PRECISION TUNING OF A PLASMA WAKEFIELD ACCELERATOR.

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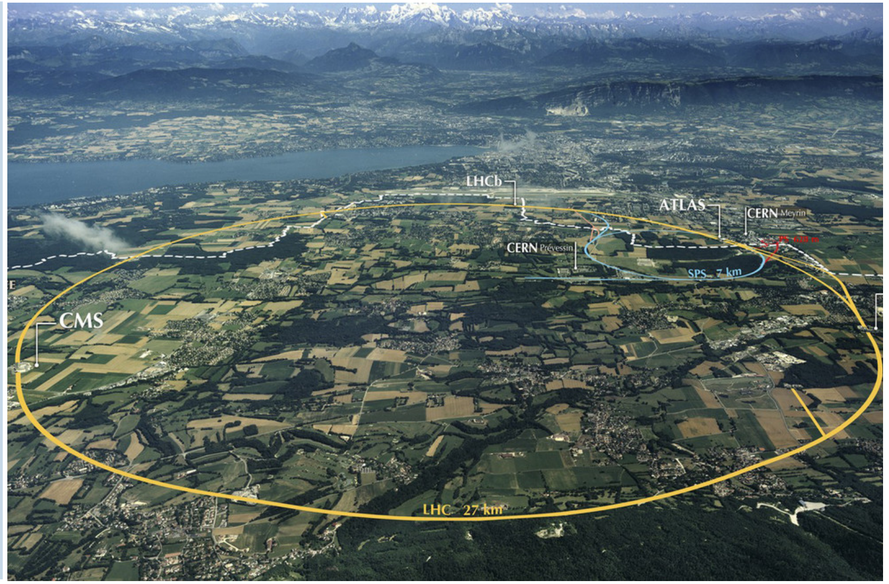
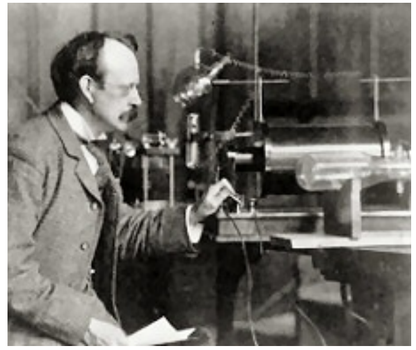
Plasma Wakefield Accelerator Research and Development
Deutsches Elektronen-Synchrotron (DESY), Hamburg, Germany

PARTICLE ACCELERATORS — EXPLORING THE SMALL SCALE OF MATTER

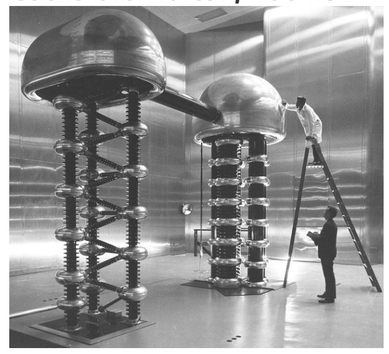
PARTICLE PHYSICS



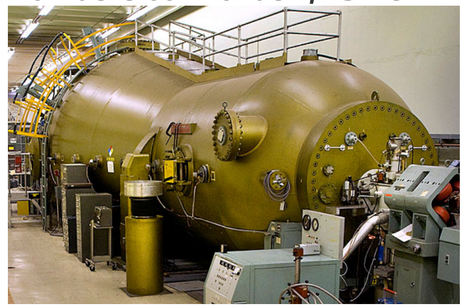
Cathode ray tube, keV



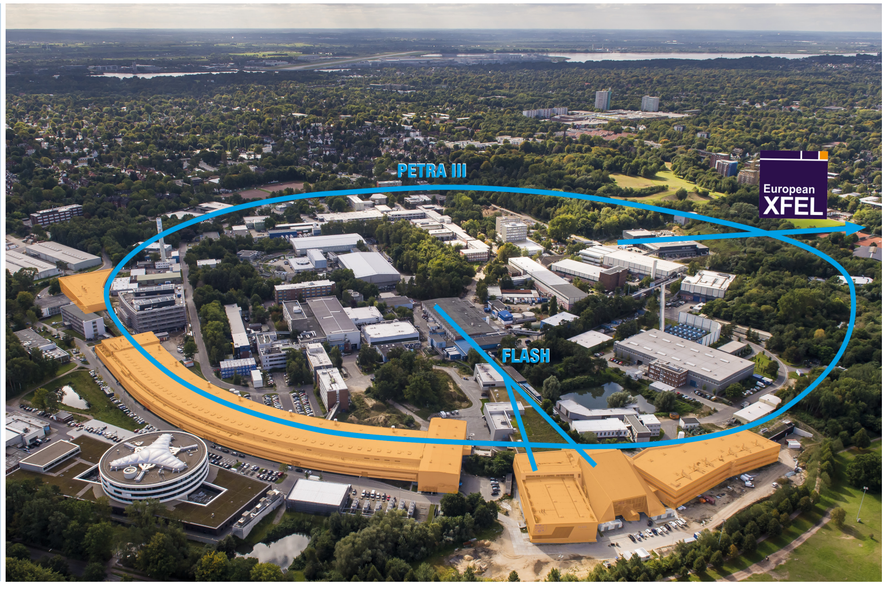
Cockcroft-Walton, 400 keV



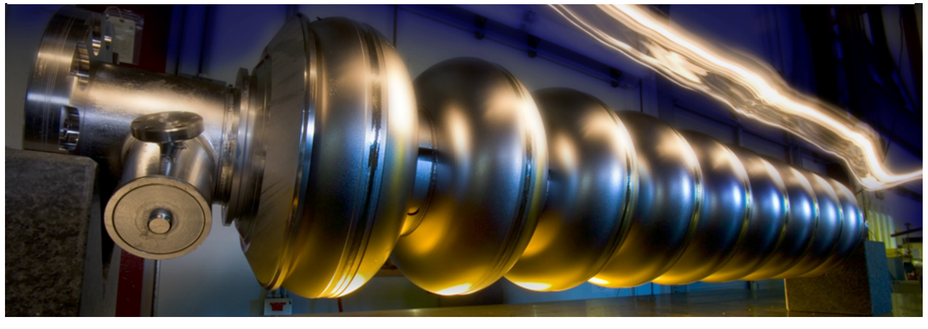
Van-de-Graaff Tandem, 25 MeV



PHOTON SCIENCE



TODAY'S TECHNOLOGY: **RADIO-FREQUENCY CAVITIES**

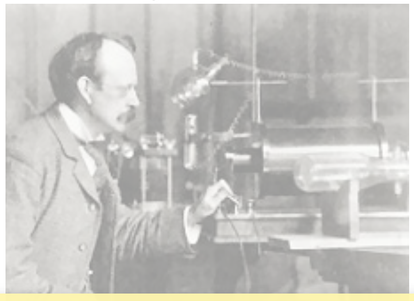


Electric/material breakdown limits the acceleration gradient to $\mathcal{O}$(100) MeV/m

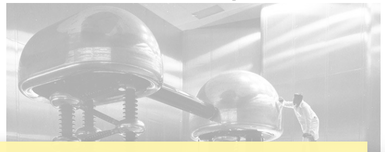
Particle accelerators — Exploring the small scale of matter

Particle physics

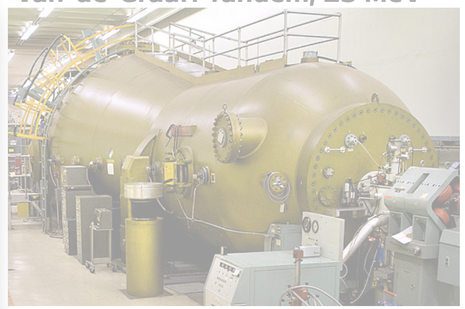
Cathode ray tube, keV



Cockcroft-Walton, 400 keV



Van-de-Graaff Tandem, 25 MeV

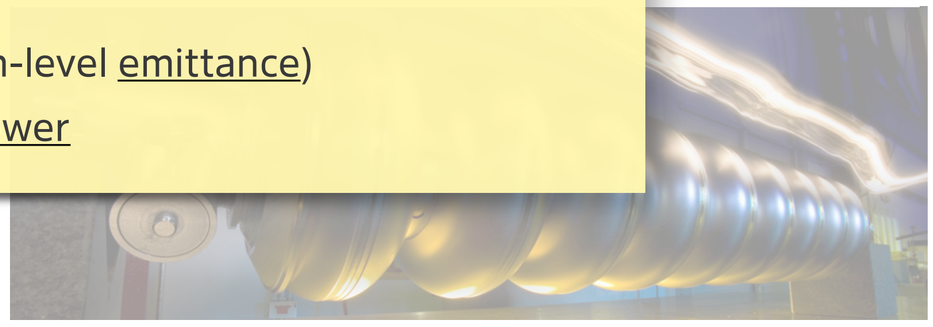


Requirements of advanced accelerator technologies:

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

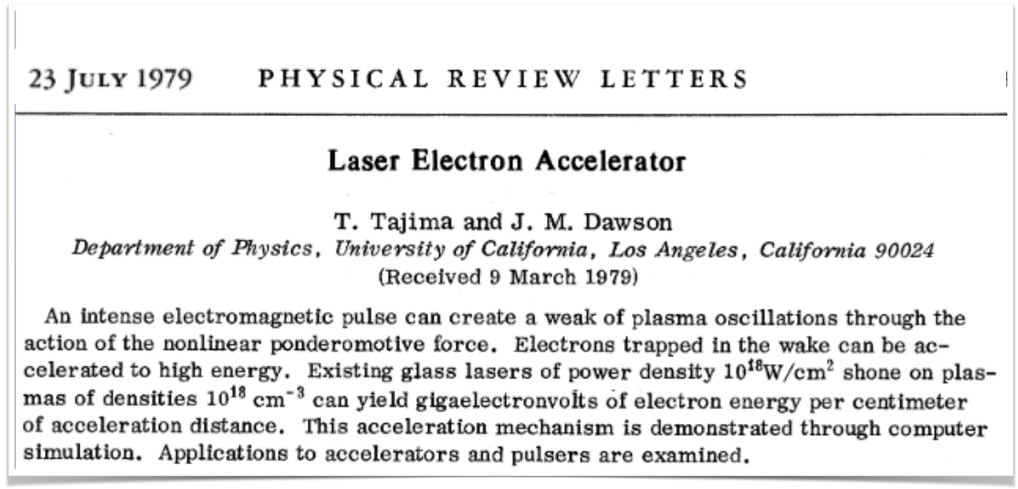
Photon science

Today's technology: radio-frequency cavities



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

PLASMA WAKEFIELD ACCELERATORS — A PROMISING TECHNOLOGY



23 JULY 1979 PHYSICAL REVIEW LETTERS

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}W/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.

𝒪(10) GEV/M ACCELERATION GRADIENT

FIRST HIGH-QUALITY BEAMS

S.P.D. Mangles et al., Nature 431, 535–538 (2004).
C.G.R. Geddes et al., Nature 431, 538–541 (2004).
J. Faure et al., Nature 431, 541–544 (2004).

HIGH EFFICIENCY

M. Litos et al., Nature 515, 92–95 (2014)

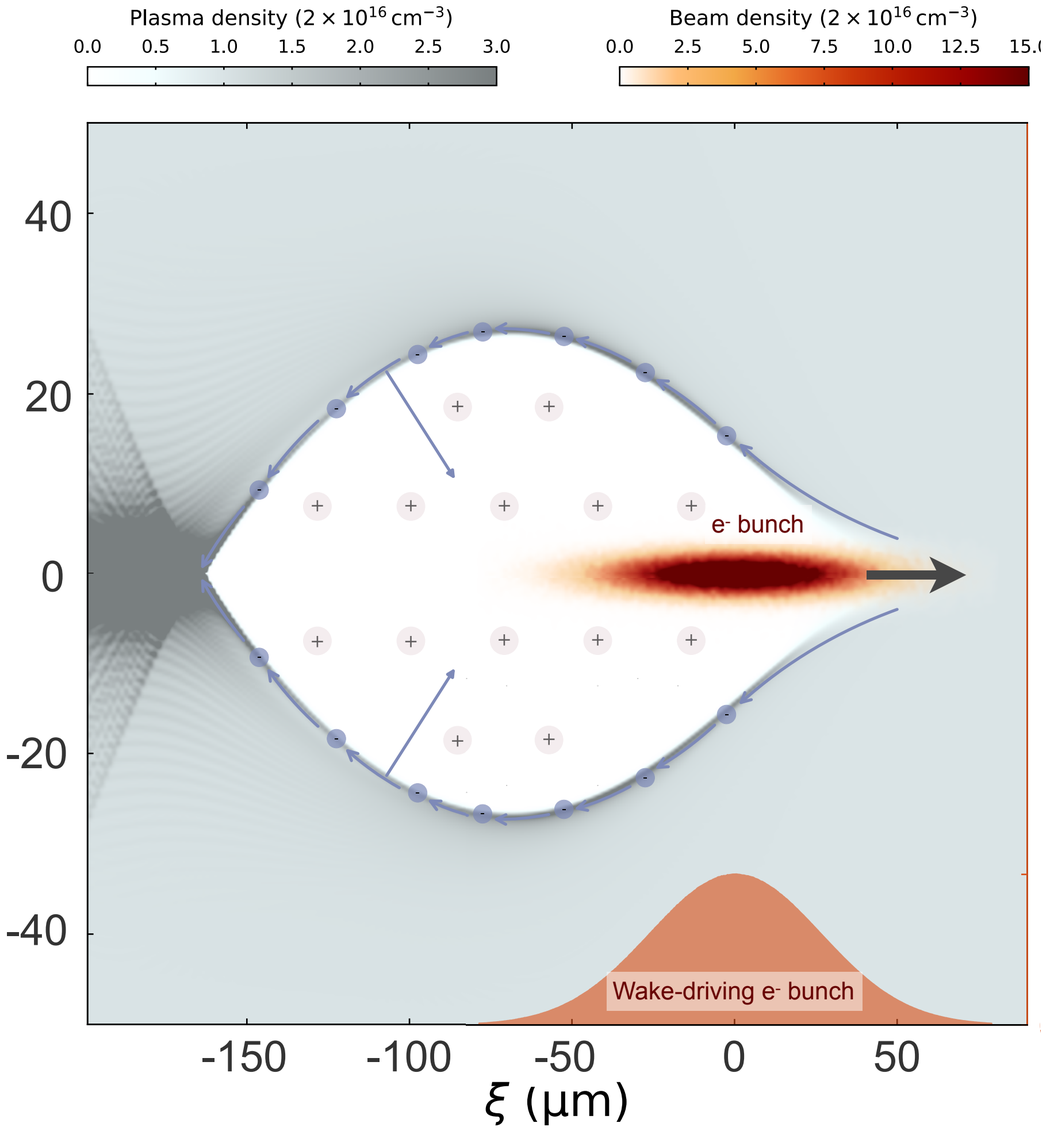
FIRST FEL GAIN

W. Wang et al., Nature 595, 516–520 (2021)

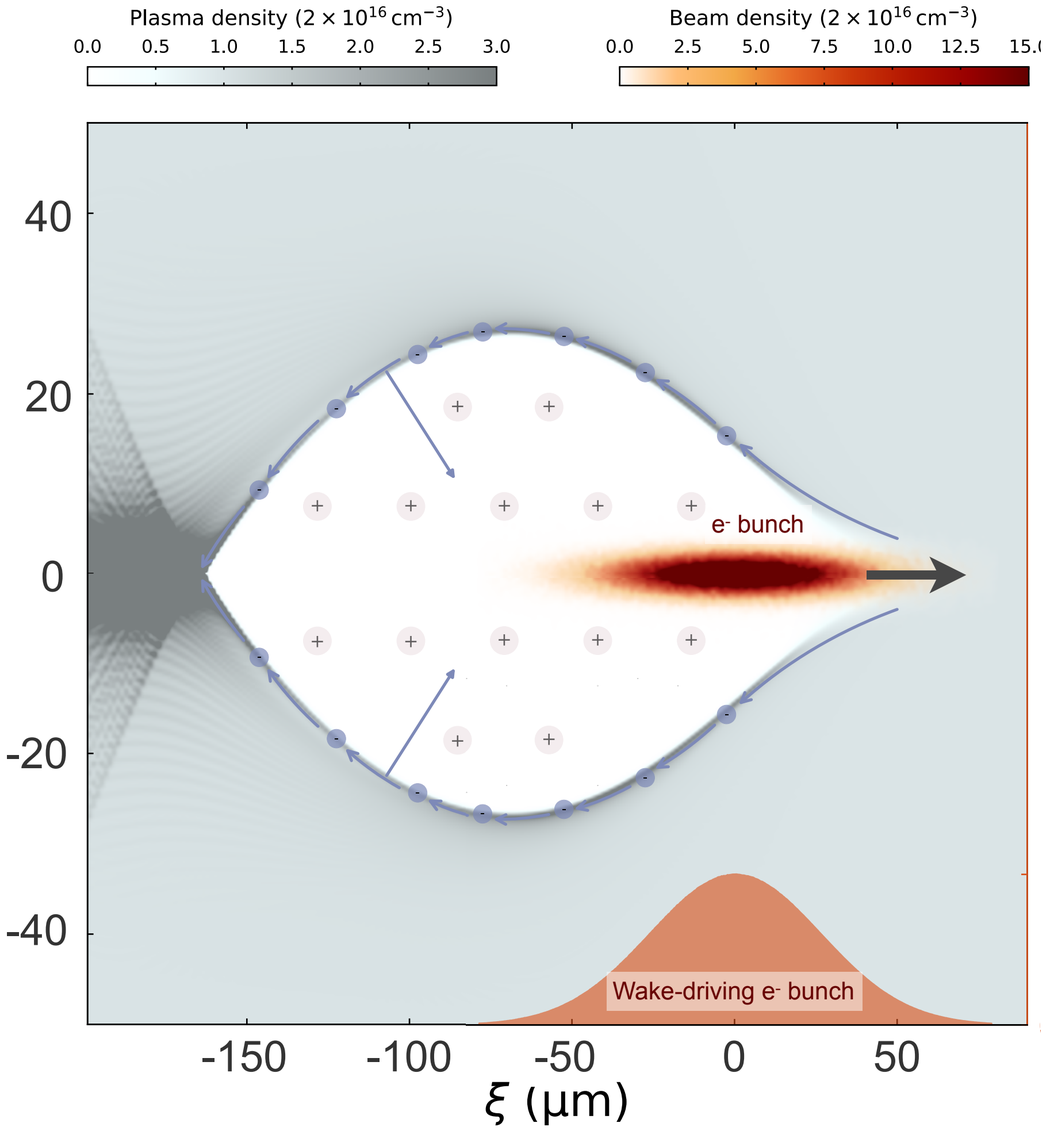
NEXT TARGETED MILESTONES:

BEAM-QUALITY PRESERVATION

Beam-driven plasma wakefield acceleration

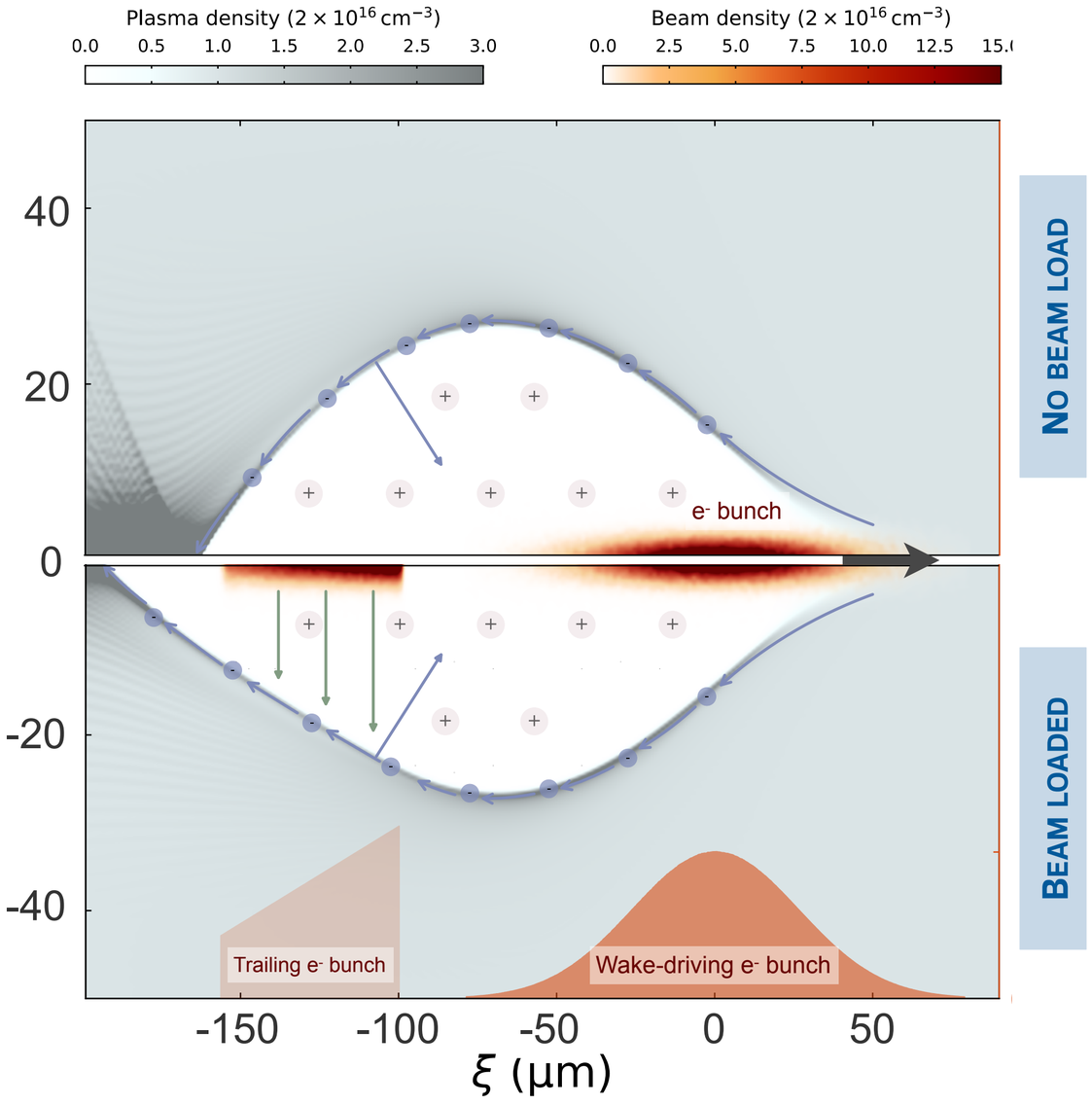


Beam-driven plasma wakefield acceleration



- Cylindrically symmetric **GV/m-level fields**.
  - Longitudinally accelerating.
  - Transversely focusing.

Beam-driven plasma wakefield acceleration



- Cylindrically symmetric **GV/m-level fields**.
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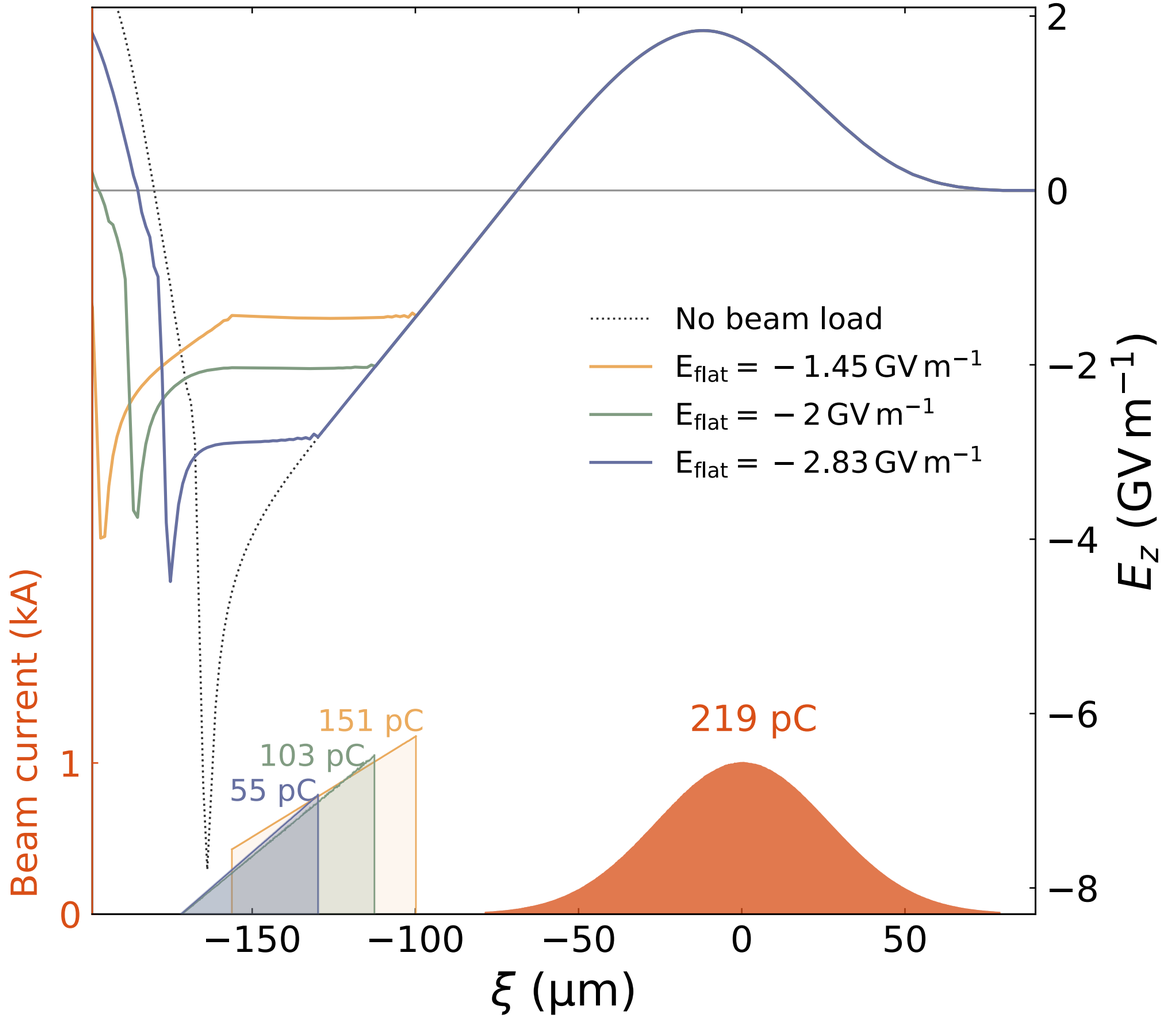
- Space charge of trailing bunch modifies field structure ≙ beam loading.

Beam-driven plasma wakefield acceleration

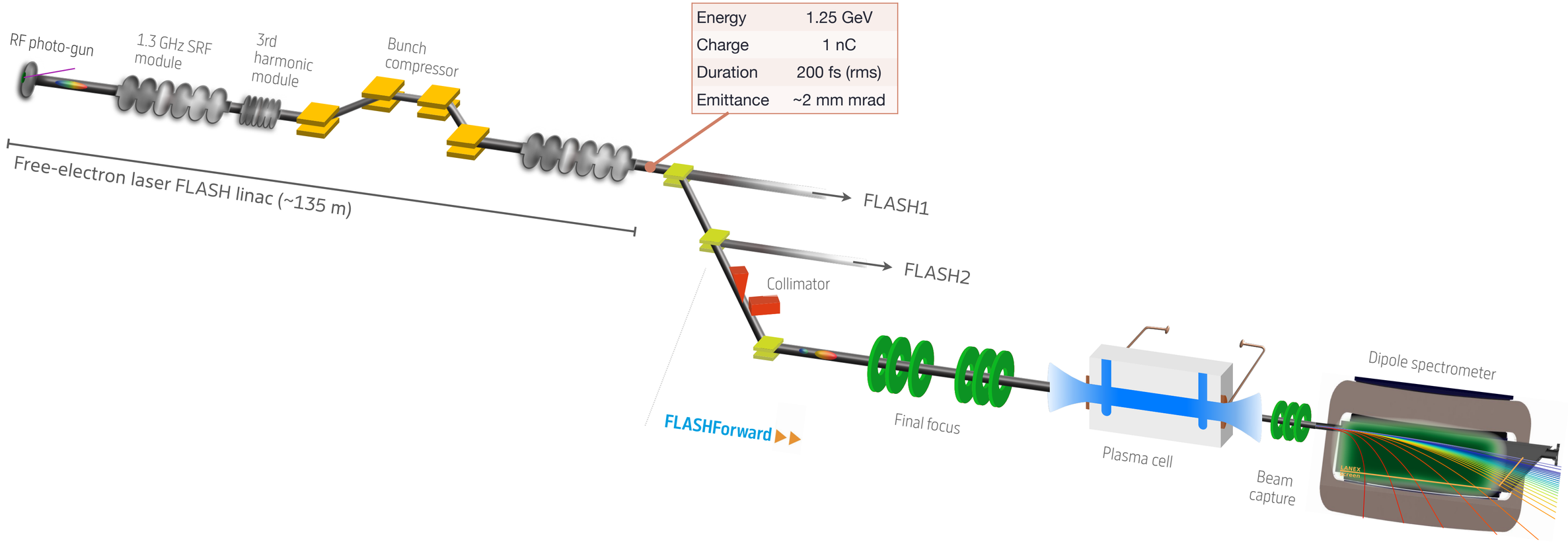


- Cylindrically symmetric **GV/m-level fields**.
  - Longitudinally accelerating.
  - Transversely focusing.
- Space charge of trailing bunch modifies field structure ≙ beam loading.
- **Energy-spread-preserving** and **high efficiency** acceleration via optimal beam loading.

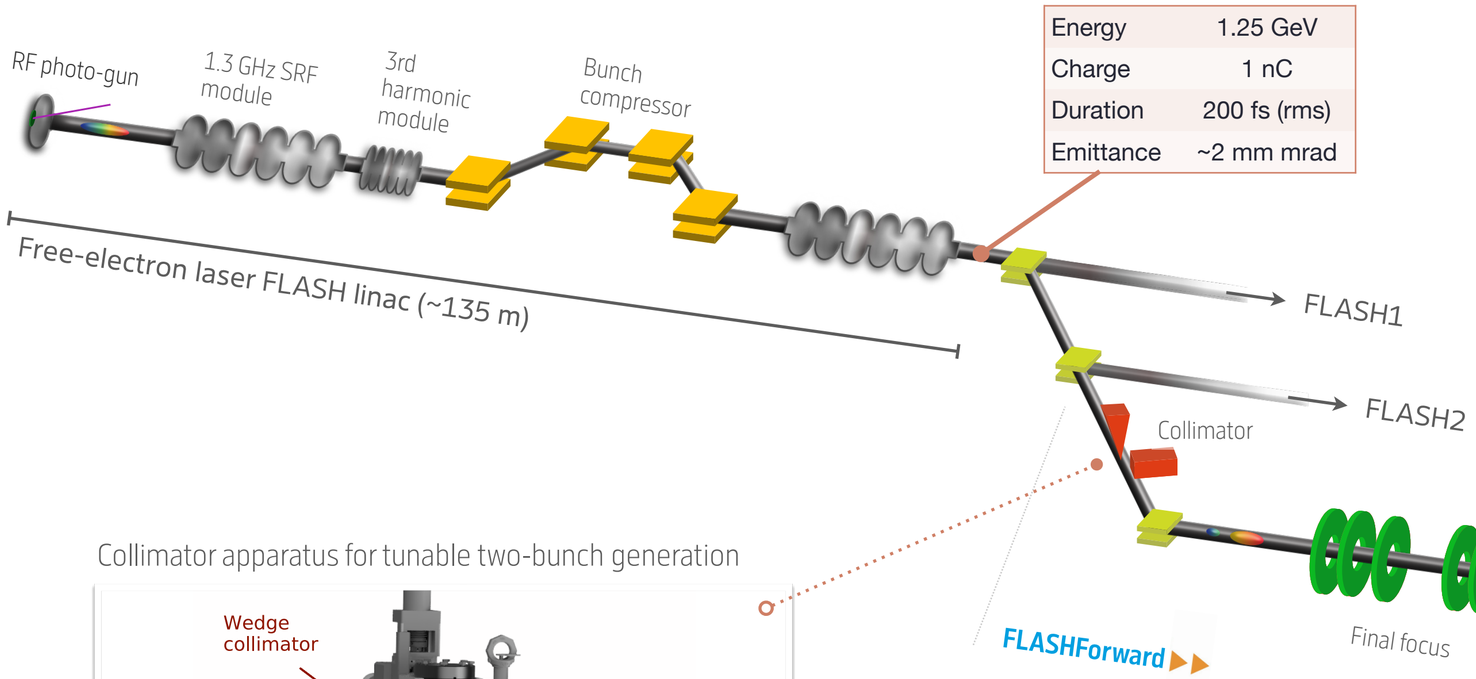
Optimising the acceleration requires:

1. **Precision control** of the bunch current profiles.
2. **Precision measurement** of the plasma wakefield.

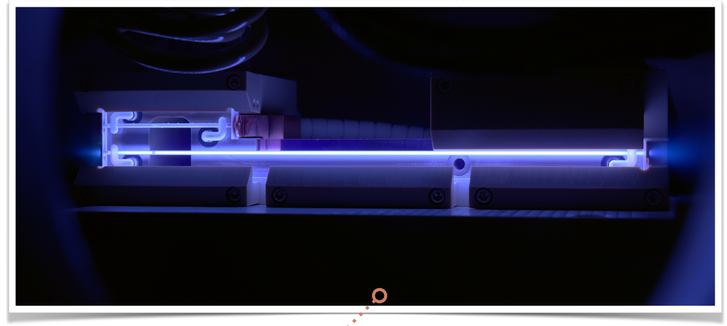
FLASHForward — A BEAM-DRIVEN PLASMA WAKEFIELD ACCELERATOR AT DESY



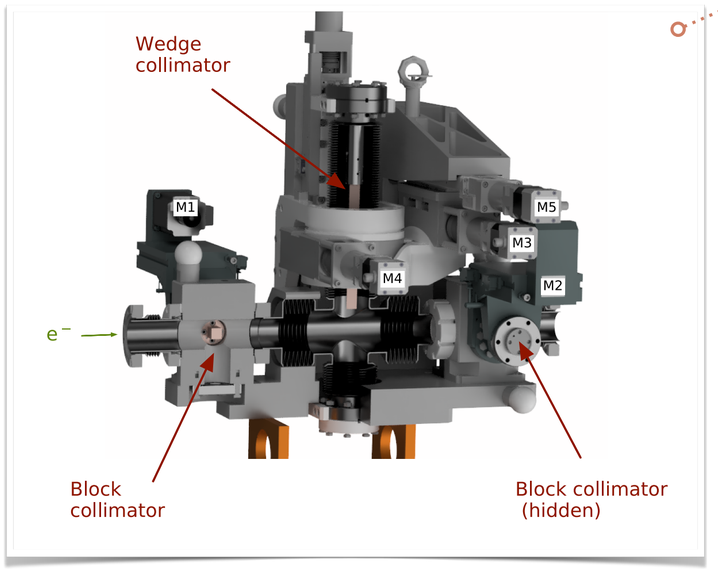
FLASHForward ▸▸ — A BEAM-DRIVEN PLASMA WAKEFIELD ACCELERATOR AT DESY



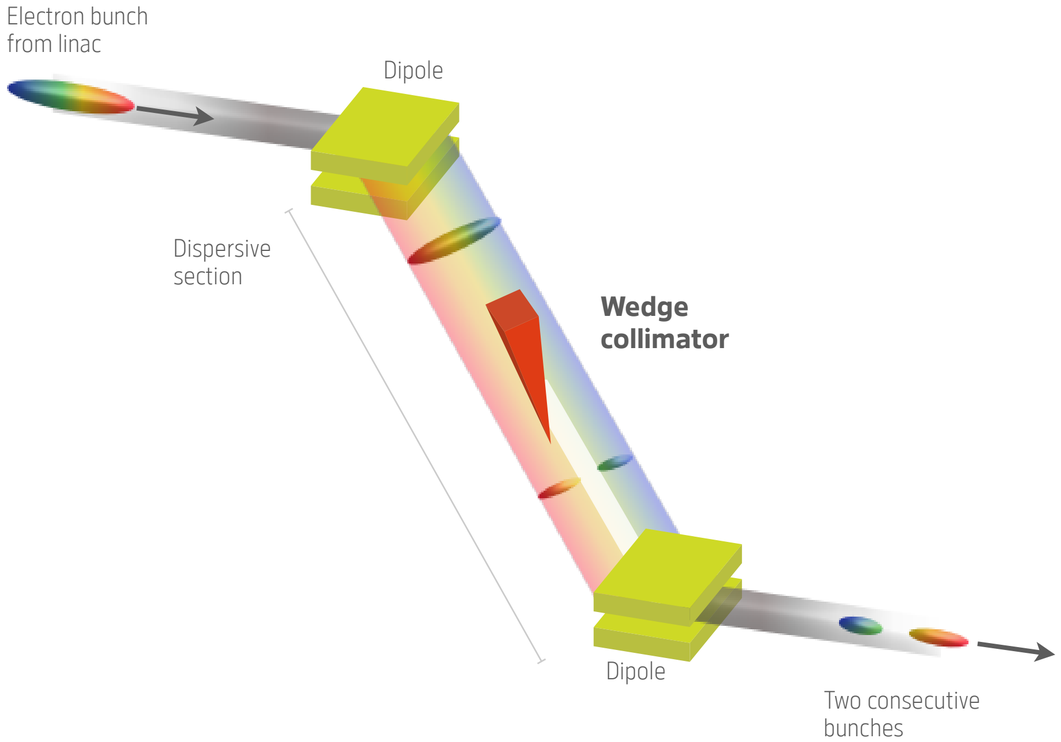
Argon discharge plasma

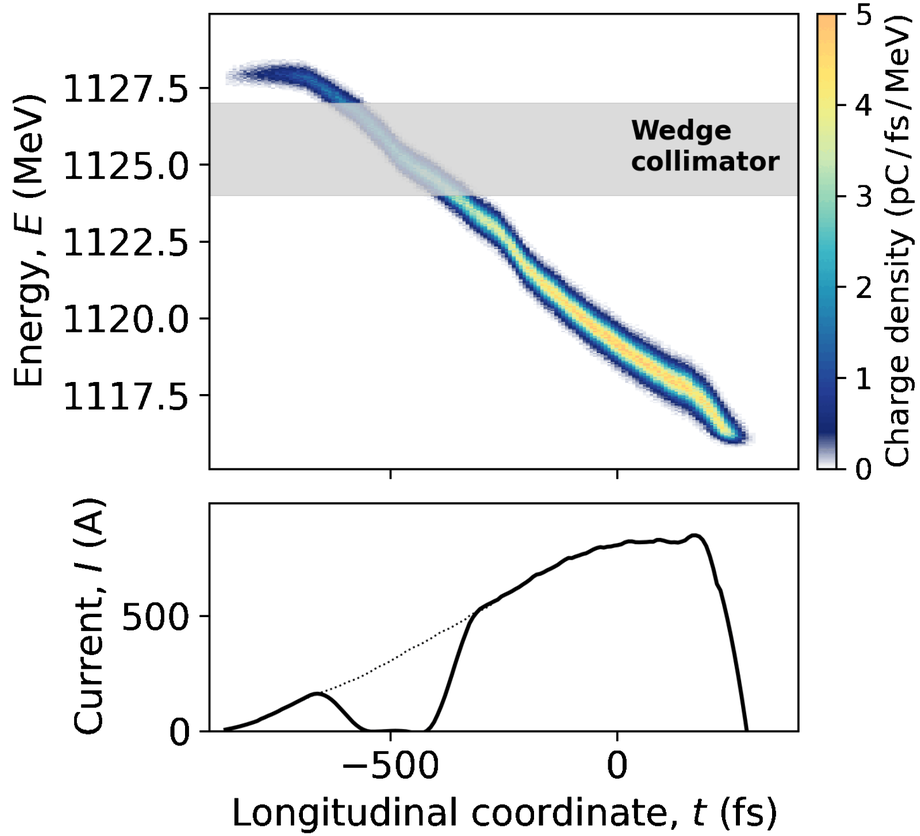


Collimator apparatus for tunable two-bunch generation



TUNABLE TWO-BUNCH GENERATION VIA ENERGY COLLIMATION

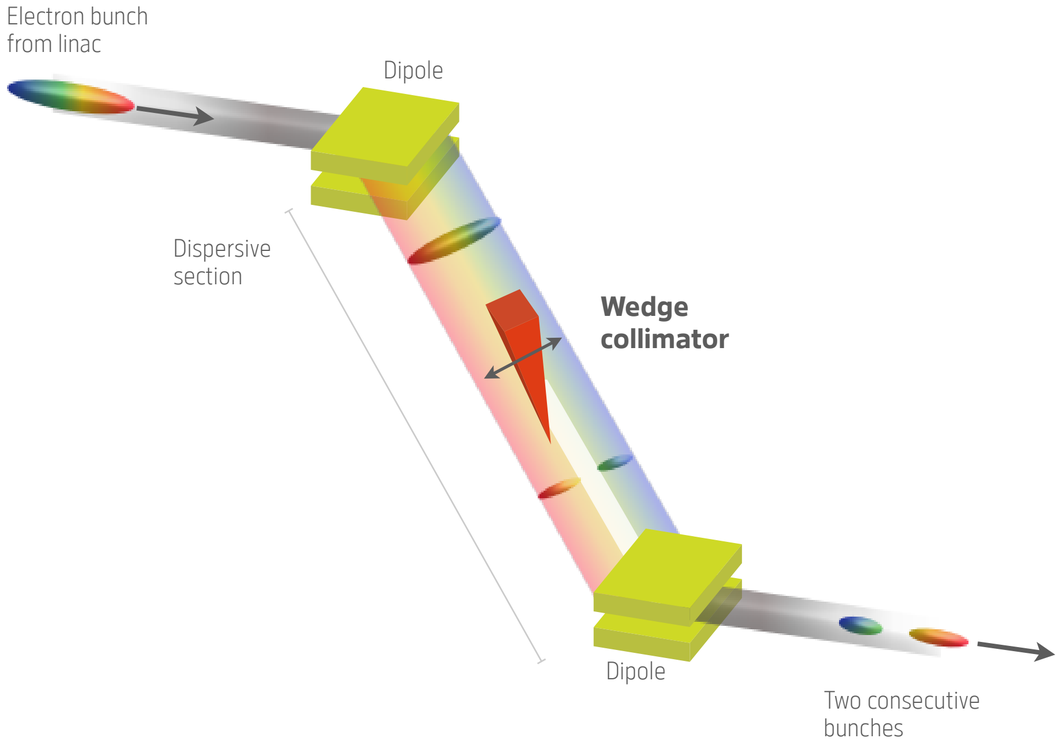


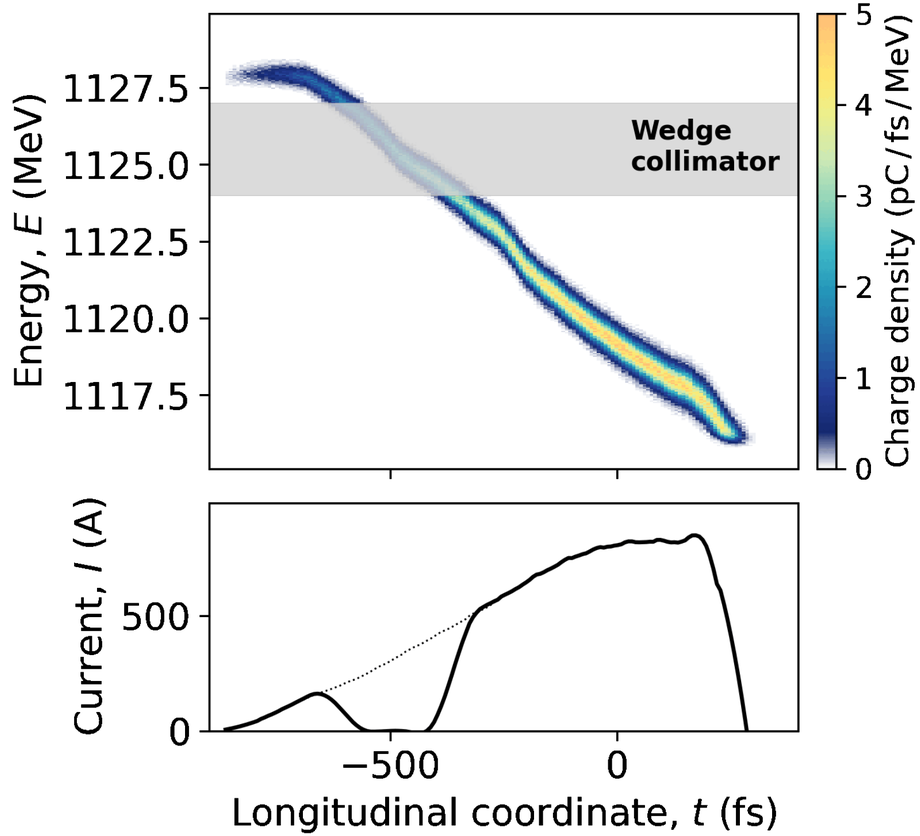


ENABLING FEMTOSECOND-PRECISION CURRENT-PROFILE MODIFICATION

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

TUNABLE TWO-BUNCH GENERATION VIA ENERGY COLLIMATION





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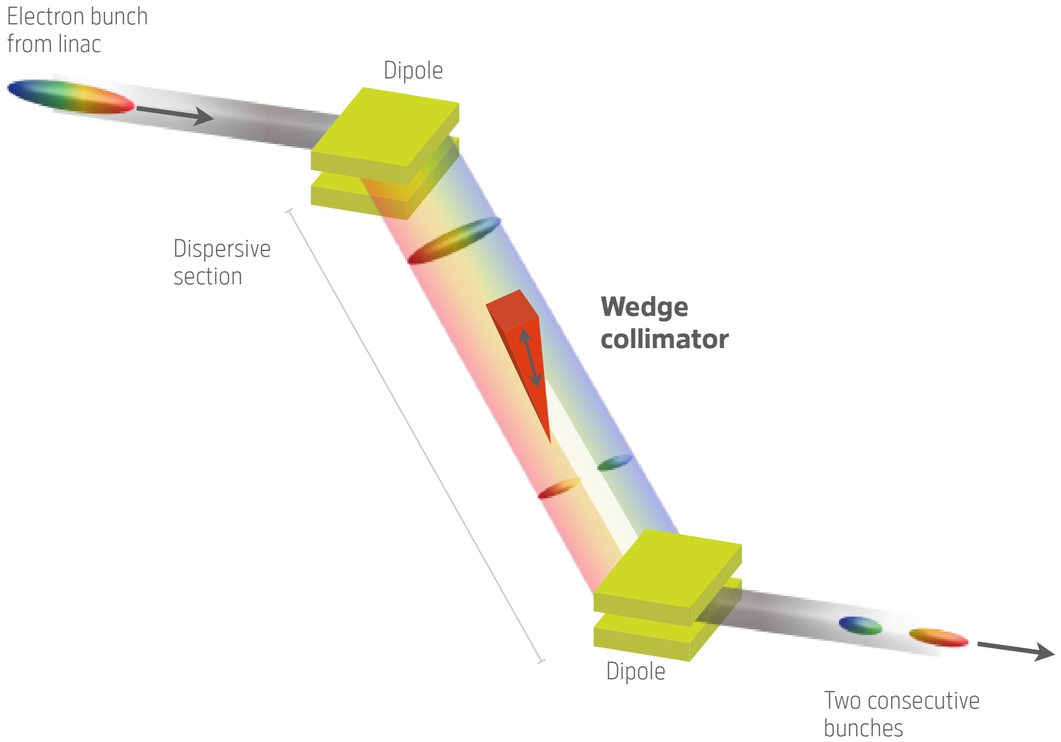
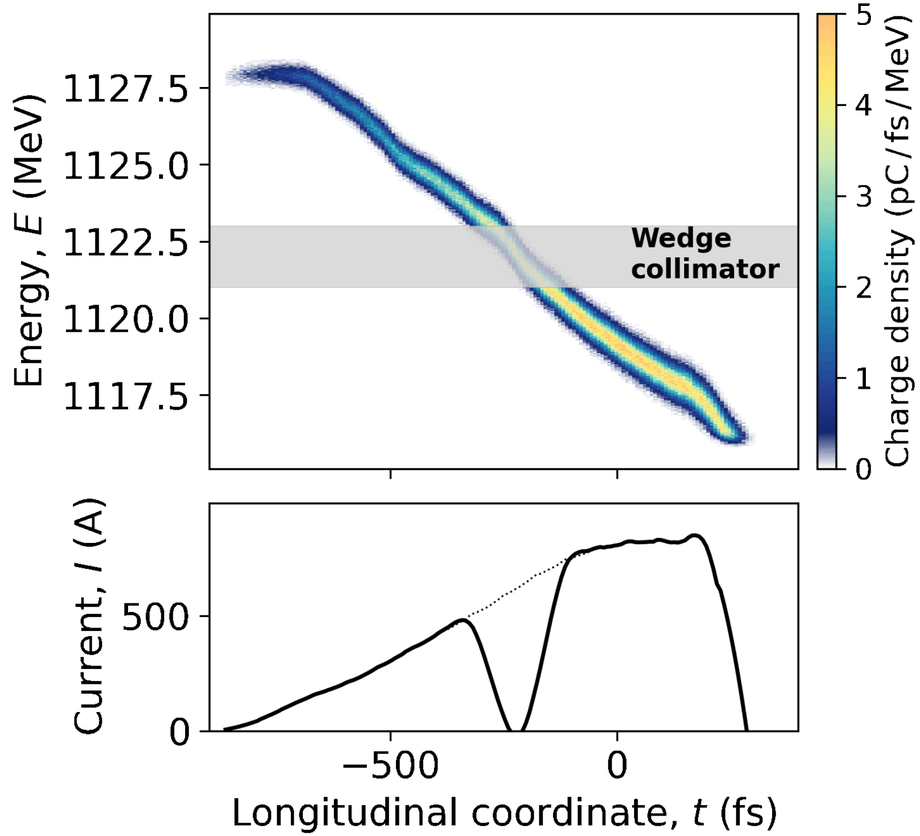
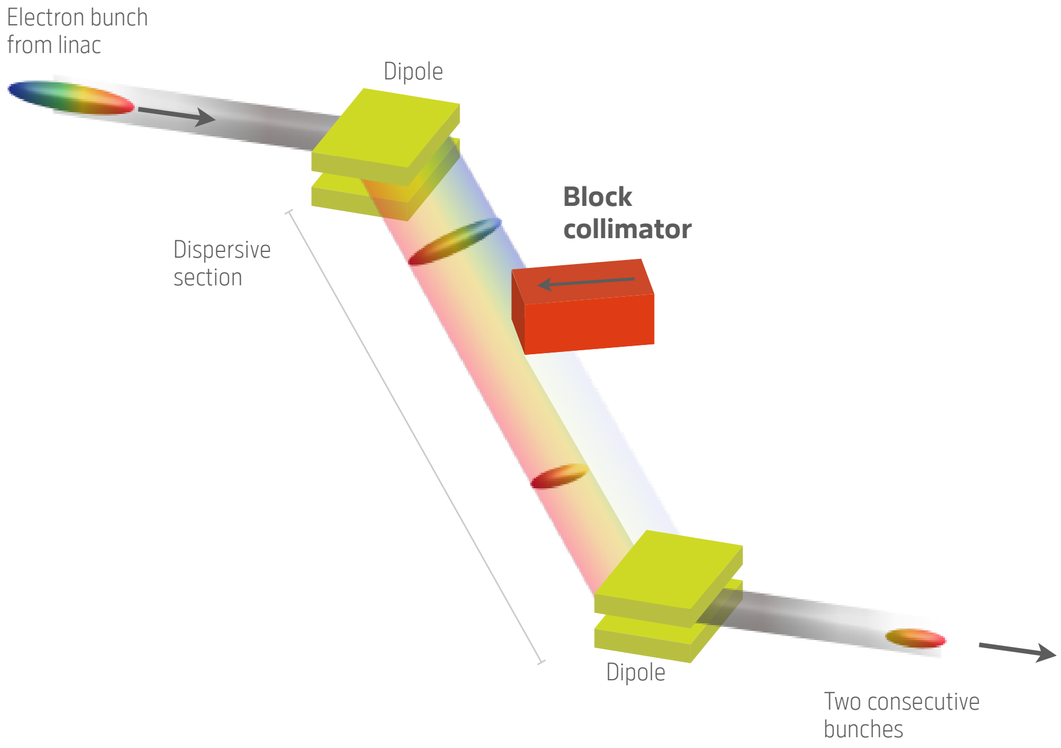


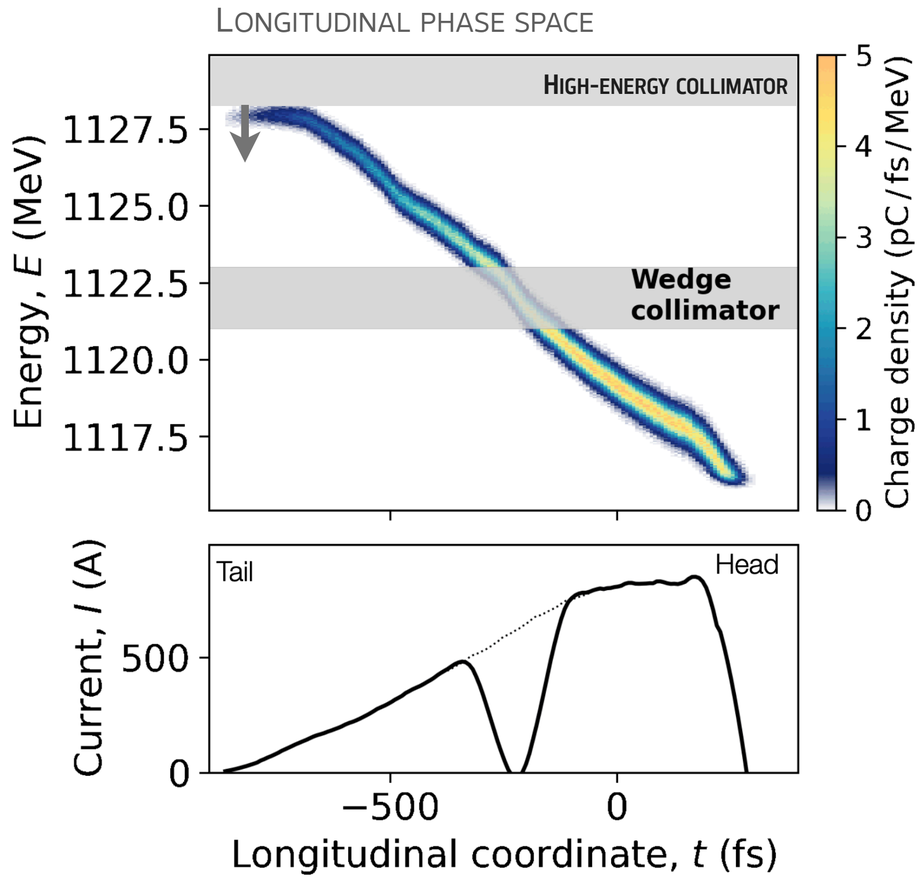


ENABLING FEMTOSECOND-PRECISION CURRENT-PROFILE MODIFICATION

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

BUNCH-LENGTH MODIFICATION VIA ENERGY COLLIMATION

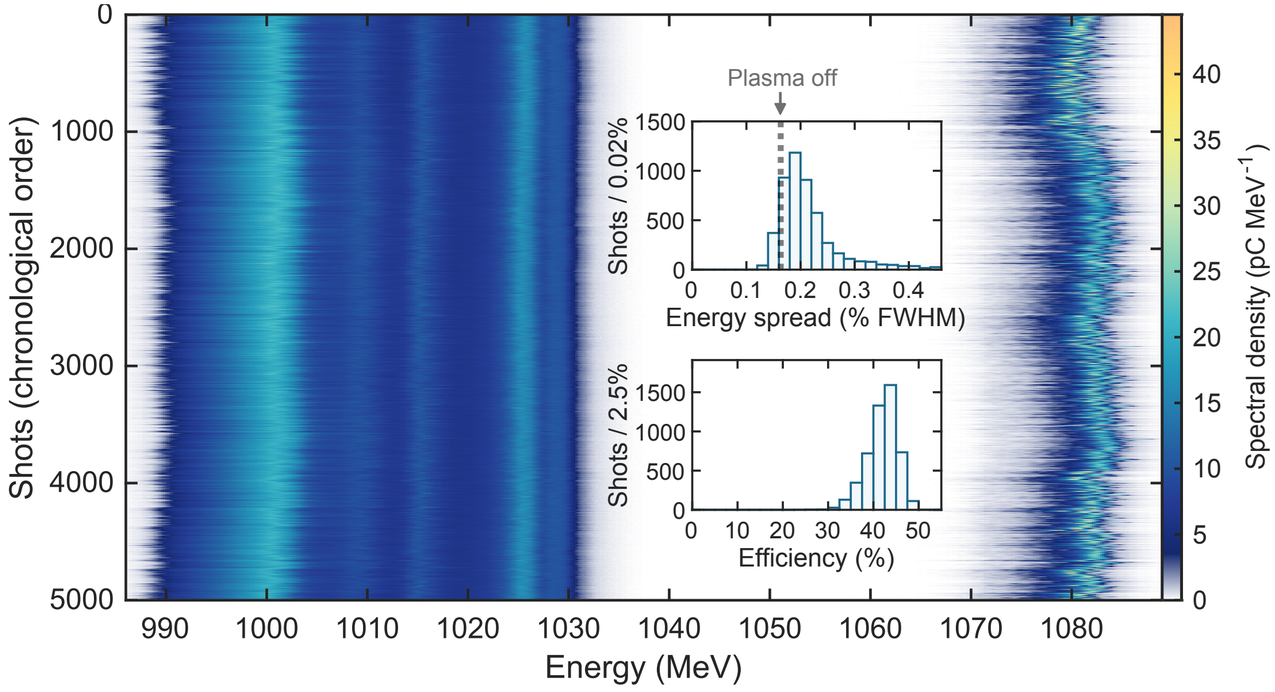


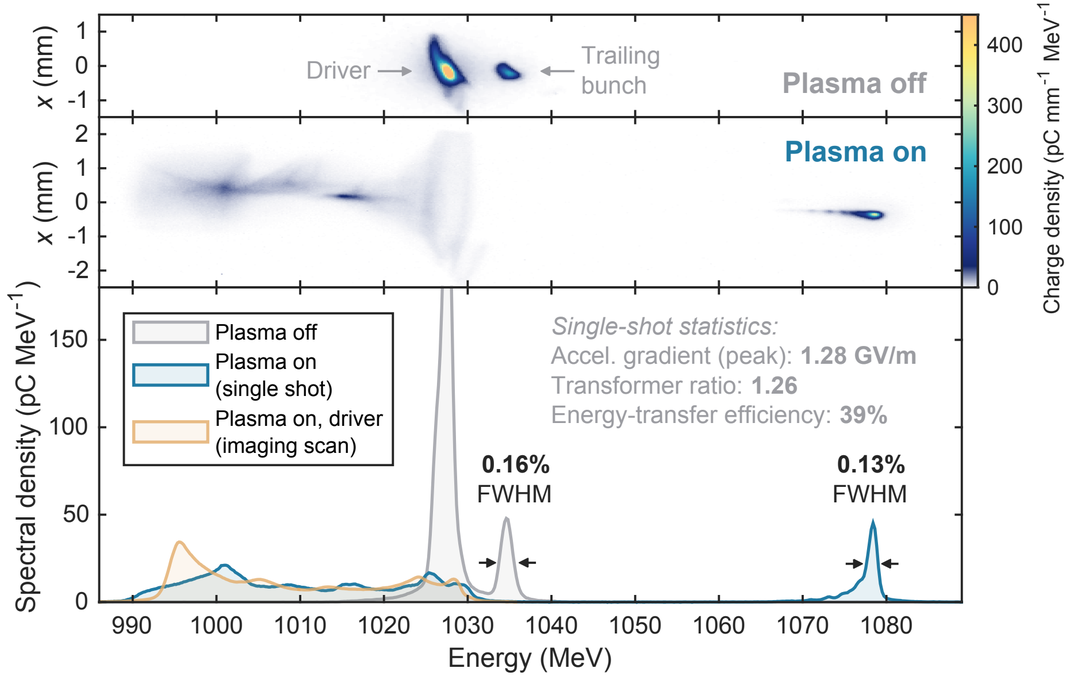


ENABLING FEMTOSECOND-PRECISION CURRENT-PROFILE MODIFICATION

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

Energy-spread-preserving plasma wakefield acceleration





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

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

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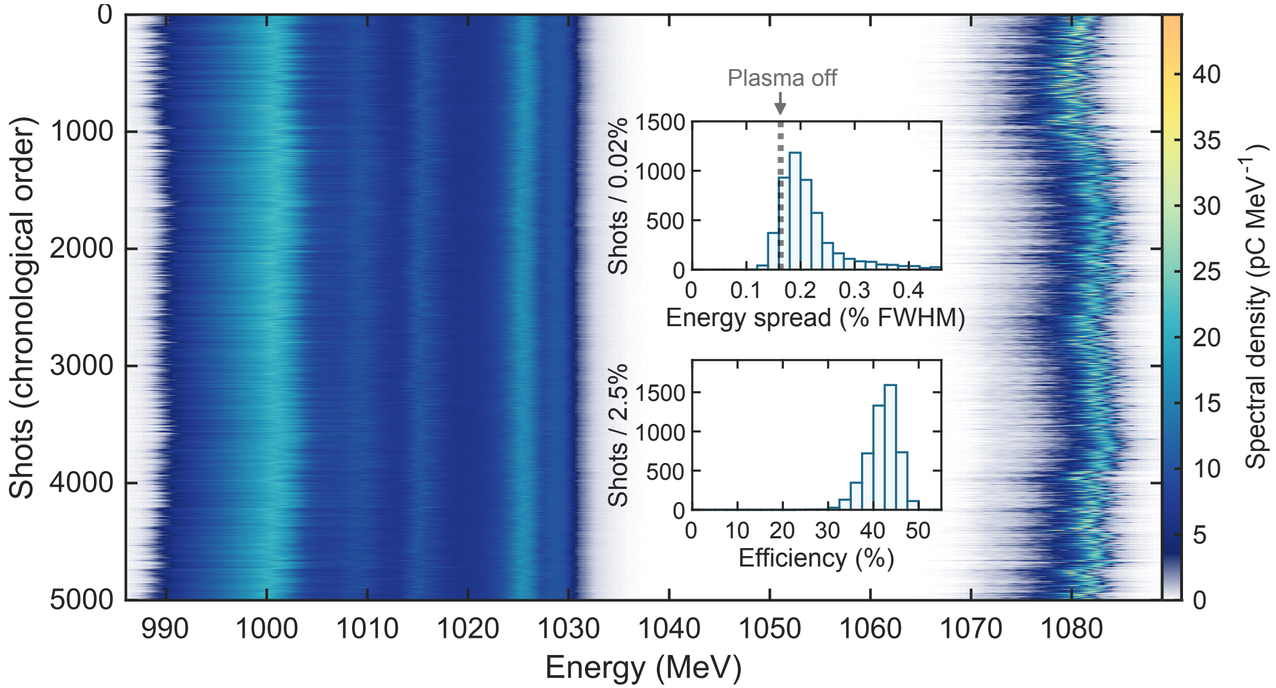

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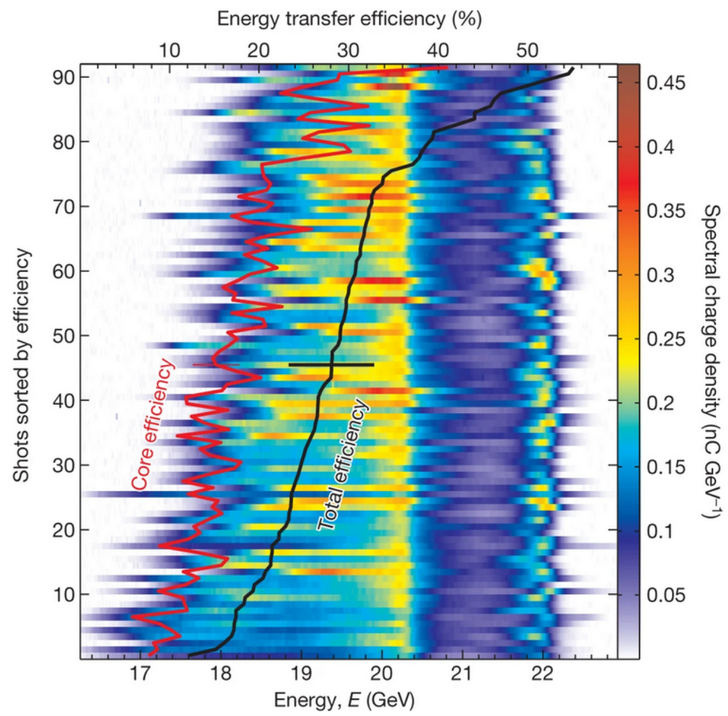
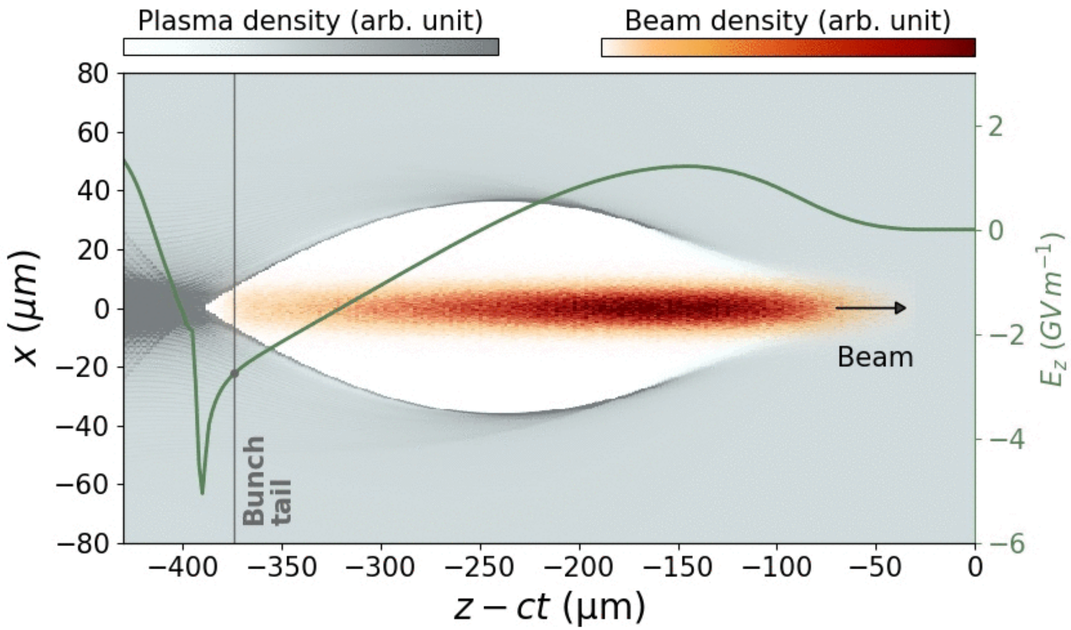
M. Litos *et al.*, Nature **515**, 92–95 (2014)

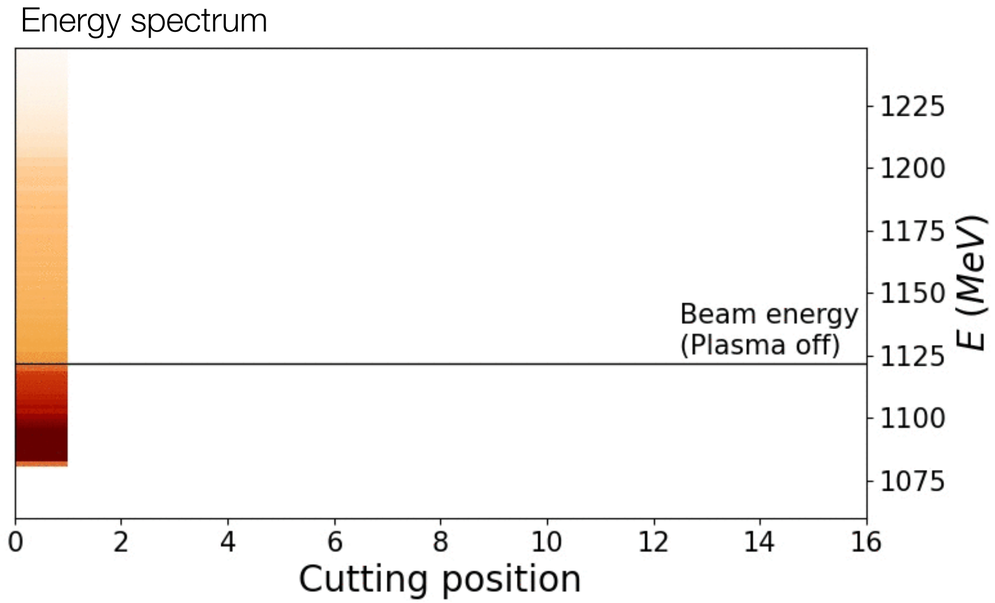


- 2% energy spread
- 17.7%±6.3% energy transfer efficiency
- 10% charge coupling

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

HIGH-RESOLUTION SAMPLING OF PLASMA WAKEFIELDS

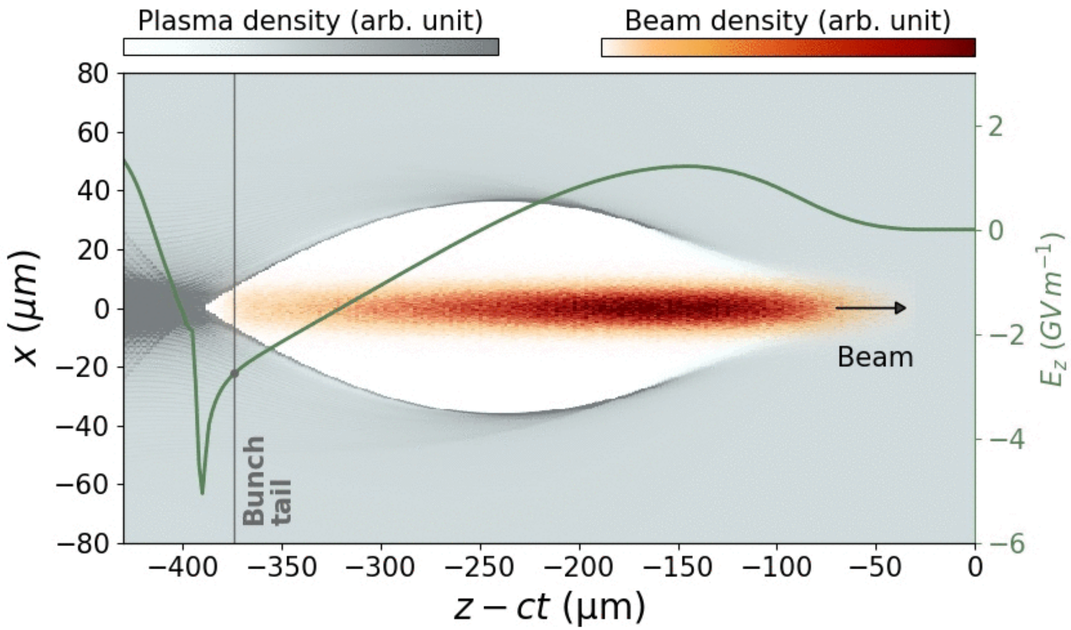


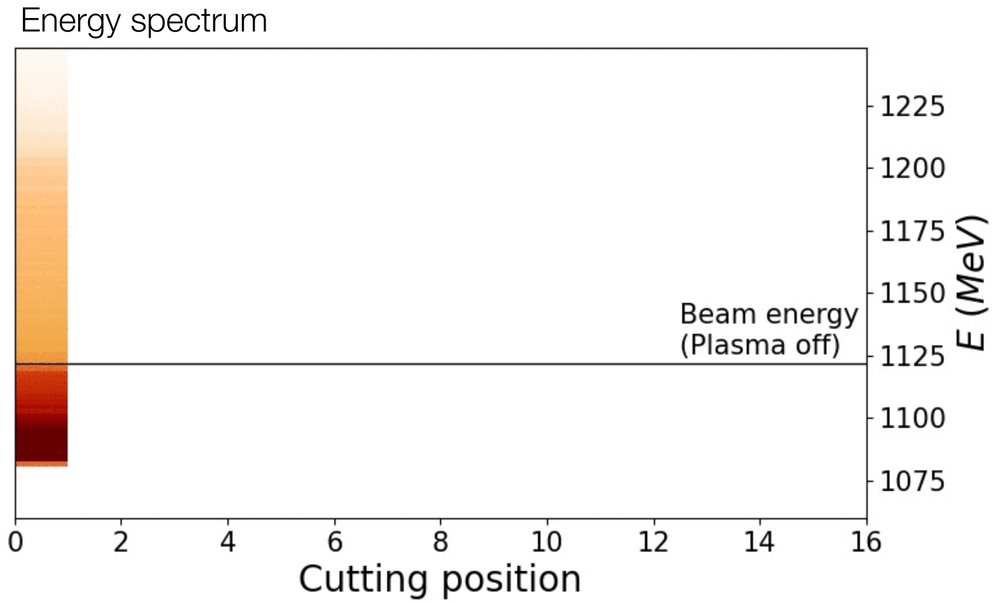


- Characteristic energy spectrum imprinted onto the bunch.
- Progressive tail-collimation samples the wakefield.

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

HIGH-RESOLUTION SAMPLING OF PLASMA WAKEFIELDS





- Characteristic energy spectrum imprinted onto the bunch.
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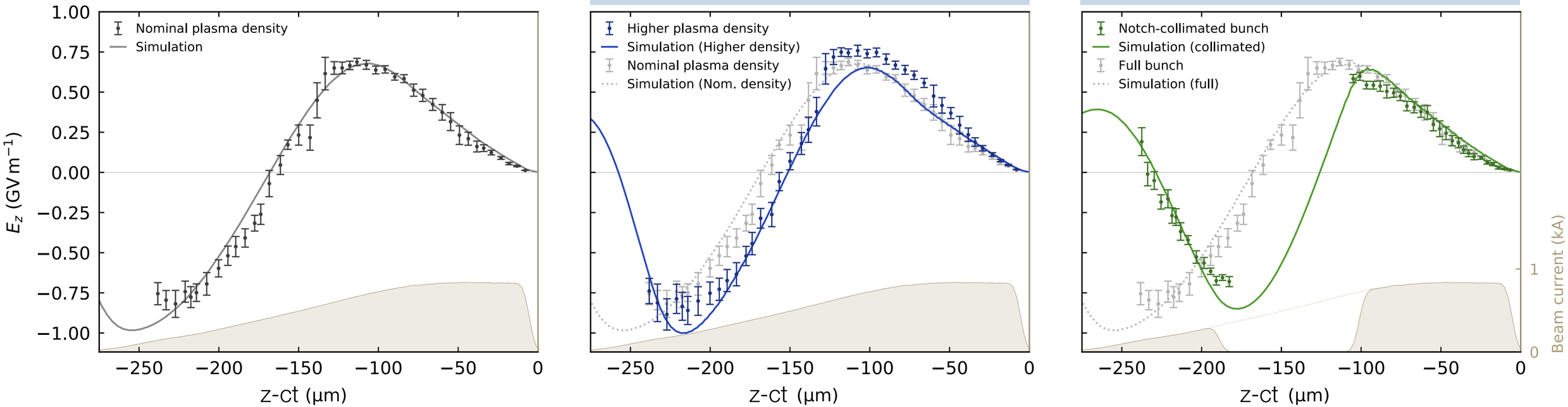
S. Schröder et al., Nat. Commun. 11, 5984 (2020)

FEMTO-SECOND RESOLVED WAKEFIELD MEASUREMENTS

CHANGING THE PLASMA DENSITY

CHANGING THE BEAM LOAD



> 15 fs resolution

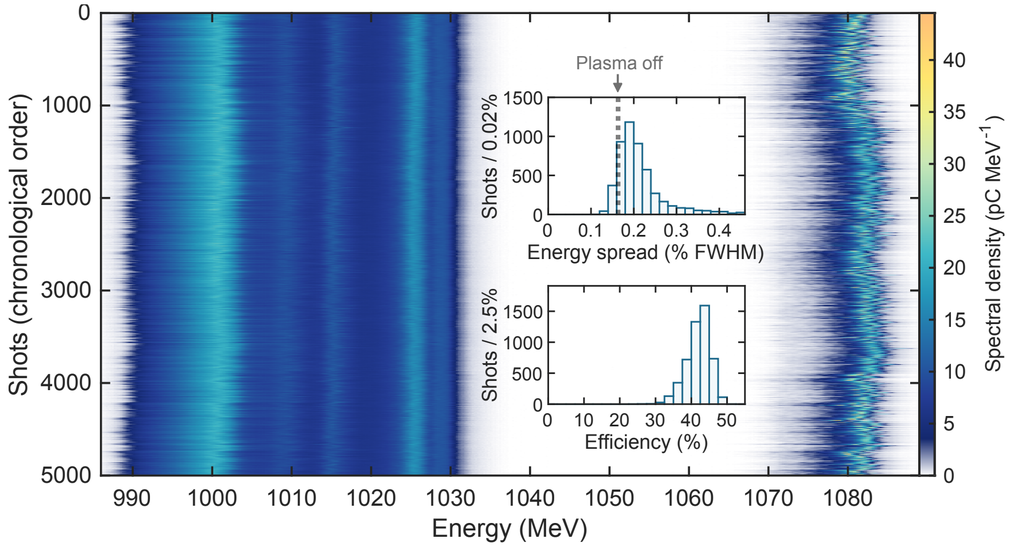
> 0.8 GV/m average accelerating fields

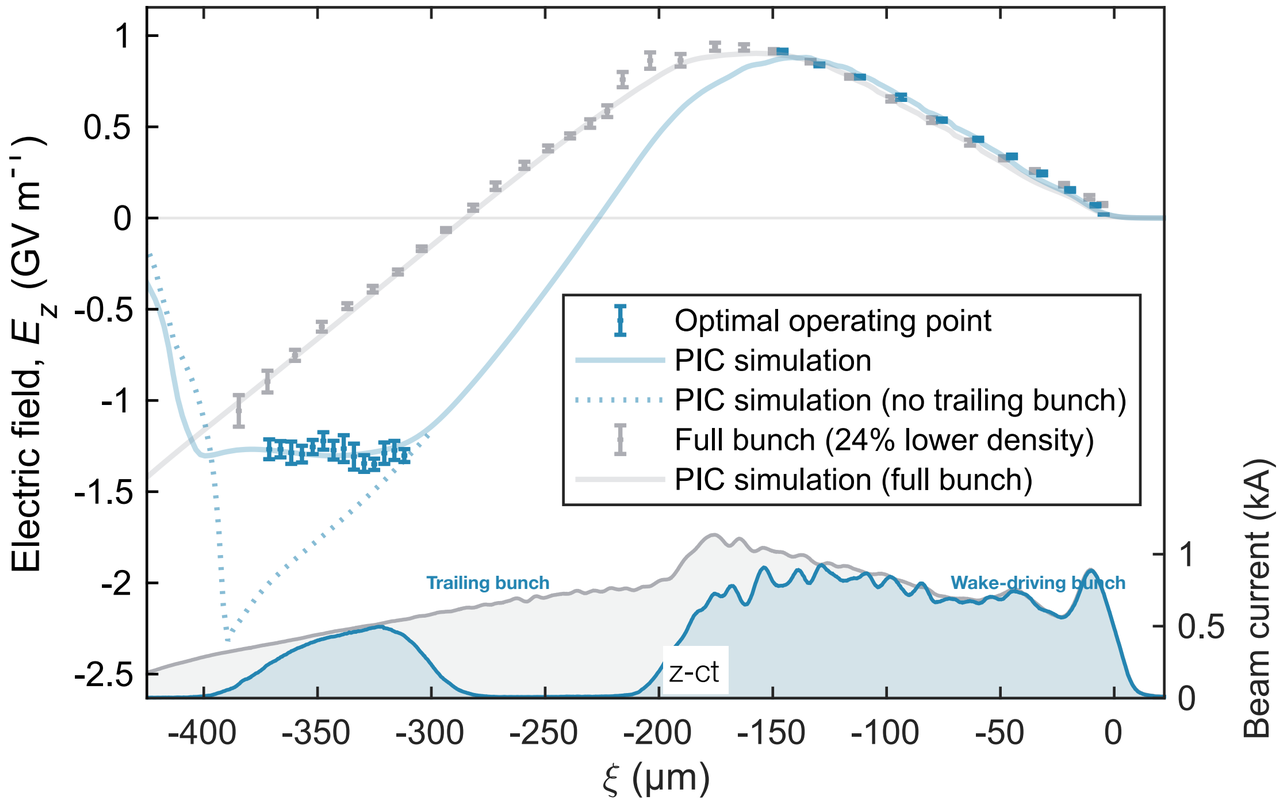
> Good agreement with simulation

ENABLING PRECISION OPTIMISATION OF THE ACCELERATION PROCESS

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

PROVING FIELD FLATTENING VIA OPTIMAL BEAM LOADING





%-LEVEL WAKEFIELD FLATTENING ACHIEVED

C.A. Lindstrøm, J.M. Garland, S. Schröder et al., Phys. Rev. Lett. 126, 014801 (2021)
S. Schröder et al., Nat. Commun. 11, 5984 (2020)

Conclusion & Outlook

- FLASHForward is a unique facility for the advancement of beam-driven plasma wakefield acceleration.
  - Access to FEL-suitable beam quality, beam stability and operation standards.
  - Test-bed for developing novel techniques and methodologies for the operation of a plasma accelerator.
- Precision measurement of plasma wakefields.
  - Femto-second resolution.
  - Robust, fairly simple and quick method.
- Demonstrated optimal beam loading.
  - Charge preservation.
  - Energy spread preservation.
  - Energy transfer efficiency: 42%

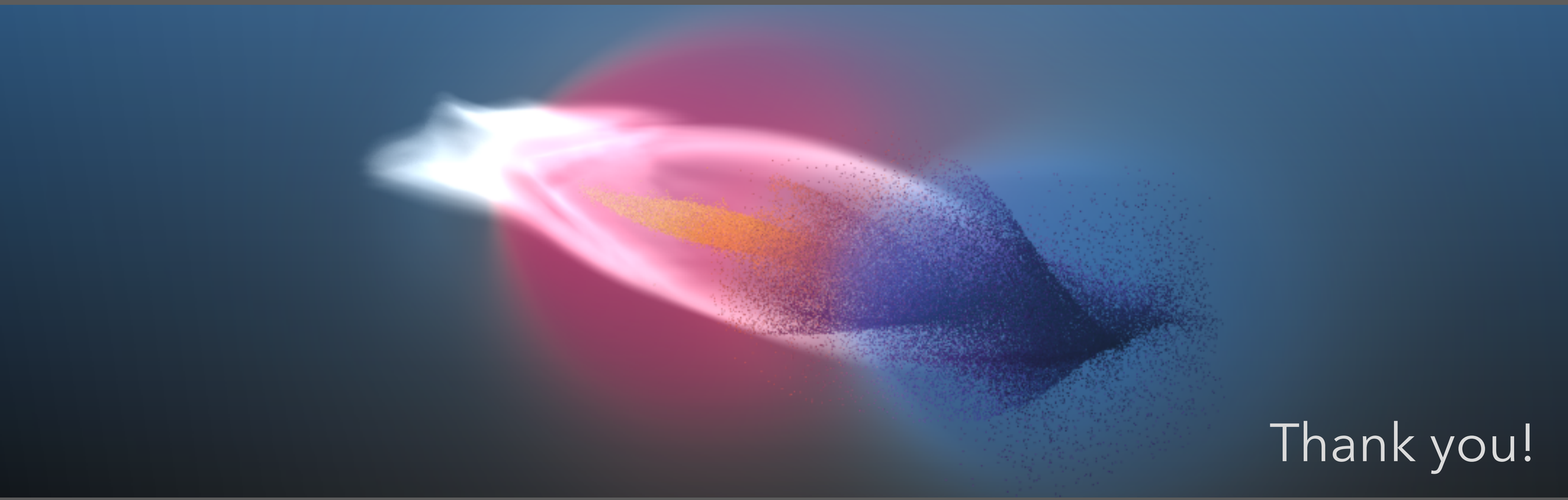
S. Schröder et al., J. Phys. Conf. Ser. 1596, 012002 (2020)
C.A. Lindstrøm et al., Phys. Rev. Lett. 126, 014801 (2021)
S. Schröder et al., Nat. Commun. 11, 5984 (2020)

Enabling FEL-suitable operation of a beam-driven plasma wakefield accelerator.

- Plasma recovery measurements indicate possible operation with MHz repetition rate.
- Emittance preservation.

R. D'Arcy et al., Nature 603, 58–62 (2022)
C. A. Lindstrøm (to be published)

Graph produced with Á. Ferran Pousa



Thank you!

Jens Osterhoff
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Brian Foster

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Jonathan Wood

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Severin Diederichs
Lewis Boulton
James Chappell
Felipe Pena
Judita Beinortaite

Vladislav Libov
Bridget Sheeran
Lucas Schaper
Pardis Niknejadi
Alex Knetsch

Kai Ludwig
Frank Marutzky
Sven Karstensen
Amir Rahali
Sandra Kottler
Technical groups (M-division)