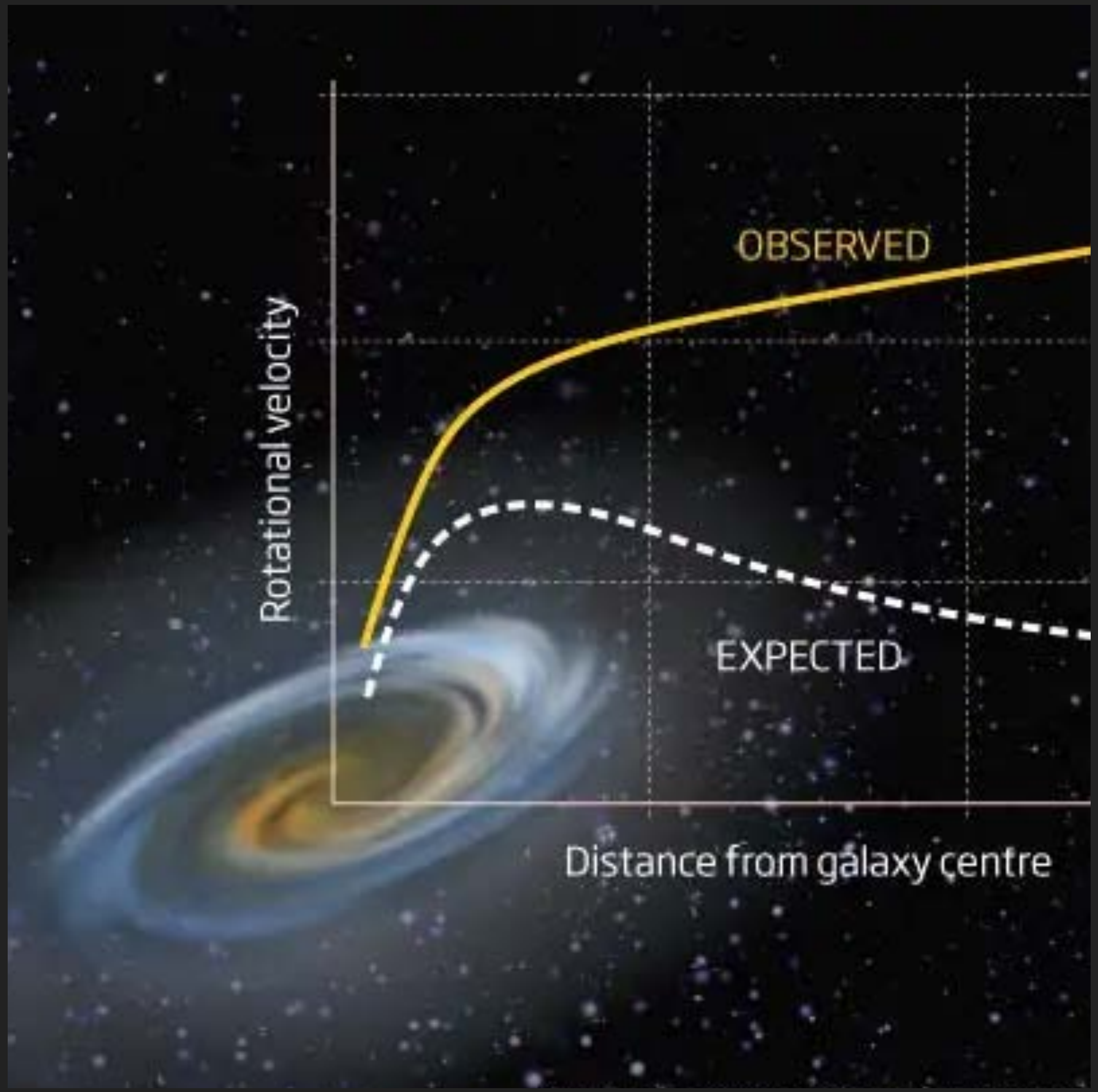
Rasmus Ischebeck

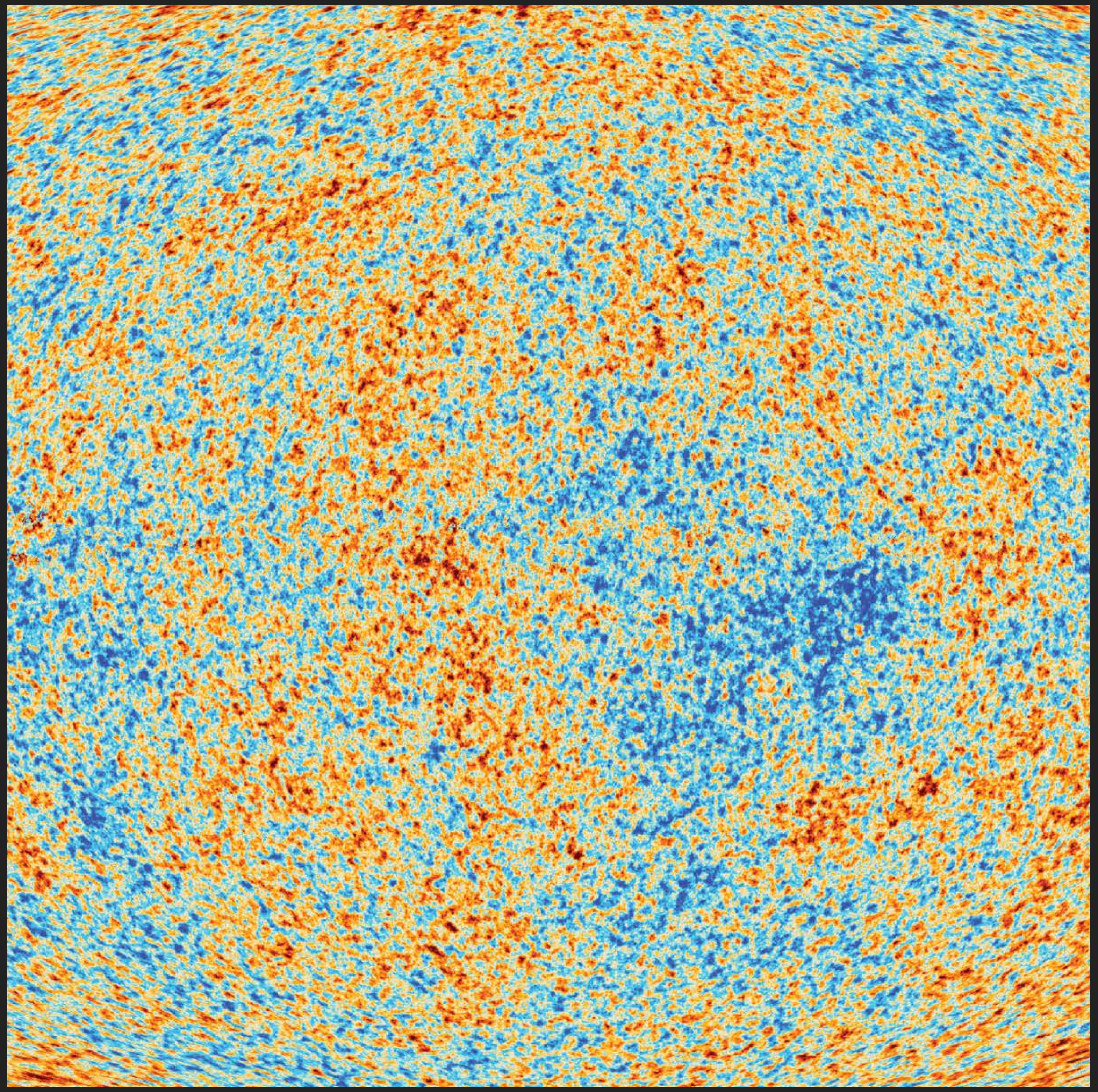
INTEGRATED PHOTONIC CIRCUIT ACCELERATORS FOR DARK MATTER SEARCH

WHAT IS DARK MATTER?

- Dark matter is **invisible**
  it does not interact with electromagnetic forces
- Dark matter has **mass**
  it interacts with gravity
- Dark matter **interacts weakly** with standard model particles and itself
  As weakly as weak nuclear forces or even weaker

DARK MATTER EVIDENCE — IN THE COSMOS



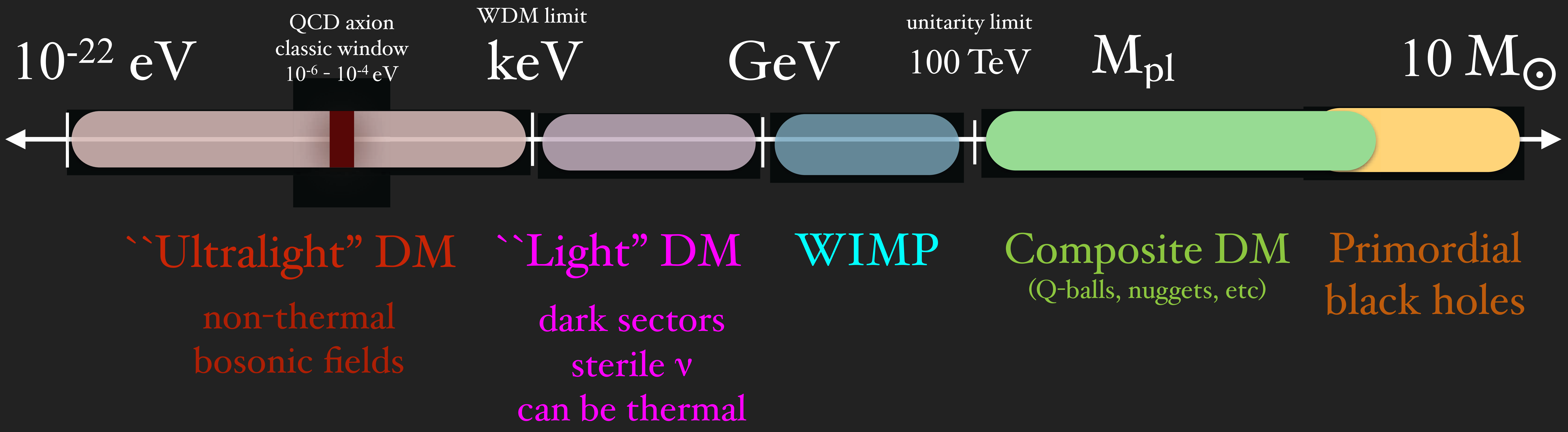


DARK MATTER EVIDENCE — IN THE LABORATORY

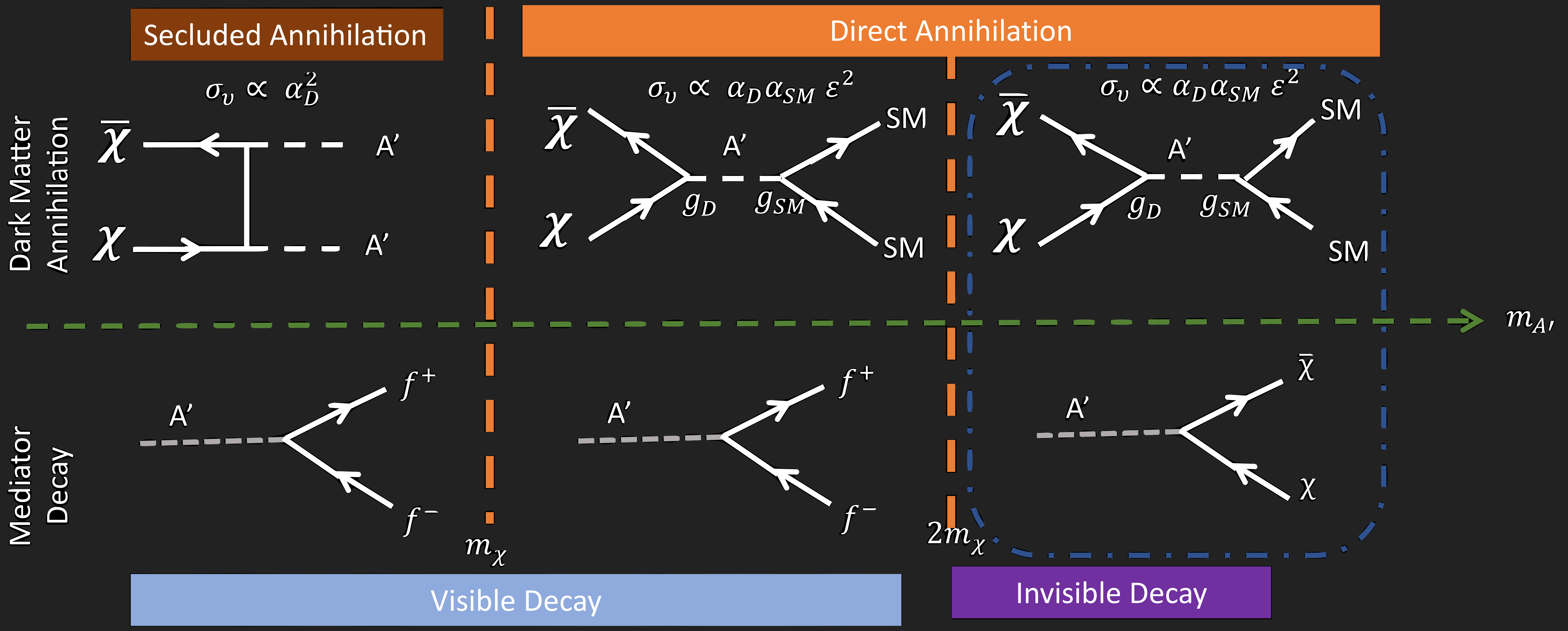
DARK MATTER SPECTRUM

Mass scale of dark matter

(not to scale)



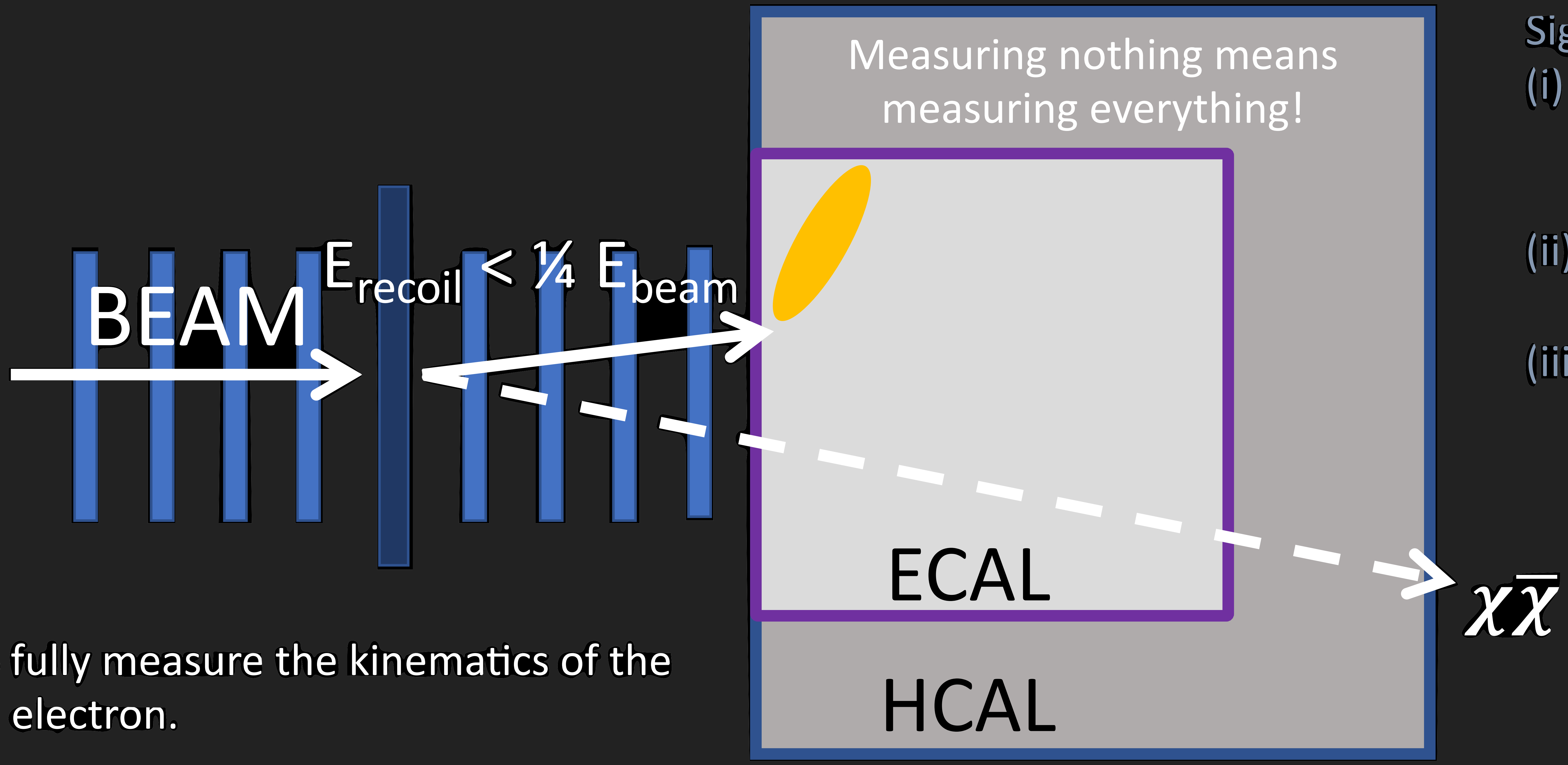
LIGHT DARK MATTER (LDM) PRODUCTION AND DECAY



Resonance, prompt or displaced decay

➔ Missing energy, mass or **momentum**

LIGHT DARK MATTER: INDIRECT DETECTION



Signature:

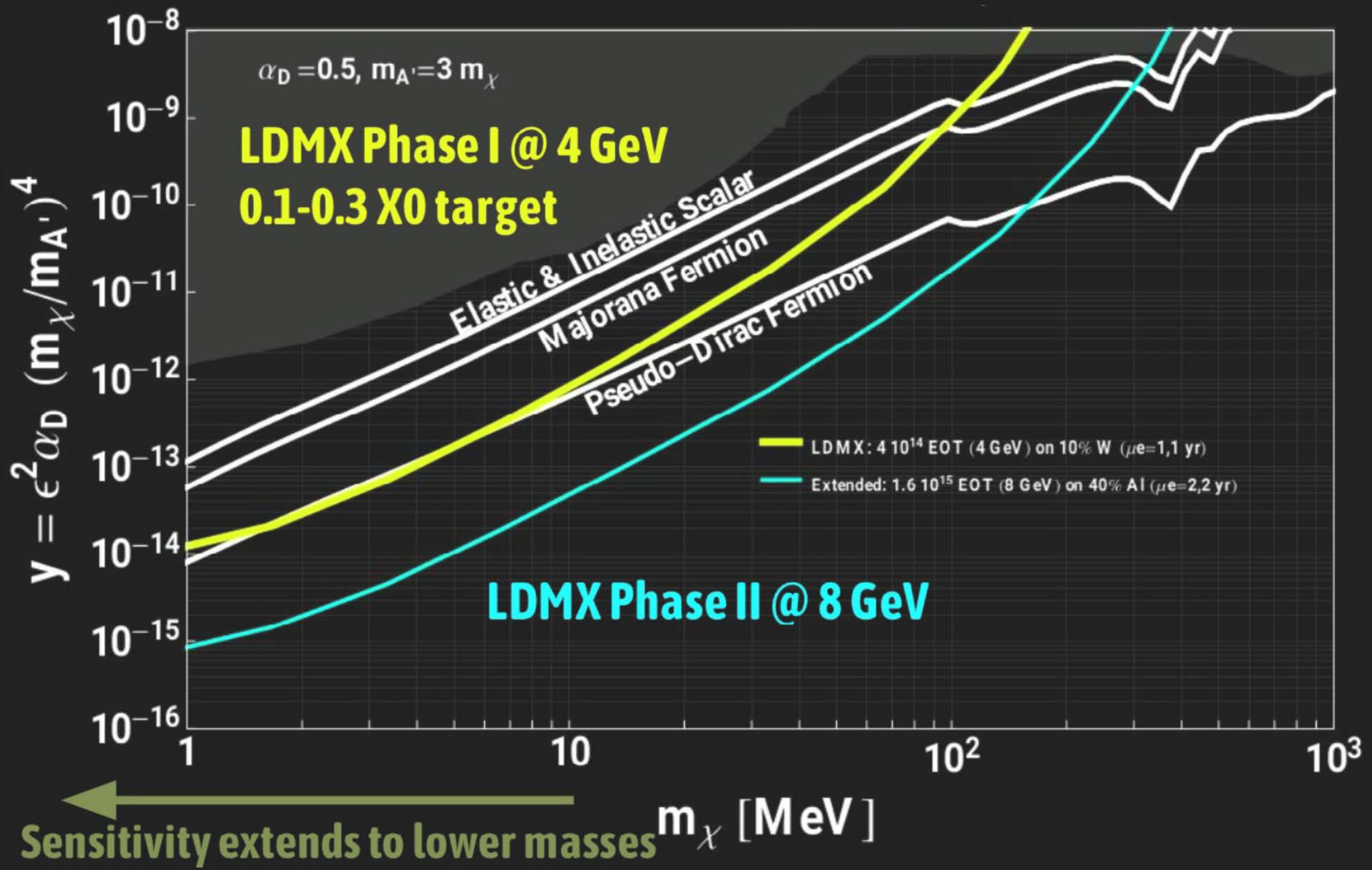
(i) Substantial energy loss by the electron (e.g. recoil with <30% of incident energy),

(ii) Potentially large transverse momentum kick, and

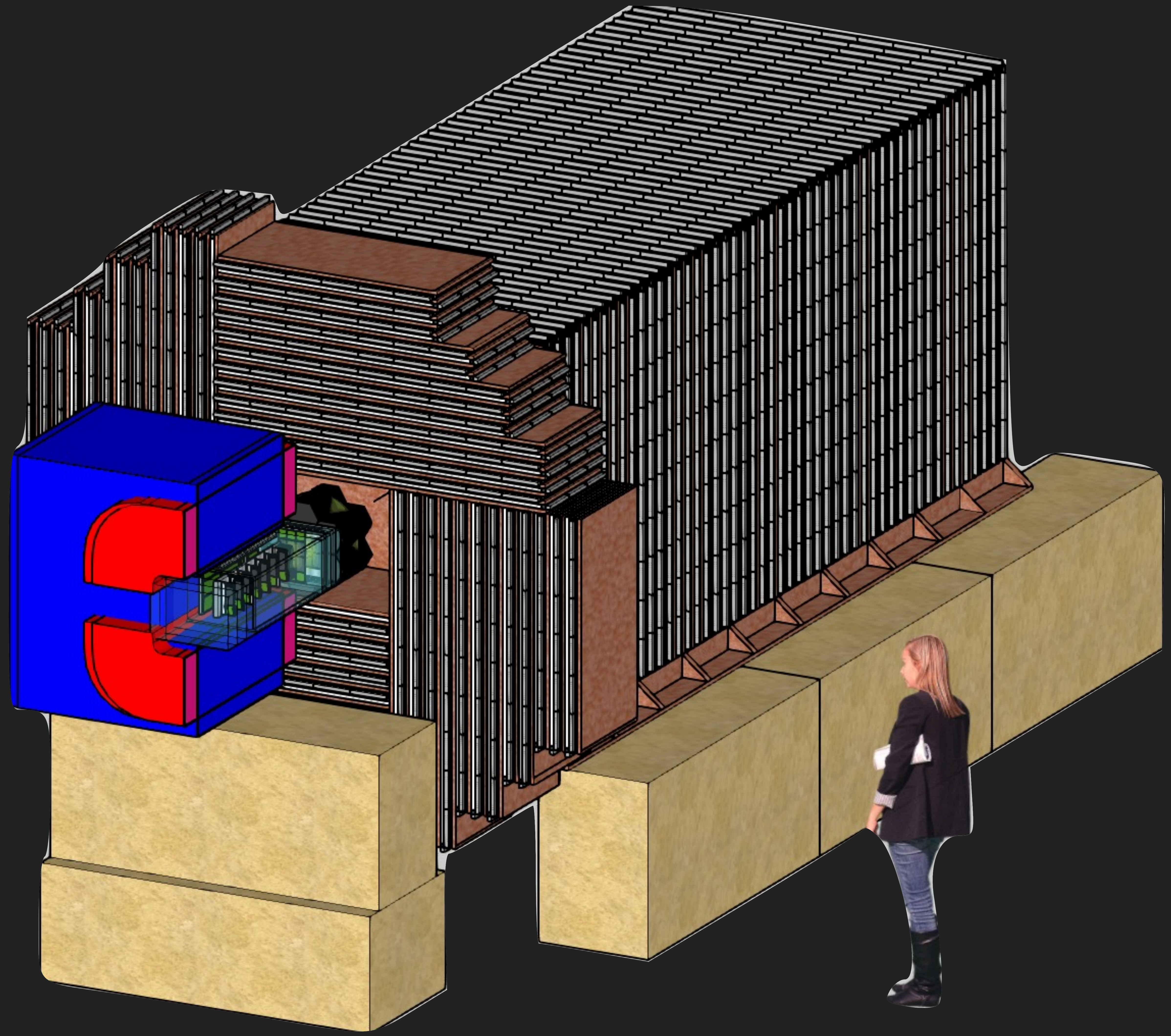
(iii) absence of any additional visible final-state particles that could carry away energy lost by the electron.

Goal: to fully measure the kinematics of the recoiling electron.

LDMX PHYSICS REACH



LDMX DETECTOR

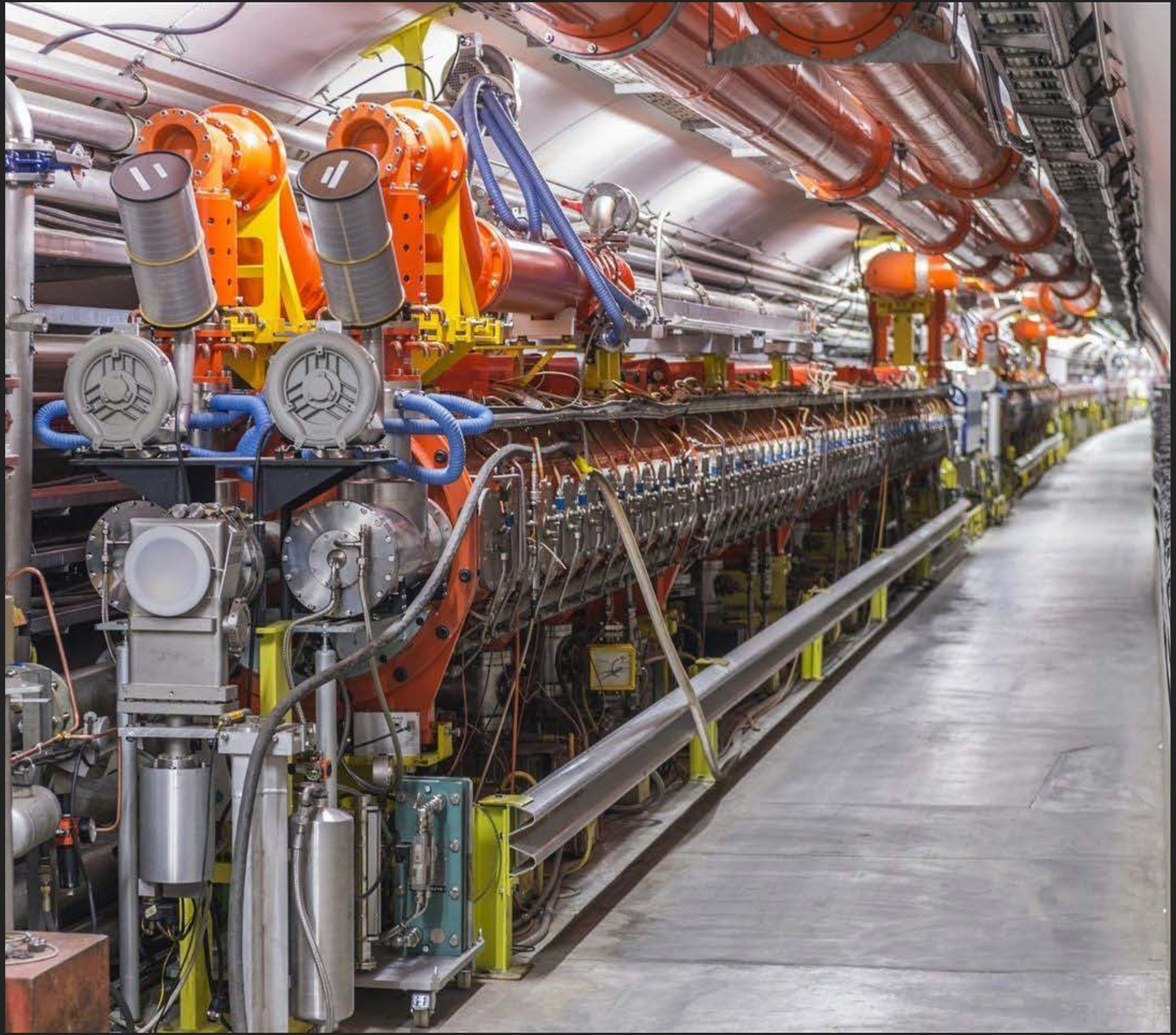


REQUIREMENTS ON THE ACCELERATOR

- Single electrons ⇒ clean initial state
- Electron energy: 4…20 GeV
- Well-defined energy and momentum:
  - Energy uncertainty: $\leq 10^{-3}$
  - Low transverse emittance
- High repetition rate

OPTIONS TO GENERATE THE ELECTRON BEAM

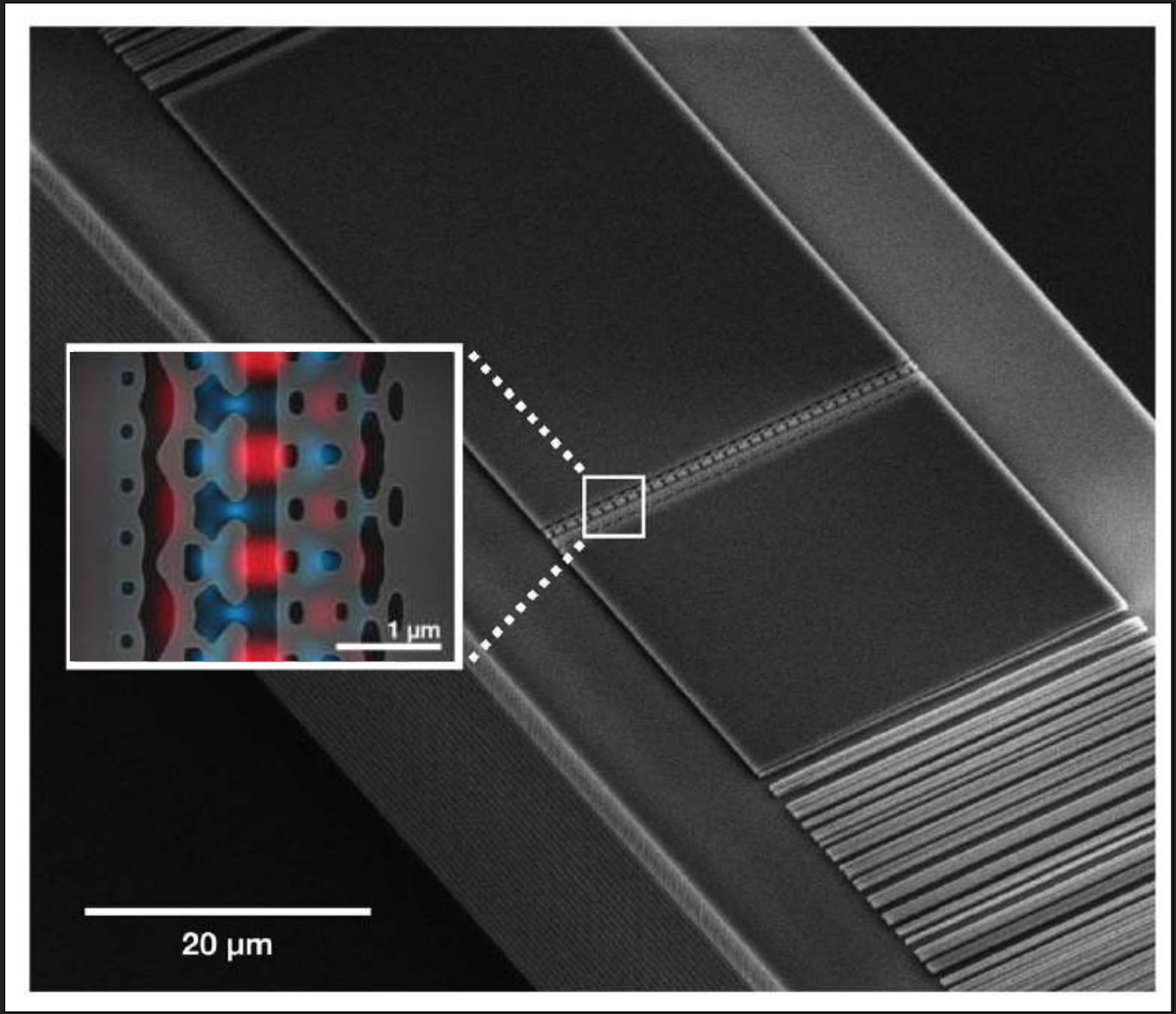
Extraction from a storage ring



Superconducting accelerator

ALTERNATIVE OPTION: LASER-DRIVEN ACCELERATION?

- Direct laser acceleration in integrated photonic circuits
- also known as:
  - dielectric laser acceleration
  - accelerator-on-a-chip



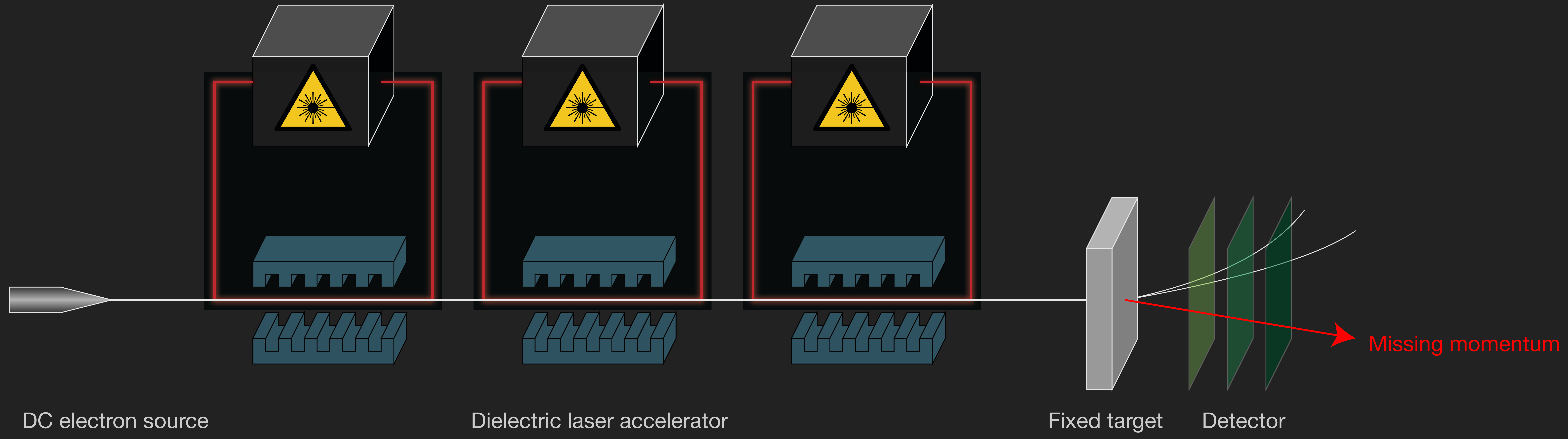
Sapra et al., Science, 367, 79-83 (2020)

DIRECT LASER ACCELERATION IN INTEGRATED PHOTONIC CIRCUITS

- Very low emittance beam
- High accelerating gradient ~ GV/m
- Staging of multiple structures
- Integrated focusing and beam control

- To be demonstrated:
  - Long structures (> 1 mm)
  - Energy efficiency
  - Repetition rate

SINGLE ELECTRON DIELECTRIC LASER ACCELERATOR



PROPOSAL FOR LASER-BASED ACCELERATORS: 63 YEARS AGO

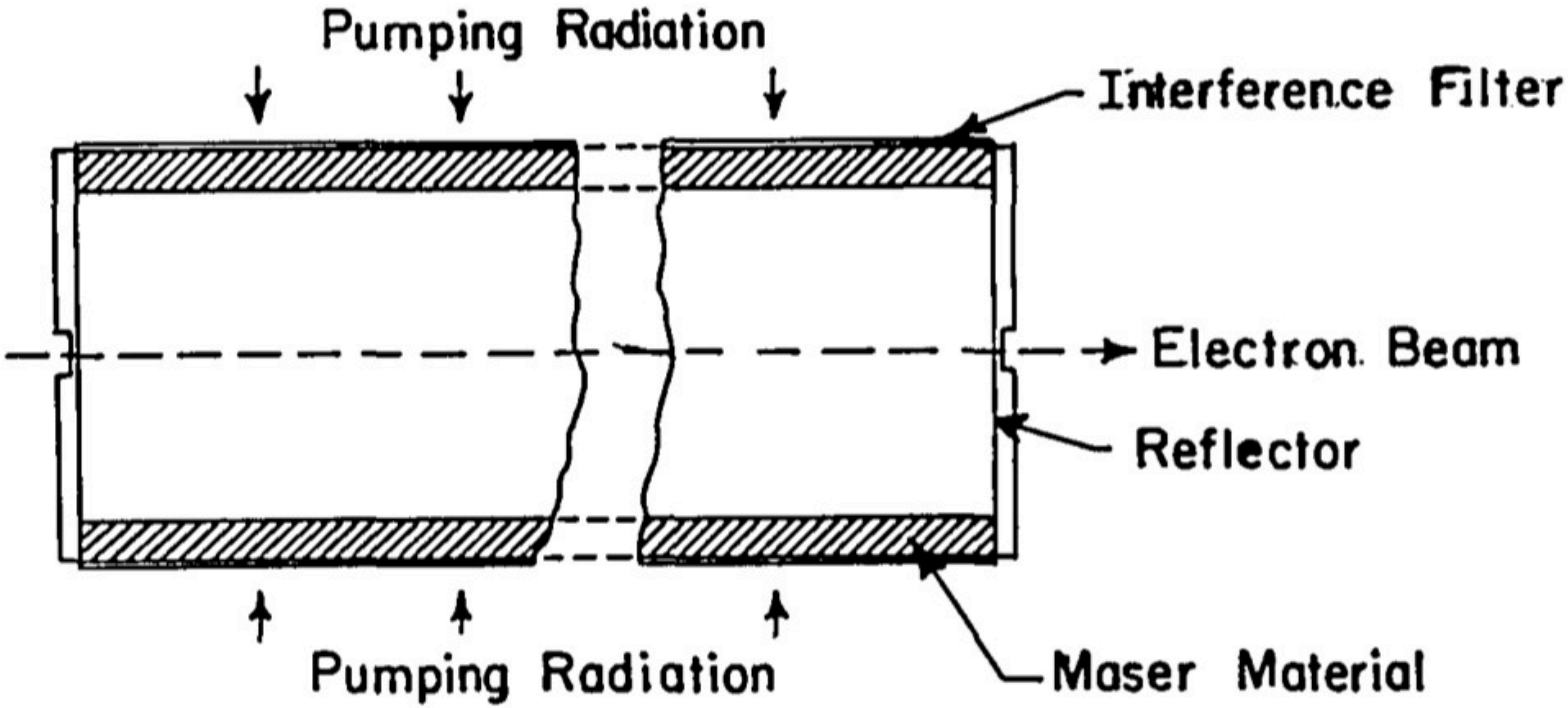
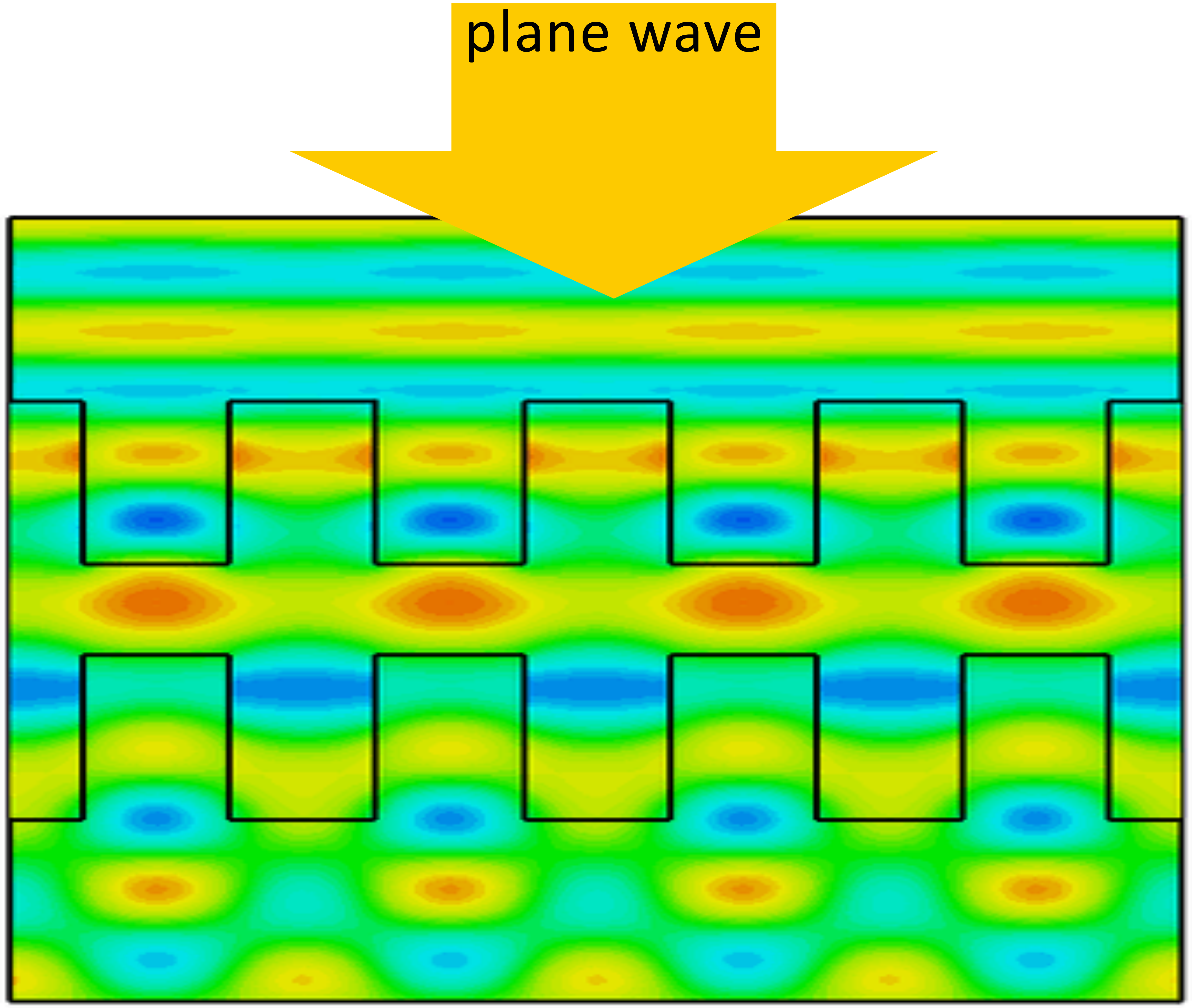


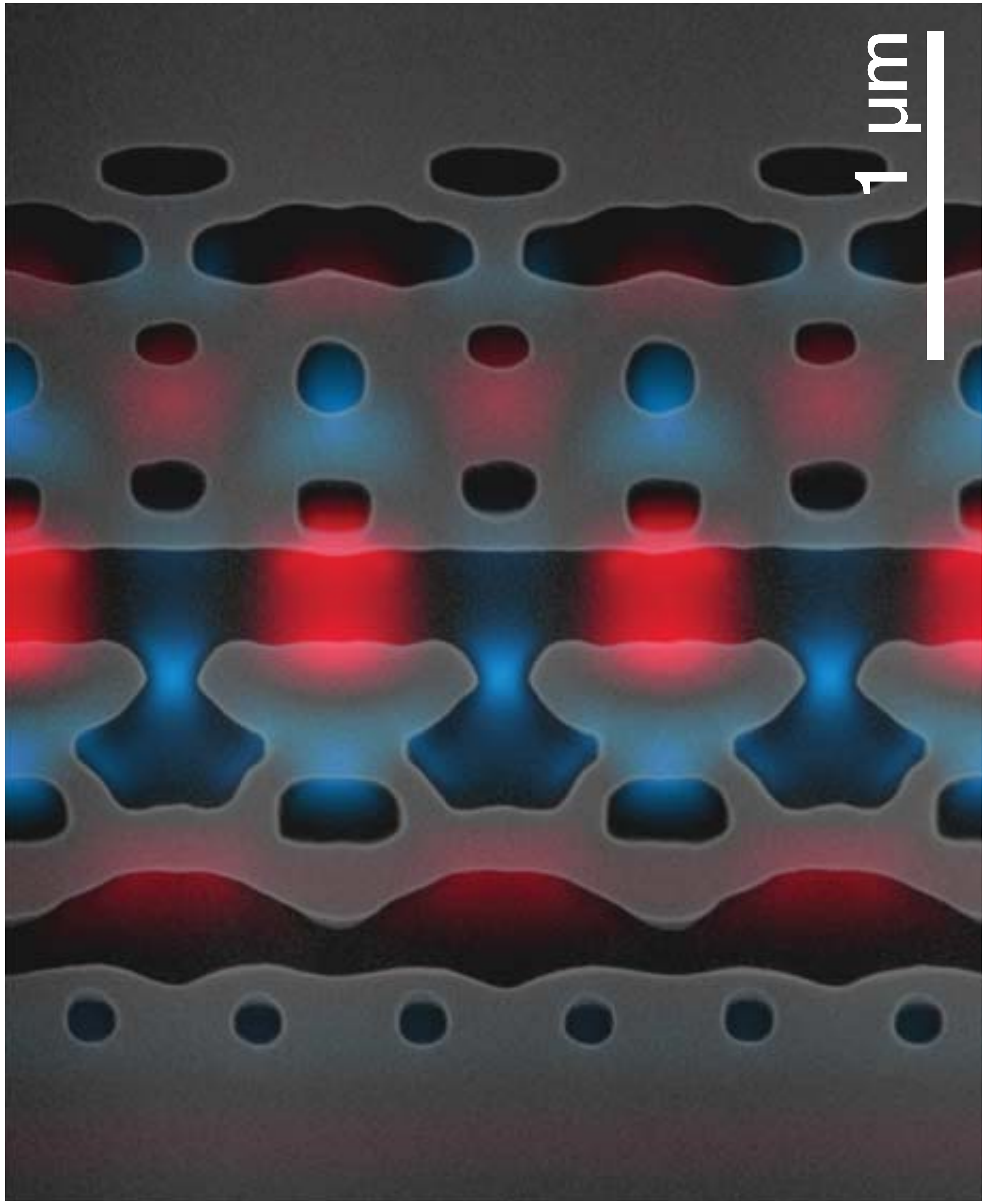
Fig. 1. Schematic diagram of an electron linear accelerator by optical maser.

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

ACCELERATING FIELDS INSIDE DIELECTRIC STRUCTURES



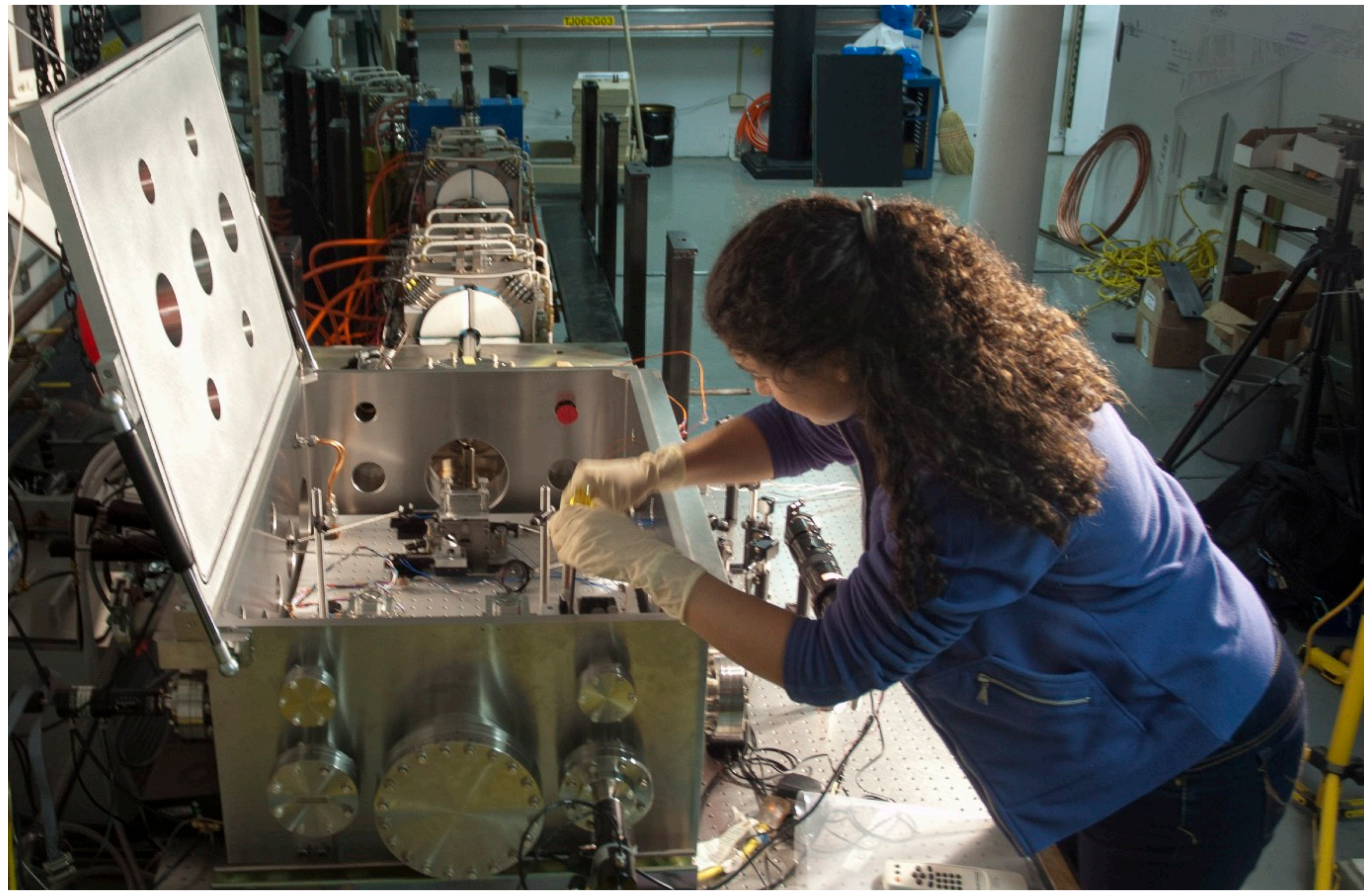
Yelong Wei

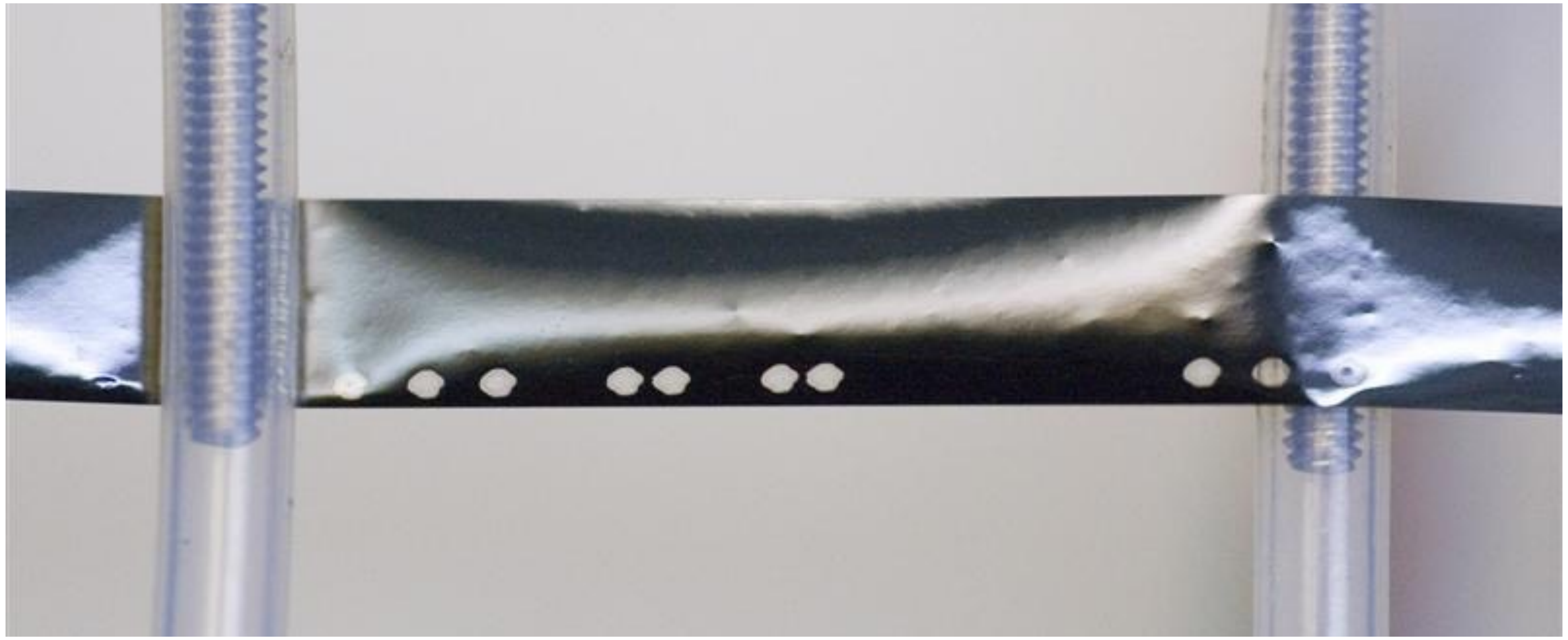


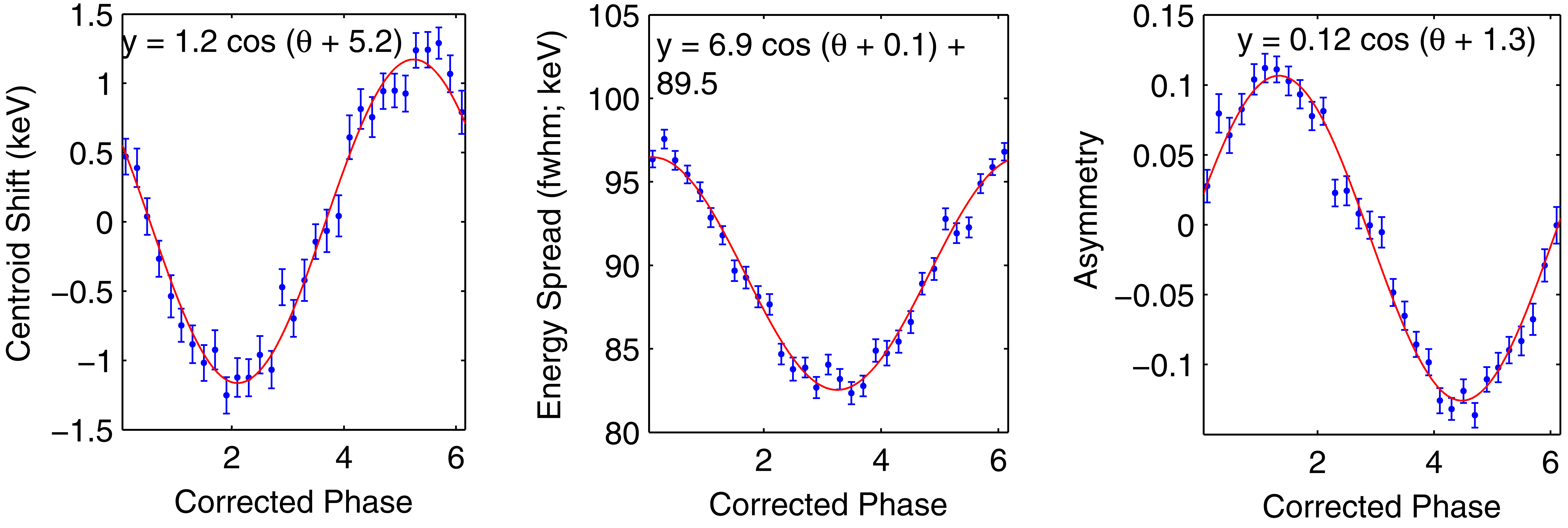
Sapra et al., Science 367, 79–83 (2020)

FABRICATION OF ACCELERATING STRUCTURES

DIELECTRIC LASER ACCELERATION 16 YEARS AGO

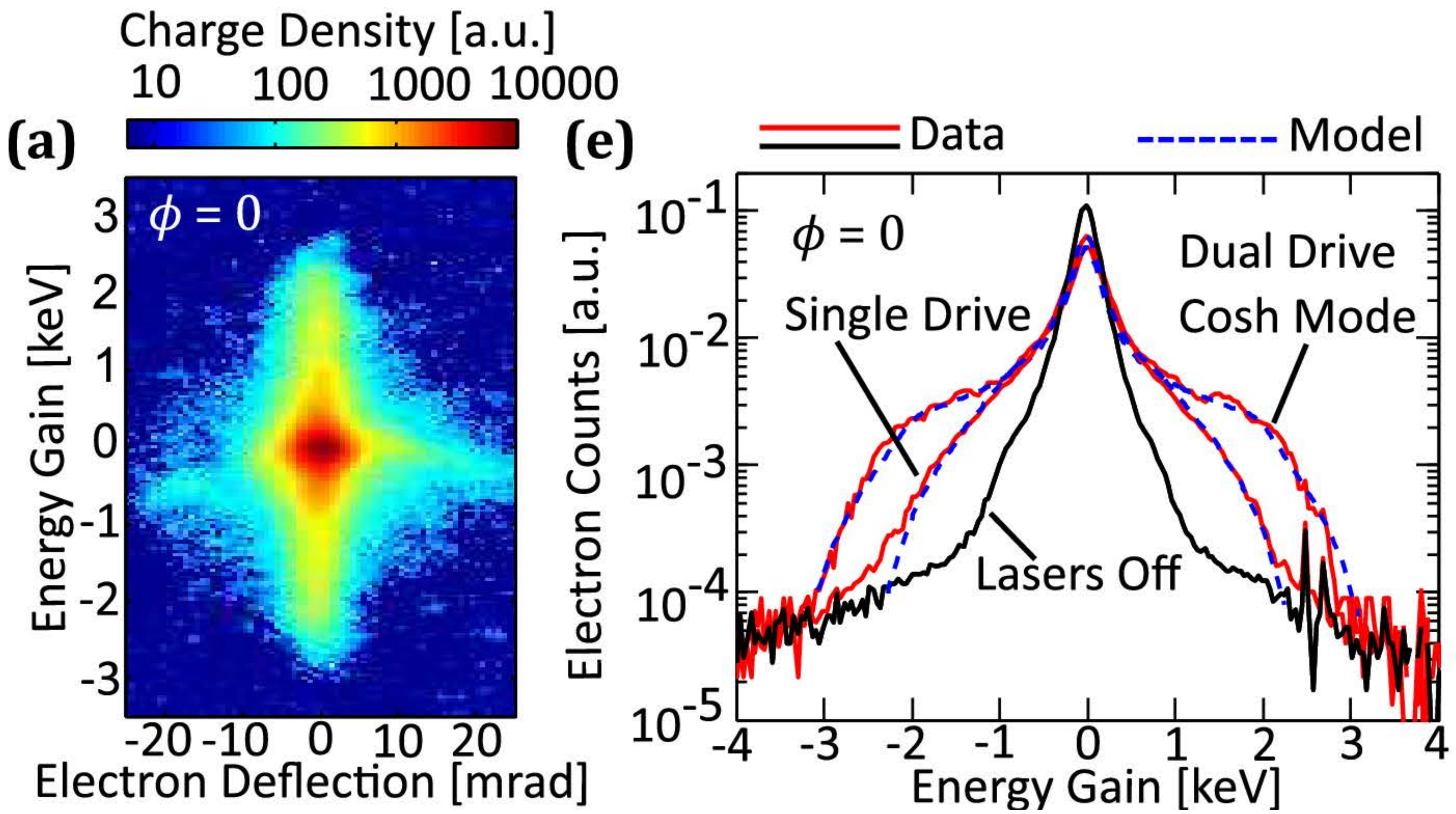




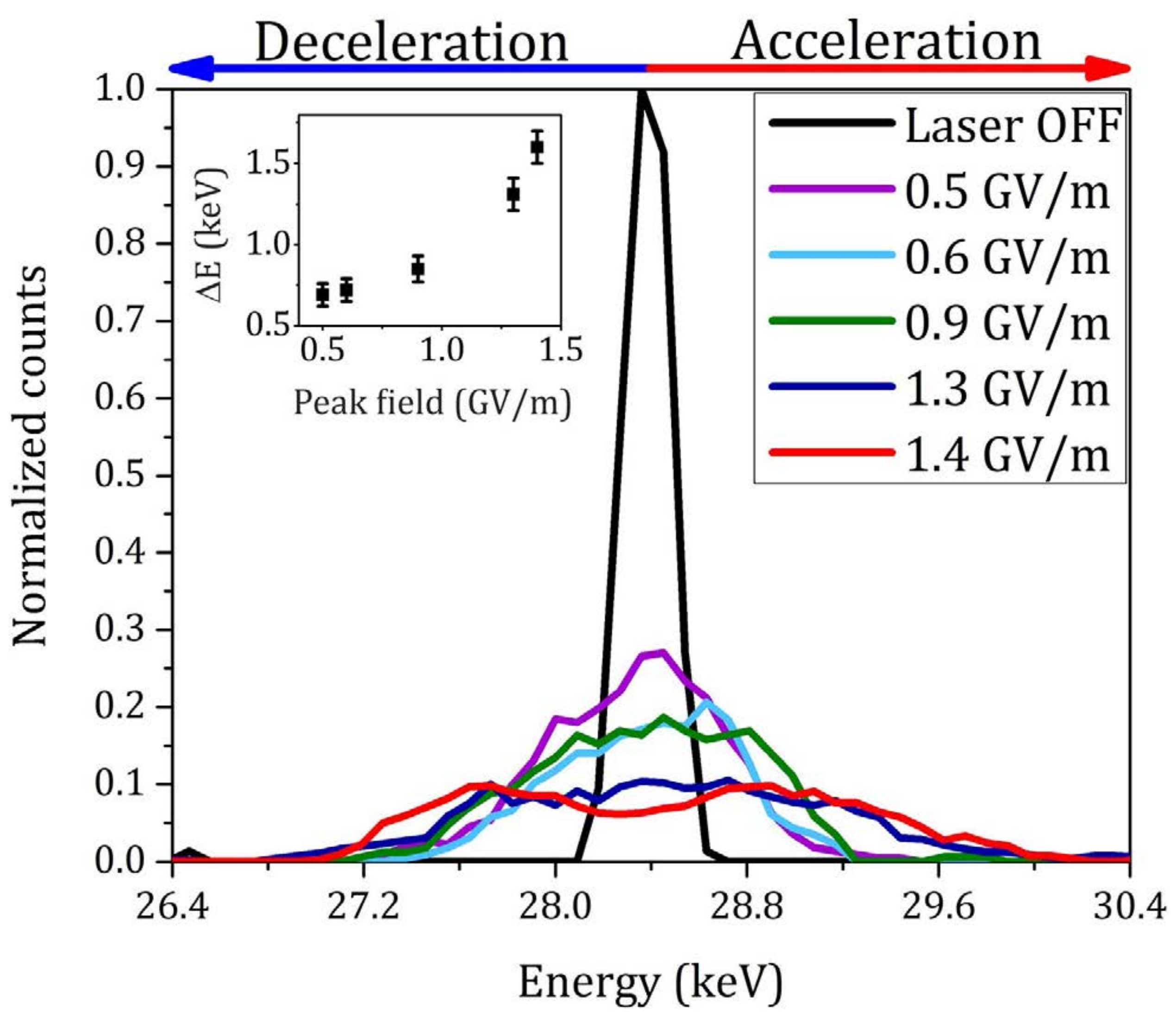


Sears et al., PRST-AB **11**, 101301 (2008)

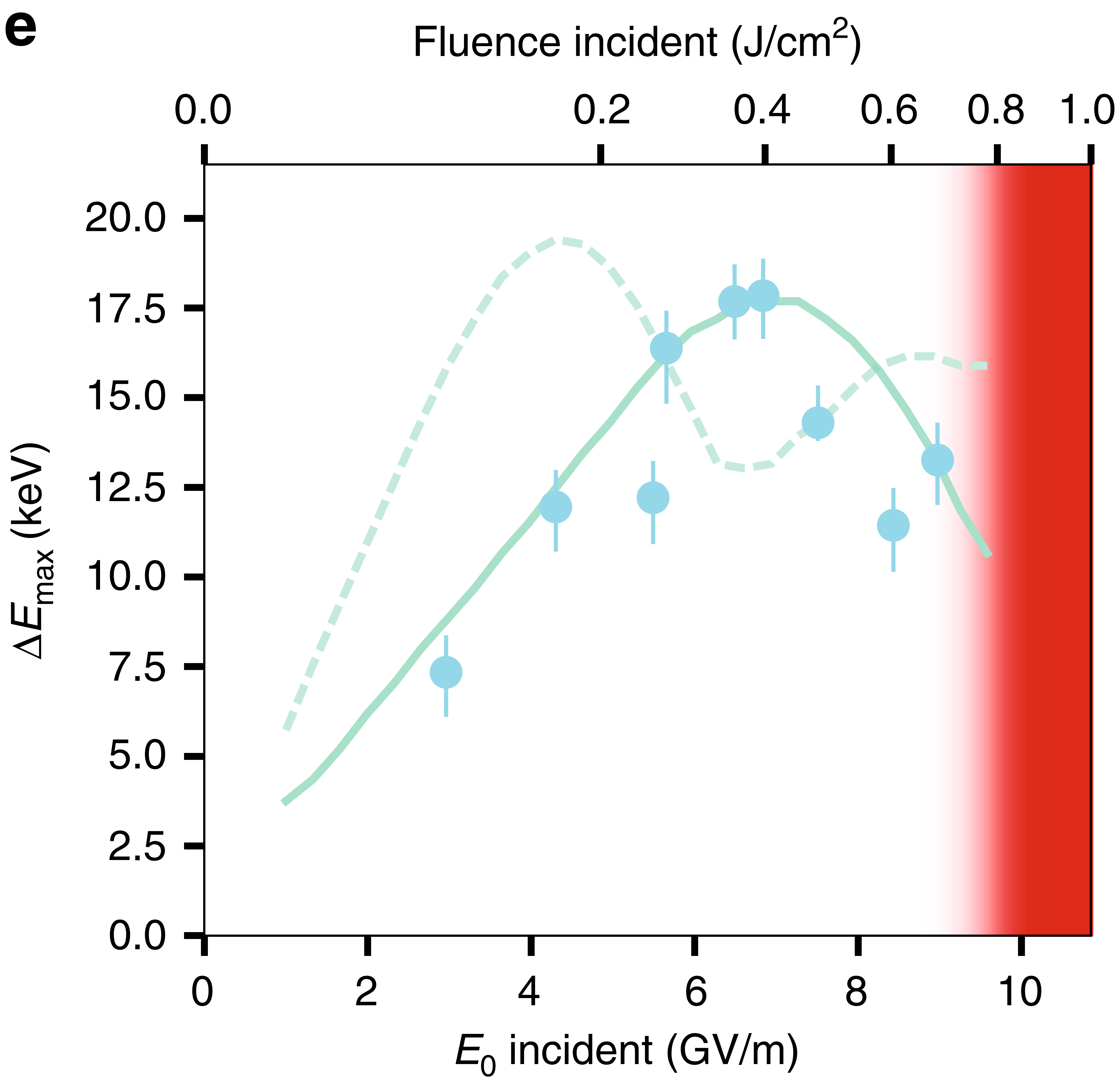
EXPERIMENTAL WORK: ACCELERATION



Leedle et al., Optics Letters 43, 9, 2181(2018)

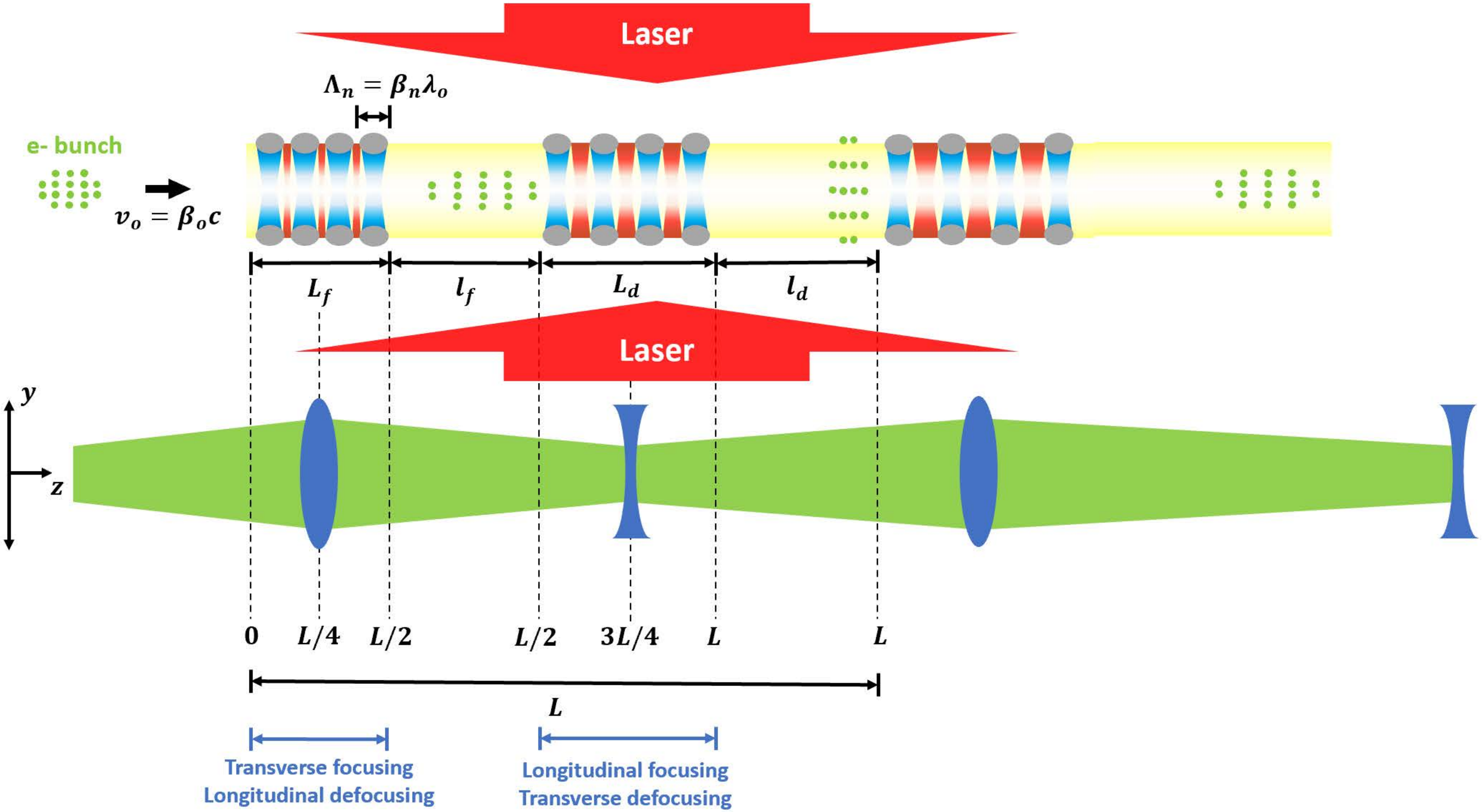


Yousefi et al., Optics Letters 44, 6, 1520-1523 (2019)

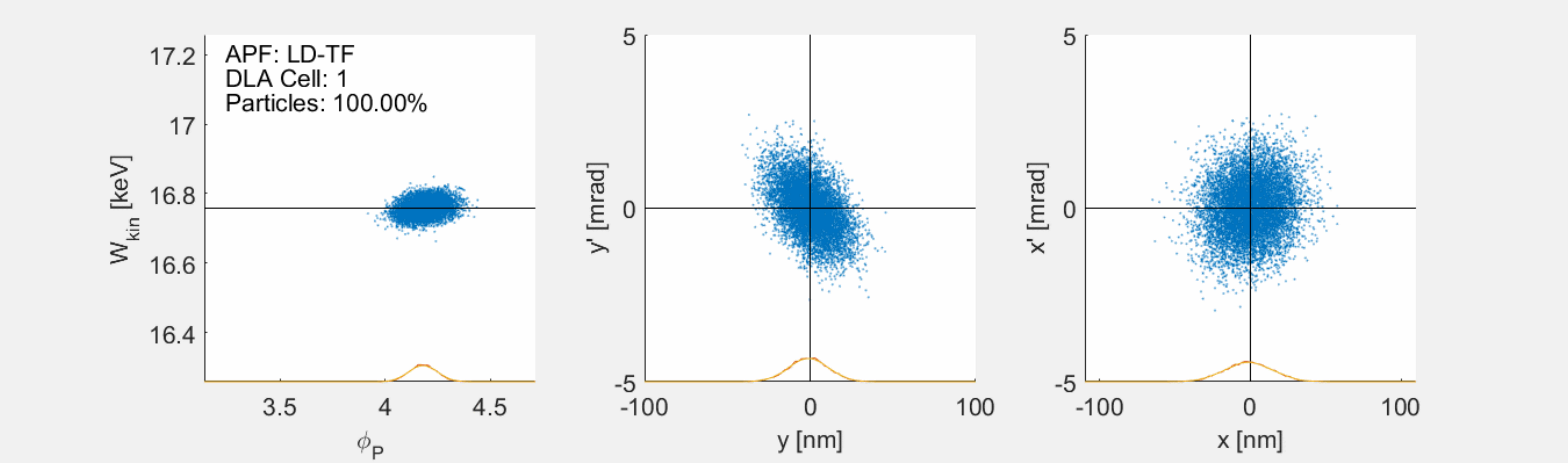


Cesar et al., Communications Physics 1, 46 (2018)

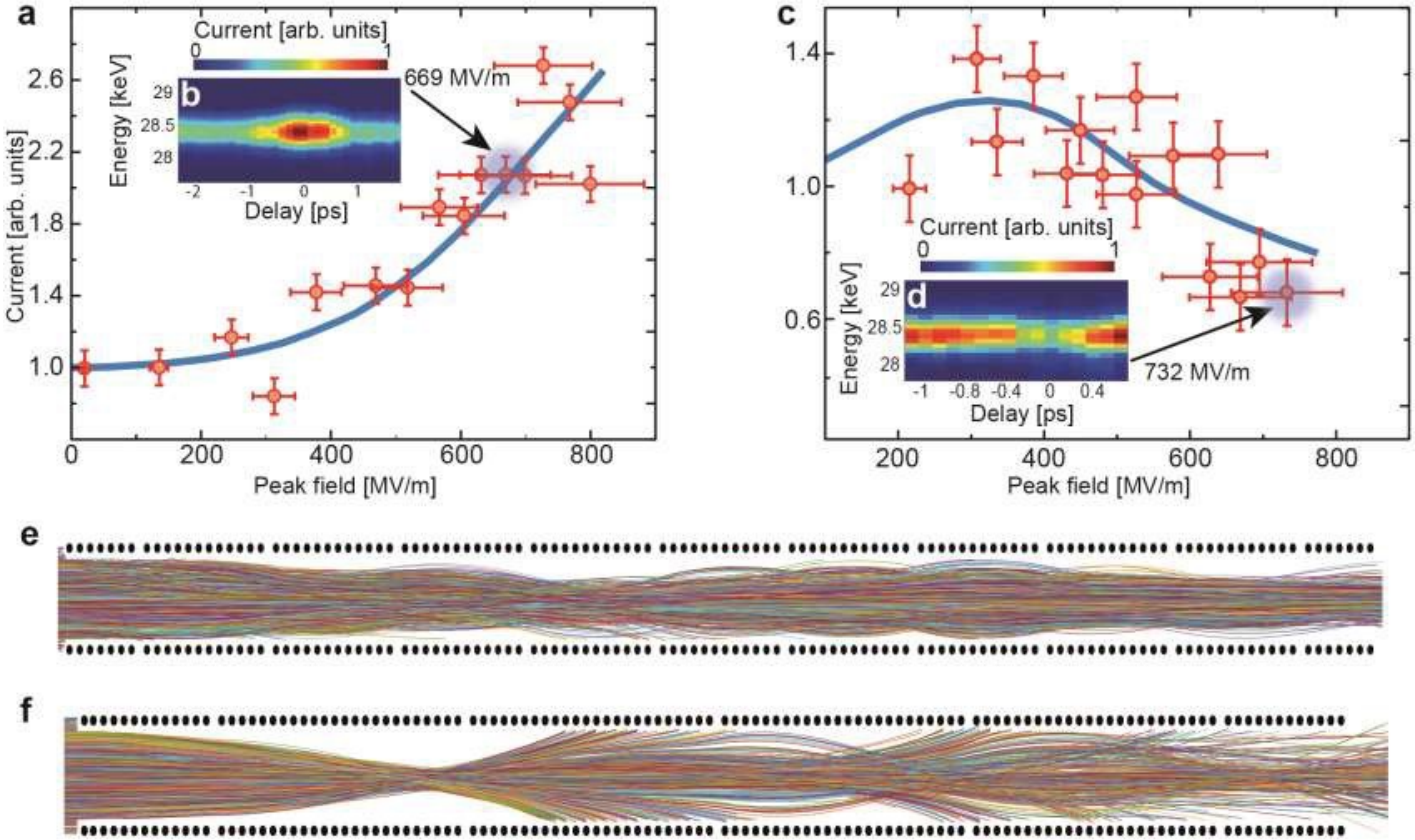
ALTERNATING PHASE FOCUSING



ALTERNATING PHASE FOCUSING



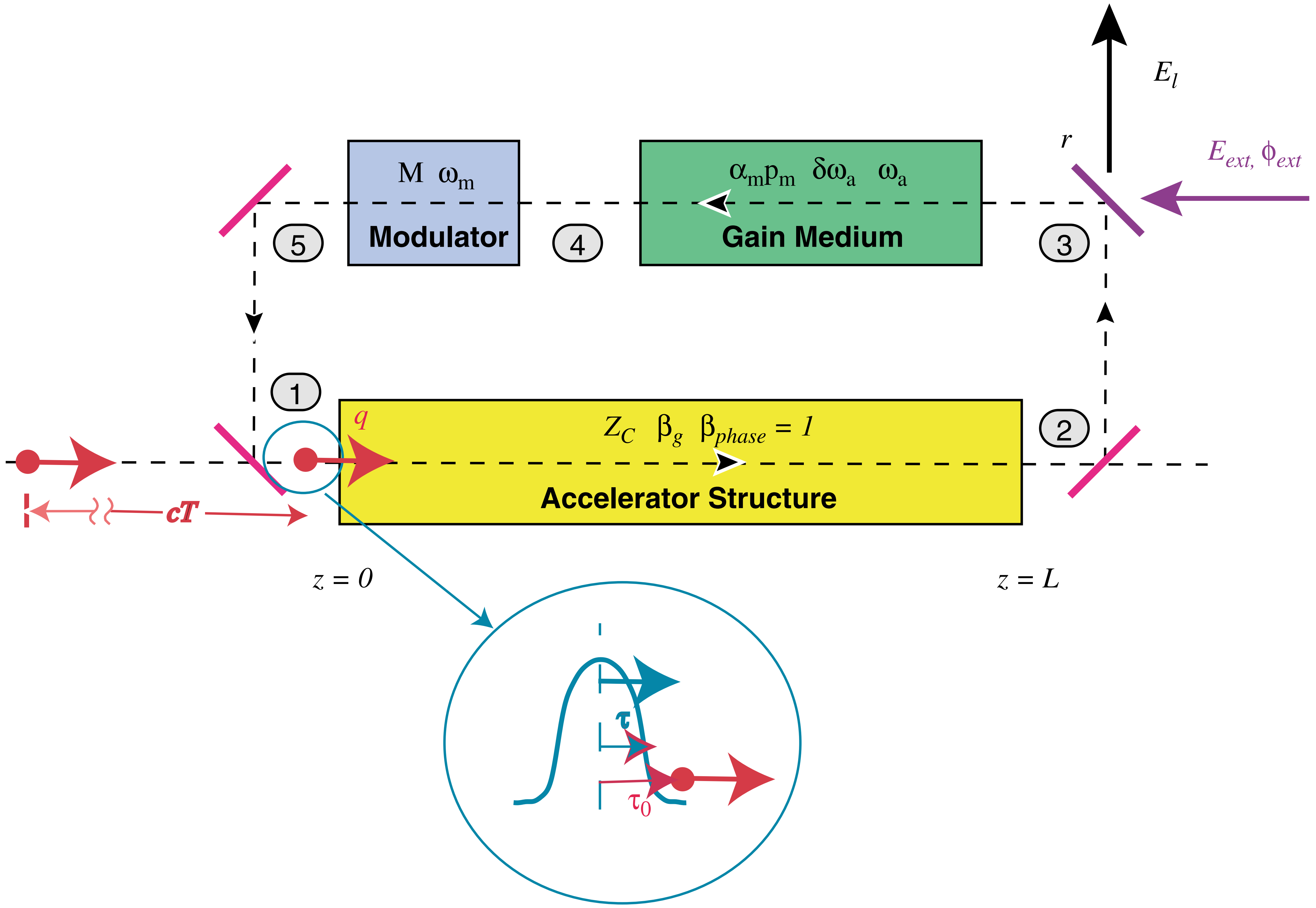
EXPERIMENTAL WORK: FOCUSING AND BEAM CONFINEMENT

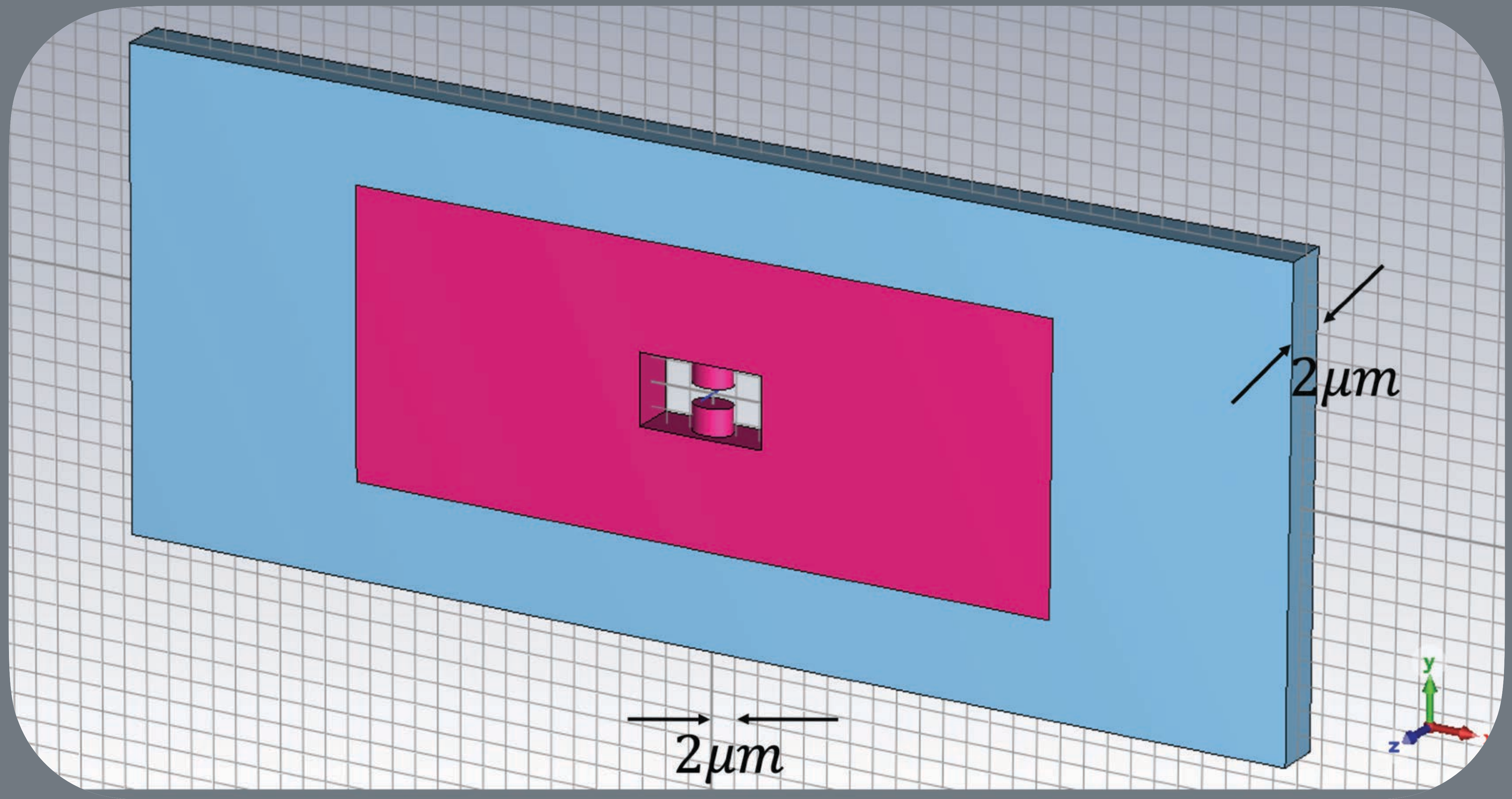


Shiloh†, Illmer†, Chlouba†, Yousefi, Schönenberger, Niedermayer, Mittelbach, Hommelhoff, Nature, in press

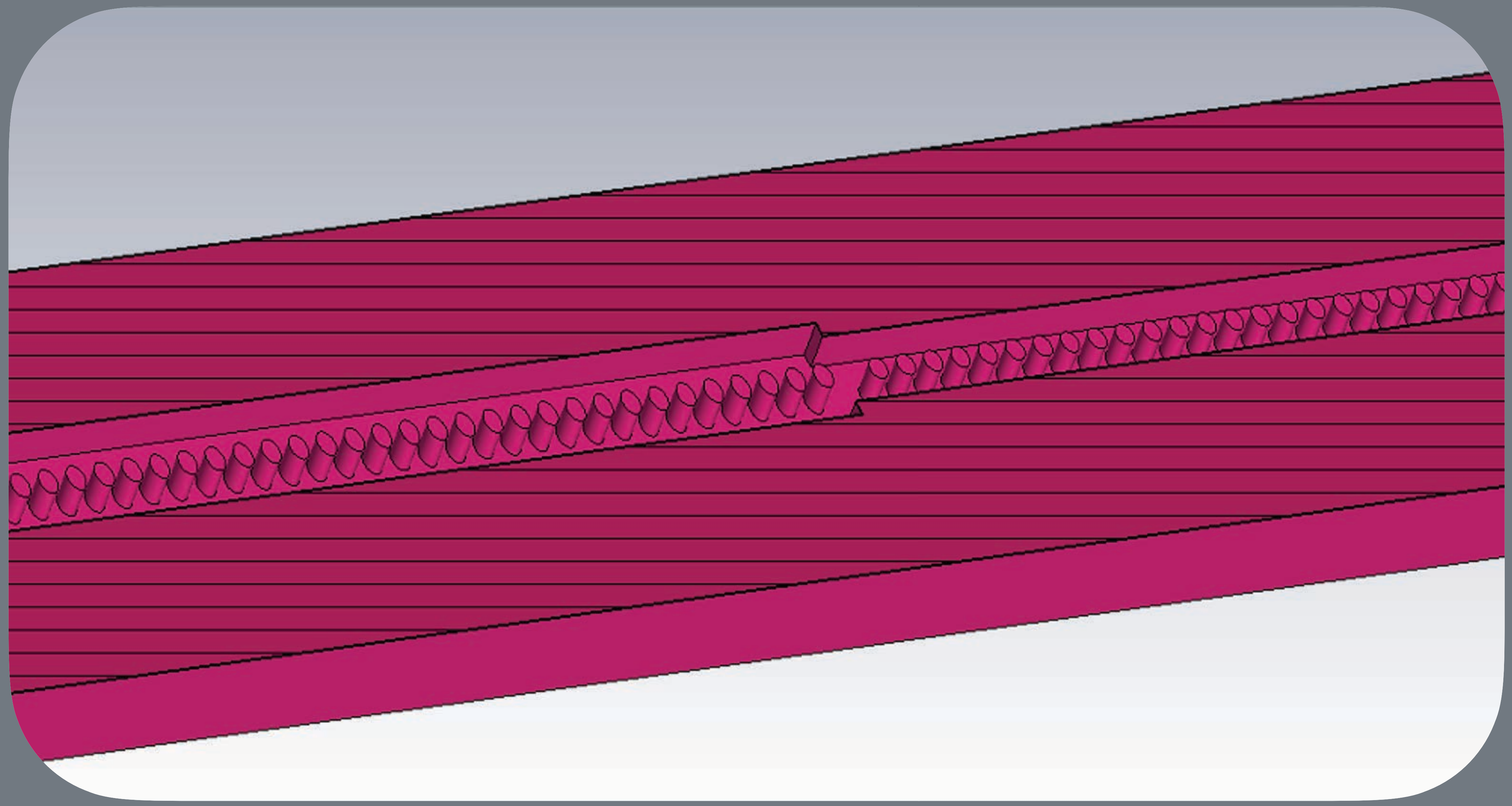
CONCEPT FOR AN ENERGY-EFFICIENT ACCELERATOR

- Incorporate an accelerating structure in a laser cavity
  - high accelerating fields ⇒ use a dielectric
  - high efficiency ⇒ recycle the laser pulse energy in the cavity





Single Cell

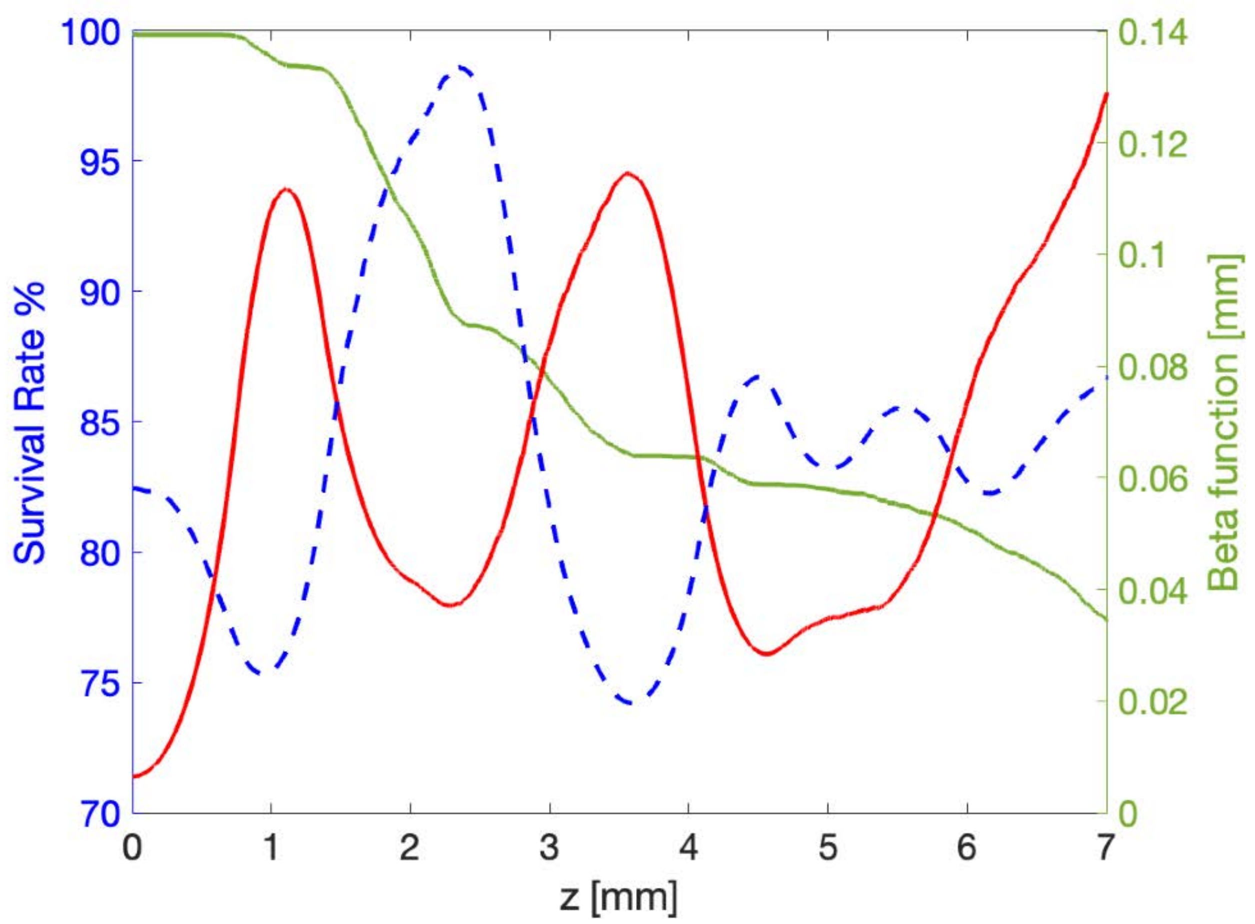


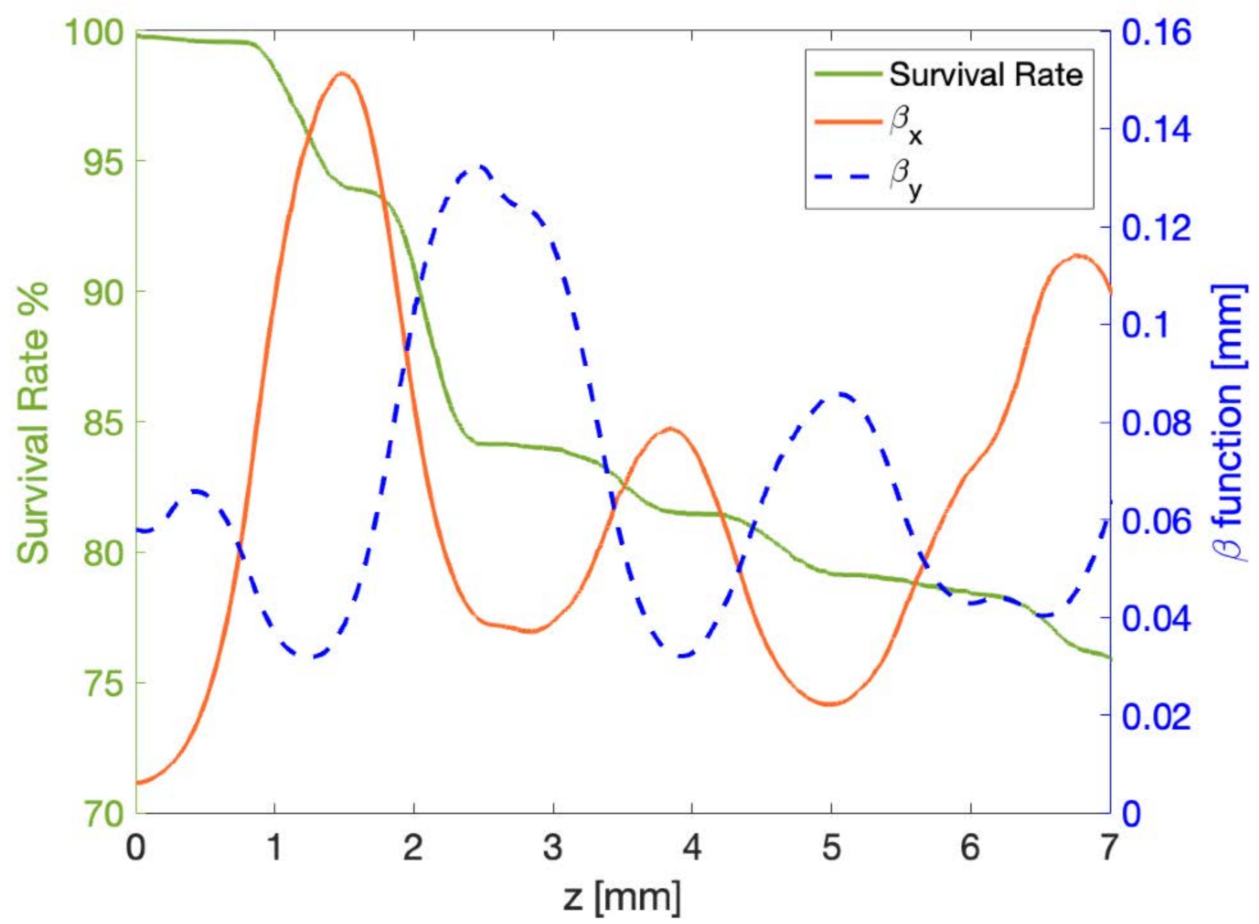
Half-view of the Structure

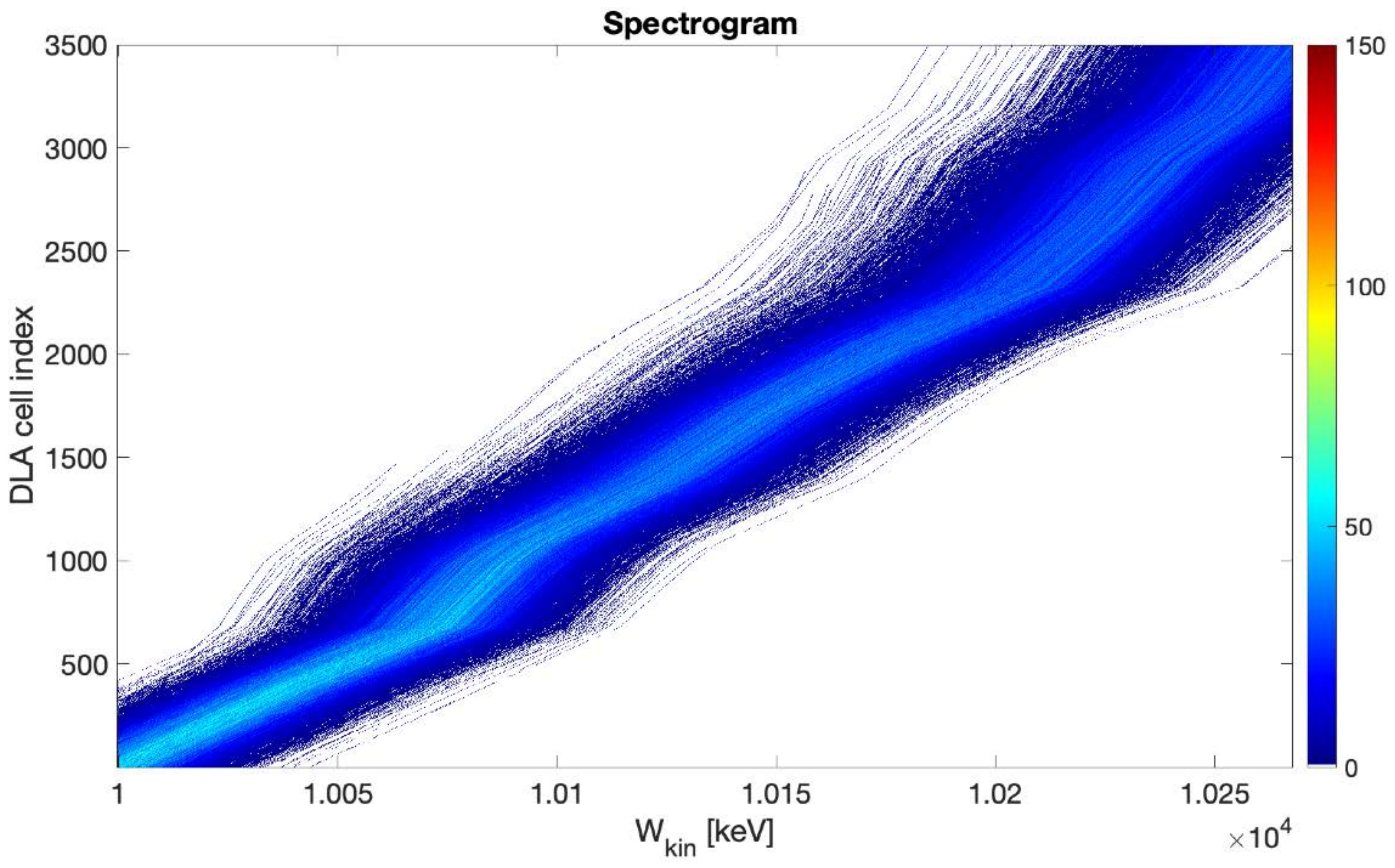
- The parameters k_x, k_y, and e_1 can be calculated for a single cell using CST Studio Suit (or vice versa).
- These parameters can change along the structure (homogenous structure) or stay identical (non-homogenous structure).

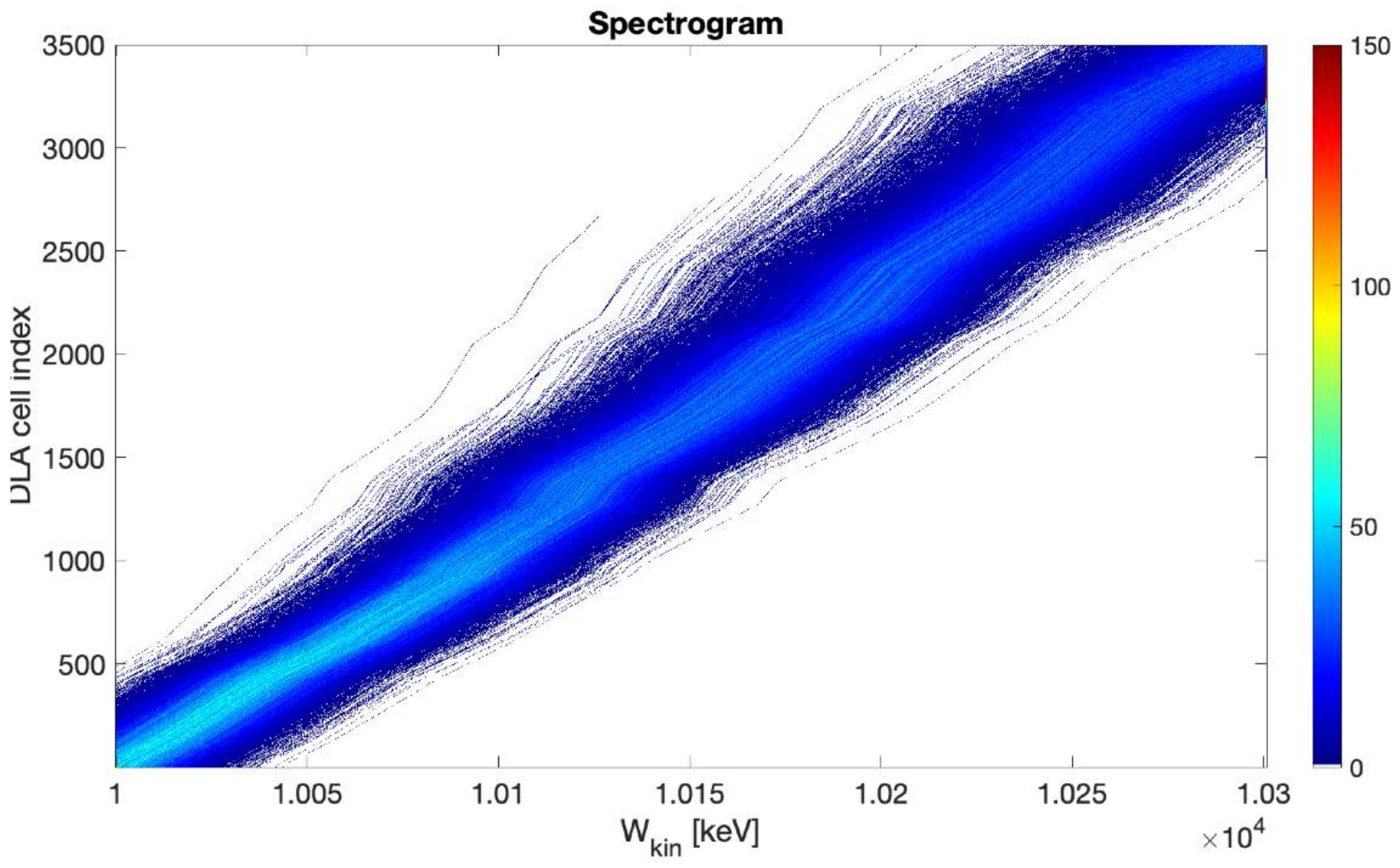
- Beam energy: 10 MeV
- Laser energy: 200 MV/m
- Number of macro-cells: 15 and 30
- Number of micro-cells: 3500
- Structure length: 7 mm
- Initial energy spread: 0.001

Increasing the Number of Drift-Sections



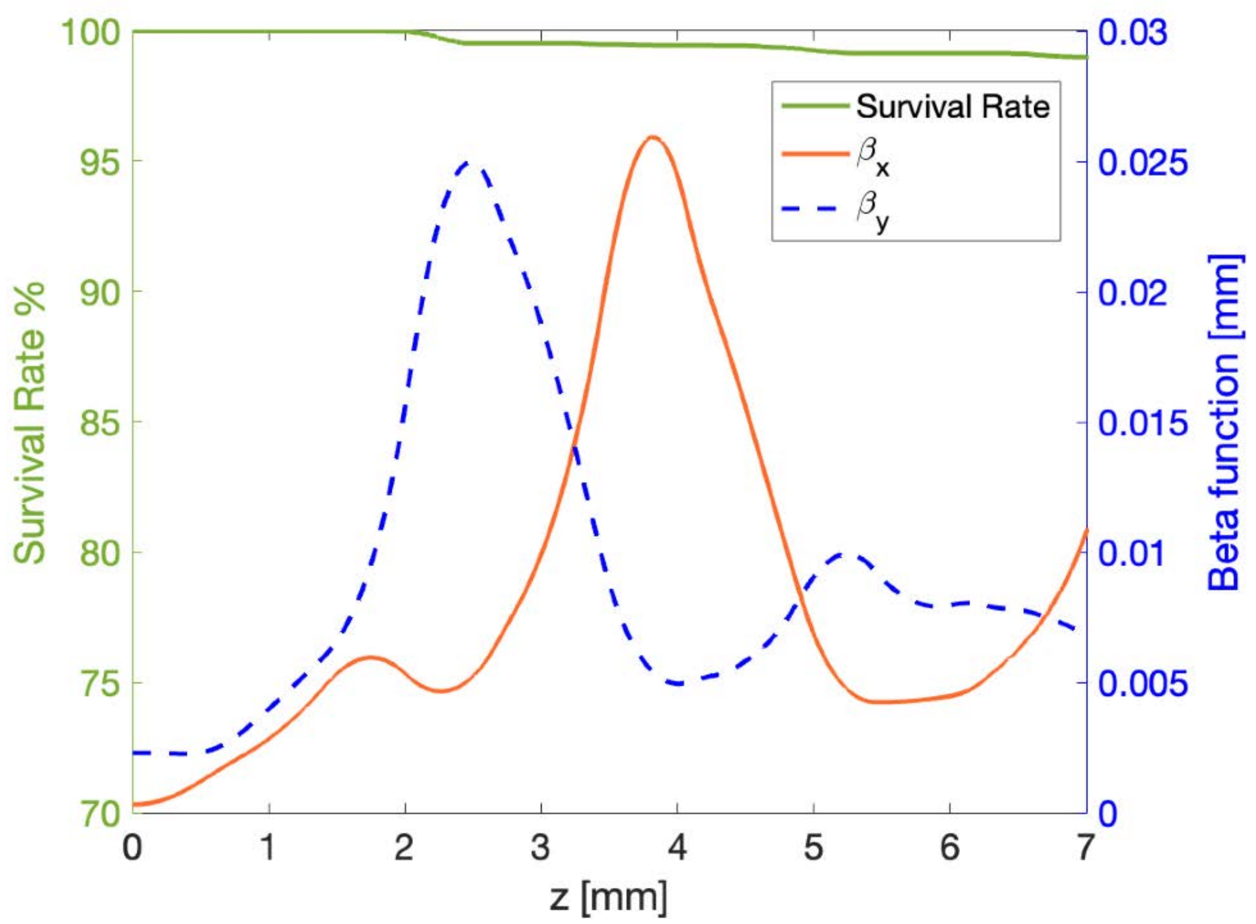


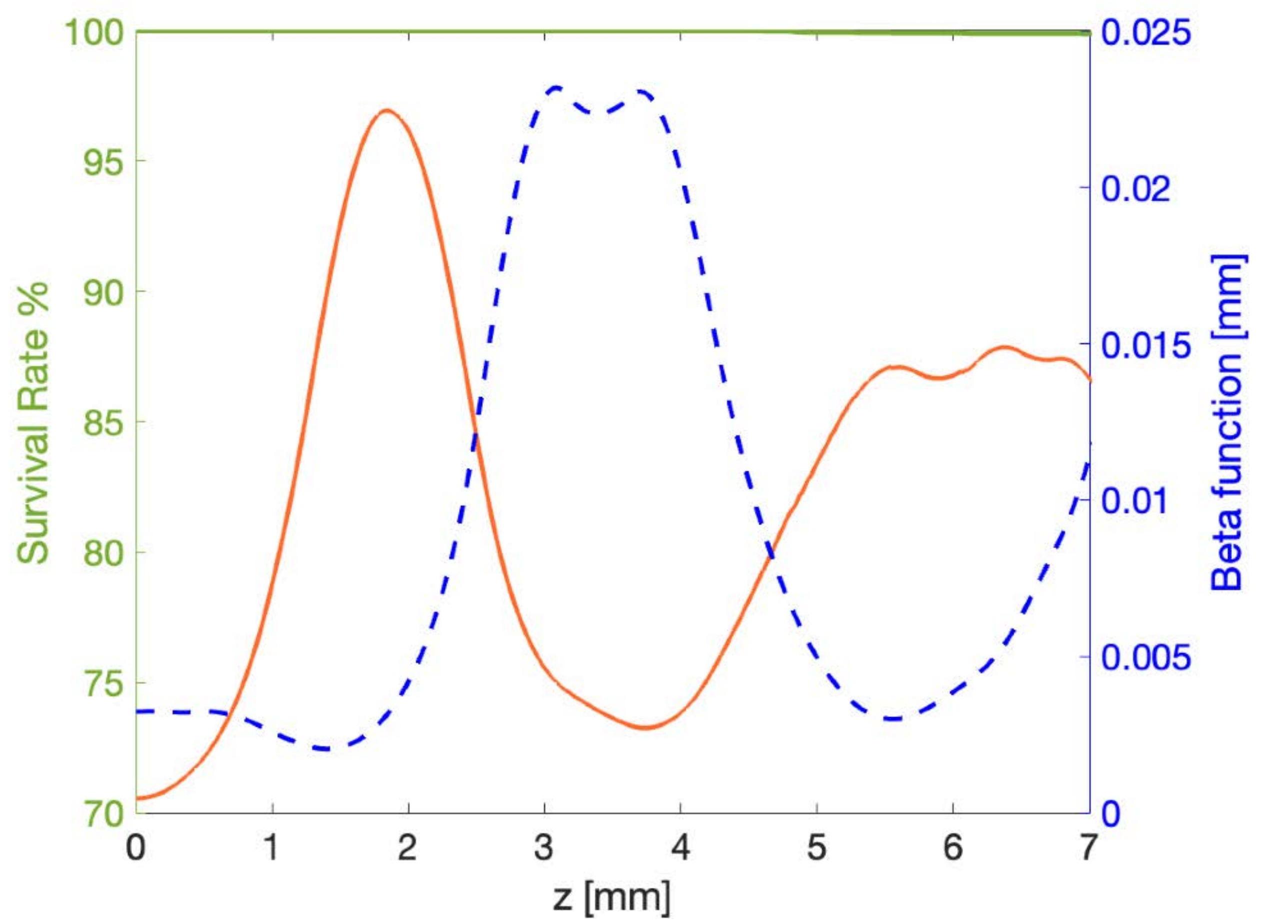


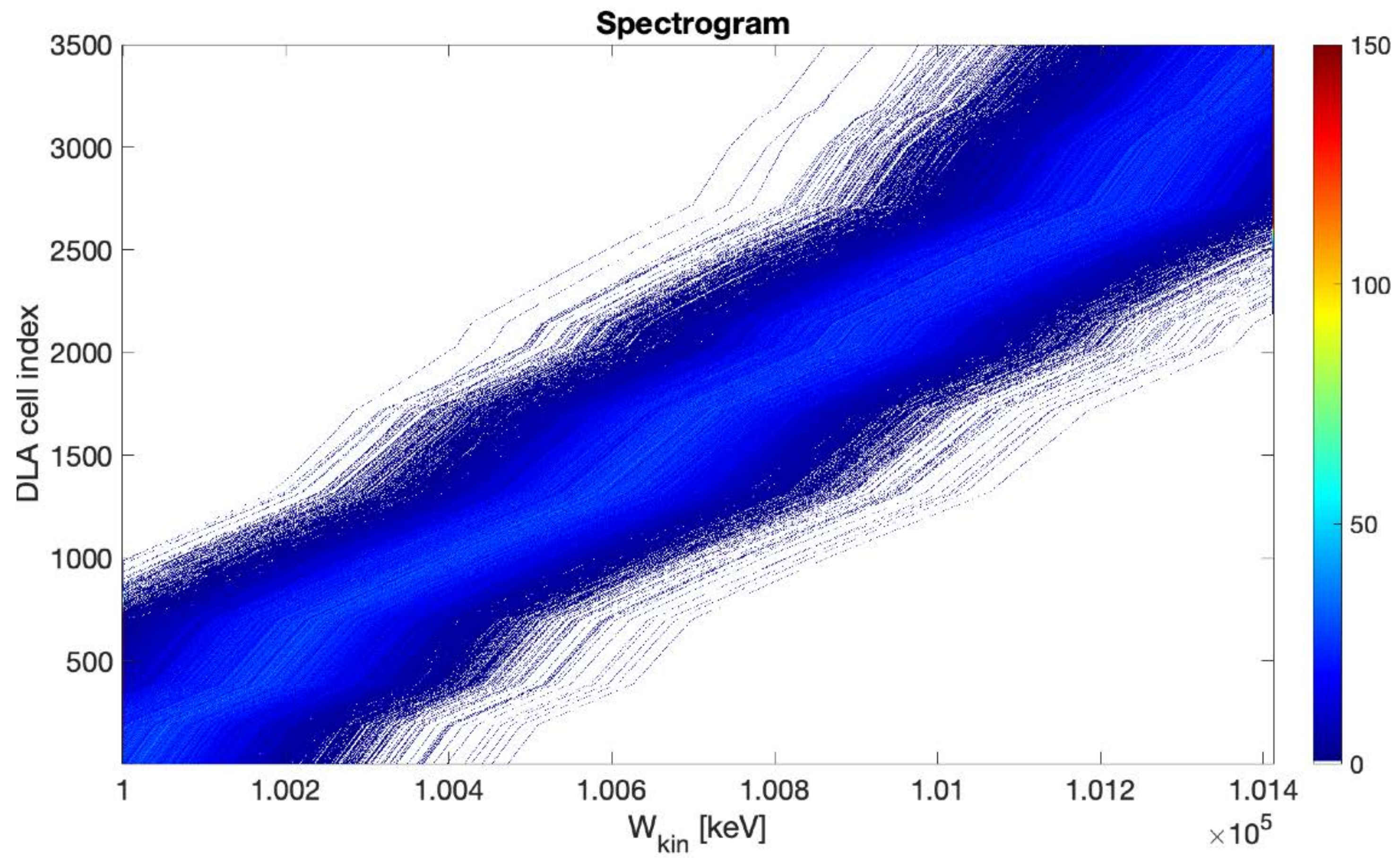


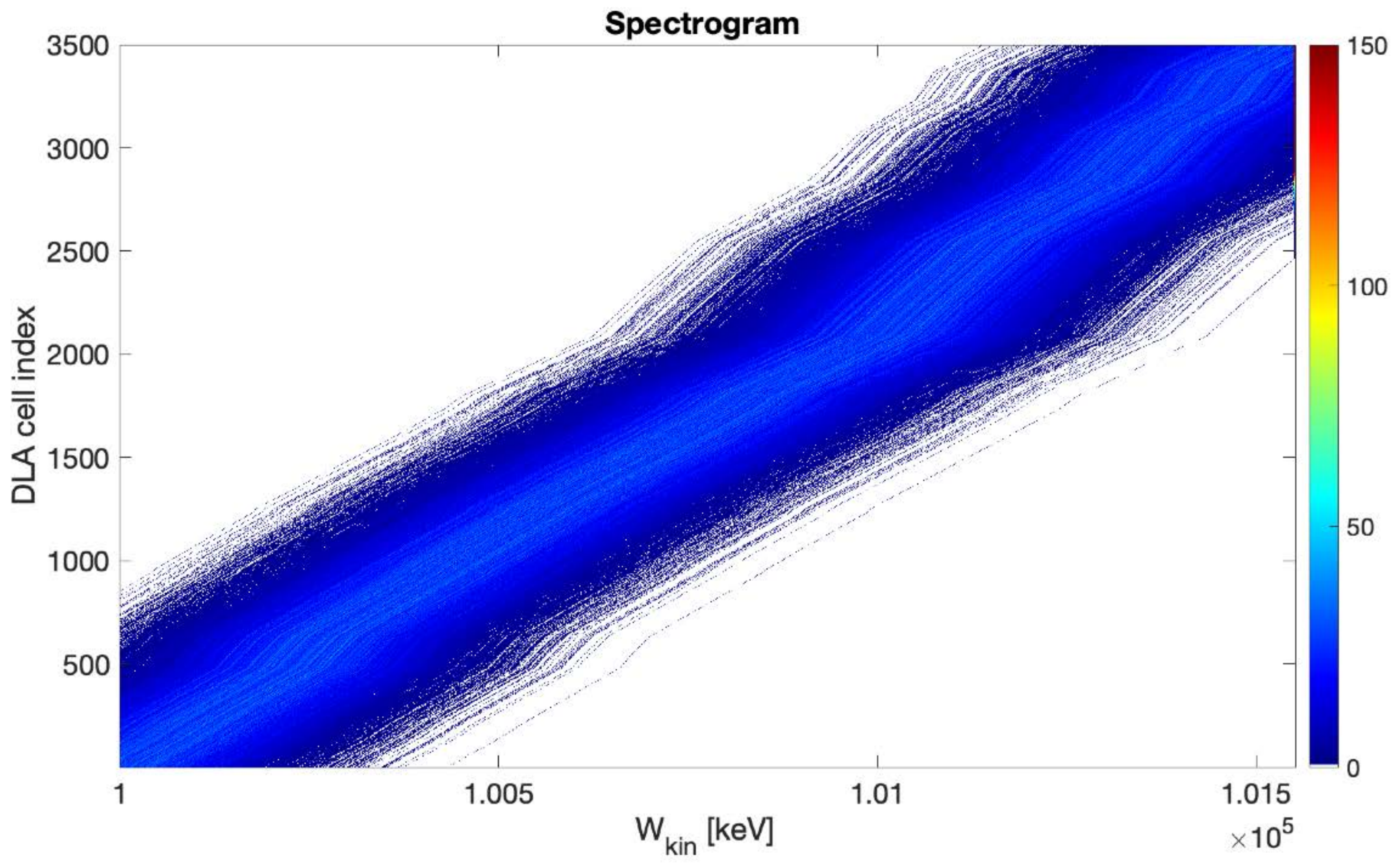
- Beam energy: 100 MeV
- Laser energy: MV/m
- Number of macro-cells: 15 and 30
- Number of micro-cells: 3500
- Structure length: 7 mm
- Initial energy spread: 0.001

Increasing the Number of Drift-Sections



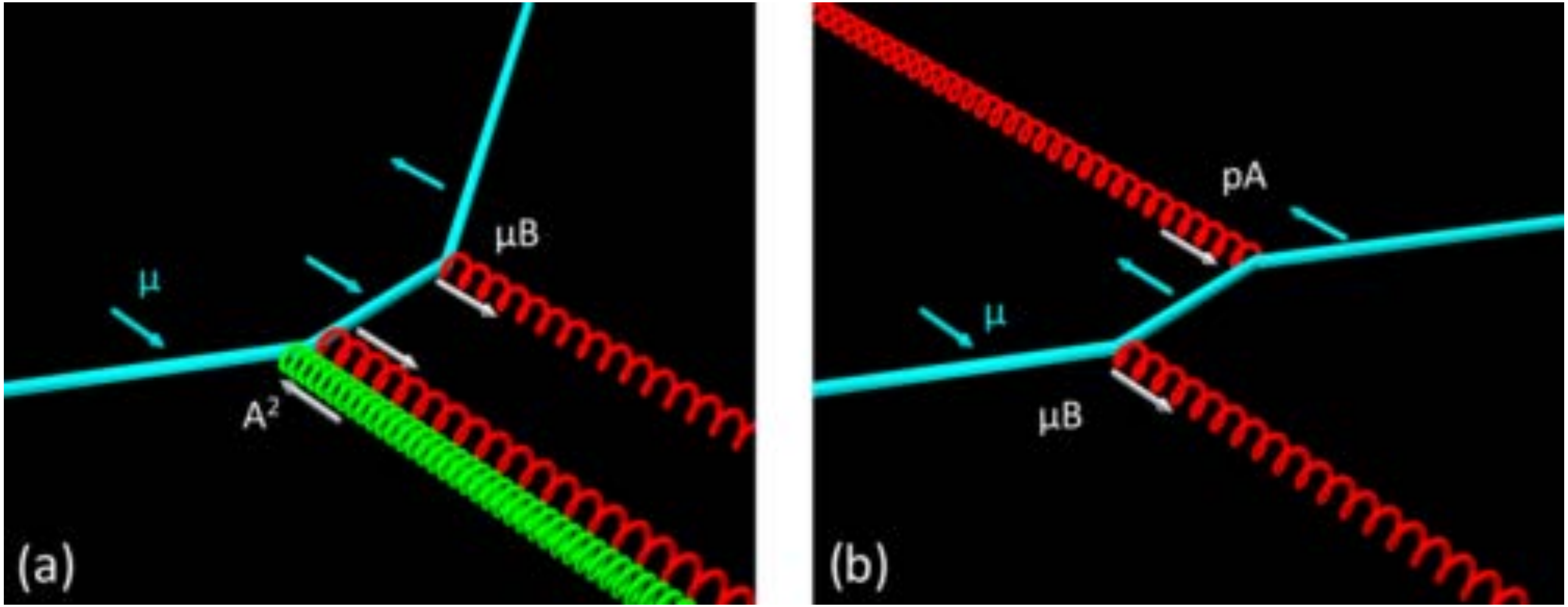






SPIN CONTROL

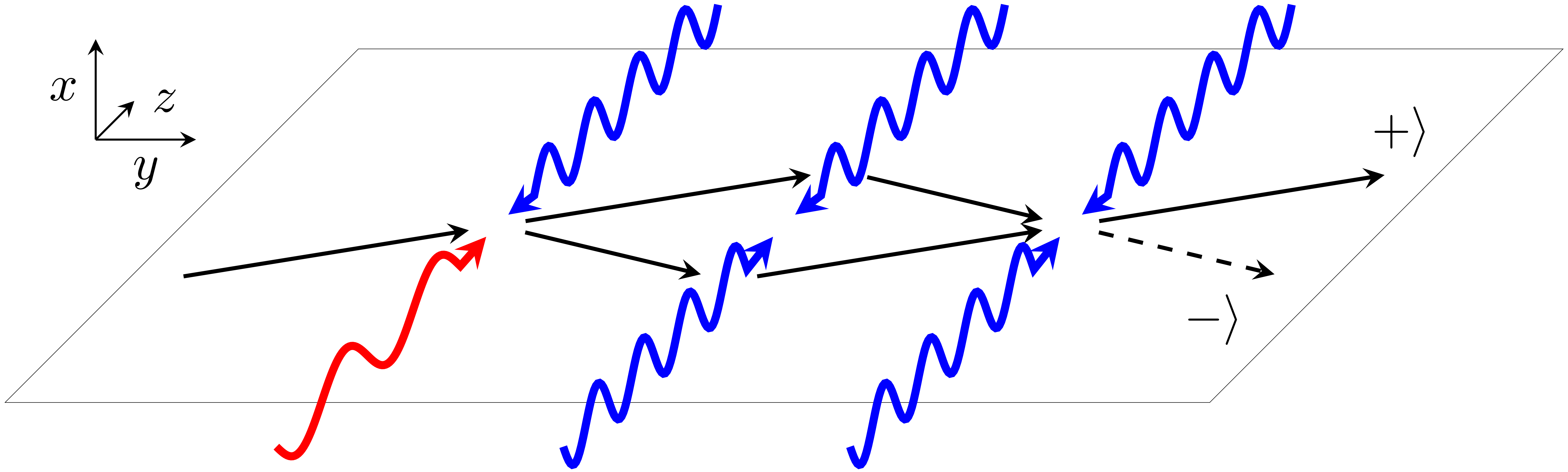
- Two-color processes (using frequencies ω and 2ω) allow flipping the spin of electrons



S. McGregor, W. C.-W. Huang, B. A. Shadwick, and H. Batelaan, Phys. Rev. A 92, 023834 (2015)

SPIN CONTROL

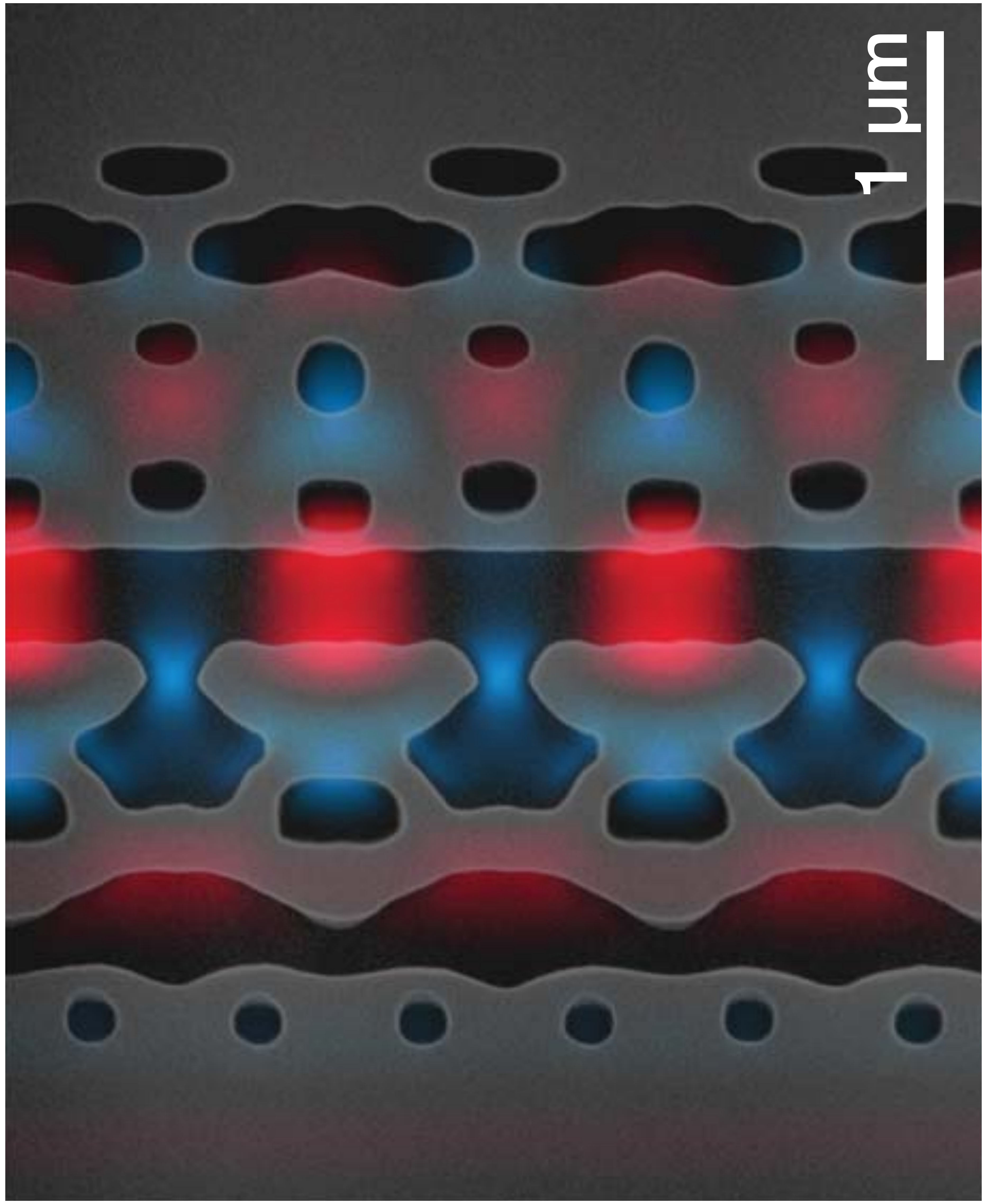
- Generation of a spin-polarized beam analogous to the Stern-Gerlach experiment polarizing atoms



Matthias Dellweg, Carsten Müller: http://arxiv.org/abs/1607.08793v2

INTEGRATED PHOTONIC CIRCUIT ACCELERATORS FOR DARK MATTER SEARCH

- Clean initial signal
- High repetition rate
- Potential for good energy efficiency
- Possibility to control the spin



Sapra et al., Science 367, 79–83 (2020)

QUESTIONS?

Thank you to Raziyeh Dadashi, Bob Byer, Peter Hommelhoff, Richard Jacobsson, Vitek Krasny, Uwe Niedermayer, Mike Seidel and Frank Zimmermann

Thank you to Gordon and Betty Moore Foundation, EPFL, and the European Union, who are funding this work

Thank you for your interest!

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