Progress in Plasma Booster R&D at FLASHFORWARD▸▸

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Head of Plasma Accelerator R&D

DESY. Accelerator Division

7th Matter and Technologies Days

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Acknowledgements

FLASHForward▸▸ Team

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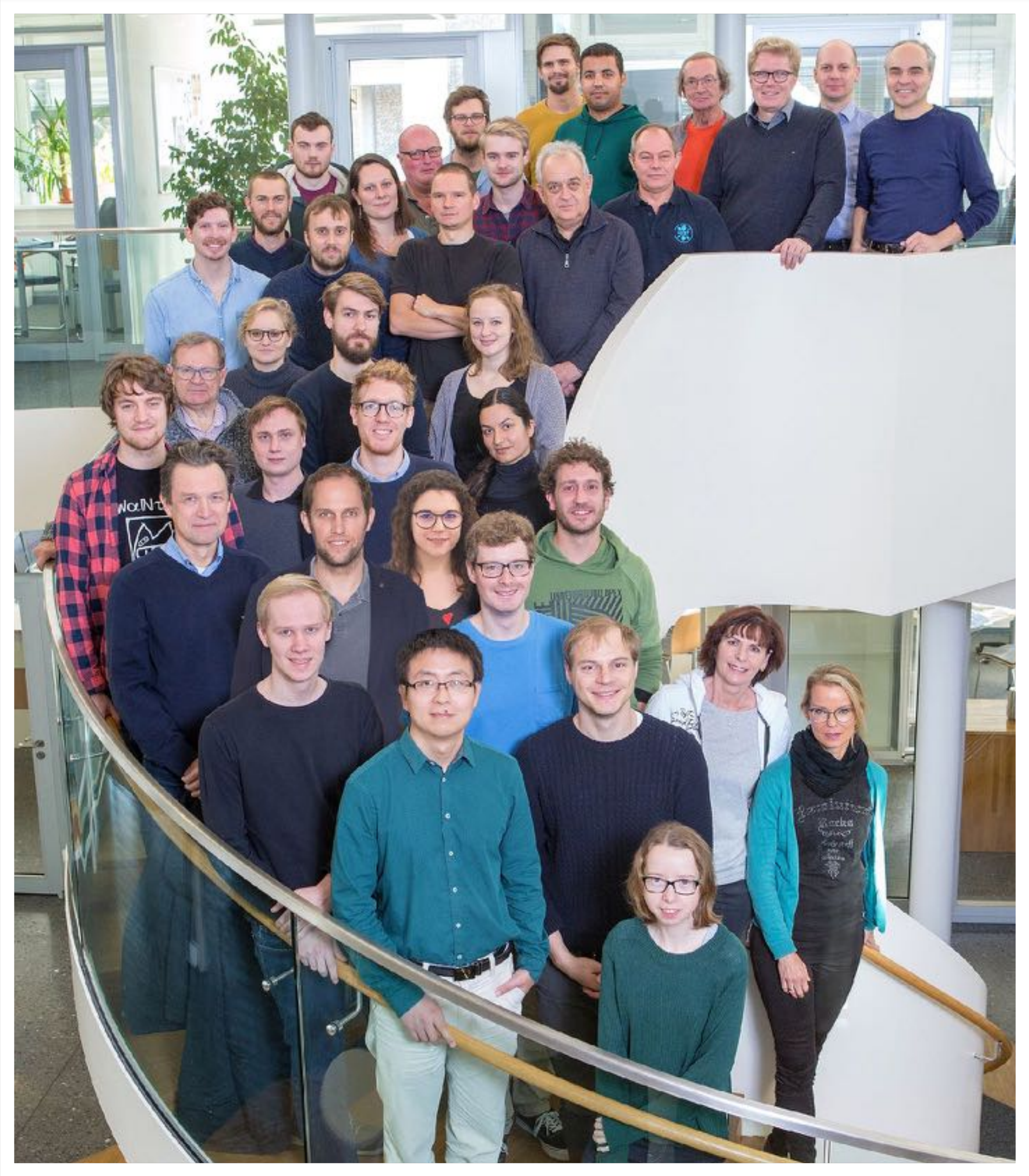
Mathis Mewes

...and the technical groups
from the accelerator and particle physics devisions!

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Plasma source
Driver (laser or charged-particles)
Depleted driver
Witness (electrons)
Accelerated witness

Plasma accelerators are a centimeter-scale source of GeV beams

Plasma wakefields can sustain accelerating fields of up to **~1-100 GV/m** with focusing gradients above **~1 MT/m**

x1000 more than RF technology

Our customers: high-energy physics and photon science

- High-energy physics and photon science demand high(est) energy at low cost.
  - *Solution:* Plasma accelerators — significantly higher acceleration gradients.
- Simultaneously, particle colliders have strict demands for luminosity:
  (FELs have similar demands for brightness)

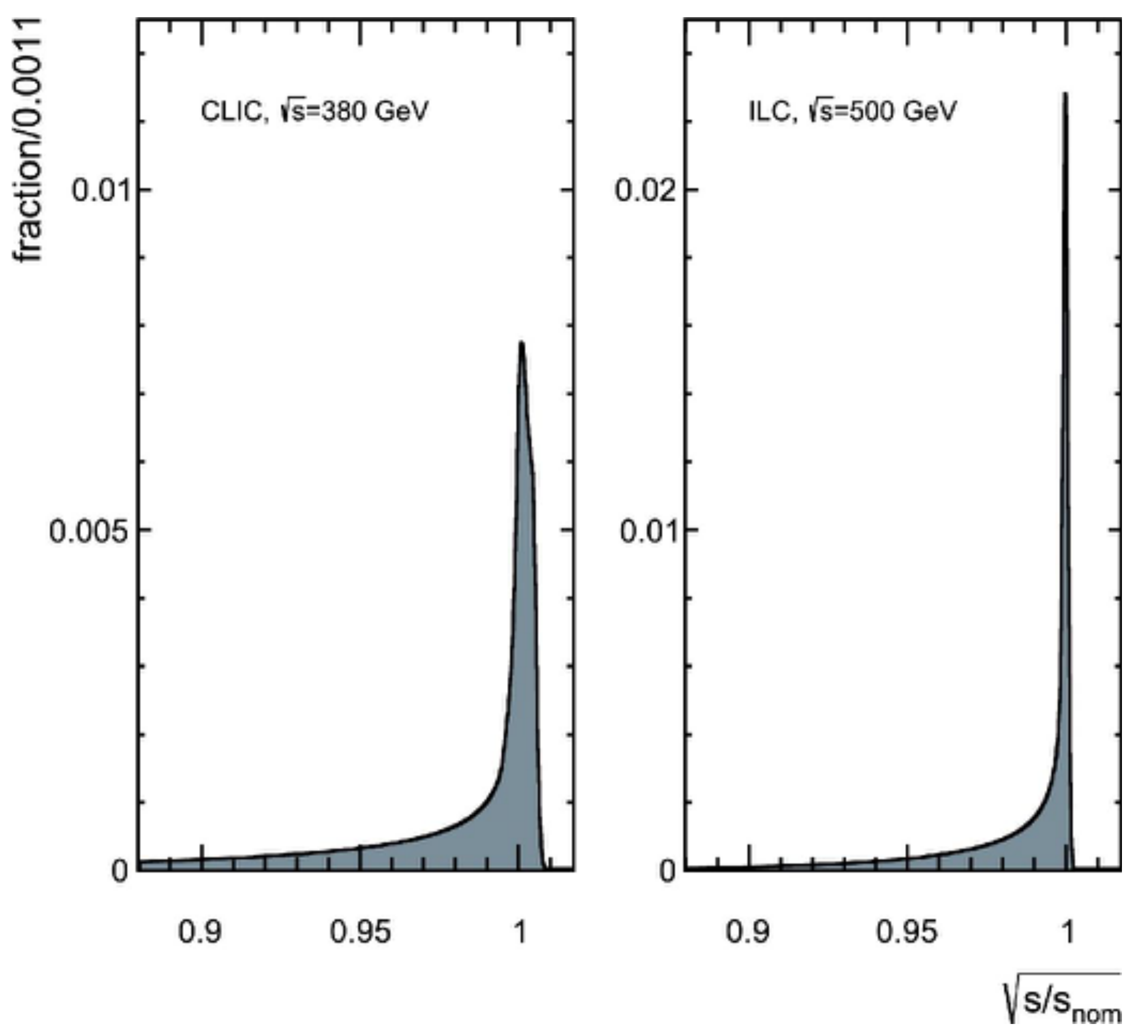
High repetition rate

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).

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

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

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

Primary goal of FLASHFORWARD▶▶

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

High efficiency

Transfer efficiency

Driver depletion

High beam quality

Energy-spread preservation

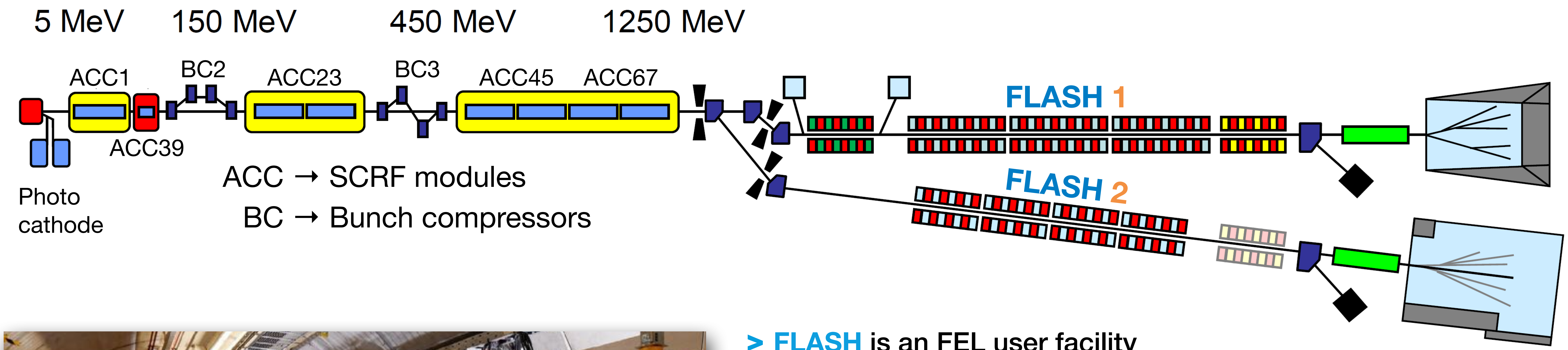
Emittance preservation

High average power

High repetition rate

FLASHFORWARD▸▸ utilizes FLASH superconducting accelerator

Plasma accelerator tightly integrated into facility and benefits from Free-Electron Laser beam quality



> **FLASH is an FEL user facility**
- 10% of beam time dedicated to generic accelerator research

> **Superconducting accelerator based on ILC/XFEL technology**
- ≲ 1.25 GeV energy with ~nC charge at few 100 fs bunch duration
- ~2 μm trans. norm. emittance
- ~10 kW average beam power, MHz repetition rate in 10 Hz bursts
- exquisite stability by advanced feedback/feedforward systems

> **Unique opportunities for plasma accelerator science**

FLASHFORWARD▸▸ utilizes FLASH superconducting accelerator

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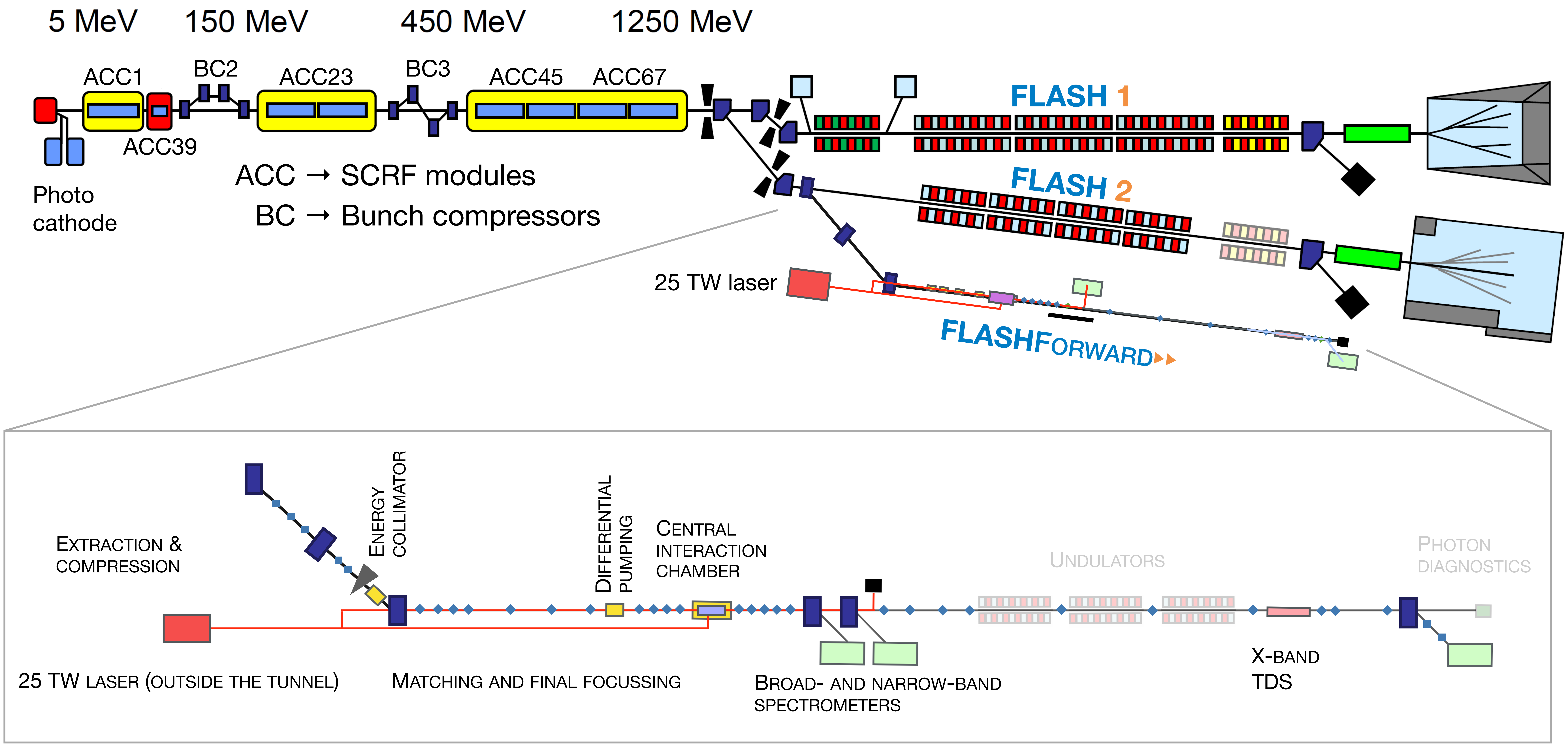
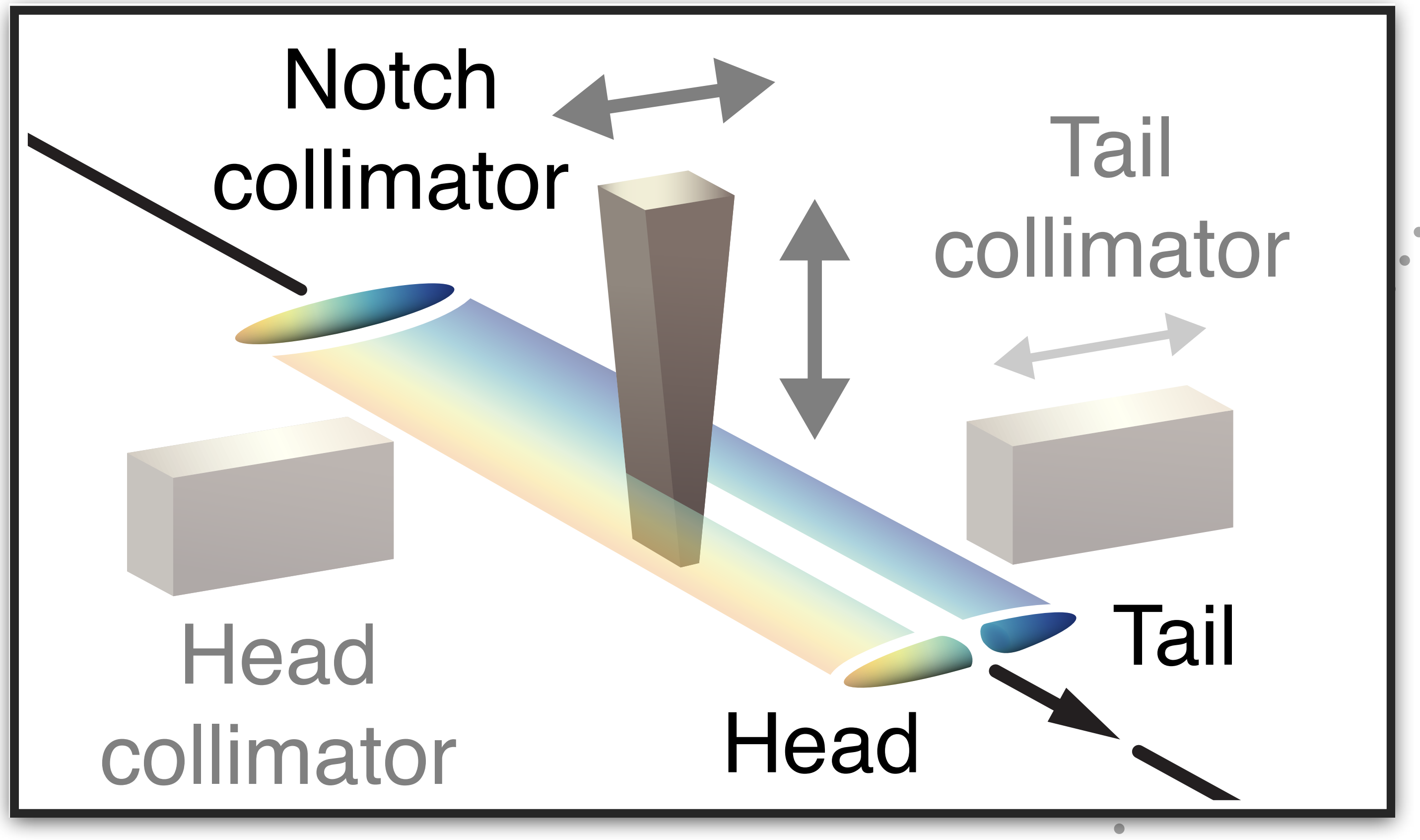


R. D'Arcy *et al.*, Phil. Trans. R. Soc. A **377**, 20180392 (2019)

Advanced collimator system for longitudinal bunch shaping

FLASHFORWARD▸▸ beamline features innovative components and methods

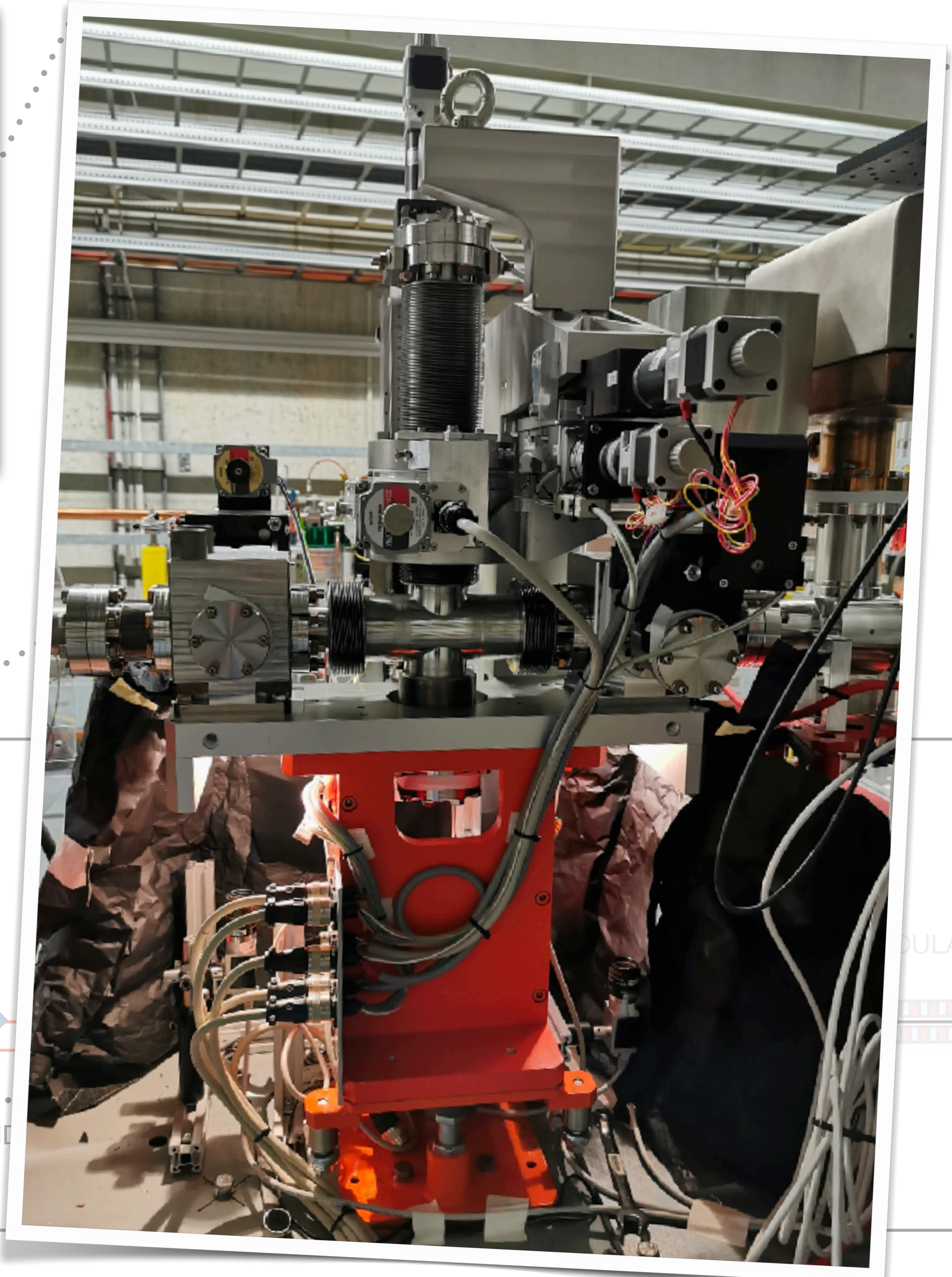


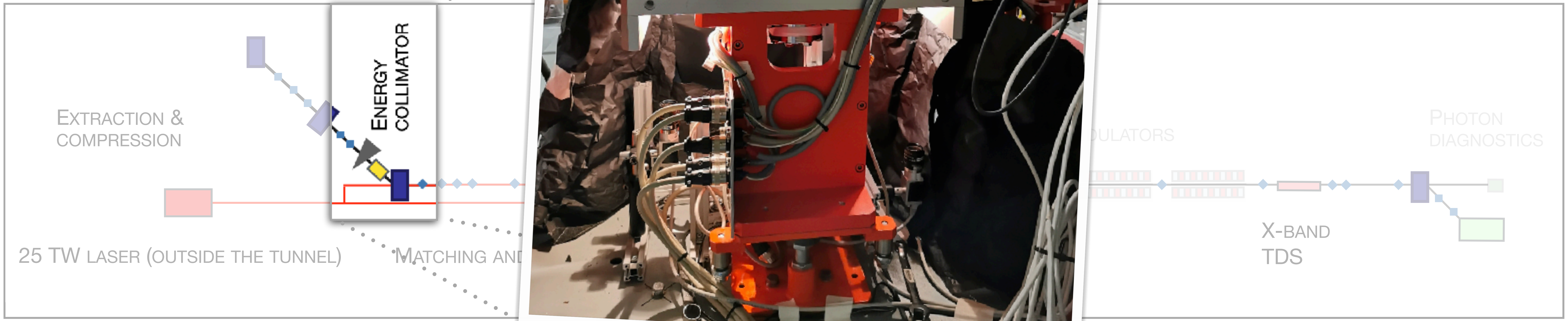
S. Schröder *et al.*,
J. Phys. Conf. Ser. **1596** 012002 (2020)

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

µm-precision movements

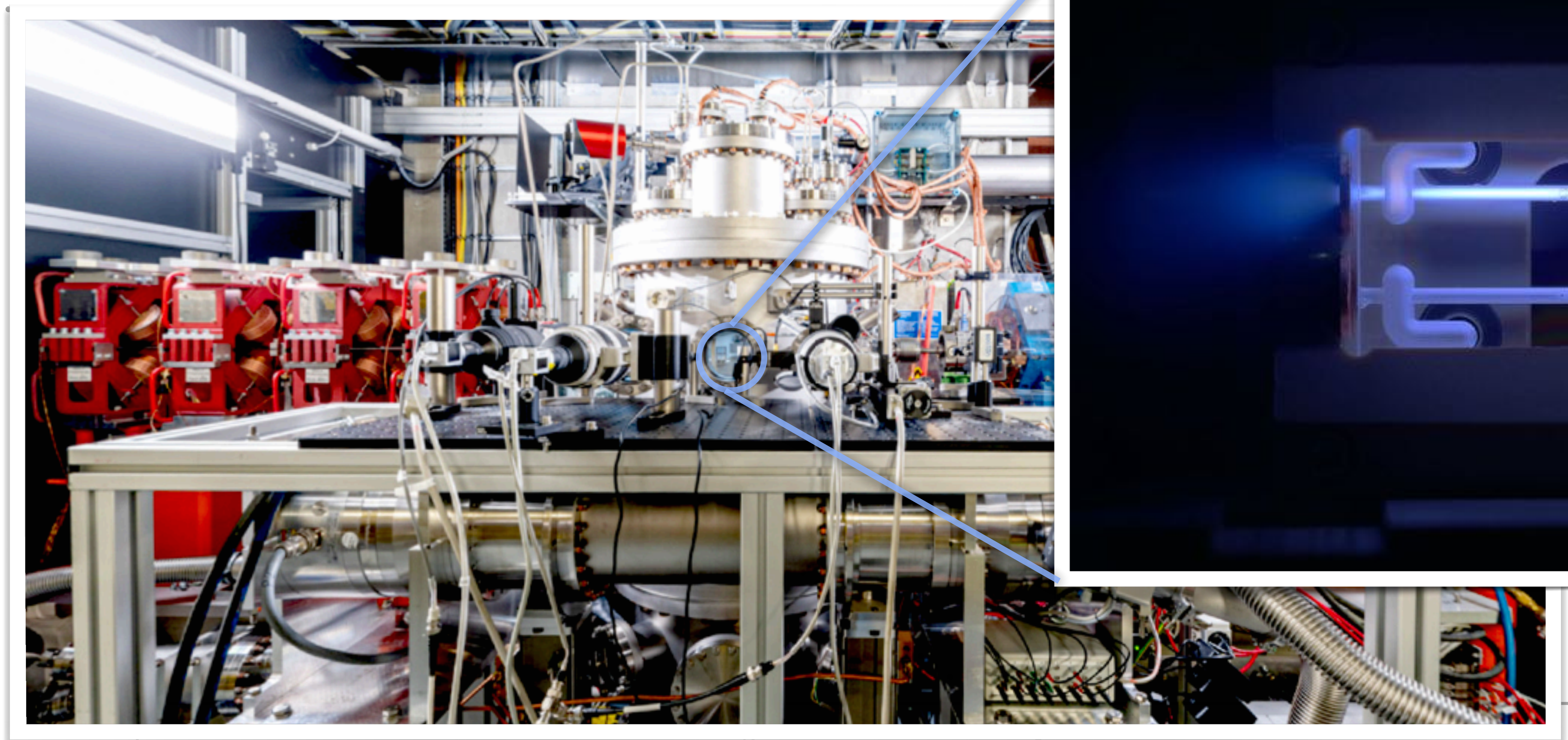
allows for precise bunch shaping
(in conjunction with
FLASH compressors and 3.9 GHz cavity)

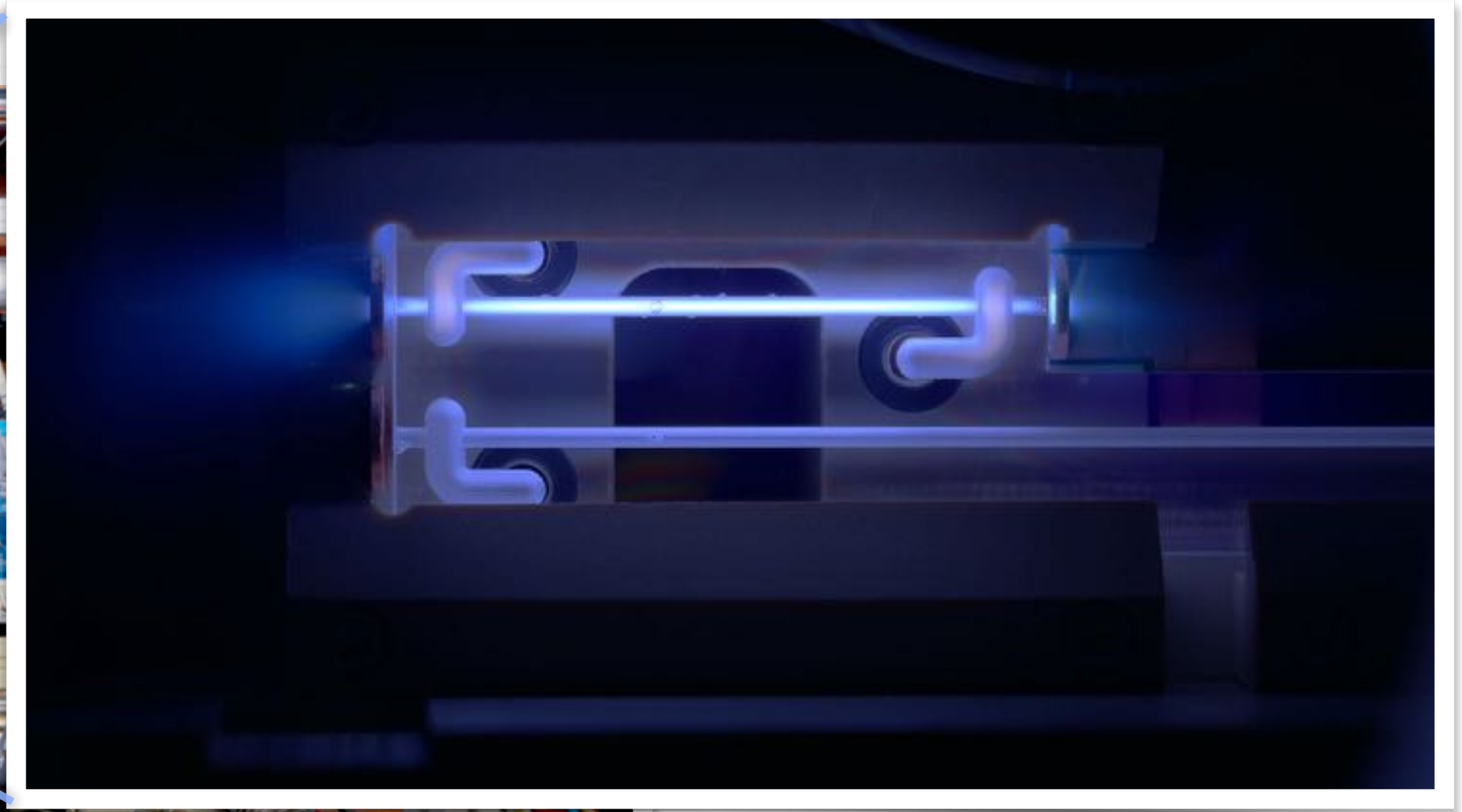




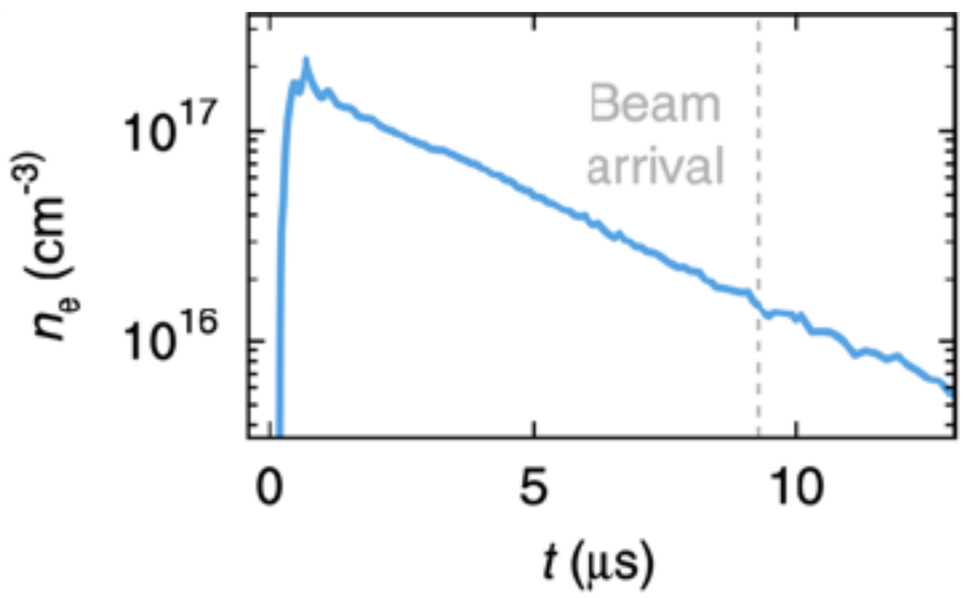
Two discharge capillaries provide density controllable plasma

FLASHForward▸▸ beamline features innovative components and methods





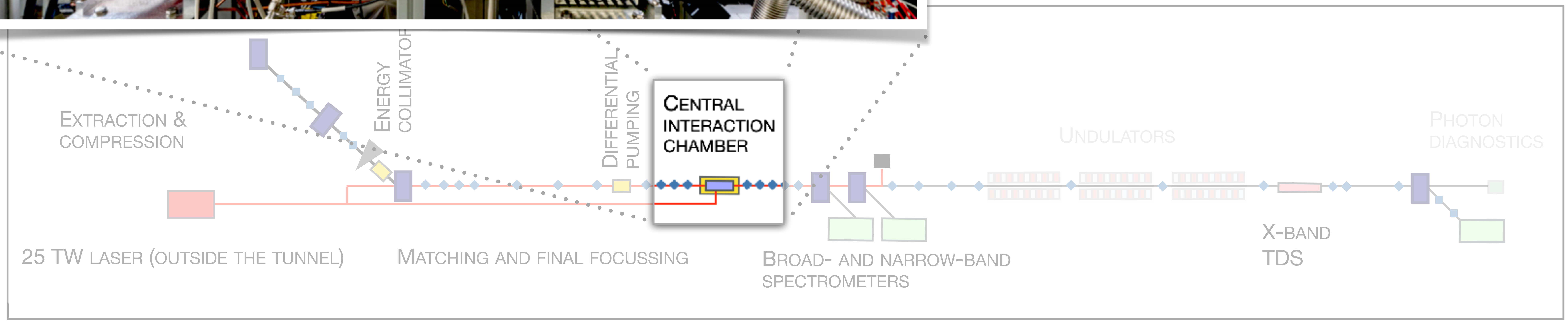
J.M. Garland *et al.*,
Rev. Sci. Instrum. **92** 013505 (2021)



High-voltage discharge

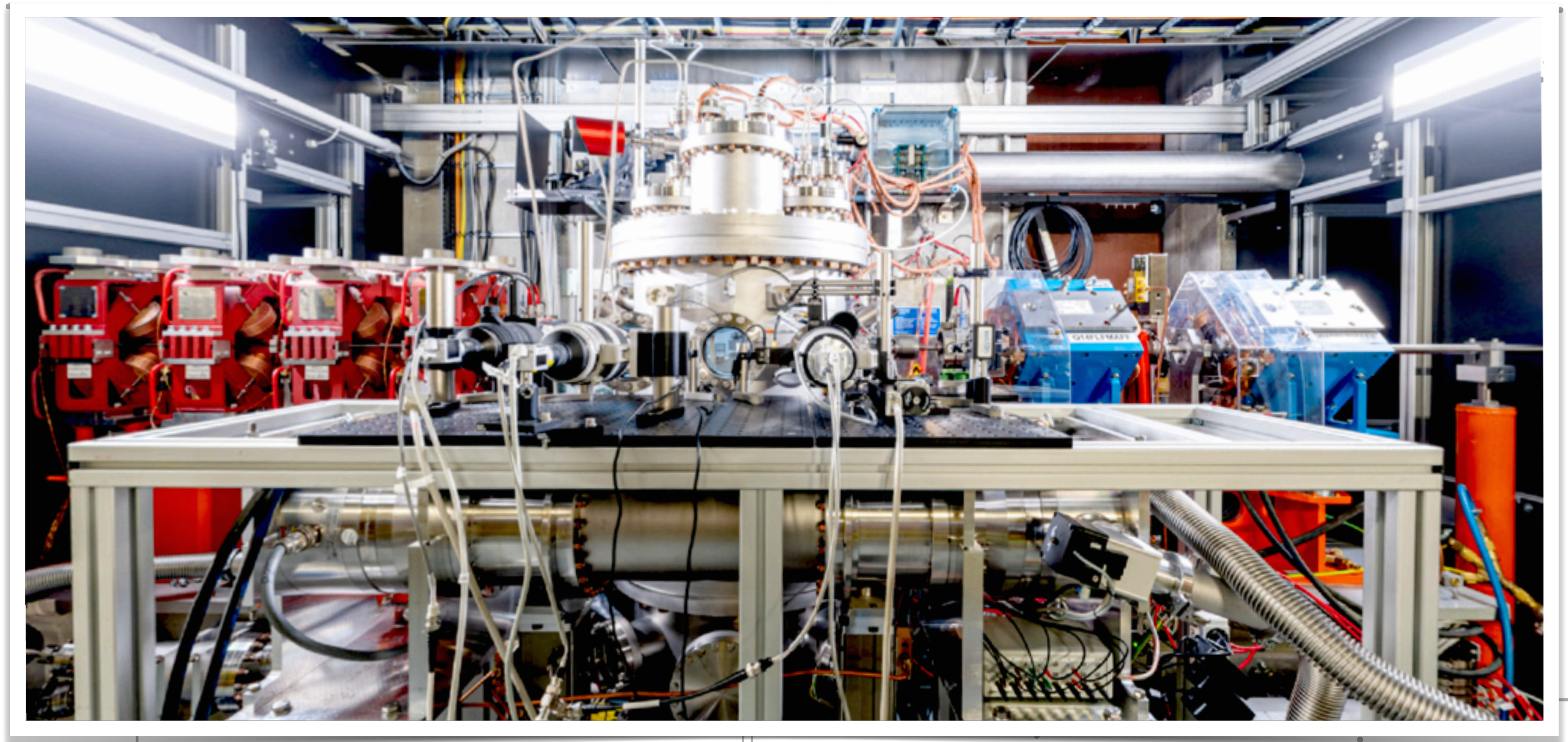
Sapphire capillaries
(50 mm and 195 mm long)

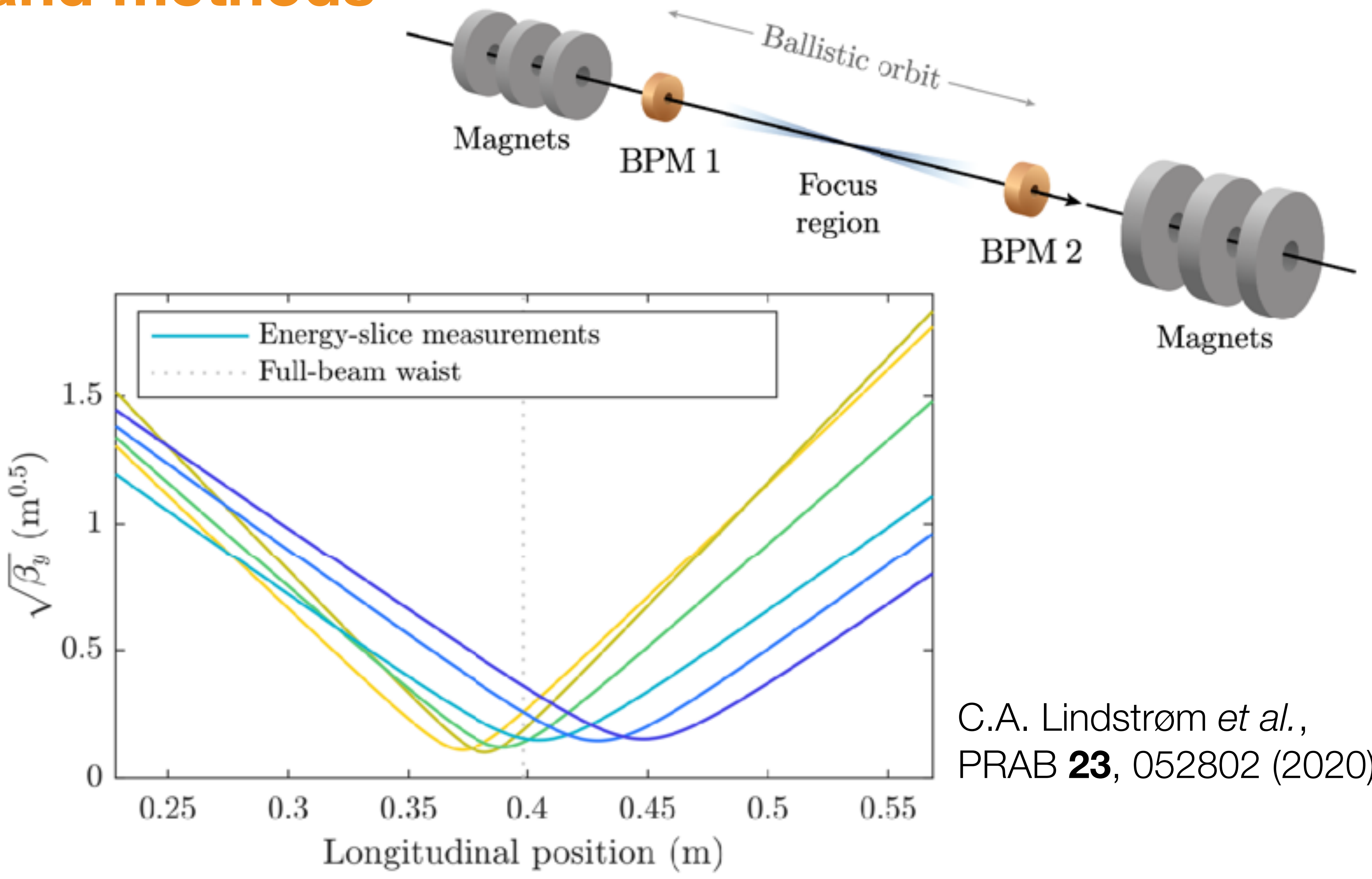
Gases: He, Ne, **Ar,** Kr, H (soon),



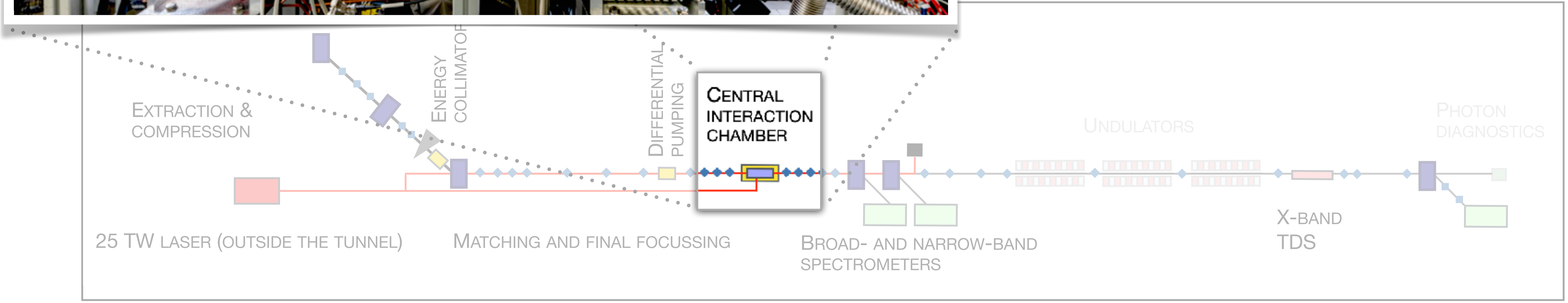
Two-BPM tomography enables accurate beam focus characterization

FLASHFORWARD▸▸ beamline features innovative components and methods



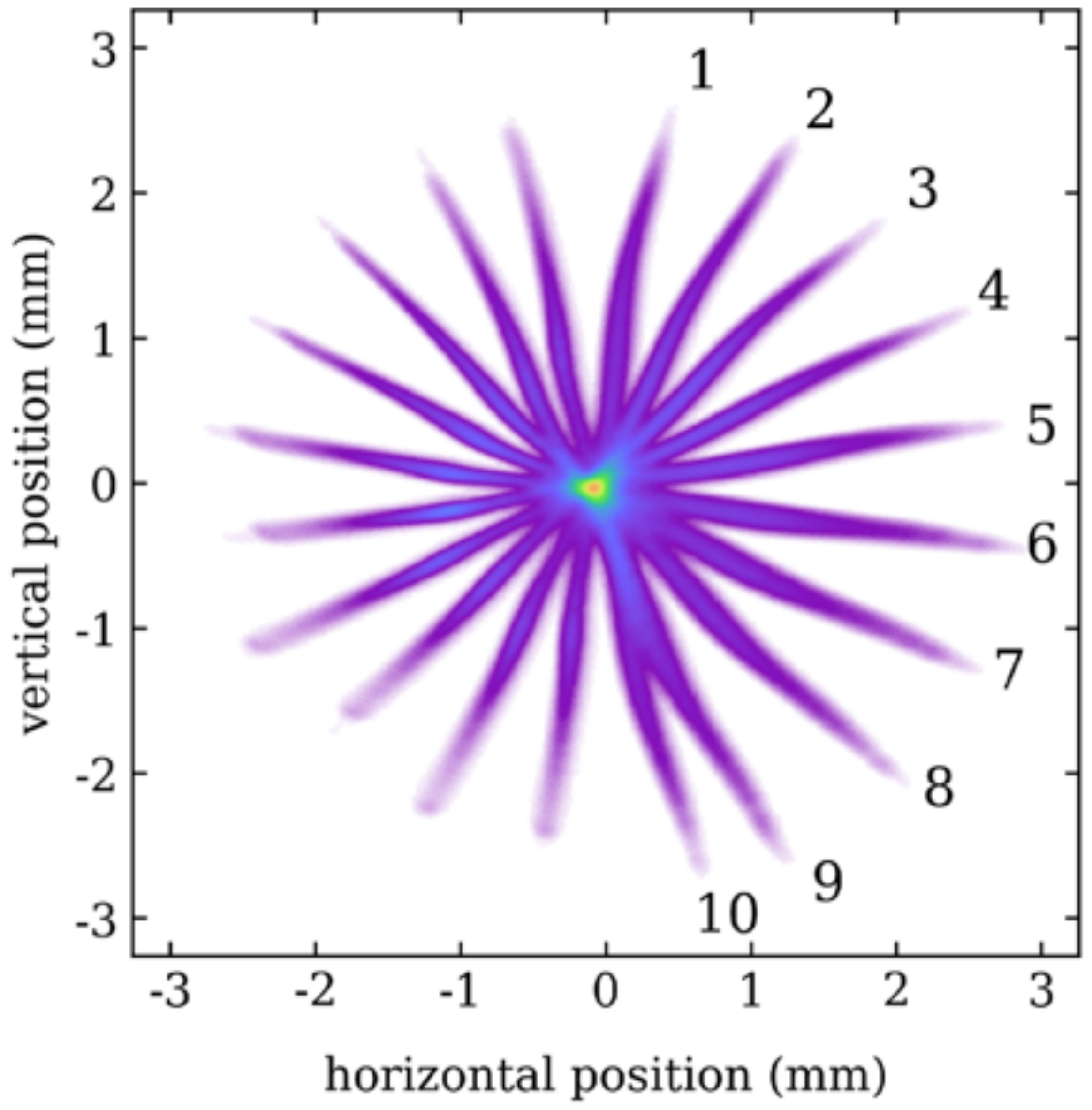


C.A. Lindstrøm *et al.*, PRAB **23**, 052802 (2020)



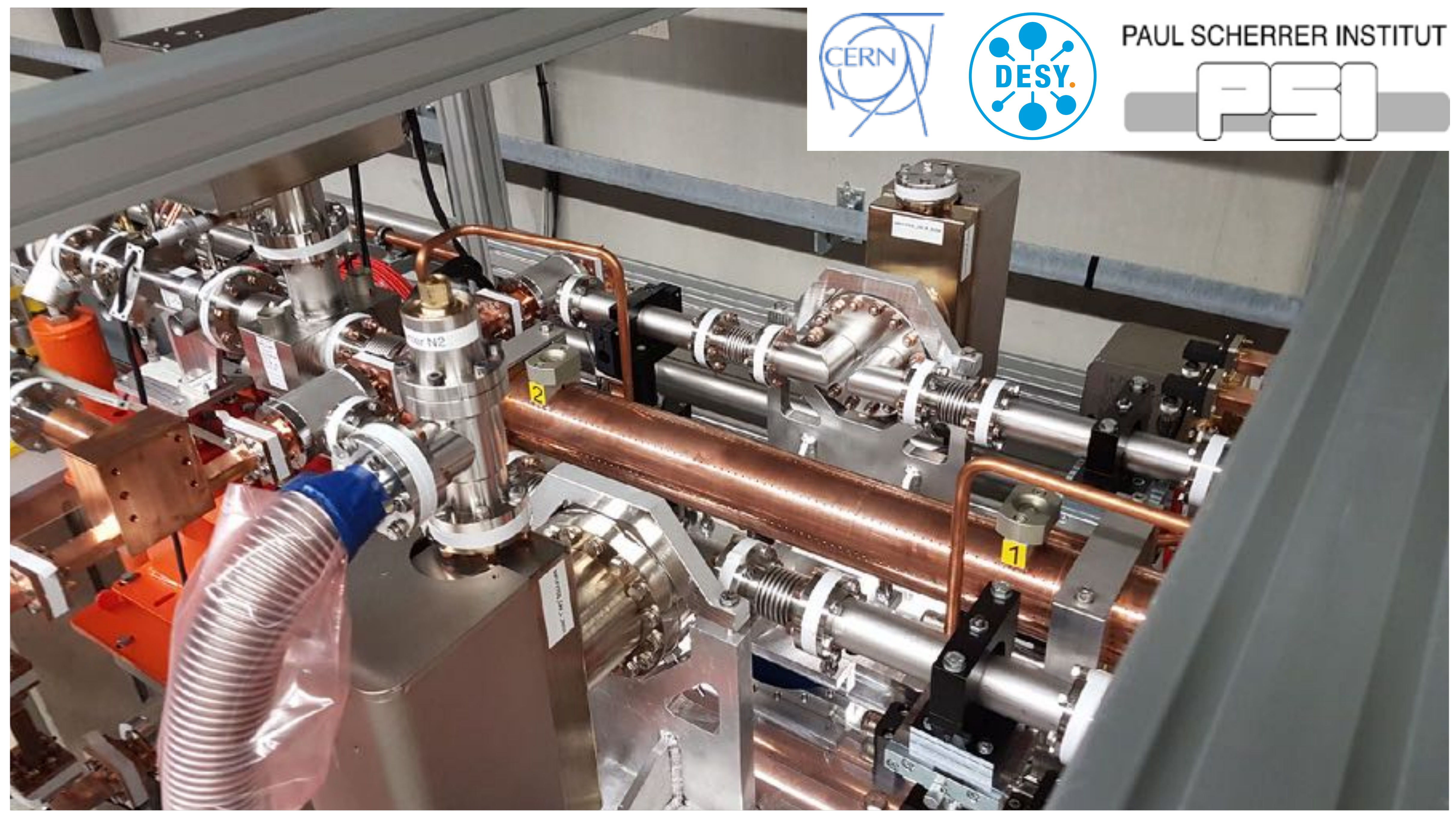
PolariX cavity enables 6D phase space measurements

FLASHFORWARD▸▸ beamline features innovative components and methods



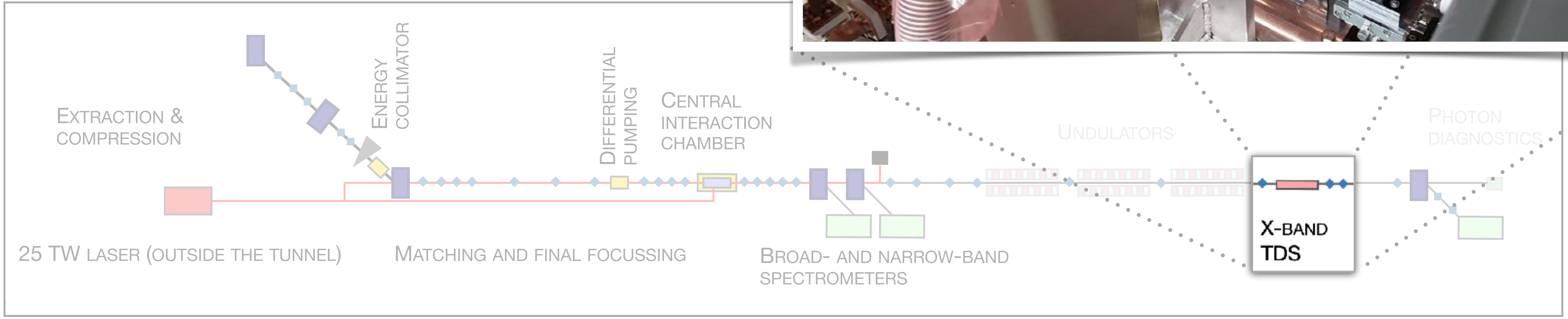
B Marchetti *et al.*, accepted for publication in Scientific Reports (2021)

P. Craievich *et al.*, PRAB **23** 112001 (2020)



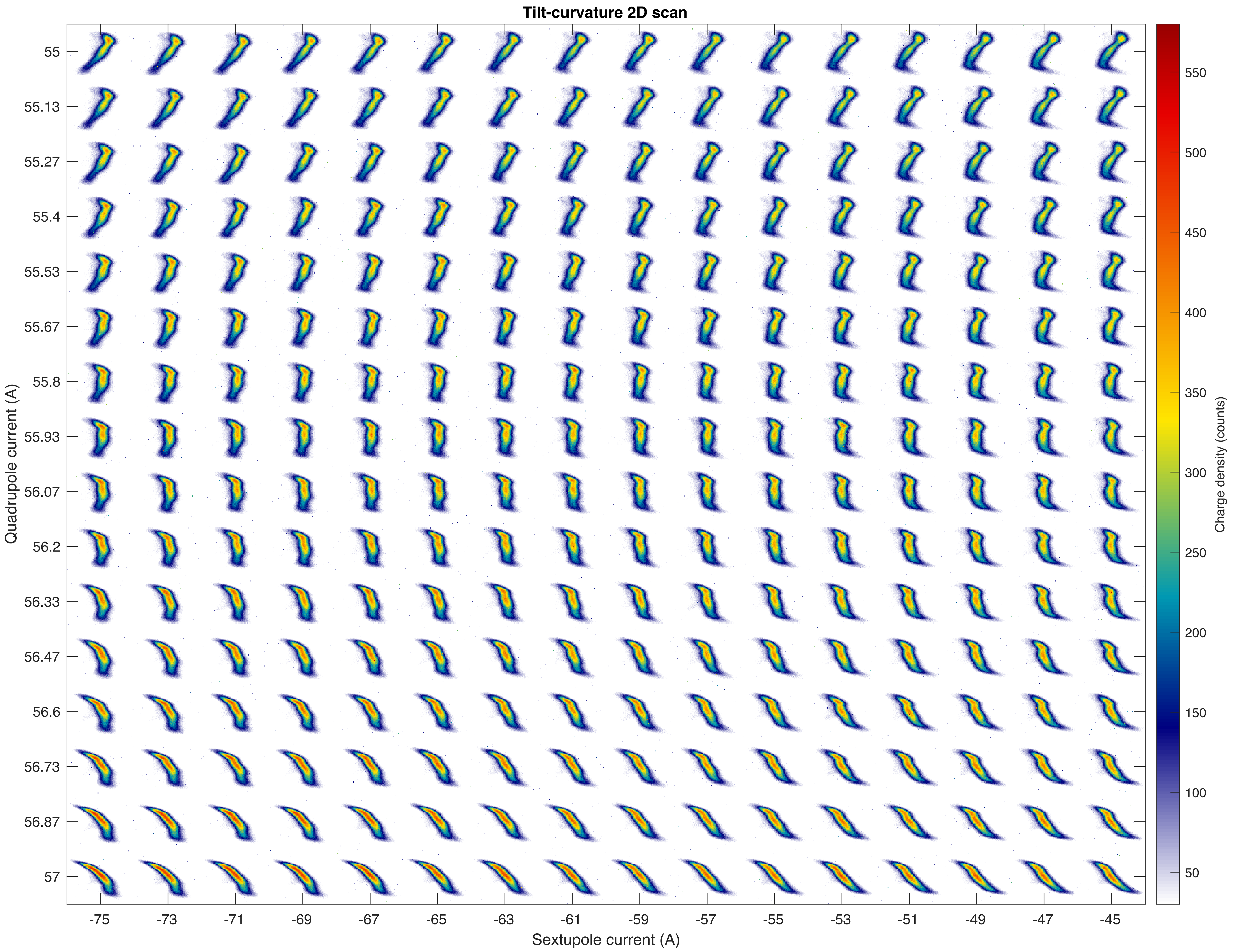
PolariX X-band cavity (12 GHz) for femtosecond resolution

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

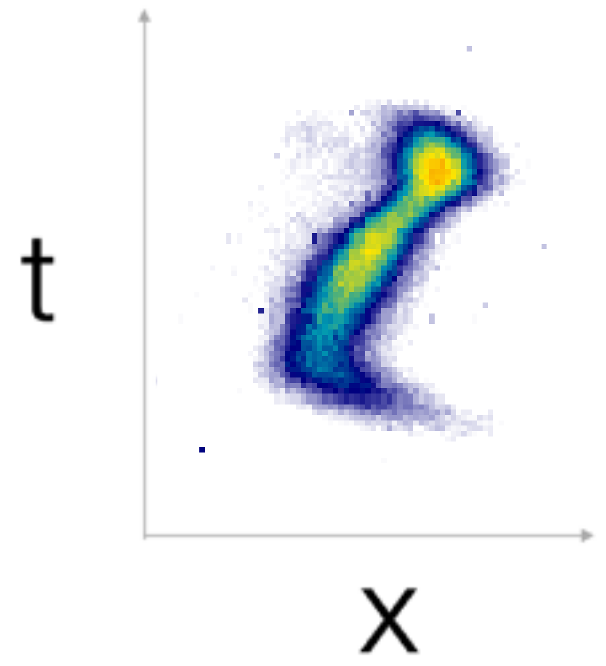


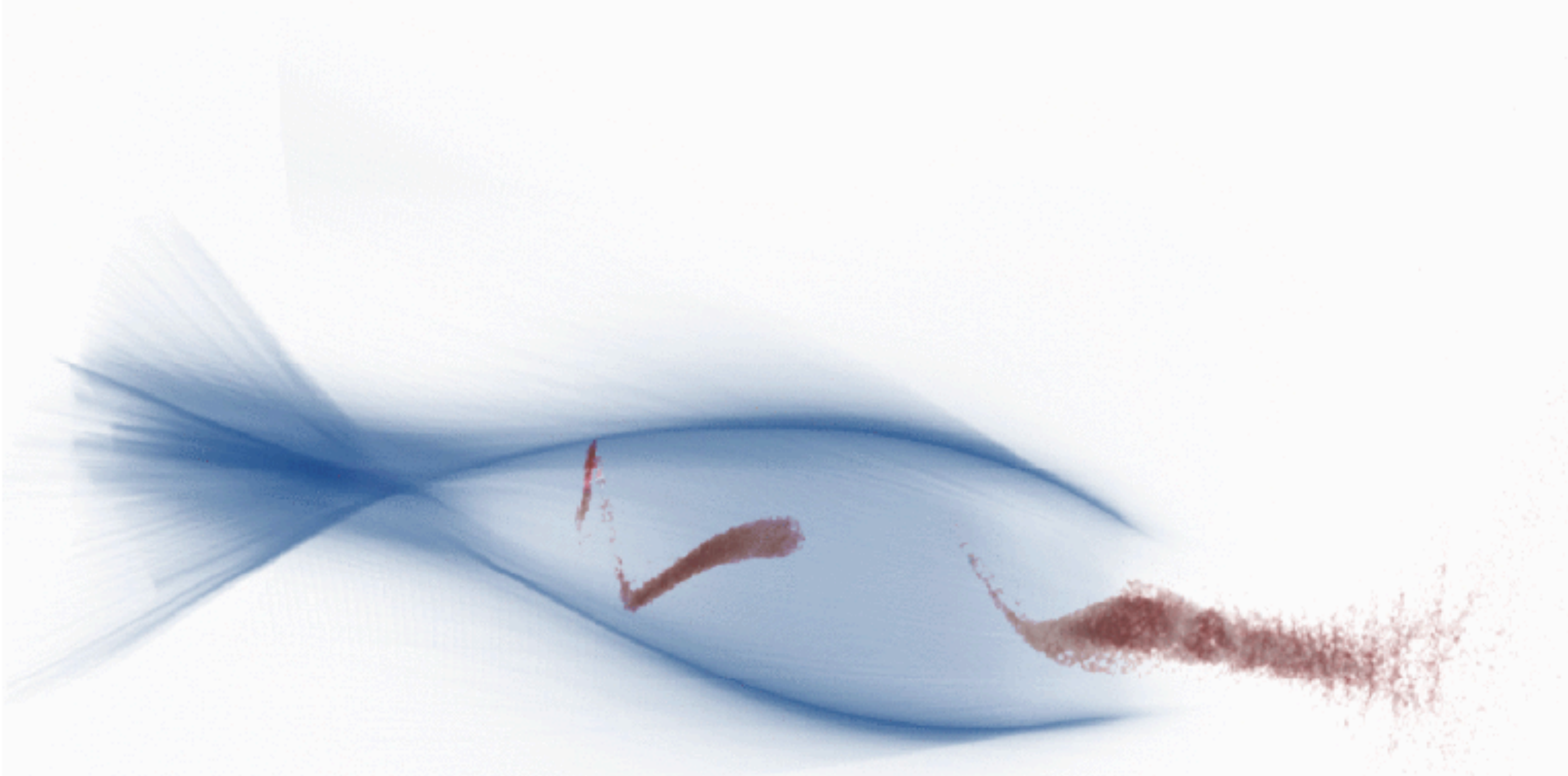
PolariX allows for diagnosis of head-to-tail beam tilts

FLASHFORWARD▸▸ beamline features innovative components and methods



- Head-to-tail centroid offsets are sources of collective beam-instabilities in plasma (“hosing”)
- Tweaking two magnets in the FLASHForward beamline controls and compensates for tilt





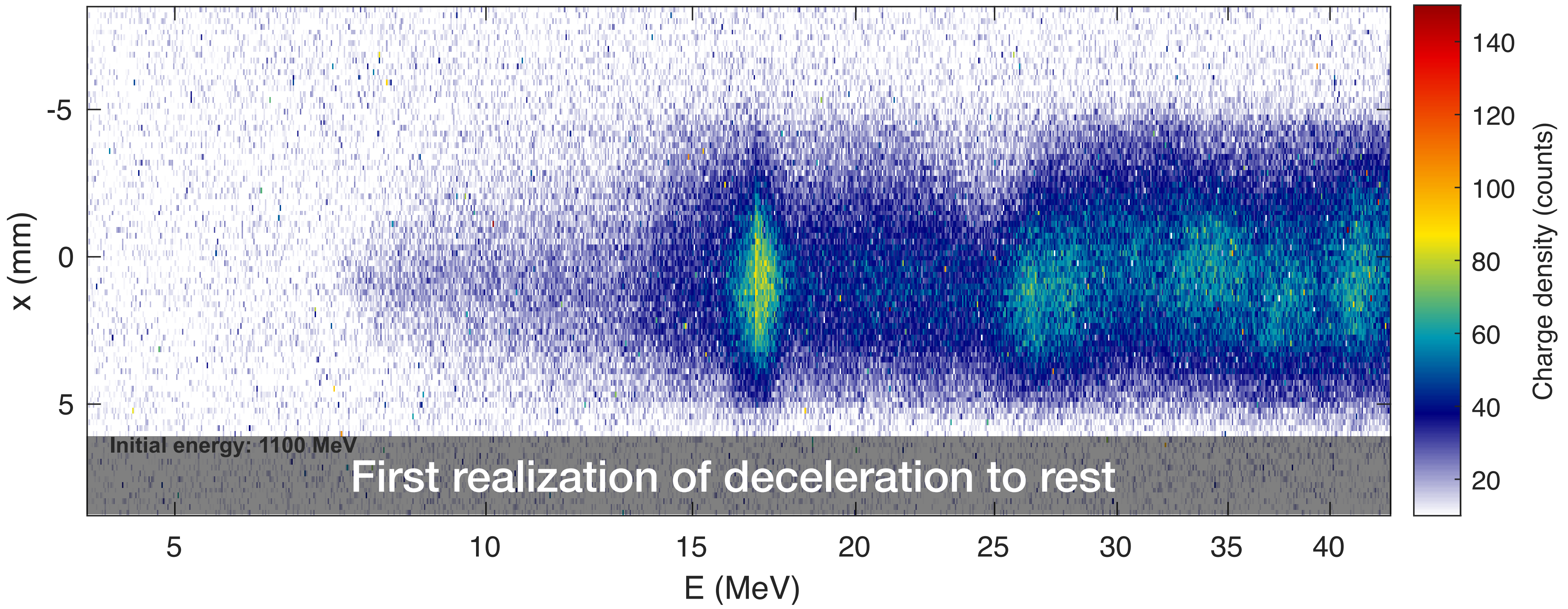
Hosing theory and control

- T.J. Mehrling *et al.*, PRL **118**, 174801 (2017)
- T.J. Mehrling *et al.*, Phys. Plasmas **25**, 056703 (2018)
- A. Martinez d.l.O. *et al.*, PRL **121**, 064803 (2018)

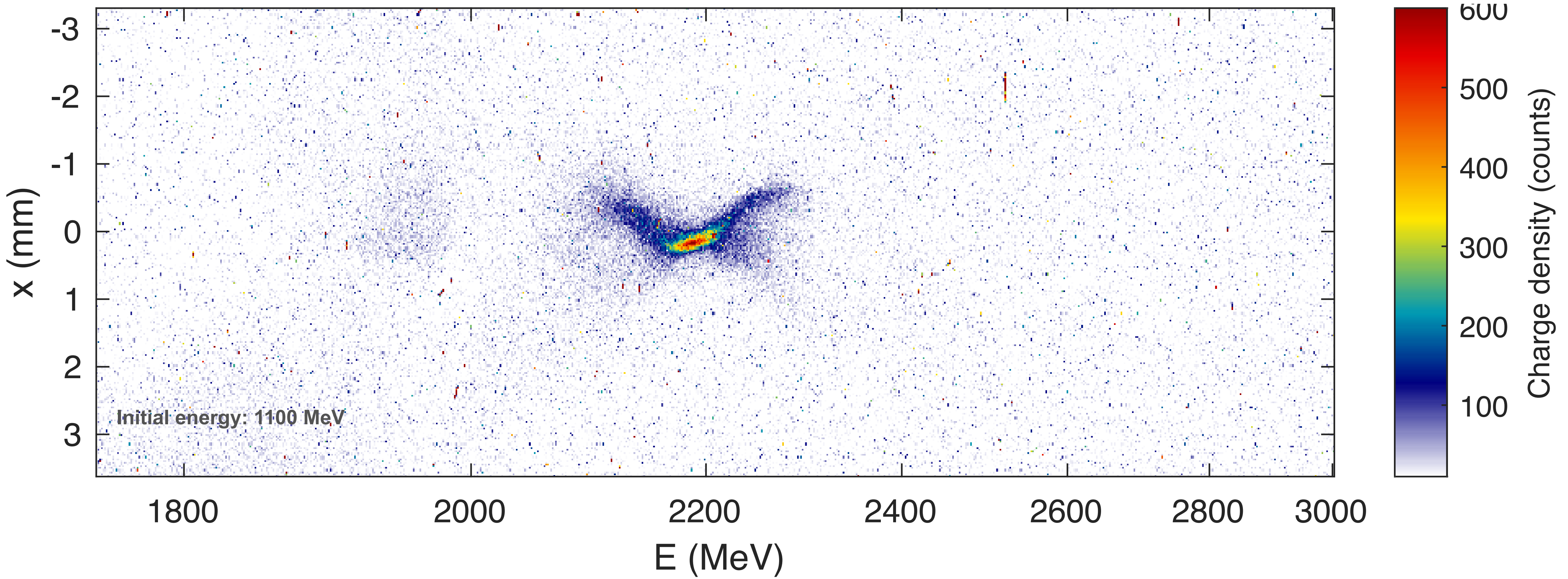
1.1 GeV energy gain and loss achieved in a 195 mm plasma module

Plasma accelerator essentials — demonstrating 6 GV/m field strength

Energy extraction → plasma beam dump (+ efficiency)



Energy doubling to 2.2 GeV → plasma booster



Optimal beam loading enables 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.

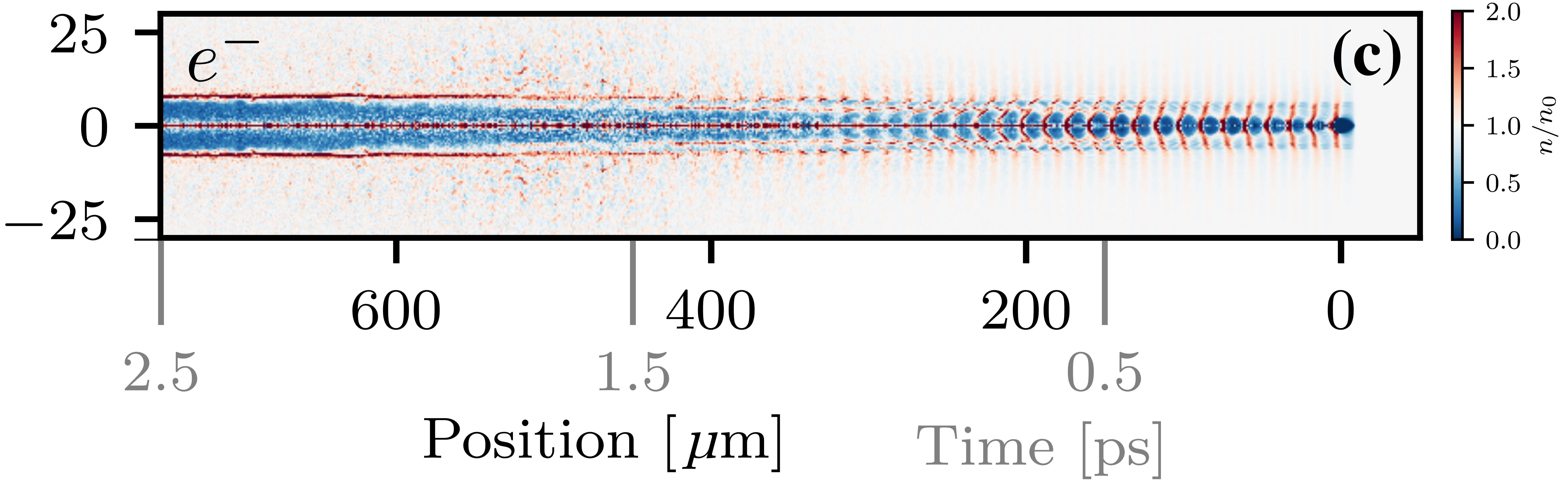


Image source: M. F. Gilljohann *et al.*, Phys. Rev. X **9**, 011046 (2019)

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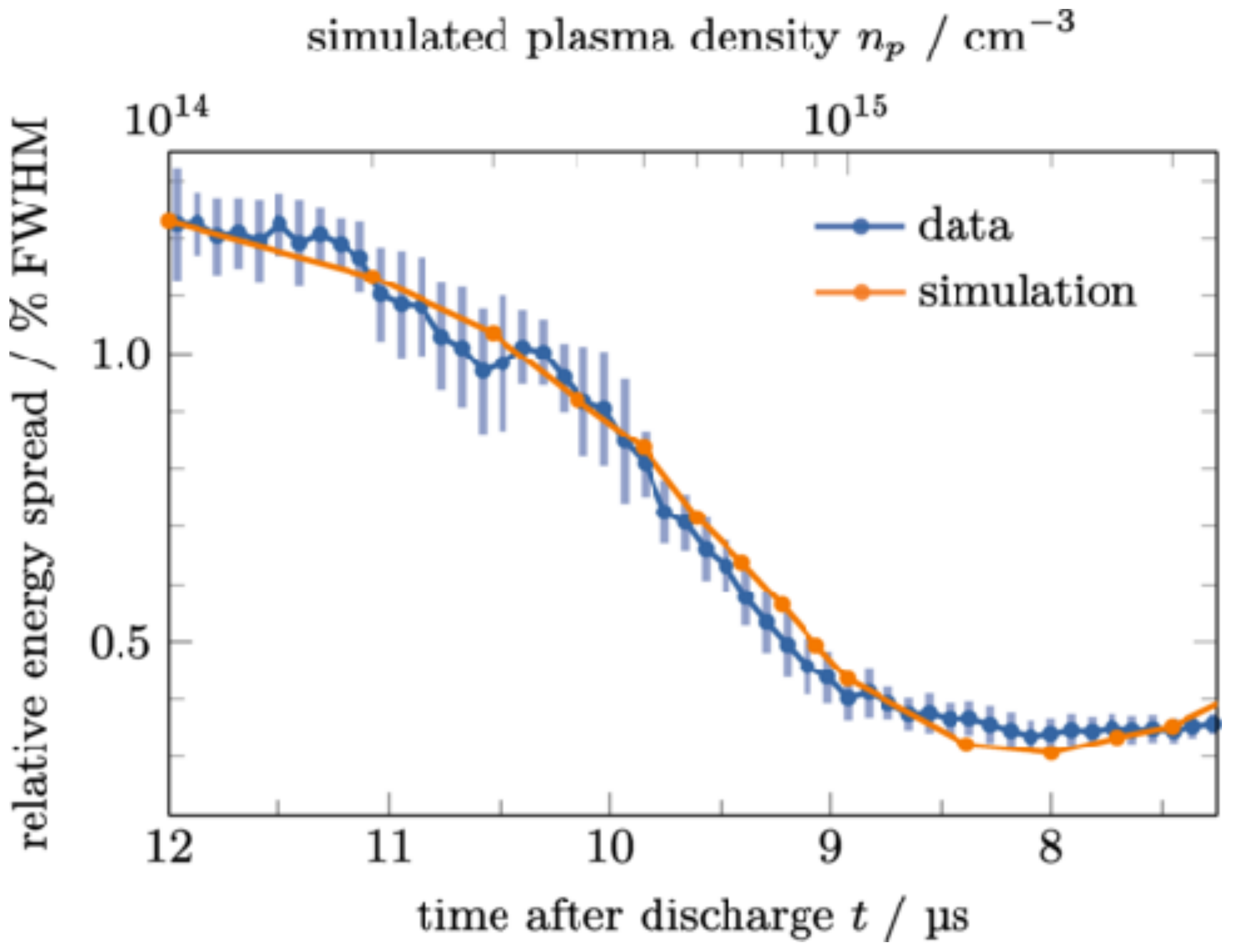
> > The energy needs to be extracted very rapidly—ideally within the first oscillation.

> > *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.

> > *Not (easily) possible:* Dechirping



R. D'Arcy *et al.*,
PRL **122**, 034801 (2019)

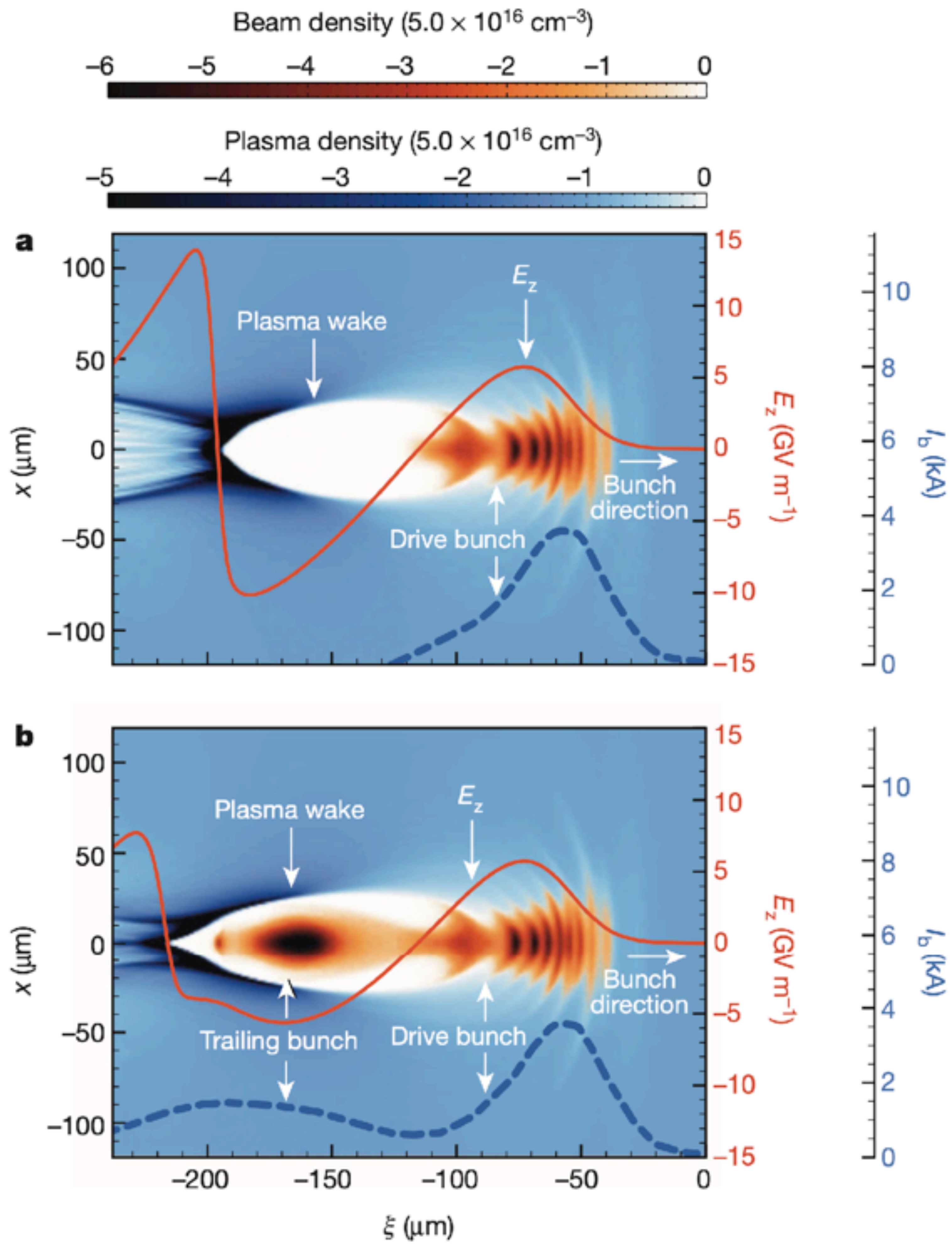


Image credit: M. Litos *et al.*, Nature **515**, 92 (2014)

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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.

> > **FLASHForward provides the tools to do that.**

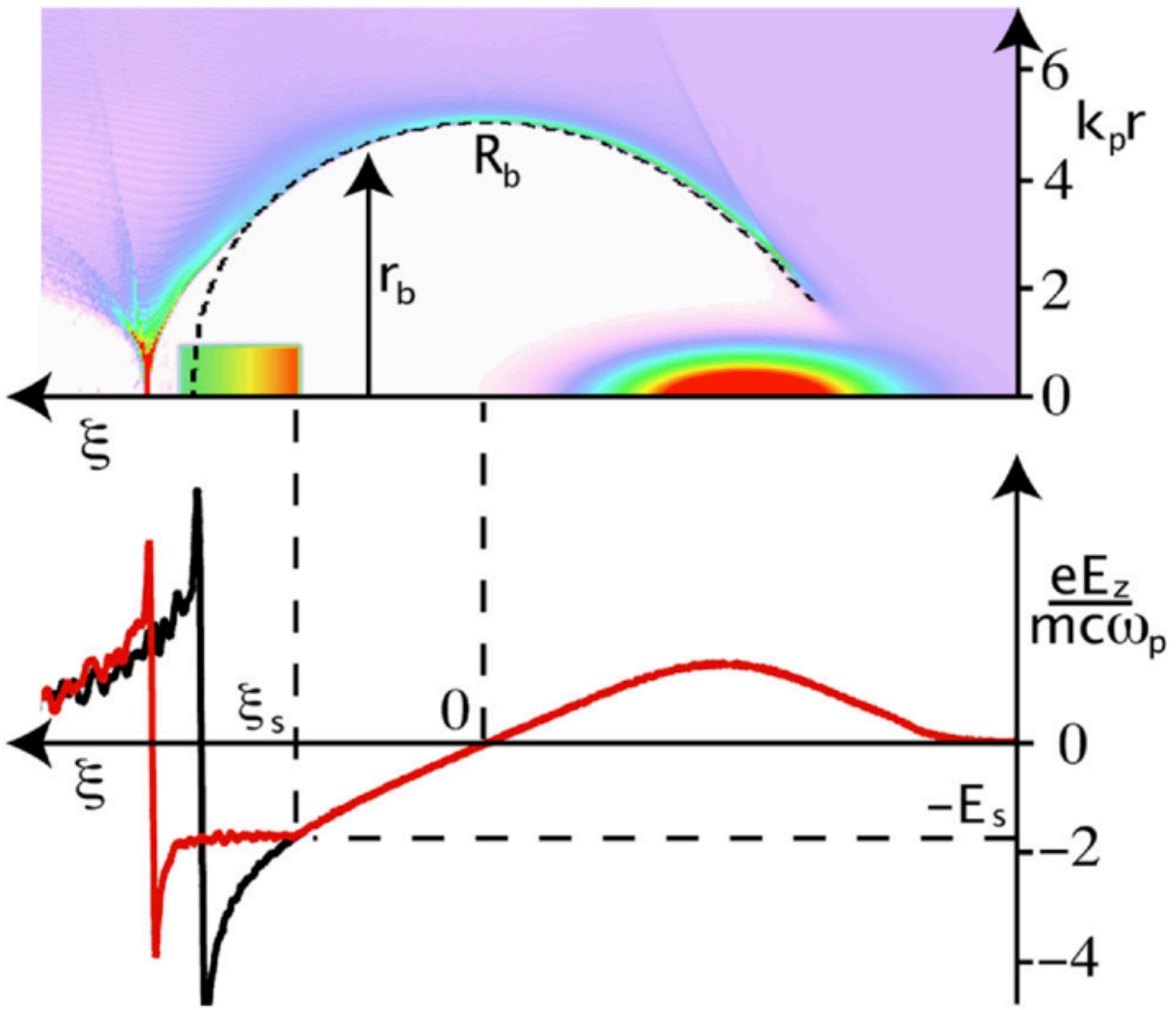
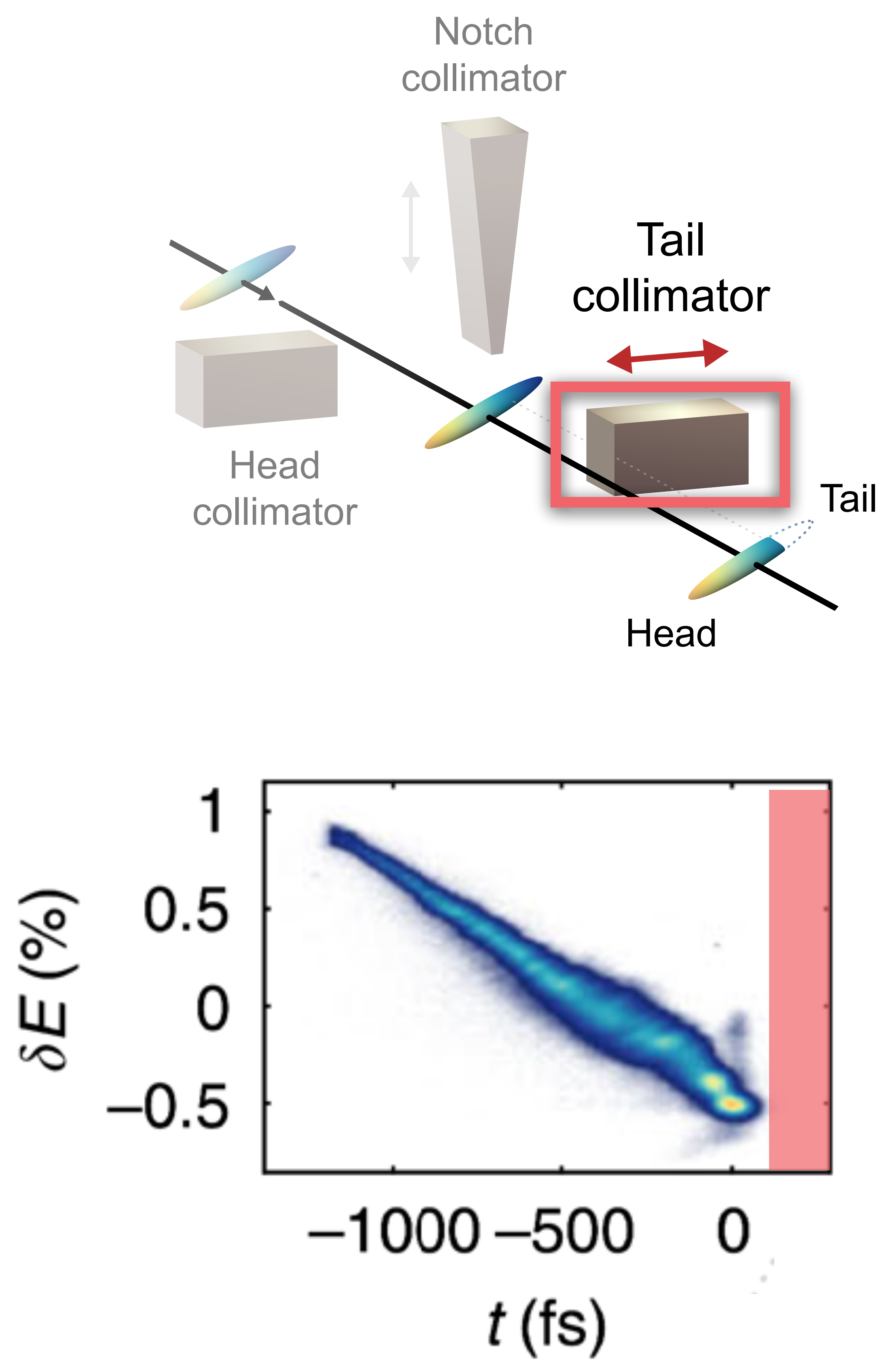


Image credit: M. Tzoufras *et al.*, Phys. Rev. Lett. **101**, 145002 (2008)

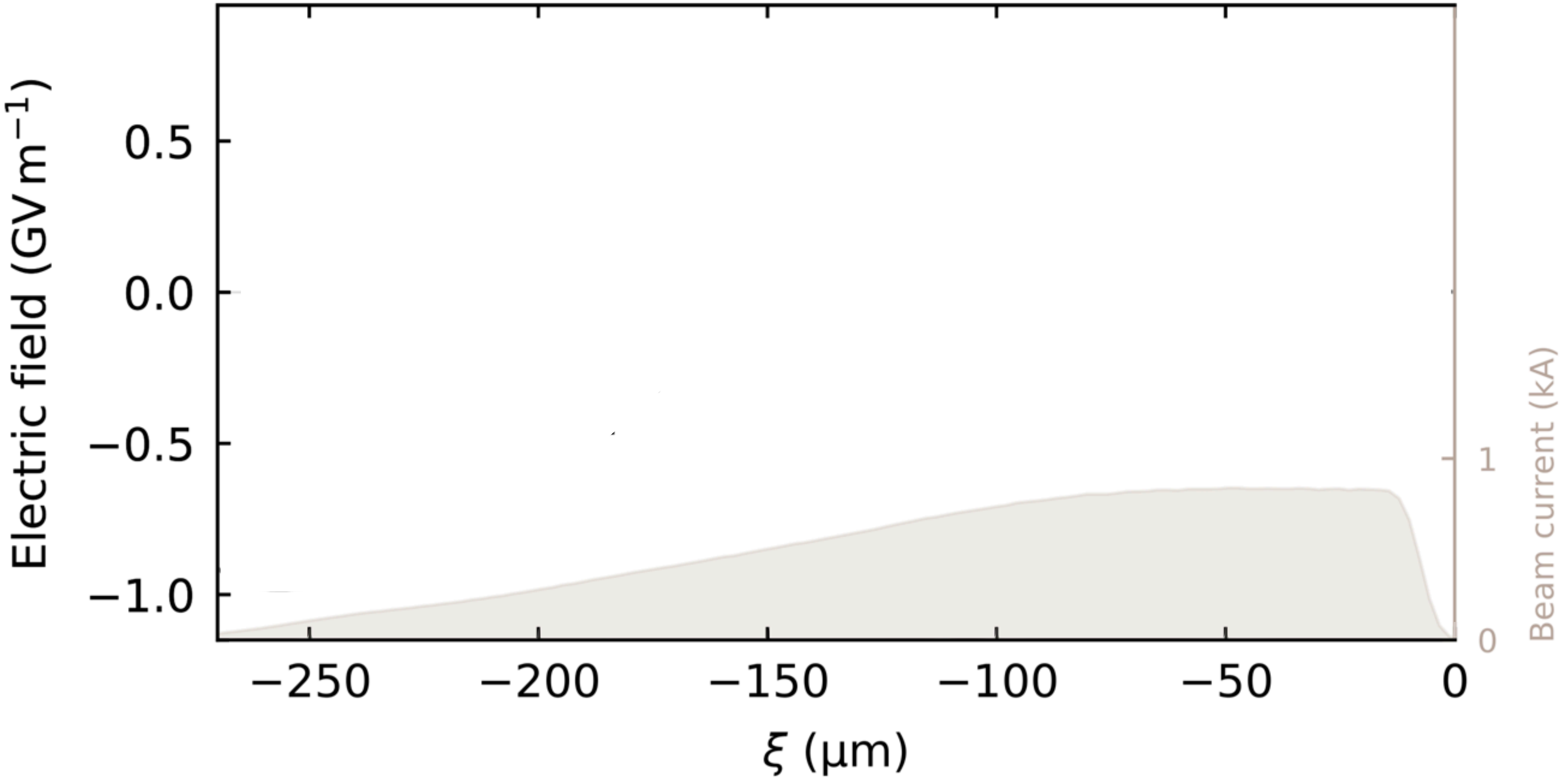
High-resolution plasma wakefield sampling demonstrated

Opens a pathway to targeted and precise field manipulation

> Beam itself acts as a probe
  → measures in-situ (under actual operation conditions) the effective field acting on beam with μm / fs resolution

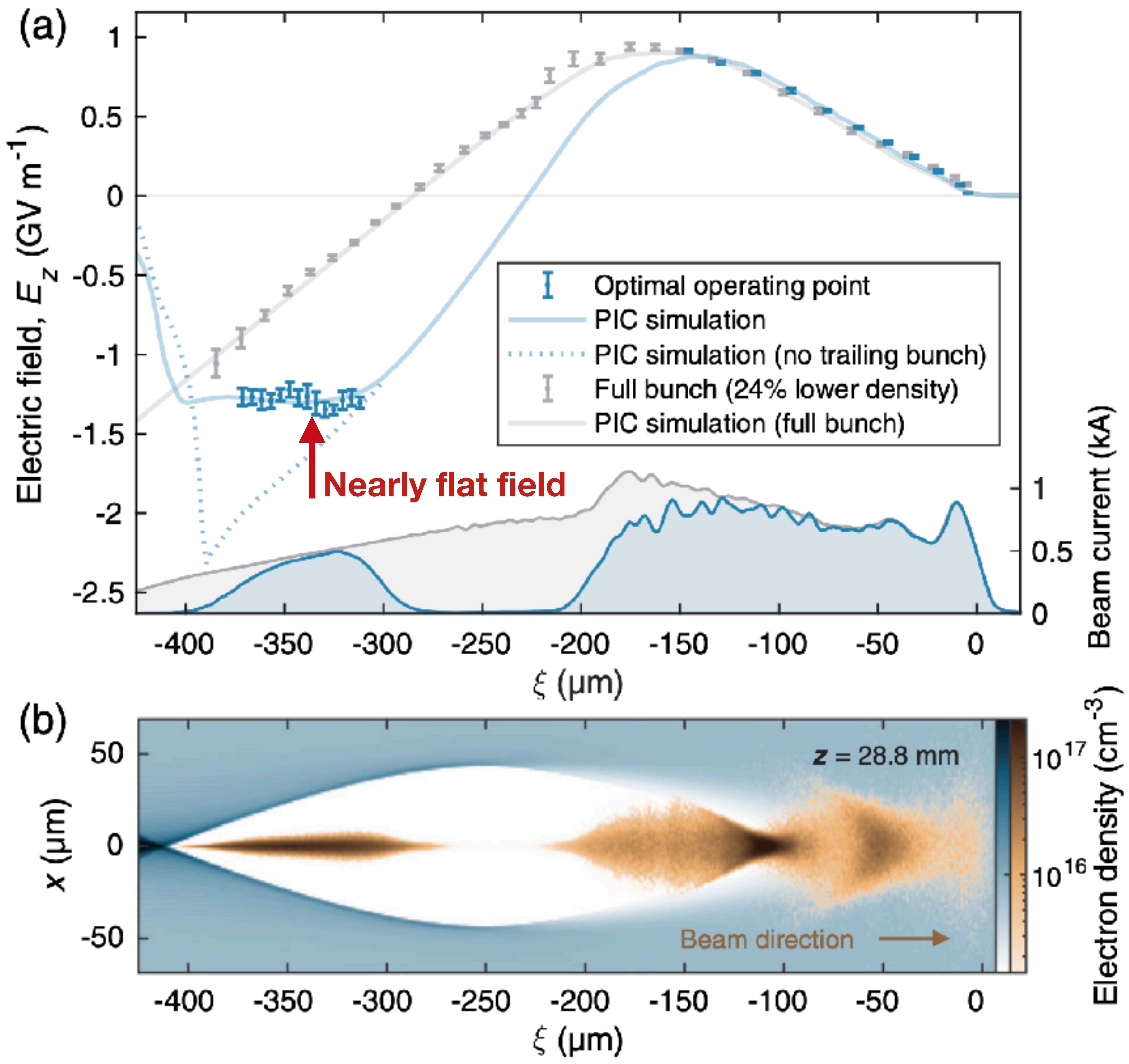


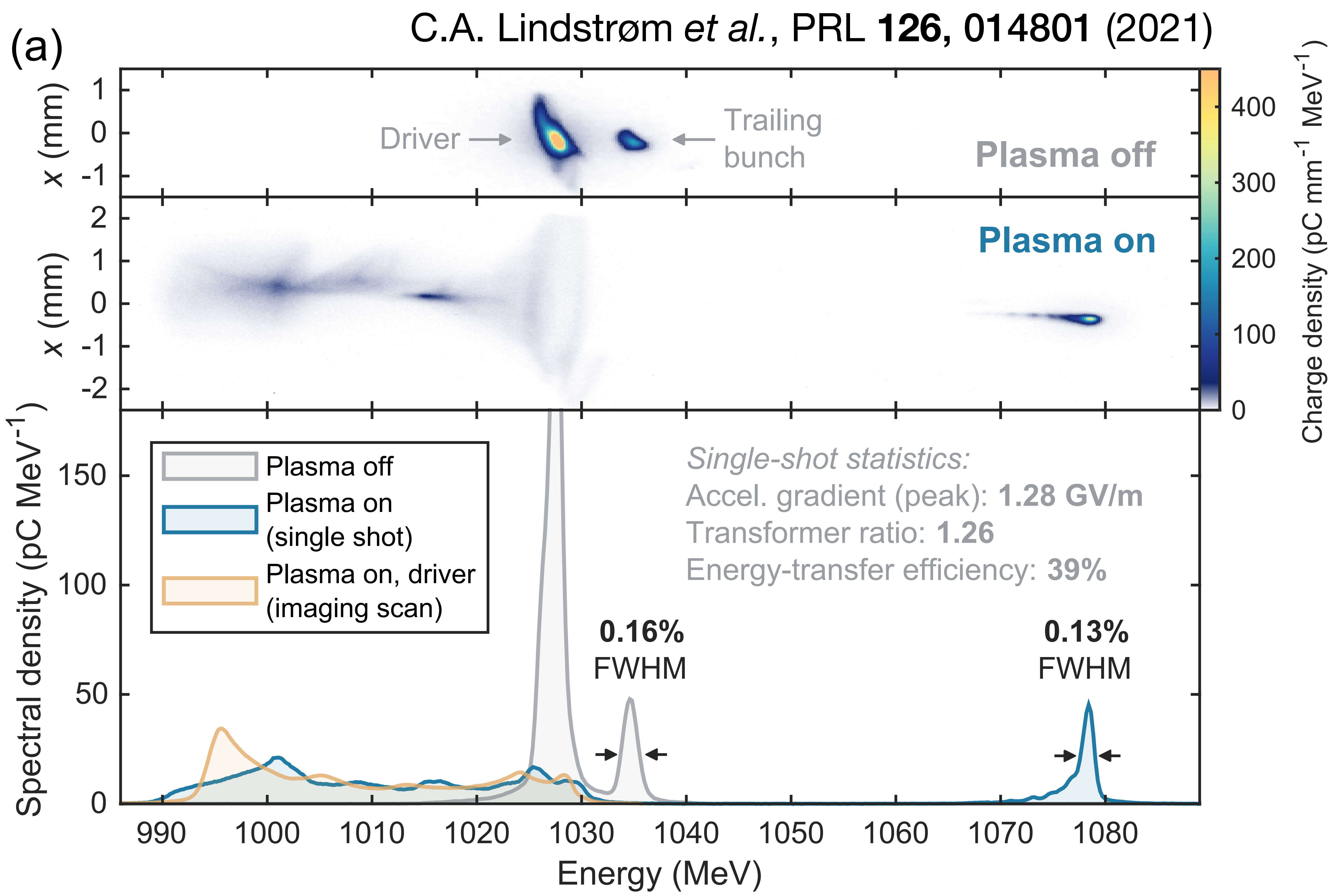
S. Schröder *et al.*, Nat. Commun. **11**, 5984 (2020)



Loading the wakefield and beam shaping flattens the gradient

Direct visualization of electric-field control by wakefield sampling

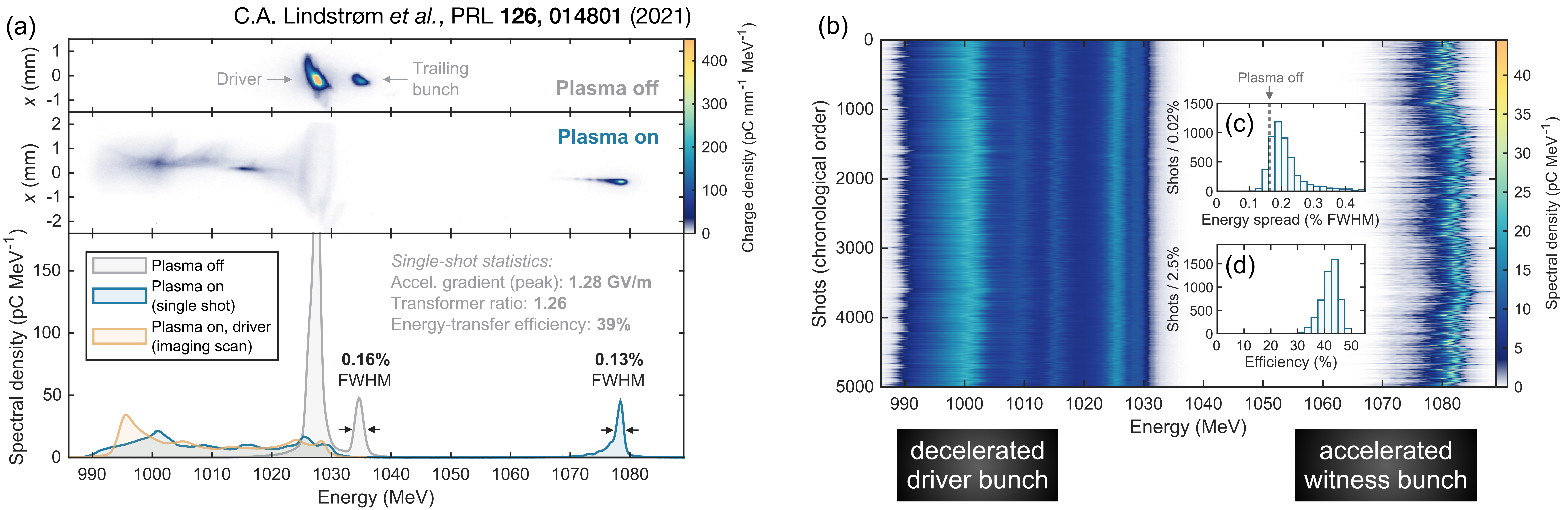




- Accelerating **gradient of 1.3 GV/m**
- Energy gain 45 MeV (over 3.5 cm distance) of 100 pC witness, with energy spread of 1.4 MeV FWHM and **no charge loss**
  - **Few-percent-level wakefield flattening demonstrated**

High-quality, efficient acceleration for sustainable applications

Beam-loading facilitates 42% energy-transfer efficiency, 0.2% energy spread with full charge coupling



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  - **Few-percent-level wakefield flattening demonstrated**

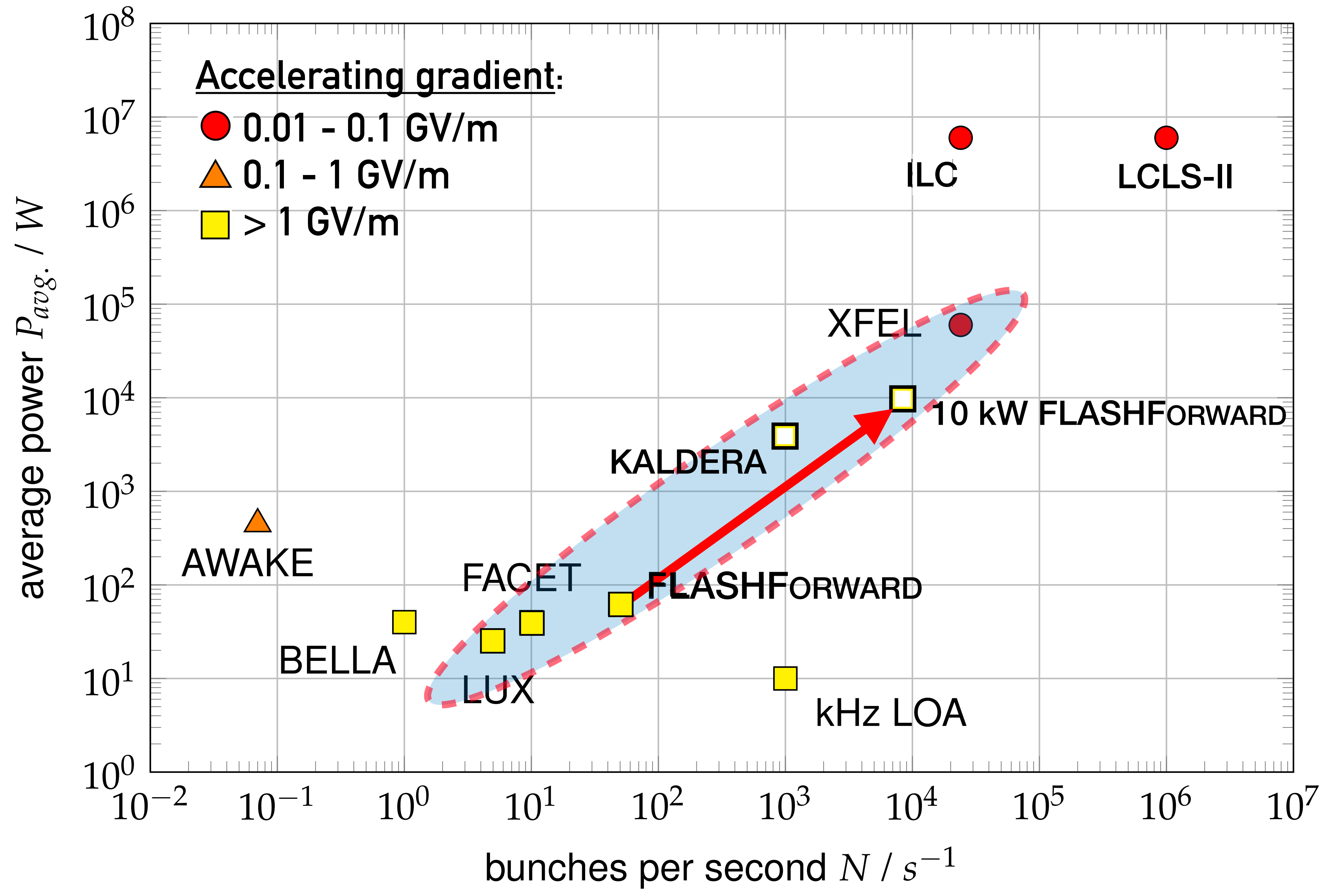
- **0.2% energy spread (input 0.16%)**
  (improvement by factor 10 over state-of-the-art)

- **(42±4)% energy transfer efficiency**
  (improvement by factor 3 over state-of-the-art)

FLASHFORWARD▸▸ roadmap aims at 10 kW with high beam quality

Plan covers major plasma accelerator challenges

- 2018 — Plasma dechirper
  - D'Arcy *et al.*, **PRL** 122, 034801 (2019)
- 2019 — Energy depletion and energy doubling
- Wakefield sampling
  - Schröder *et al.*, **Nat. Commun. 11** **5984** (2020)
- 2020 — Energy spread preservation by beam loading control
  - Lindstrøm *et al.*, **PRL** **126, 014801** (2021)
- Emittance preservation
- 2022 — High overall efficiency and gain for sustainable operation
- Detection of slice properties with fs resolution
- 2024 — kHz-to-GHz plasma response
- 2026 — 10 kW avg. power operation
- 2030



10 kW stage with 50% efficiency & beam quality conservation

→ **FLASH:** increase FEL energies, access oxygen K-edge at 2.33 nm wavelength

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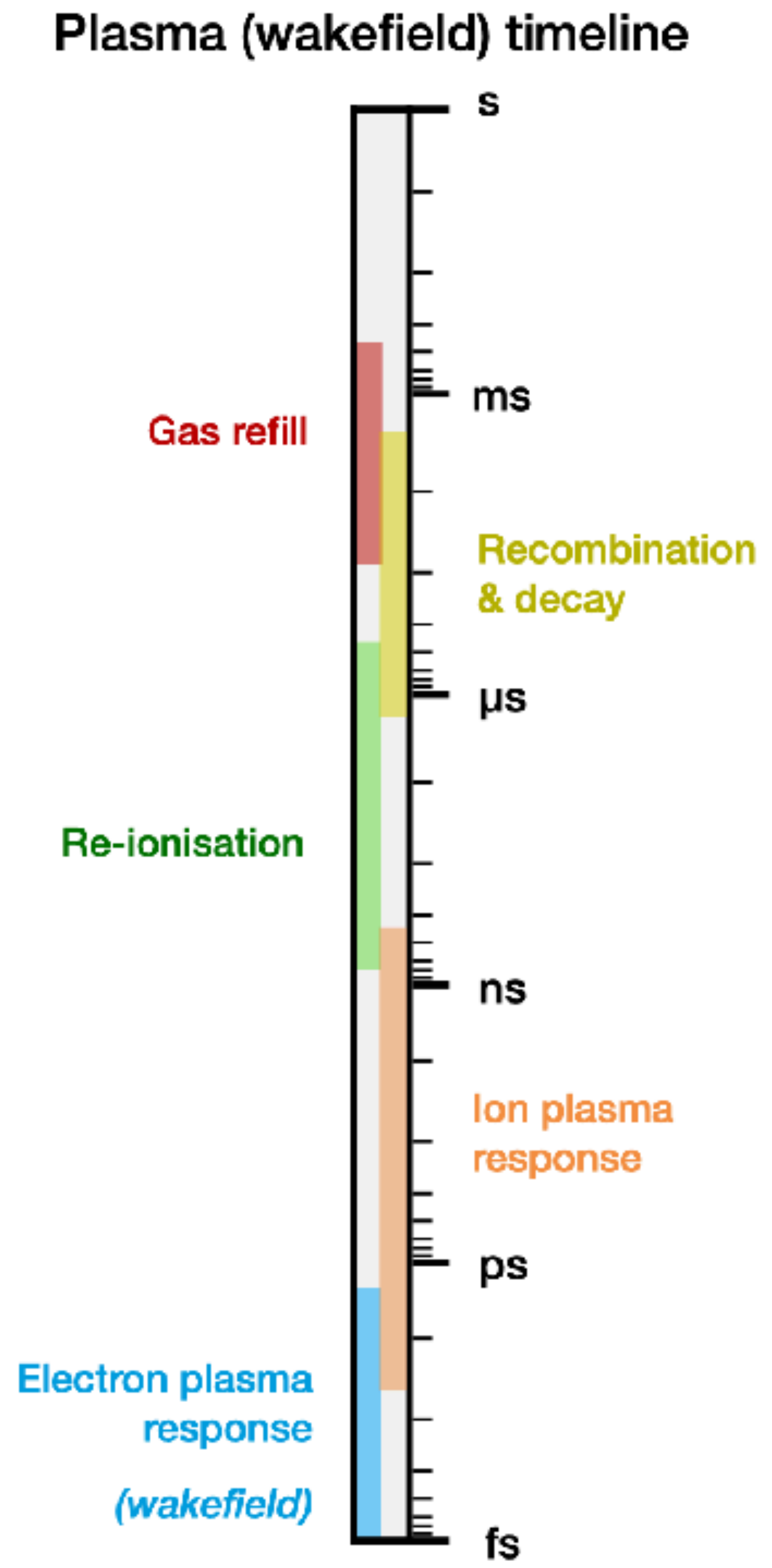
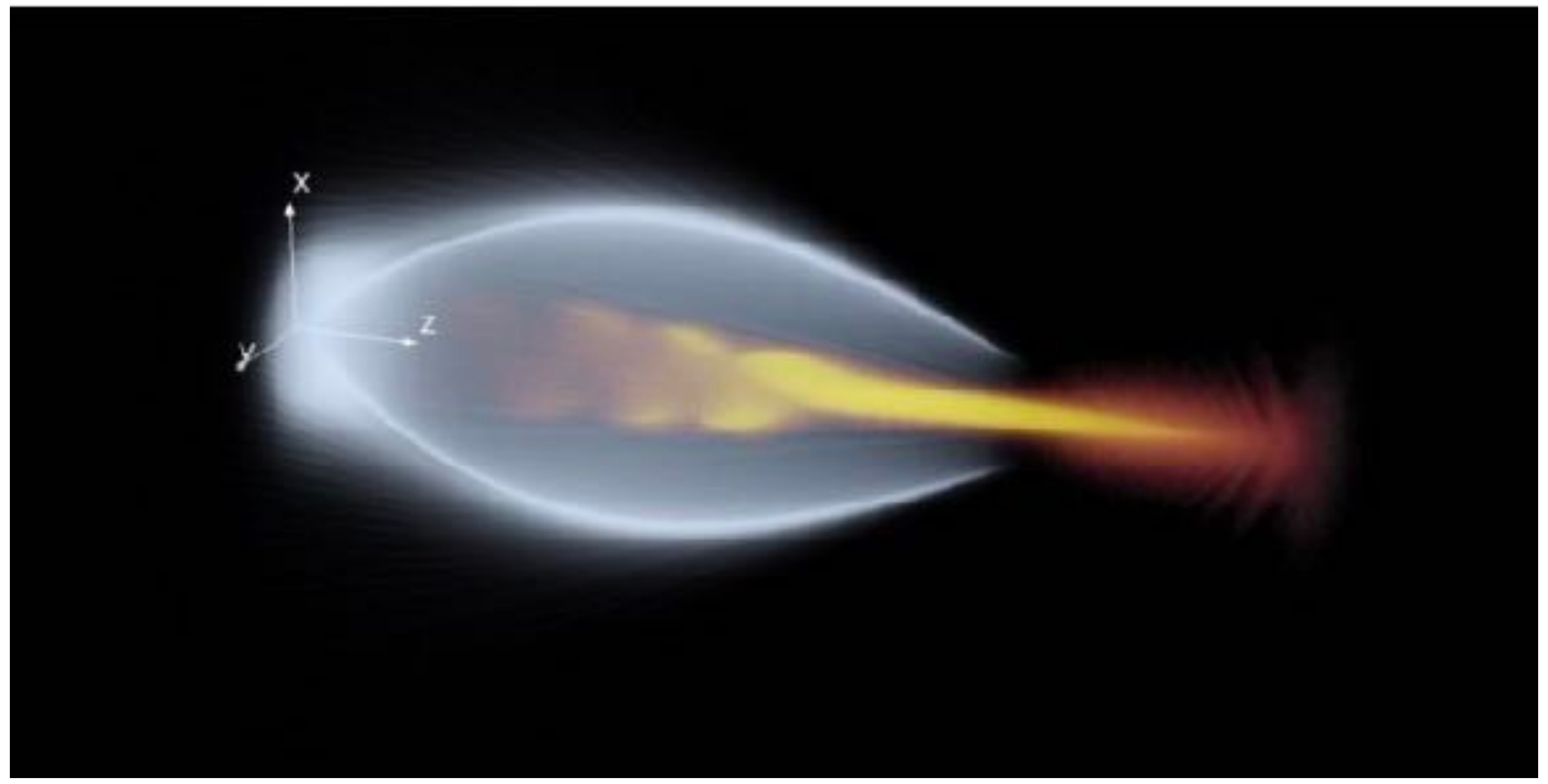


Simulations play a crucial role for research at FLASHFORWARD▸▸

Long-time-scale plasma dynamics challenge current capabilities

> Accurate simulations are essential

- to predict new phenomena
- to prepare and plan experimental studies
- to verify and analyze measurements



> Simulations for plasma accelerators require High-Performance Computing (HPC)

- **~M core hour** for single simulation with full particle-in-cell (PIC) scheme
  → ensemble of simulations are (prohibitively) expensive
- **Development of specialized codes / efficient and accurate algorithms critical**

> HPC is a dynamic field

- **Performance portability** on heterogeneous platforms required
- **Inter-operability** of HPC tools
- Advanced numerical methods and **AI** increasing in importance (→ ACCLAIM)

Maxence Thévenet
Group leader

> New group on Plasma Accelerator Theory and Simulations

State-of-the-art code development

- **WarpX** – full 3D electromagnetic, **open-source, GPU** *(LBNL)*
- **FBPIC** – quasi-RZ, Python, **open-source, GPU** *(LBNL, UHH, DESY)*
- **Hipace** – quasi-static, 3D, **work in progress…** *(DESY, LBNL)*

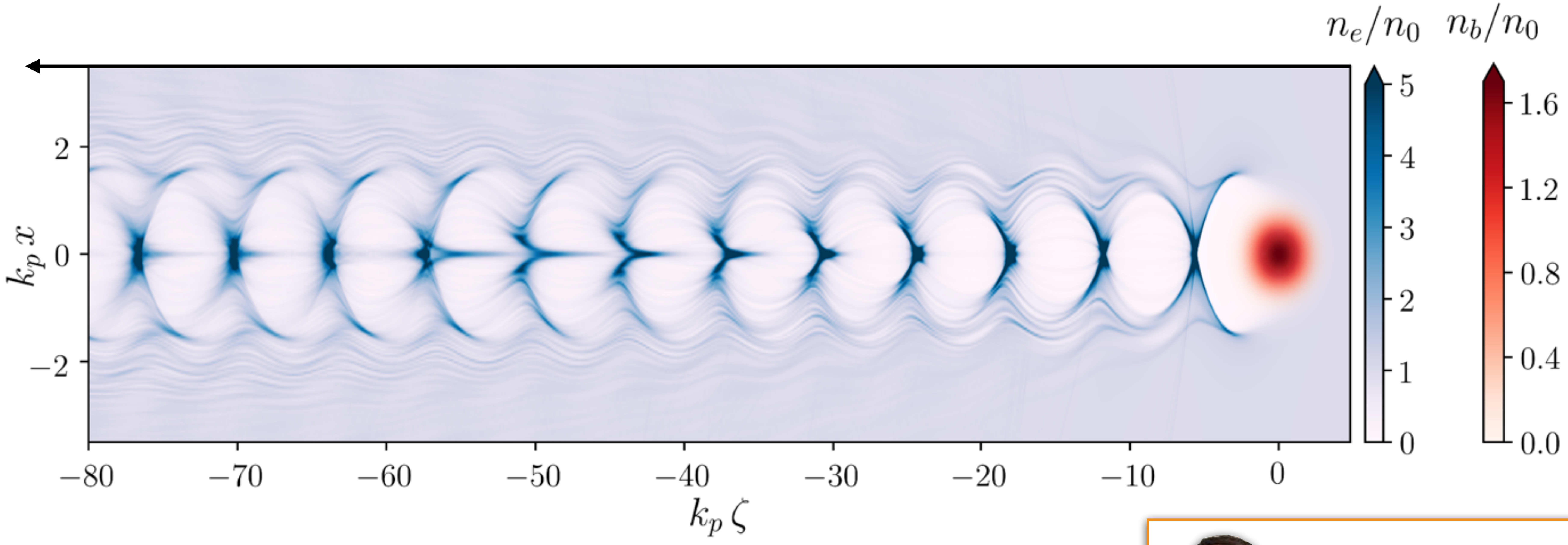
Enabling ensembles of S2E multi-physics simulations

- Adoption of the **openPMD I/O** standard *(HZDR)*
- **AI** to improve productivity *(UHH & DESY)*
- Capability to study **long-time plasma dynamics**

Understanding ultimate repetition rate limits of plasma accelerators

Long-time-scale plasma dynamics challenge current capabilities

- Need to simulate **> 10^4 plasma oscillations** to investigate plasma recovery
- Requires new ideas and new low-noise codes
- **Critical to understand energy dissipation, power density limits, repetition rate limits**
- Will catalyze the experimental progress at FLASHForward and beyond



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Progress in Plasma Booster R&D at FLASHFORWARD▸▸

Summary and outlook

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

High efficiency

- ☑ Transfer efficiency
- ☐ Driver depletion

High beam quality

- ☑ Energy-spread preservation
- ☐ Emittance preservation

High average power

- ☐ High repetition rate

- **Impactful and exciting research programme will help advance plasma accelerators to application-readiness**