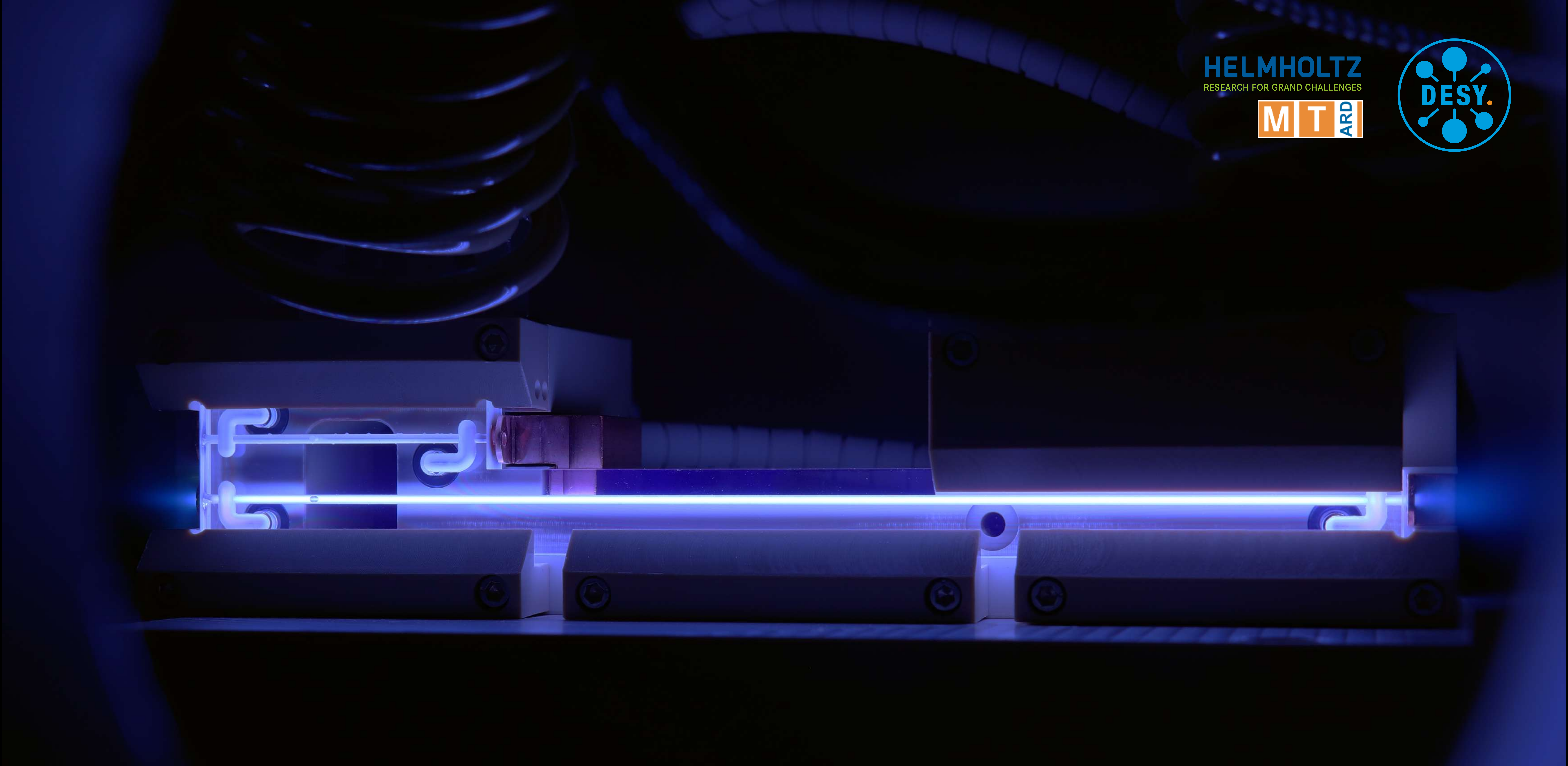


Energy-spread preservation in a plasma accelerator at FLASHFORWARD▸▸

by Carl A. Lindstrøm (DESY)

IAS Program on High Energy Physics (HEP 2021), 14 Jan 2021

OUR CUSTOMERS: HIGH ENERGY PHYSICS AND PHOTON SCIENCE

> High-energy physics and photon science demand higher energy and lower cost:

  > *Solution:* Plasma accelerators — significantly higher acceleration gradients.

> Simultaneously, particle colliders have strict demands for luminosity:
(FELs have similar demands for brightness)

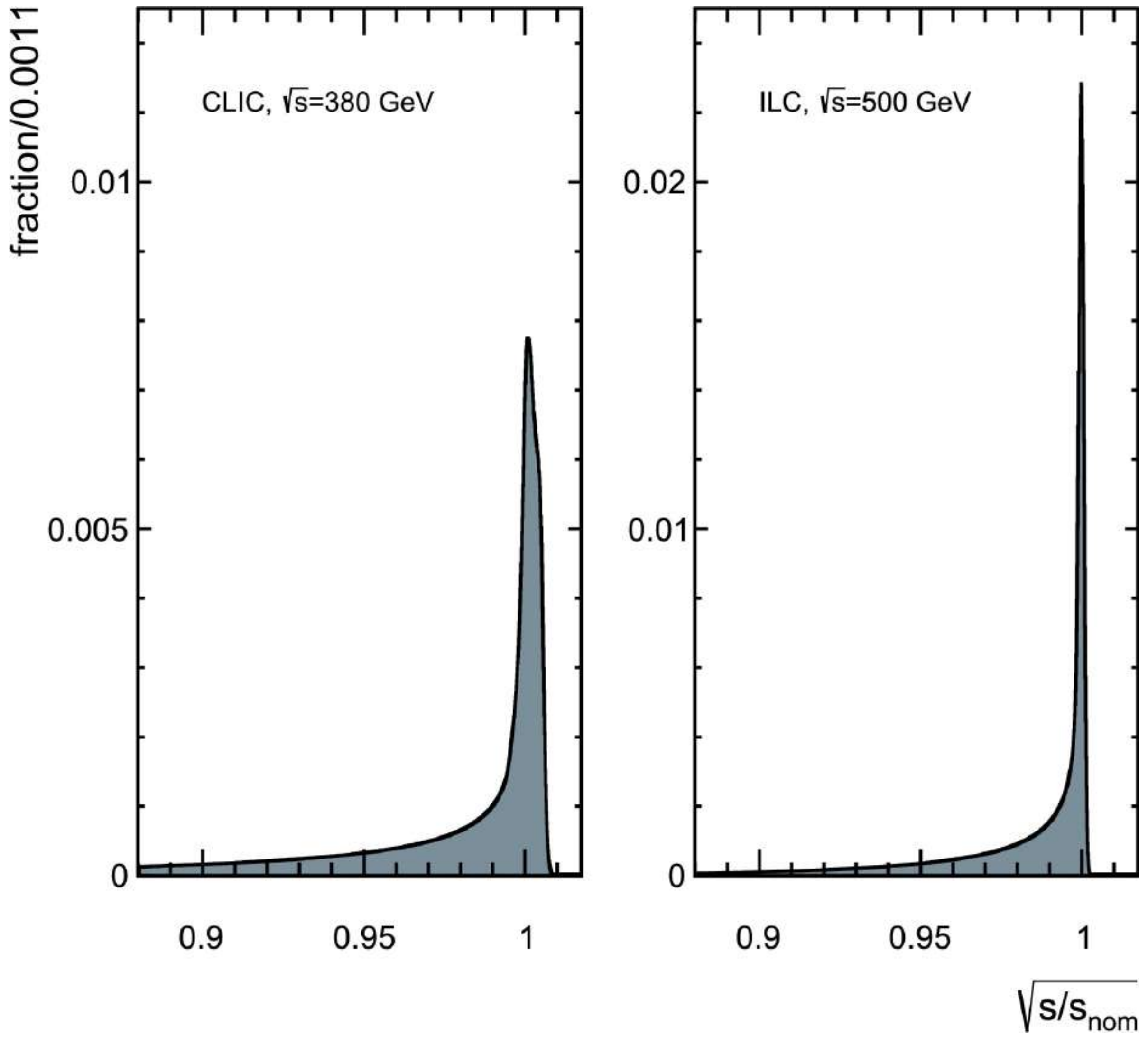
High repetition rate

High energy efficiency

$$\mathscr{L} = \frac{H_D}{8\pi m_e c^2} \frac{P_{\text{wall}}}{\sqrt{\beta_x \beta_y}} \frac{\eta N}{\sqrt{\epsilon_{nx}\epsilon_{ny}}}$$

Low energy spread
(luminosity spectrum, final focusing)

Low emittance



Luminosity distribution across collision energies.
Source: M. Boronat *et al.*, Phys. Lett. B 804, 135353 (2020).

$$\eta = \eta_{wall \rightarrow DB} \times \eta_{DB \rightarrow WB}$$

Beam-drivers are orders of magnitude more efficient
than laser-drivers (for now)

> Energy efficiency motivates use of beam-driven plasma acceleration.

SCIENTIFIC GOALS AT FLASHFORWARD

Primary goal:

Develop a self-consistent plasma-accelerator stage
with high-efficiency, high-quality, and high-average-power

High efficiency

Beam loading

Driver depletion

High beam quality

Energy-spread preservation

Emittance preservation

High average power

High repetition rate

Scientific goals at FLASHForward▸▸

Primary goal:

Develop a self-consistent plasma-accelerator stage
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This talk

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OPTIMAL BEAM LOADING — UNIFORM AND EFFICIENT ACCELERATION

- *Problem 1:* Compared to RF cavities (Q ~ 10^4–10^{10}), the electric fields in a plasma decay very rapidly (Q ~ 1–10).
  - The energy needs to be extracted very rapidly —ideally within the first oscillation.

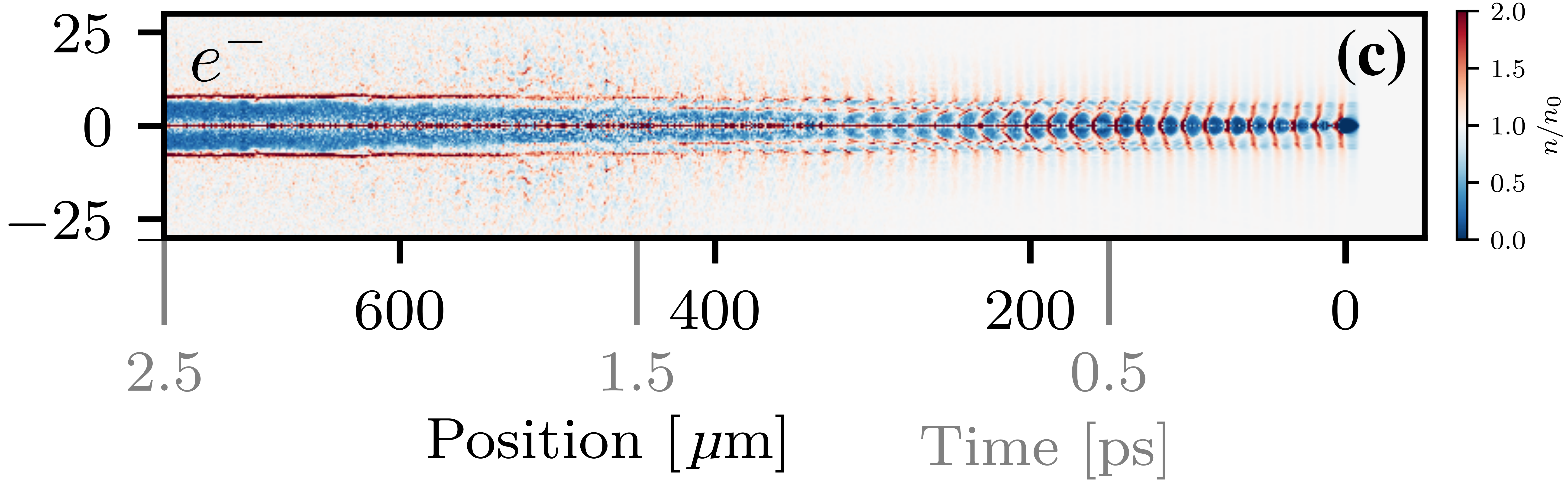

Image source: M. F. Gilljohann *et al.*, Phys. Rev. X **9**, 011046 (2019)

OPTIMAL BEAM LOADING — UNIFORM AND EFFICIENT ACCELERATION

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  - *Solution:* Beam loading
    The trailing-bunch wakefield “destructively interferes” with the driver wakefield—extracting energy.
- Problem 2: to extract a large fraction of the energy, the beam will cover a large range of phases (~90 degrees or more).
  - Large energy spread is induced.

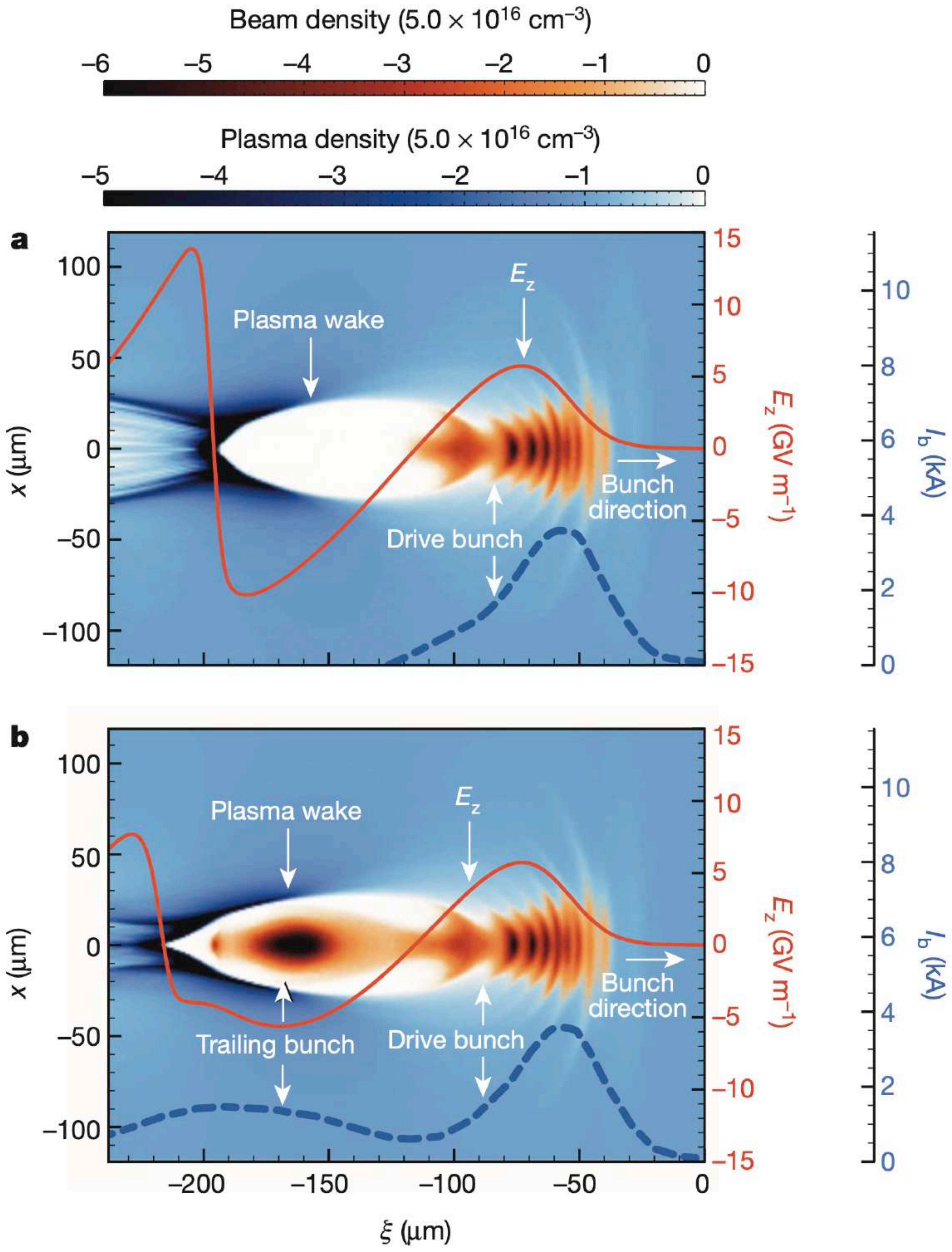

Image credit: M. Litos et al., Nature 515, 92 (2014)

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- Problem 2: to extract a large fraction of the energy, the beam will cover a large range of phases (~90 degrees or more).
    - Large energy spread is induced.
    - *Solution:* Optimal beam loading
      The current profile of the trailing bunch is *precisely tailored* to exactly flatten the wakefield.
- This requires extremely precise control of the current profile.
    - State-of-the-art FEL facilities are ideally suited for such experiments.

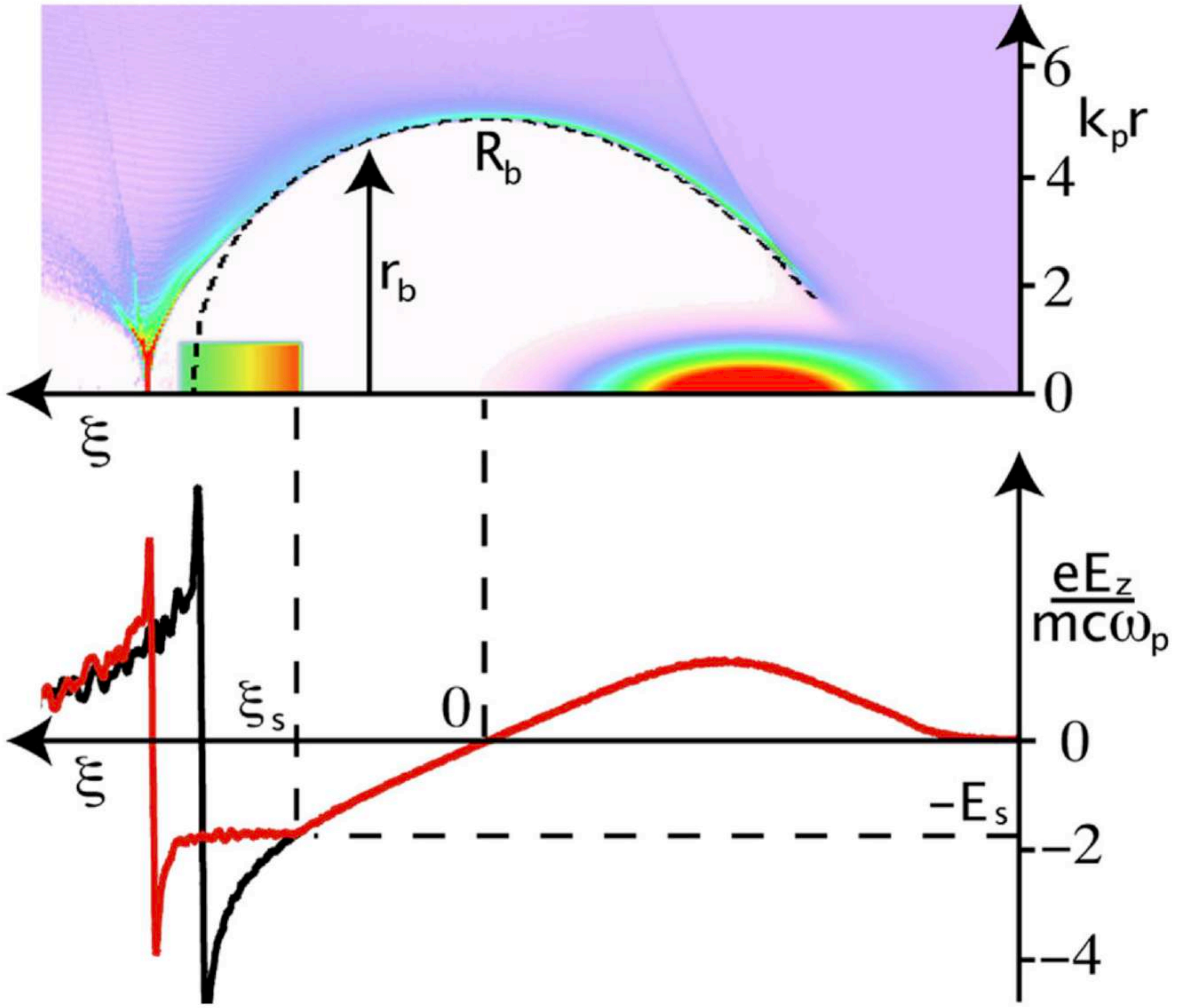
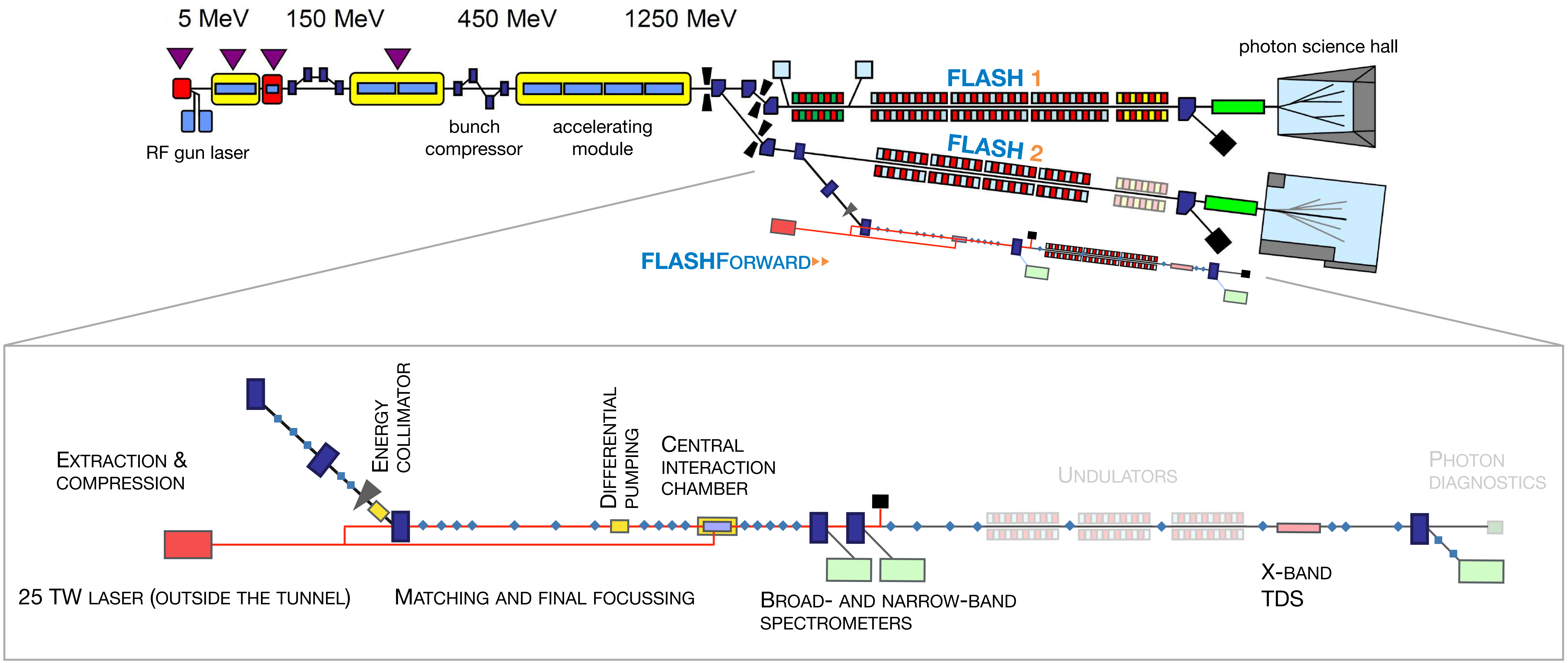


Image credit: M. Tzoufras *et al.*, Phys. Rev. Lett. **101**, 145002 (2008)

THE FLASHFORWARD FACILITY AT DESY

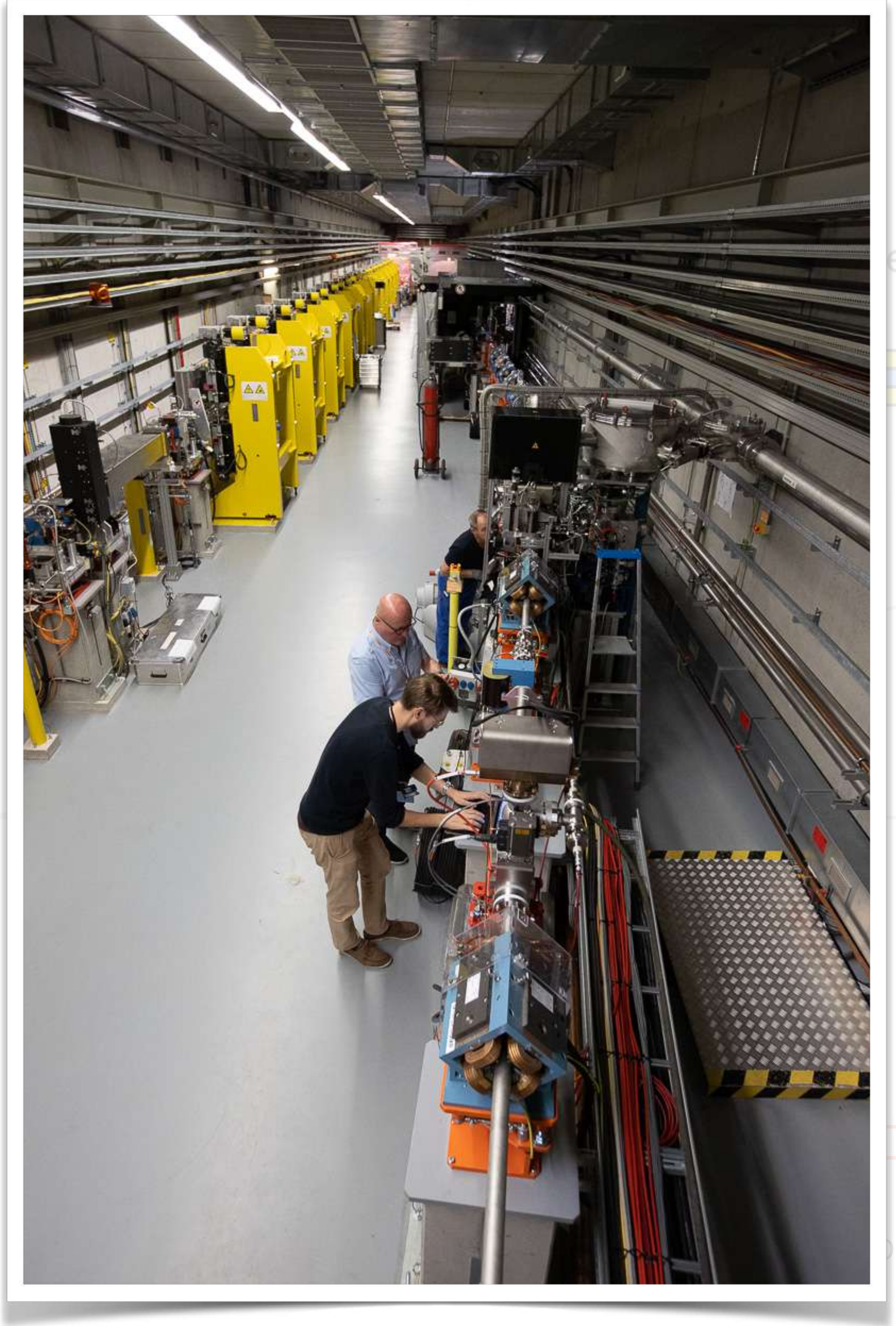
> **High-quality, high-stability** electron bunches provided by the free-electron-laser facility FLASH.

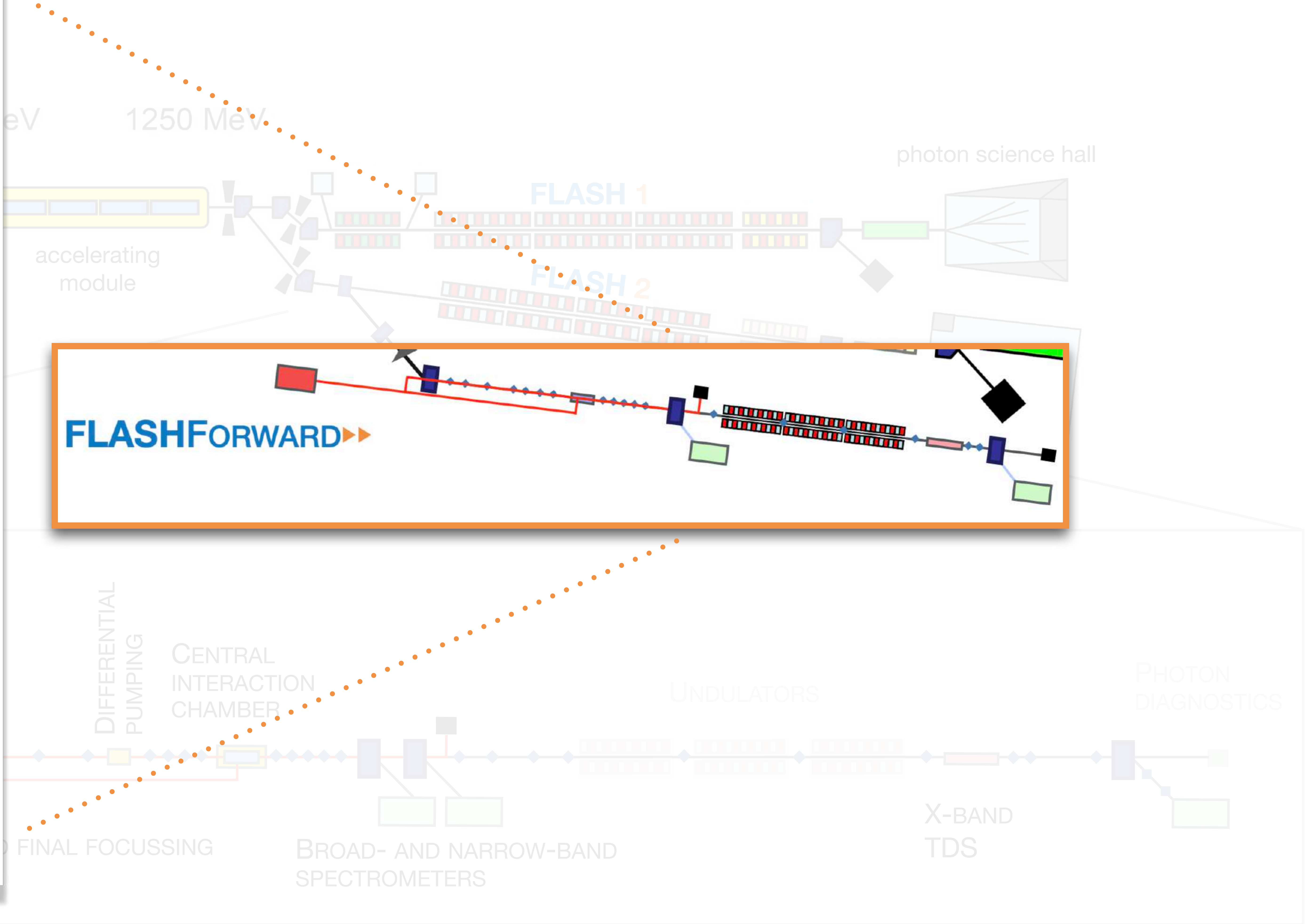
> Superconducting RF cavities with **MHz repetition rate** — can supply up to 10 kW of beam power.



THE FLASHFORWARD FACILITY AT DESY

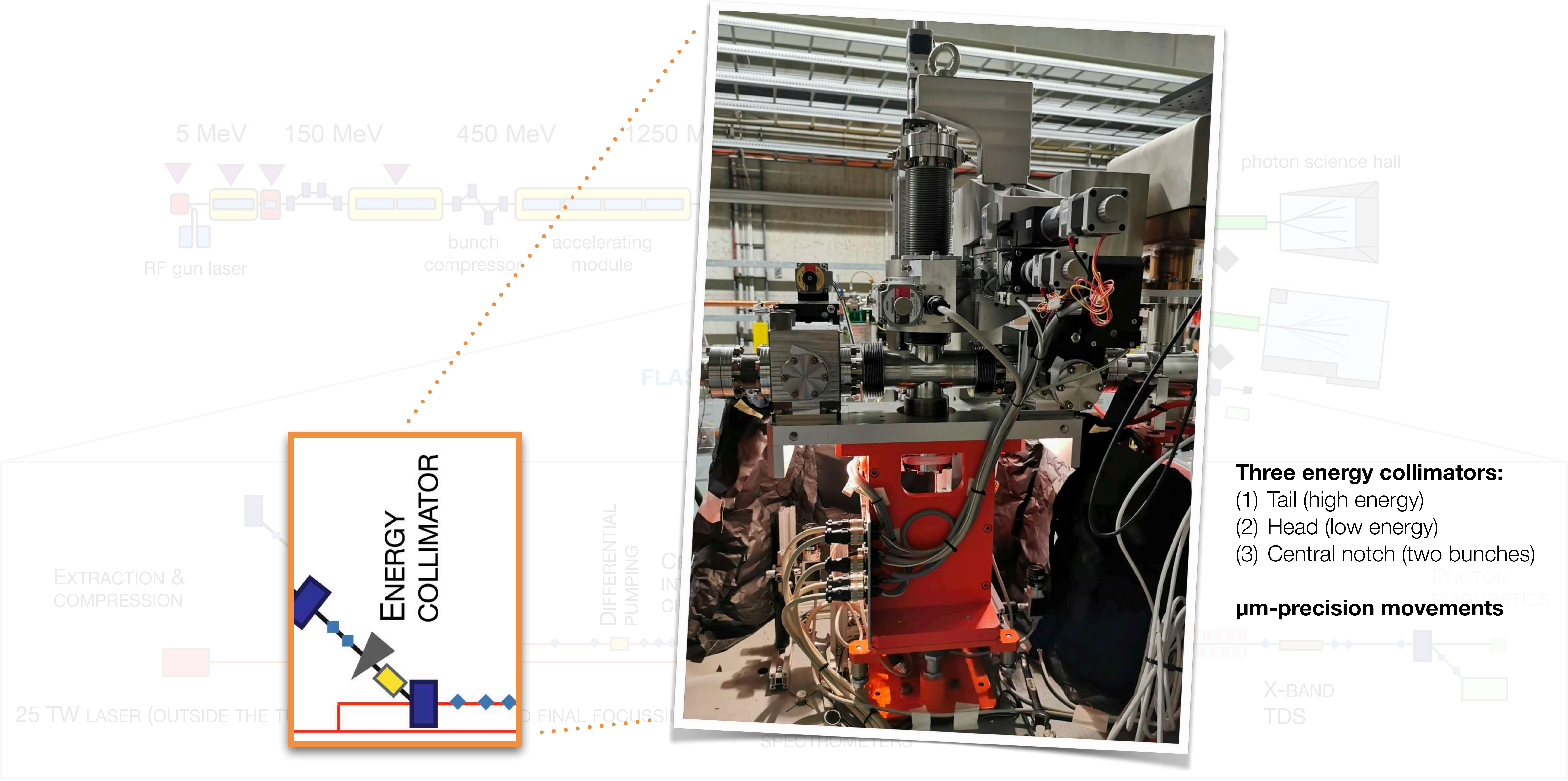
R. D'Arcy *et al.*, Phil. Trans. R. Soc. A **377**, 20180392 (2019)





THE FLASHFORWARD FACILITY AT DESY

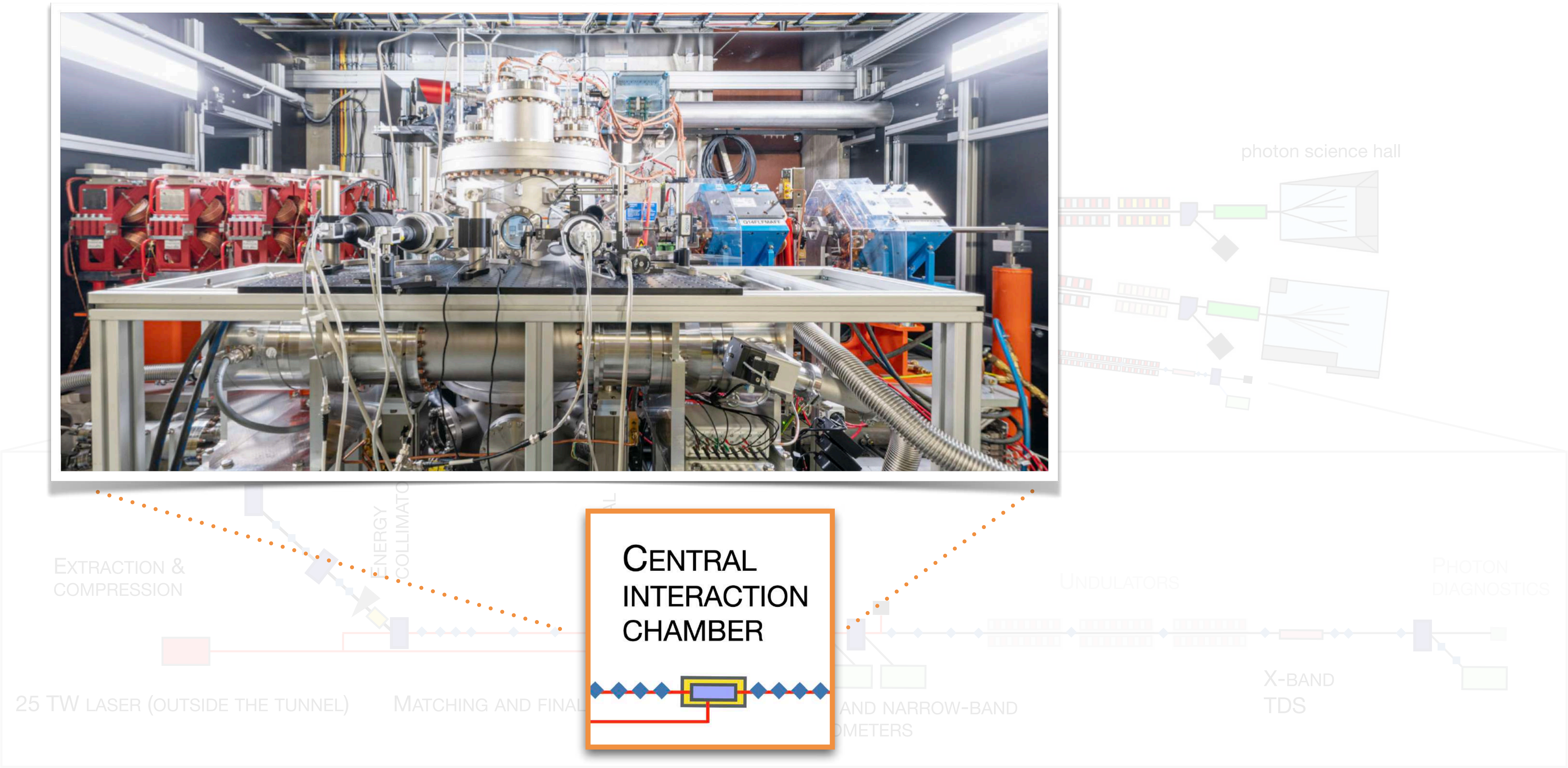
S Schröder *et al.*, J. Phys. Conf. Ser. **1596** 012002 (2020)



Three energy collimators:
(1) Tail (high energy)
(2) Head (low energy)
(3) Central notch (two bunches)

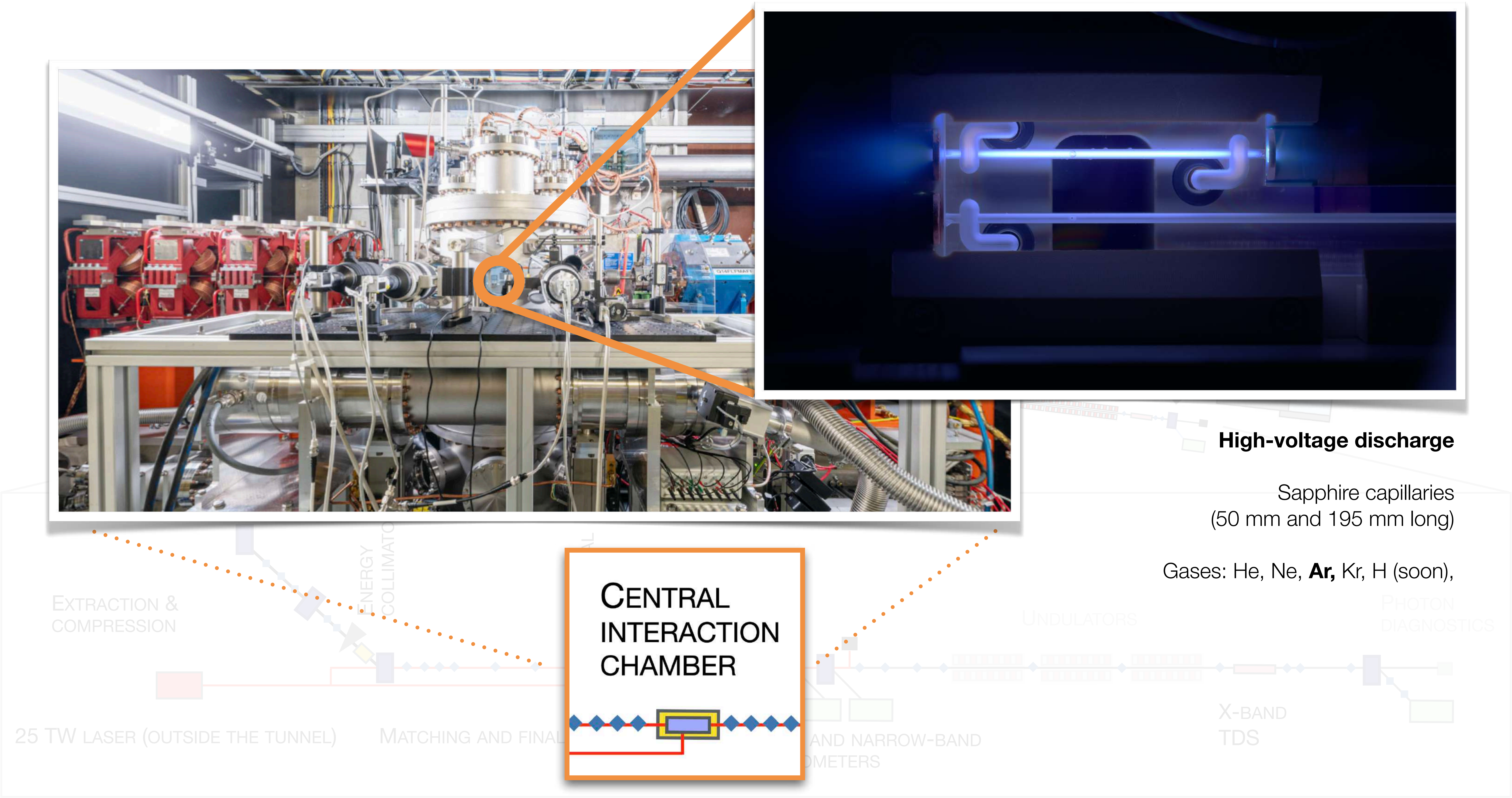
µm-precision movements

THE FLASHFORWARD FACILITY AT DESY



CENTRAL INTERACTION CHAMBER

THE FLASHFORWARD FACILITY AT DESY

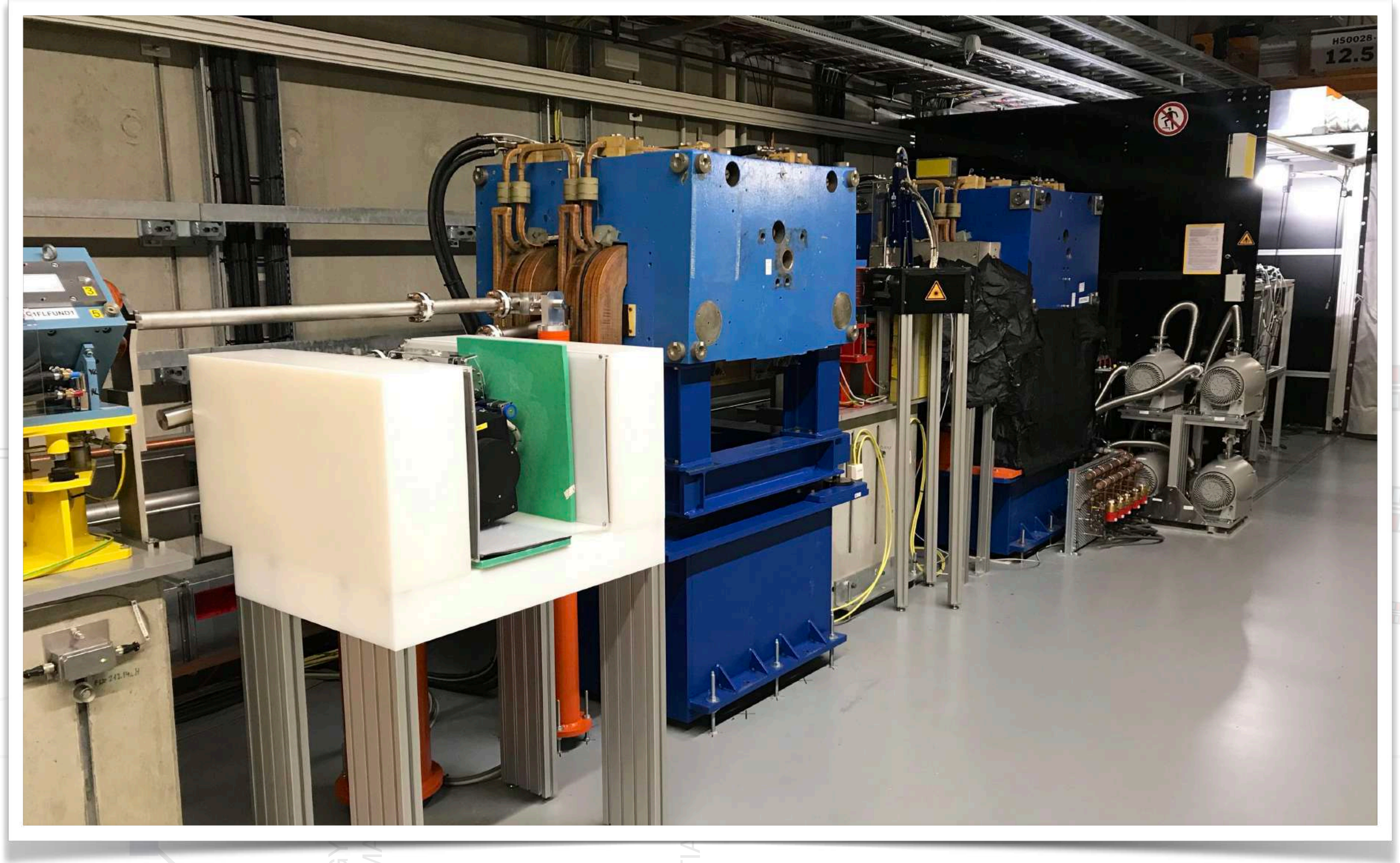


High-voltage discharge

Sapphire capillaries
(50 mm and 195 mm long)

Gases: He, Ne, **Ar,** Kr, H (soon),

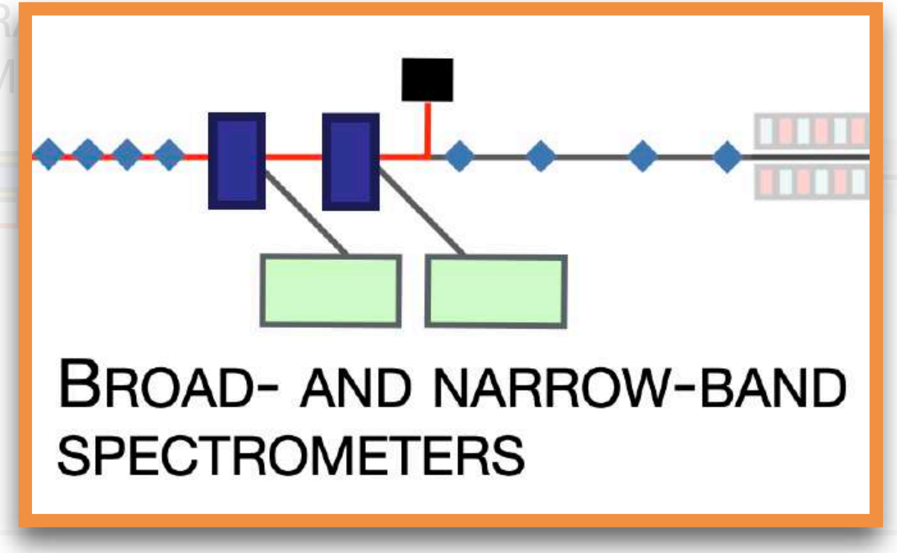
THE FLASHFORWARD FACILITY AT DESY



Imaging spectrometer

High-resolution, narrow-band screen for mm-mrad emittance measurements

Low-resolution, broad-band screen for MeV–GeV energy range



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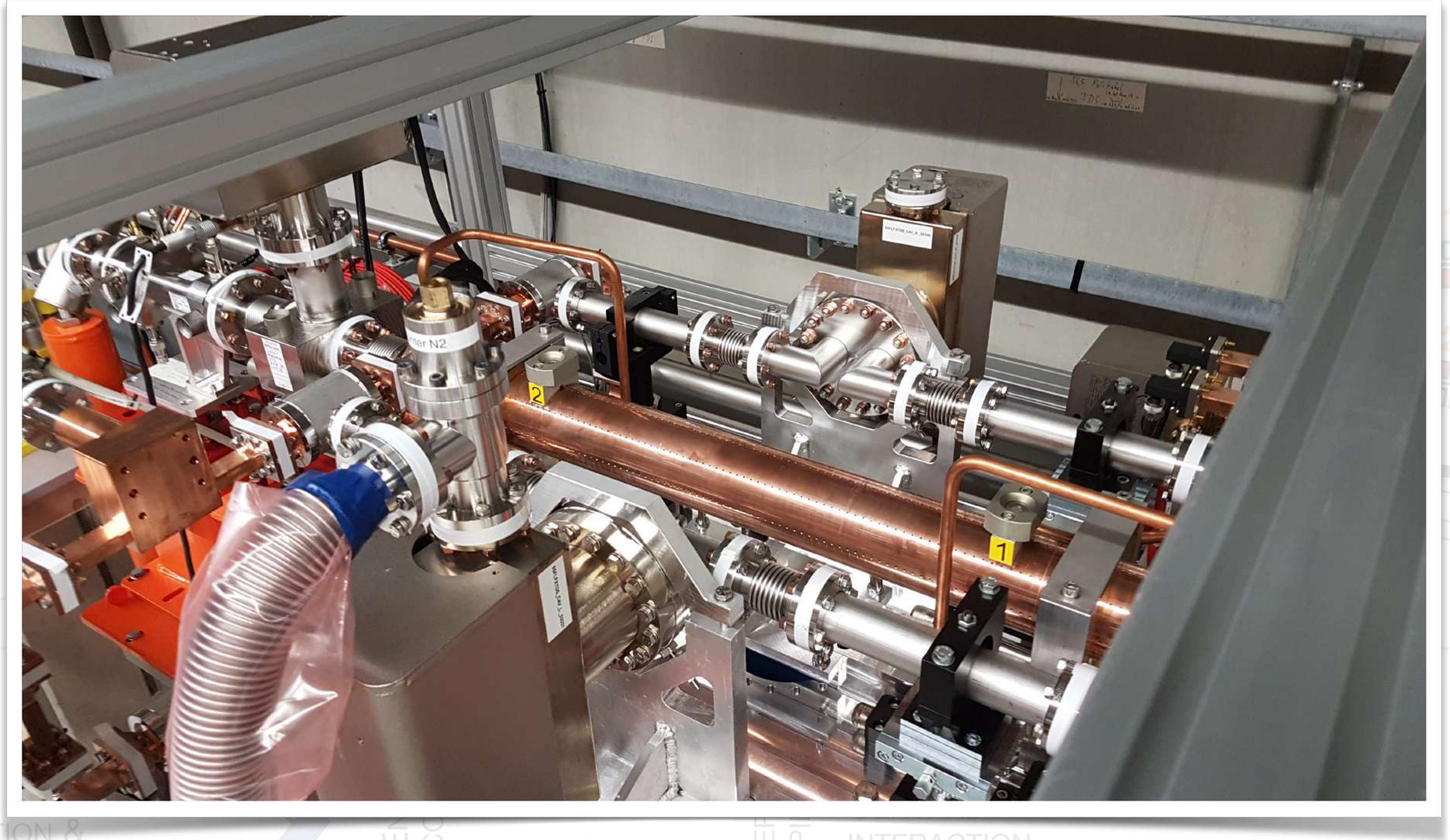
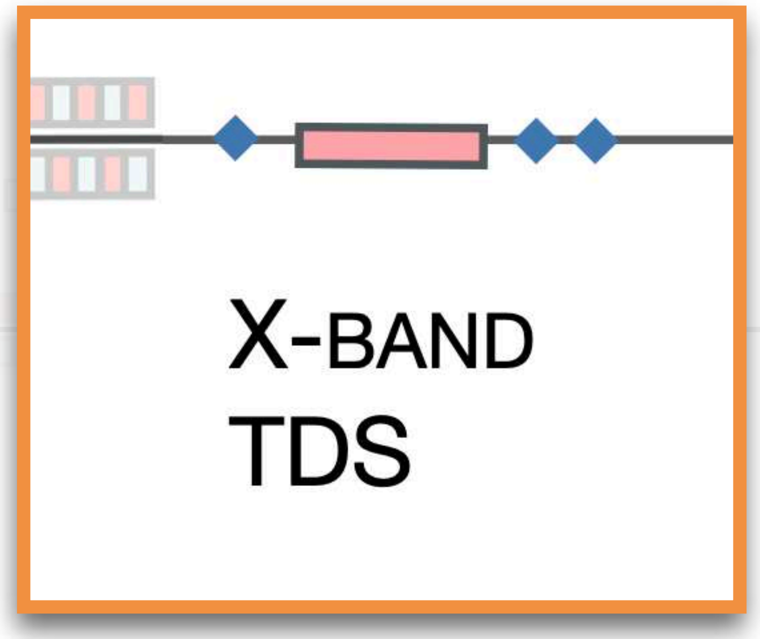


X-band cavity (12 GHz)
for femtosecond resolution

Polarizable streak (any direction)
allowing 6D phase space measurements



THE X-2 EXPERIMENT: HIGH-QUALITY PLASMA ACCELERATION

Experimental goals:

- **Energy-spread preservation**
  (with ~100% charge coupling)
- **High overall efficiency acceleration**
  (strong beam loading, driver depletion)
- **Emittance preservation**
  (over many betatron oscillations)

The ultimate PWFA stage

Accelerating gradient:

Less relevant ← *Lower gradient* **~1 GV/m** *Higher gradient* → *More challenging*

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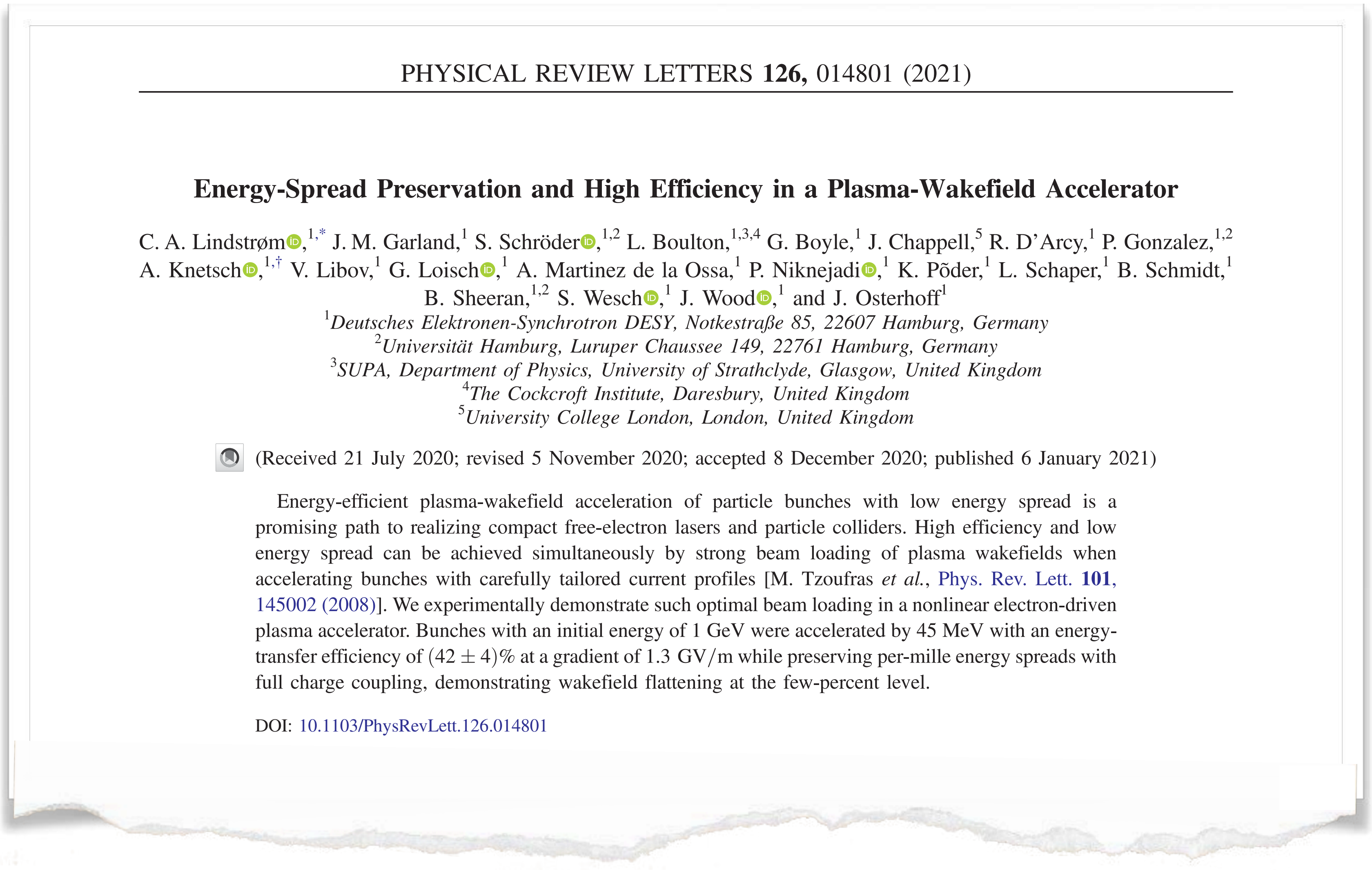
  (strong beam loading, driver depletion)
  ✓
- **Emittance preservation**
  (over many betatron oscillations)

Recently published:

Experimental demonstration of optimal beam loading

C. A. Lindstrøm *et al.*, Phys. Rev. Lett. **126**, 014801 (2021)



PHYSICAL REVIEW LETTERS **126,** 014801 (2021)

Energy-Spread Preservation and High Efficiency in a Plasma-Wakefield Accelerator

C. A. Lindstrøm,[1,*] J. M. Garland,[1] S. Schröder,[1,2] L. Boulton,[1,3,4] G. Boyle,[1] J. Chappell,[5] R. D'Arcy,[1] P. Gonzalez,[1,2]
A. Knetsch,[1,†] V. Libov,[1] G. Loisch,[1] A. Martinez de la Ossa,[1] P. Niknejadi,[1] K. Põder,[1] L. Schaper,[1] B. Schmidt,[1]
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[2]*Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany*
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(Received 21 July 2020; revised 5 November 2020; accepted 8 December 2020; published 6 January 2021)

Energy-efficient plasma-wakefield acceleration of particle bunches with low energy spread is a promising path to realizing compact free-electron lasers and particle colliders. High efficiency and low energy spread can be achieved simultaneously by strong beam loading of plasma wakefields when accelerating bunches with carefully tailored current profiles [M. Tzoufras *et al.*, Phys. Rev. Lett. **101**, 145002 (2008)]. We experimentally demonstrate such optimal beam loading in a nonlinear electron-driven plasma accelerator. Bunches with an initial energy of 1 GeV were accelerated by 45 MeV with an energy-transfer efficiency of $(42 \pm 4)\%$ at a gradient of 1.3 GV/m while preserving per-mille energy spreads with full charge coupling, demonstrating wakefield flattening at the few-percent level.

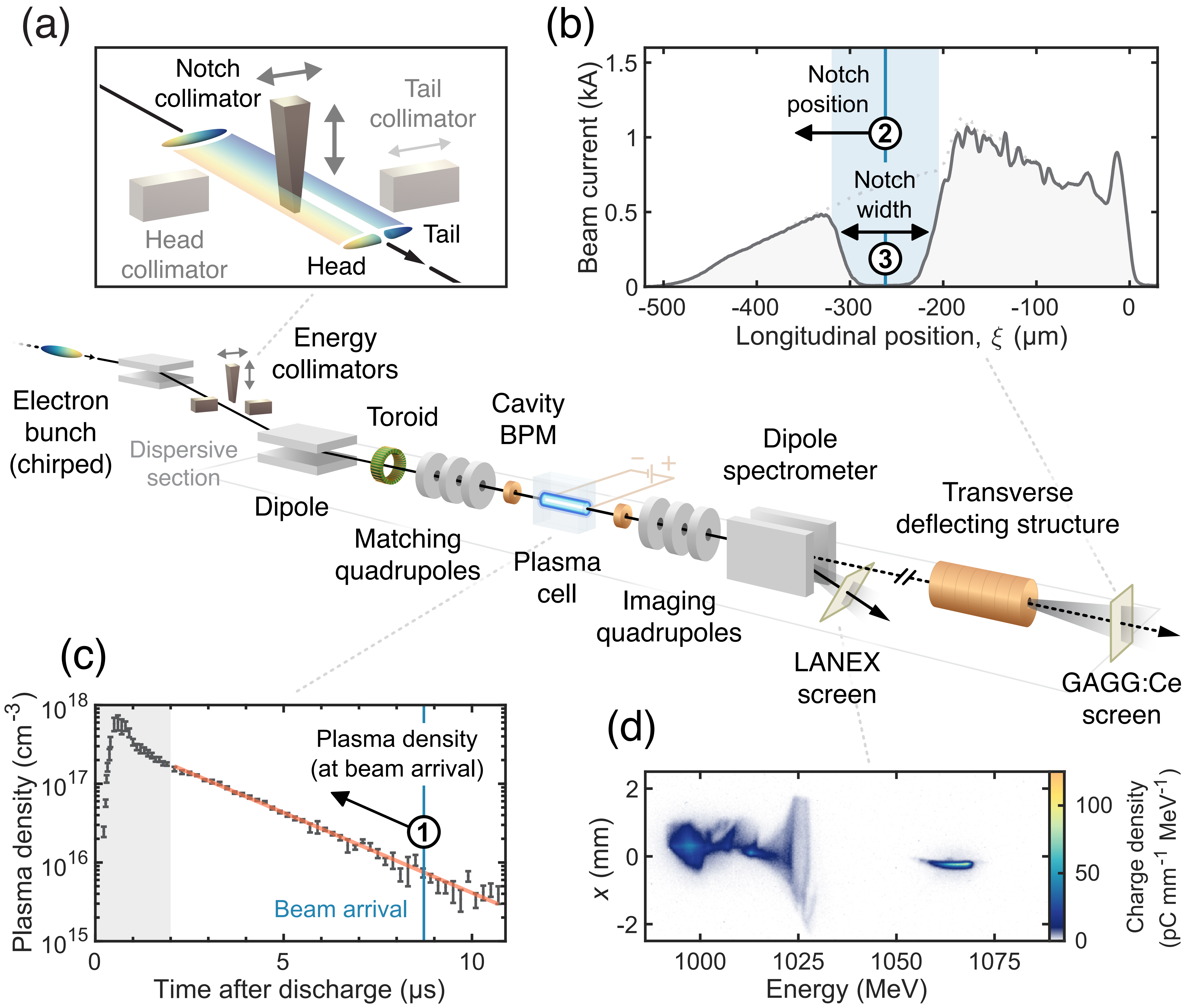
DOI: 10.1103/PhysRevLett.126.014801

Accelerating gradient:

Less relevant ← *Lower gradient* **~1 GV/m** *Higher gradient* → *More challenging*

SETUP AND OPTIMIZATION OF THE PLASMA ACCELERATOR

- Electron beam:
  - Energy: 1 GeV; charge: 1 nC.
  - Linear chirp in longitudinal phase space (using a third-harmonic cavity)
  - Ramped current profile (~1 kA peak).
  - Tight focusing: ~10x10 mm beta functions
  - Straightening with quads and sextupoles.
- Plasma:
  - 50 mm capillary, ~34 mm flat-top plasma length
  - Decays exponentially on the μs timescale.
  - Density measured with Stark broadening of the H-alpha line (Ar doped with 3% H).
- **Scanning three parameters:**
  - *(1) Plasma density (beam arrival time)*
  - *(2) Current-notch position*
  - *(3) Current-notch width*

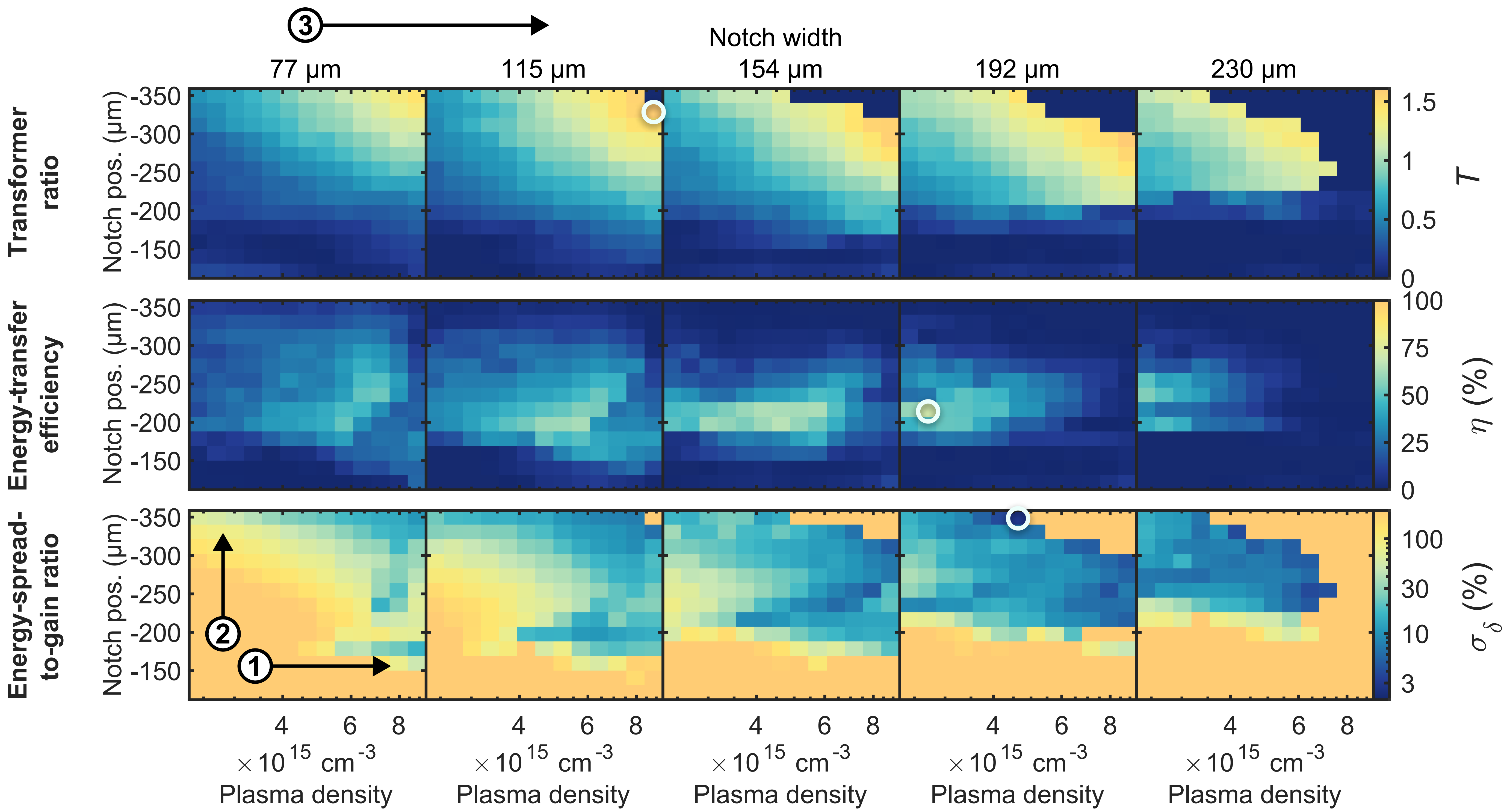


FINDING AN OVERALL OPTIMUM

- High stability and reproducibility.
- Single-parameter optima:
  - ~1.6 transformer ratio
  - ~70% efficiency
  - ~3% FWHM energy-spread-to-gain ratio

(3D scan with ~13,000 shots)

○ Single-parameter optima



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- Single-parameter optima:
  - ~1.6 transformer ratio
  - ~70% efficiency
  - ~3% FWHM energy-spread-to-gain ratio
- Define new *wakefield-shape parameter* for optimization:

Optimization parameter

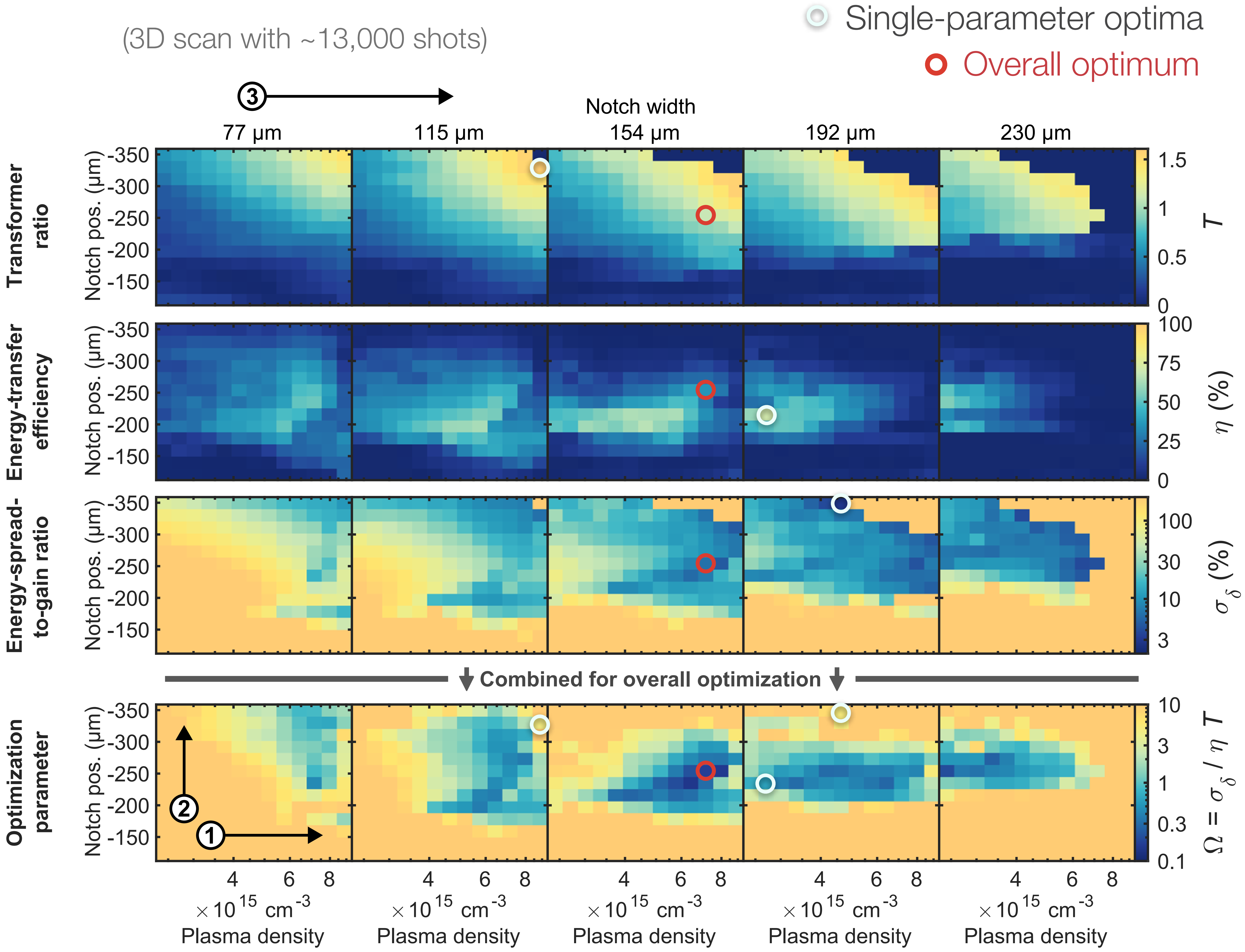
Energy-spread -to-gain ratio

$$\Omega = \frac{\sigma_\delta}{\eta T}$$

Energy-transfer efficiency

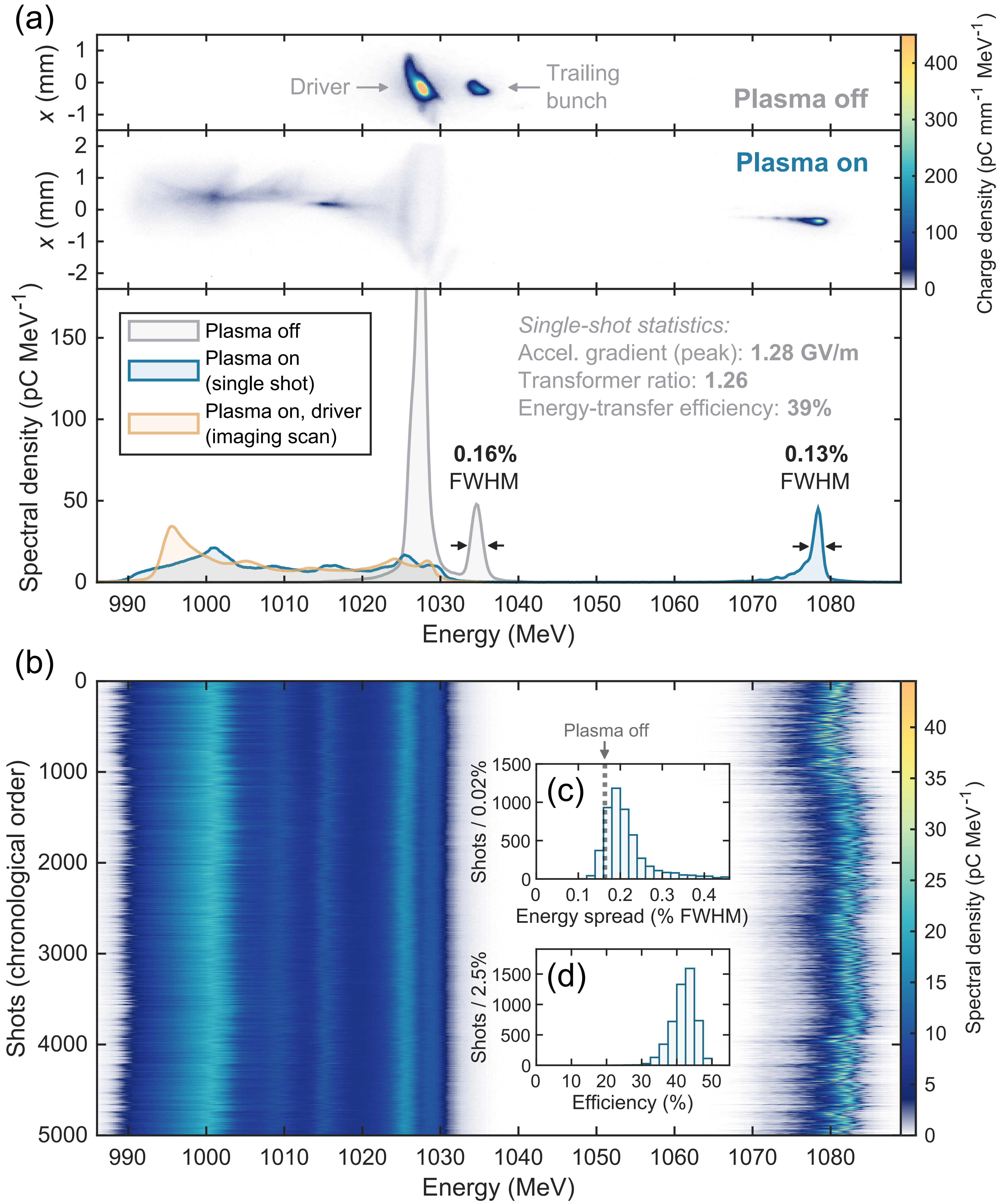
Transformer ratio

(3D scan with ~13,000 shots)

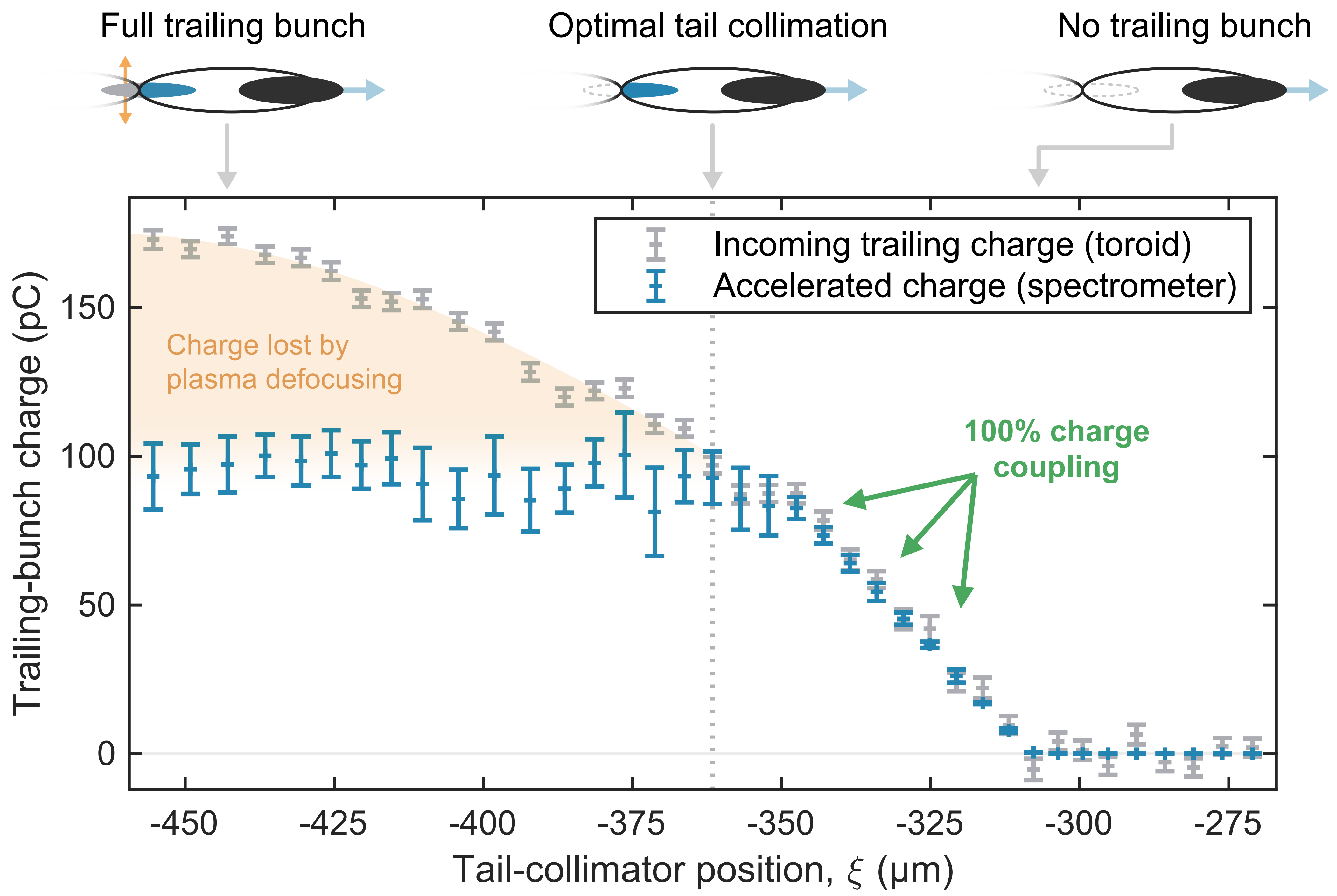


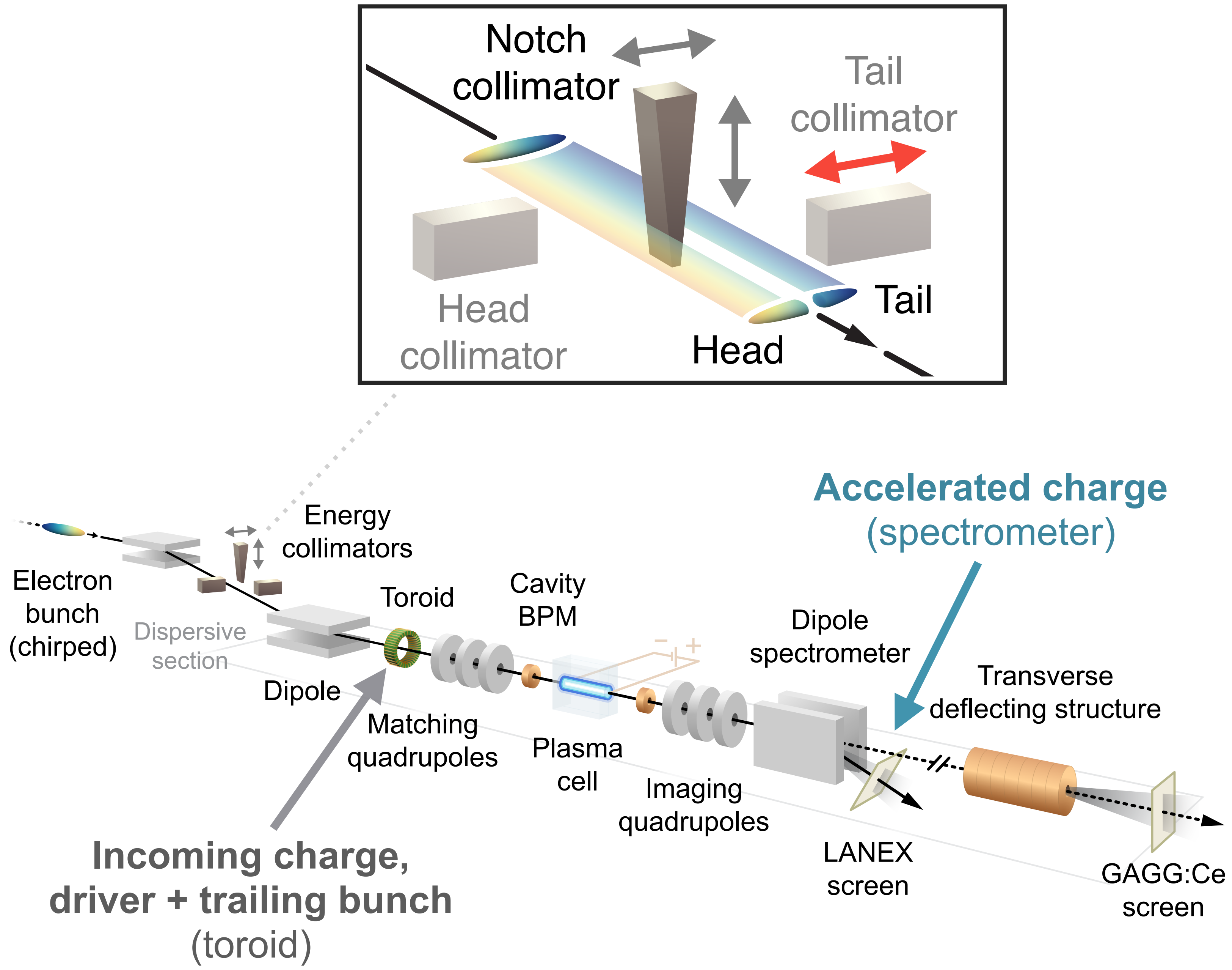
RESULT #1: ENERGY-SPREAD PRESERVATION AND HIGH EFFICIENCY

- **Demonstration of per-mille energy-spread preservation**
  - A small low-energy tail is introduced due to imperfect beam loading.
- Simultaneously, **(42±4)% energy-transfer efficiency**
  - Measured the true energy-spectrum using an imaging-energy scan
- Accelerating gradient of 1.3 GV/m.
- Energy gain 45 MeV and energy spread 1.4 MeV FWHM:
  - **Few-percent-level wakefield flattening demonstrated**
- High stability (3% rms in energy gain) across 5000 shots



RESULT #2: **FULL CHARGE COUPLING**

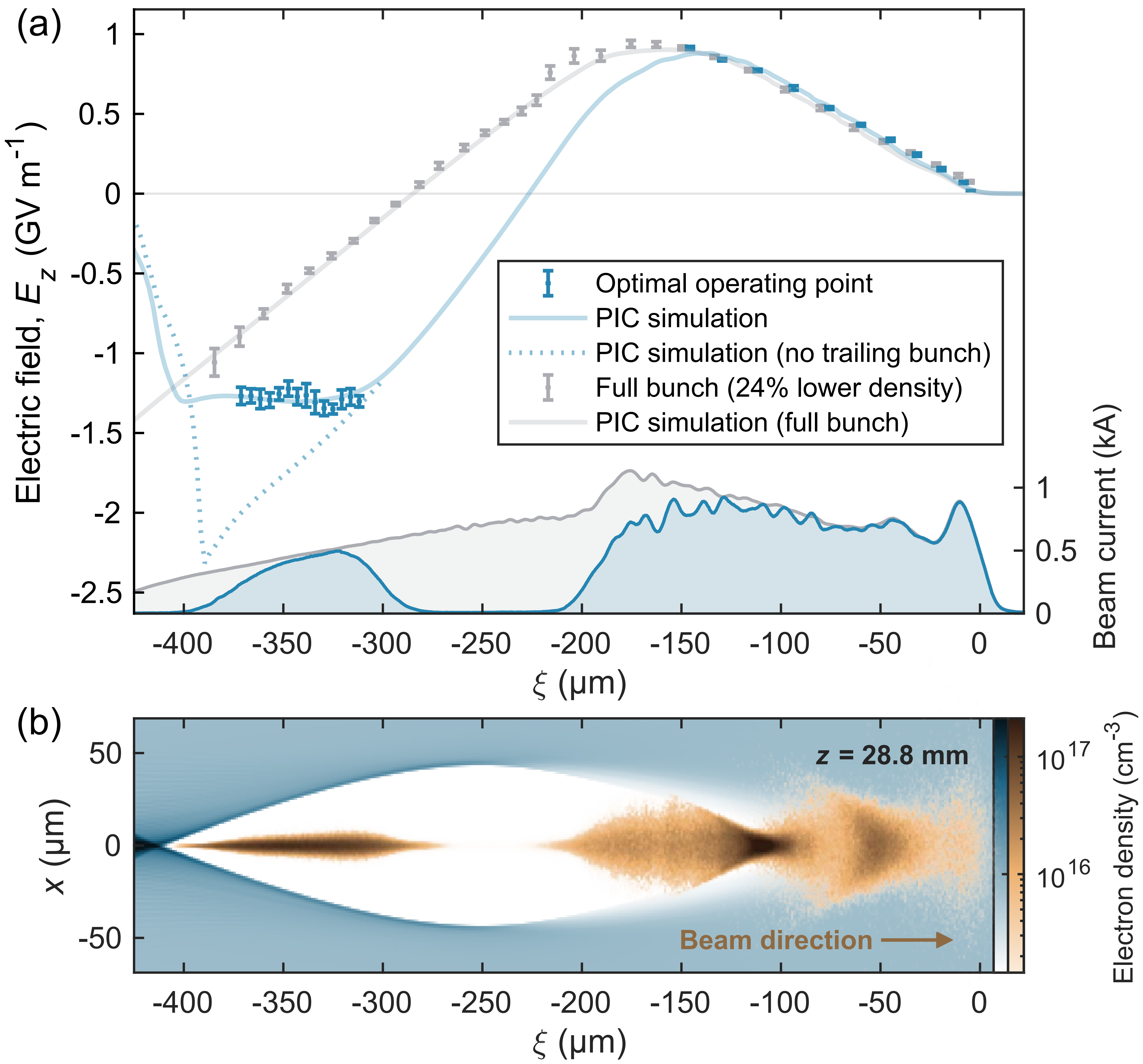




- Energy-spread preservation would not be meaningful without charge preservation.
- Charge is lost from the tail of the trailing bunch — **tail collimation results in 100% charge coupling (of 100 pC).**

RESULT #3: DIRECT MEASUREMENT OF WAKEFIELD FLATTENING

- Newly developed wakefield-sampling technique:
  - *S. Schröder et al., Nat. Commun.* ***11****, 5984 (2020)*
  - Using a chirped beam and a tail collimator, longitudinal (TDS) and energy (dipole) measurements can be decoupled.
  - ~10 fs time resolution and %-level precision.
- **Direct demonstration of field flattening** (temporally resolved).
- PIC simulations based on a full 6D beam-phase space reconstruction:
  - Excellent agreement between simulation and experiment.
- **Beam loading demonstrated indirectly** by comparison to a simulation without a trailing bunch.

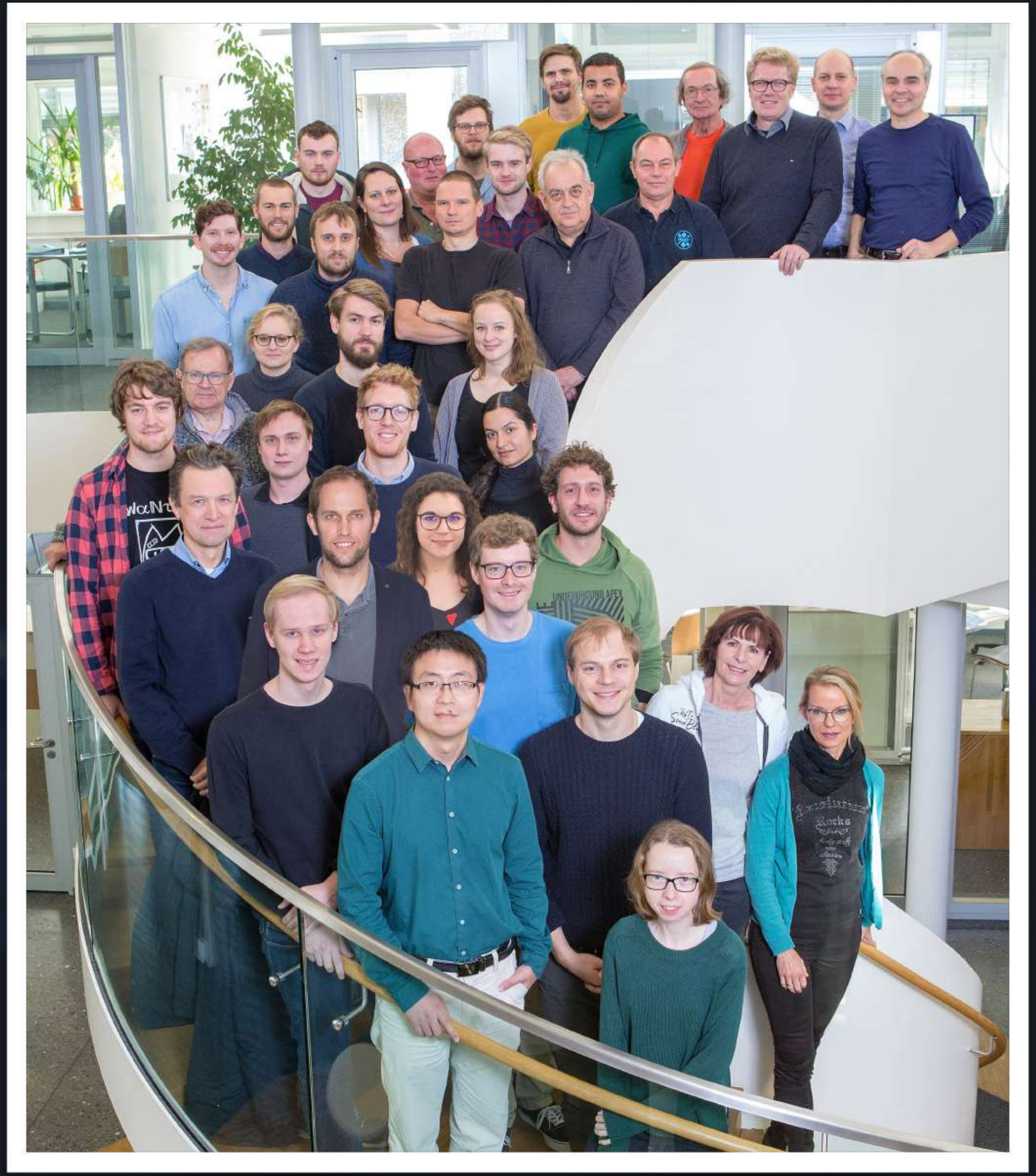


SUMMARY

- FLASHForward aims to develop the “ultimate” plasma-accelerator stage for high-energy physics and photon science.
  - Goal: High quality — high efficiency — high average power
- Recent progress: demonstration of optimal beam loading.
  - Multi-dimensional parameter scan to locate the optimum: $\Omega = \frac{\sigma_\delta}{\eta T}$
  - **Energy-spread preservation and high-efficiency (42%) acceleration of an externally injected bunch.**
  - Full charge coupling of 100-pC bunches
  - Direct measurement of wakefield flattening at the few-percent level.

C. A. Lindstrøm et al., Phys. Rev. Lett. 126, 014801 (2021)

- Next up:
  - Larger energy gains (and driver depletion)
  - Emittance preservation
  - High-repetition-rate acceleration



Thanks to the FLASHForward team and technical/engineering groups at DESY!