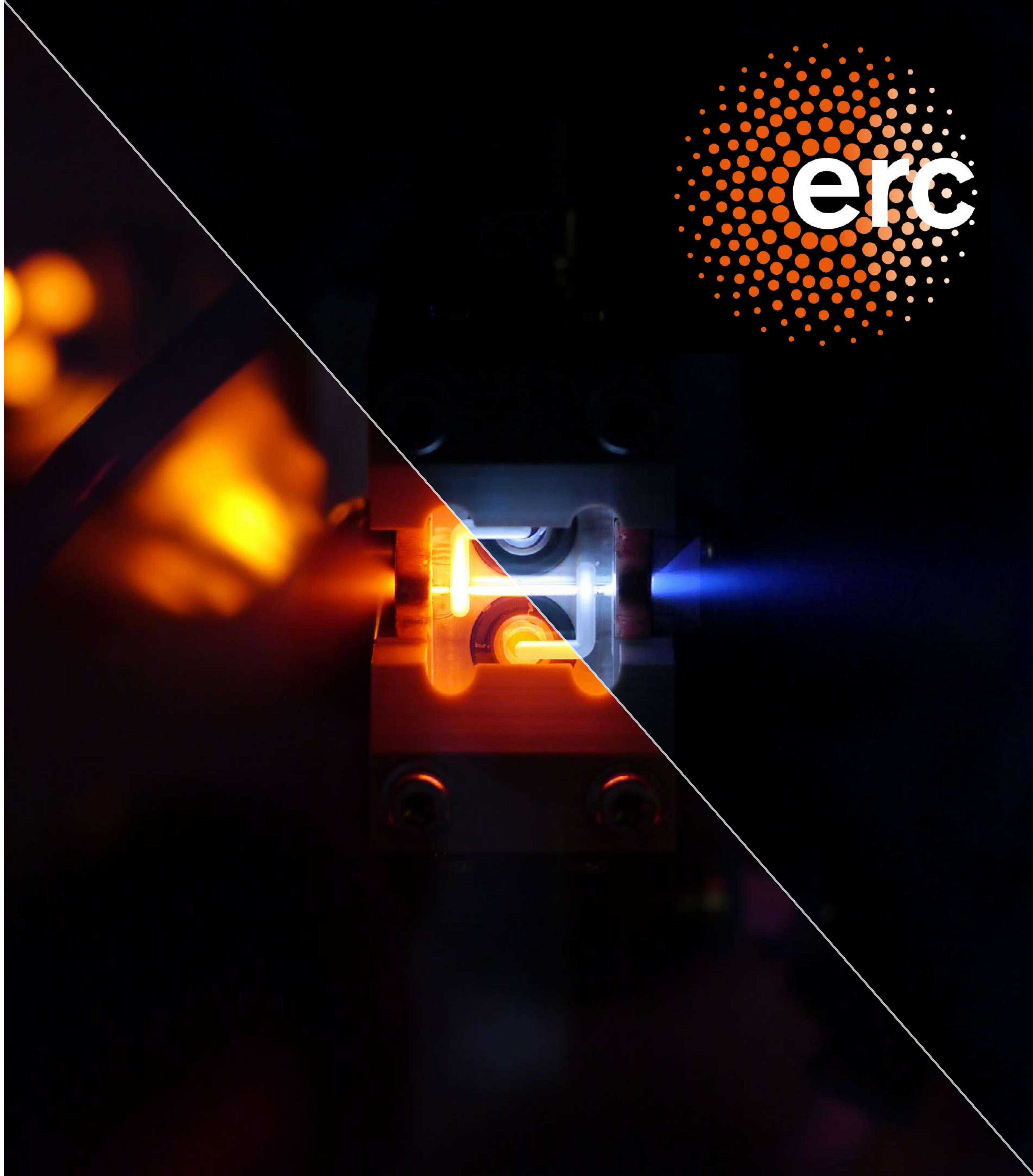
The **SPARTA** project

Staging of Plasma Accelerators for Realizing Timely Applications

UNIVERSITY OF OSLO



The SPARTA project

Progress toward a multistage plasma accelerator for strong-field QED

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Part 0:

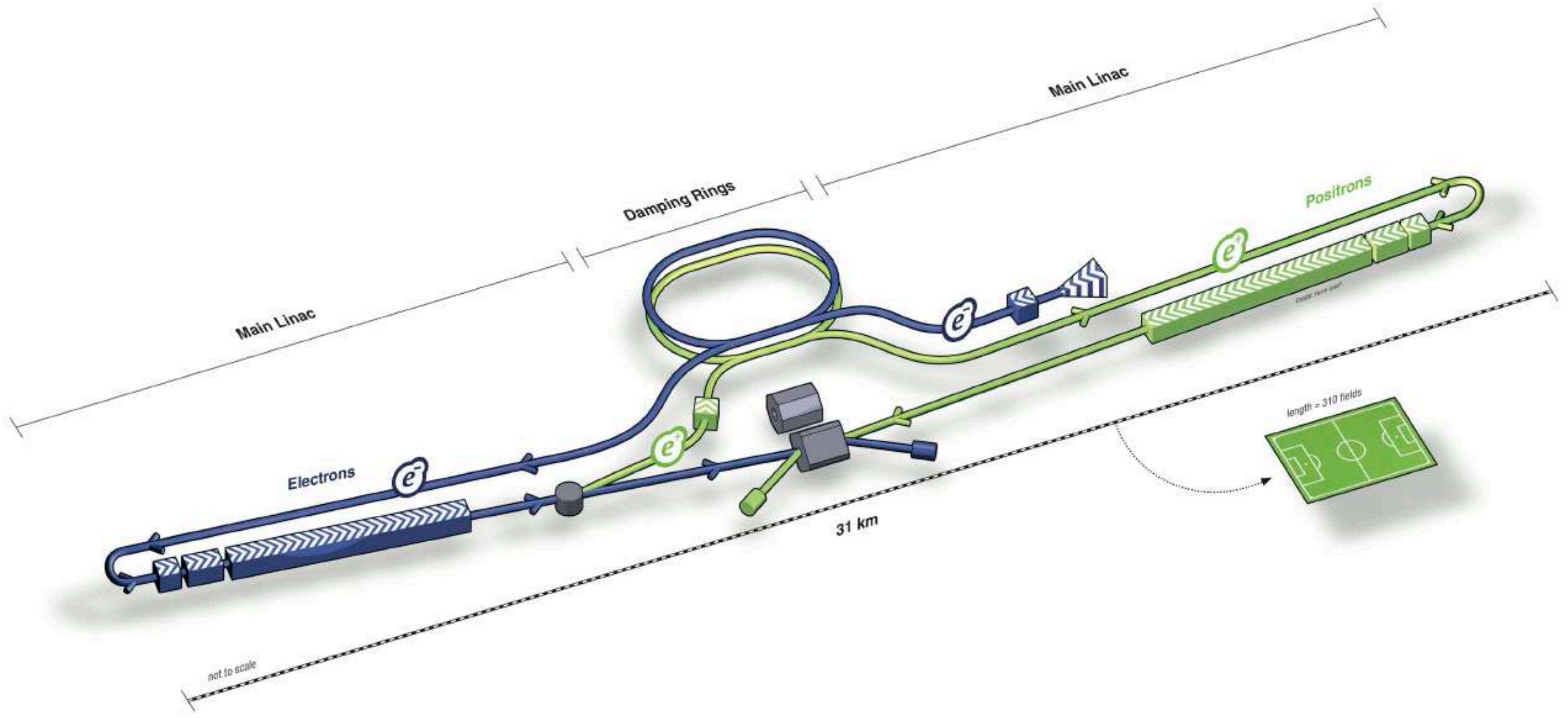
Motivation

for **staging**, **stability** and **SFQED**

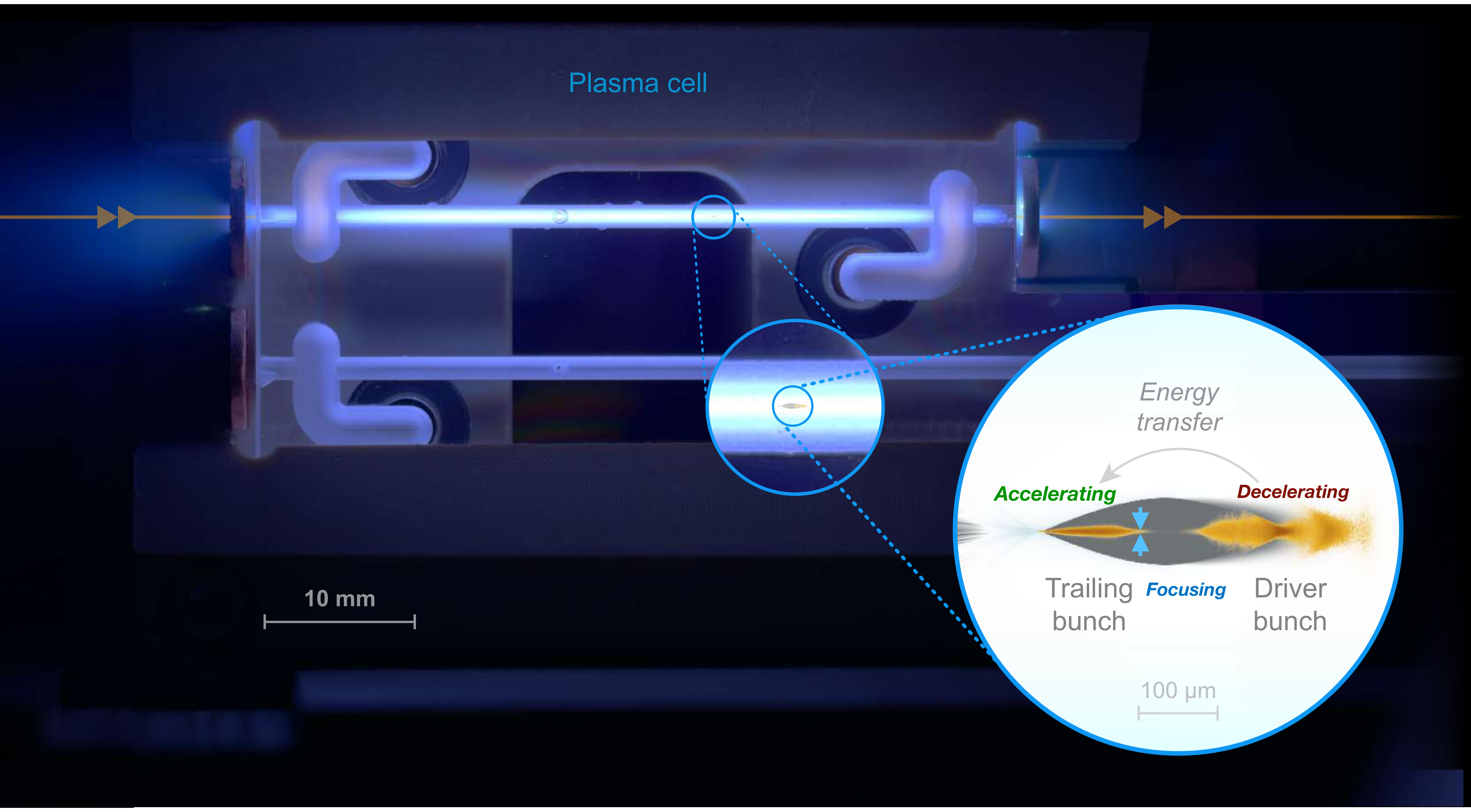
The cost of high-energy particles is too $^{\text{damn}}$ high

Motivating a new accelerator technology

- Consensus: **build e^+–e^- collider**, circular or linear → €10B scale
  - Cost driven by RF accelerating gradient (~100 MV/m)
- Use **plasma accelerators** driven by lasers/beams (1–100 GV/m)
  - Requires: high energy + stability + rep. rate + beam quality



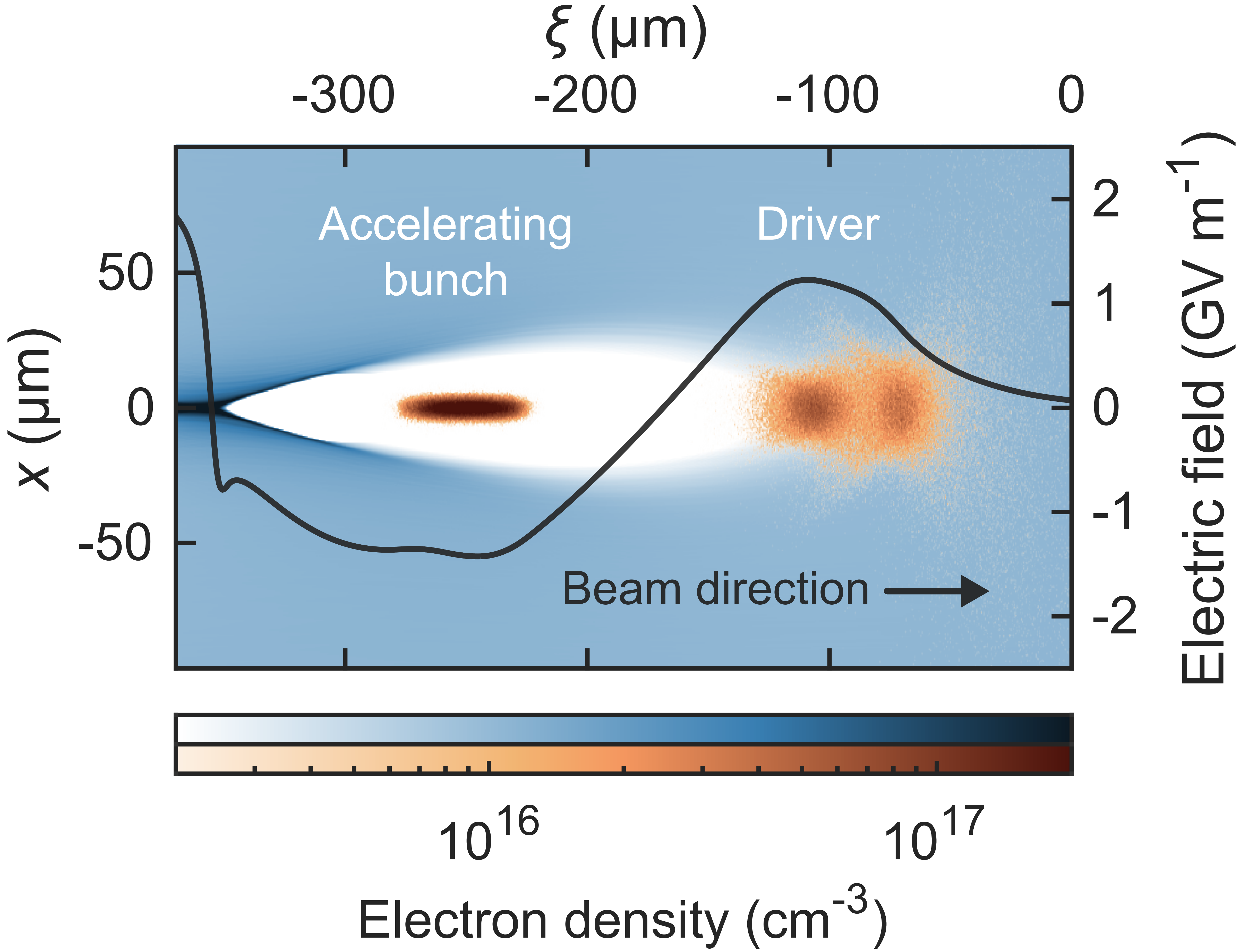
International Linear Collider



- Significant progress since Tajima and Dawson 1979.
  - High theoretical understanding
  - Many key experimental demonstrations
  - Increasing TRL — recent applications to FELs
- **Why aren't we delivering HEP machines?**

Just like a (relativistic) speedboat!

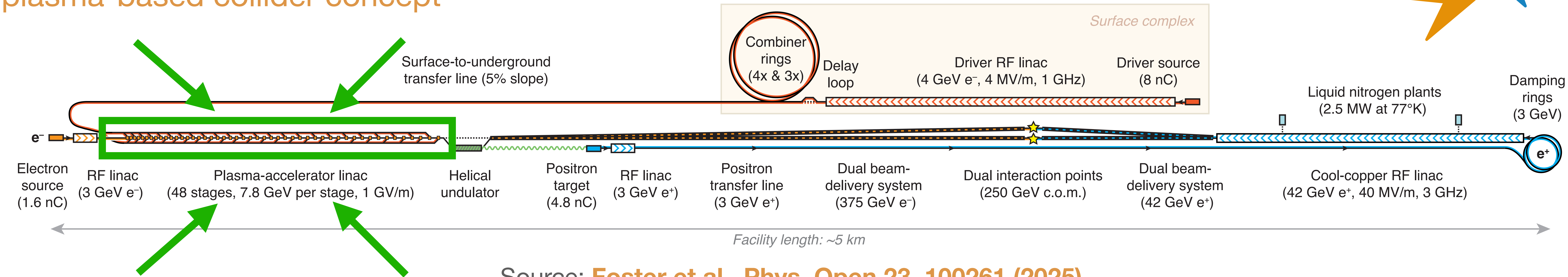
Our favourite analogy



Lindstrøm *et al.*, "Beam-driven plasma-wakefield acceleration" (submitted to RMP, arXiv:2504.05558)

HALHF: a hybrid, asymmetric, linear Higgs factory

A plasma-based collider concept



Source: Foster et al., Phys. Open 23, 100261 (2025)

> **Concept: Accelerate e⁻ with plasma and e⁺ with RF**

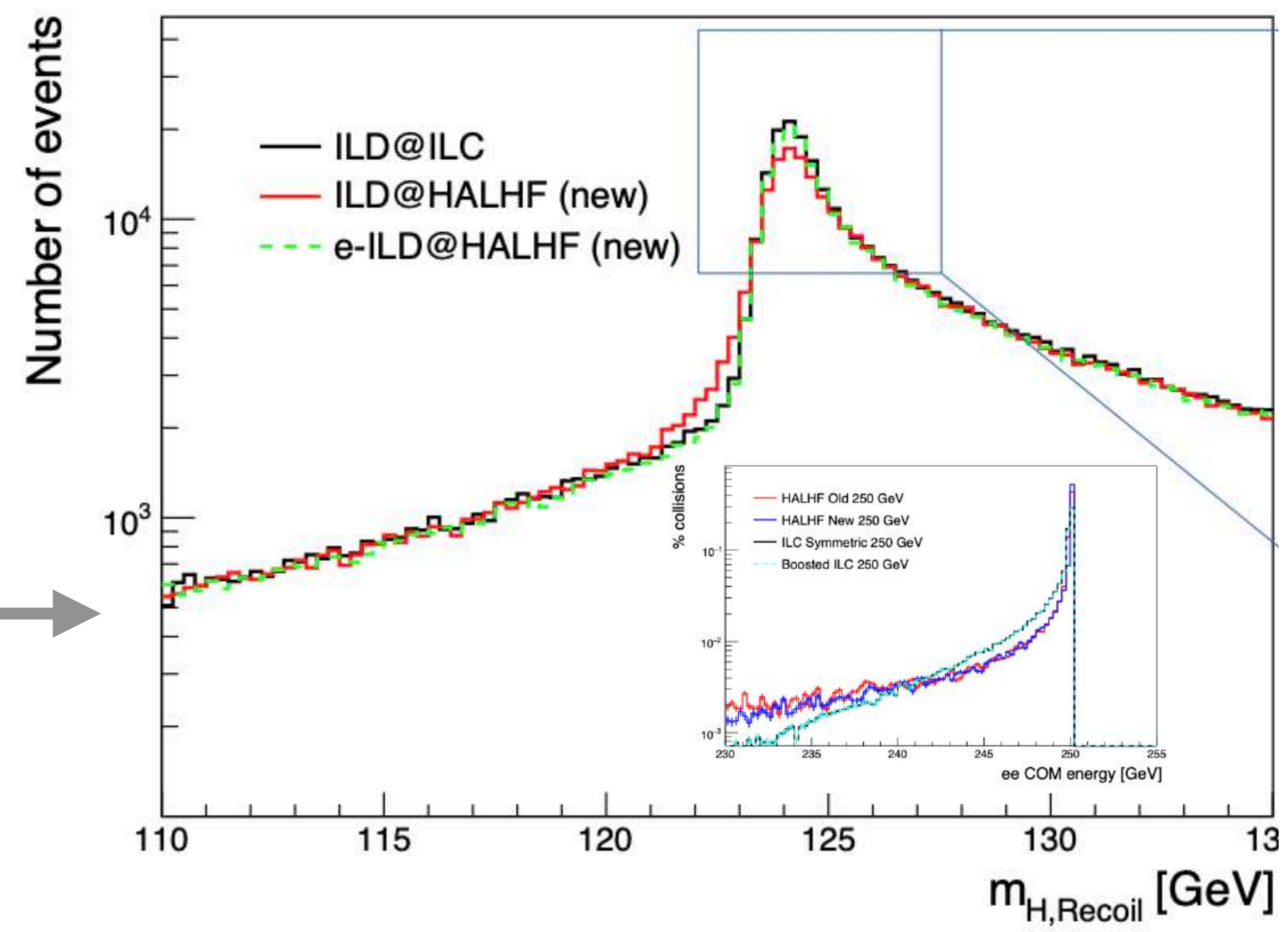
> Asymmetric beam energy to minimise length/cost

> > *e⁻: Lower charge, higher emittance (👍 for plasma accelerator)*

> Boosted collisions — regain sensitivity with elongated detector

> HALHF Collaboration: plasma-, RF- and particle-physics experts

> > *"Self-consistent" design, preliminary start-to-end simulations*

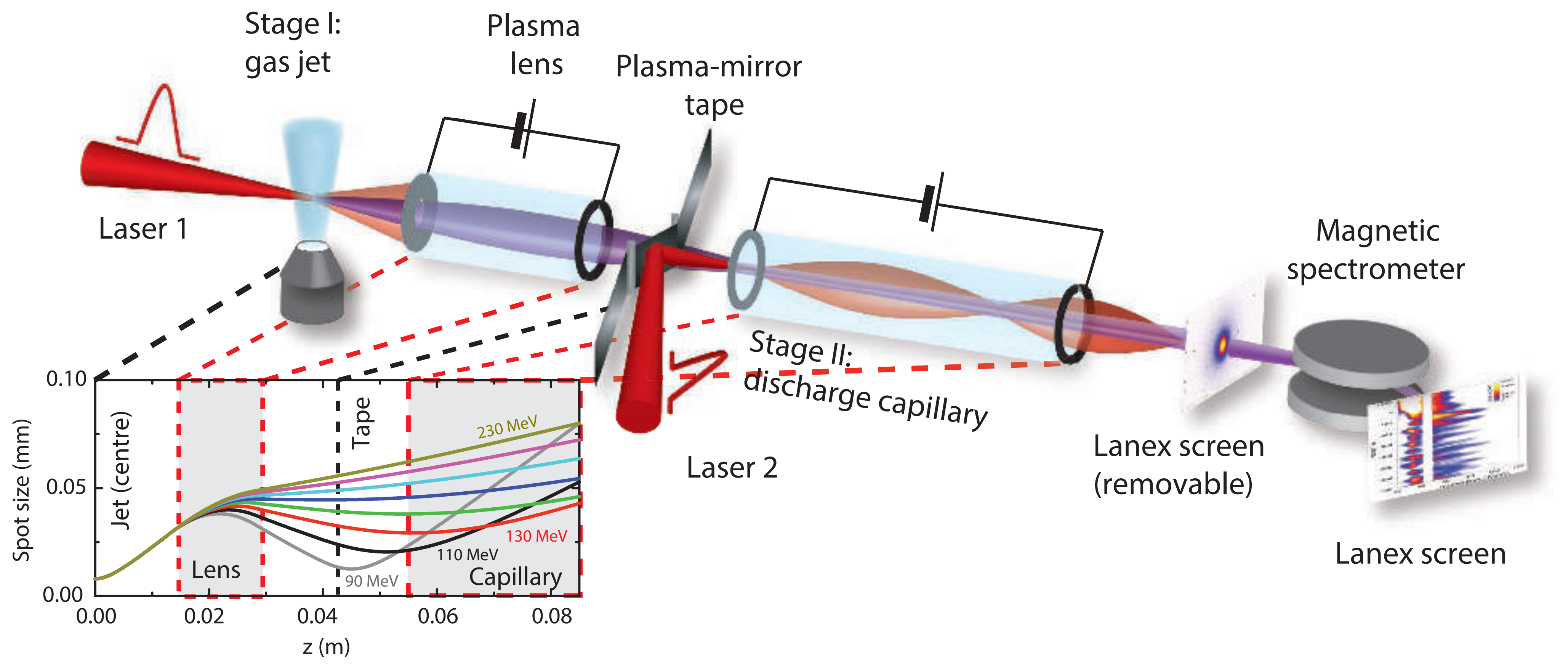


Source: S. Ranjan and J. List (unpublished)

Key challenges in high-energy plasma acceleration

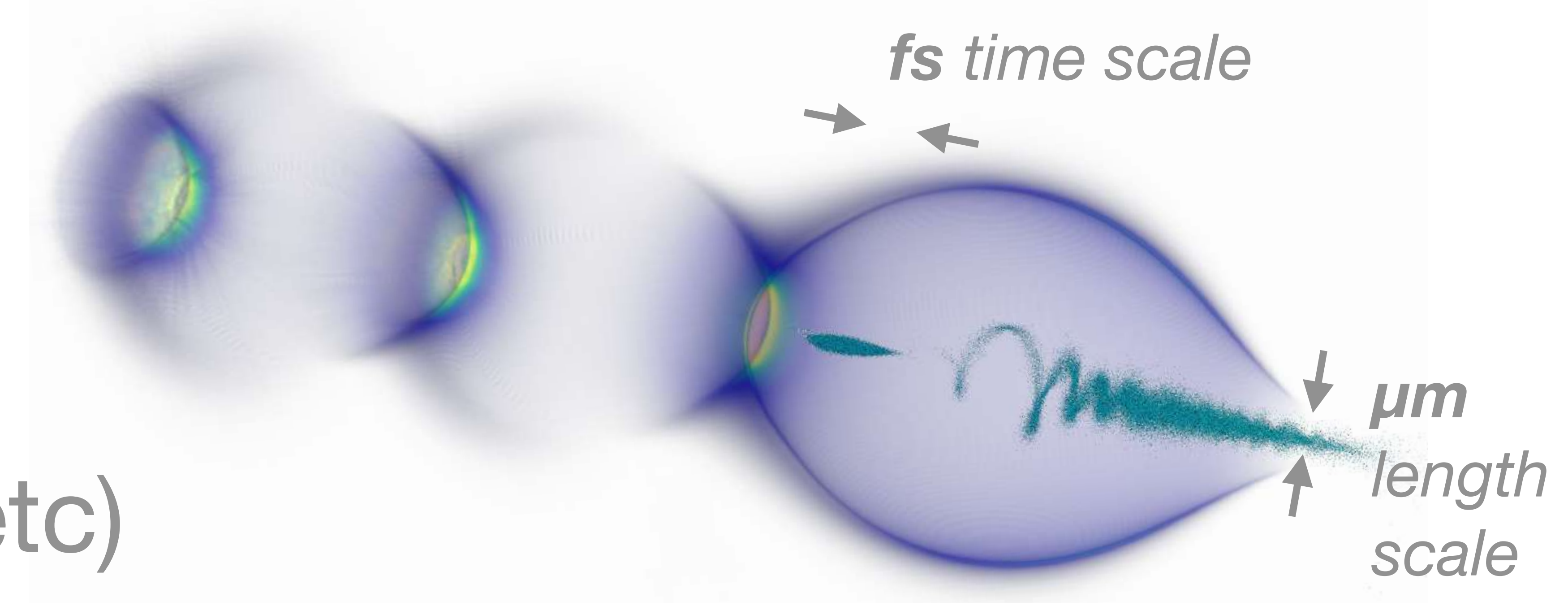
Staging and **stability** – forming the backbone of the machine

- **Staging problem**: coupling beams between plasma accelerators (stages)
  - In- and out-coupling of drivers
  - Refocusing high-divergence beams with finite energy spread → ***chromaticity***



Steinke et al., Nature 530, 190 (2016)

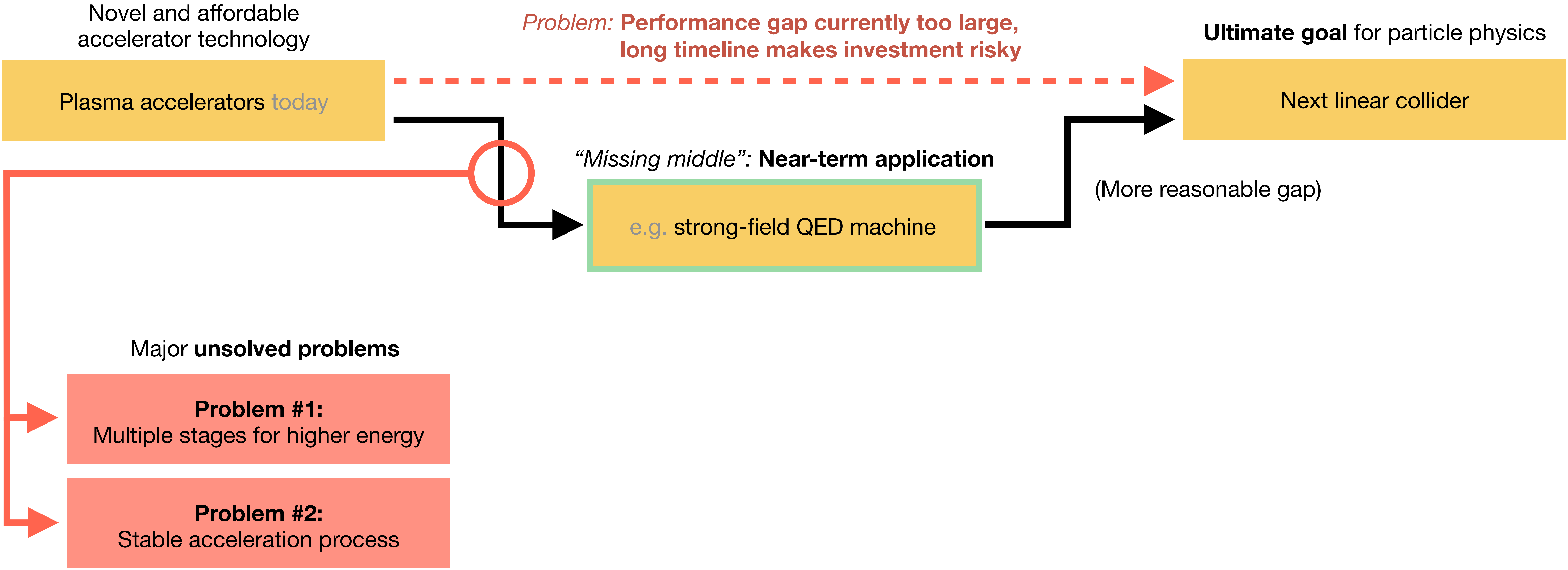
- **Stability problem**:
  - Shrinking the accelerating structure (μm/fs scale) …without shrinking the alignment/timing jitter
  - Beam–plasma instabilities (hosing, beam breakup, etc)



Source: VisualPIC

Mapping the landscape

A flow chart



The market problem

Plasma accelerators and “the innovator’s dilemma”

> *The innovator’s dilemma*
  (1997 book by Clayton Christensen)

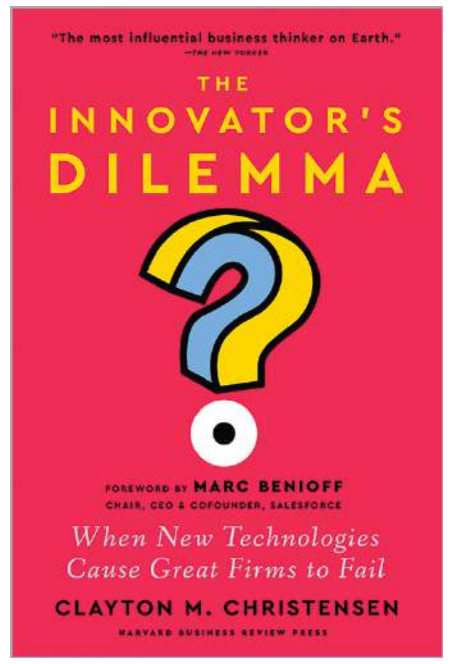
> Plasma acceleration is a disruptive technology

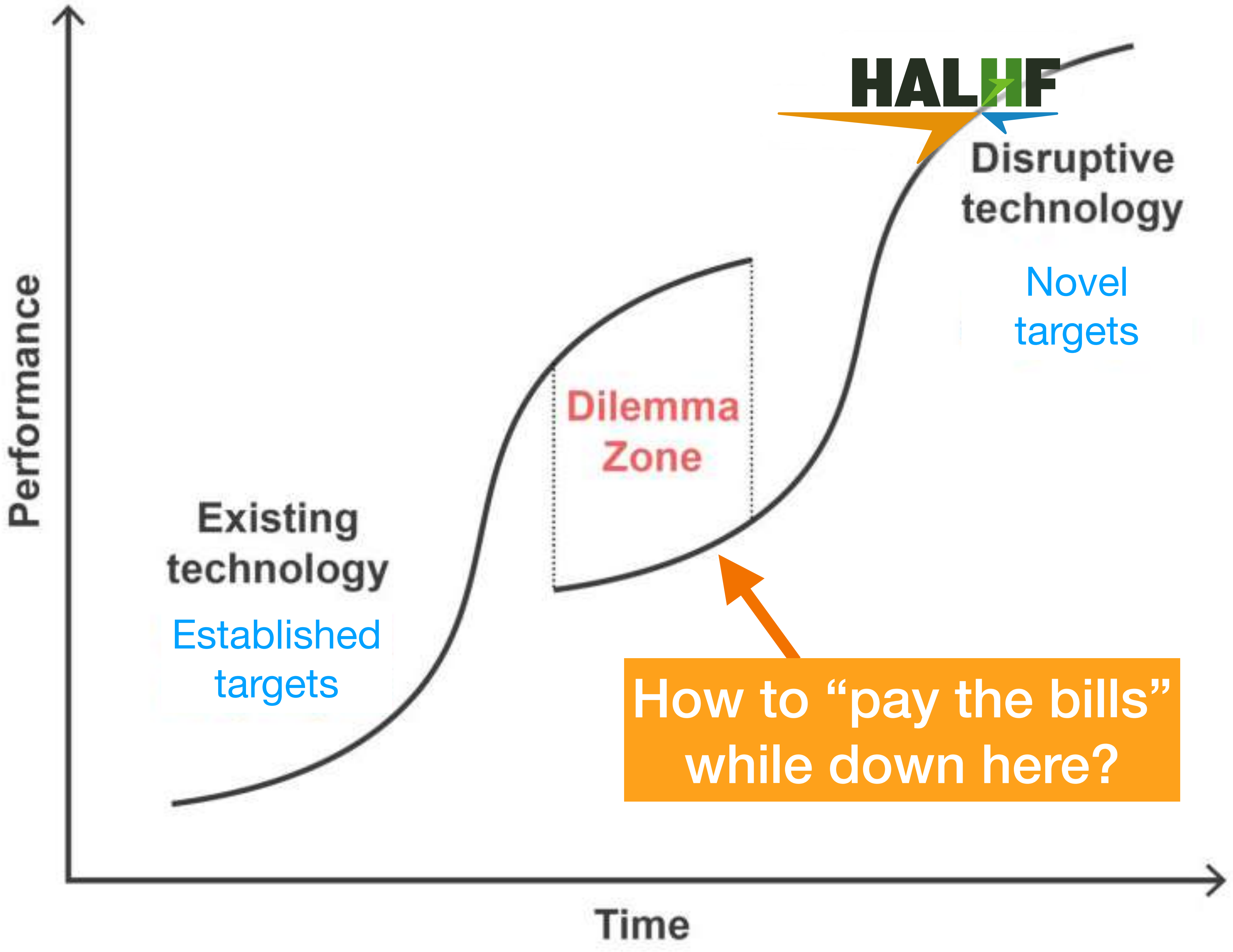
> Much higher gradient, but…
  RF accelerators still outperforms in other metrics:

  > *Repetition rate, stability, power/efficiency, beam quality, luminosity, etc.*

  > *Plasma accelerators will take time to mature*

> Christensen: To survive in the meantime, the disruptive technology must not compete directly, but identify a *new, smaller market*



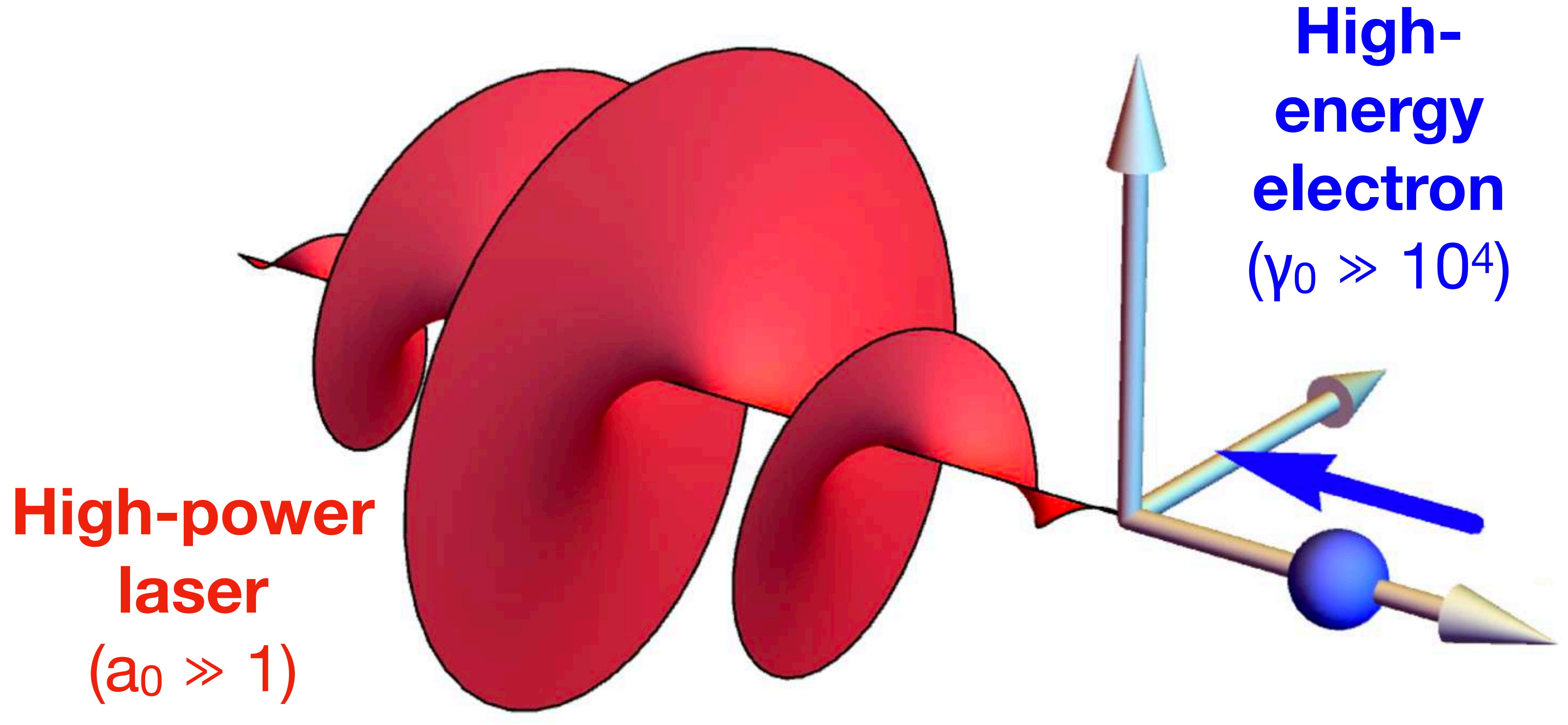


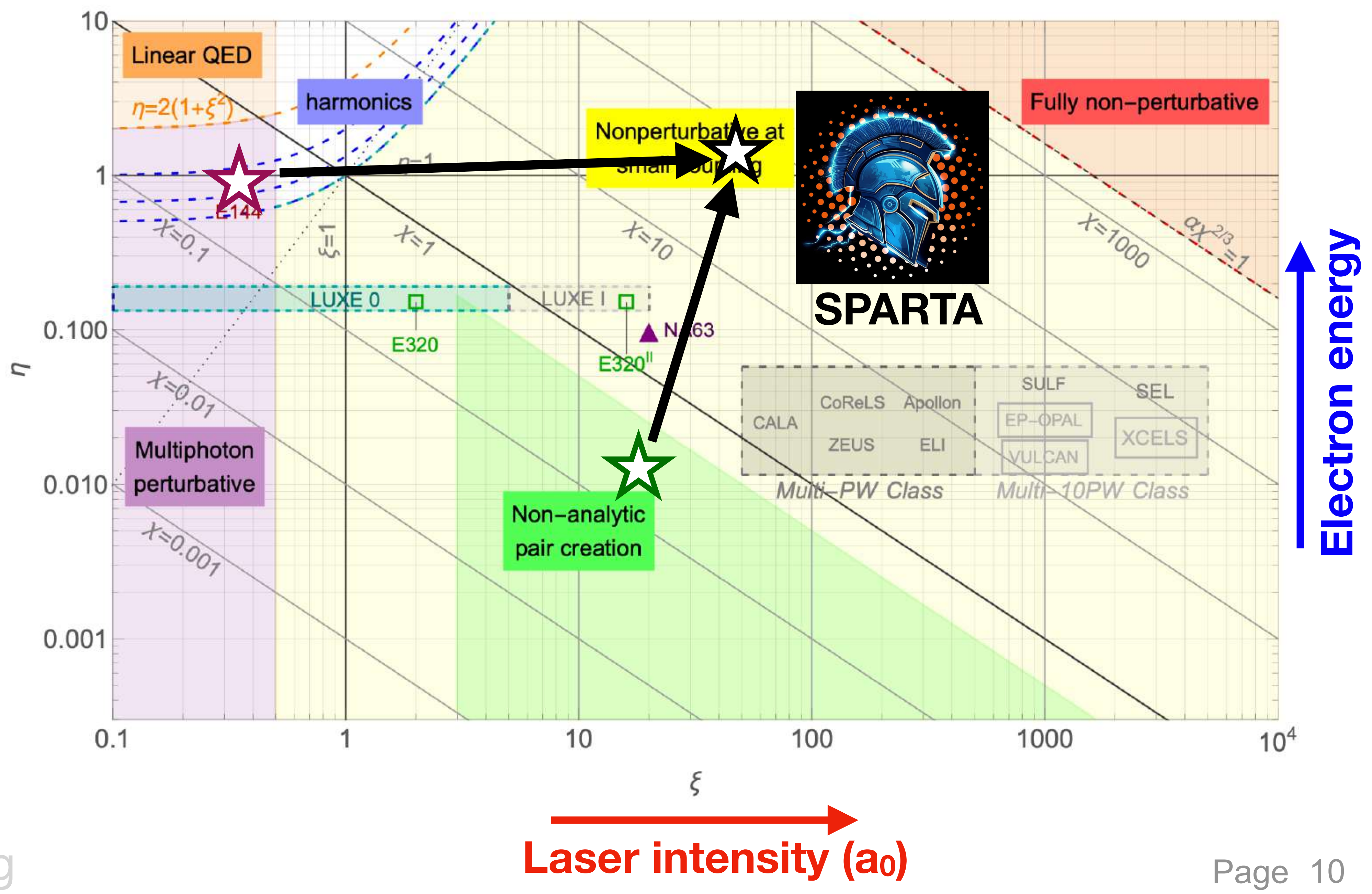
A medium-term application: SFQED

New physics with moderate beam requirements

Blackburn et al., Phys. Plasmas 25, 083108 (2018)

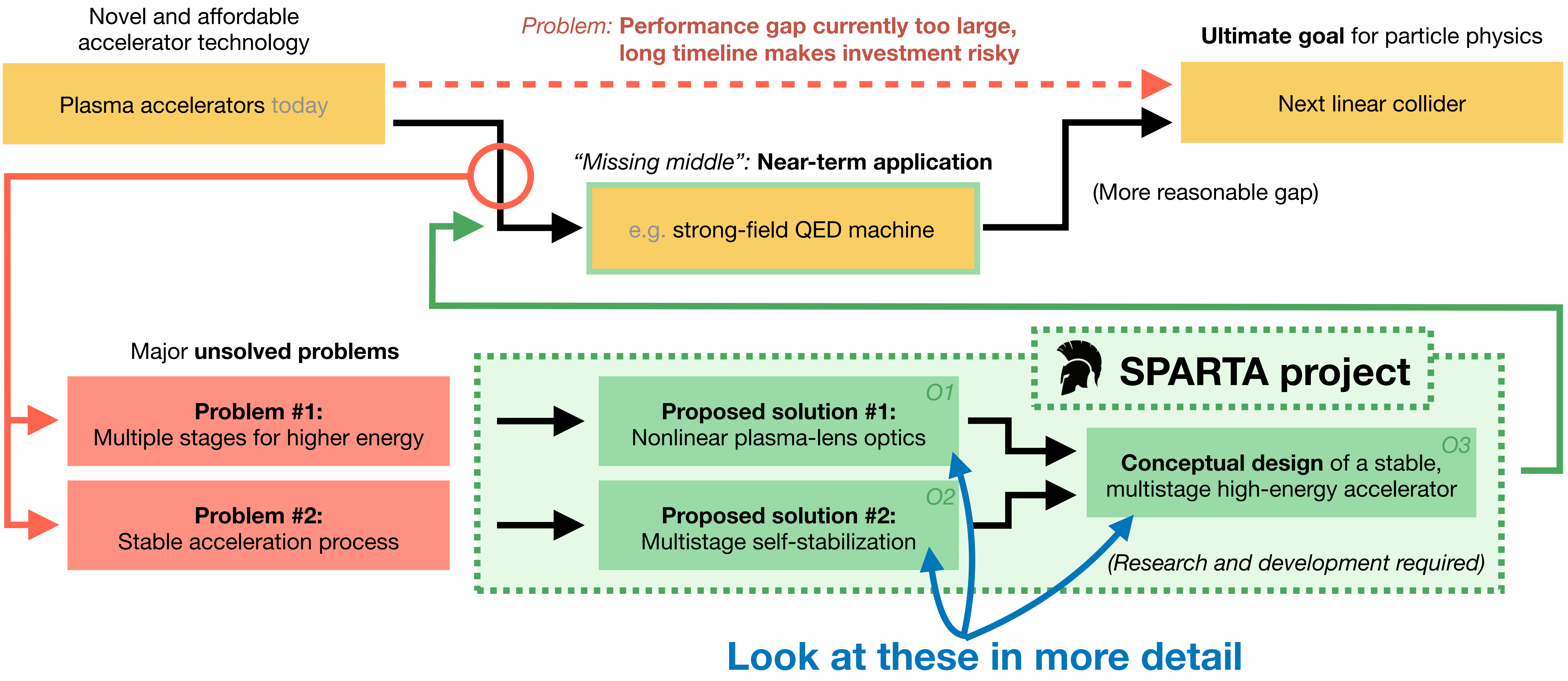
- Schwinger field: ~10^{18} V/m (χ =1) ⋙ high-power laser
  - Collide with high-energy e^-
    → **Lorentz boost the laser field (in the e^- frame)**
- Experiments reached $\chi \approx 0.3$ (soon ~1)
- $\chi \approx$ 10–100 → “laboratory astrophysics”
  (e.g., B-field at surface of magnetars)
  - *Requires 50+ GeV e^- and multi-PW laser*
  - *Too expensive for a small research field…*
- Multistage plasma-accelerator for SFQED = **win-win!**
  - *SFQED gets cheap, high energy e– (new physics)*
  - *First “HEP” for plasma (with moderate requirements)*





The SPARTA project

A flow chart



Part 1:

Staging

Achromatic optics and **nonlinear plasma lenses**

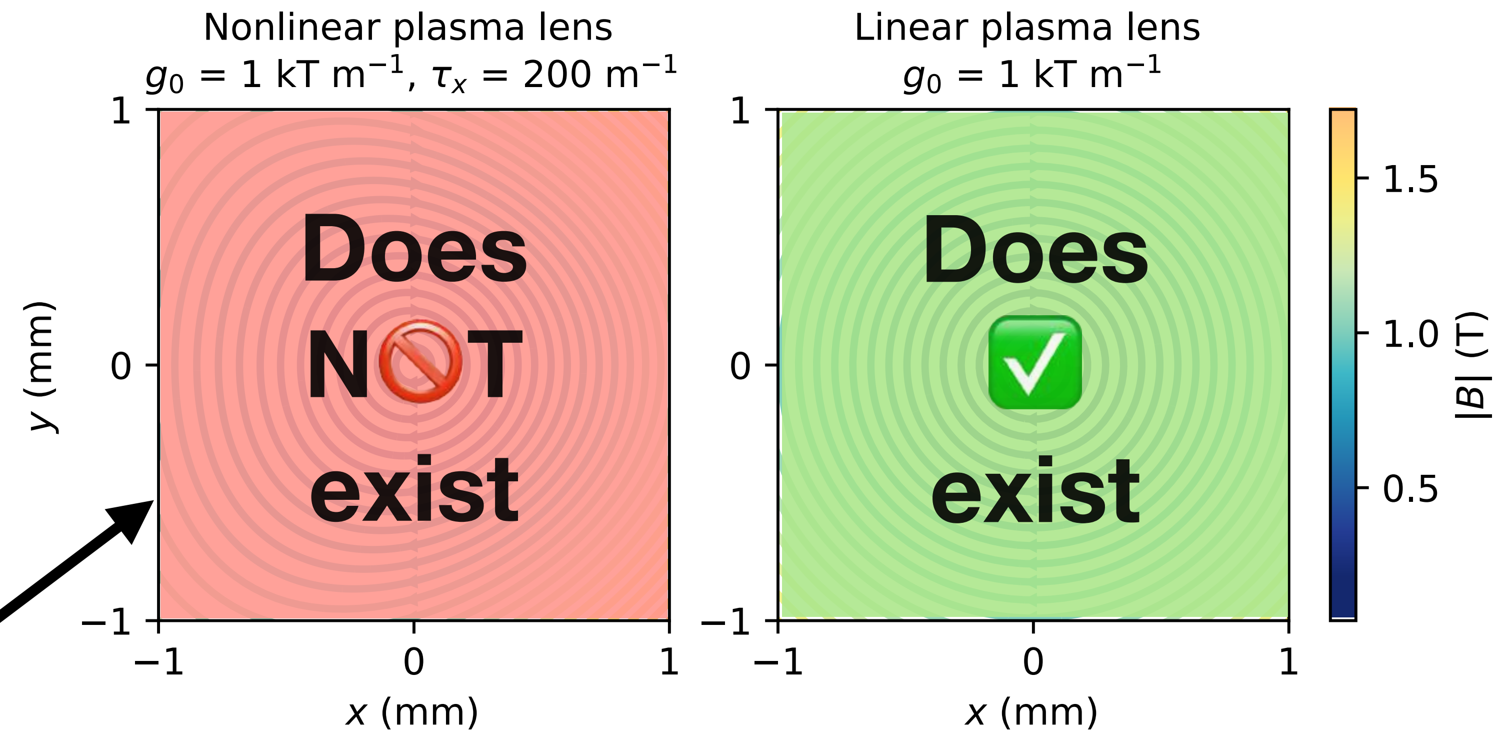
Novel achromatic staging optics

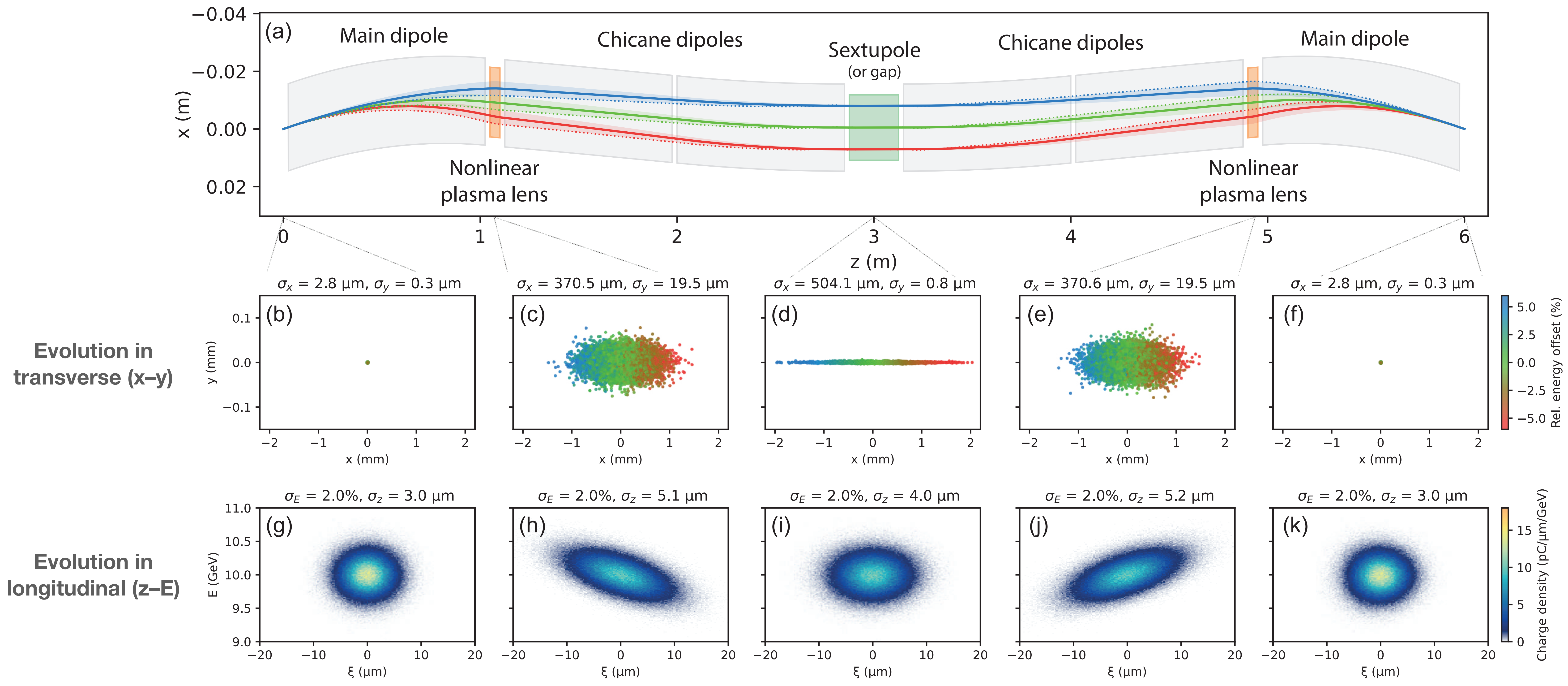
Local chromaticity correction and a new plasma lens

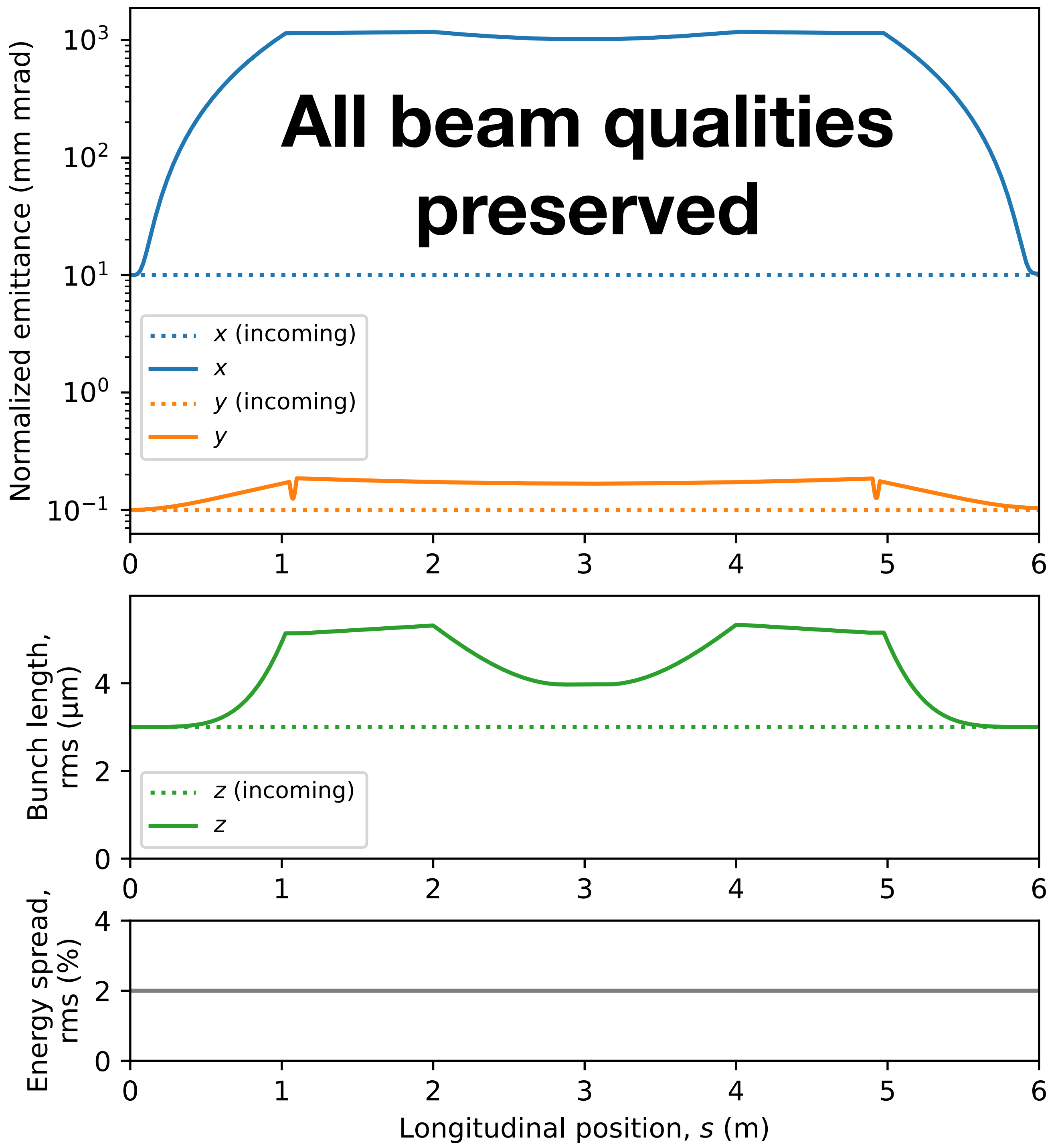
> Inspiration: chromaticity correction in collider final focusing
>> *Disperse, apply stronger focusing for higher energies (+ vice versa)*

> Made compact and simple using a **nonlinear plasma lens**

Development required!



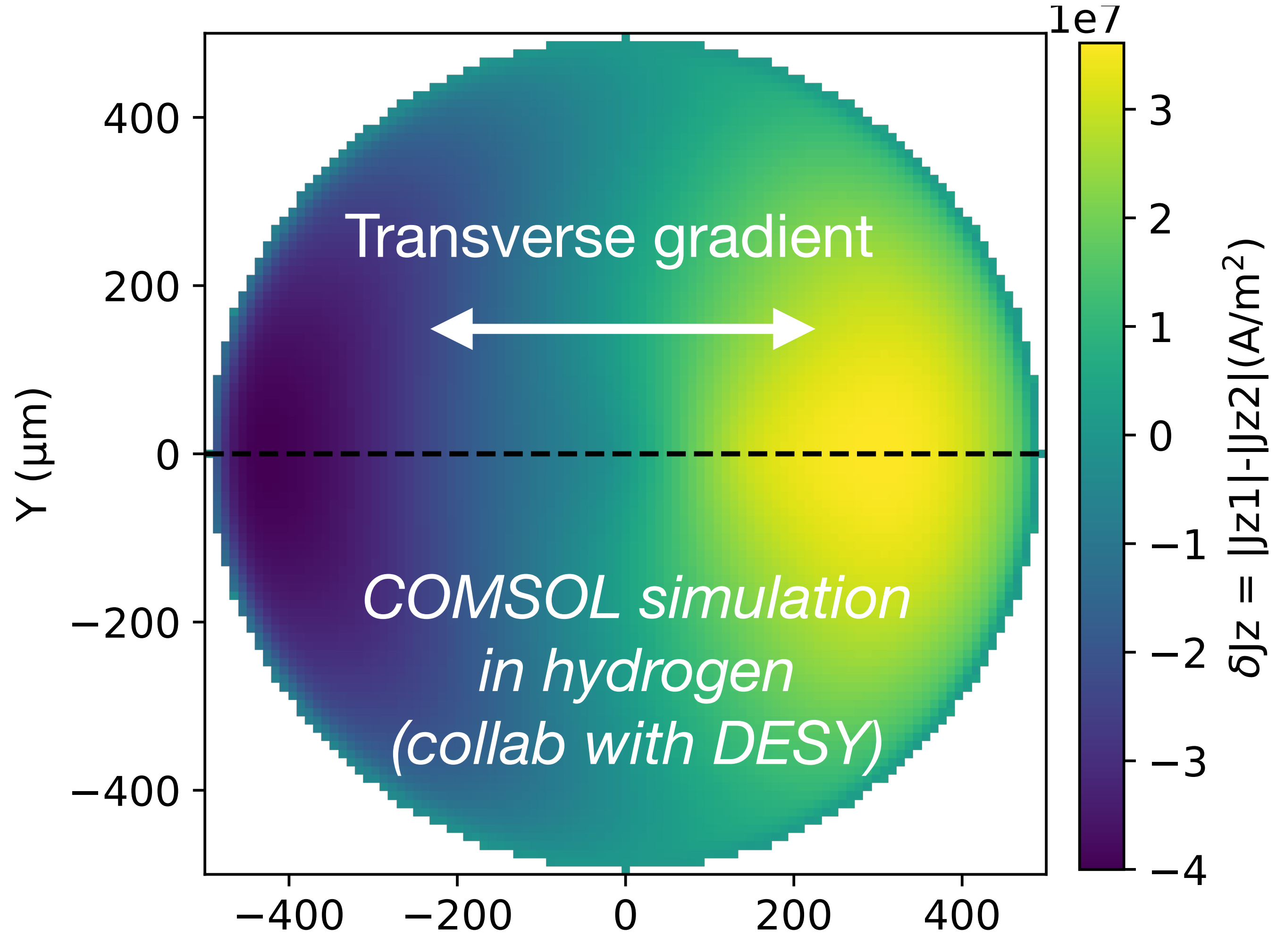




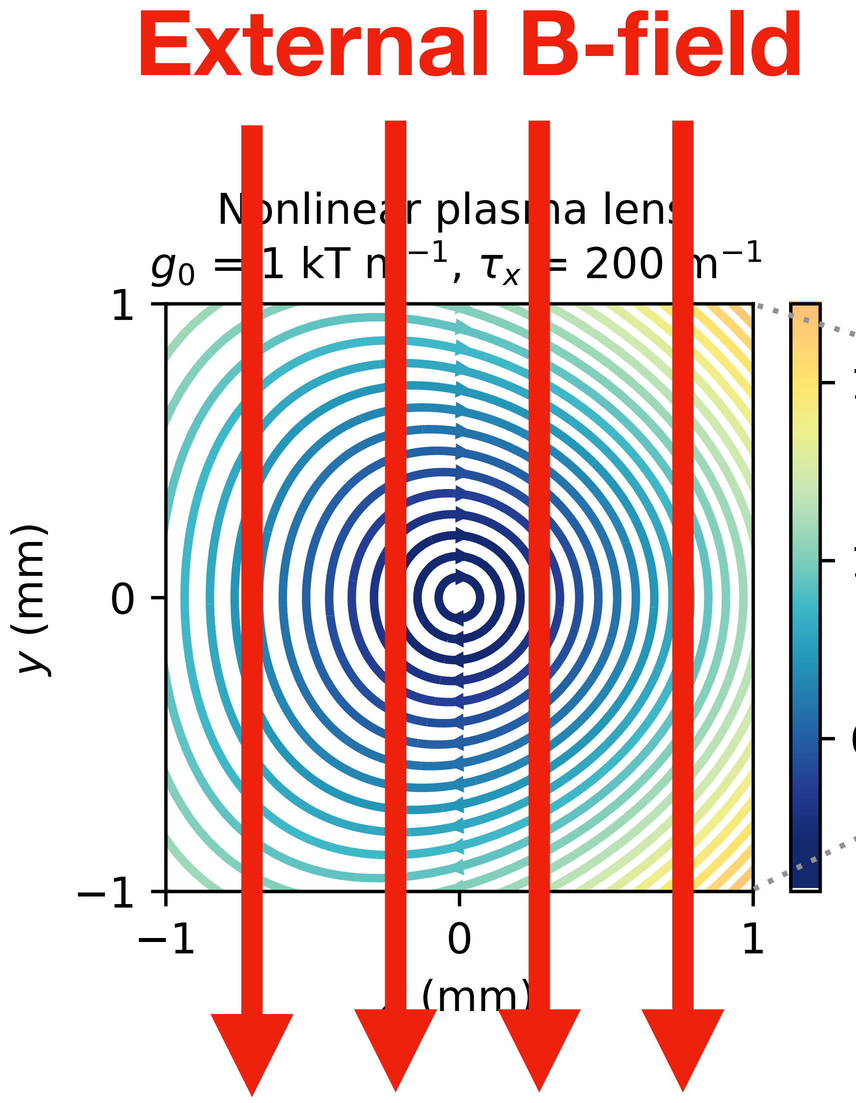
Source: ***Lindstrøm et al., arXiv:2604.17605 (2026)***

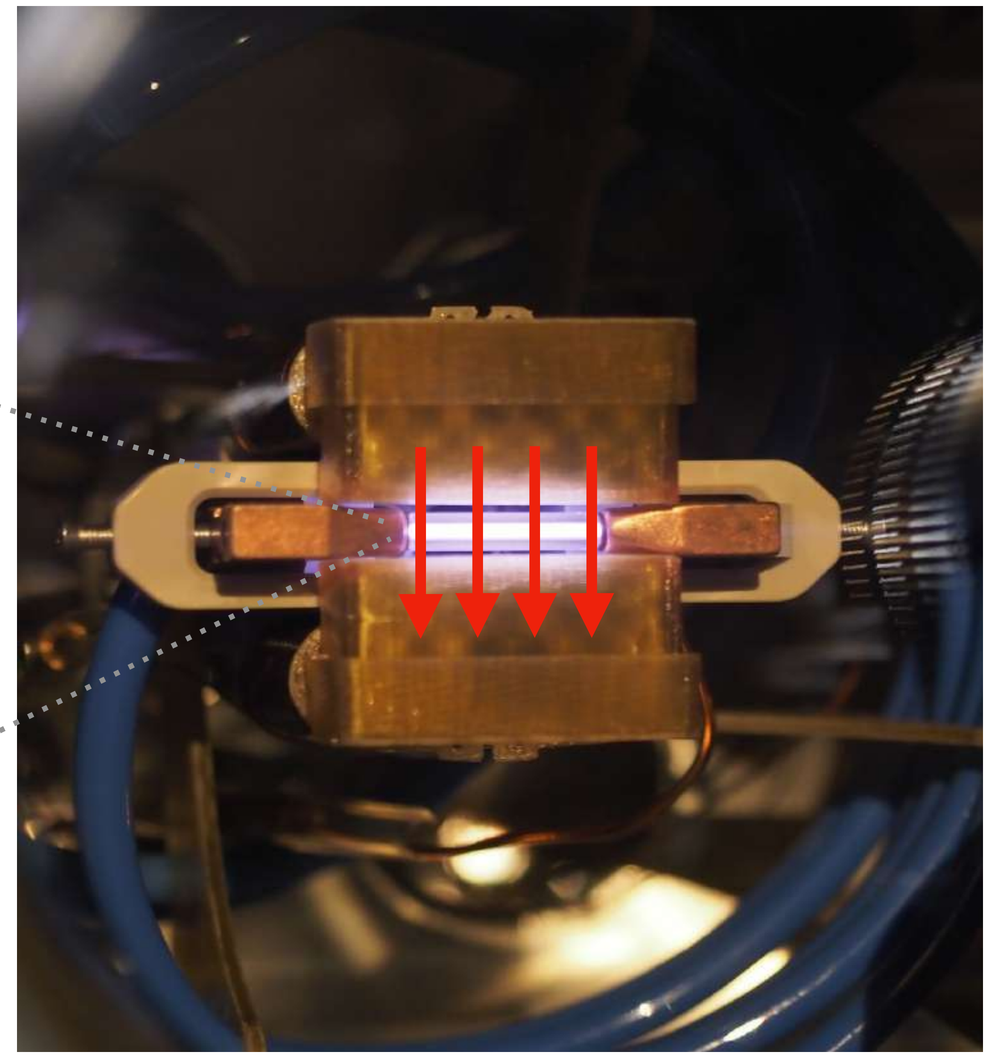
Development of a nonlinear plasma lens

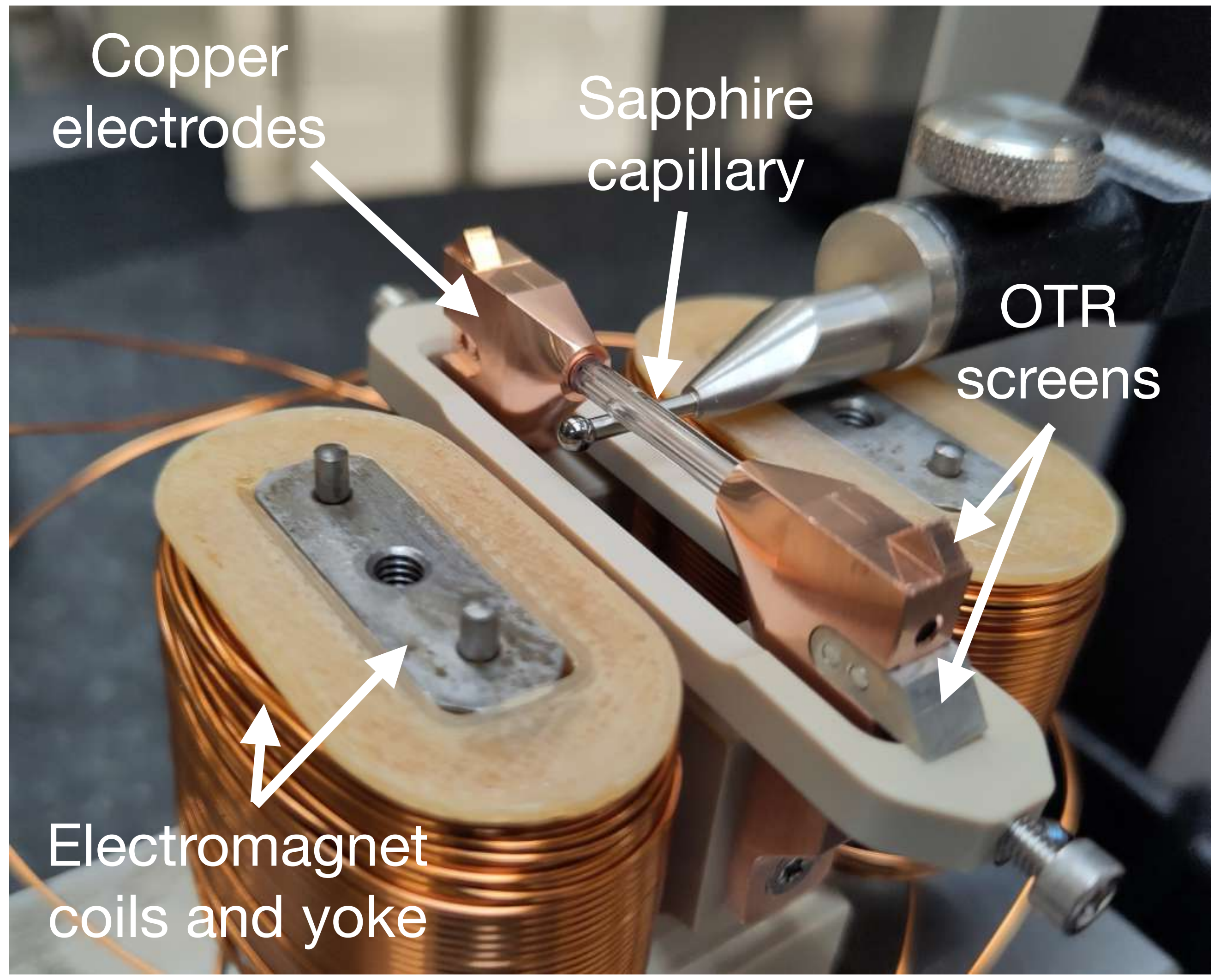
Exciting a nonlinearity through the Hall effect



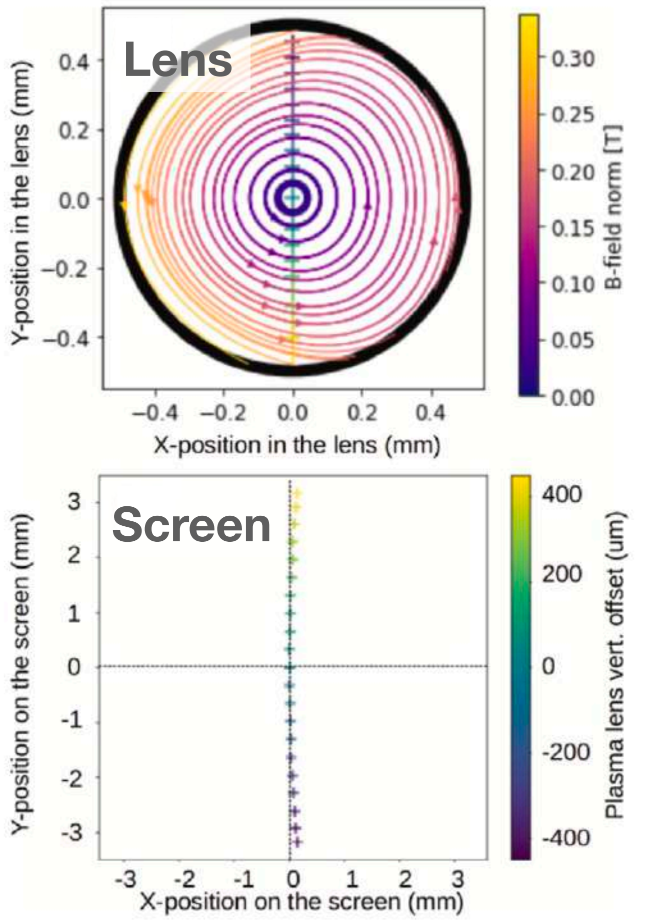
Source: P. Drobniak et al., Proc. IPAC (2025), p. 641

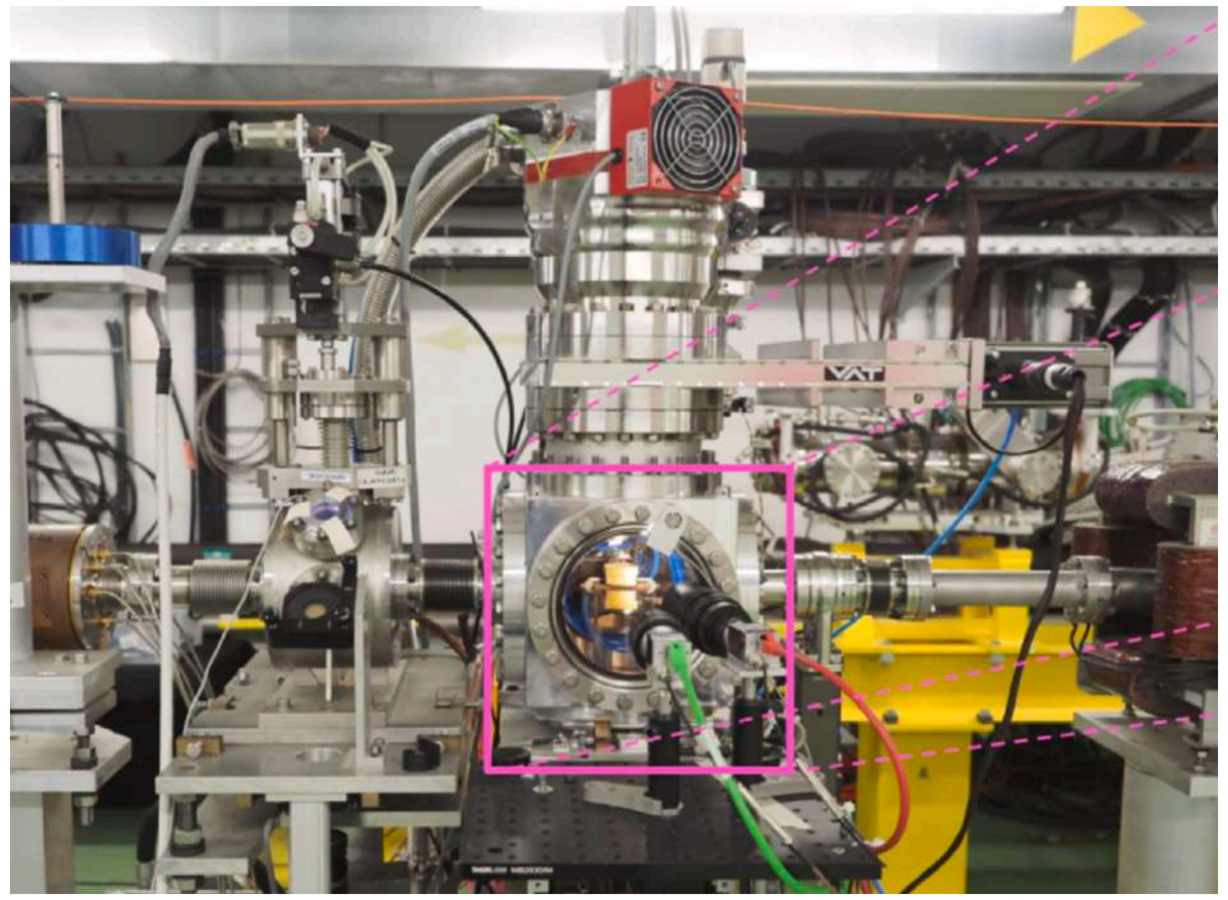






- Concept: apply an external B-field to induce Hall effect
  - *Shifts the discharge current to one side*
- MHD simulations (COMSOL) indicates the principle works.
- Designed/manufactured at Uni. Oslo (P. Drobniak *et al.*).
- Characterized with *e*-beam in CLEAR @ CERN (June 2025).





Source: P. Drobniak et al., NIM A 1072, 170223 (2025)

Part 2:

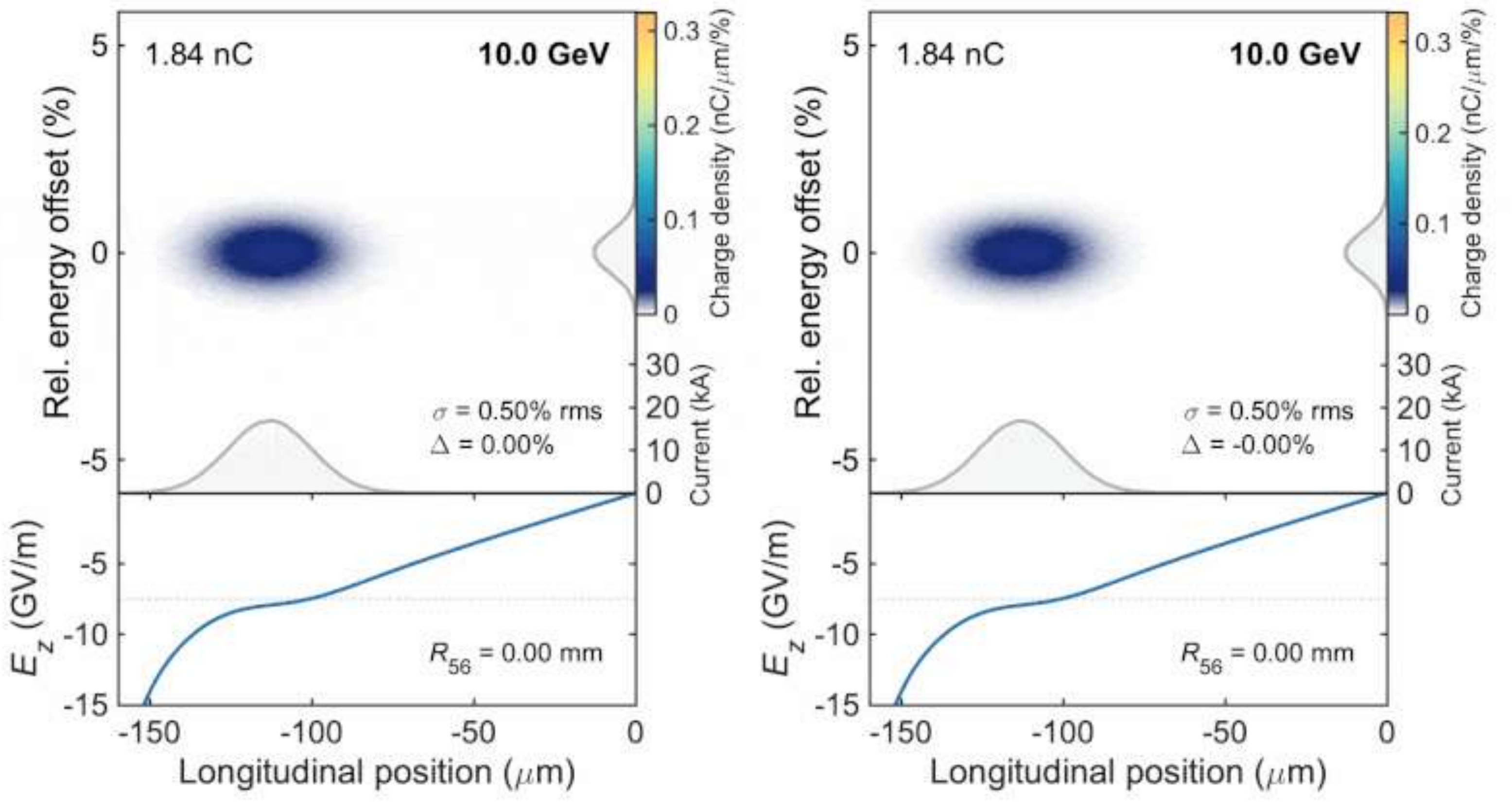
Stabilization

Through **passive stabilization mechanisms**

Passive stabilization mechanisms

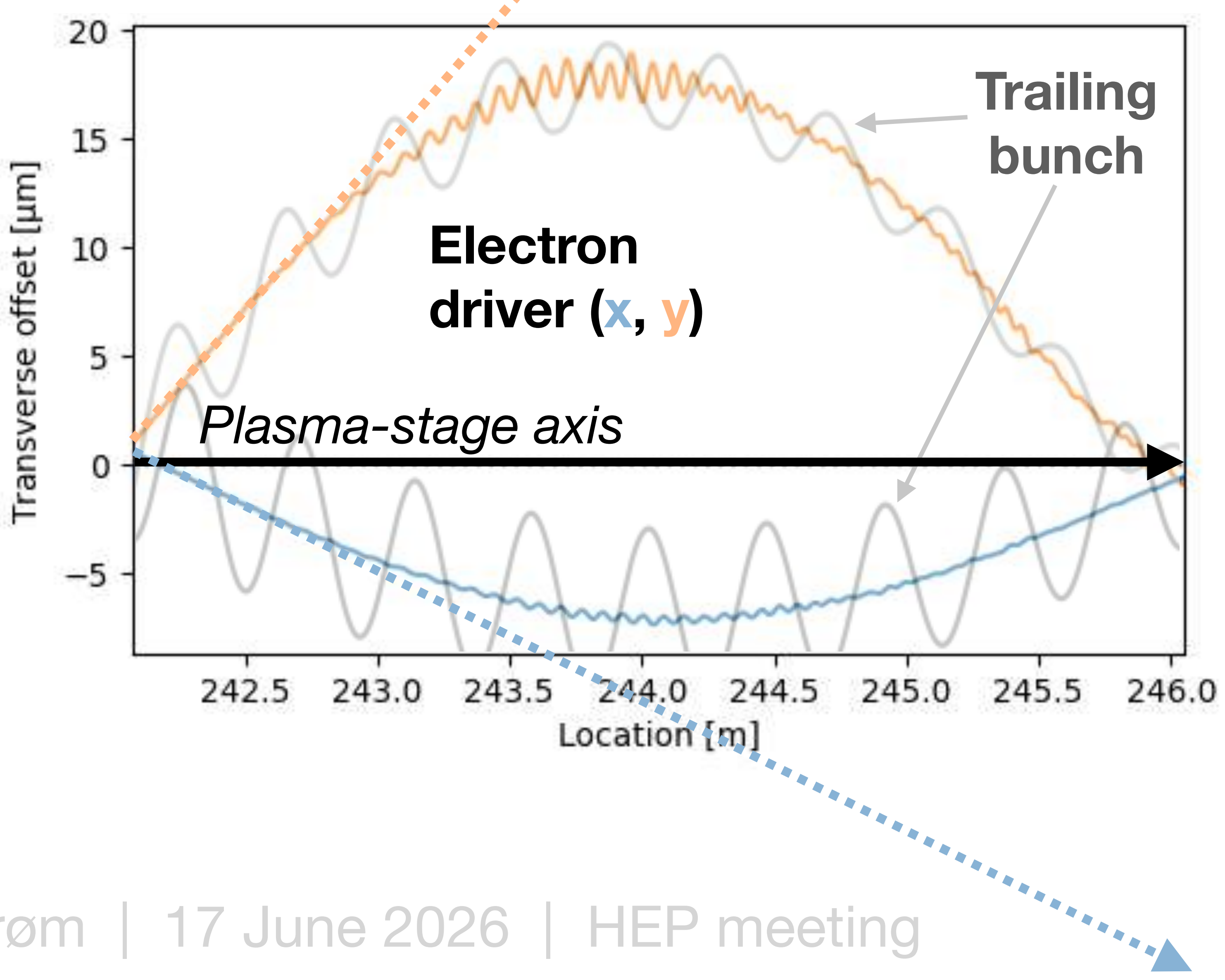
In the longitudinal and transverse phase space – critical for operation with realistic jitter

> **Self-correction in longitudinal phase space**
>
> > Introduce $\underline{R_{56}}$ between stages
>
> > Stabilizes the accel. phase (reduces energy offset)
>
> > Automatic wakefield flattening (reduces energy spread)

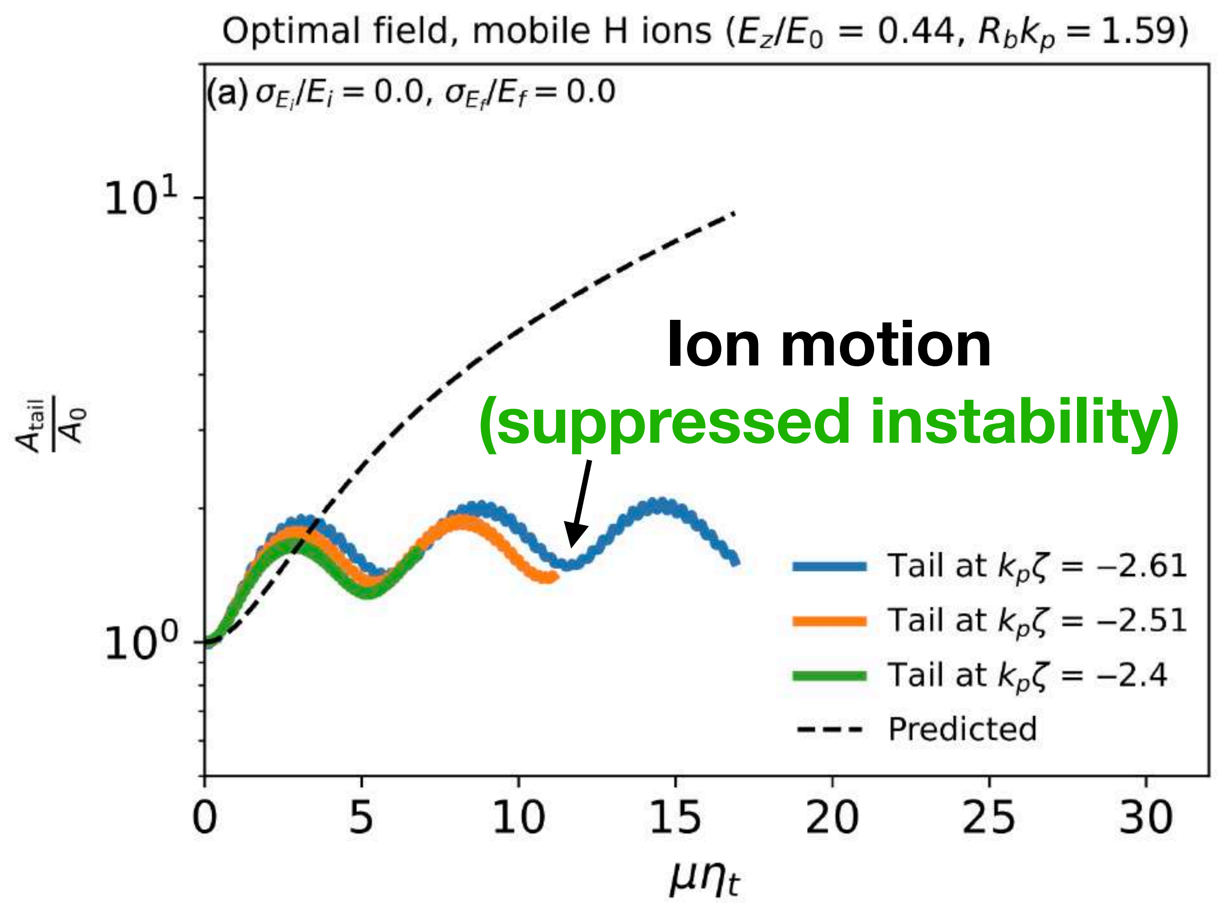


Source: Lindstrøm, arXiv:2104.14460 (2021)

> **PWFA driver guiding**
>
> > Introduce weak <u>APL field</u> in plasma source (180° phase advance)
>
> > Cancels transverse offset from incoming driver angle



> **Ion motion for beam-breakup suppression**
>
> > Use <u>light ions</u> (H or He) to introduce some nonlinear focusing
>
> > Suppresses BBU instability



Source: Finnerud et al. PRAB 28, 071301 (2025)

Part 3:

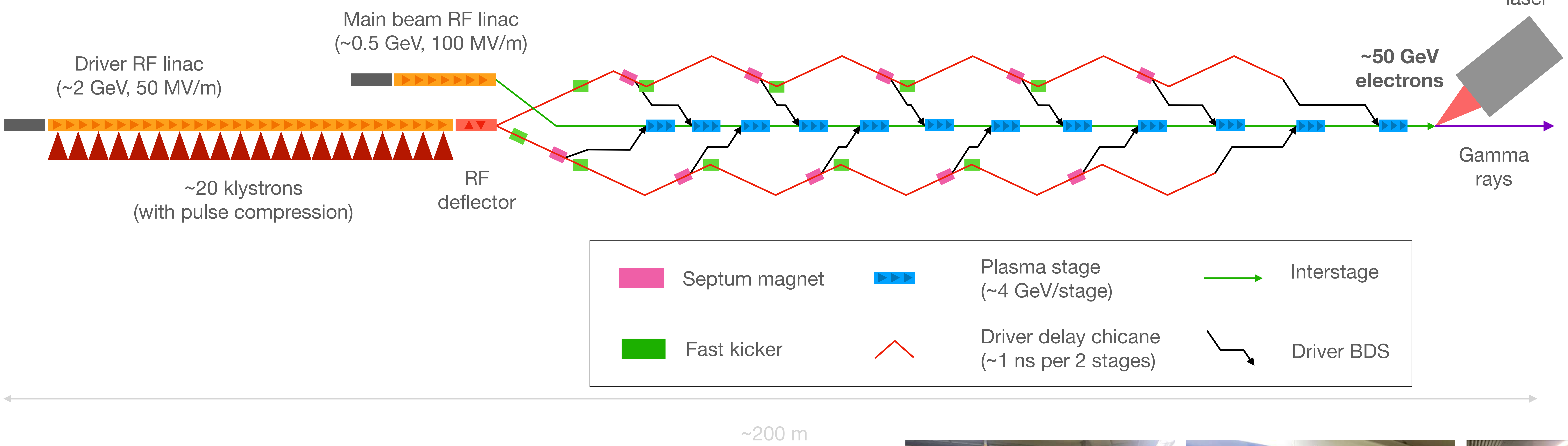
Demonstrator

Conceptual design of a 50-GeV SFQED facility

Conceptual design of a multistage plasma accelerator

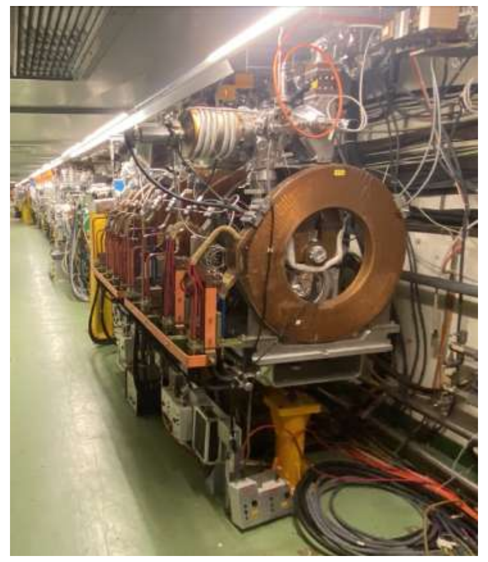
The SPARTA demo machine – a first step toward a collider-grade beams

> *Ultimate goal:* Design a self-consistent, multistage plasma accelerator with a SFQED application

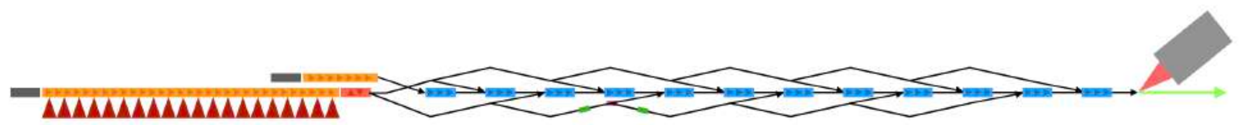


> *Example: ~2 GeV e⁻ drivers, 12 stages @ 1 GV/m*
> *→ 50 GeV e⁻ + 2 PW laser → $\chi \approx$ **10–50***

> **Discussions ongoing toward implementation at DESY, re-using CERN infrastructure (no commitments yet)**

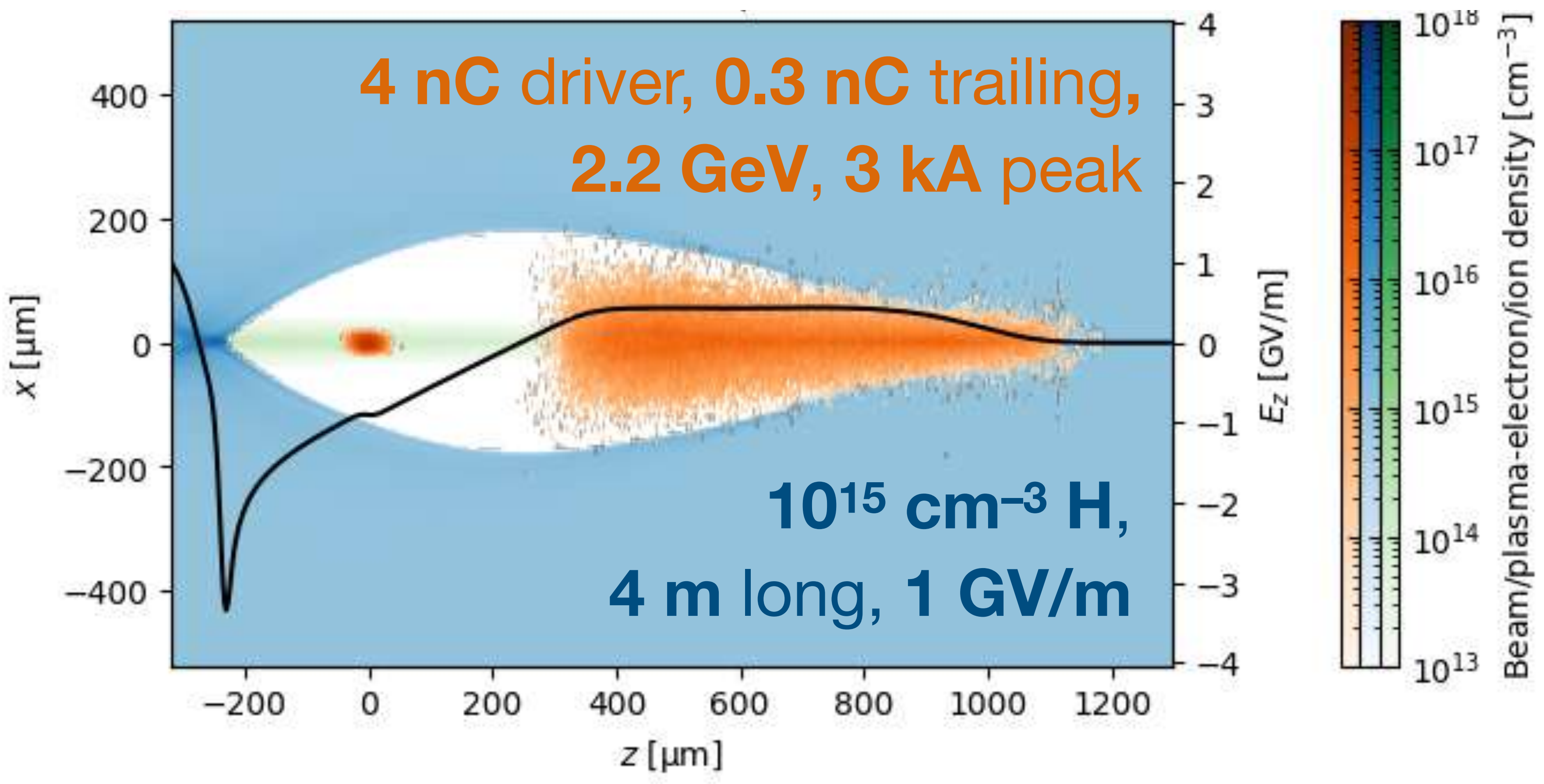


Start-to-end simulations of the SPARTA demo

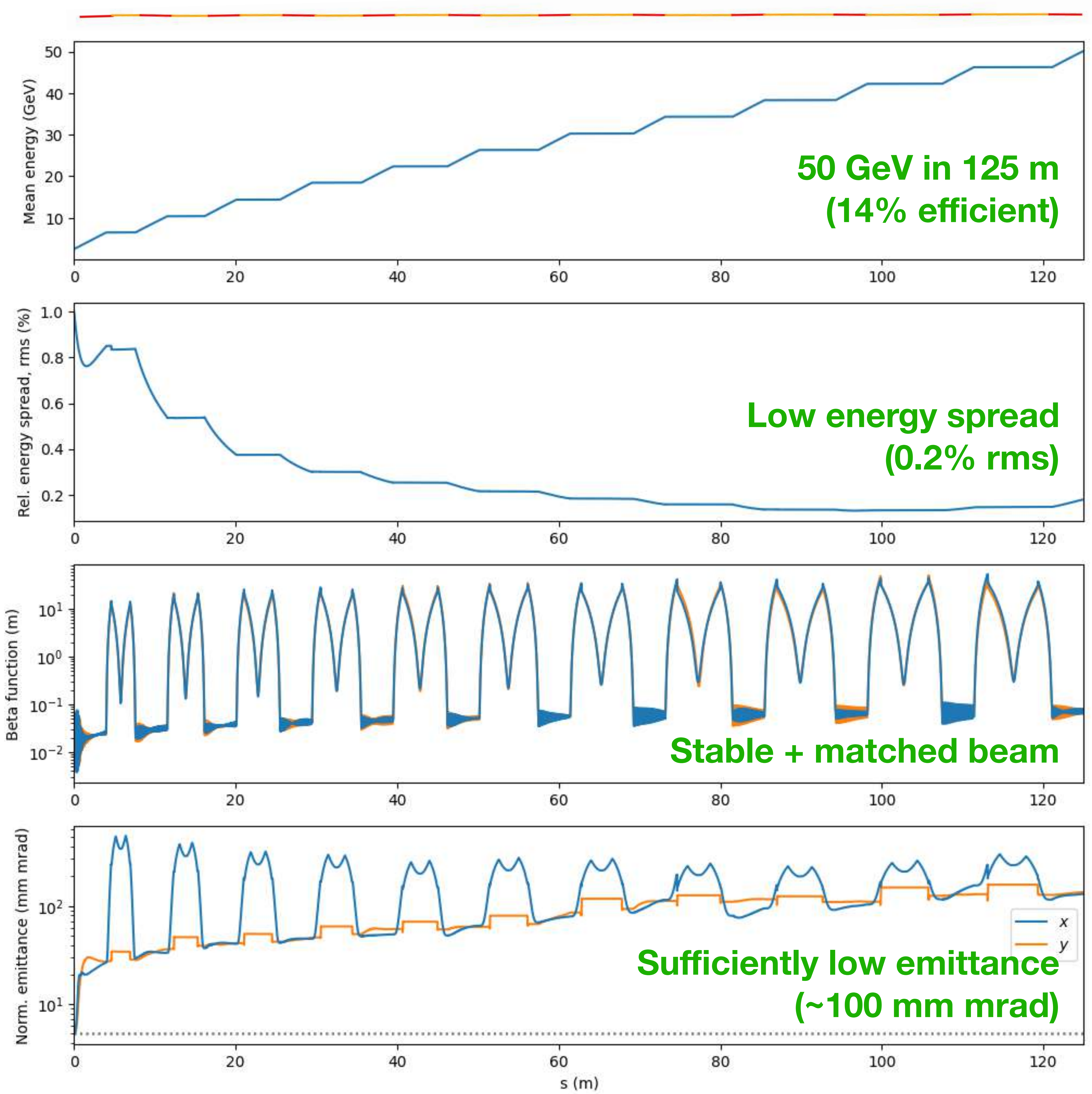


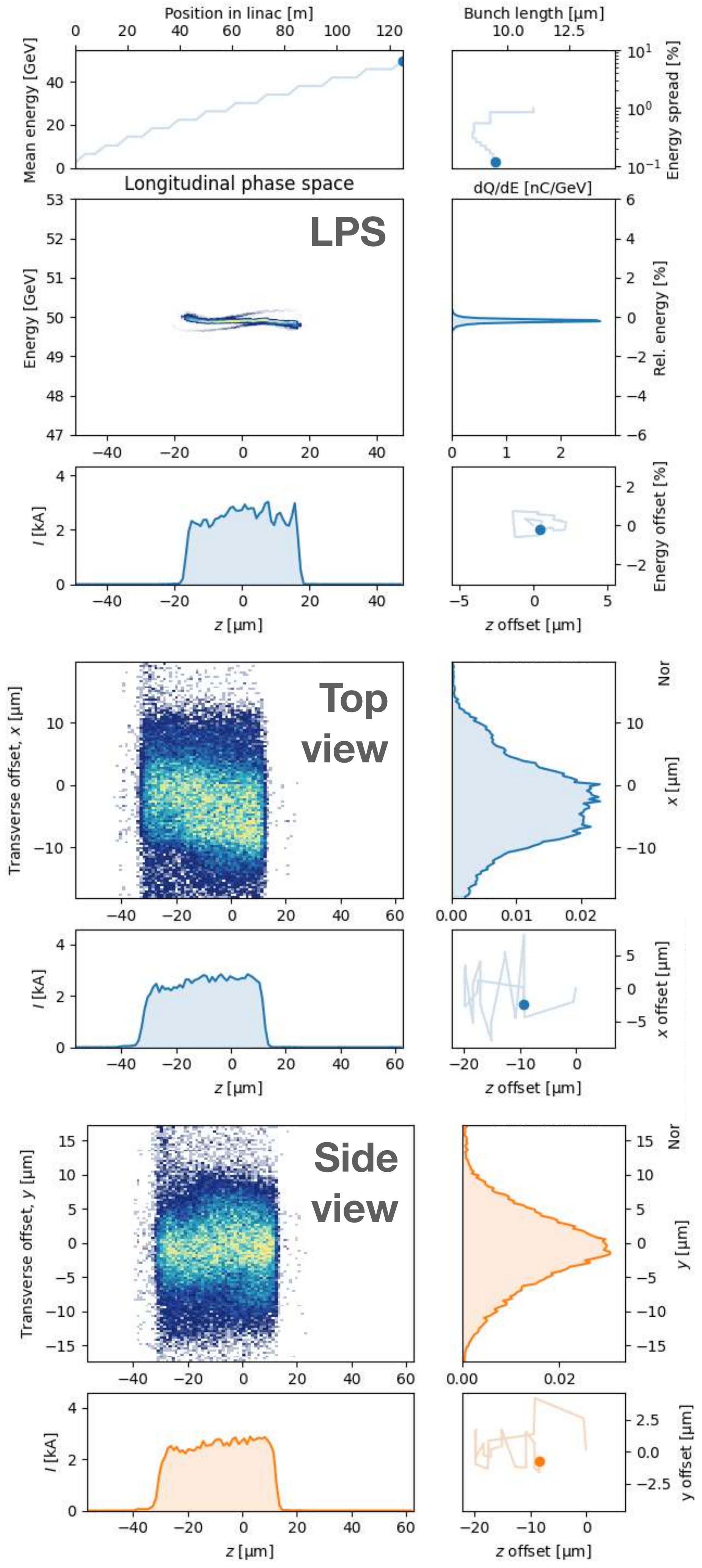
A preliminary working point

- HiPACE++ and ImpactX in ABEL
  - “Full” physics, 3D, high resolution
  - ~300 GPU hours per shot



- **Realistic jitters** (sampled in 3 shots)
  — Driver synchronization: 10 fs rms
  — Driver jitter emit.: 0.04 mm mrad
  — Plasma lenses: 1 µm rms (offsets)
  (Gaussian, sampled at every stage)



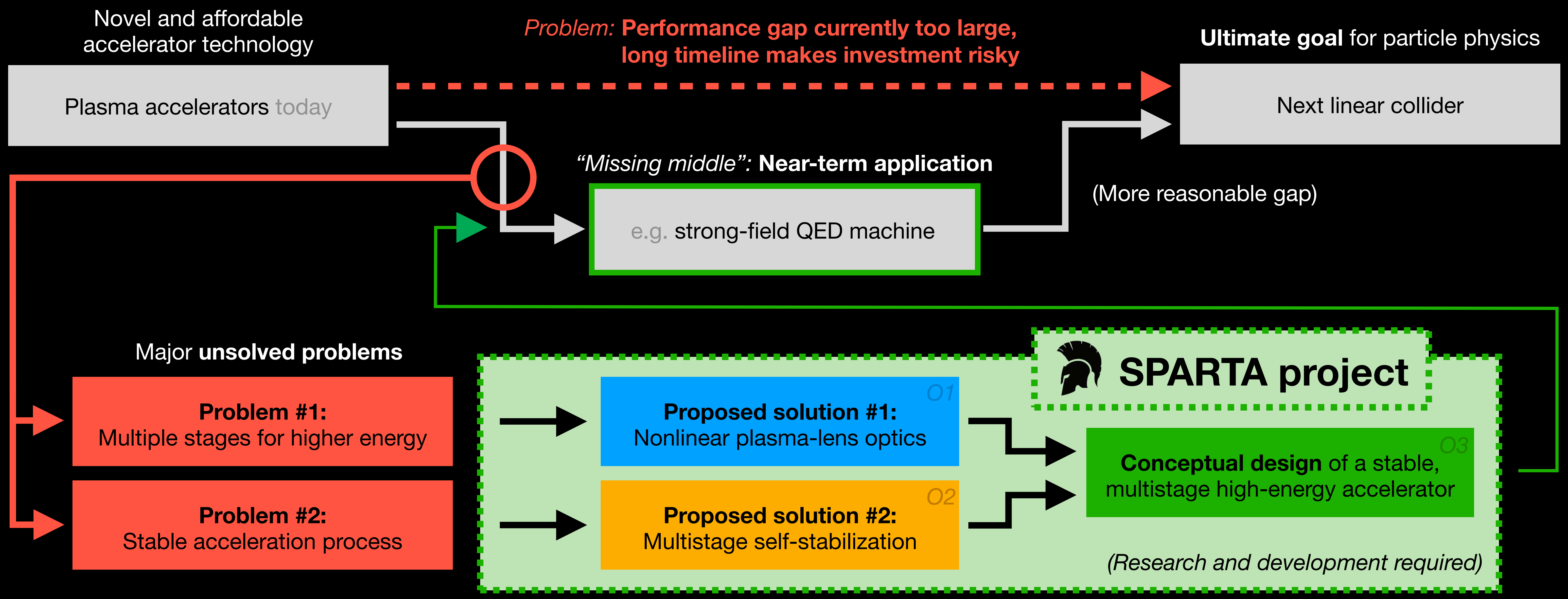


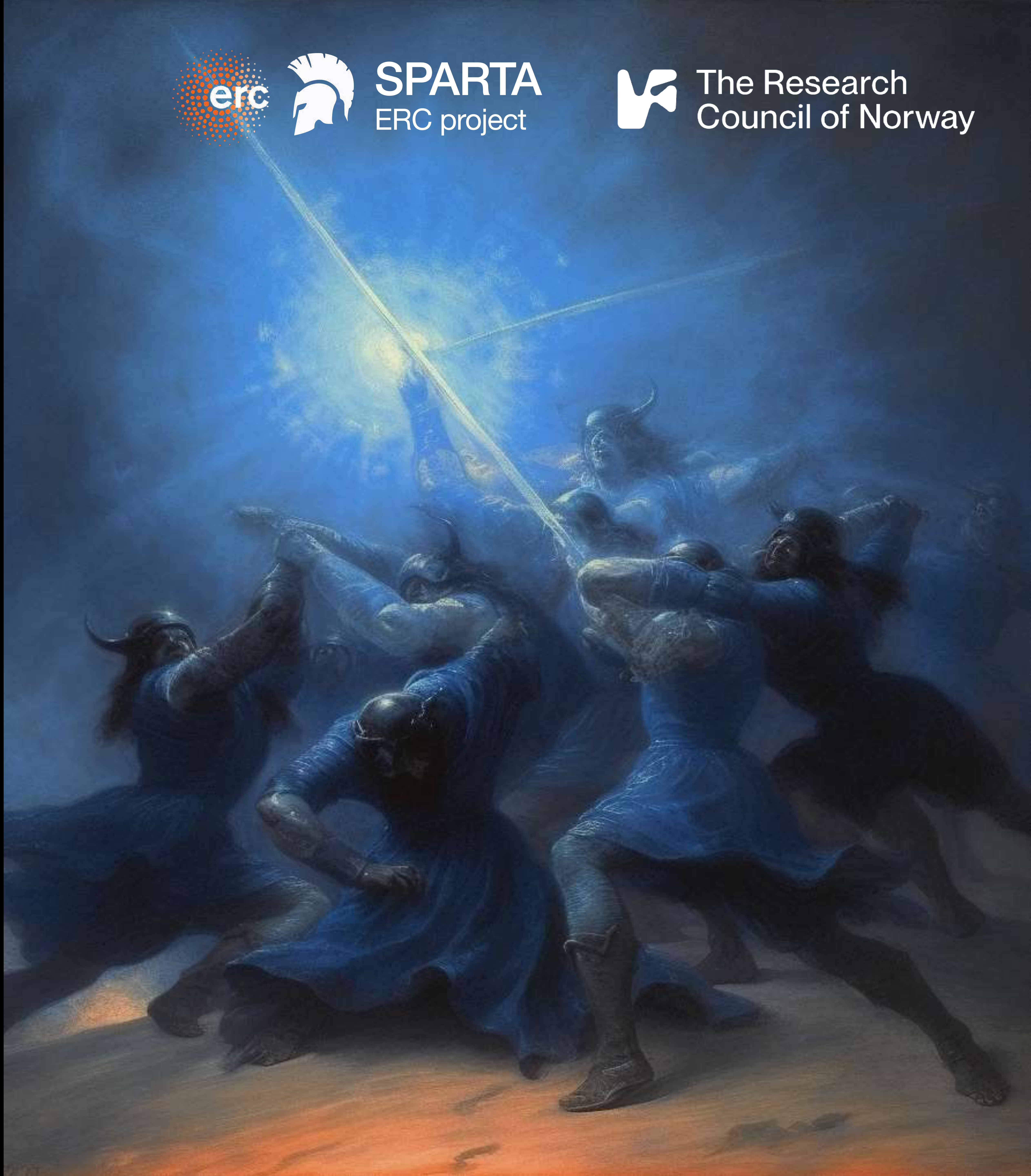
The SPARTA project

A summary

> Solve staging and stability → design multistage plasma accelerator → applications

> Good progress so far → discussions on implementation ongoing





Acknowledgements

Oslo accelerator group:
Erik Adli, Pierre Drobniak, Abélia Ellingsen,
Ole Gunnar Finnerud, Daniel Kalvik,
Carl A. Lindstrøm, Kyrre N. Sjøbæk

Funding:
European Research Council (ERC)
The Research Council of Norway