

TOWARDS BEAM-QUALITY-PRESERVING PLASMA ACCELERATORS: ON THE PRECISION TUNING OF THE WAKEFIELD



Universität Hamburg

DER FORSCHUNG | DER LEHRE | DER BILDUNG

HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

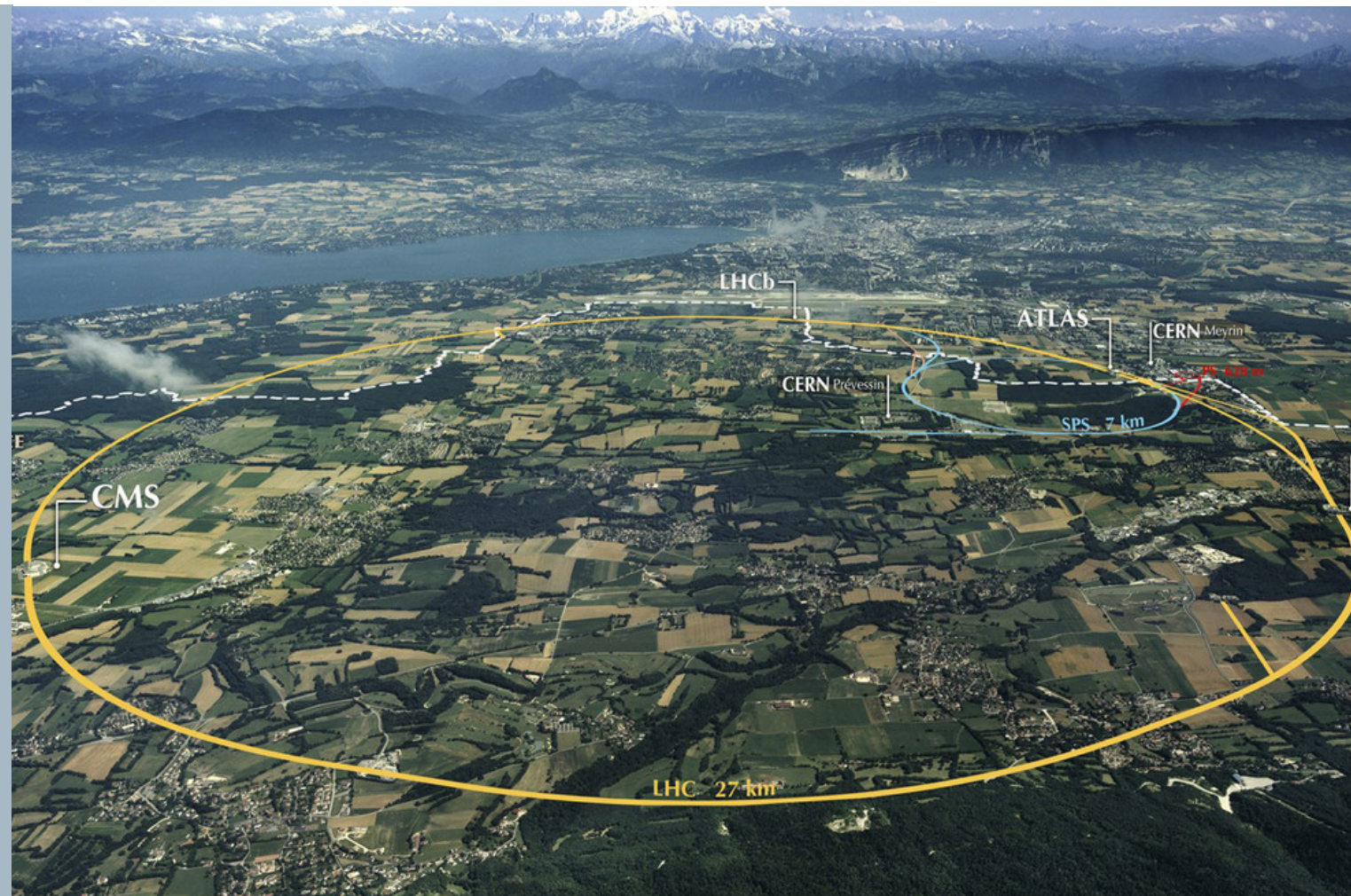
Dr. Sarah Schröder

Research Fellow (DESY)

Plasma Wakefield Accelerator Research and Development
Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany

PARTICLE ACCELERATORS – EXPLORING THE SMALL SCALE OF MATTER

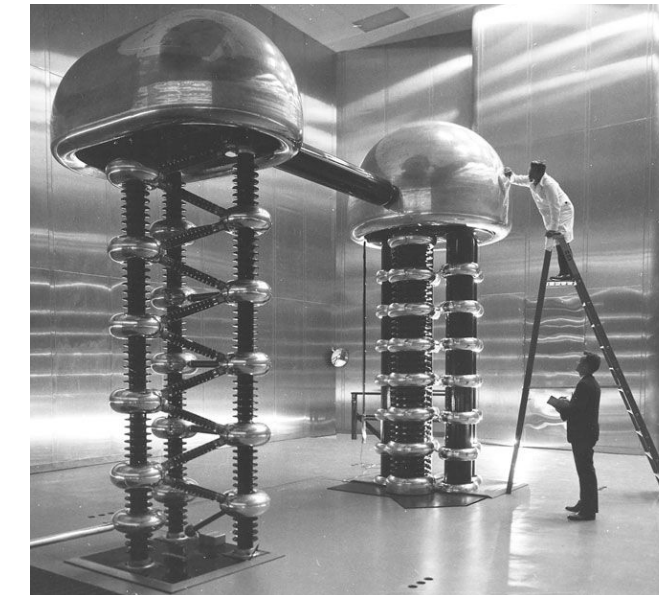
PARTICLE PHYSICS



Cathode ray tube, keV



Cockcroft-Walton, 400 keV



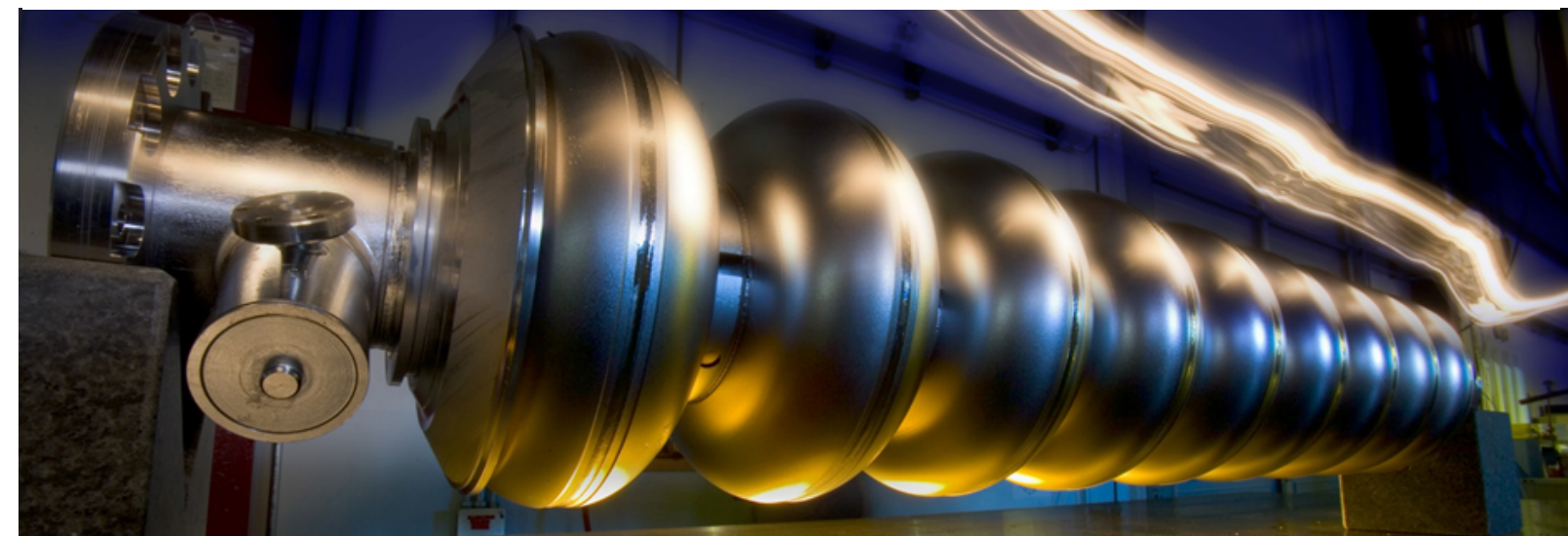
Van-de-Graaff Tandem, 25 MeV



PHOTON SCIENCE



Today's technology: radio-frequency cavities



Electric/material breakdown limits the acceleration gradient @ **(100 MeV/m)**

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PARTICLE PHYSICS



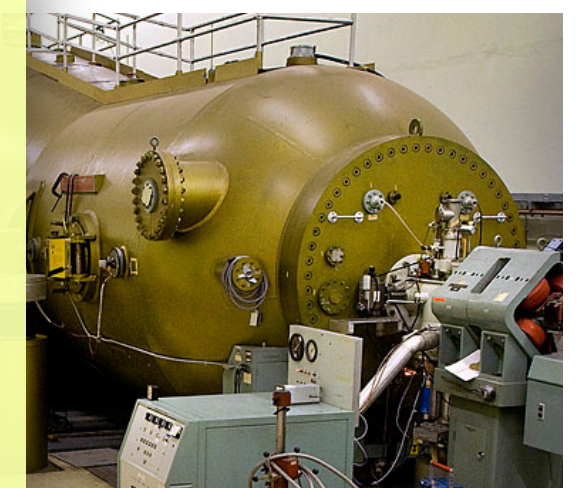
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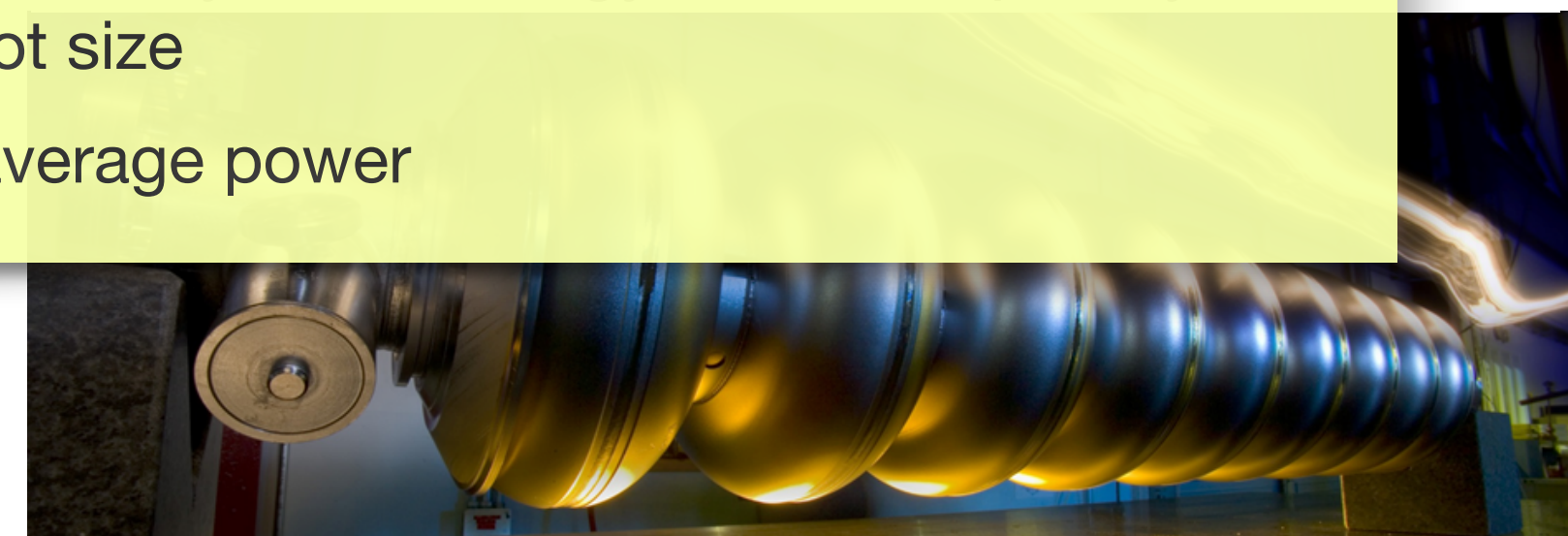
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PARADIGM SHIFT IN ACCELERATOR TECHNOLOGY NEEDED:

- > Compact design ↔ **Acceleration gradient** ($> \text{GeV/m}$)
- > Affordable operation ↔ **Power efficiency** ($> 10\%$ wall-plug)
- > Luminosity / Brilliance ↔ excellent **beam quality**:
 - > $\%$ -level energy spread
 - > nm-level focus spot size
 - > kW-to-MW-level average power

PHOTON SCIENCE



Electric/material breakdown limits the acceleration gradient $\mathcal{O}(100 \text{ MeV/m})$

PLASMA-BASED ACCELERATORS – A PROMISING TECHNOLOGY

PHYSICAL REVIEW LETTERS

23 JULY 1979

Laser Electron Accelerator

T. Tajima and J. M. Dawson

Department of Physics, University of California, Los Angeles, California 90024

(Received 9 March 1979)

An intense electromagnetic pulse can create a weak of plasma oscillations through the action of the nonlinear ponderomotive force. Electrons trapped in the wake can be accelerated to high energy. Existing glass lasers of power density $10^{18}\text{W}/\text{cm}^2$ shone on plasmas of densities 10^{18}cm^{-3} can yield gigaelectronvolts of electron energy per centimeter of acceleration distance. This acceleration mechanism is demonstrated through computer simulation. Applications to accelerators and pulsers are examined.



S.P.D. Mangles et al., Nature **431**, 535–538 (2004).
C.G.R. Geddes et al., Nature **431**, 538–541 (2004).
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W. Wang et al., Nature **595**, 516–520 (2021)

LIMITATION OF LASER-DRIVEN PLASMA WAKEFIELD ACCELERATION

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LIMITATIONS OF STATE-OF-THE-ART HIGH-INTENSITY LASERS:

- > Low wall-plug efficiency ($\sim 0.1\%$)
- > Low average power ($\sim 100\text{ W}$)



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FIRST HIGH-QUALITY BEAMS



FIRST FEL GAIN



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LIMITATIONS OF STATE-OF-THE-ART HIGH-INTENSITY LASERS

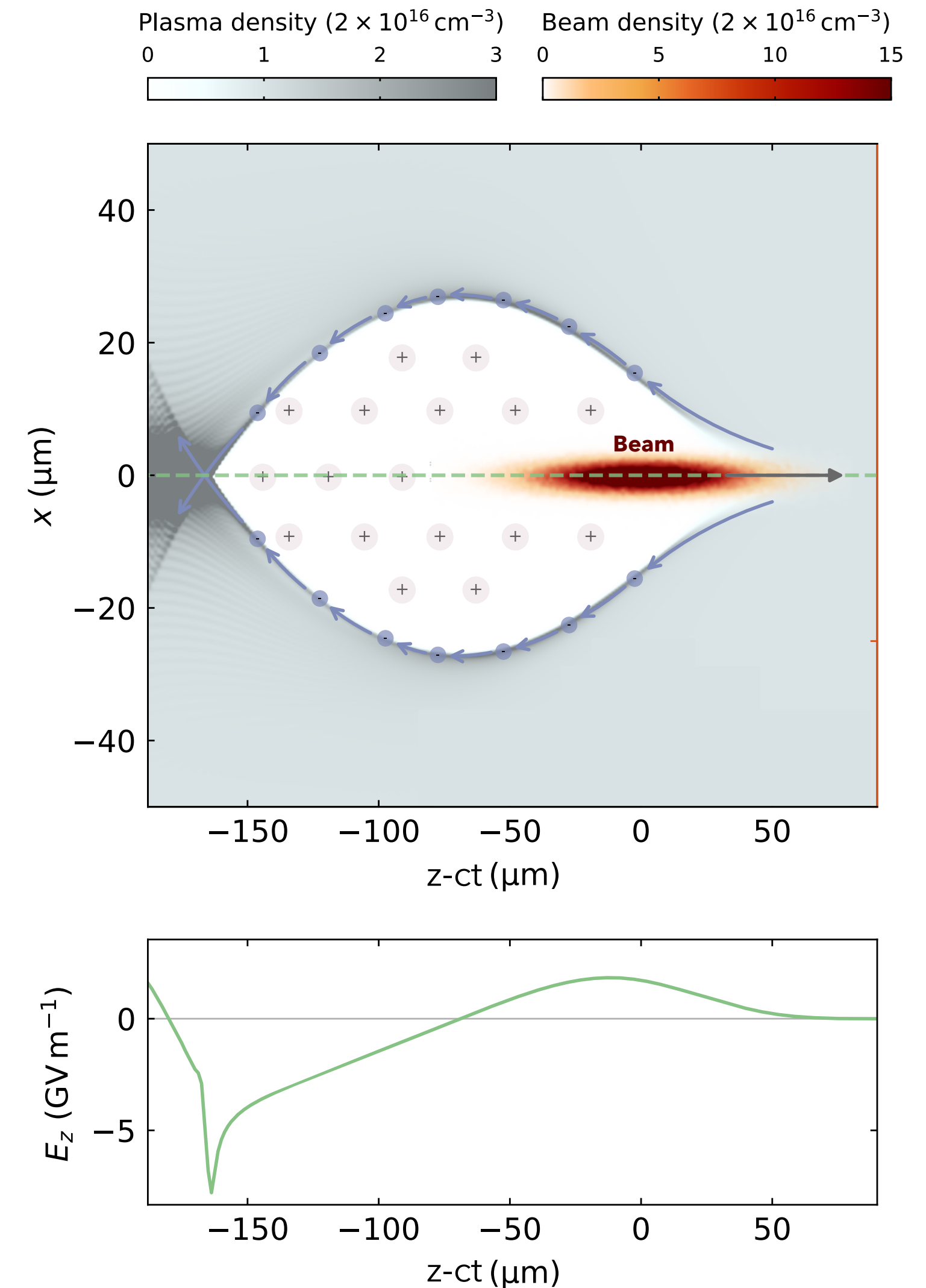
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➡ **BEAM-DRIVEN PLASMA WAKEFIELD ACCELERATION**

BEAM-DRIVEN PLASMA WAKEFIELD ACCELERATION

WAKE EXCITATION

- > Plasma: ionised gas
- > Electron beam drives a wake
- > Cylindrically symmetric GV/m-level fields
 - > Longitudinally accelerating
 - > Transverse focusing



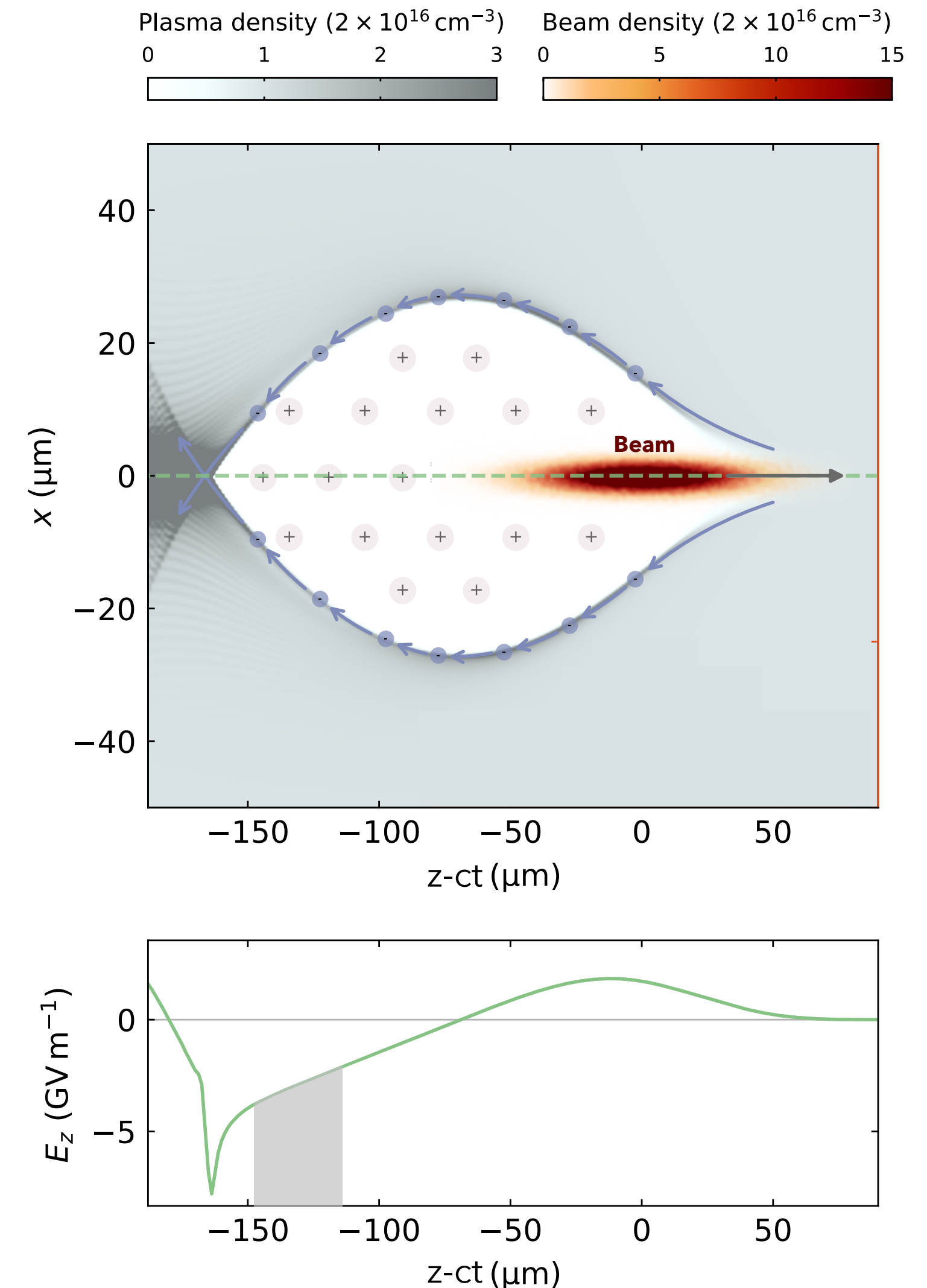
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INJECTION OF AN EXTERNAL BUNCH

- > Excellent focus control required¹
- > Acceleration efficiency: $\eta \propto \Delta E_{acc} \cdot Q_{acc}$
- > Concepts for energy-spread mitigation:
 - > External device²
 - > Optimal beam loading³

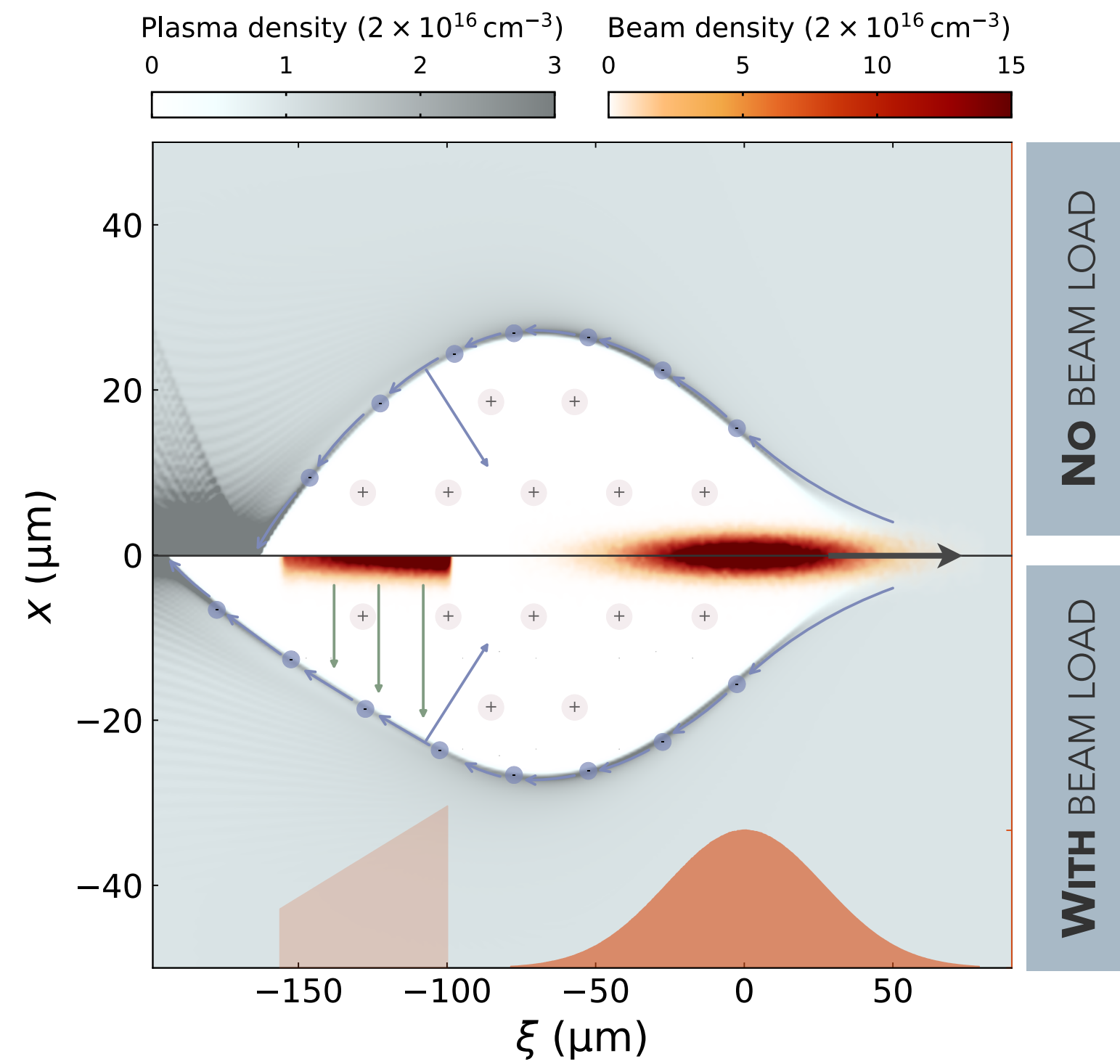


¹ C.A. Lindstrøm, ..., **S. Schröder** *et al.*, Phys. Rev. Accel. Beams 23, 052802 (2020)

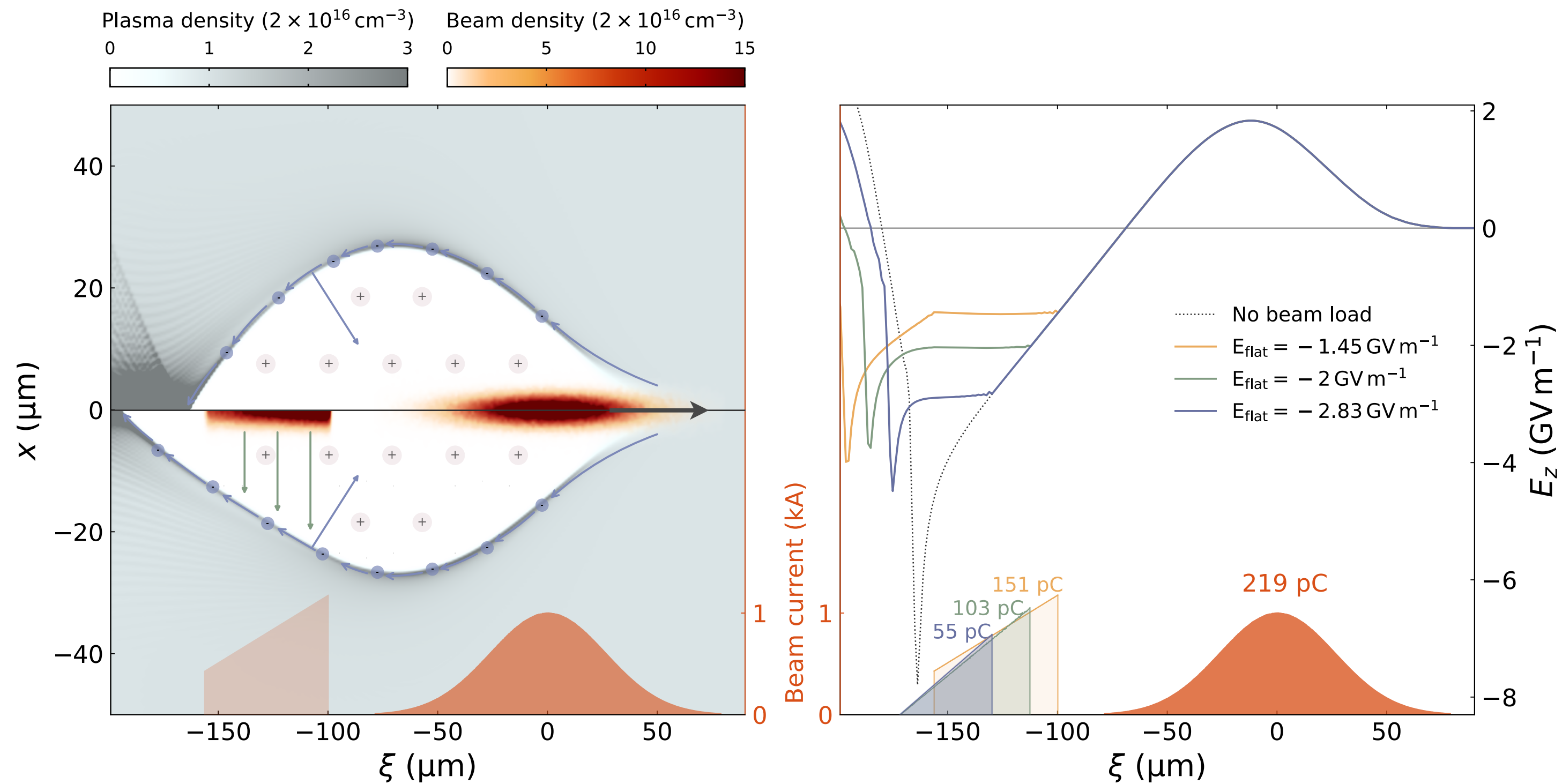
² R. D'Arcy, ..., **S. Schröder** *et al.*, Phys. Rev. Lett 122 034801 (2019)

³ M. Tzoufras *et al.*, Phys. Rev. Lett. **101**, 145002 (2008)

FLATTENING THE WAKEFIELD VIA OPTIMAL BEAM LOADING

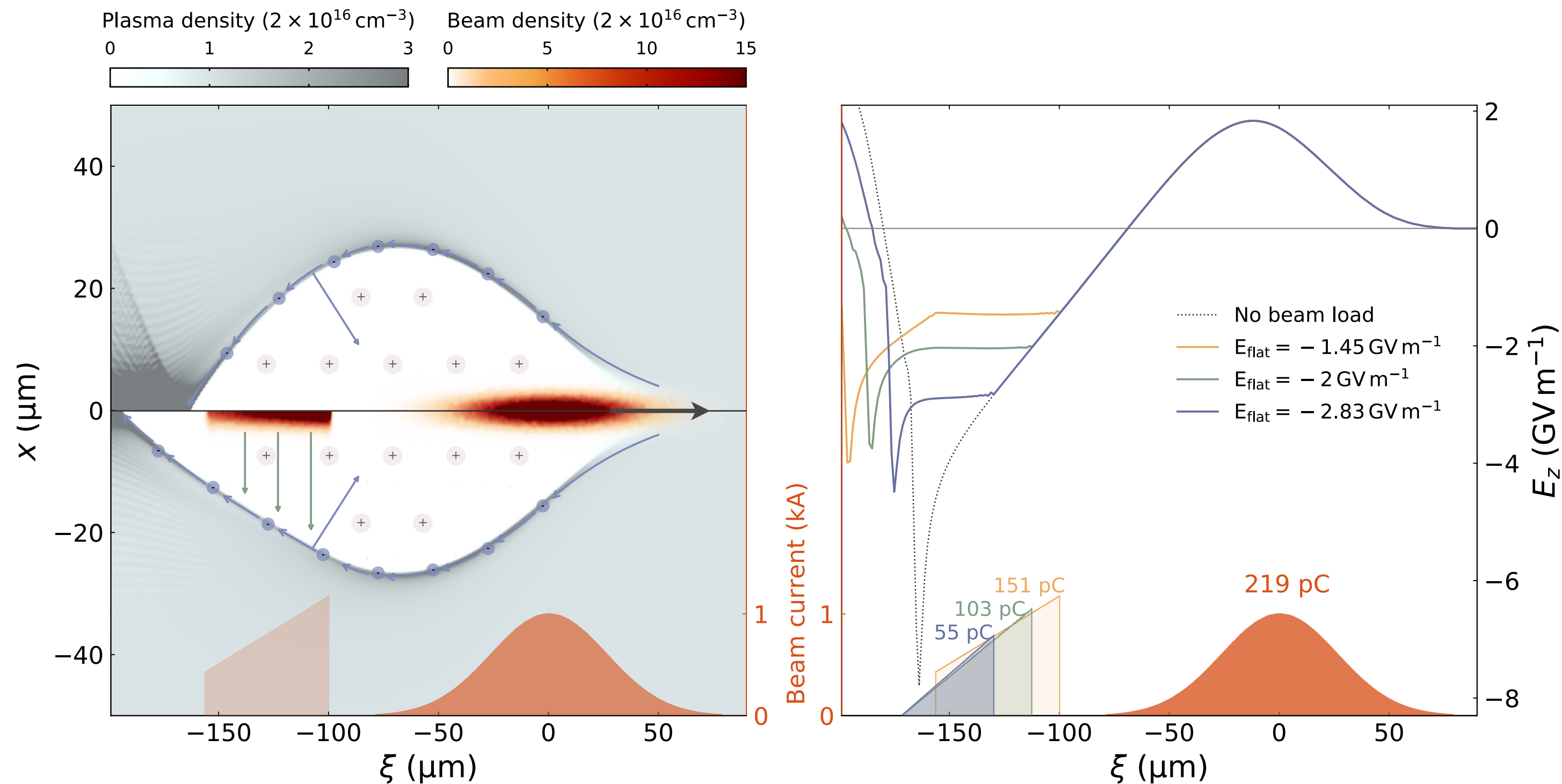


FLATTENING THE WAKEFIELD VIA OPTIMAL BEAM LOADING



SCALABLE **ENERGY-SPREAD-PRESERVING** AND **HIGH-EFFICIENCY** ACCELERATION

FLATTENING THE WAKEFIELD VIA OPTIMAL BEAM LOADING



CONTROLLING AND OPTIMISING THE ACCELERATION PROCESS REQUIRES:

1. Precision control of the current profiles
2. Robust method for measuring the plasma wakefield

STATE-OF-THE-ART BEAM-DRIVEN PLASMA WAKEFIELD ACCELERATION



LETTER

doi:10.1038/nature13882

High-efficiency acceleration of an electron beam in a plasma wakefield accelerator

M. Litos¹, E. Adli^{1,2}, W. An³, C. I. Clarke¹, C. E. Clayton⁴, S. Corde¹, J. P. Delahaye¹, R. J. England¹, A. S. Fisher¹, J. Frederico¹, S. Gessner¹, S. Z. Green¹, M. J. Hogan¹, C. Joshi⁴, W. Lu⁵, K. A. Marsh⁴, W. B. Mori³, P. Muggli⁶, N. Vafaei-Najafabadi⁴, D. Walz¹, G. White¹, Z. Wu¹, V. Yakimenko¹ & G. Yocky¹

M. Litos *et al.*, Nature 515, (2014):

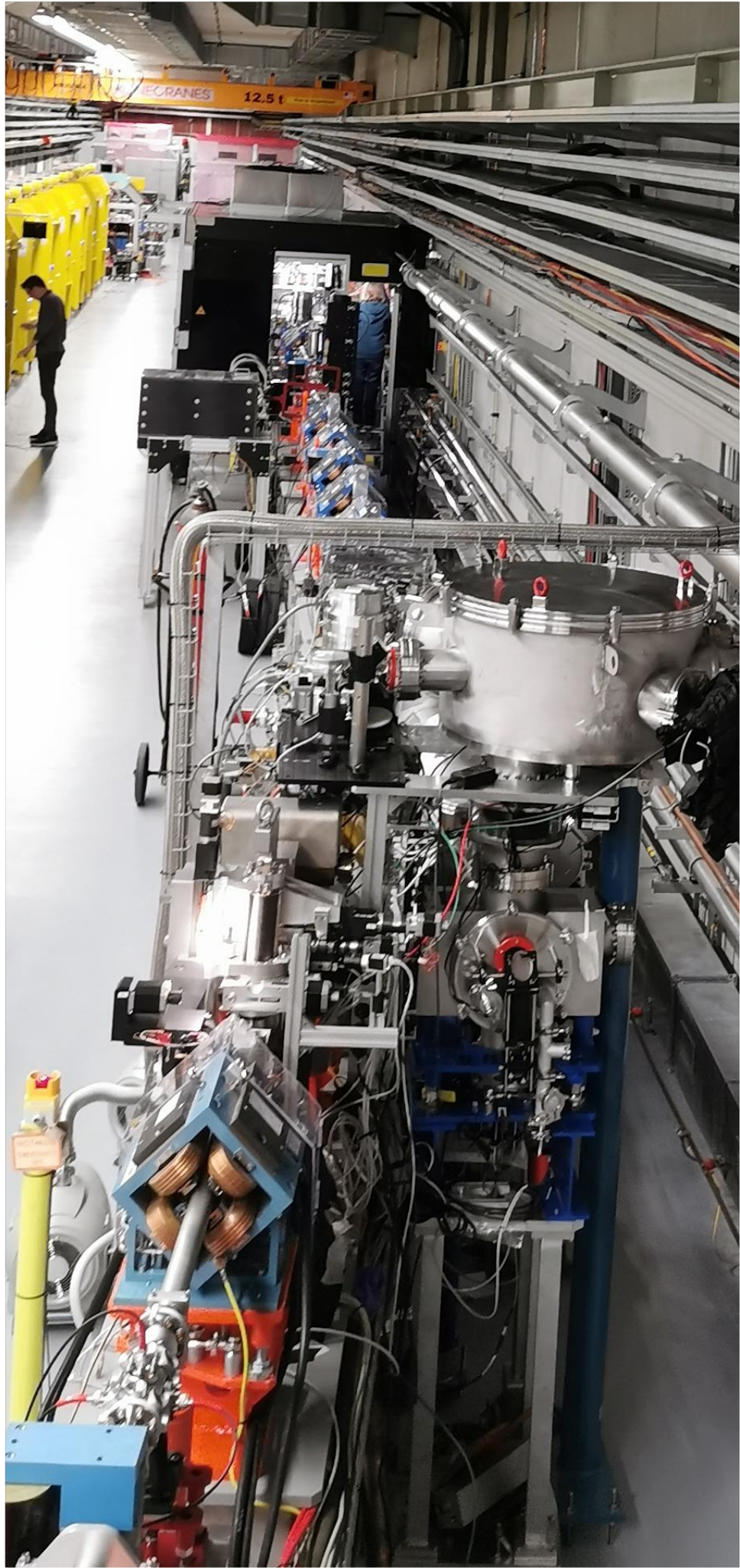
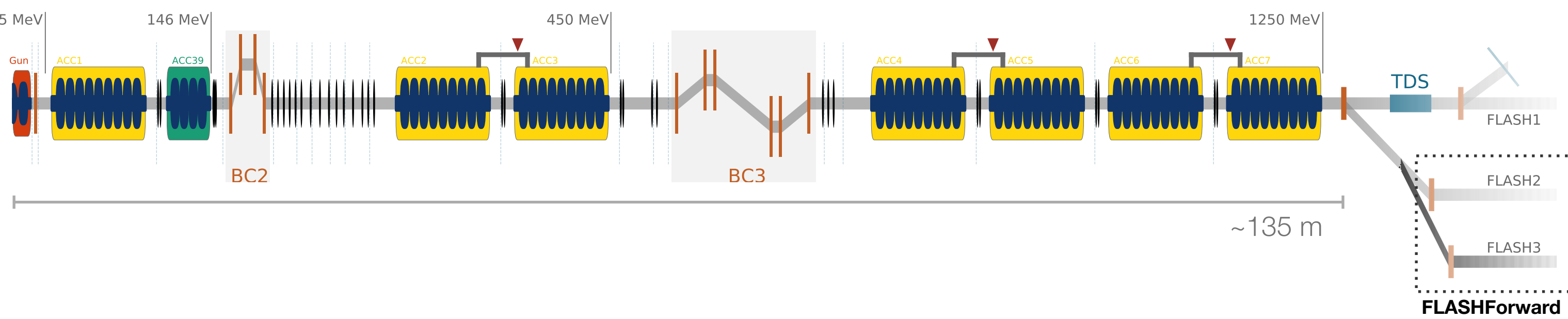
- > 4.4 GeV m⁻¹ acceleration gradient
- > 17.7% energy efficiency
- > 10% charge coupling
- > 2% energy spread

TARGETED NEXT MILESTONES:

BEAM-QUALITY PRESERVATION

FLASHForward▶▶ – A BEAM-DRIVEN PLASMA WAKEFIELD ACCELERATOR

FLASH linac

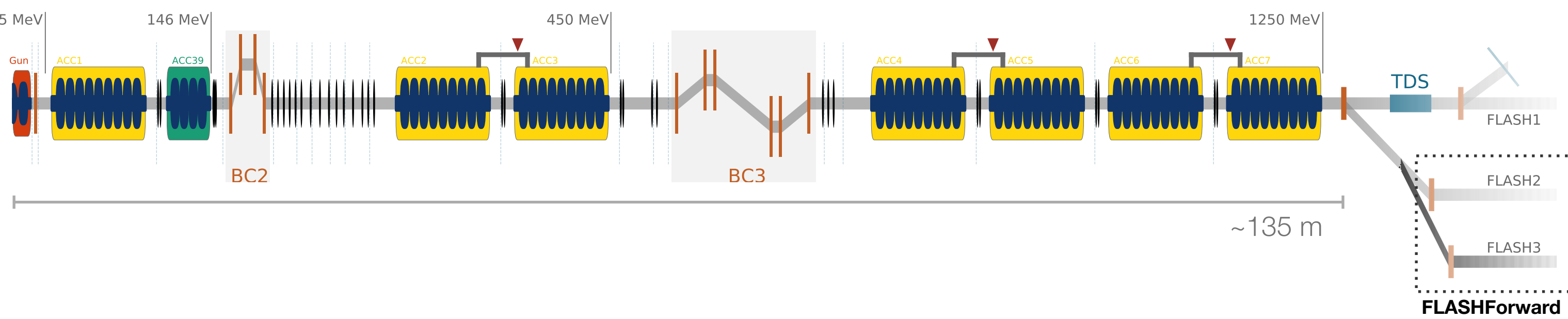


- > Electron bunch source: FLASH FEL linac
 - > Stable operation
 - > High-quality electron bunches

Energy	~1.25 GeV
Charge	1 nC
Duration	200 fs (rms)
Emittance	~2 mm mad

FLASHForward▶▶ – A BEAM-DRIVEN PLASMA WAKEFIELD ACCELERATOR

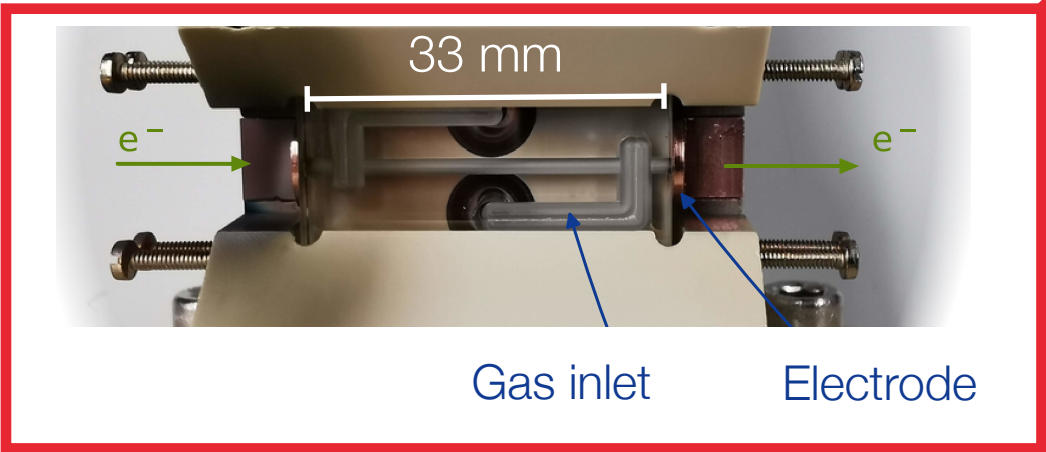
FLASH linac



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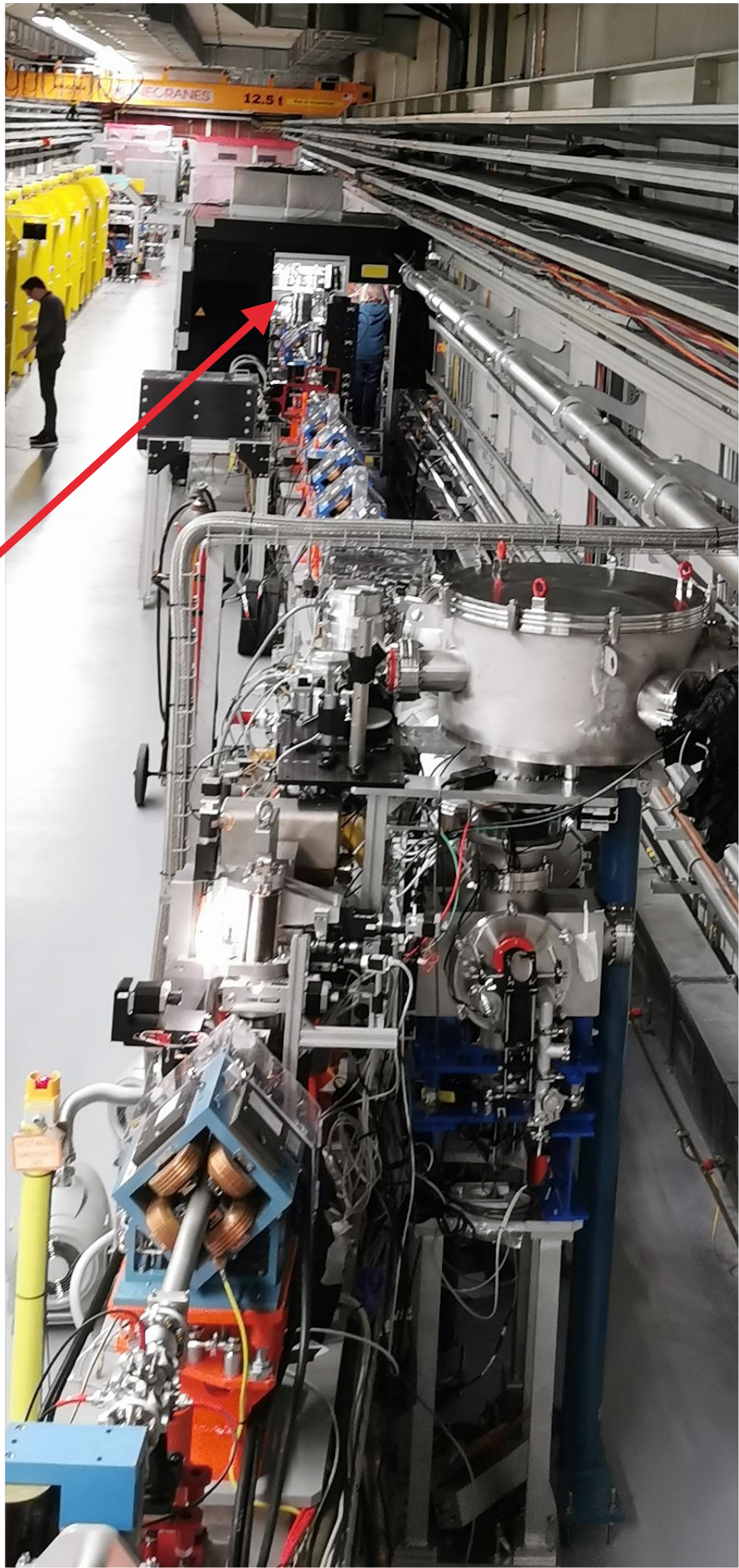
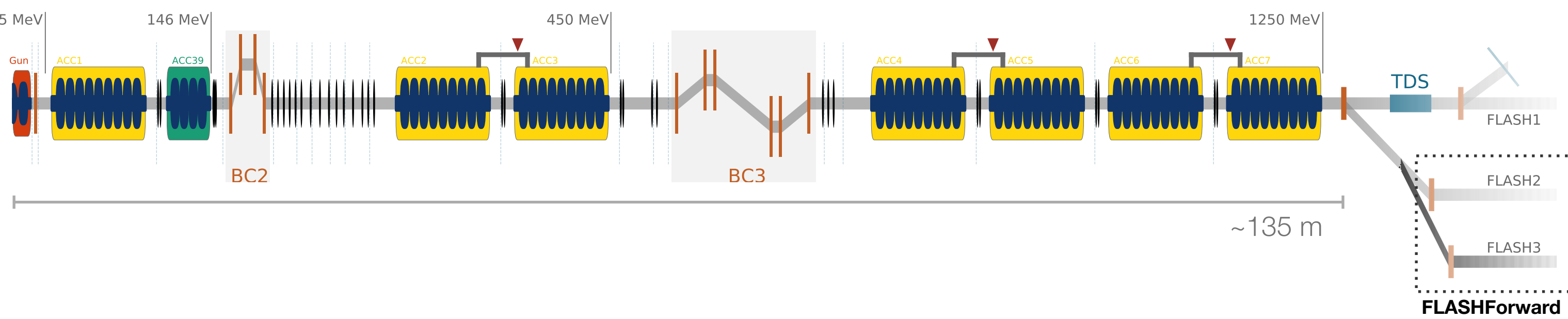
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- > Plasma source:
 - > Capillary in sapphire structure
 - > Discharge-ignited Argon



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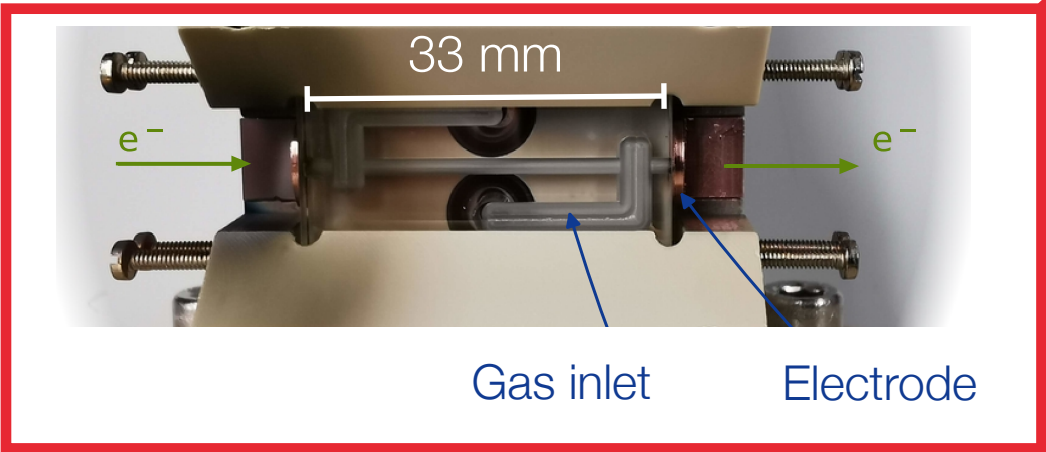
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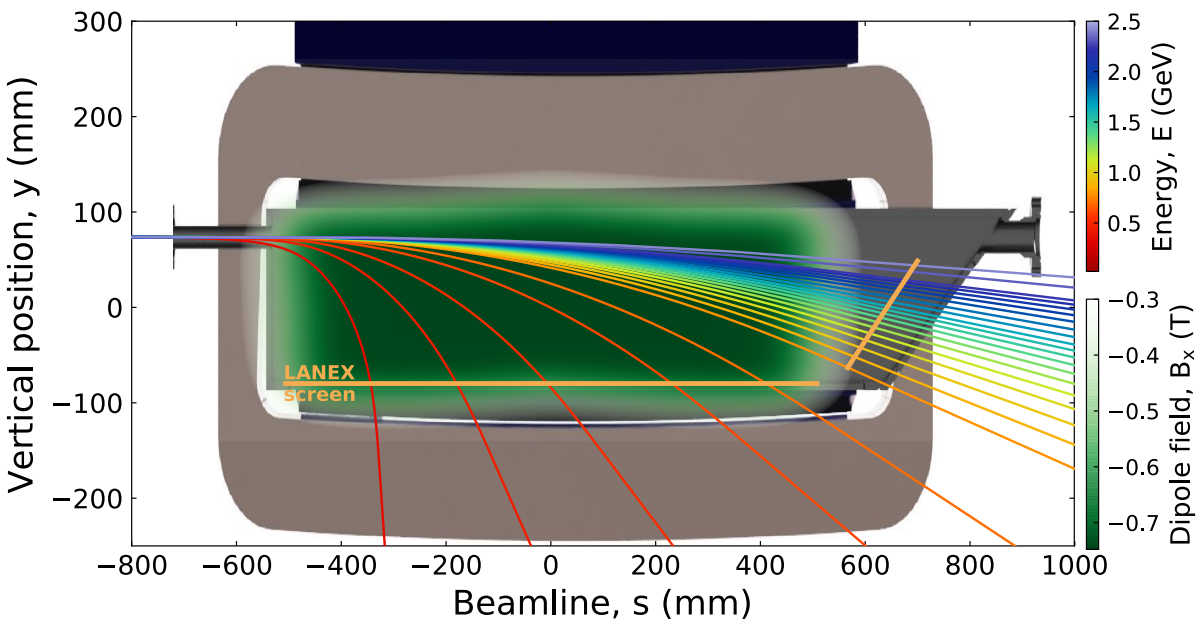
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> Diagnostics:

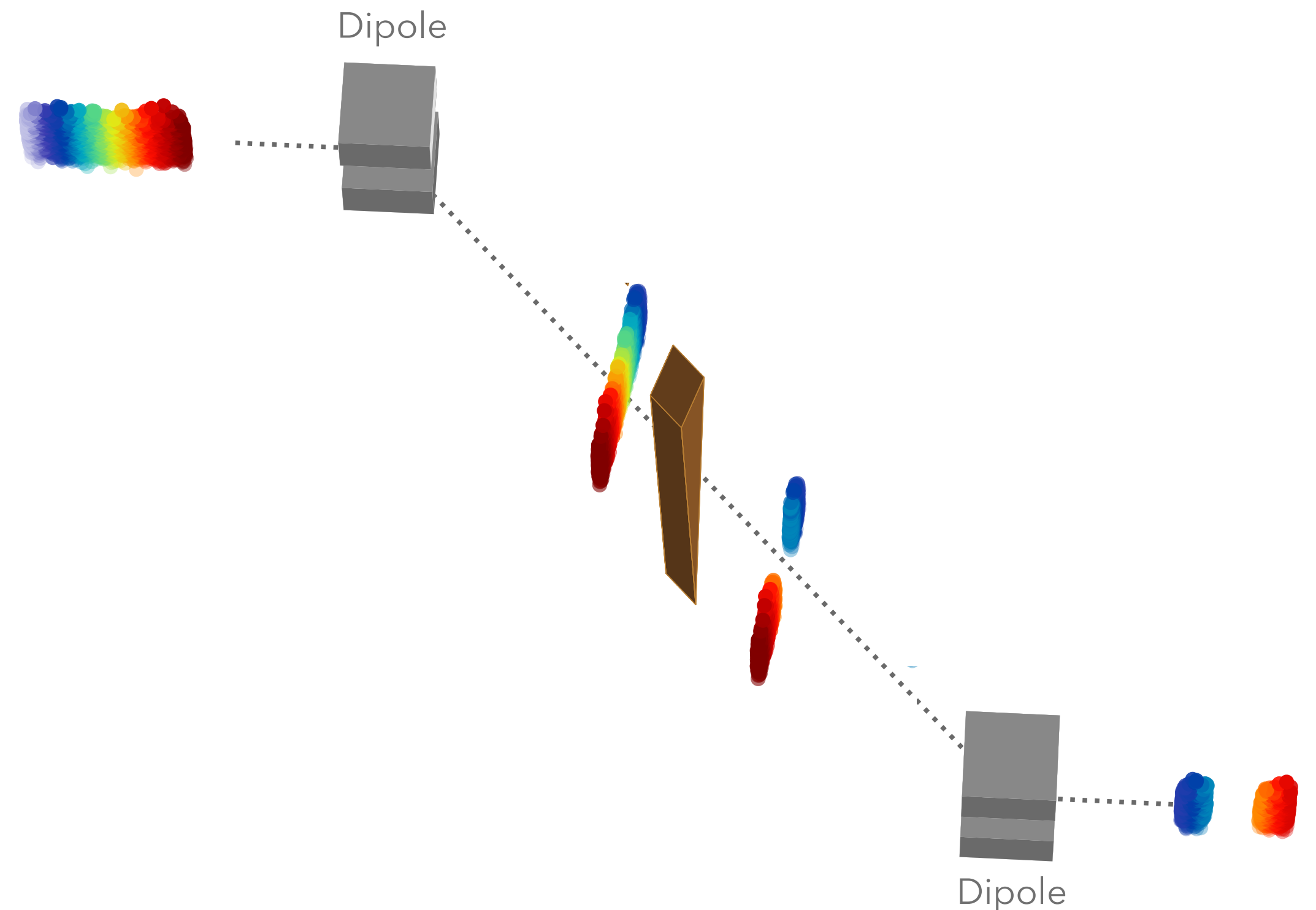
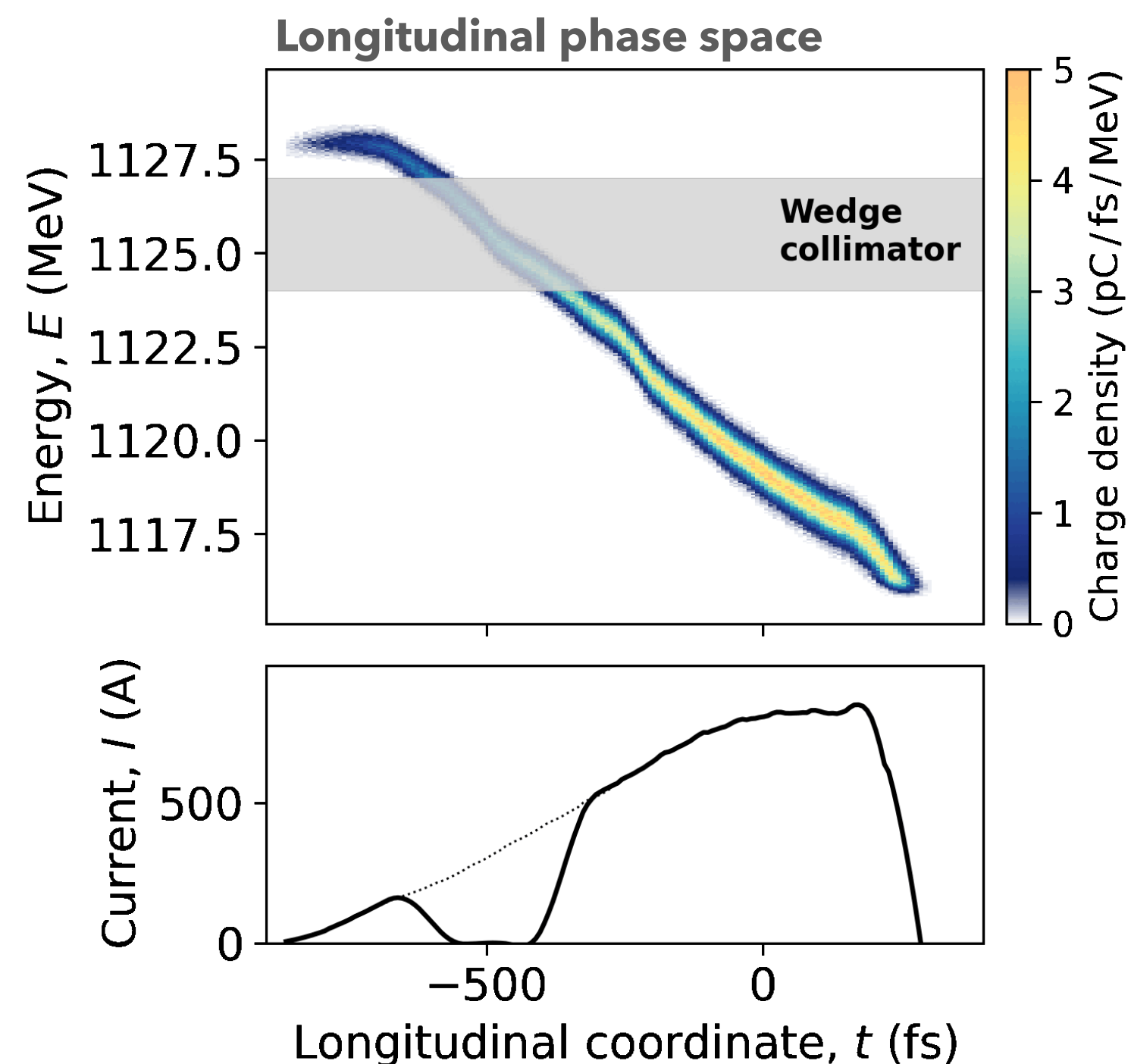
- > Dipole spectrometer



TUNABLE TWO-BUNCH GENERATION VIA ENERGY COLLIMATION

S. Schröder *et al.*, J. Phys. Conf. Ser. 1596, 012002 (2020)

- > Linearised longitudinal phase space
- > Collimators in dispersive extraction section

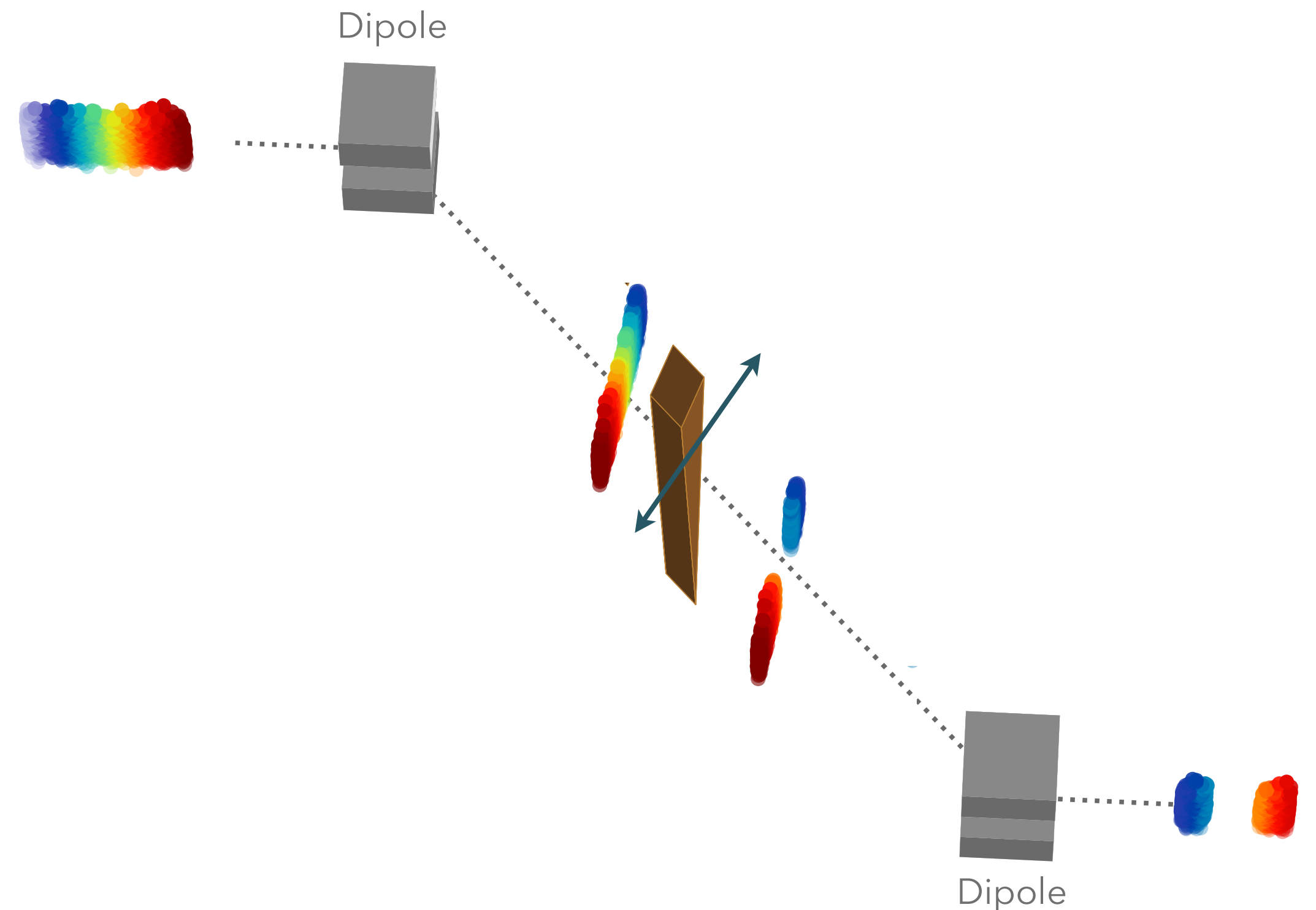
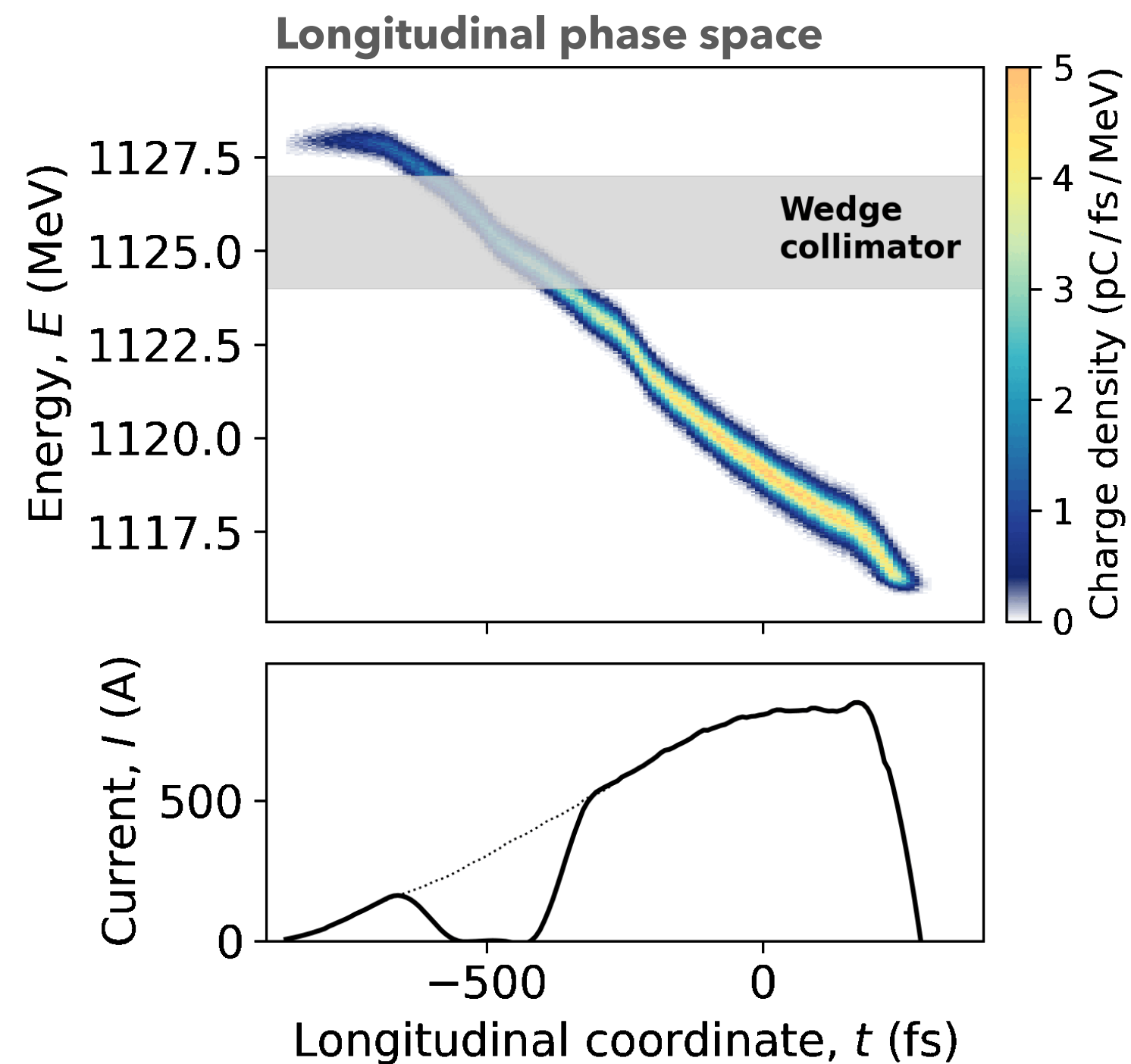


ENABLING FEMTOSECOND-PRECISION CURRENT-PROFILE MODIFICATION

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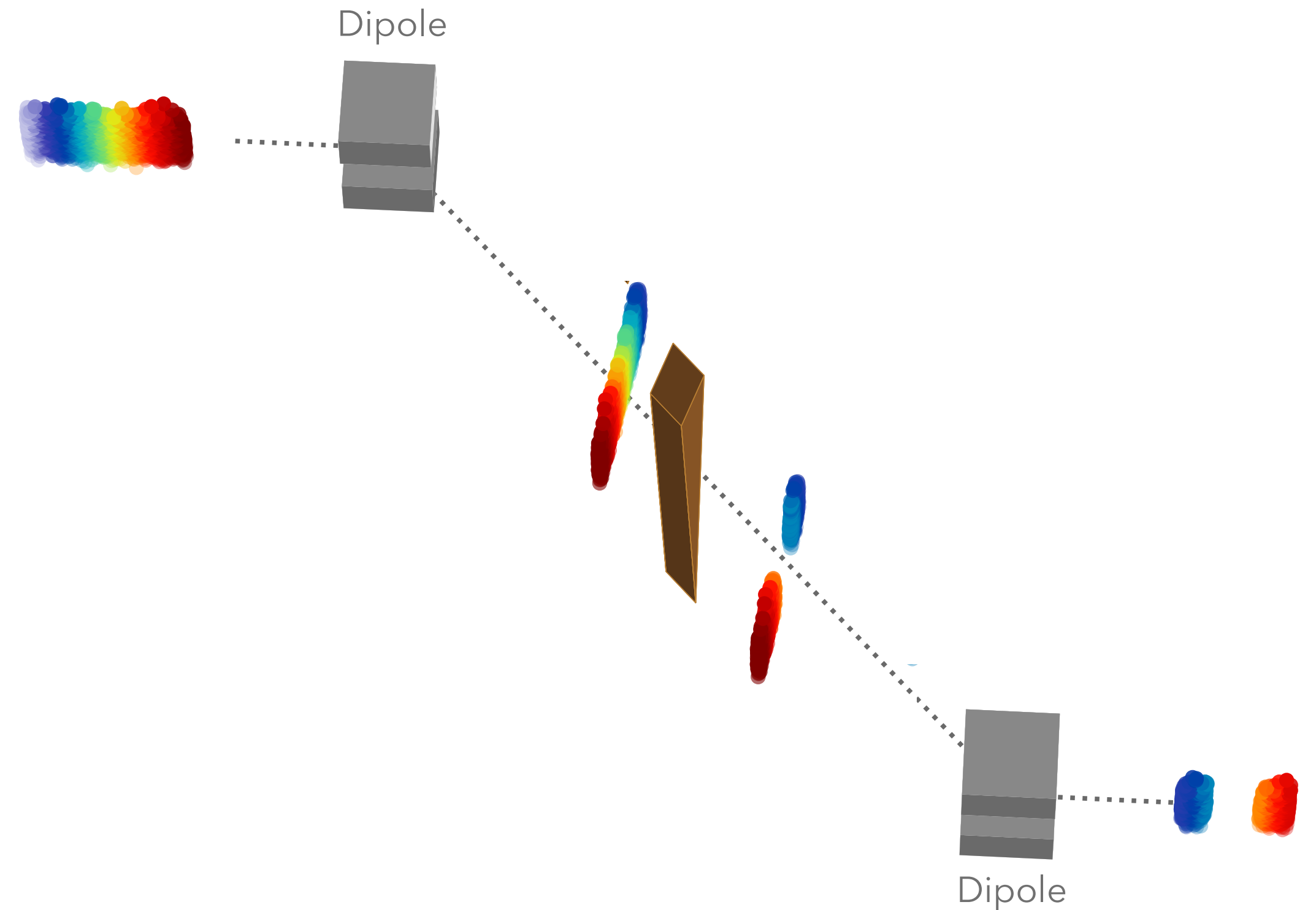
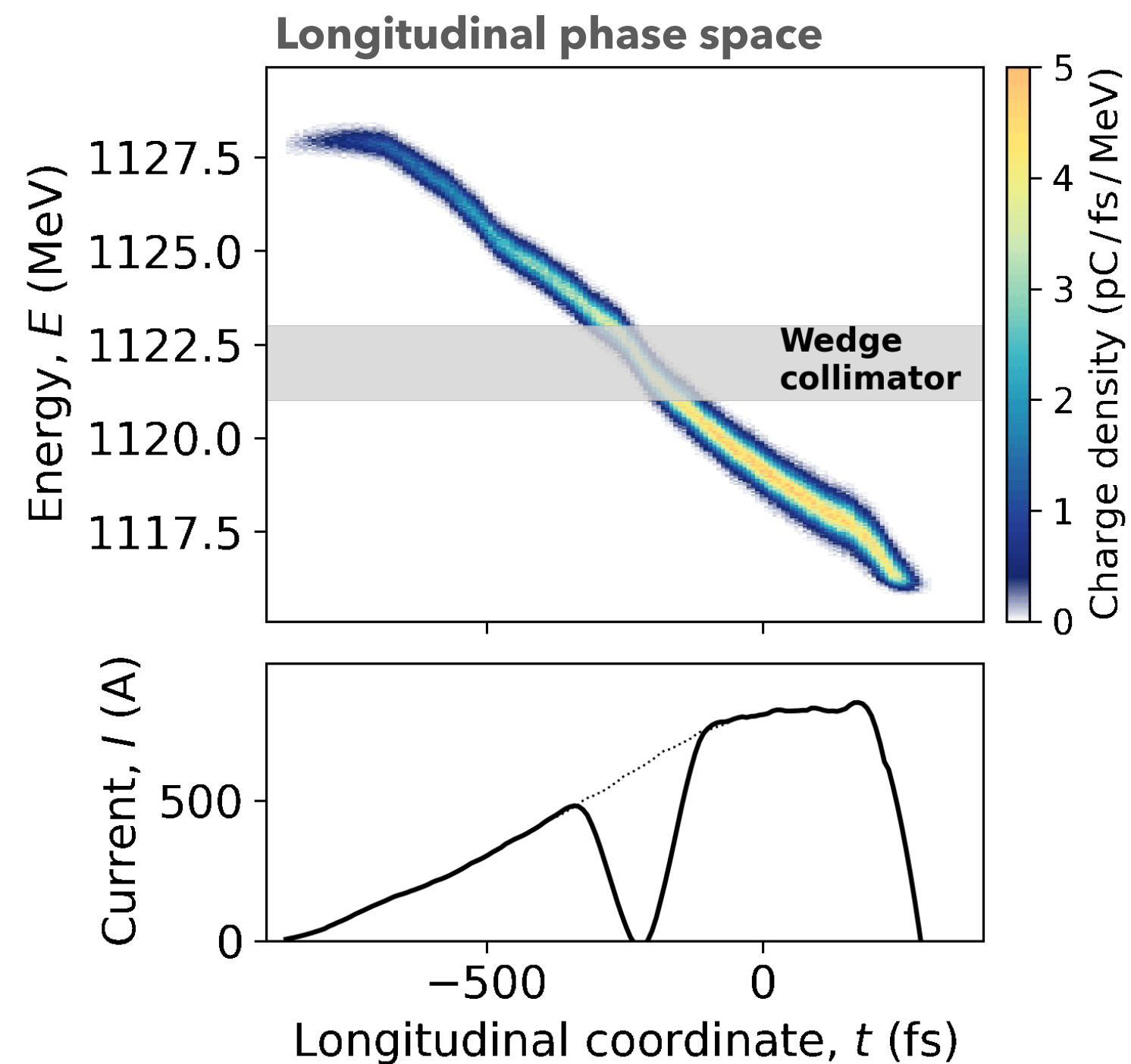


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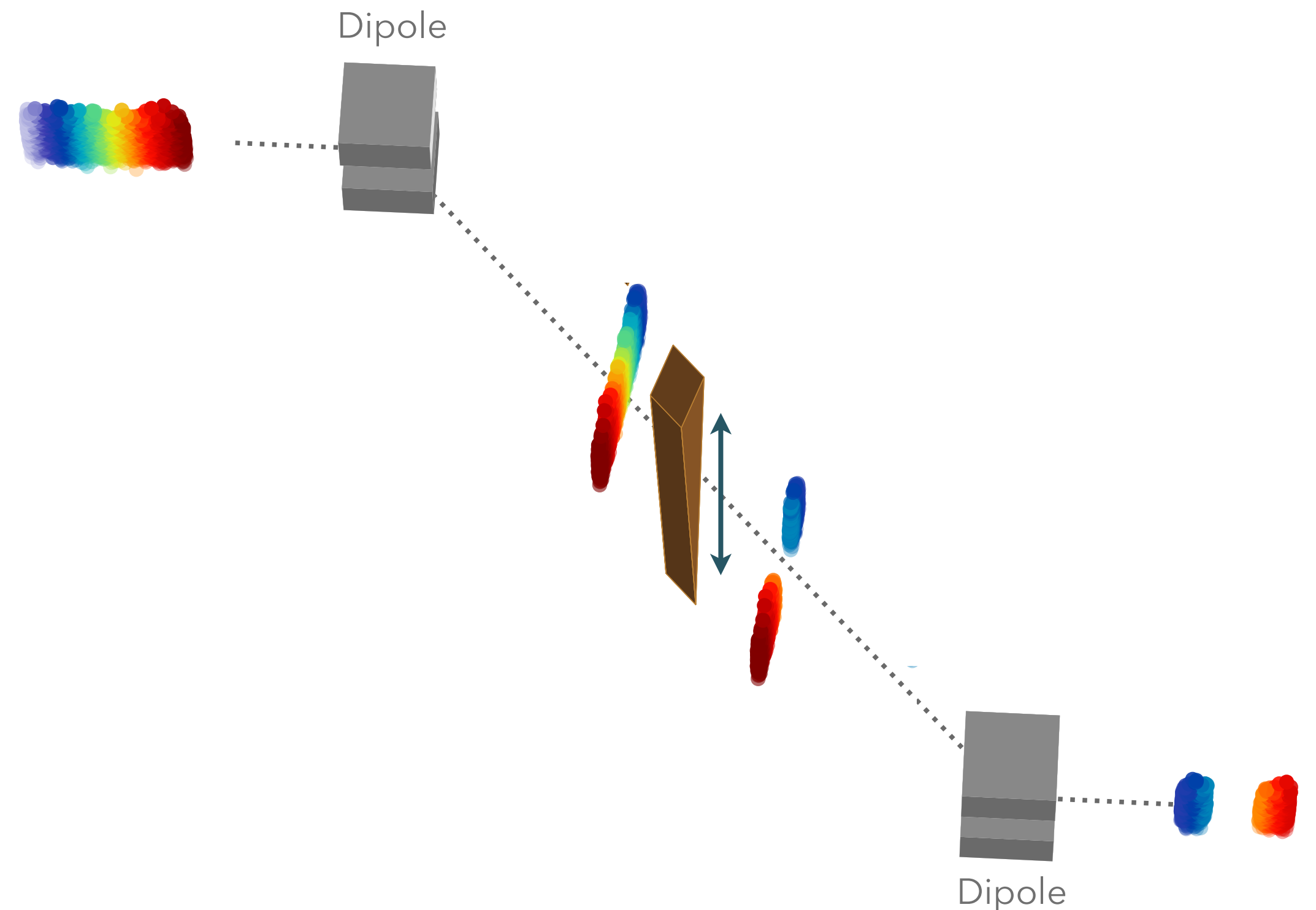
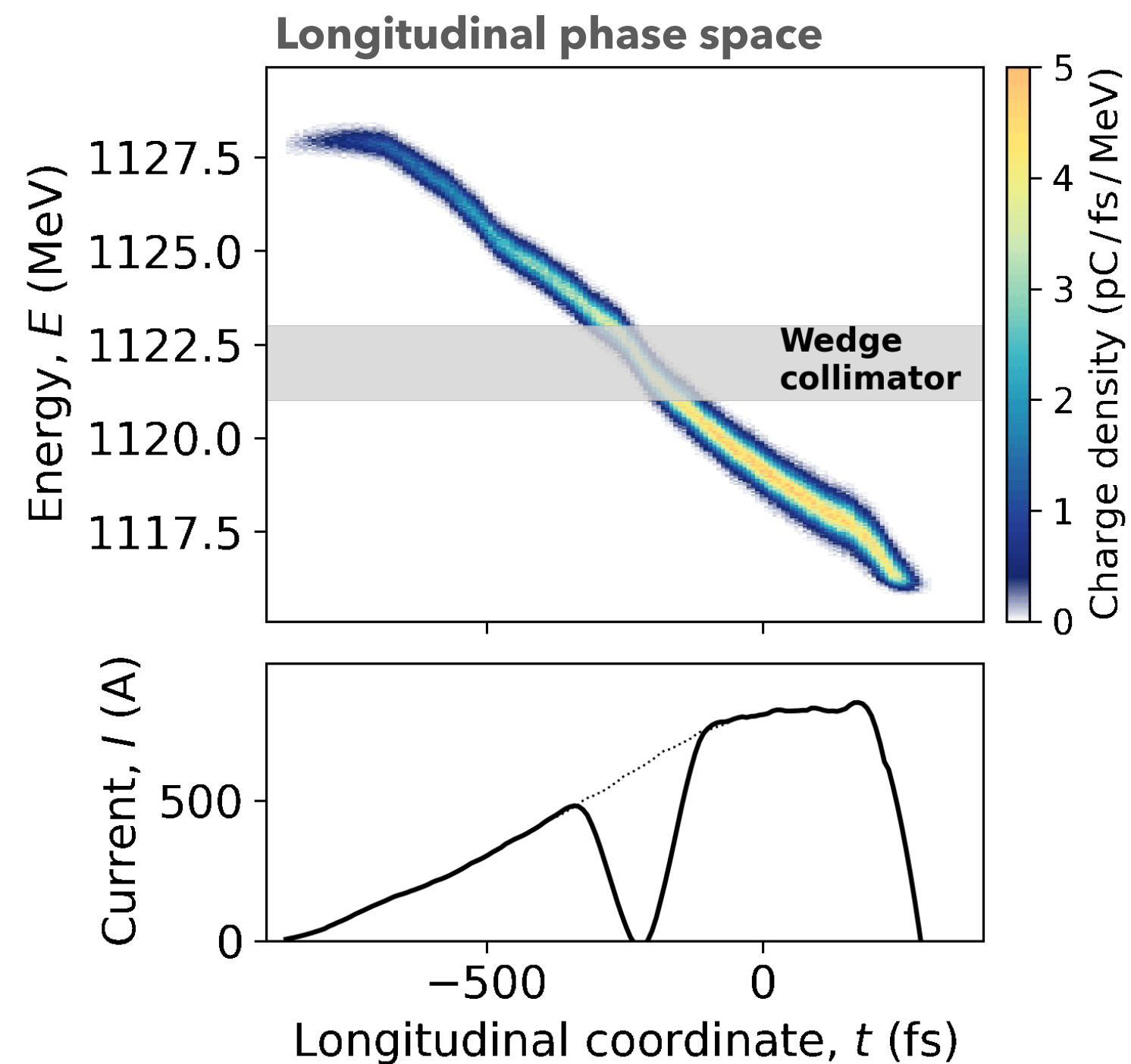


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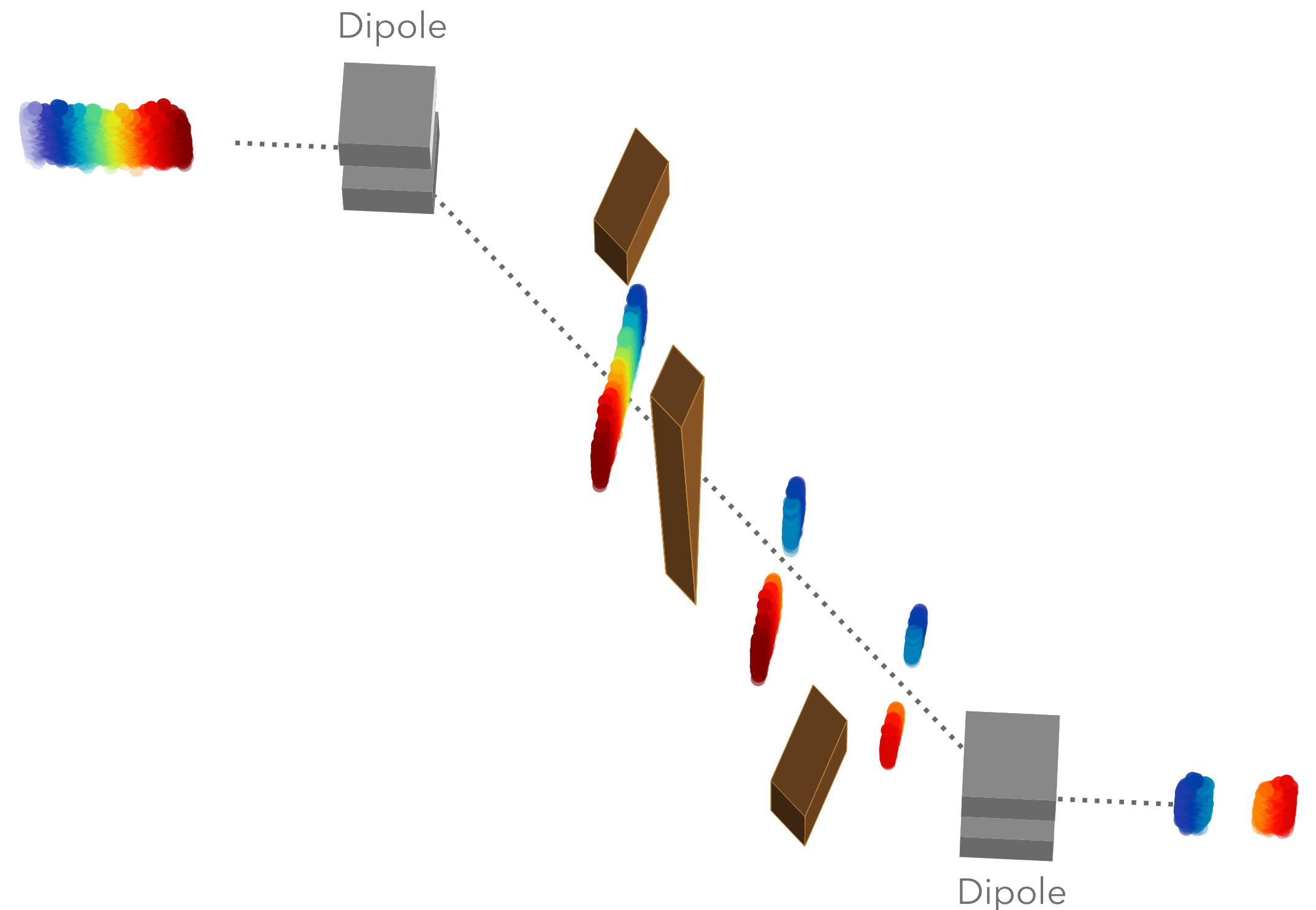
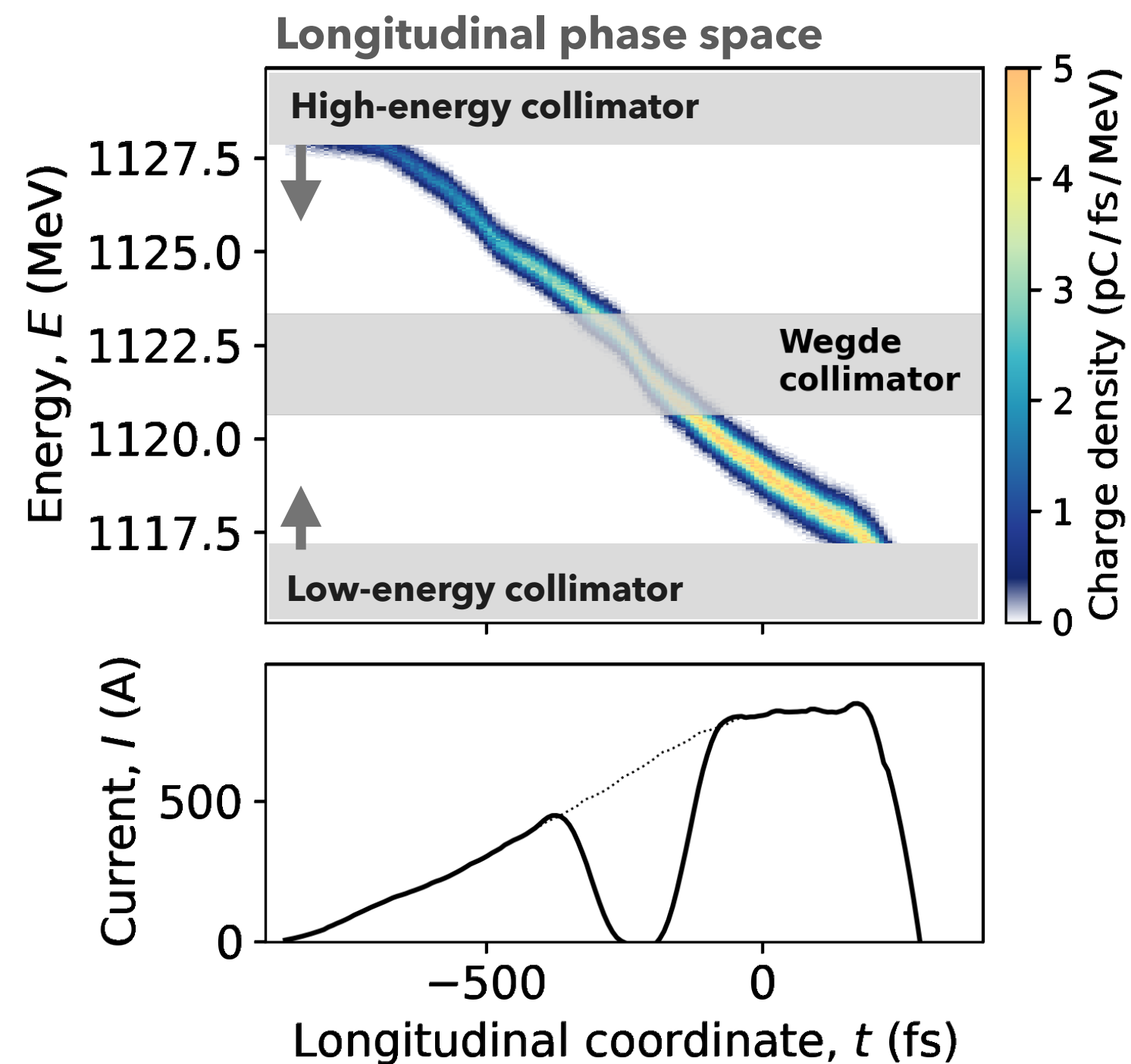


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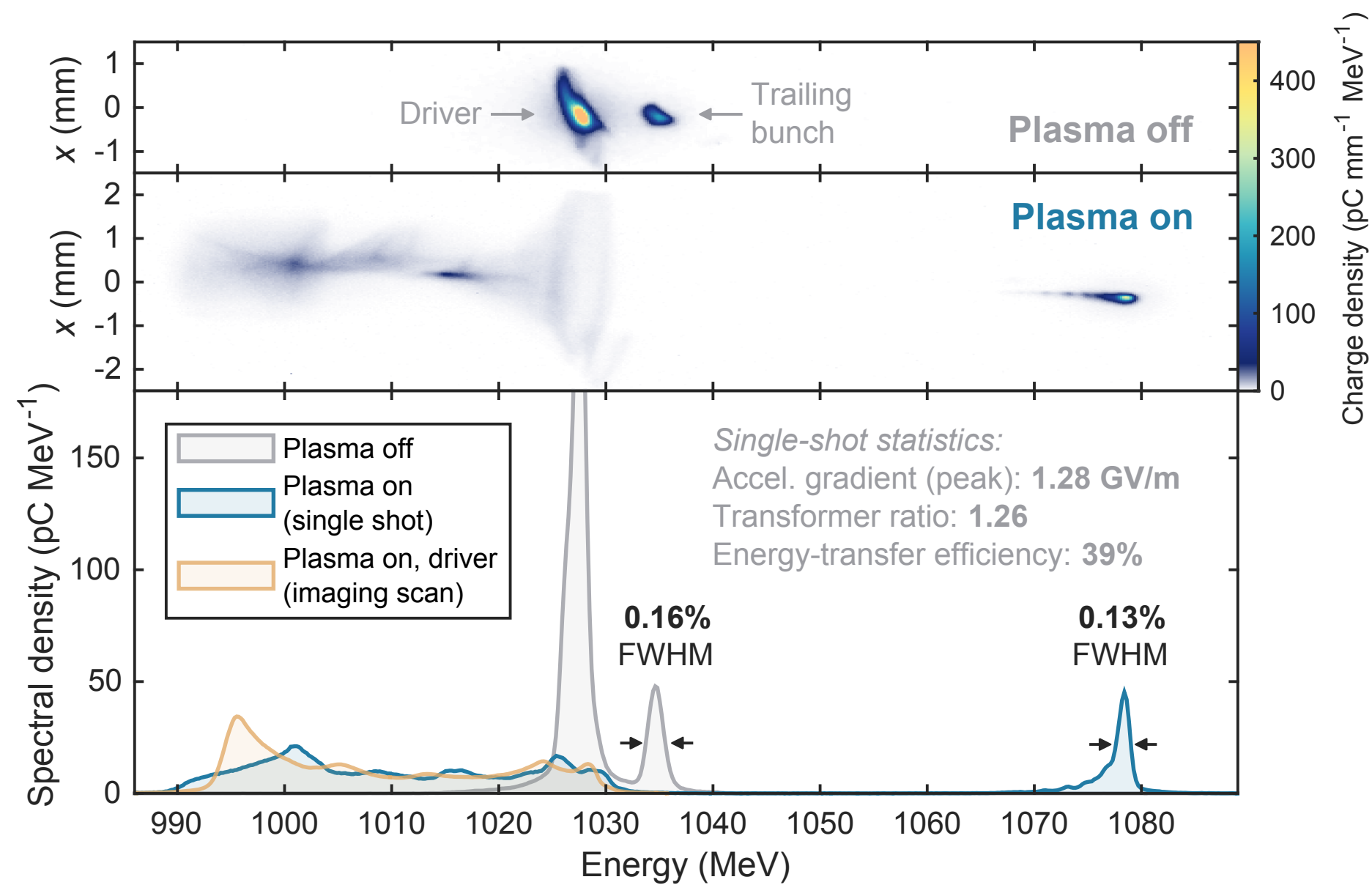
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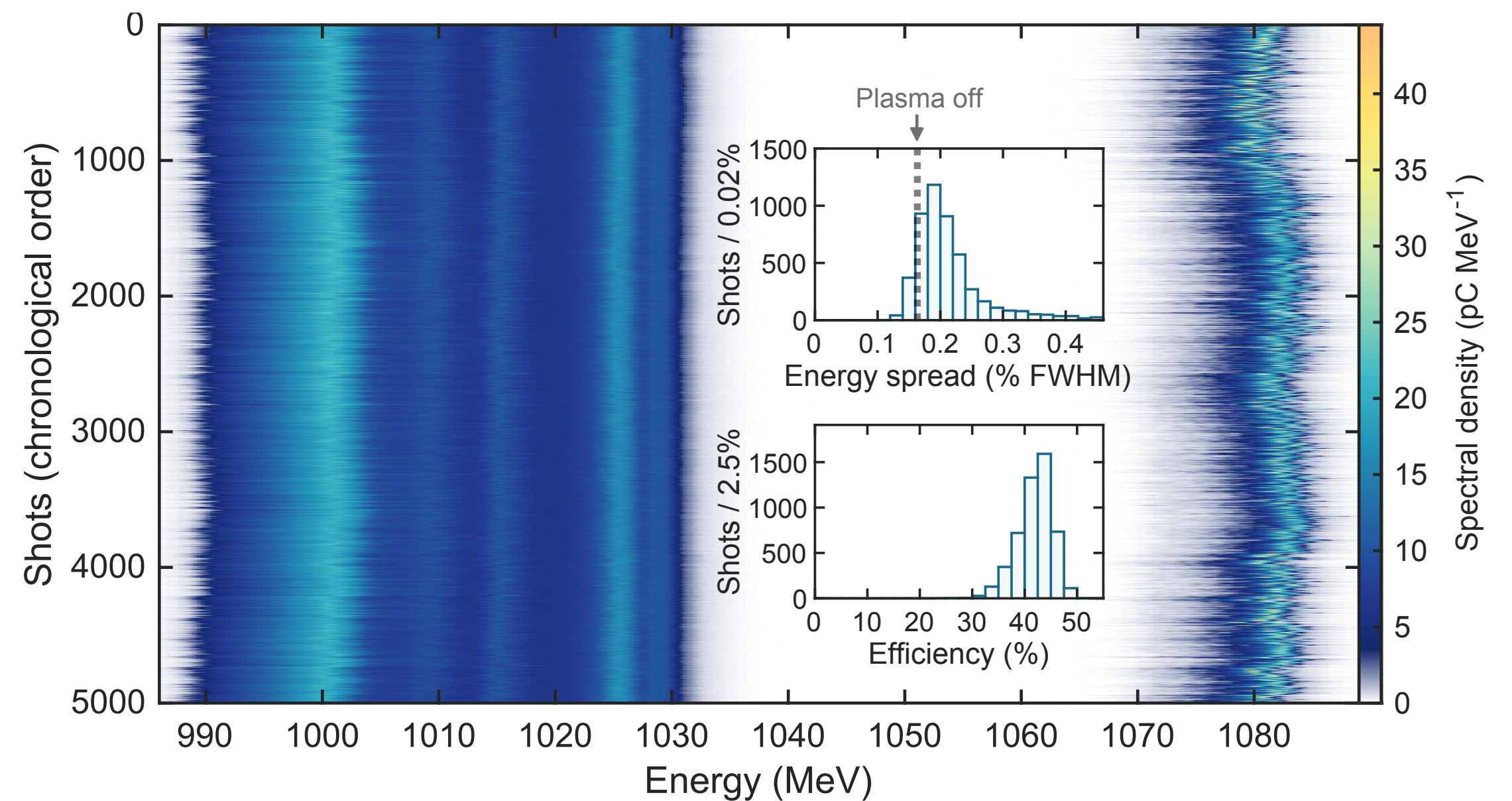
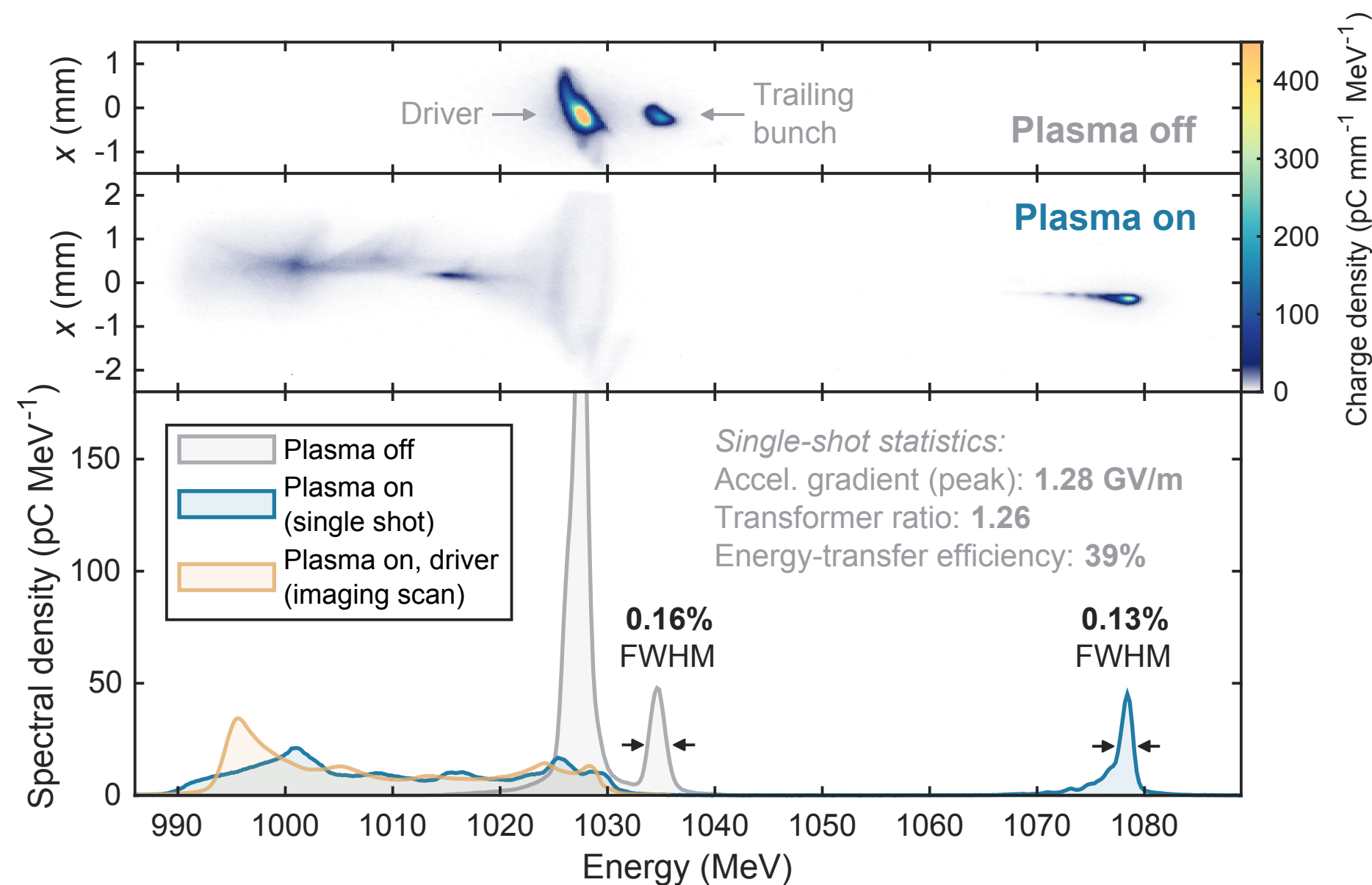
ENERGY-SPREAD-PRESERVING PLASMA WAKEFIELD ACCELERATION

C.A. Lindstrøm, J.M. Garland, **S. Schröder** *et al.*, Phys. Rev. Lett. 126, 014801 (2021)



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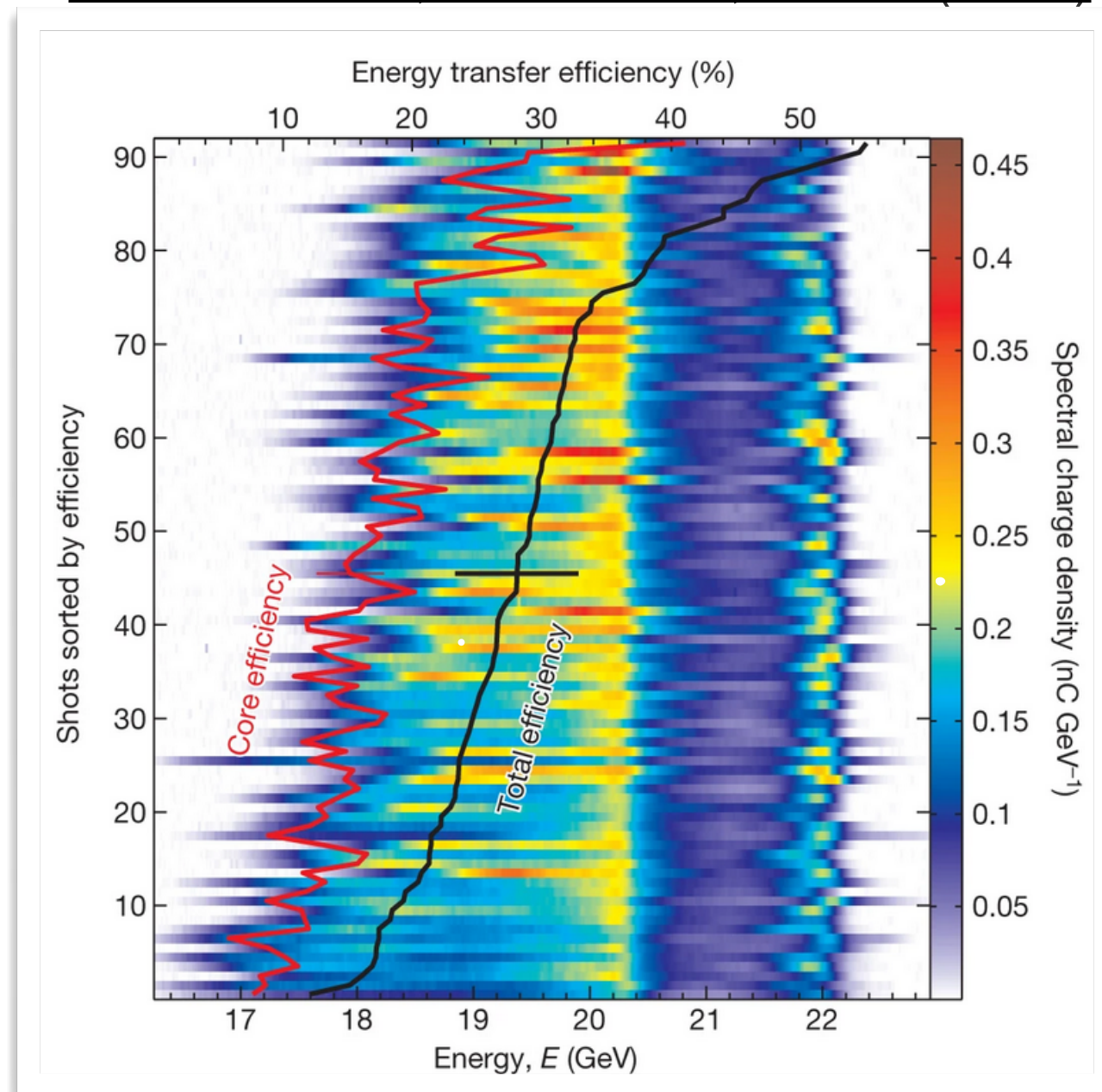


- > 0.16% (FWHM) energy spread preserved
- > 42%±4% energy-transfer efficiency
- > 100% charge coupling

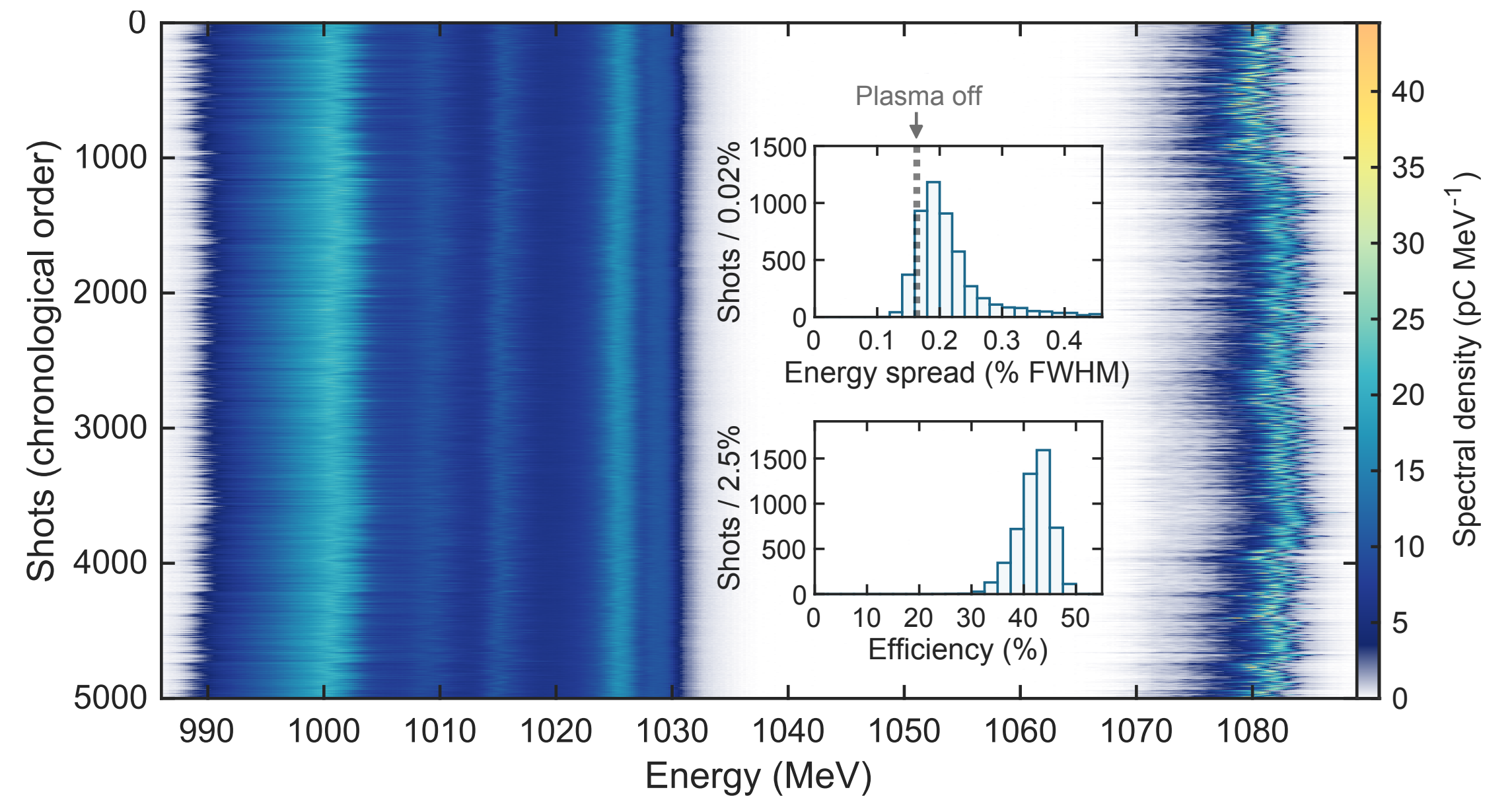
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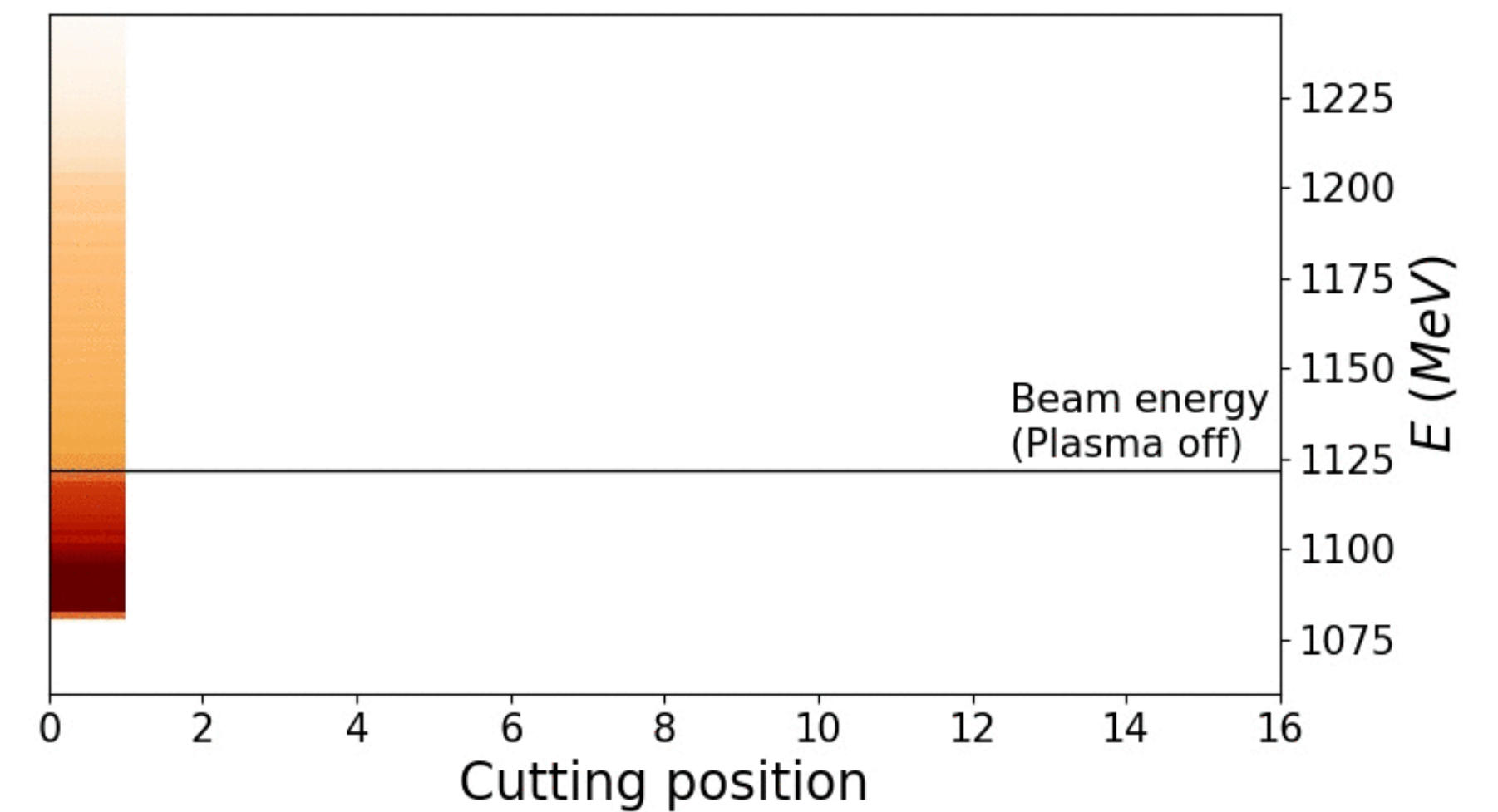
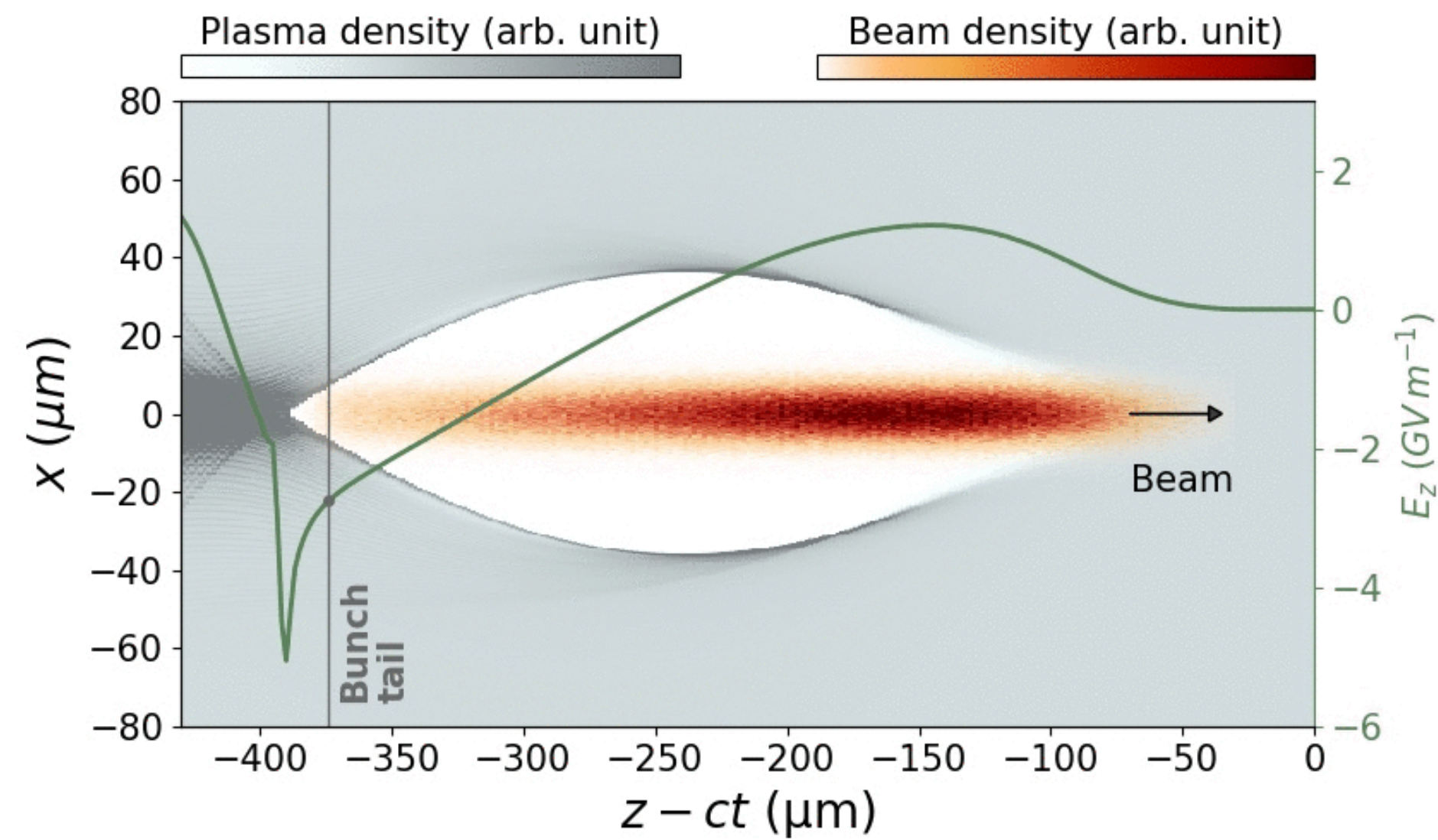
- > 2% energy spread
- > 17.7 ± 6.3 % energy transfer efficiency
- > 10% charge coupling



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- > $42\% \pm 4\%$ energy-transfer efficiency
- > 100% charge coupling

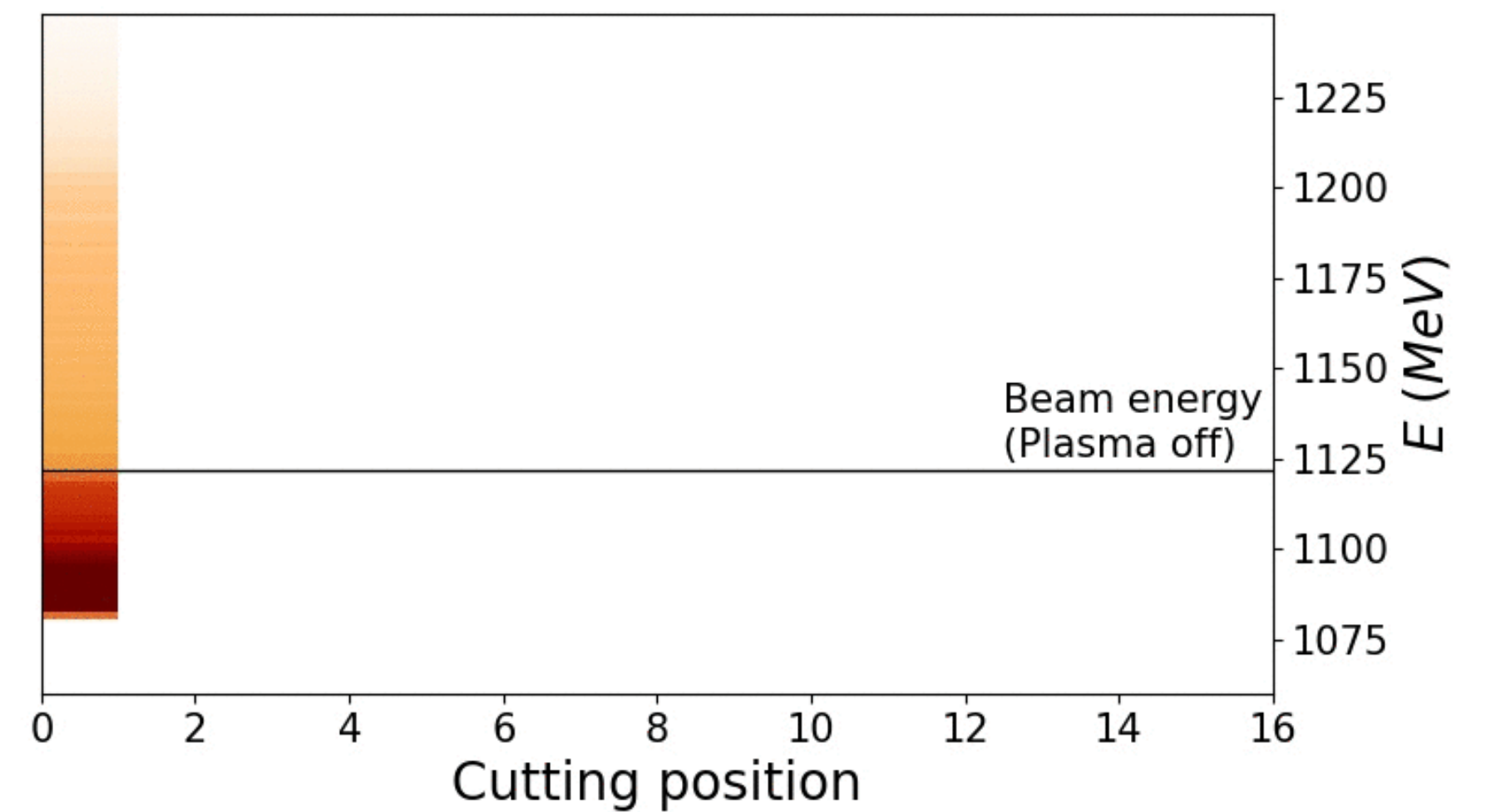
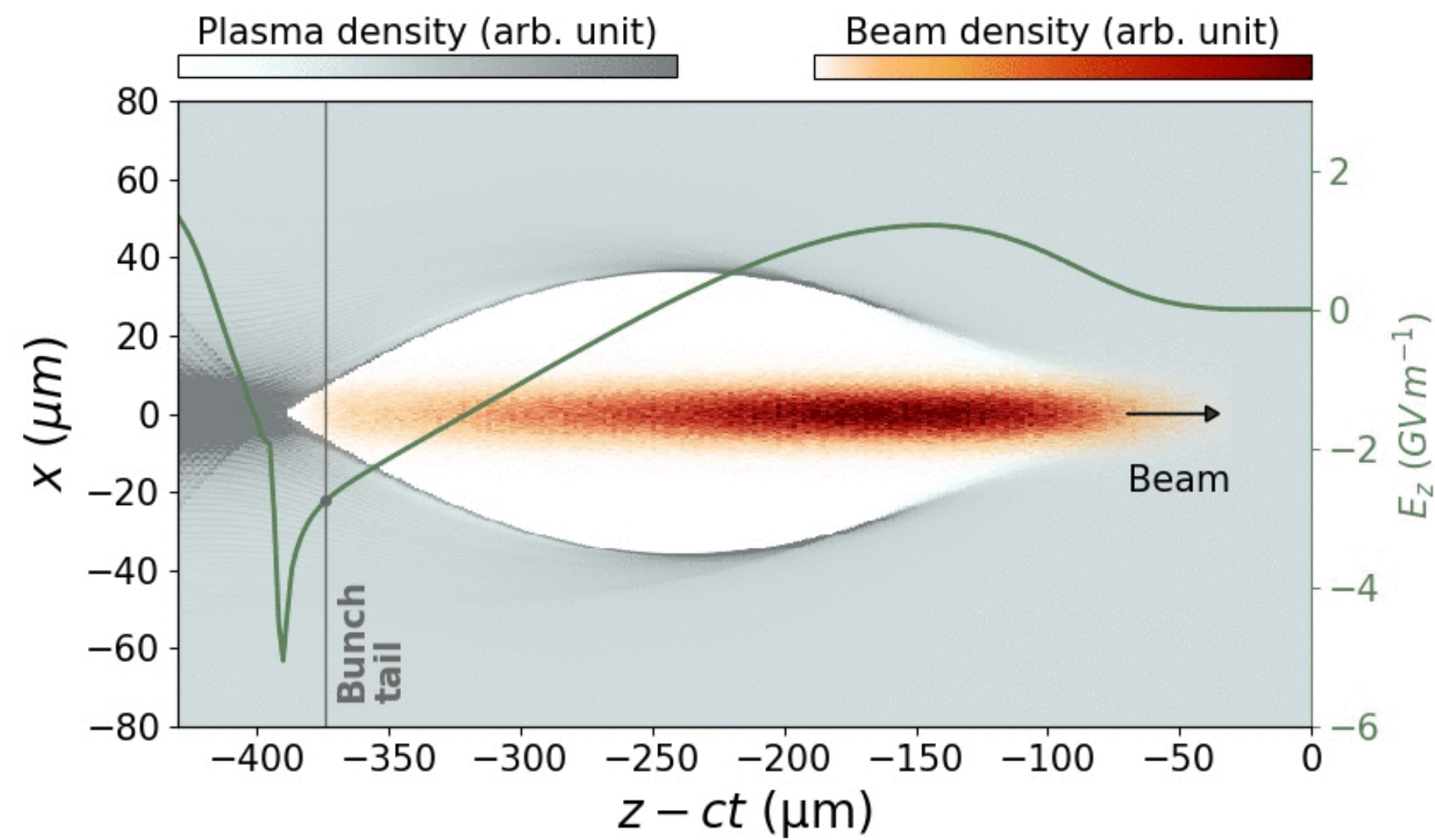
HIGH-RESOLUTION SAMPLING OF PLASMA WAKEFIELDS

S. Schröder *et al.*, Nat. Commun. 11, 5984 (2020)



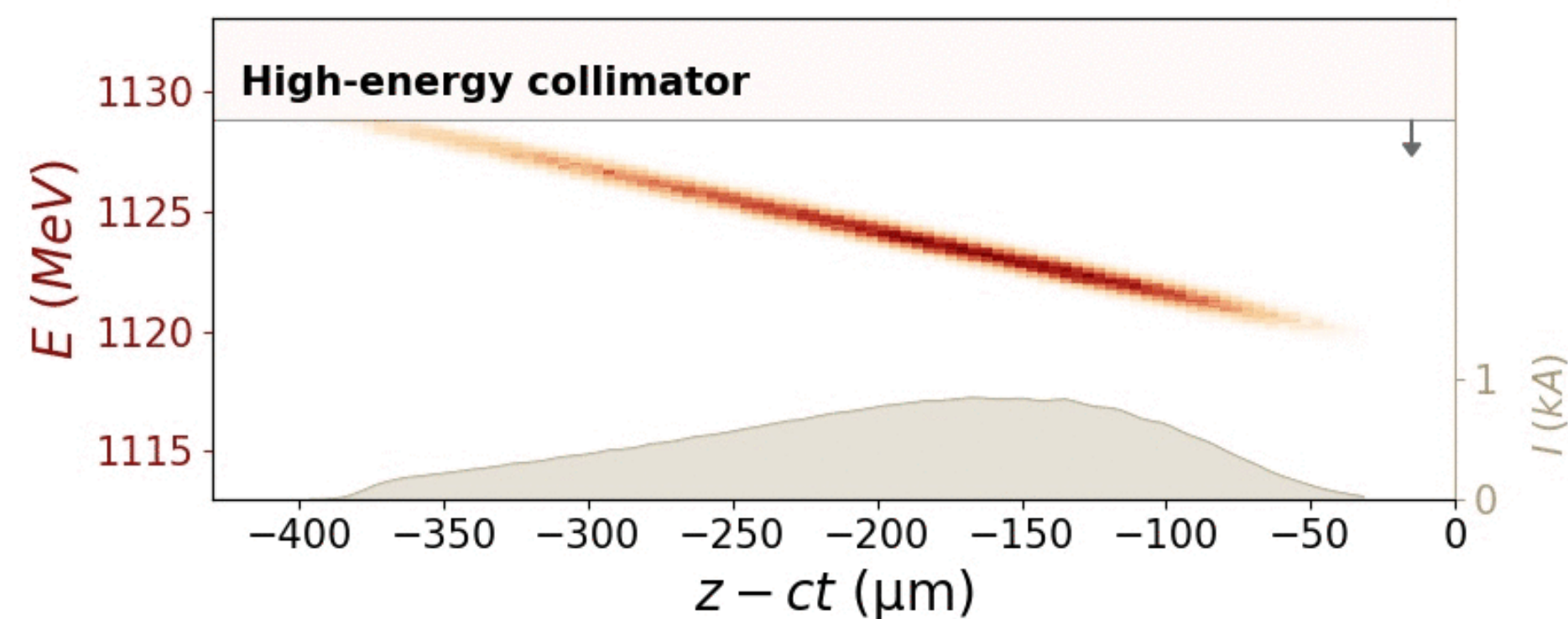
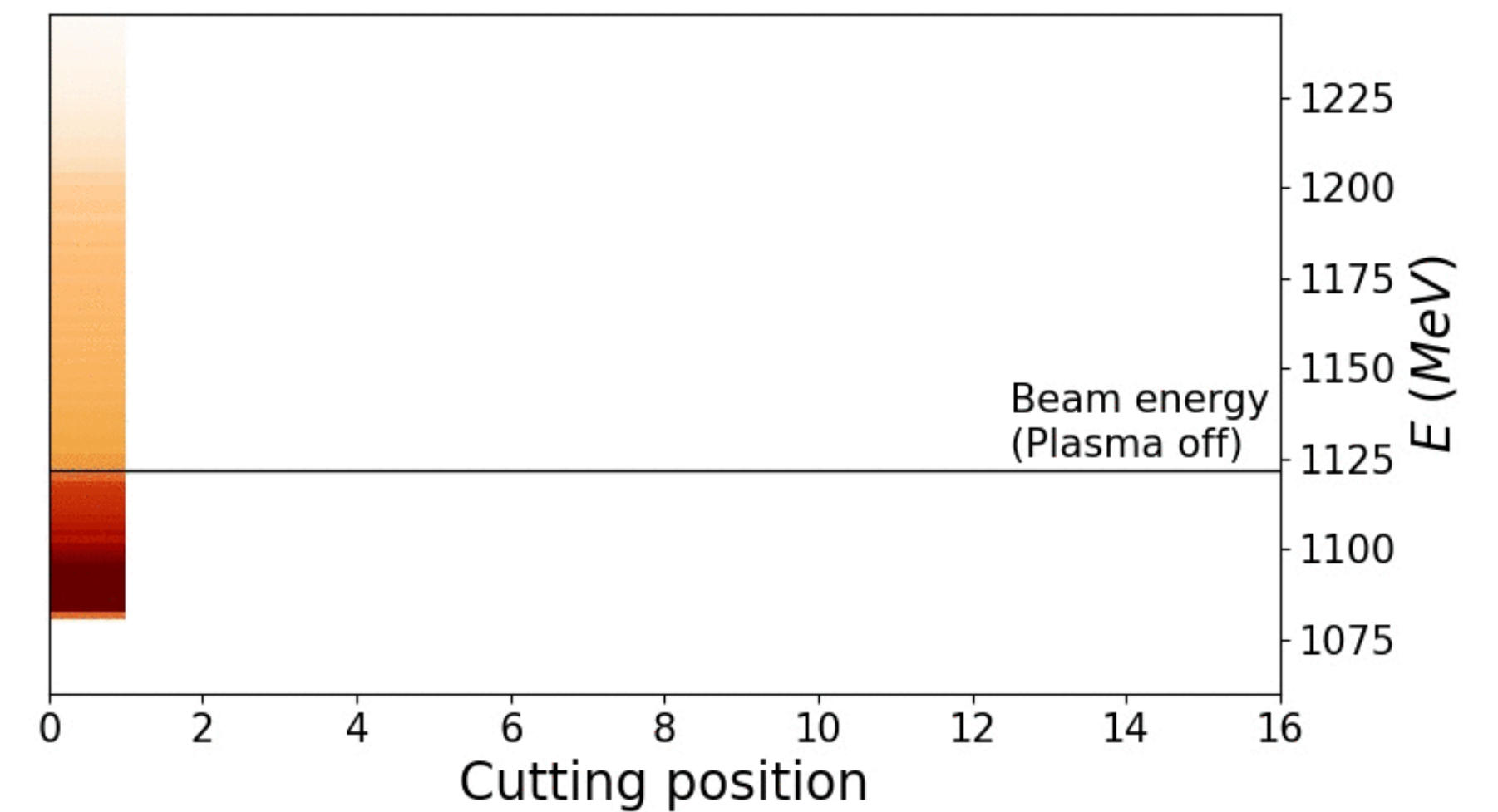
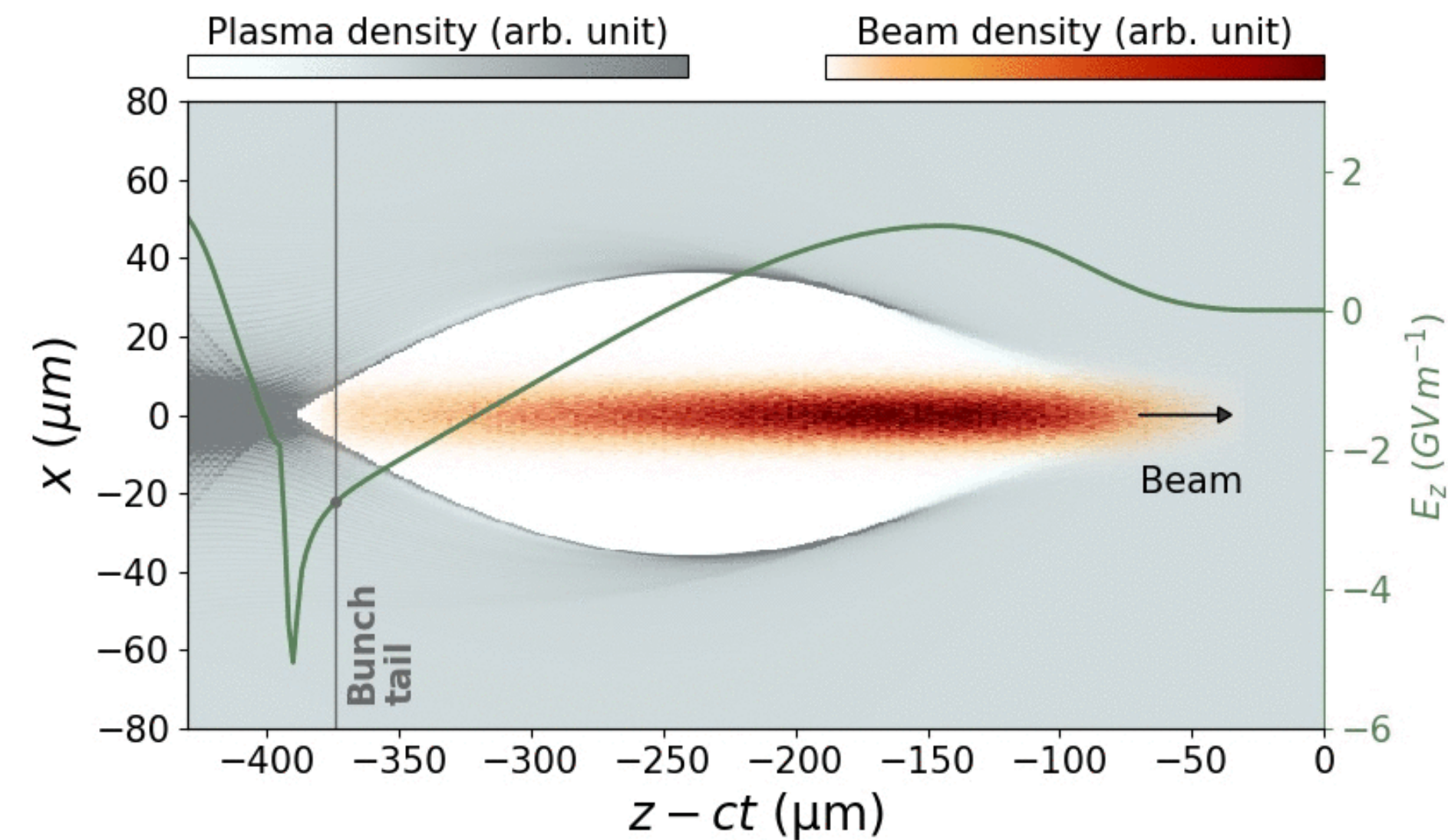
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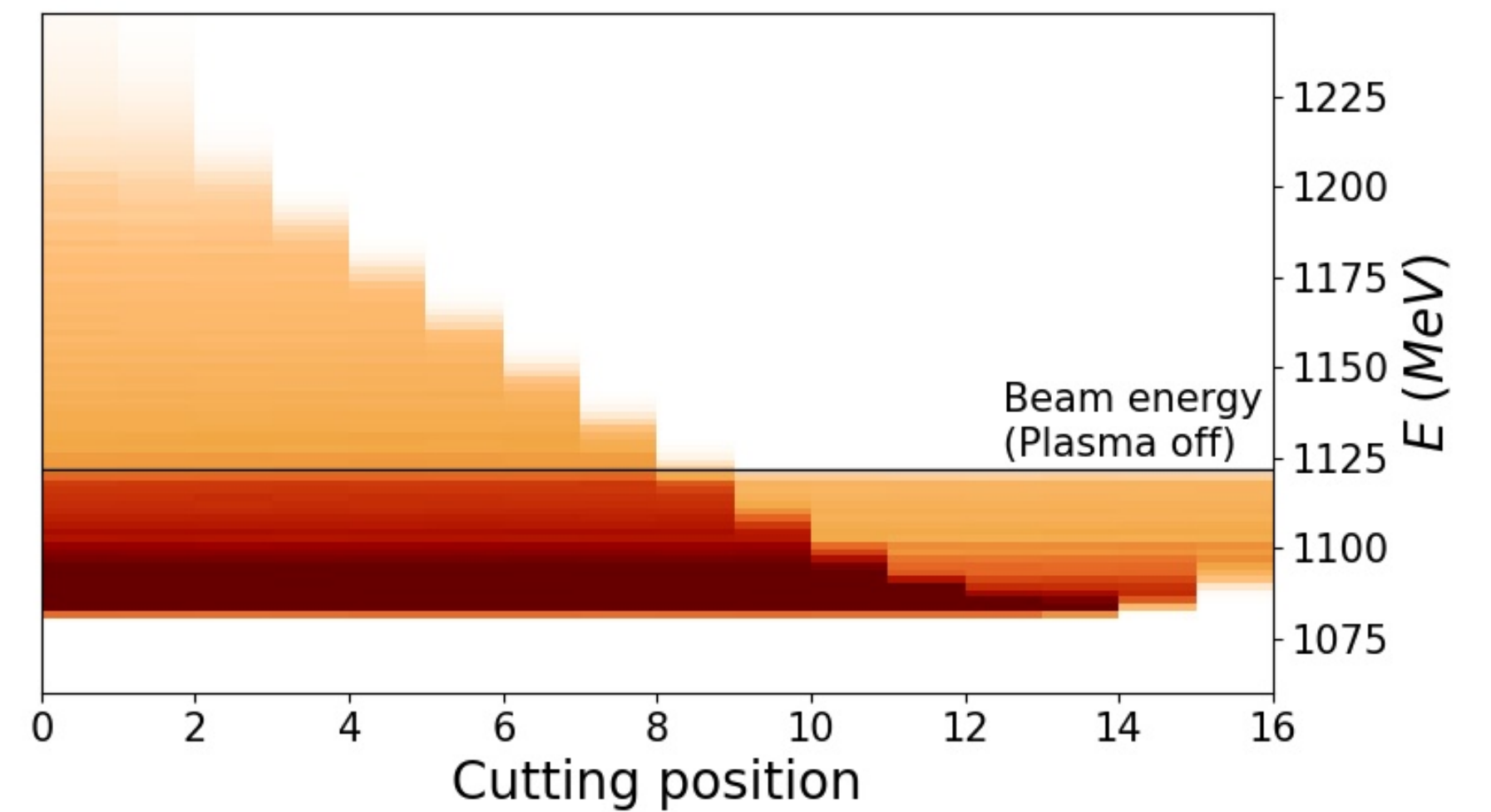
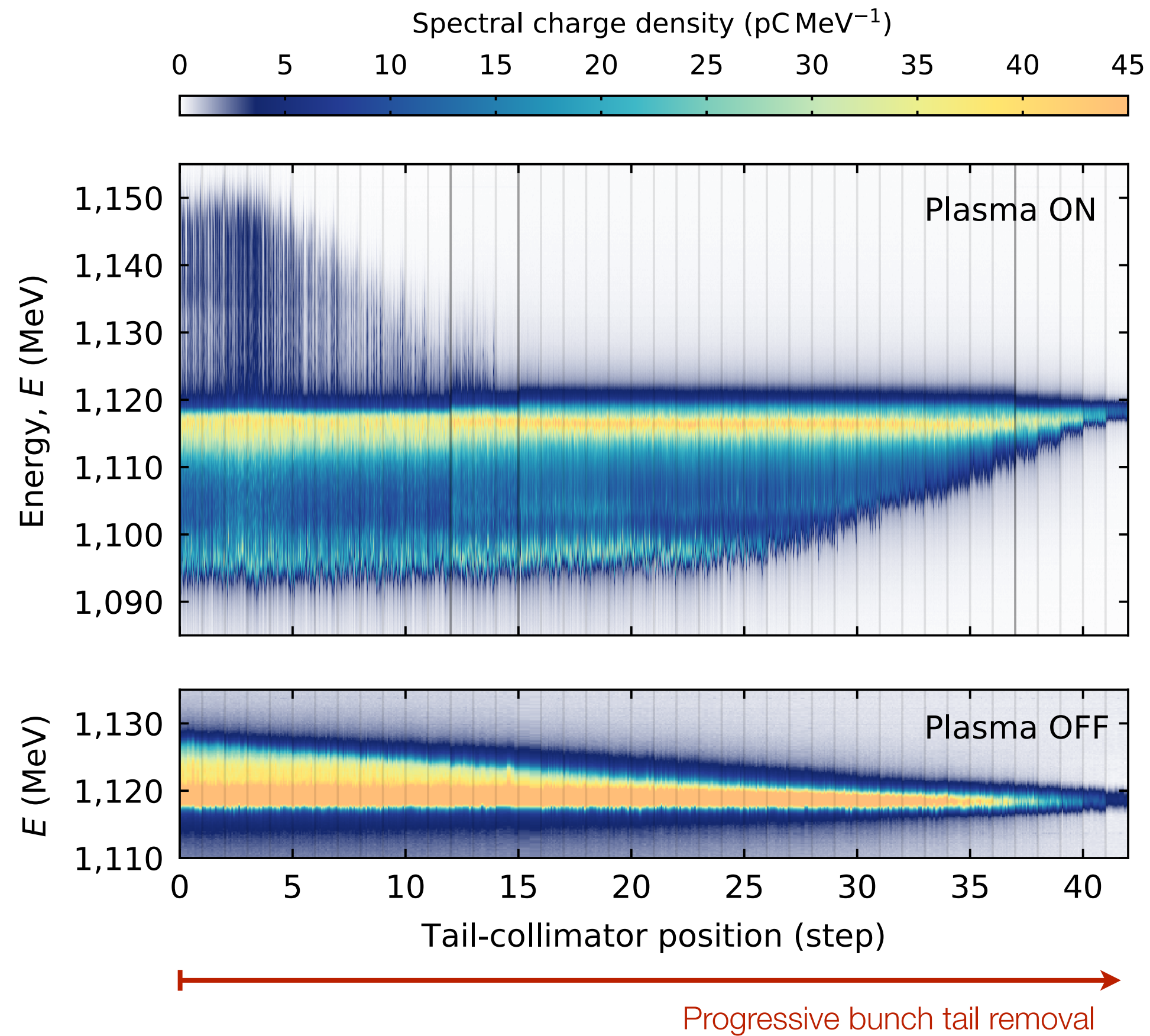


FEMTOSECOND RESOLVED WAKEFIELD MEASUREMENT:

1. Longitudinal phase space measurement of incoming bunch
2. Collimator position scan

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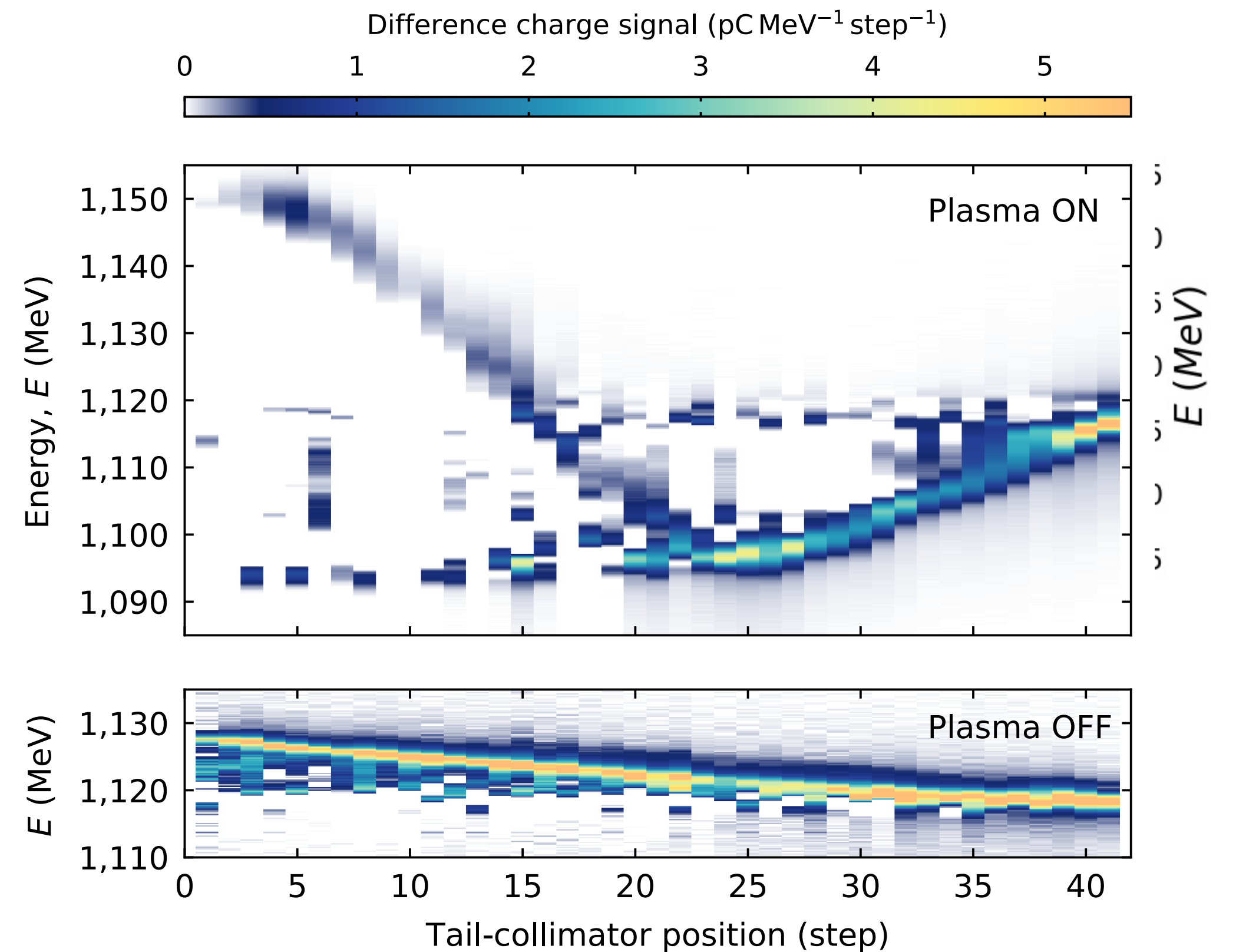
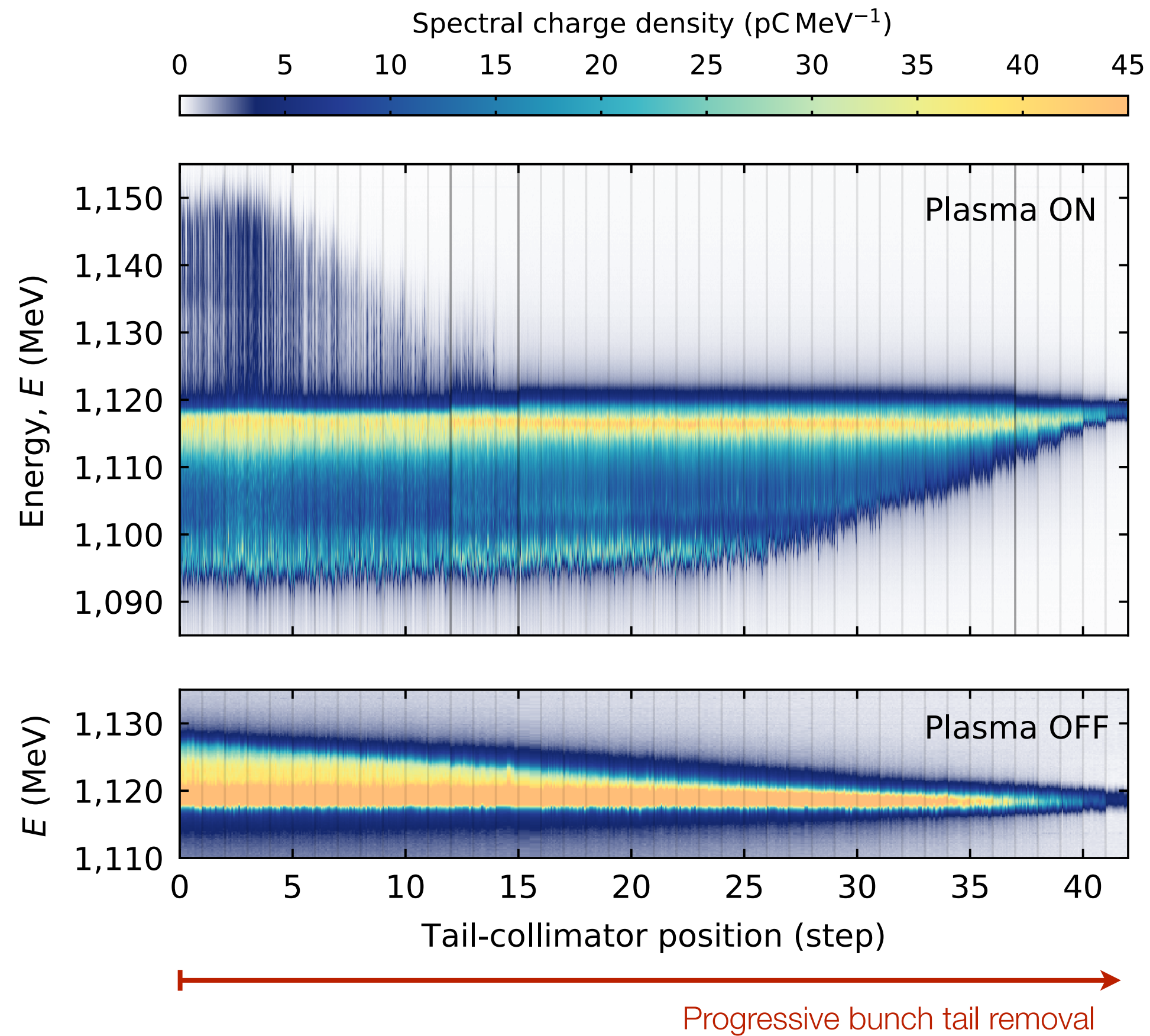


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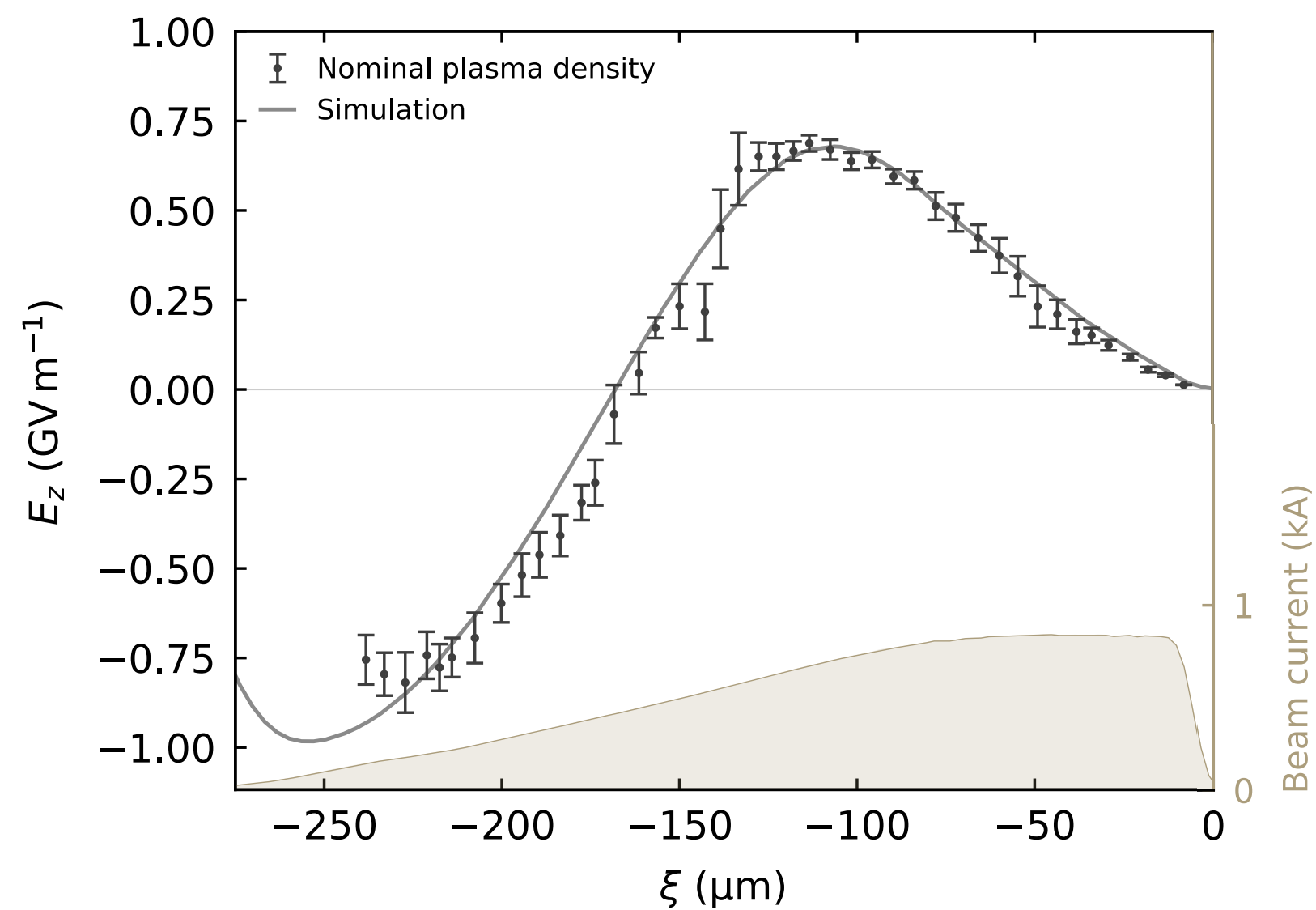
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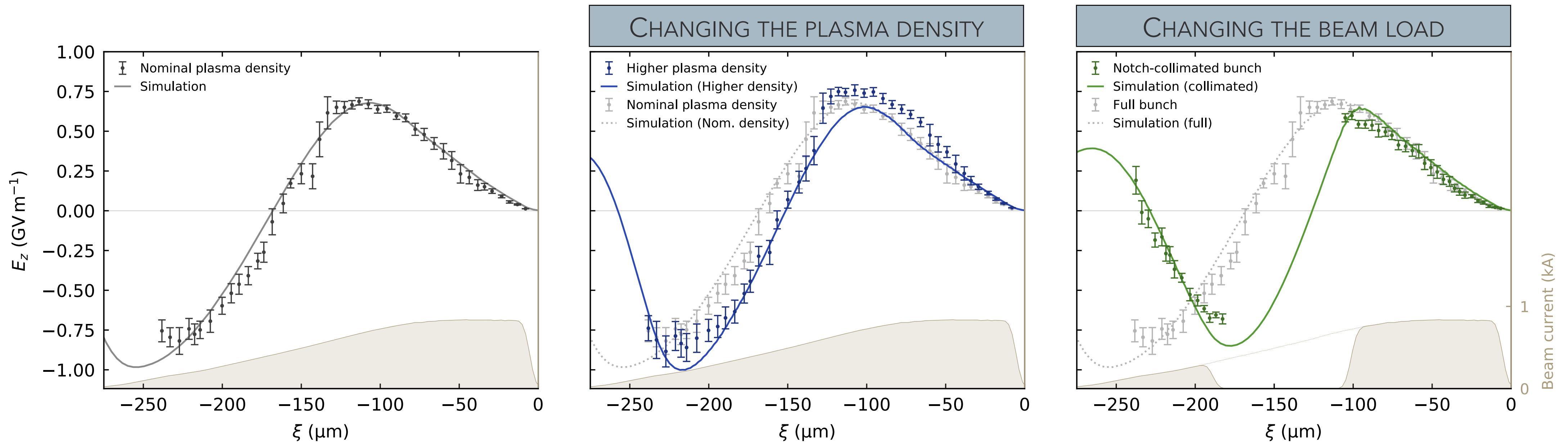
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- > 15 fs resolution
- > 0.8 GV/m average accelerating fields
- > Good agreement with simulation

TUNING THE WAKEFIELD

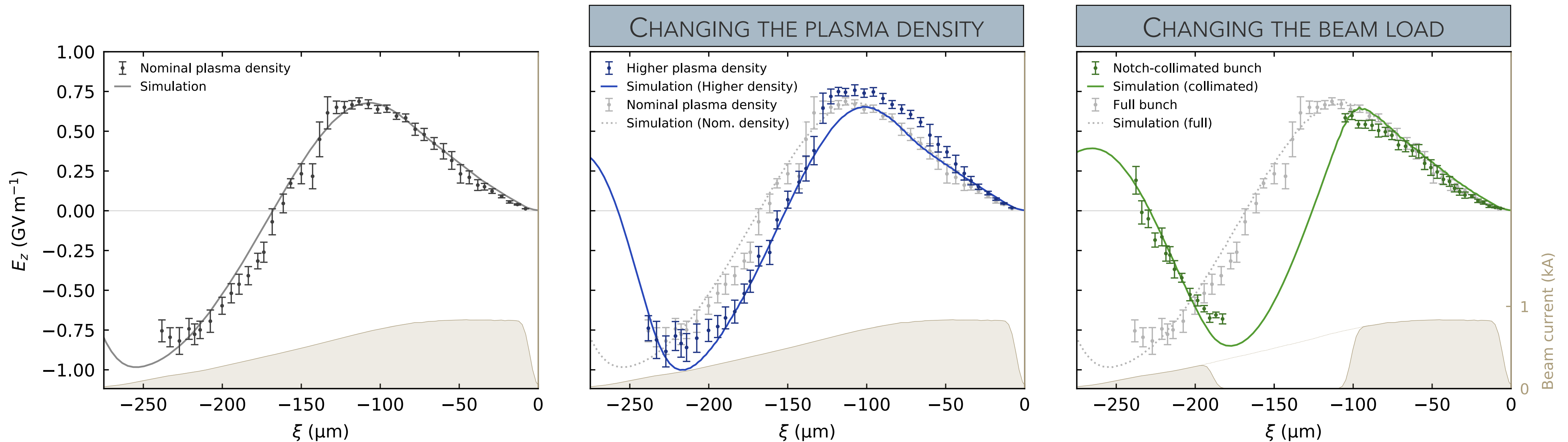
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- > Good agreement with simulation

TUNING THE WAKEFIELD

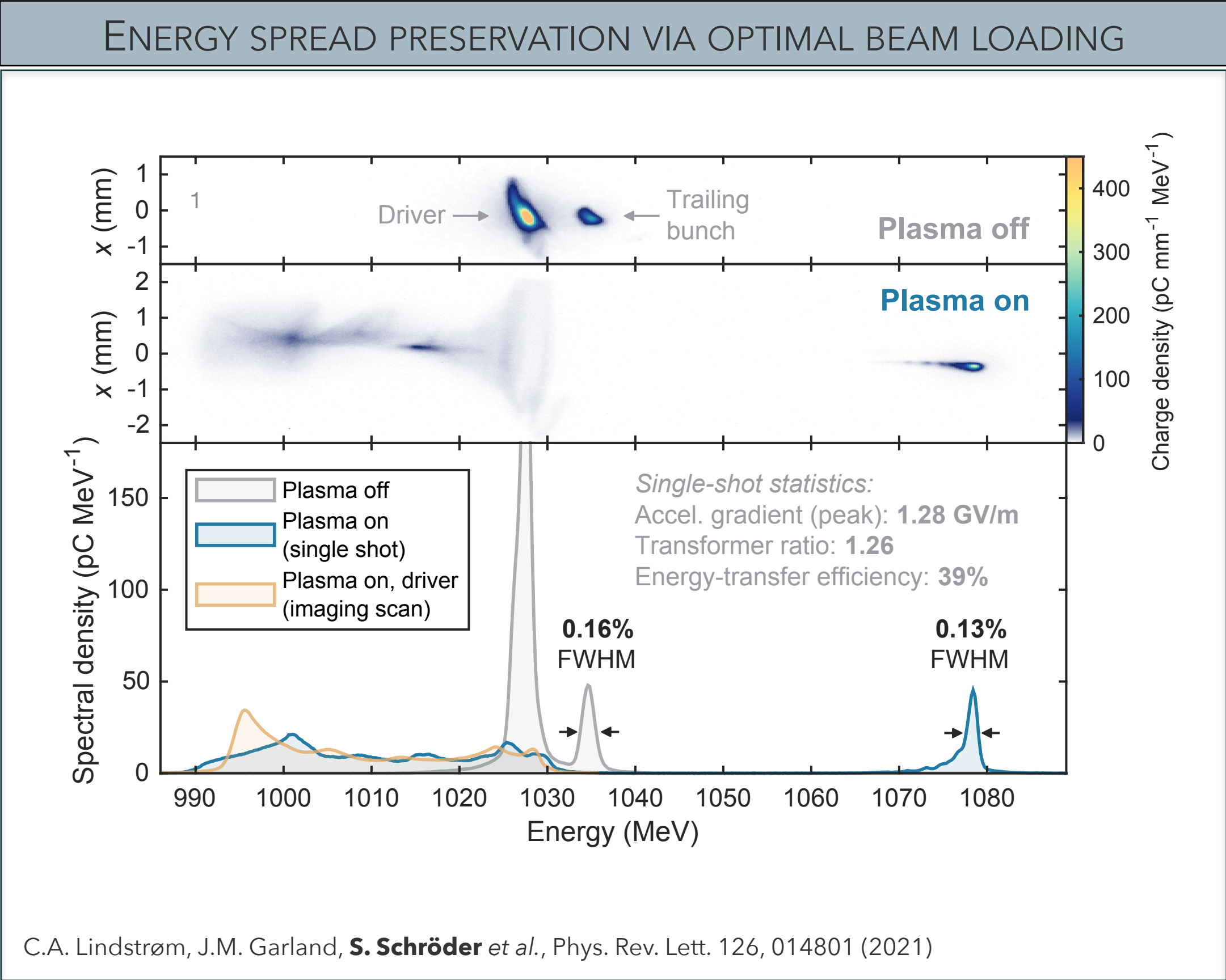
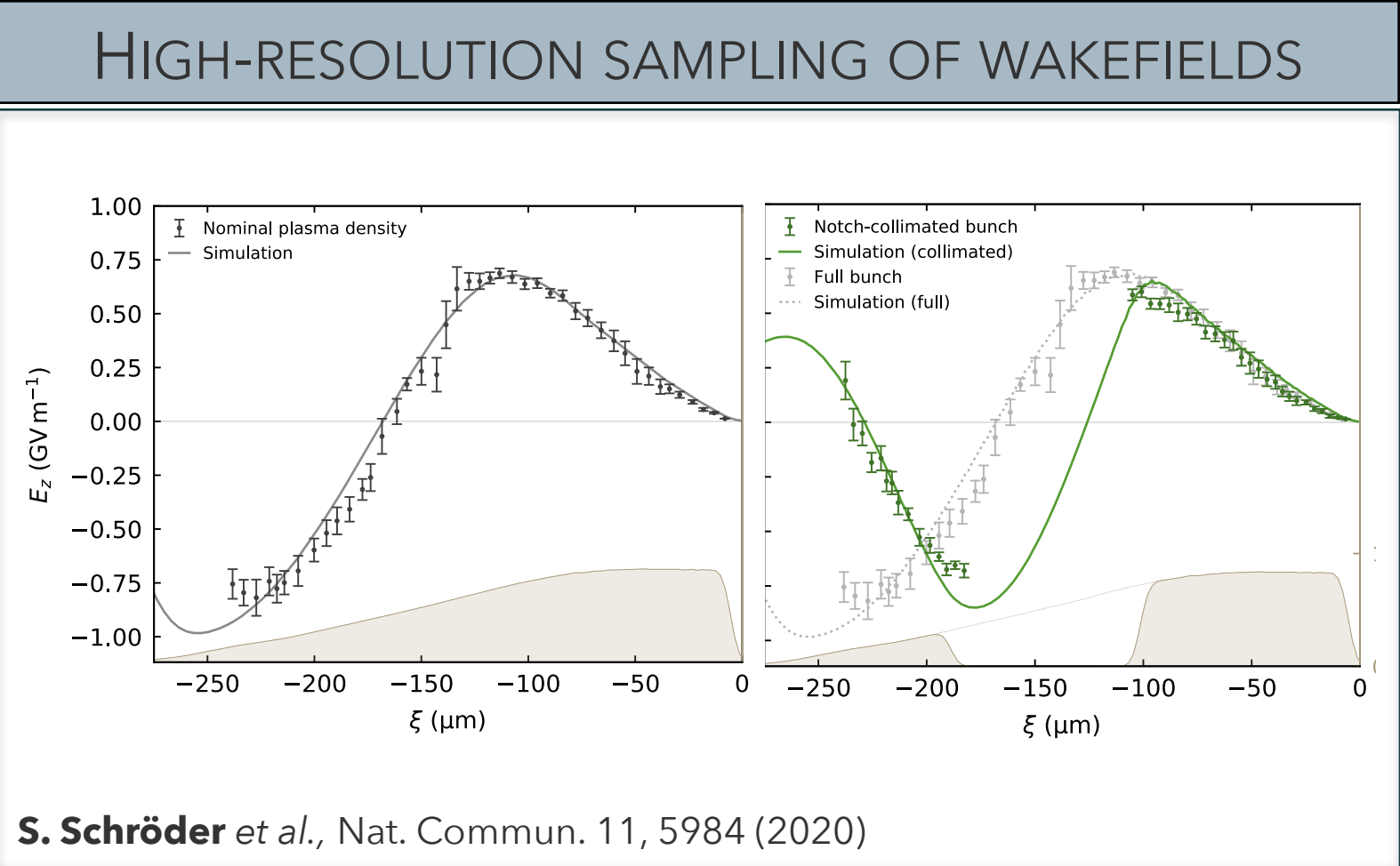
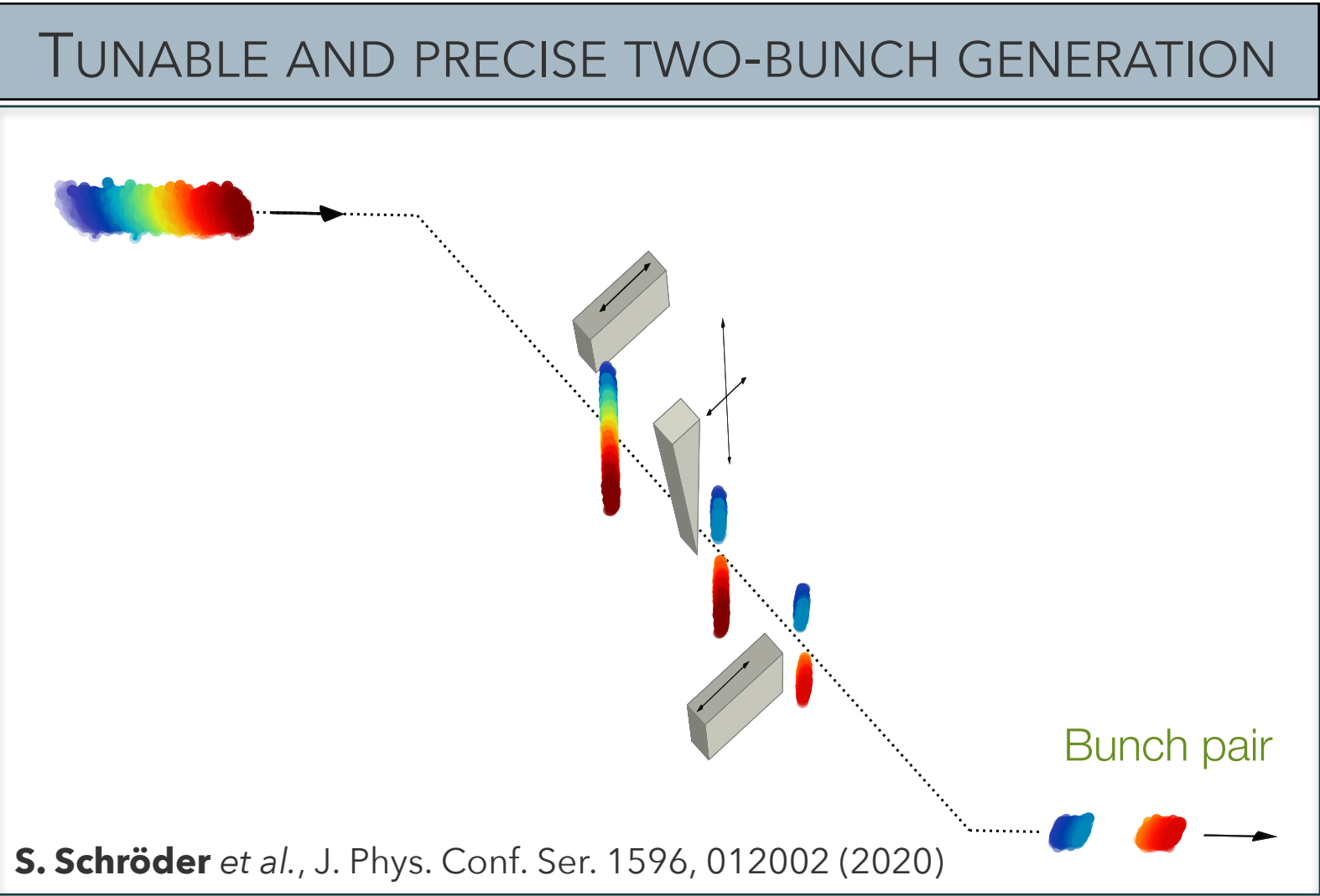
S. Schröder *et al.*, Nat. Commun. 11, 5984 (2020)



- > 15 fs resolution
- > 0.8 GV/m average accelerating fields
- > Good agreement with simulation

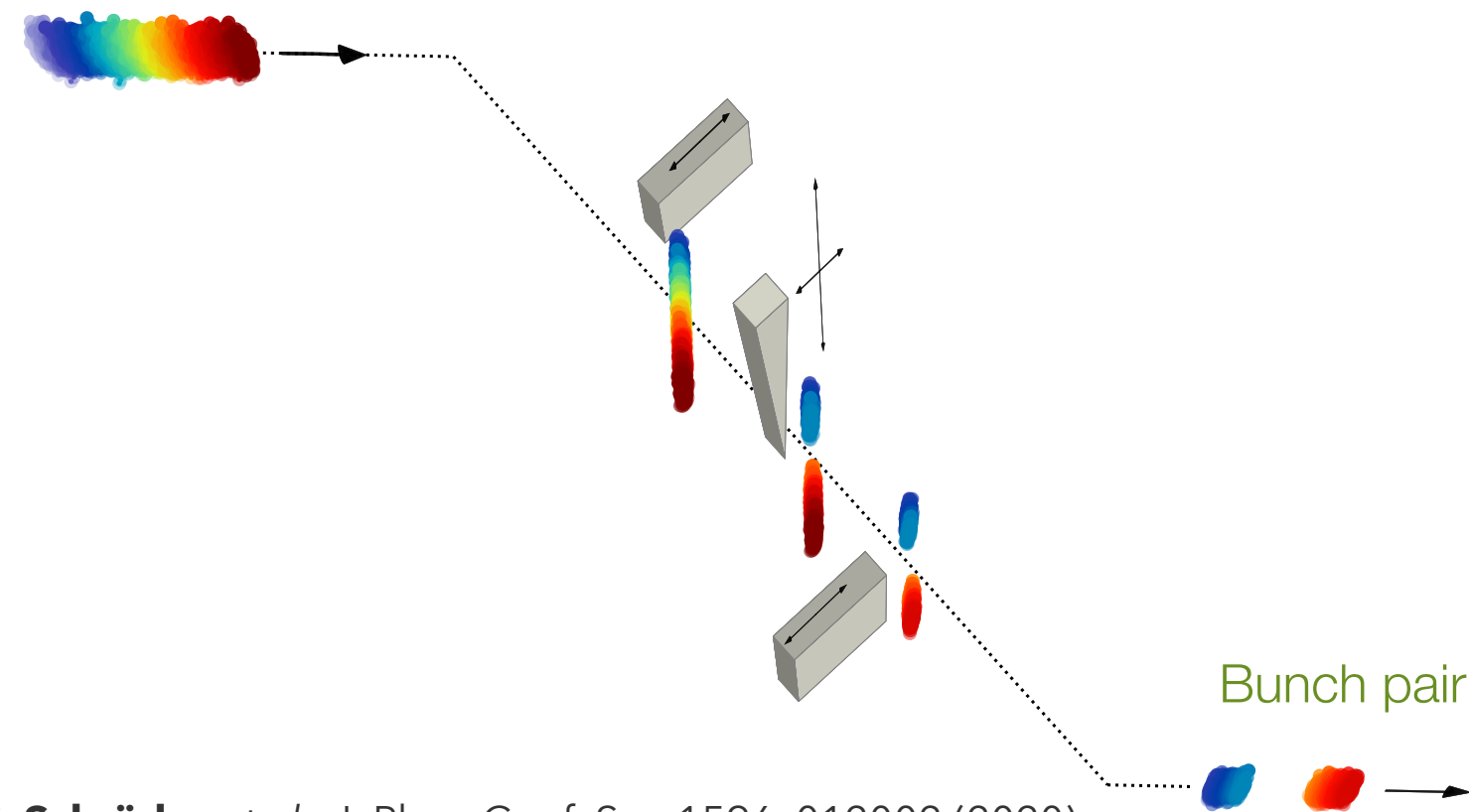
ENABLING PRECISION OPTIMISATION OF THE ACCELERATION PROCESS

PRESERVING THE ENERGY SPREAD VIA OPTIMAL BEAM LOADING



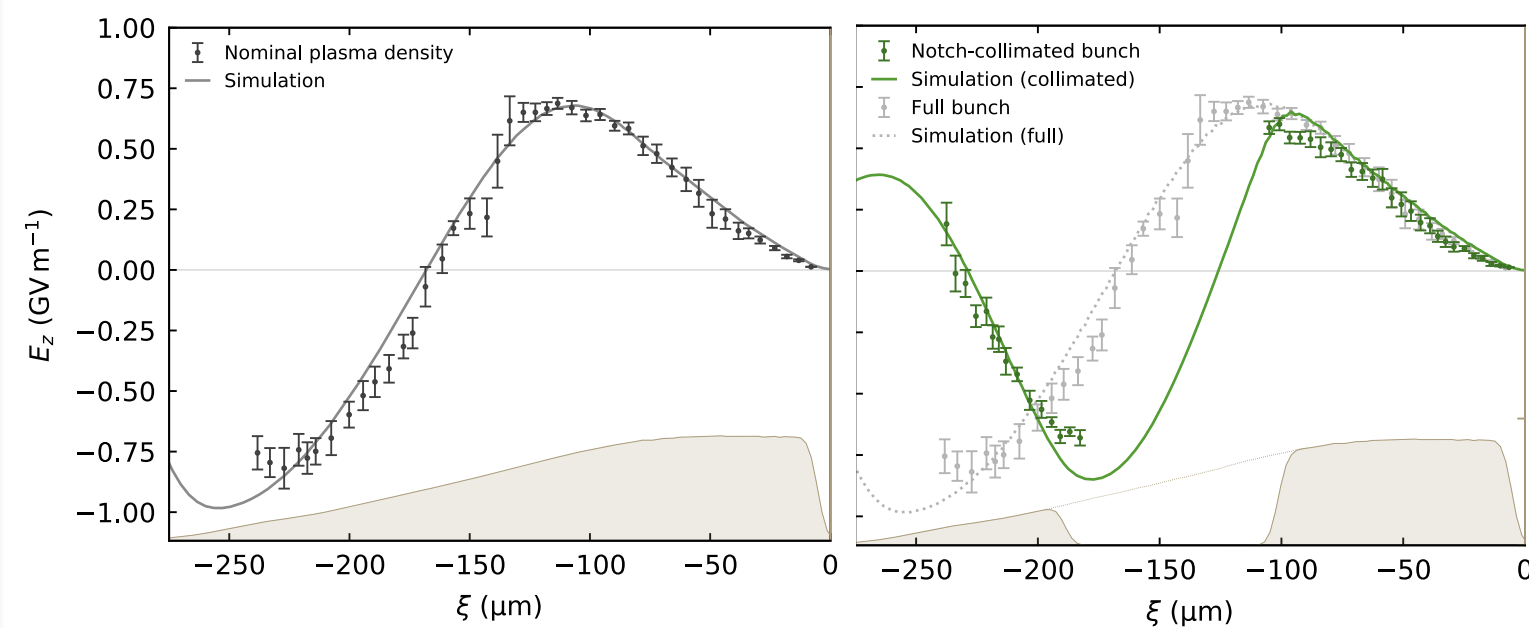
FEMTOSECOND-RESOLUTION MEASUREMENT OF A FLATTENED WAKEFIELD

TUNABLE AND PRECISE TWO-BUNCH GENERATION



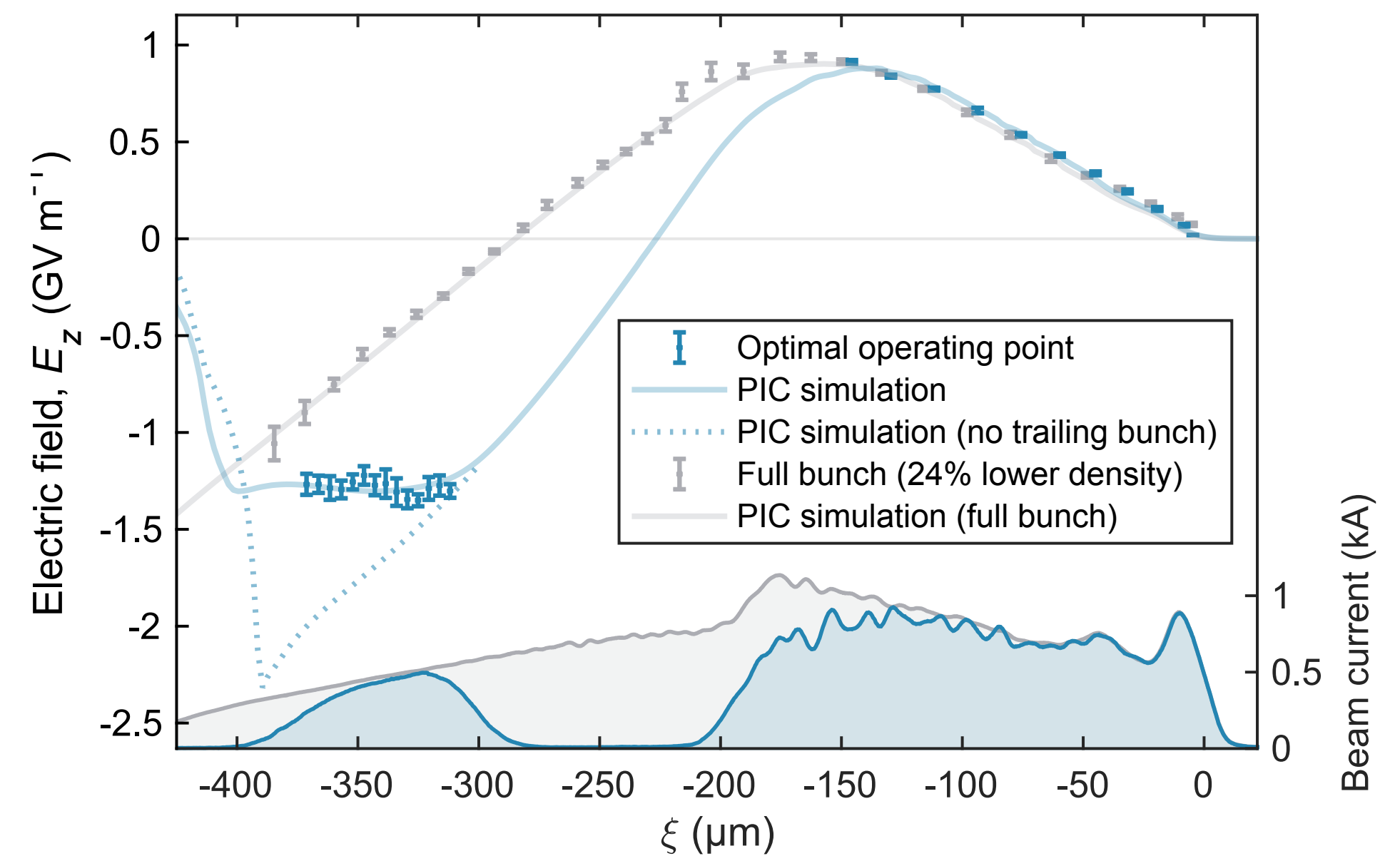
S. Schröder et al., J. Phys. Conf. Ser. 1596, 012002 (2020)

HIGH-RESOLUTION SAMPLING OF WAKEFIELDS



S. Schröder et al., Nat. Commun. 11, 5984 (2020)

ENERGY SPREAD PRESERVATION VIA OPTIMAL BEAM LOADING



%-LEVEL WAKEFIELD FLATTENING ACHIEVED

C.A. Lindstrøm, J.M. Garland, S. Schröder et al., Phys. Rev. Lett. 126, 014801 (2021)

CONCLUSION

- > Beam-driven plasma wakefield acceleration is a promising technology for future compact linear accelerators
- > FLASHForward is a unique facility to exploit precision operation of a beam-driven plasma wakefield accelerator

- > Tunable two-bunch generation with femtosecond-level current profile control

S. Schröder *et al.*, J. Phys. Conf. Ser. 1596, 012002 (2020)

- > Demonstrated optimal beam loading

C.A. Lindstrøm, J.M. Garland, **S.Schröder** *et al.*, Phys. Rev. Lett. 126, 014801 (2021)

- > Energy spread preservation

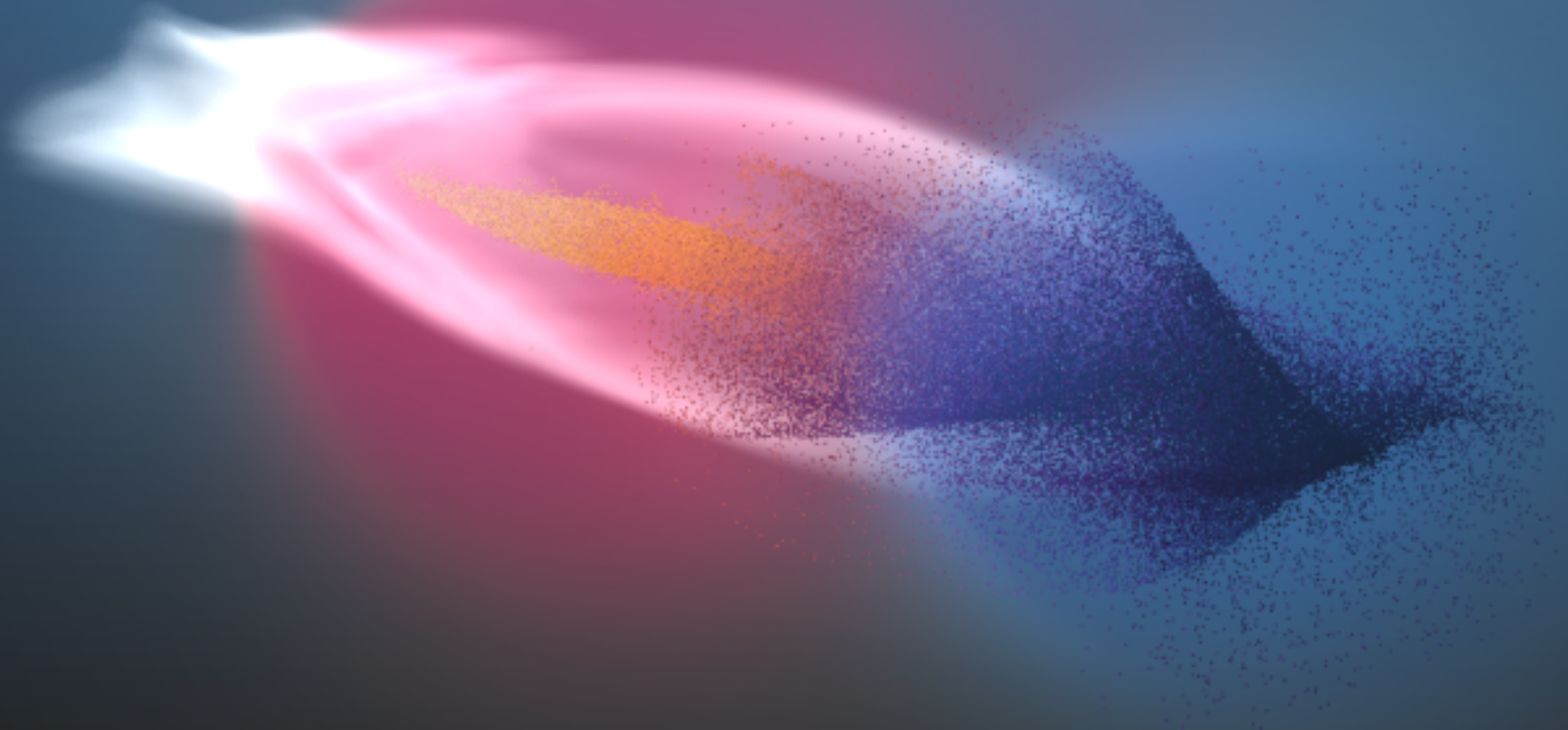
- > Charge preservation

- > Energy transfer efficiency: 42%

- > Femtosecond-resolution sampling of plasma wakefield

S. Schröder *et al.*, Nat. Commun. 11, 5984 (2020)

ENTERING **PRECISION OPERATION** OF BEAM-DRIVEN PLASMA WAKEFIELD ACCELERATORS



THANK YOU FOR YOUR ATTENTION!