The **SPARTA** project

Staging of Plasma Accelerators for Realizing Timely Applications

UNIVERSITY OF OSLO

The SPARTA project

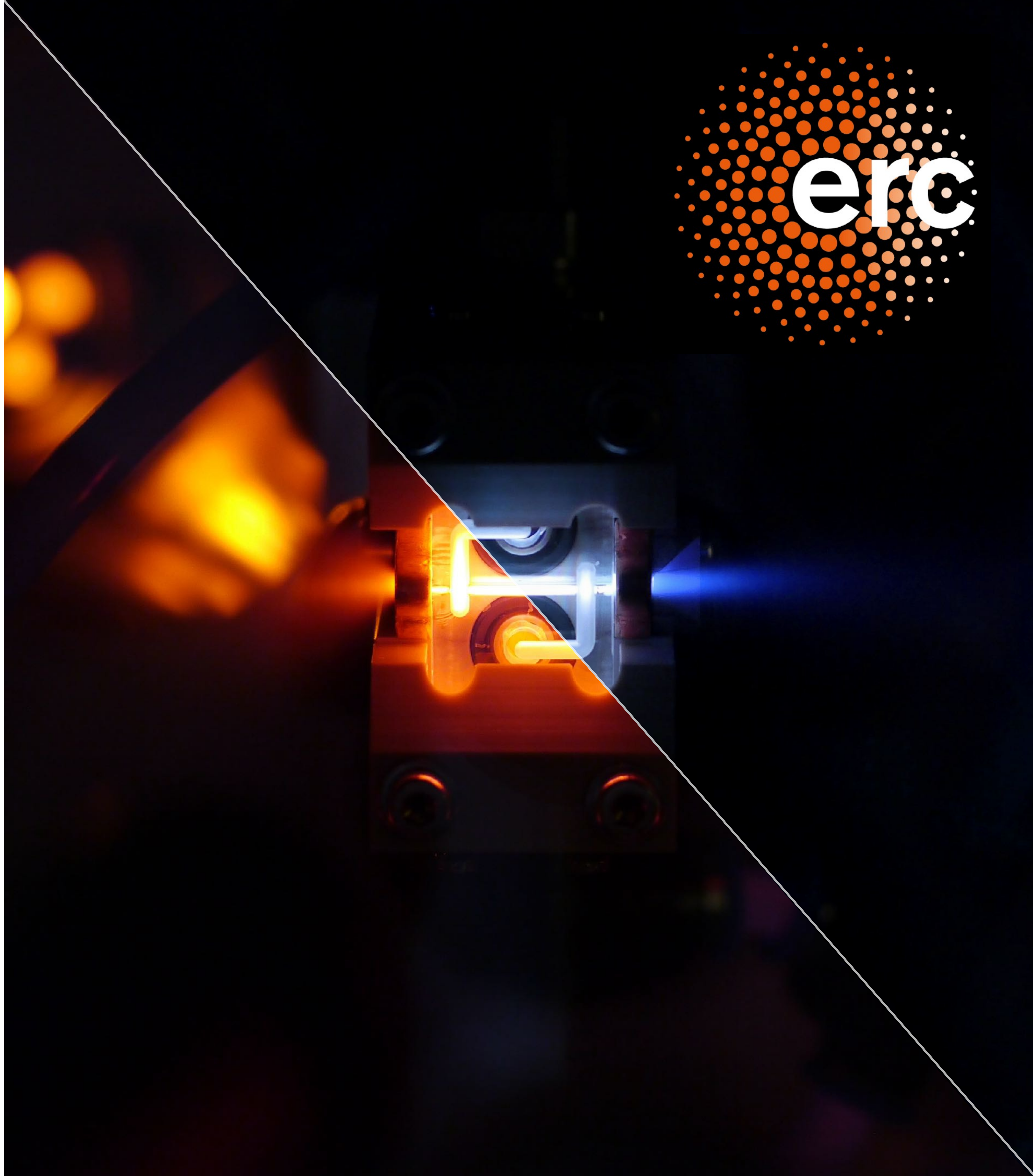
Designing a multistage plasma-accelerator facility

Carl A. Lindstrøm

Department of Physics, University of Oslo

SPARTA team: *Pierre Drobniak, Daniel Kalvik, Felipe Peña, Hektor B. Anderson, Didrik Larsen*

22 Sep 2025 | EAAC workshop 2025



Part 0:

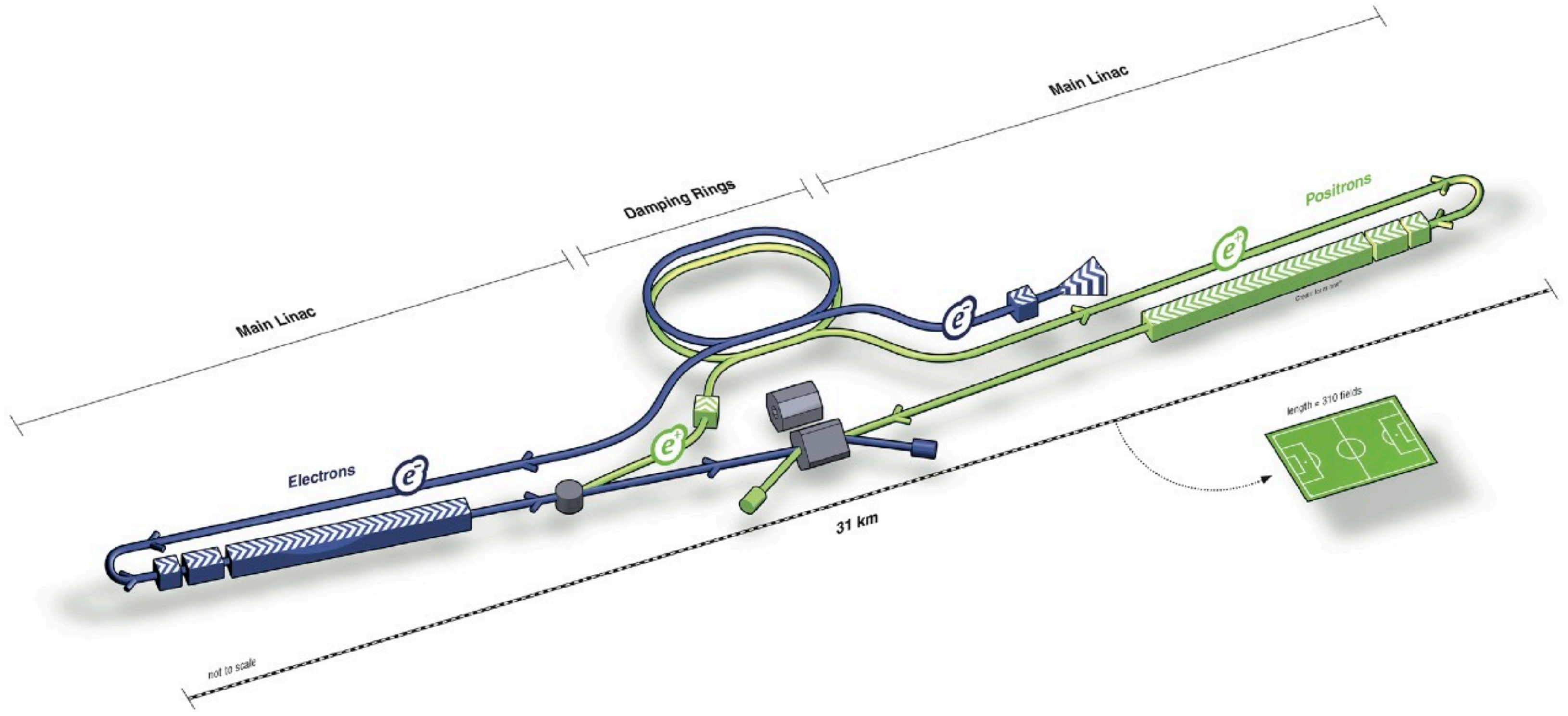
Motivation

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

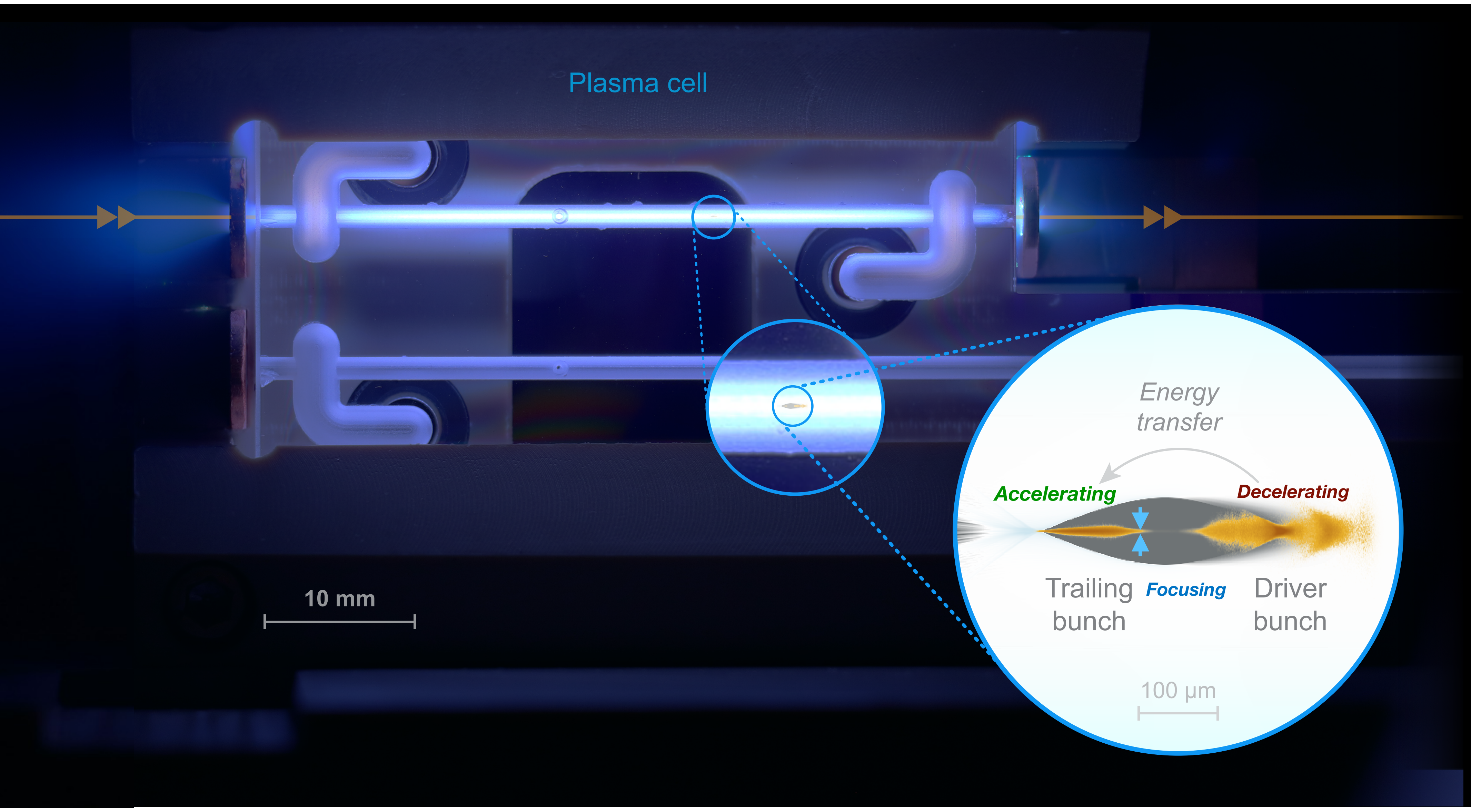
The cost of high-energy particles is too $^{\text{damn}}$ high

Motivating a new accelerator technology

- Consensus: **build e^+–e^- collider**, circular or <u>linear</u> → €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

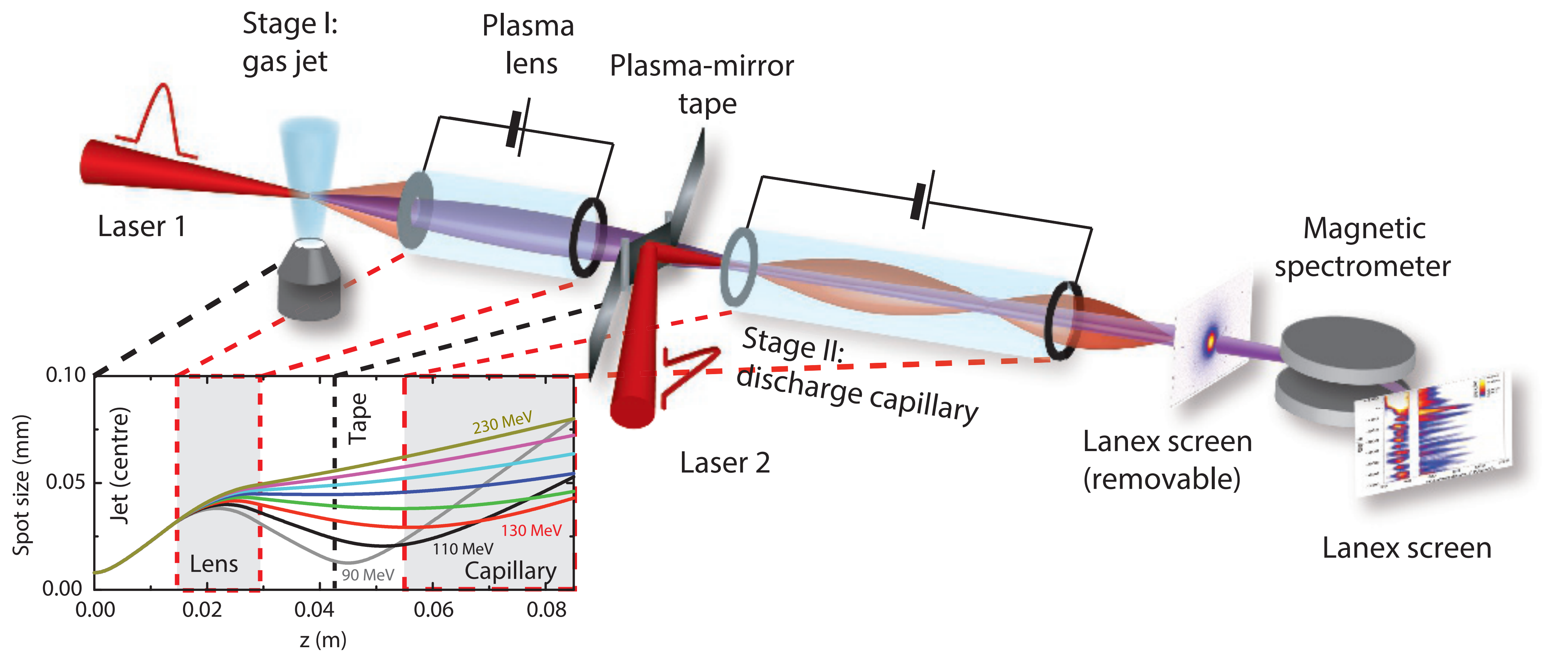


- Significant progress since Tajima and Dawson 1979.
  - High theoretical understanding
  - Many key experimental demonstrations
  - Increasing TRL — recent applications to FELs
- **Why aren't we delivering HEP machines?**

Key challenges in high-energy plasma acceleration

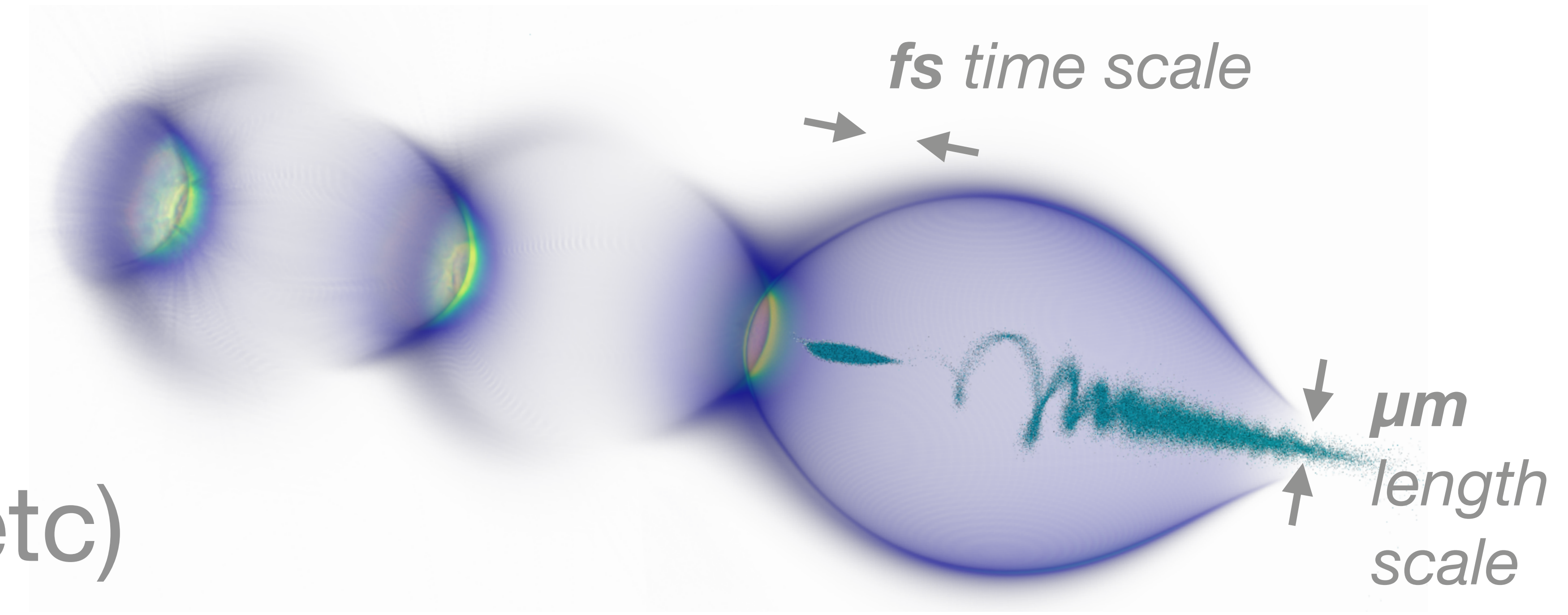
Staging and **stability** – forming the backbone of the machine

- **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)

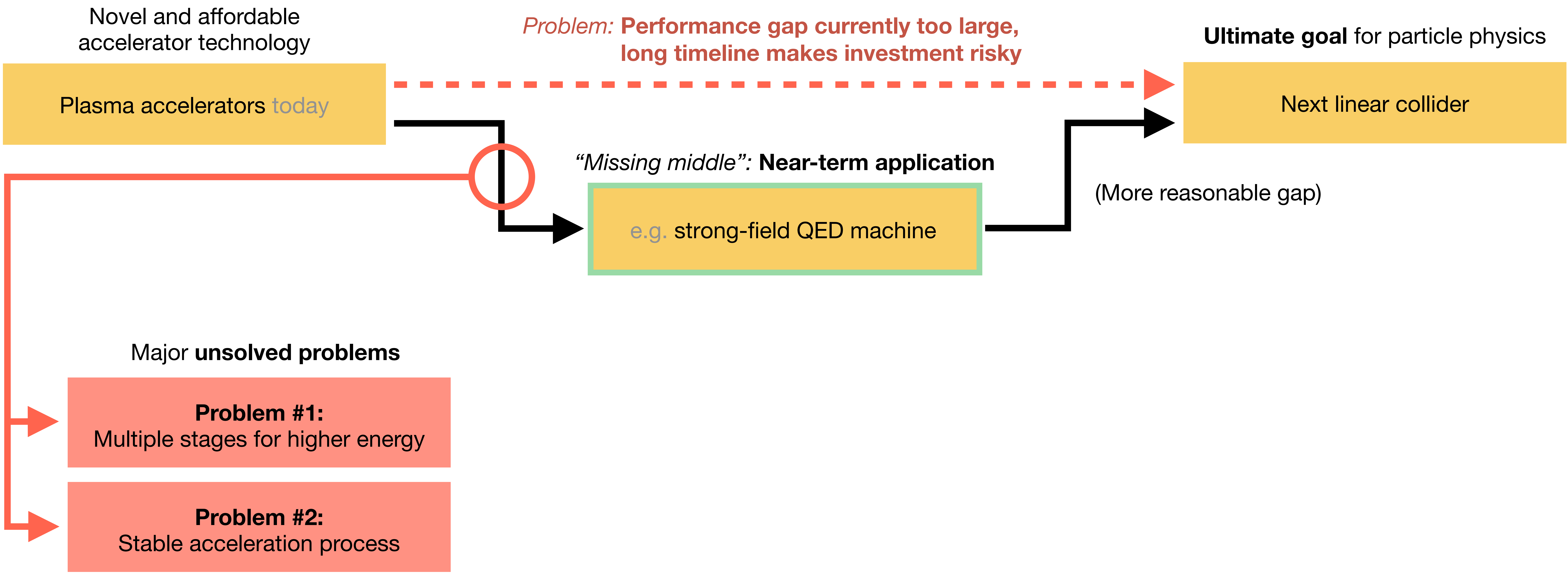
- **Stability problem**:
  - Shrinking the accelerating structure (μm/fs scale) …without shrinking the alignment/timing jitter
  - Beam–plasma instabilities (hosing, beam breakup, etc)



Source: VisualPIC

Mapping the landscape

A flow chart (part 1 of 2)

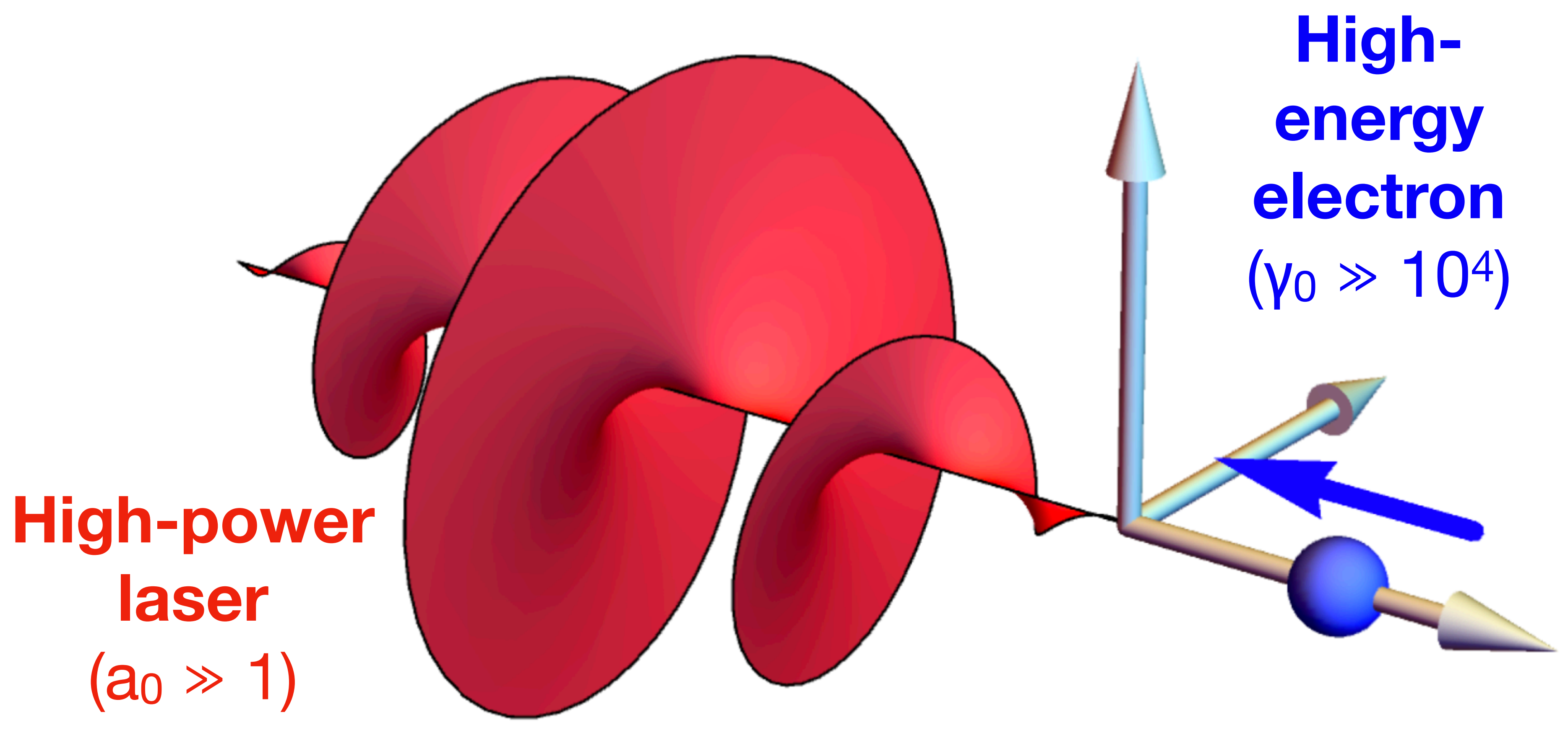


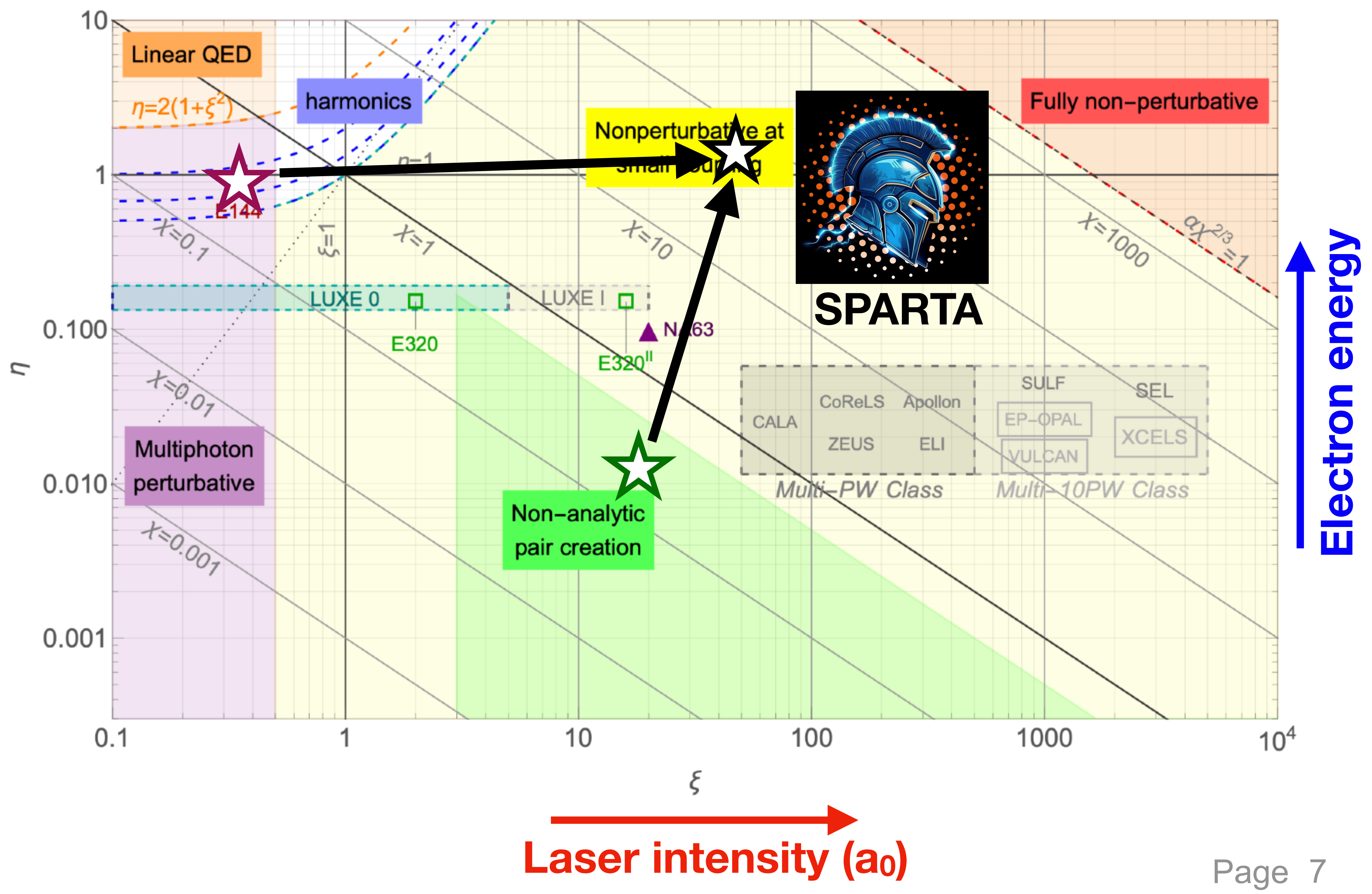
A medium-term application: SFQED

New physics with moderate beam requirements

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

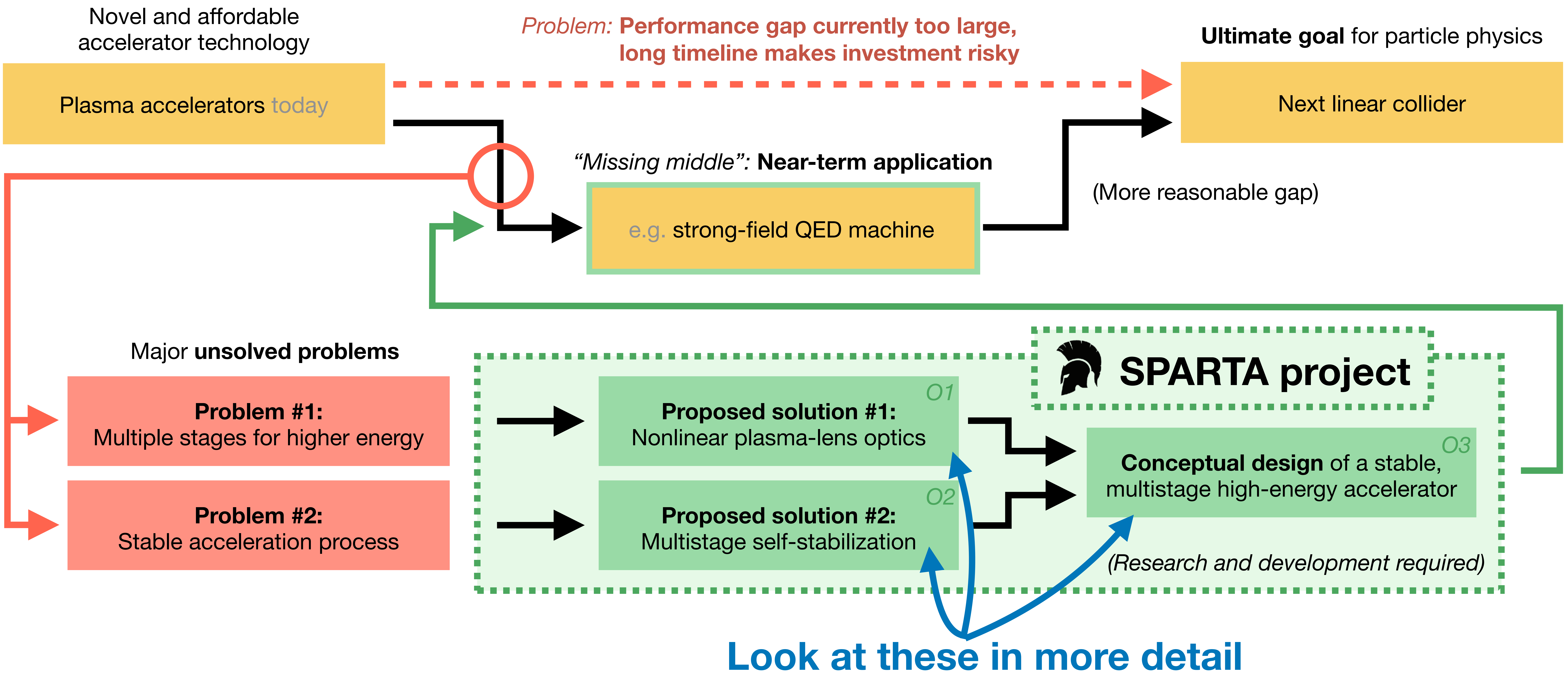
- Schwinger field: ~10^{18} V/m (χ =1) $\ggg$ high-power laser
  - Collide with high-energy e^-
    → **Lorentz boost the laser field (in the e^- frame)**
- Experiments reached $\chi \approx 0.3$ (soon ~1)
- $\chi \approx 10$–100 → “laboratory astrophysics”
  (e.g., B-field at surface of magnetars)
  - *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 2 of 2)



Part 1:

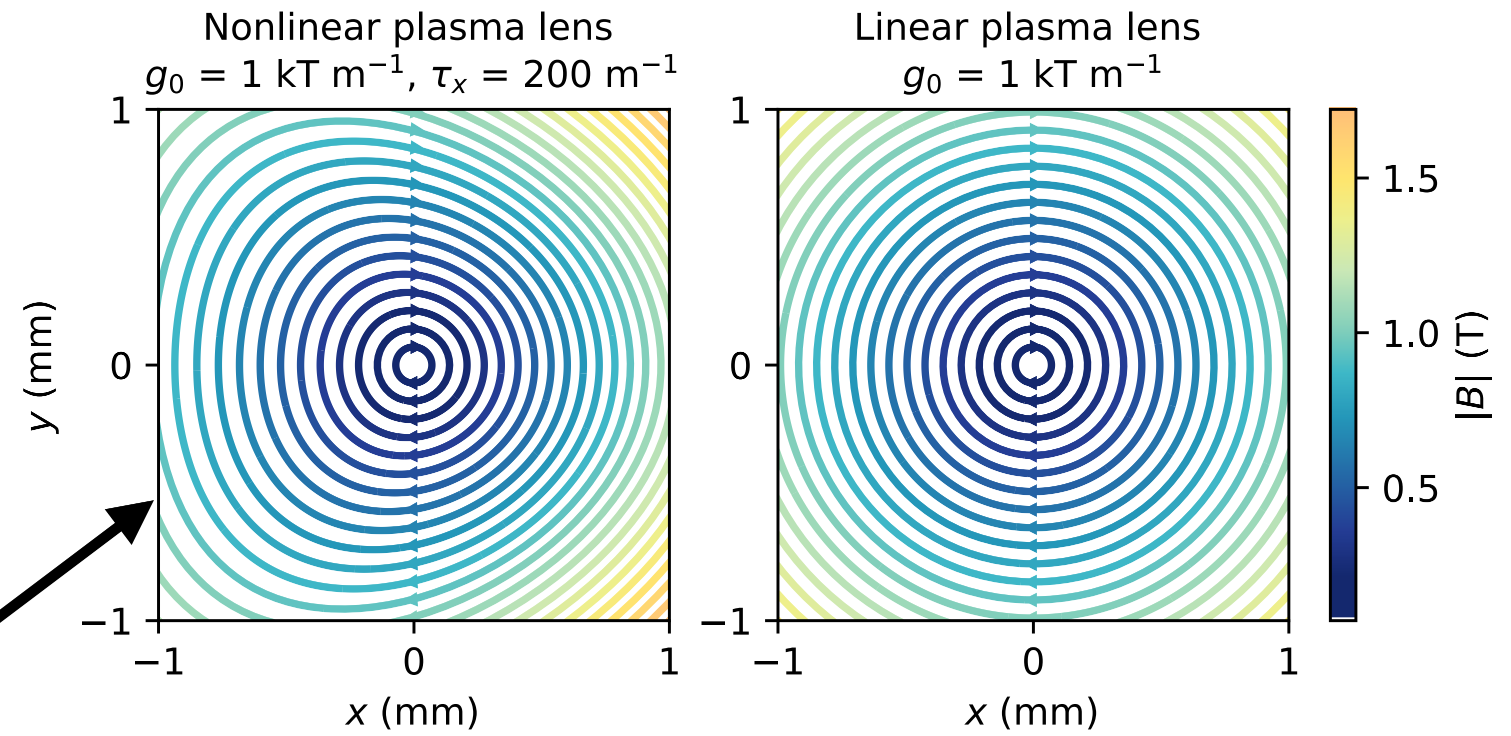
Staging

Achromatic optics and **nonlinear plasma lenses**

Novel achromatic staging optics

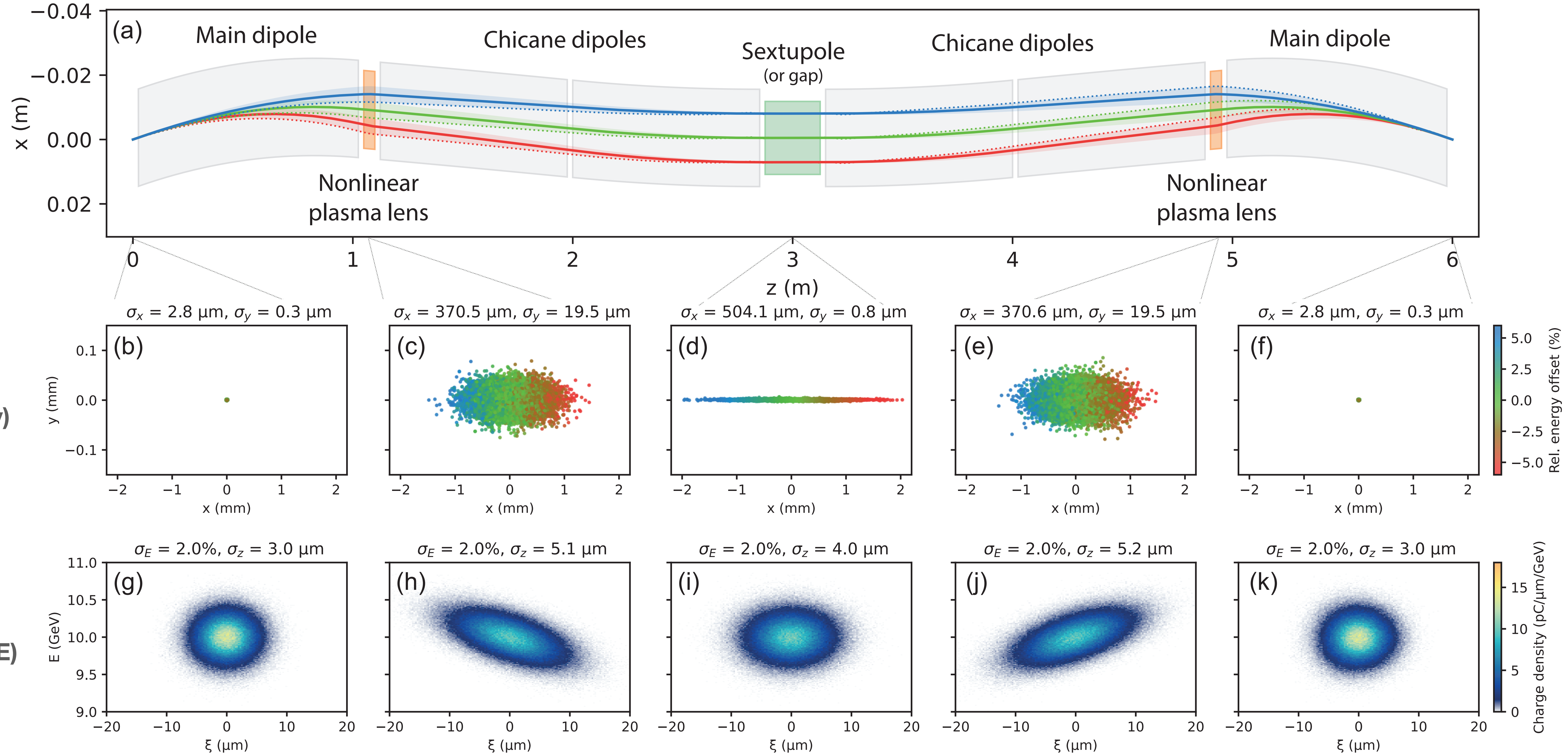
Local chromaticity correction and a new plasma lens

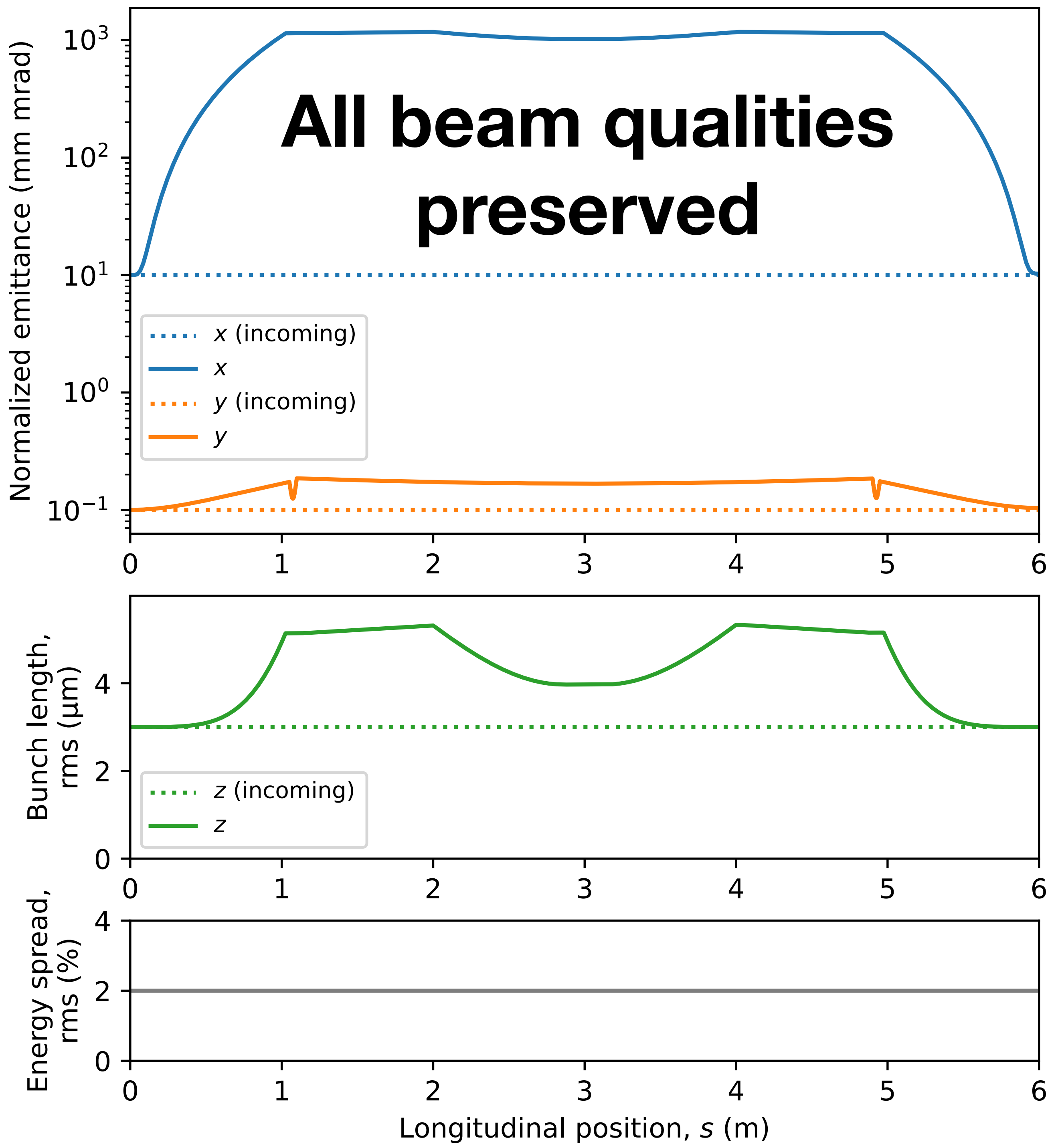
- Inspiration: chromaticity correction in collider final focusing
  - *Disperse, apply stronger focusing for higher energies (+ vice versa)*
- Made compact and simple using a **nonlinear plasma lens**



Evolution in transverse (x–y)

Evolution in longitudinal (z–E)





Source: ***Lindstrøm et al., (manuscript in preparation)***

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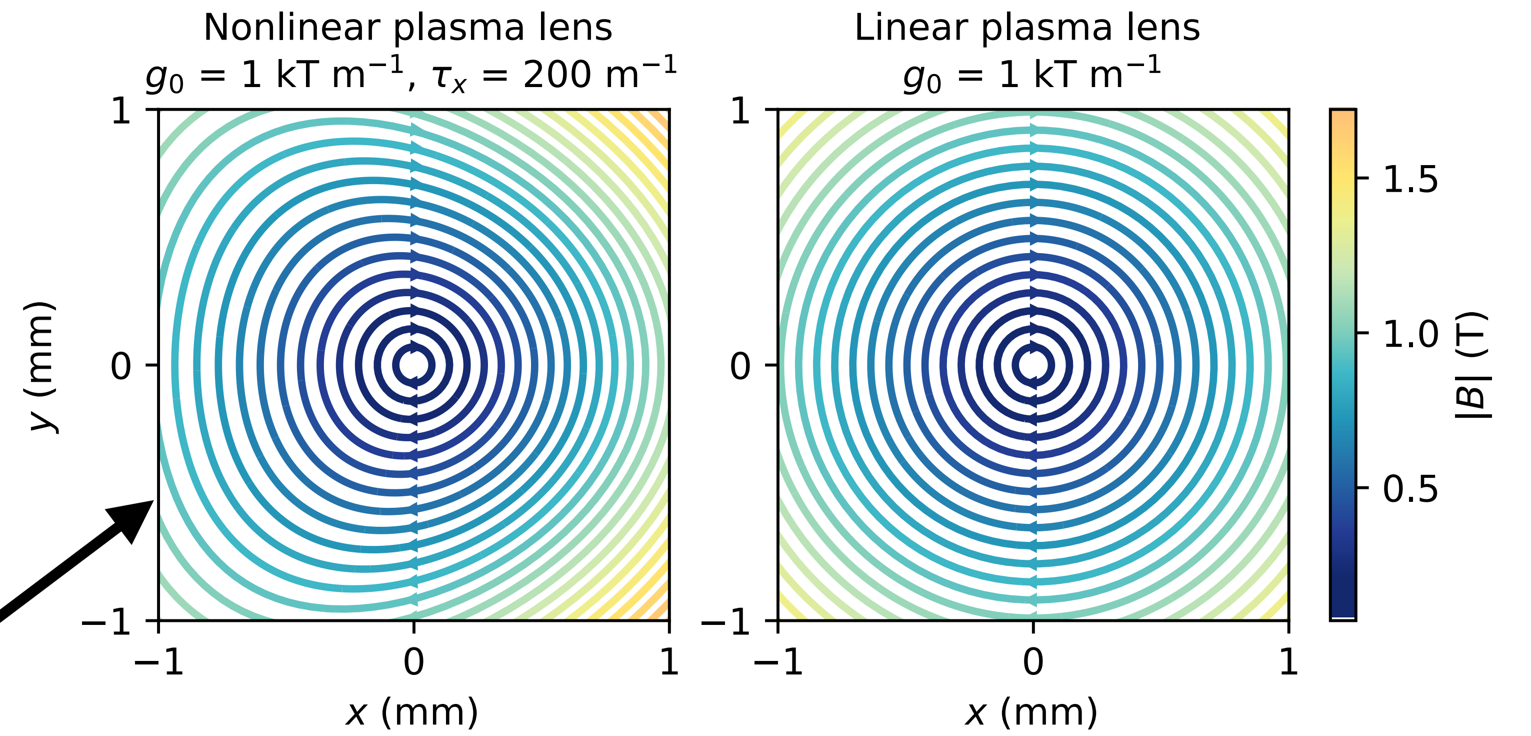

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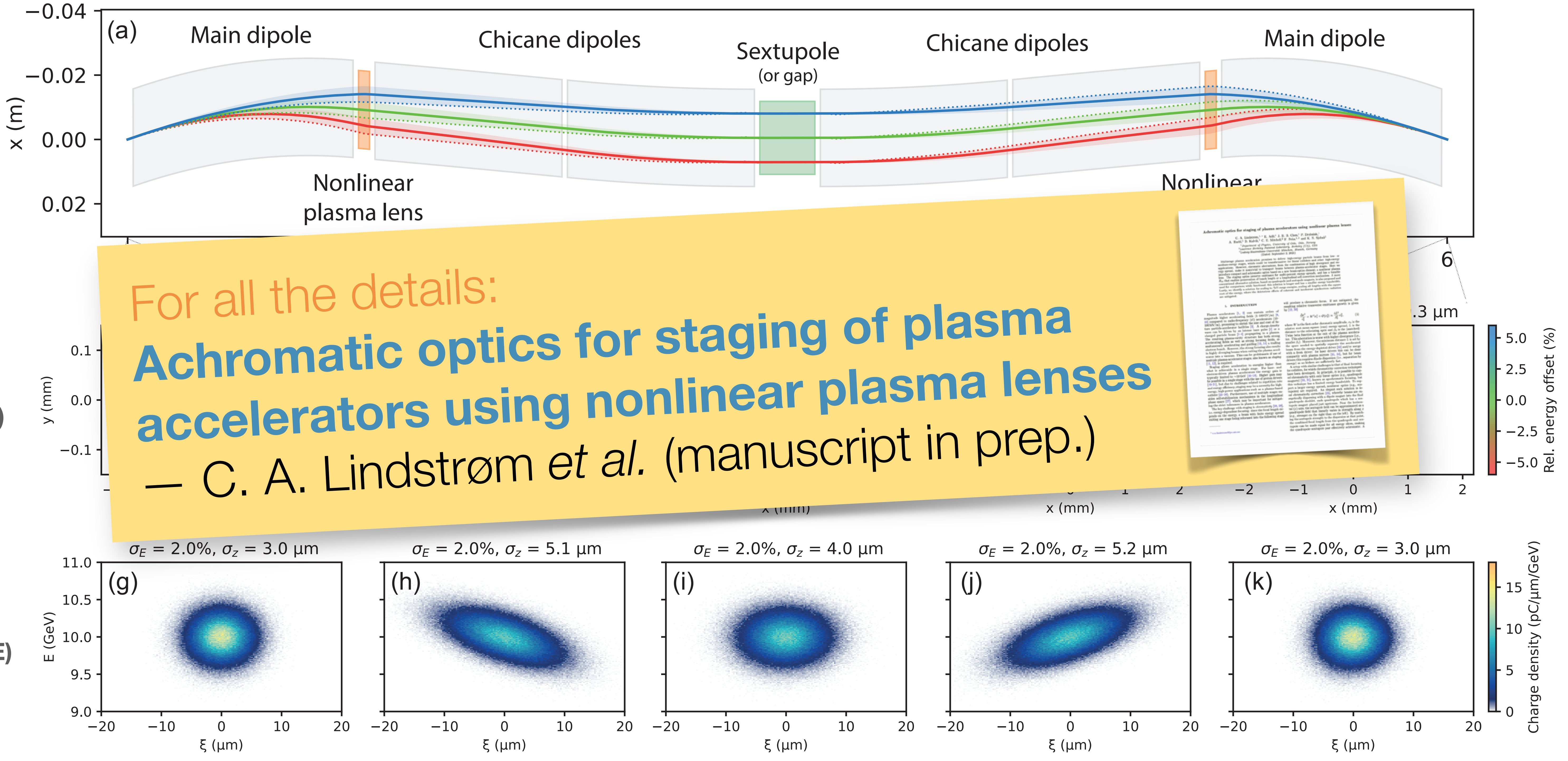
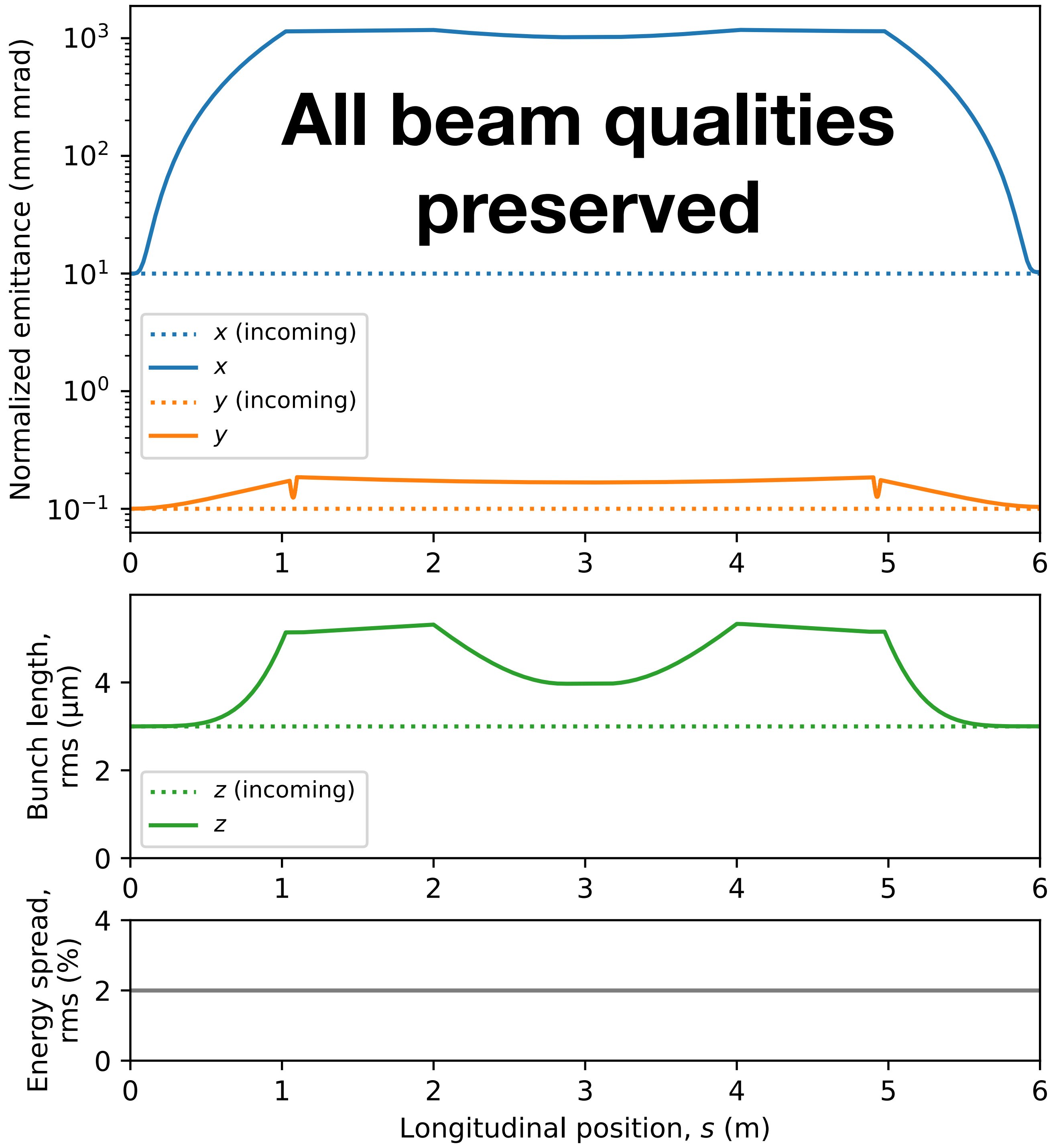


For all the details:
Achromatic optics for staging of plasma accelerators using nonlinear plasma lenses
— C. A. Lindstrøm *et al.* (manuscript in prep.)



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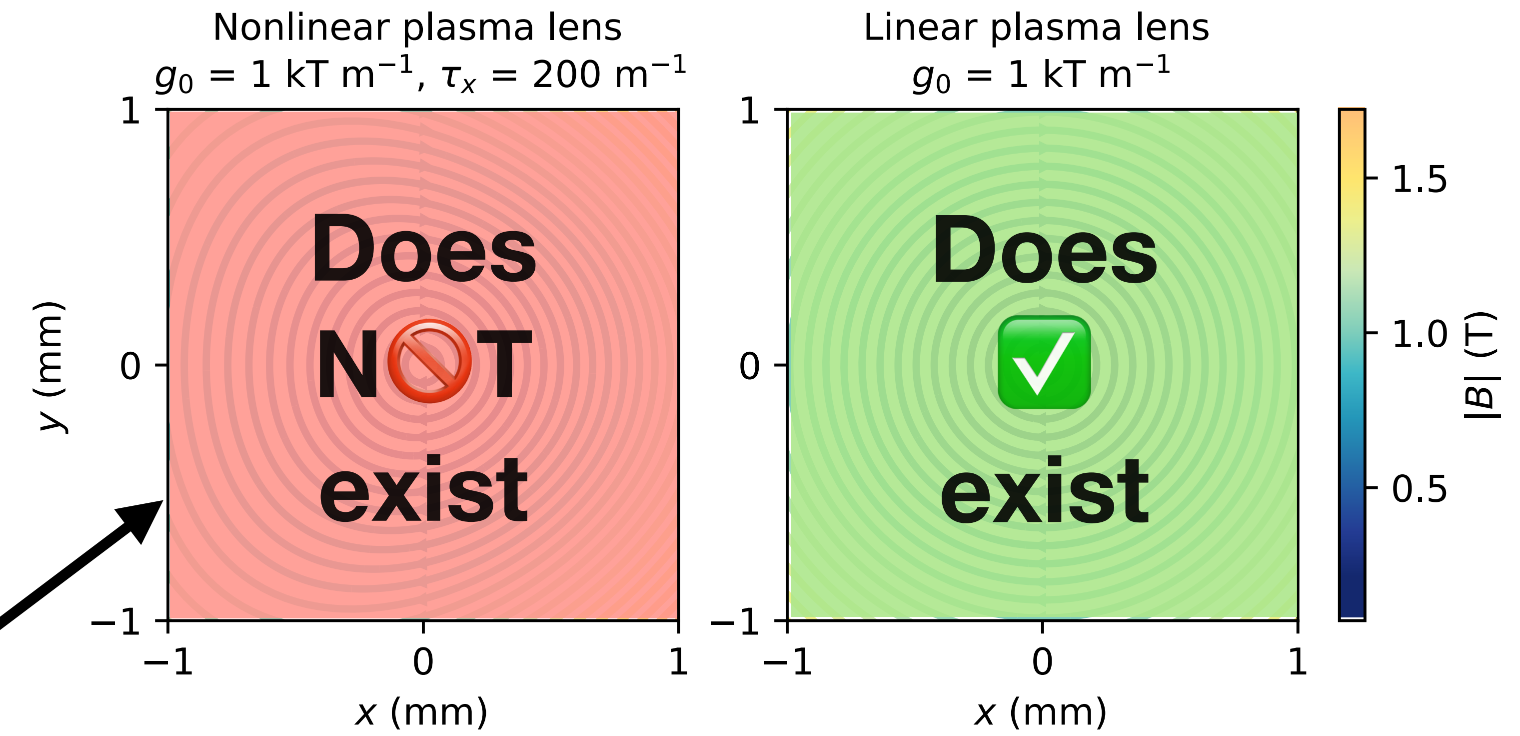
Development required!



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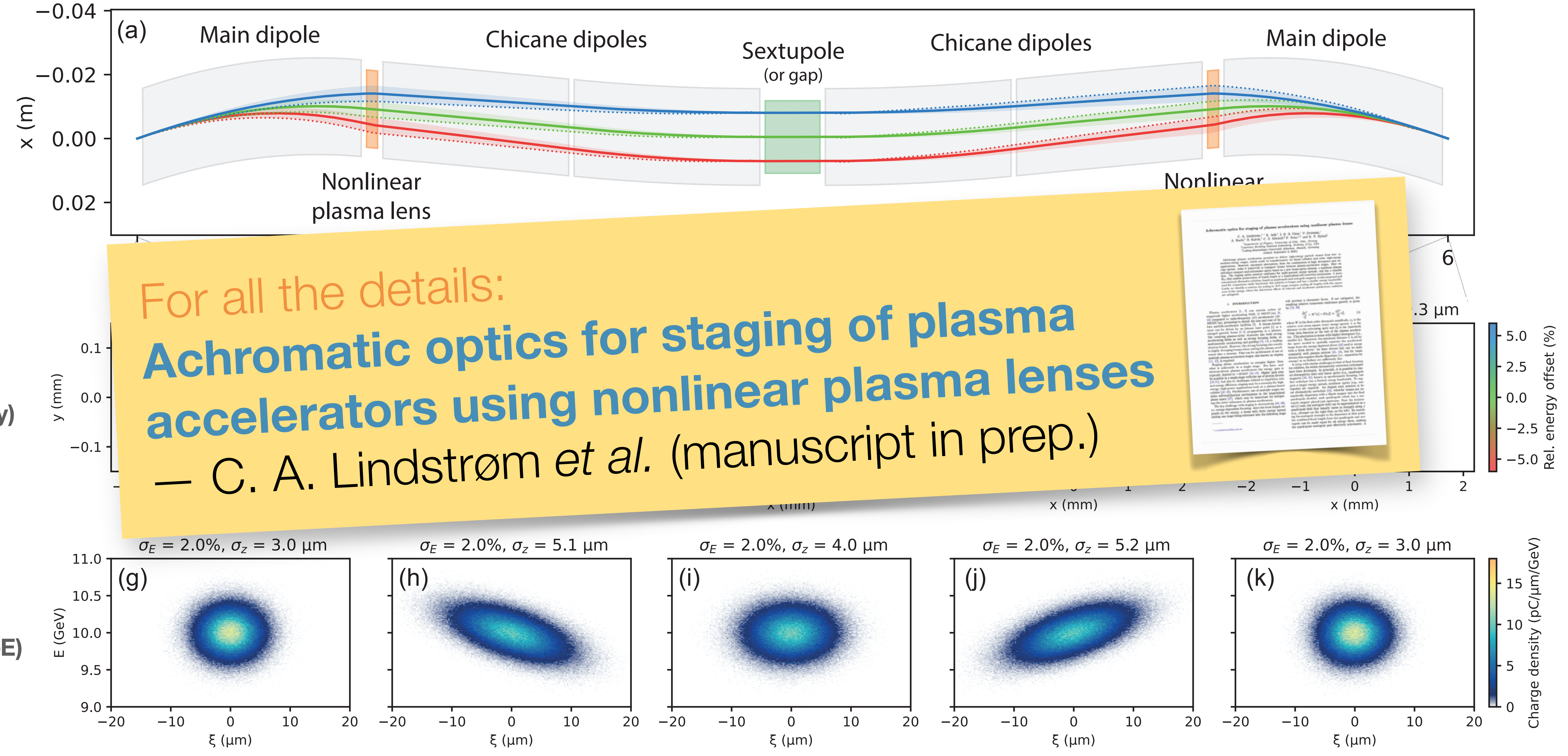
Evolution in longitudinal (z–E)



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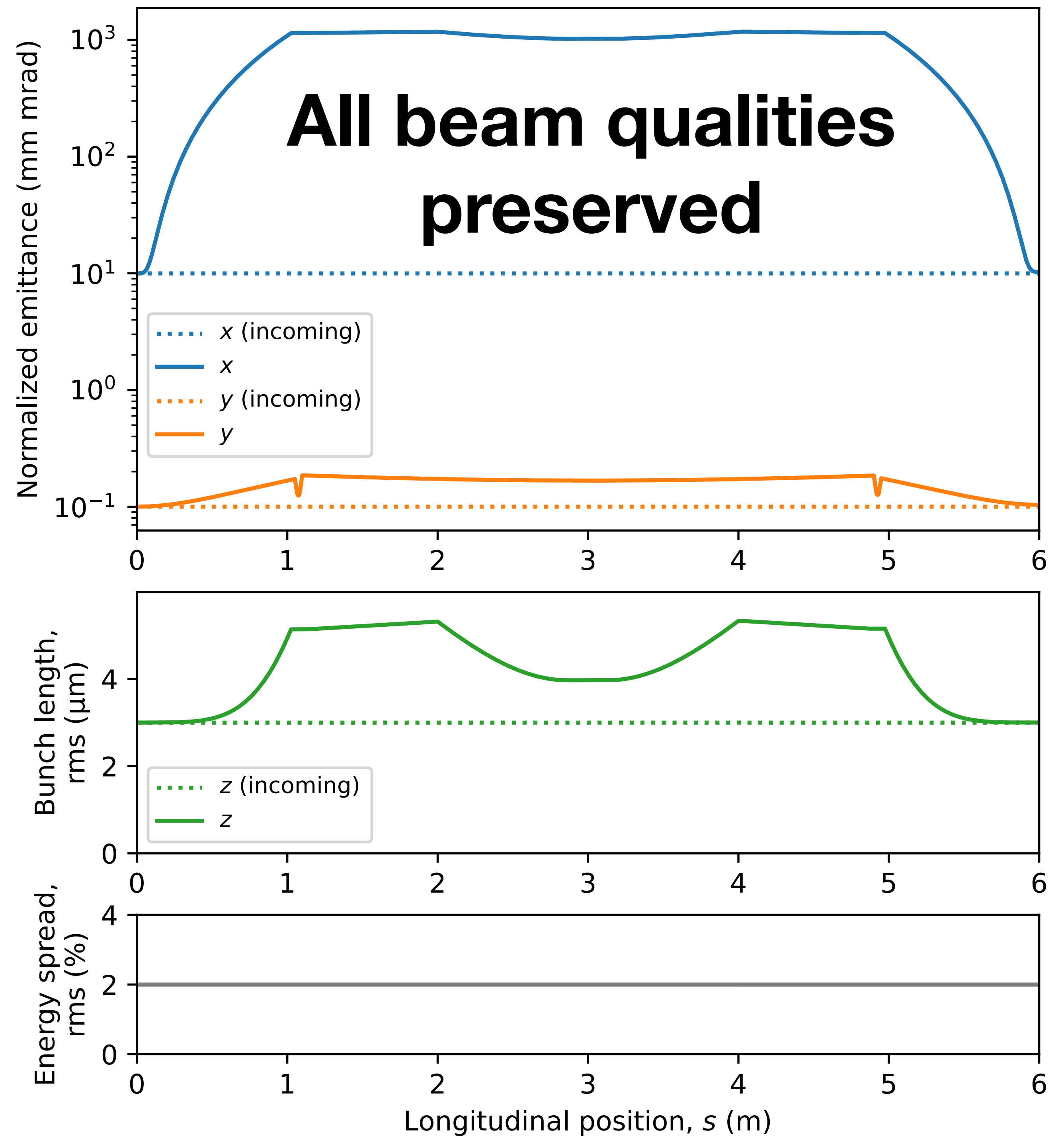
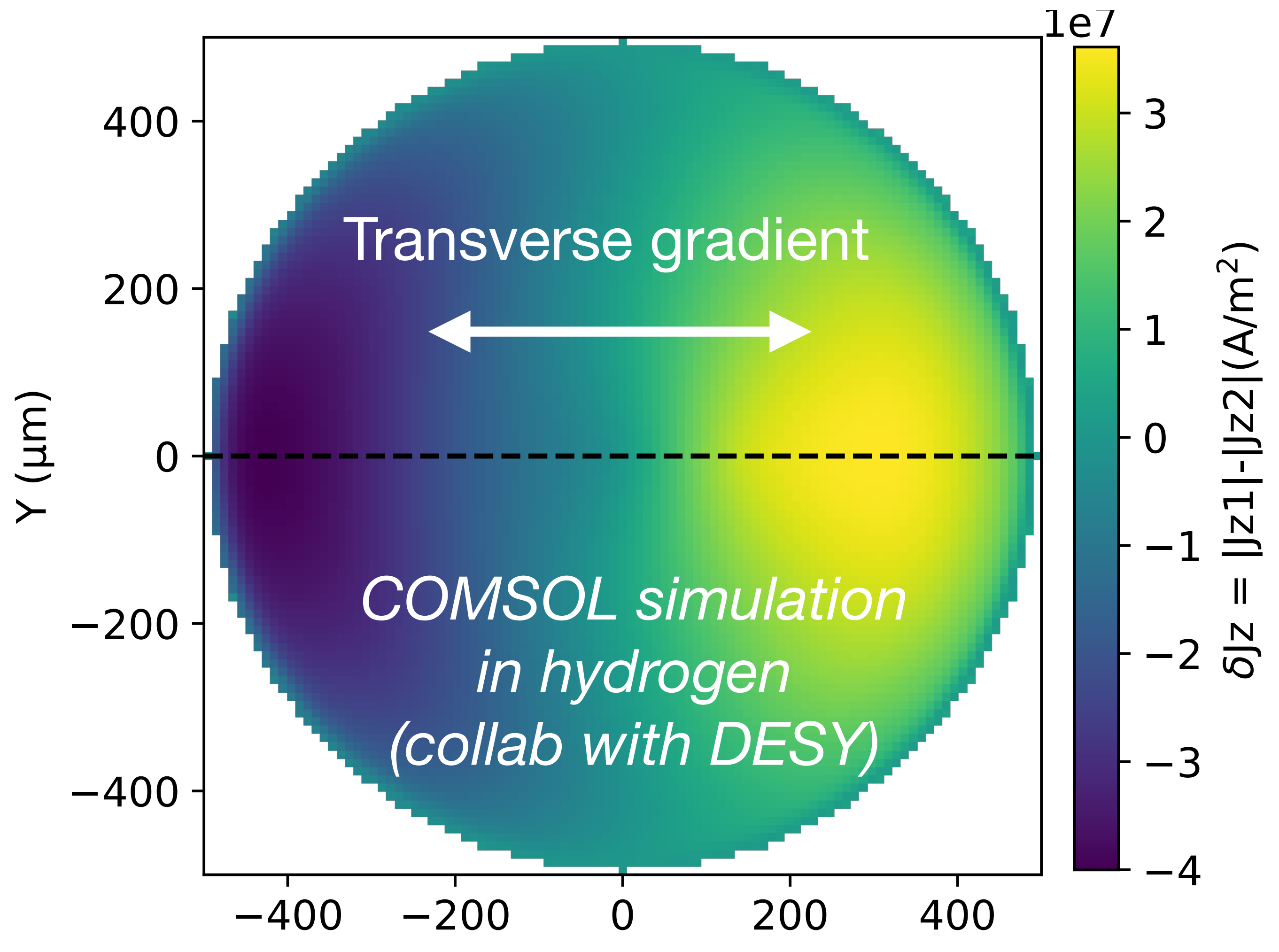


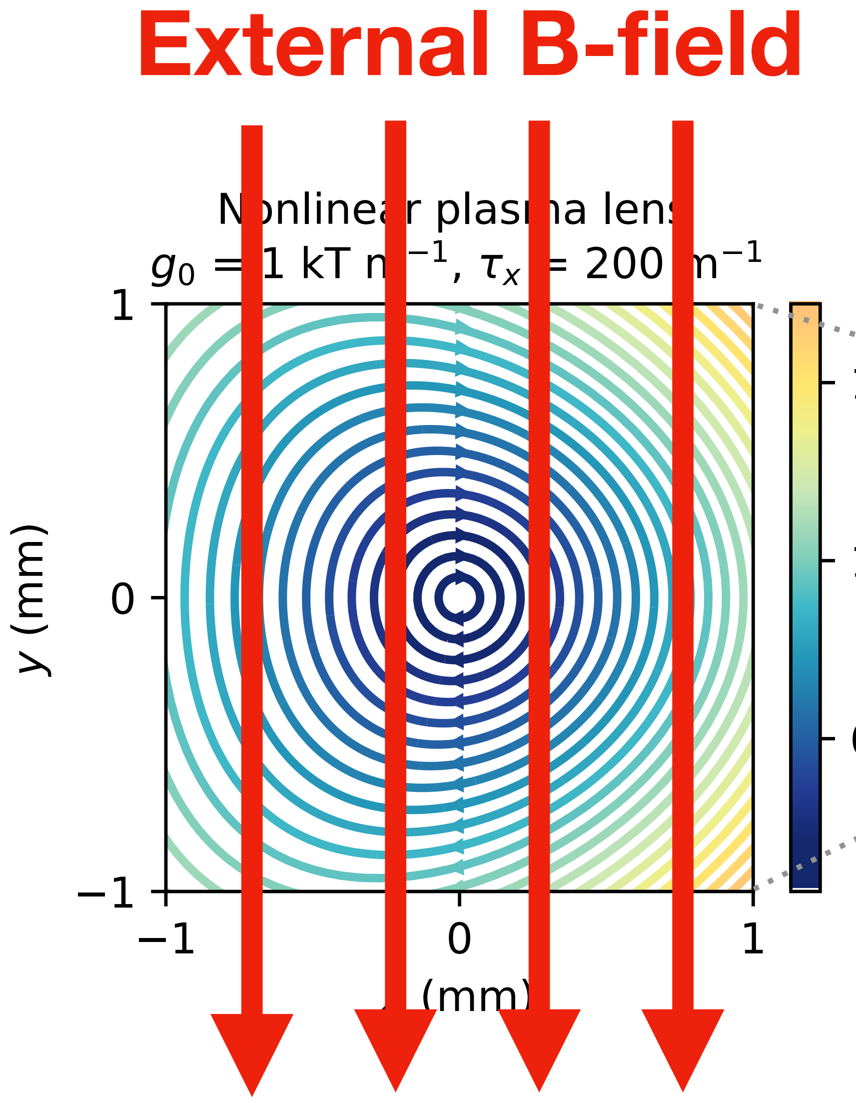
Source: ***Lindstrøm et al., (manuscript in preparation)***

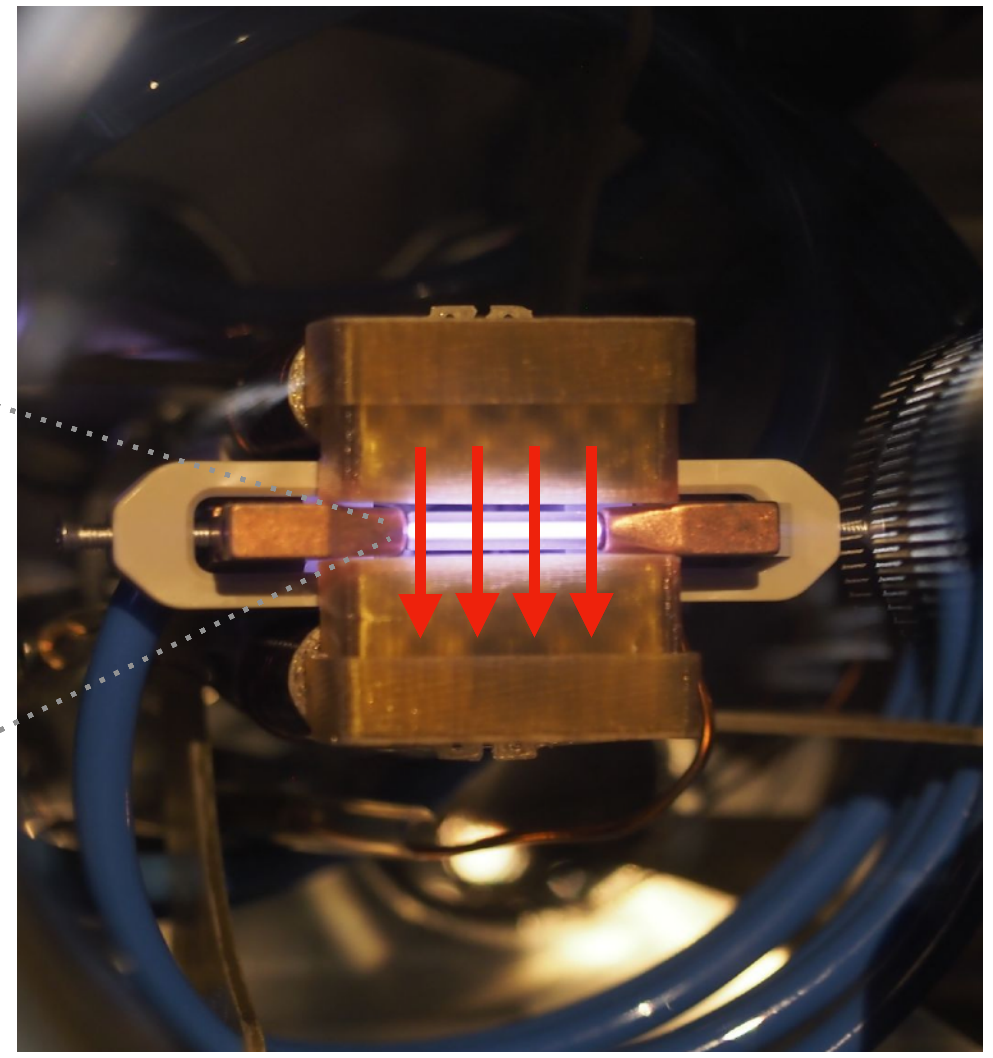
Development of a nonlinear plasma lens

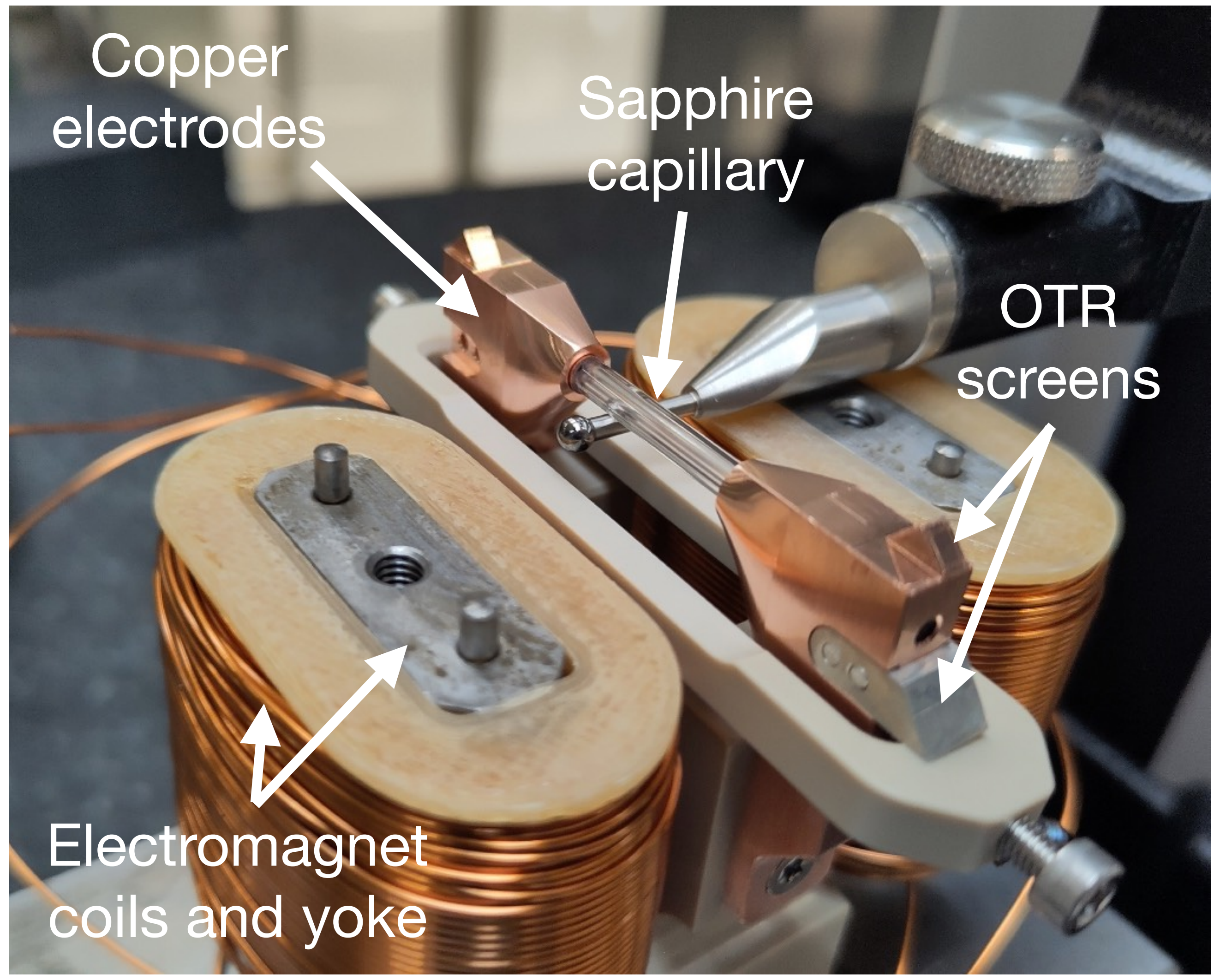
Exciting a nonlinearity through the Hall effect



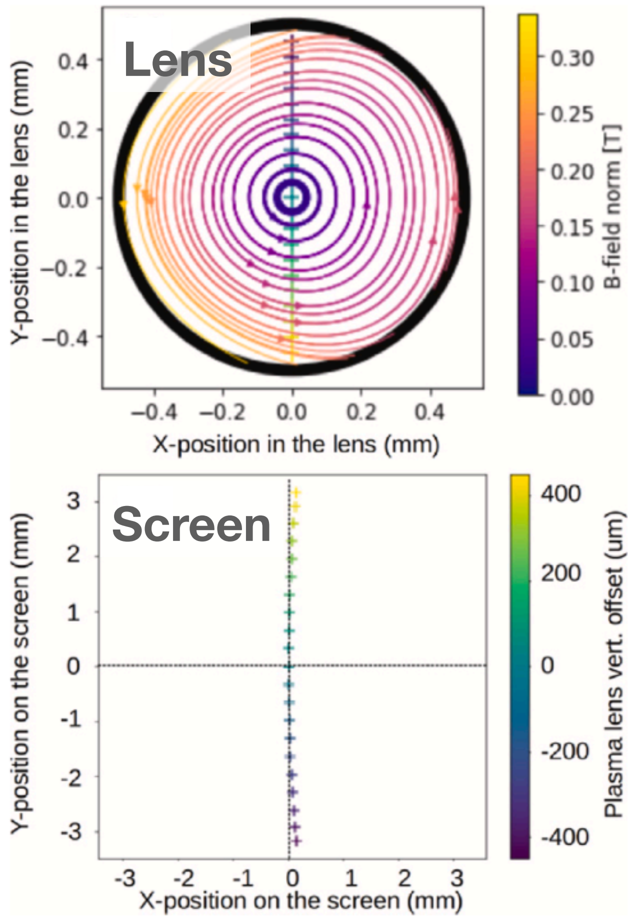
Source: P. Drobniak et al., Proc. IPAC (2025), p. 641

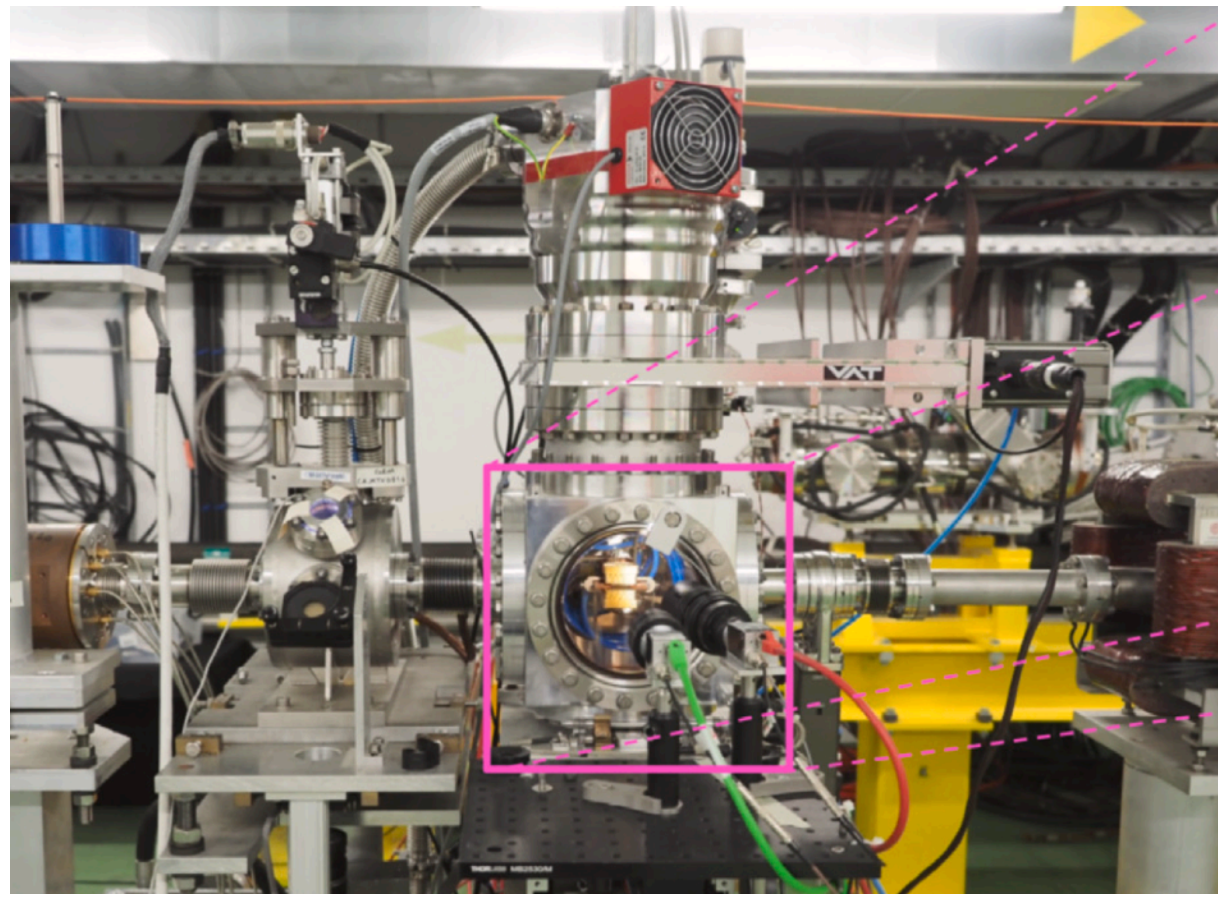






- Concept: apply an external B-field to induce Hall effect
  - *Shifts the discharge current to one side*
- MHD simulations (COMSOL) indicates the principle works.
- Designed/manufactured at Uni. Oslo (P. Drobniak *et al.*).
- Characterized with *e*-beam in CLEAR @ CERN (June 2025).

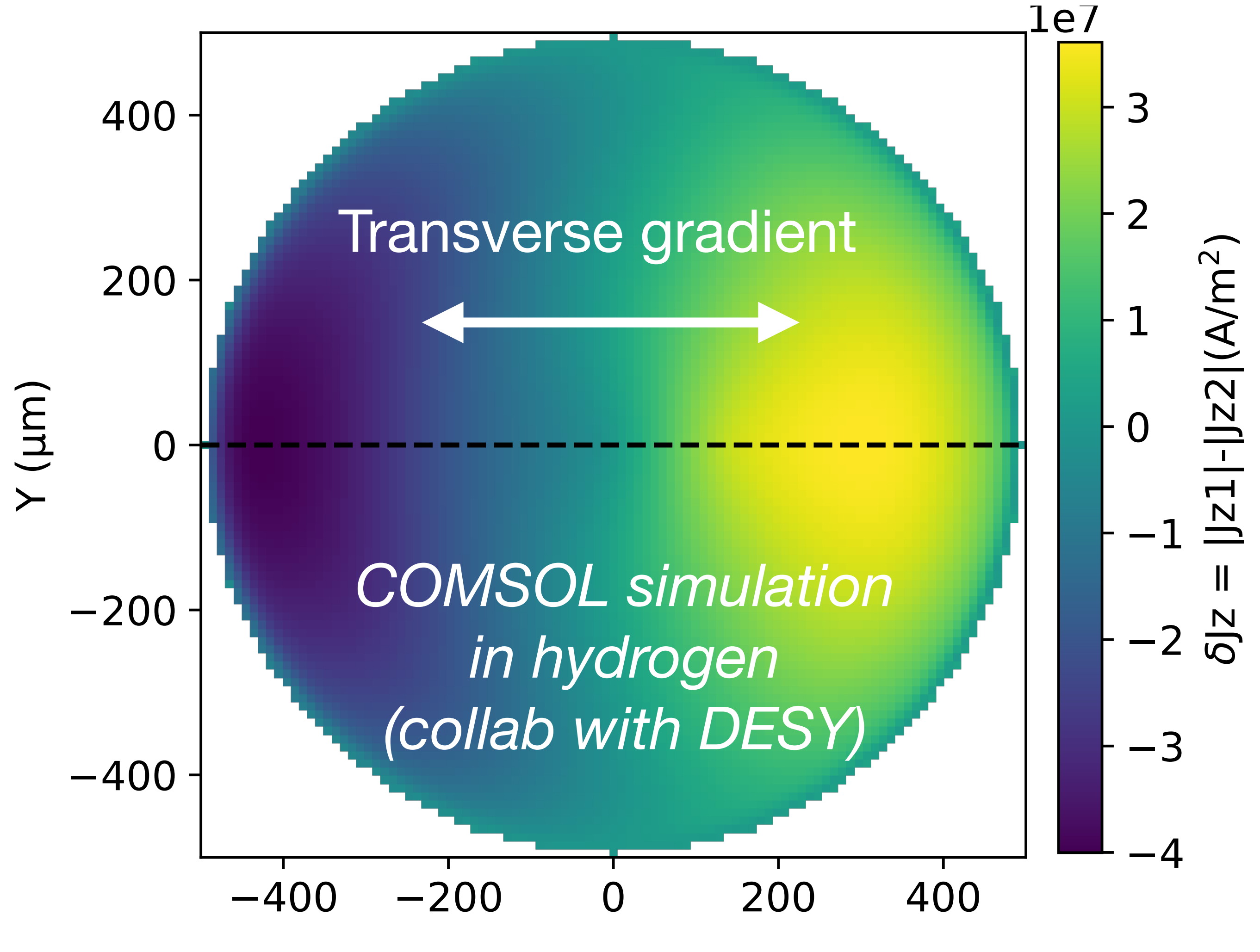




Source: P. Drobniak et al., NIM A 1072, 170223 (2025)

Development of a nonlinear plasma lens

Exciting a nonlinearity through the Hall effect



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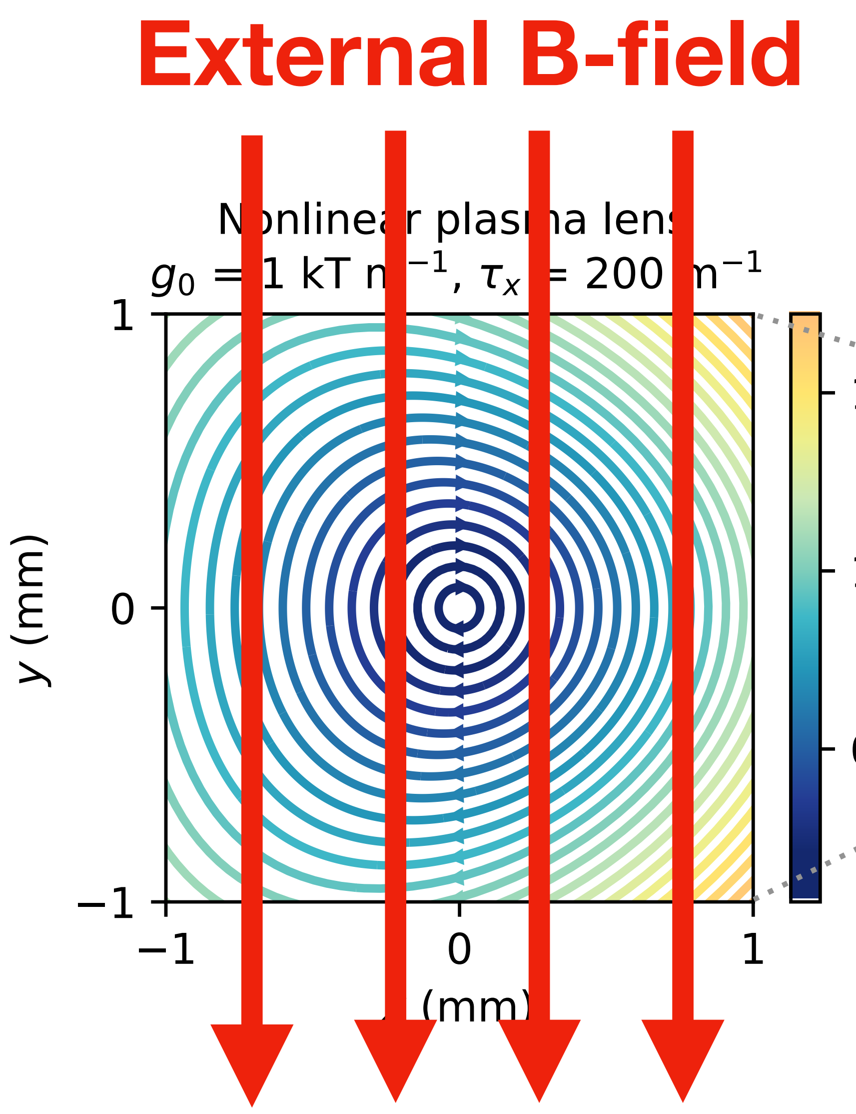
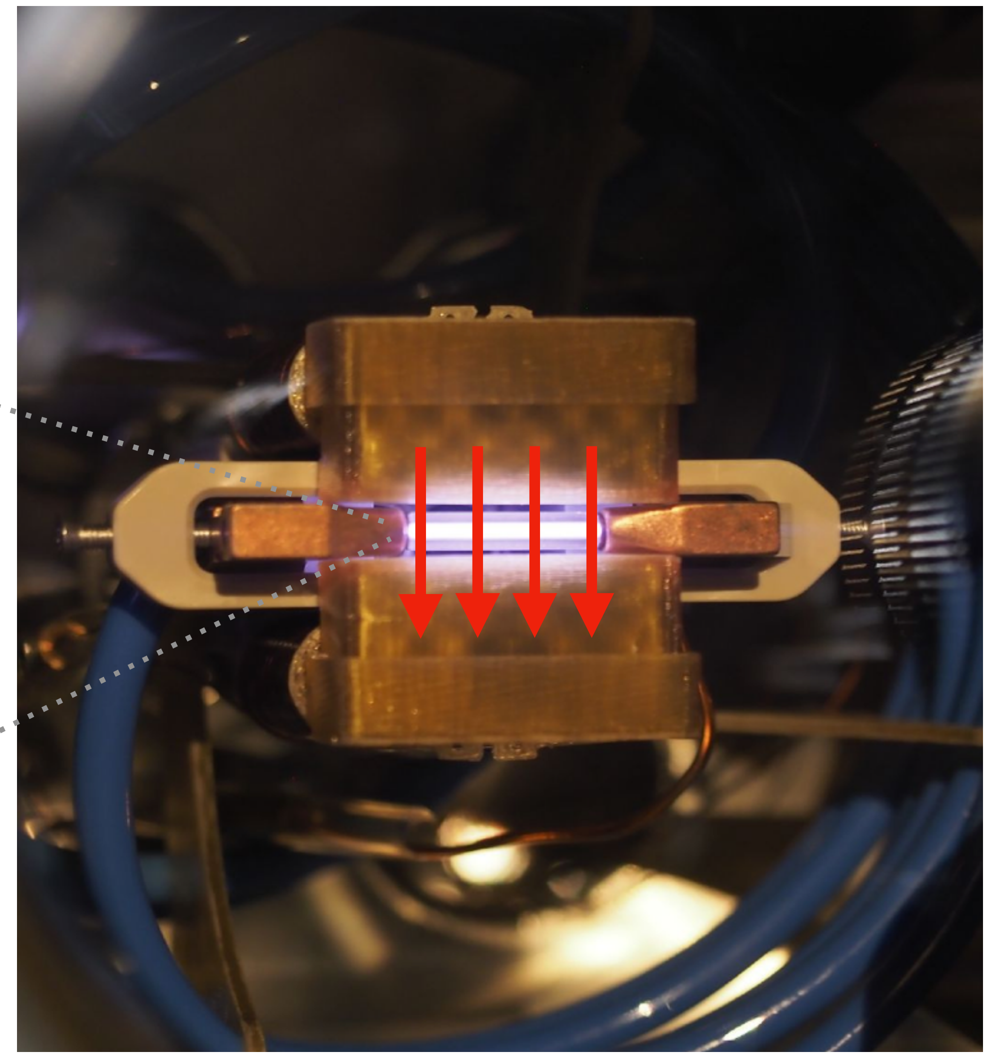
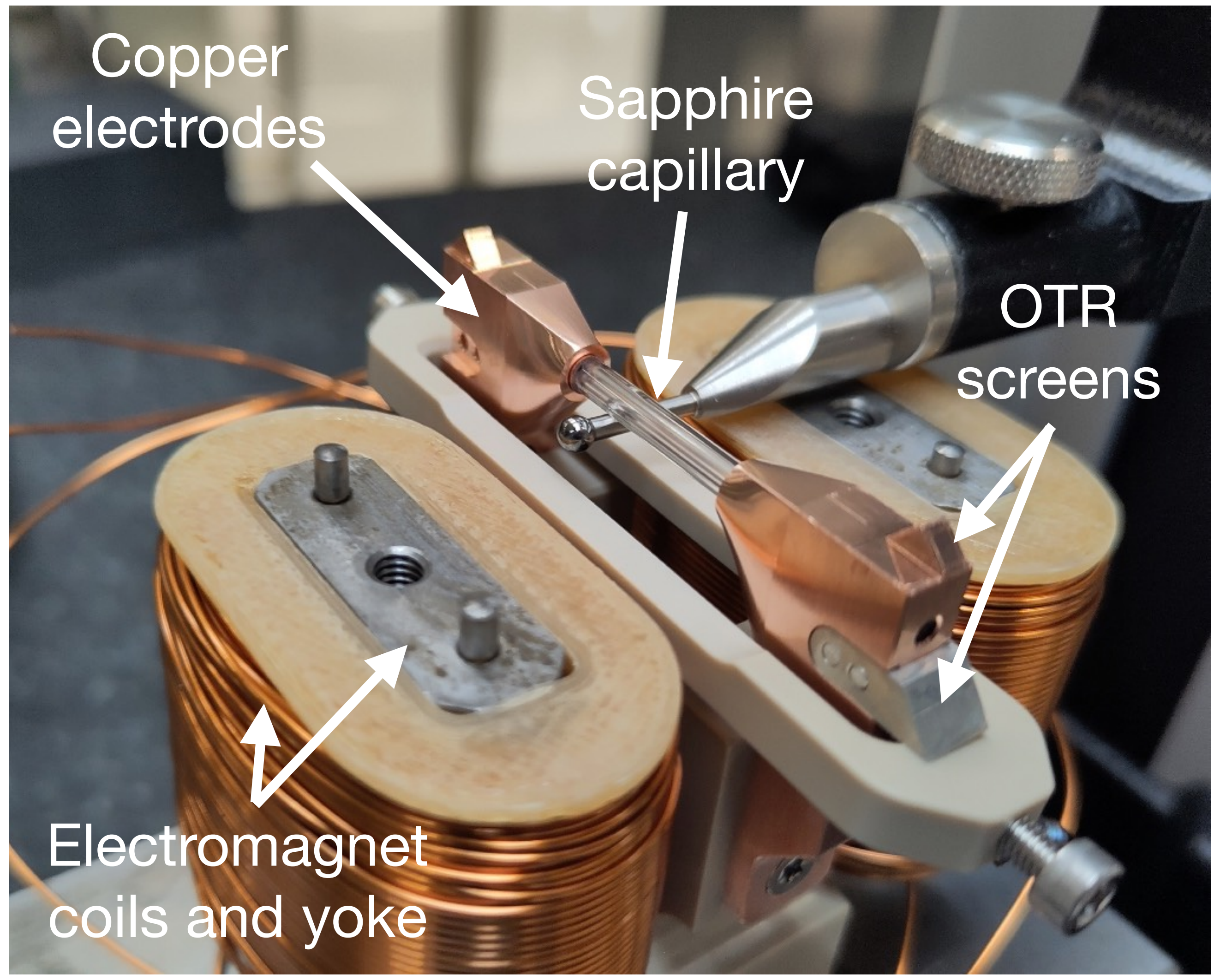






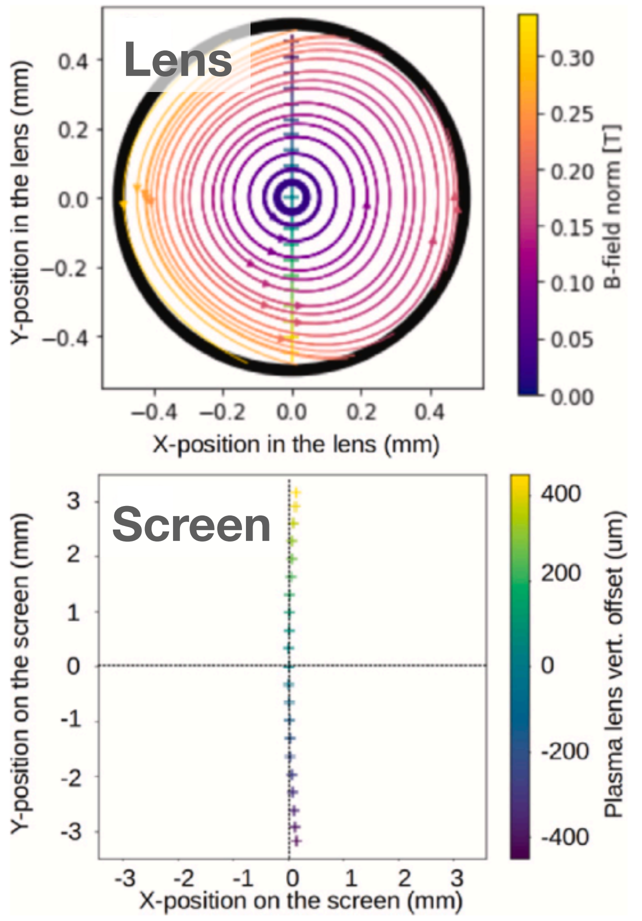
> Concept: apply an external B-field to induce Hall eff...

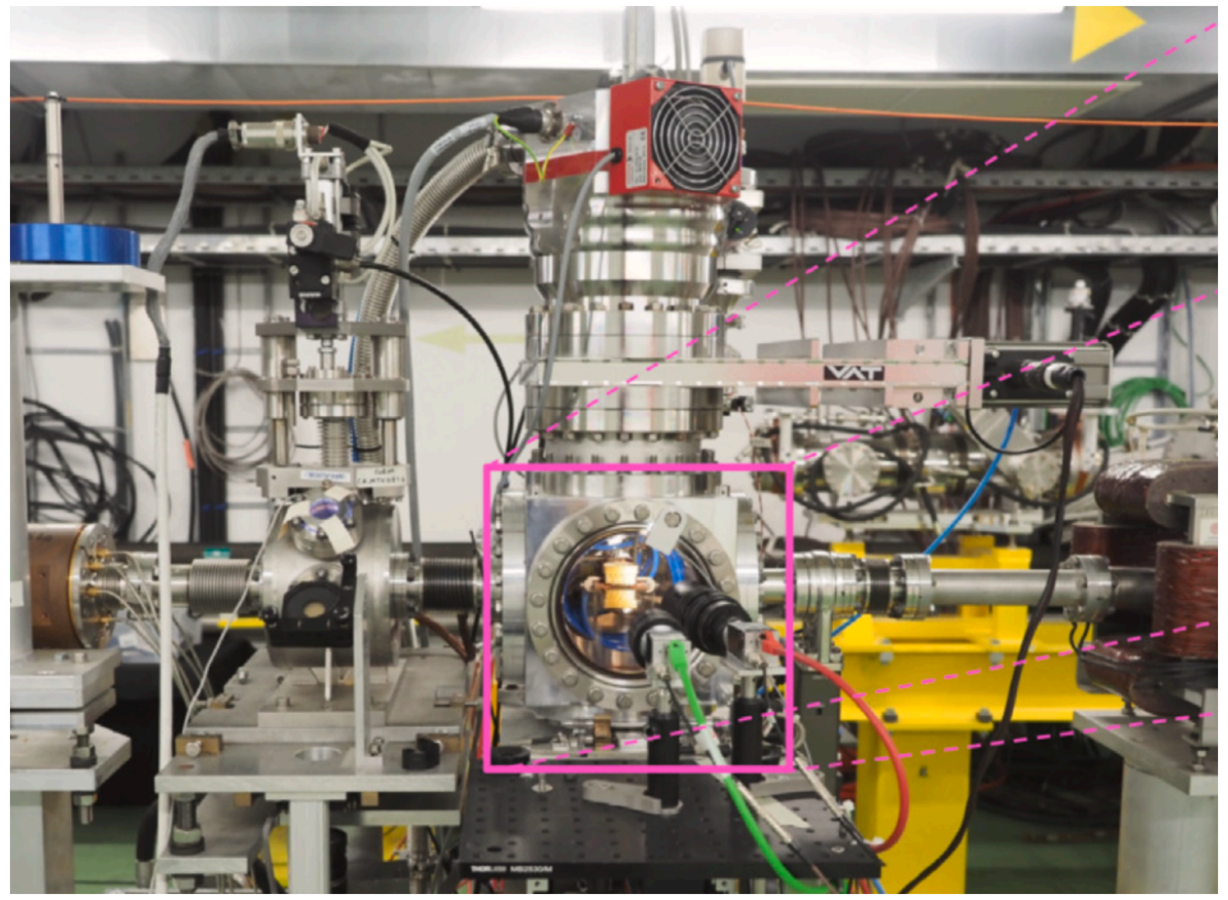
Poster #463 (Monday 19:00)

Nonlinear plasma lens for achromatic staging: follow-up on latest simulation and experiment

— Pierre Drobniak *et al.*

> Characterized with e-beam in CLEAR @ CERN (June 2025).





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

Part 2:

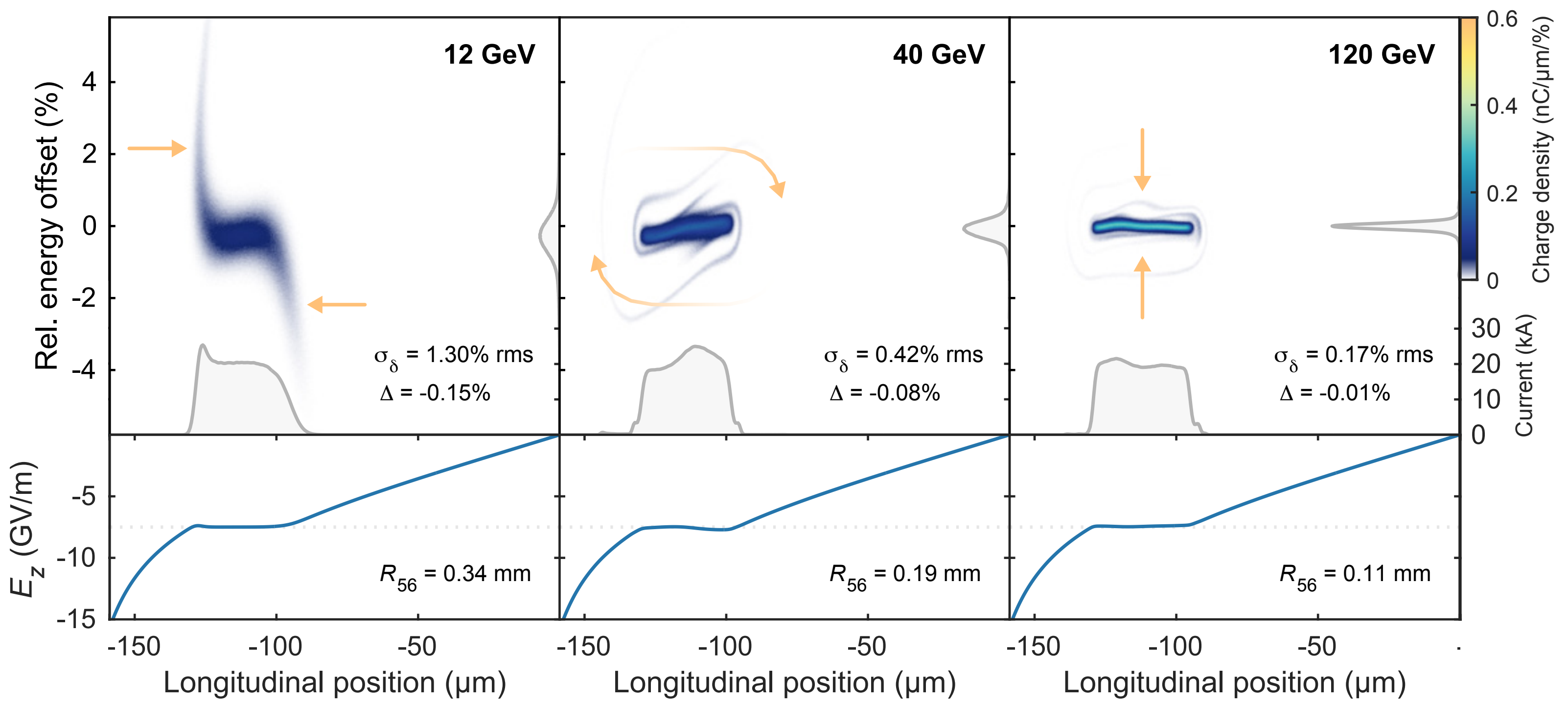
Stabilization

Through **passive stabilization mechanisms**

Passive stabilization mechanisms

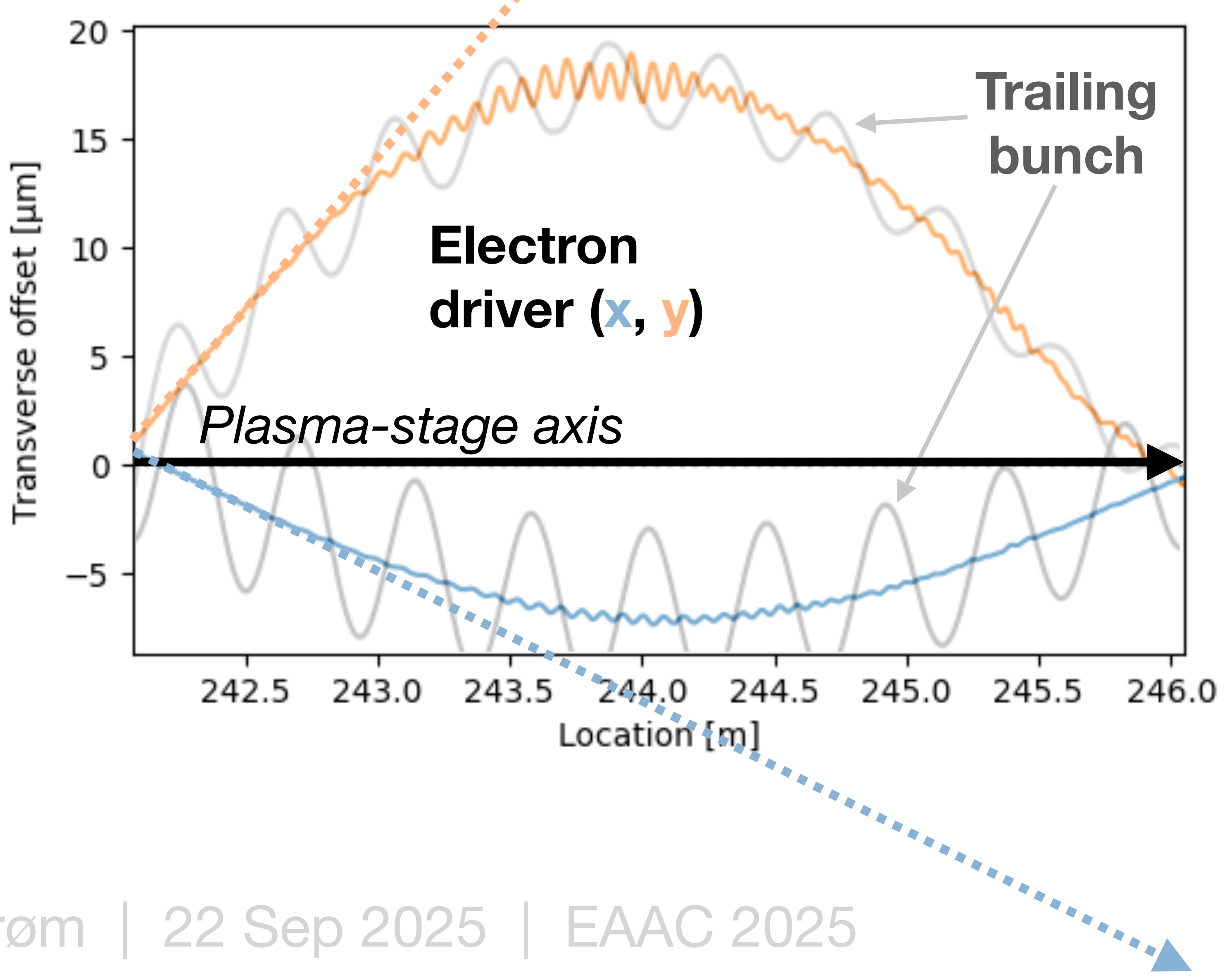
In the longitudinal and transverse phase space – critical for operation with realistic jitter

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

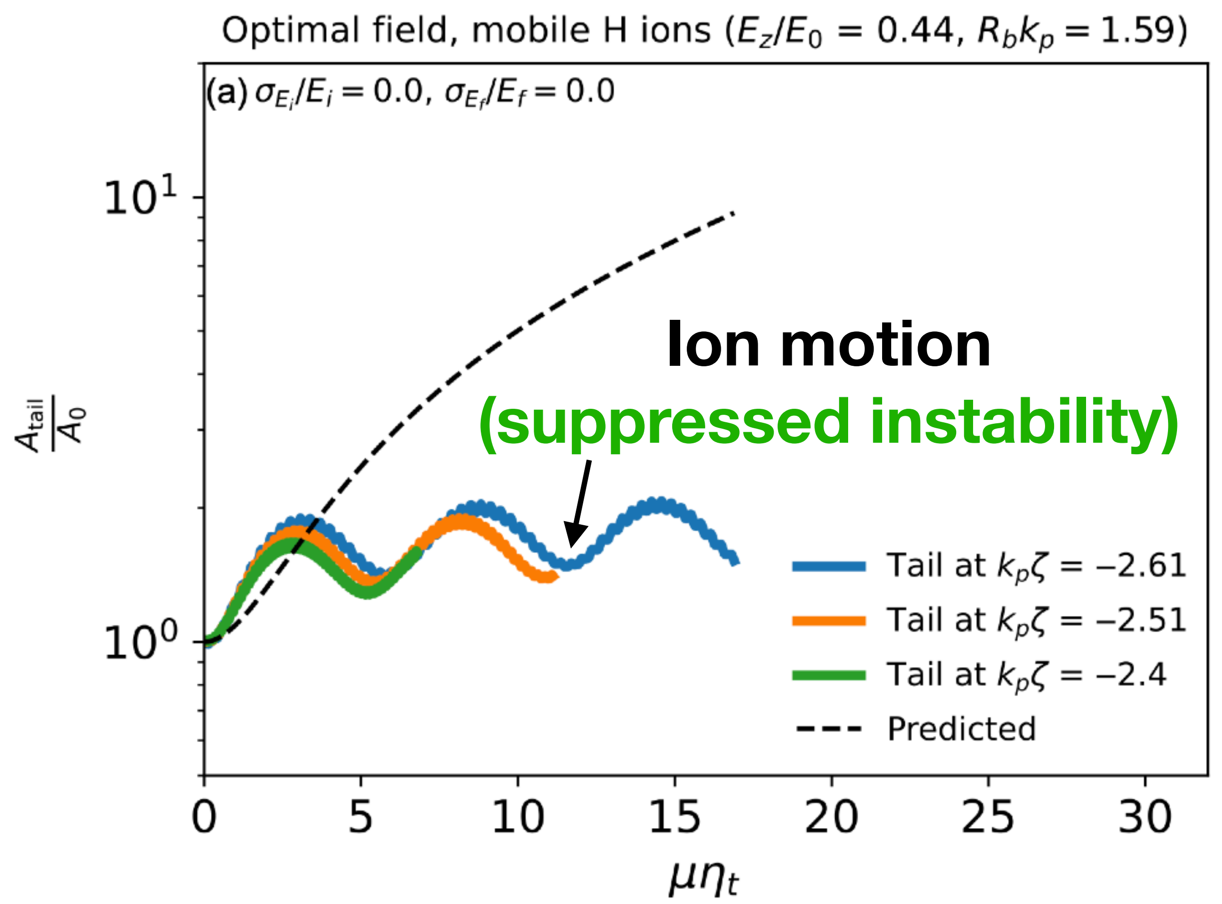


Source: Lindstrøm, arXiv:2104.14460 (2021)

> **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)

Passive stabilization mechanisms

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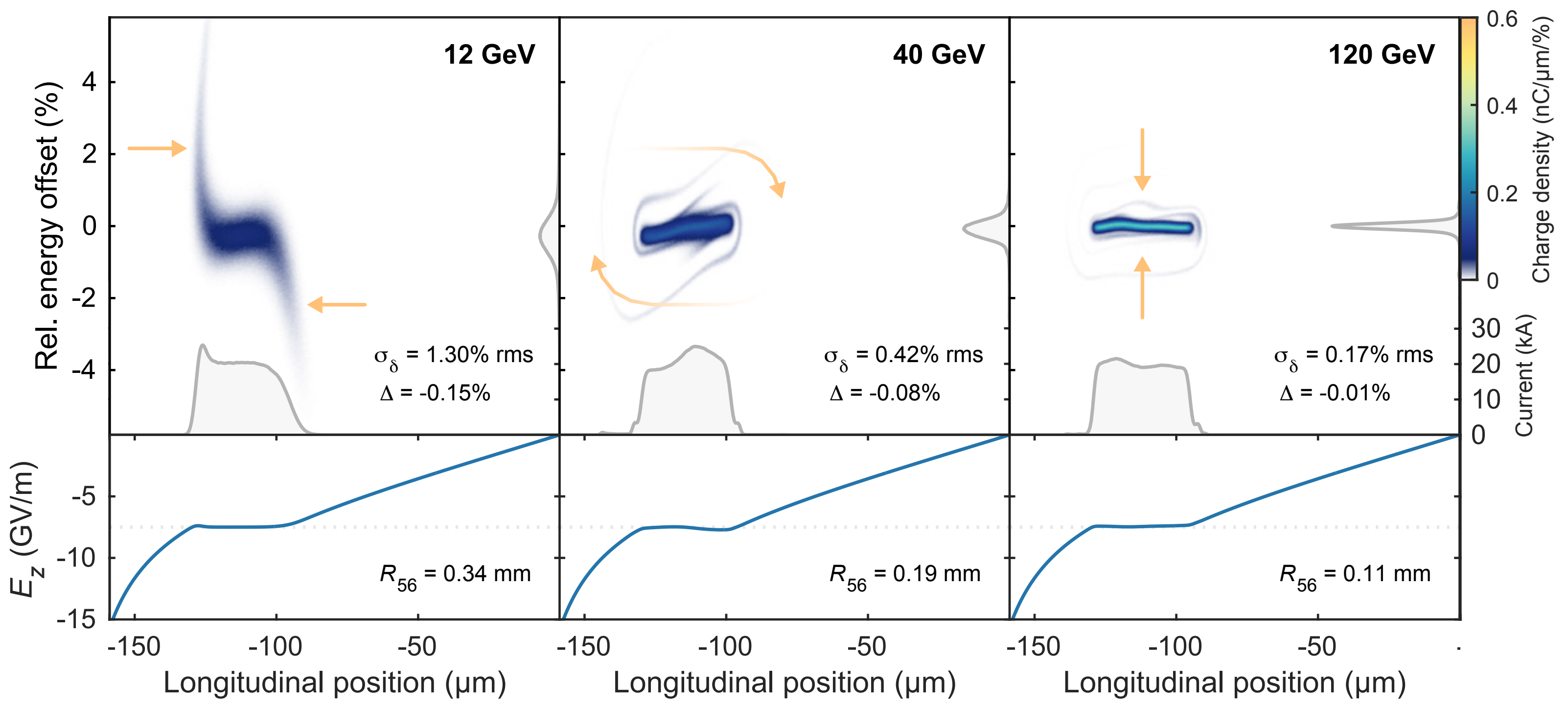

Source: Lindstrøm, arXiv:2104.14460 (2021)

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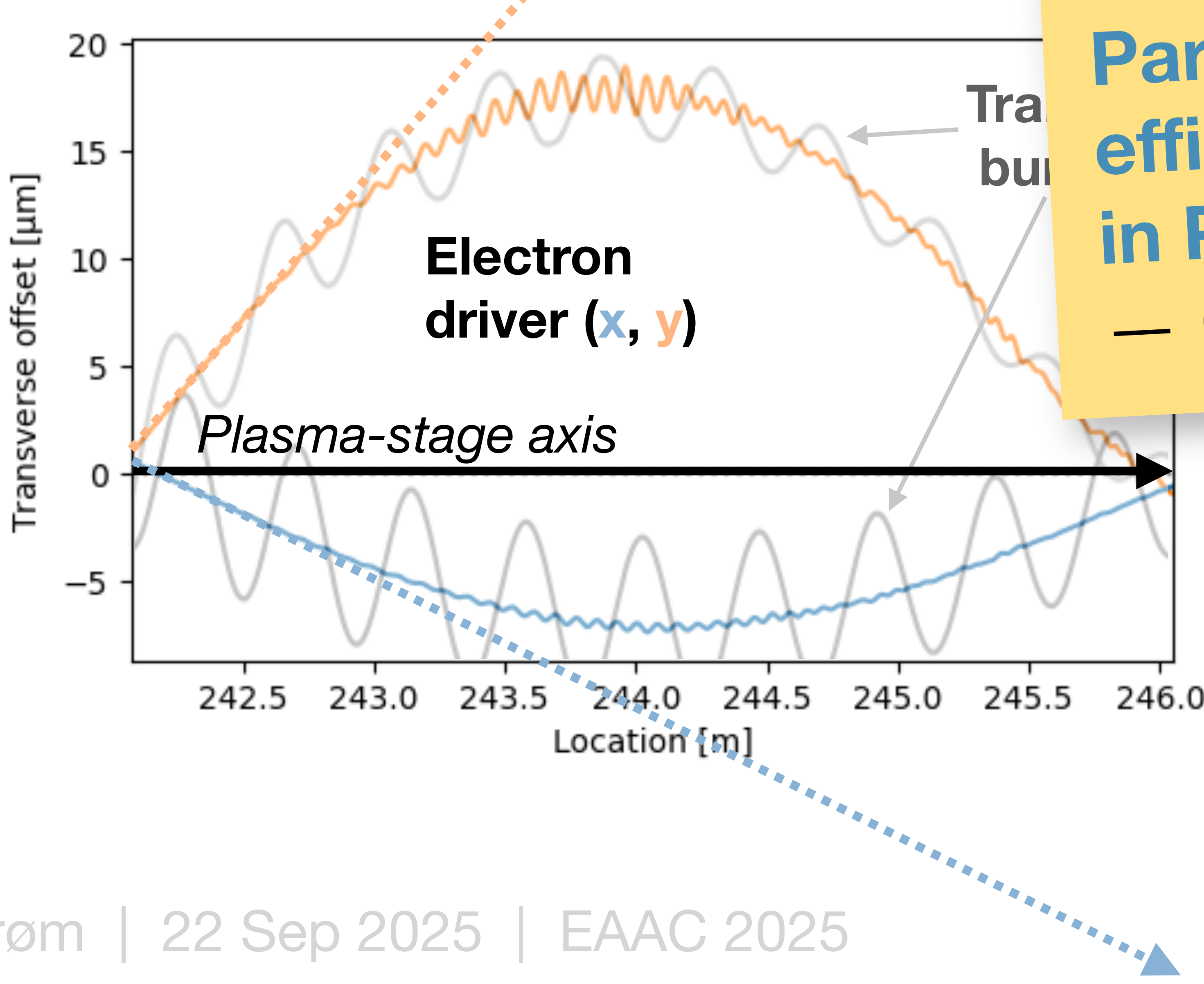
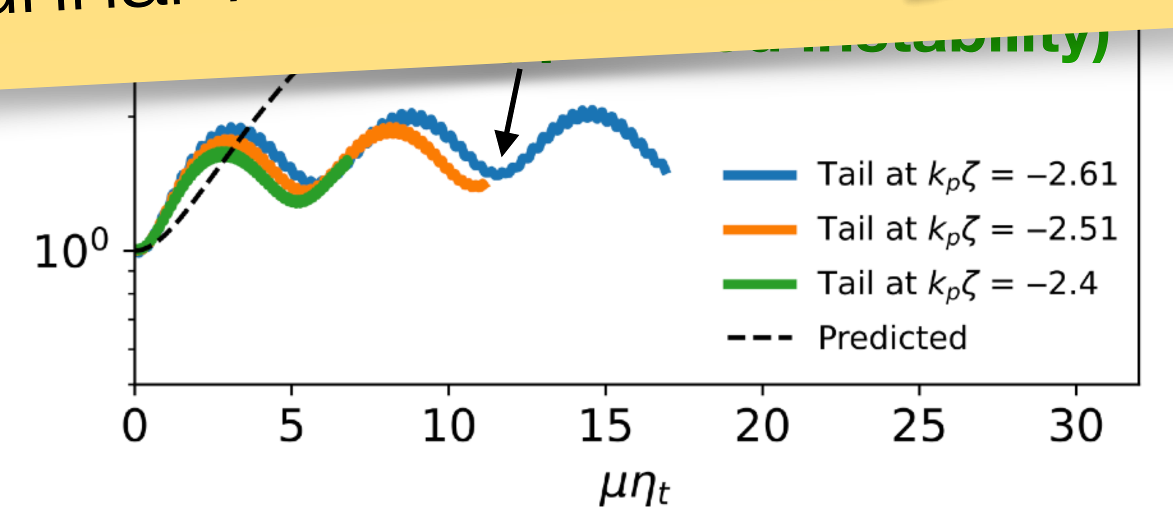


- **Ion motion for beam-breakup suppression**
  - Use light ions (H or He) to introduce some nonlinear focusing

Contributed talk (Wed. 17:20)
Parametric mapping of the efficiency–instability relation in PWFAs
— Ole Gunnar Finnerud *et al.*



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

Part 3:

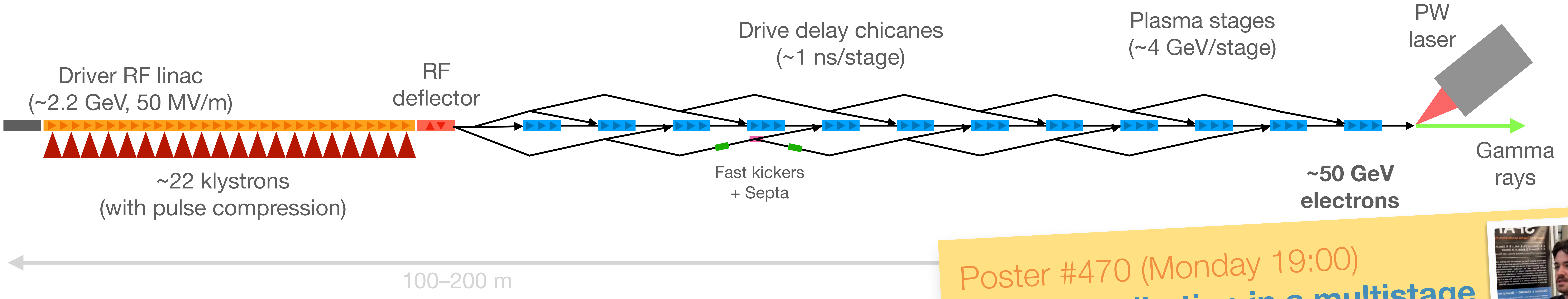
Demonstrator

Conceptual design of a 50-GeV SFQED facility

Conceptual design of a multistage plasma accelerator

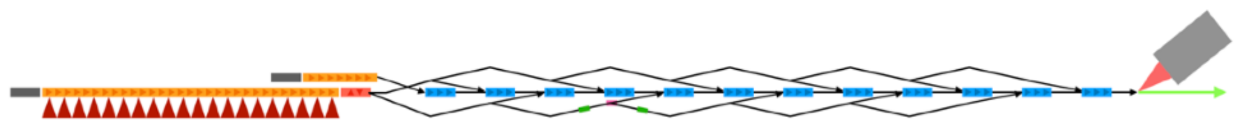
The SPARTA demo machine – first step toward a HALHF demonstrator

- Ultimate goal: Design a self-consistent, multistage plasma accelerator with SFQED application
  - *example: 2.2 GeV e⁻ drivers, 12 stages @ 1 GV/m → 50 GeV + ~2 PW laser → χ ≈ 10–50*



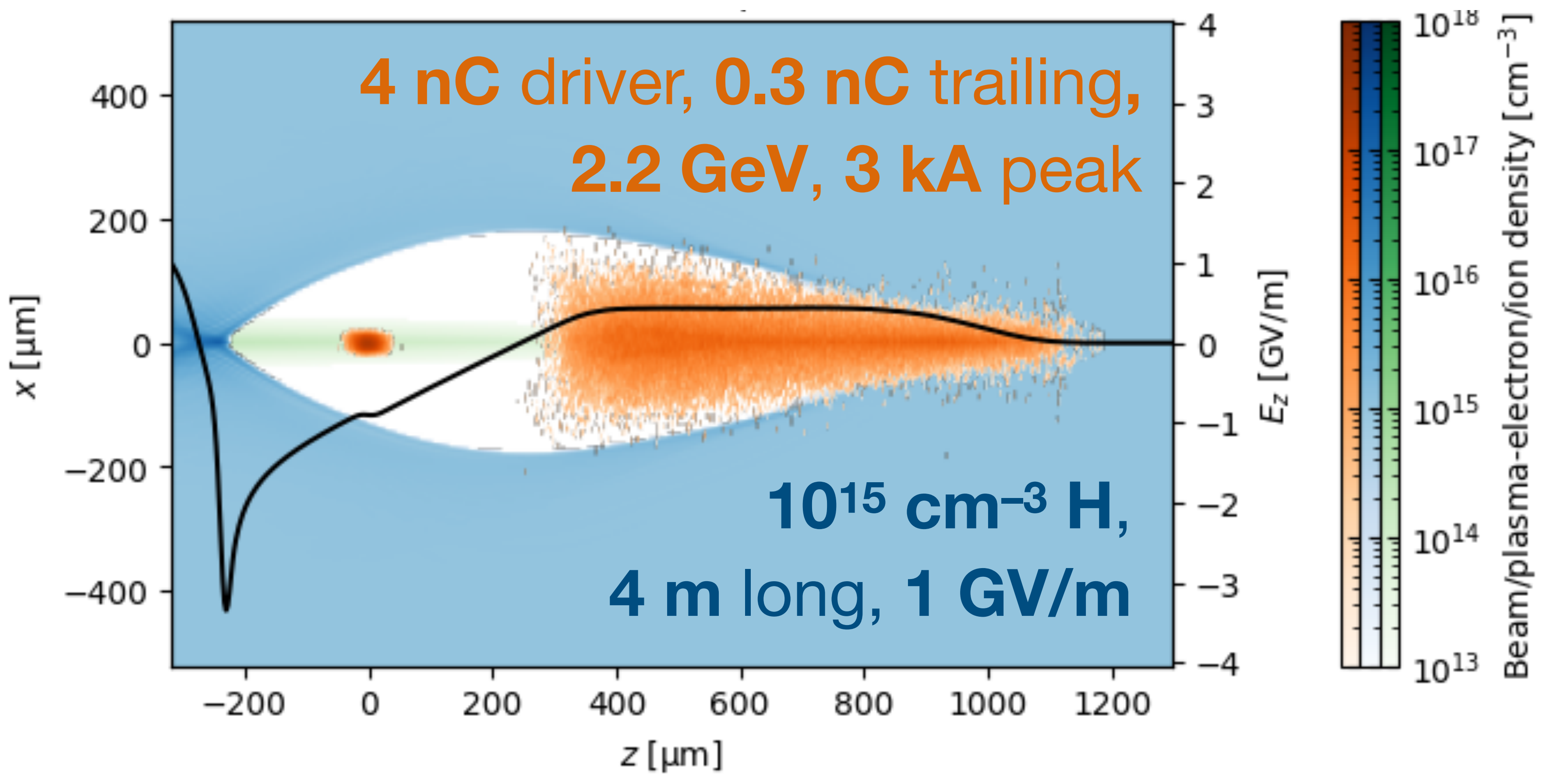
- Ongoing work: lattice design of the driver distribution system
- Early discussions with DESY on possible implementation:
  - *Project cost frame of up to €250M (incl. HALHF-like upgrades for beam quality, rep rate, spin)*
  - *Would start construction after the PETRA-IV upgrade (2032+), e.g., in an old HERA hall*

Start-to-end simulations of the SPARTA demo

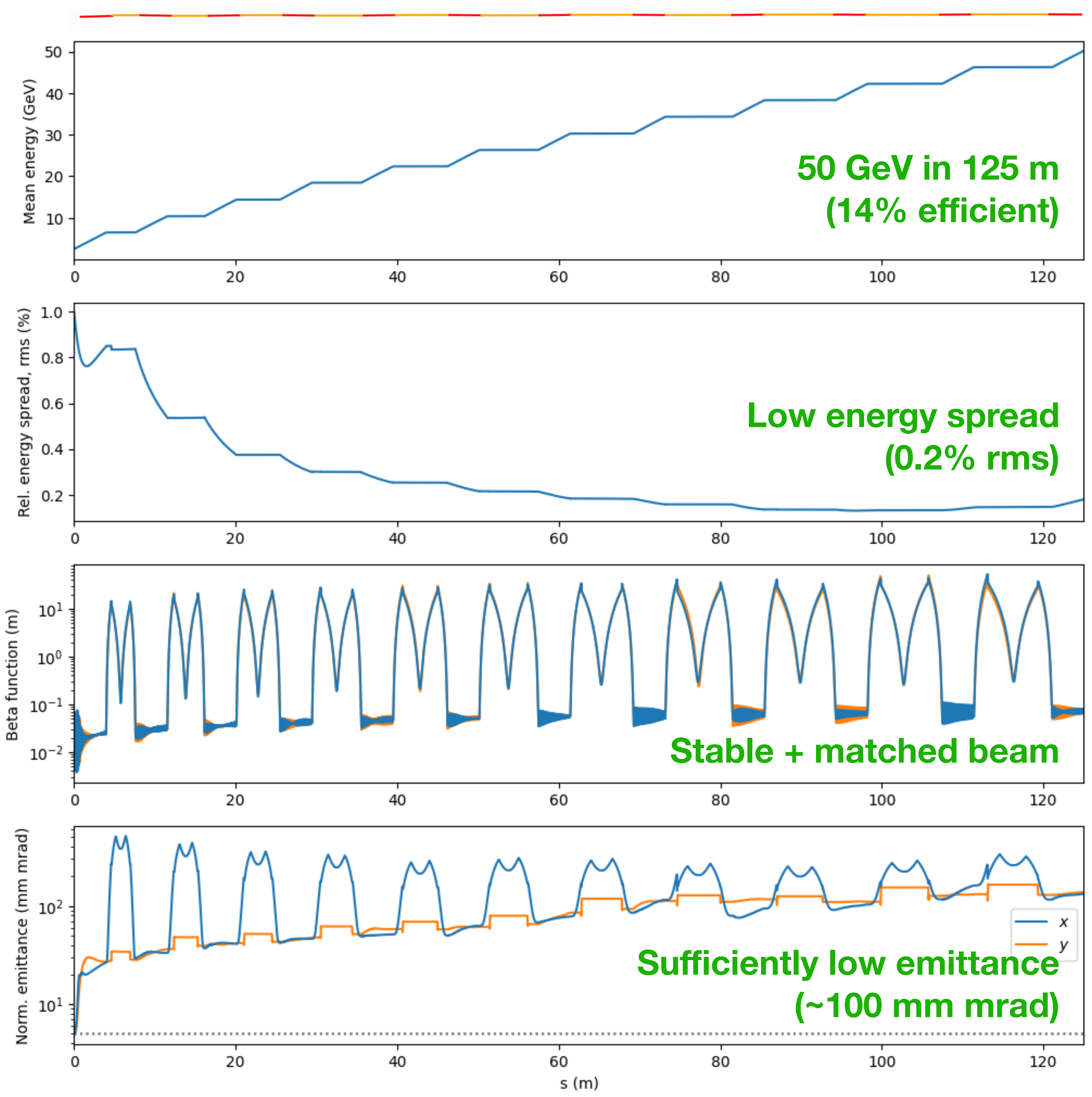


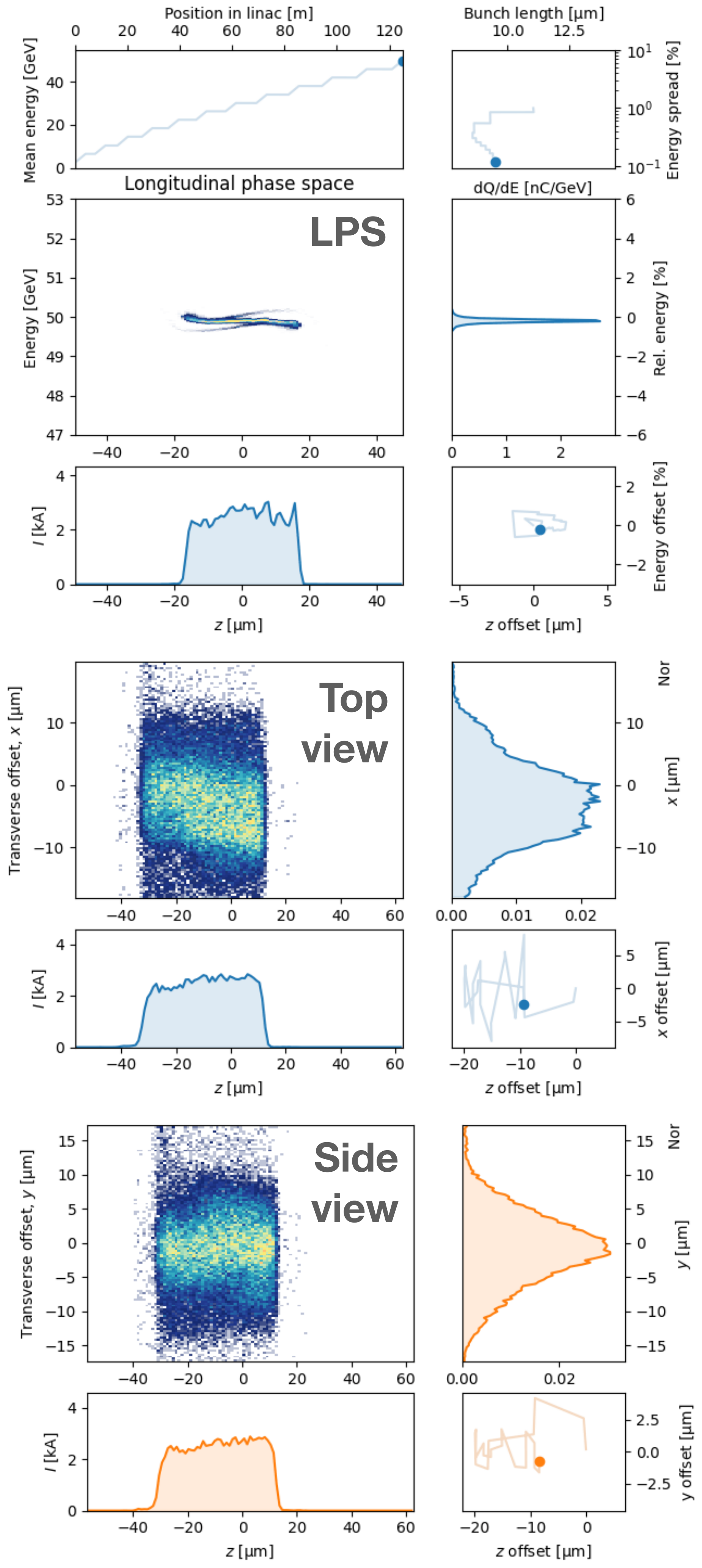
A preliminary working point

- > 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)



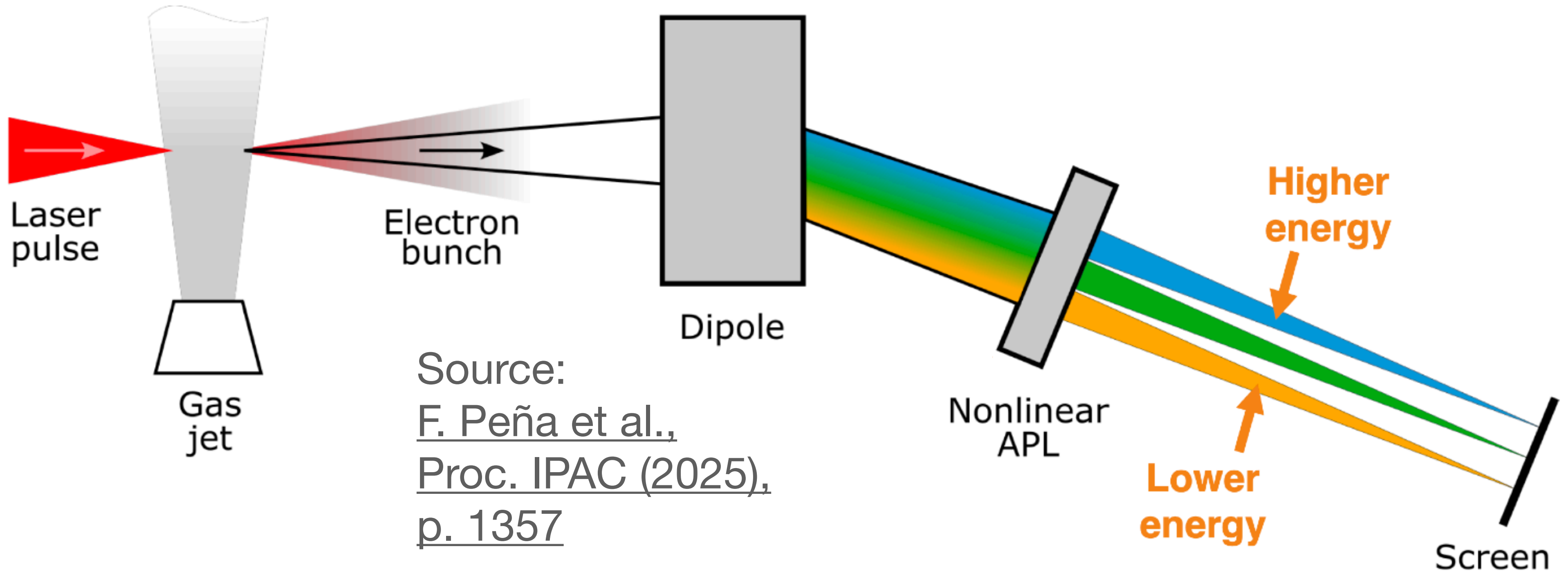


Next steps – toward a CDR and increased TRL

Experimental and theoretical work toward a credible conceptual design

> **Optimize** the SFQED performance, resilience and cost of the SPARTA demo in ABEL

> Implement a nonlinear plasma lens as an (broadband, high-resolution) “**achromatic spectrometer**” for LWFA beams at CALA/LMU



Source: F. Peña et al., Proc. IPAC (2025), p. 1357

> Preparing for experimental demonstration of **full staging optics** – at CLARA @ Daresbury

Contributed talk (Tuesday 16:20)
ABEL: A Start-to-End Simulation and Optimisation Framework for Plasma-Based Accelerators and Colliders
— Ben Chen *et al.*

Poster #512 (Tuesday 19:00)
Development of an achromatic spectrometer for a LWFA experiment
— Felipe Peña *et al.*

Postdoc opportunity in SPARTA / Uni Oslo
Get in touch if you’re interested!

The SPARTA project

Solving staging and stability → affordable high-energy electrons

> **Rapid progress toward:**

> **Solving staging:**
> - Novel achromatic lattice
> - Nonlinear plasma lens simulated, designed, and characterized
> - Scaling up experiments

> **Solving stability:**
> - Passive stabilization mechanisms required
>   - *LPS self-correction*
>   - *PWFA driver guiding*
>   - *Ion motion for BBU*

> **Demonstrator machine:**
> - 50-GeV SFQED application
> - Full-scale simulations
> - Work on driver-distribution system

> **Aiming to write a CDR by 2028**

Acknowledgements

Oslo accelerator group:

Erik Adli, Kyrre N. Sjøbæk, J. B. Ben Chen,
Ole Gunnar Finnerud, Daniel Kalvik,
Carl A. Lindstrøm, Pierre Drobniak

Funding:

European Research Council (ERC)
The Research Council of Norway

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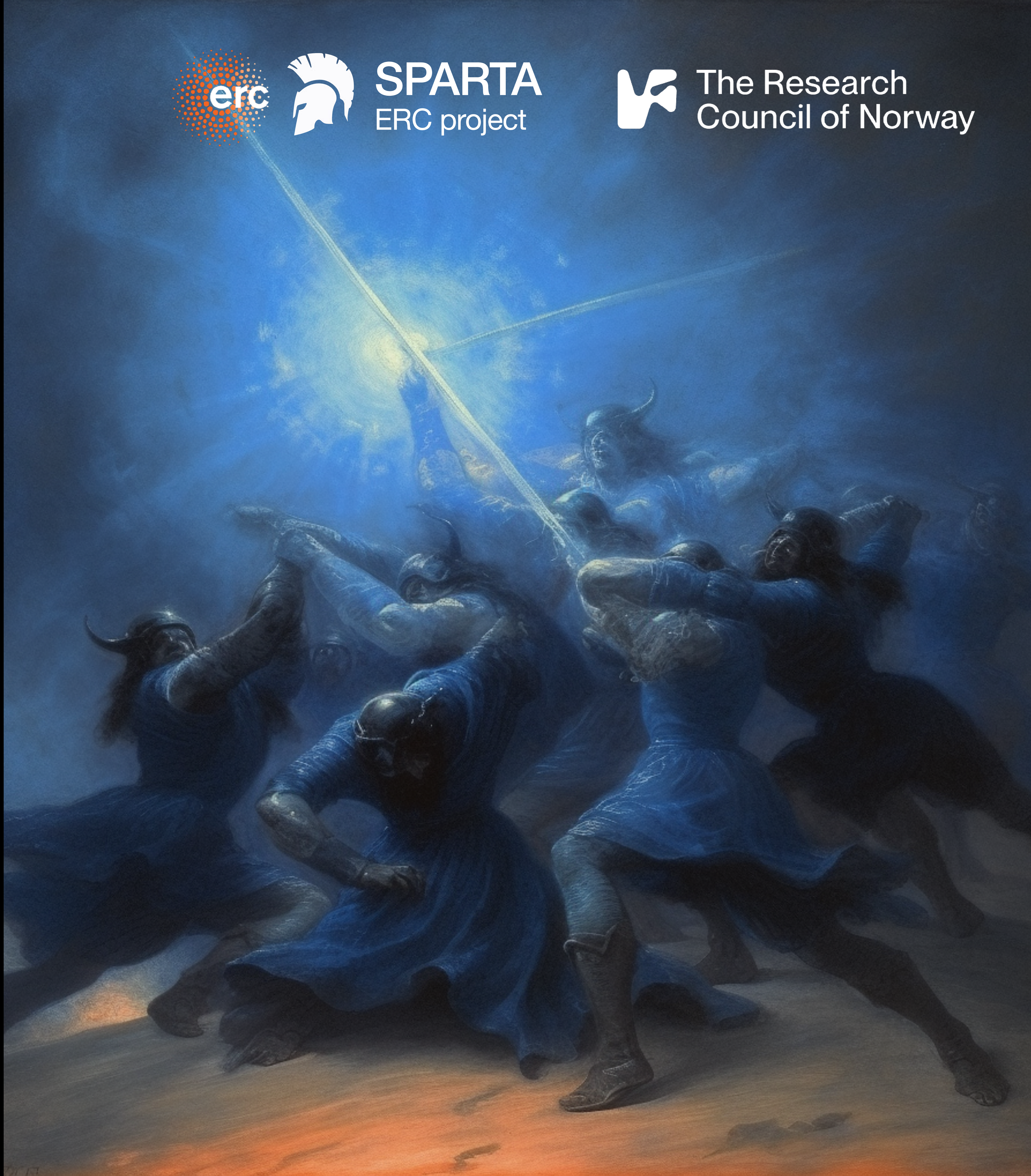

Backup slides

ABEL input script for SPARTA demo

```python
E0 = 2.2e9
E_final = 50e9
trans_ratio = 2
num_stages = 12
enable_jitter = True

# define driver
driver = SourceTrapezoid()
driver.charge = -4e-9 # [C]
driver.energy = E0
driver.rel_energy_spread = 0.01
driver.bunch_length = 780e-6 # [m]
driver.gaussian_blur = 30e-6 # [m]
driver.current_head = 0e3
driver.z_offset = 1155e-6 - 2.5e-6 # [m]
driver.emit_nx, driver.emit_ny = 10e-6, 20e-6 # [m rad]
driver.beta_x, driver.beta_y = 0.3, 0.3 # [m]
driver.alpha_x, driver.alpha_y = 1/driver.beta_x, -1/driver.beta_y # [m]
driver.num_particles = 1000000
driver.symmetrize = True
driver.norm_jitter_emittance_x = float(enable_jitter)*0.04e-6 # [m]
driver.norm_jitter_emittance_y = float(enable_jitter)*0.04e-6 # [m]
driver.jitter.t = float(enable_jitter)*10e-15

# define stage
stage = StageHipace()
stage.driver_source = driver
stage.ion_motion = True
stage.beam_ionization = True
stage.ion_species = 'H'
stage.num_cell_xy = 511
stage.nom_energy_gain_flattop = (E_final-E0)/num_stages # [eV]
stage.nom_accel_gradient_flattop = 1e9 # [GV/m]
stage.plasma_density = 1e21 # [m^-3]
stage.external_focusing = True
```

```python
# define beam
source = SourceBasic()
source.charge = -0.3e-9 # [C]
source.energy = E0 # [eV]
source.rel_energy_spread = 0.01
source.bunch_length = 11e-6 # [m]
source.emit_nx, source.emit_ny = 5e-6, 5e-6 # [m rad]
source.beta_x = stage.matched_beta_function(source.energy)
source.beta_y = source.beta_x
source.num_particles = 100000
source.symmetrize = False
source.norm_jitter_emittance_x = float(enable_jitter)*0.01e-6 # [m]
source.norm_jitter_emittance_y = float(enable_jitter)*0.01e-6 # [m]

# define interstage
interstage = InterstagePlasmaLensImpactX()
interstage.beta0 = lambda E: stage.matched_beta_function(E)
interstage.length_dipole = lambda E: 0.75 * np.sqrt(E/10e9) # [m(eV)]
interstage.R56 = lambda E: -min(0.5e-3, 0.3e-3 / np.sqrt(E/10e9)) # [m(eV)]
interstage.field_dipole = 1.0 # [T]
interstage.lens_radius = 0.75e-3 # [m]
jitter_interstage = float(enable_jitter)*1e-6 # [m]
interstage.jitter.lens_offset_x = jitter_interstage
interstage.jitter.lens_offset_y = jitter_interstage
interstage.jitter.sextupole_offset_x = jitter_interstage
interstage.jitter.sextupole_offset_y = jitter_interstage

# define linac
linac = PlasmaLinac()
linac.source = source
linac.stage = stage
linac.interstage = interstage
linac.num_stages = num_stages
linac.alternate_interstage_polarity = True
```

Beam evolution in SPARTA demo (average of 3 shots)