UNIVERSITY
OF OSLO

SPARTA
ERC project

The Research
Council of Norway

Plasma-based colliders

Current status and required R&D

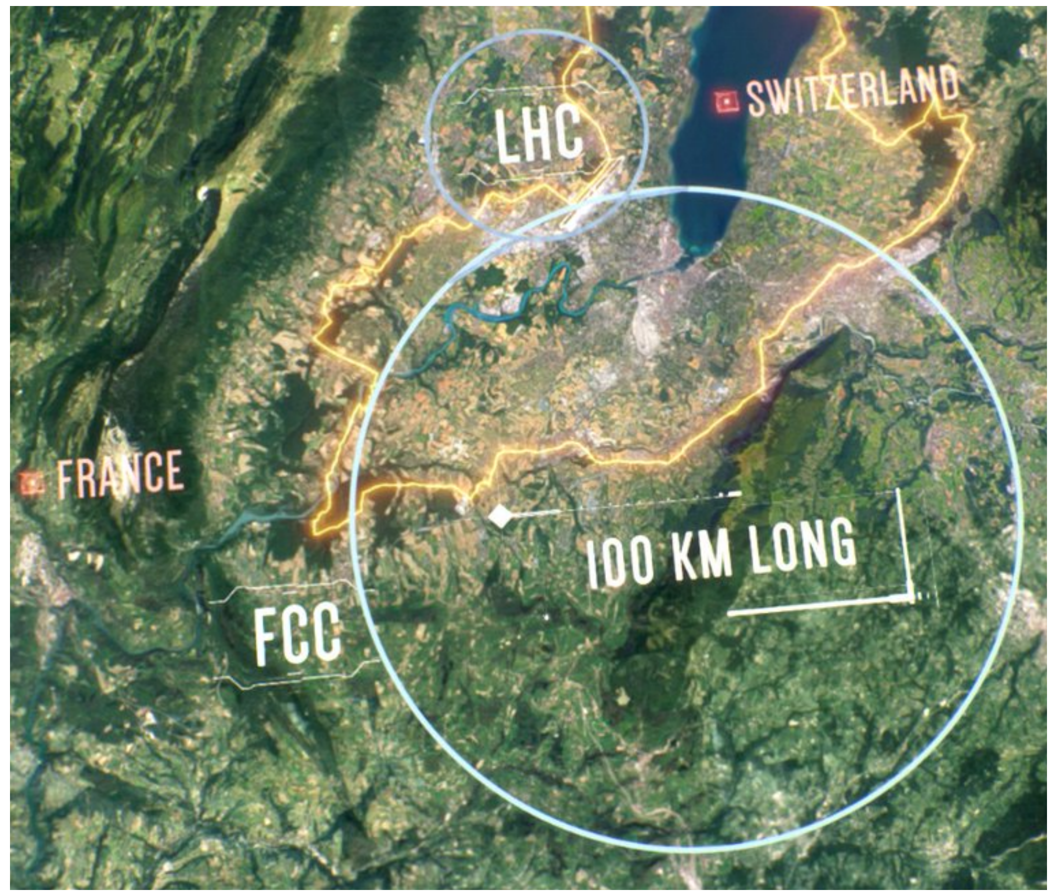
Carl A. Lindstrøm
Department of Physics, University of Oslo

4 Dec 2024 | Fundamental research and applications with the EuPRAXIA facility at LNF

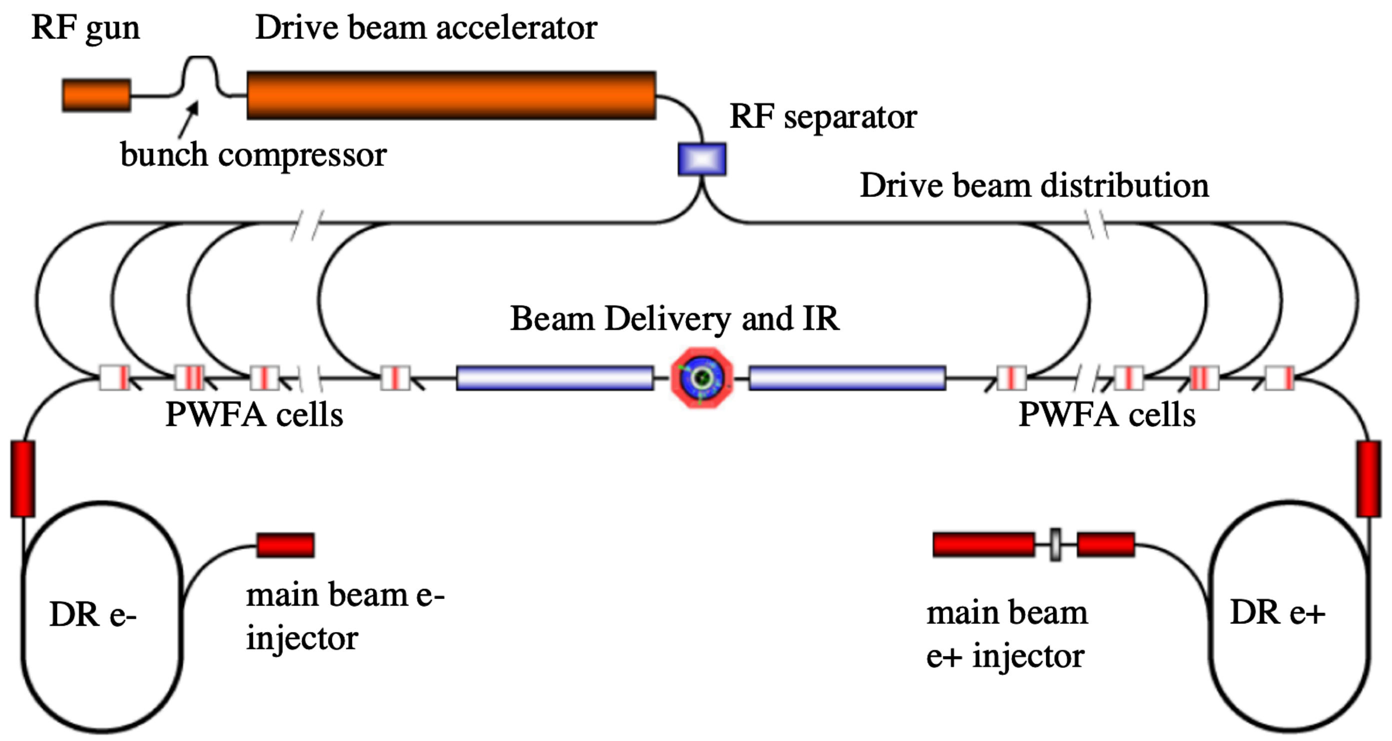
Particle physics and the promise of plasmas

High accelerating gradient means compact main linacs

- **Critical time for particle physics — we need to plan the post-LHC era.**
  - FCC-ee would be fantastic, but prohibitively expensive (~€20B).
  - Linear colliders (ILC, CLIC) promise much reduced cost (~€7–12B)
- **A key cost driver in linear colliders is gradient (~100 MV/m):**
  - Plasma acceleration promises higher gradient (1–100 GV/m)
  - What are the other important cost drivers?
    (This drives further design choices for plasma accelerators)
- **Several plasma-based collider designs proposed since the 90s.**
  - Useful for identifying the remaining challenges.
  - Where are we conceptually and experimentally?



FCC. Image: CERN.



Strawman design of a plasma-based collider.
Image source: Pei et al., Proc. PAC (2009).

How to *actually* improve a particle collider

Optimising for cost goes beyond just the accelerating gradient

Cost = (power source) + (accelerator) + (energy usage) + other

= (beam power) / (source-to-beam efficiency)
***(cost per power delivered from source)**

Energy depletion, energy-transfer,
transverse instabilities

Driver technology (laser or beam),
bunch pattern

+ (beam energy) / (accelerating gradient)
***(cost per length of accelerator)**

Frequency (plasma density),
peak power (driver intensity),
fill factor (staging)

+ (integrated luminosity) / (luminosity per power)
***(cost per energy)**

$$\frac{\mathscr{L}}{P_{\text{wallplug}}} = \frac{H_D}{8\pi m_e c^2}\frac{1}{\sqrt{\beta_x\beta_y}}\frac{\eta N}{\sqrt{\epsilon_{nx}\epsilon_{ny}}}$$

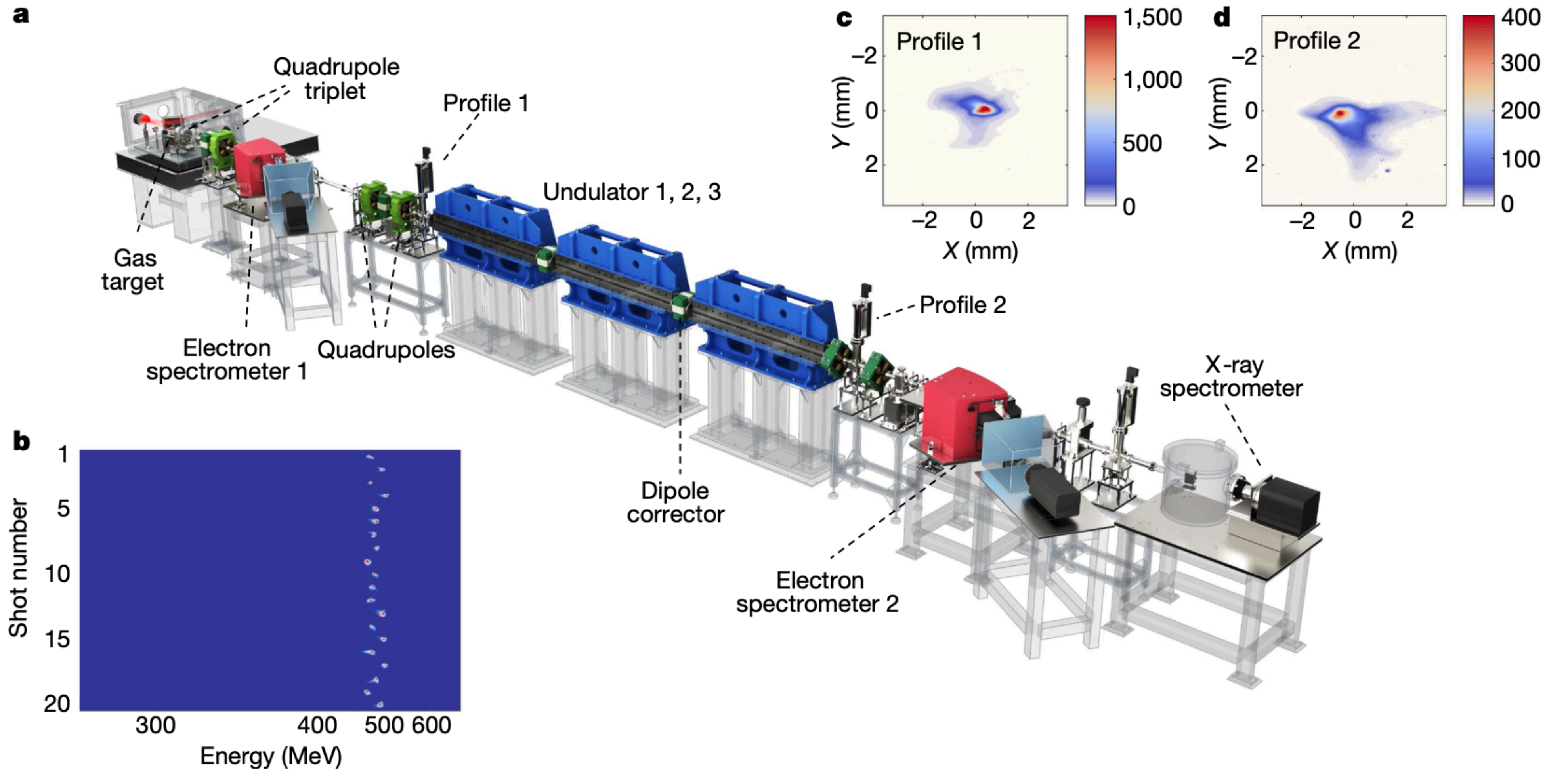
Charge, emittance,
energy spread, collision rate

+ other

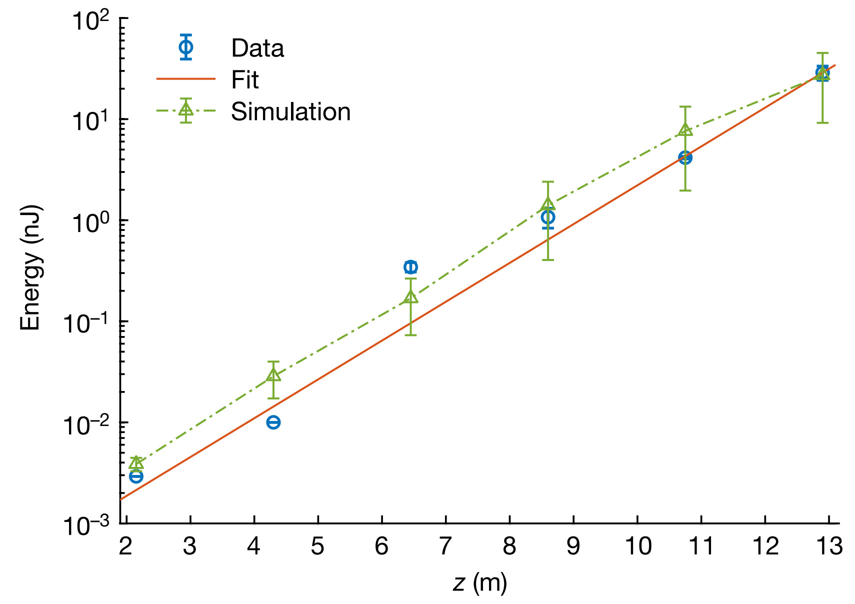
Current status of plasma acceleration

How far away are we from a plasma-based collider?

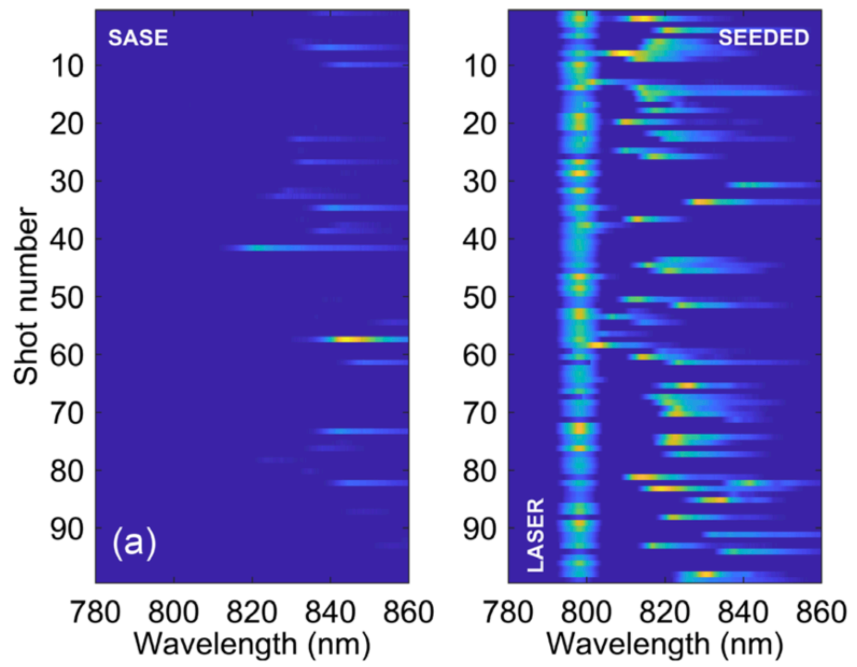
- **Maturation of toward “real-life” applications:**
  - Strong-field QED (Põder *et al.* & Cole *et al.* 2018)
  - Free-electron lasing
- **Six key aspects relevant to colliders:**
  - Positron acceleration
  - Energy efficiency
  - Repetition rate and average power
  - Beam-quality preservation
  - Staging
  - Stability



LWFA FEL. From: Want *et al.* Nature (2021)



PWFA FEL. From: Pompili *et al.*, Nature (2022)



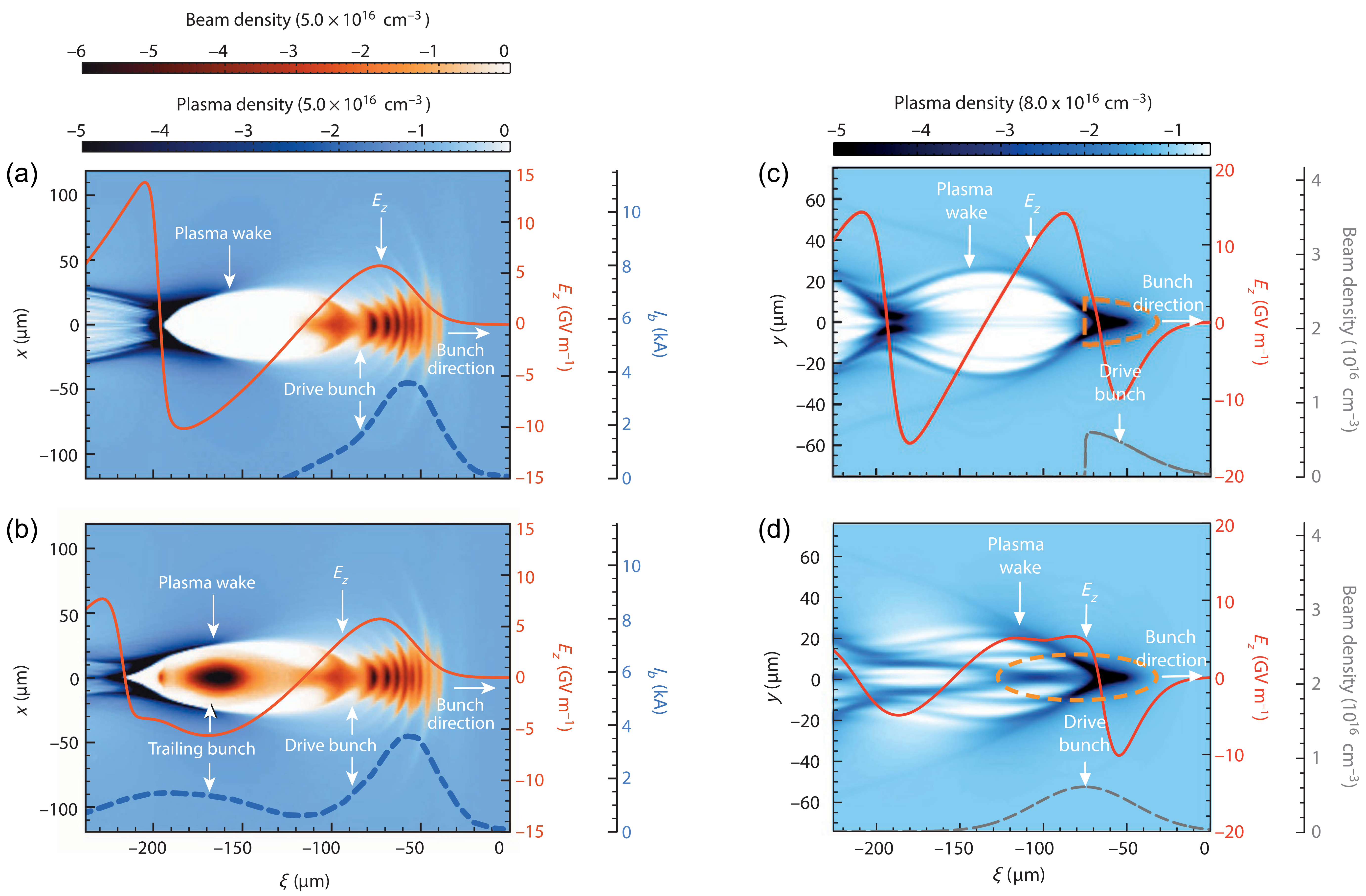
From: Galletti *et al.* PRL (2022)

Positron acceleration

Not currently suitable for colliders

- Plasmas are charge asymmetric
  - No “blowout regime” for e^+
- Positron acceleration has been demonstrated experimentally.
  - However, luminosity per power still orders of magnitude below RF and e^- PWFA.

Recent review: Cao, Lindstrøm, Adli, Corde & Gessner, PRAB 27, 034801 (2024)

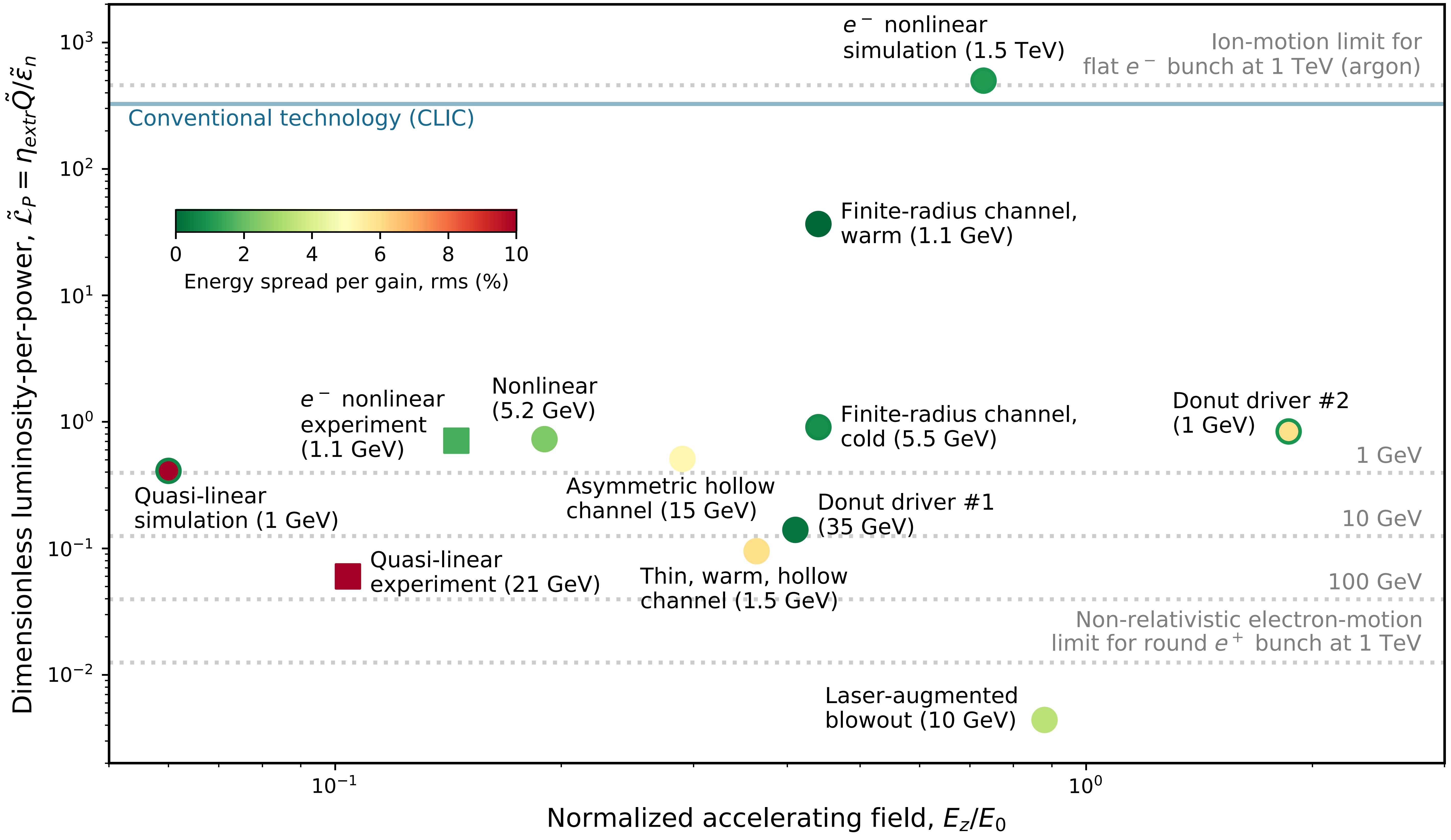


Positron acceleration

Not currently suitable for colliders

- Plasmas are charge asymmetric
  - No “blowout regime” for e^+
- Positron acceleration has been demonstrated experimentally.
  - However, luminosity per power still orders of magnitude below RF and e^- PWFA.
- Main challenge: Electron motion (equivalent to ion motion for e^+, but plasma electrons are lighter)

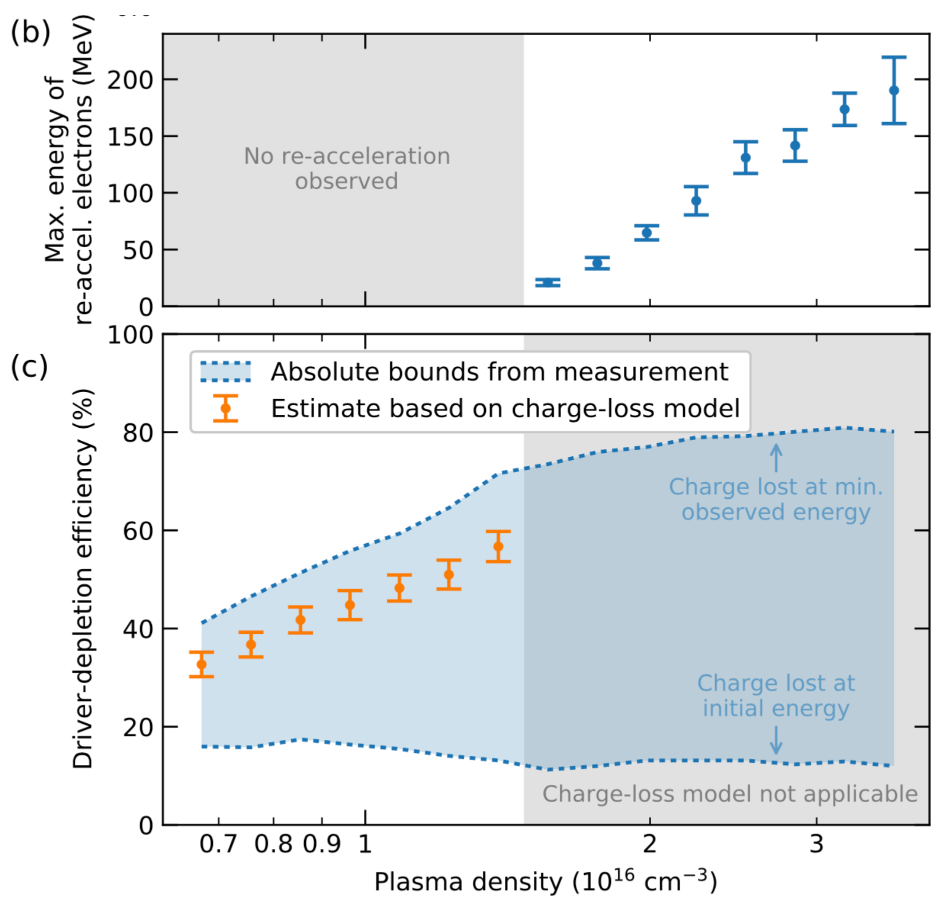
Recent review: Cao, Lindstrøm, Adli, Corde & Gessner, PRAB 27, 034801 (2024)



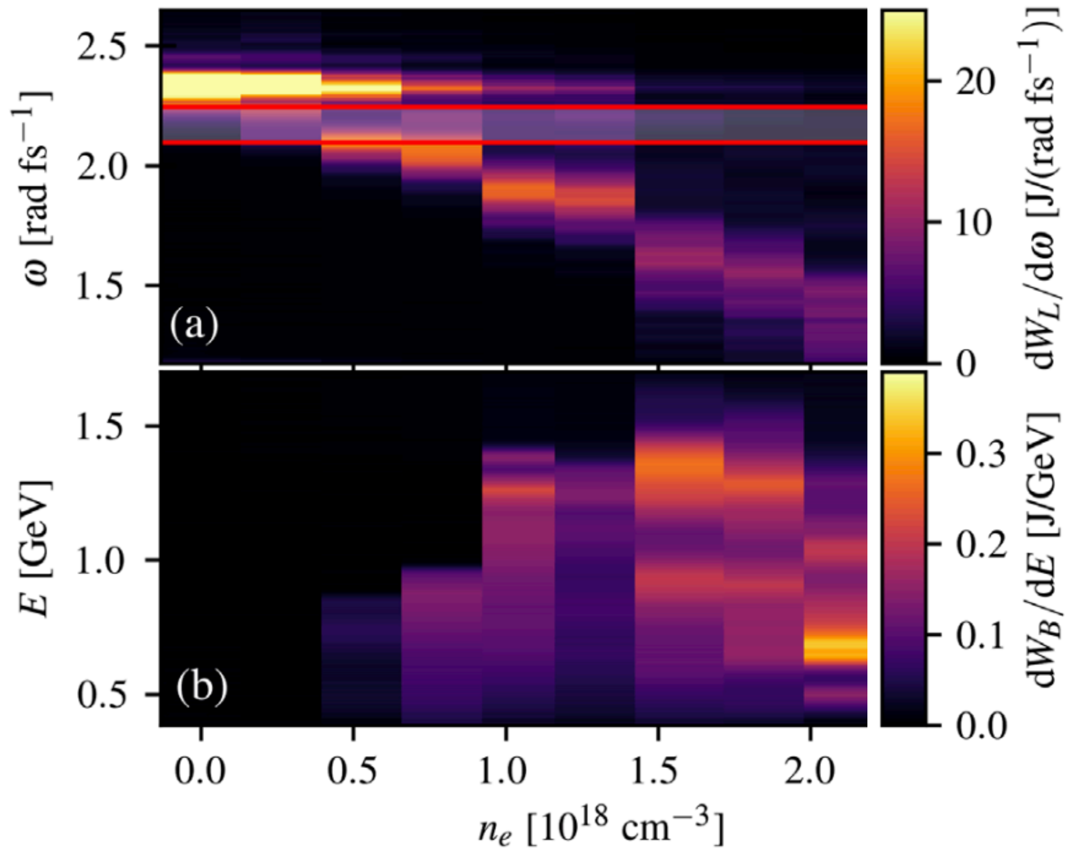
Energy efficiency

Currently favours electron-driven PWFA

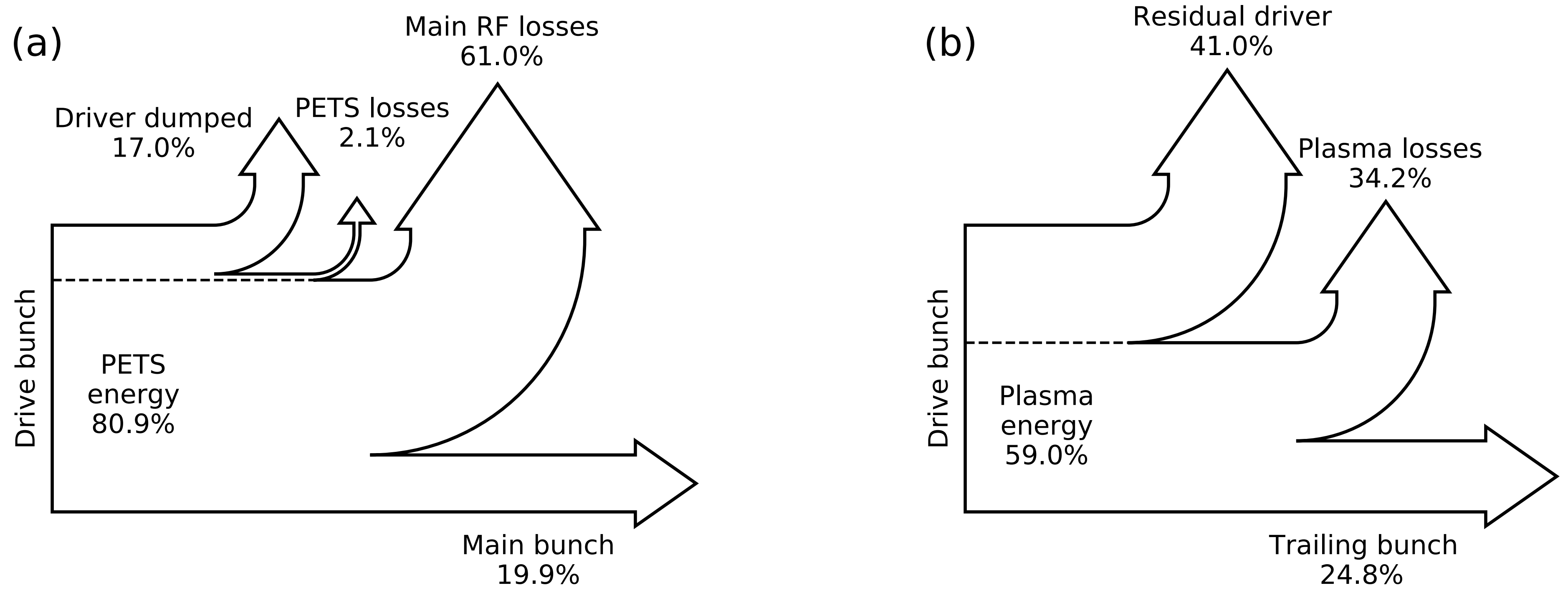
- Three efficiencies: $\eta_{\mathrm{wp}\to\mathrm{b}} = \eta_{\mathrm{wp}\to\mathrm{d}} \times \eta_{\mathrm{d}\to\mathrm{wf}} \times \eta_{\mathrm{wf}\to\mathrm{b}}$
- Driver production efficiency: $\eta_{\mathrm{wp}\to\mathrm{d}}$
  - Laser drivers: ~0.1% in Ti:sapphire, possibly 10+ % (fibre, Thulium, thin-disk, …)
  - Proton drivers: ~1% (SPS)
  - Electron drivers: ~50% (RF linac with few MV/m)
- Driver depletion efficiency: $\eta_{\mathrm{d}\to\mathrm{wf}}$
  - (57±3)% demonstrated (electron-driven)
- Wakefield energy extraction efficiency: $\eta_{\mathrm{wf}\to\mathrm{b}}$
  - (42±4)% demonstrated (electron-driven, optimal loading)
  - (19±3)% demonstrated (laser-driven)
- Theoretically, ~90% is achievable in both depletion and extraction.



PWFA depletion efficiency.
From: Peña et al., PRR (2024)



Efficient LWFA.
From: Streeter et al. PRAB (2022)

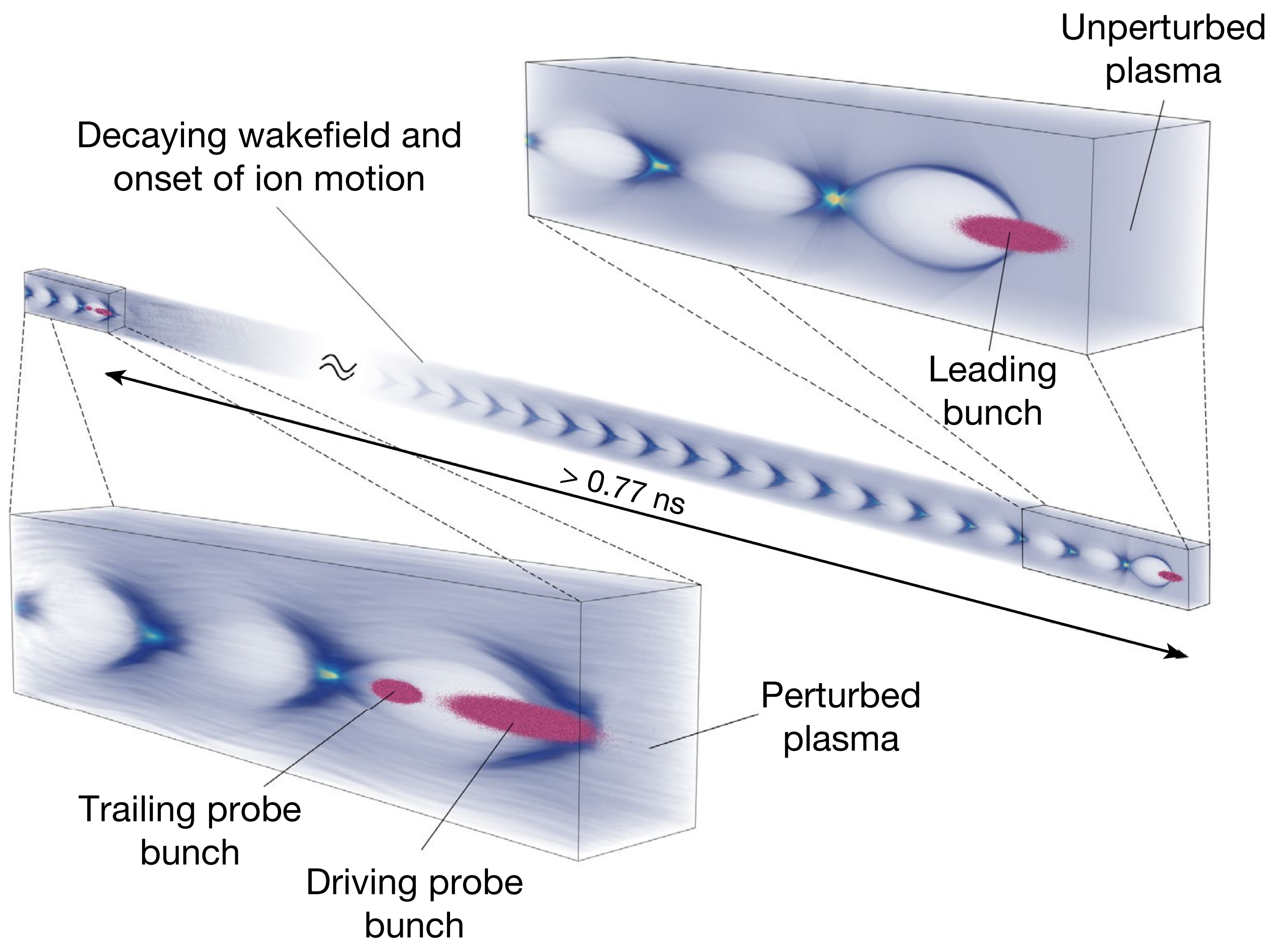


(a) CLIC vs. (b) PWFA experiments (combination of best results).
From: Peña, PhD thesis (2024)

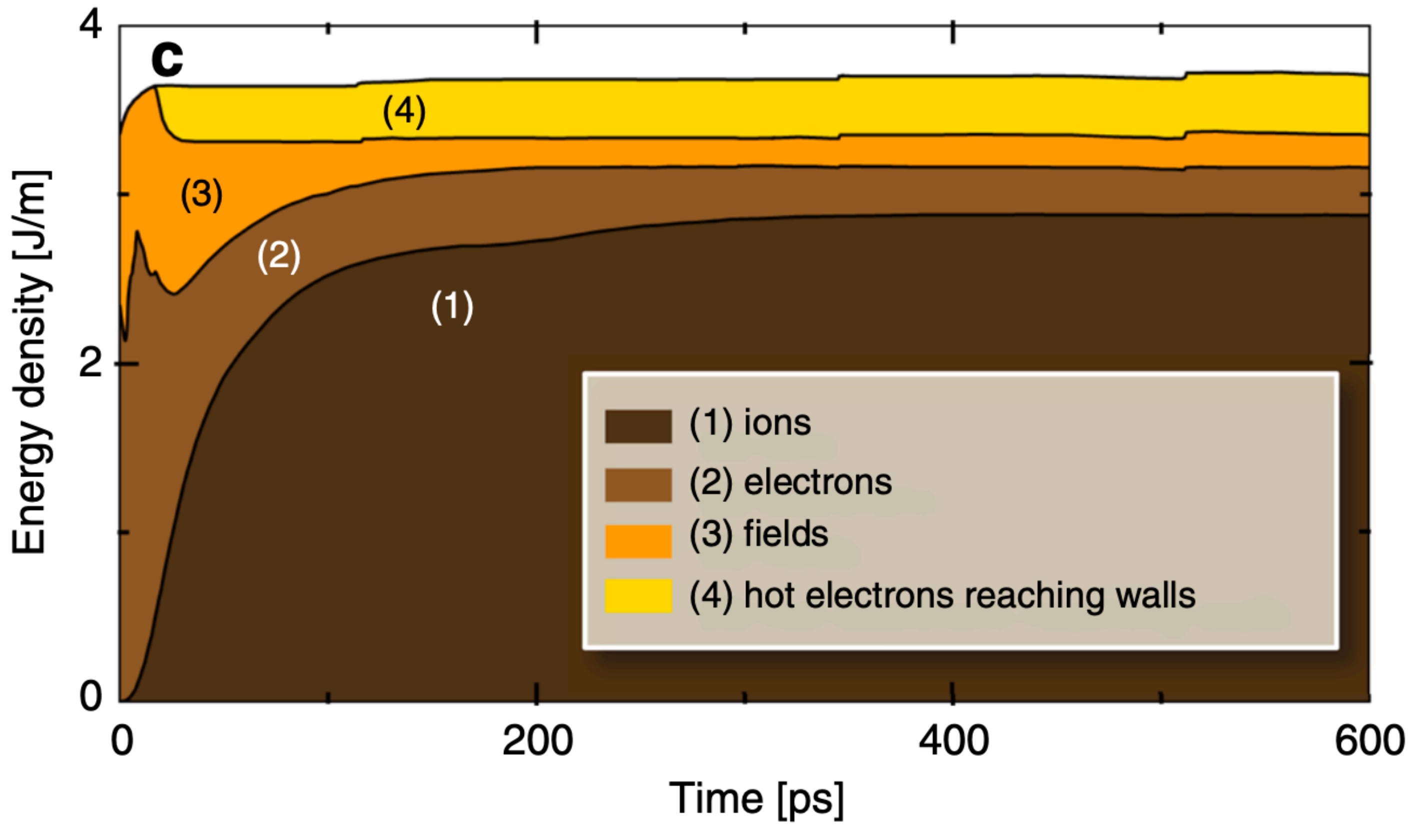
Repetition rate and high average power

The most critical outstanding R&D problem

- What is the optimal bunch train pattern for a plasma accelerator?
  - *Pulsed or CW?*
- Bunch spacing? Limited by ion motion effects:
  - *Recent experiments indicate 1–100 ns (species dependent)*
- Bunch train length? Limited by plasma-temperature effects:
  - *Wakefield structure changes above 1–10 keV*
  - *Radiation cooling (e.g., bremsstrahlung) likely not sufficient*
  - *Magnetic confinement may be required*
- Train repetition rate? Limited by plasma expulsion/refilling:
  - *Preliminary experiments indicate 0.1–10 ms*



From: D’Arcy et al. Nature 603, 58 (2022)

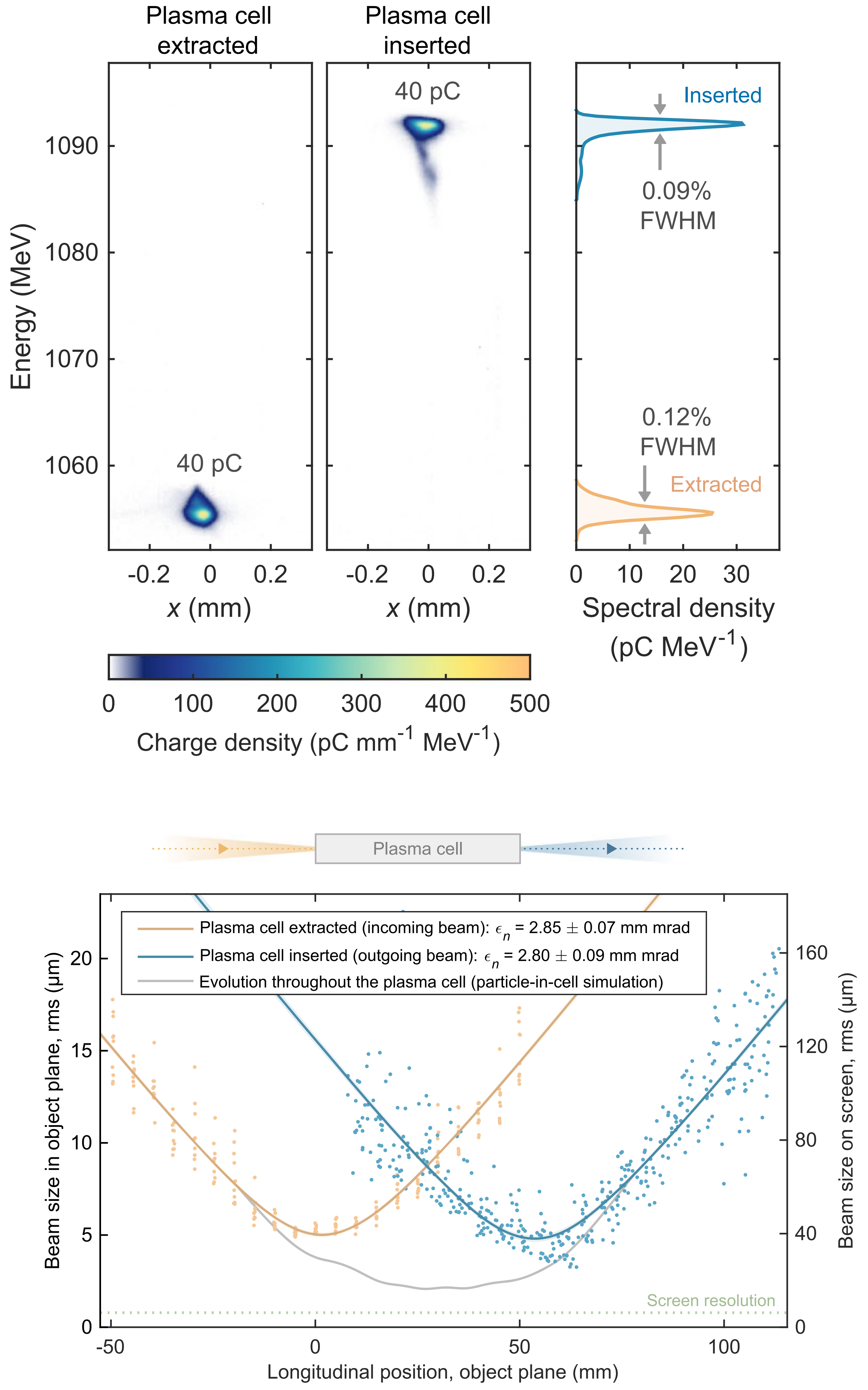


From: Zgadzaj et al. Nat. Commun. 11, 4753 (2020)

Beam quality preservation

A challenging topic with much recent progress

- Energy spread (0.1% required for colliders):
  - *~0.1% rms preserved at %-level field uniformity, ~1% with large energy gain. Optimal beam loading achieved.*
- Emittance preservation (0.1 µm–level required for colliders):
  - *2.8 mm mrad preserved (within ±3%) with moderate energy gain*
- Spin polarization (~50+% "required" for colliders):
  - *Can likely be preserved for flat beams if using vertical polarization*
  - *No evidence yet (LWFA experiments ongoing)*
- Recent advances have lead to first high-impact applications:
  - *Free-electron lasers based on LWFA (Wang et al., Nature 2021) and PWFA (Pompili et al., Nature 2022)*



Charge, energy-spread and emittance preservation in a PWFA with 40 MeV energy gain.
From: Lindstrøm et al., Nat. Commun. 15, 6097 (2024)

Staging

New ideas based on nonlinear plasma lensing

- First experiments at LBNL in ~2016.
- Main challenges:
  - *In- and out-coupling of drivers*
  - *Chromaticity in re-focusing*
- Achromatic transport possible with *nonlinear plasma lenses*
  - *Based on nonlinear correction used in collider final focusing*
  - *Can transport ~5% rms energy spread without emittance growth.*
  - *Under development in the SPARTA project—experiments at CERN.*

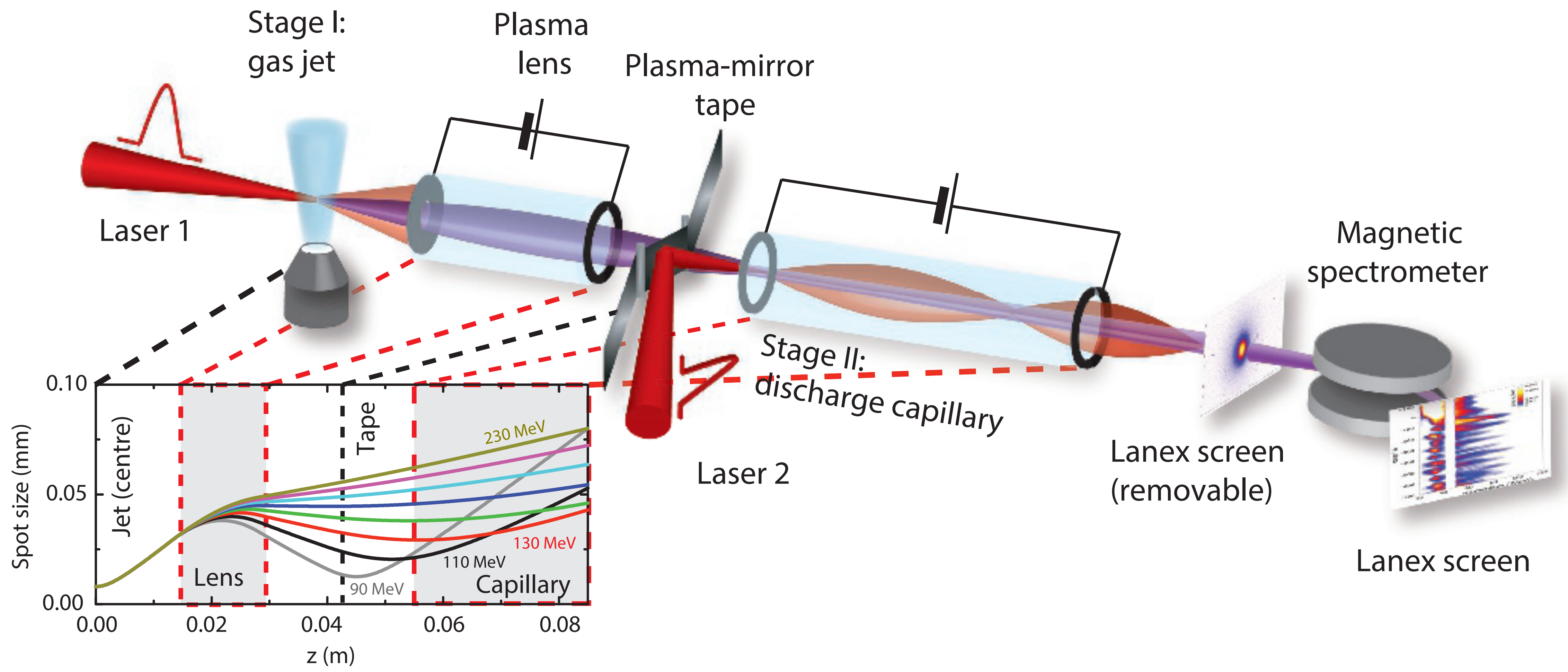
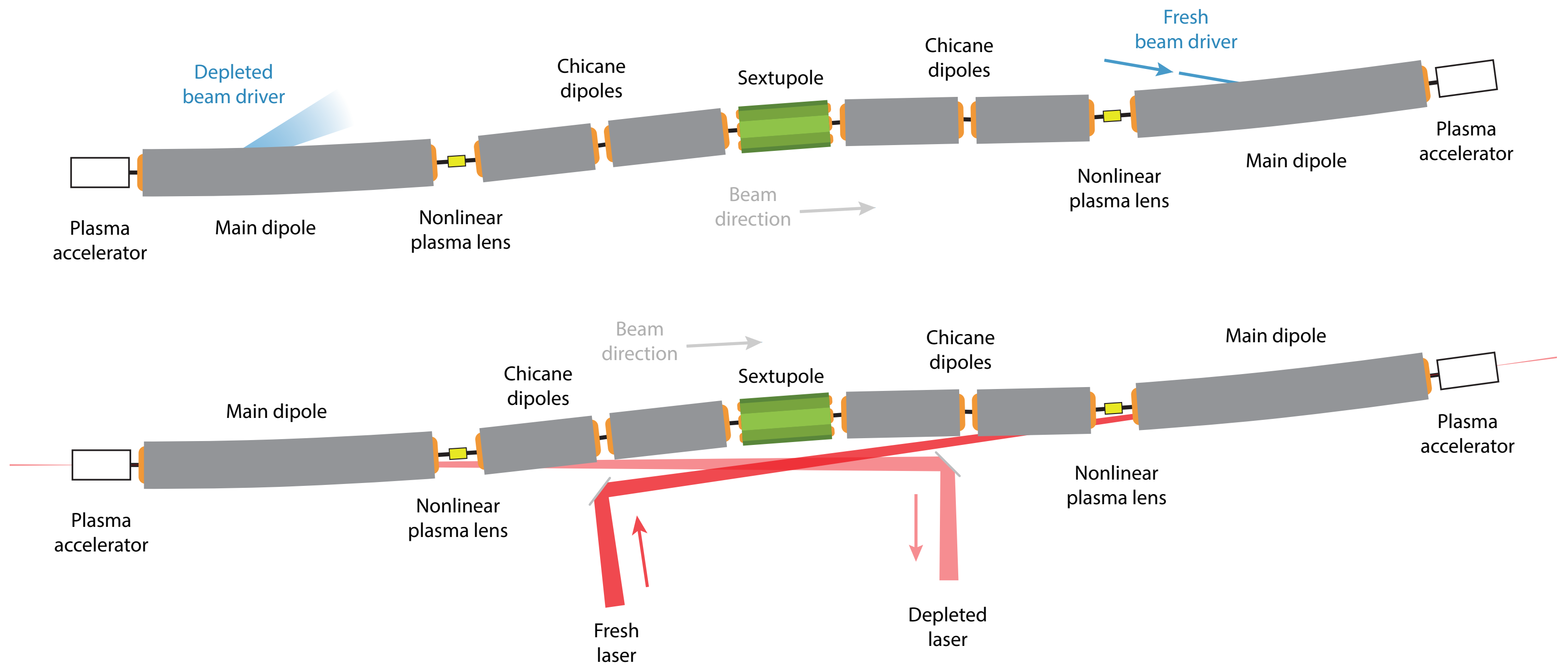
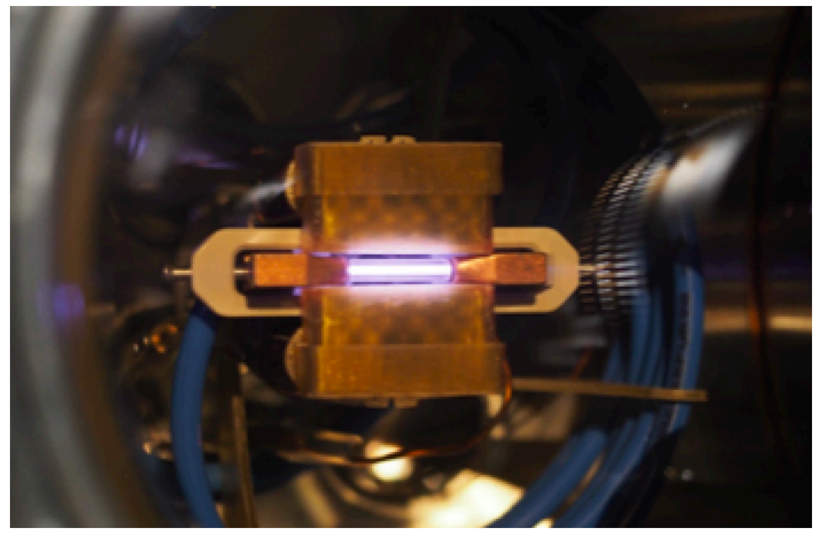


Image source: Steinke et al., Nature 530, 190 (2016).



PWFAs (top) and LWFAs (bottom) connected via achromatic lattice.

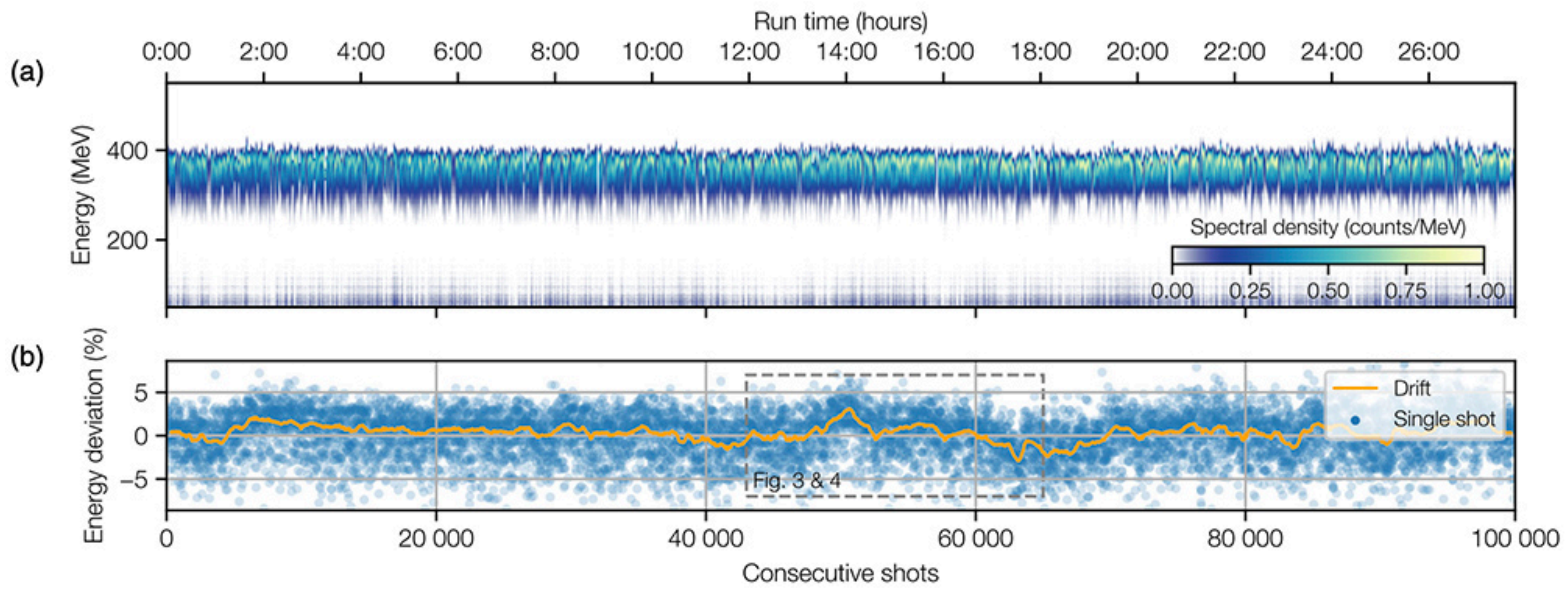


Prototype tested at CLEAR (Sep 2024). Image: K. Sjøbæk & P. Drobniak

Stability

Self-stabilization mechanisms are key

- Beam synchronization and energy stability:
  - *Active stabilisation demonstrated in LWFA*
  - *New concept: multistage self-correction using compression (R_{56}) between stages.*

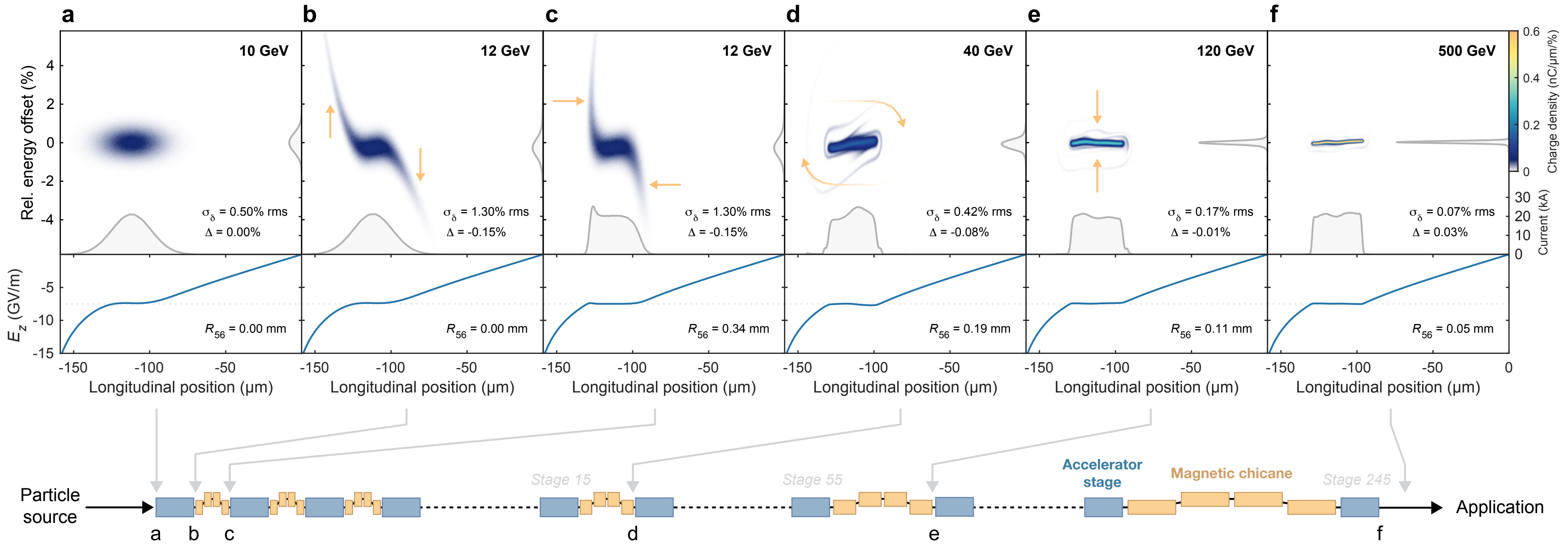


Active stabilisation over ~28 hours.
From: Maier et al., PRX (2020)

Stability

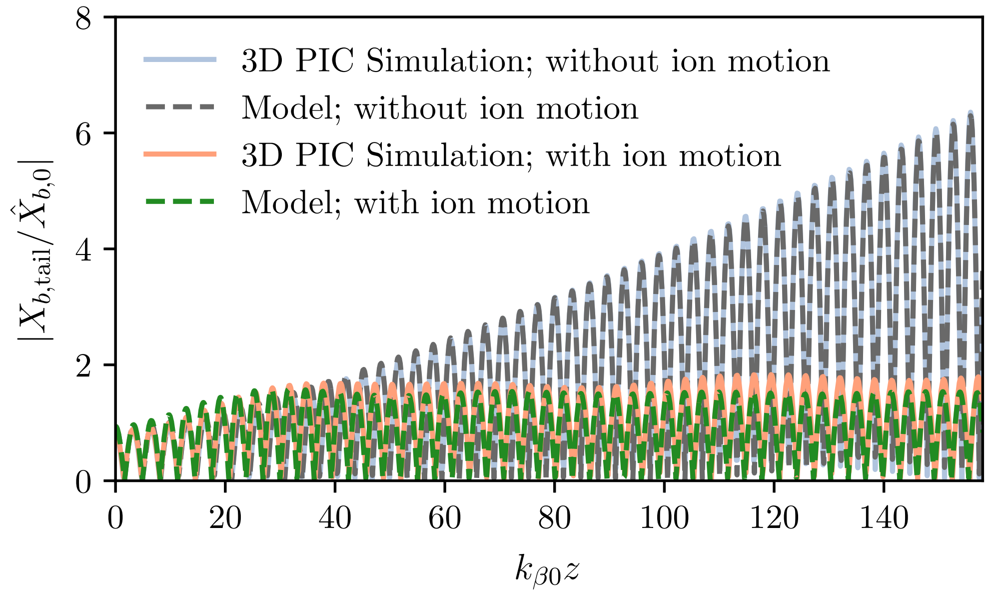
Self-stabilization mechanisms are key

- Beam synchronization and energy stability:
  - *Active stabilisation demonstrated in LWFA*
  - *New concept: multistage self-correction using compression (R_{56}) between stages.*

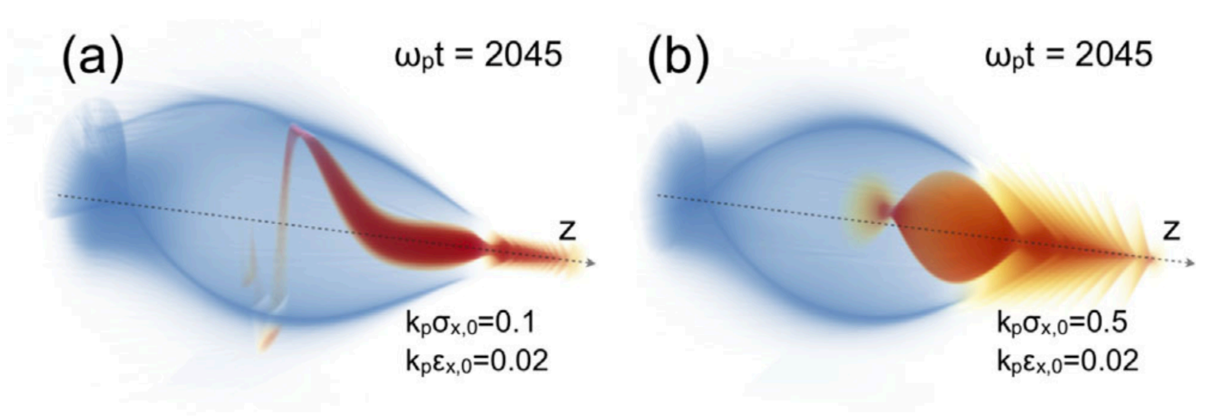


Multistage self-correction mechanism. From: Lindstrøm, arXiv:2104.14460

- Transverse instability:
  - *Major challenge in experiments.*
  - *Hosing/beam-breakup instability:*
    - *Not yet observed in experiments.*
    - *Can be suppressed with ion motion*



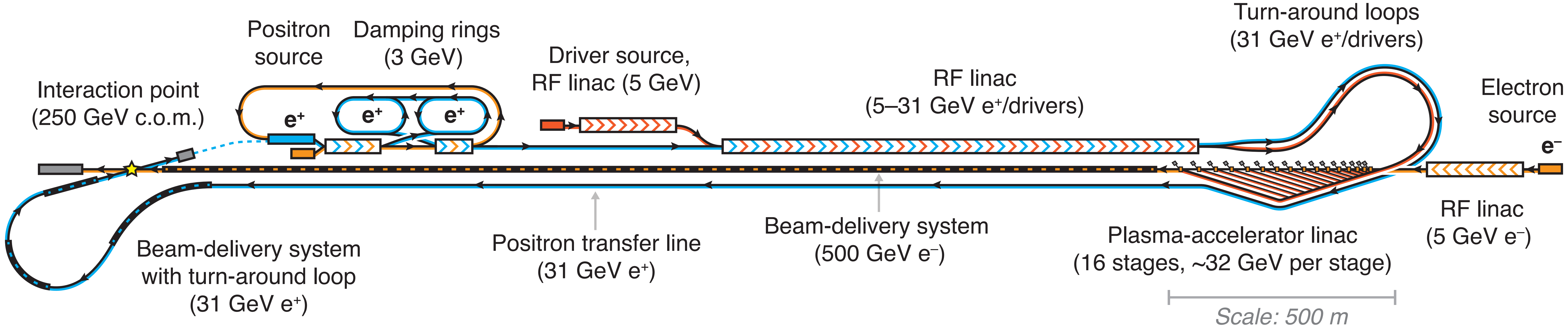
Hosing suppressed with ion motion.
From: Mehrling et al. PRL (2018)



Hosing suppressed with large driver size.
From: Martinez de la Ossa et al. PRL (2018)

HALHF — a hybrid, asymmetric, linear Higgs factory

A pragmatic approach to plasma-based colliders



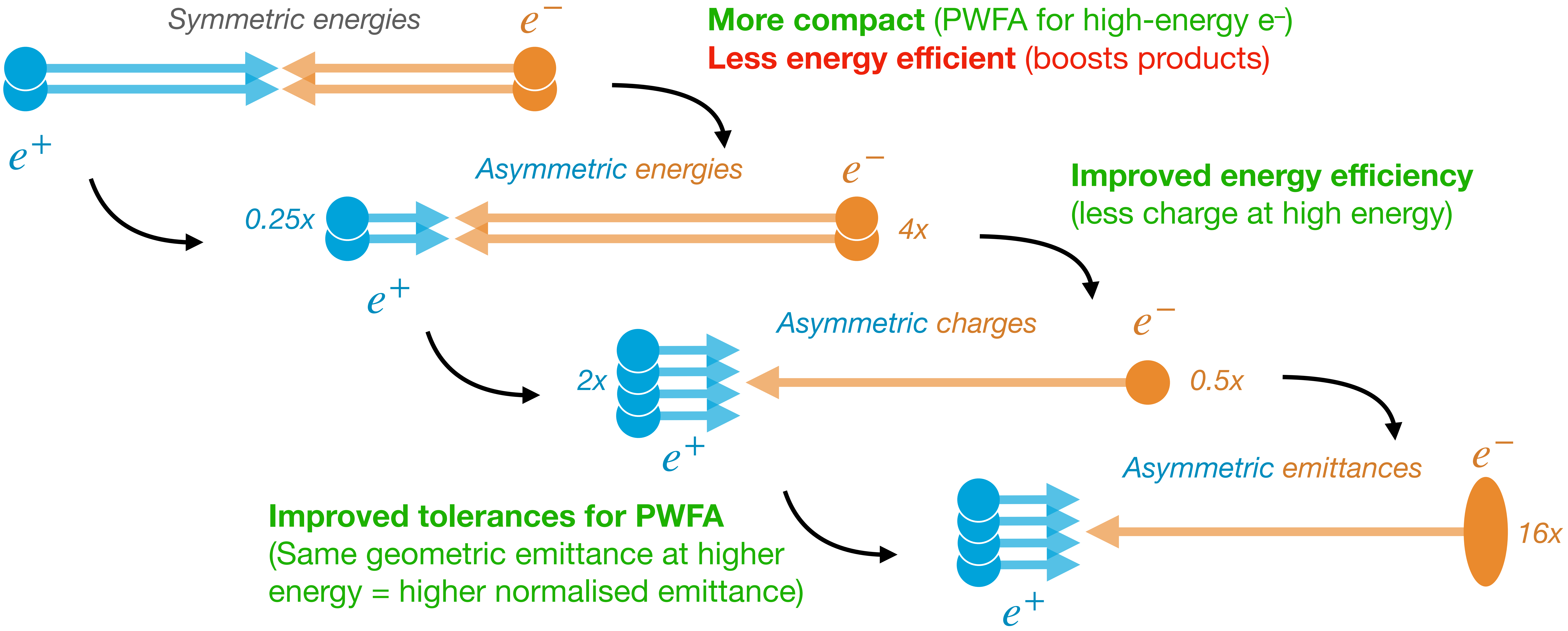
Original concept for HALHF. From: Foster, D'Arcy & Lindstrøm, *New J. Phys.* **25**, 093037 (2023).

The HALHF Collaboration at Erice, Sicily (Oct 2024)

- What can we produce based on current limitations?
  - *Positron acceleration is not currently available* — ***use RF accelerator for positrons***
  - *Electron production currently most energy efficient* — ***use electron-driven PWFA***
- Asymmetric collisions — **use higher-energy e⁻ and lower-energy e⁺.**

An asymmetric collider: can it work?

The more asymmetric, the better



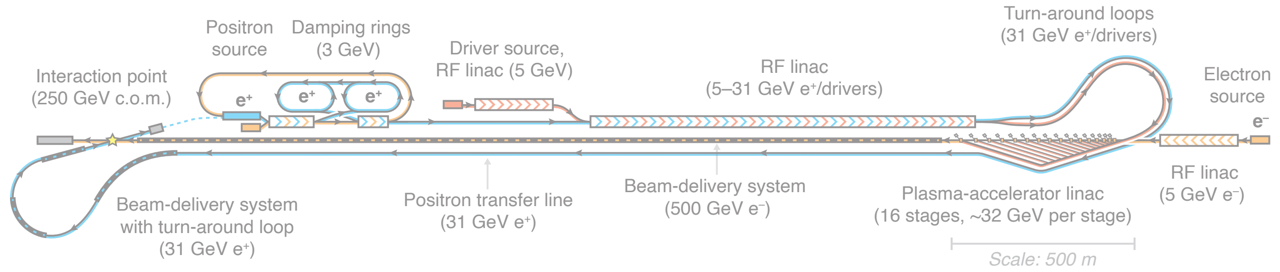
More compact (PWFA for high-energy e^-)
Less energy efficient (boosts products)

Improved energy efficiency
(less charge at high energy)

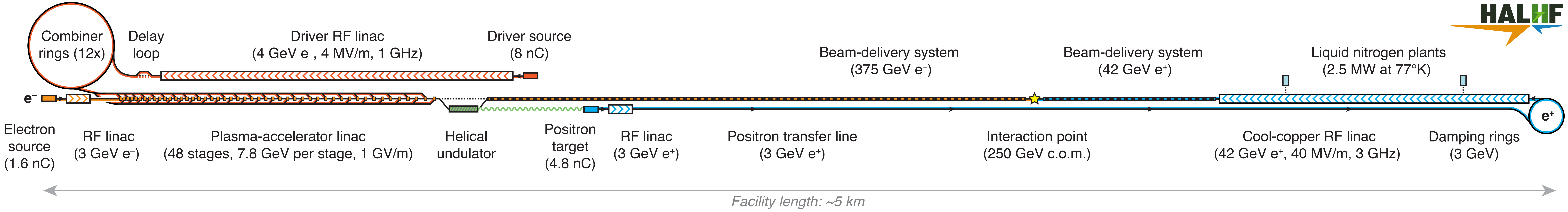
Improved tolerances for PWFA
(Same geometric emittance at higher energy = higher normalised emittance)

A new baseline for HALHF

Based on detailed feedback and Bayesian optimization



Original baseline (not to scale)



HALHF

Combiner rings (12x)

Delay loop

Driver RF linac (4 GeV e^-, 4 MV/m, 1 GHz)

Driver source (8 nC)

Beam-delivery system (375 GeV e^-)

Beam-delivery system (42 GeV e^+)

Liquid nitrogen plants (2.5 MW at 77°K)

e^-

e^+

Electron source (1.6 nC)

RF linac (3 GeV e^-)

Plasma-accelerator linac (48 stages, 7.8 GeV per stage, 1 GV/m)

Helical undulator

Positron target (4.8 nC)

RF linac (3 GeV e^+)

Positron transfer line (3 GeV e^+)

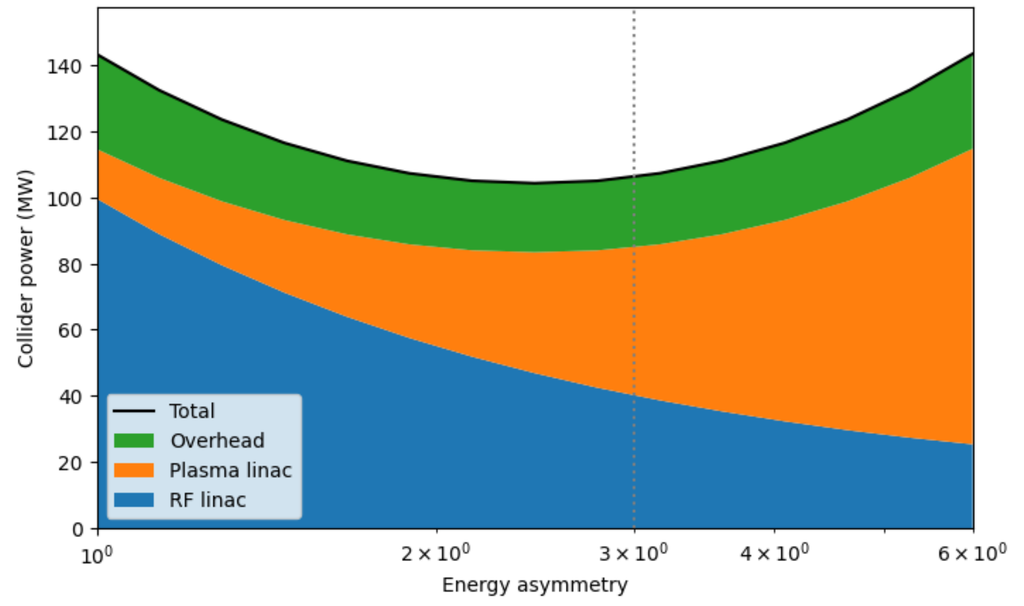
Interaction point (250 GeV c.o.m.)

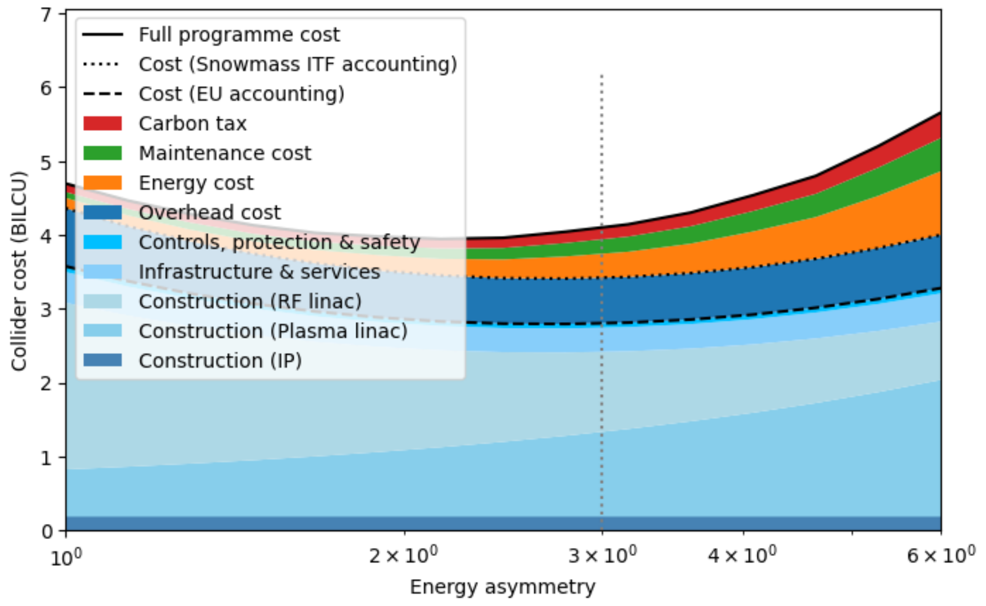
Cool-copper RF linac (42 GeV e^+, 40 MV/m, 3 GHz)

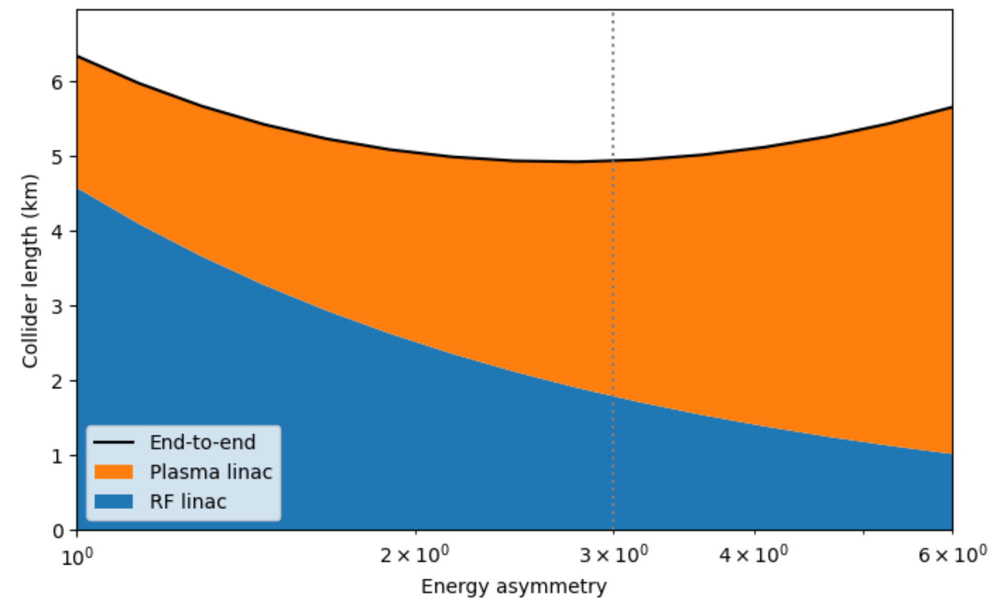
Damping rings (3 GeV)

Facility length: ~5 km

- Two separate RF linacs for drivers and positrons:
  - *CLIC-like drive beam linac + cool copper RF linac for positrons.*
- Optimised based on detailed physics+cost model.
  - *Length: ~5 km (250 GeV c.o.m.)*
  - *Power: ~106 MW.*
  - *Cost: ~½ of CLIC; ~⅓ of ILC; ~⅕ of FCC*







Lessons learned from HALHF

Based on Bayesian optimization of a detailed collider physics+cost model

- Cost of power dominates (not length)
  - *Must design the plasma accelerator for the driver, not vice versa.*
- Lower density are greatly favoured
  - *Little need for gradients beyond 1 GV/m (for sub-TeV machines)*
  - *Suppresses further beam ionisation of plasma.*
  - *High charge is required (multi-nC)*
- Maximize the *effective* transformer ratio (transformer ratio × number of stages)
- Ion motion is required for transverse stability
- The key R&D issue will be plasma heating, cooling and confinement.

Conclusions and outlook

- Much experimental and theoretical progress toward a plasma-based collider
  - *Cost and length can indeed likely be reduced*
  - *Single-shot dynamics in simulation is just around the corner*
  - *A key R&D topic will be repetition rate and high average power.*

- Possible R&D topics for EuPRAXIA@SPARC_LAB:
  - *Repetition rate, temperature effects (e.g., long trains with ~10 ns separation)*
  - *Energy efficiency (e.g., optimized driver depletion with triangular bunches)*
  - *Beam quality preservation (e.g., controlled plasma density ramps)*
  - *Transverse instability (e.g., suppression with ion motion)*