UNIVERSITY OF OSLO

SPARTA
ERC project

The Research Council of Norway

Particle accelerators based on plasma

Toward high-energy electrons and photons (at an *affordable* cost)

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12 June 2026 | Mini Workshop @ NuPECC Town Meeting

Part 1:

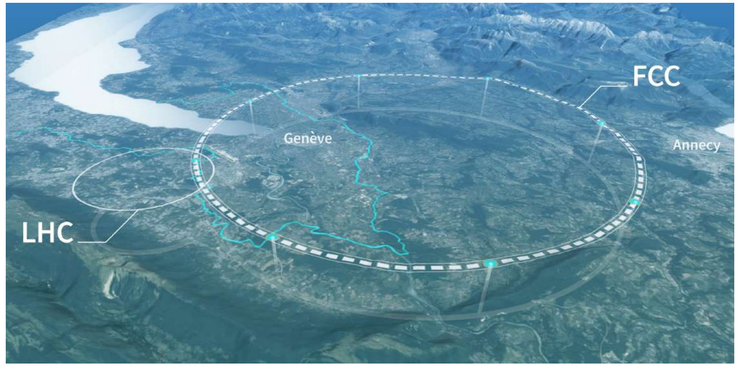
Motivation

Grand accelerators, high costs

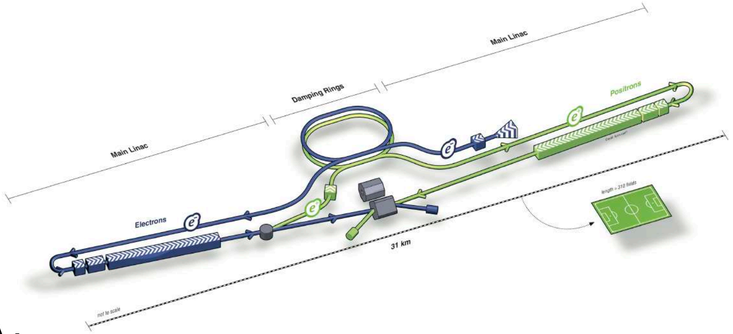
The future of particle physics

A discussion that revolves around costs

- *Consensus:* build an electron–positron collider (Higgs factory)
  - **Circular collider?**
    More expensive ($15B+) – less risky
  - **Linear collider?**
    Less expensive ($7B+) – more risky
- "Decided" on FCC (circular), but still big risk related to cost
- Motivates continued R&D into cheaper accelerator technology
  - *Circular accelerators: Stronger magnetic fields for bending (above 10T)*
  - ***Linear accelerators: Stronger electric fields for acceleration (>100 MV/m)***



Future Circular Collider

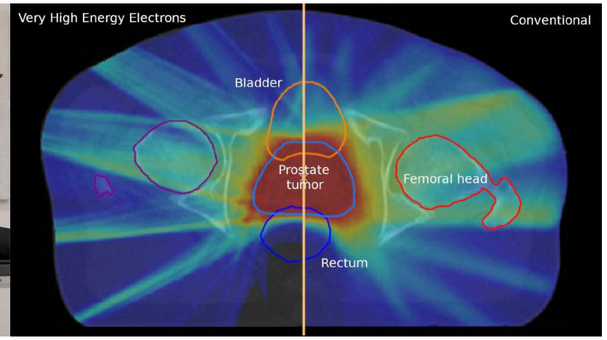


International Linear Collider

New uses for (linear) high-energy particle accelerators

Emerging technologies, all held back by high costs

> 0.1–1 GeV:
Medical applications
VHEE, FLASH, imaging



> 1–10 GeV:
Photon science
synchrotron light sources (FELs)

> 10–100+ GeV:
Laboratory astrophysics – Strong-field QED

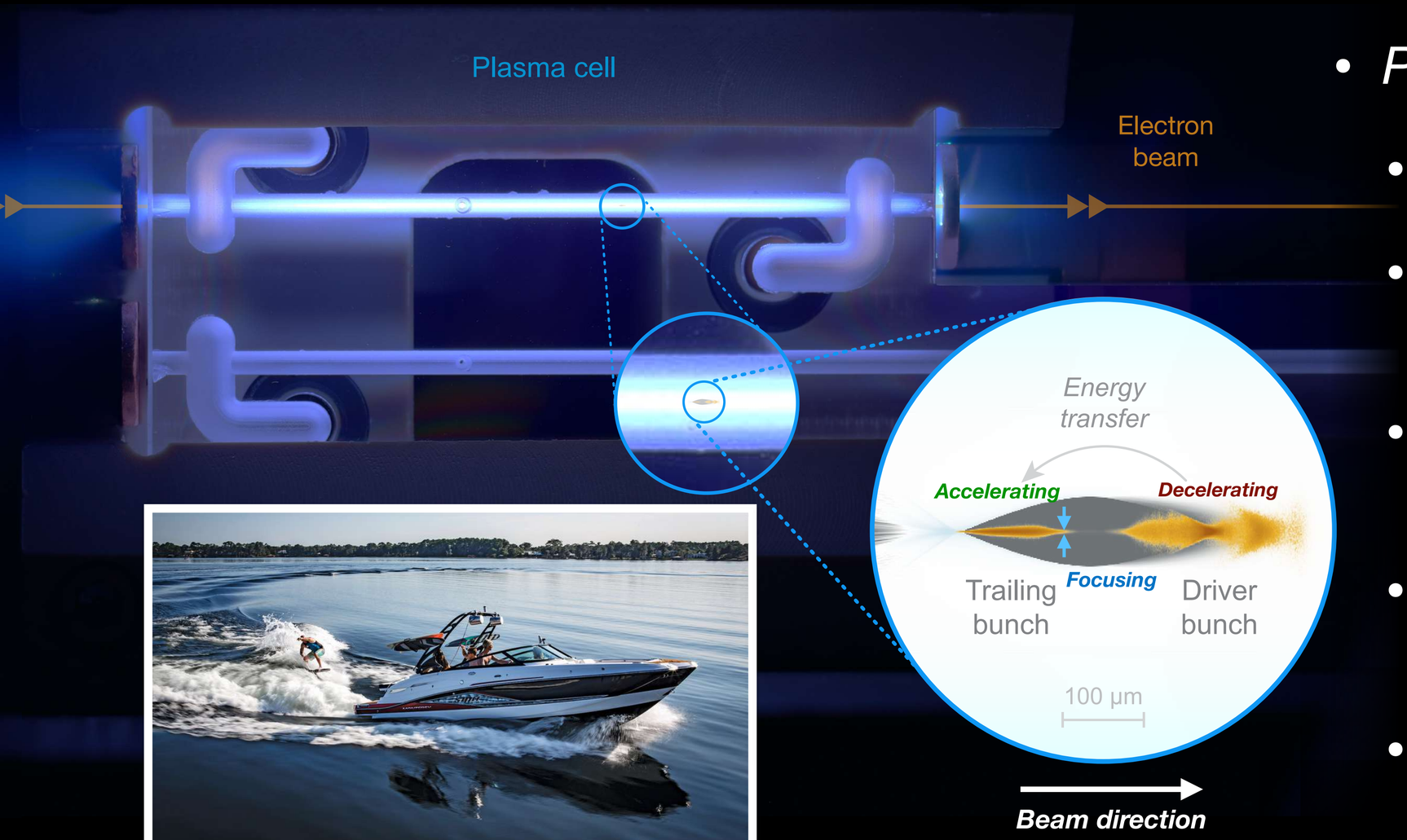
Part 2:

Plasma acceleration

A new, compact and cheaper technology

Plasma accelerators

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

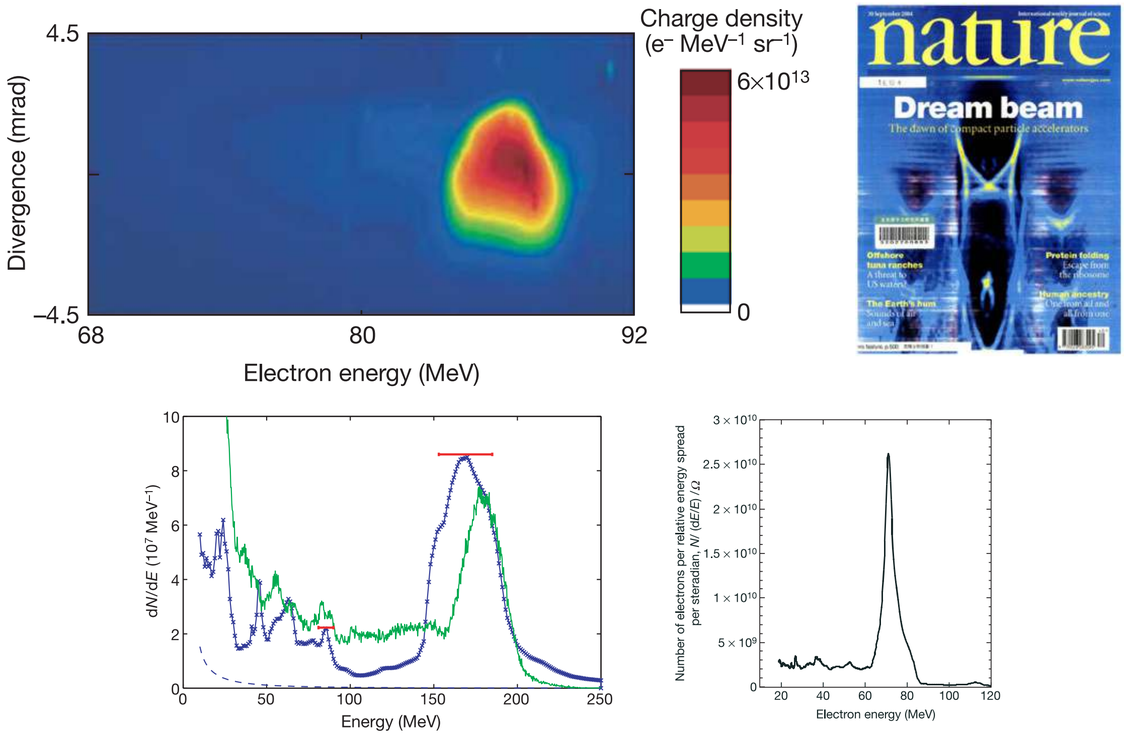


- *Plasma wakefields*:
  - Tajima and Dawson (1979)
  - Driven by **lasers** or **particle beams**
  - Electron-density wave; moves at speed of light
  - Very strong fields: **Accelerating**, **focusing**
  - 10–100 μm-scale (tiny!)

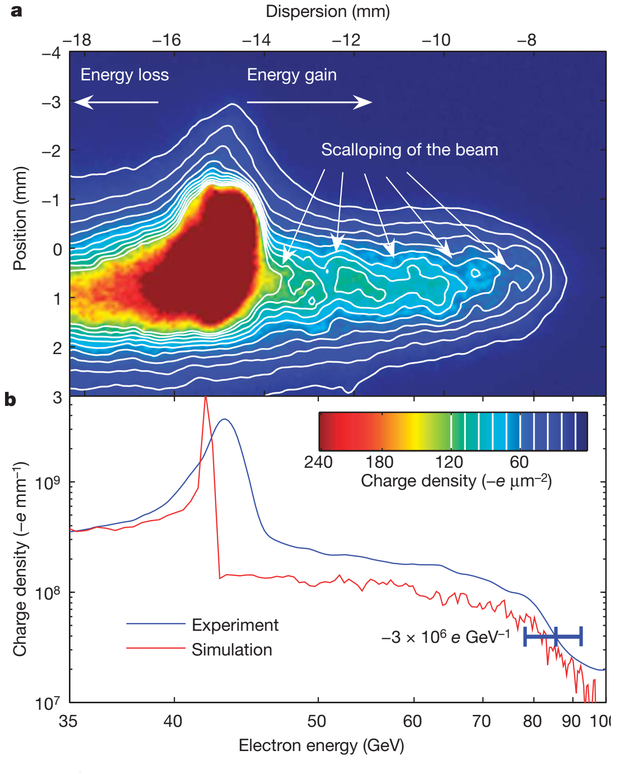
Proof of principle experiments

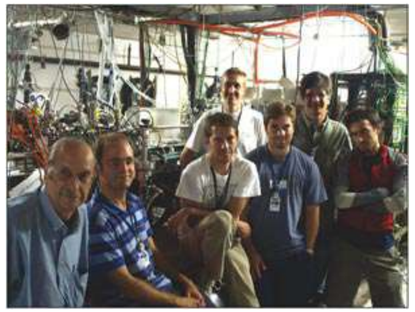
Showing the promise of plasma acceleration

> Laser-driven – **Monochromatic beams** (LBNL / RAL / Ecole Poly. – Dream beams!)



> Beam-driven – **42 GeV energy doubling** (FFTB facility at SLAC)





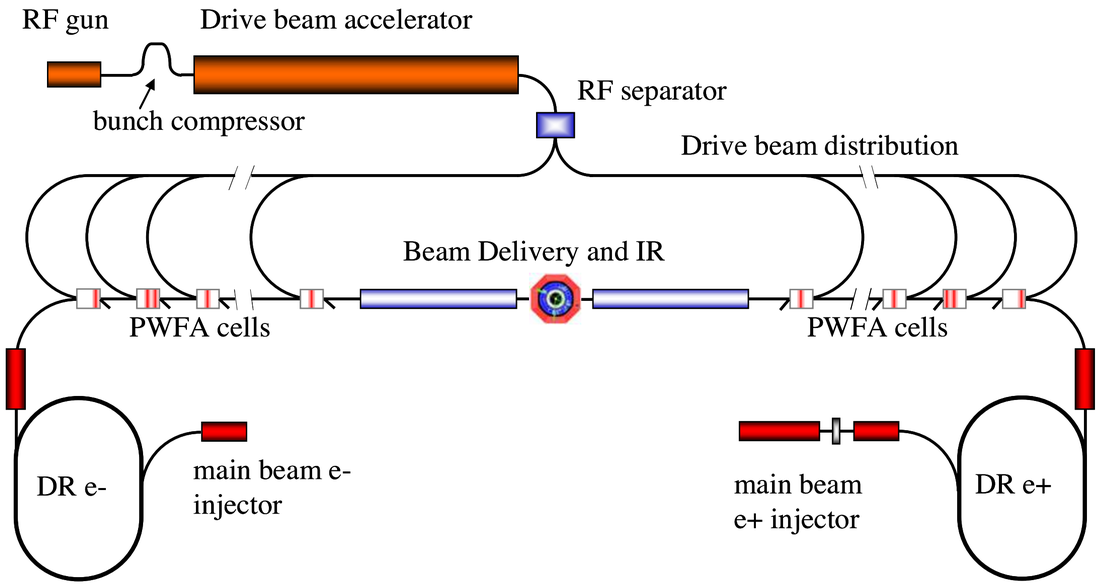
Sources: Geddes et al., Faure et al., Mangles et al., Nature (2004)

Source: Blumenfeld et al., Nature 2007

Plasma-based colliders

The ultimate challenge in plasma acceleration

- HEP was the motivation from the start (1980s)
- Several collider design studies since then.
  - *Linear collider with plasma-based main linacs*



Source: Pei et al. (2009)

- Very high demands:
  - *10 kHz rep. rate (MW beam power),*
    10% wall plug efficiency,
    0.1 mm mrad emittance,
    0.1% energy spread/stability

High repetition rate — High energy efficiency

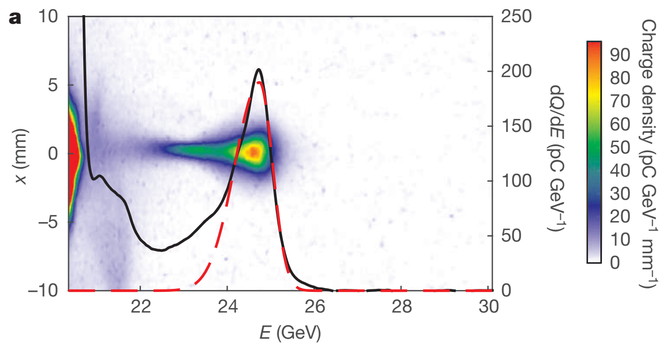
$$\mathscr{L} = \frac{H_D}{8\pi m_e c^2} \frac{P_{\text{wall}}}{\sqrt{\beta_x \beta_y}} \frac{\eta N}{\sqrt{\epsilon_{nx}\epsilon_{ny}}}$$

Low energy spread (luminosity spectrum, final focusing)

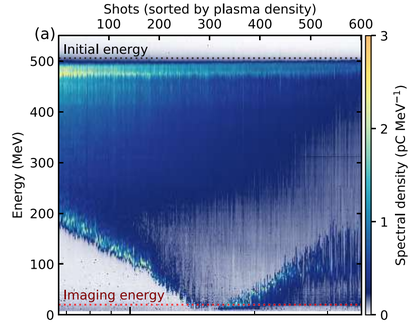
Low emittance
High stability

State-of-the-art experiments

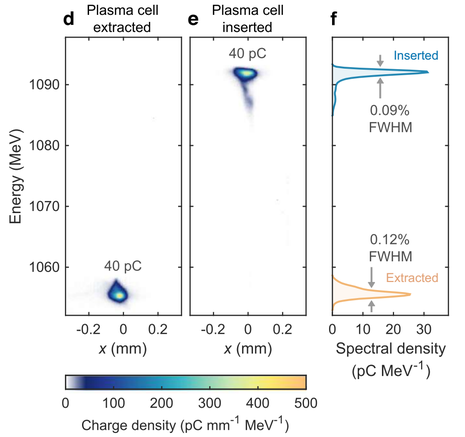
- Driven by lasers, electrons, positrons and protons
  - accelerating **e^- (42 GeV gain)** and **e^+ (4 GeV gain)**
- **300+ GV/m** gradient (laser driven)
- Energy-transfer efficiency:
  - **57% driver-to-wake**
  - 42% wake-to-beam
- **Beam-quality preservation** @ ~40 MeV gain:
  - charge preservation (40 pC)
  - energy spread preserved (at 0.1%)
  - emittance preservation (2.8 mm mrad)
- Repetition rate (**MHz** proof of principle)
- But not all the above at once yet…
  - However, have **demonstrated FEL gain** (**LWFA** and PWFA)

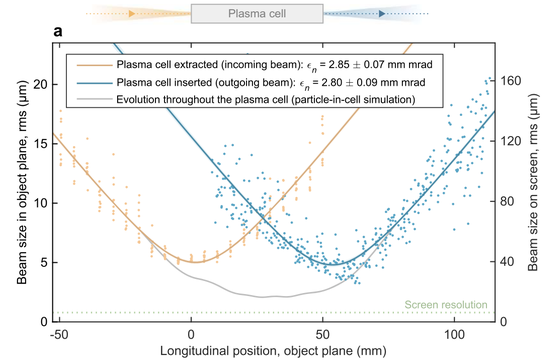


Source: Corde et al., Nature (2015)

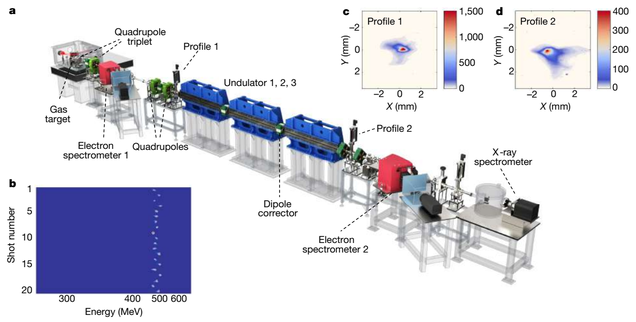


Source: Peña et al., Phys. Rev. Research (2024)





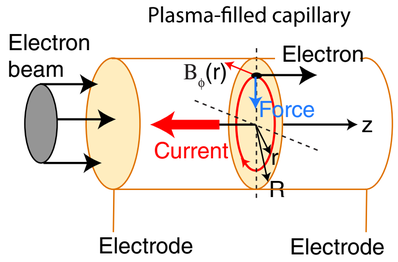
Source: Lindstrøm et al., Nat. Commun. (2024)



Source: Wang *et al.*, Nature (2021)

The staging problem (a key challenge)

How to couple plasma accelerators without destroying the beam

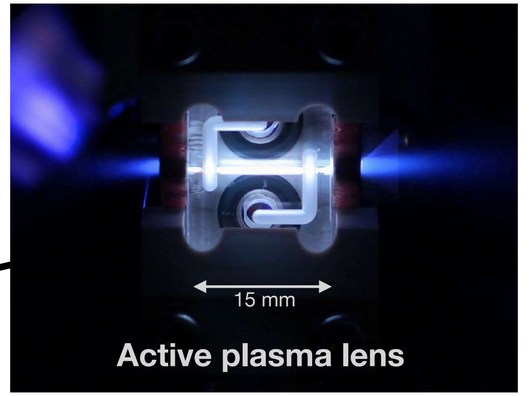


> **Proof-of-principle experiment at LBNL:**

- > Demonstrated feasibility of staging.
- > Used a compact *active plasma lens*
- > Also **highlighted many challenges** (e.g., only ~3% of charge was coupled)

> **Staging is non-trivial for <u>four</u> reasons:**

1. > Reduced average gradient (compactness)
2. > In- and out-coupling of drivers
3. > Emittance growth from chromaticity
4. > Tight synchronization tolerances



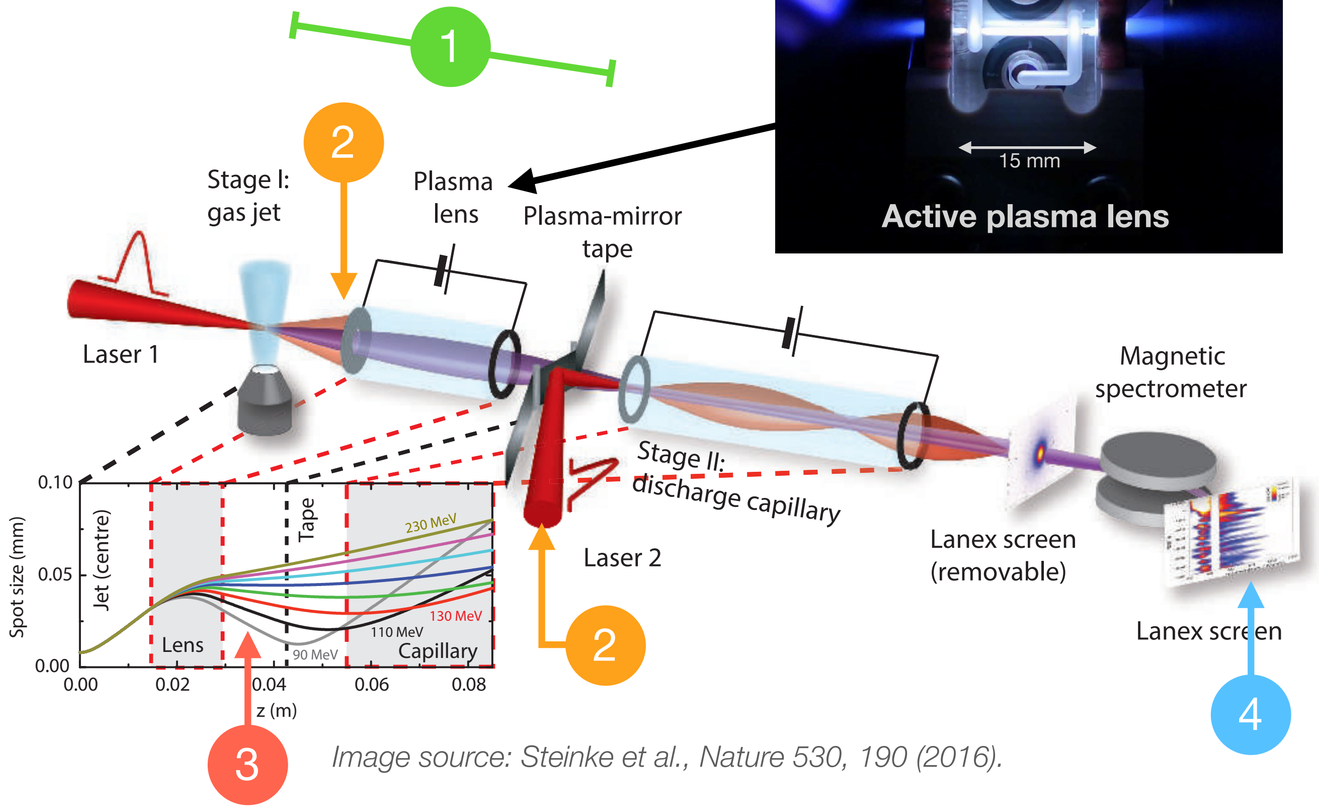


Image source: Steinke et al., Nature 530, 190 (2016).

Part 3:

The SPARTA project

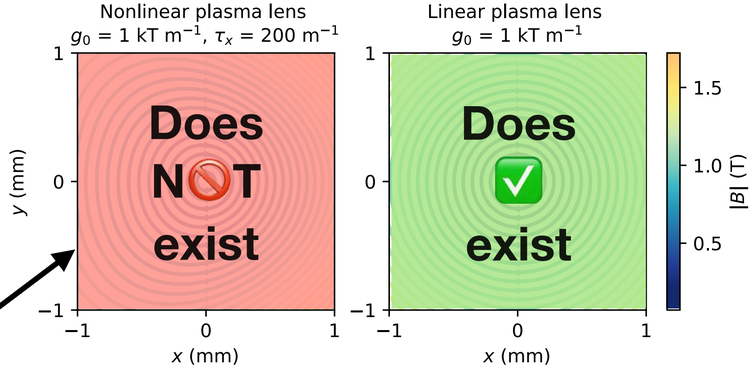
Designing a multistage plasma accelerator

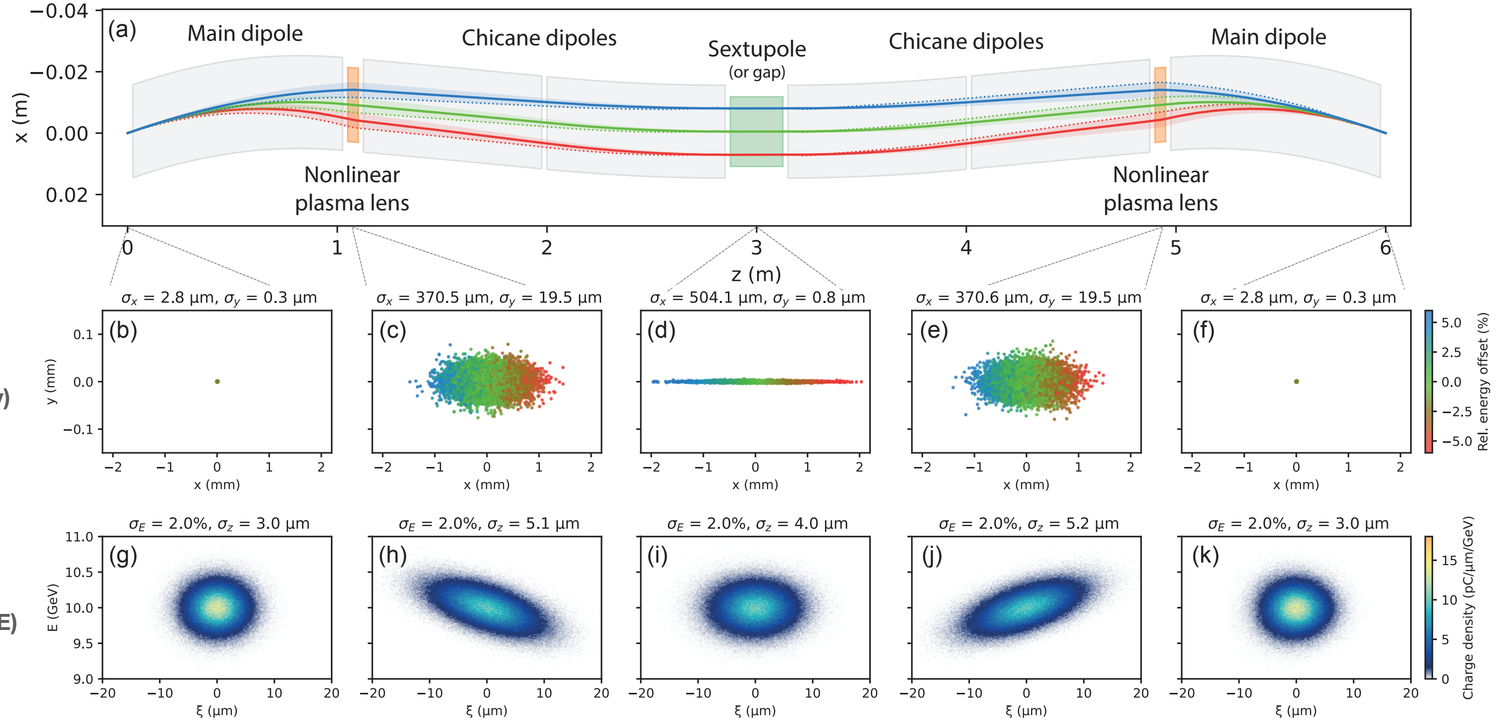
Solution: **Novel achromatic staging optics**

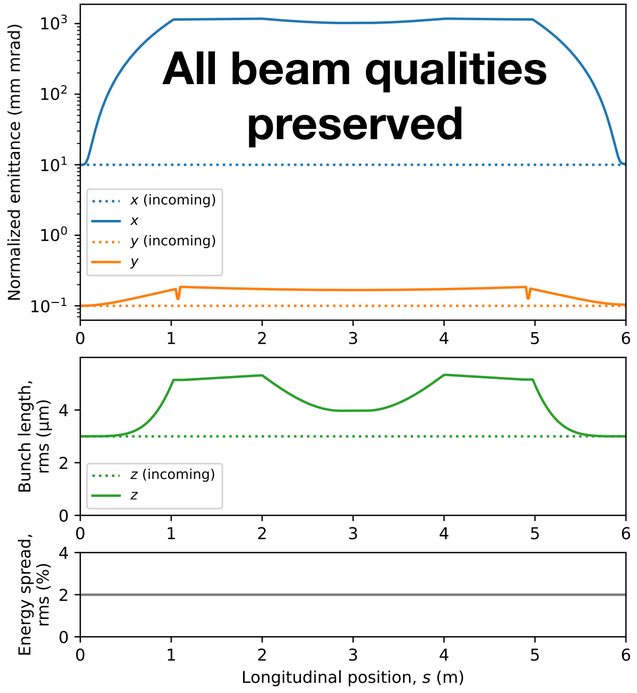
"Local chromaticity correction" and a new plasma lens

- *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!



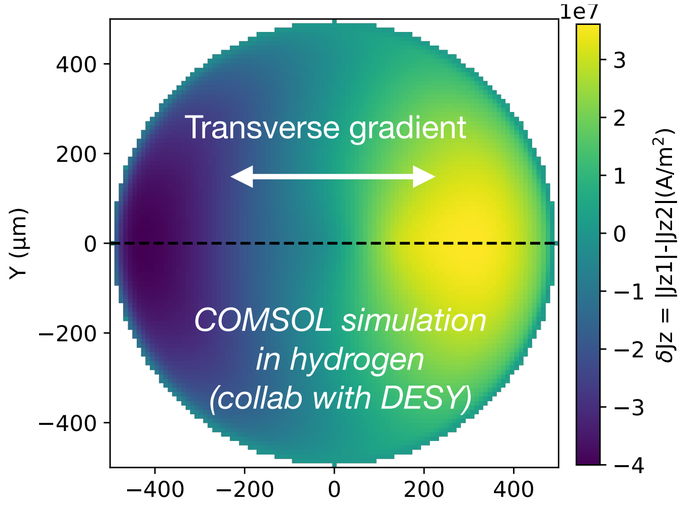


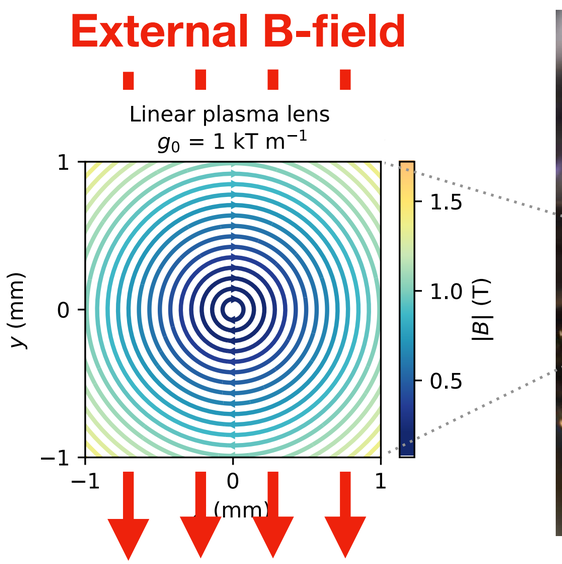


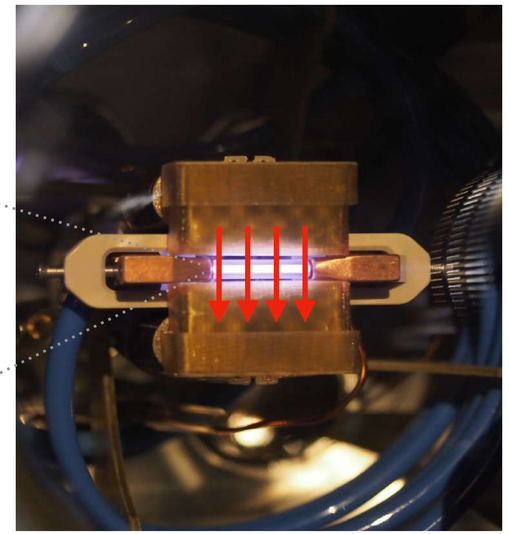
Source: ***Lindstrøm et al., (submitted)***

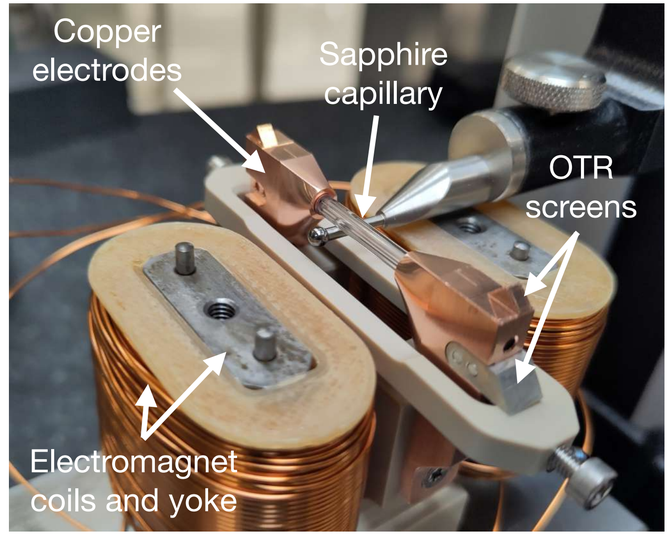
Development of a nonlinear plasma lens

Exciting a nonlinearity through the Hall effect



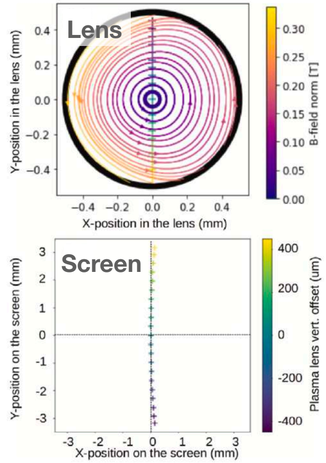


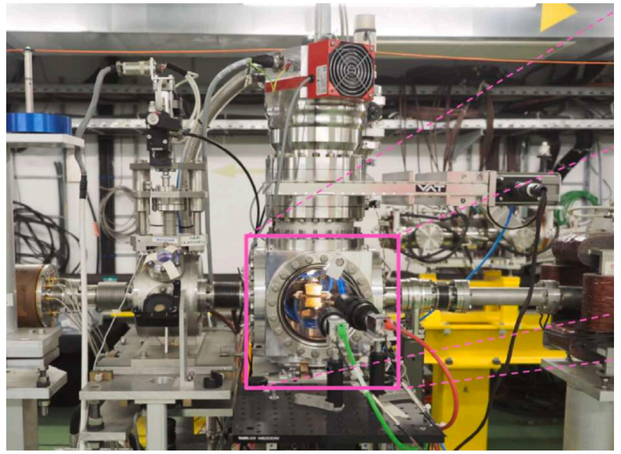




Source: P. Drobniak et al., Proc. IPAC (2025), p. 641

- 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).



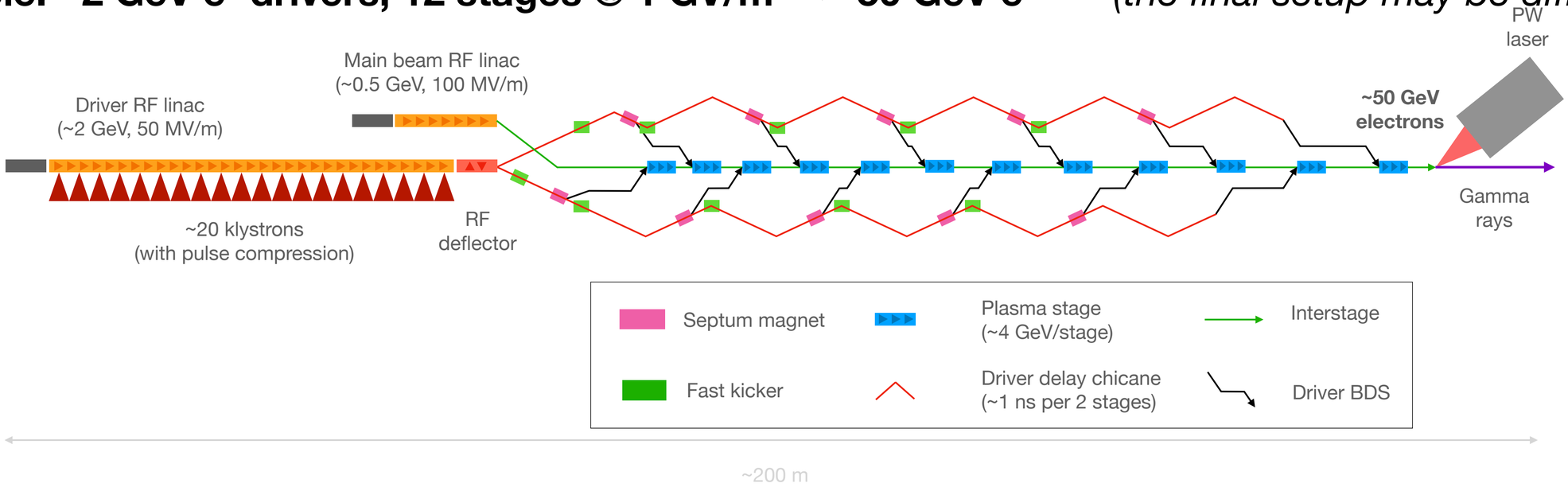


Source: P. Drobniak et al., NIM A 1072, 170223 (2025)

Conceptual design of a multistage plasma accelerator

The SPARTA demo machine – a stepping stone toward collider-relevant beams

- *Ultimate goal:* Design a self-consistent, multistage plasma accelerator for non-collider applications
- **Example: ~2 GeV e⁻ drivers, 12 stages @ 1 GV/m → 50 GeV e⁻** *(the final setup may be different)*



- Application: Strong-field QED experiment – collide with 2 PW laser → $\chi \approx 10$–50 (× Schwinger limit)
  - *(Produces 10-GeV-level gamma ray beams)*
- Currently working to implement this at a major accelerator lab – please join us if you have a use case!

Thanks!

Acknowledgements

Oslo accelerator group:
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Carl A. Lindstrøm, Pierre Drobniak

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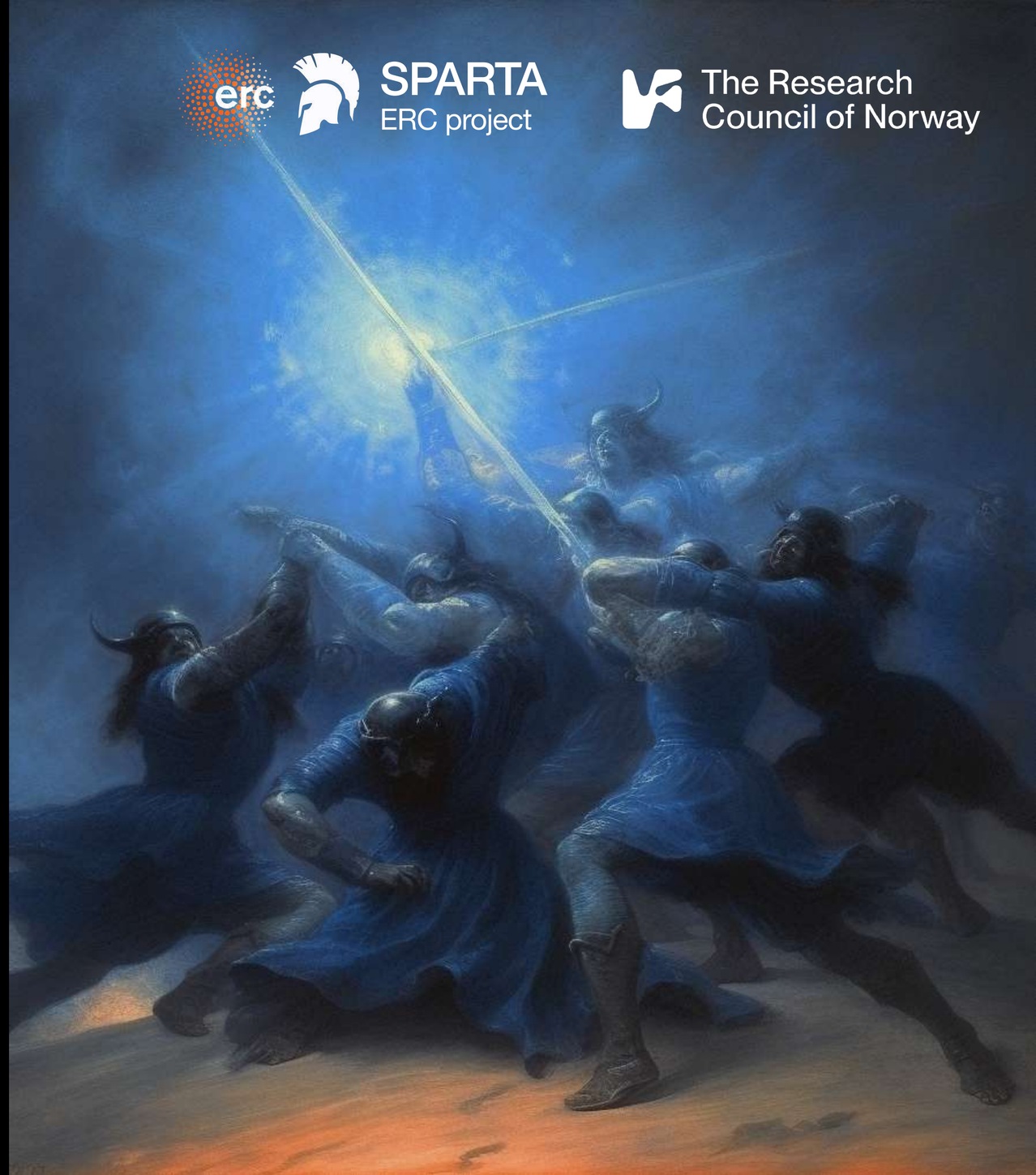
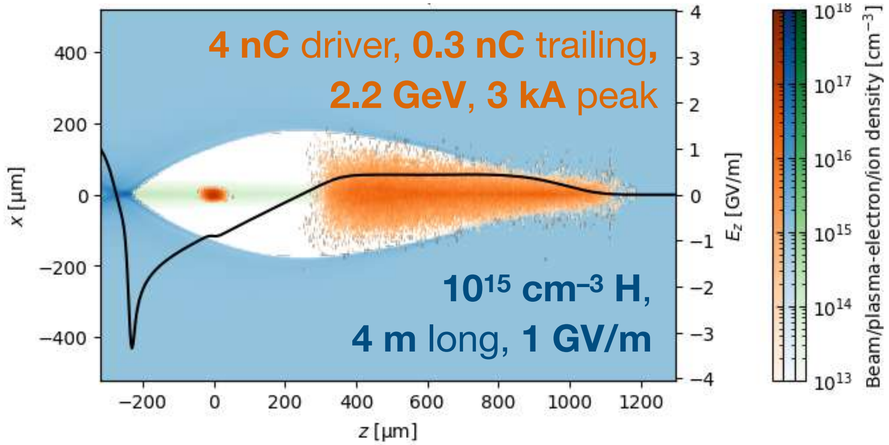


Backup slides

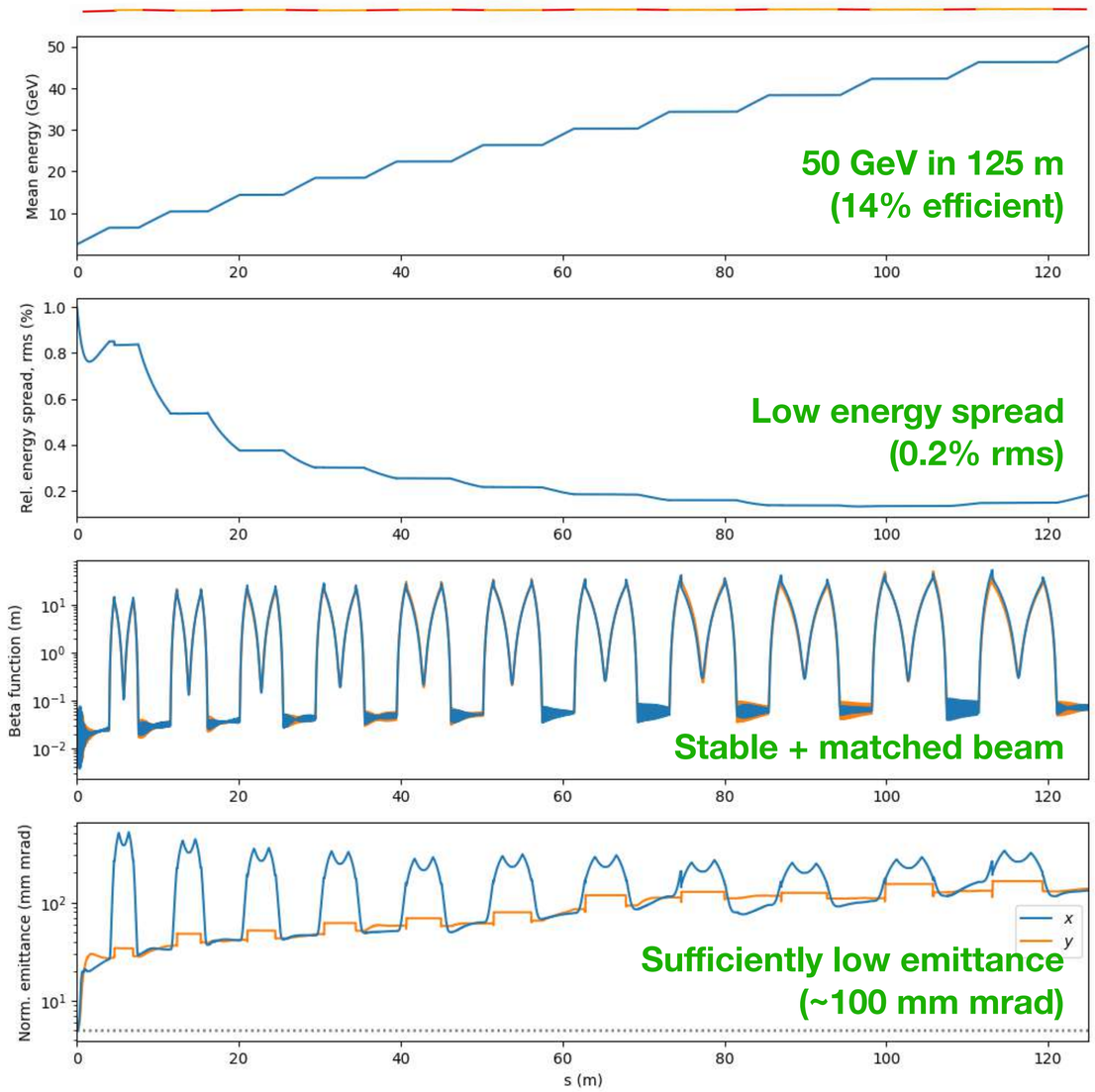
Start-to-end simulations of the SPARTA demonstrator

- HiPACE++ and ImpactX in ABEL
  - “Full” physics, 3D, high resolution
  - ~300 GPU hours per simulation
    (512 GPUs in parallel @ LUMI)



- **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)

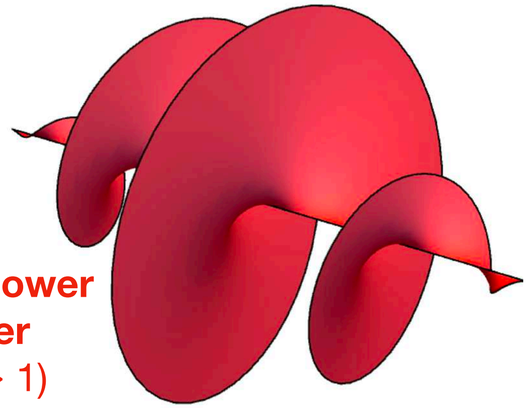
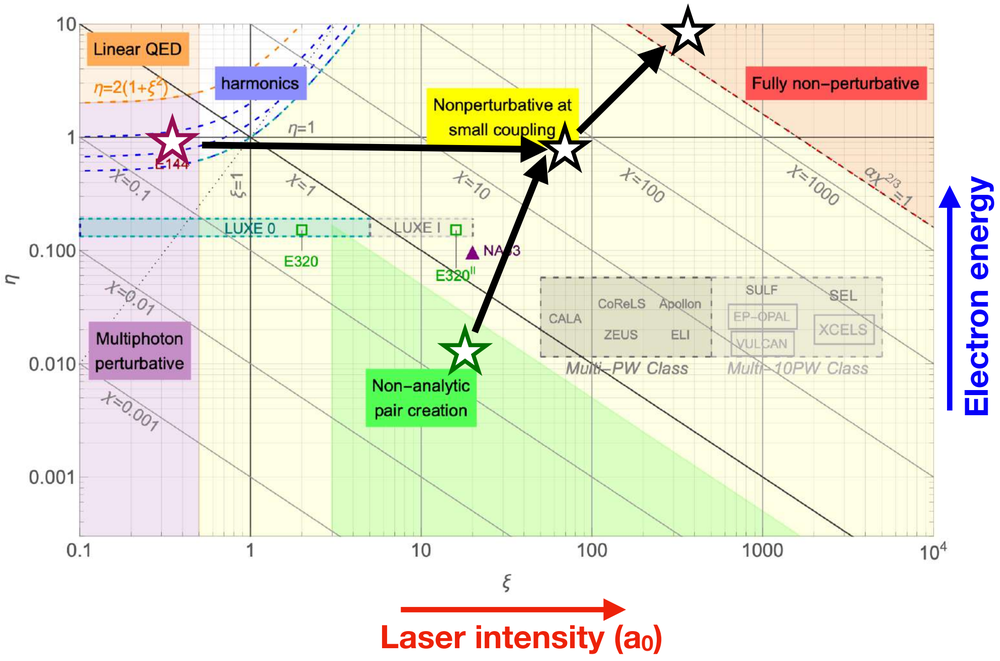


Strong-field QED explained

New physics beyond the Schwinger limit

- 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 so far 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…*
- $\chi \approx 1600$ → fully non-perturbative, no theory
- **Significant progress in SFQED requires access to cheaper high-energy e^-**

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



High-power laser
($a_0 \gg 1$)