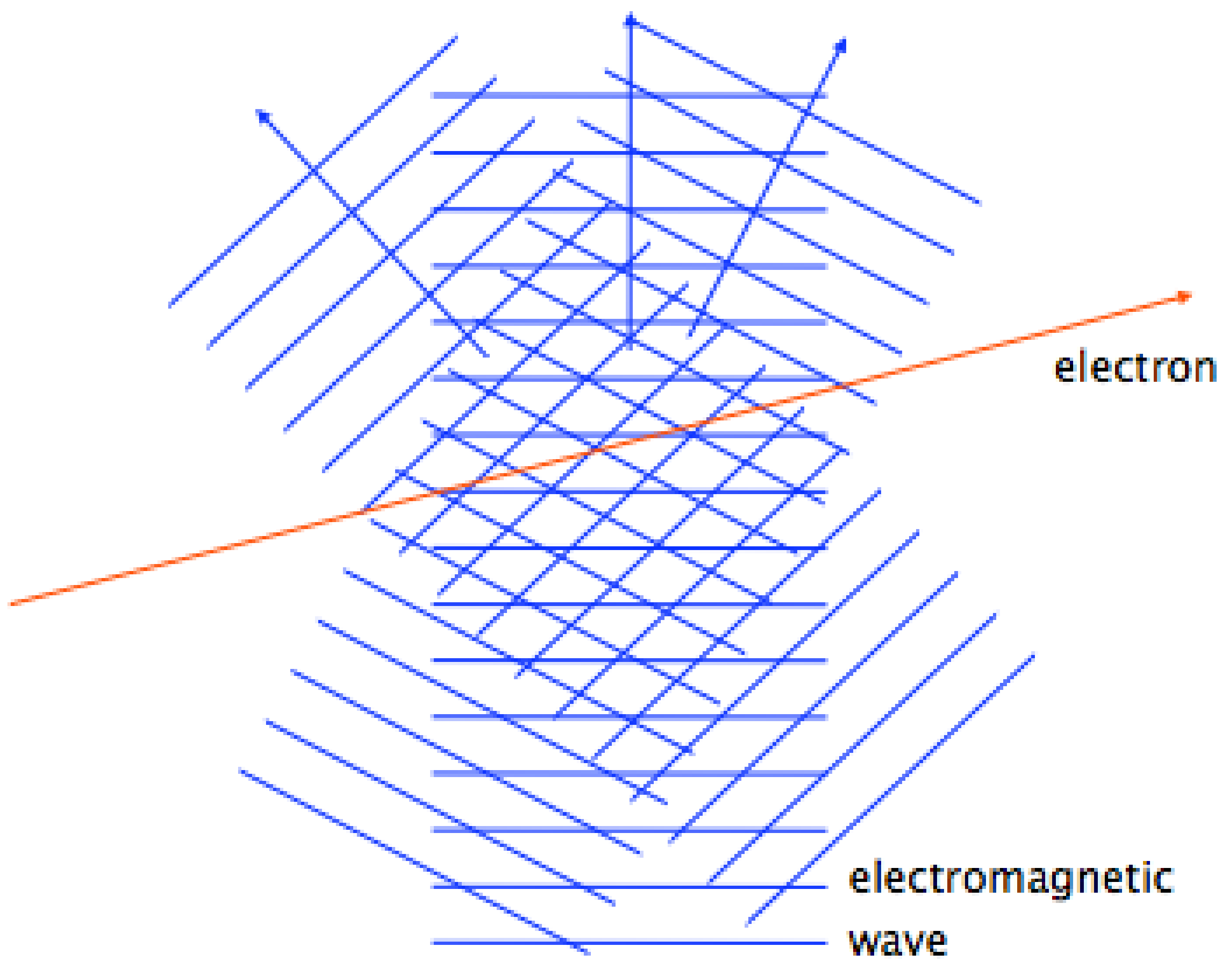
No net acceleration of ultra-relativistic electrons by far-field radiation.

→ Near-field structures

Lawson Woodward Theorem

- Every wave in far field can be written as a superposition of plane waves
- The Lawson–Woodward Theorem states:
  - the total acceleration
    - of ultrarelativistic particles
    - by far–field electromagnetic waves
  - is zero

⇒ Need near–field structures



Woodward, J. IEE 93 (1947)
Lawson, IEEE Trans. Nucl. Sci. 26 (1979)
Palmer, Part. Accel. 11 (1980)

RF Accelerators (GHz, cm)

DESY

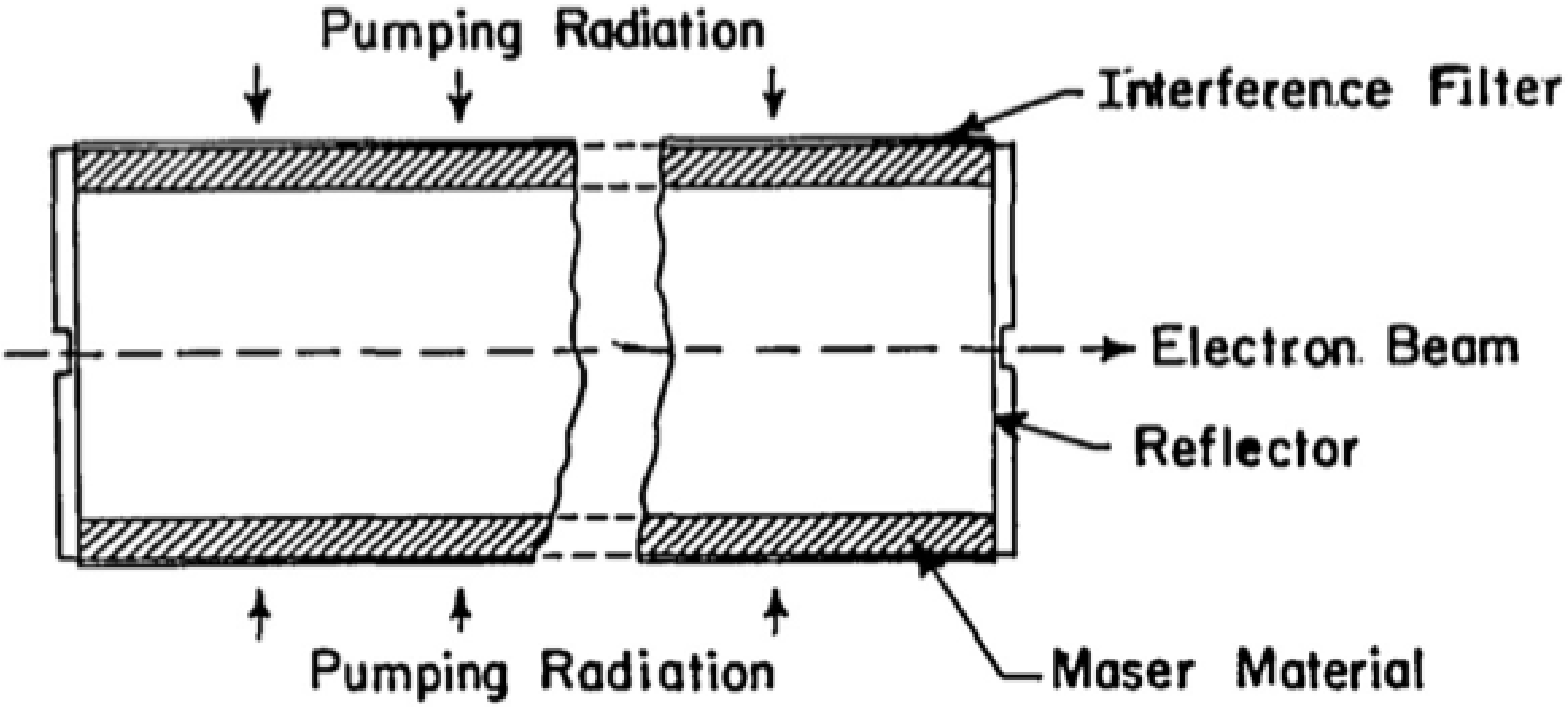


Fig. 1. Schematic diagram of an electron linear accelerator by optical maser.

Shimoda
Appl. Opt. **1 (1)**, 33 (1961)

Simulation of a Grating DLA

Unit cell
periodic boundary conditions

$\mathcal{E} = 1$ GV/m (incident field strength

$E_{init.} = 3$ GeV (initial electron energ

Synchronicity condition: $\lambda_P = \lambda_L \beta n$

λ_P: structure period

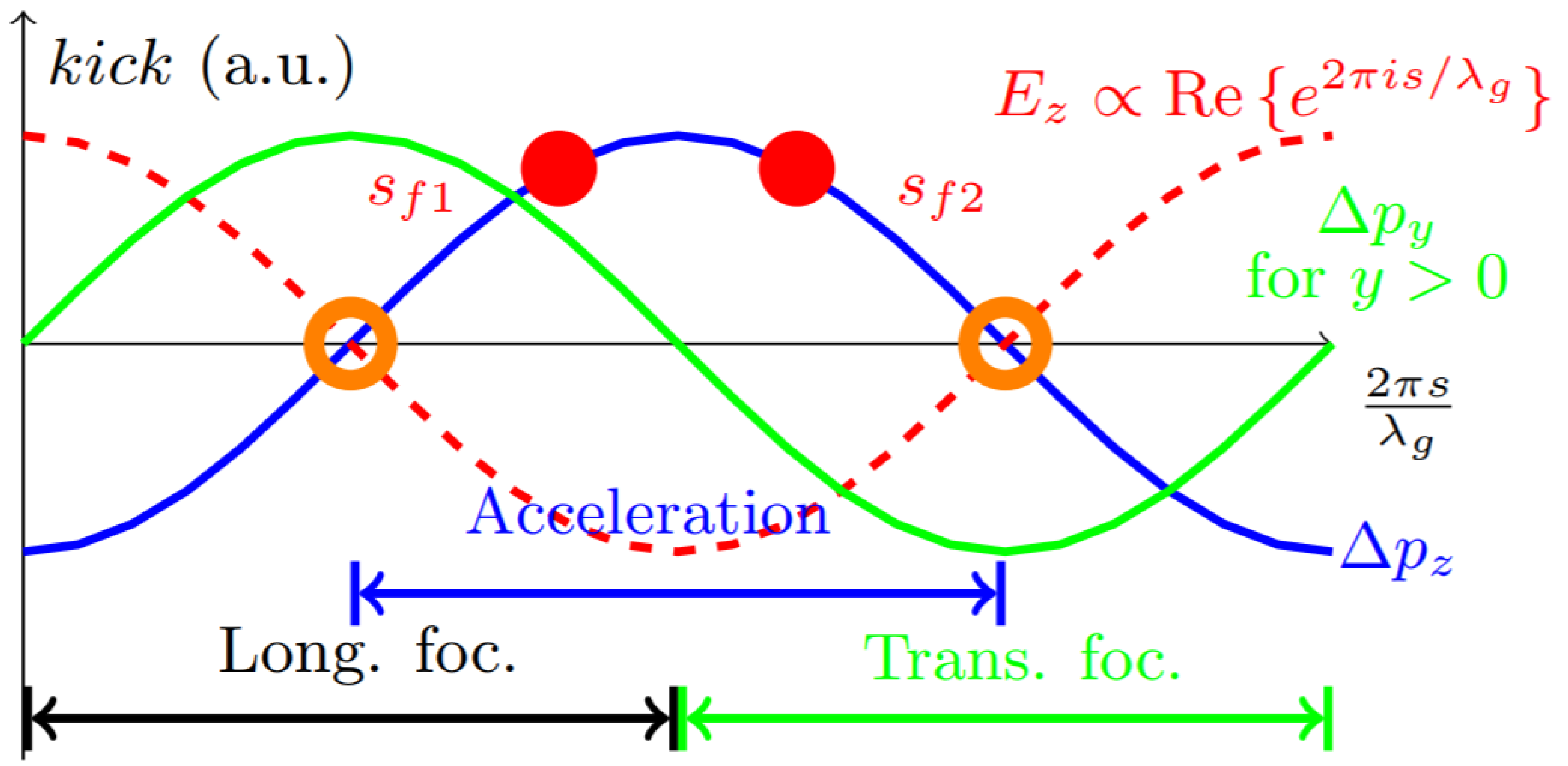
λ_L: laser wavelength

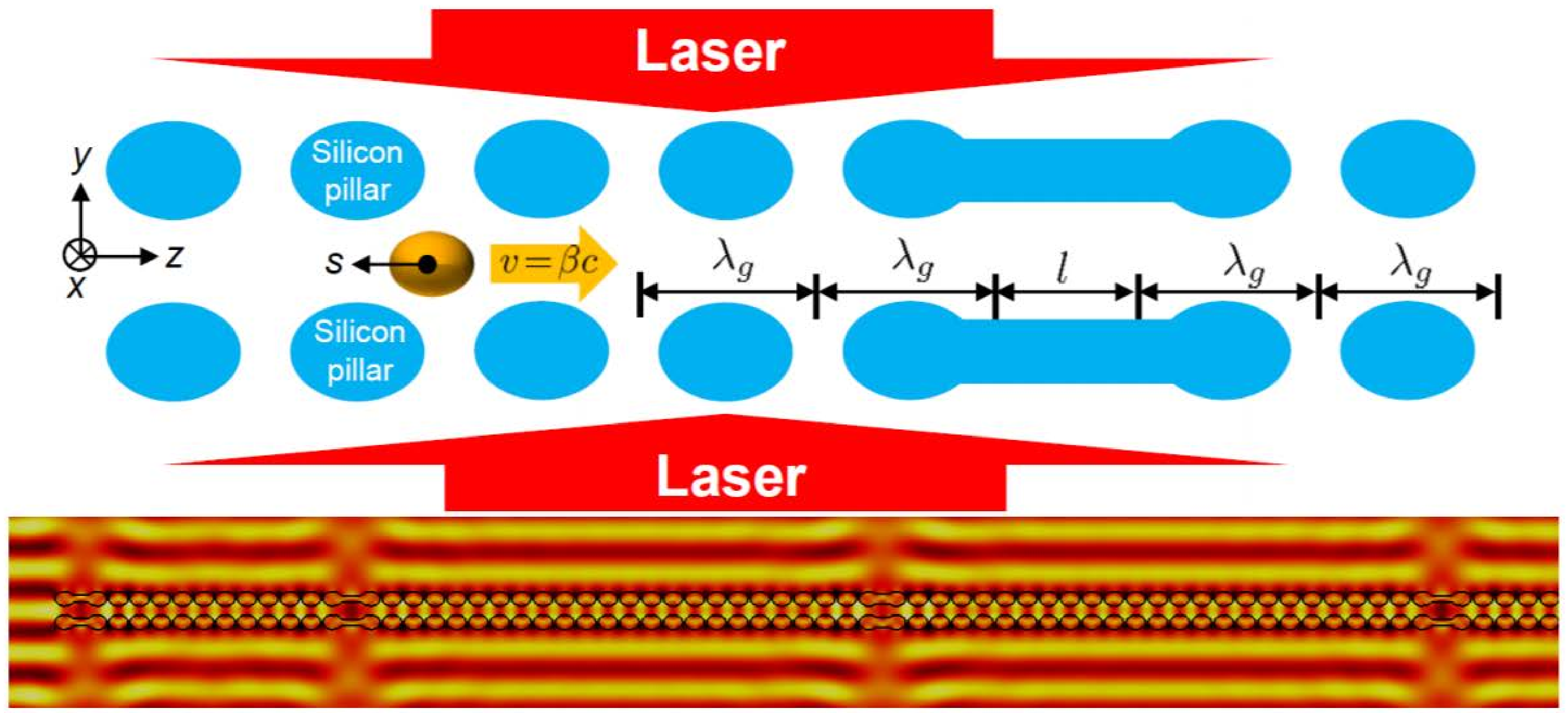
β: electron velocity / c

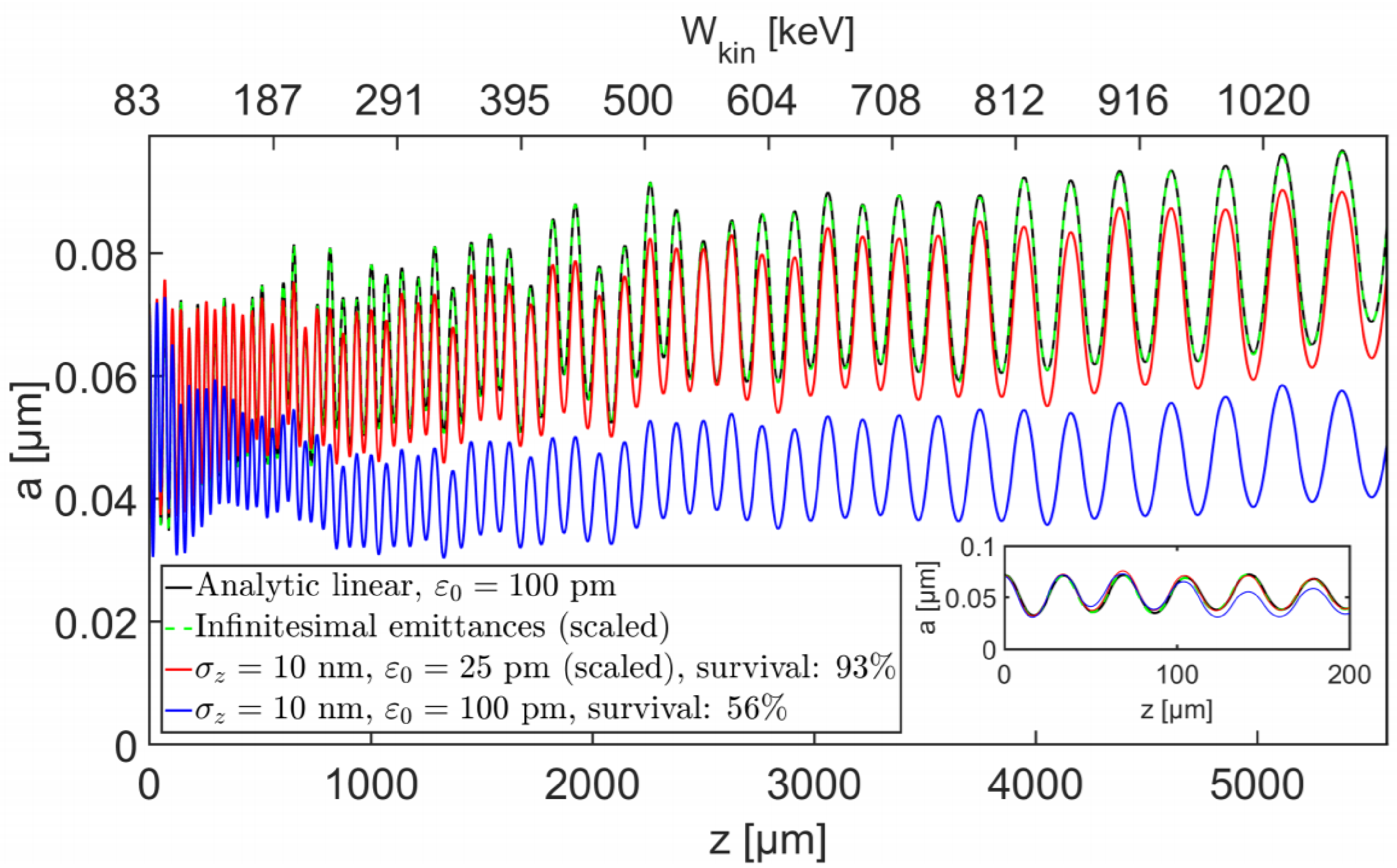
n: mode order

Transverse Focusing Simulation

- Transverse confinement crucial for long DLA
- Alternating Phase Focusing (APF)



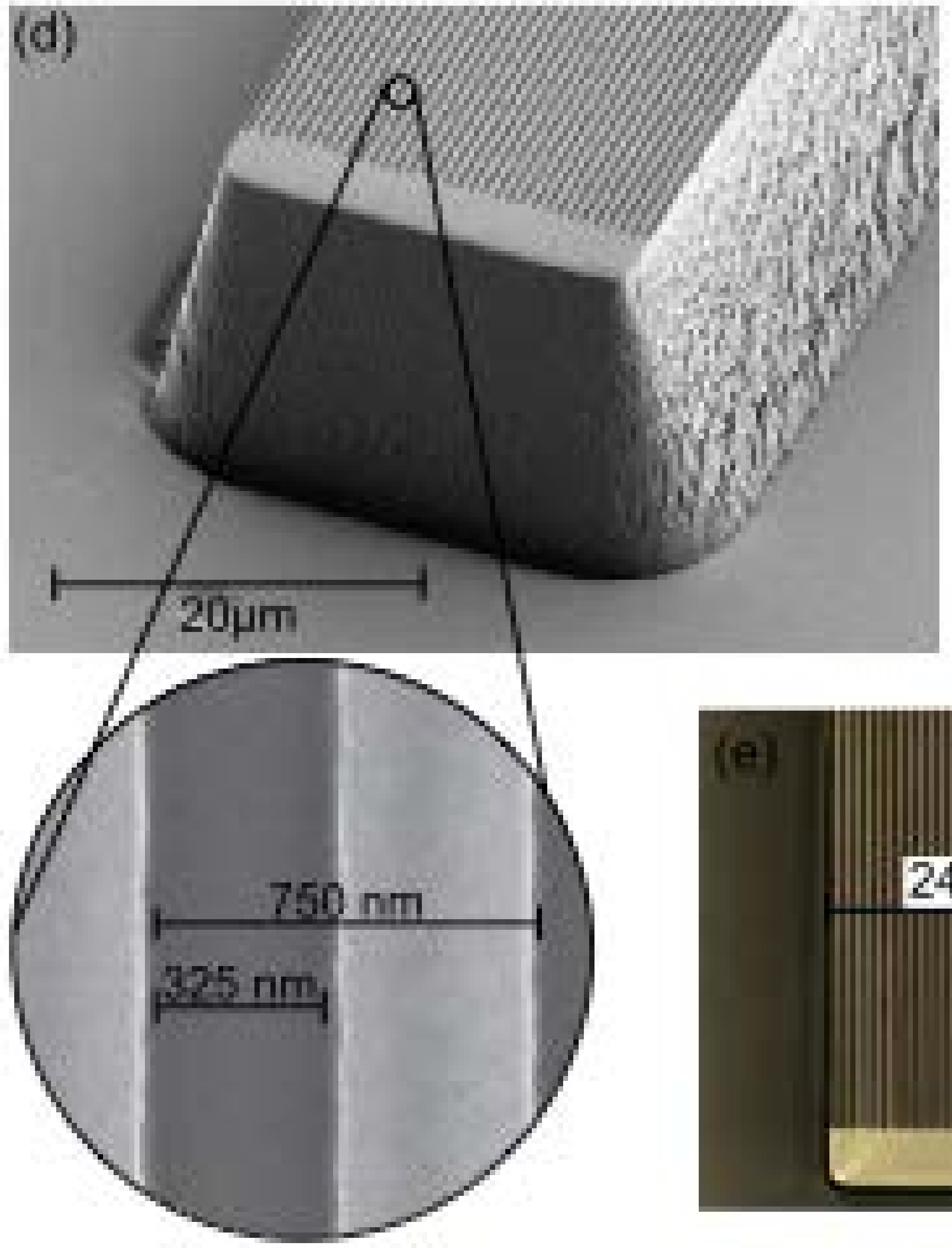


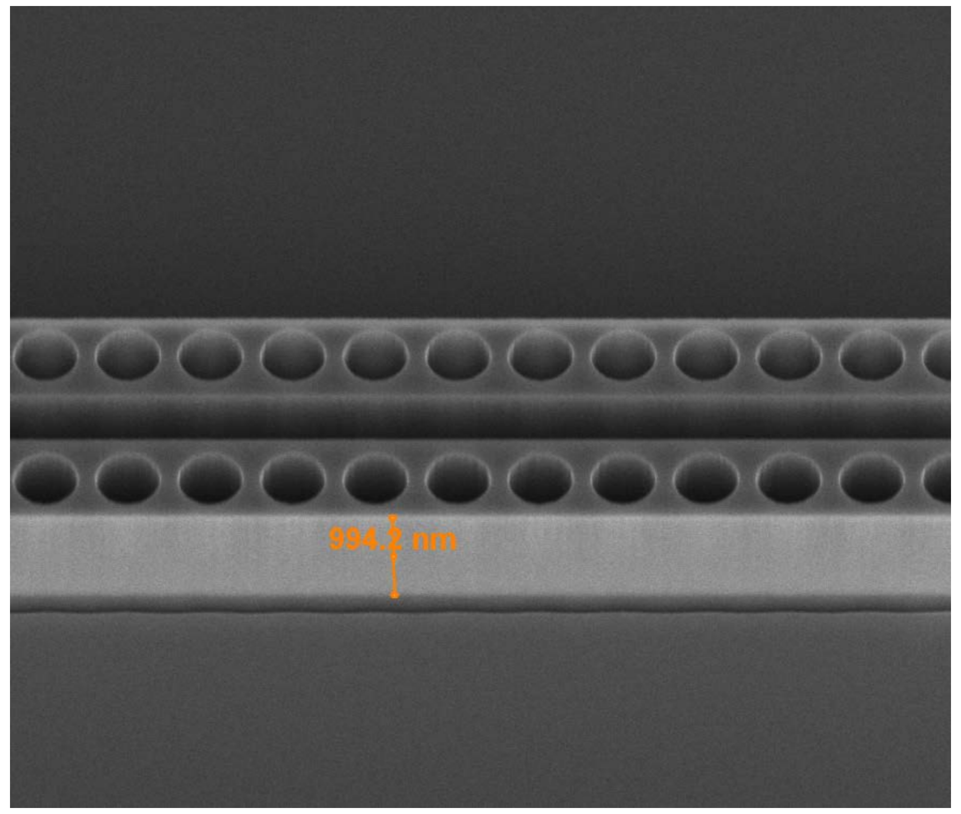


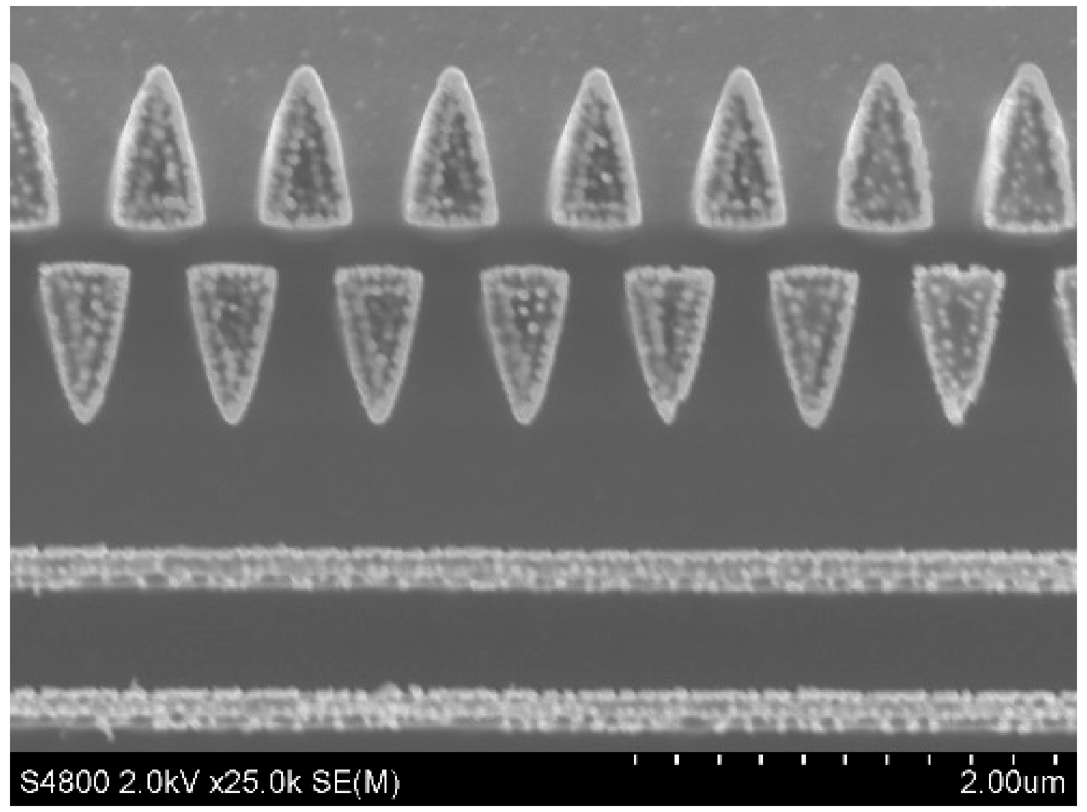
Analytical and numerical (rms) beam envelopes, scaled to identical initial beam size at ε = 100 pm.

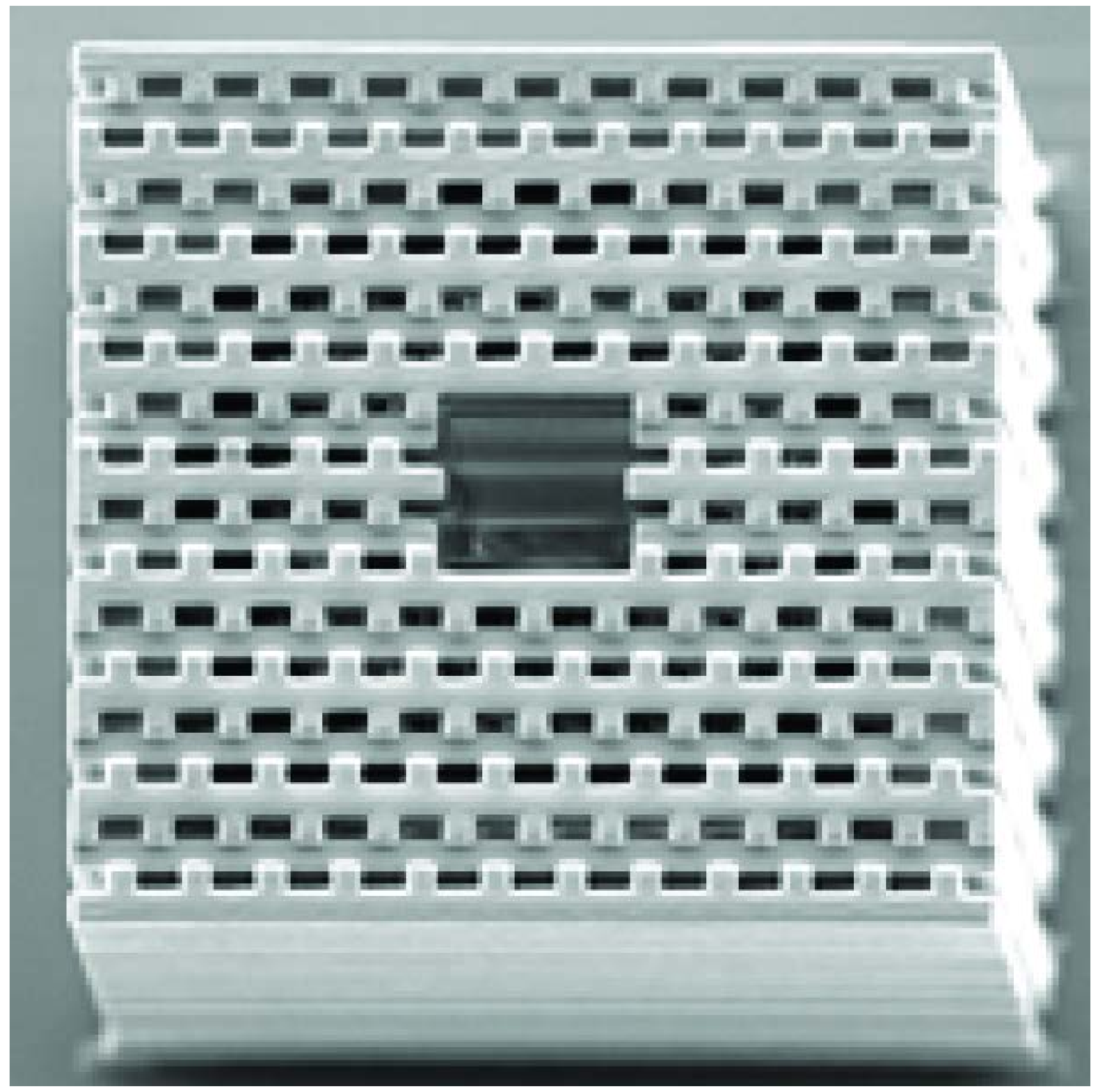
U. Niedermayer, 2018
https://arxiv.org/pdf/1806.07287.pdf

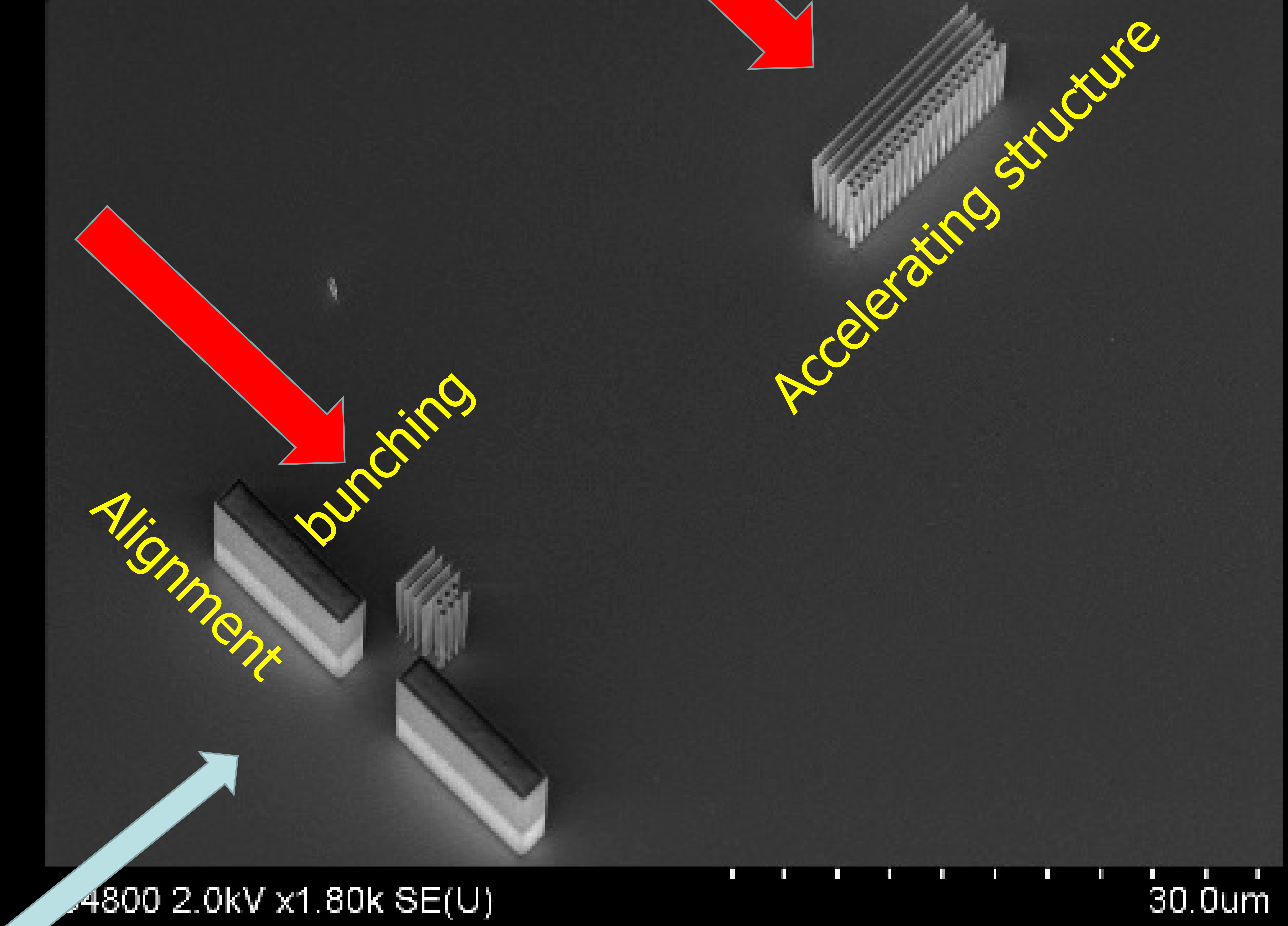
Manufacturing of Accelerating Structures







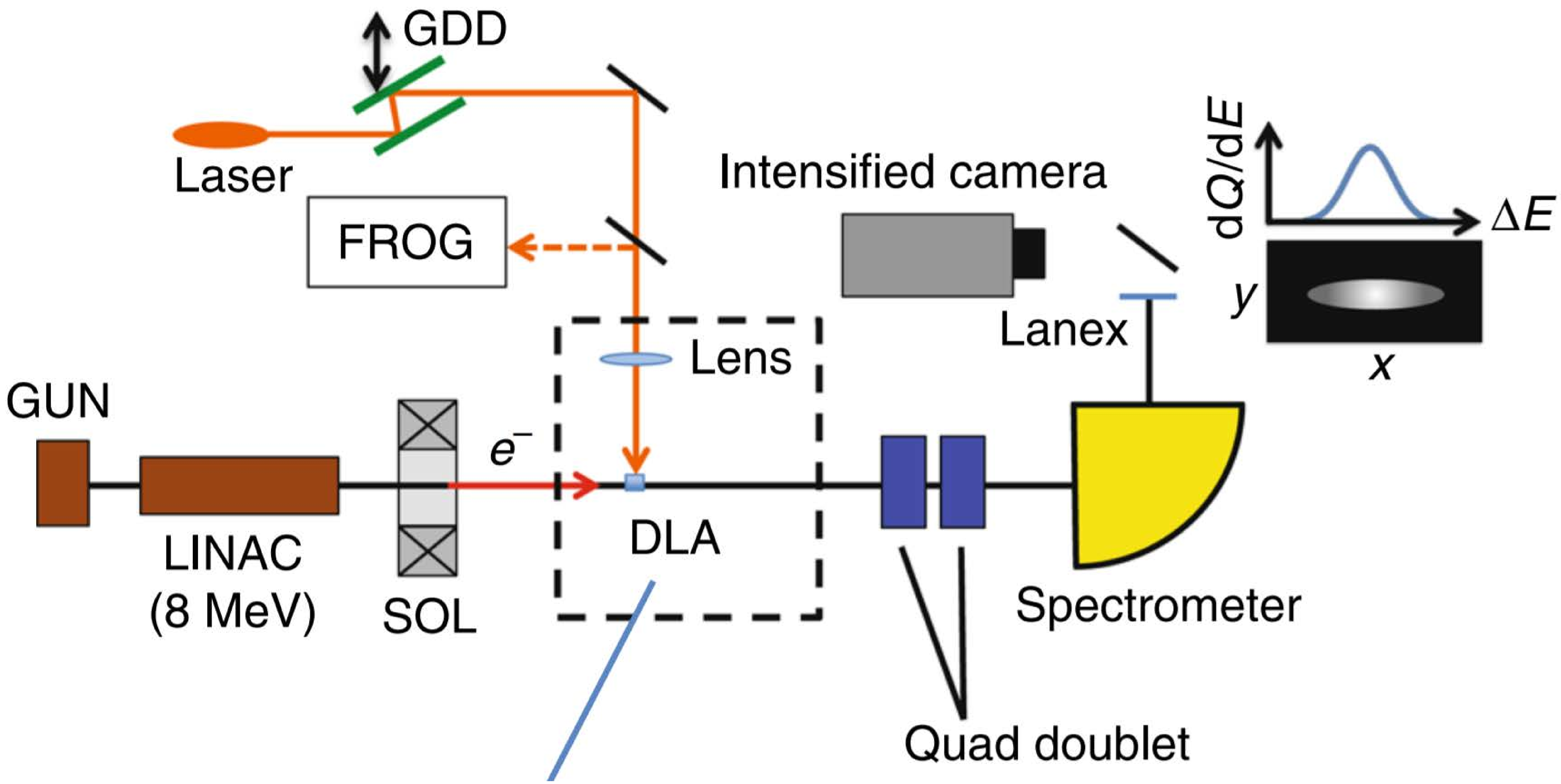



Accelerating structure
bunching
Alignment
4800 2.0kV x1.80k SE(U)
30.0um

ACHIP Collaboration

+ students and guest scientists from Cockcroft Institute, Los Alamos National Laboratory, Uni Pisa, National Tsing Hua University, TU Wien & ETH Zürich

DLA Experiment at UCLA, SLAC

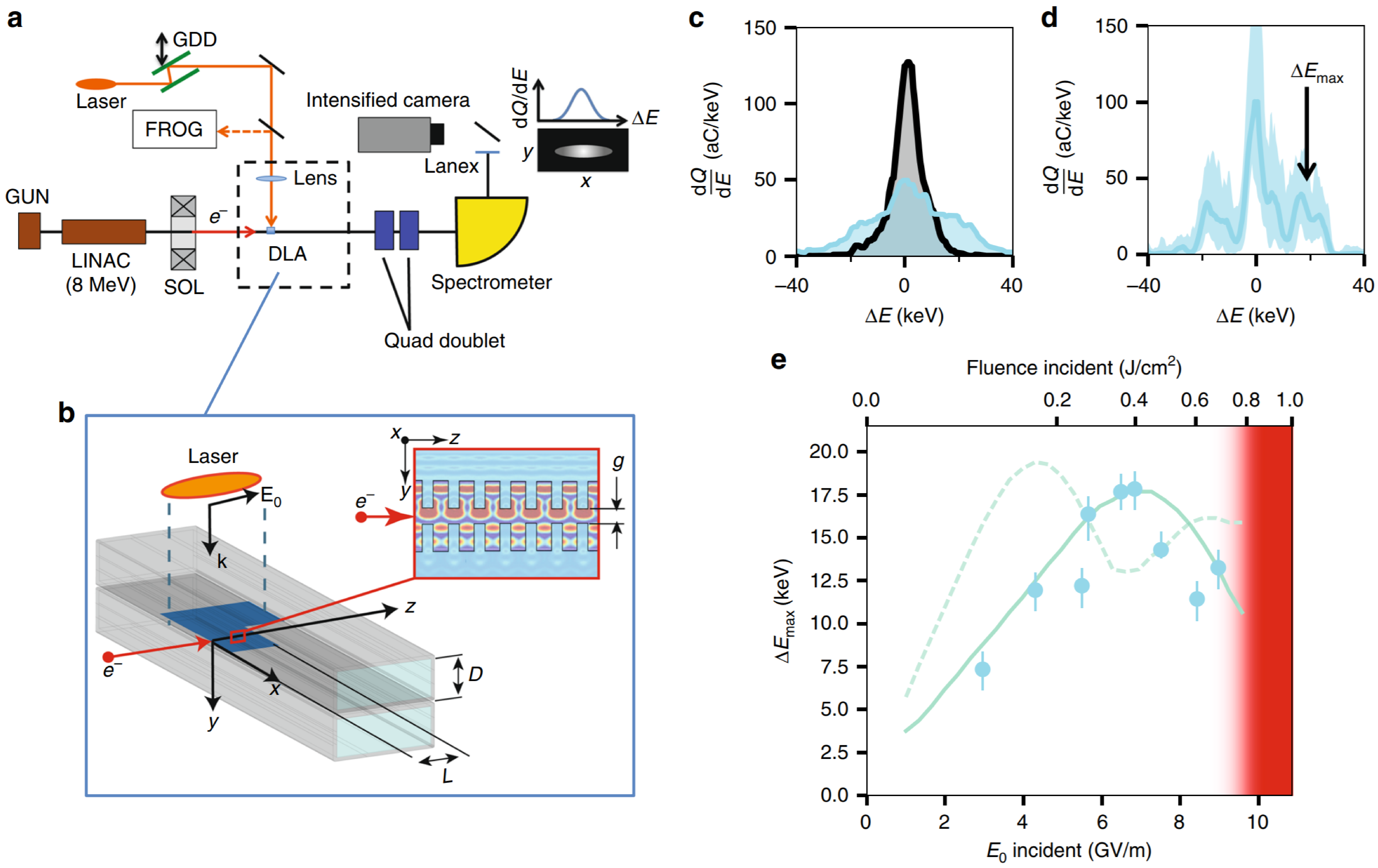


850 MeV/m measured acceleration gradient

Non-linear phase modulation observed (Kerr effect)

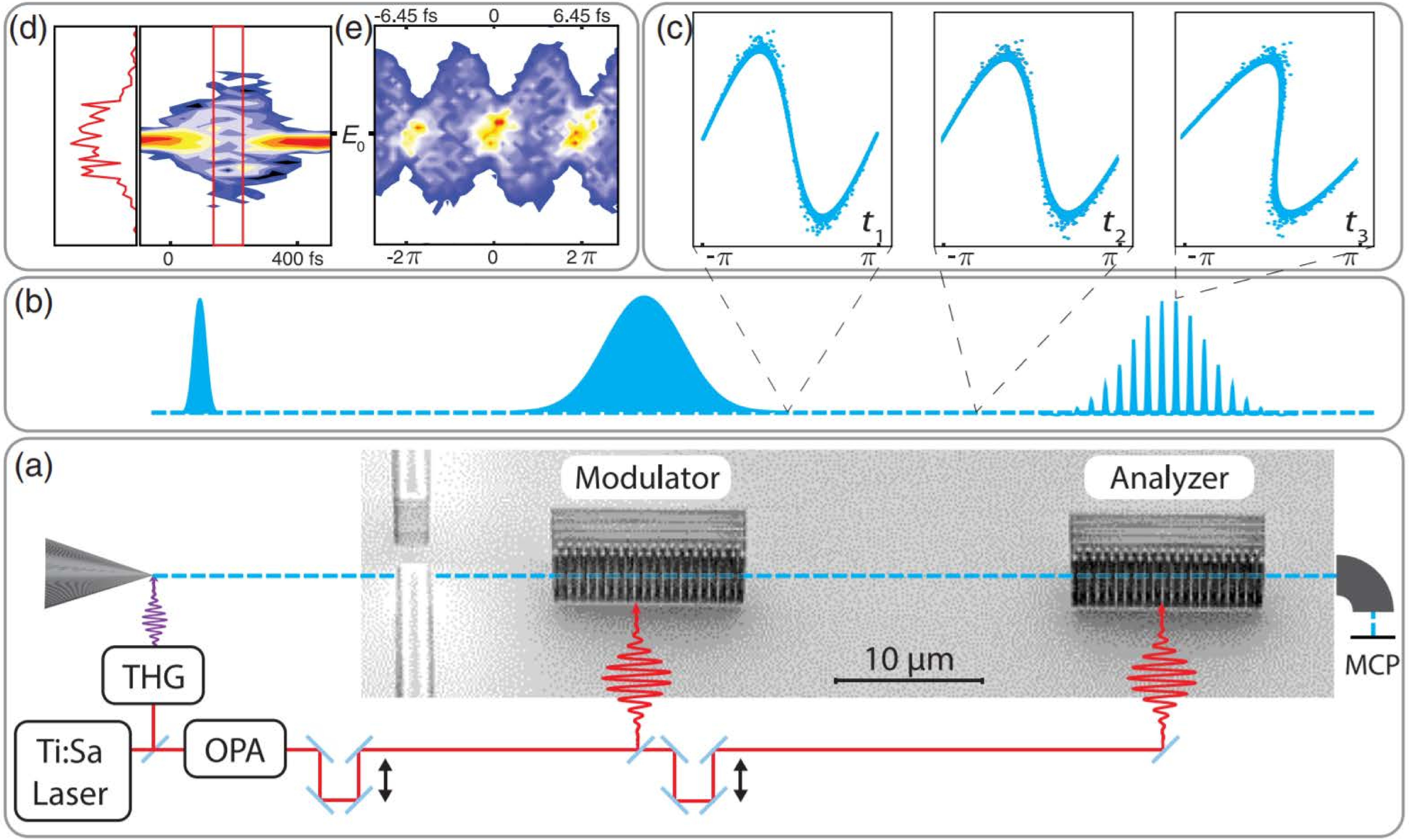
D. Cesar, Communications Physics Volume 1, 46 (2018)
https://www.nature.com/articles/s42005-018-0047-y

Recent Experiment (UCLA, SLAC)



D. Cesar, Communications Physics Volume 1, 46 (2018)
https://www.nature.com/articles/s42005-018-0047-y

Attosecond Pulse Trains
(FAU Erlangen, 30 keV)



N. Schönenberger et al, 2019, Physical Review Letters.
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.123.264803

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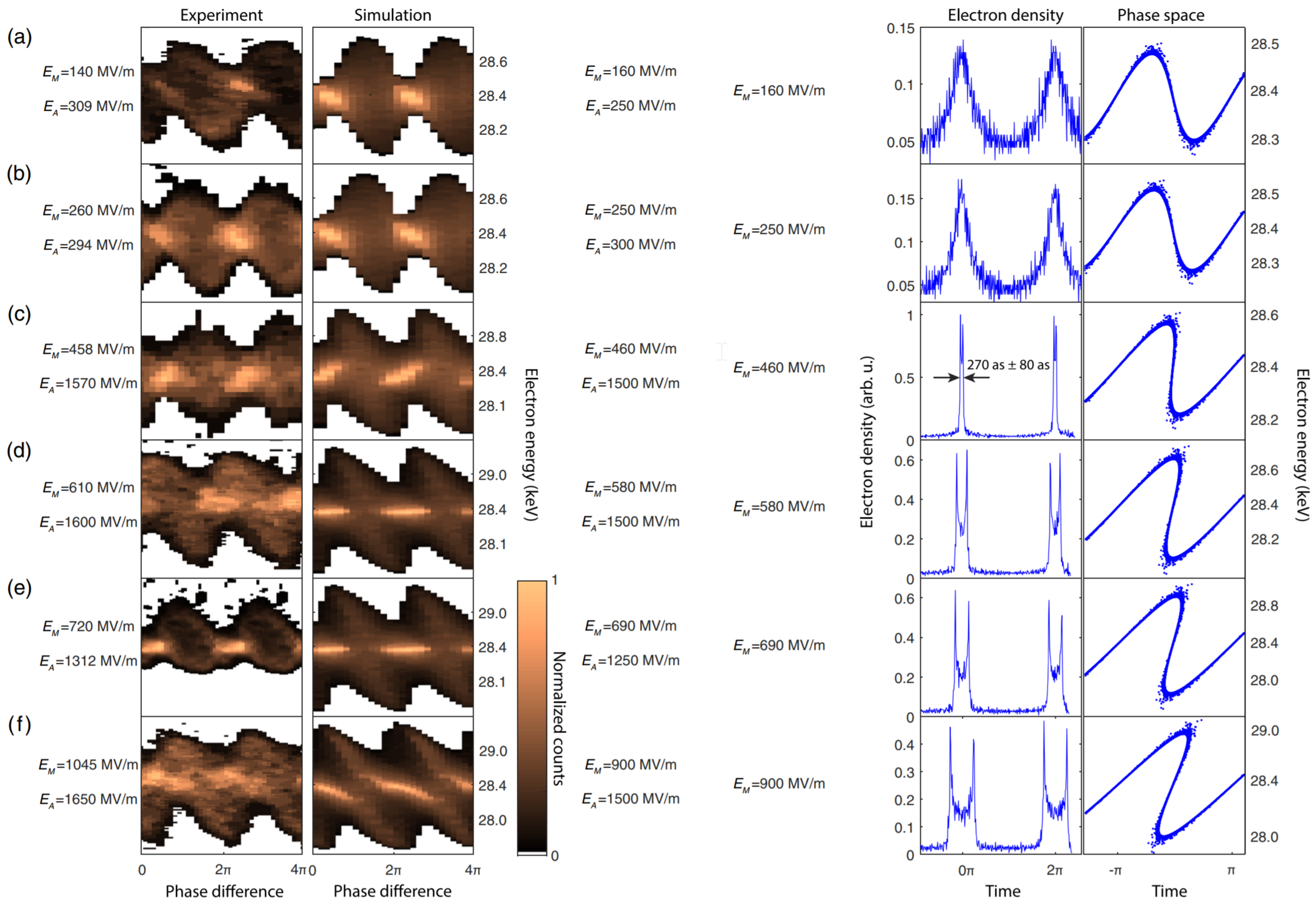
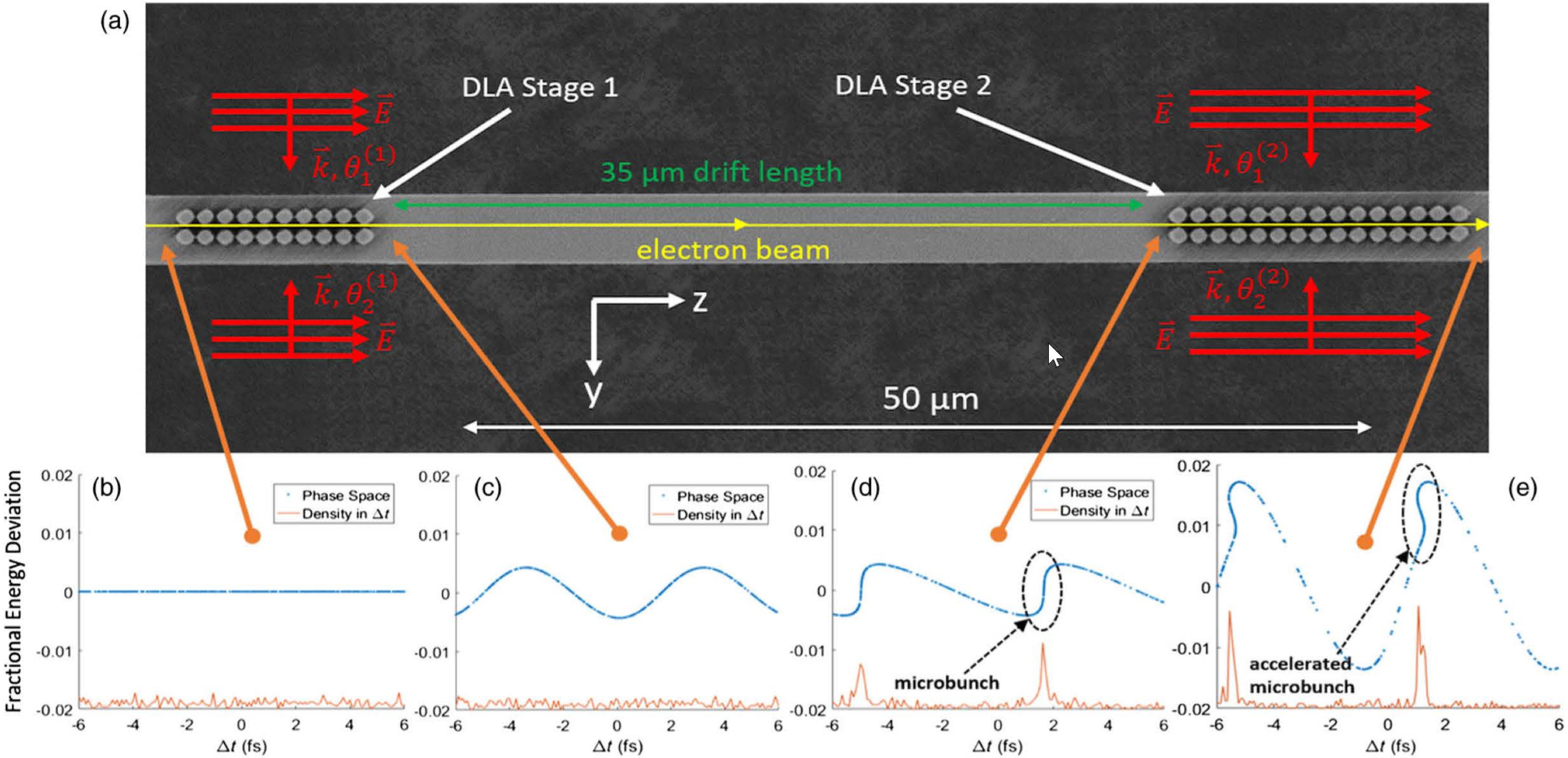


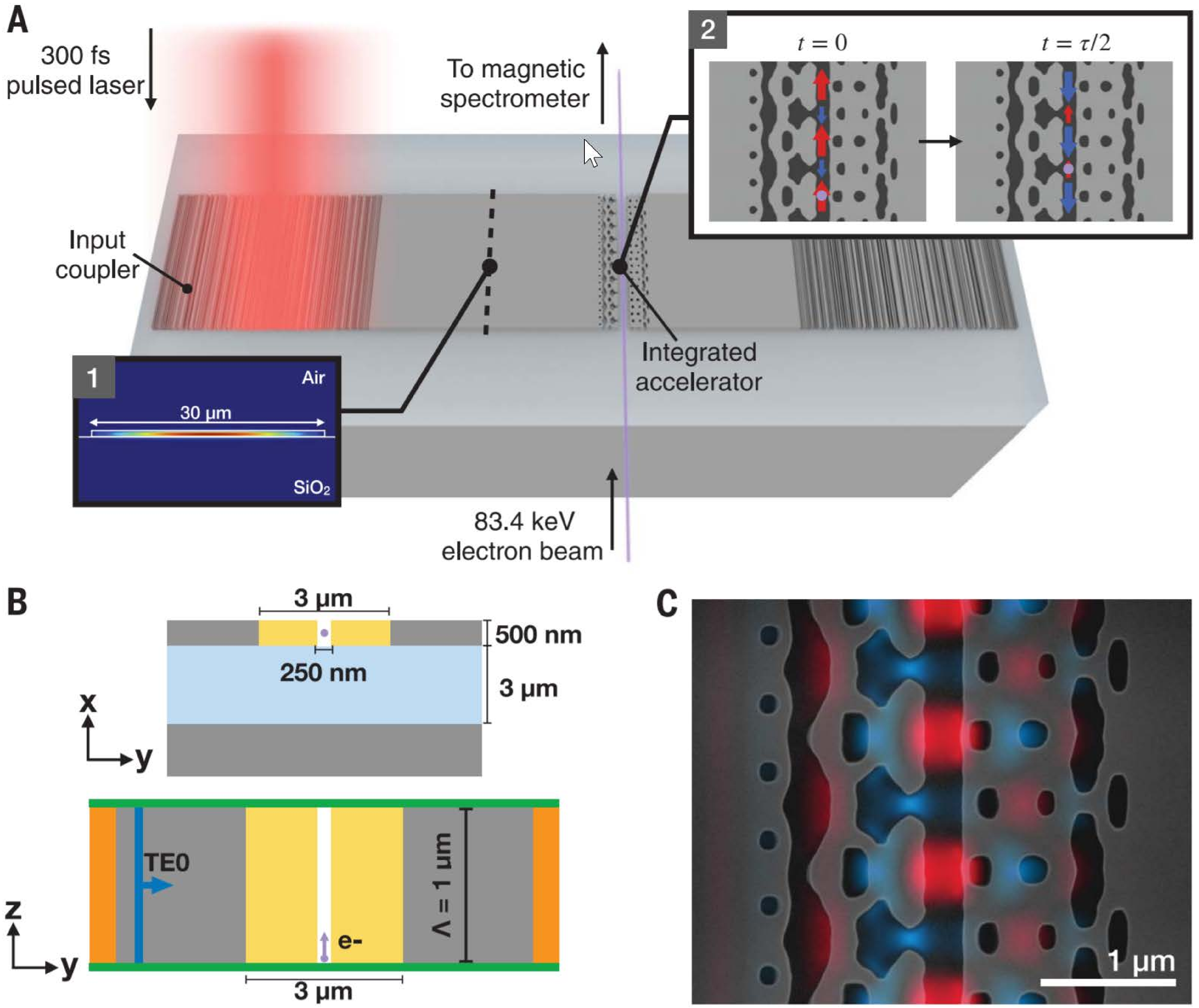
N. Schönenberger et al, 2019, Physical Review Letters.
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.123.264803

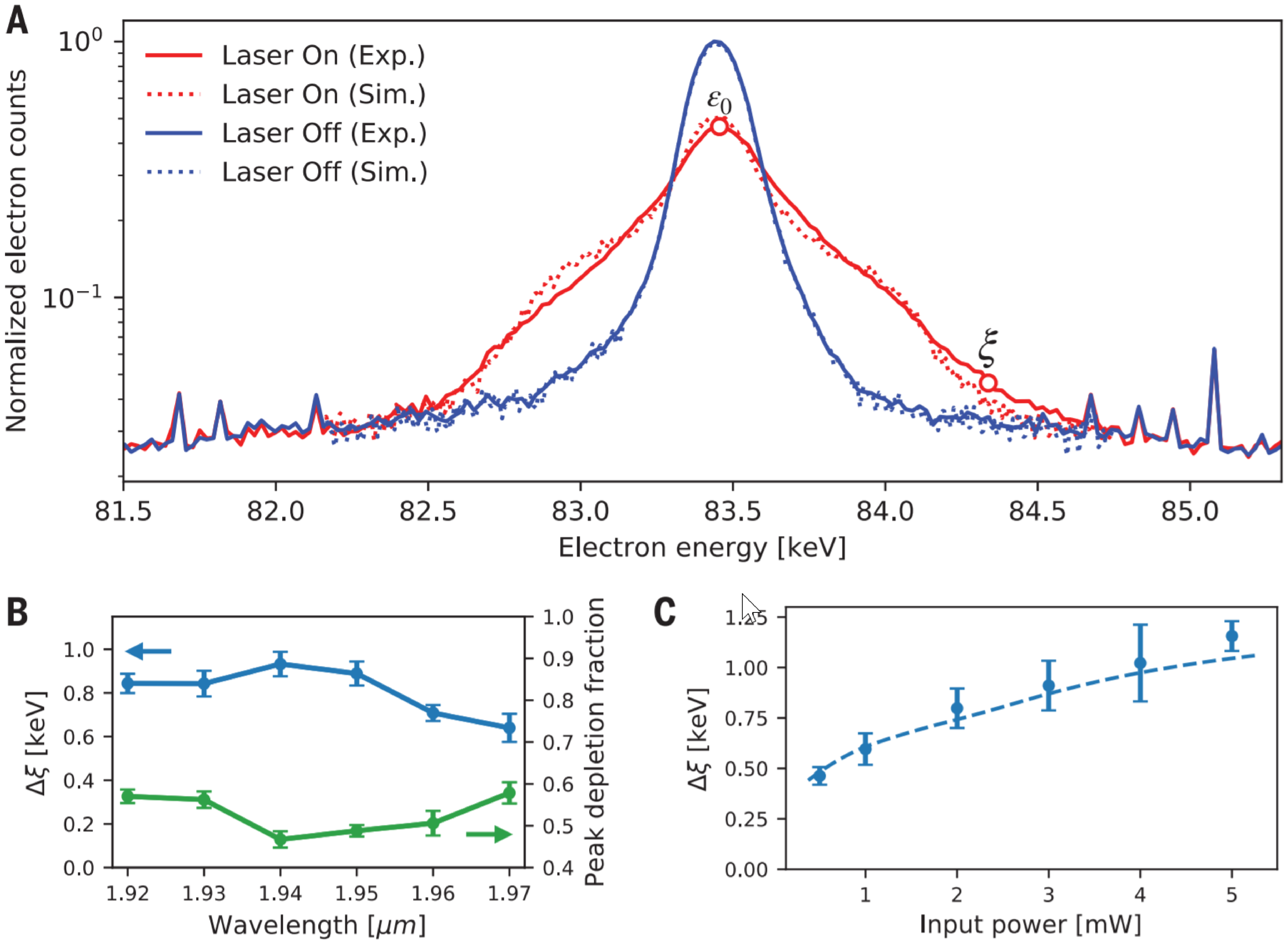
Attosecond Pulse Trains (Stanford, 57 keV)



D. S. Black et al, 2019, Physical Review Letters.
https://journals.aps.org/prl/abstract/10.1103/PhysRevLett.123.264802

On-chip Integrated Laser-Driven Particle Accelerator (Inverse Design)





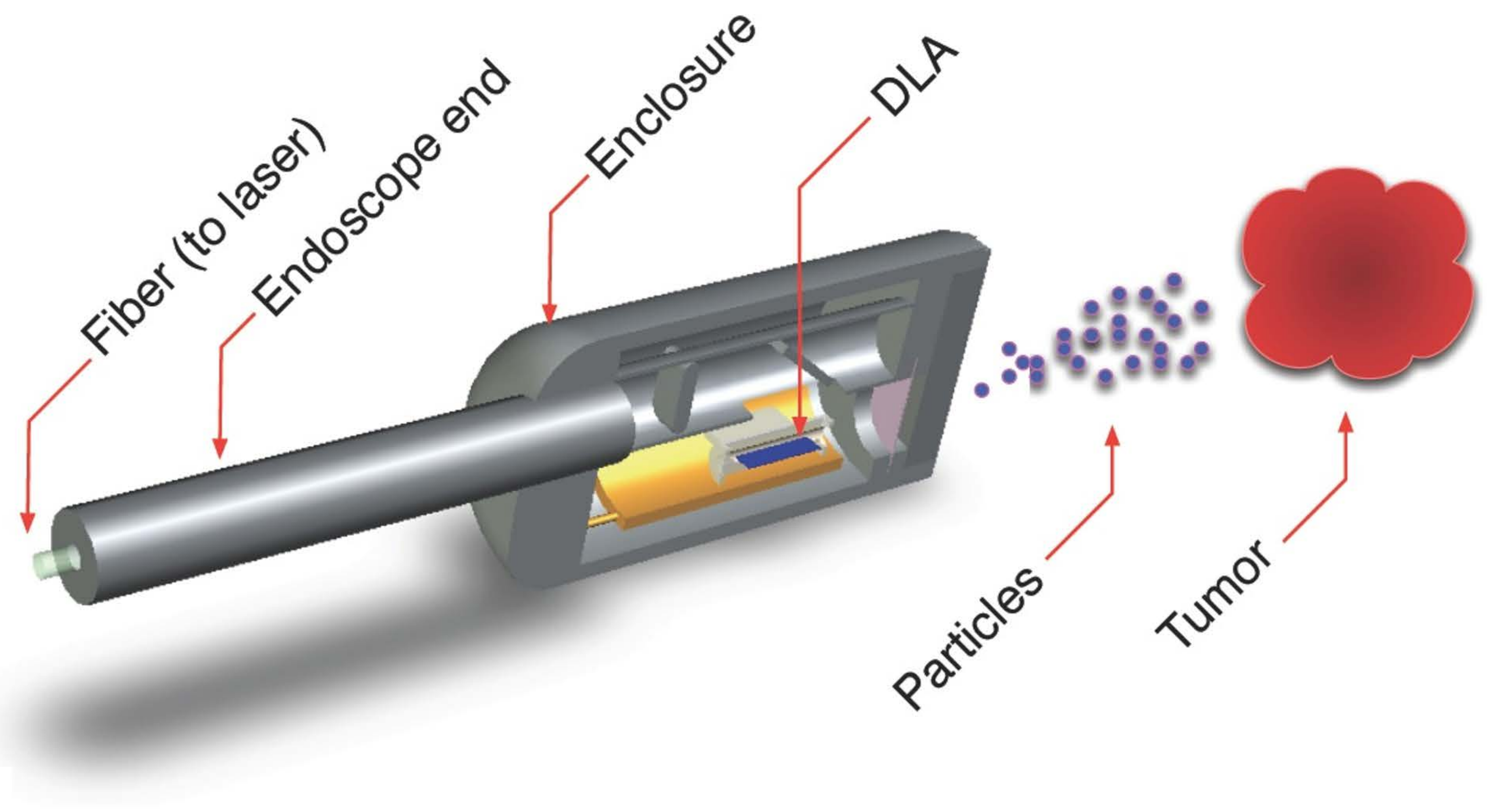
N. V. Sapra et al, 2020, Science.
https://science.sciencemag.org/content/367/6473/79/tab-pdf

Applications of DLAs

Endoscopic Radiation Therapy

R.J. England, Rev. Mod. Phys. 86, 1337 (2014)

https://journals.aps.org/rmp/abstract/10.1103/RevModPhys.86.1337



- very low charge

+ small beam
+ low cost
+ low power consumption

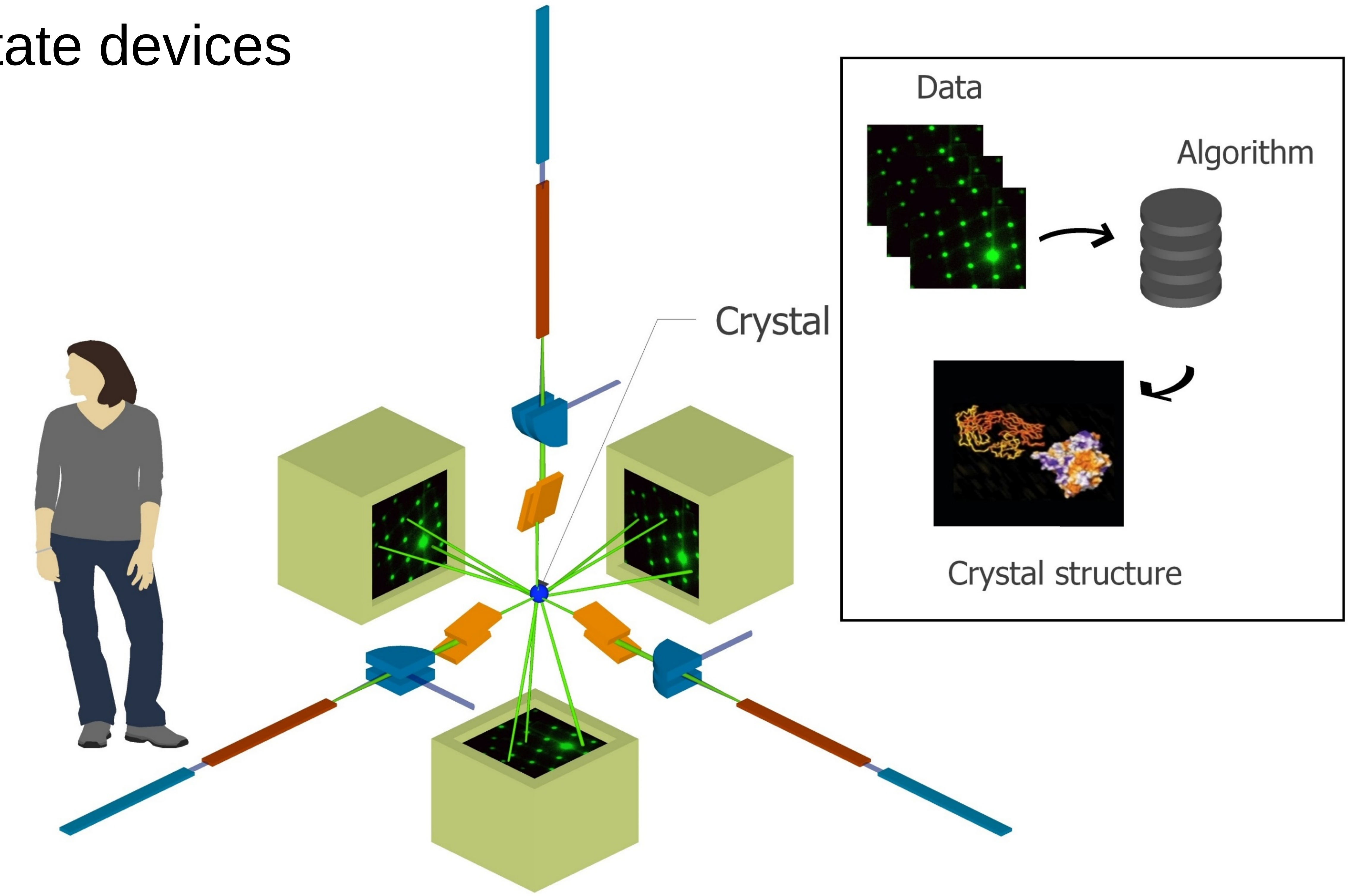
Electron Diffraction

Single-shot atto-sec tomography at MHz repetition rates

+ Compact device, university lab size

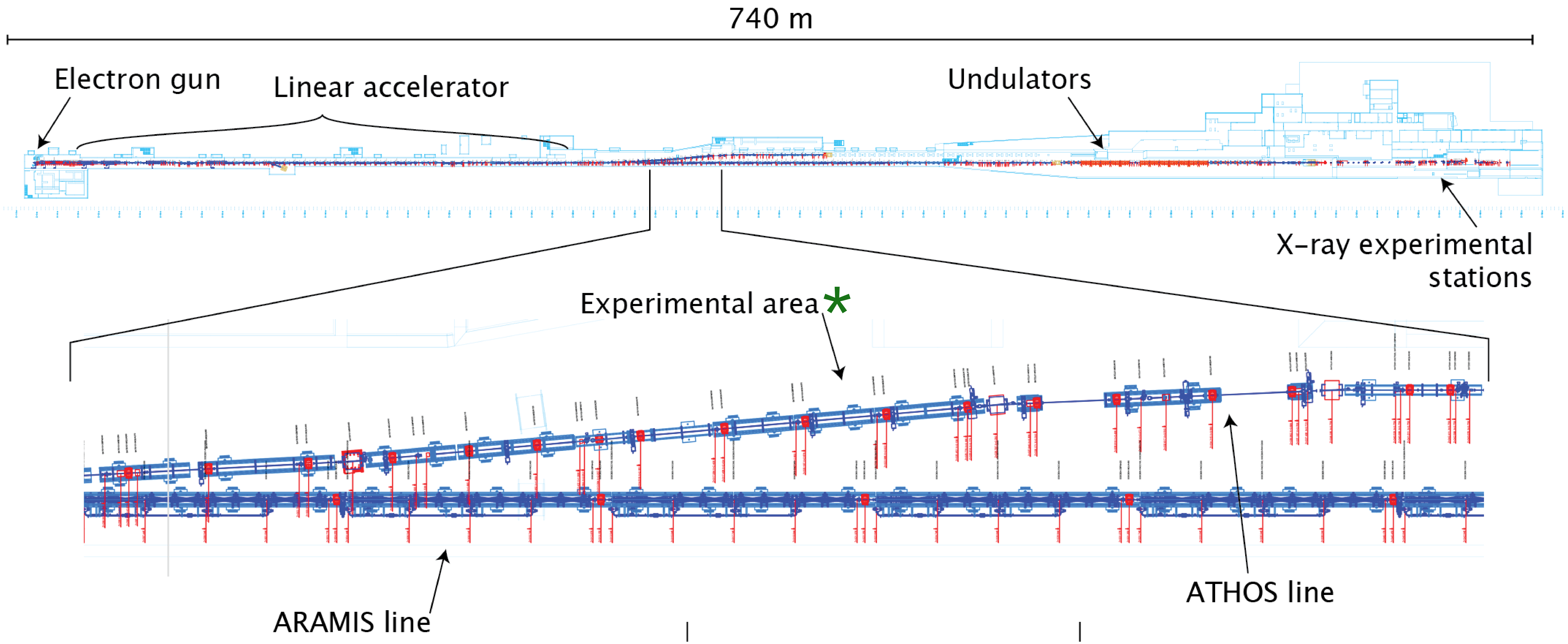
+ Ultrafast (atto-sec) pulses: time-resolved molecular, atomic physics

+ Inexpensive solid state devices



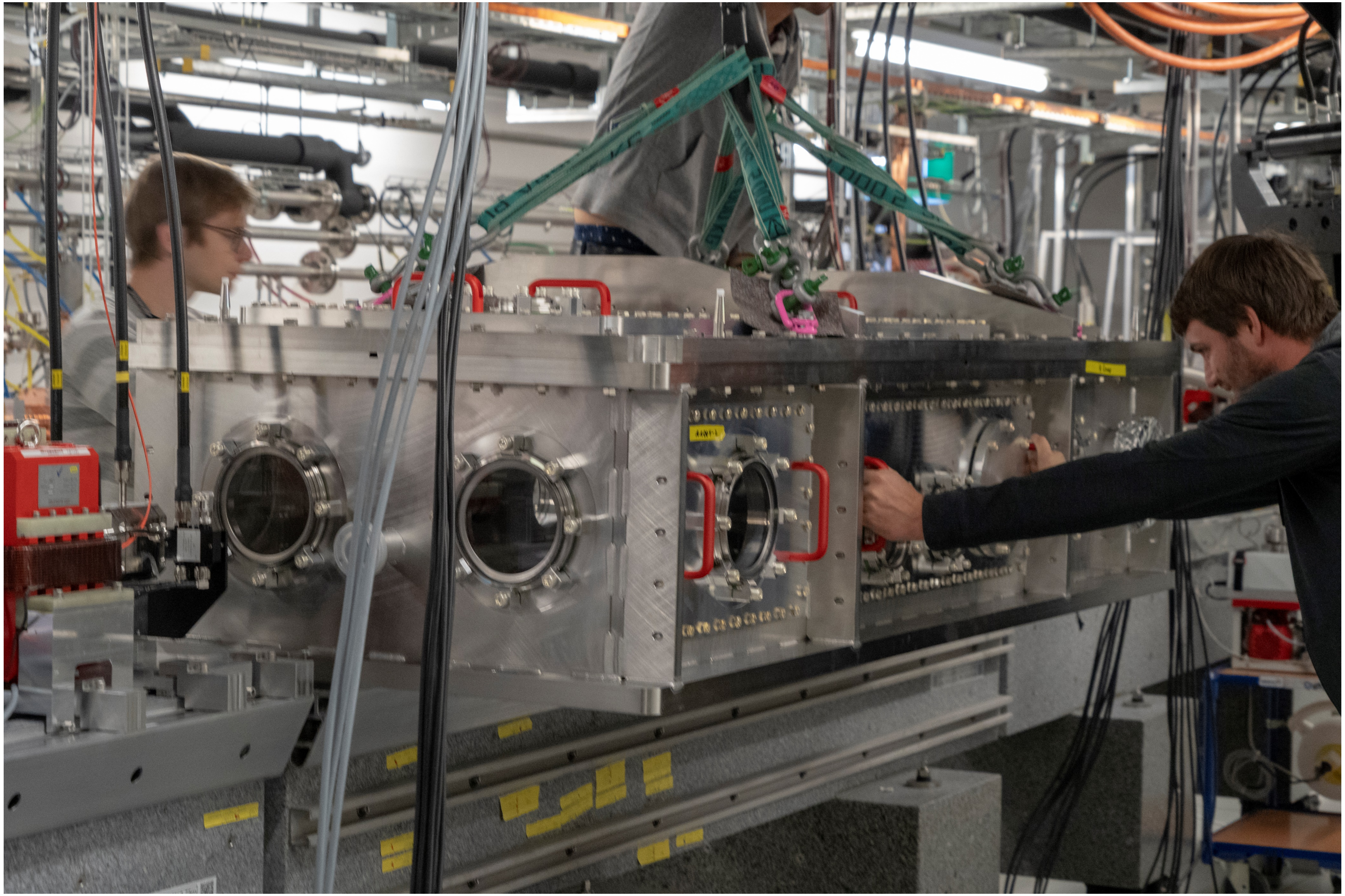
Z. Huang, Y-C. Huang, Applications Group ACHIP Collaboration Meeting 09/2018

ACHIP at SwissFEL



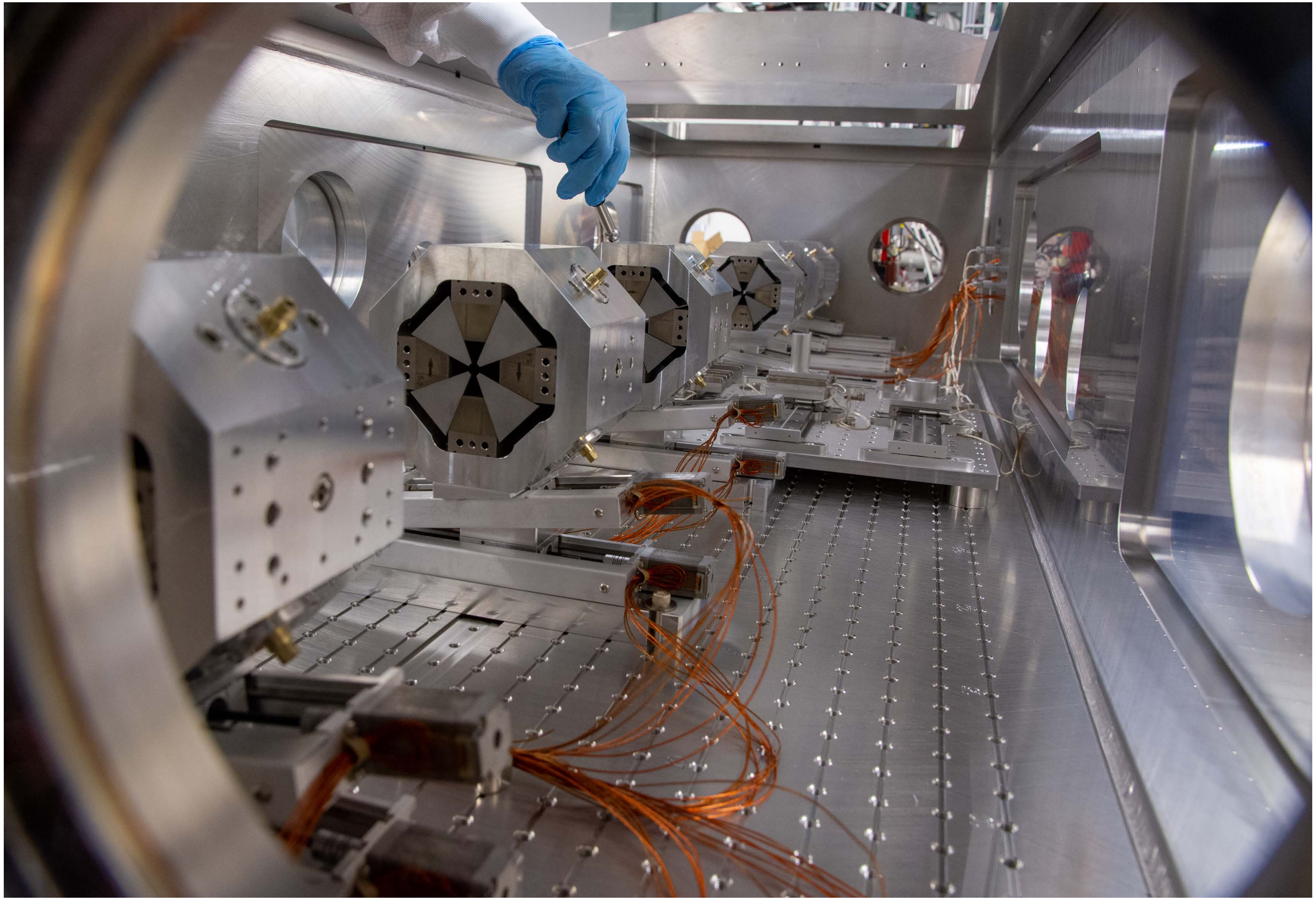
ACHIP-ATHOS Chamber Electron Beam Parameters	
Energy (GeV)	3.0
Bunch Charge (pC)	0.1 - 200
Transverse Size (µm, rms)	0.3
Bunch length (fs)	1-1000

ACHIP Chamber at SwissFEL



- 2 m long
- 1200 kg
- Vacuum: 5e-8 mbar

ACHIP Chamber at SwissFEL

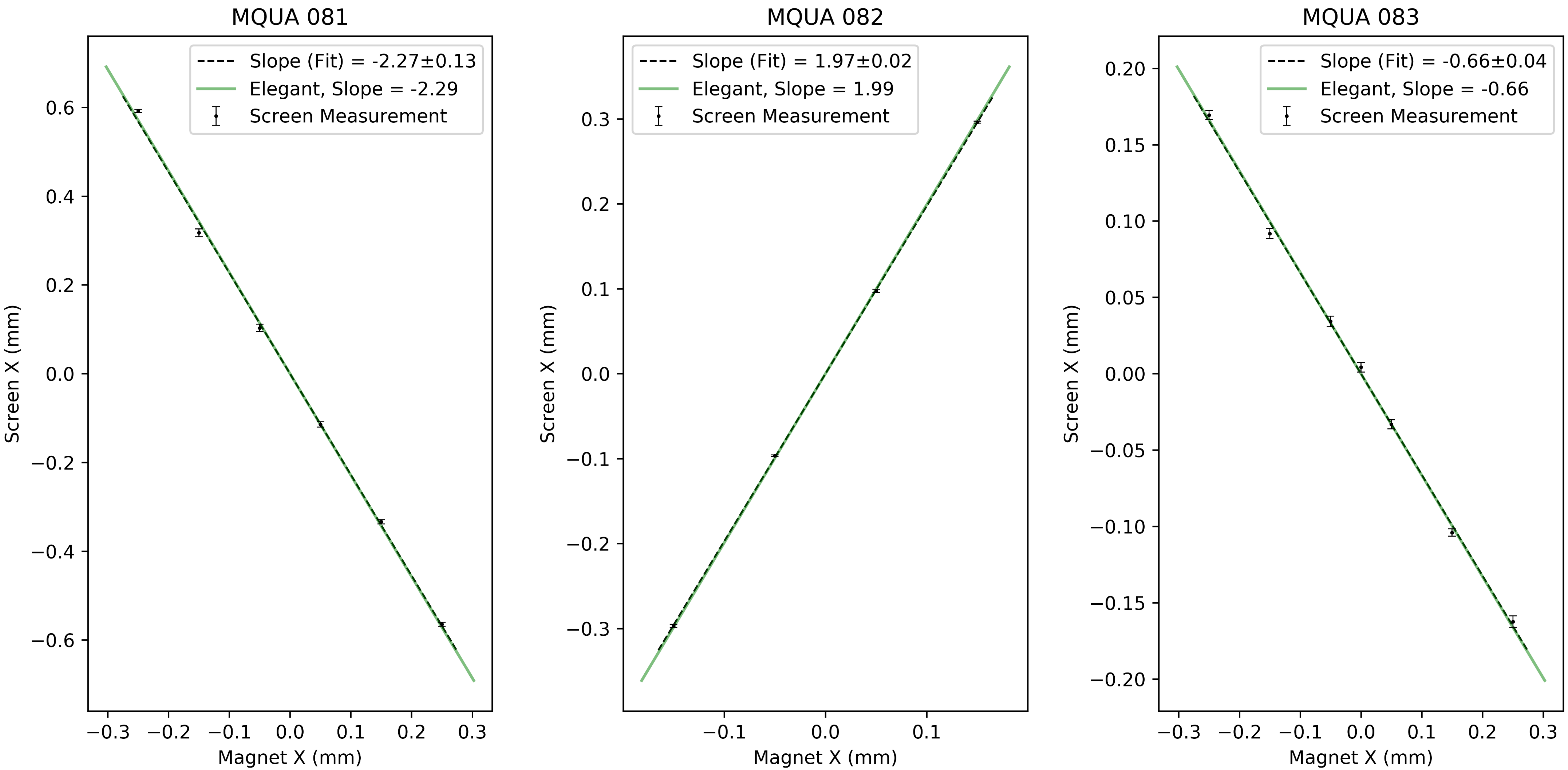


- Permanent magnet quadrupole triplet focusing
- Gradient: 400 T/m
- Removable with stages

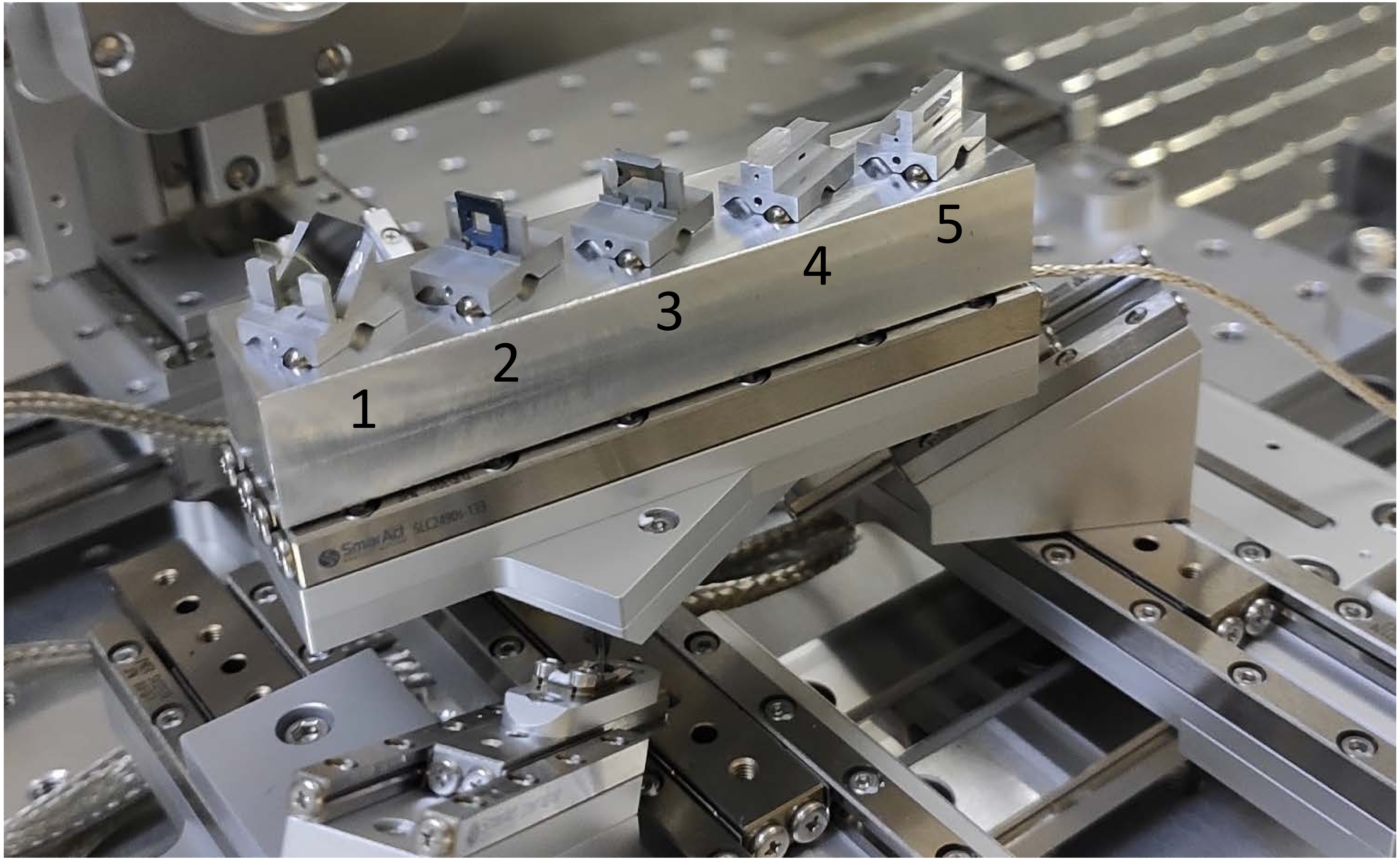
PAUL SCHERRER INSTITUT PSI

Permanent Quad Strength Measurement

Position offset → Transverse momentum kick → Beam position (YAG screen)

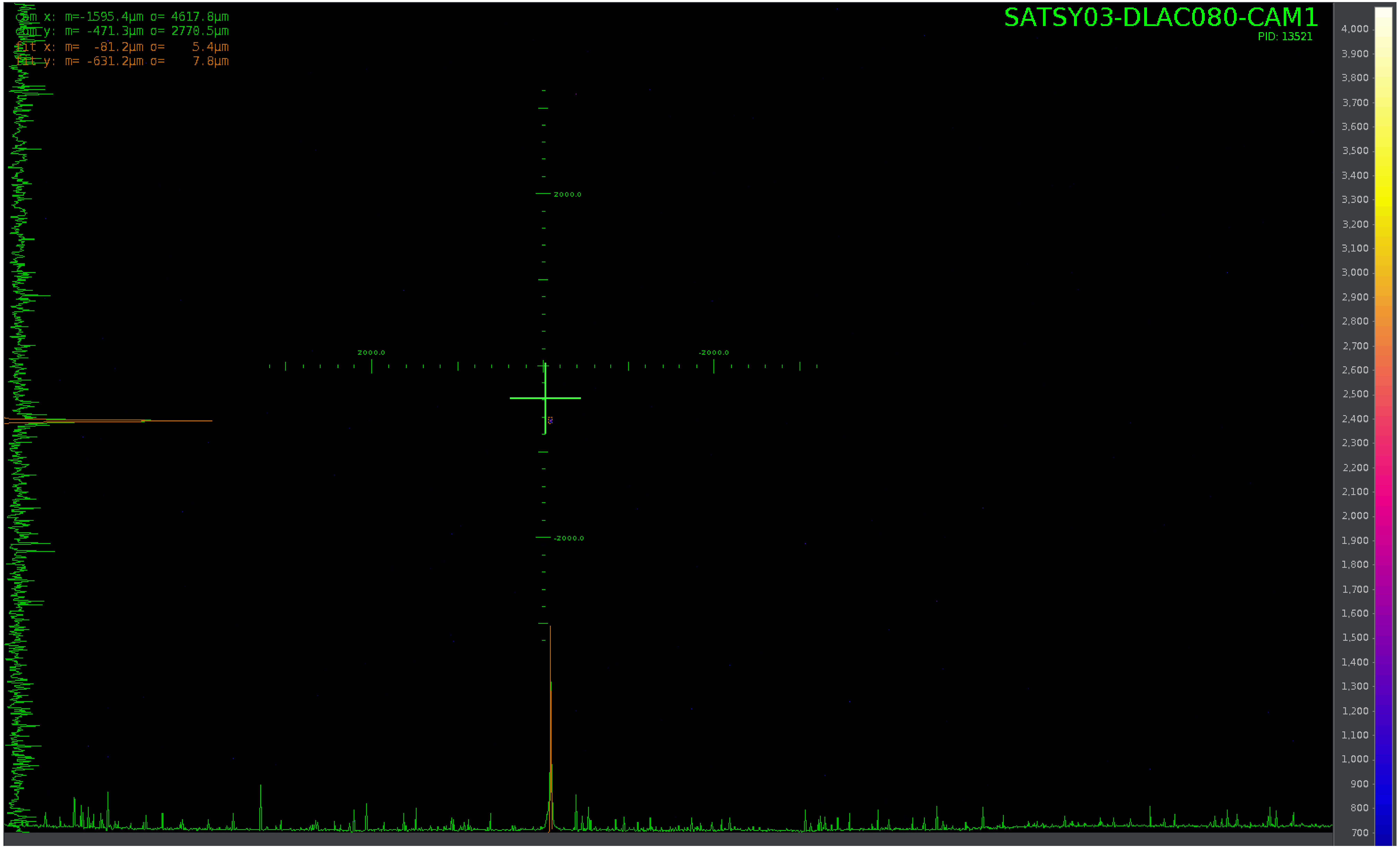


ACHIP Chamber Sample Hexapod

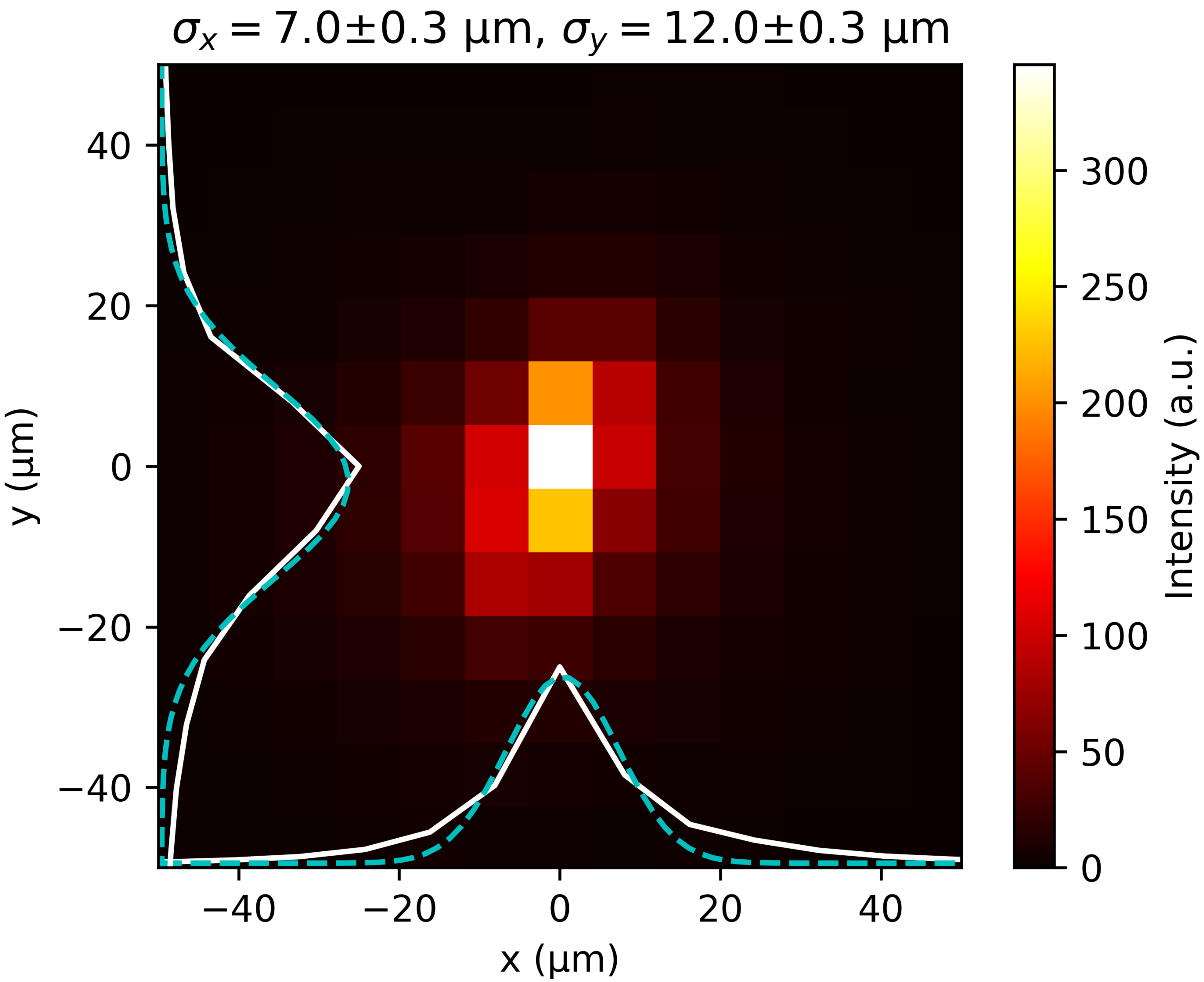


- YAG Screen (1)
- Nano Wire Scanner (2,3)
- Dielectric Grating (4,5)

YAG Screen + CCD Camera (1 pC)



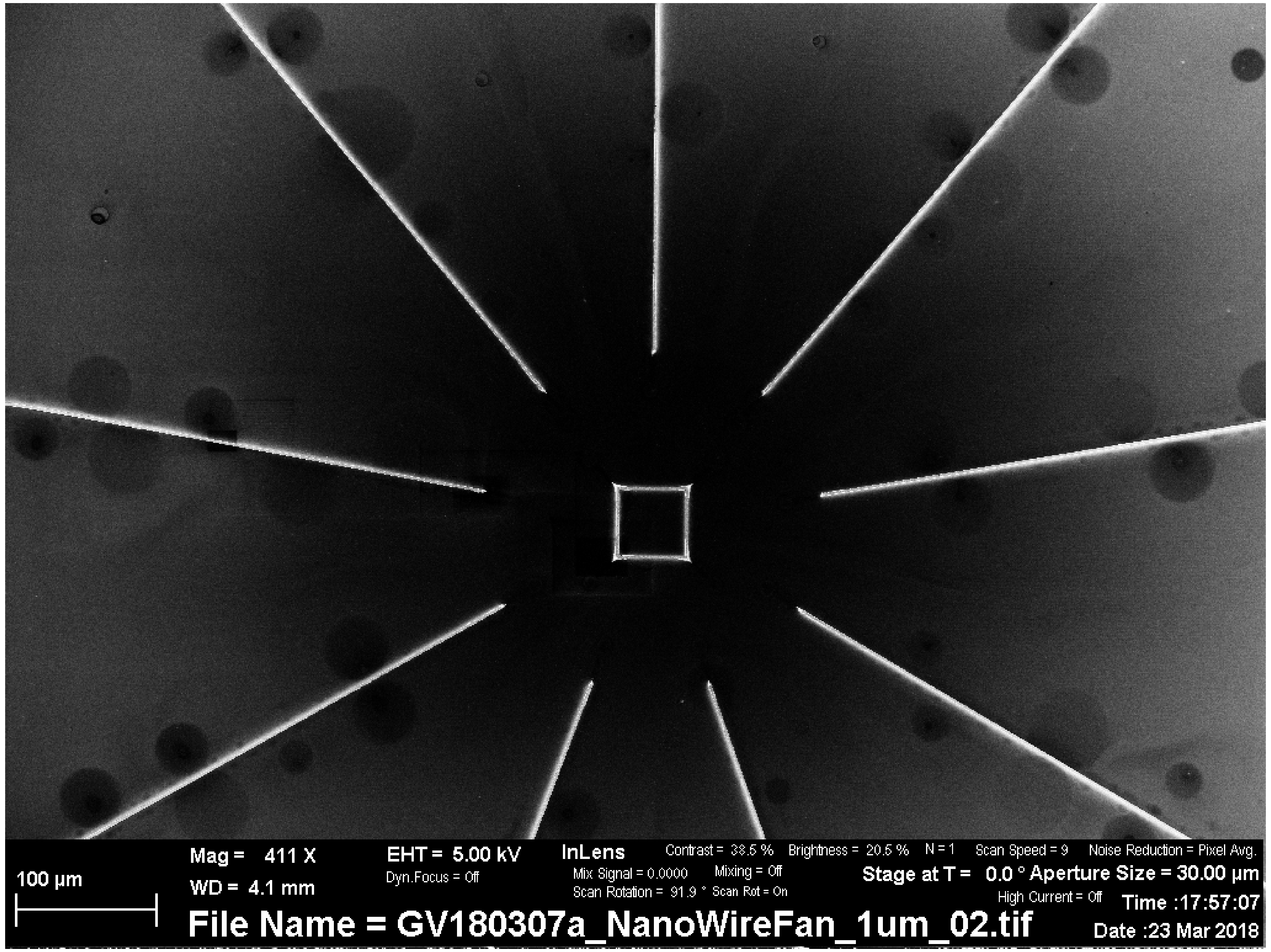
YAG Screen + CCD Camera (1 pC)

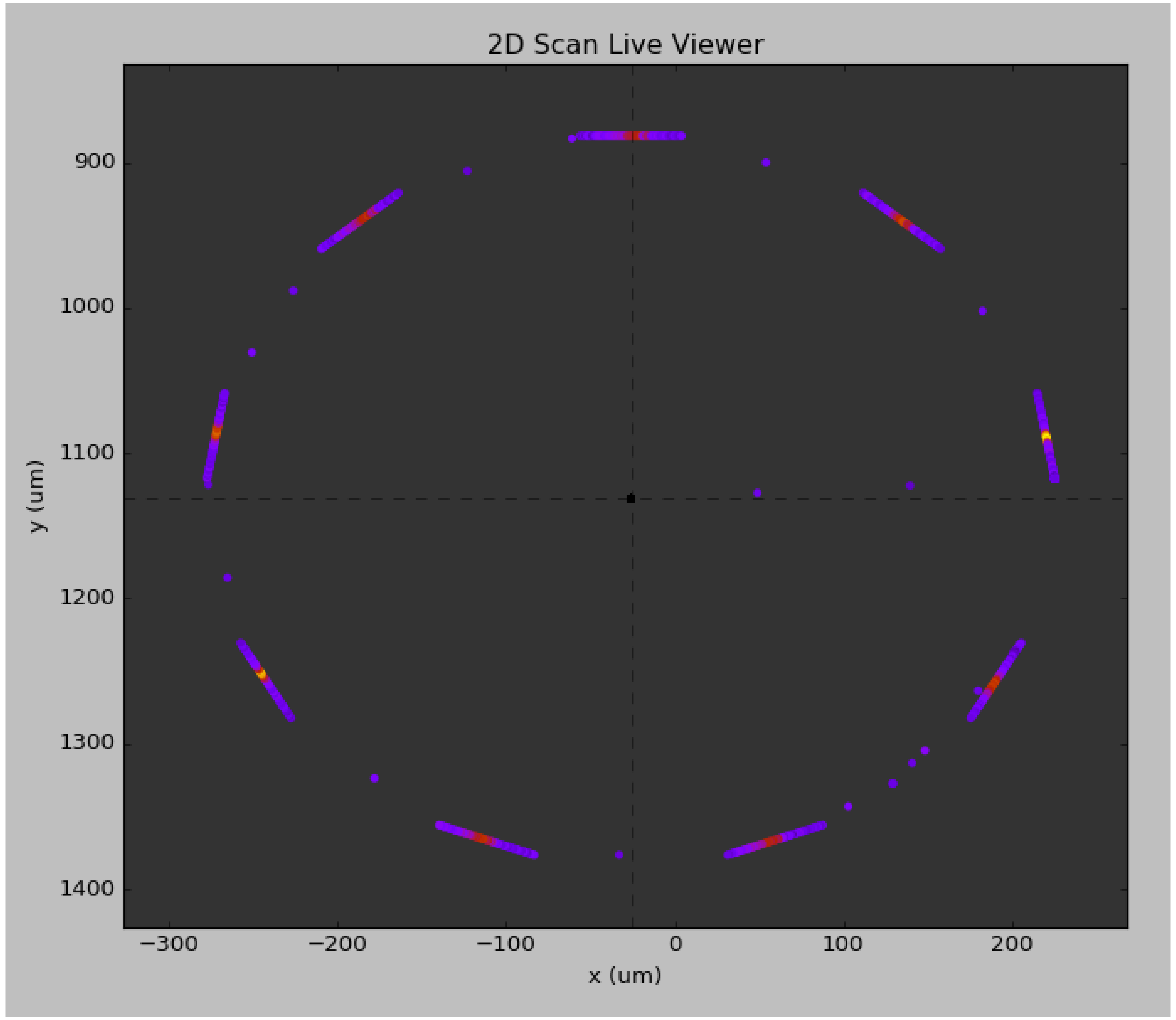


Pixel Size = 8 um
Resolution Limit reached

→ High resolution microscope will be installed. (Sigmakoki)

Wire Scan Tomography



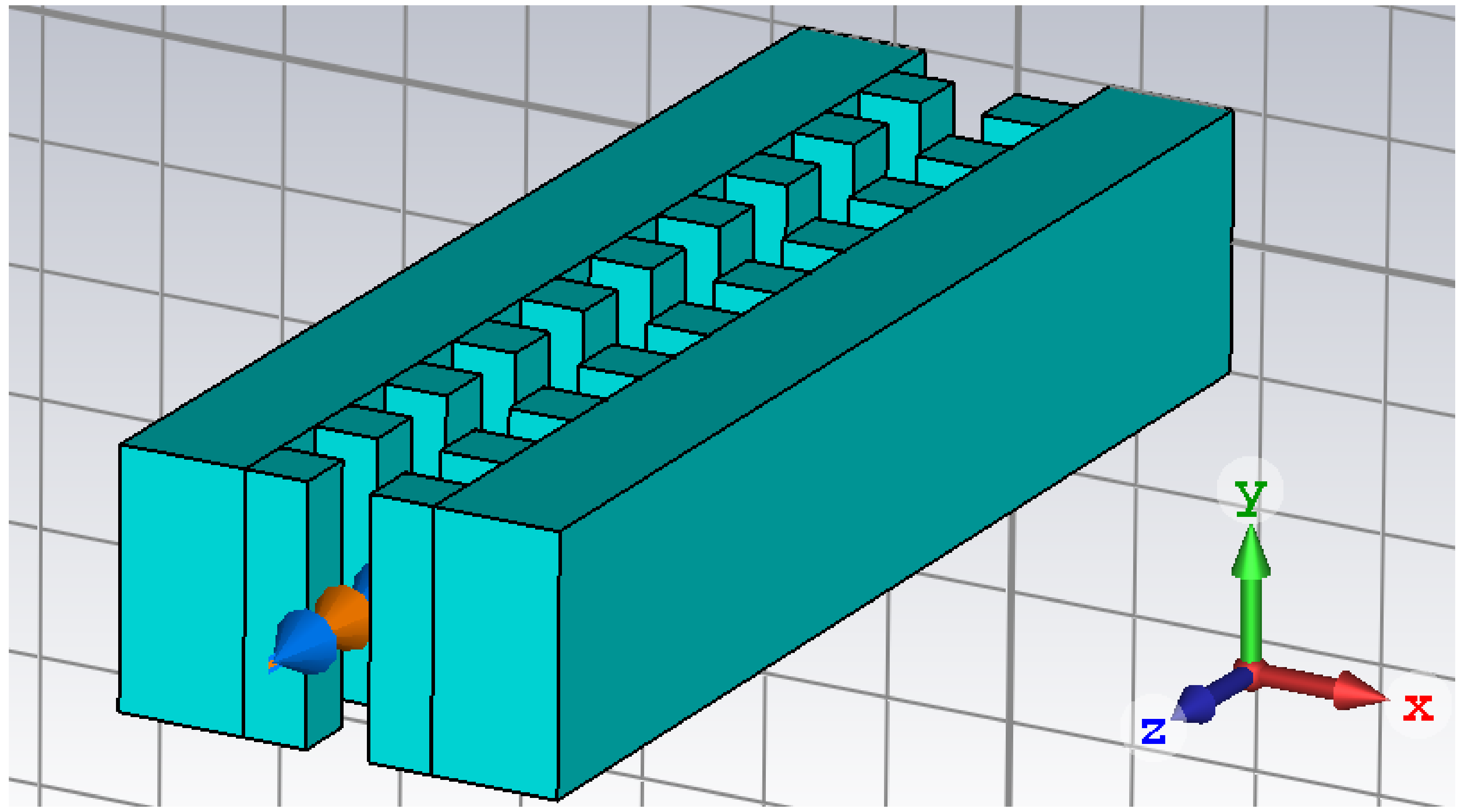


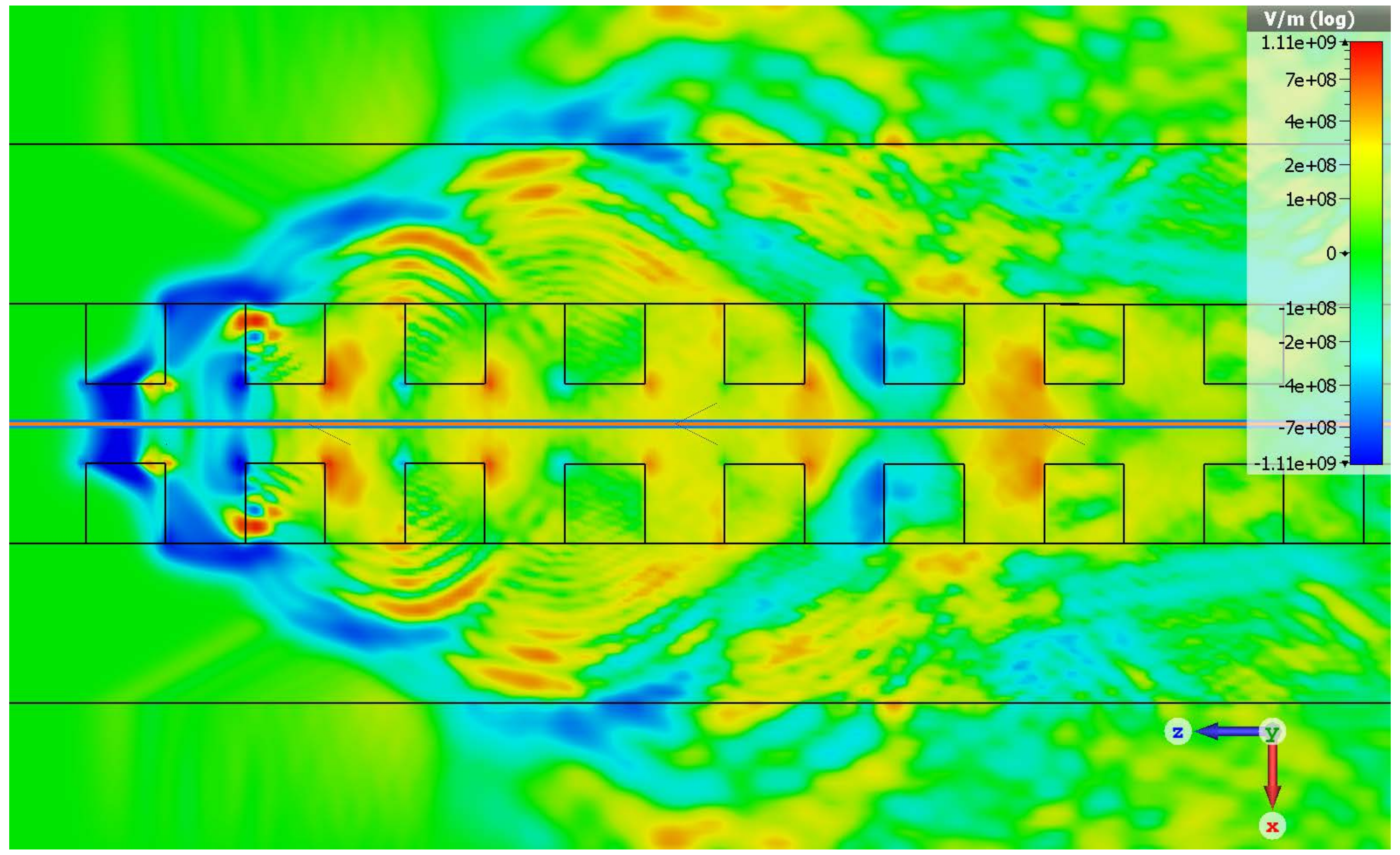
1 um gold wires on SiN membrane (e-beam lithography at PSI, LMN)

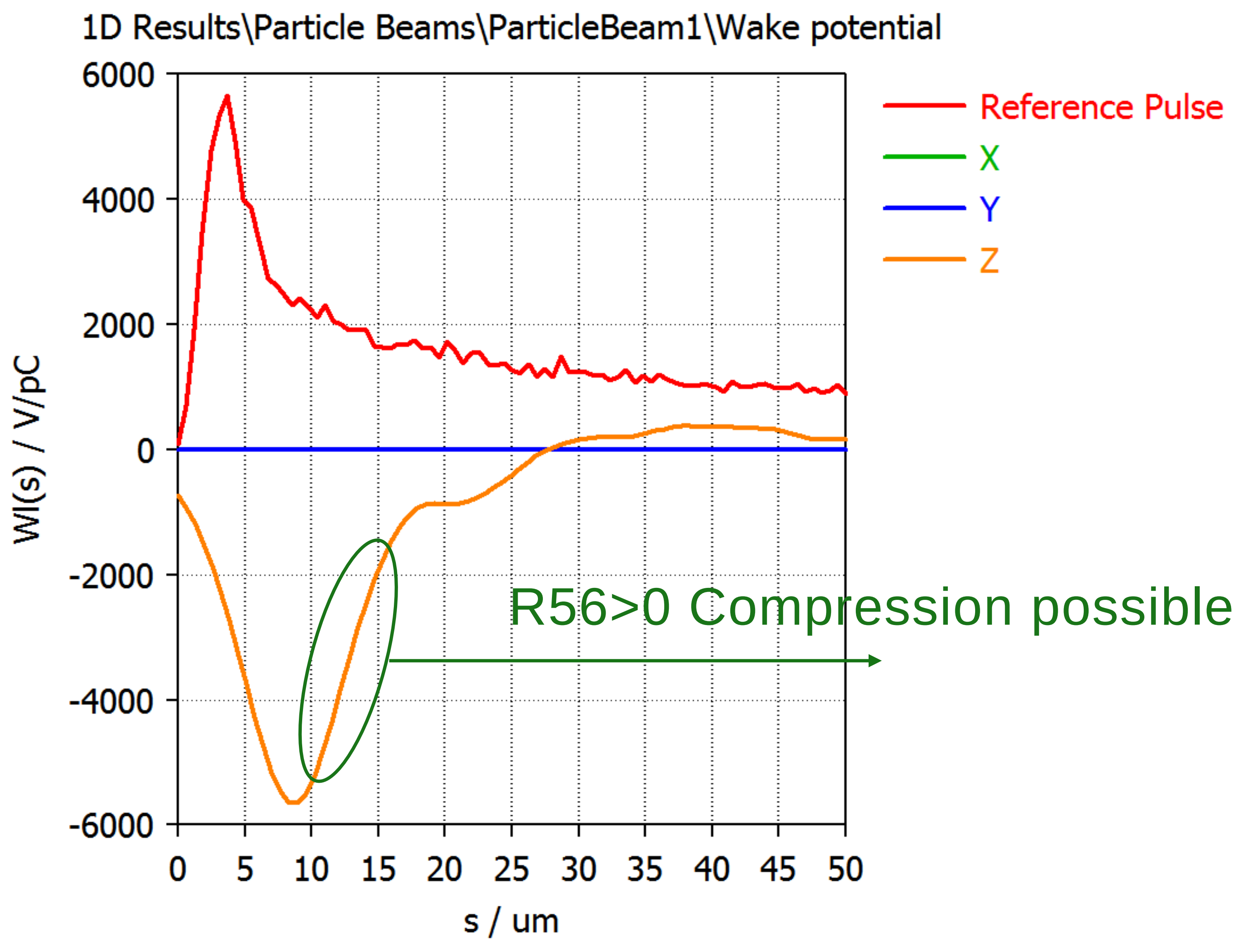
Move wires with Hexapod through Beam

Beam loss monitor

Dielectric Wake Field Structures





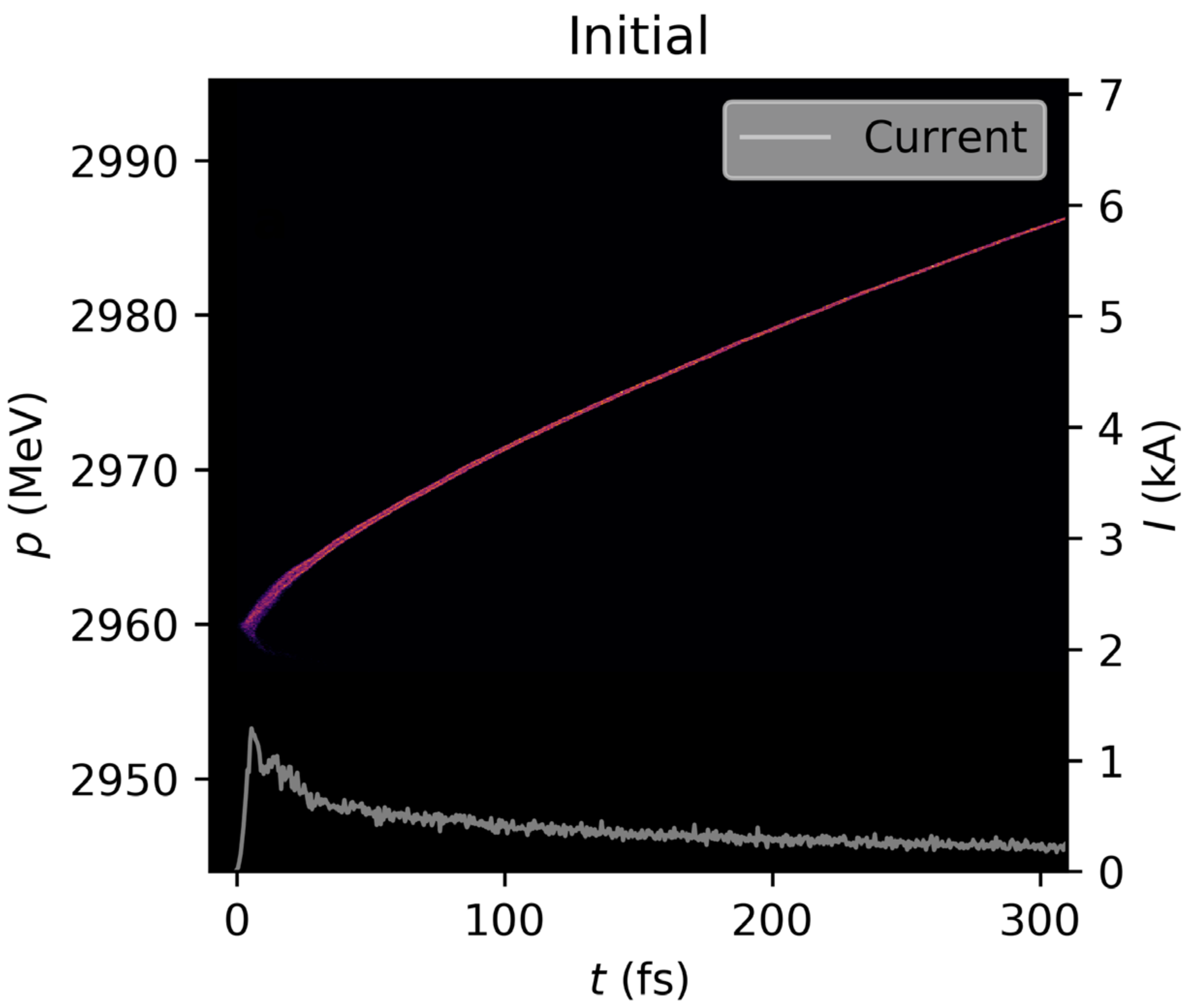


Structure:
Double Grating
Periodicity = 50 μm
Length = 500 μm

Excite fields in the structure with the self-field of the bunch
→ Wake Field Response

Integrated Wake Potential

Dielectric Wake Field + Compression

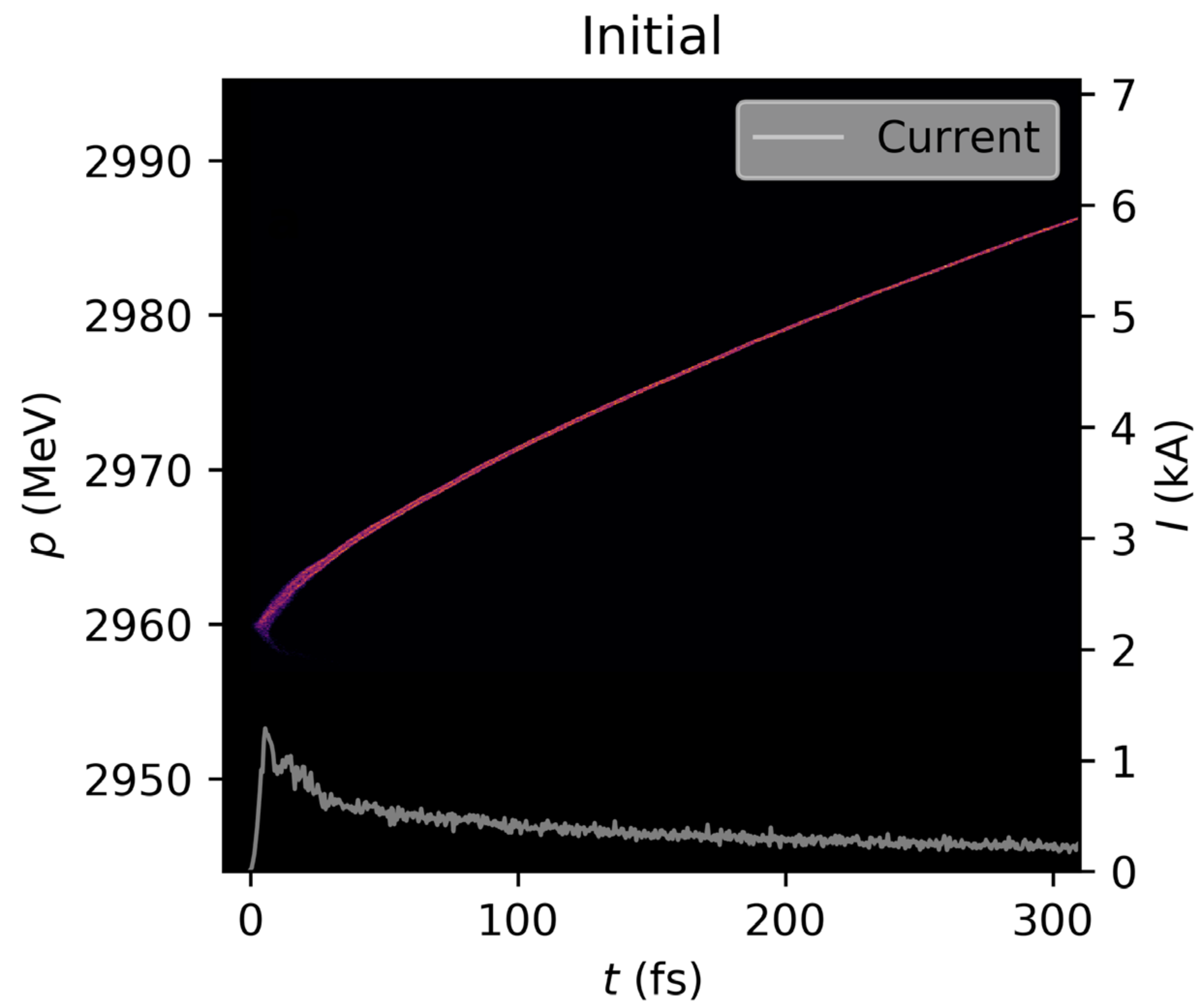


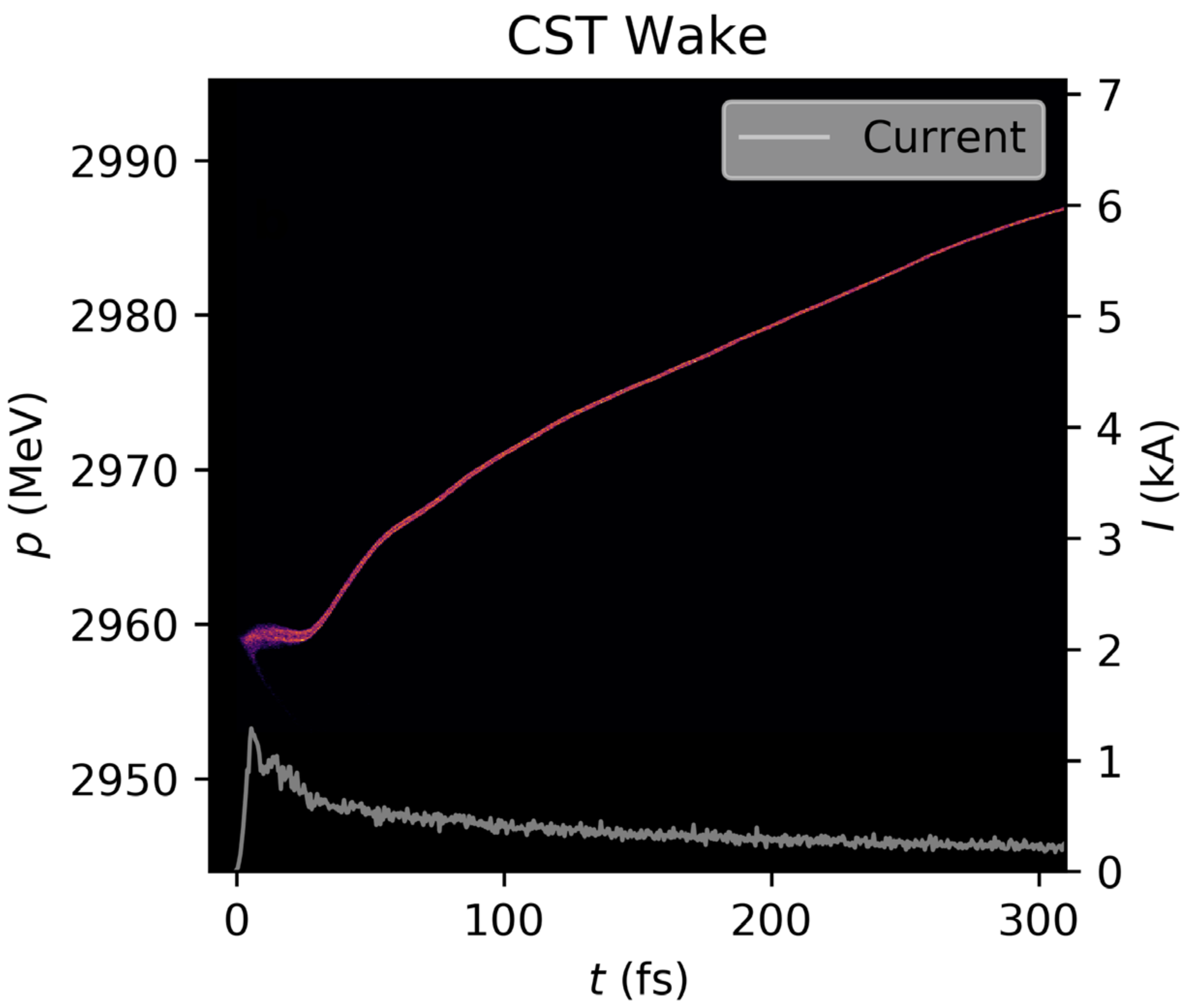
$Q = 200\ \text{pC}$

Non – Linear Compression

- Linac phase
- Linearizer amplitude
- Compression

Dielectric Wake Field + Compression





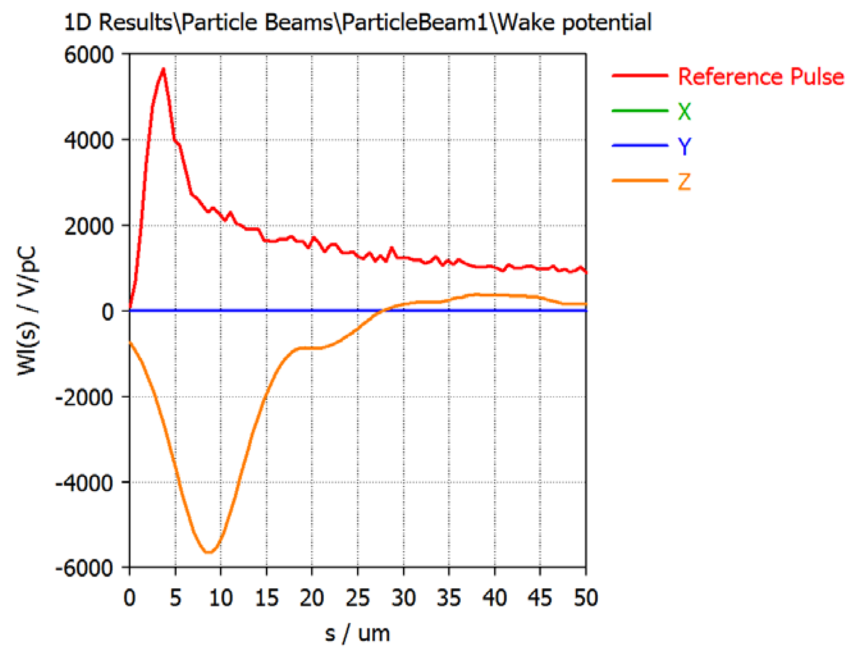
$Q = 200\ \mathrm{pC}$

Non – Linear Compression

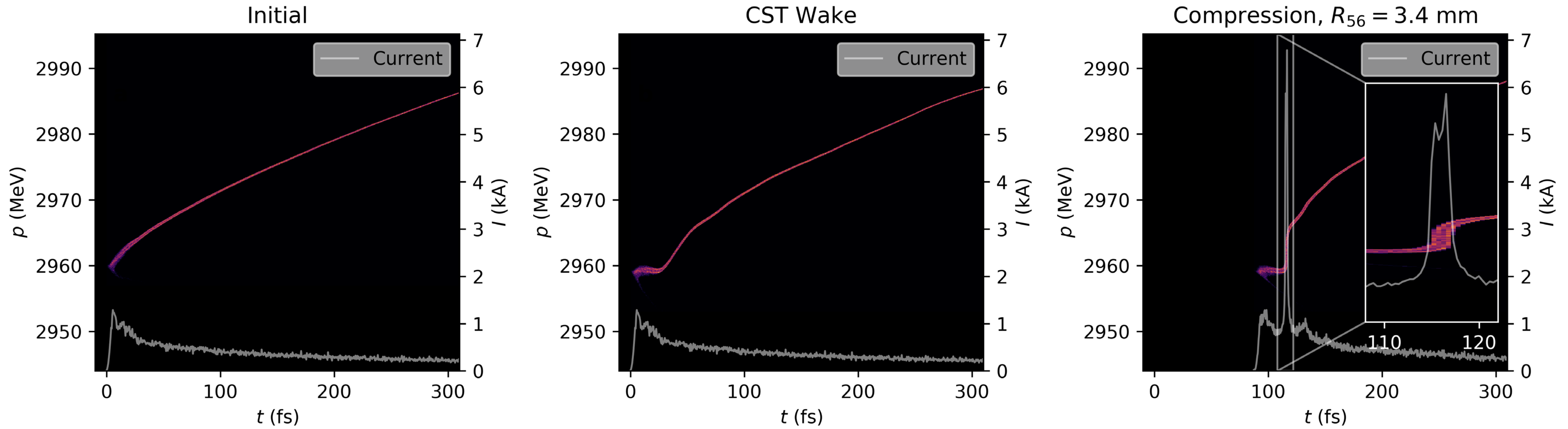
- Linac phase
- Linearizer amplitude
- Compression

CST Wakefield Solver

- Add longitudinal wake



Dielectric Wake Field + Compression



$Q = 200$ pC

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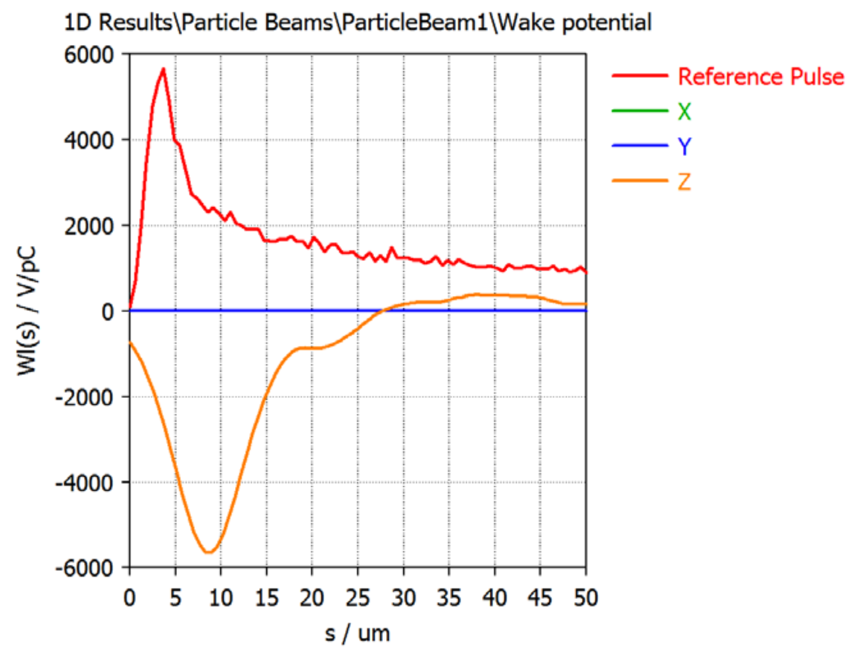
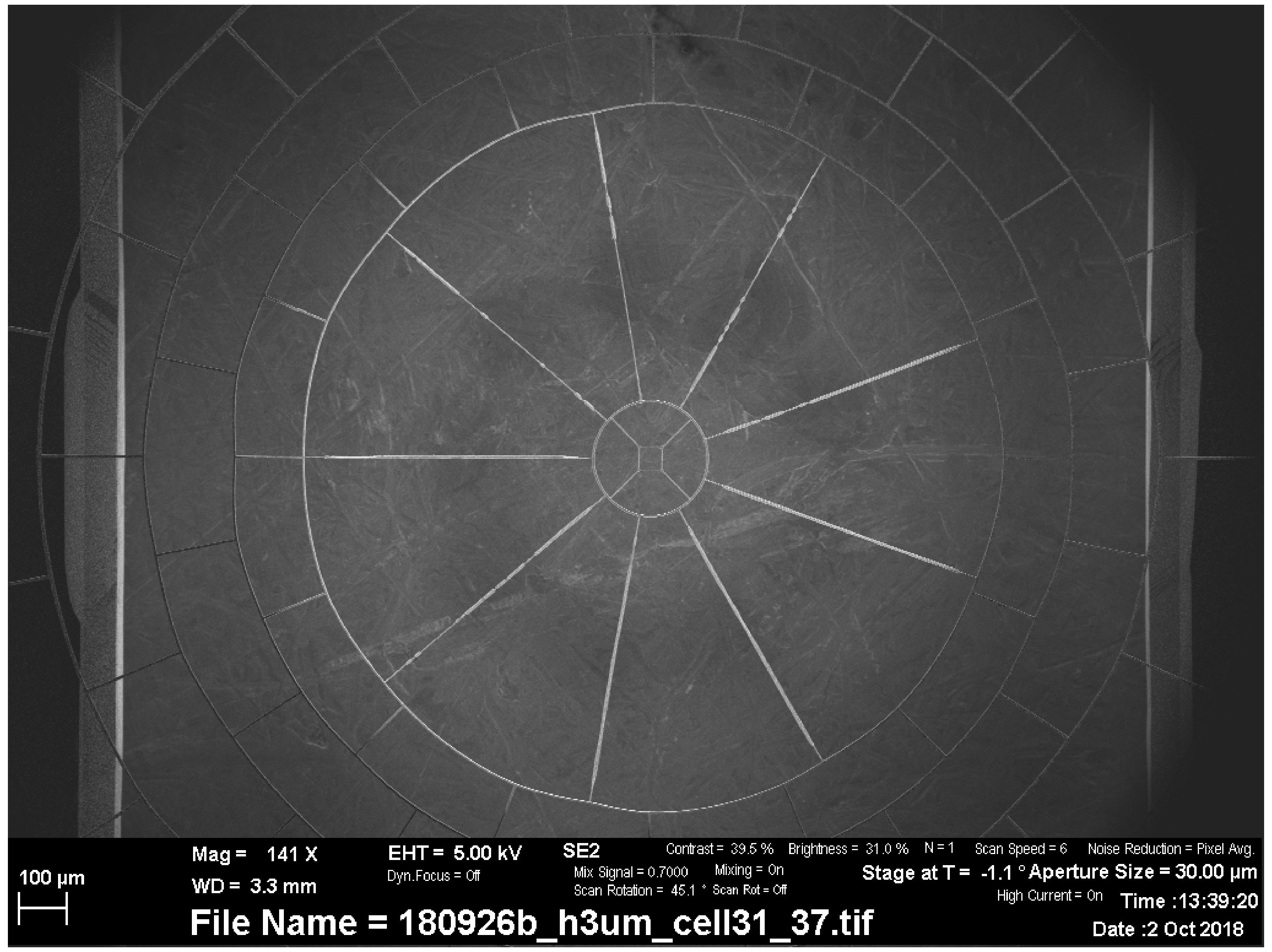


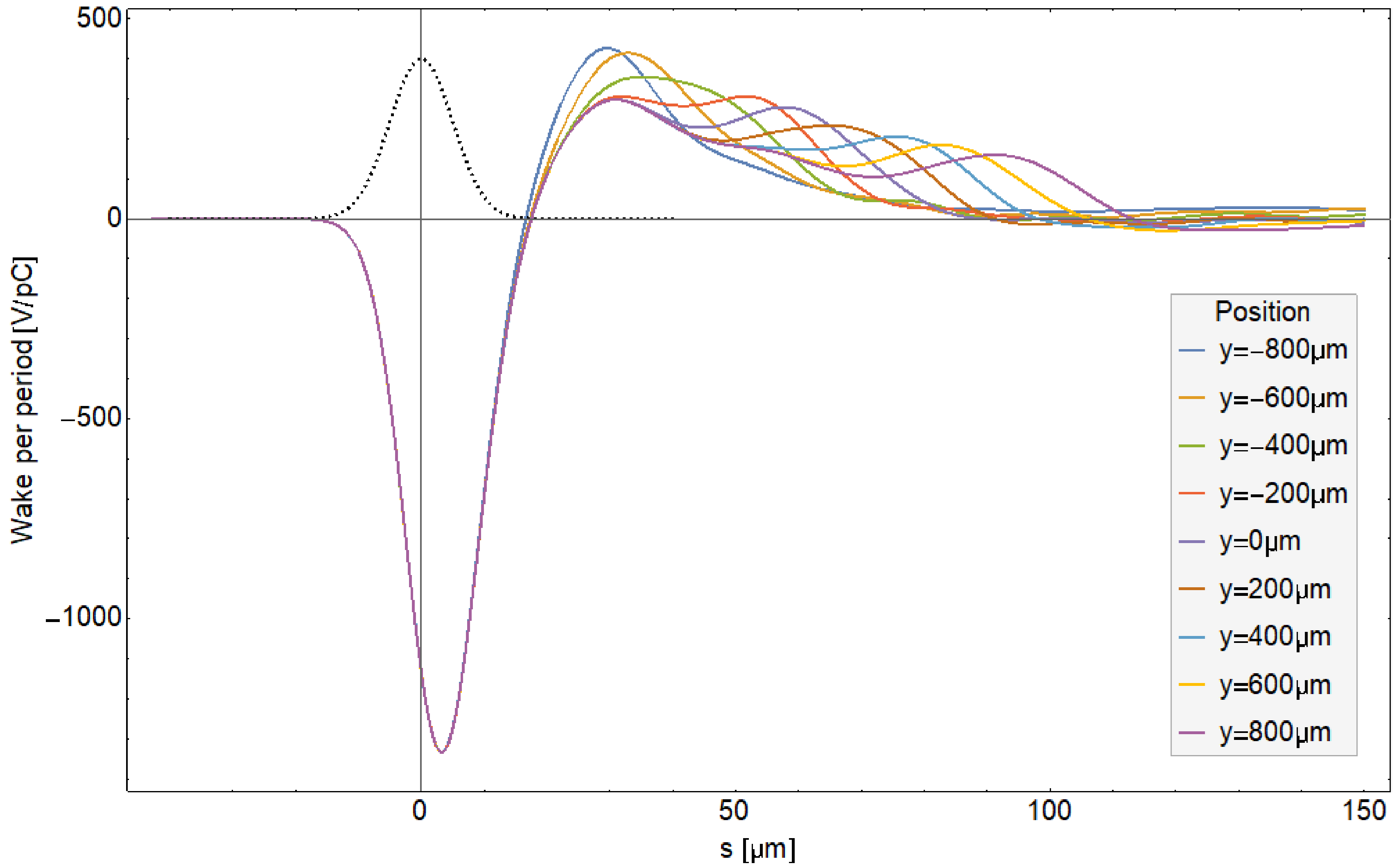
- 6-7 kA peak current
- ~1 fs rms spike length

Outlook



- Sub-Micron Beam Tomography with free-standing "spider-web"
- 4D phase-space tomography
  → Emittance measurement

- Tunable wake structure
  (Design, Fabrication Femtoprint, Experiment)
  → Wake Shaping for Athos FEL



Thank you!

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Goran Kotrle
Adrian Kirchner
Willi Kuropka
Csaba Lombosi
Alexander Malyzhenkov
Frank Mayet
Uwe Niedermayer
Gian Luca Orlandi
Eduard Prat
Sven Reiche
Thomas Schietinger
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