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

Richard D’Arcy

FLASHFORWARD▸▸ Project Coordinator | Group Leader for Beam-Driven Plasma Accelerators

DESY. Accelerator Division

91st DESY PRC Meeting

May 4th, 2021

HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Acknowledgements

FLASHForward▸▸ Scientific Team

Richard D'Arcy (Project Coordinator)
Stephan Wesch (Technical Coordinator)
Judita Beinortaite
Jonas Björkland Svensson
Simon Bohlen
Lewis Boulton
James Chappell
Jimmy Garland (PI)
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Felipe Peña Asmus
Kris Põder
Adam Scaachi
Sarah Schröder
Bridget Sheeran
Jon Wood (PI)

Theory group

Maxence Thévenet
Gregory Boyle
Severin Diederichs
Mathis Mewes

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

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FLA
↓
MPA
FTX

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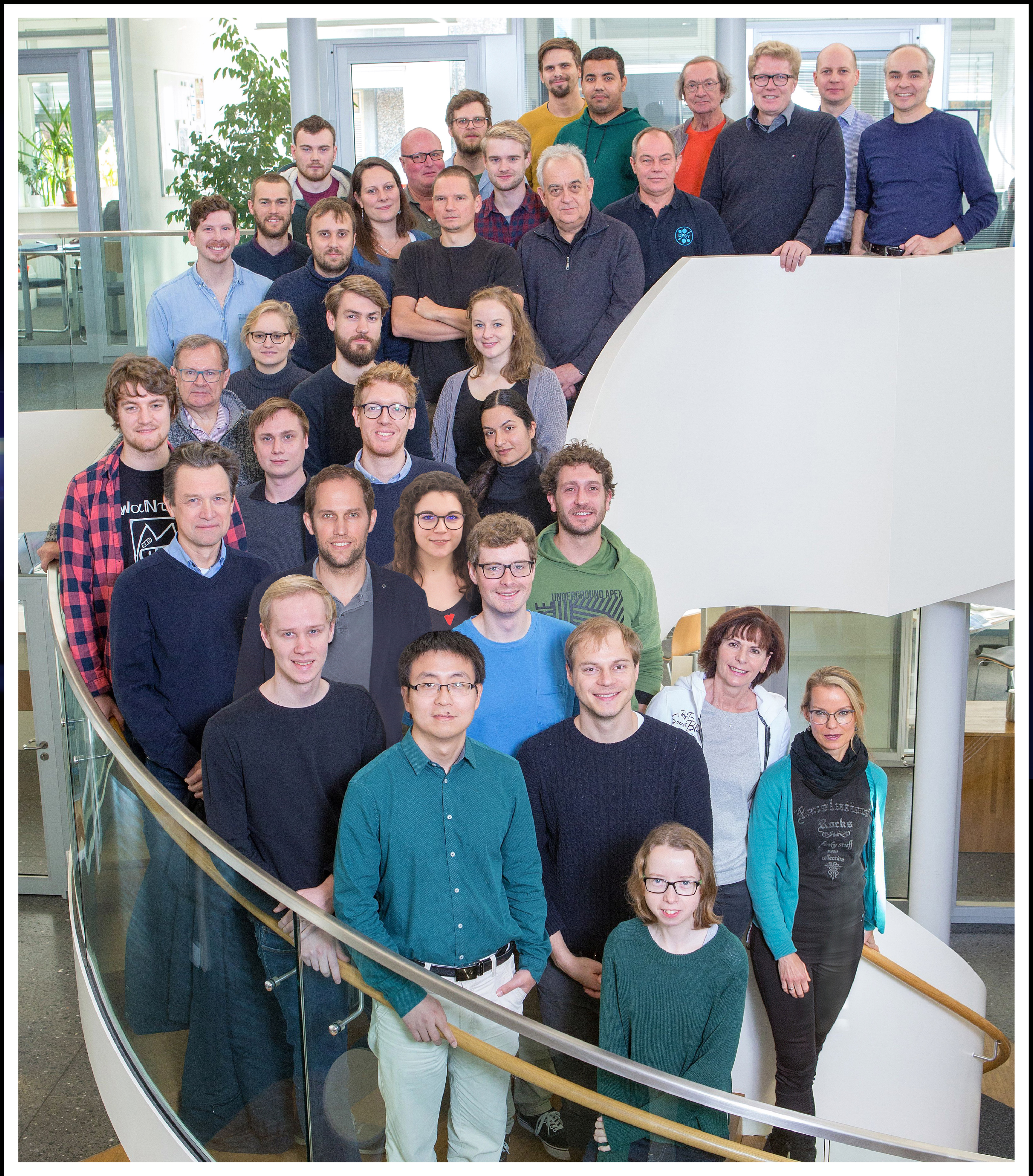

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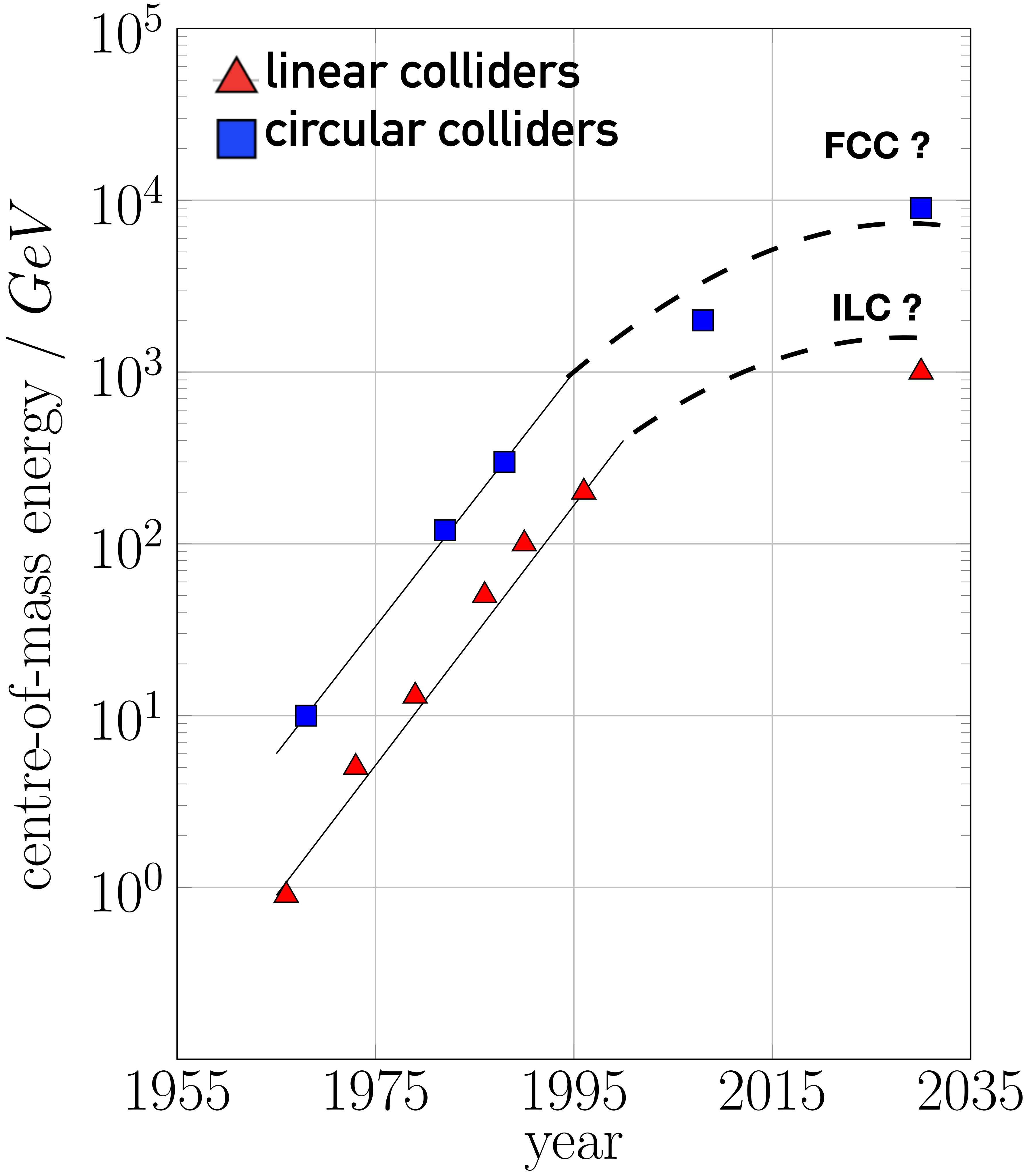
Limitations of current accelerator technology

(Superconducting) Radio-frequency cavity

Limited by electrical breakdown to $\mathcal{O}$(100 MV/m)



Limitations of current accelerator technology

(Superconducting) Radio-frequency cavity

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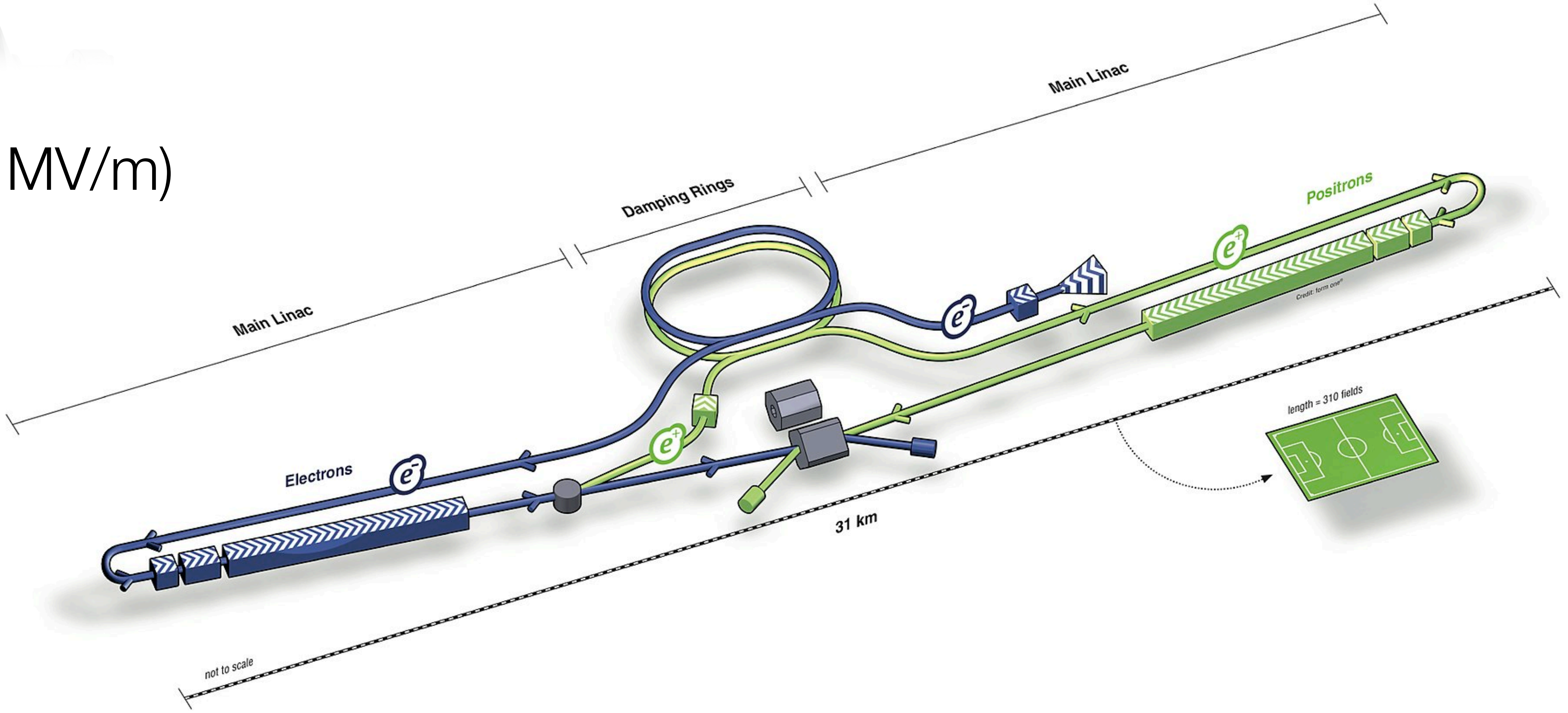
1 TeV e^+e^- collider example

→ tens of km of cavities

→ >10 billion euros

IS A PARADIGM SHIFT REQUIRED?




Plasma
source
Driver (laser or charged-particles)
Depleted driver
Witness
(electrons)
Accelerated witness
centimeter-scale
© Kyrre Ness Sjøbæk (2020)

Plasma accelerators are a centimeter-scale source of GeV beams

Plasma wakefields can sustain accelerating fields of up to **~1-100 GV/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)

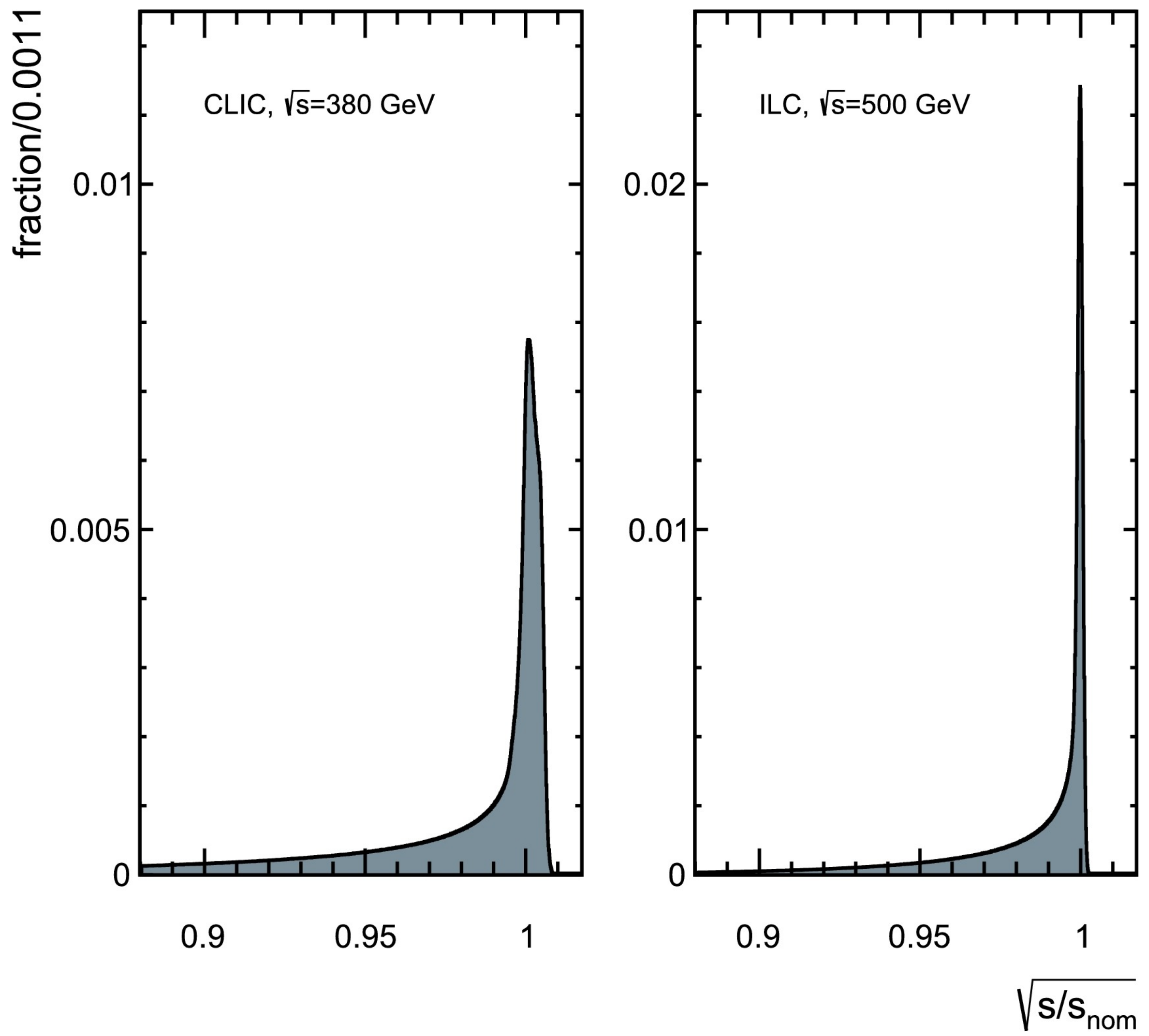
High repetition rate

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.

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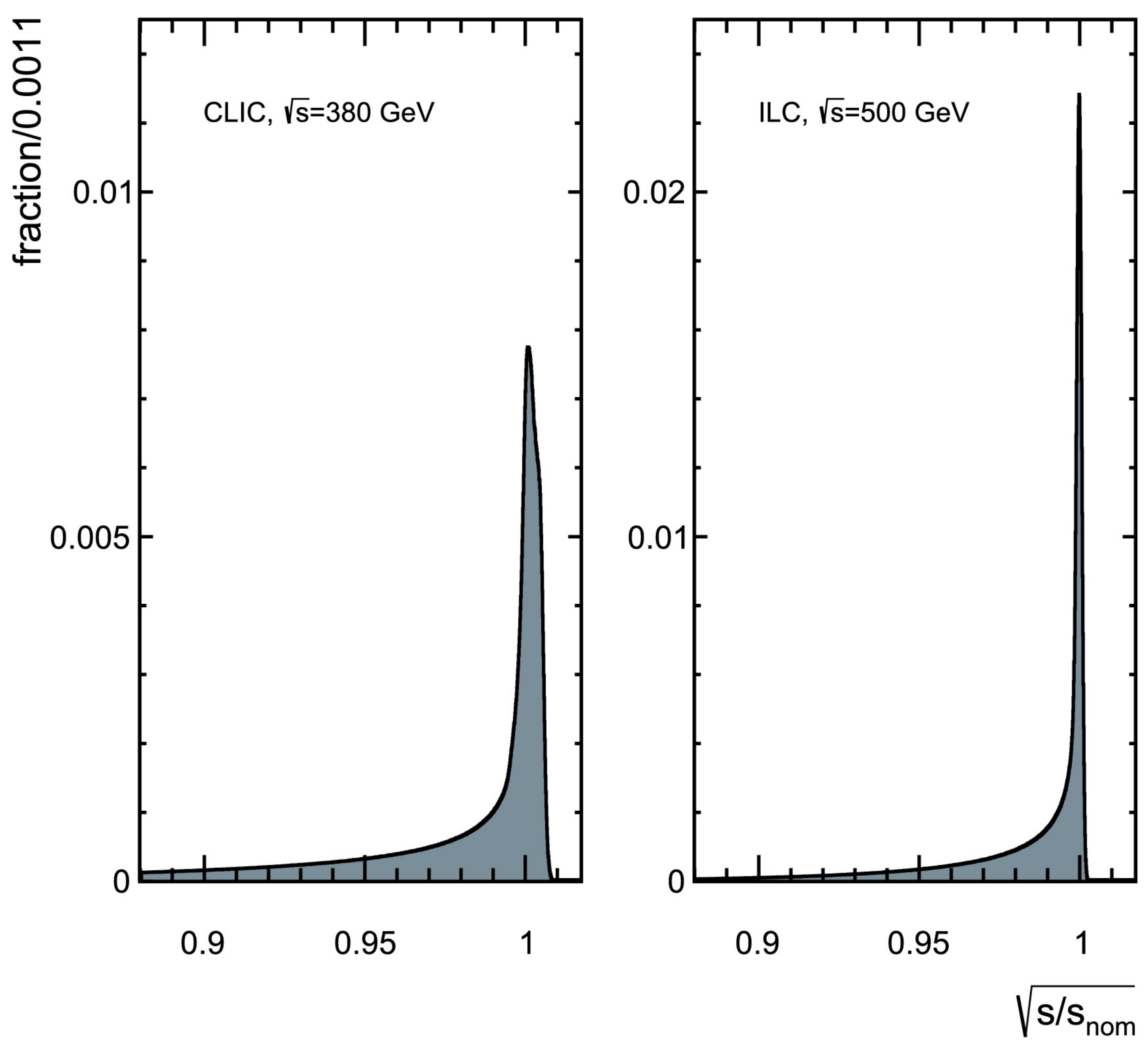

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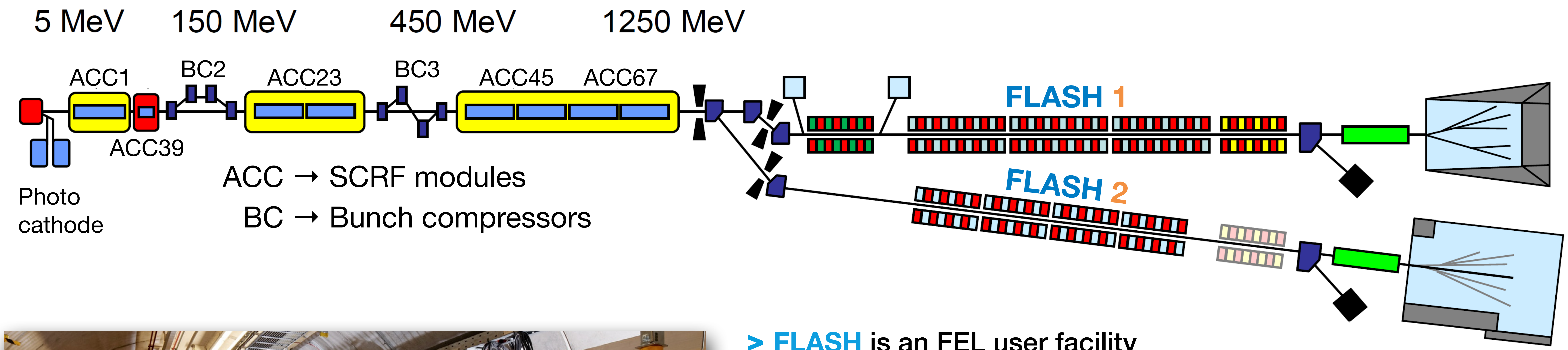
FLASHFORWARD▸▸

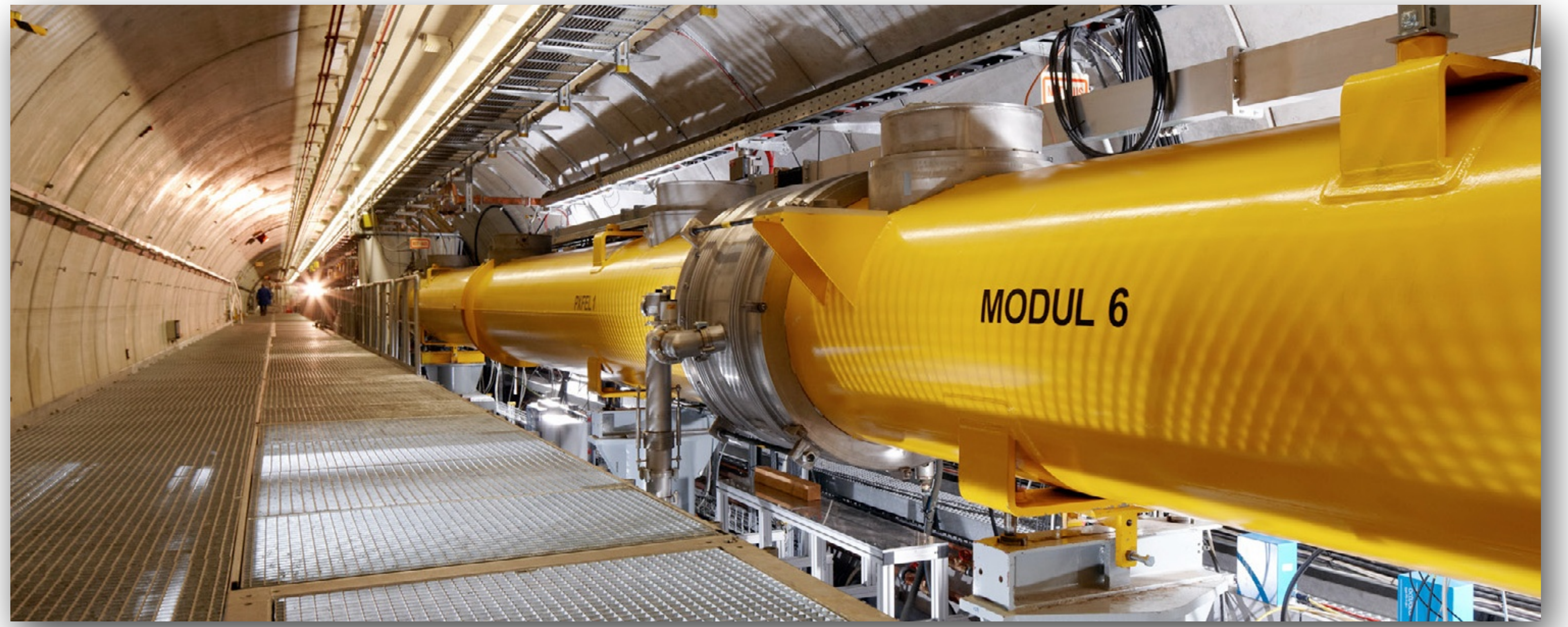
Develop a self-consistent plasma-accelerator stage
with high efficiency, high quality, and high average power

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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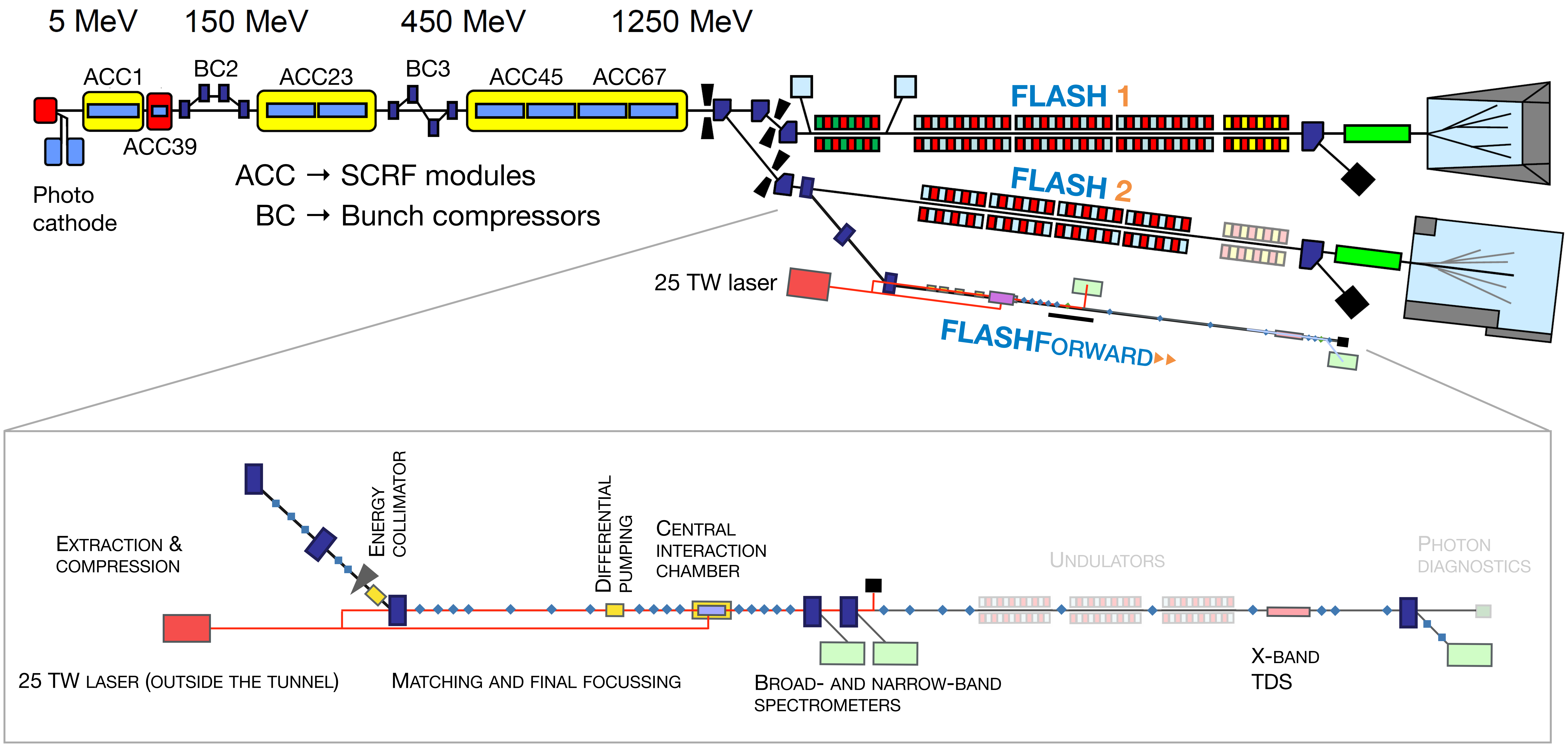
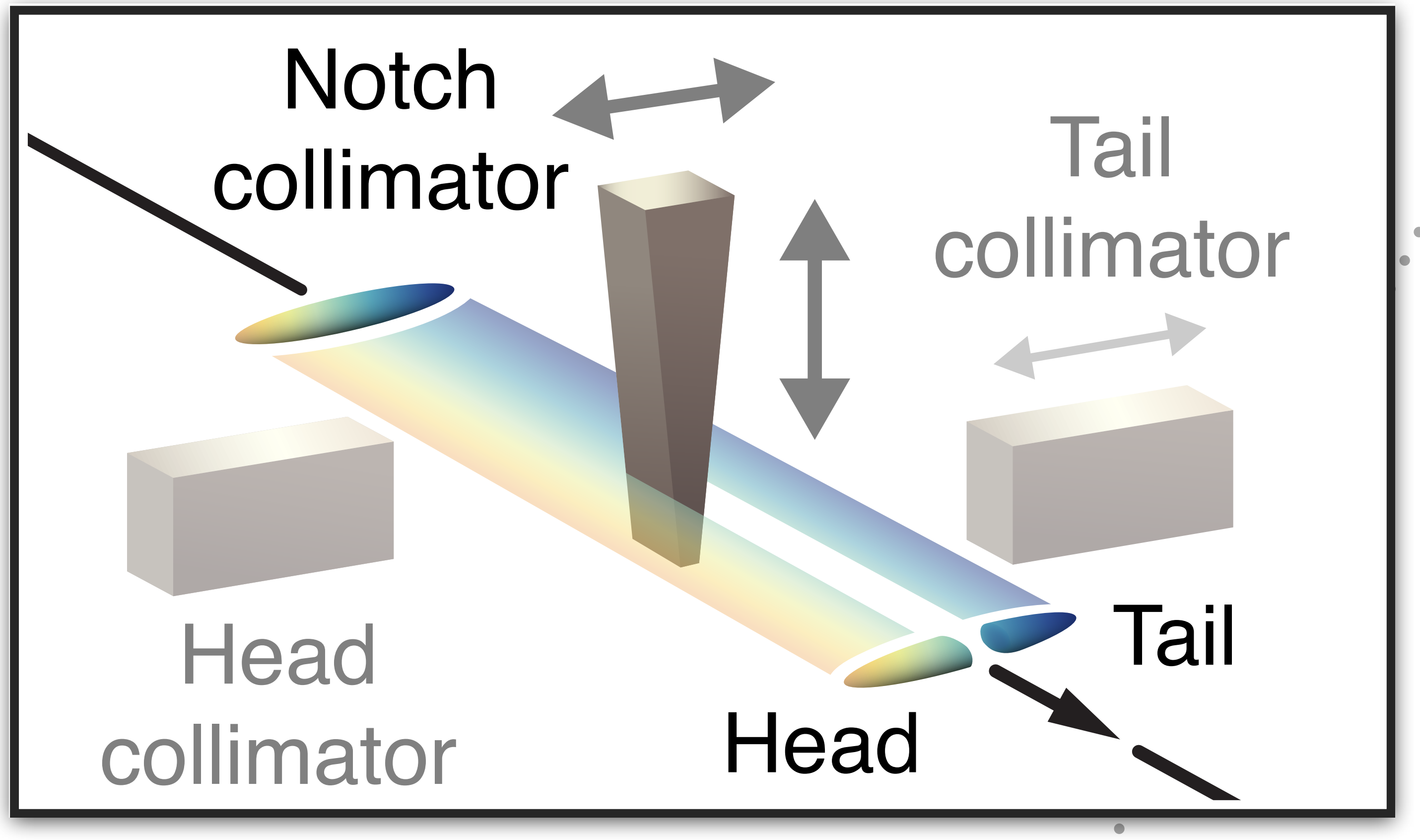
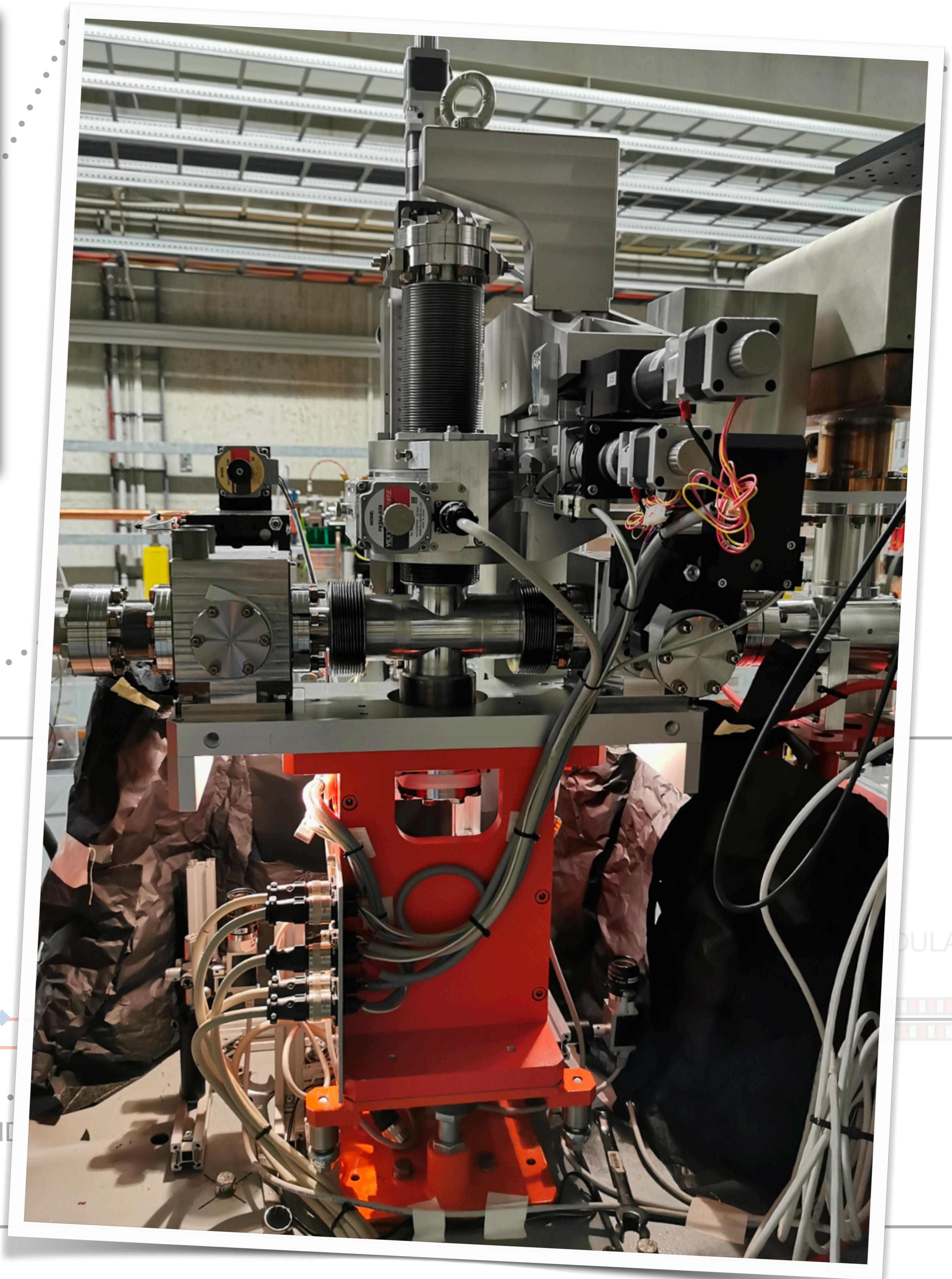


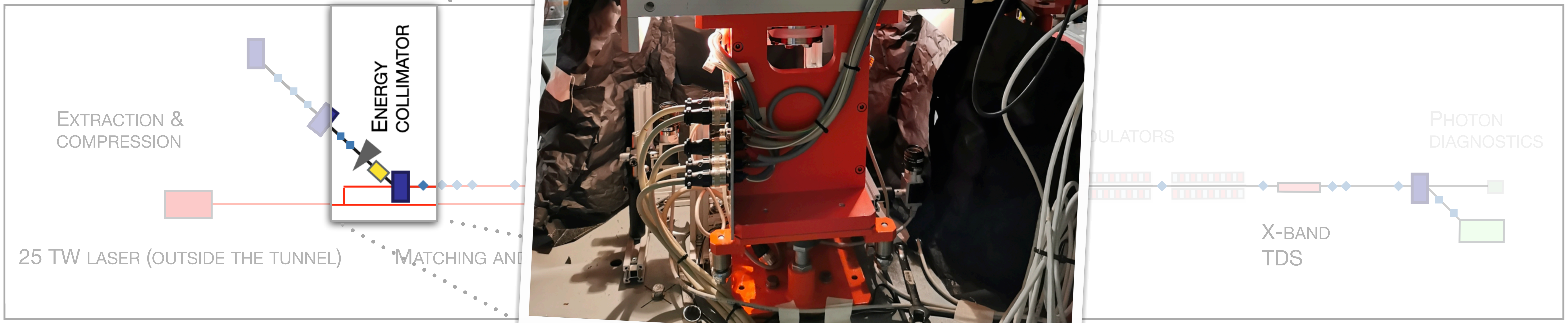
R. D'Arcy *et al.*, Phil. Trans. R. Soc. A **377**, 20180392 (2019)

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)

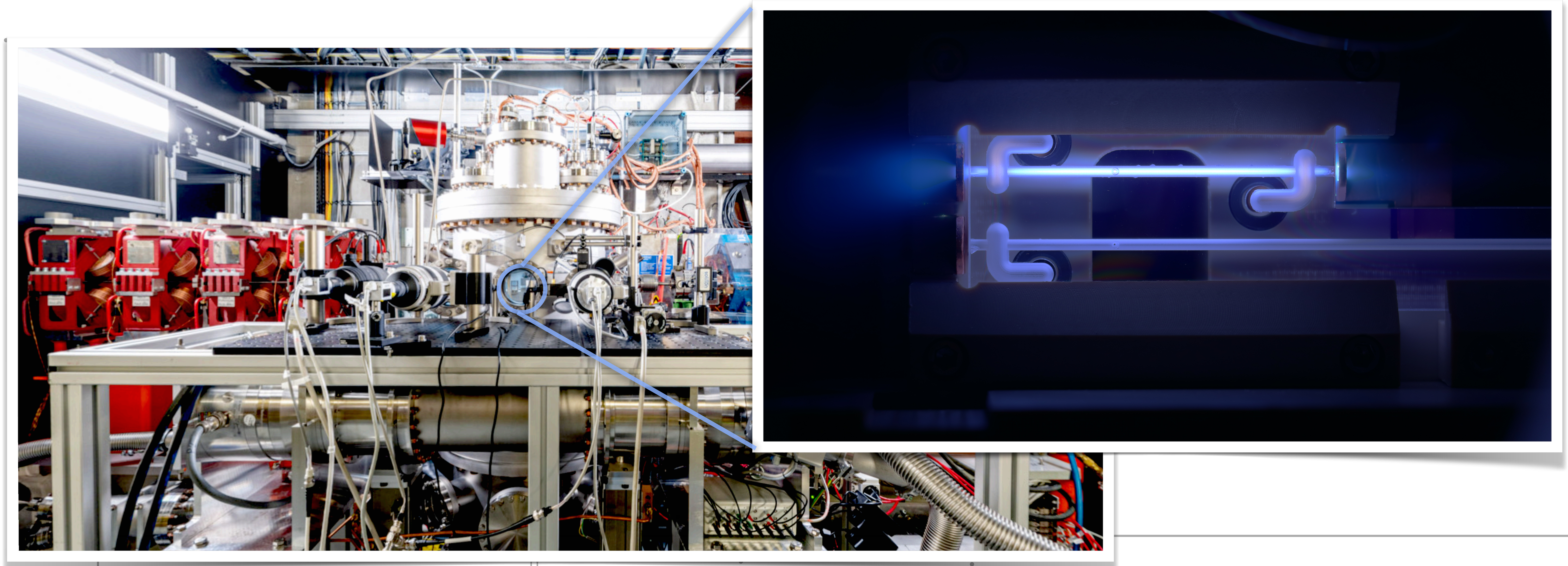
Three energy collimators:
(1) Tail (high energy)
(2) Head (low energy)
(3) Central notch (two bunches)

µm-precision movements

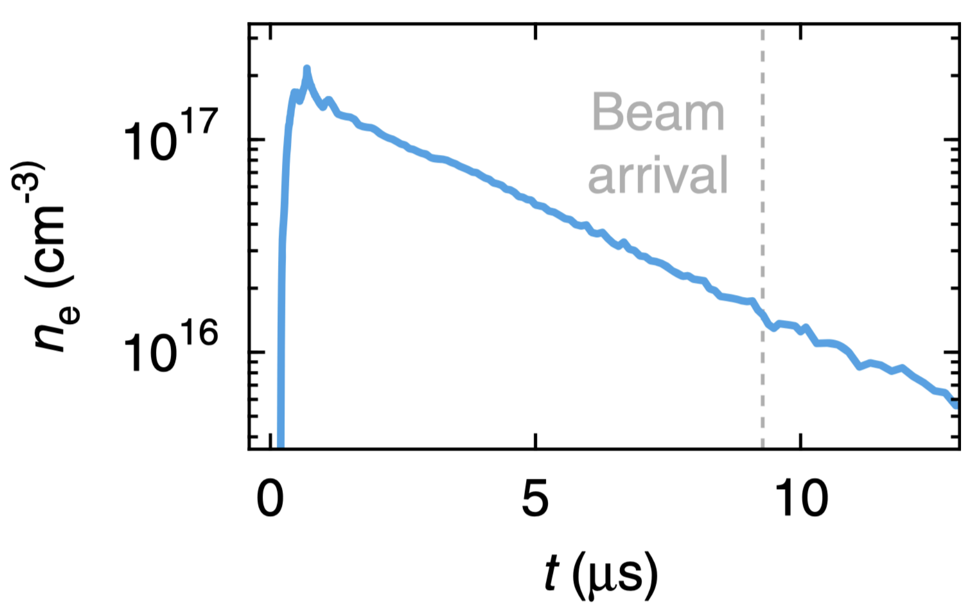
allows for precise bunch shaping (in conjunction with FLASH compressors and 3.9 GHz cavity)

Two discharge capillaries provide density-controlled plasma

FLASHForward▸▸ beamline features innovative components and methods



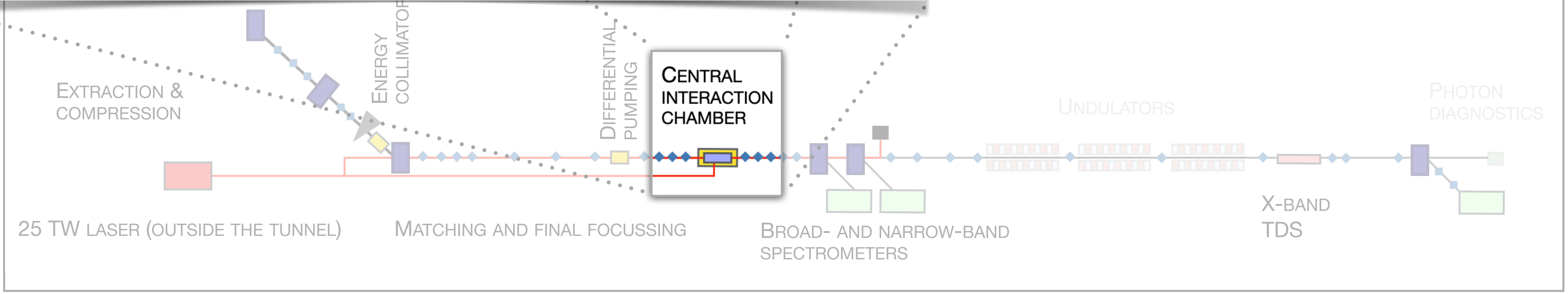
J.M. Garland *et al.*,
Rev. Sci. Instrum. **92** 013505 (2021)



High-voltage discharge

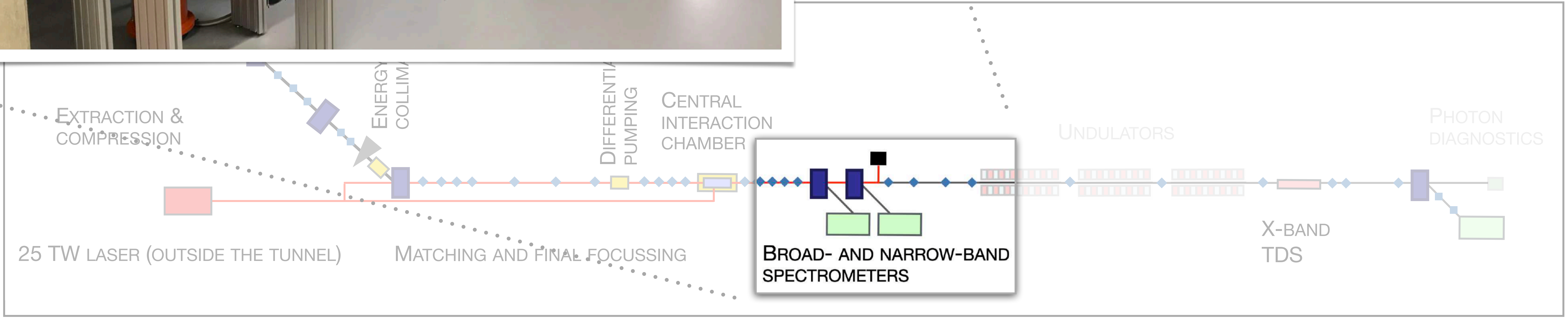
Sapphire capillaries
(50 mm and 195 mm long)

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



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

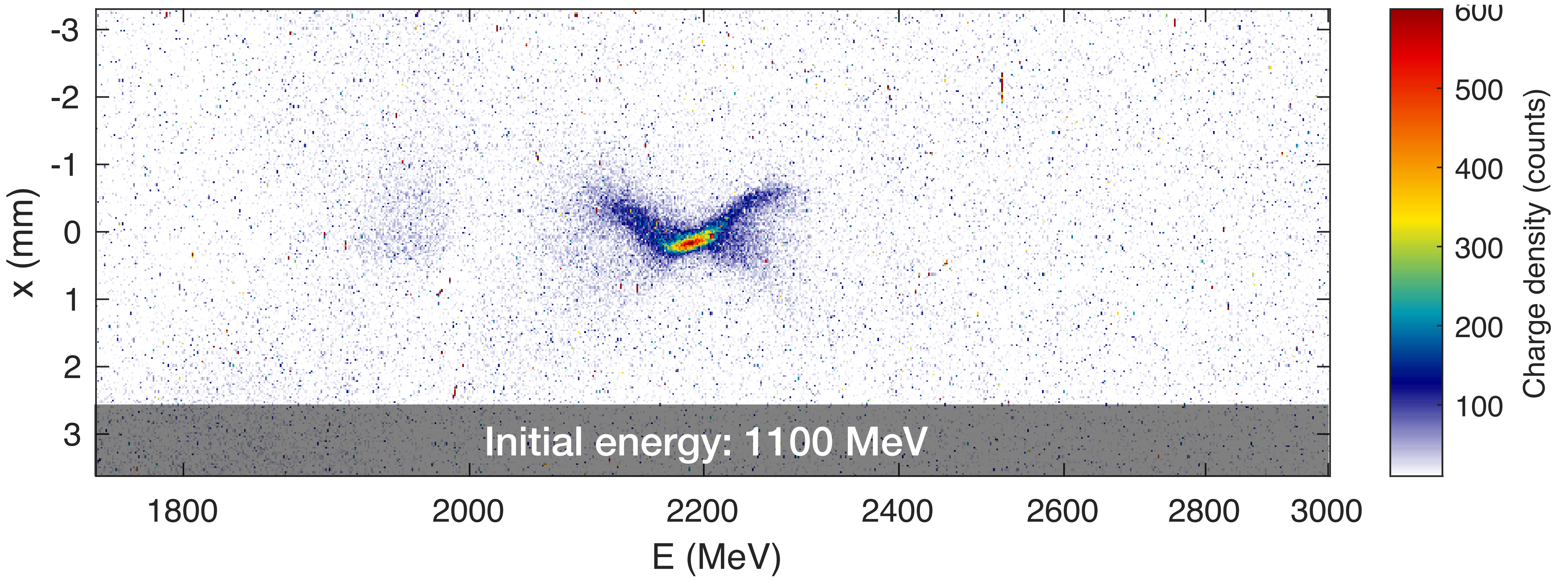
Low-resolution, broad-band screen for MeV—GeV energy range

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

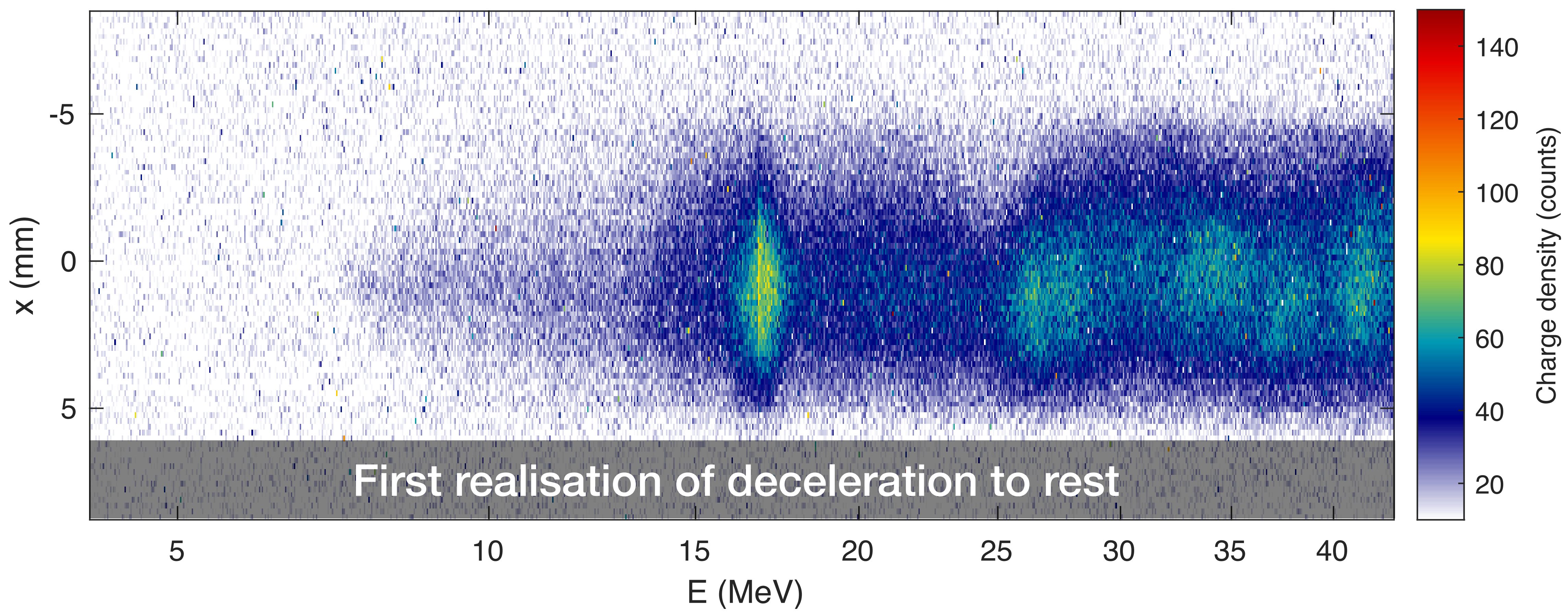
Plasma accelerator essentials — demonstrating 6 GV/m field strength

Taking plasma accelerator technology from ‘academia to application’ doesn’t end with high-gradient acceleration

Energy doubling to 2.2 GeV → plasma booster



Energy extraction → plasma beam dump



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

High repetition rate

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High efficiency	High beam quality	High average power
Transfer efficiency	**Energy-spread preservation**	High repetition rate
Driver depletion	Emittance preservation	

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.

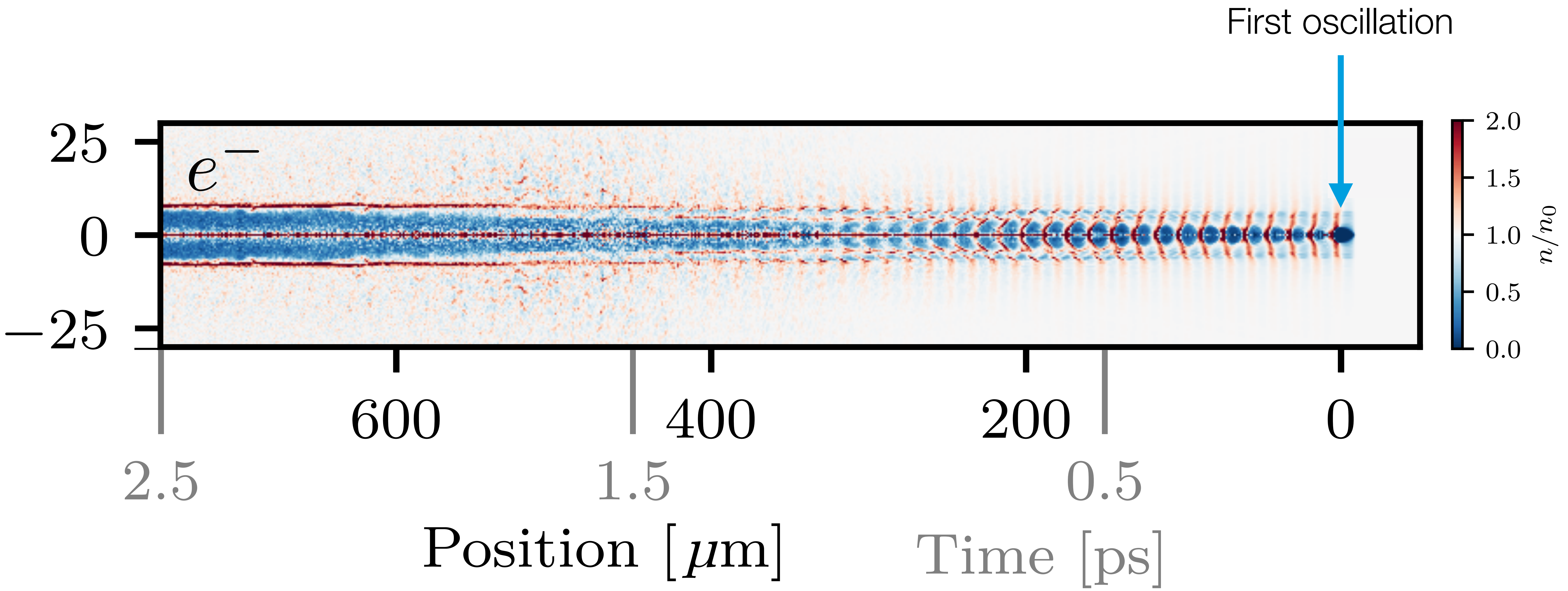

Image source: M. F. Gilljohann *et al.*, Phys. Rev. X **9**, 011046 (2019)

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

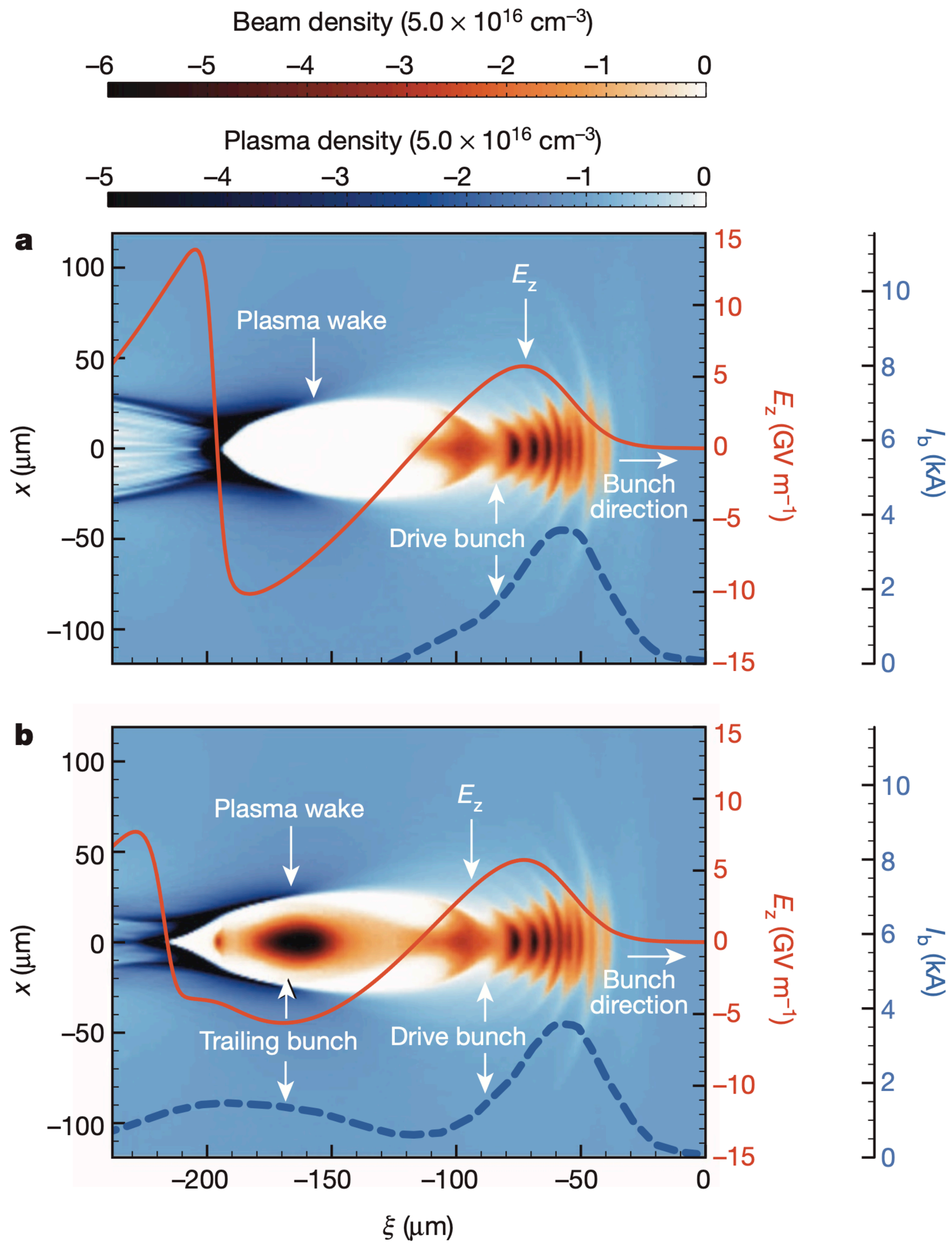

Image credit: M. Litos *et al.*, Nature **515**, 92 (2014)

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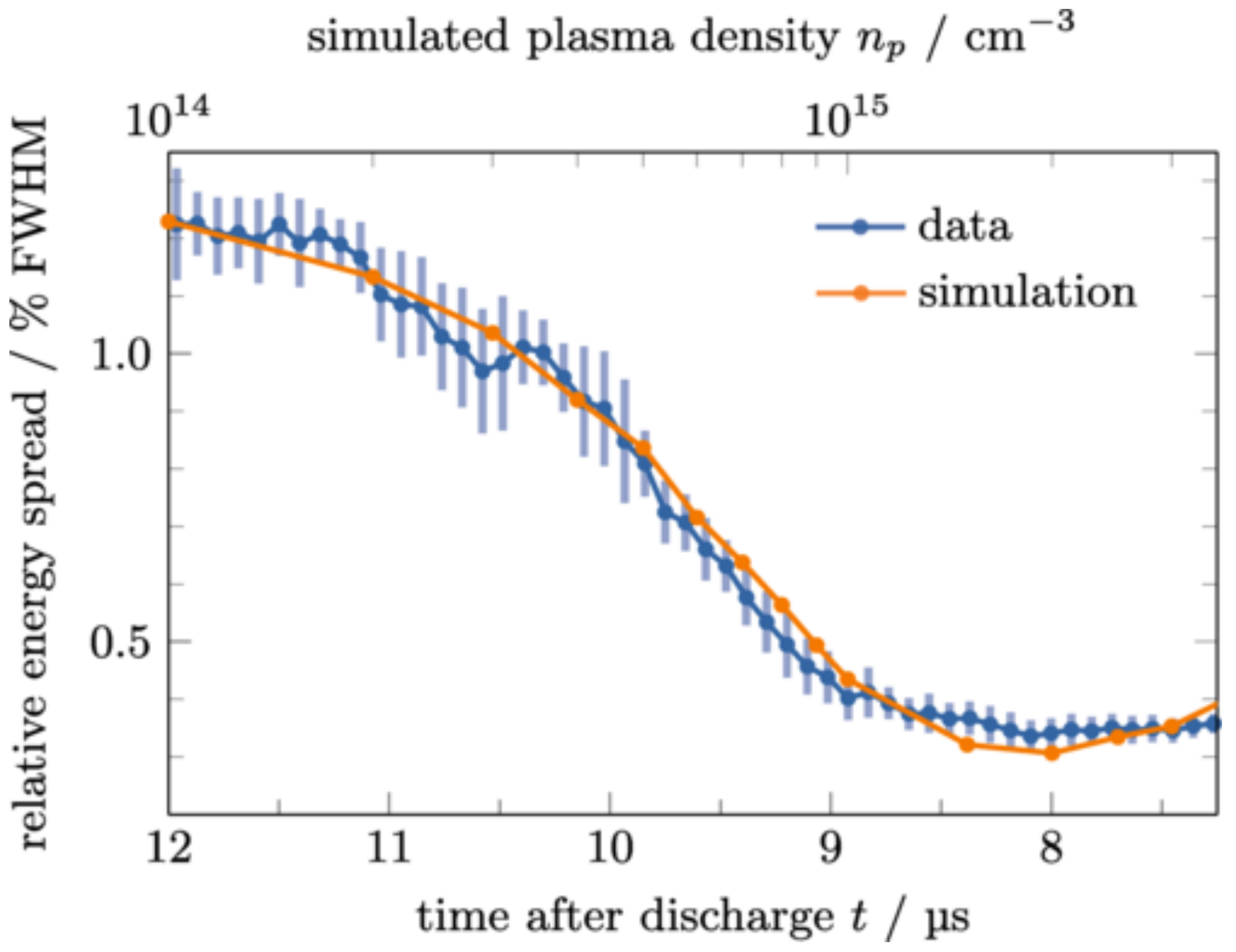
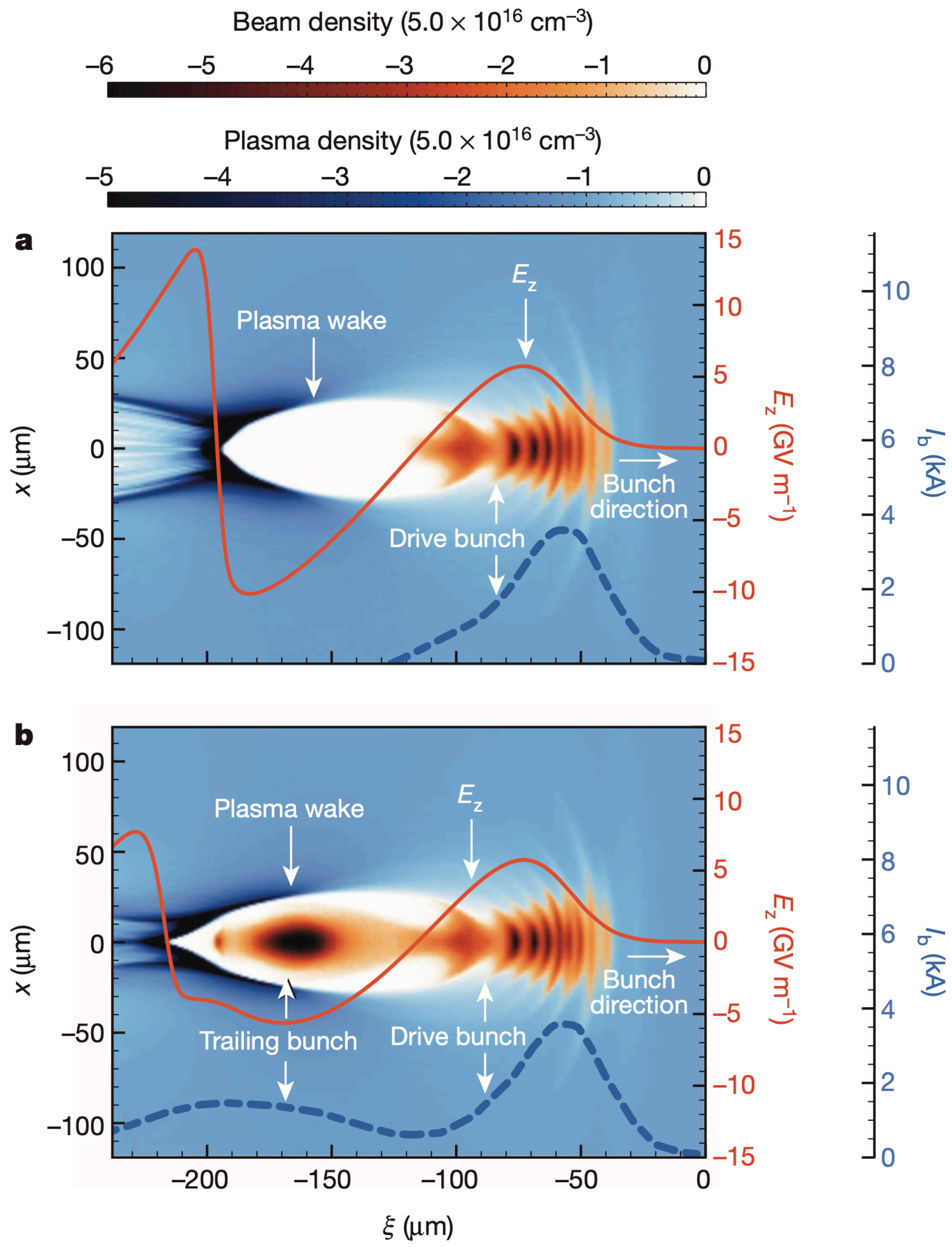
    The trailing-bunch wakefield "destructively interferes" with the driver wakefield—extracting energy.
- *Problem 2*: To extract a large fraction of the energy, the beam will cover a large range of phases (~90 degrees or more).
  - Large energy spread is induced.
  - *Not (easily) possible:* Dechirping



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



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> > 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 <u>extremely precise control</u> of the current profile.

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

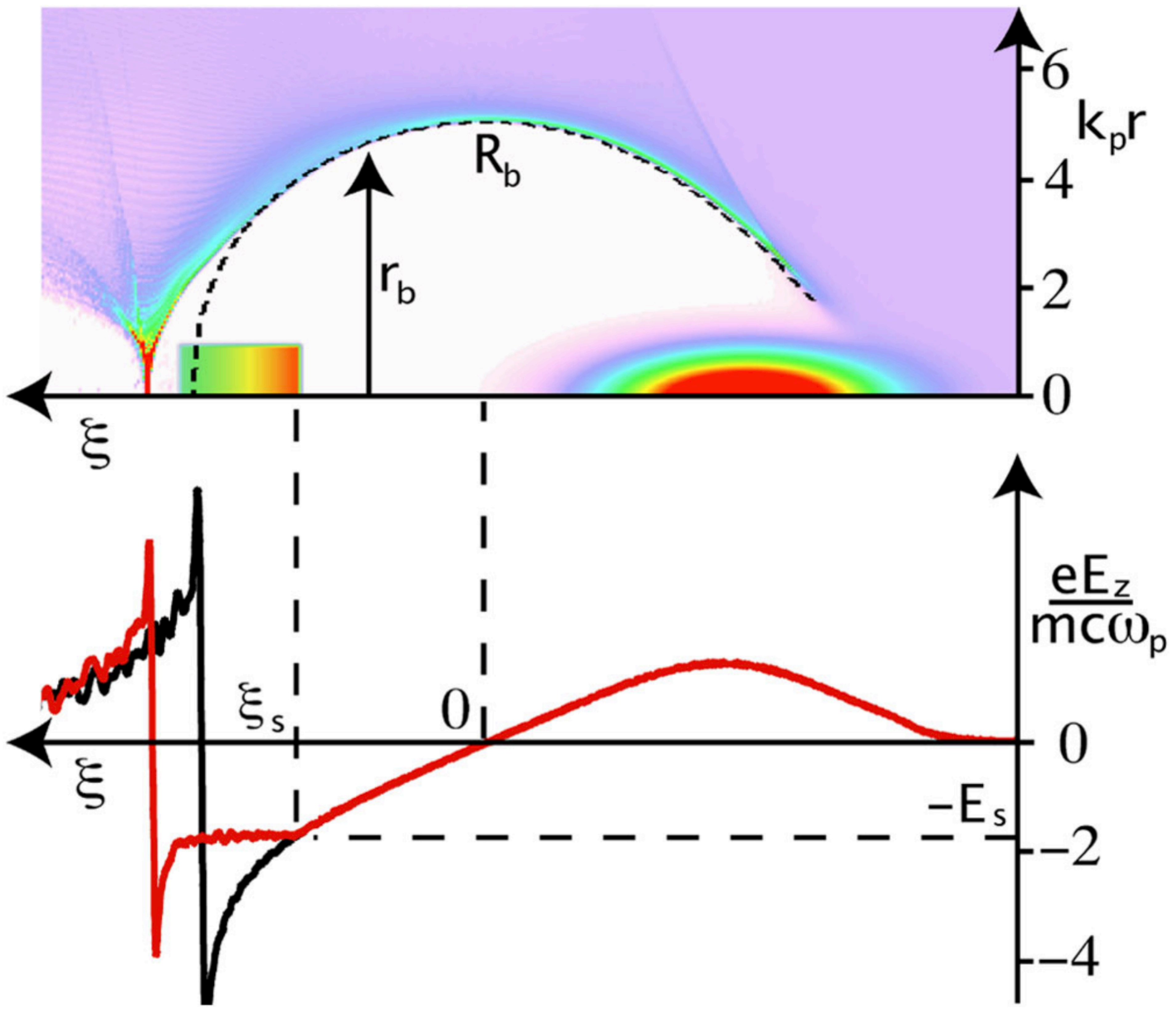
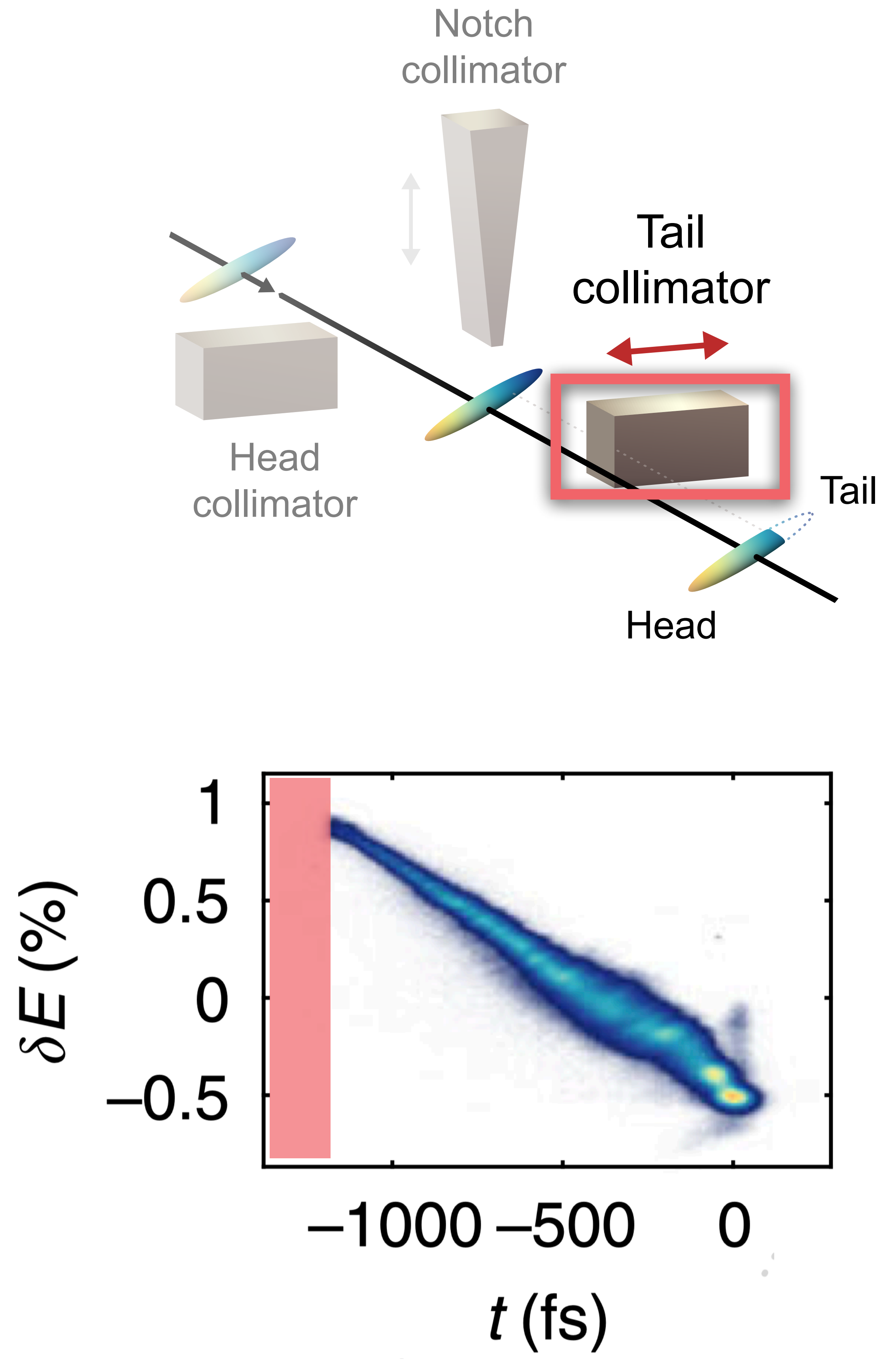


Image credit: M. Tzoufras *et al.*, Phys. Rev. Lett. **101**, 145002 (2008)

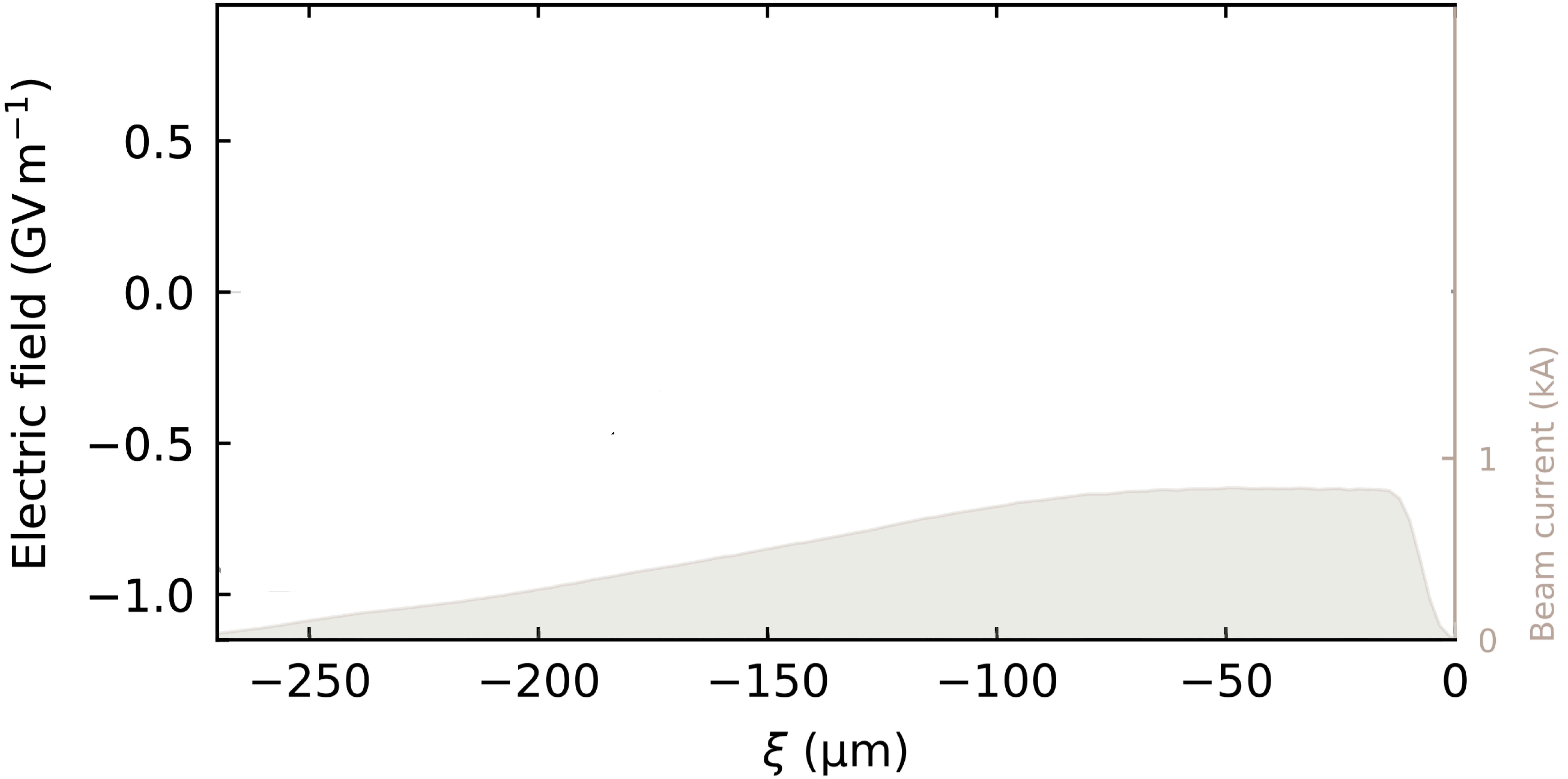
High-resolution plasma wakefield sampling demonstrated

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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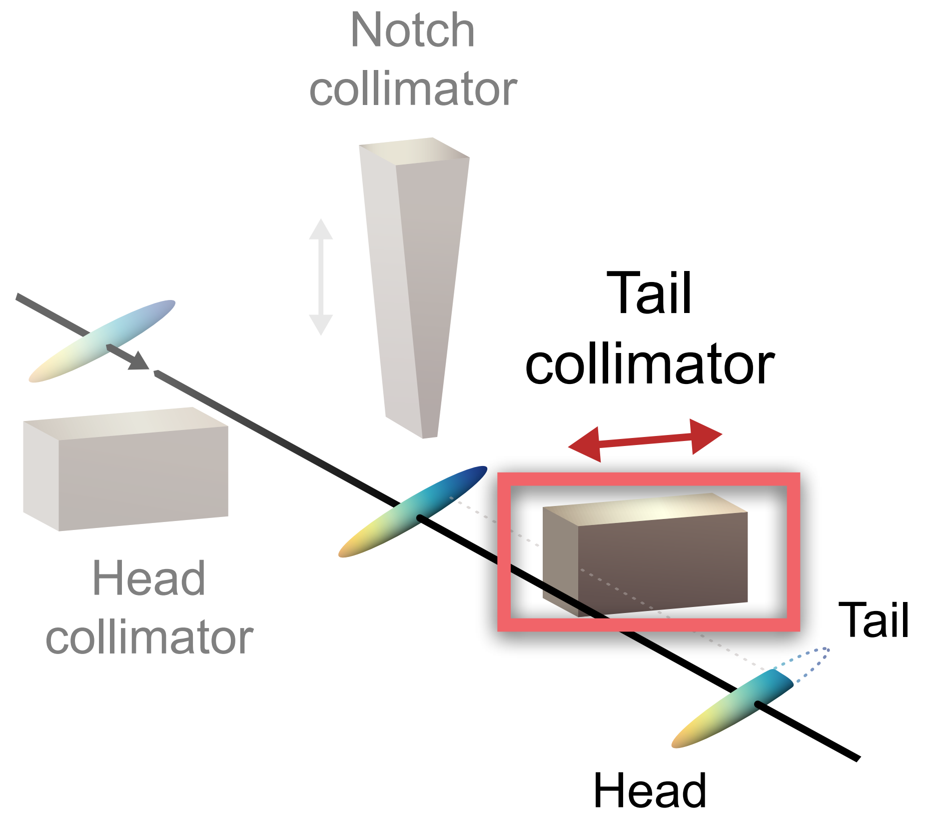

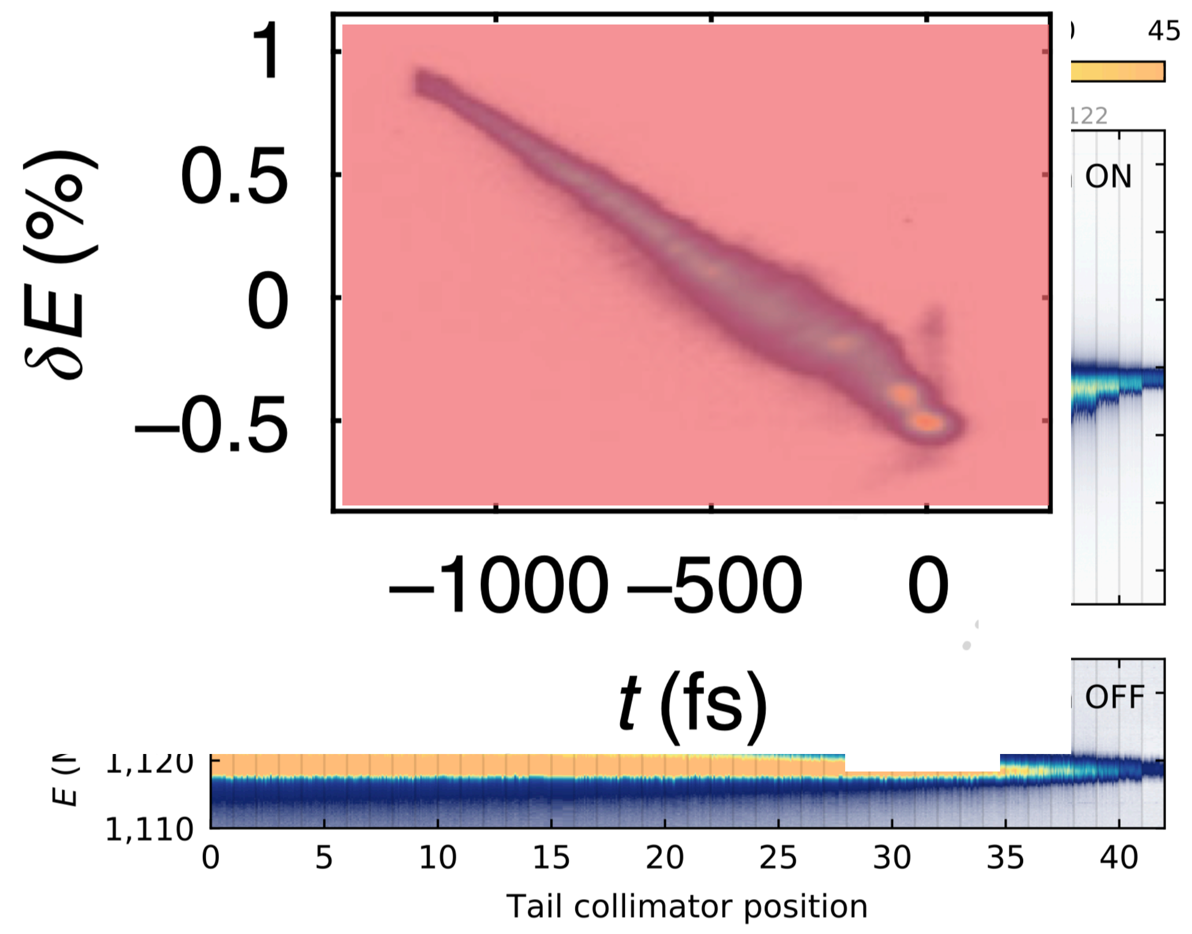

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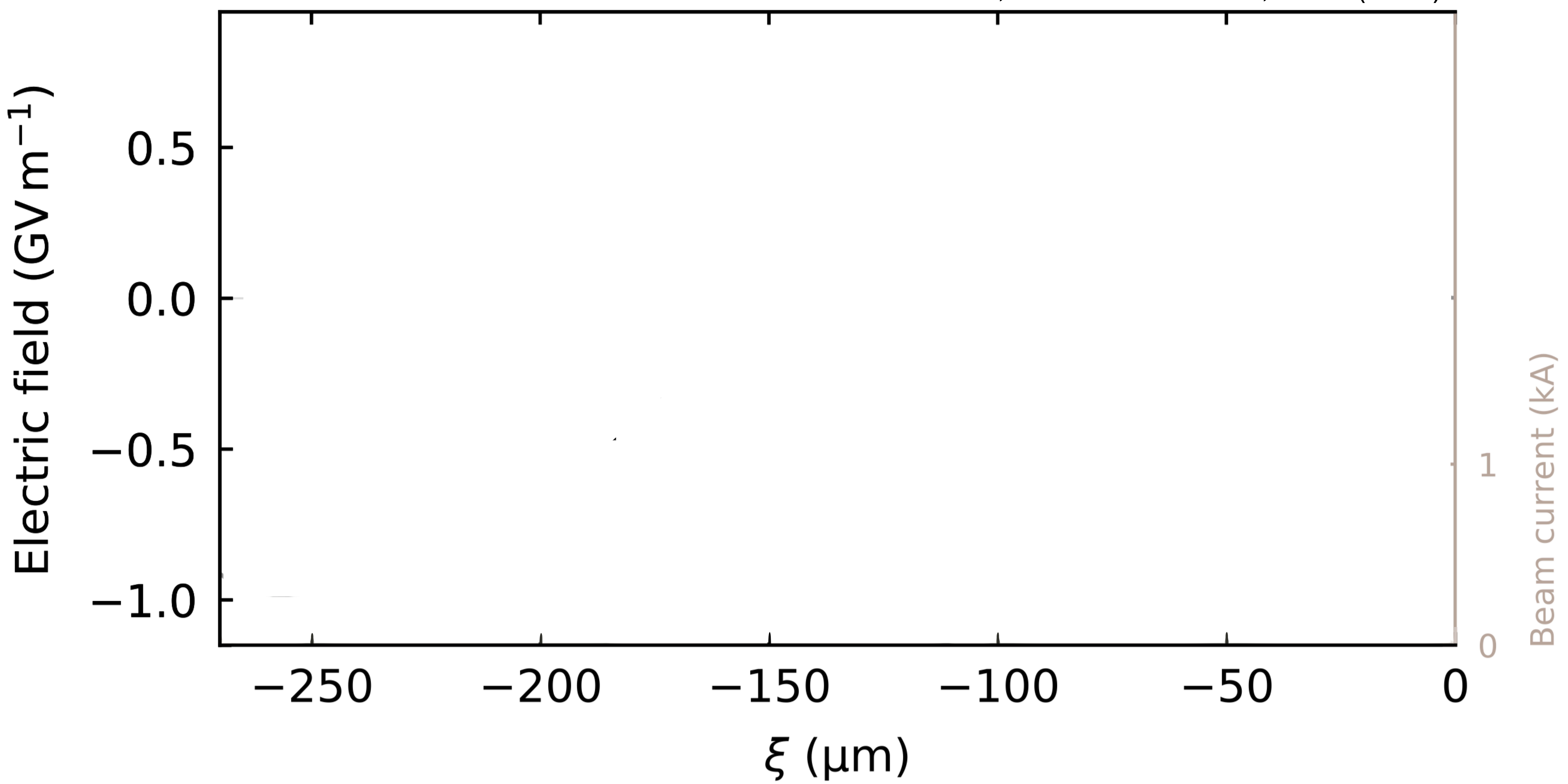
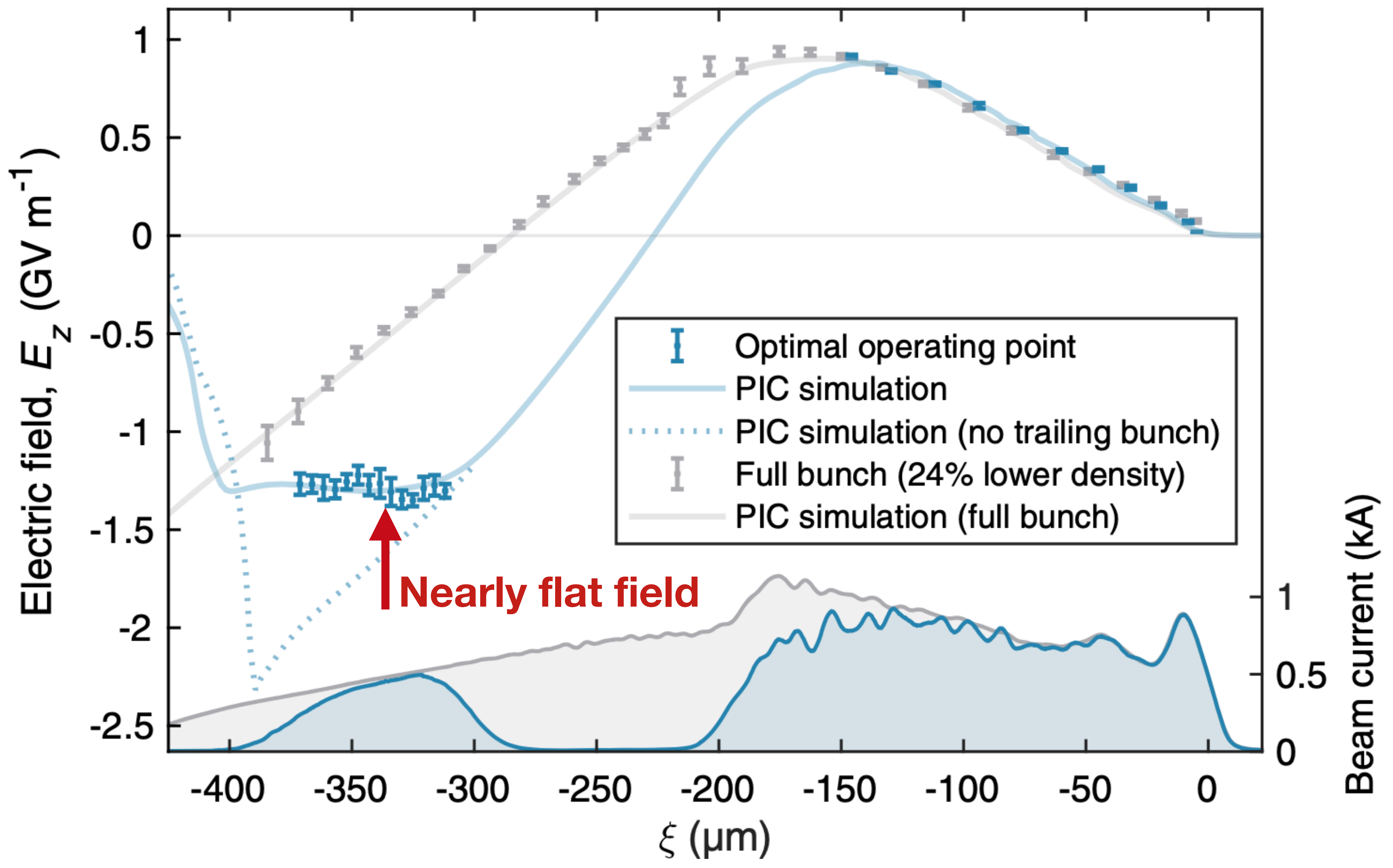
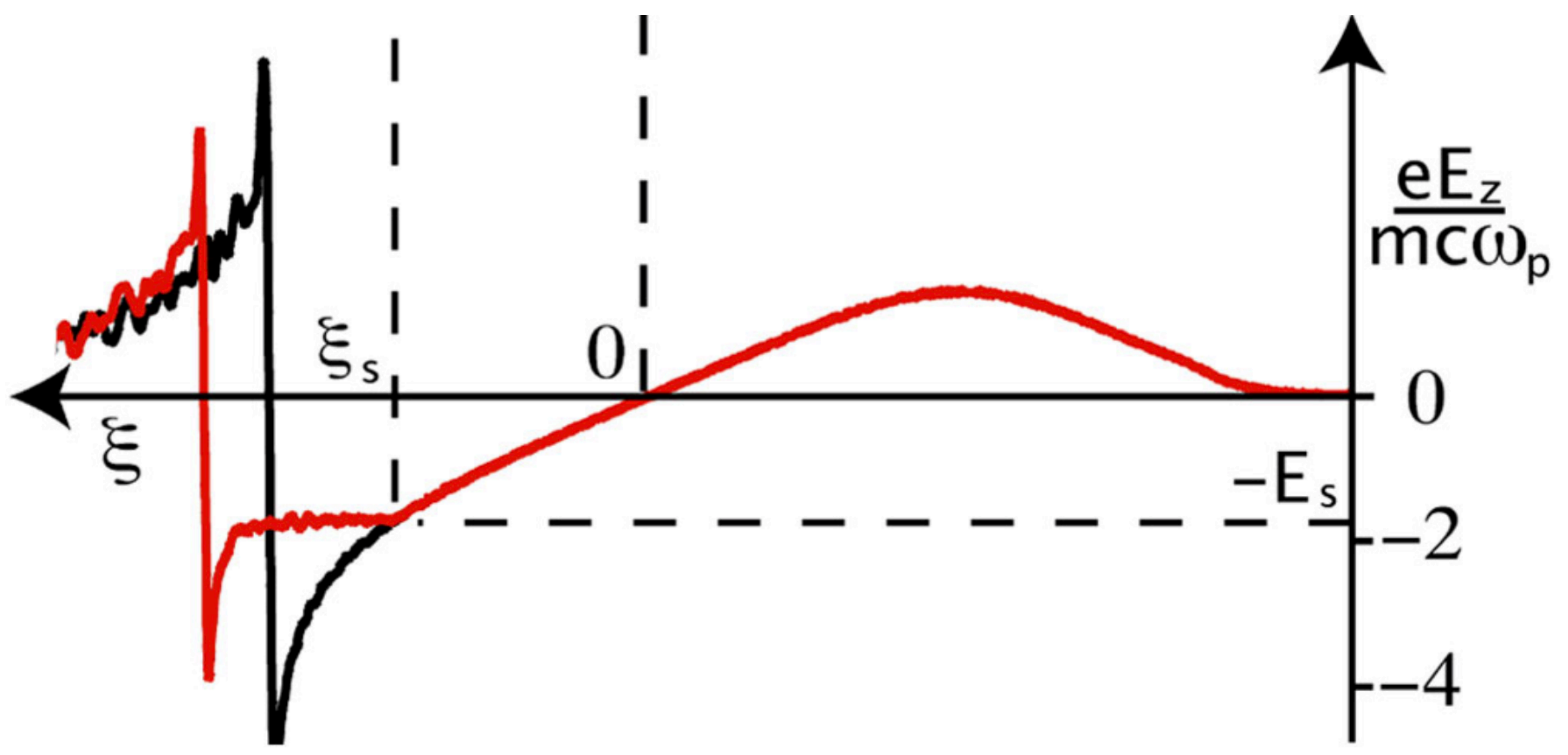


Loading the wakefield and beam shaping flattens the gradient

Direct visualization of electric-field control by wakefield sampling

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





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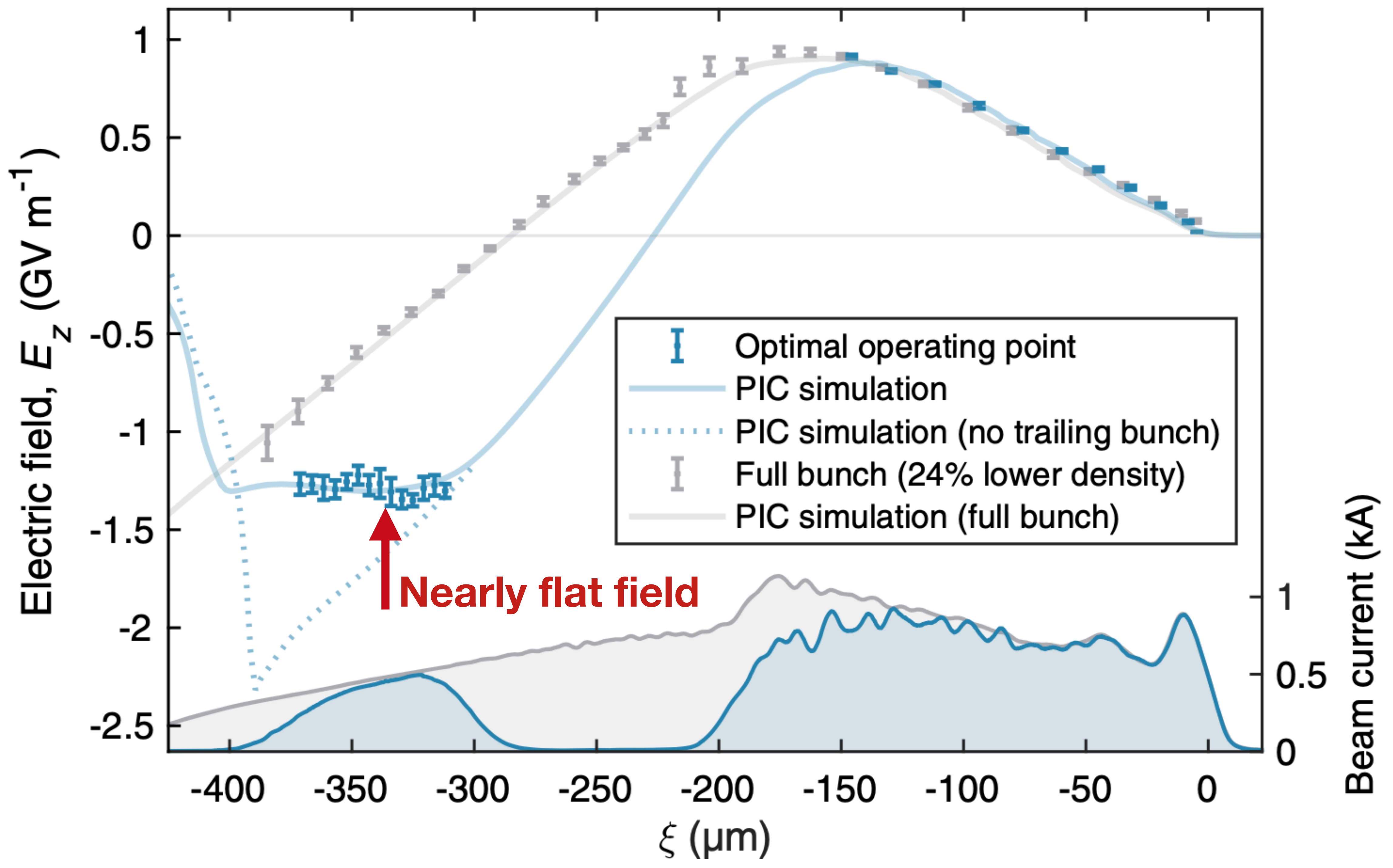
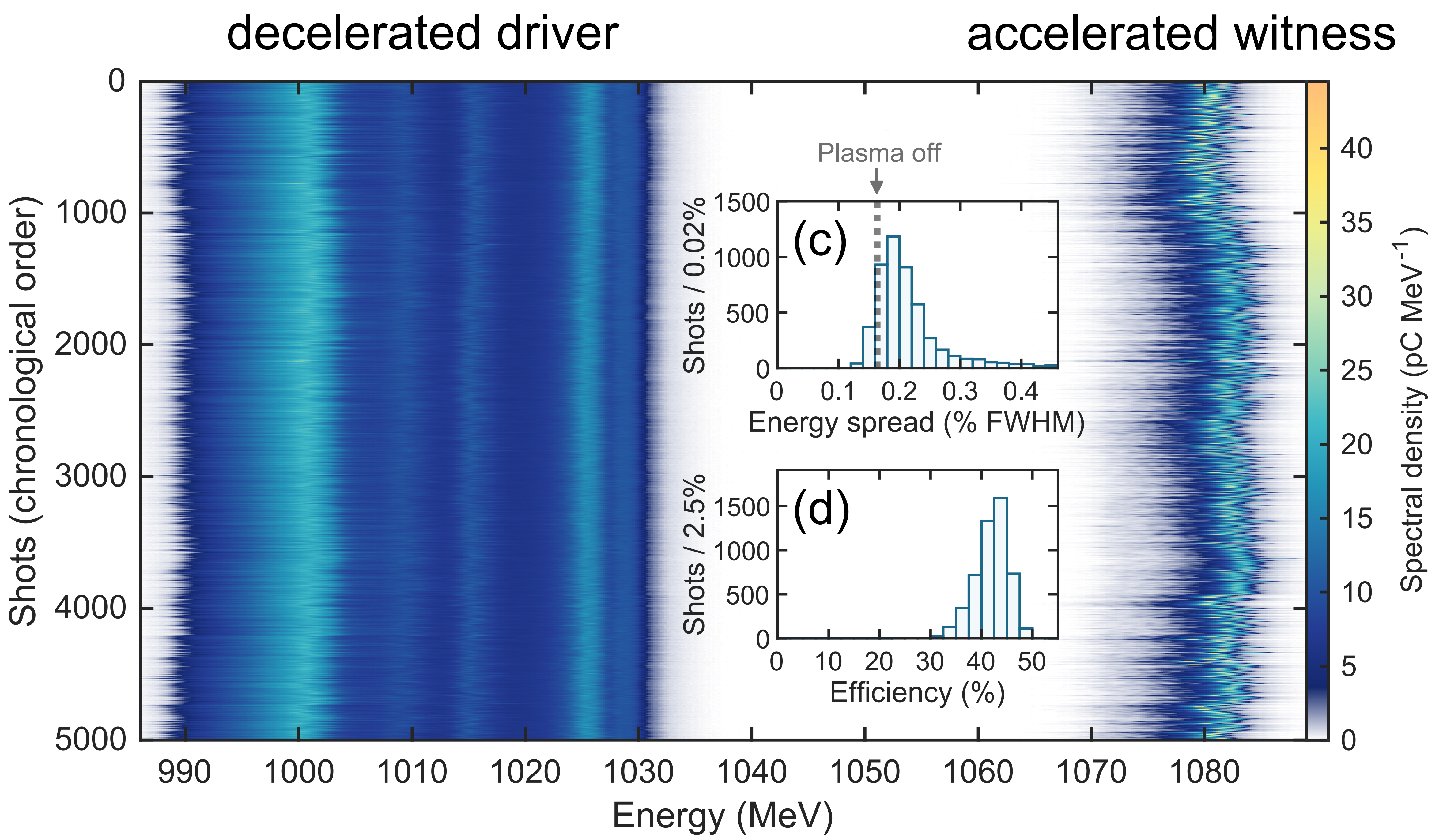
- Accelerating **gradient of 1.3 GV/m**
- **No charge loss**
- Few-percent-level wakefield flattening

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)





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

- **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

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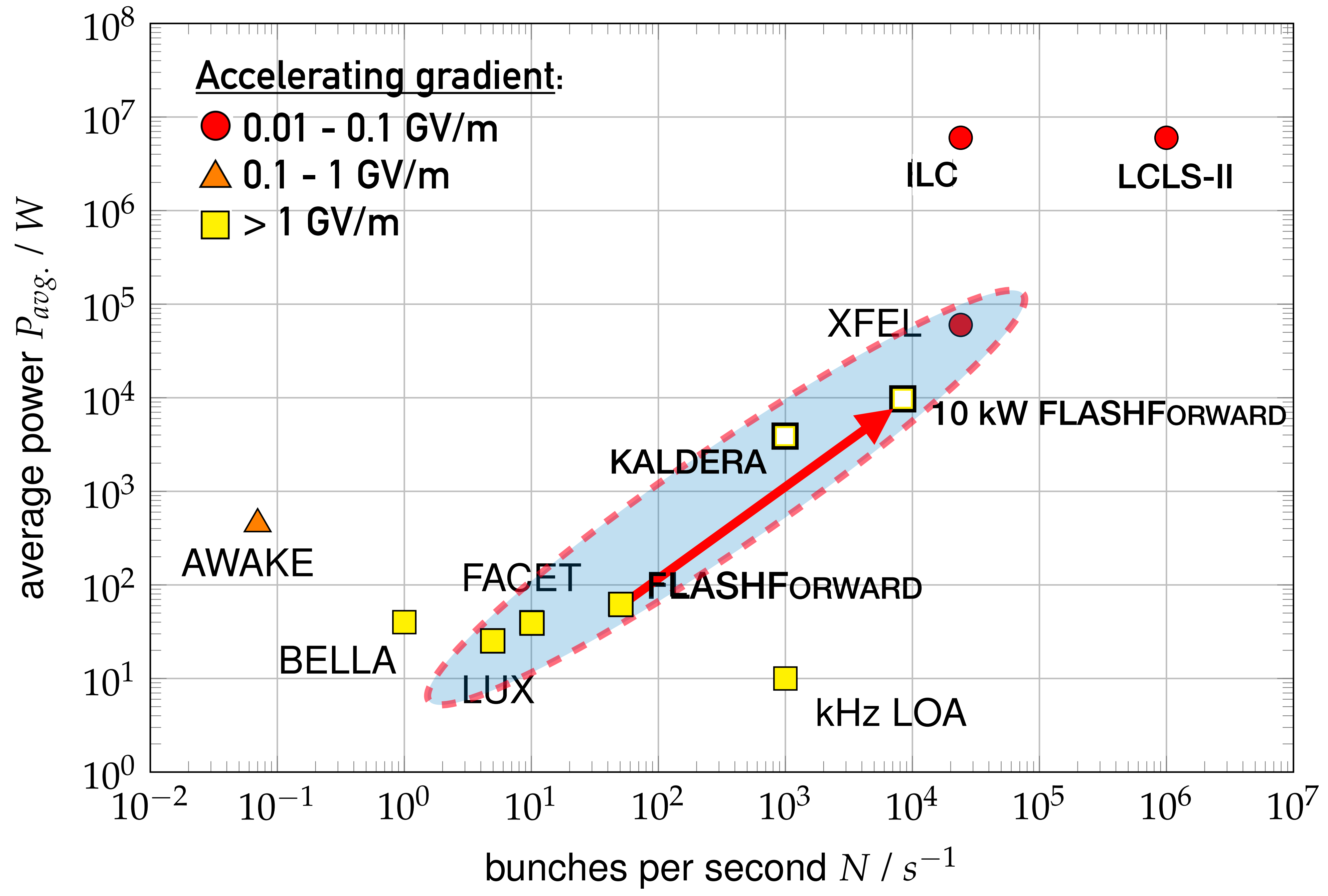

10 kW stage with 50% efficiency & beam quality conservation

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

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

- [x] Transfer efficiency
- [ ] Driver depletion

High beam quality

- [x] Energy-spread preservation
- [ ] Emittance preservation

High average power

- [ ] High repetition rate

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