FLASHForward▸▸ — Beam-driven plasma-wakefield research at DESY

Richard D'Arcy

FLASHForward▸▸ Coordinator | Group Leader for Beam-Driven Plasma Accelerators

DESY. Accelerator Division

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HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Acknowledgements

FLASHForward▸▸ Scientific Team

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Theory group

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Gregory Boyle
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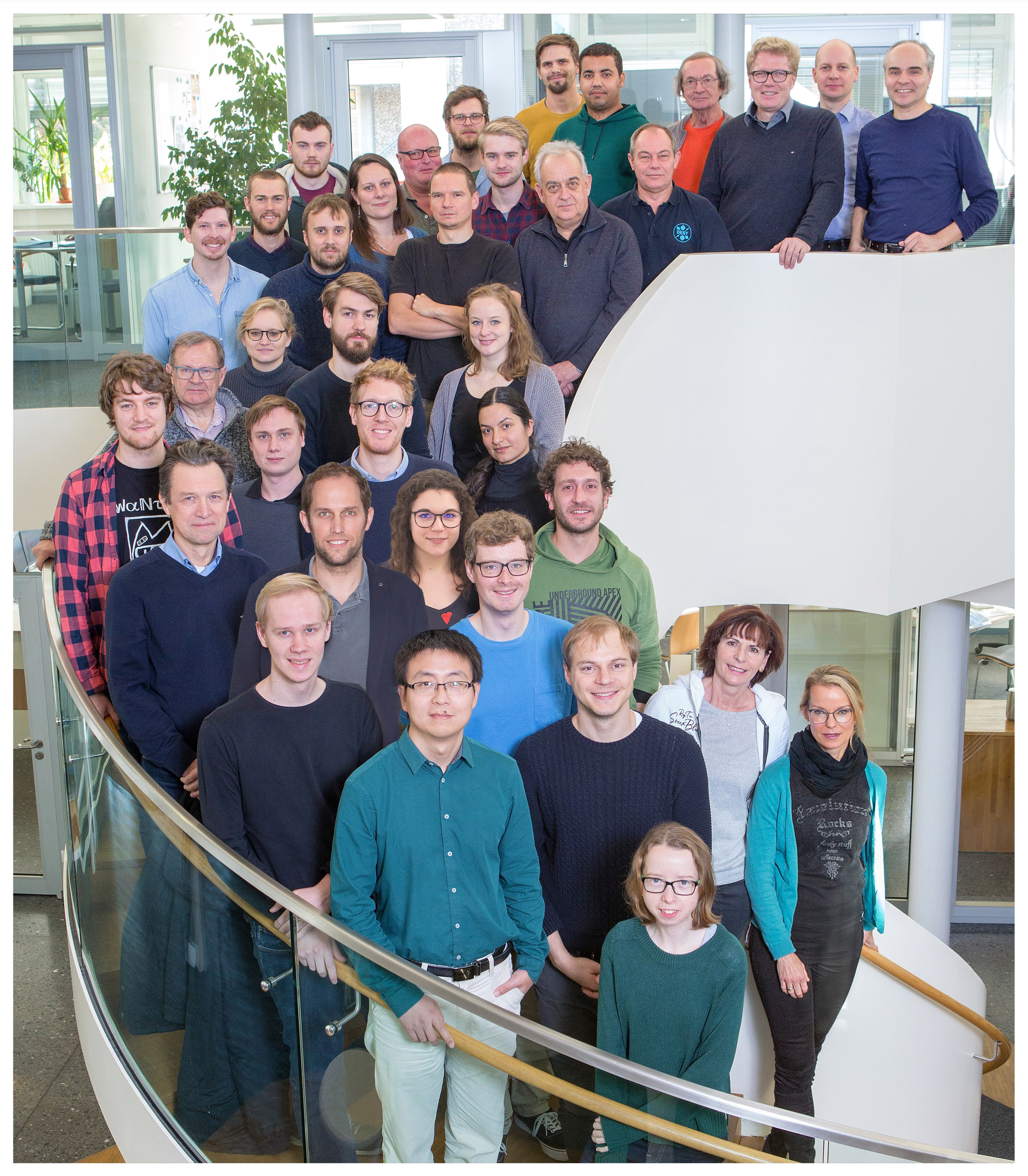
Mathis Mewes

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



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)

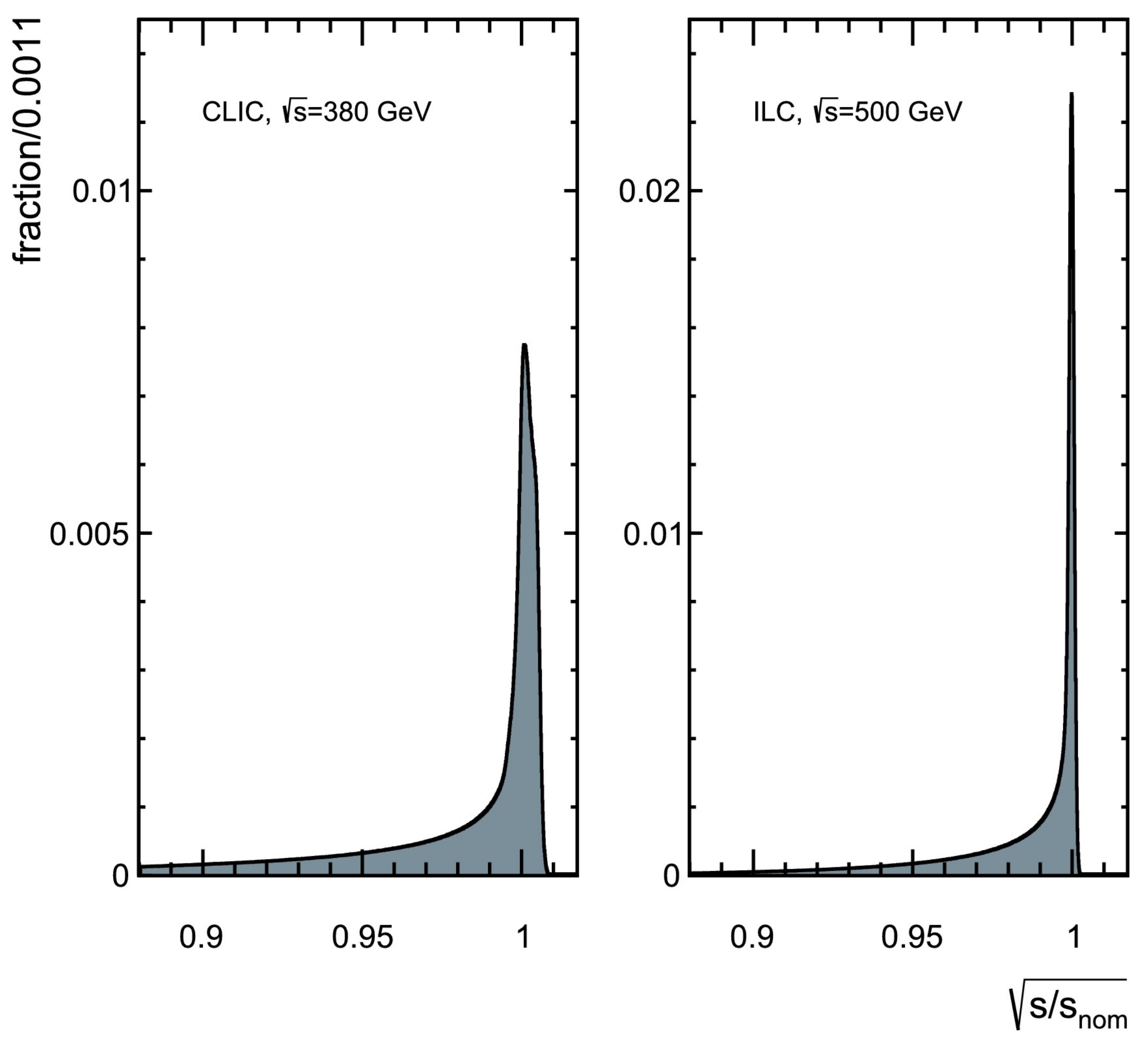
High repetition rate

High energy efficiency

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

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.

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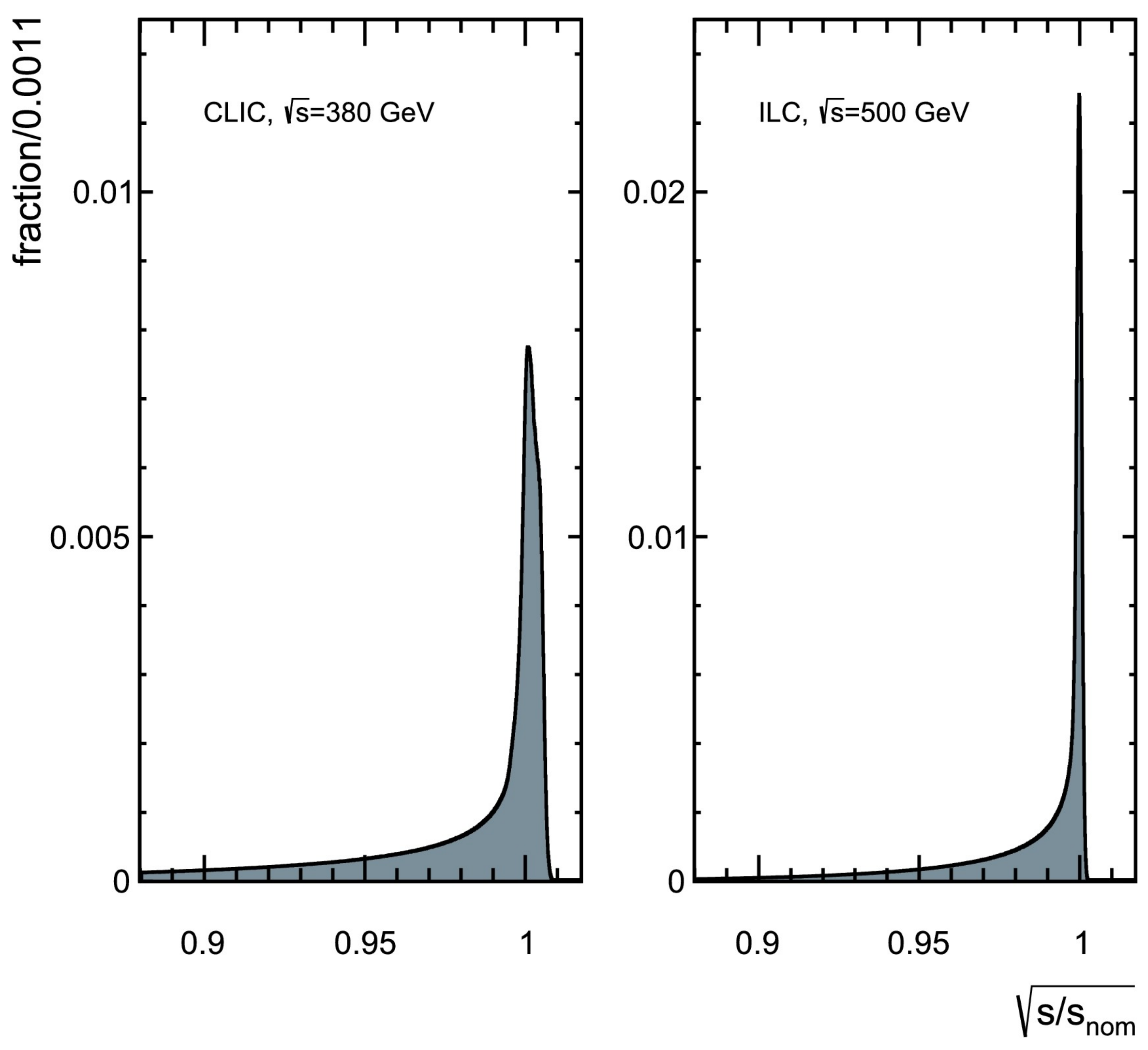

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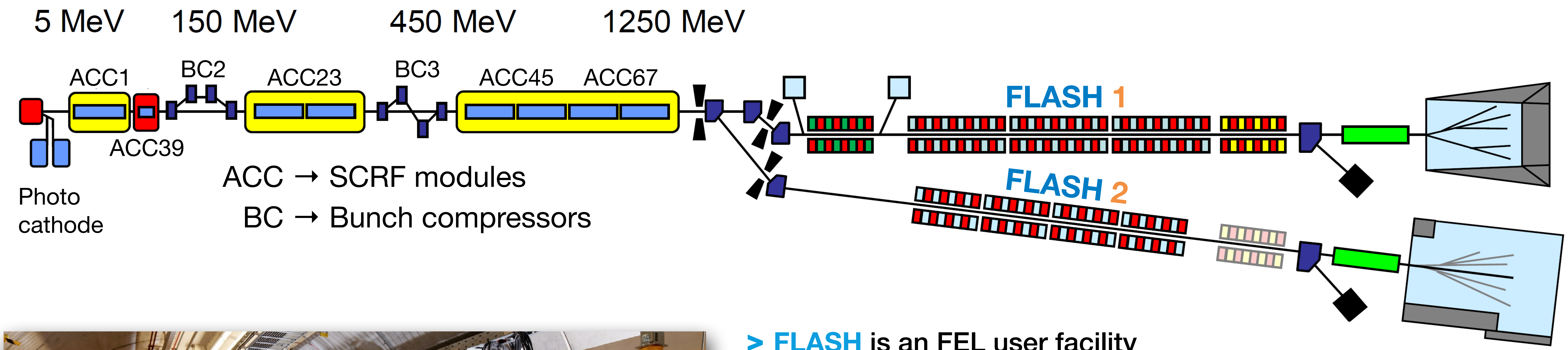
FLASHFORWARD

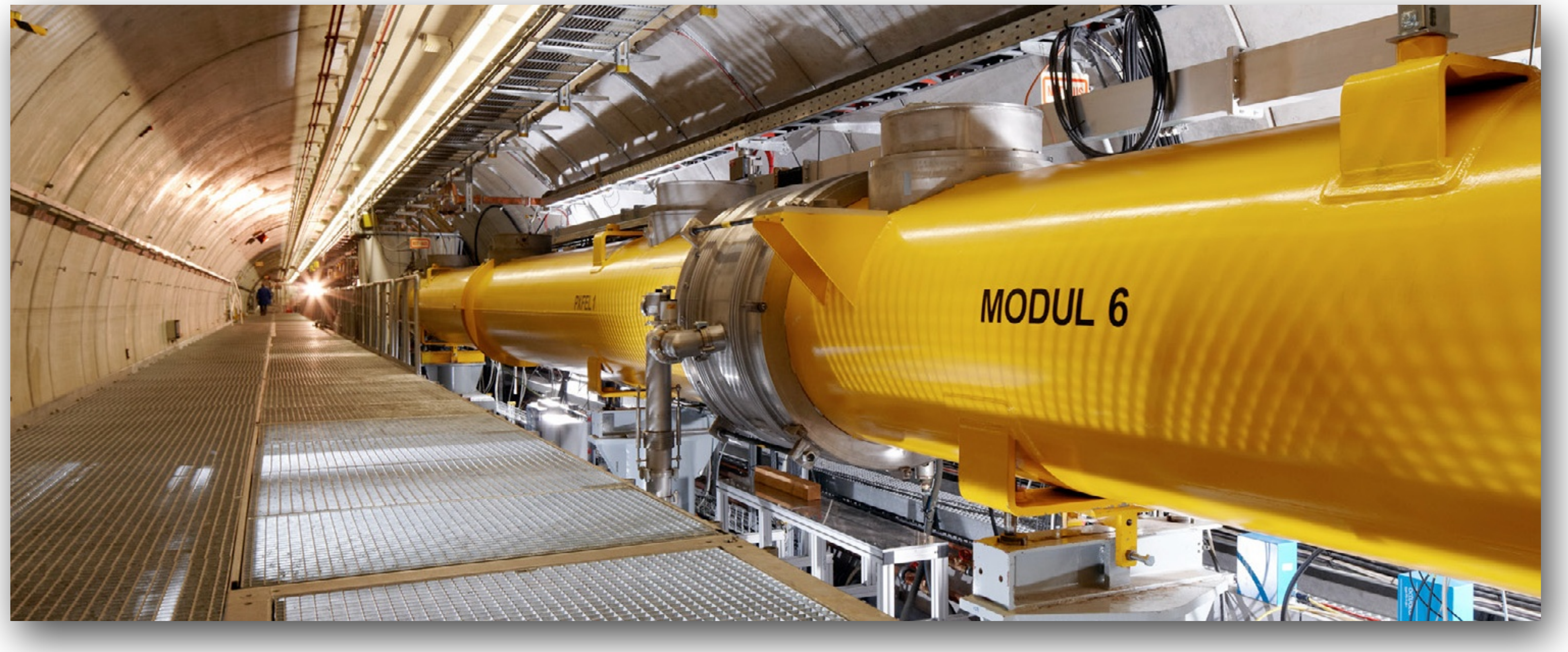
Develop a self-consistent plasma-accelerator stage
with high efficiency, high quality, and high average power

FLASHForward▸▸: The Facility

FLASHFORWARD▸▸ utilises 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▸▸ utilises FLASH superconducting accelerator

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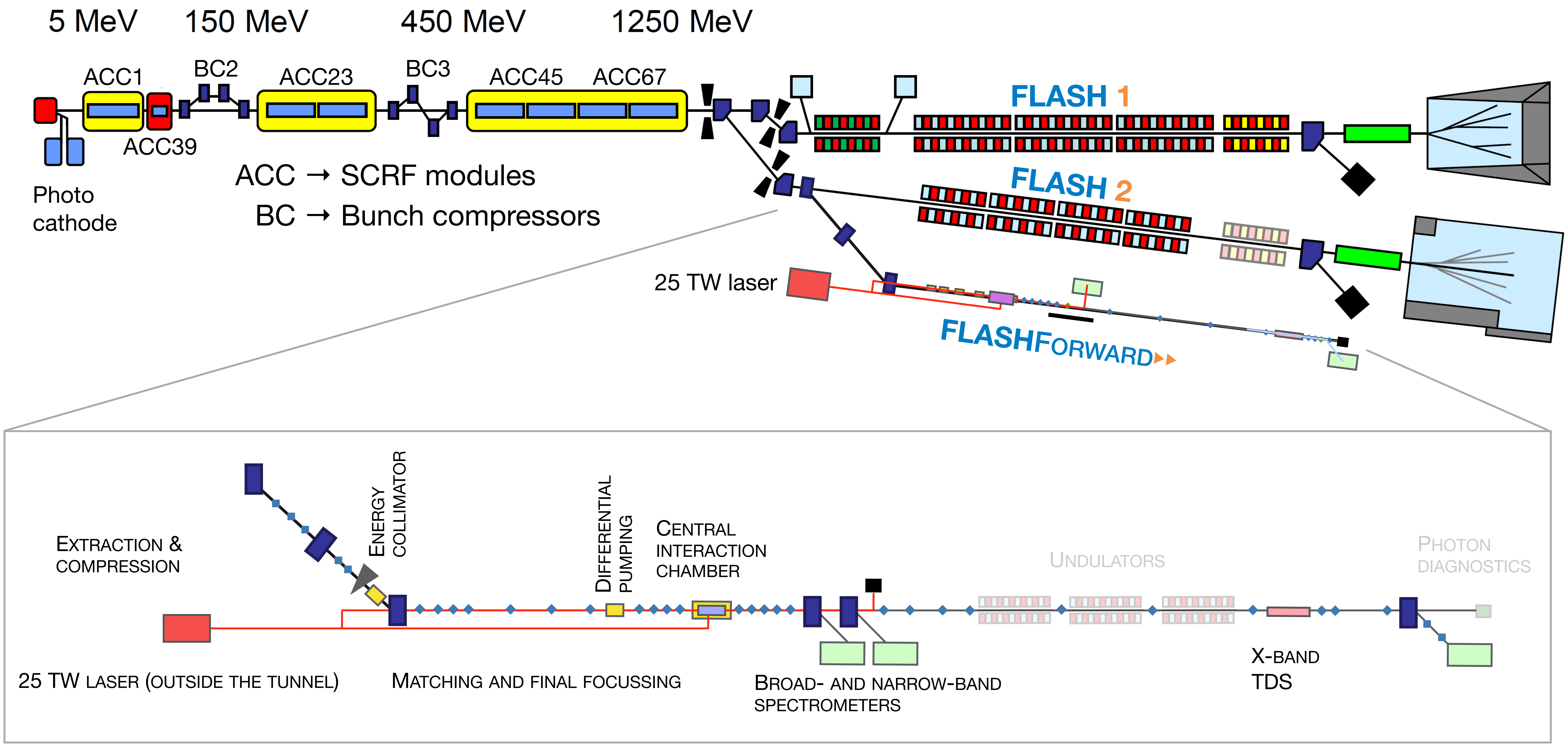
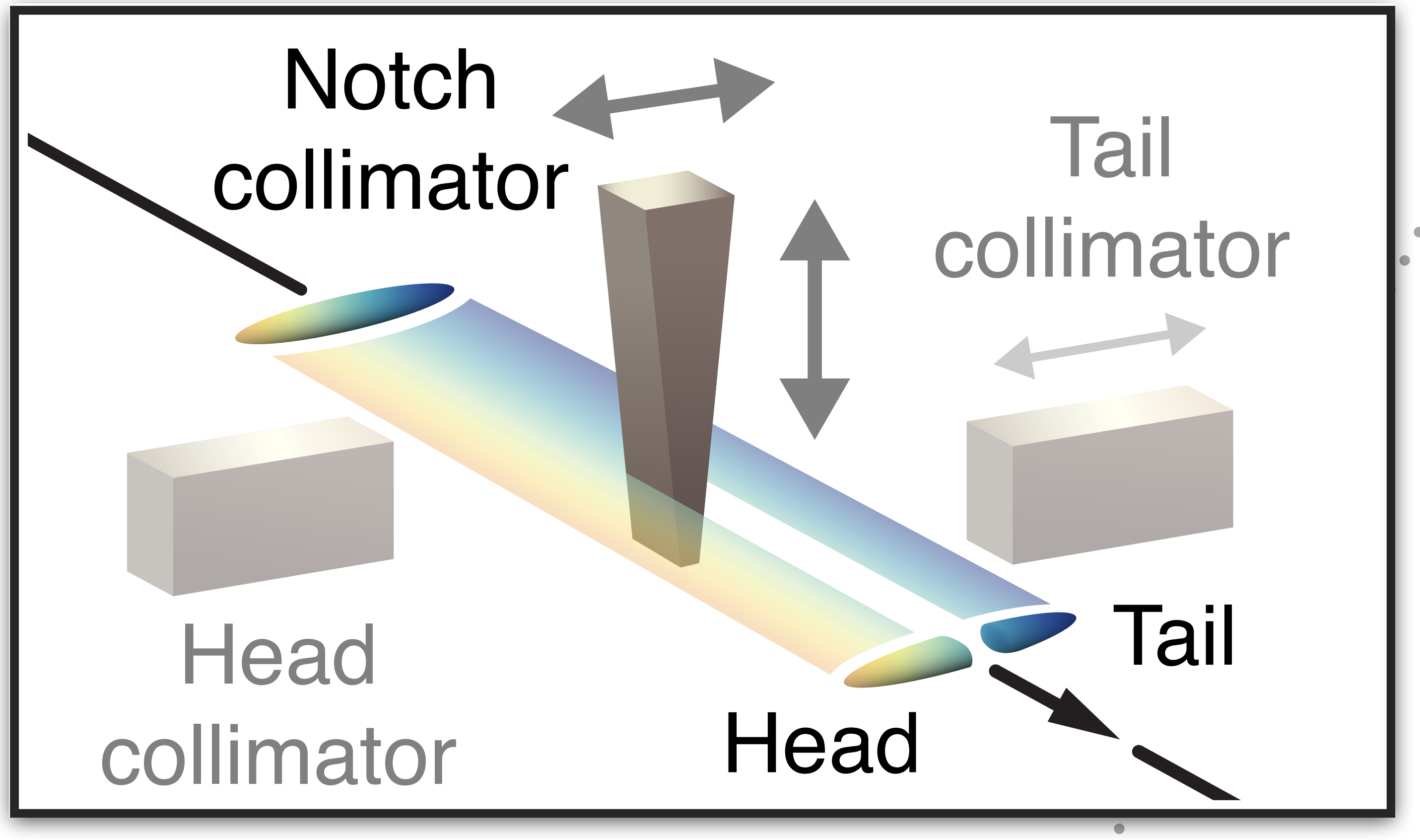
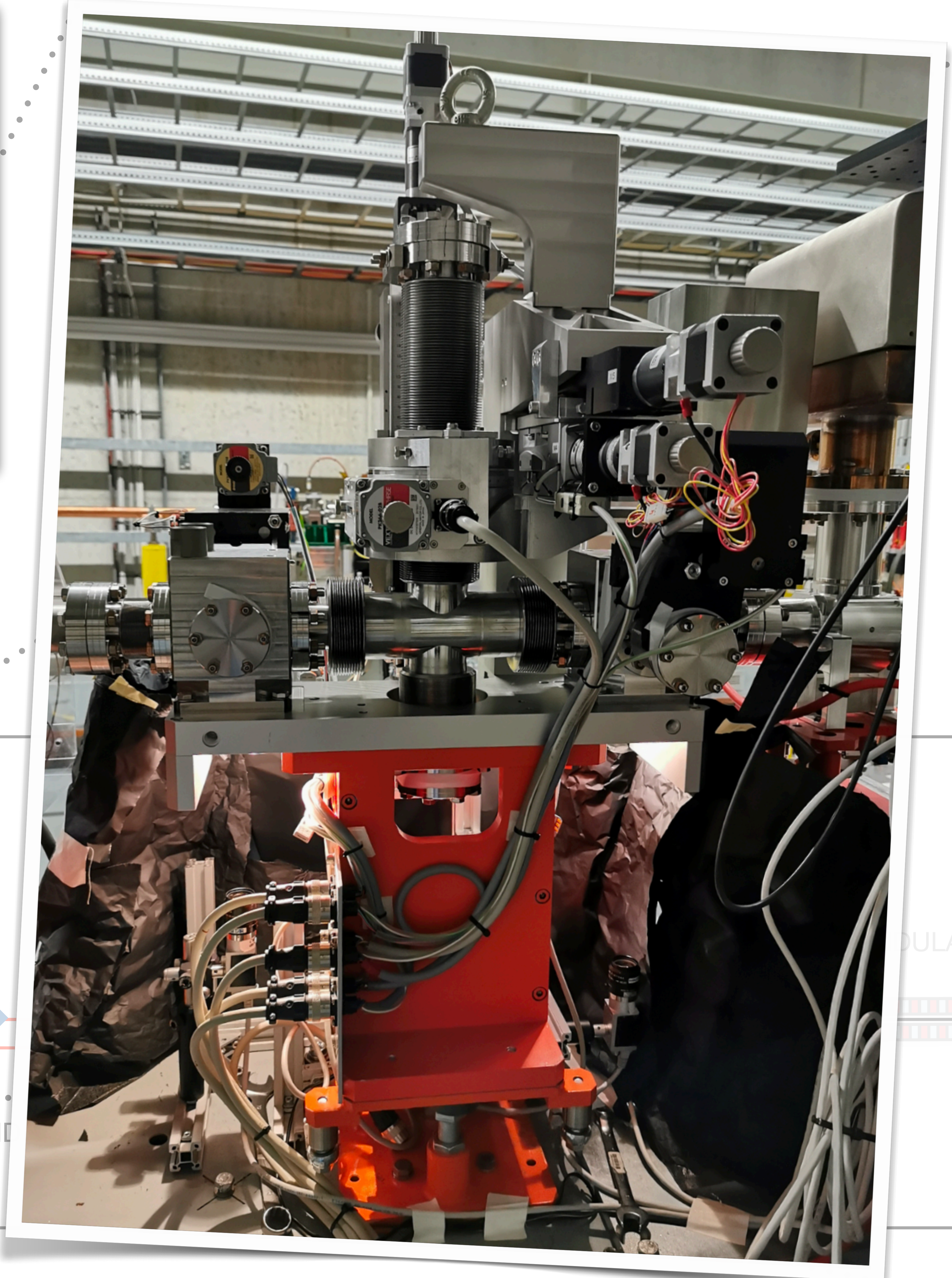


R. D'Arcy *et al.*, Phil. Trans. R. Soc. A **377**, 20180392 (2019)

Advanced collimator system for longitudinal bunch shaping

FLASHFORWARD▸▸ beamline features innovative components and methods





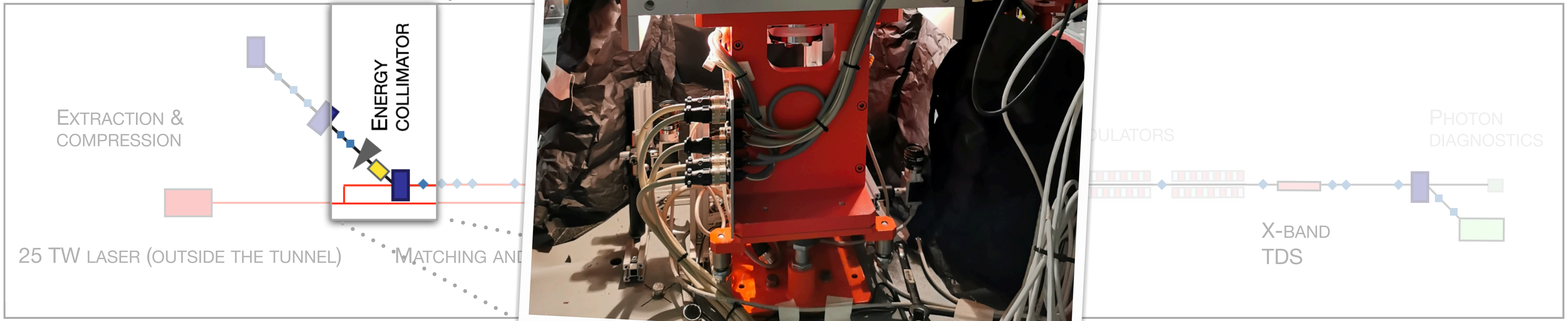
S. Schröder *et al.*,
J. Phys. Conf. Ser. **1596** 012002 (2020)

Three energy collimators:

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

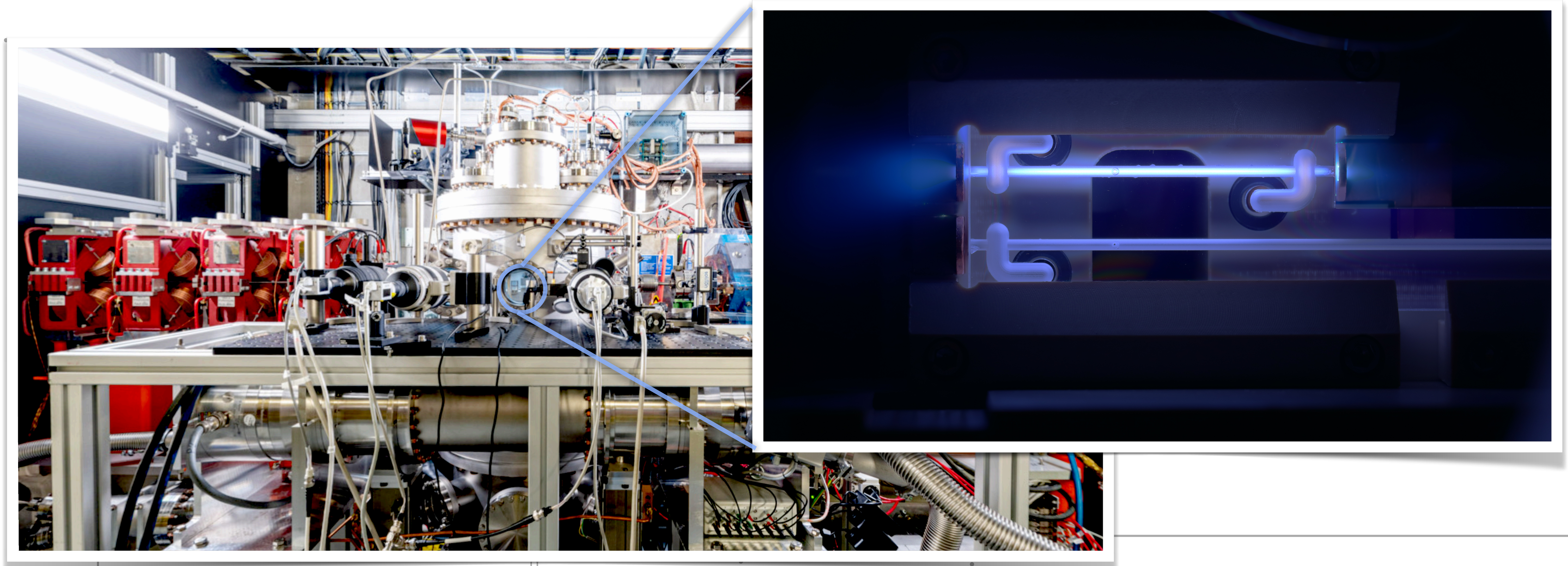
µm-precision movements

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

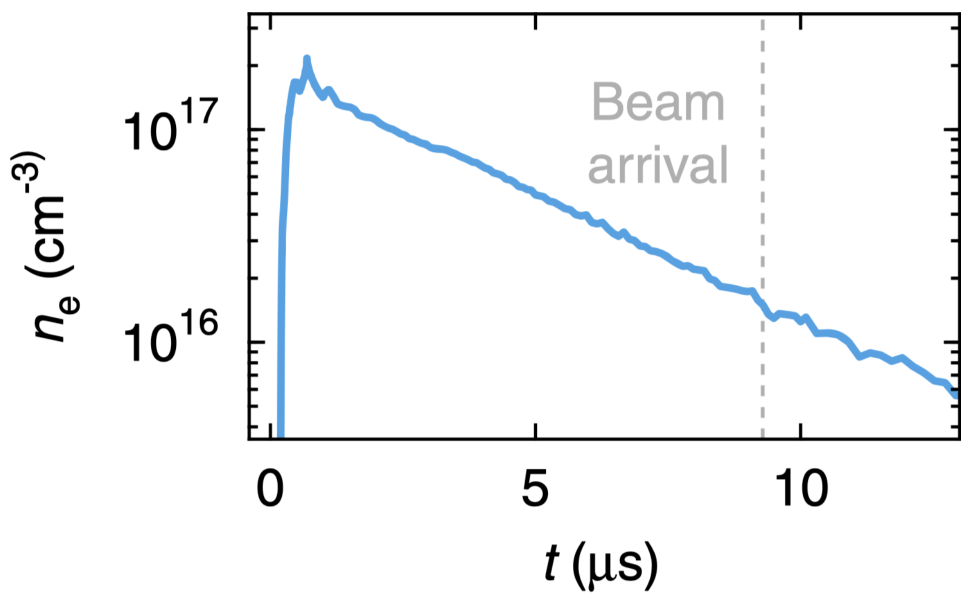


Two discharge capillaries provide density-controlled plasma

FLASHFORWARD▸▸ beamline features innovative components and methods



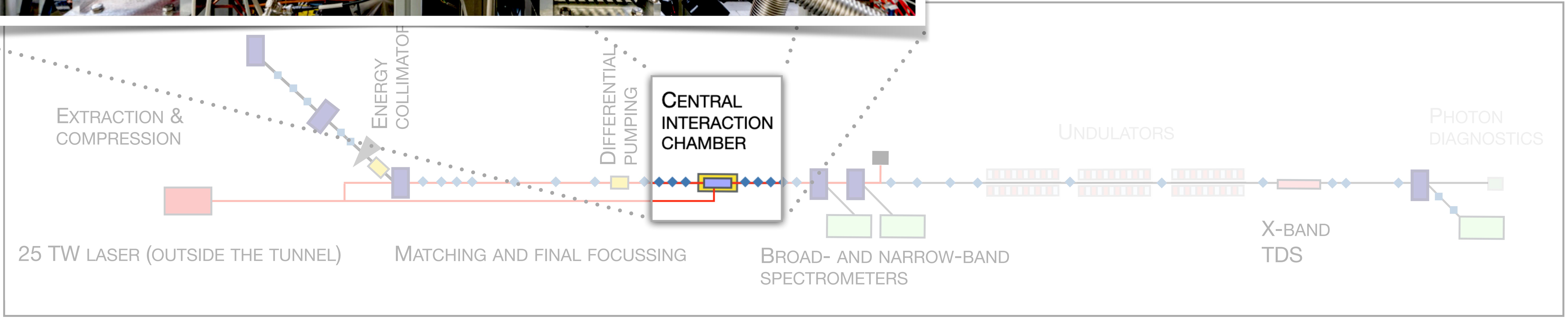
J.M. Garland *et al.*,
Rev. Sci. Instrum. **92** 013505 (2021)



High-voltage discharge

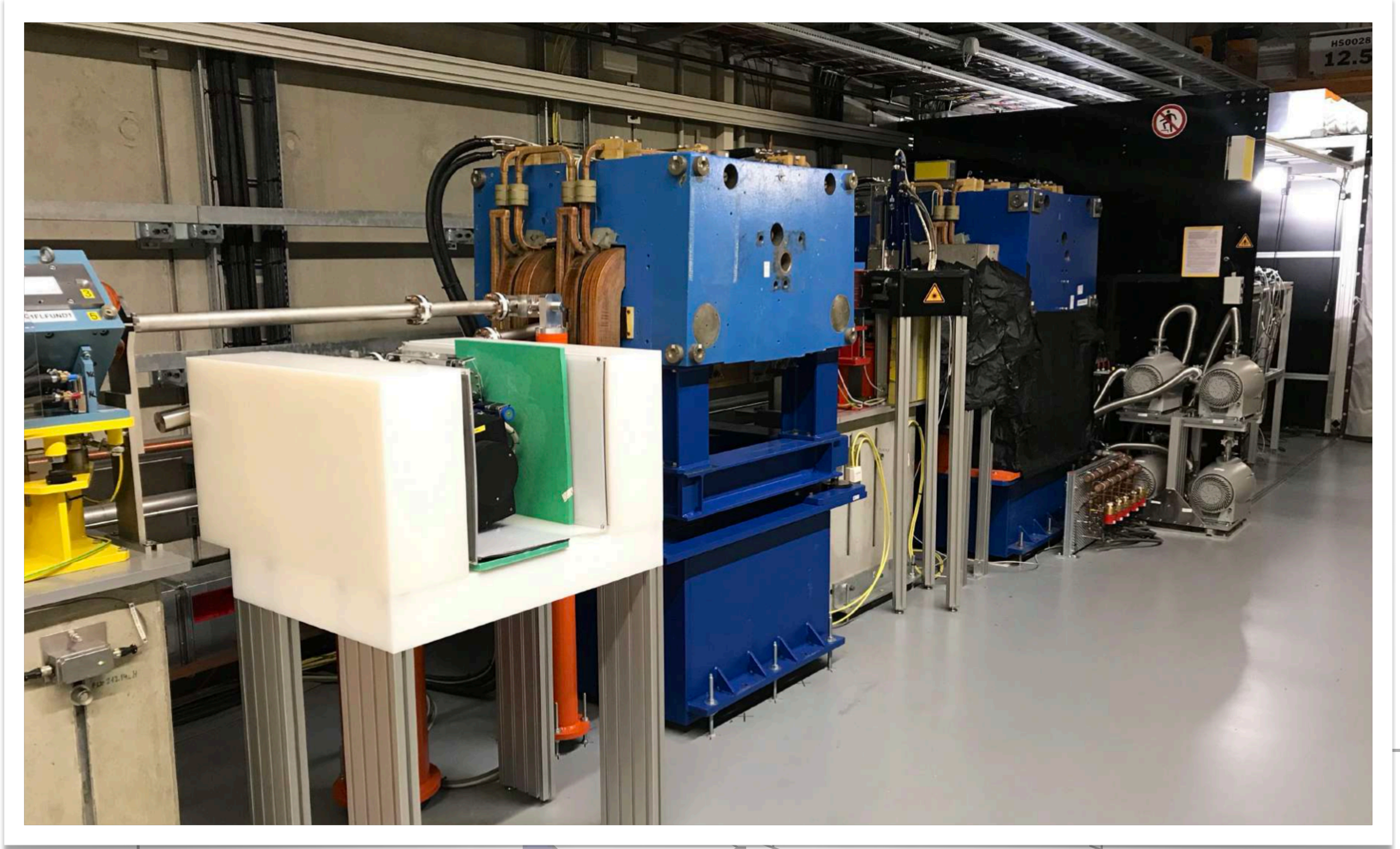
Sapphire capillaries
(50 mm and 195 mm long)

Gases: He, Ne, **Ar**, Kr, H



Two electron spectrometers used for diagnostic purposes

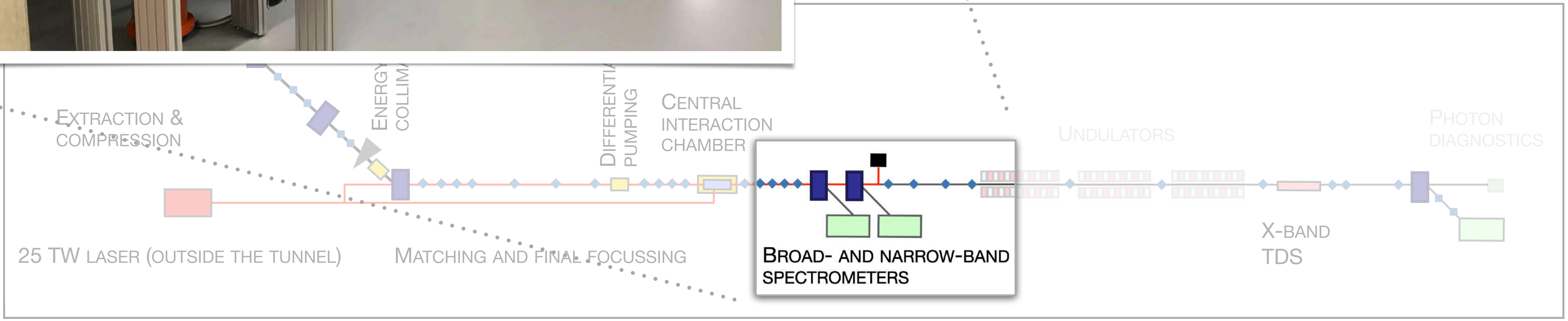
FLASHFORWARD▸▸ beamline features innovative components and methods



Imaging spectrometer

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

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



FLASHFORWARD▸▸: Beam-driven plasma-wakefield experimentation

Primary goals 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

Recovery time

Bunch-train pattern

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High efficiency	High beam quality	High average power
Transfer efficiency	Energy-spread preservation	Recovery time
Driver depletion	Emittance preservation	Bunch-train pattern

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 quickly —ideally within the first oscillation.

First oscillation

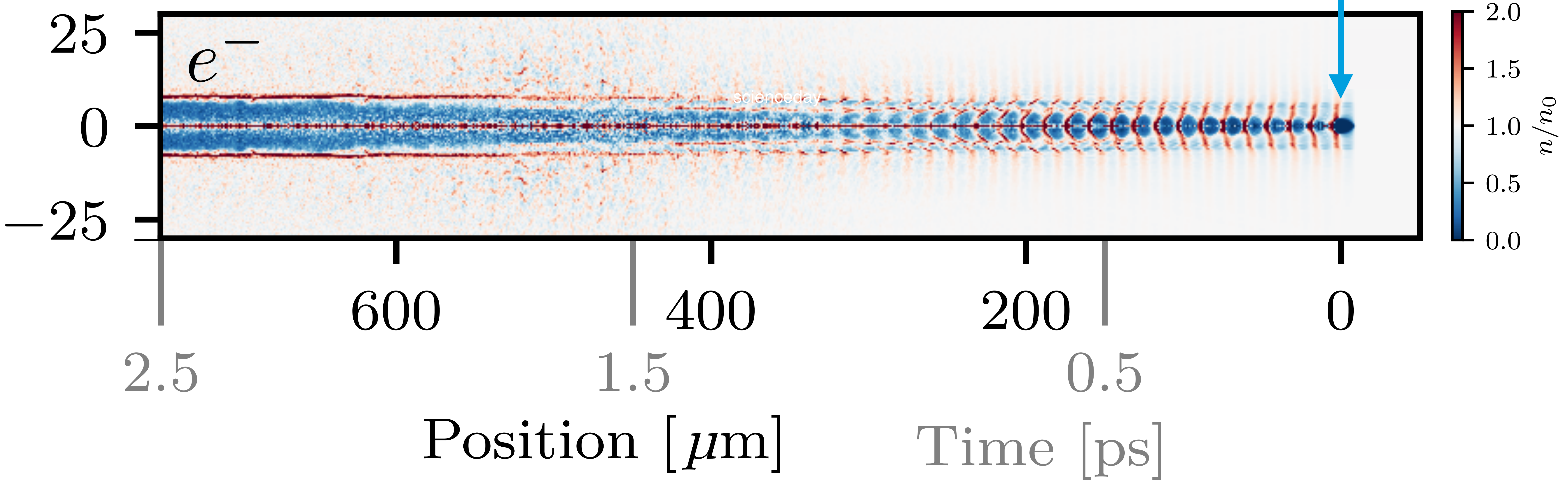

Image source: M. F. Gilljohann *et al.*, Phys. Rev. X **9**, 011046 (2019)

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> **The trailing-bunch wakefield "destructively interferes" with the driver wakefield—extracting energy.**

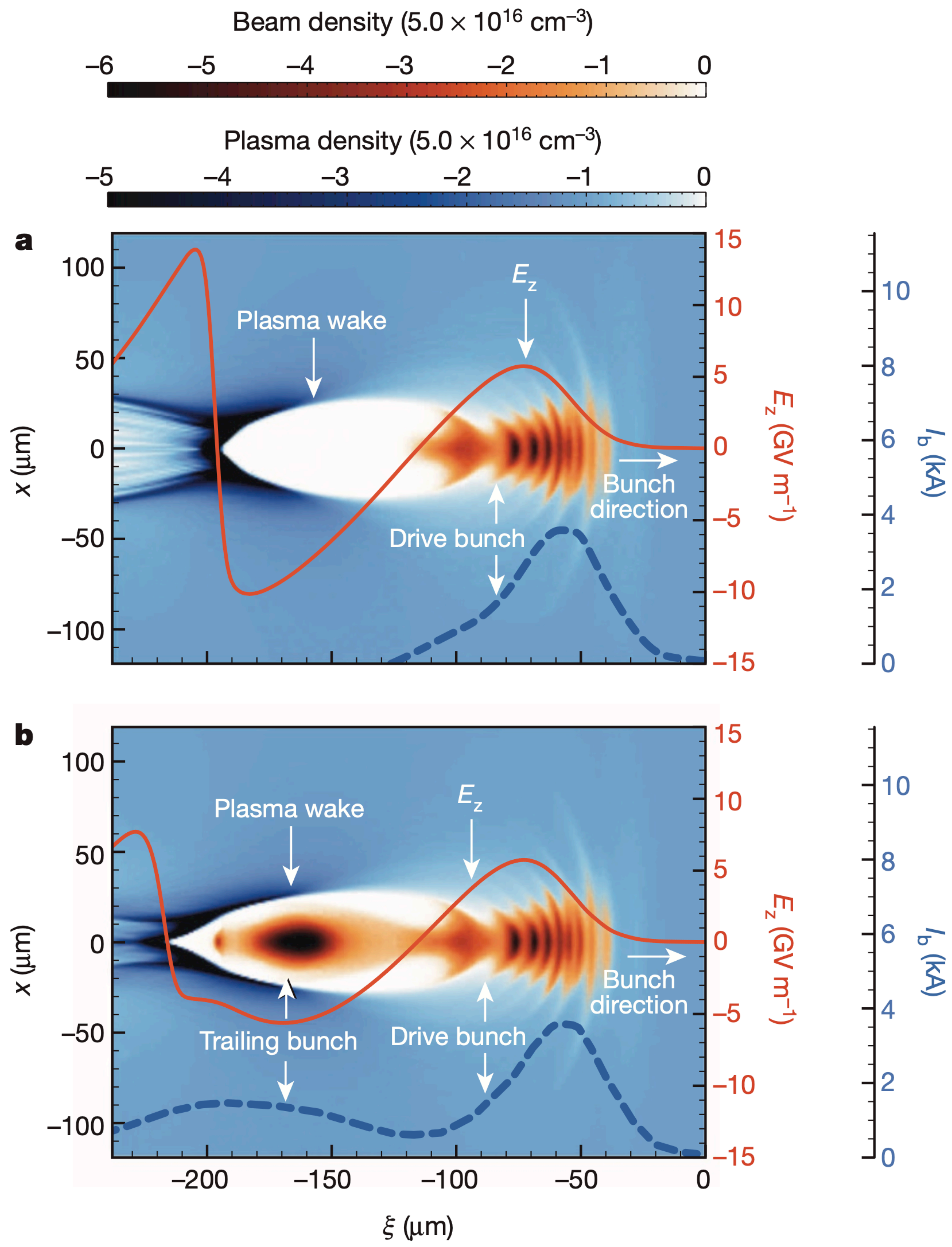

Image credit: M. Litos *et al.*, Nature **515**, 92 (2014)

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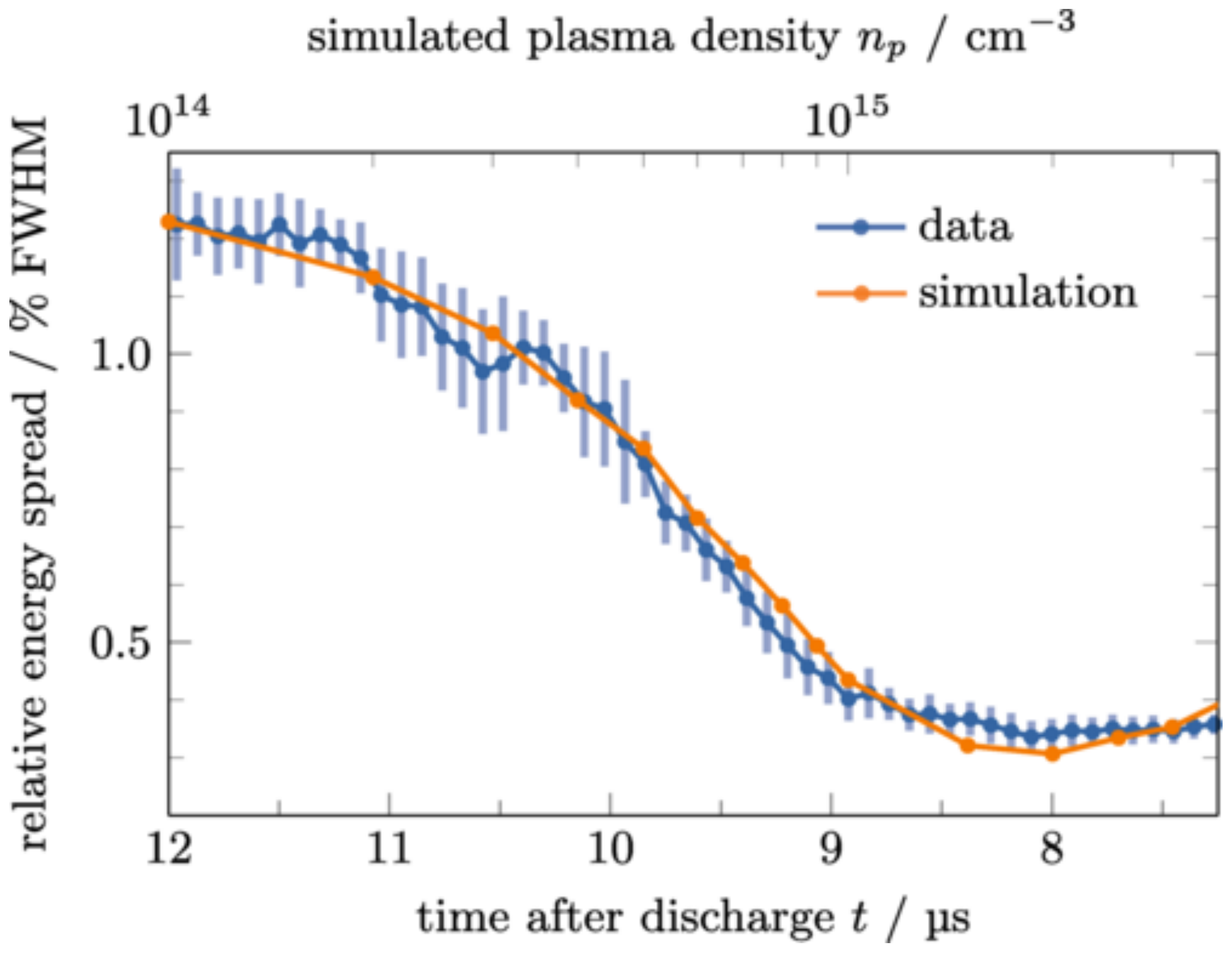
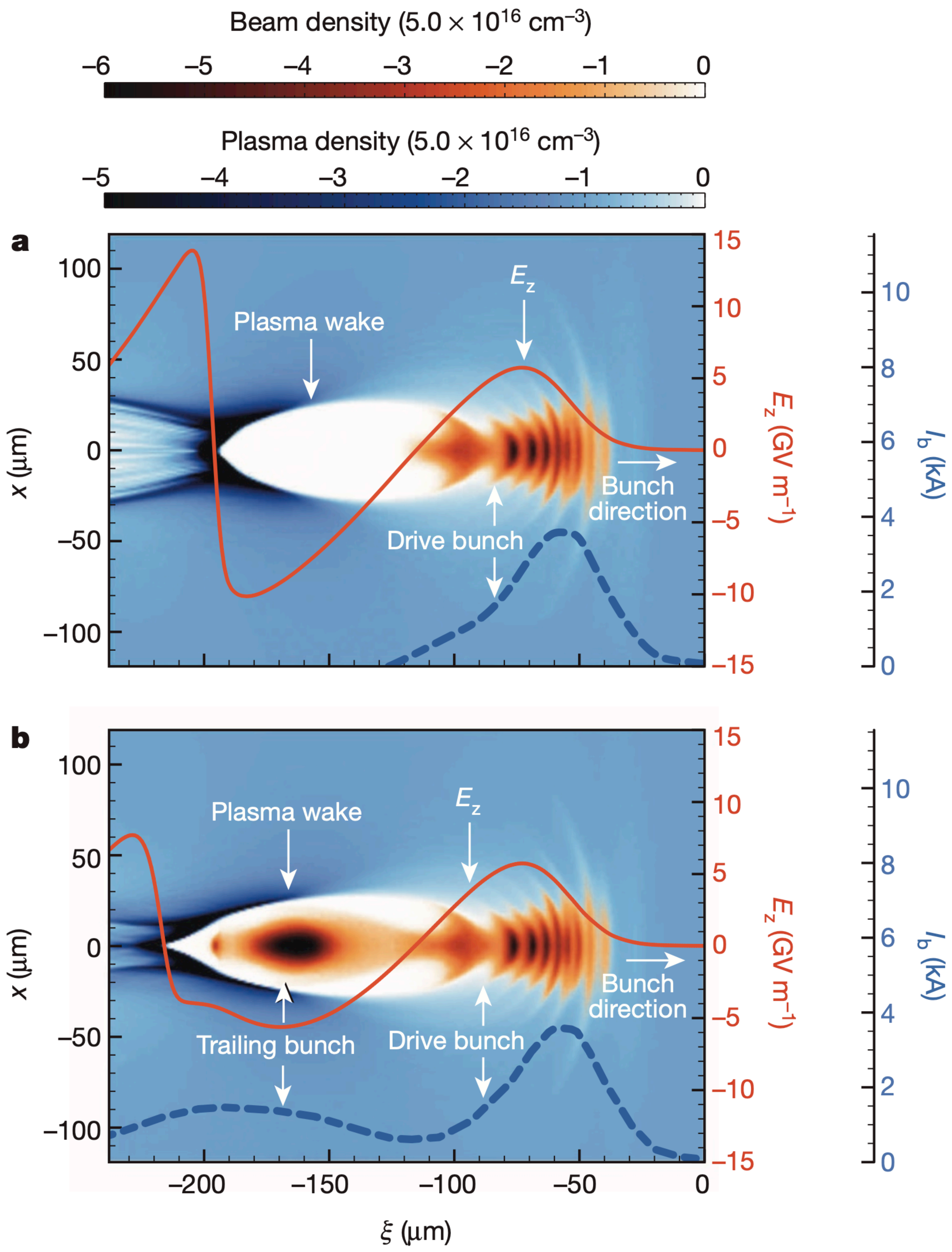
> *Problem 2*: To extract a large fraction of the energy, the beam will cover a large range of phases (~90 degrees or more).

> > Large energy spread is induced.

> > *Not (easily) possible:* Dechirping



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



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> *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.**

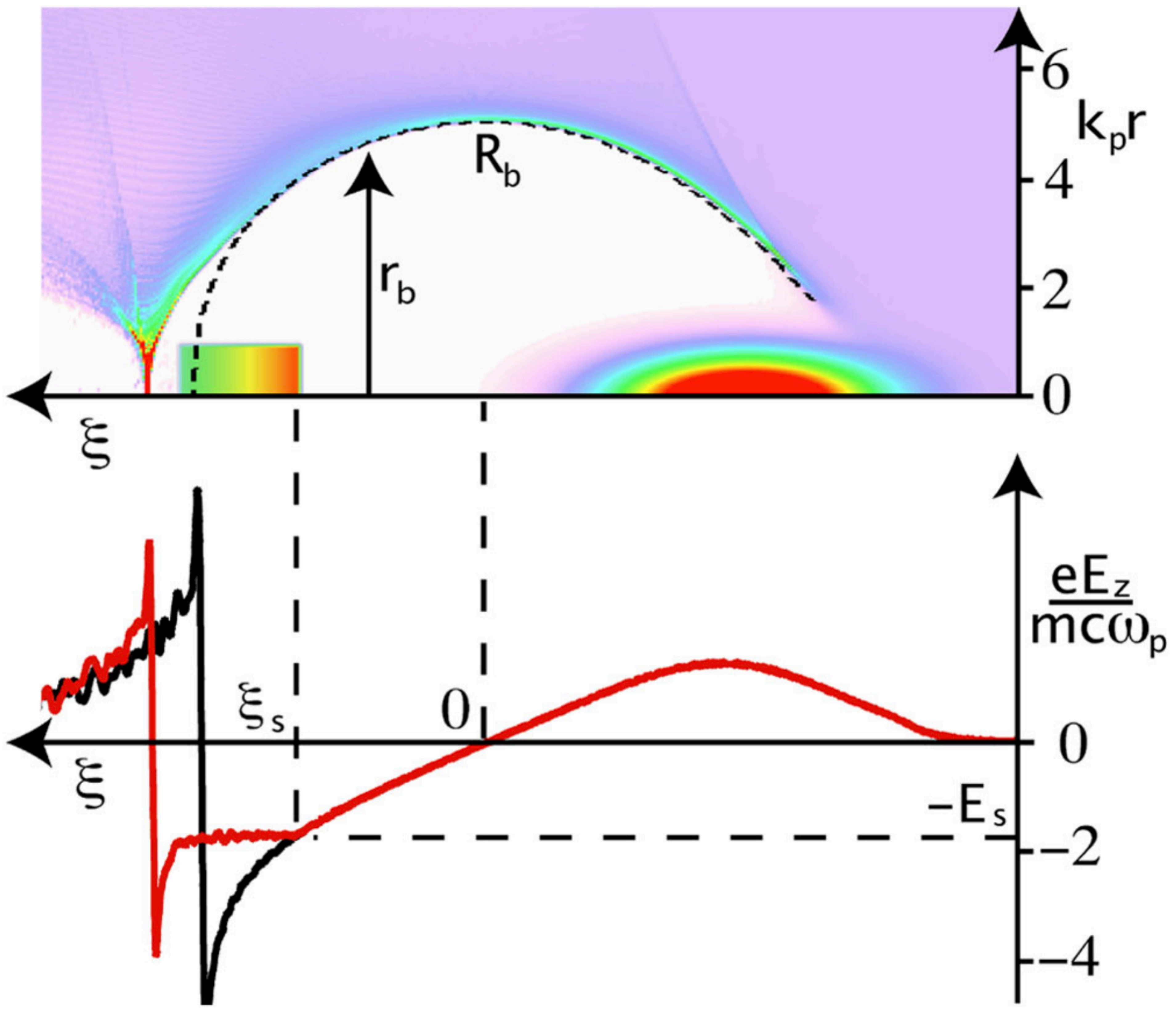
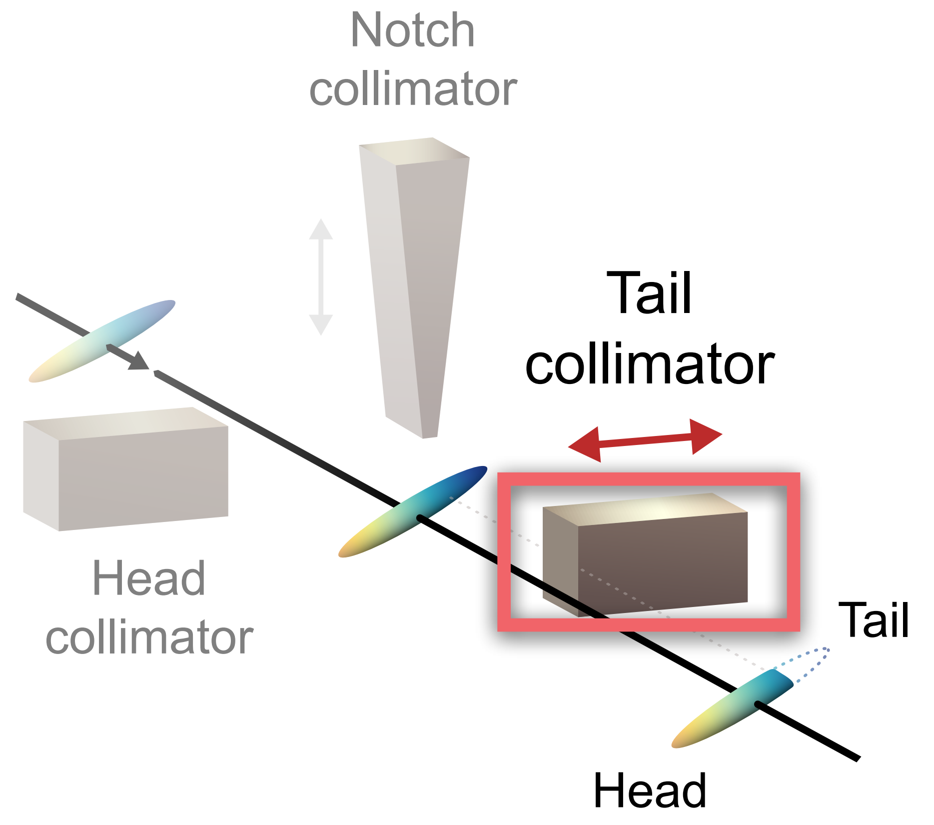


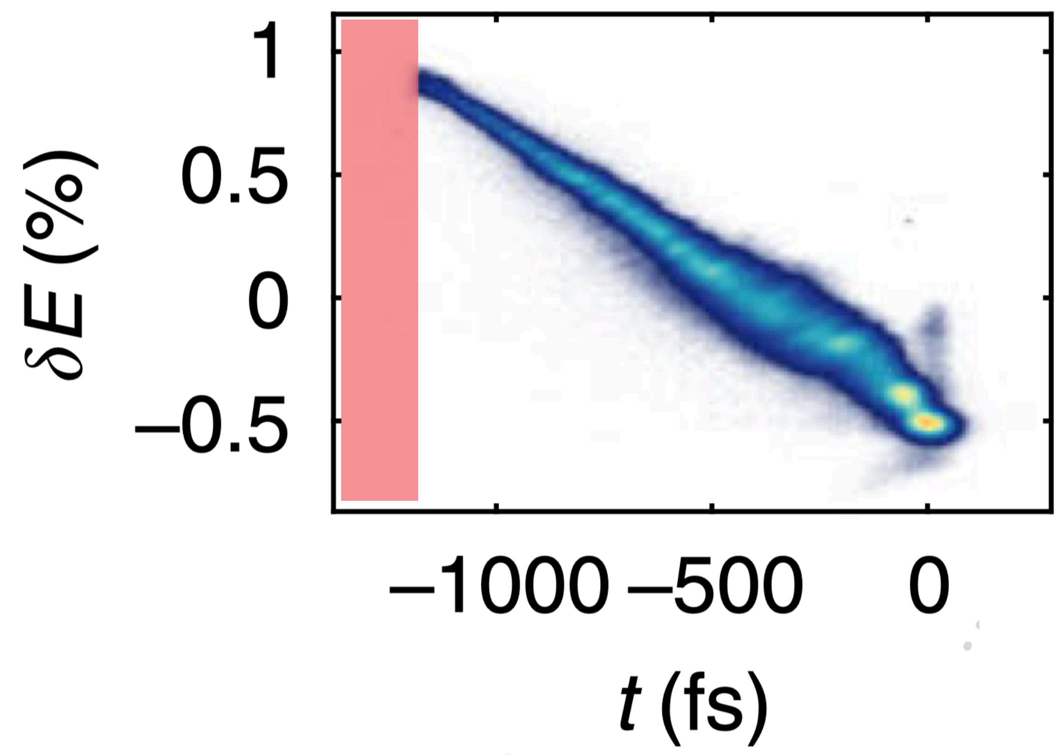
Image credit: M. Tzoufras *et al.*, Phys. Rev. Lett. **101**, 145002 (2008)

High-resolution plasma wakefield sampling demonstrated

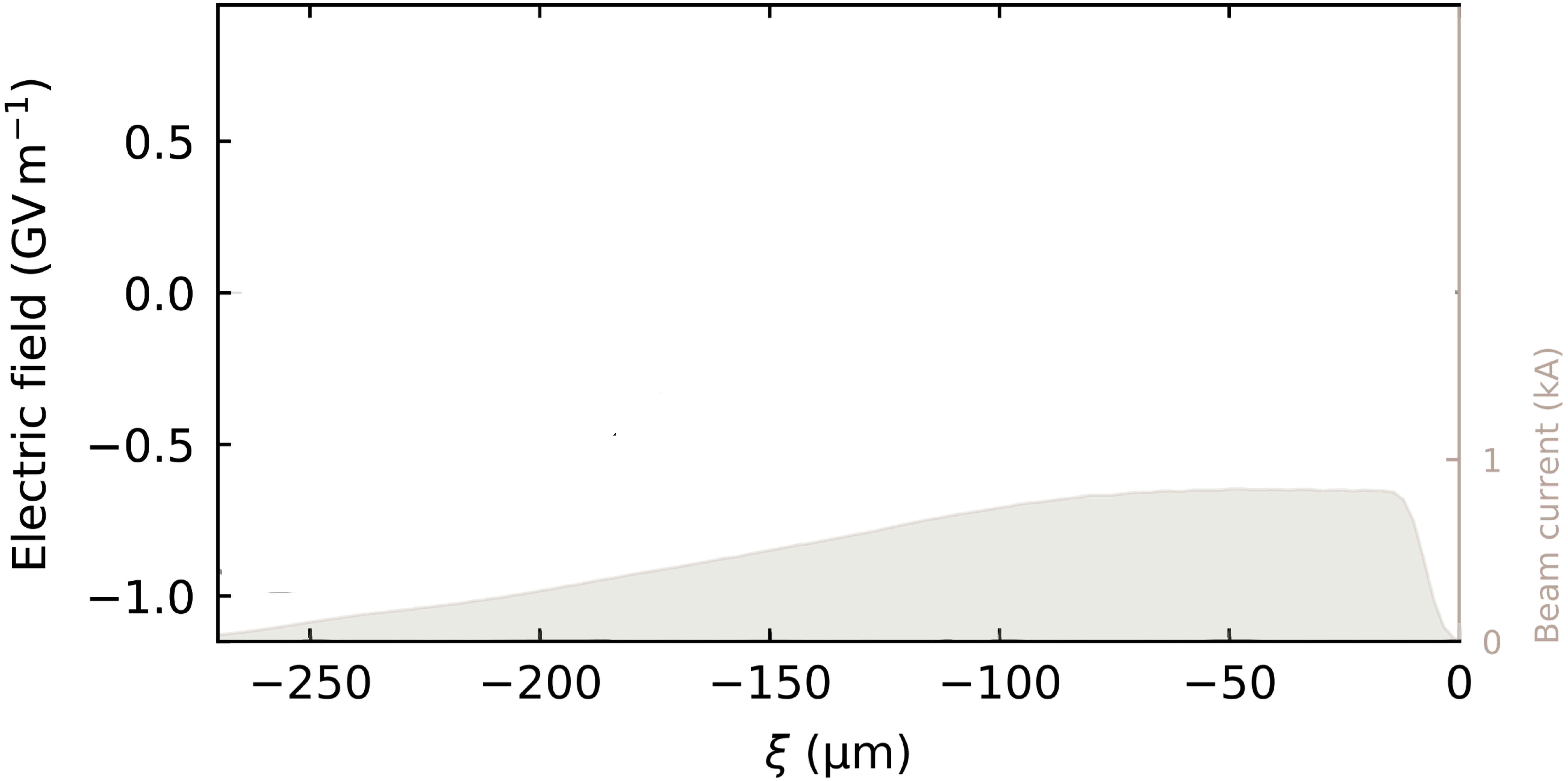
Opens a pathway to targeted and precise field manipulation

- **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)



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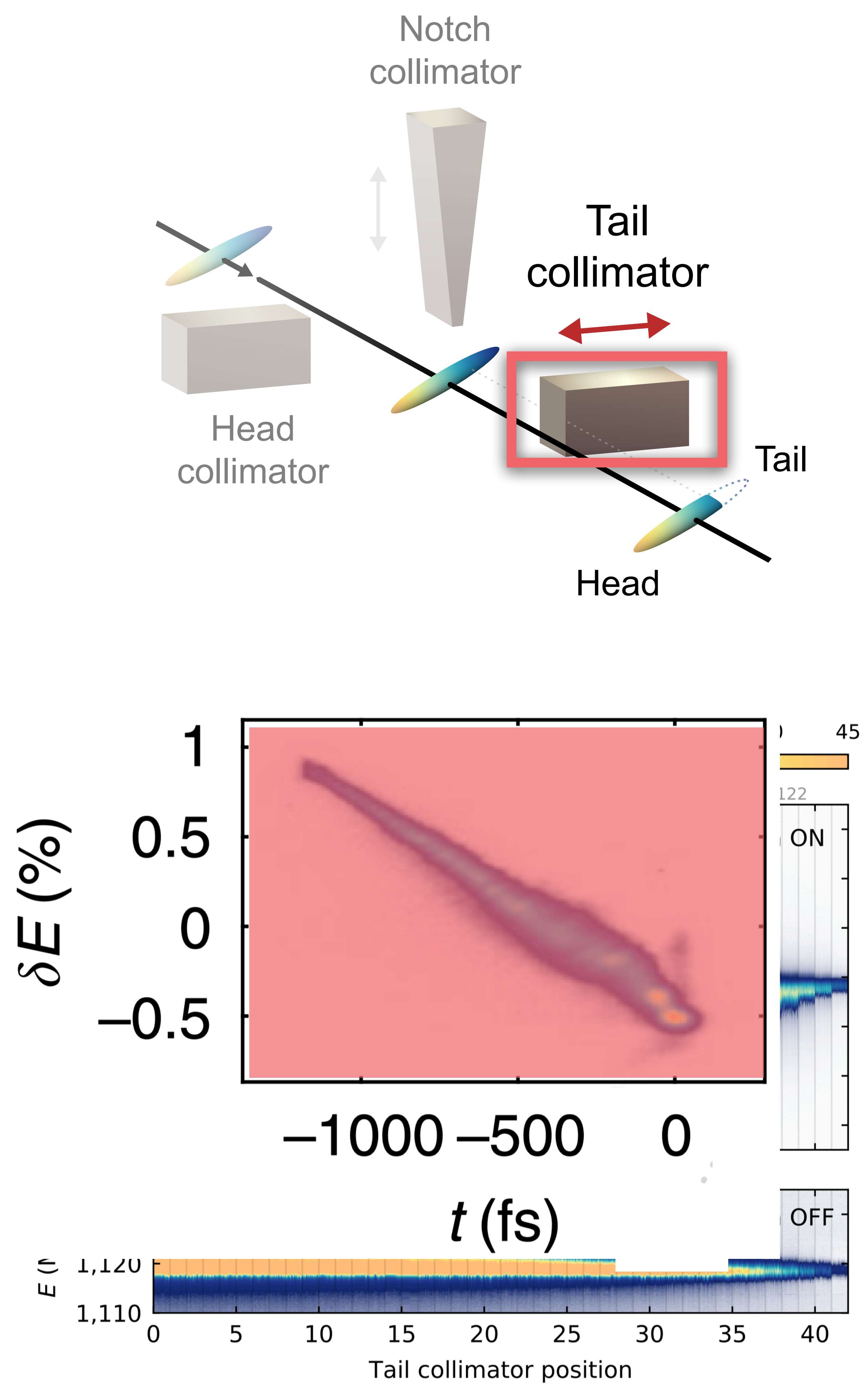

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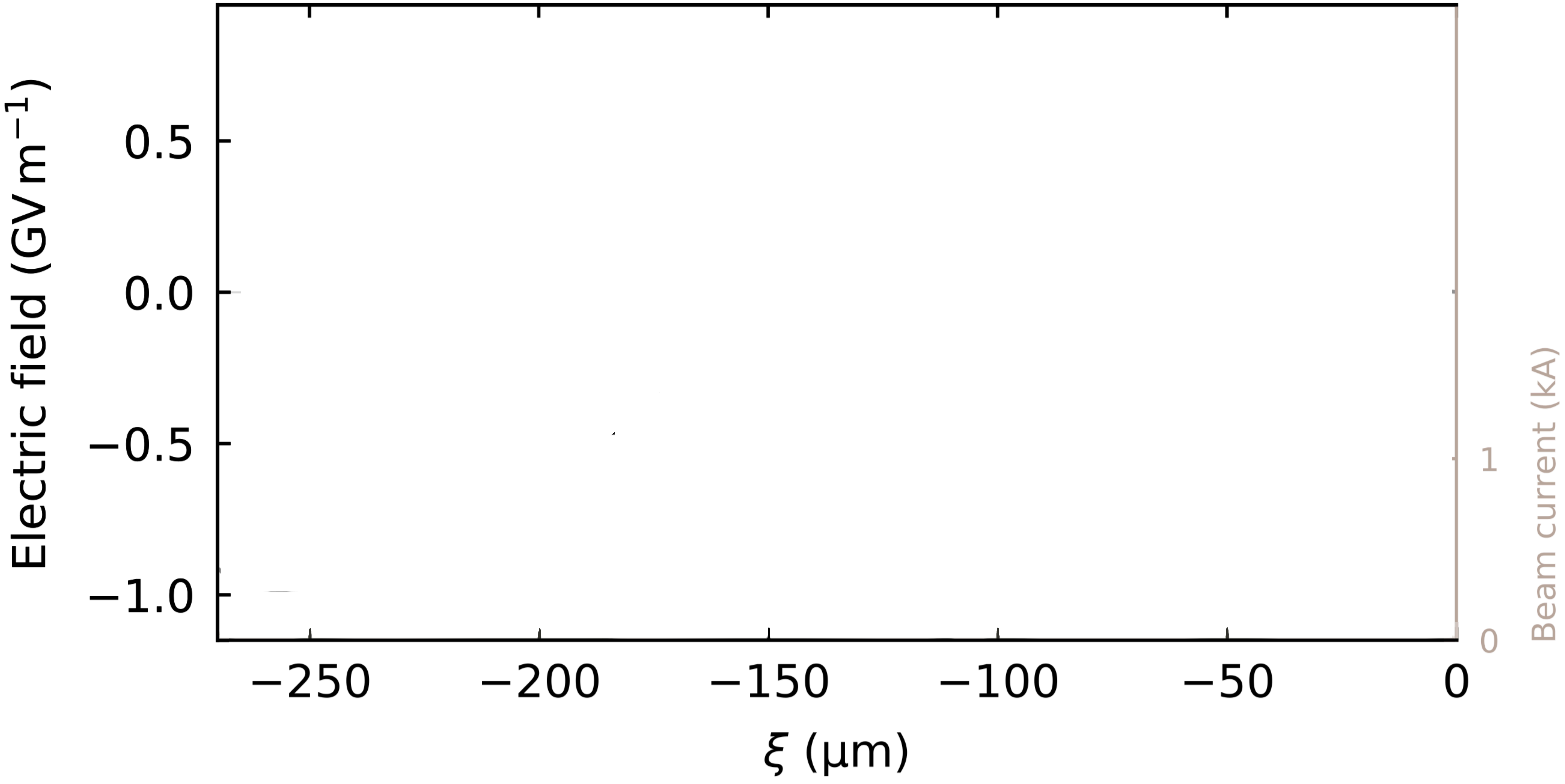
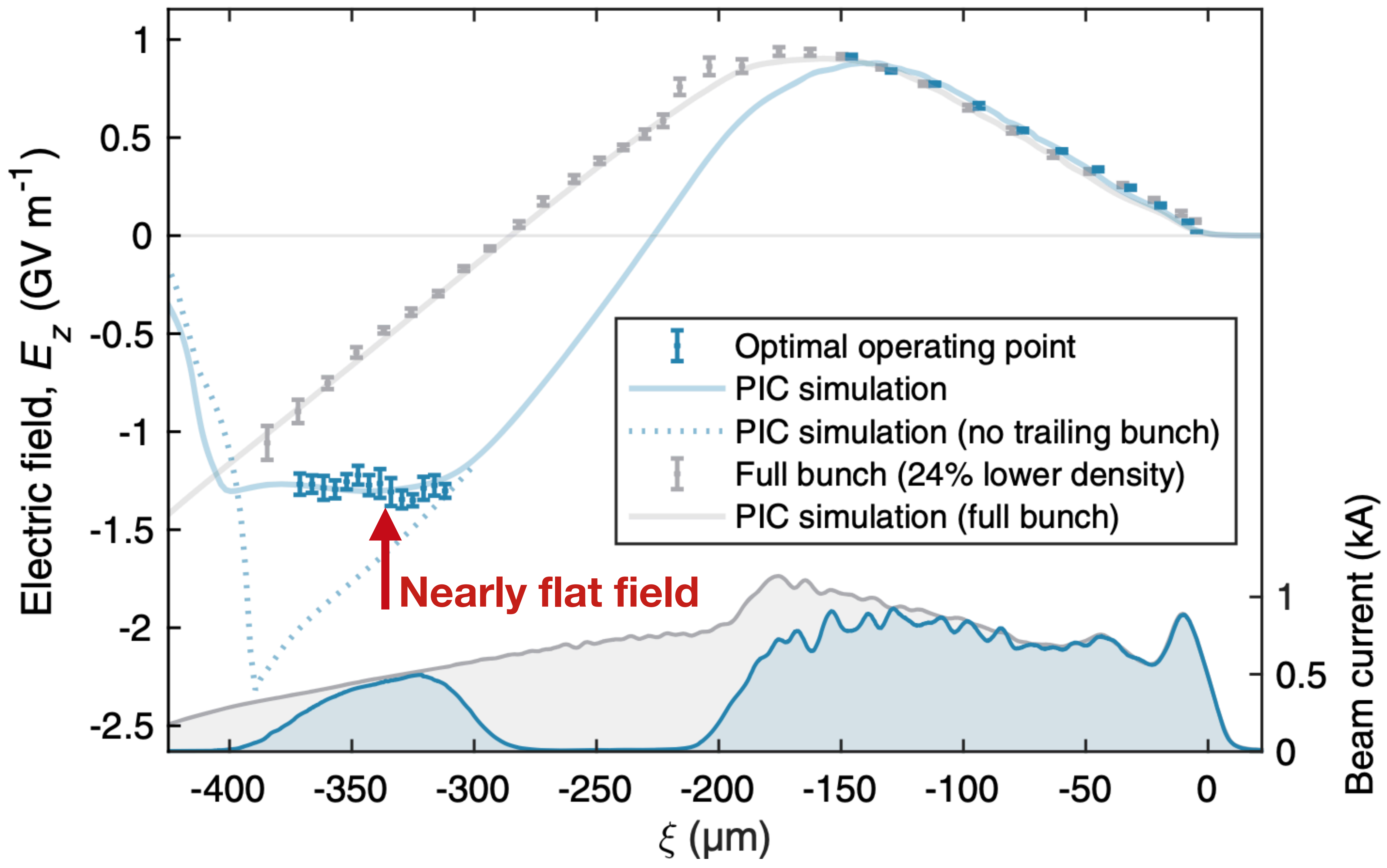


Loading the wakefield and beam shaping flattens the gradient

Direct visualization of electric-field control by wakefield sampling

C.A. Lindstrøm *et al.*, PRL **126, 014801** (2021)



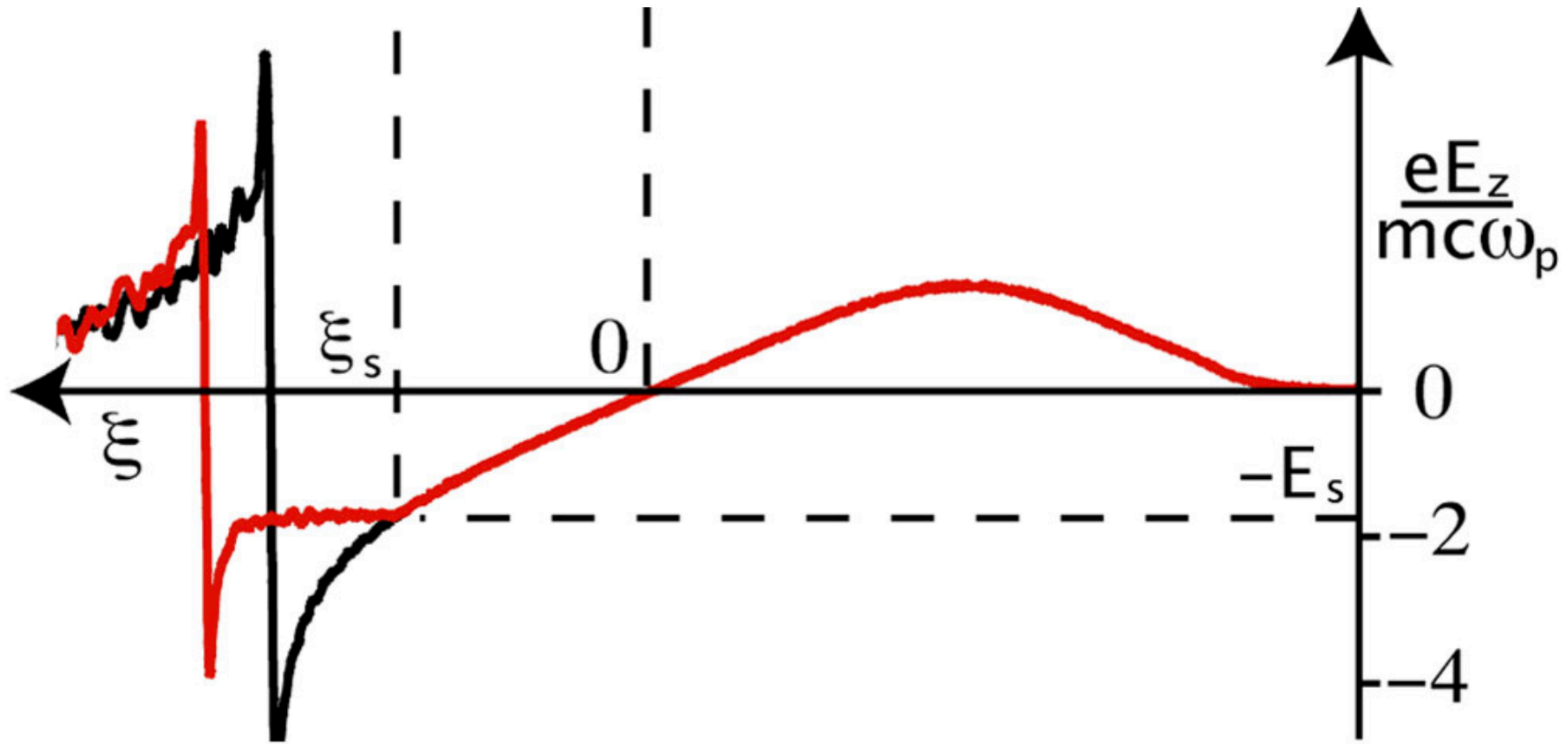


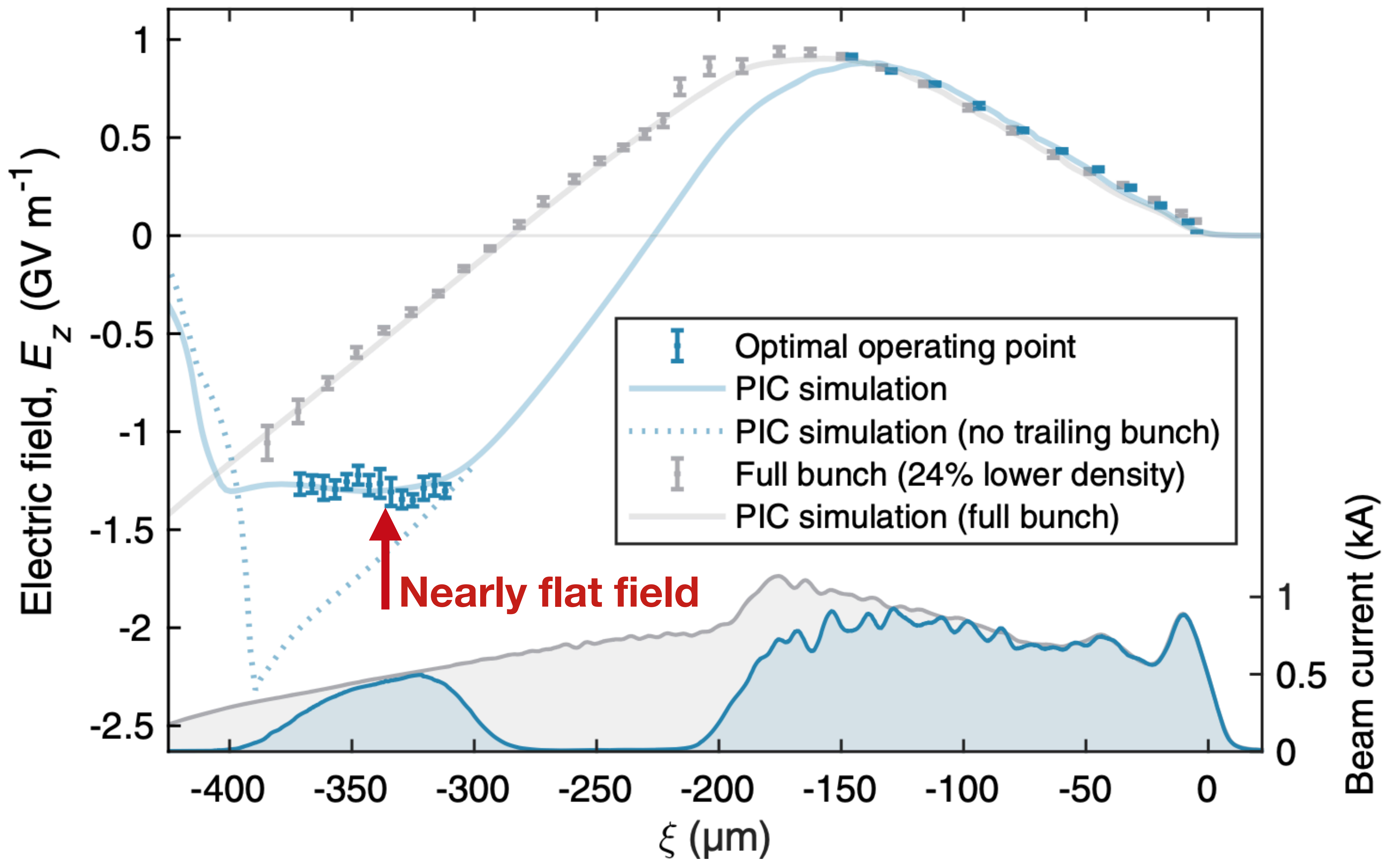
Image credit: M. Tzoufras *et al.*, Phys. Rev. Lett. **101**, 145002 (2008)

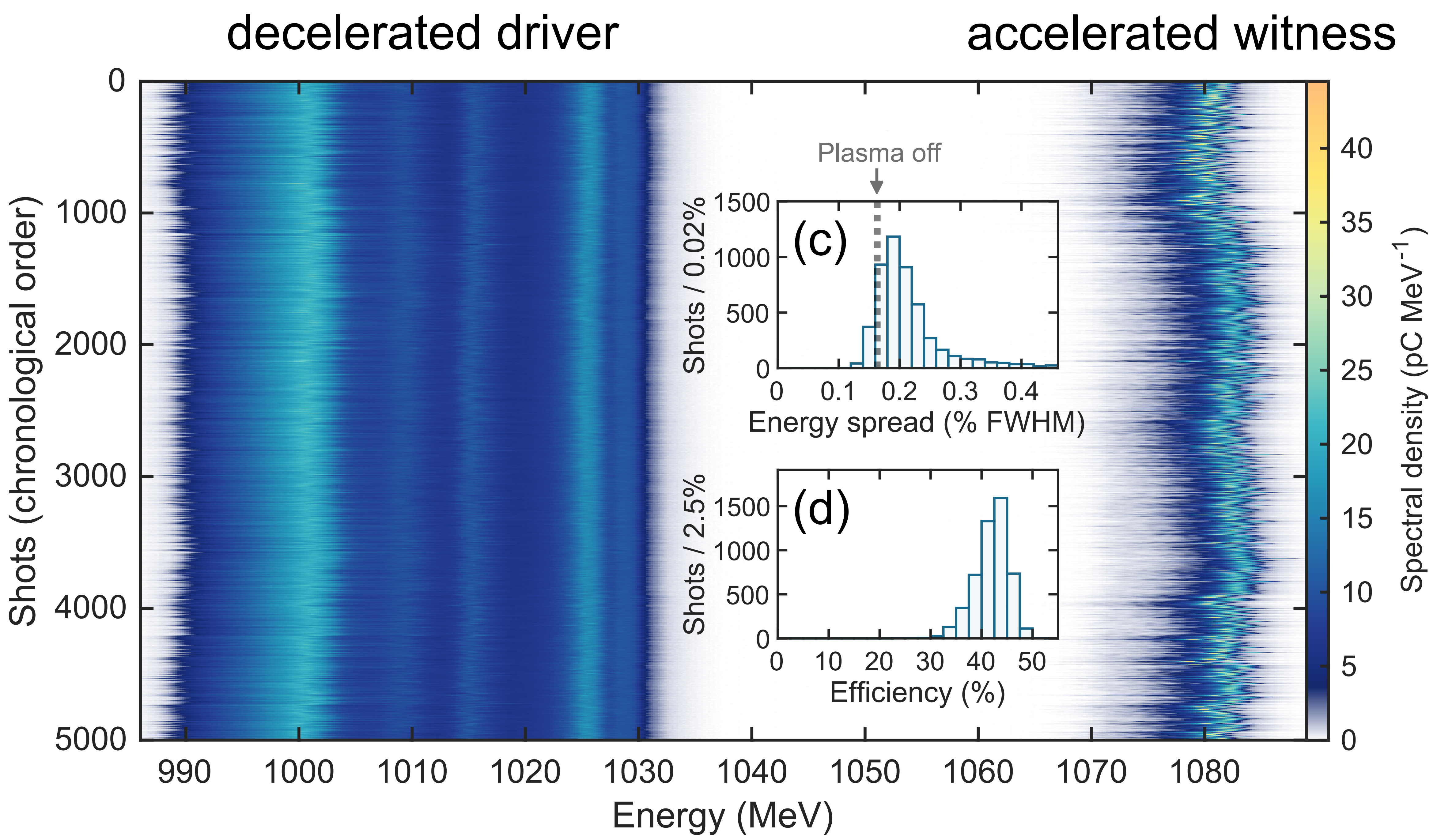
- Accelerating **gradient of 1.3 GV/m**
- **No charge loss**
- Few-percent-level wakefield flattening

High-quality, efficient acceleration for sustainable applications

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

C.A. Lindstrøm *et al.*, PRL **126, 014801** (2021)





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- **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)

High repetition rate — How fast can we go?

- *Problem 3:* Future colliders require at least kHz operation with FELs demanding up to MHz — is this possible with plasma accelerators?
    - Once the first oscillation is utilised, what happens to the perturbed plasma? For how long does it live?
    - The time it takes to recover places the most fundamental limit on repetition rate

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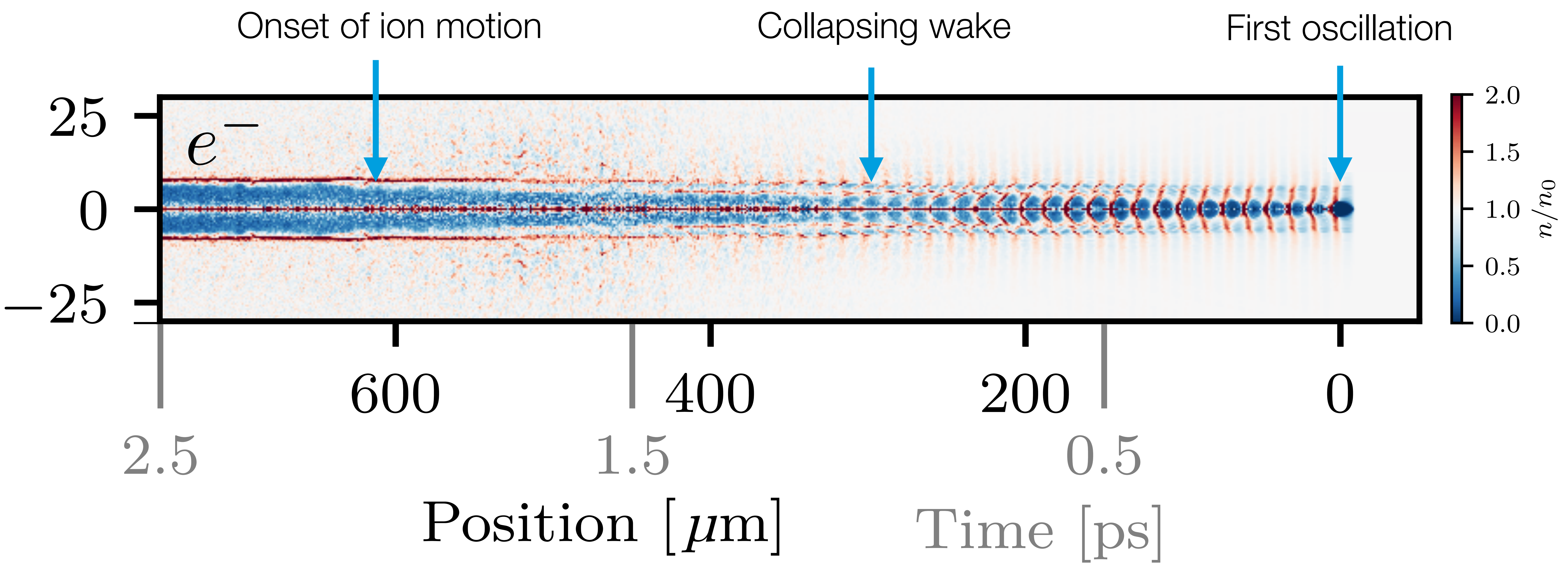

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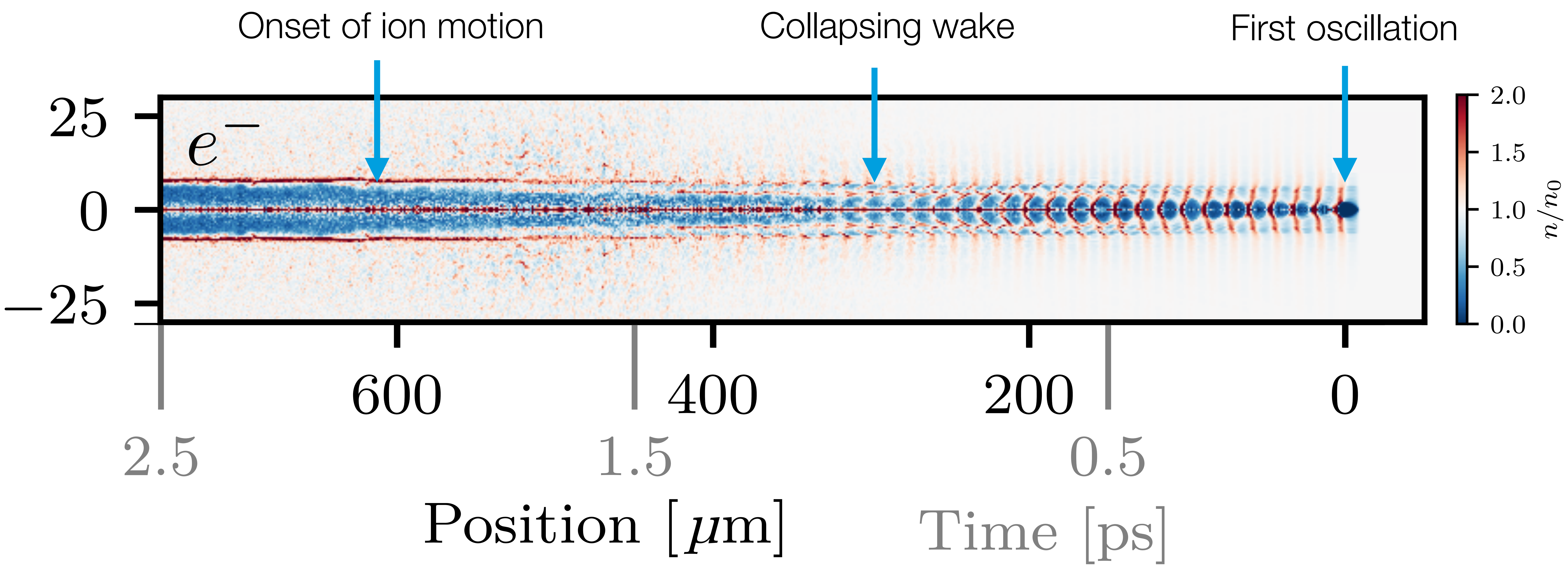
  > Once the first oscillation is utilised, what happens to the perturbed plasma? For how long does it live?
  > The time it takes to recover places the most fundamental limit on repetition rate
  > *Solution:* Experimentally map the recovery process of the plasma
  A new diagnostic technique based on the plasma-wakefield process is used to define the maximum inter-bunch repetition rate



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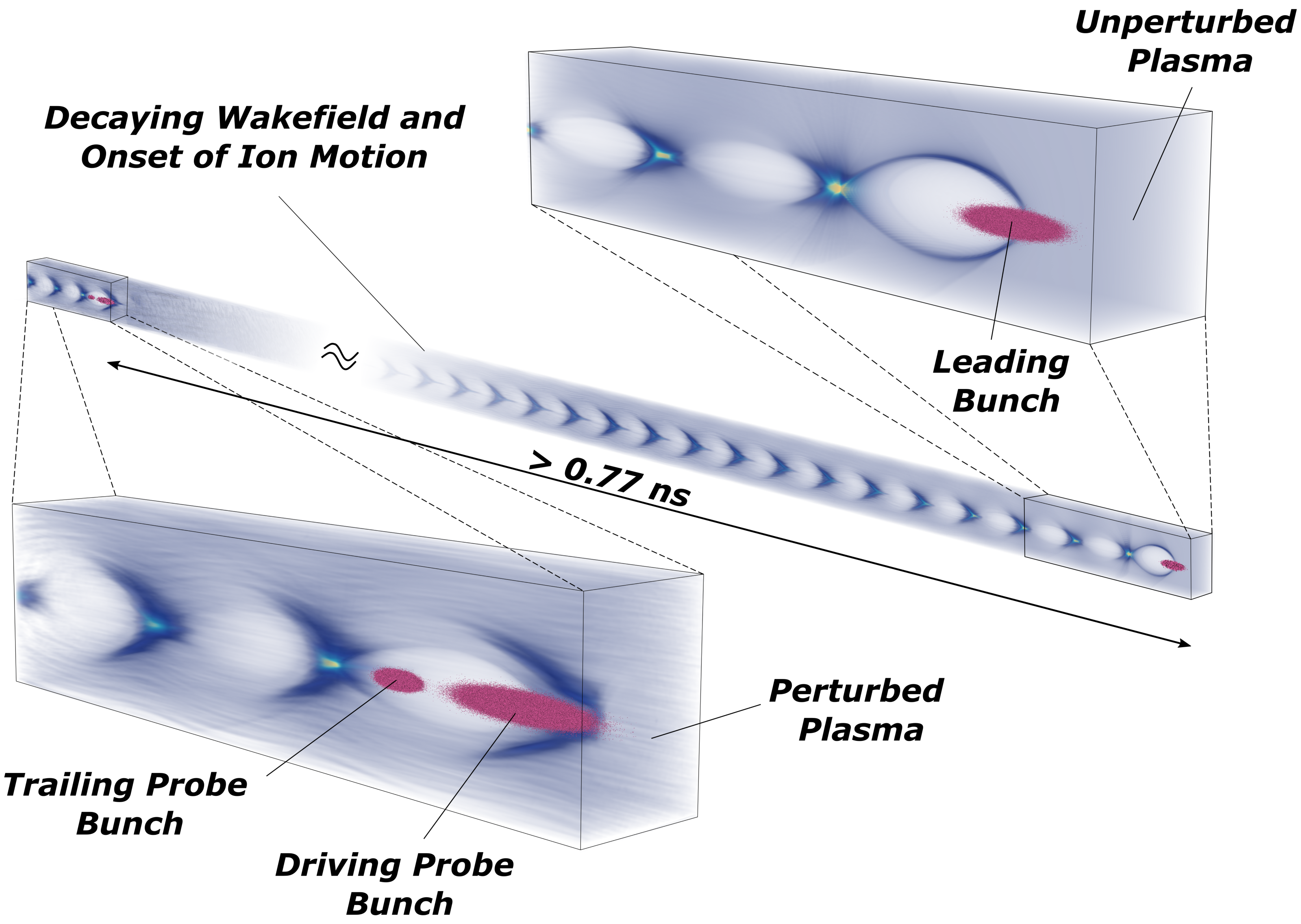
The recovery time of a plasma-wakefield accelerator

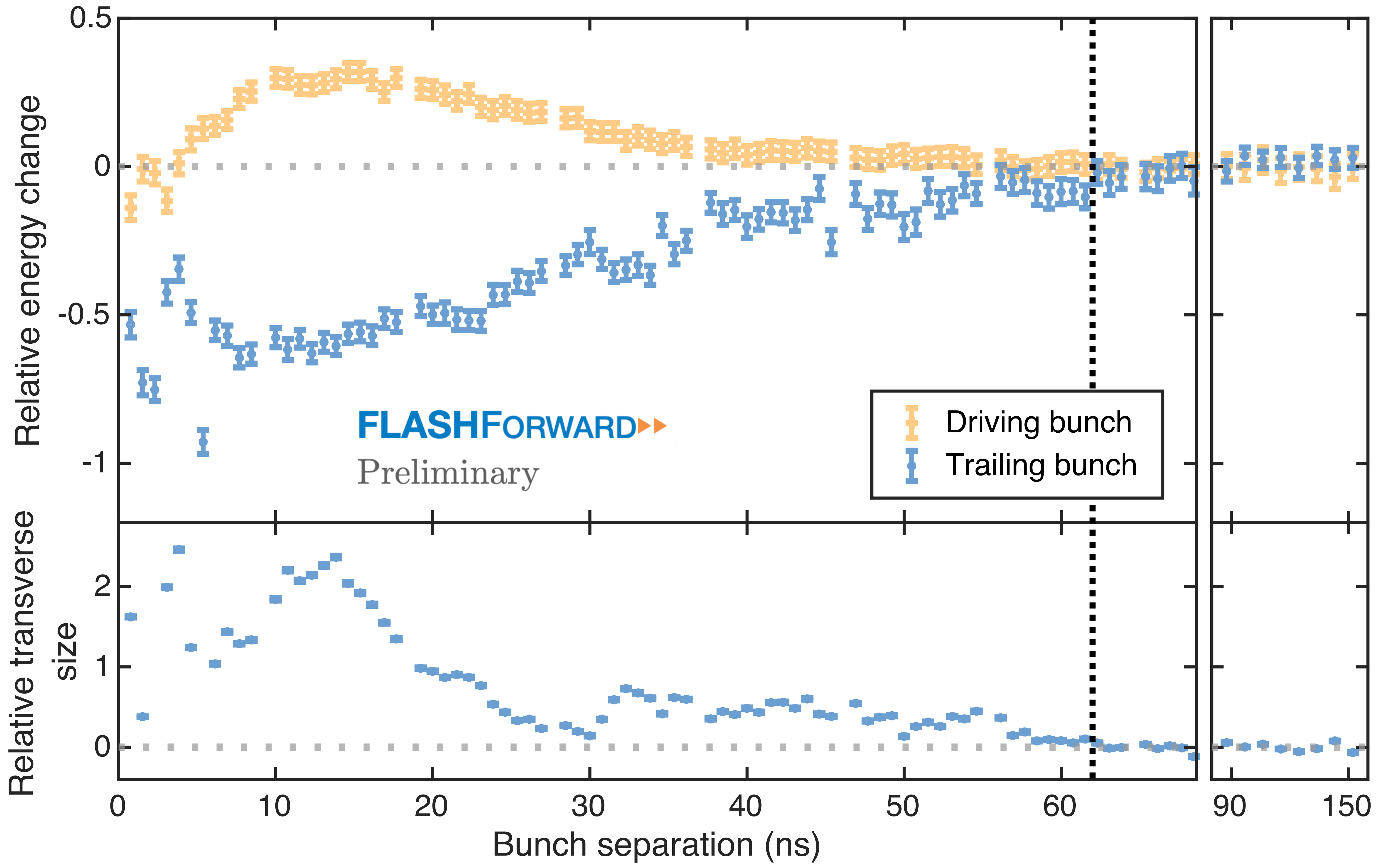


- A leading bunch perturbs the plasma by driving a wake
- A second probe-bunch pair arrives >0.77 ns behind the leading bunch and samples the plasma at that point in time
- The nature of the plasma can be inferred from the probe-bunch properties after driving its own wake
- The delay of the probe bunch can be changed in order to map out the evolution
- Analogous to pump-probe methodology in photon science

The recovery time of a plasma-wakefield accelerator

- ***All residuals consistent with zero at 63 ns***
- Separations extended up to 160 ns
- Bunch properties remain consistent over this time
- ***Equivalent to a repetition-rate upper limit of O(10 MHz)***

R. D'Arcy *et al.*, under review



Progress in Plasma-Accelerator 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

- ☑ Recovery time
- ☐ High repetition rate

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