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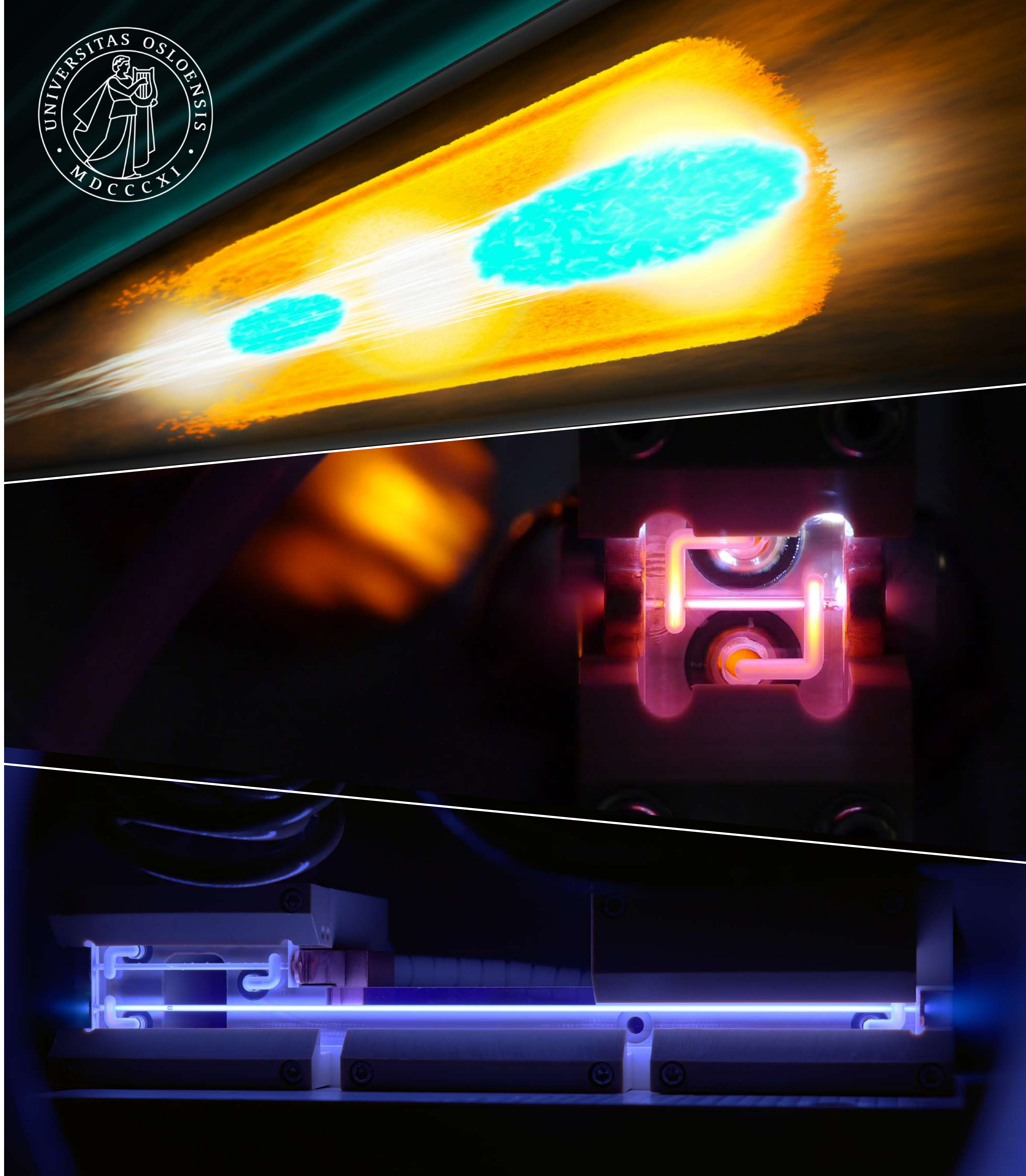
PWFA staging:
A compact energy multiplier for the C^3 demonstrator?

Carl A. Lindstrøm
University of Oslo

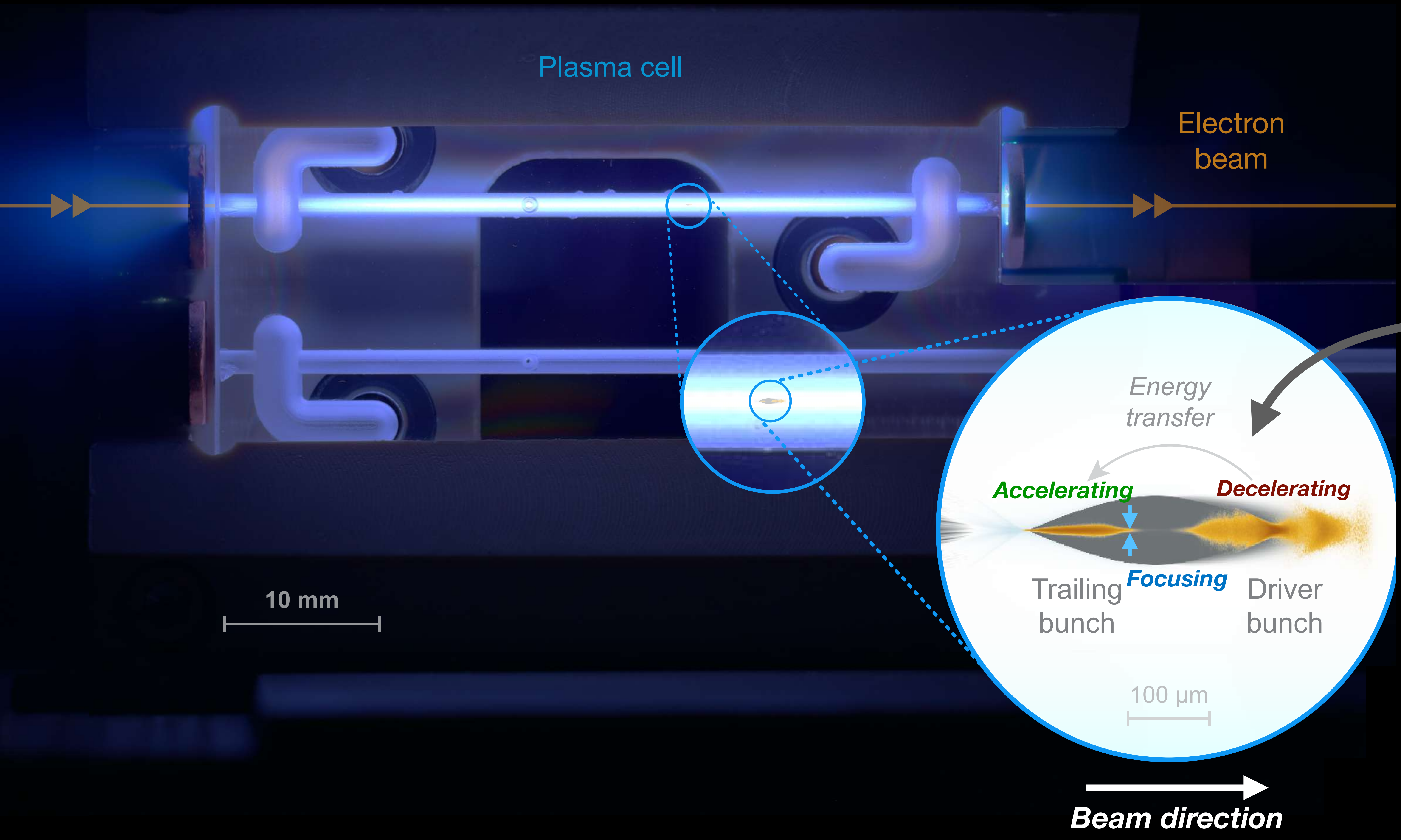
ERC Starting Grant — project SPARTA

13 Feb 2024 | C^3 Workshop



Plasma-based particle accelerators

Higher gradients (10–1000×, GV/m-scale) → even shorter/cheaper accelerators



- *Plasma wakefields*:
  - Driven by **lasers** or **particle beams**
  - **Accelerating**, **focusing**
  - 10–100 μm-scale (tiny!)

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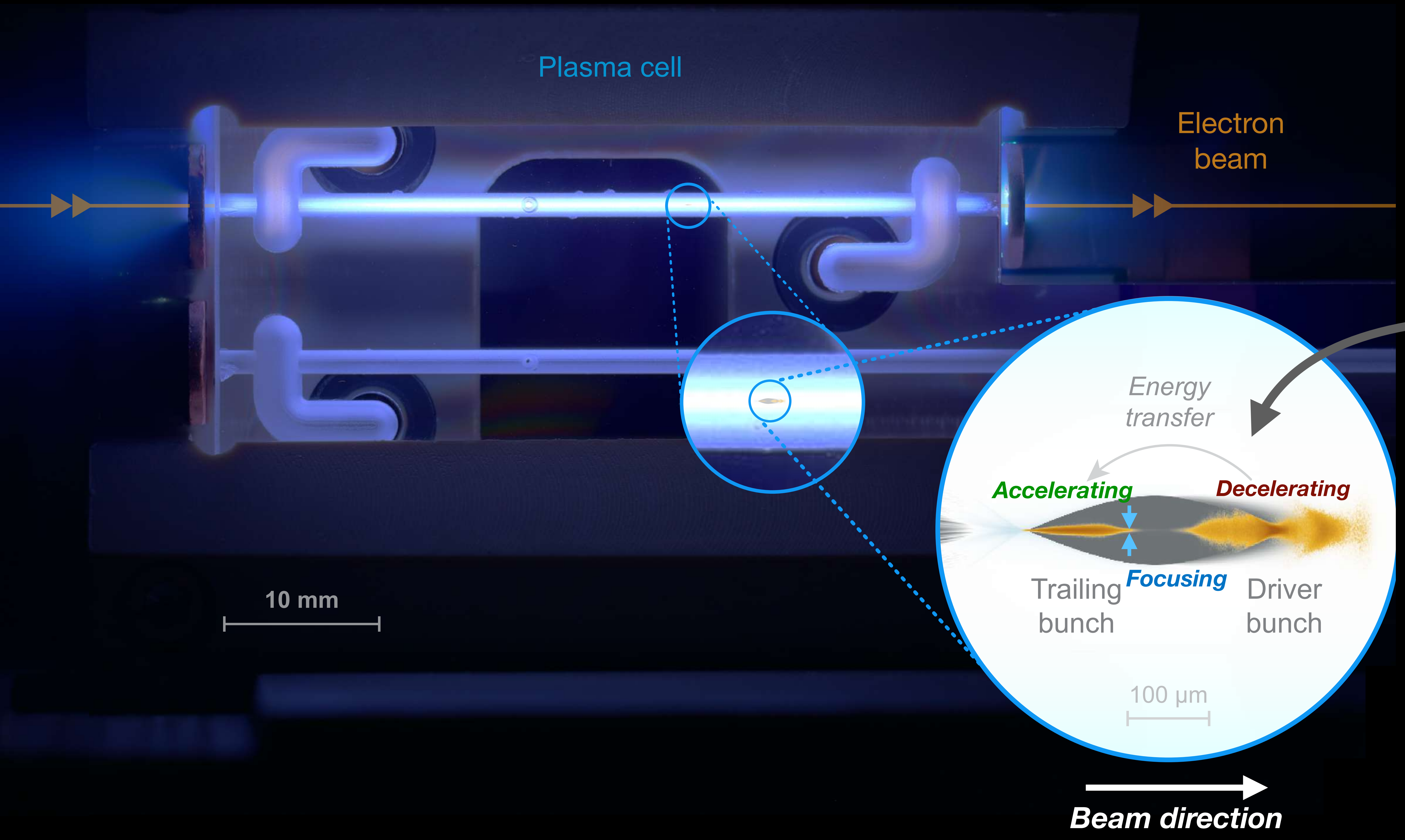

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  - Driven by lasers or **particle beams**
  - **Accelerating**, **focusing**
  - 10–100 μm-scale (tiny!)
- Recent application: FELs[2,3]
  - Why not HEP?

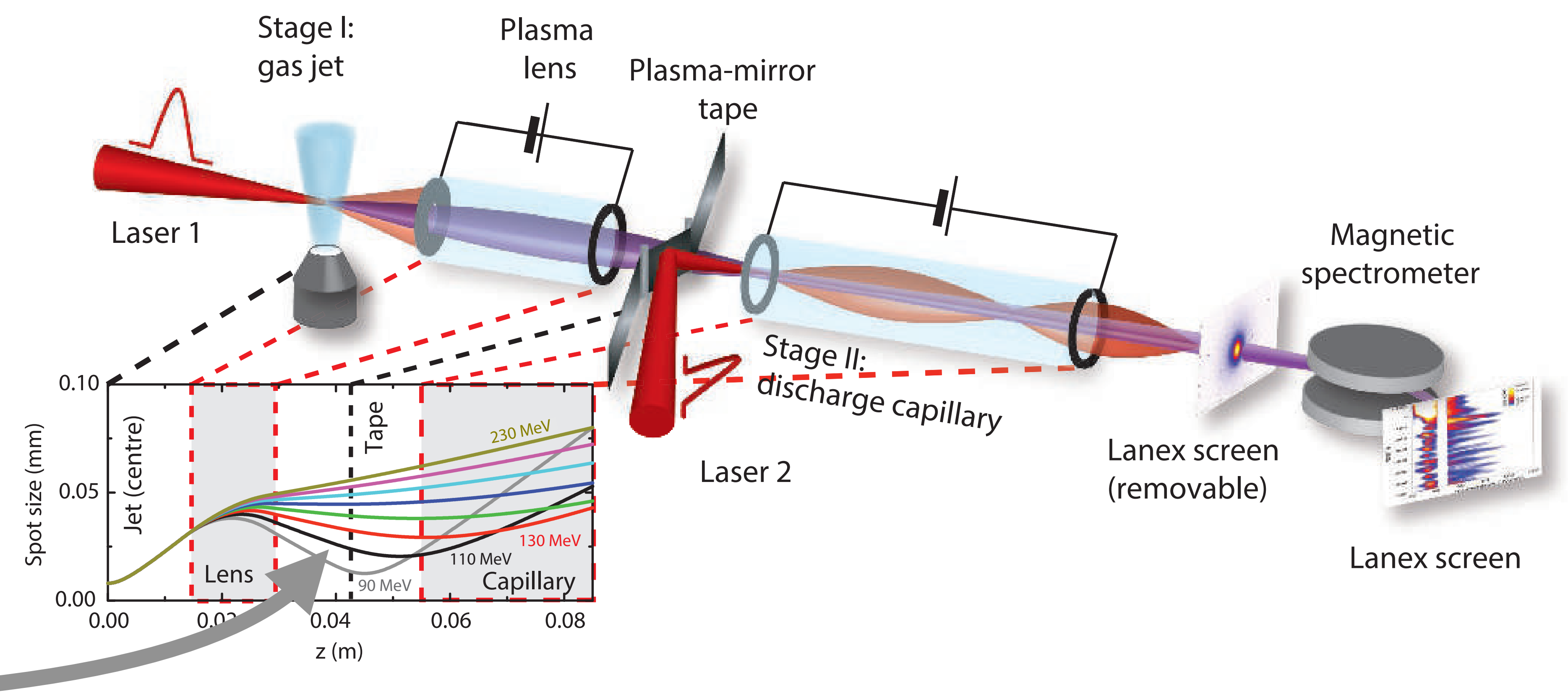
[2] Wang *et al.*, **Nature** 595, 516 (2021)
[3] Pompili *et al.*, **Nature** 605, 659 (2022)

Fundamental challenges: Prompting rethink of plasma accelerators

Staging (high energy unreachable in single stage) and ***stability***

1. **Staging problem**: *coupling beams between plasma accelerators (stages)*

- <u>In- and out-coupling</u> of drivers
- Refocusing beams → <u>chromaticity</u>



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

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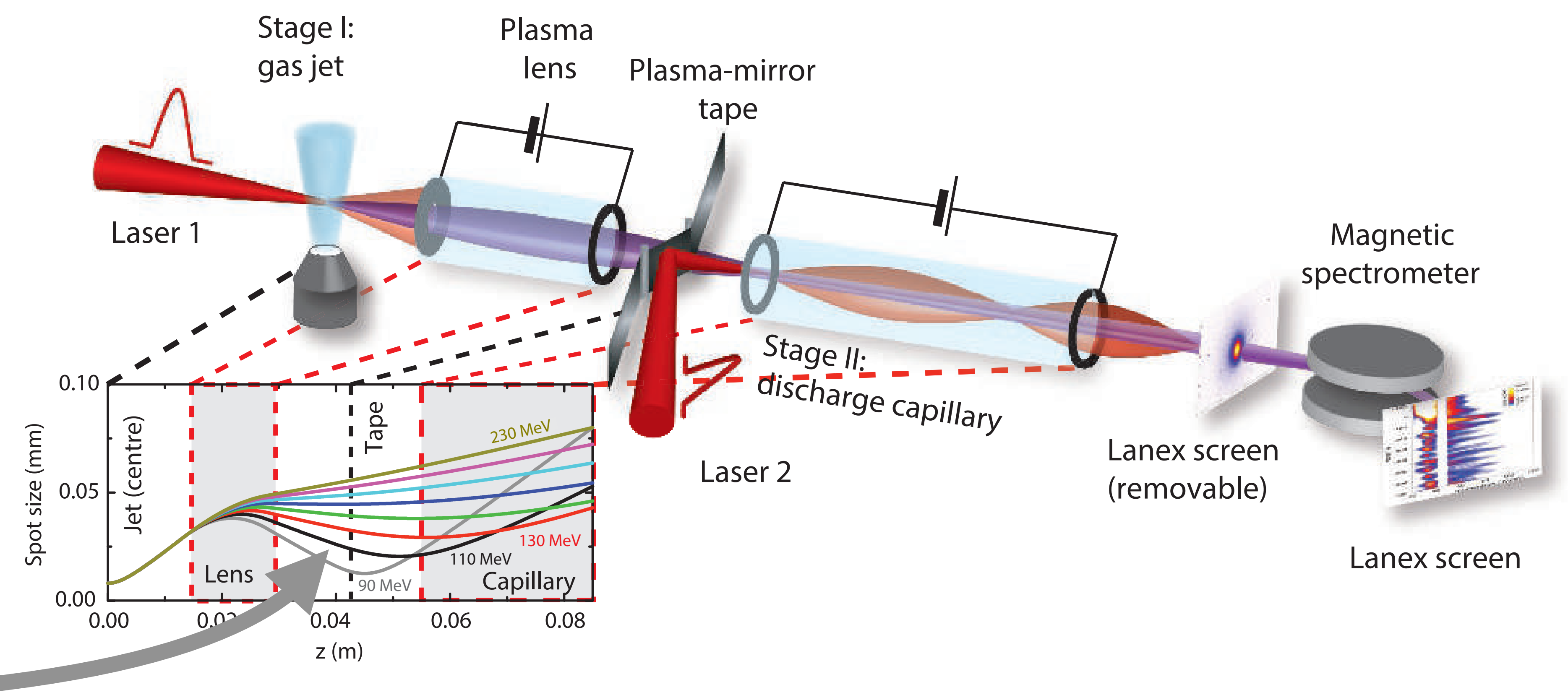

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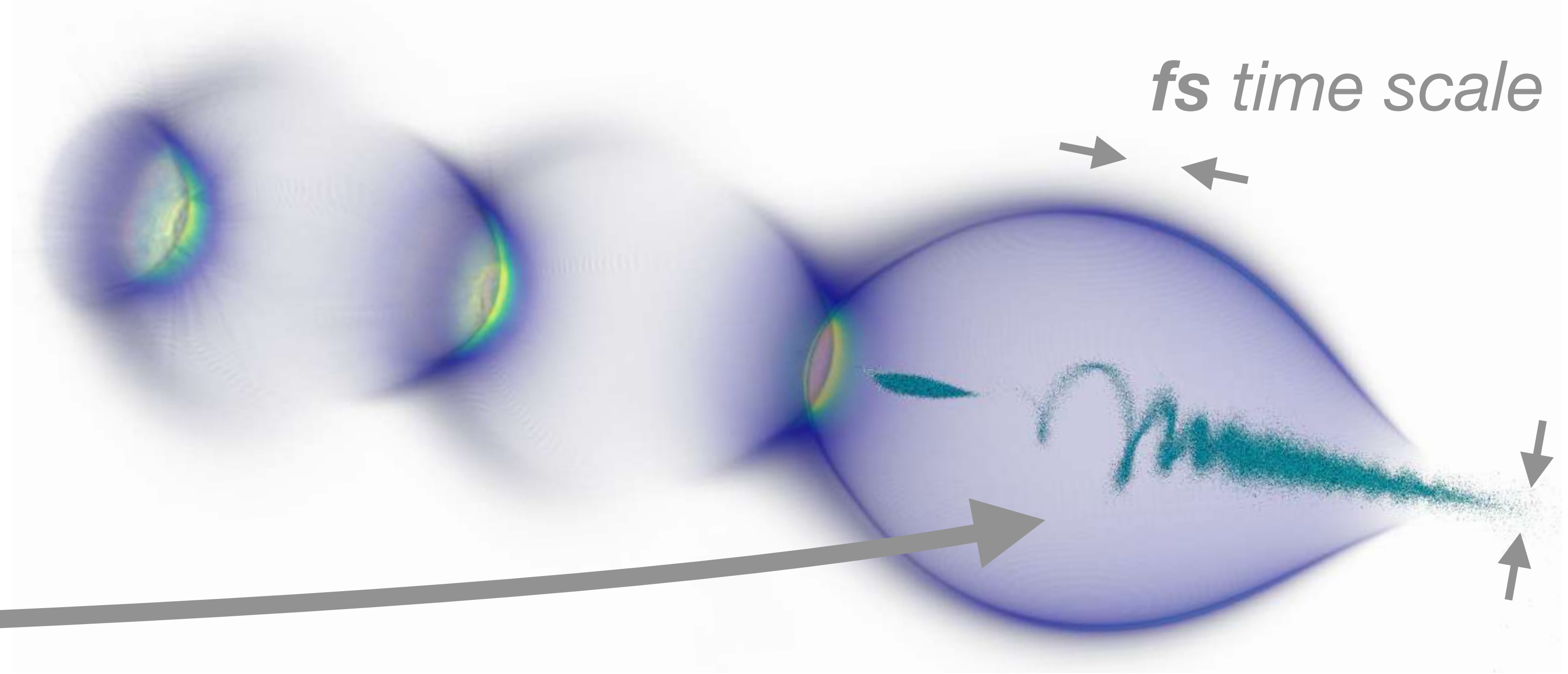
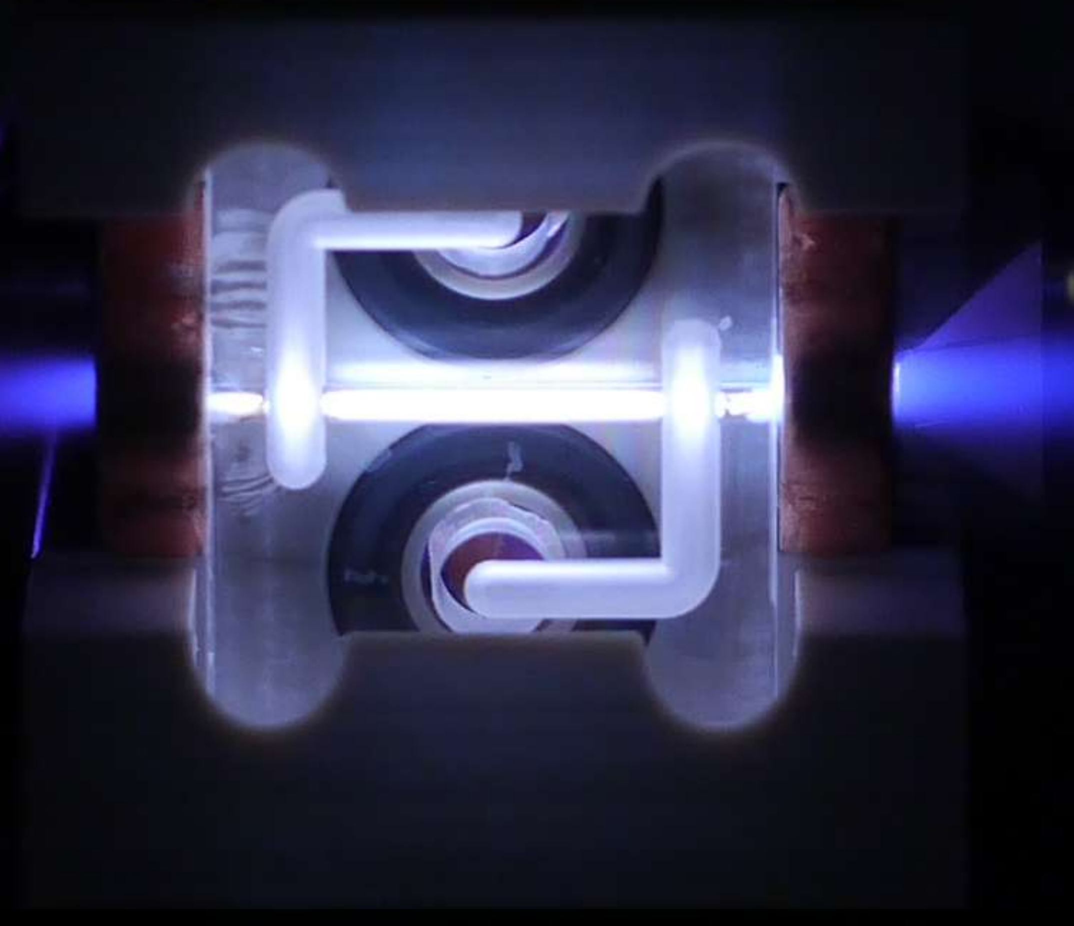
2. **Stability problem**: *extreme sensitivity*
    - μm/fs tolerances on alignment/timing
    - Instabilities



Particle-in-cell (PIC) simulation. Source: VisualPIC



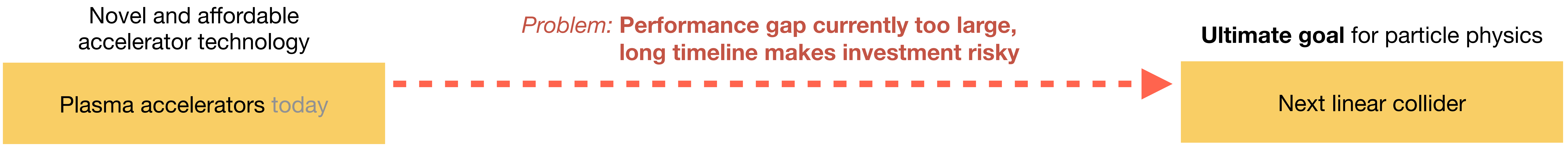
(Image of an “active” plasma lens)

SPARTA:

Staging of Plasma Accelerators for Realizing Timely Applications

The SPARTA project

A flow chart



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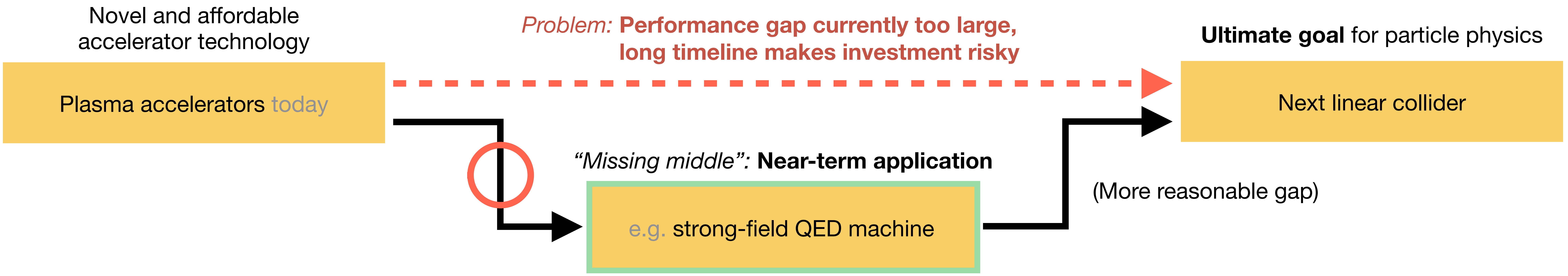

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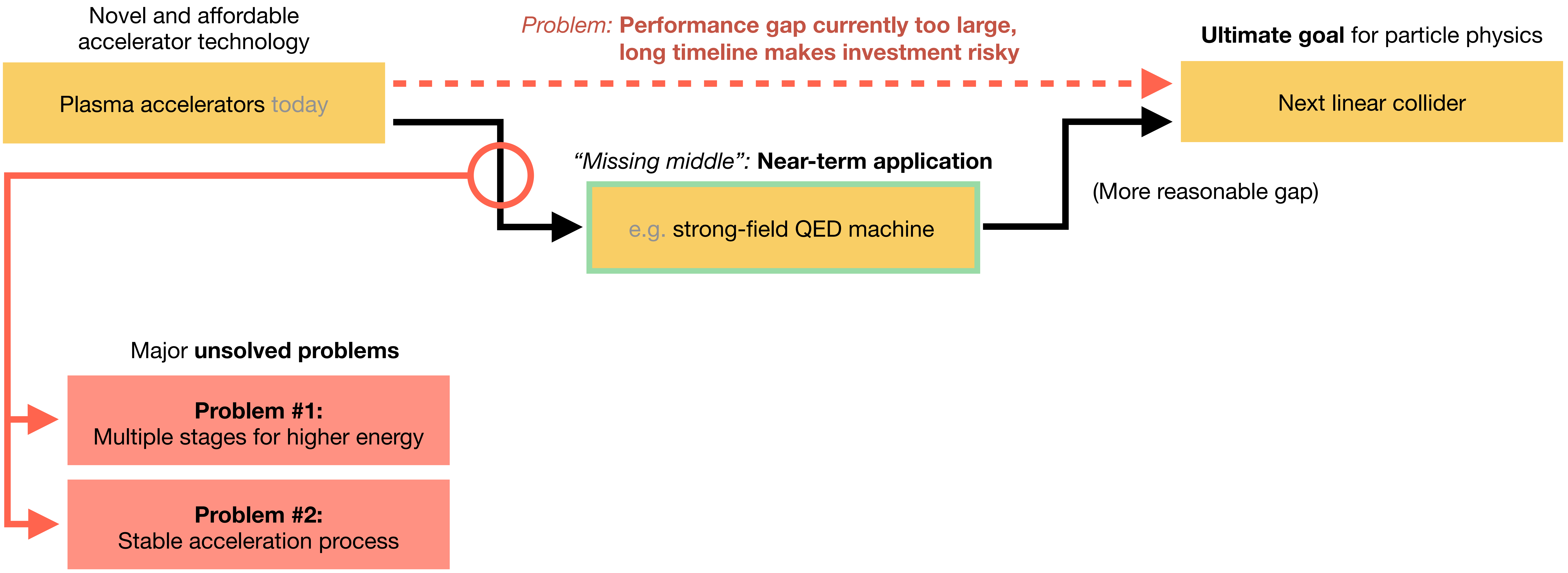

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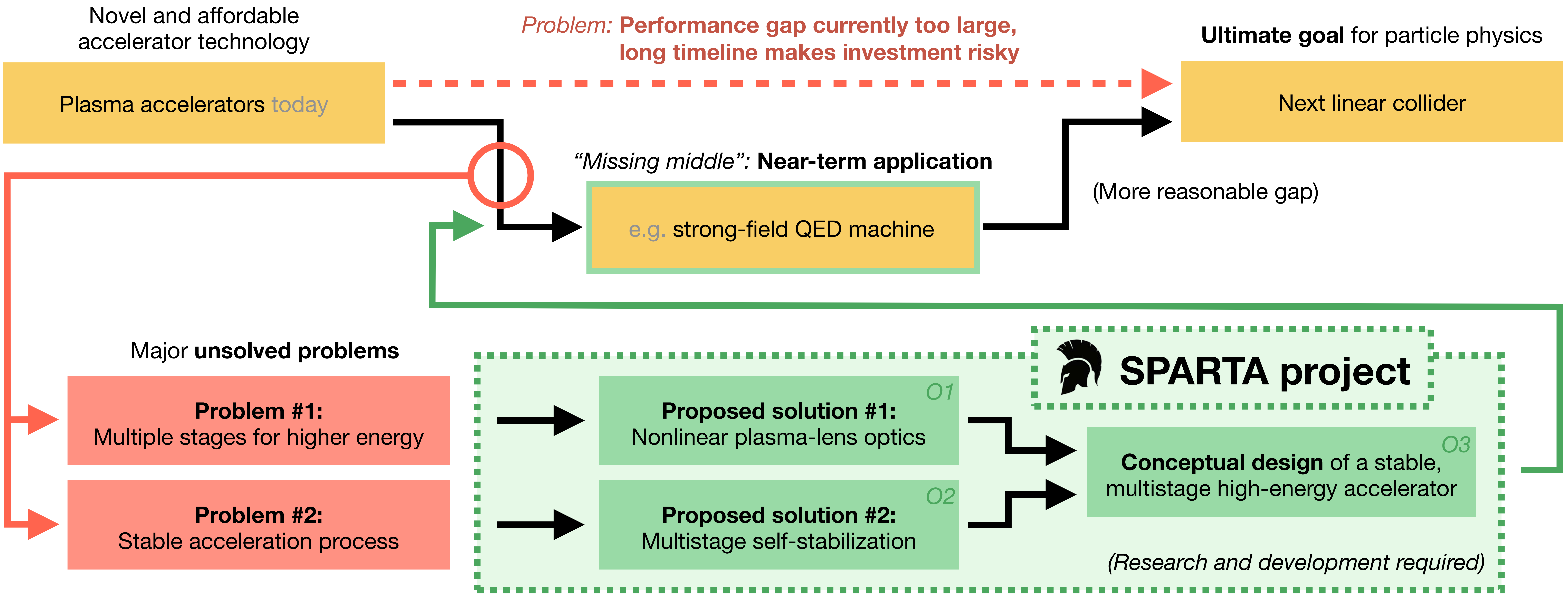

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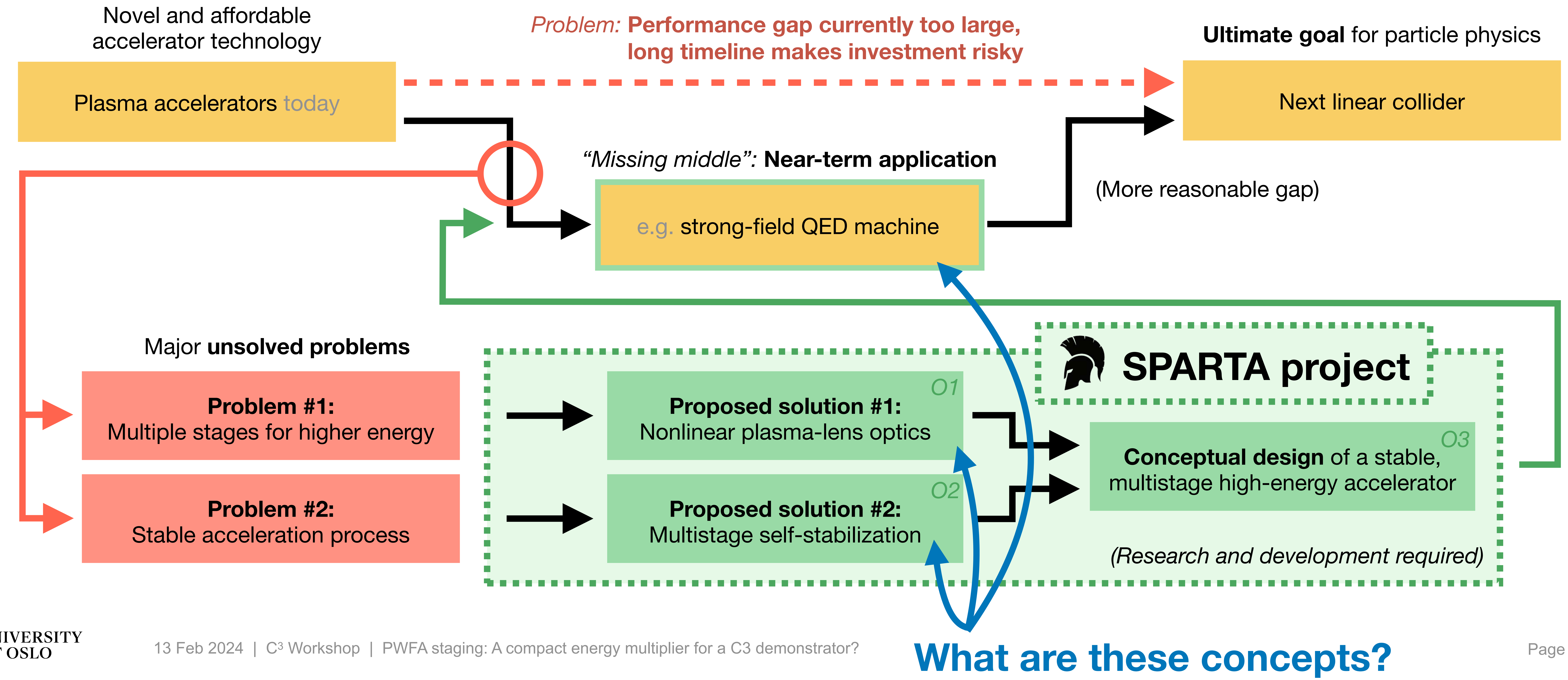
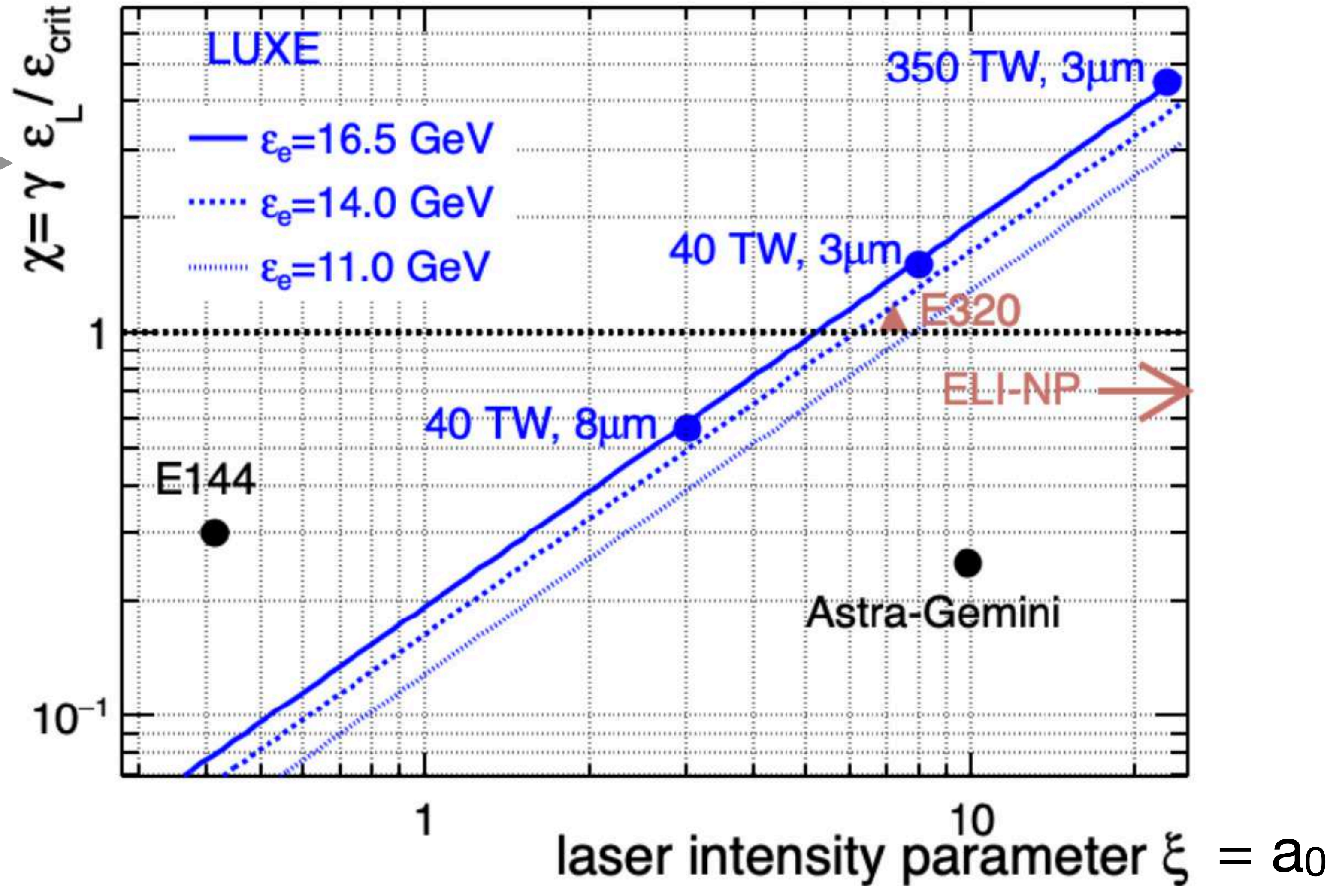


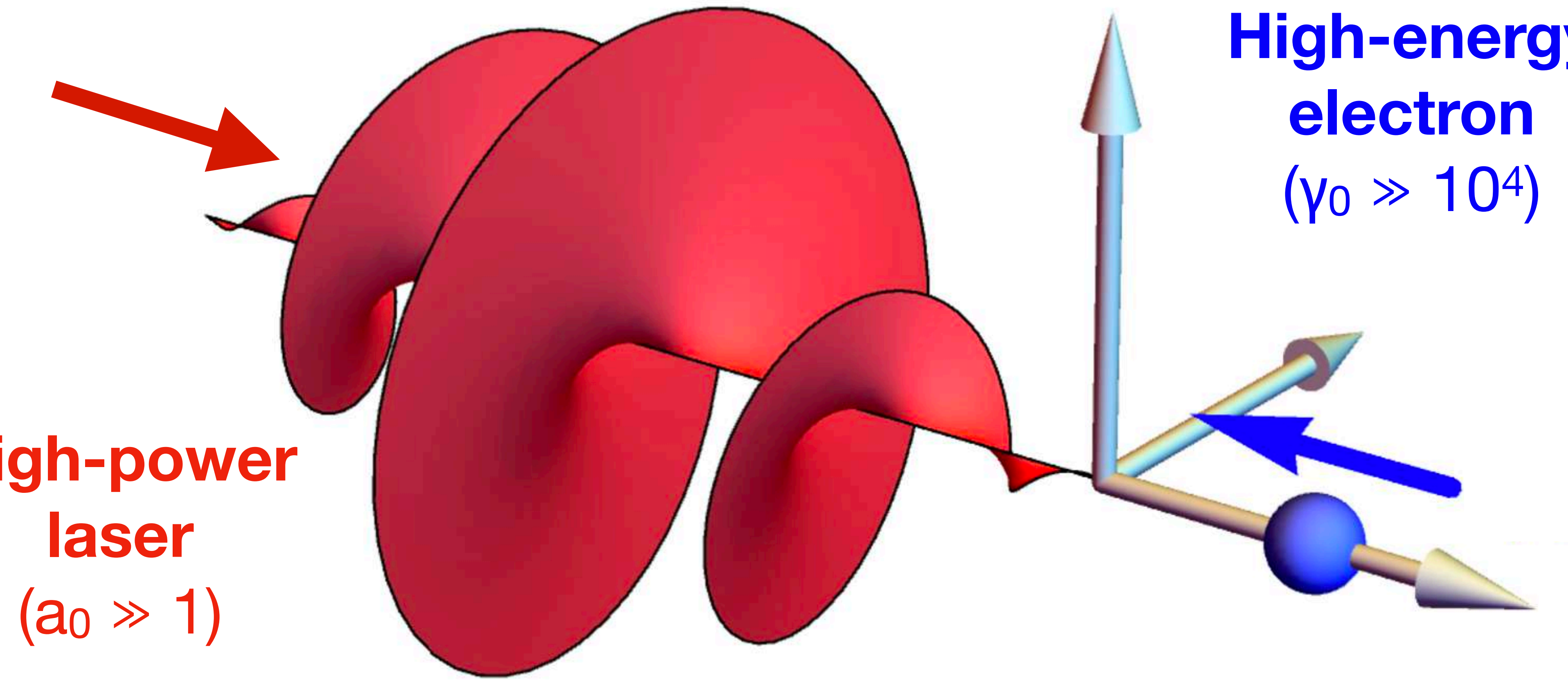
Possible near-term application: Strong-field QED

Tech demonstrator for *high energy* and *stability*

- Schwinger field: $\sim 10^{18}$ V/m ⋙ high-power lasers
- Collide high-power laser with high-energy e^- → boost field
- Experiments reached $\chi \approx 0.3$ (fraction of Schwinger field)
  - $\chi \approx 10\text{–}100$ → lab astrophysics (e.g., surface of magnetars)
  - $\chi \gtrsim 1000$ → no theory! (new physics, emergent properties?)



LUXE Collaboration, EPJ-ST 230, 2445 (2021)



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

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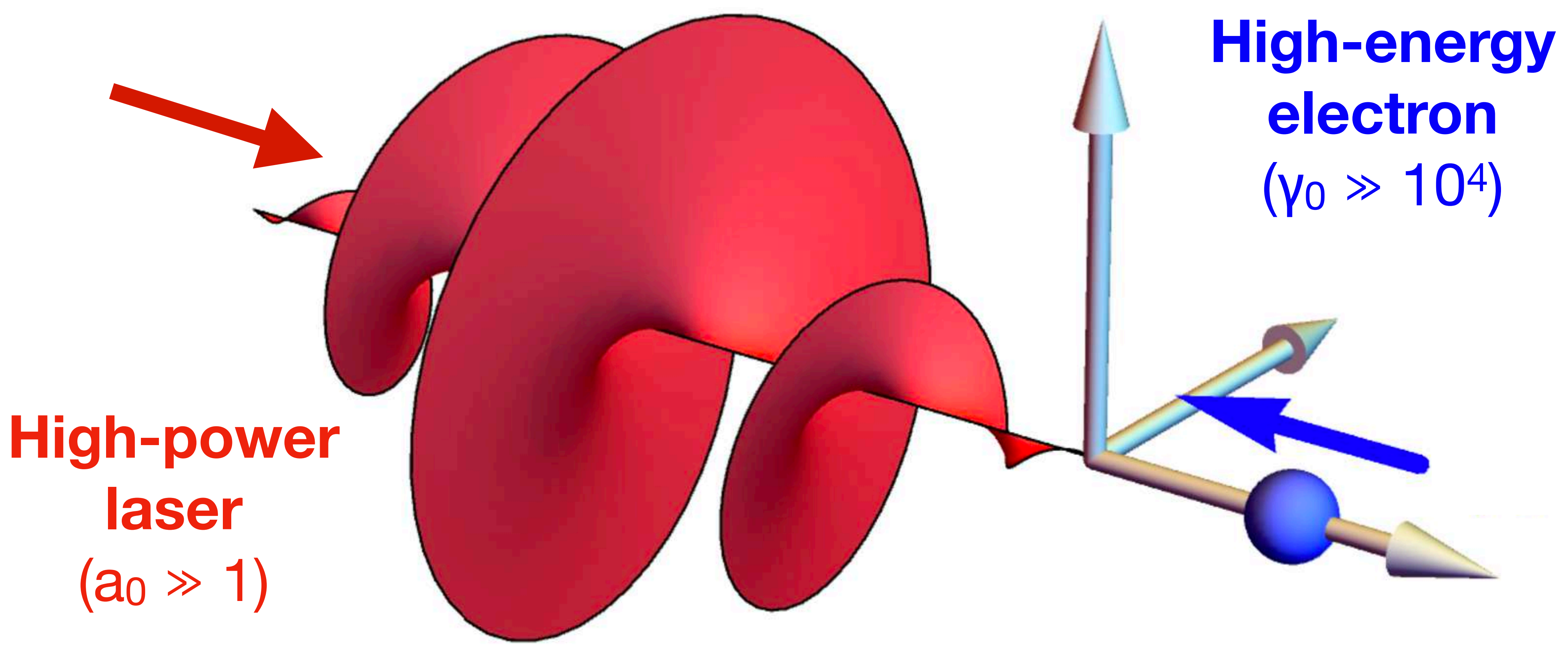

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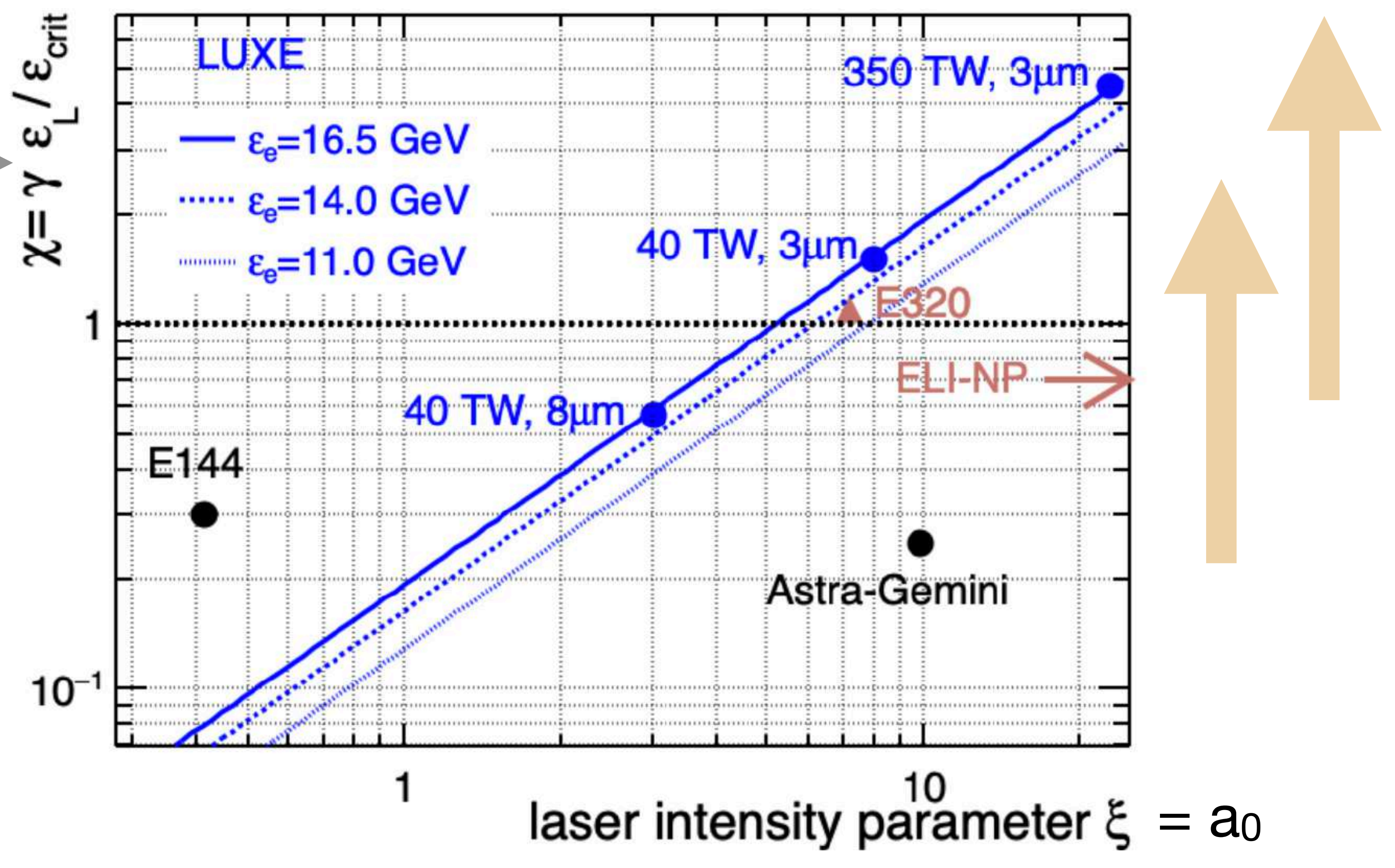

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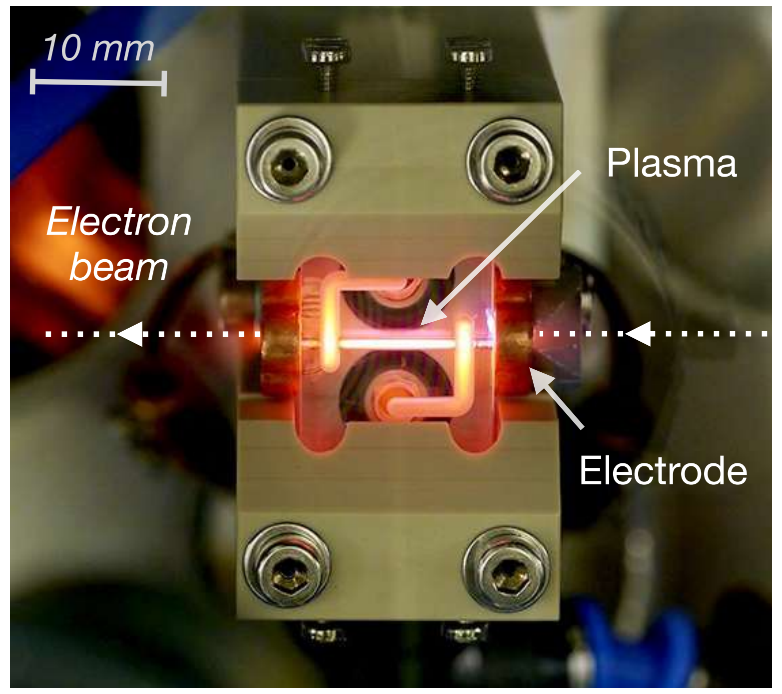
New concept #1: Nonlinear plasma lenses

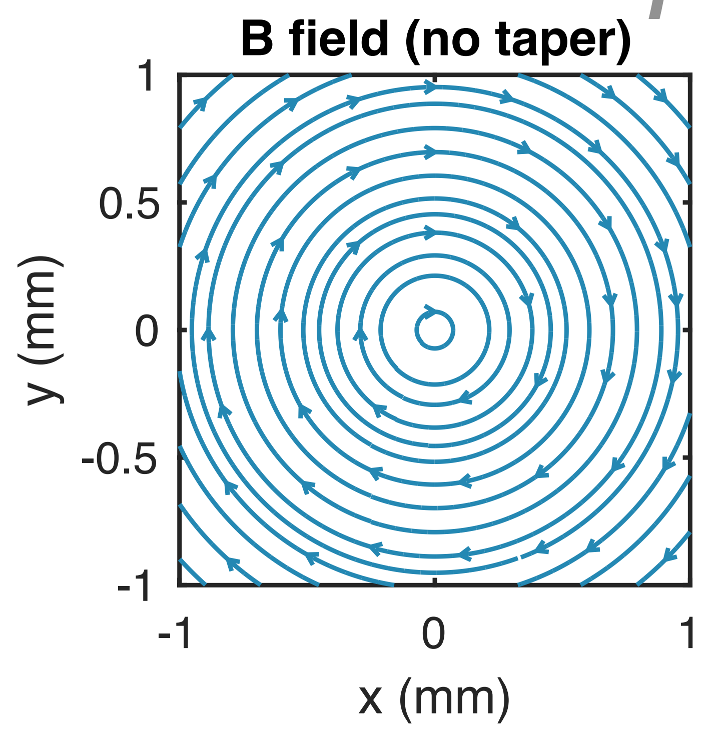
A new kind of plasma accelerator — ***solving staging***

- Plasma lens = strong, compact focusing device



“Active” plasma lens
= discharge current

Linear
(chromatic)



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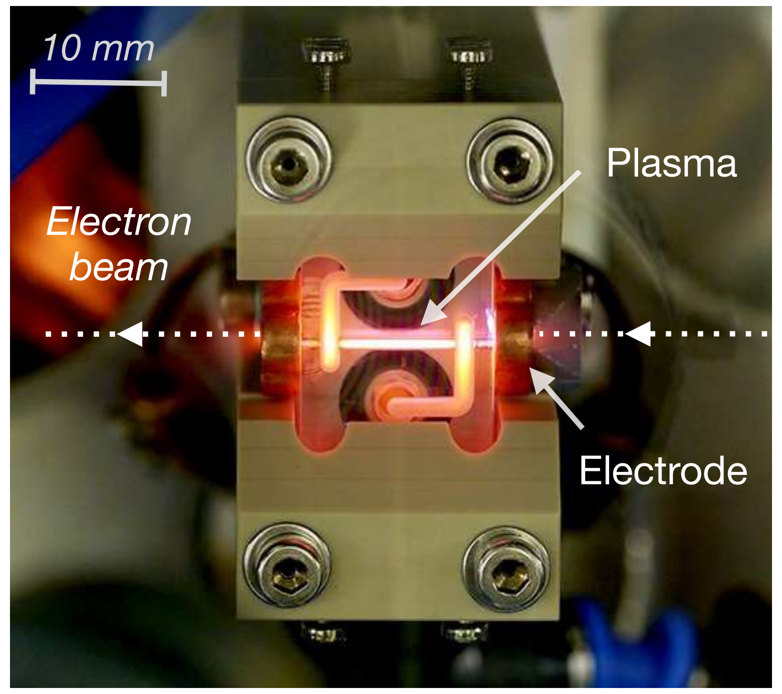

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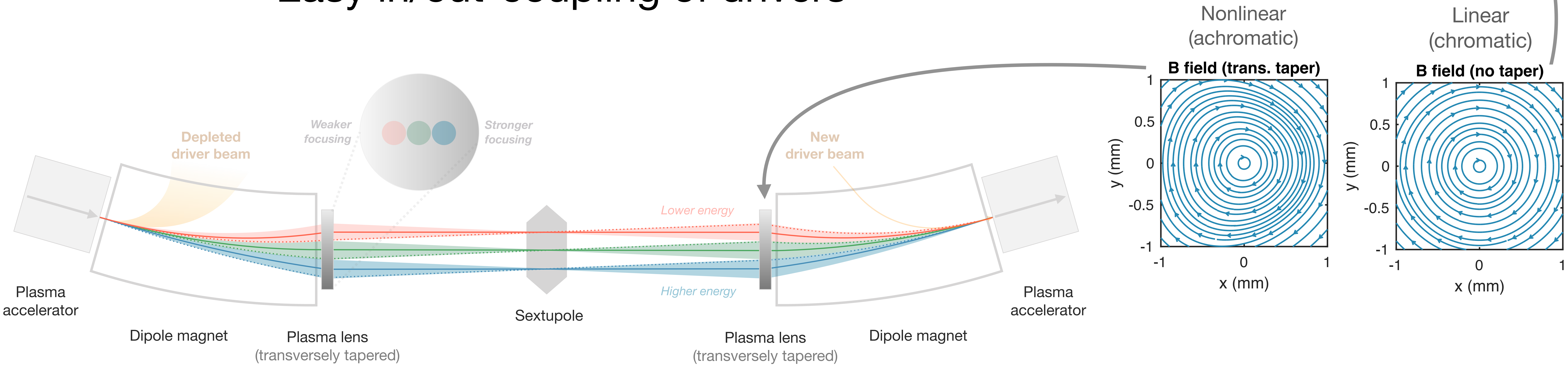

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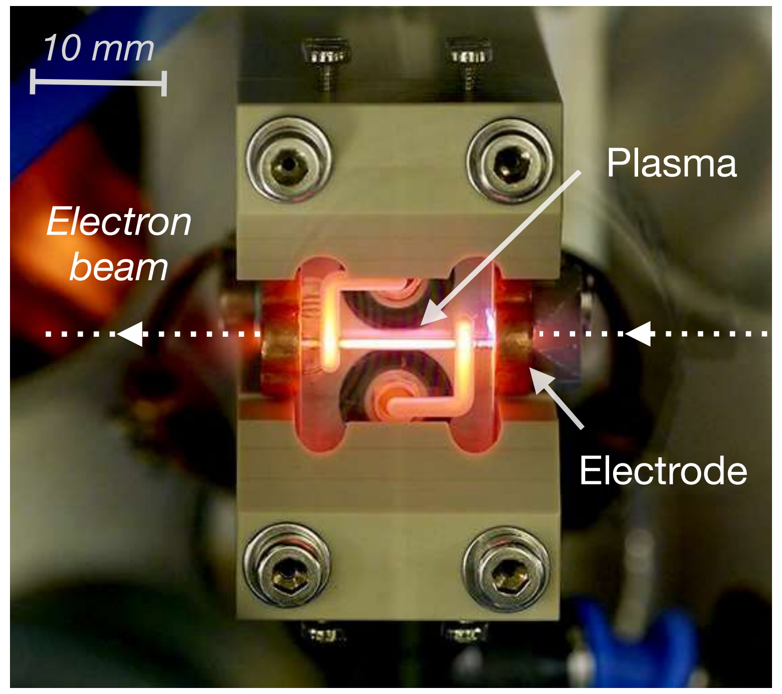

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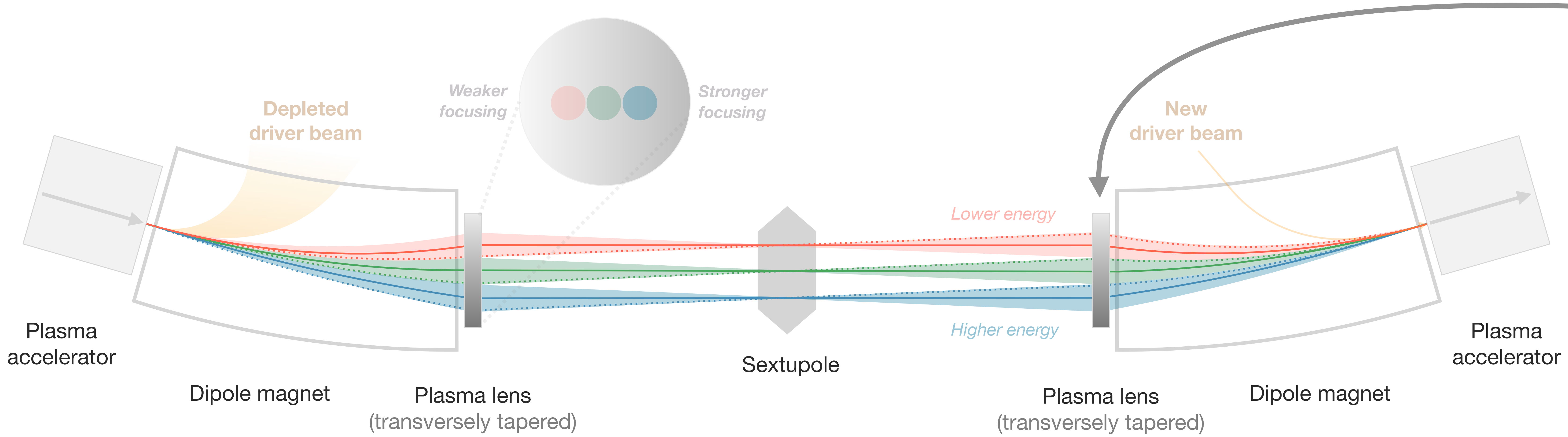
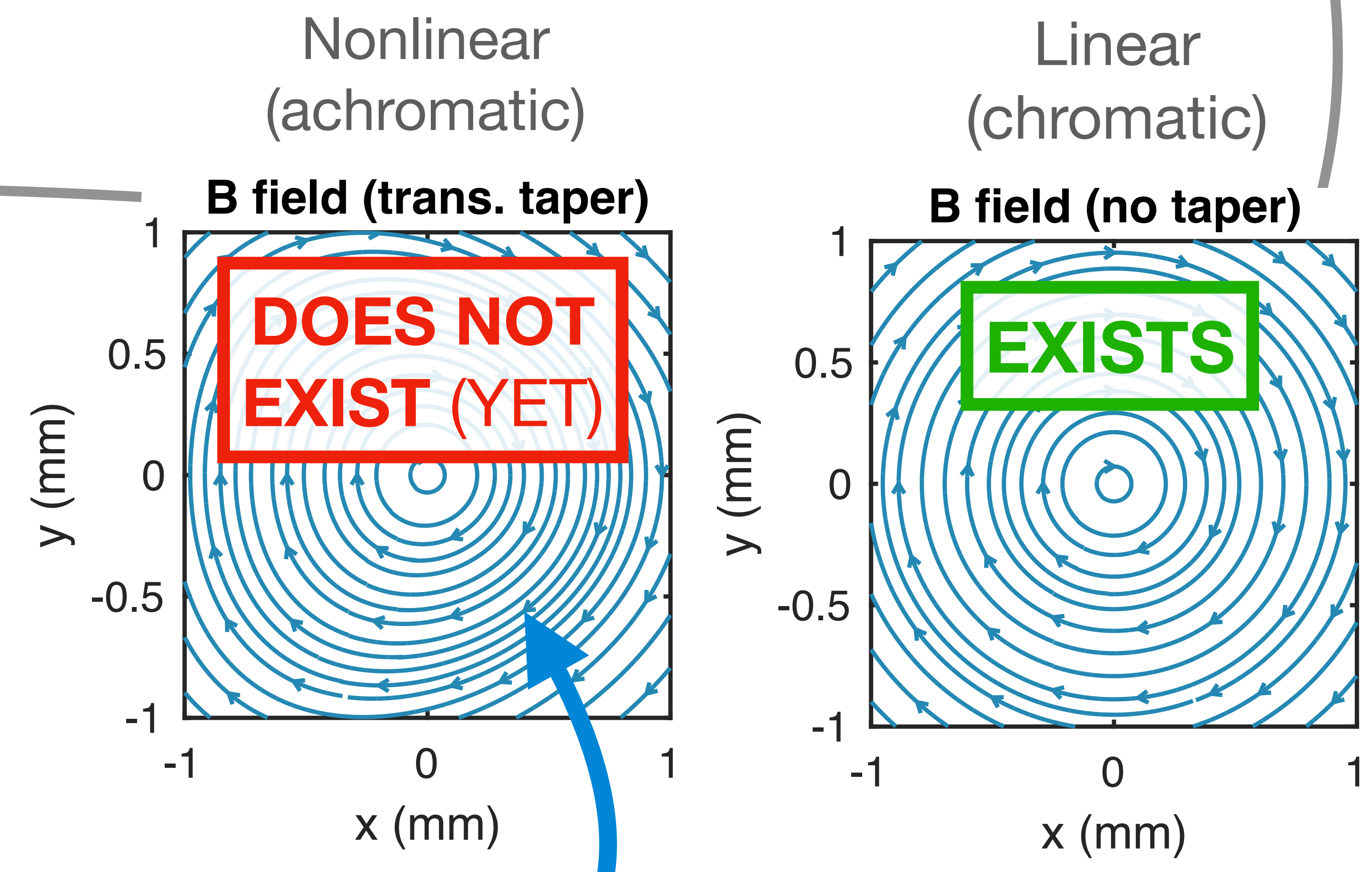


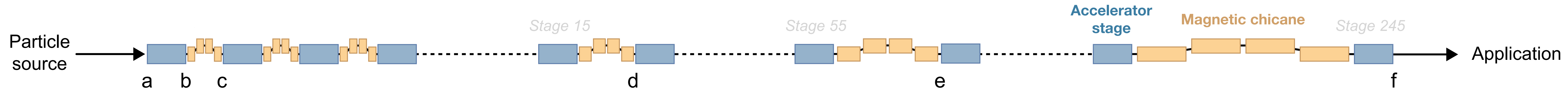


Research question:
Can we make this lens?

New concept **#2: Self-correction mechanisms**

A new kind of plasma accelerator — ***solving stability***

- Achromatic beamline between stages → longitudinal dispersion (R_{56})



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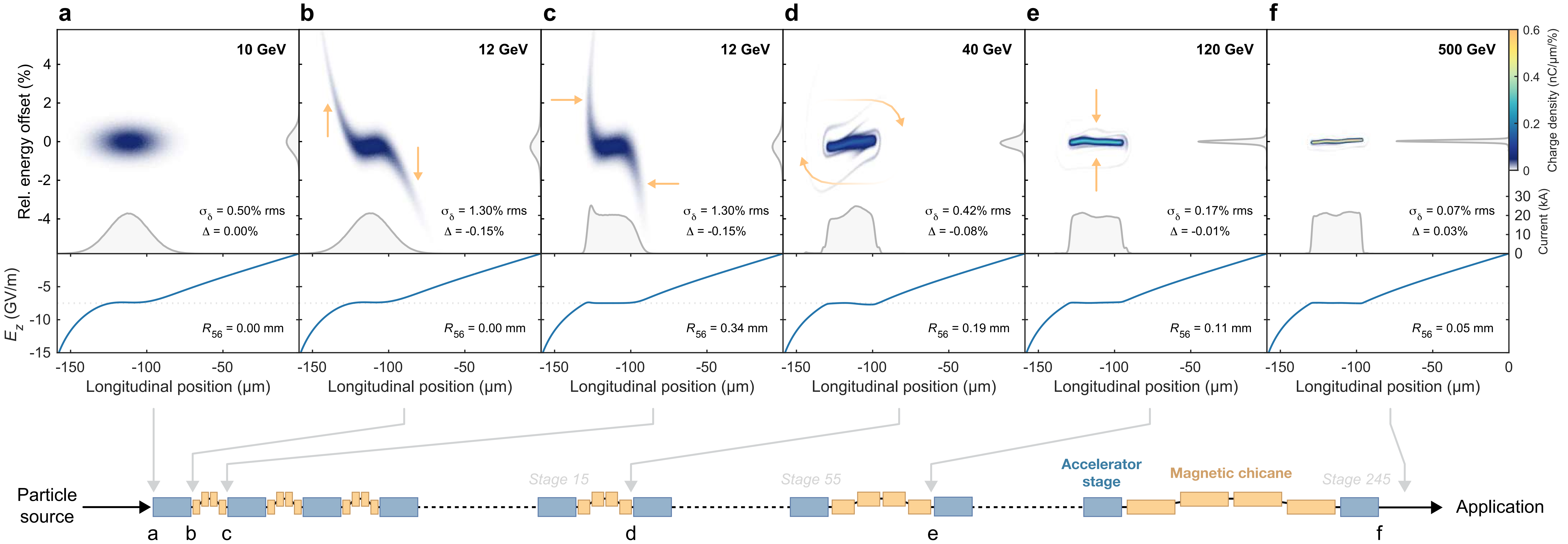
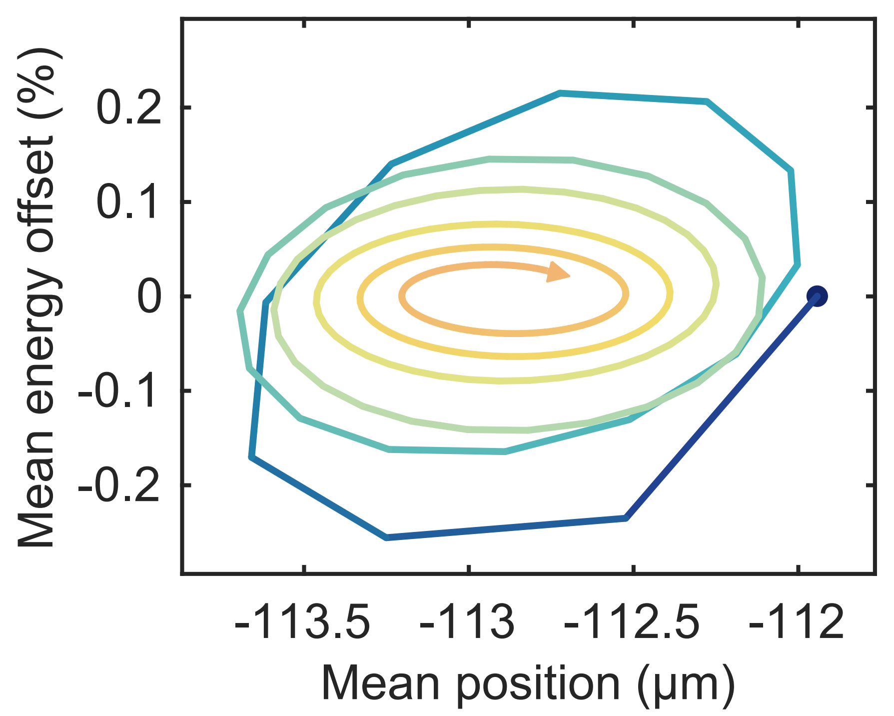
- *Discovery:* Simulation shows feedback loop between field and beam → **self-stabilization**

→ Damps energy spread and energy offset

→ Greatly improves tolerances (e.g., sub-fs → 10 fs)





Lindstrøm, arXiv:2104.14460 (2021)

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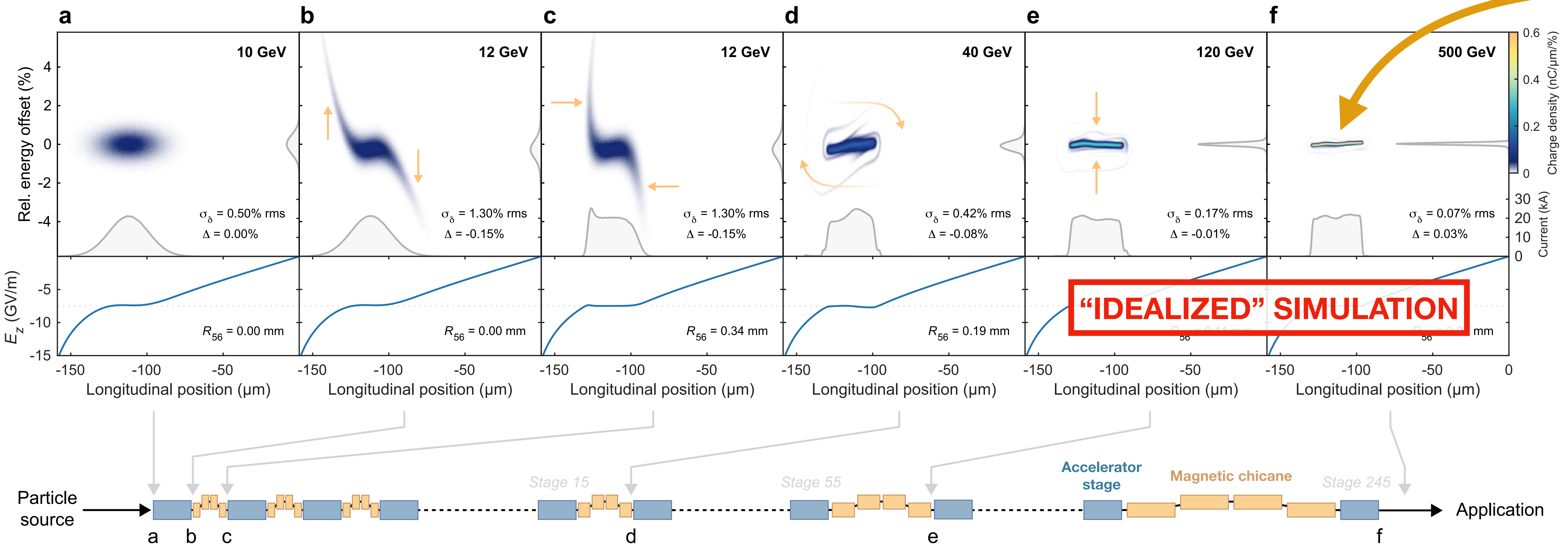
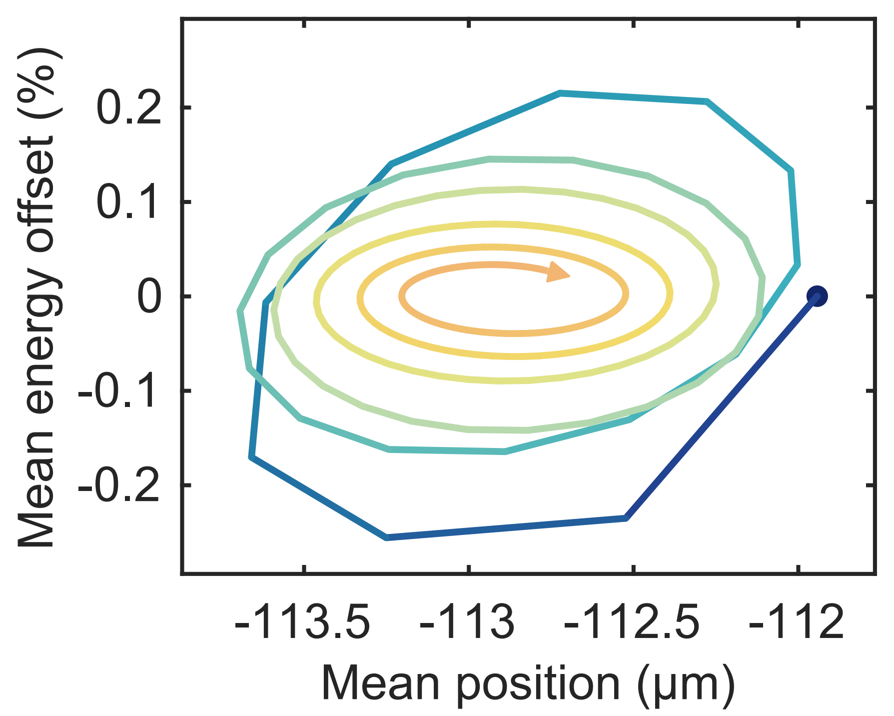
Will this occur in a "real" machine?





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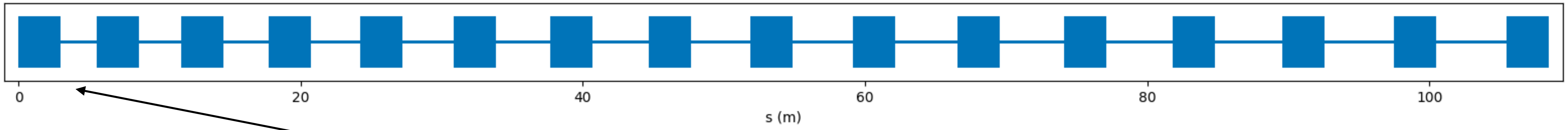
A C^3-based PWFA staging facility?

- Assuming C^3-like beam parameters, used as drive beams for PWFA:
  - Example used: **Charge 2 nC, energy 2 GeV, spaced by 3 ns** — *can be optimised.*

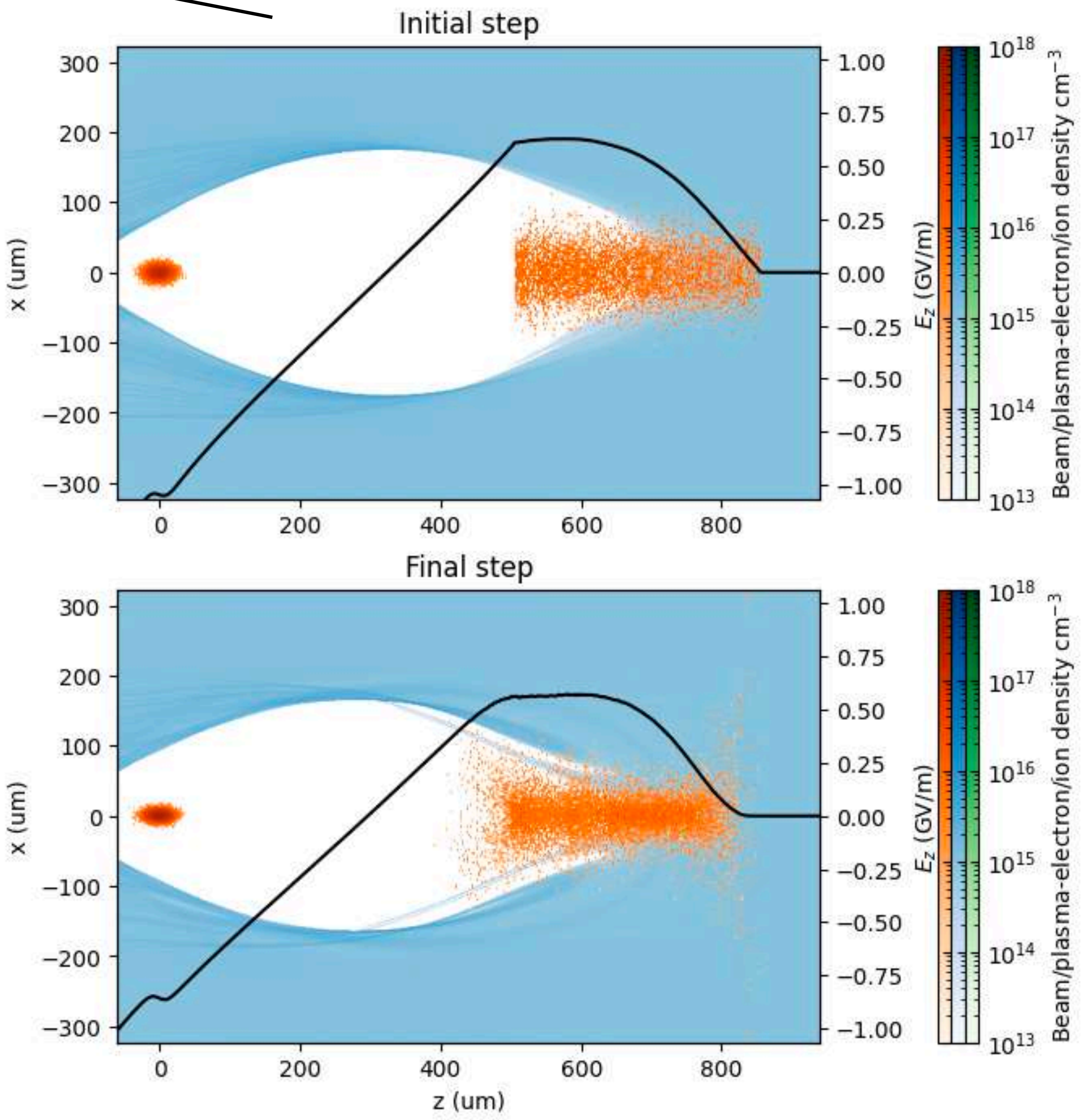
A C^3-based PWFA staging facility?

- Assuming C^3-like beam parameters, used as drive beams for PWFA:
  - Example used: **Charge 2 nC, energy 2 GeV, spaced by 3 ns** — *can be optimised.*
- Design requirements:
  - PWFA requirements — *important to achieve*
    - Minimum **10 stages** (self-correction)—high energy (**50 GeV**), high stability
    - Acceleration gradient > ~0.5 GV/m
    - Energy efficiency > ~10%
  - Strong-field QED application requirements (TBC) — *fairly relaxed*
    - Emittance < ~100 mm mrad,
    - Charge > ~0.1 nC
    - Energy spread < 1% rms.

SPARTA demo machine — initial ideas and simulations



- 2 GeV drivers, 2 nC
  (C^3-like parameters)
- 16 stages, ~100 m long
- Plasma density: 10^{15} cm^{-3}
- Final energy: 50 GeV
- Accelerated charge: 0.2 nC
- ~20% energy efficiency



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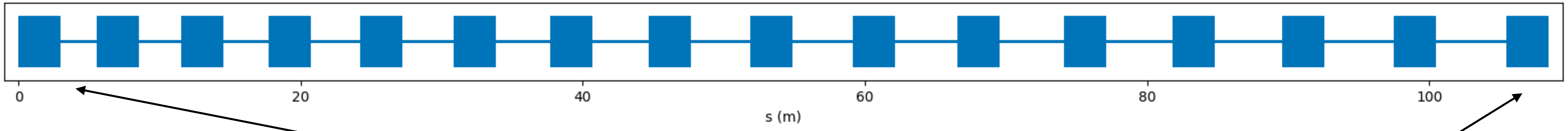

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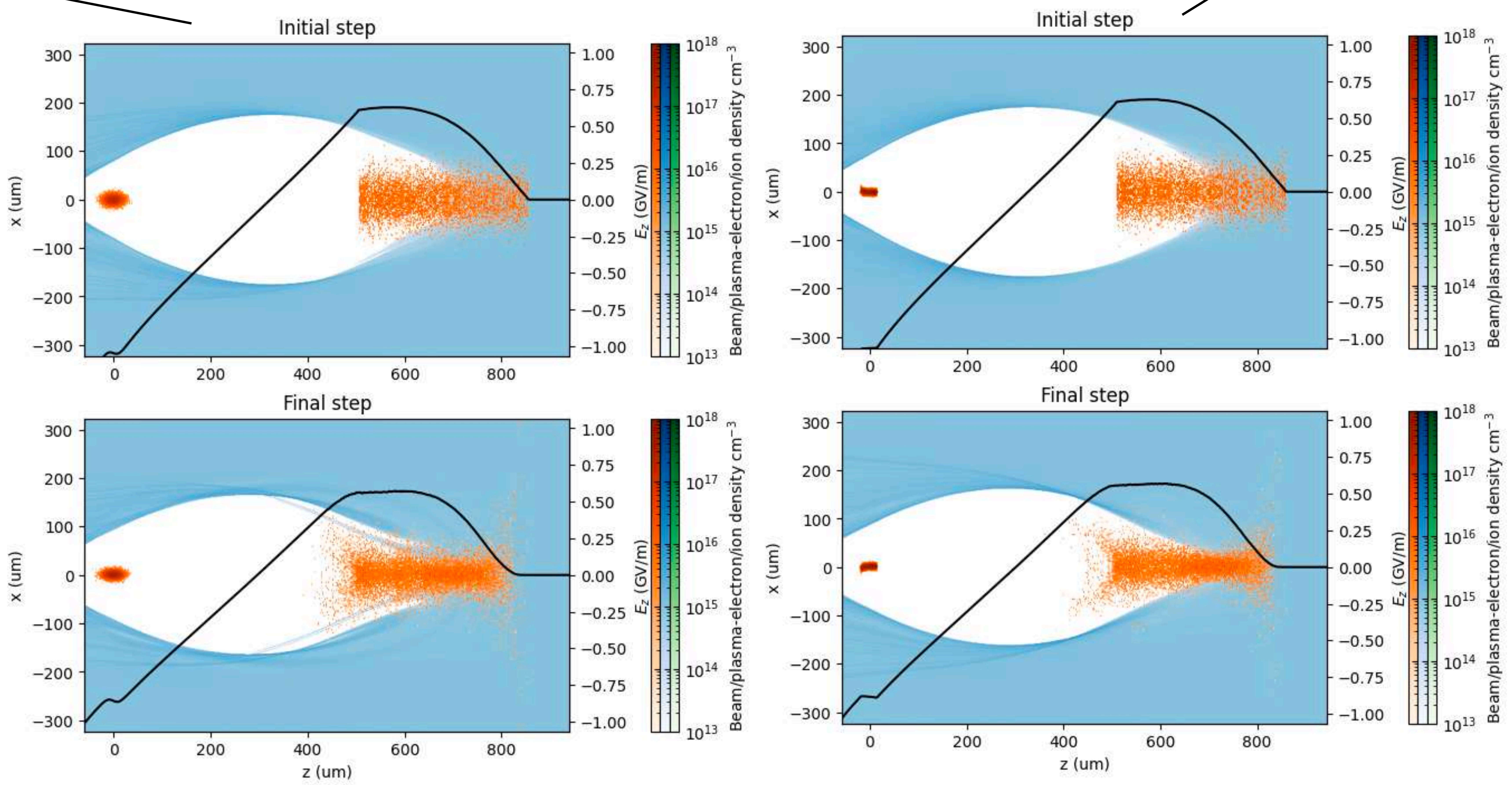

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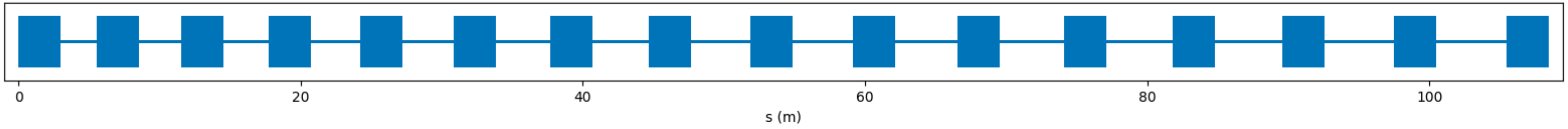

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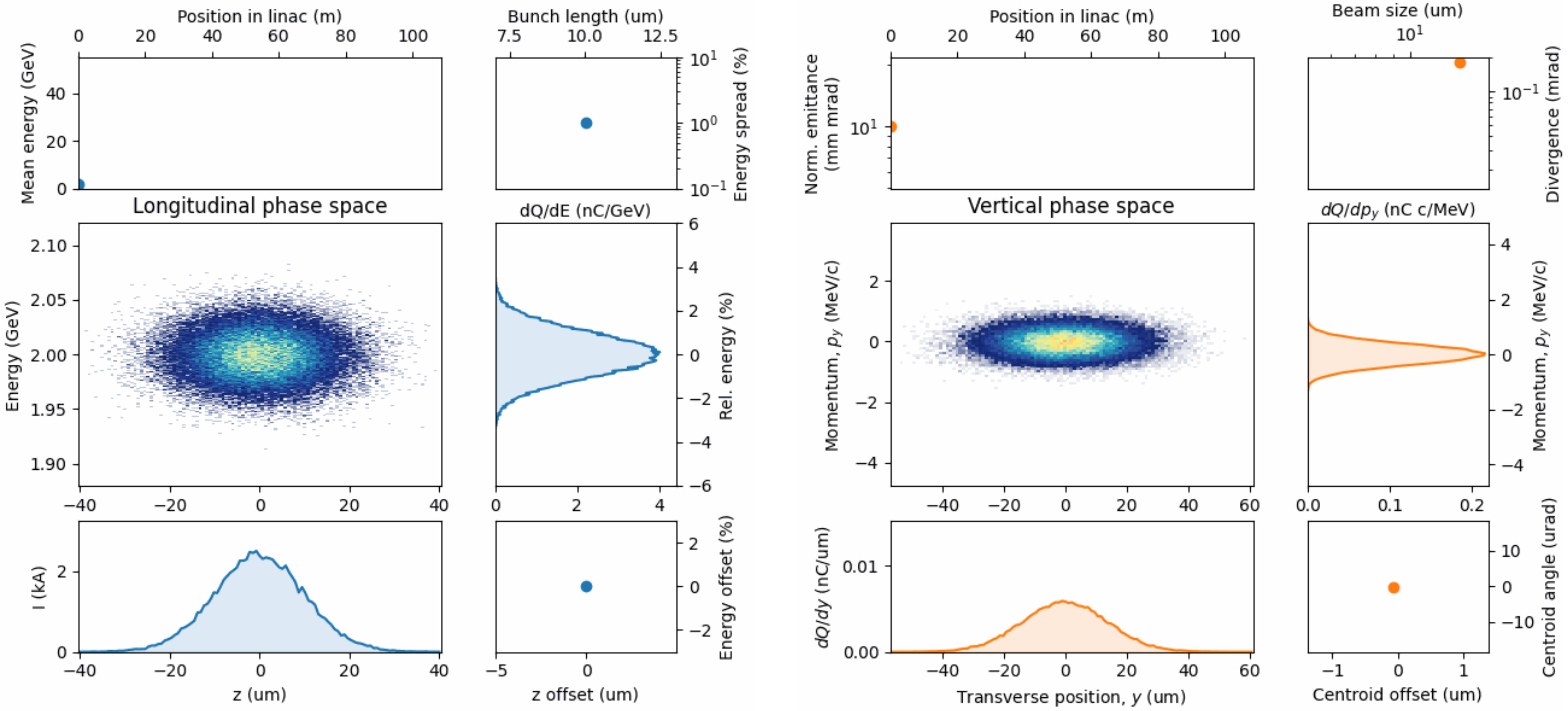

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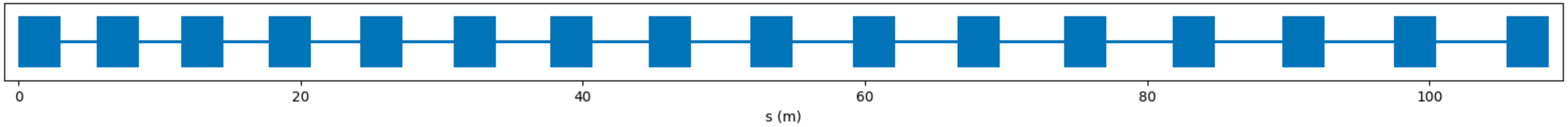

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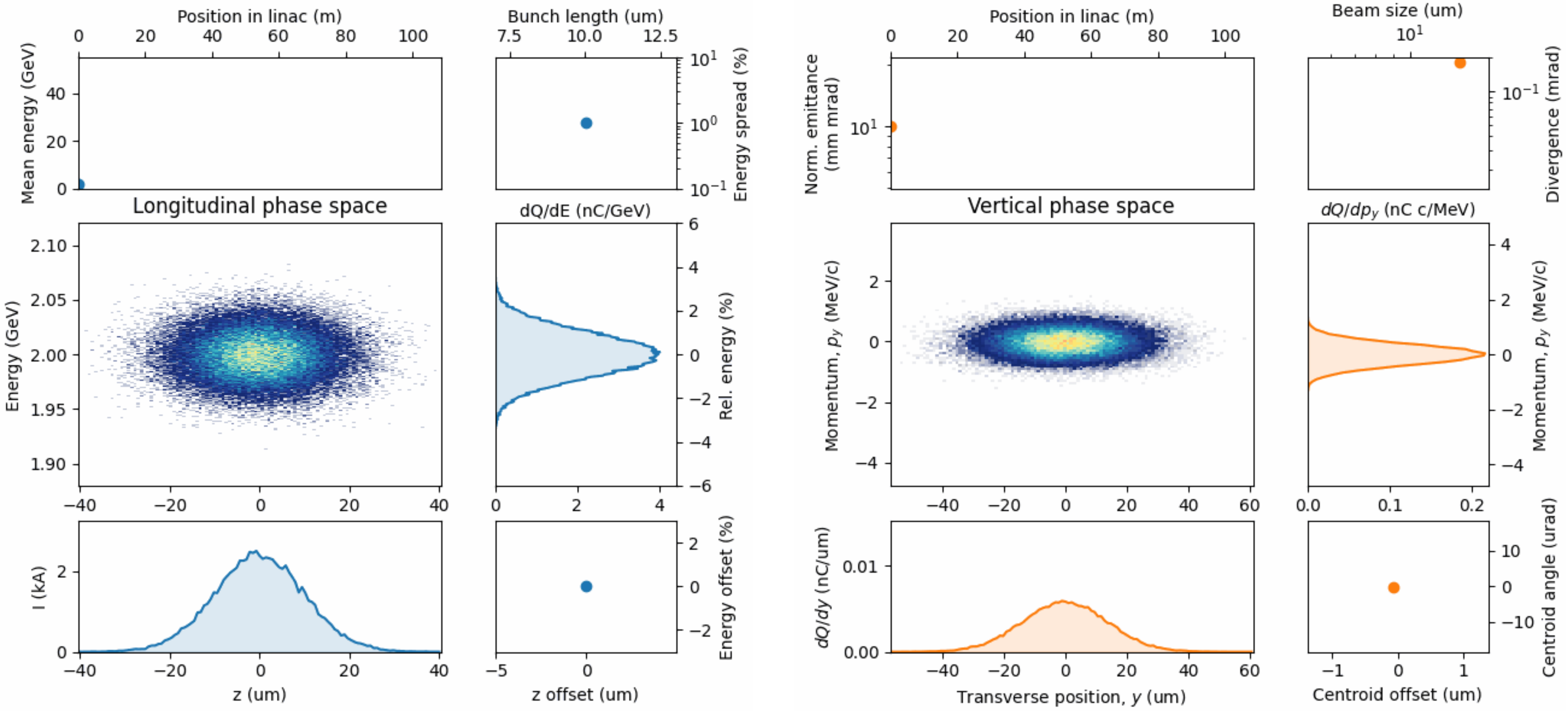

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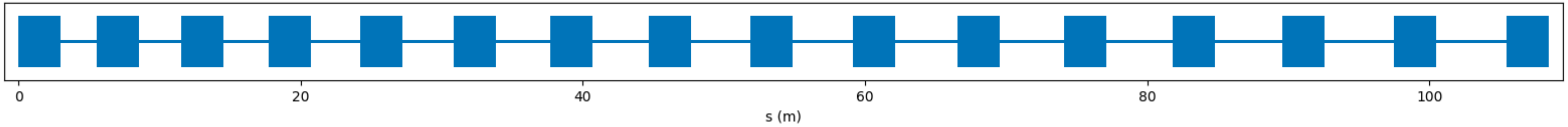

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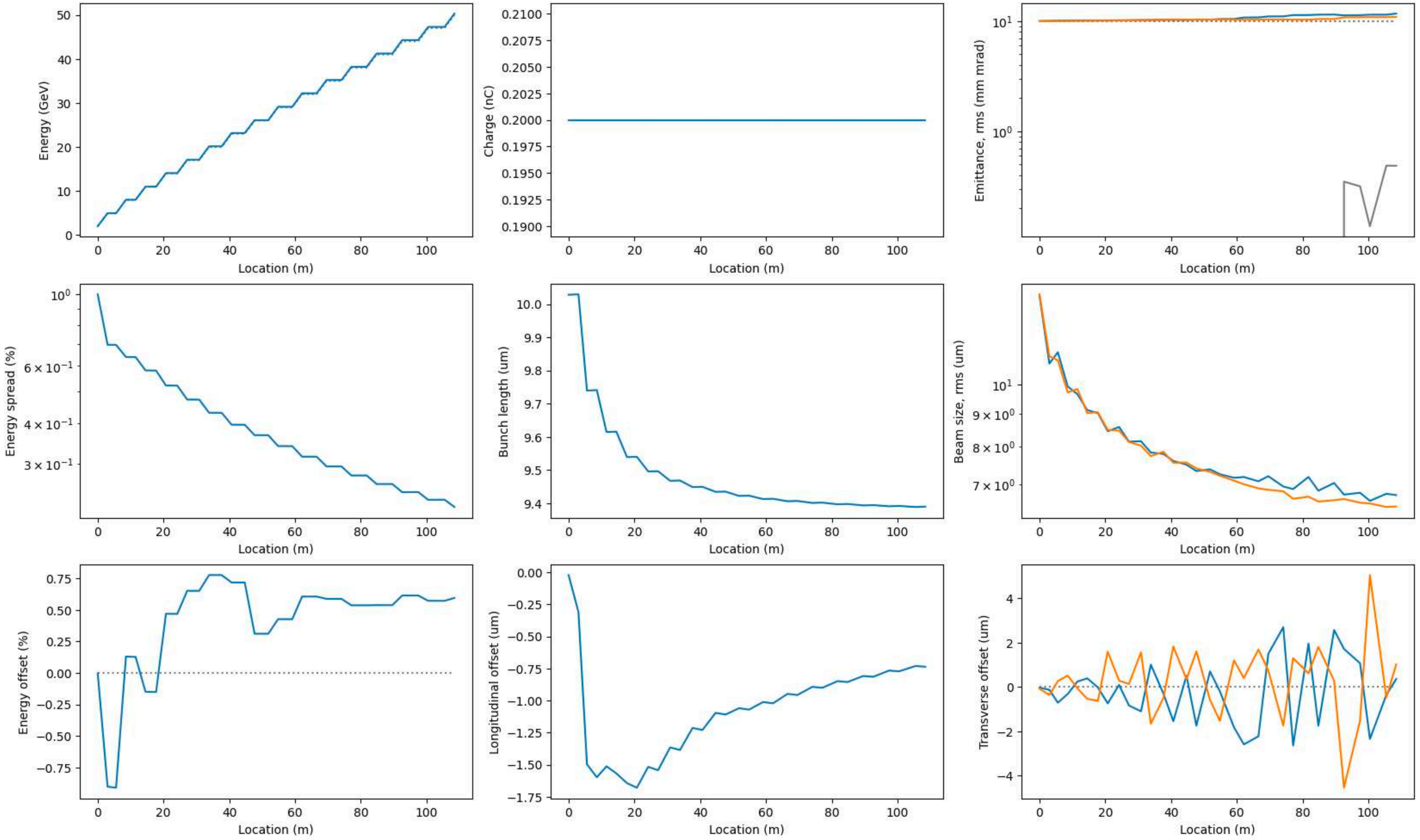
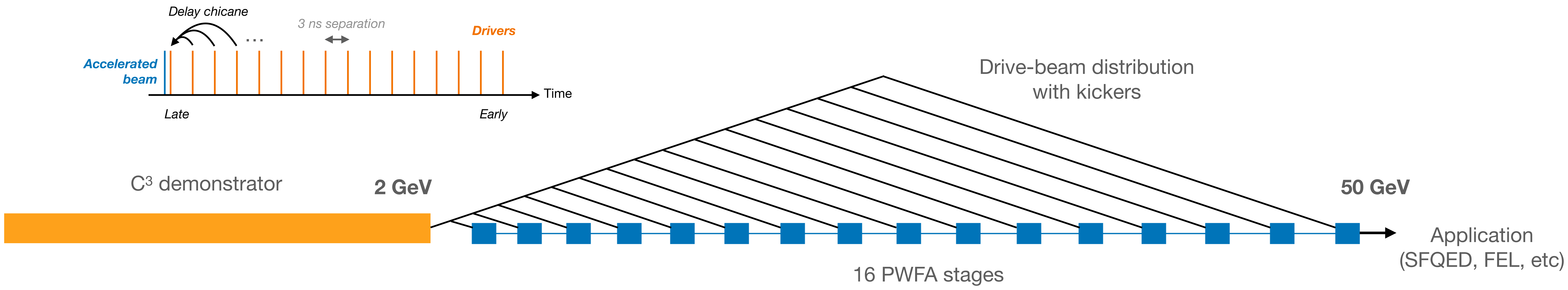
- Medium/high emittance (10 mm mrad), but negligible emittance growth



Distributing drivers to PWFA stages with kickers



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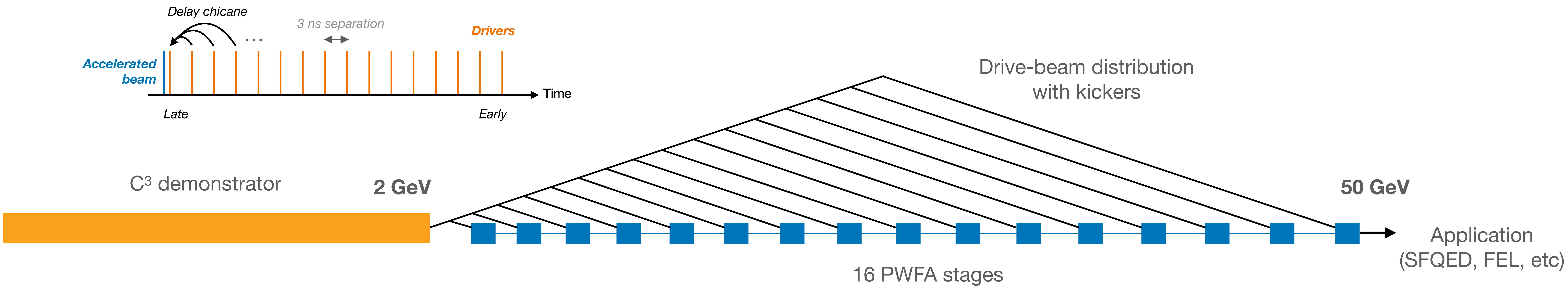

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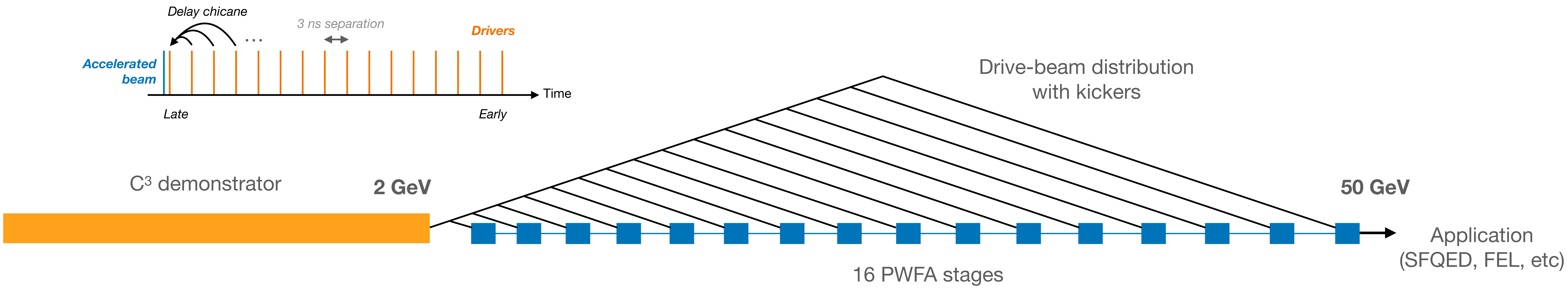

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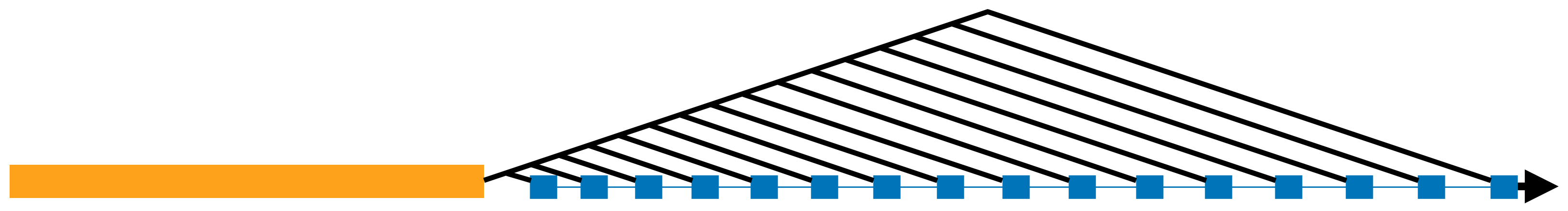
- Angle required: ~30 degrees
  - Requires transverse space: ~25 meters (~1/4 of the PWFA length)

Conclusions



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  - *SFQED as a near-term application: needs high energy, but not high quality*

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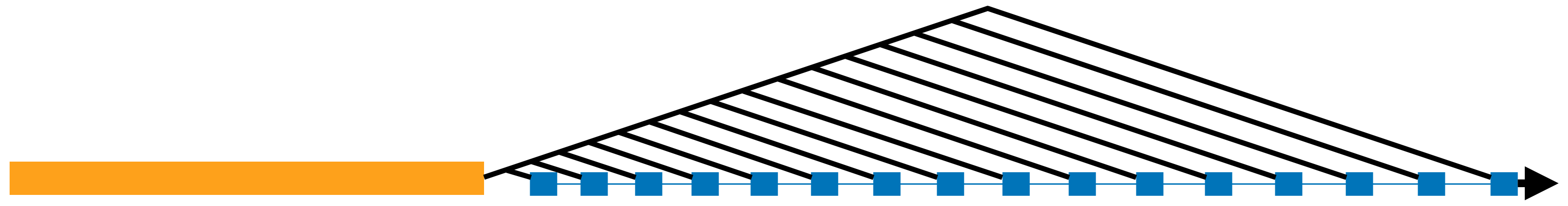

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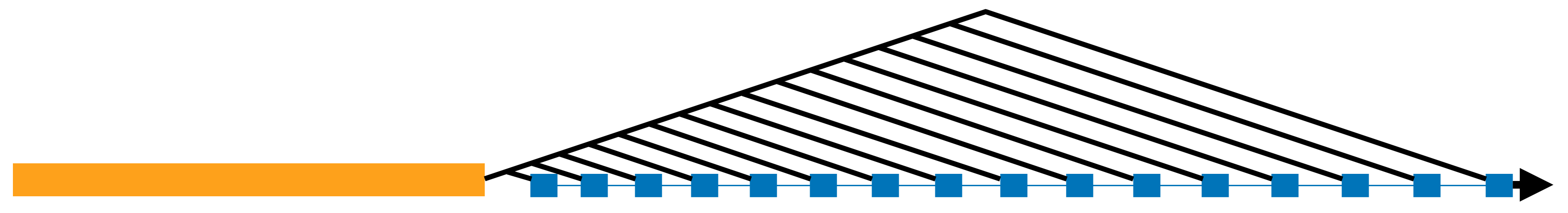

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- C^3 technology is well suited for producing electron drivers for PWFA

- Could be a **win–win–win situation** for three communities:
  - *C^3 — an energy multiplier and useful/challenging application.*
  - *PWFA — a medium-scale facility reliably delivering high-energy electrons.*
  - *Applications (e.g., SFQED) — “cheap”, dedicated access to high-energy electrons.*