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HALHF

A Hybrid, Asymmetric, Linear Higgs Factory

New challenges for positron production

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On behalf of ***the HALHF Collaboration***

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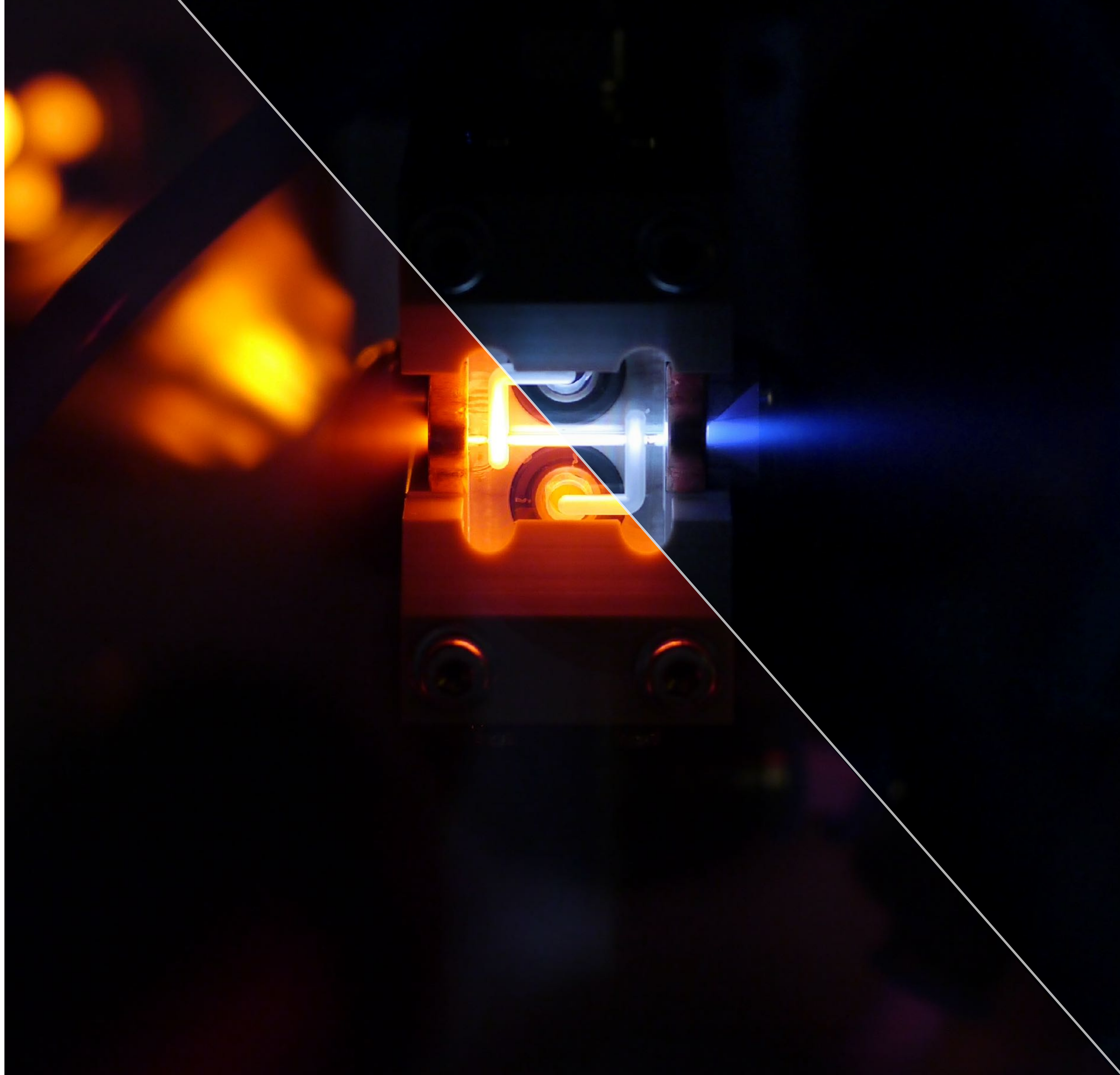
erc SPARTA ERC project
The Research Council of Norway

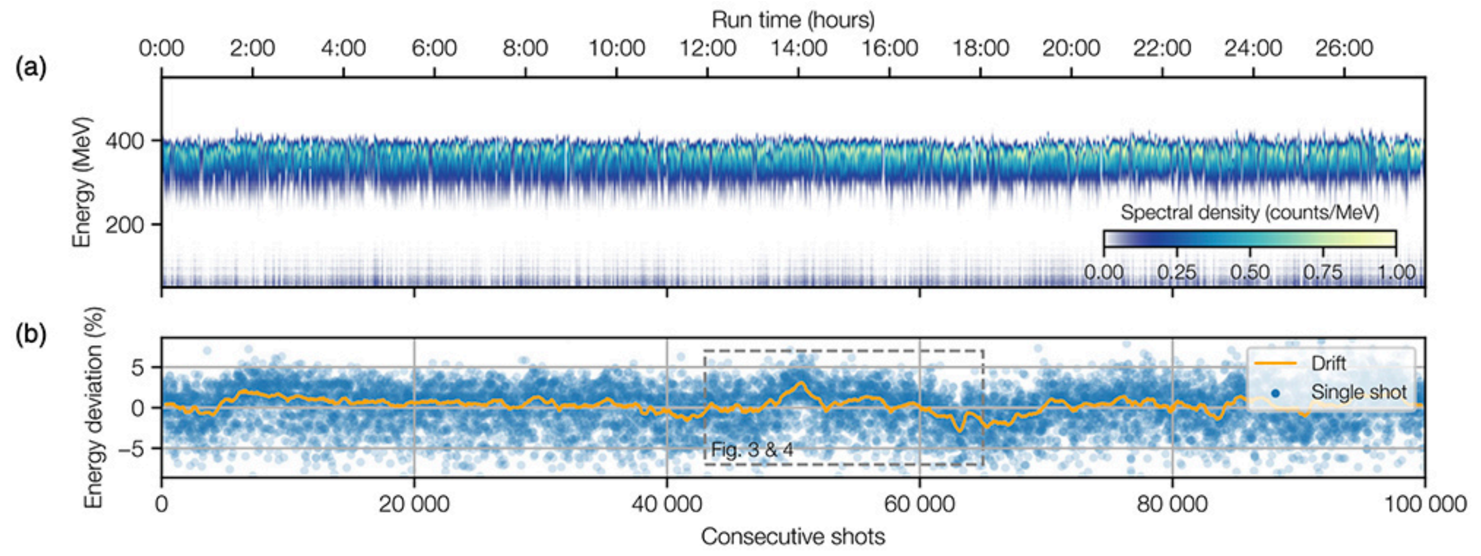


Motivation

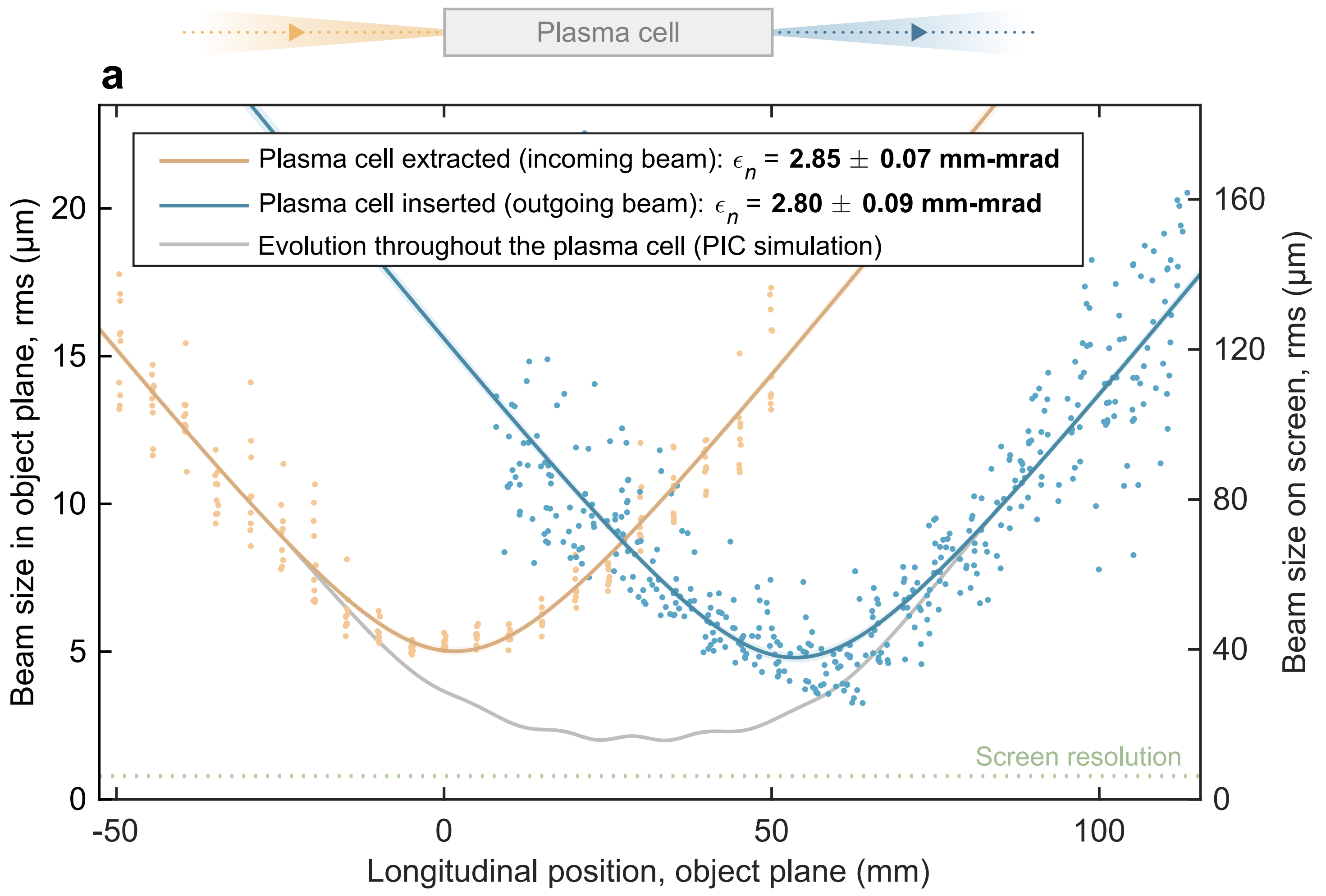
Plasma acceleration for increased gradient

Utilising the potential for cheaper high-energy physics

- > Plasma-wakefield acceleration:
  - > GV/m gradients, high beam quality, high beam power
- > Many promising developments in plasma acceleration over the past few years:
  - > Increased stability (Maier et al. PRX)
  - > FEL application (Wang *et al.*, Pompili *et al.* Nature)
  - > High rep rate (D'Arcy *et al.* Nature)
  - > Beam-quality preservation (Lindstrøm *et al.*)
  - > High energy efficiency, e⁻ driven (Litos *et al.*, Peña *et al.*)



24 hour stability, laser-plasma accelerator
Source: Maier et al. PRX 10, 031019 (2020)



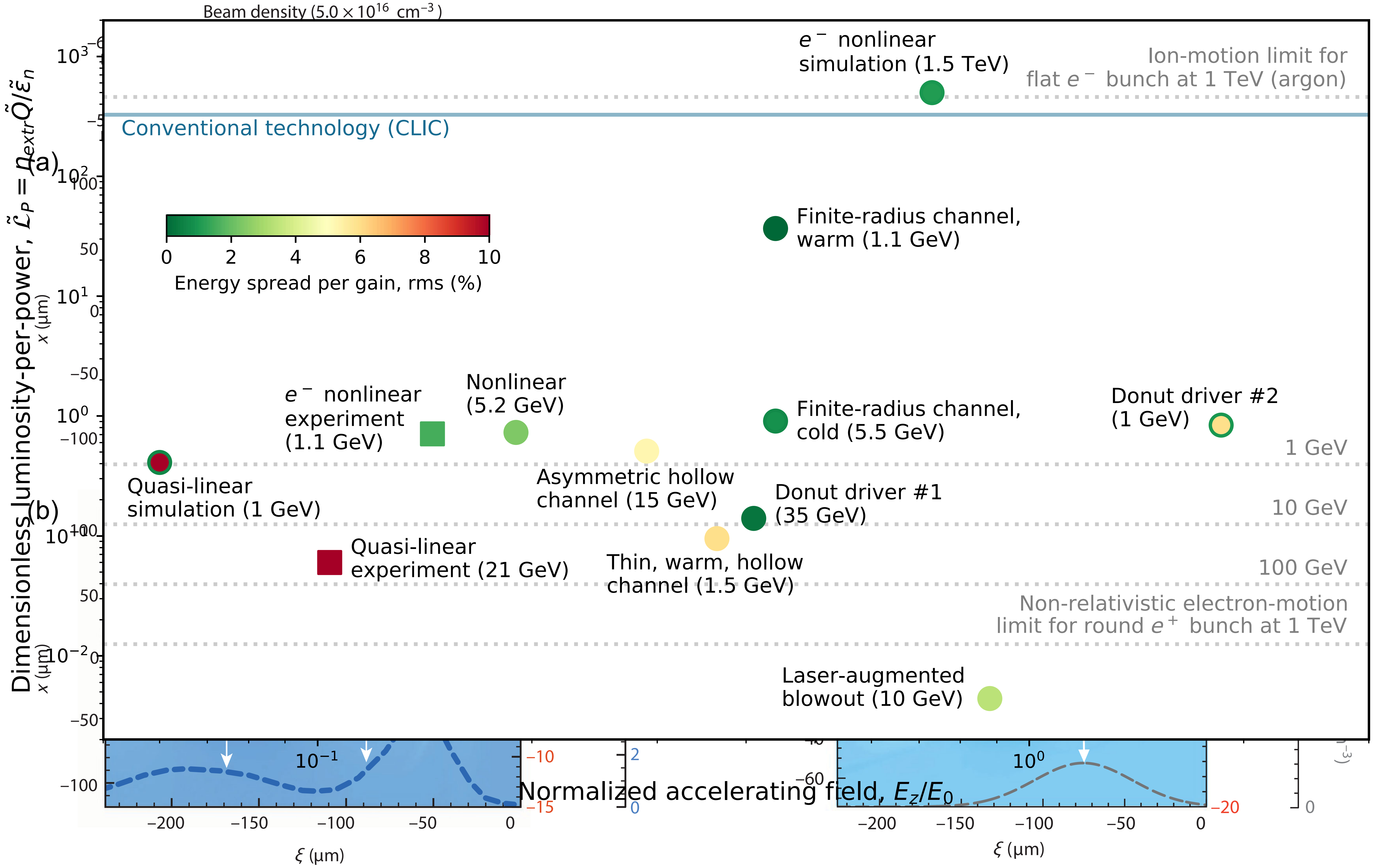
Emittance, energy-spread and charge preservation
Source: Lindstrøm et al., Nat. Commun. 15, 6097 (2024)

Positron acceleration in plasma

The biggest unsolved problem

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

- 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)



The HALHF concept

An asymmetric collider: can it work?

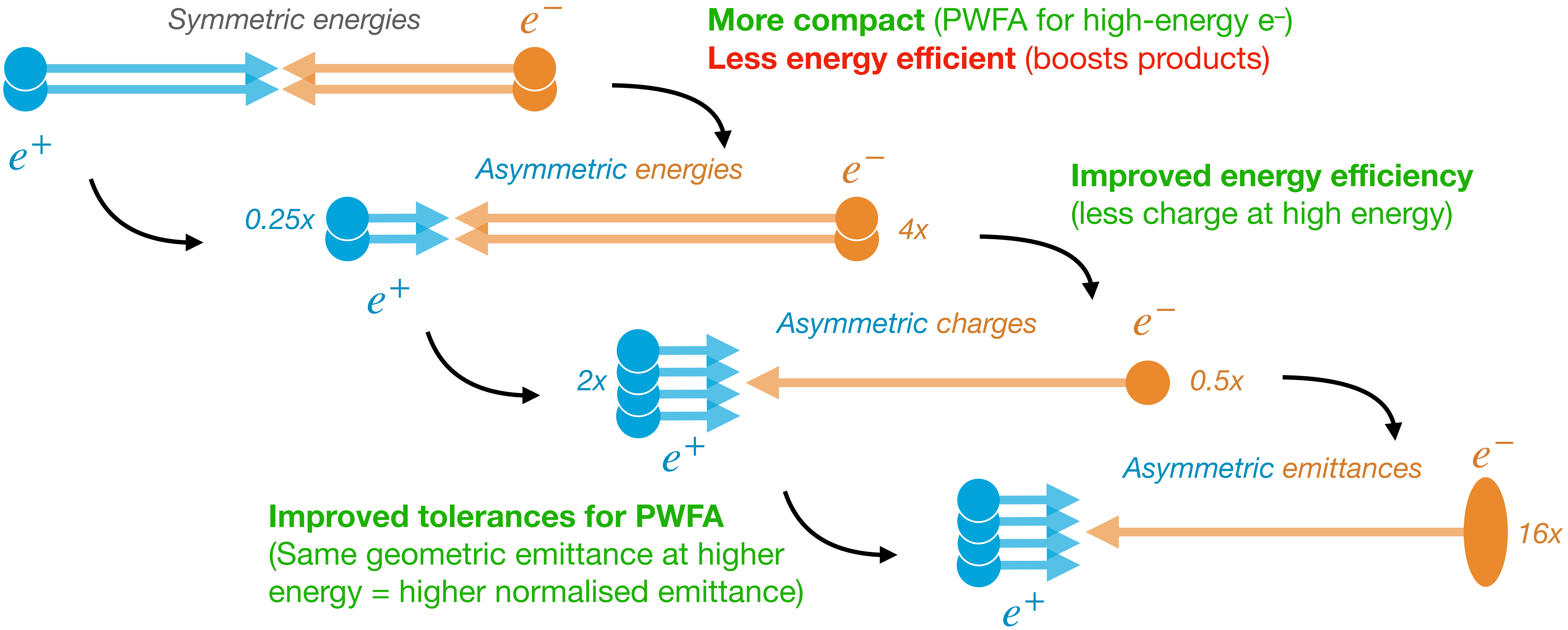
The more asymmetric, the better

More compact (PWFA for high-energy e⁻)

Less energy efficient (boosts products)

Improved energy efficiency
(less charge at high energy)

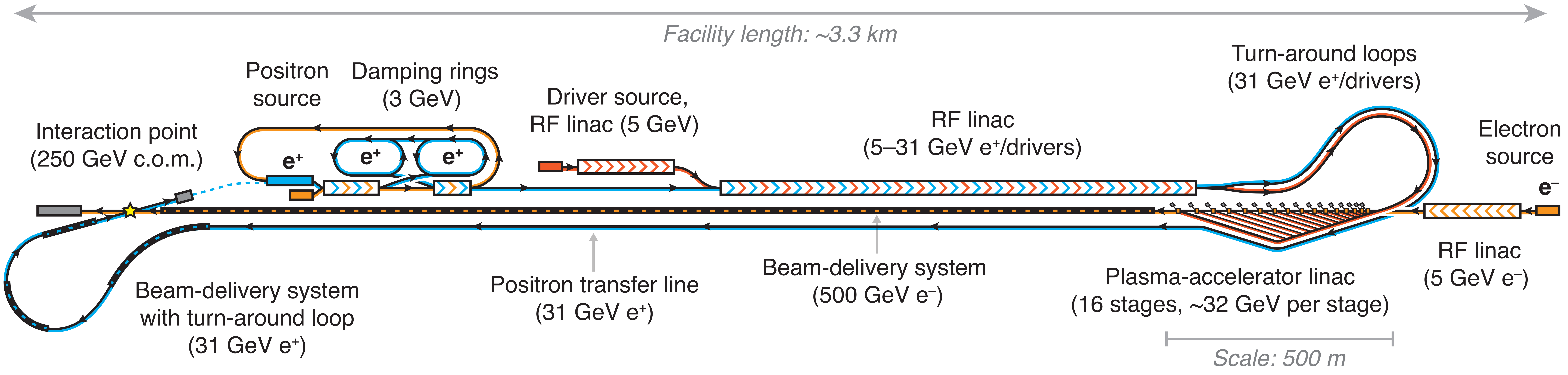
Improved tolerances for PWFA
(Same geometric emittance at higher energy = higher normalised emittance)



HALHF: a hybrid, asymmetric collider concept

Plasma acceleration for electrons + RF acceleration for positrons

> Solving the plasma positron problem by accelerating positron with RF linacs.



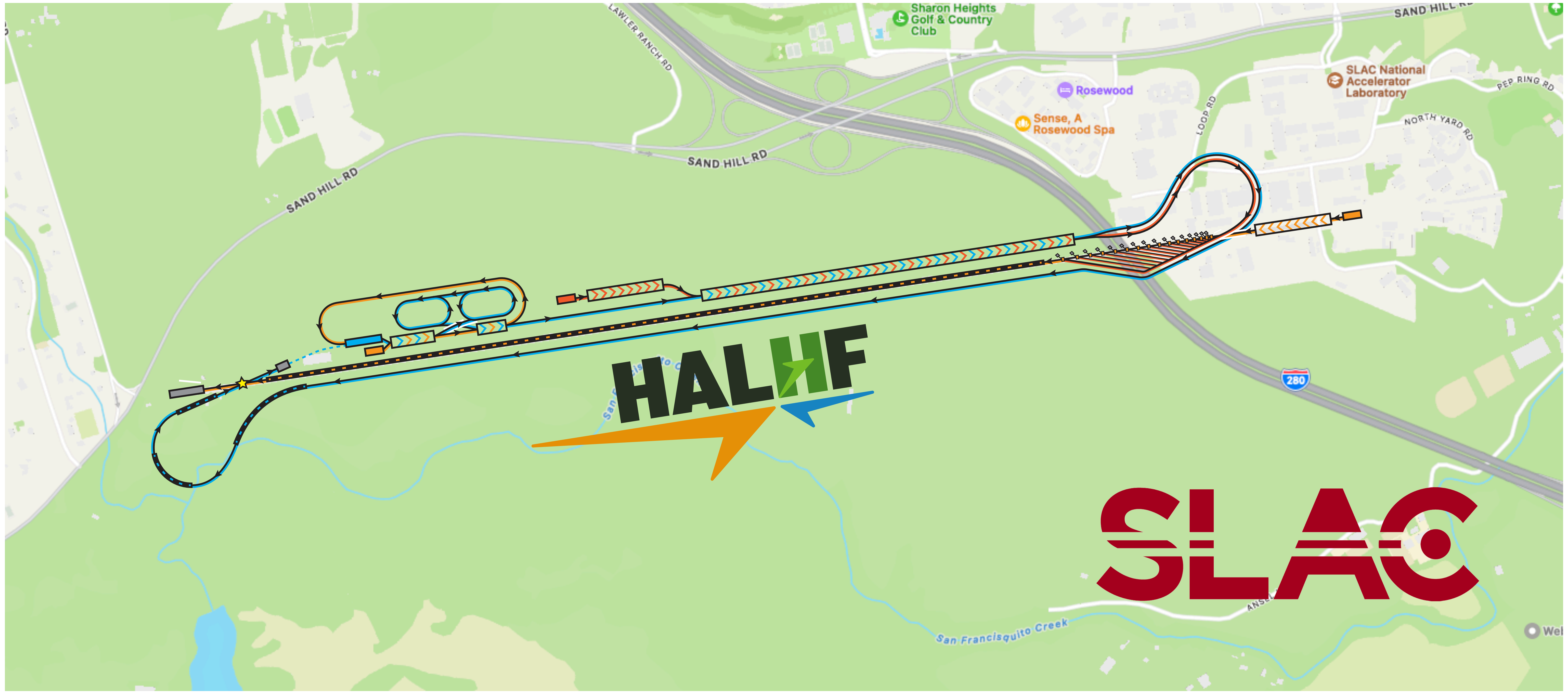
Source: Foster, D'Arcy & Lindstrøm, New. J. Phys. 25, 093037 (2023)

> Original HALHF proposal includes a combined RF linac for positrons and e⁻ drivers.

> Length dominated by the beam-delivery system. Cost dominated by the RF linac.

A collider on a “national” scale

Plasma acceleration for electrons + RF acceleration for positrons



> Overall footprint: 3–5 km (TBD): Fits in most major particle-physics laboratories

> Construction cost estimate around €2–4B (TBD) — national, not international scale.

Recent progress

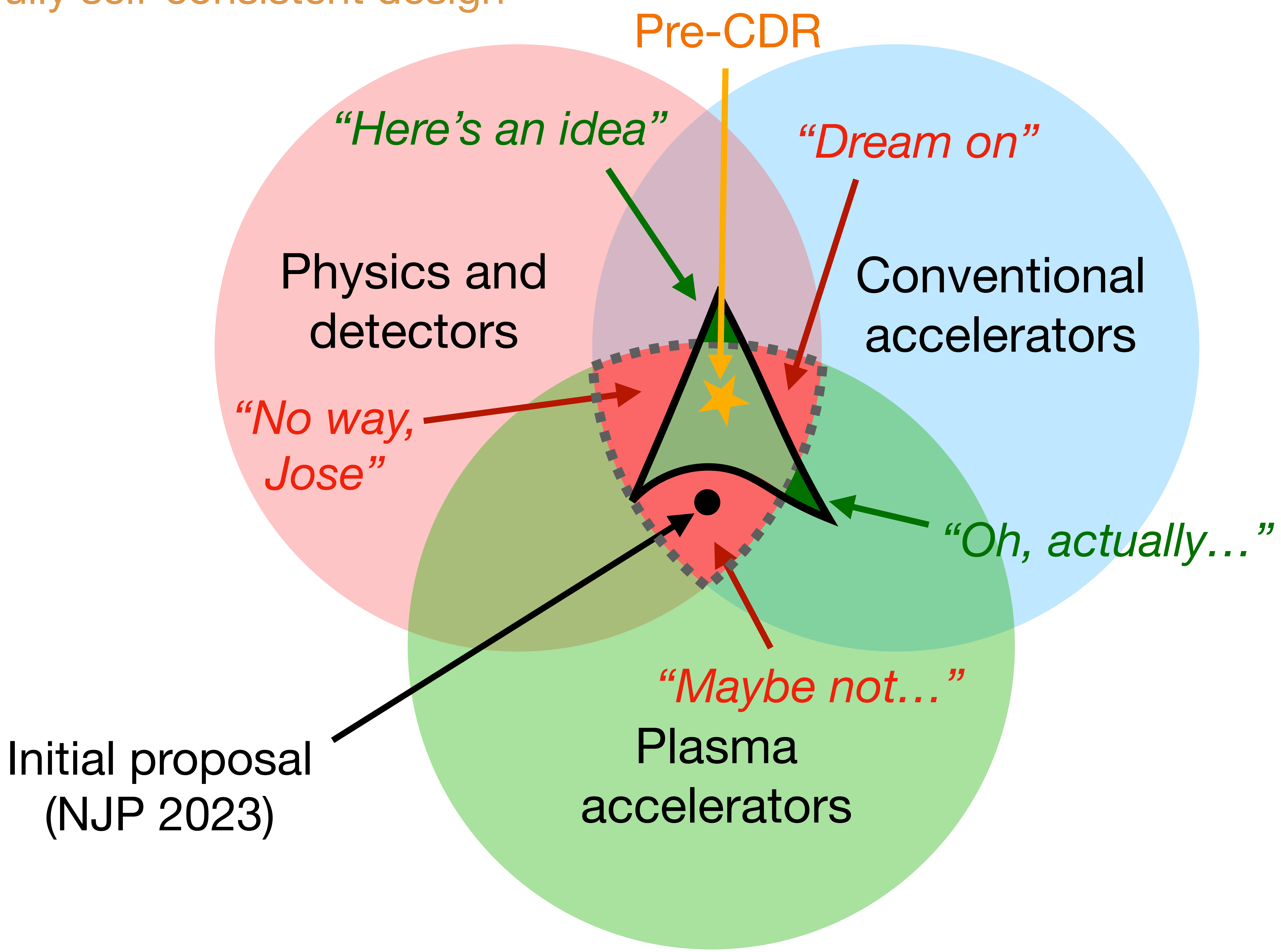
Challenges in the original design: a “laundry list”

Identified as a result of much community input and engagement

- Transverse instability, tolerances are too tight.
- Beam ionisation of the higher-order ionisation levels for argon (chosen to avoid ion motion).
- Cross-plane emittance mixing (Diederichs *et al.*): large horizontal emittance leaks into vertical emittance.
- Plasma-cell cooling: too much cooling required per length (~90 kW/m).
- Radiation reaction at high energy: large induced energy spread (%-level).
- Bunch pattern may not be compatible with PWFA: too much temperature increase? Effect on wakefields? Confinement?
- Exceeded the Oide limit in the final focusing magnets.
- High-energy turn-arounds: too much energy loss to synchrotron radiation.
- The required delay chicanes are (transversely) large and costly. Strong bending magnets (SR is problematic).
- Combined RF accelerator has too high gradient given its high power.
- Required driver bunch length is too short: problematic beam loading in the RF linac (beam current too high).
- The instantaneous luminosity is too low
- **High positron bunch charge: problematic for production and for collisions.**
- **Need polarised beams for physics.**
- Unknown if we can preserve spin polarization of electrons in plasma stages and interstages.

A delicate balance of three worlds

Moving toward a fully self-consistent design

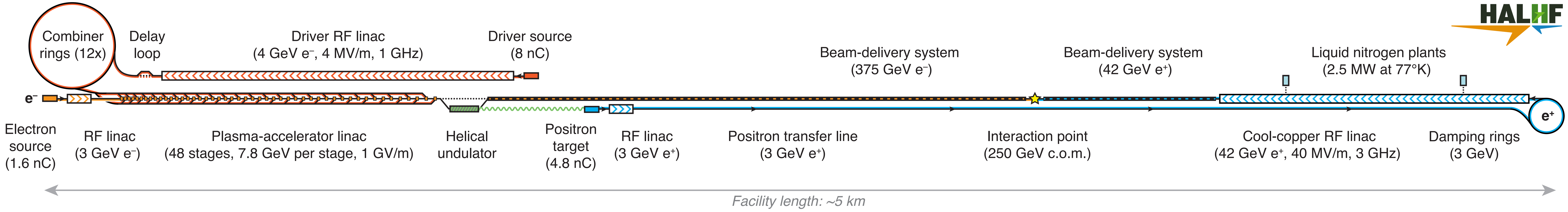



HALHF Workshop
Oslo, 4–5 April 2024

You are very welcome to join the HALHF Collaboration!

Toward an updated baseline

Work in progress—aim to finish before the ESPP input deadline (March 2025)

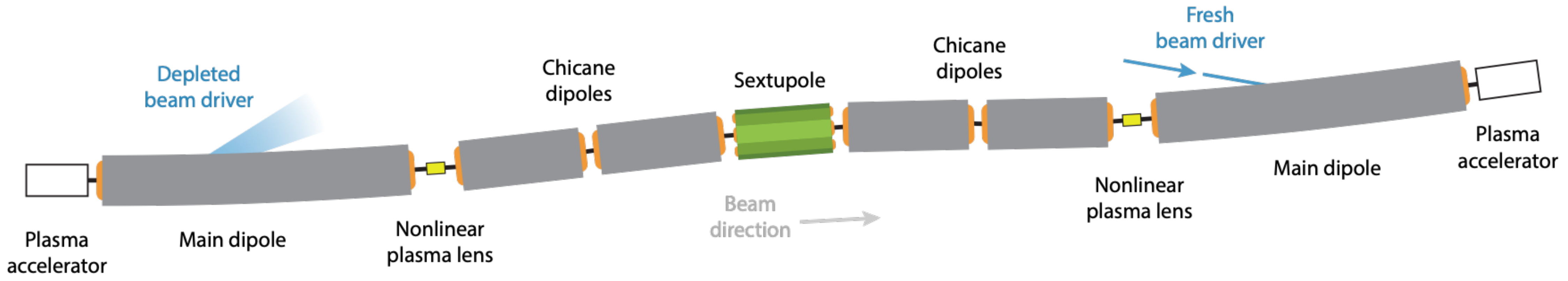


> Main changes in the updated baseline (to be confirmed):
  > Lower-density plasma acceleration (lower gradient, improved tolerances)
  > Separate RF linacs for PWFA drivers (high current, low gradient) and positrons (low current, high gradient):
    L-band driver linac (CLIC-like) + S-band positron linac (warm or cool copper).
  > Combiner ring to decrease current in the (high-power) driver linac.
  > Polarised electrons and positrons (ILC-like helical undulator source).

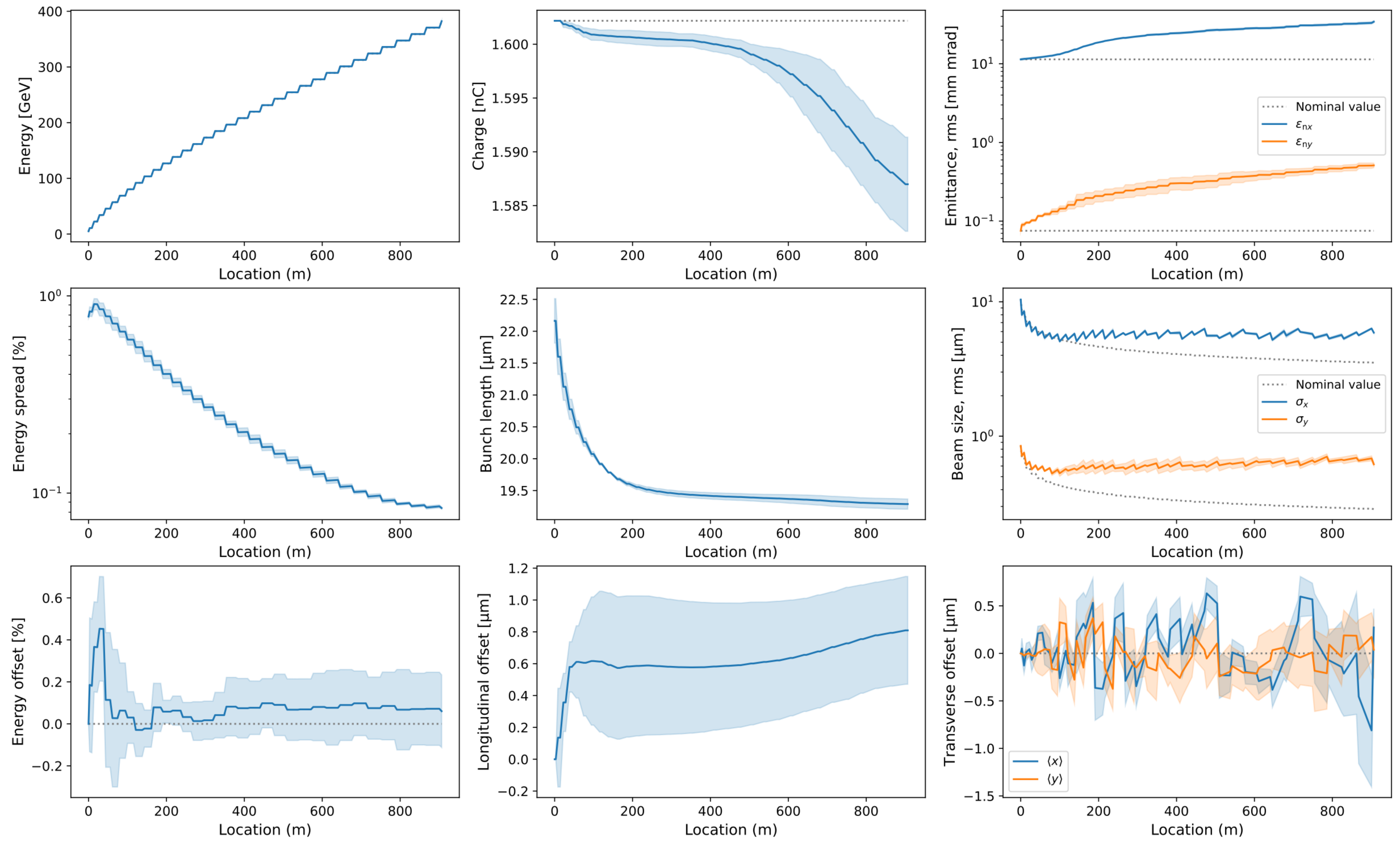
Toward a self-consistent plasma linac

Start-to-end simulations (by Ben Chen, Uni Oslo)

- Multi-stage PWFA linac (here 33 stages)
- Nonlinear plasma-lens optics for stage coupling (SPARTA project, ERC)
- Flat-beam issue (Diederichs et al. 2024) suppressed with vertically flat driver
- Ion motion suppresses transverse instability.
- Longitudinal self-stabilization from compression between stages
- Full simulation (minor simplifications only):
  - PIC simulation in stages (HiPACE++)
  - Particle tracking in interstages (ELEGANT)



Staging optics with nonlinear plasma lenses (SPARTA project).

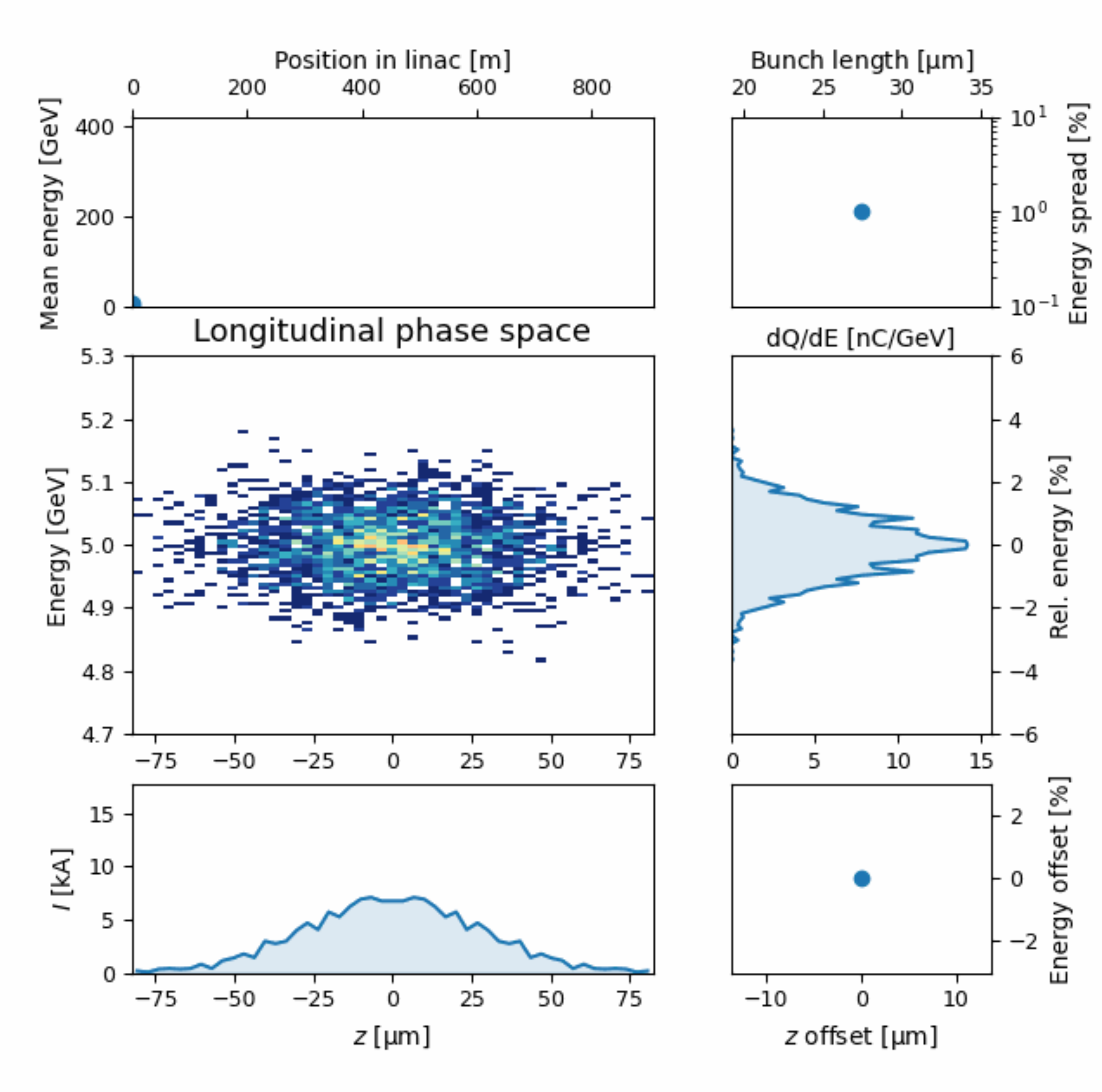


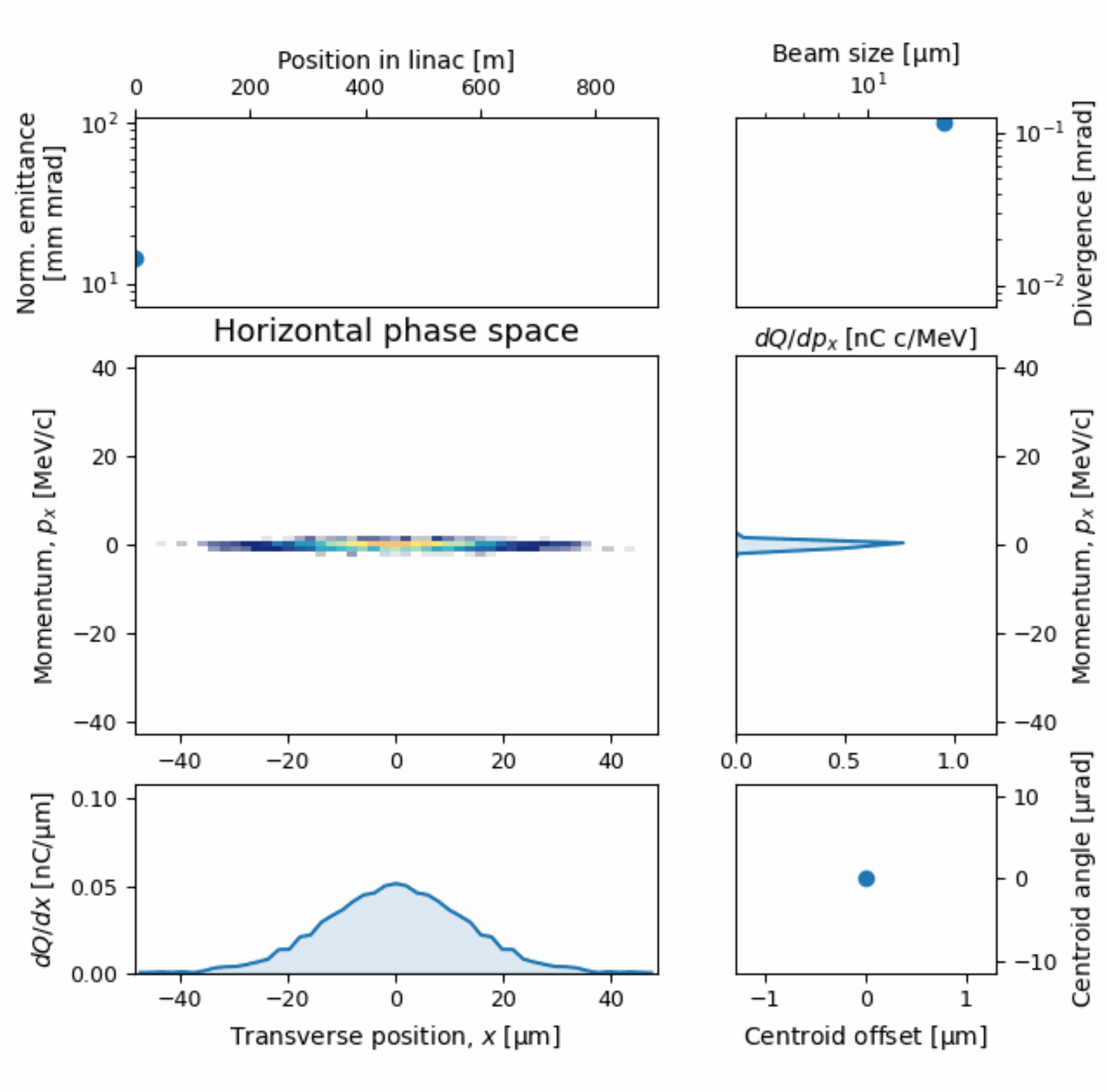
Preliminary start-to-end simulations
Source: B. Chen (University of Oslo)

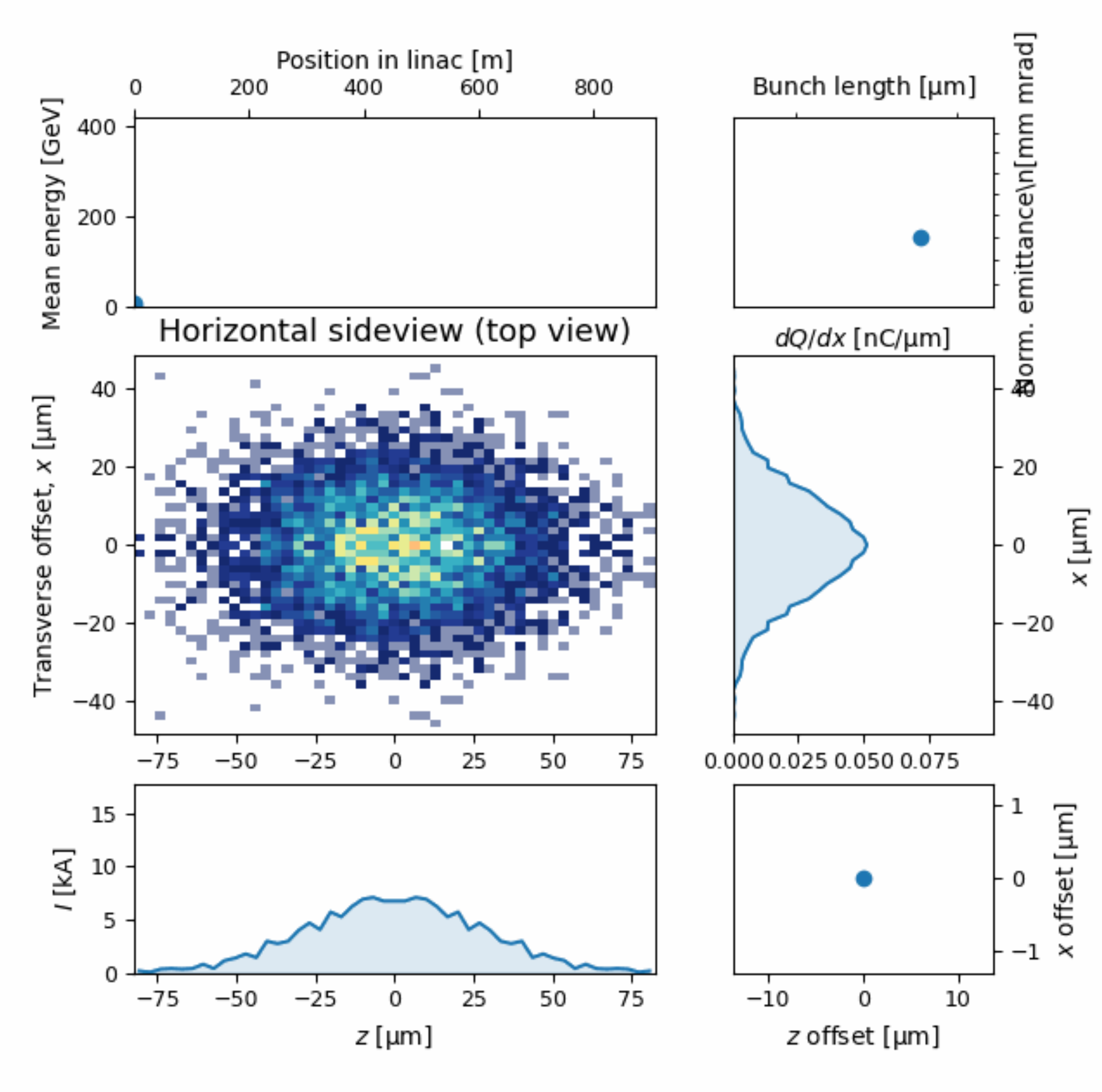
Toward a self-consistent plasma linac

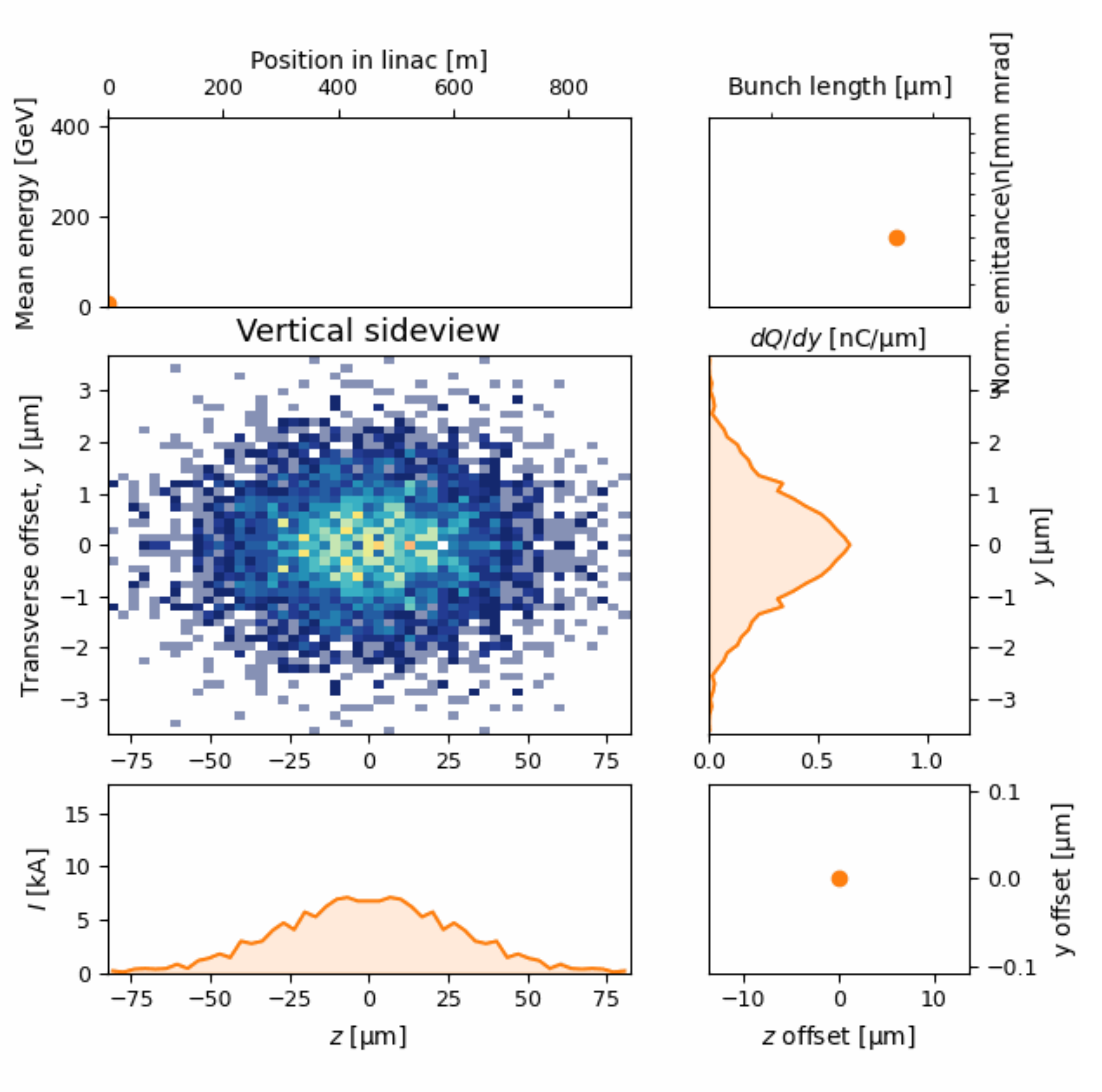
Start-to-end simulations (by Ben Chen, Uni Oslo)

- Using 100 nm rms driver offset jitter (similar to state-of-the-art)
- **Final emittance around 0.5x34 mm mrad: very close to requirement for HALHF**
- Synchronisation tolerance around 10 fs rms (similar to state-of-the-art)





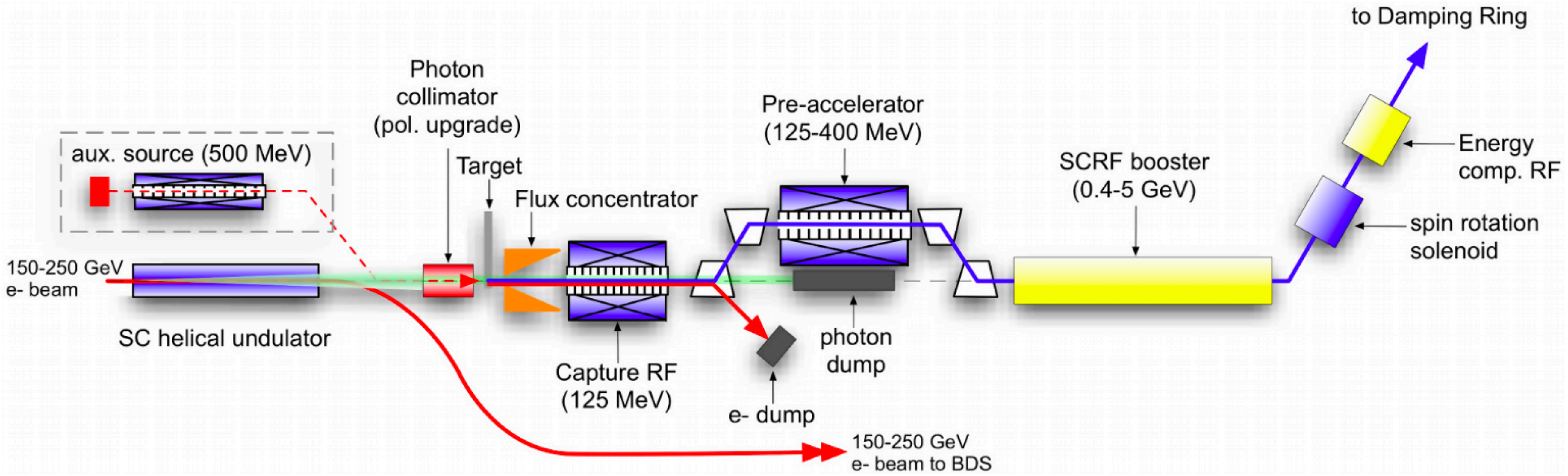




A polarised positron source for HALHF

Positron requirements

New challenges compared to ILC positron source



> Higher bunch charge:
  ~4.8 nC per e+ bunch (1.5x ILC)

> Higher overall number required as in the ILC luminosity upgrade:

  > 4.8×10^{14} e+/s in HALHF compared to 2.6×10^{14} e+/s in ILC upgrade

> Different train structure to ILC (shorter if CLIC-like RF linacs, longer if CW):

  > 160 pulses in ~2.6 µs at ~100 Hz rep rate (compared 1000s on a ms-timescale at ILC)

> The electron beam is lower: 1.6 nC per e– bunch (50% of ILC)

  > **Requires higher positron yield** (3–4 e+ per e–, compared to 1–1.5 e+ per e– in ILC)

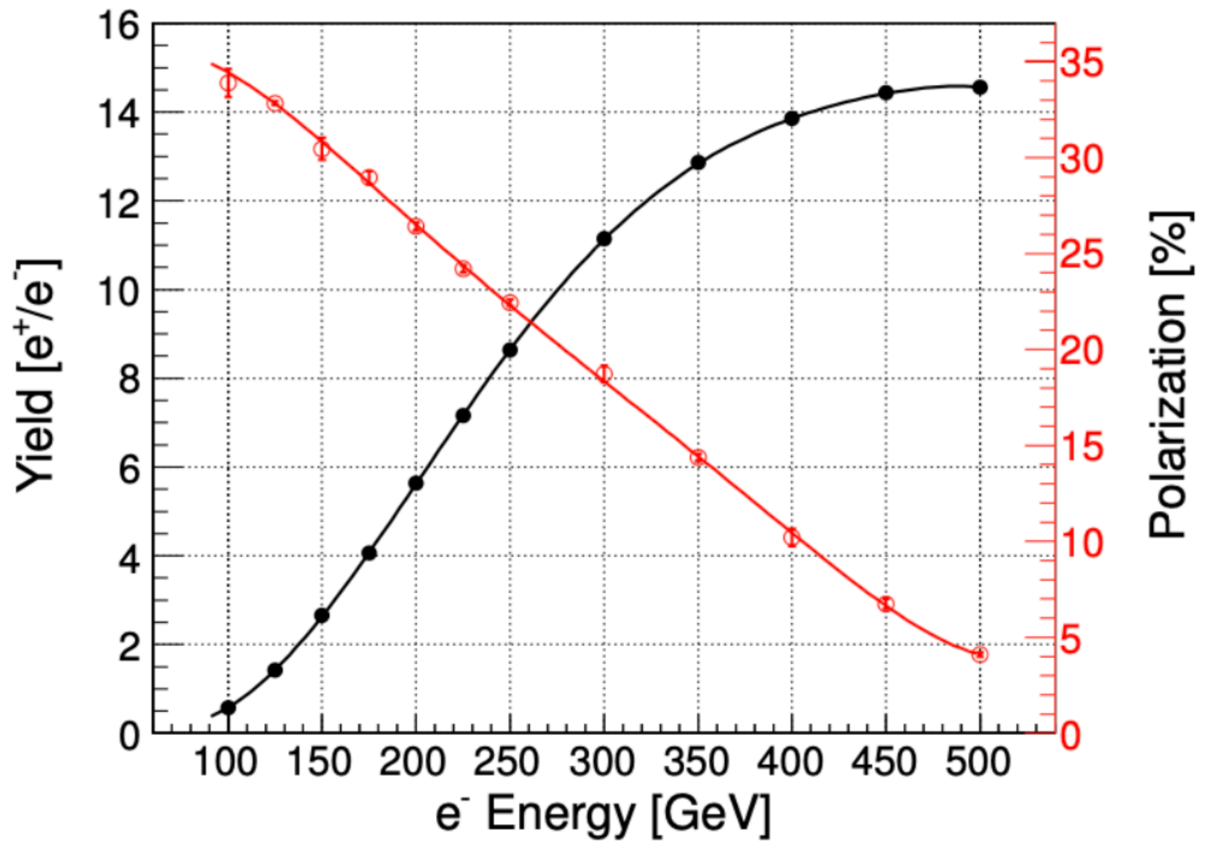
> The electron beam is 3× higher energy: ~375 GeV (compared to ~125 GeV in ILC)

  > Requires changes in the helical undulator

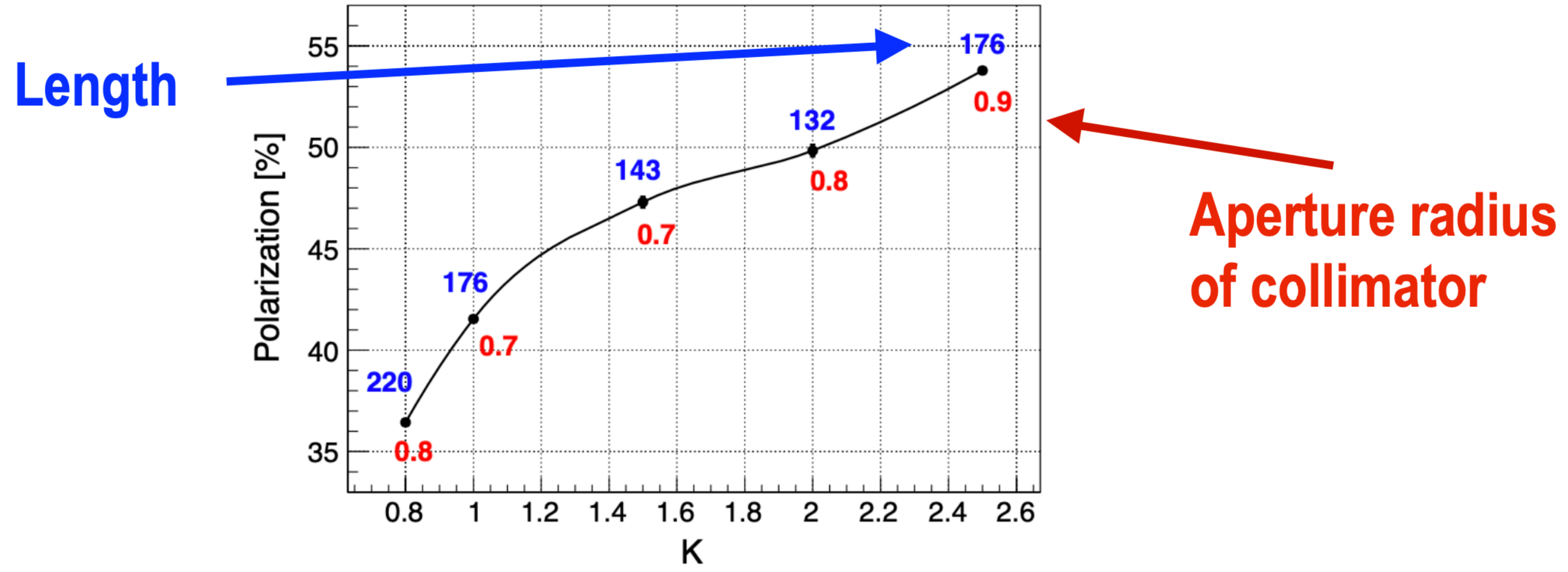
Previous studies of a positron source at 500 GeV

By G. Moortgat-Pick *et al.*

Ushakov et al., arXiv:1301.1222 (2013)



Assuming the ILC undulator (K=0.92, λ=11,5 mm).
Source: Ushakov et al. (2013)



Possible new undulator setup
Source: Ushakov et al. (2013)

> Not ideal to use ILC undulator (K = 0.92, λ = 11.5 mm): Low polarization at 500 GeV

> Instead use new setup: higher K = 2.5, period λ = 43 mm

> > Can achieve ~55% polarization, higher yield.

> > Larger γ-ray spot: May be more challenging to capture the positrons.

Conclusion

Conclusion

HALHF: a project with large forward momentum!

- > HALHF: a plasma-based collider concept that sidesteps the "positron problem" in PWFA
- > Collaboration formed—several very productive workshops
- > Much recent progress toward a self-consistent and credible design.
  - > Working toward an updated baseline by March 2025 (ESPP input deadline).
- > Polarized positron source likely required:
  - > Changes required wrt. ILC polarised positron source, but currently seems feasible.