UNIVERSITY OF OSLO

UNIVERSITY OF OXFORD

HALHF

A hybrid, asymmetric, linear Higgs factory

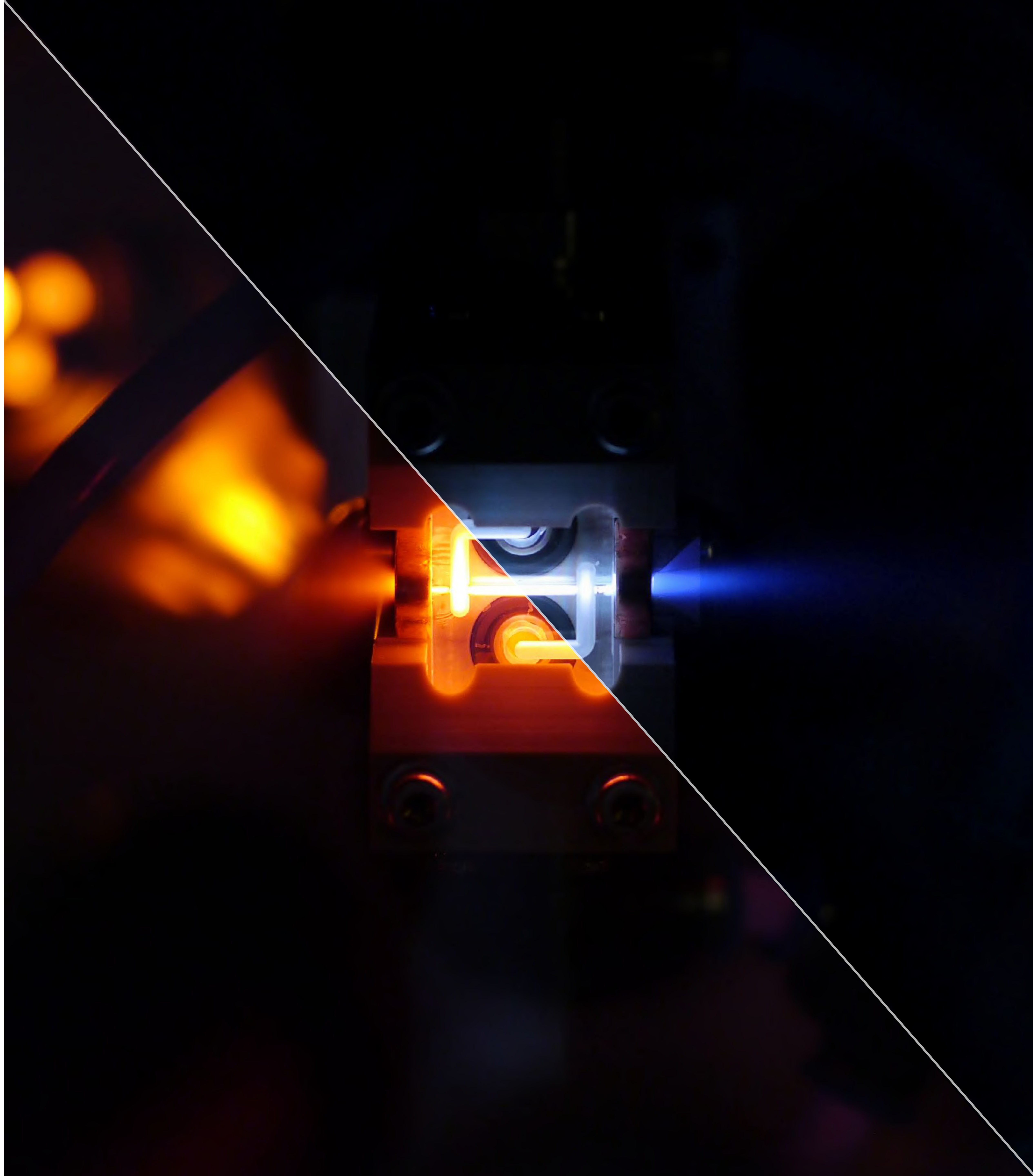
Progress toward a self-consistent
plasma- and RF-based collider design

Carl A. Lindstrøm
University of Oslo

Richard D'Arcy
University of Oxford

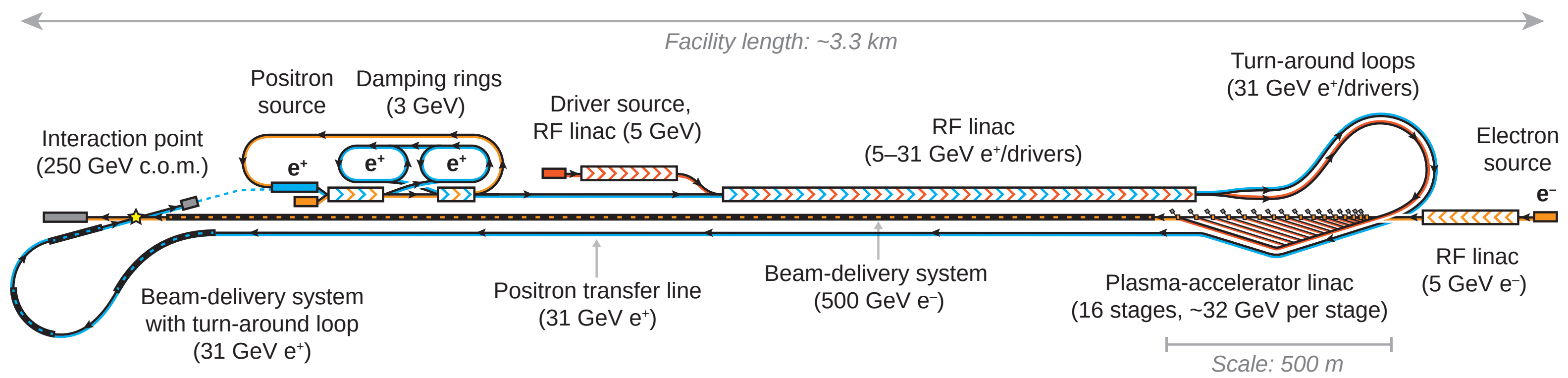
On behalf of the HALHF Collaboration

7 June 2024



The HALHF concept

A brief reminder



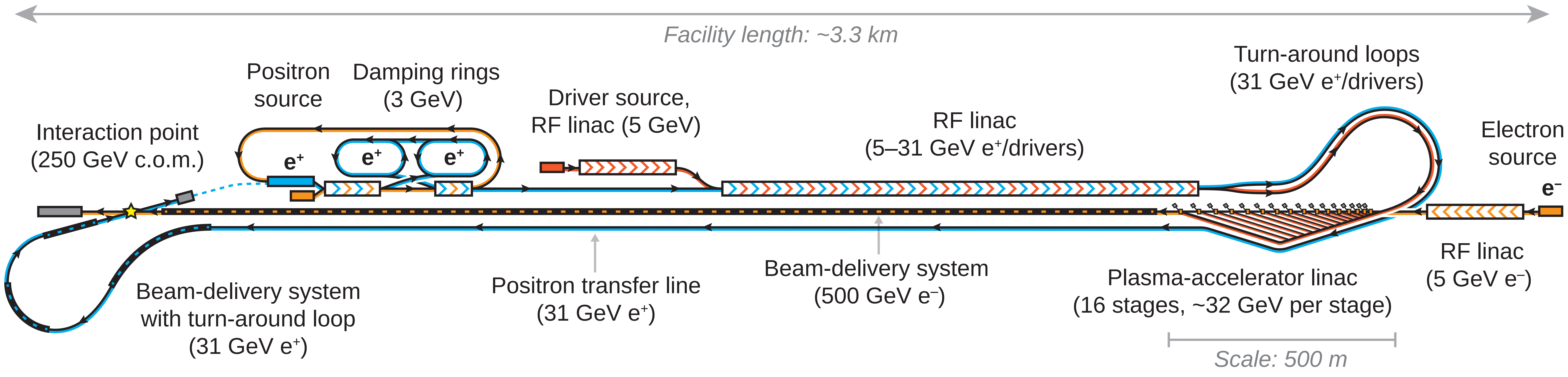
Foster, D'Arcy and Lindstrøm, New J. Phys. 25, 093037 (2023)

- Plasma accelerators have the potential to produce more compact/cheaper colliders
  - GV/m gradients demonstrated
  - Potential for high luminosity (100% charge coupling, beam-quality preservation, in-principle 10 MHz rates, etc.)
- Plasmas are not ideal for accelerating positrons due to the charge asymmetry of plasma ions and electrons
  - Currently no good regime known for accelerating positrons known (although some promising routes proposed)
- HALHF sidesteps this problem by avoiding positron acceleration in plasma
  - The most promising option at present (in terms of power efficiency) is to use electron-beam-driven plasma acceleration
  - Efforts made to future-proof the design for the sufficient maturation of laser technology
- Asymmetric beam energies minimise the footprint and cost
  - *Finding*: The more asymmetries (charge, emittance, energy), the better!

The HALHF concept

A brief reminder

> Plasma acc
  > GV/m
  > Potent
> Plasmas are
  > Curren
> HALHF side
  > The m … ation
  > Efforts made to future-proof the design for the sufficient maturation of laser technology



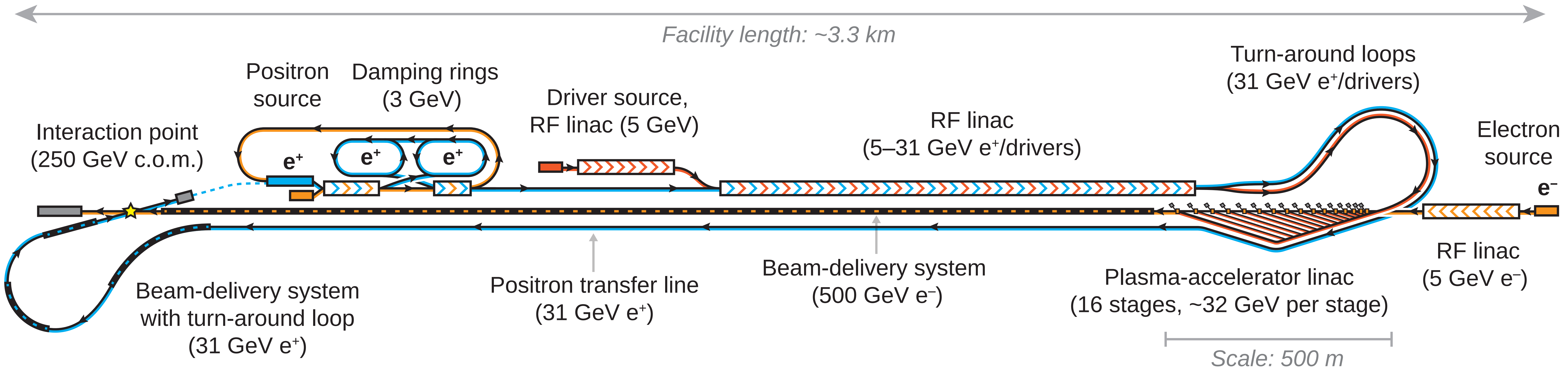
Source: **Foster, D'Arcy and Lindstrøm, New J. Phys. 25, 093037 (2023)**

> Asymmetric beam energies minimise the footprint and cost
  > *Finding*: The more asymmetries (charge, emittance, energy), the better!
> Potentially 4x smaller, cheaper, and greener than counterparts based solely on RF
> Fits in most major particle-physics laboratories

The HALHF concept

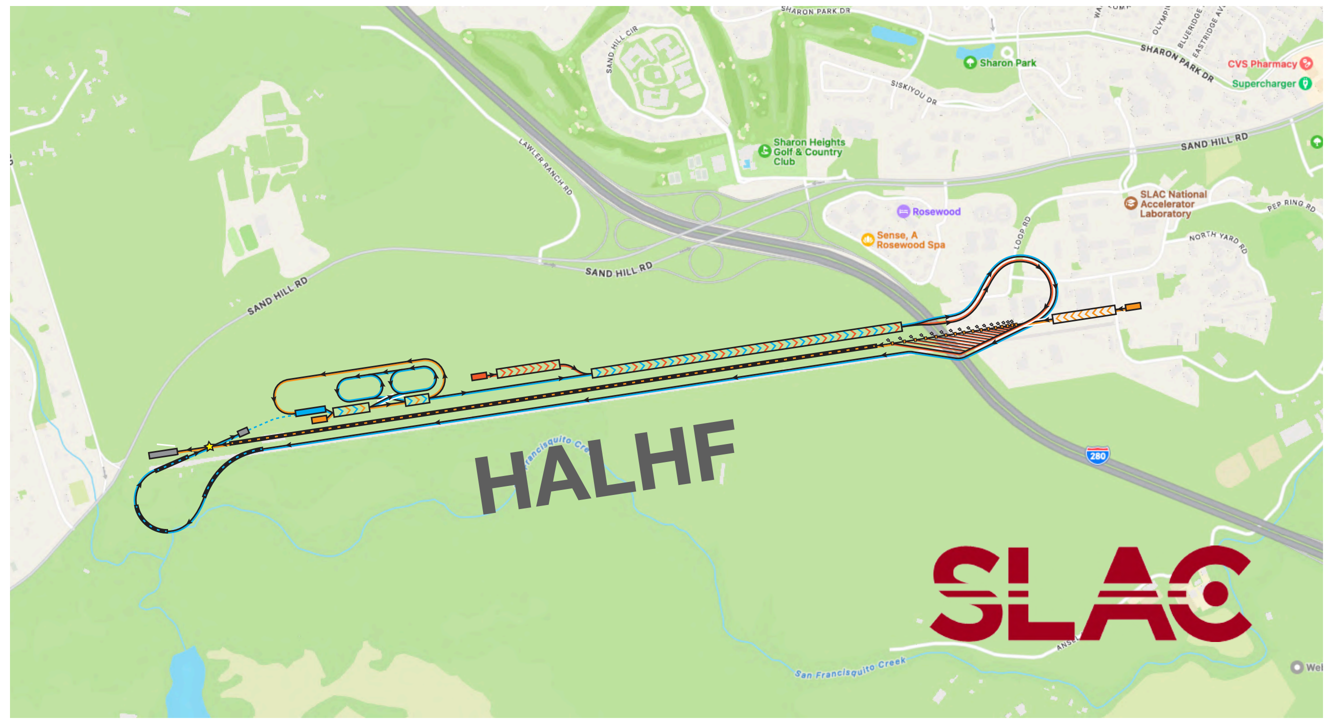
A brief reminder

- Plasma acc
  - GV/m
  - Potent
- Plasmas are
  - Curren
- HALHF side
  - The m … ation
  - Efforts made to future-proof the design for the sufficient maturation of laser technology



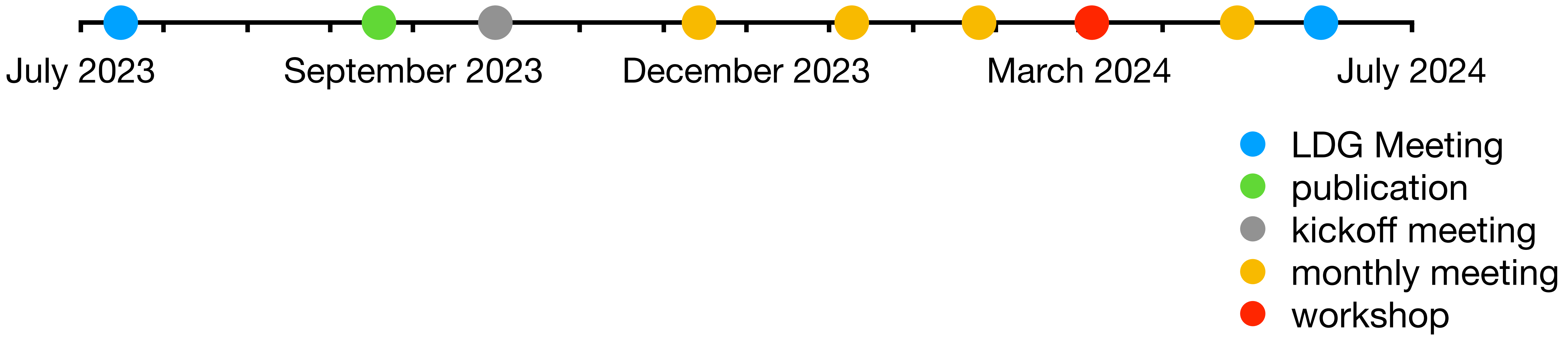
Source: **Foster, D'Arcy and Lindstrøm, New J. Phys. 25, 093037 (2023)**

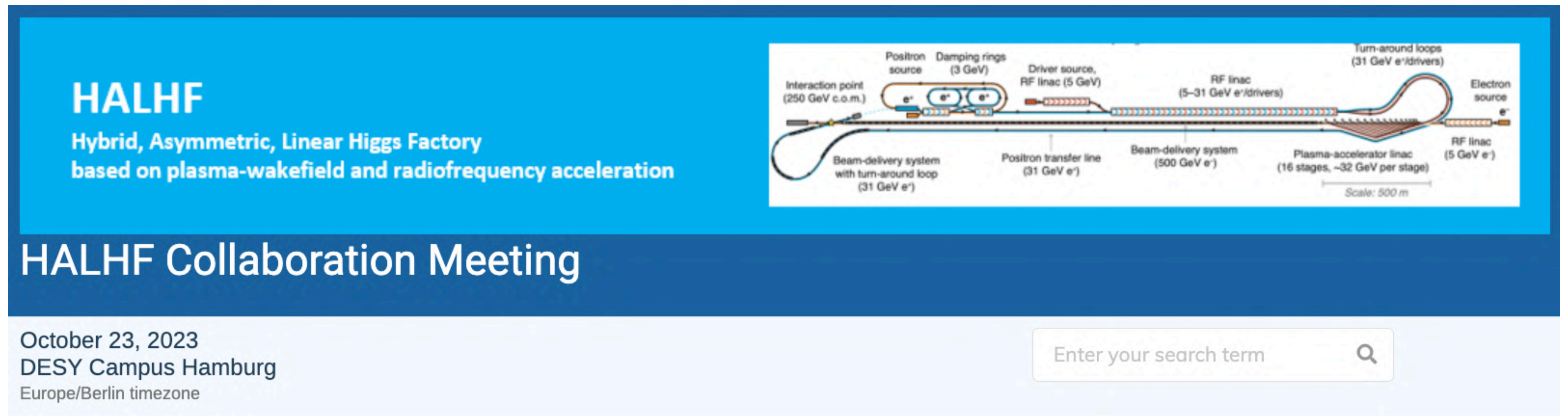
- Asymmetric beam energies minimise the footprint and cost
  - *Finding*: The more asymmetries (charge, emittance, energy), the better!
- Potentially 4x smaller, cheaper, and greener than counterparts based solely on RF
- Fits in most major particle-physics laboratories

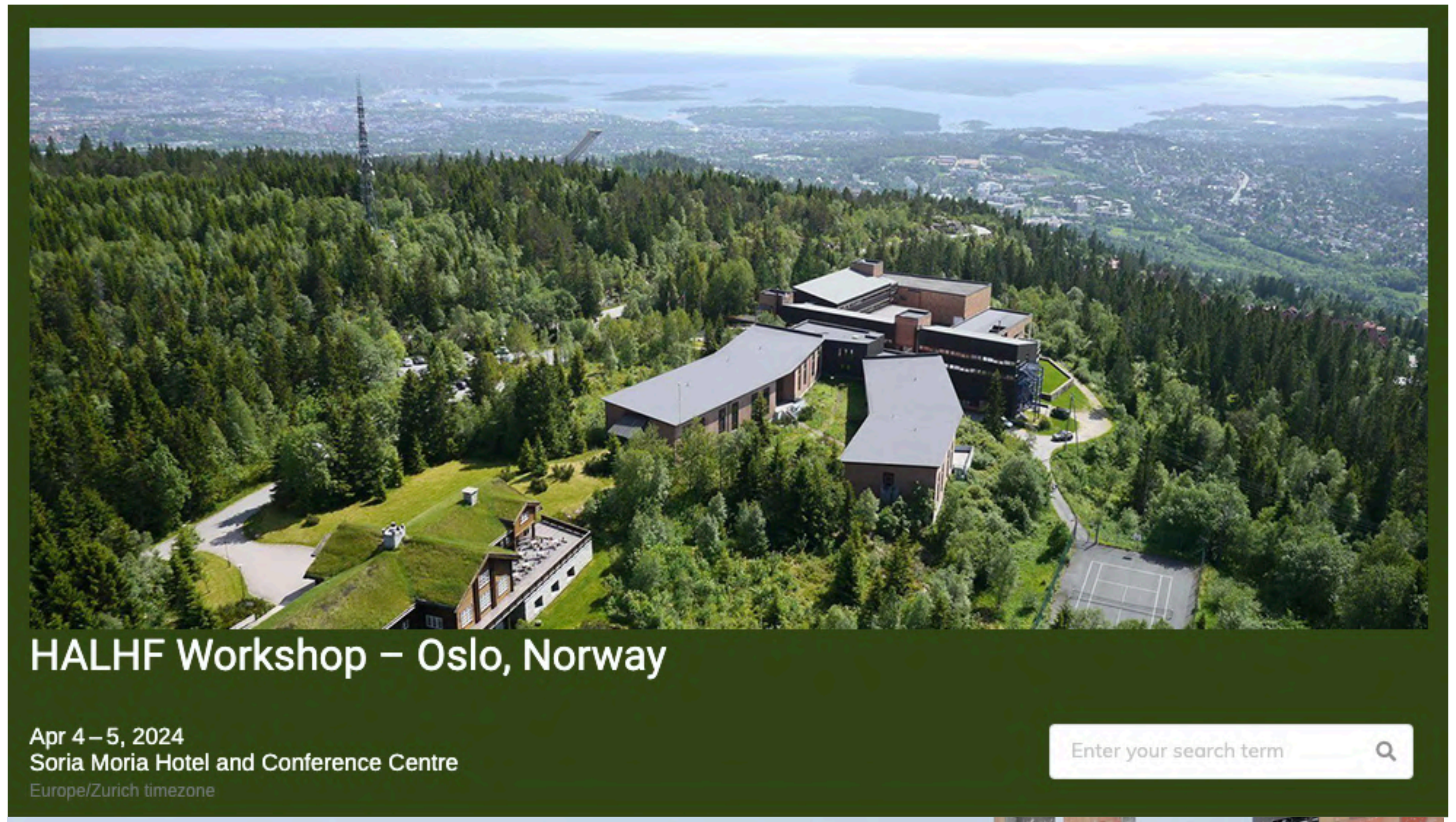


Forming the HALHF Collaboration

Active group of experts has been assembled to address challenges







- First report given at the LDG meeting (Frascati), Jul 2023
- Publication of the HALHF concept, Sept 2023:
  (B Foster *et al* 2023 *New J. Phys.* **25** 093037)
- HALHF kickoff meeting (DESY), Oct 2023
  - Attendance: ~50
- Monthly design meetings (online)
- HALHF Workshop (University of Oslo), Apr 2024
  - Attendance: ~30 (in-person + zoom)

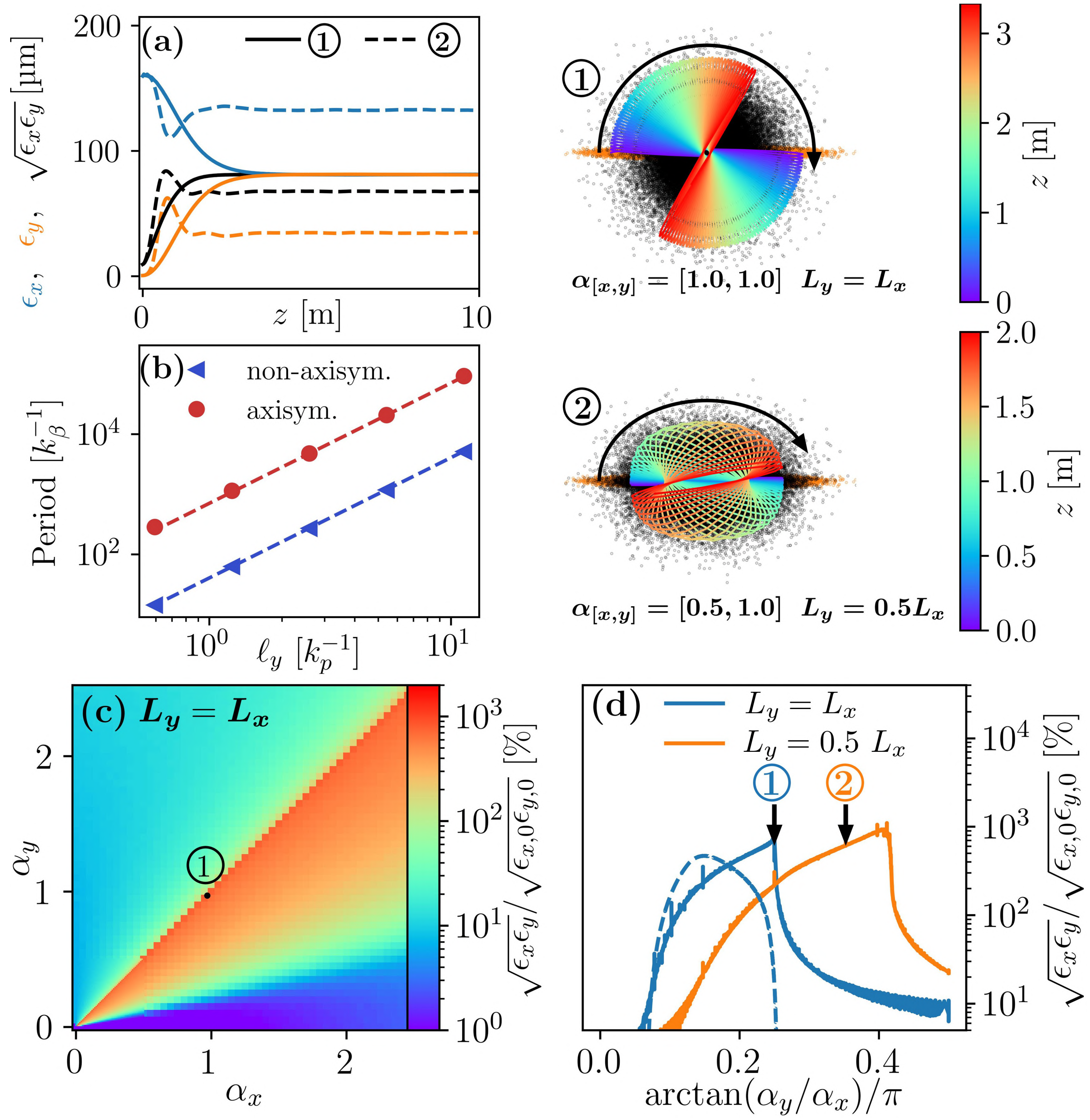
New findings and ongoing studies

Key questions to be answered toward a self-consistent design

Resonant emittance mixing in flat beams

A new issue (but also solution) discovered

- New finding by S. Diederichs, M. Thévenet *et al.*
- If plasma ions move (even slightly), the nonlinear focusing mixes emittances between x/y planes.
  - *Implication: Flat beams don't stay flat.*
  - *Applies to all plasma-based accelerators, not just HALHF.*
- Proposed solution:
  - *Use an asymmetric electron driver (flat in the opposite direction) to detune x/y oscillations.*
  - *This appears to work for HALHF parameters.*

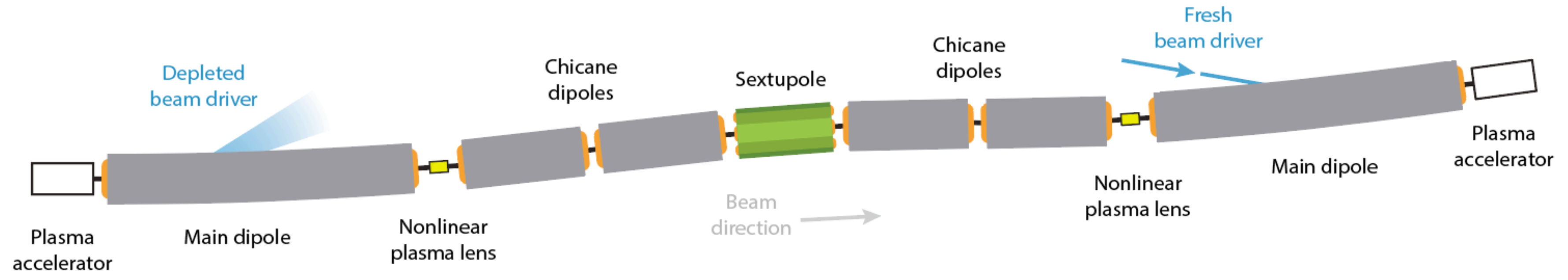


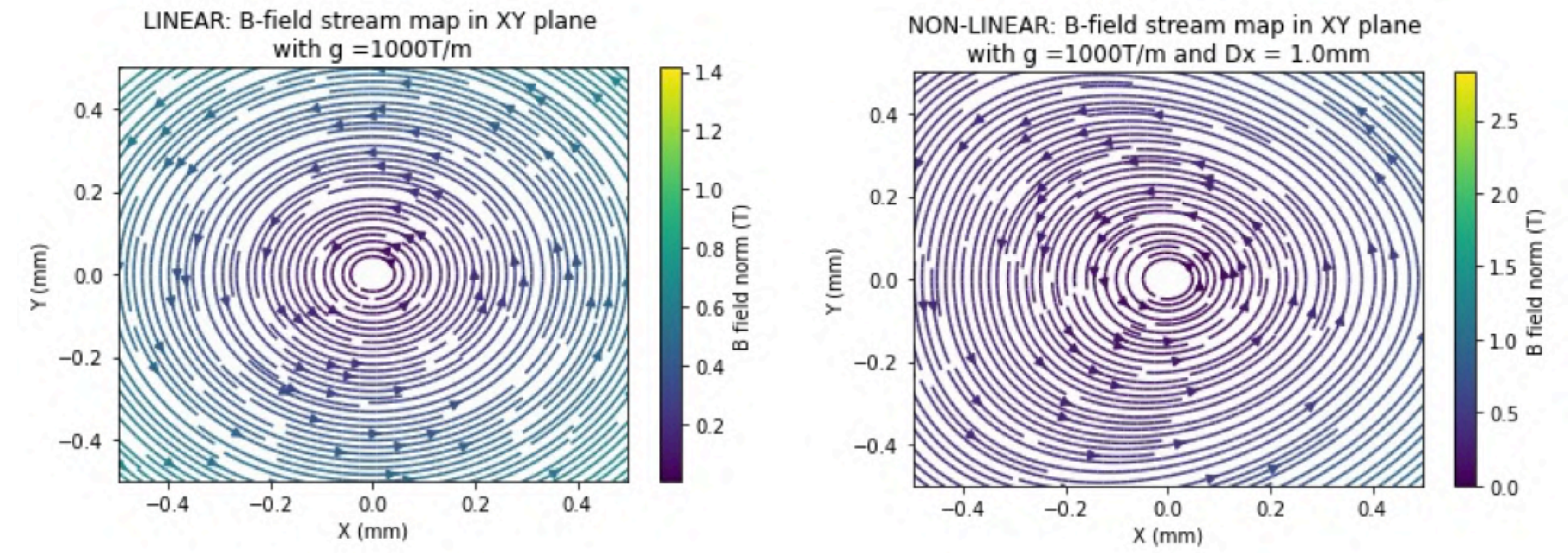
Source: Diederichs et al., preprint arXiv:2403.05871 (2024)

Staging, transverse instabilities, radiation reaction

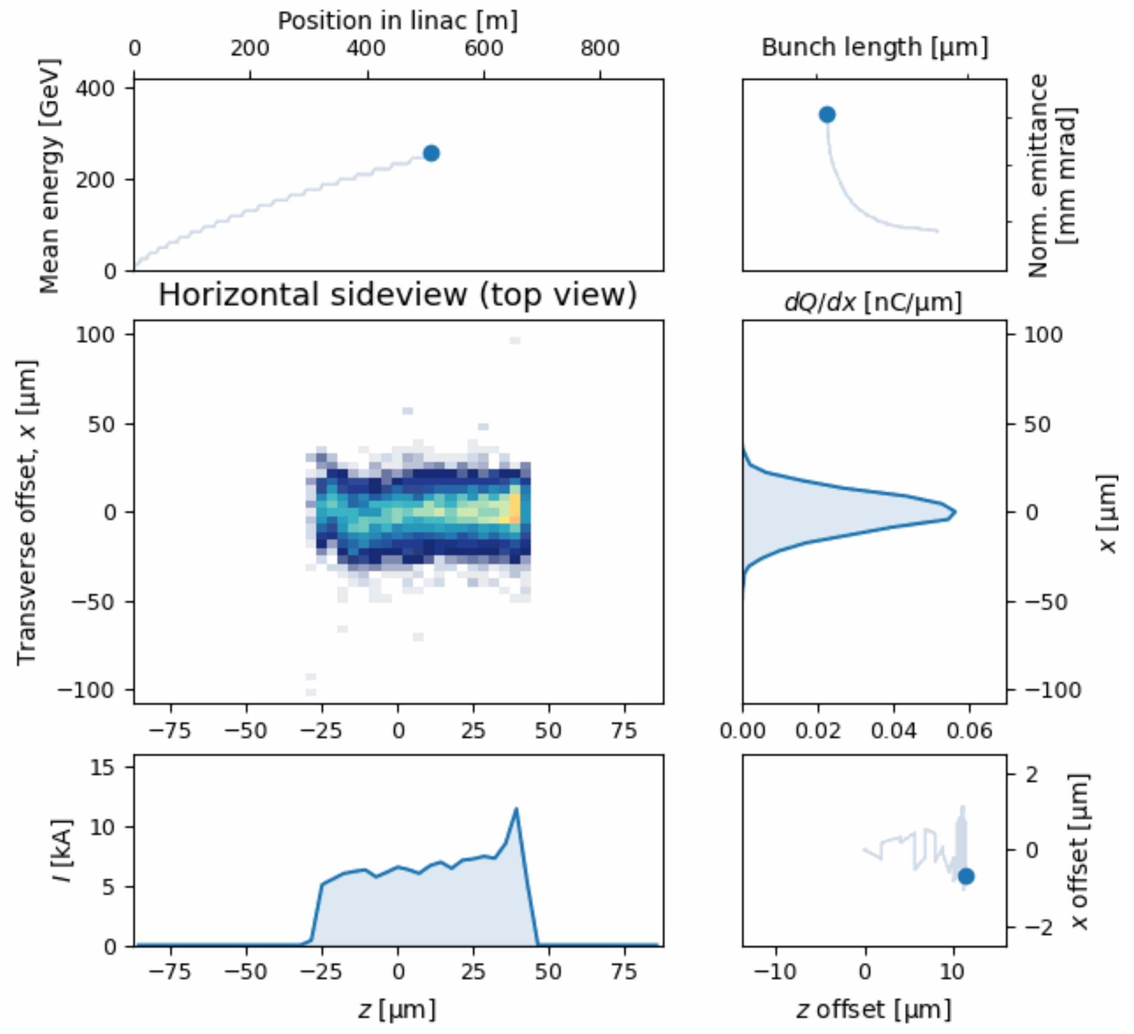
Plasma-accelerator challenges under investigation

- Staging: Requires achromatic transport line between plasma stages—use nonlinear plasma lenses.
  - *The SPARTA ERC project started Jan 2024.*
  - *Rapid progress on demonstrating a nonlinear plasma lens: MHD simulations are promising, hardware being manufactured (P. Drobniak)*
- Transverse instabilities appear to be under control when introducing some ion motion (B. Chen).
- Synchrotron radiation from plasma focusing introduces an energy spread at final HALHF stages
  - *Not an issue at lower plasma density (D. Kalvik)*





B-fields in nonlinear plasma lens. Credit: P. Drobniak

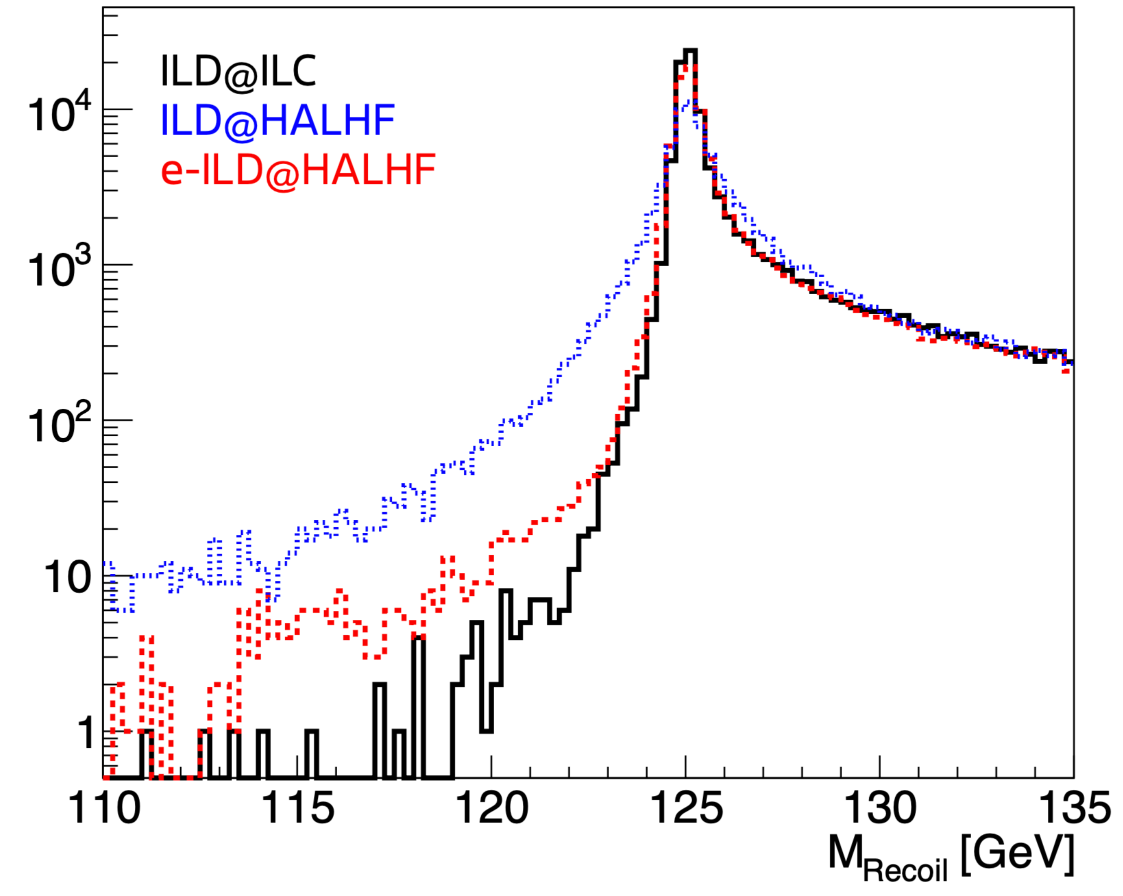


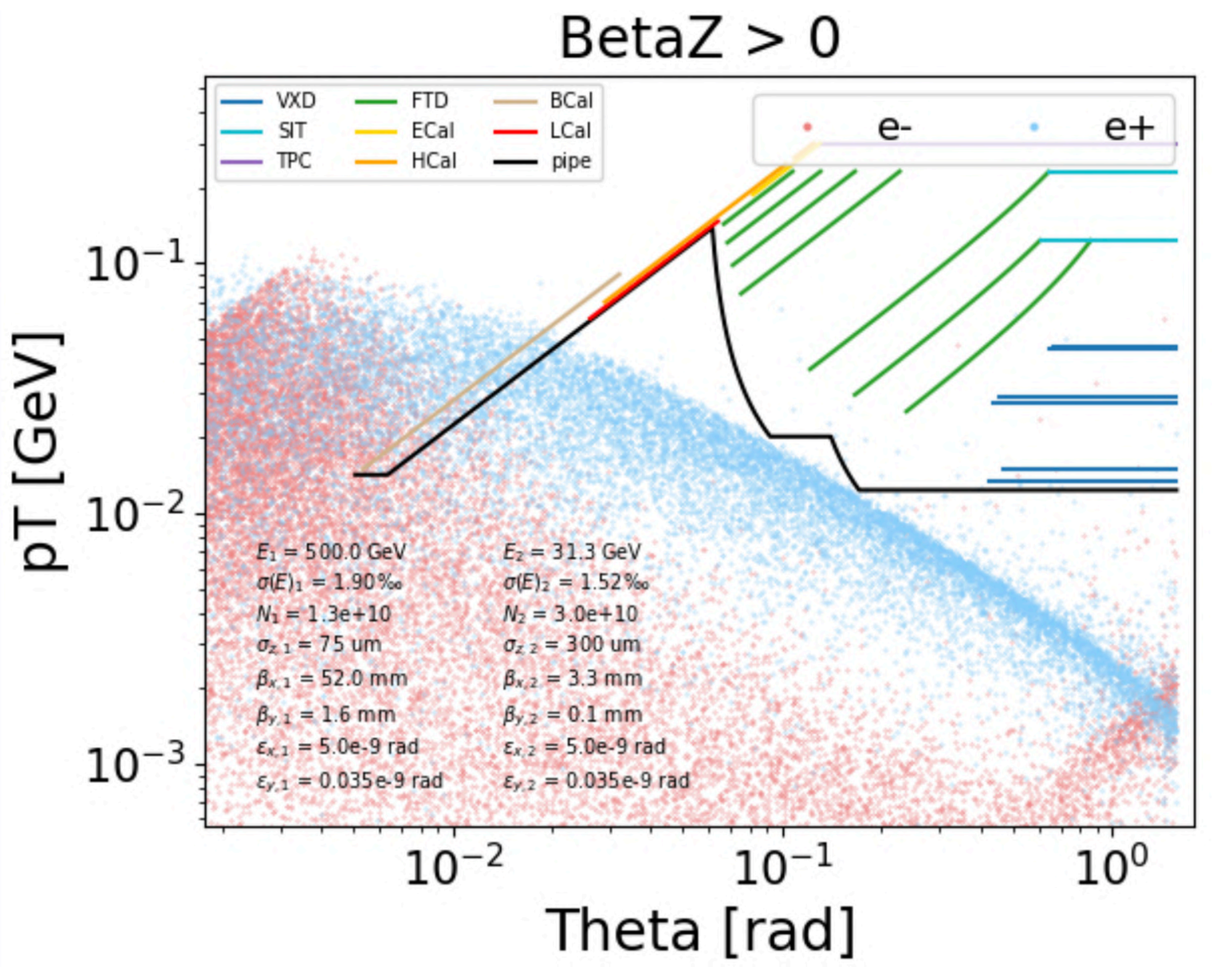
Animation by Ben Chen.

Asymmetric detectors, polarization, positron source, etc.

Work in progress

- Preliminary asymmetric detector studies (J. List, A. Laudrain):
  - *The energy asymmetry does not appear to be problematic*
  - *Reducing the positron peak current reduces the important coherent-pair background*
- Currently unclear if spin polarization can be preserved in the plasma linac (future work; K. Põder *et al.*).
- Positron polarisation can be preserved in linac and important tool for physics:
  - *Can likely integrate an ILC-like undulator system in the high-energy electron BDS (G. Moortgat-Pick)*
- High-energy turnarounds have too much radiation—increase radius



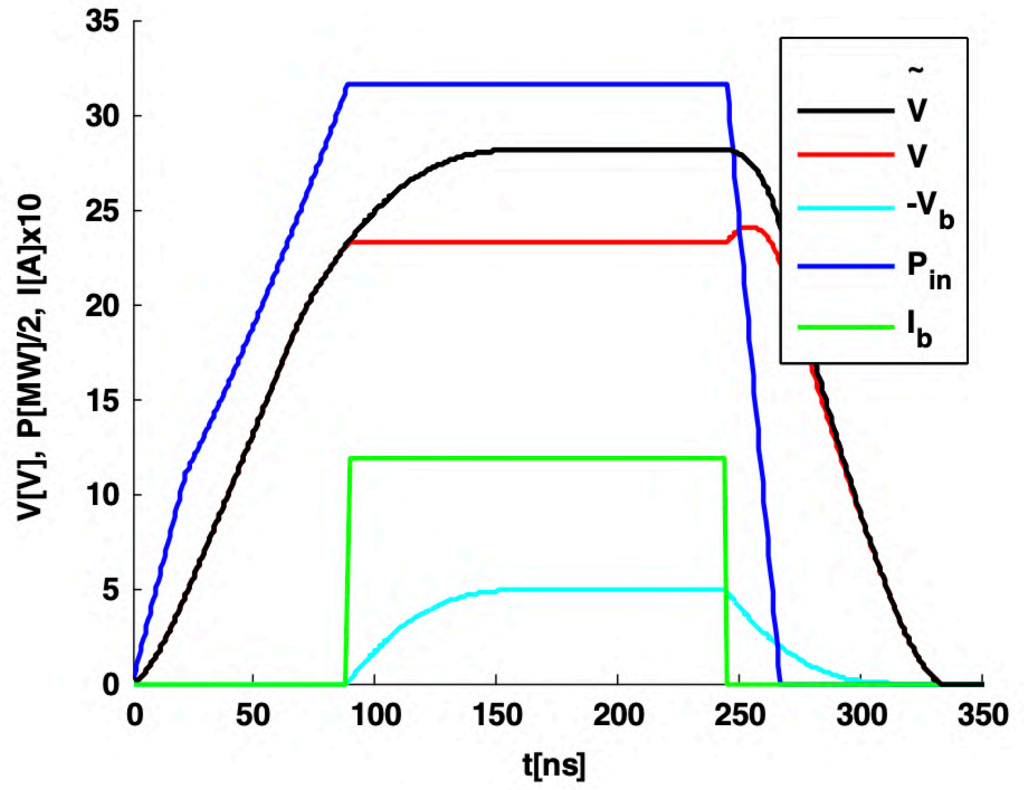


Detector simulations by A. Laudrain, J. List, *et al.*

Open question: choice of RF technology

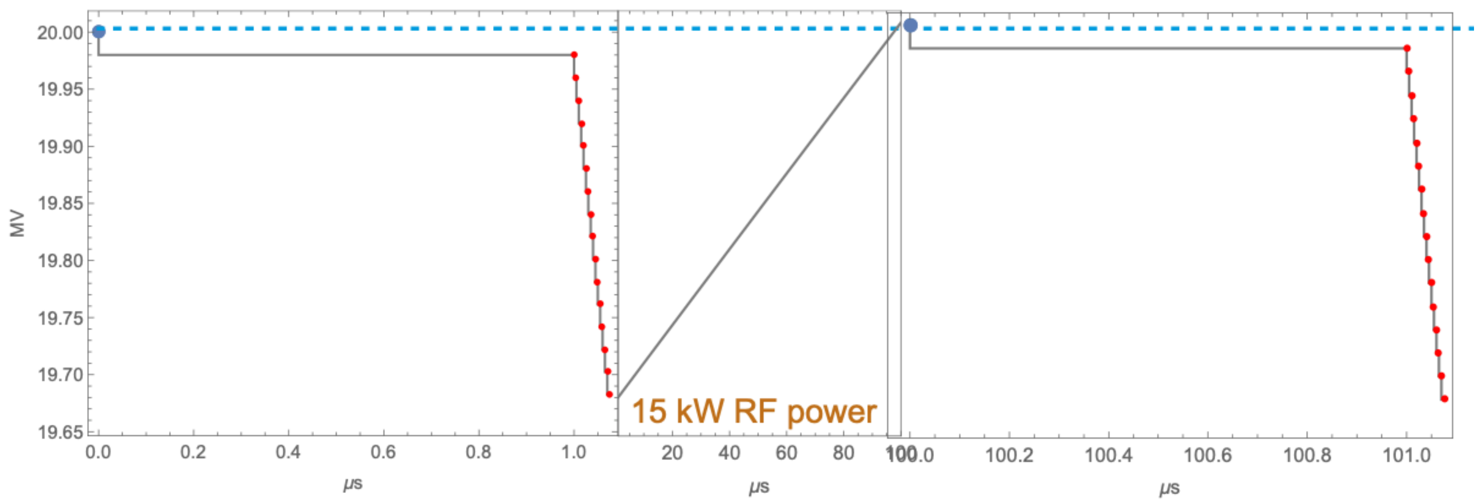
Normal-conducting vs. super-conducting RF linacs

- Normal-conducting (CLIC-like) is the nominal solution:
  - *Multi-bunch wakefield effects place limits on the RF frequency: ~2 GHz or less (B. List)*
  - *Single-bunch beam loading effects indicate a need for longer electron drivers: ~150 µm rms or more (B. List).*
  - *Working on simulating realistic RF structures (K. Sjøbæk)*



Structure optimization framework
Source: Lunin et al. PRSTAB (2011)

- Super-conducting RF option may also be viable (N. Walker):
  - *The bunch pattern is crucial*
  - *Issue of voltage changing between drive bunches can potentially be solved by optimized phasing*



Loss of voltage in SRF cavity from beam loading.
Credit: N. Walker

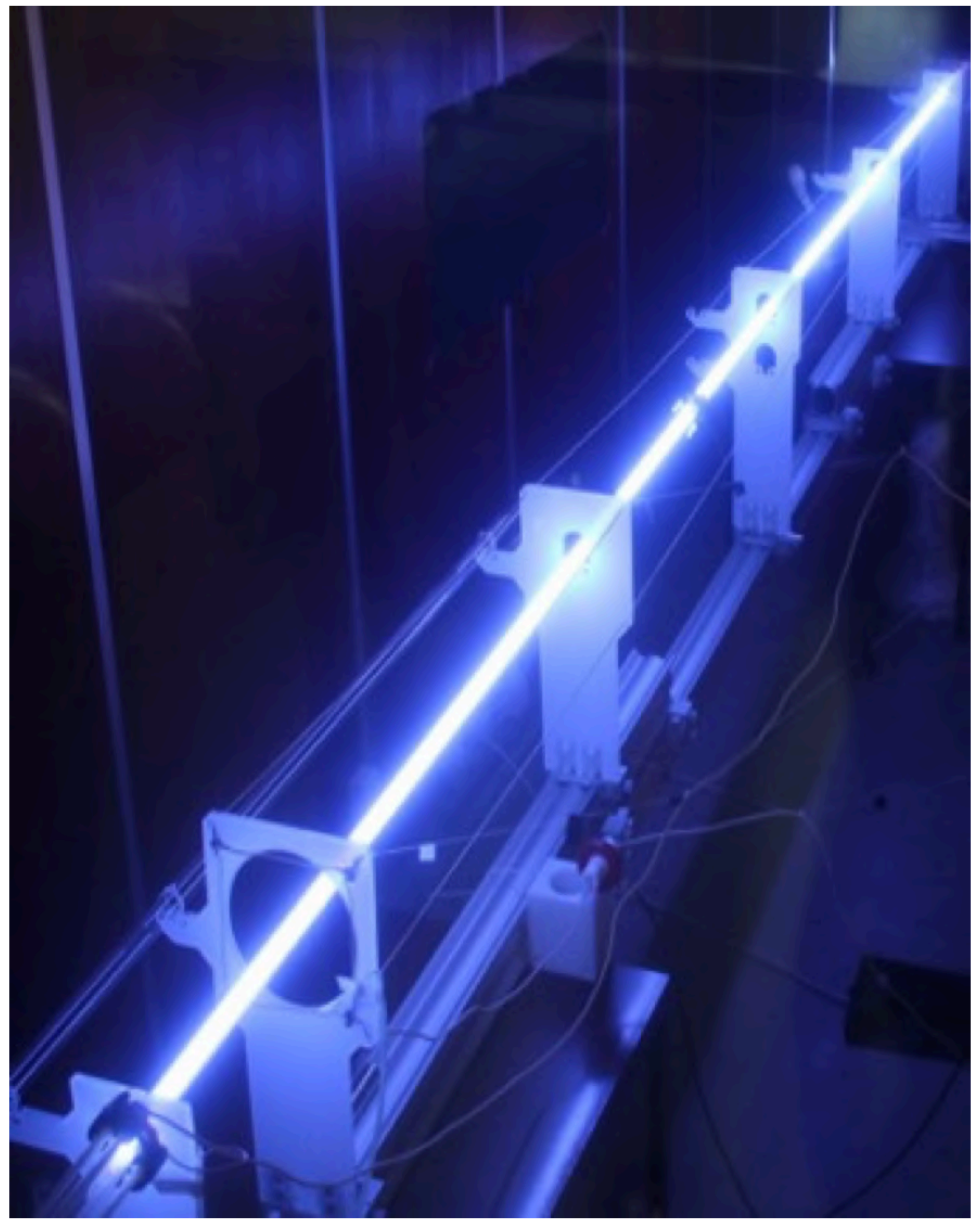
Toward HALHF 2.0

Making a self-consistent and cost-minimised design

Possible baseline changes

New baseline based on lessons learned (general trends—numbers not yet optimized)

- Lower plasma density in the plasma stages (7×10^{15} cm^{-3} ➝ ~6×10^{14} cm^{-3})
  - *Lower gradient (6.4 ➝ ~1.5 GV/m), with little effect on overall collider cost*
  - *Reduced cooling requirements (90 ➝ ~45 kW/m)*
  - *Longer bunches and improved alignment and timing tolerances (~3x), avoids beam-ionisation of plasma*
  - *Synergy: the required plasma cells are very similar to AWAKE cell*
- Fewer positrons (4×10^{10} ➝ ~2×10^{10} e^+)
  - *ILC-like positron source design can be assumed*
  - *Fewer issues with beam-strahlung at IP*
  - *Increased repetition rate can compensate for luminosity loss*
- Two separate linacs (straight geometry)

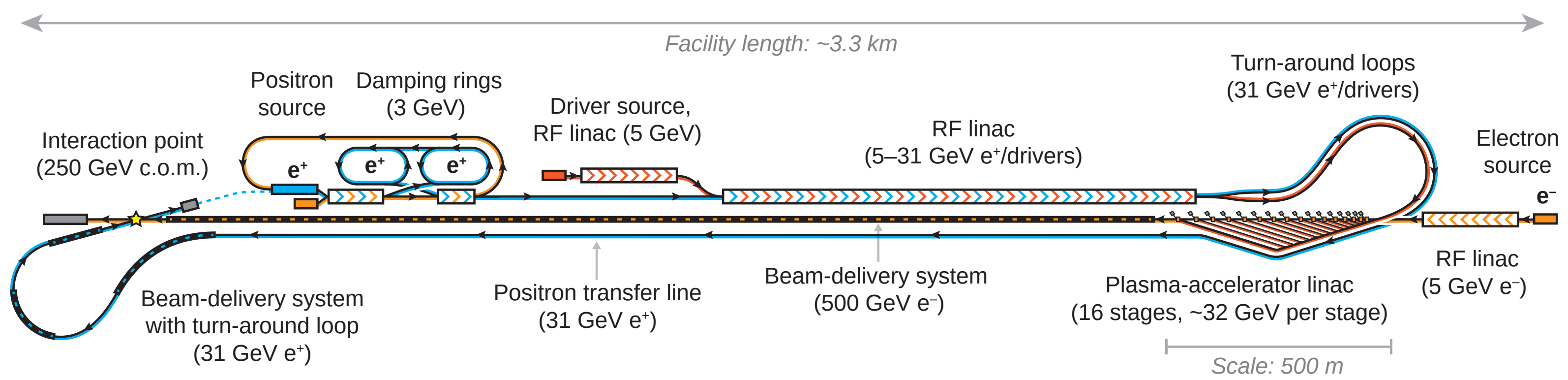


Long plasma cell at AWAKE.
Image credit: AWAKE

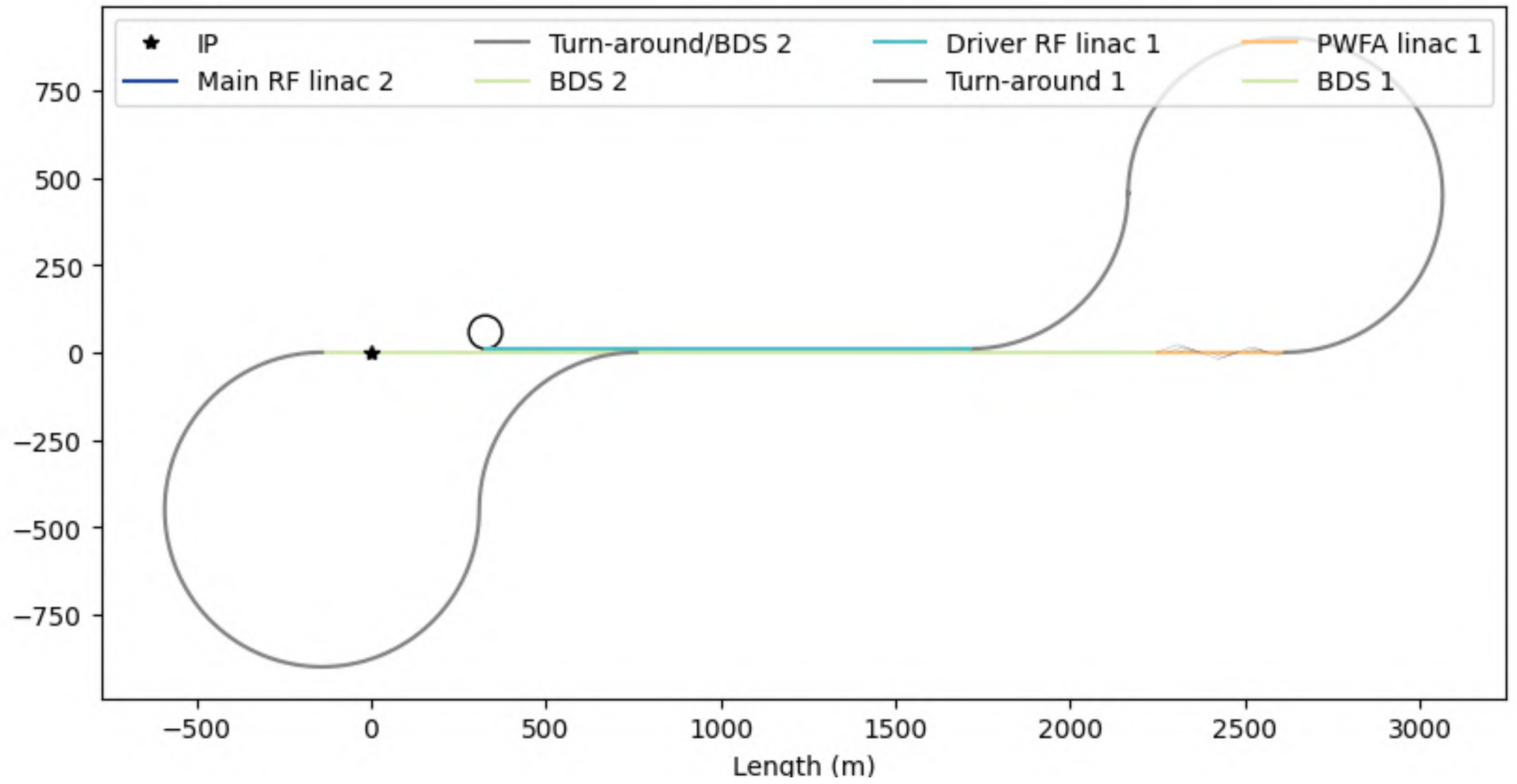
Possible geometry change

Combined-function or separate RF linacs?

- Realistic turnarounds with minimal radiation losses are longer: *expensive!*
- The combined-function RF linac is both high-power and high-voltage: *expensive!*
- Benefits of separate linacs motivate evaluation of costs:
  - *Individually optimized power/voltage*
  - *Can have different driver and e+ energies (flexible PWFA design)*
  - *No high-energy turnarounds*



Baseline (turn-arounds too small)



Re-calculated baseline (correct turn-arounds)

New geometry (keeping a driver turn-around)

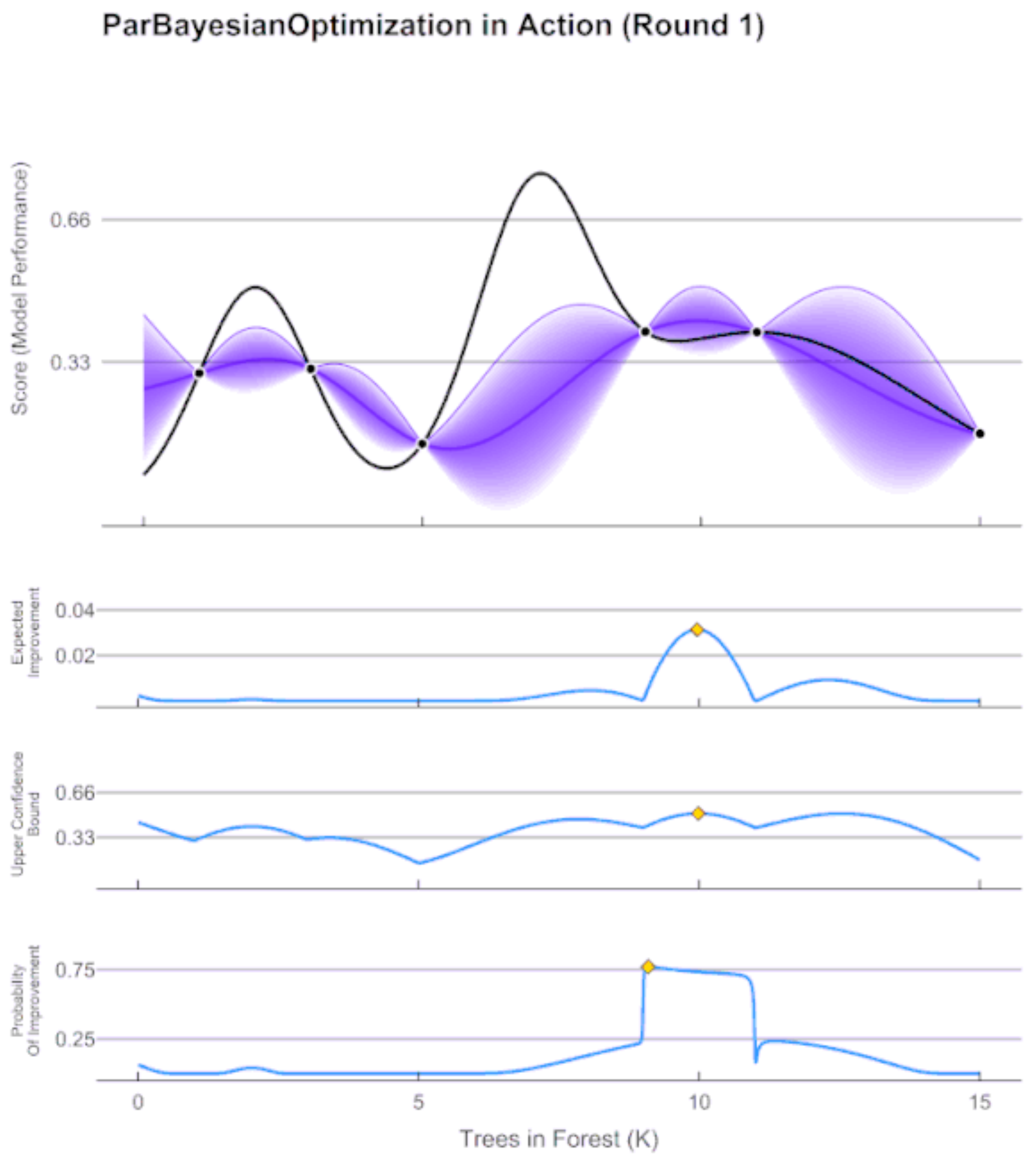
New geometry (no driver turn-around)

Cost modelling and Bayesian optimization

Using machine learning to design a cost-effective collider

- Framework implemented to parametrize the cost of all subsystems, civil engineering, overheads, power etc.
- Using Bayesian optimization for quickly locating the global optimum in large parameter space (~8 or more variables)
- What exactly should we optimize for?
  - **Full programme cost = (construction cost) + (overheads) + (energy cost for collecting the required data) + (maintenance cost for full period)**
  - *Can add a carbon tax (125–800 \$/ton CO_2e) to take into account greenhouse gas emissions.*
- The goal is *not* mainly to estimate the collider cost, but to *optimally balance* the relative cost of different subsystems.

Repository: https://github.com/carlandreaslindstrom/ColliderCostModel/tree/main

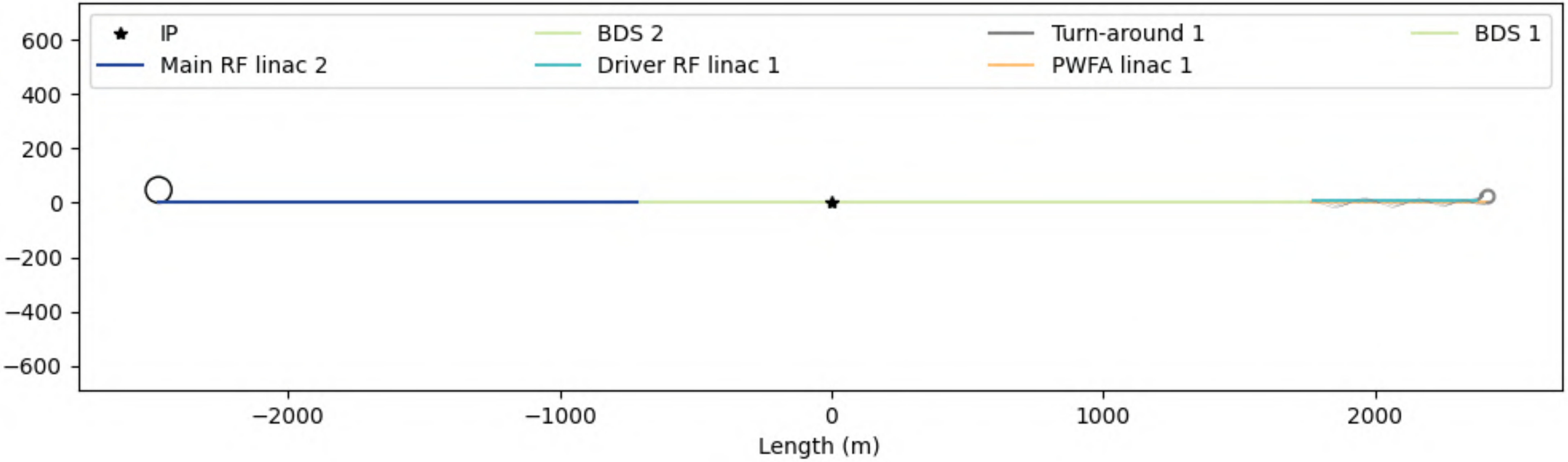


Example of a cost-minimised design (250 GeV)

For illustration only—further improvements in accuracy expected

```
>> Total construction cost        = 1 cost unit
>> ITF cost (excl. run costs)     = 1.52 cost units
>> Full programme cost (0.9/ab)   = 2.15 cost units
>> Full programme cost + CO2 tax  = 2.21 cost units
```

```
>> Geometric luminosity           = 4.5e+33 cm^-2 s^-1
>> Collider wall-plug power       = 82.4 MW
>> Collider length (end-to-end)   = 4.9 km
>> Emissions                      = 207 kton CO2e
```



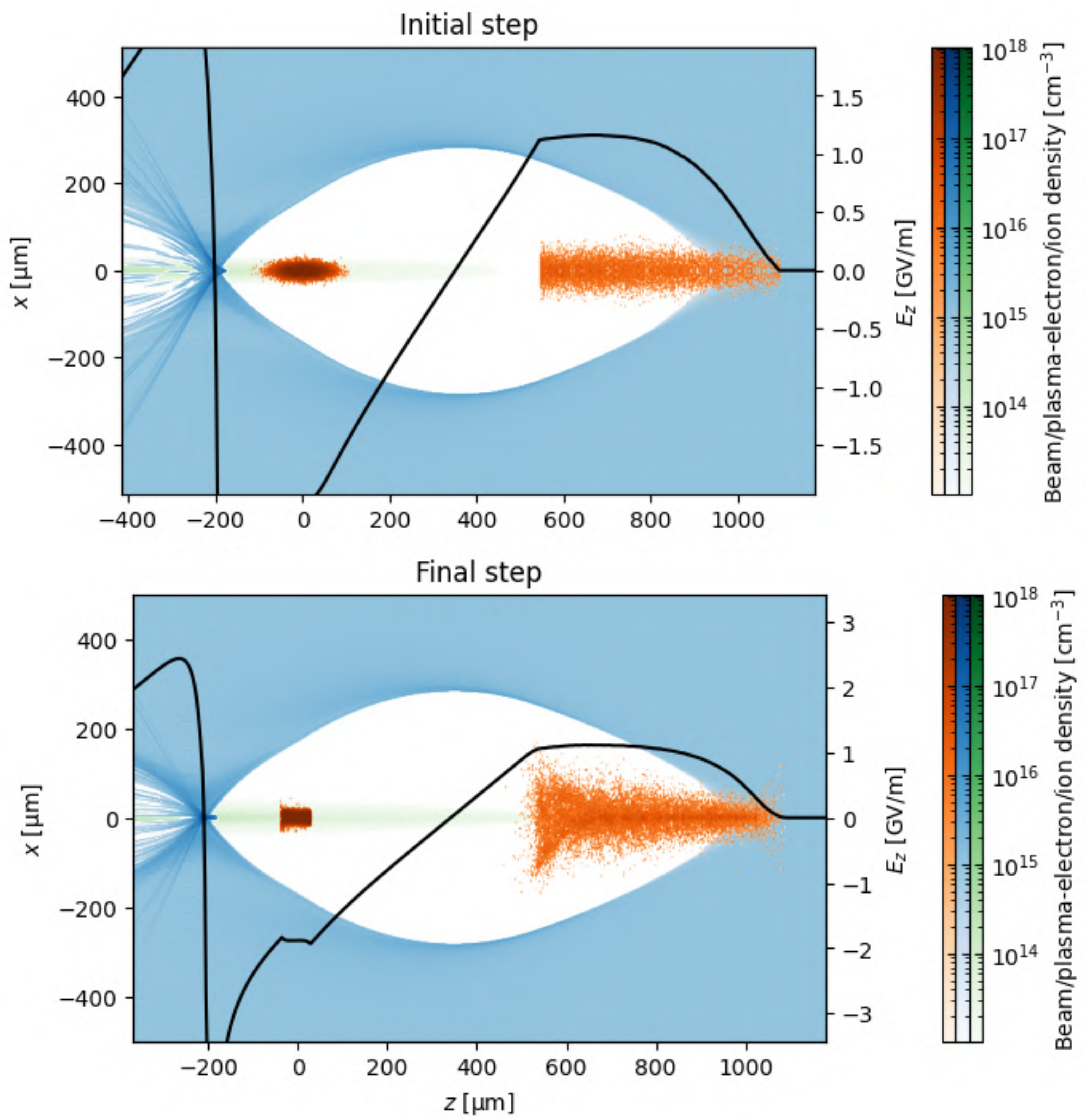
Disclaimer: take exact costs/lengths with a pinch of salt

1 cost unit ≈ construction cost as estimated in the original proposal.
The absolute value varies with inputs and cost estimates (to be consolidated)

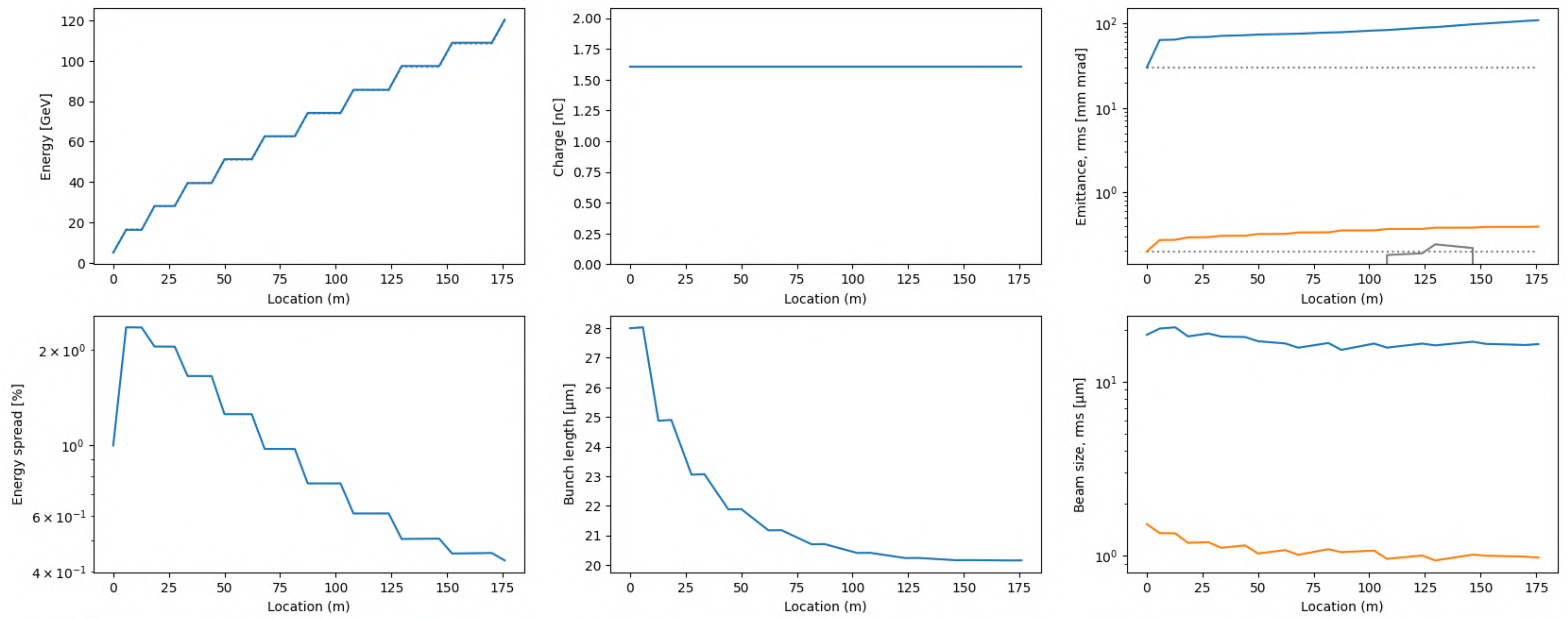
Preliminary self-consistent simulations of the plasma linac

Incorporating all the findings

- Full-scale simulation (HiPACE++ and ELEGANT) of 40% of the plasma linac (10 stages)
- Includes (nearly) all physics effects, as well as timing and alignment jitters



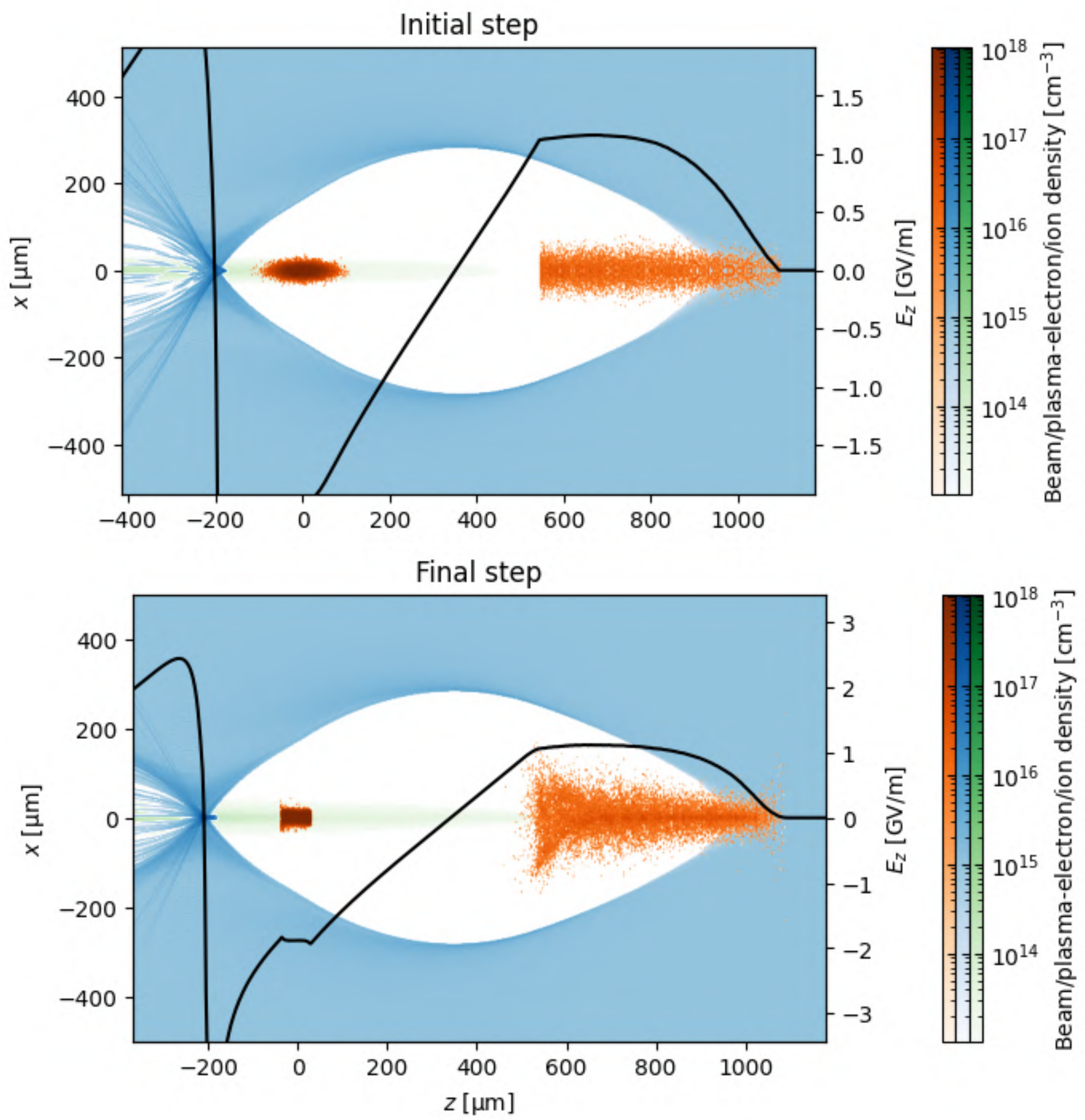
Beam parameter evolution (from 5 to 120 GeV)

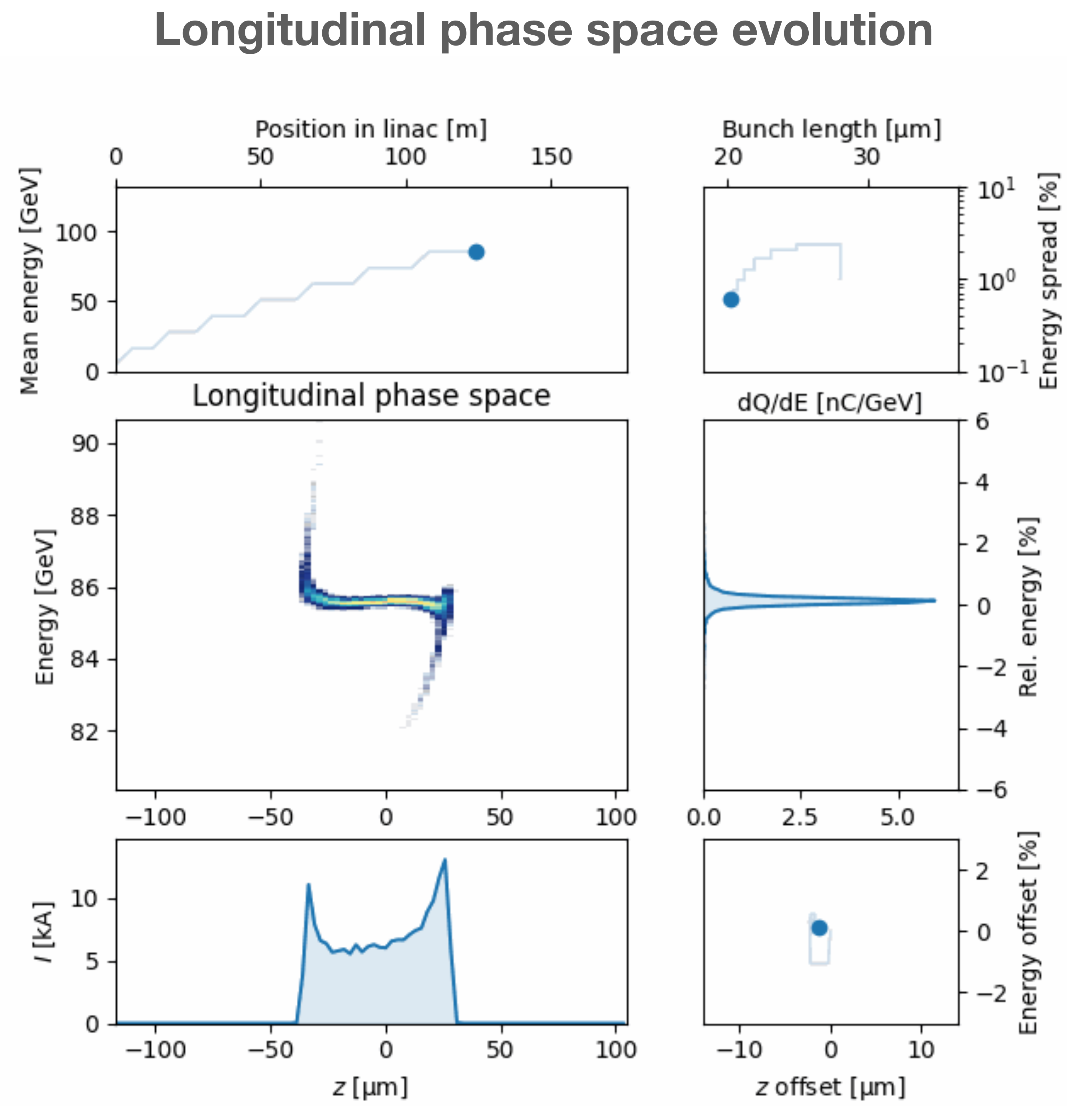


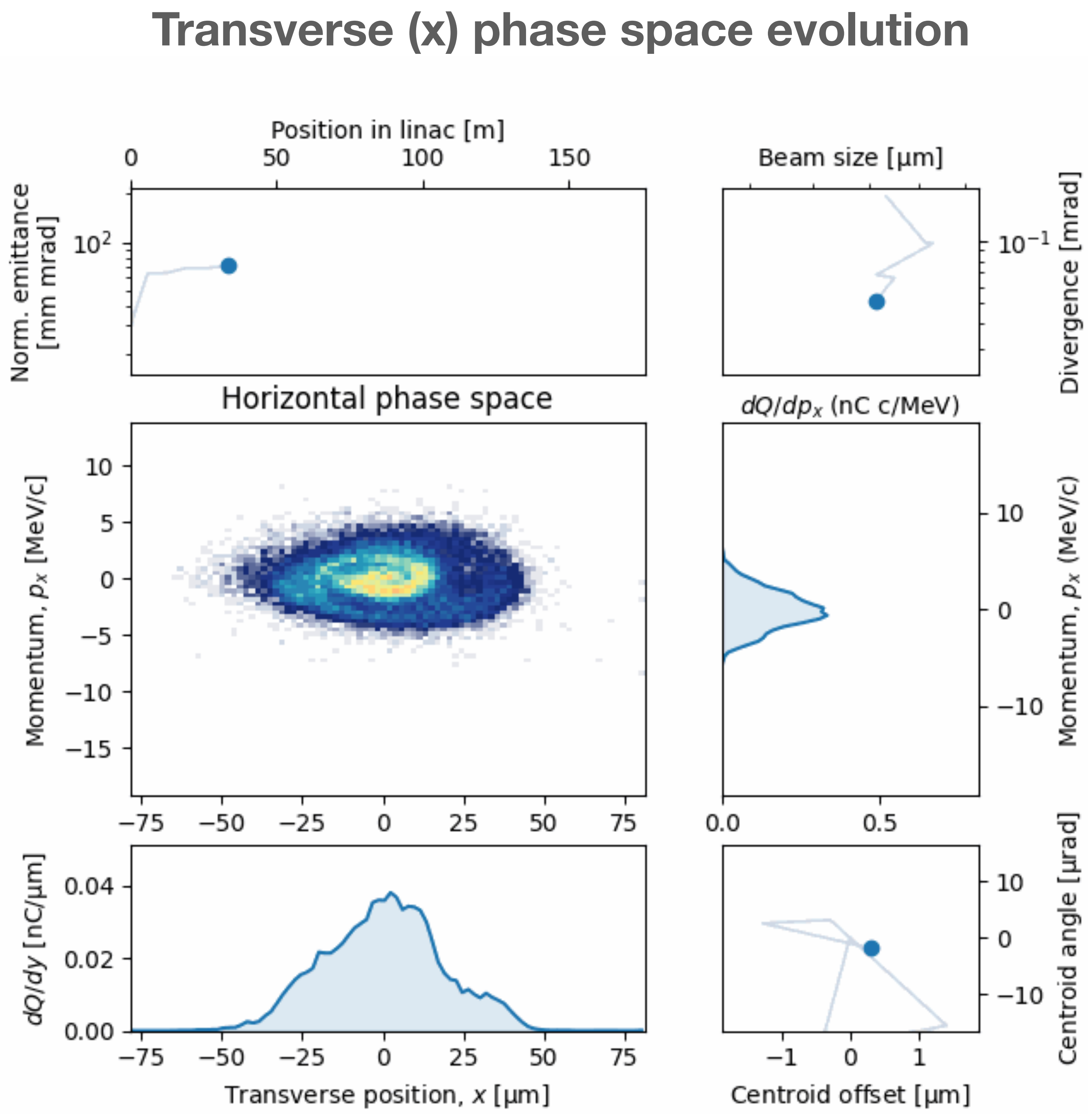
Preliminary self-consistent simulations of the plasma linac

Incorporating all the findings

- Full-scale simulation (HiPACE++ and ELEGANT) of 40% of the plasma linac (10 stages)
- Includes (nearly) all physics effects, as well as timing and alignment jitters







Upgrade paths

Toward higher energies, energy-booster option

380 GeV, 550 GeV and beyond?

How does the length and cost scale with energy?

> Higgs-physics motivations for higher energies:

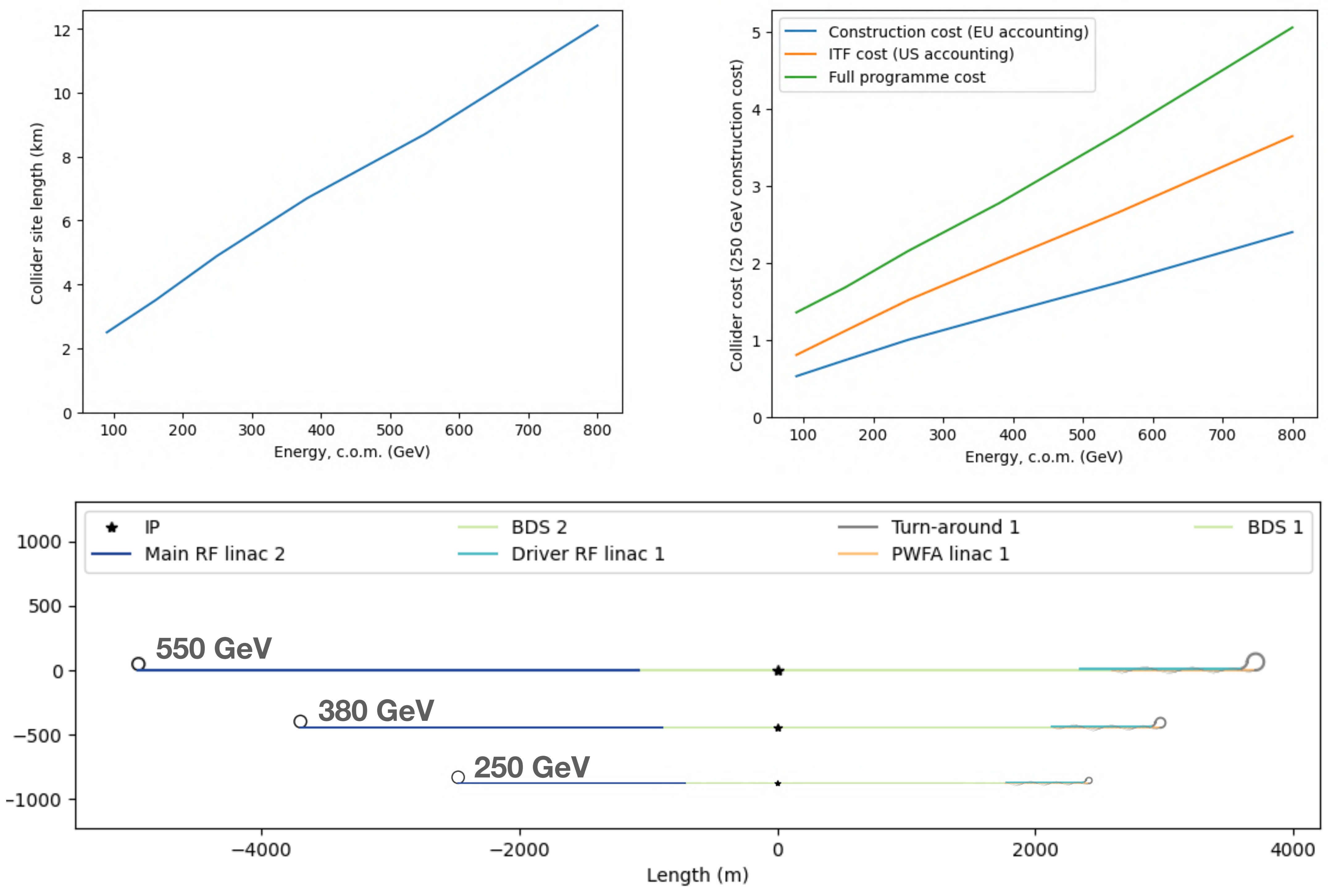
Energy c.o.m. (GeV)	***Length (km)***	***EU / US / Full Programme Cost (norm. cost units)***
250 (HZ)	4.9	1 / 1.5 / 2.2
380 (ttbar)	6.7	1.3 / 2.0 / 2.8
550 (HHH)	8.7	1.7 / 2.7 / 3.7
800	12.1	2.4 / 3.6 / 5.1

> Can also reach 10 TeV-scale as a γ–γ collider using two e⁻ beams and similar PWFA linacs.

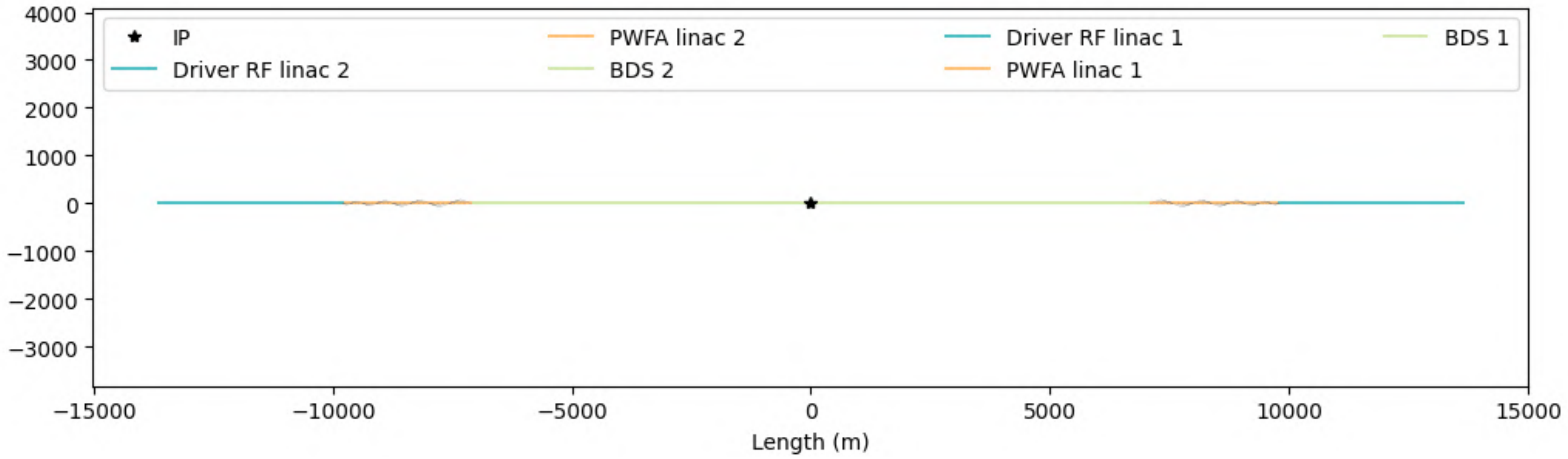
> *Estimated length: ~27 km (BDS is~14 km)*

> *Luminosity and cost is difficult to estimate due to unknowns in gamma conversion (should not be scaled from HALHF).*

Electron–positron collider



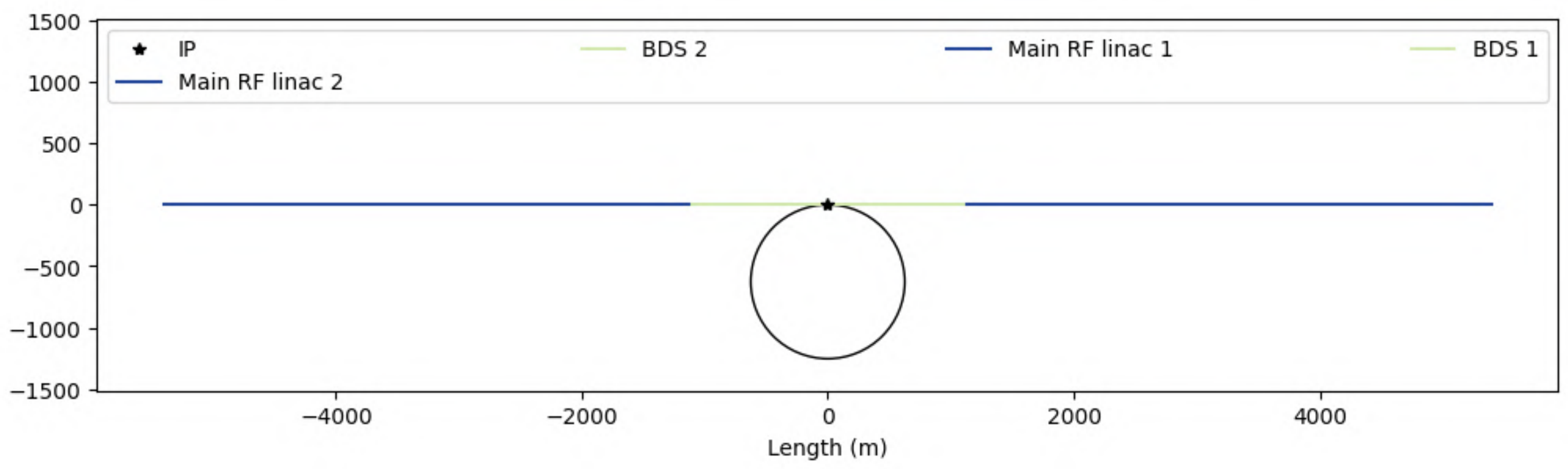
Gamma–gamma collider



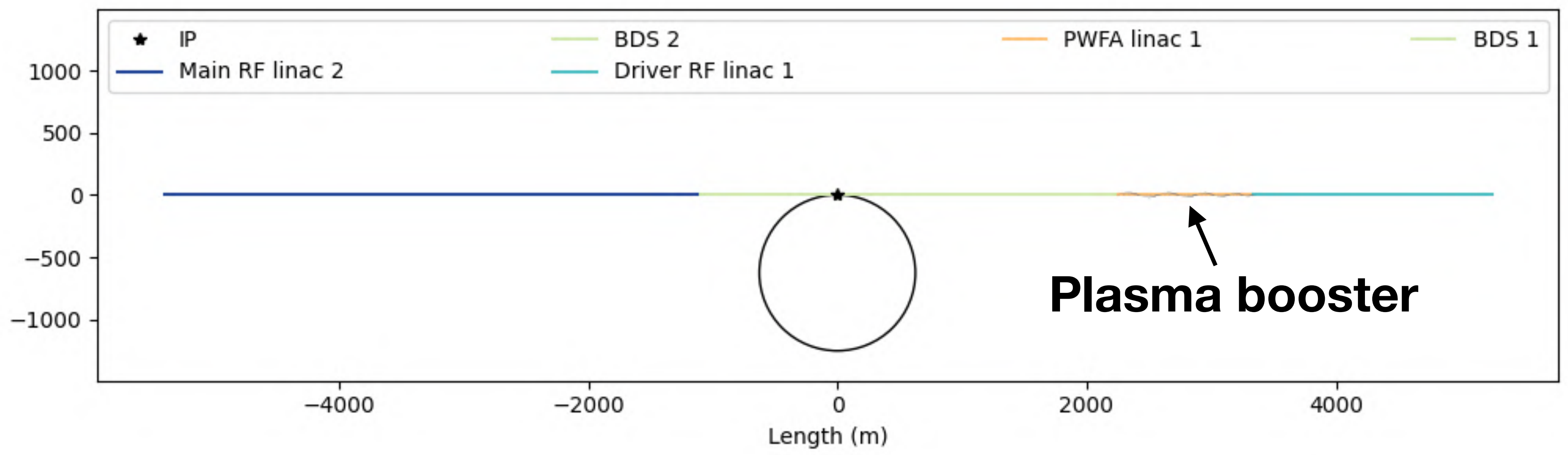
Alternative: HALHF as an energy booster

A cost-effective increase in energy reach of an existing linear collider

- New take on the "plasma afterburner" (anno ~2000):
  - *Proposed by B. List*
  - *Operate positron arm as before, but electron arm as driver linac with higher current, lower voltage (e.g., 32× bunches at 10% energy)*
  - *e.g. 125/500 GeV e^+/e^- gives 500 GeV c.o.m.*
- Additional cost of order ~10% only (for adding a plasma linac, more RF power/klystrons)
- Added difficulty compared to green-field HALHF:
  - *Reduced benefit from asymmetry: requires lower emittance in the PWFA (only factor 2 higher).*



Starting point: ILC-like collider at 250 GeV



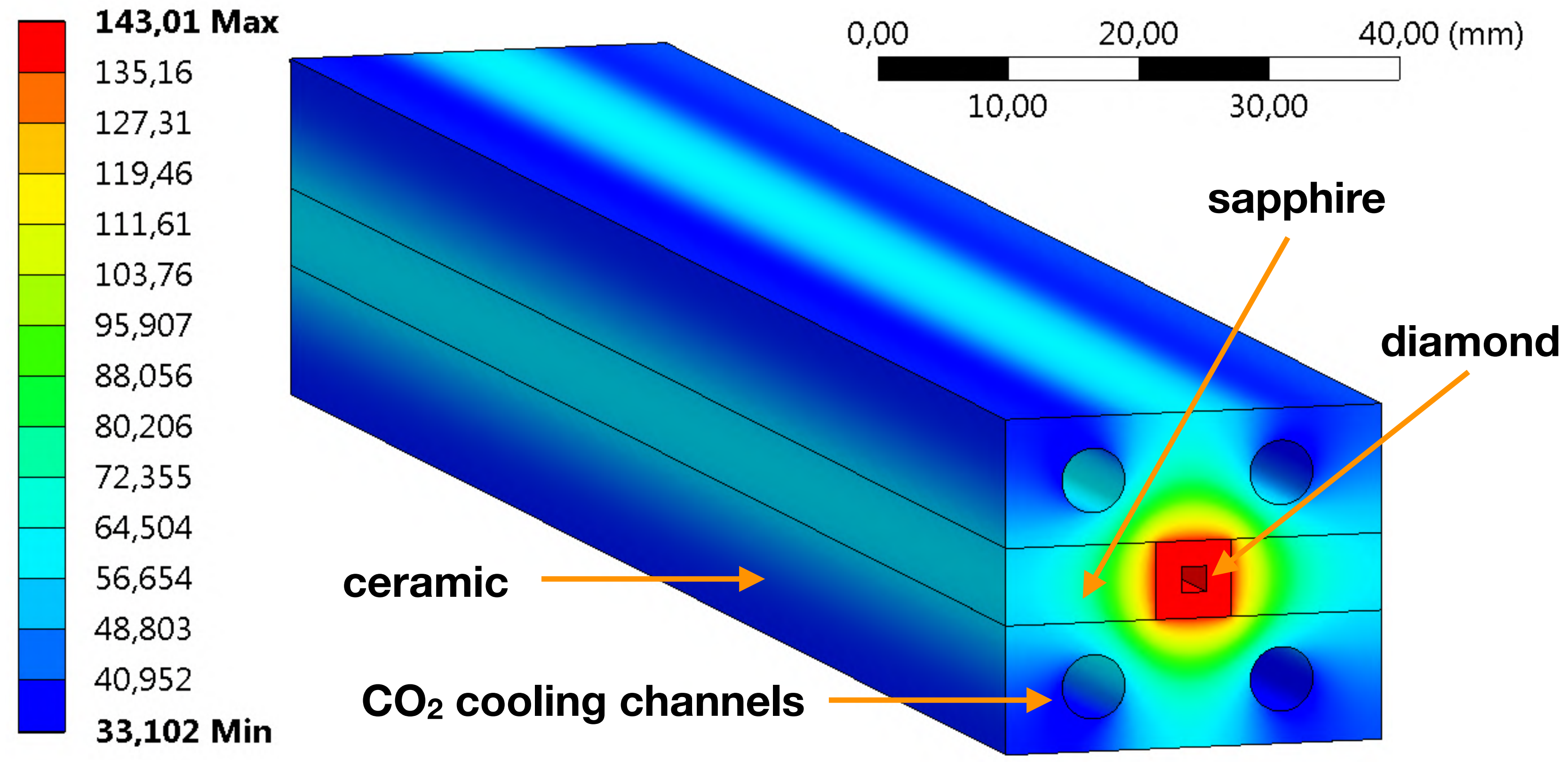
Plasma-boosted ILC-like collider at 500 GeV

Outlook and plans

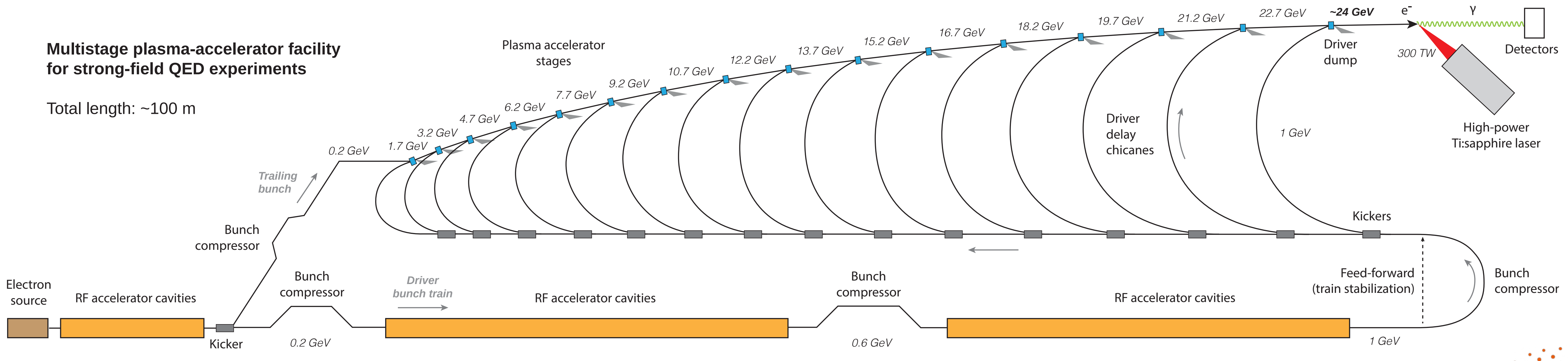
Mid-term outlook and R&D

Key steps toward HALHF

- *Experimental R&D in existing facilities:*
  - Single-stage operation with large energy gain and beam-quality preservation, with high overall efficiency.
  - High-rep-rate (bunch pattern)
  - **High-average power (plasma heating, cell cooling)**
  - Achromatic transport between stages
  - Flat beams
- *Required new experimental facilities:*
  - **Multi-stage demonstrator facility**
    - *~$100M scale*
    - *Conceptual design in progress (ERC project SPARTA).*
  - Spin polarisation



Concept for cooled plasma cells.
Image credit: R. D'Arcy



Concept for multi-stage demonstrator facility with strong-field QED experiment.
Image credit: C. A. Lindstrøm

Near-term plans toward the European Strategy Update

Concluding on and documenting a self-consistent design

- **Main goal**: prepare ESPP input (10-page summary of concept) by 31 Mar 2025
- **Internal goal**: produce a pre-CDR in 2025
- **Next steps**:
  - An ‘experts’ workshop in Erice, Sicily (3–8 Oct 2024)
    - *Consolidation of design (geometry, technology choices, required subsystems, first draft of baseline parameters, etc.)*
    - *Produce a skeleton structure for the ESPP input summary*
  - Continued monthly meetings for drafting the input

‘Experts Meeting’ in Erice, Sicily hosted by the Ettore Majorana Foundation and Centre for Scientific Culture

Summary

Making great strides toward a plasma-based collider design

> **The HALHF concept proposes a compact, cheaper, greener, possibly quicker Higgs factory**

> > HALHF benefits from maximal asymmetry: energy — charge — emittance

> **A collaboration of experts has been assembled to identify issues requiring more R&D** and help guide design decisions towards HALHF 2.0

> > **Many physics issues have been ironed out since 2023:** getting close to self-consistency

> > **A powerful optimization framework implemented:** currently improving cost model accuracy

> **Upgrade path to higher energy, output, and integration:** not just a one-trick pony!

> **Continued community engagement required to conclude on the path forward towards a pre-CDR and input to ESPP update**