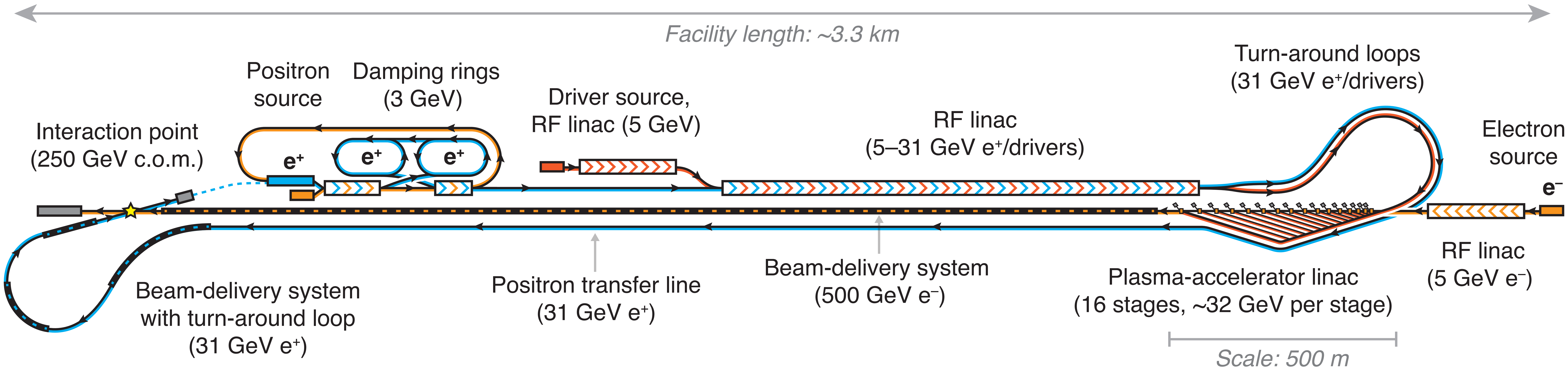


HALHF: A Hybrid, Asymmetric, Linear Higgs Factory

Current Status, Optimisation, and Future Plans

Richard D'Arcy

University of Oxford

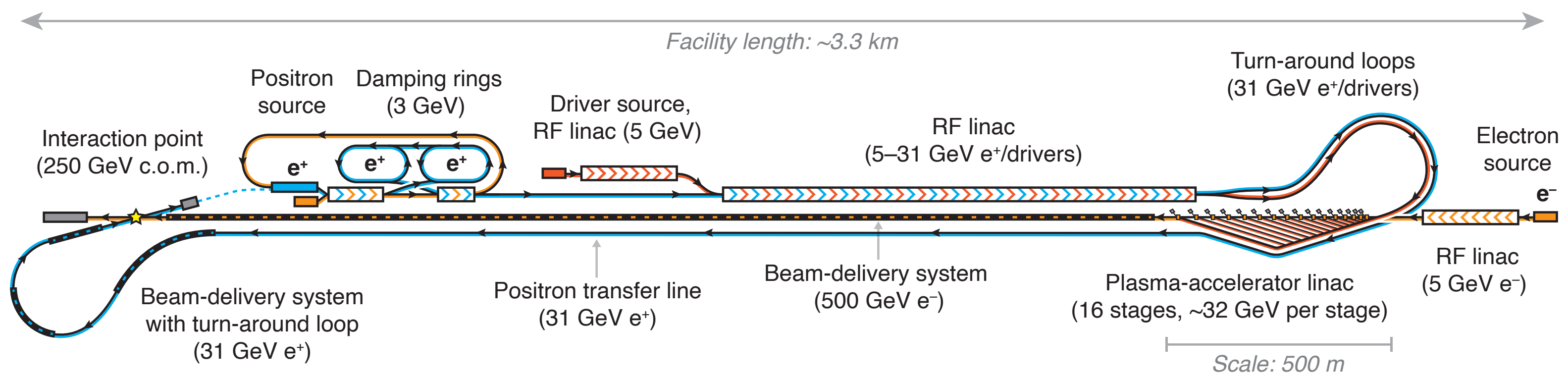
Brian Foster, Carl A. Lindstrøm

University of Oxford/DESY & University of Oslo

9th July 2024 | International Workshop on Future Linear Colliders (LCWS2024)

The HALHF concept

A brief reminder



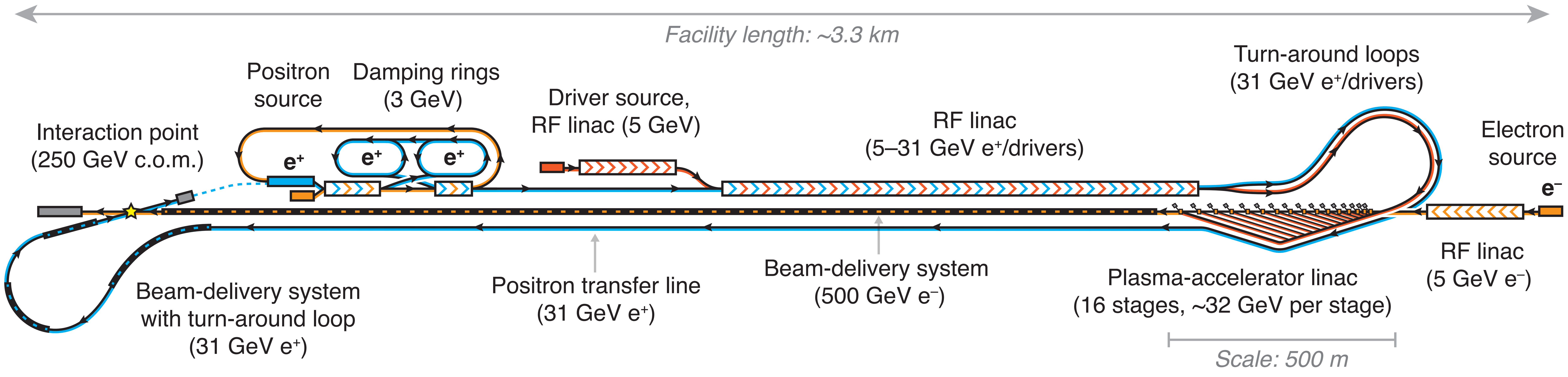
[Foster, D'Arcy and Lindstrøm, New J. Phys. 25, 093037 (2023)]

- 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



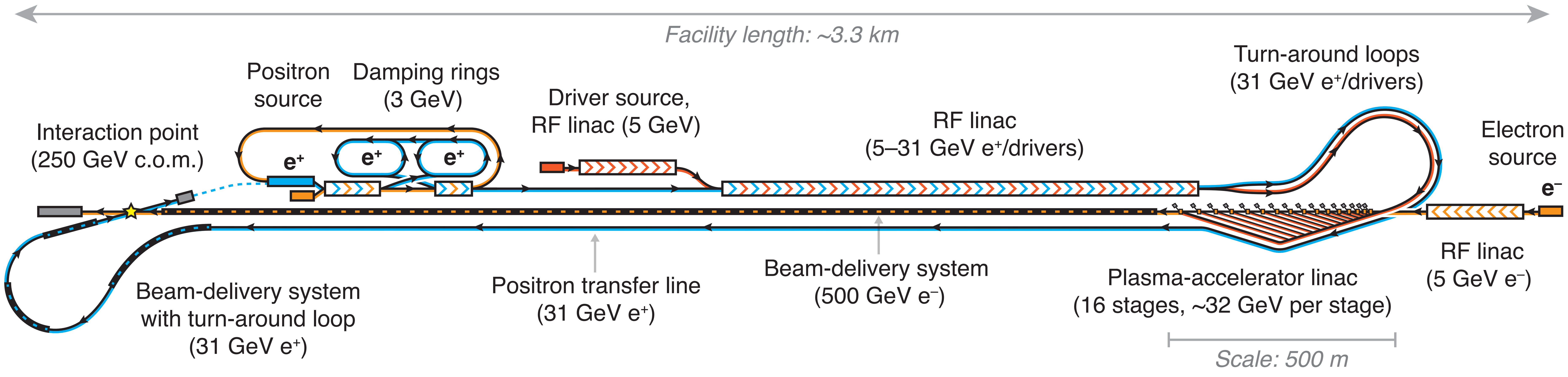
Source: **Foster, D'Arcy and Lindstrøm, New J. Phys. 25, 093037 (2023)**

- 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

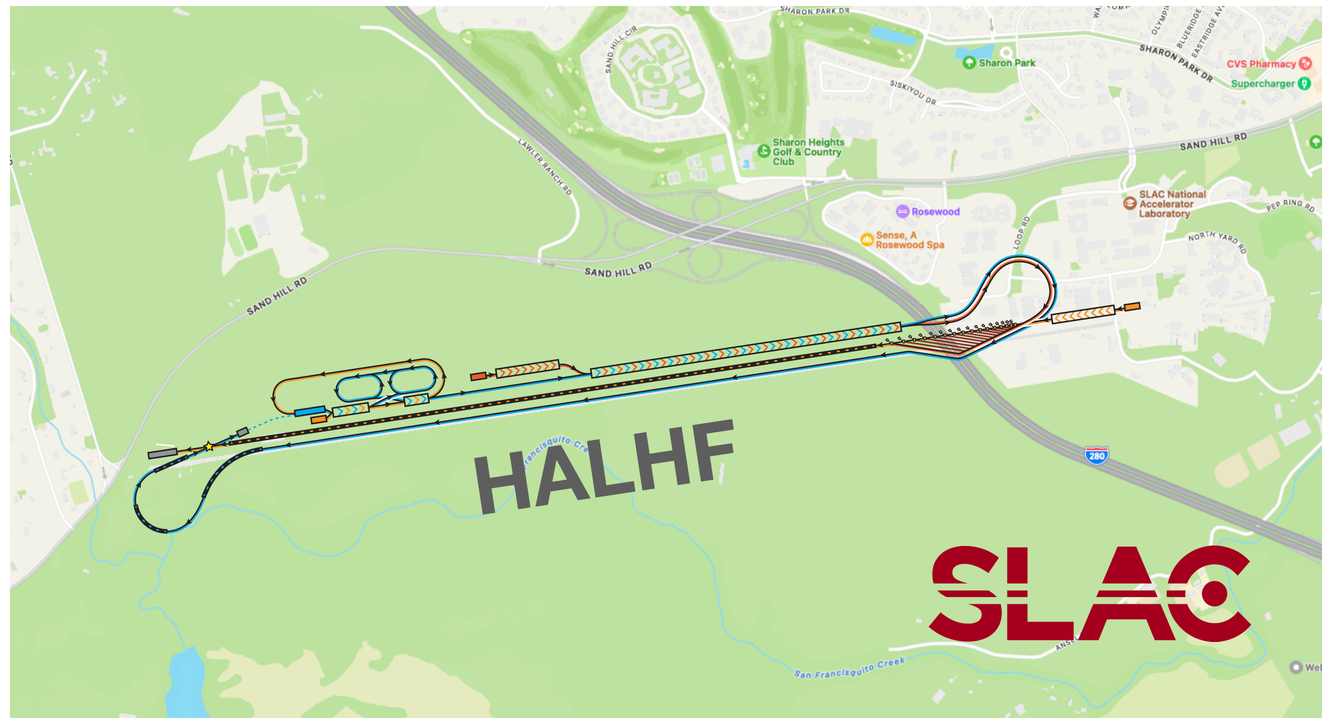
The HALHF concept

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
- 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

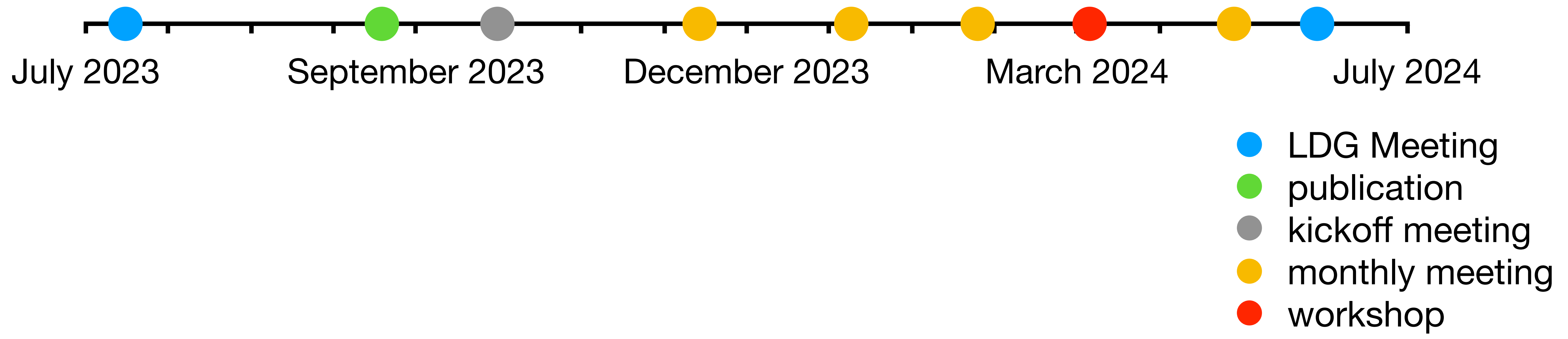


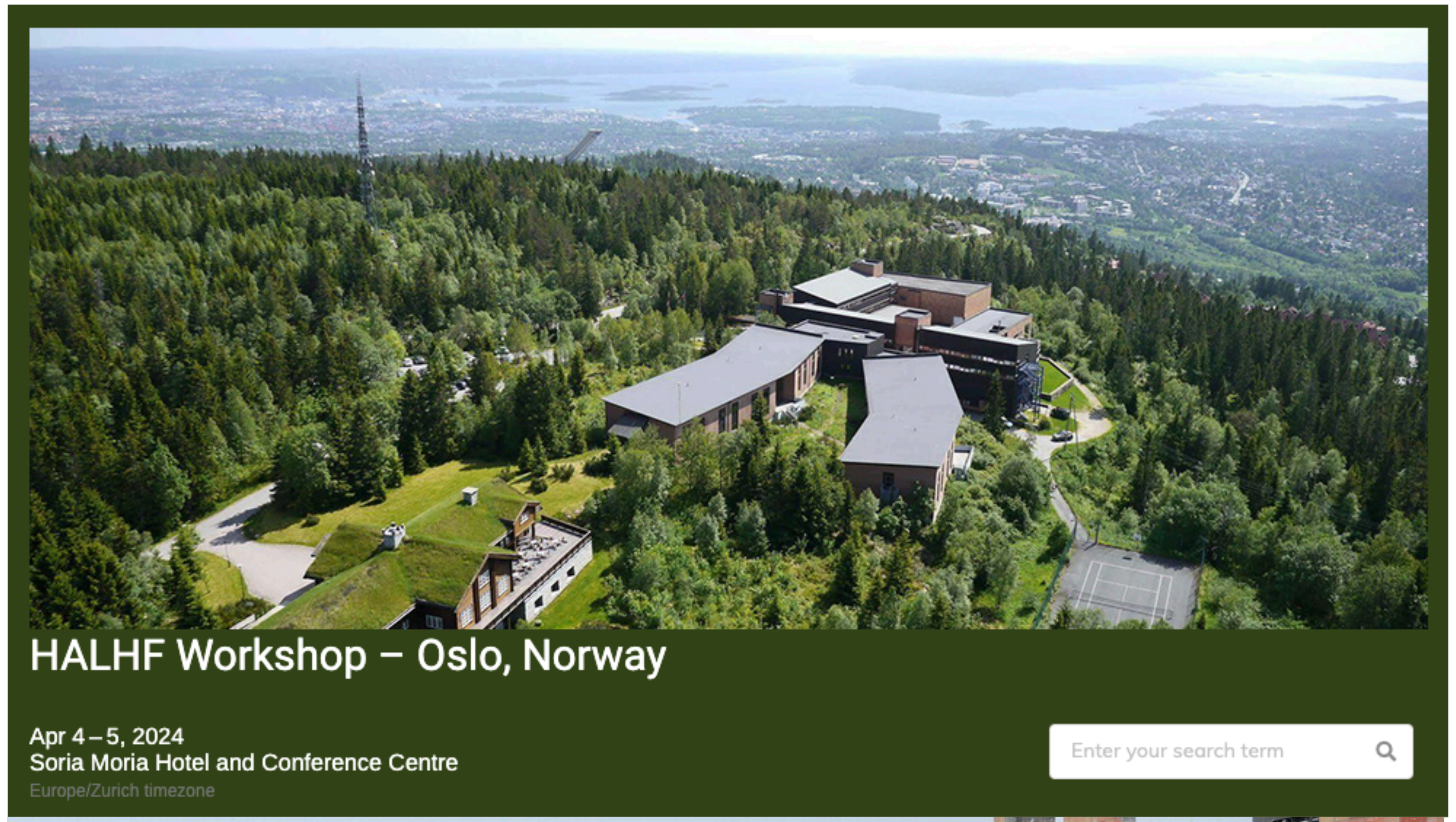
Source: Foster, D'Arcy and Lindstrøm, New J. Phys. 25, 093037 (2023)



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

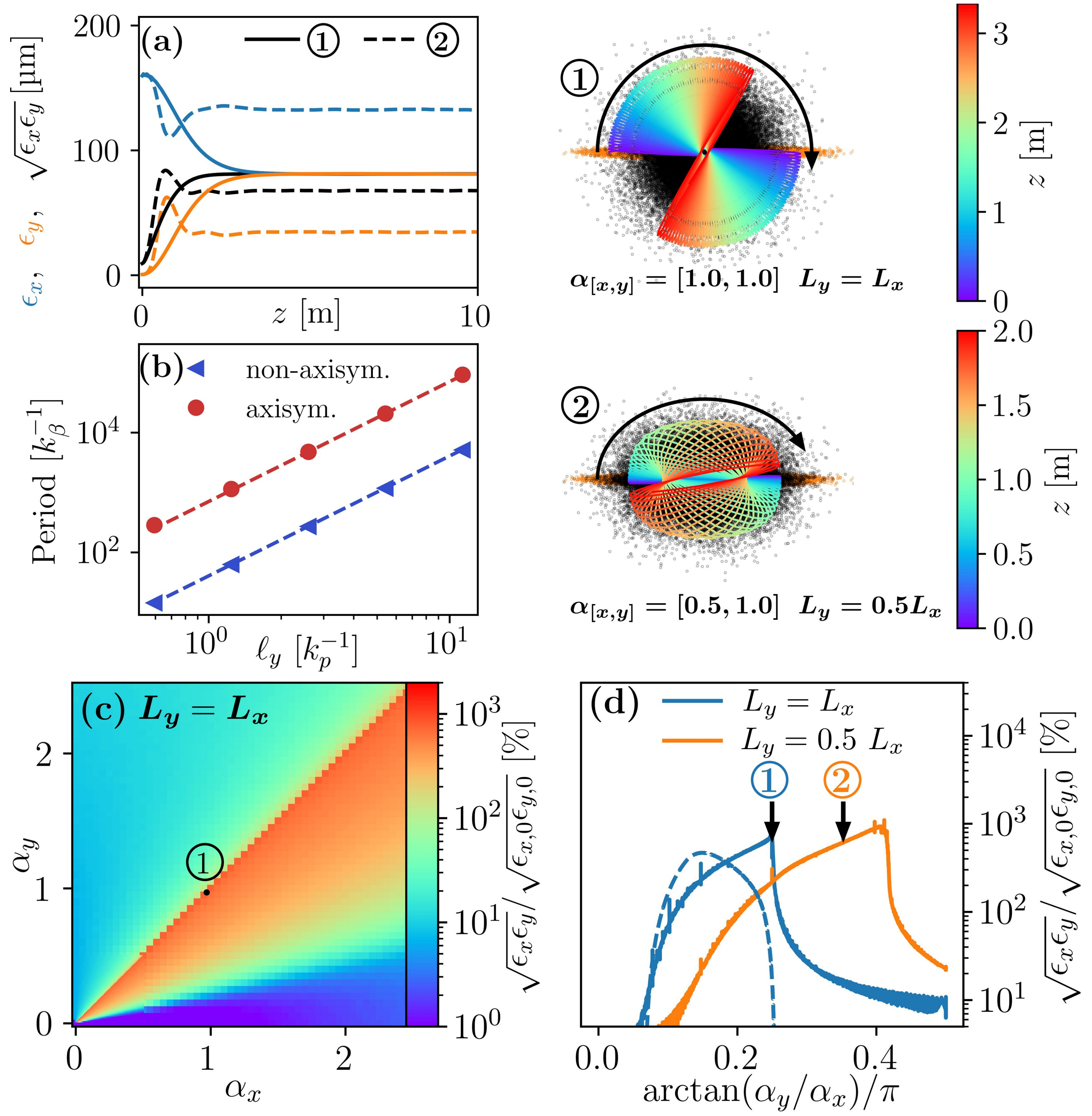
Key questions to be answered toward a self-consistent design

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:

LCWS2024 Talk
— M. Thévenet (DESY), July 10th, 14:15

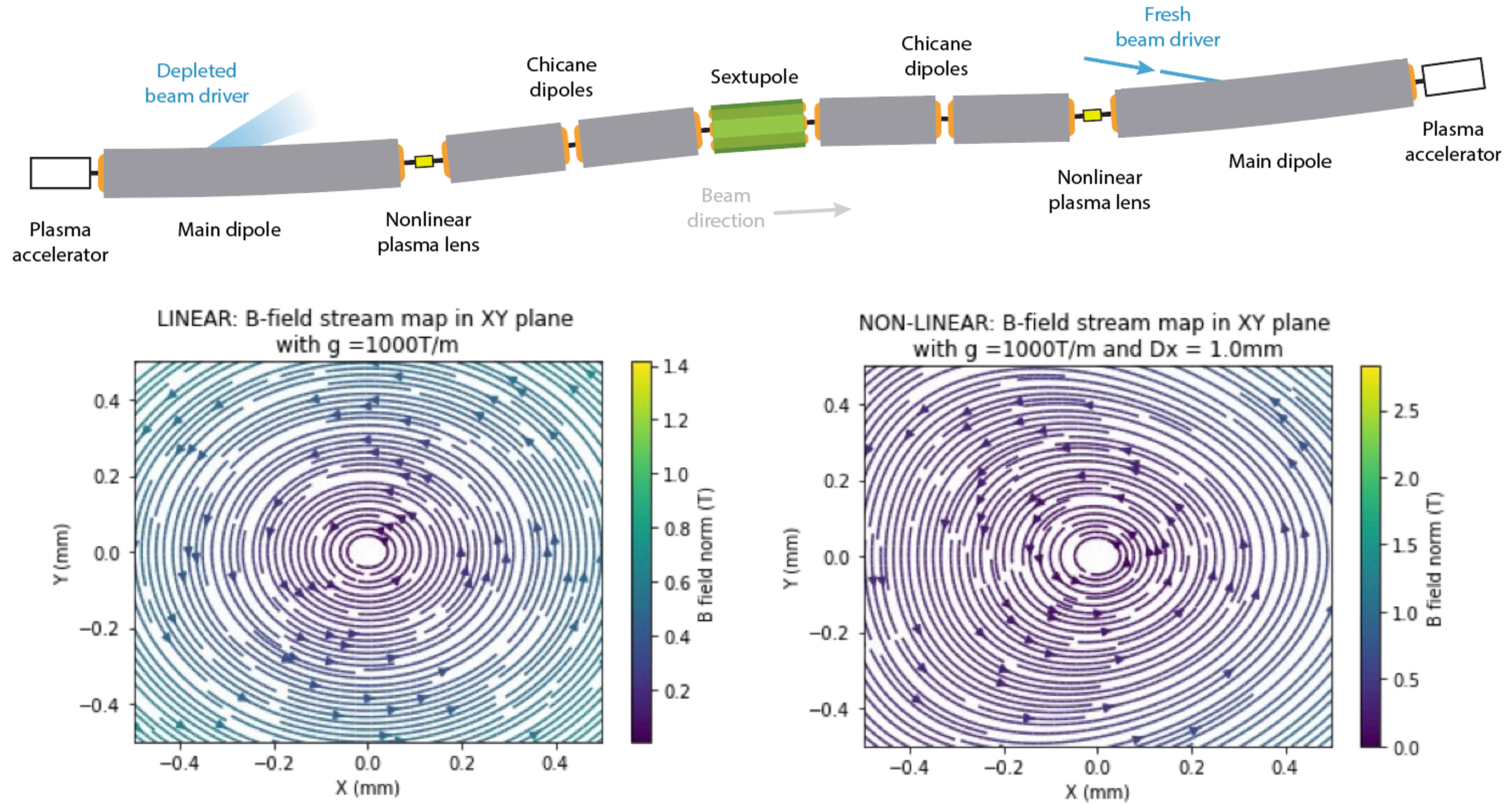


Source: Diederichs et al., preprint arXiv:2403.05871 (2024)

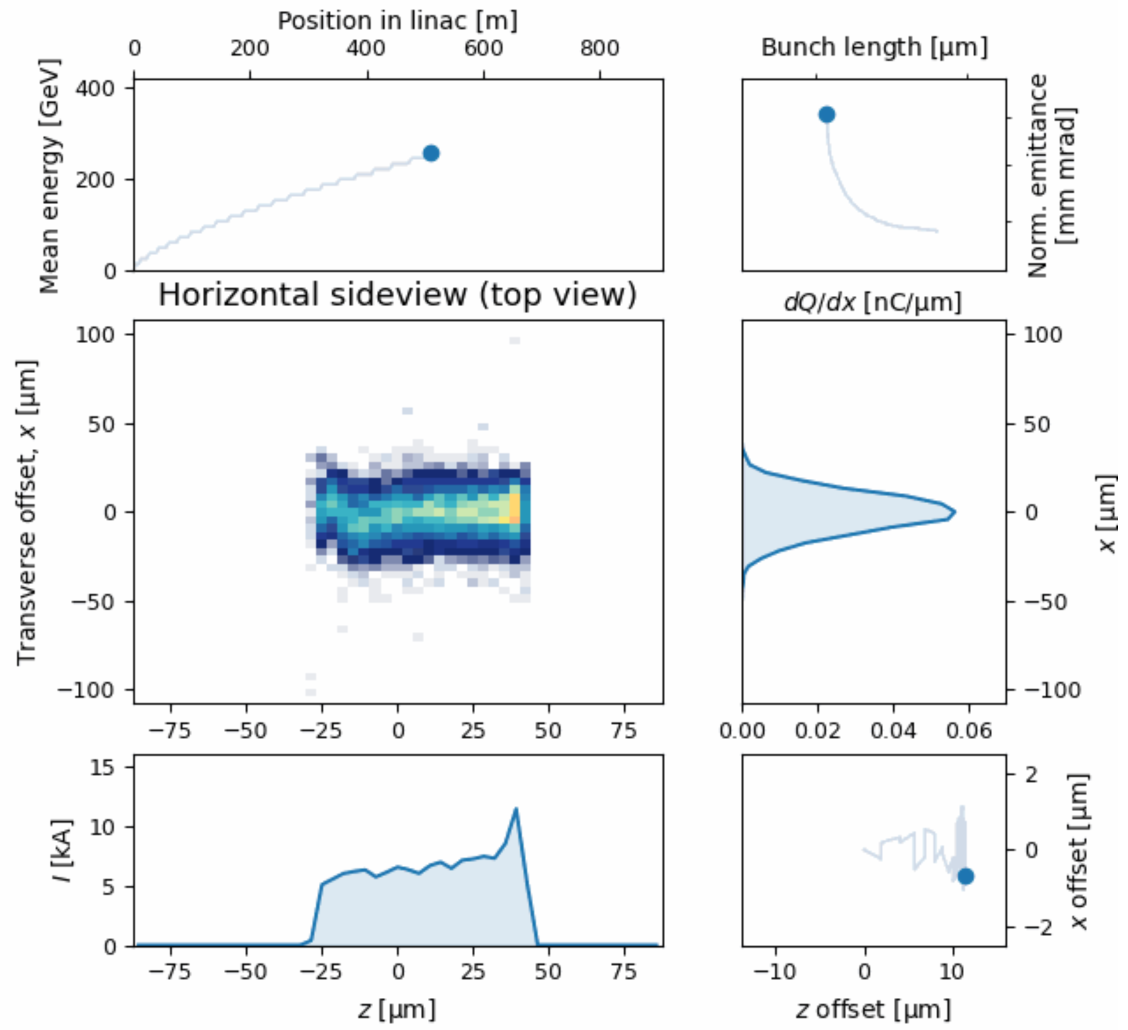
Staging, transverse instabilities, radiation reaction

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



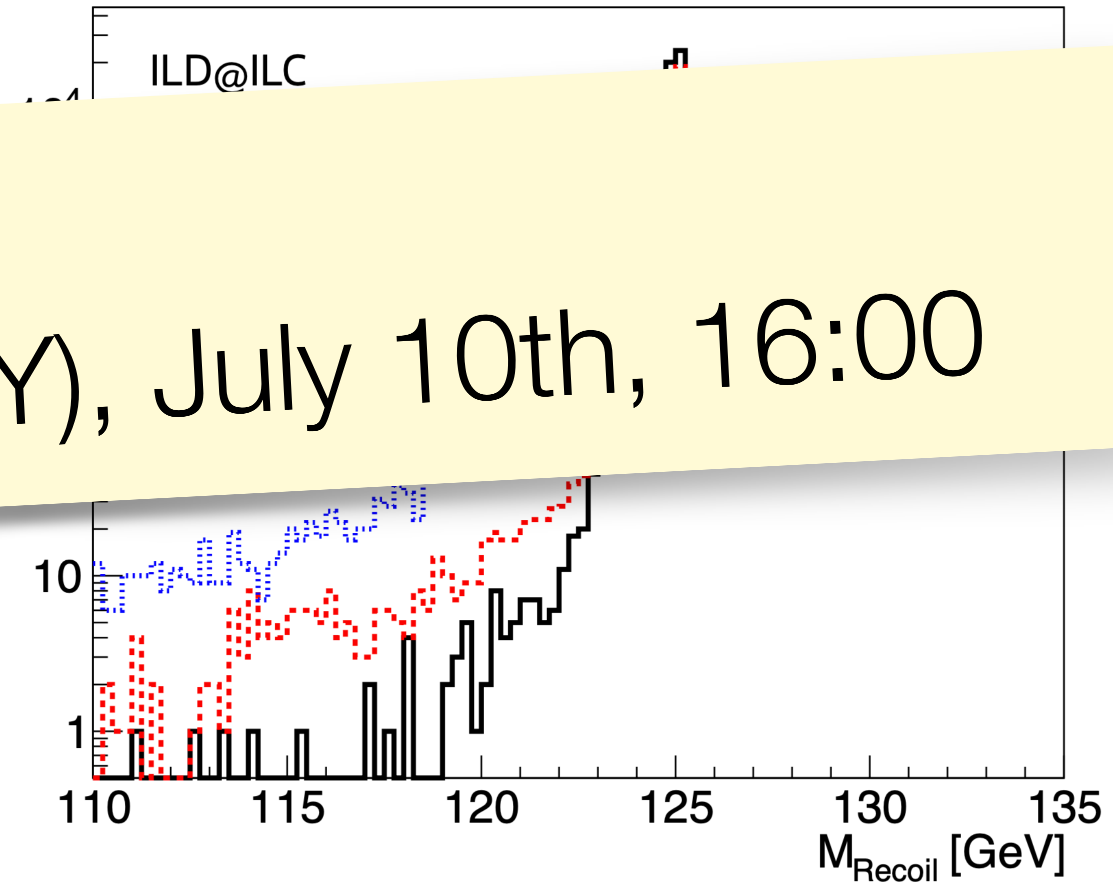
Animation by Ben Chen.

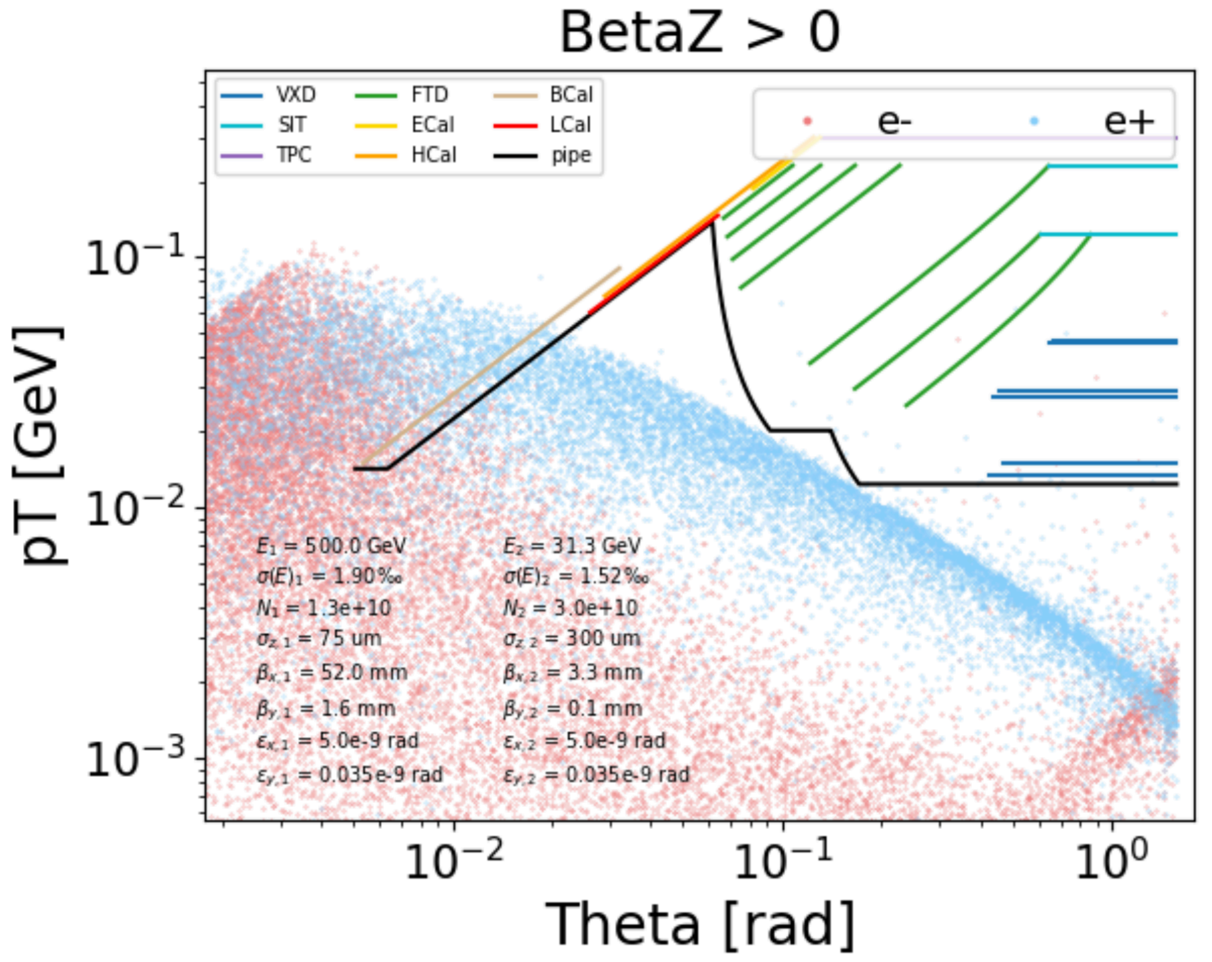
Asymmetric detectors, polarization, positron source, etc.

Work in progress

- Preliminary asymmetric detector studies (J. List, A. Laudrain):
  - *The energy asymmetry does not appear to b*
  - *Reducing the positron peak current reduces t 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

LCWS2024 Talk
— A. Laudrain (DESY), July 10th, 16:00





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

Open question: choice of RF technology

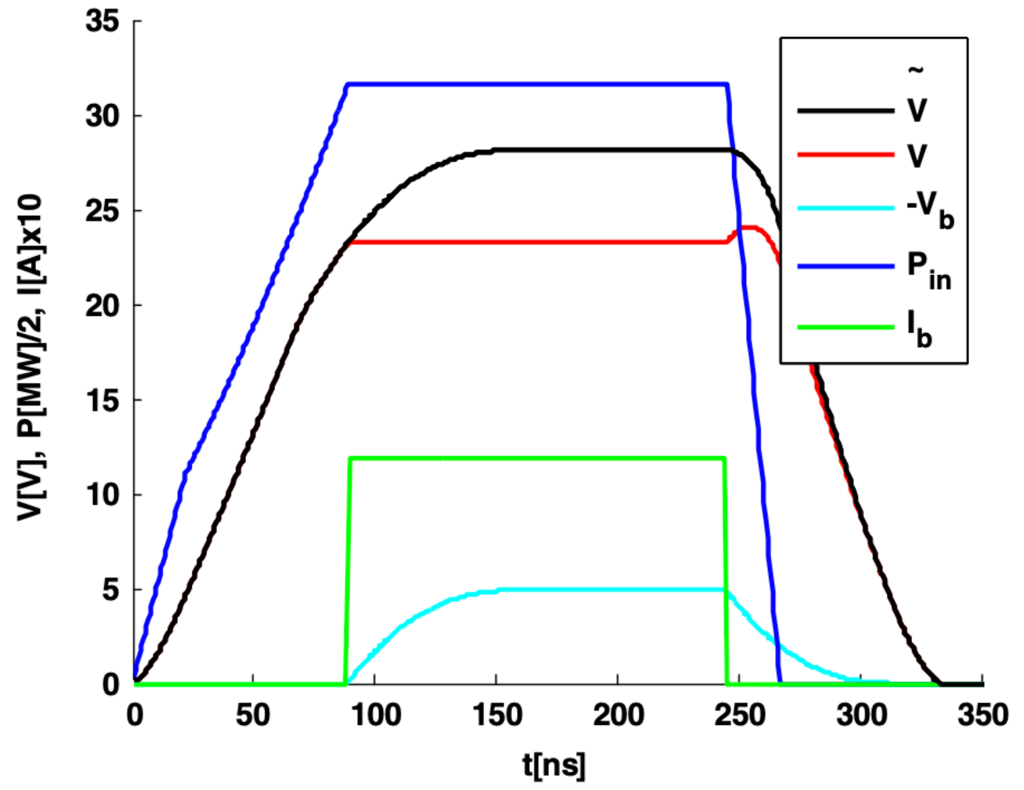
Normal-conducting vs. super-conducting RF linacs

> 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)*

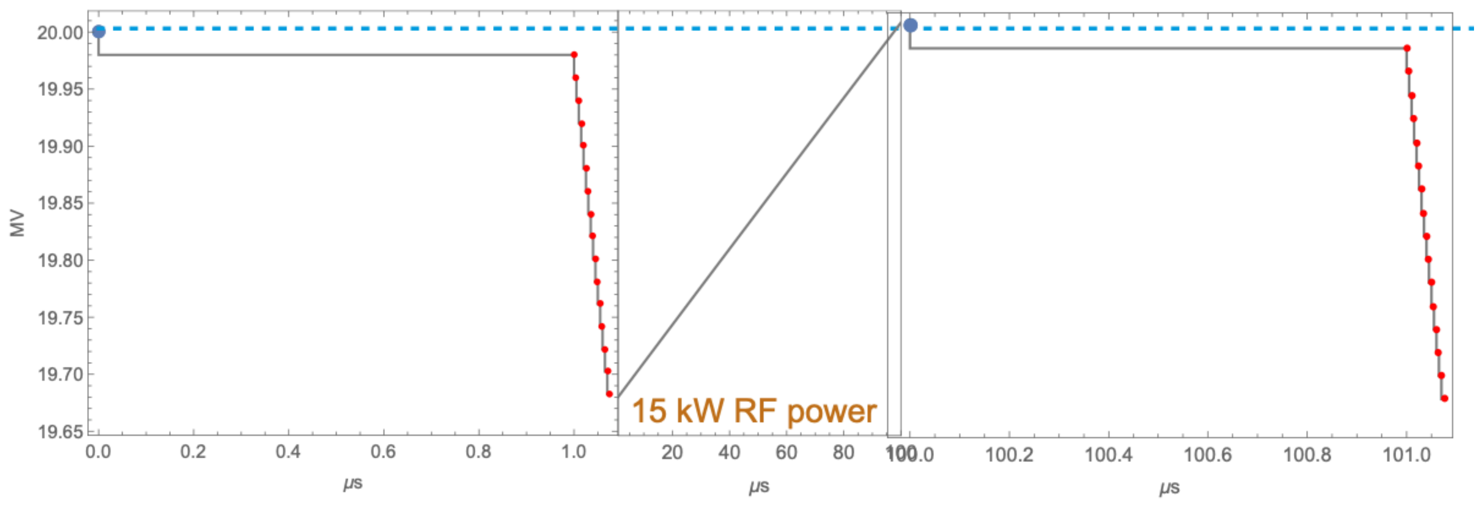


Structure optimization framework
Source: Lunin et al. PRSTAB (2011)

> 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

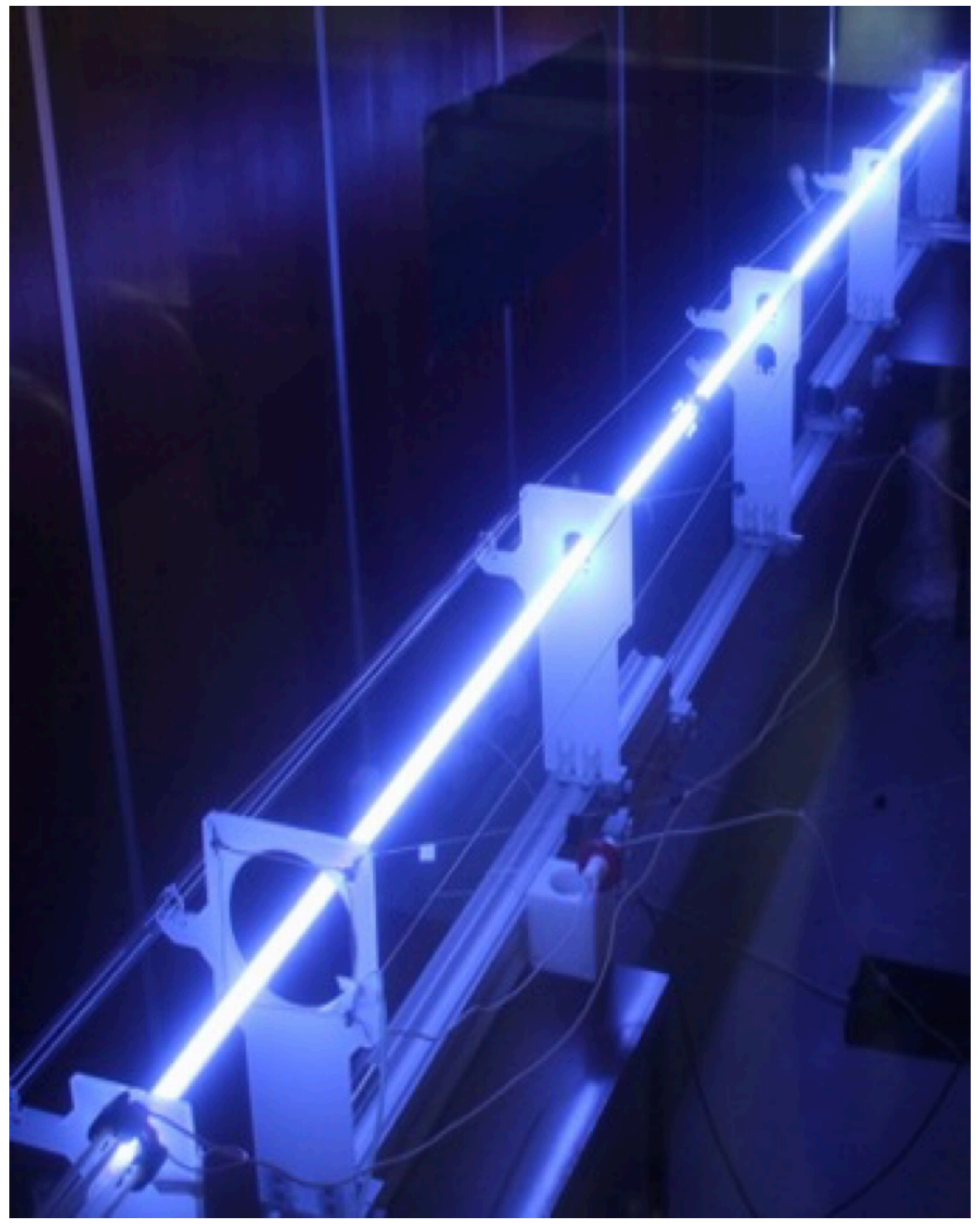
Toward HALHF 2.0

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)

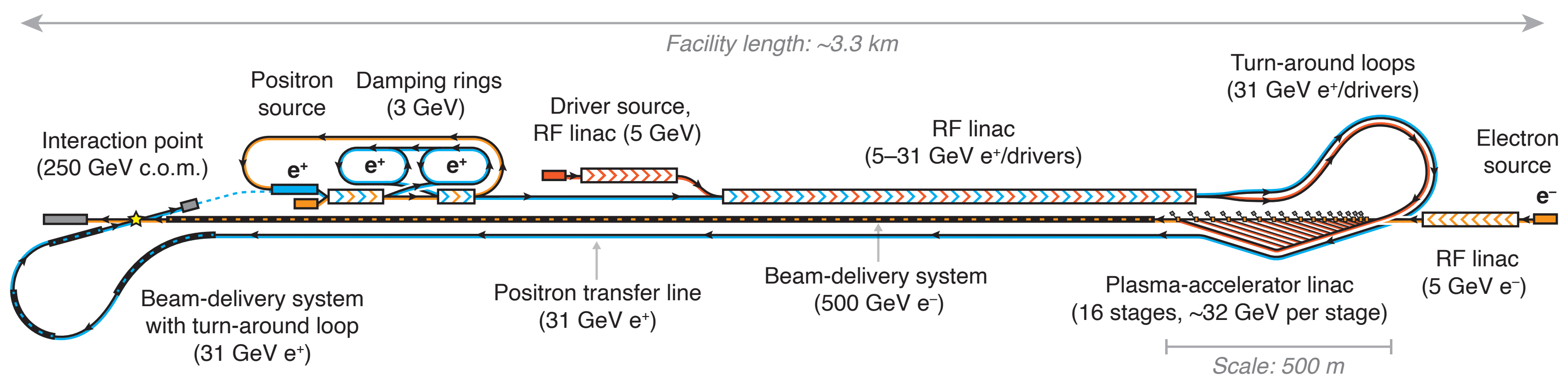


Long plasma cell at AWAKE.
Image credit: AWAKE

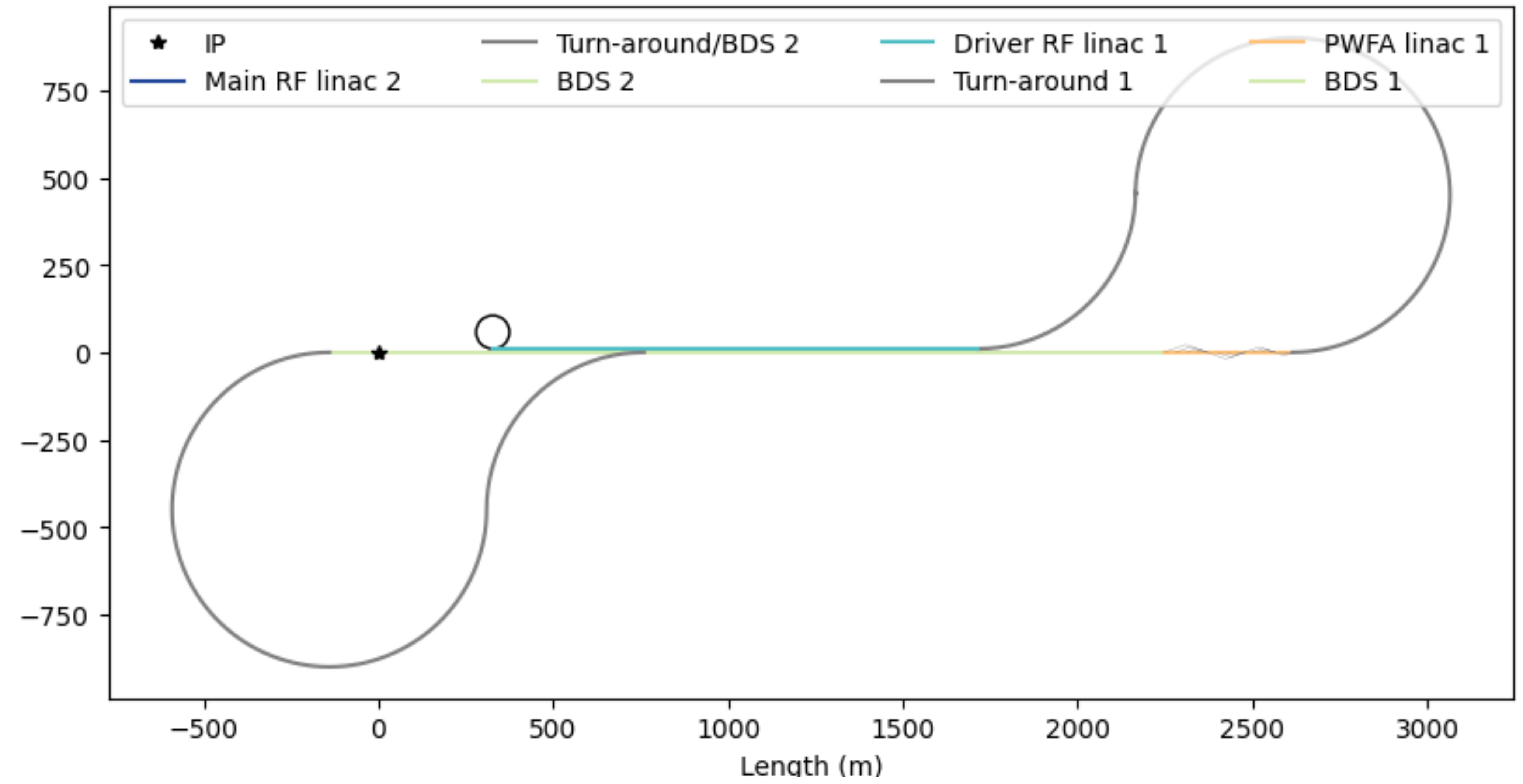
Possible geometry change

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)

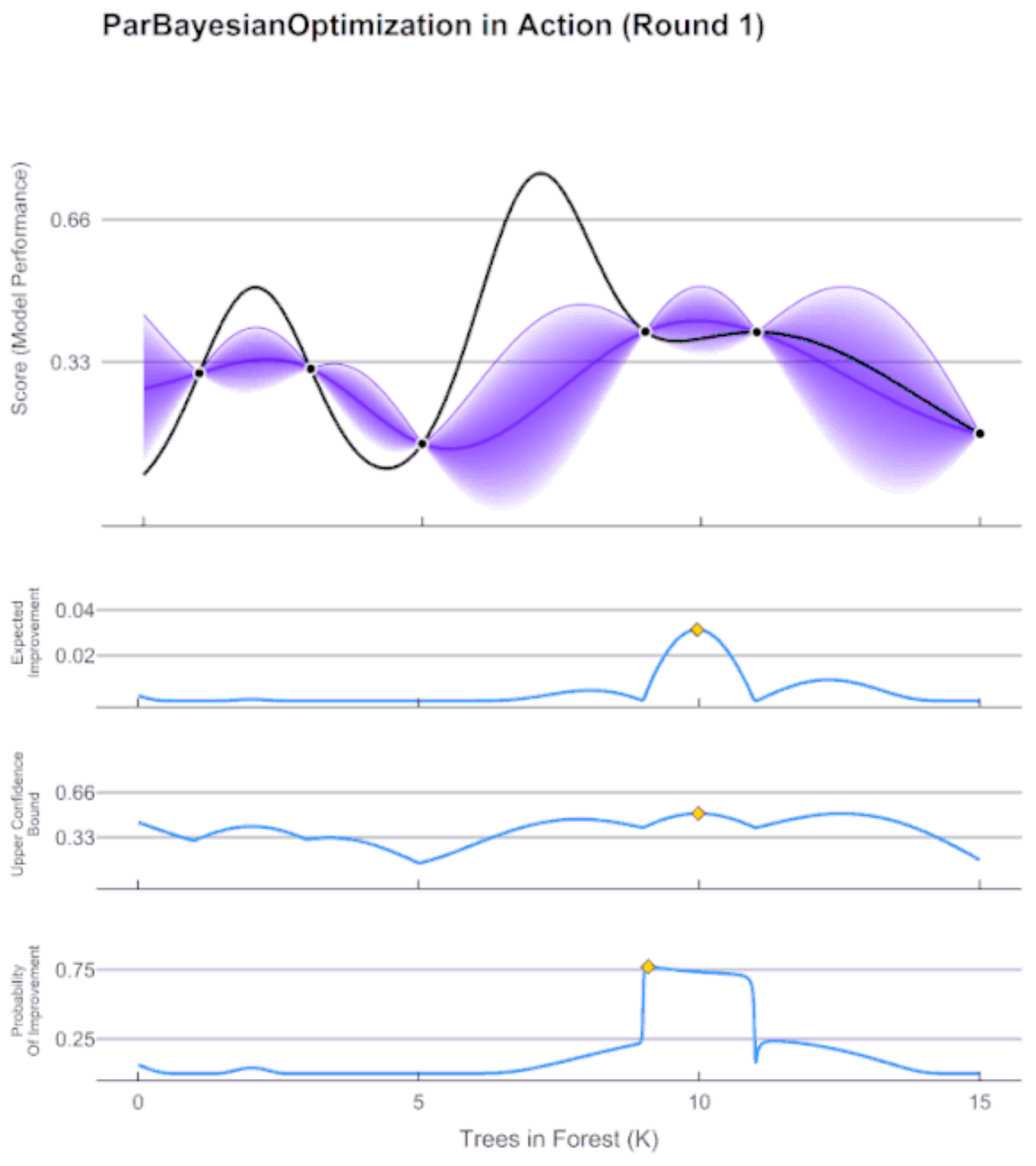
> What exactly should we optimize for?

  > **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

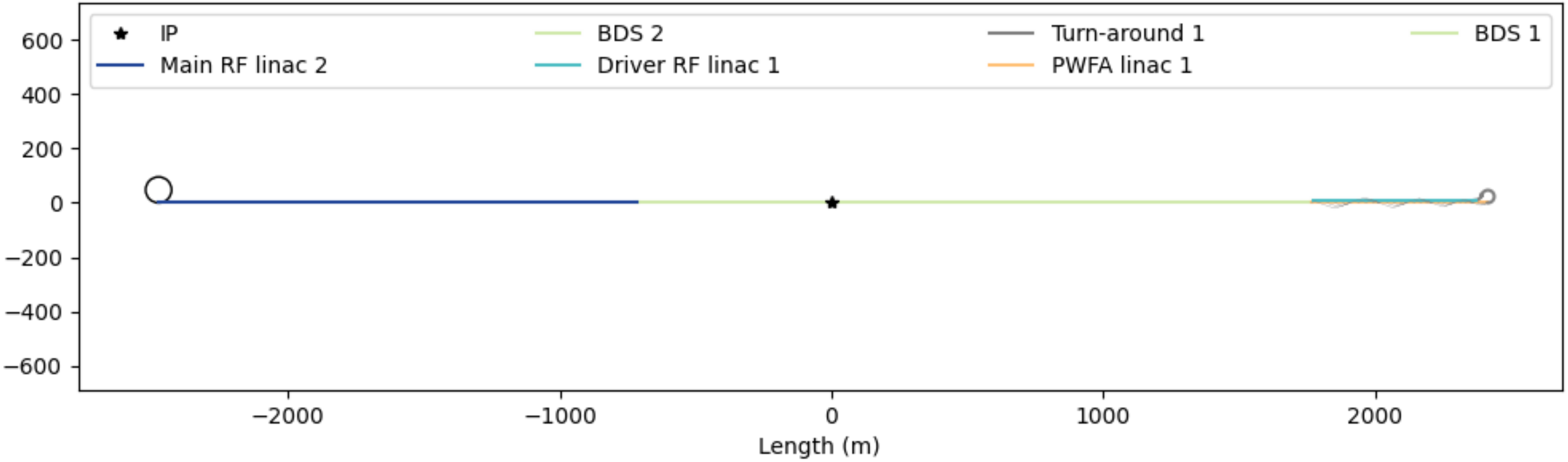


Example of a cost-minimised design (250 GeV)

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

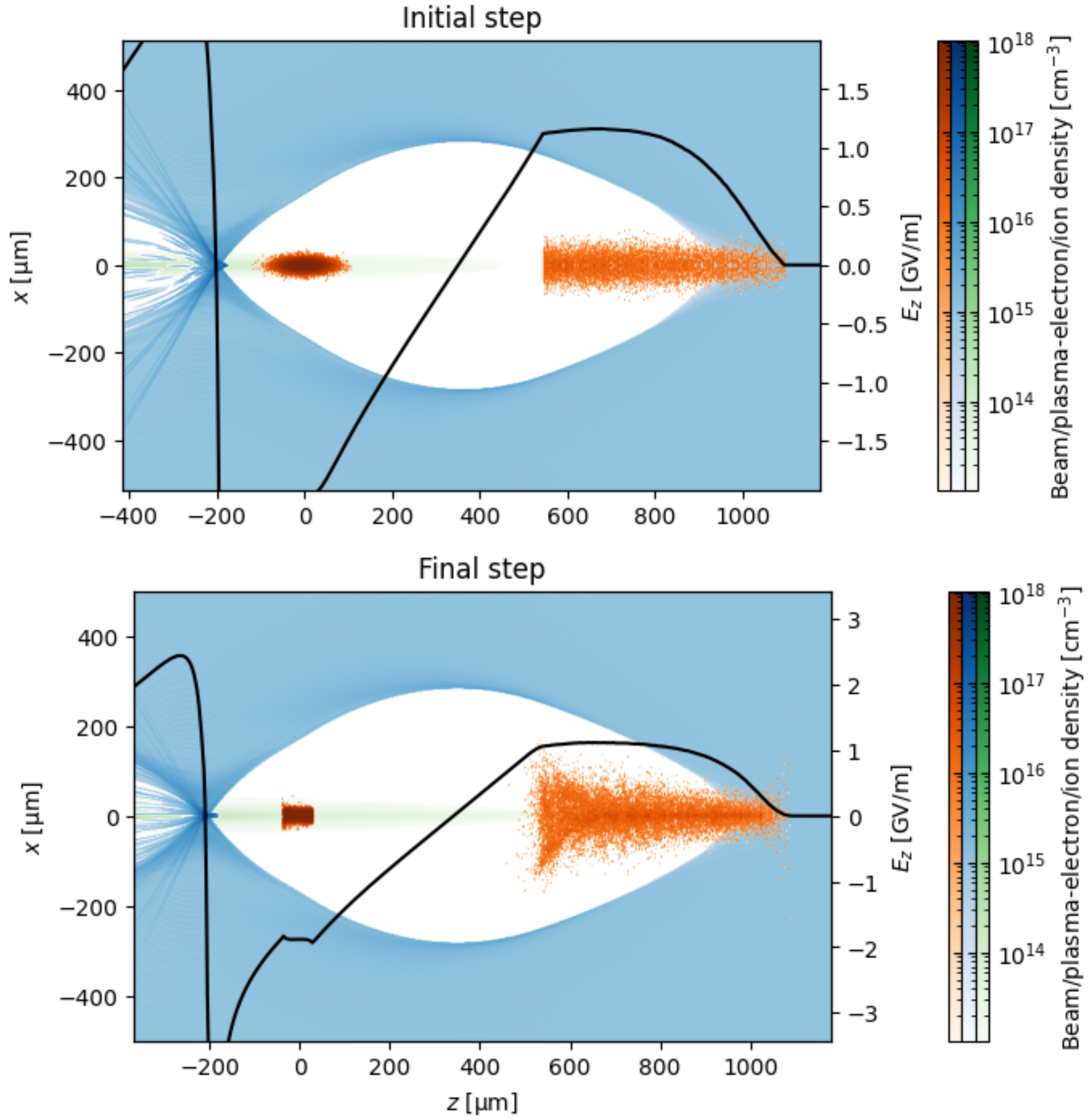
1 cost unit ≈ construction cost as estimated in the original proposal.
The absolute value varies with inputs and cost estimates (to be consolidated)

Preliminary self-consistent simulations of the plasma linac

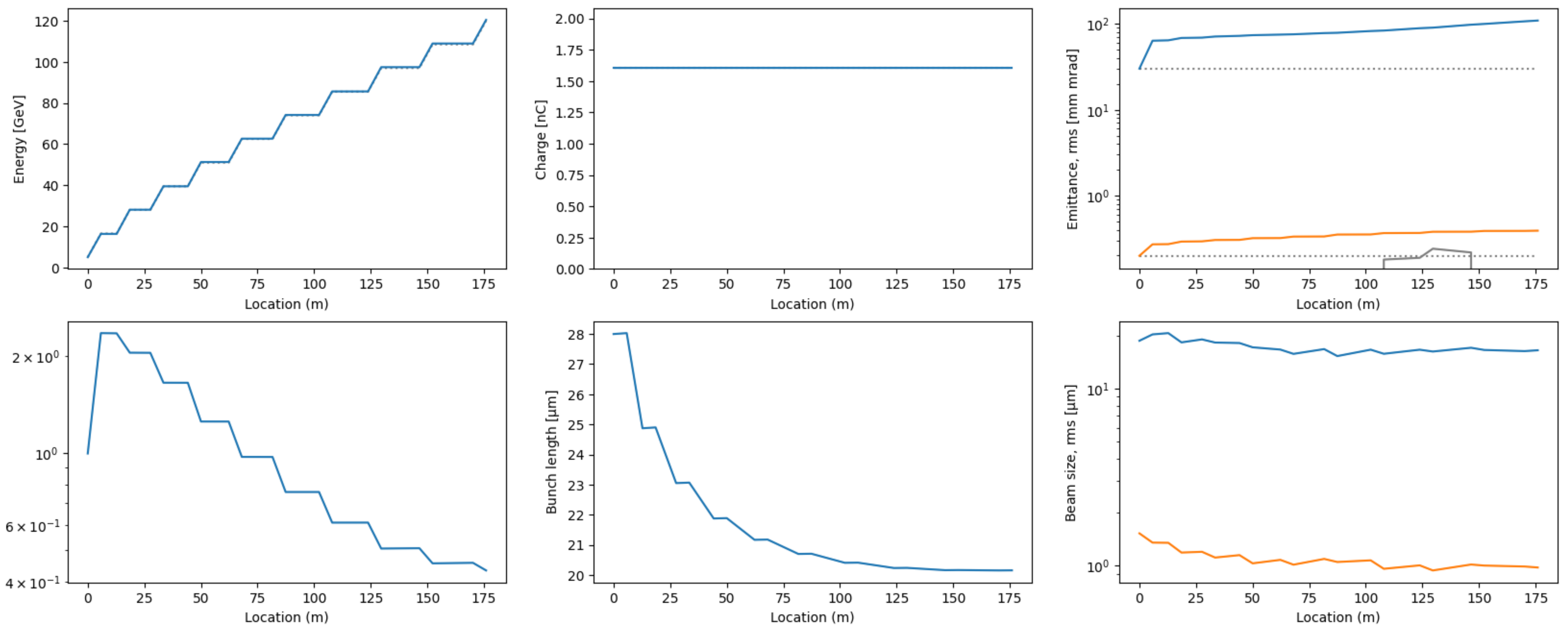
Incorporating all the findings

> 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)

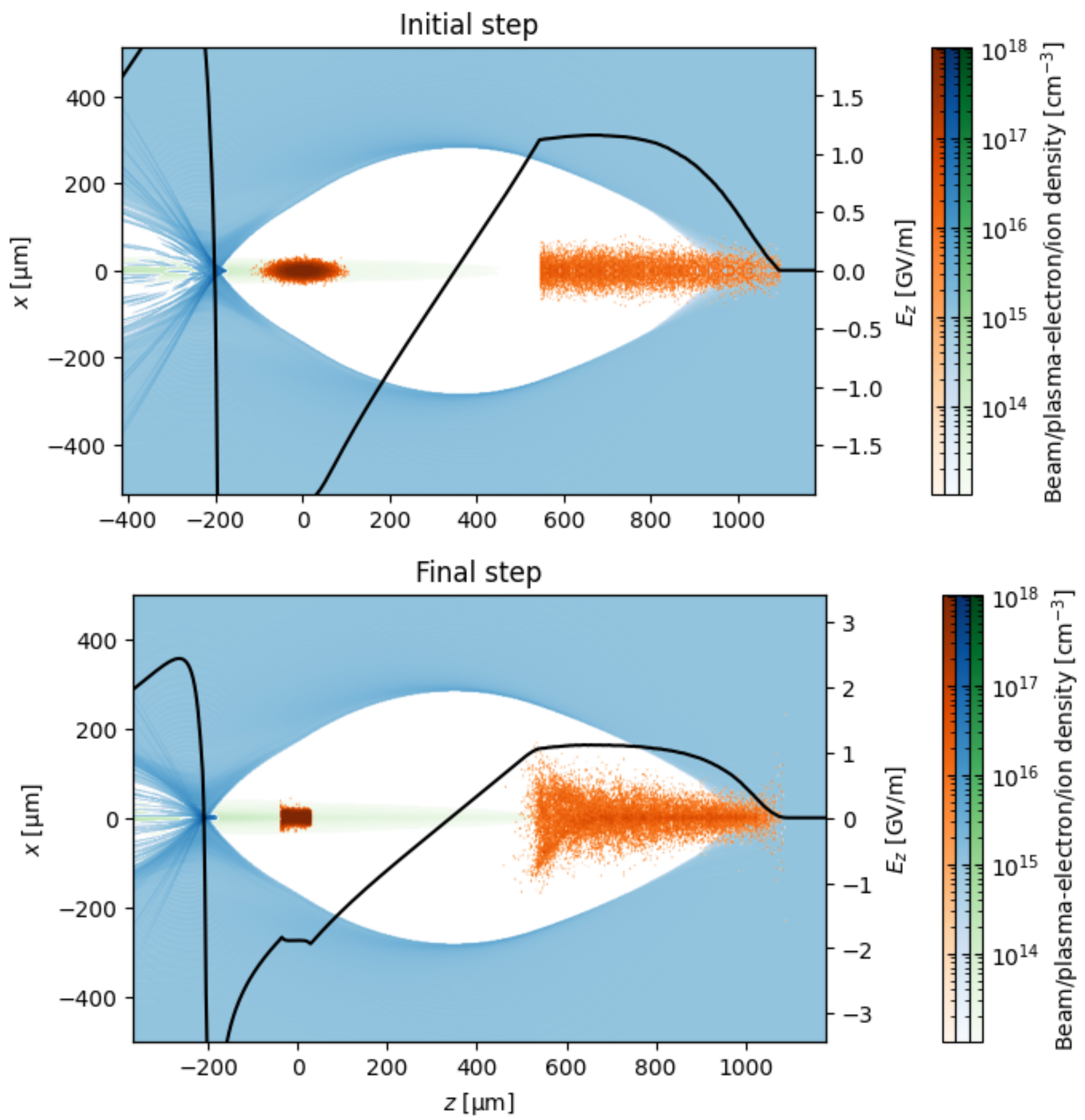


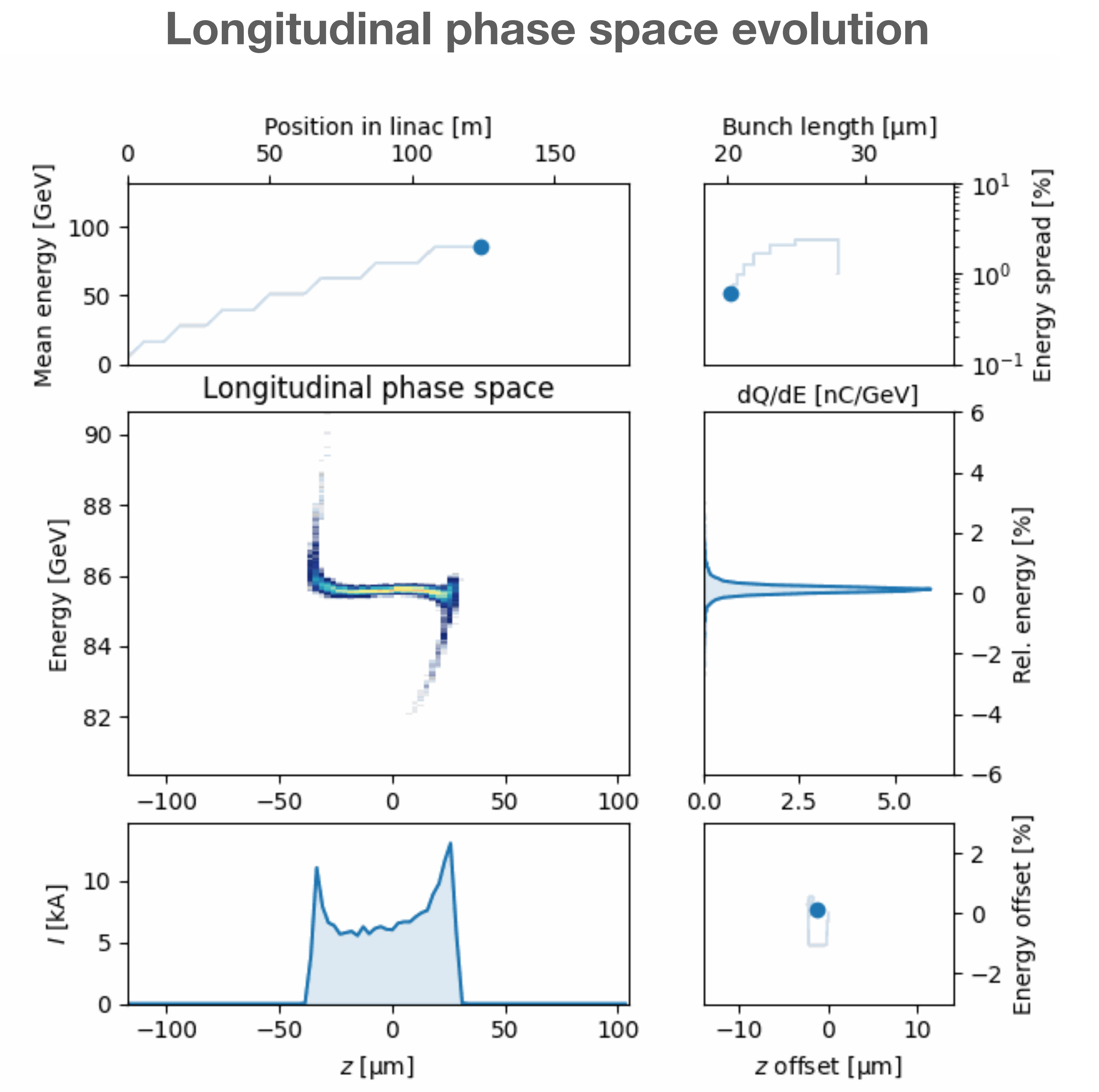
Preliminary self-consistent simulations of the plasma linac

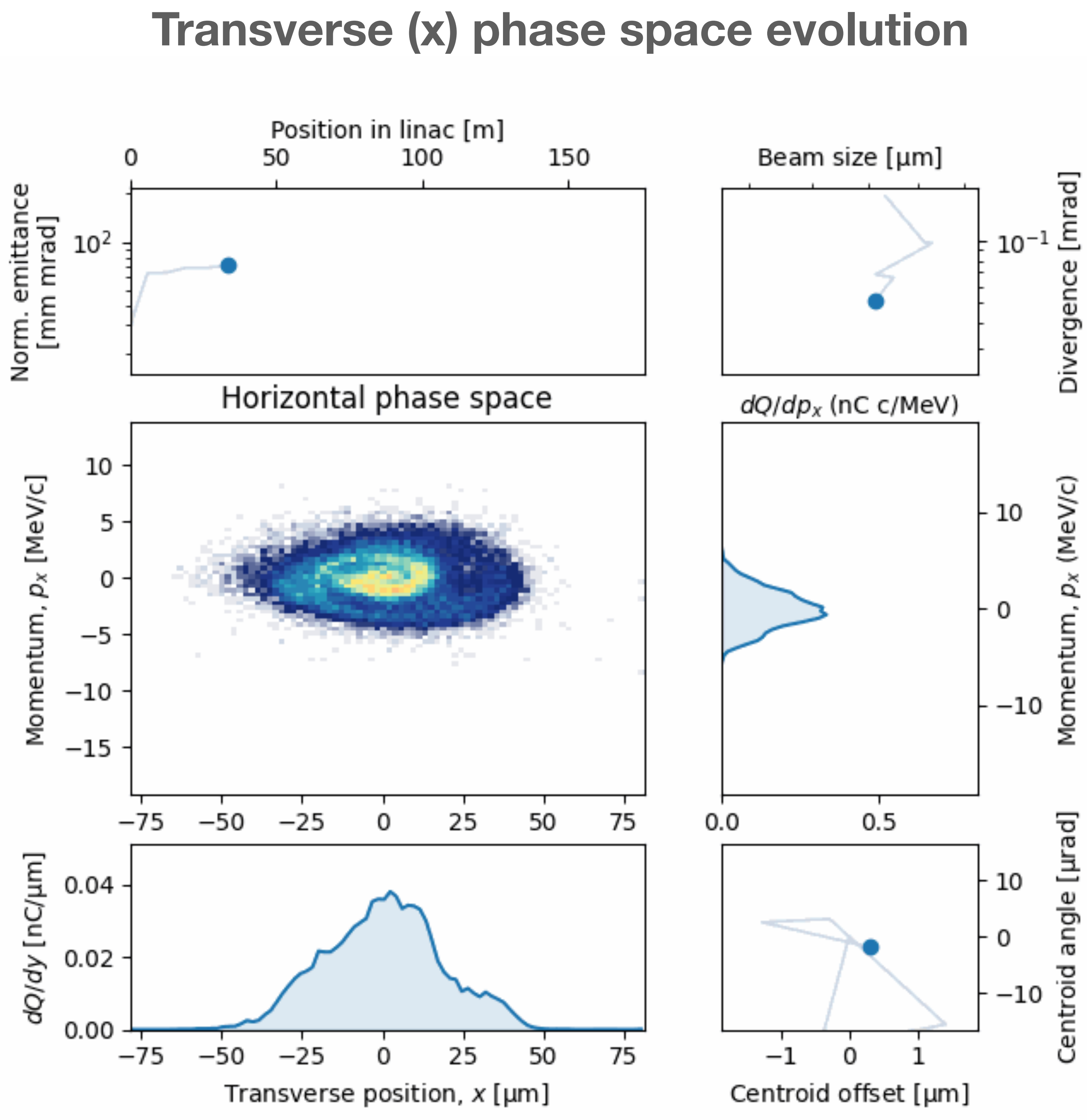
Incorporating all the findings

> 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:

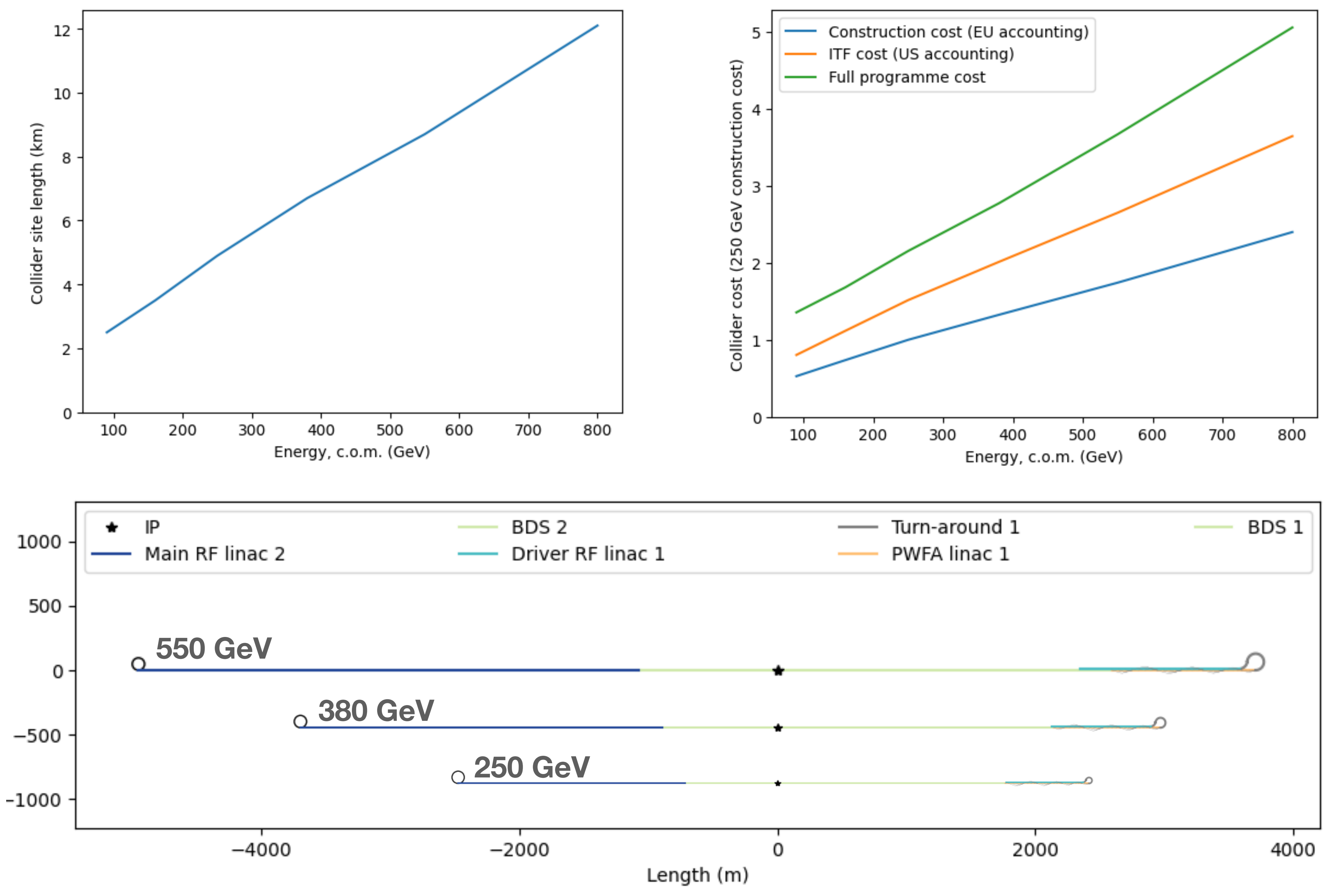
Energy c.o.m. (GeV)	***Length (km)***	***EU / US / Full Programme Cost (norm. cost units)***
250 (HZ)	4.9	1 / 1.5 / 2.2
380 (ttbar)	6.7	1.3 / 2.0 / 2.8
550 (HHH)	8.7	1.7 / 2.7 / 3.7
800	12.1	2.4 / 3.6 / 5.1

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

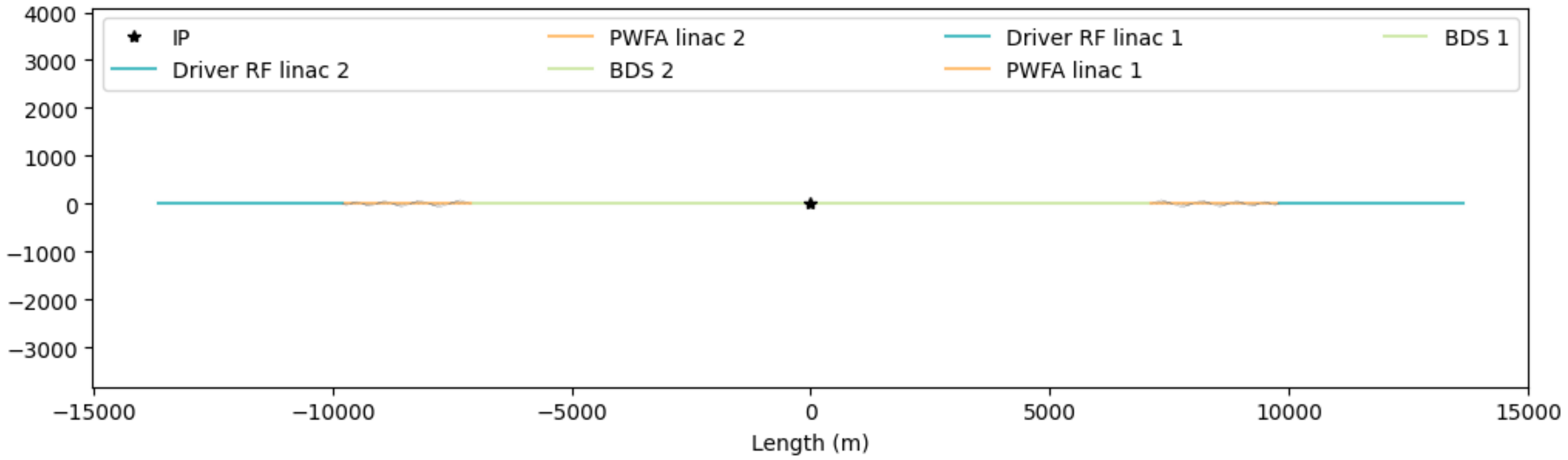
> *Estimated length: ~27 km (BDS is~14 km)*

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

Electron–positron collider



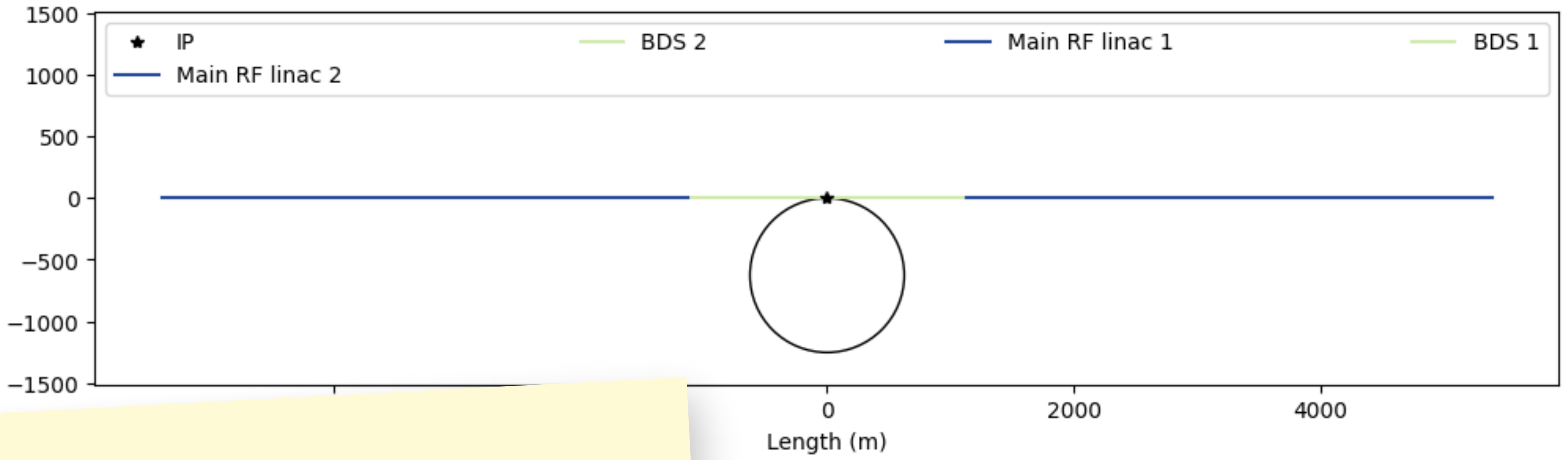
Gamma–gamma collider



Alternative: HALHF as an energy booster

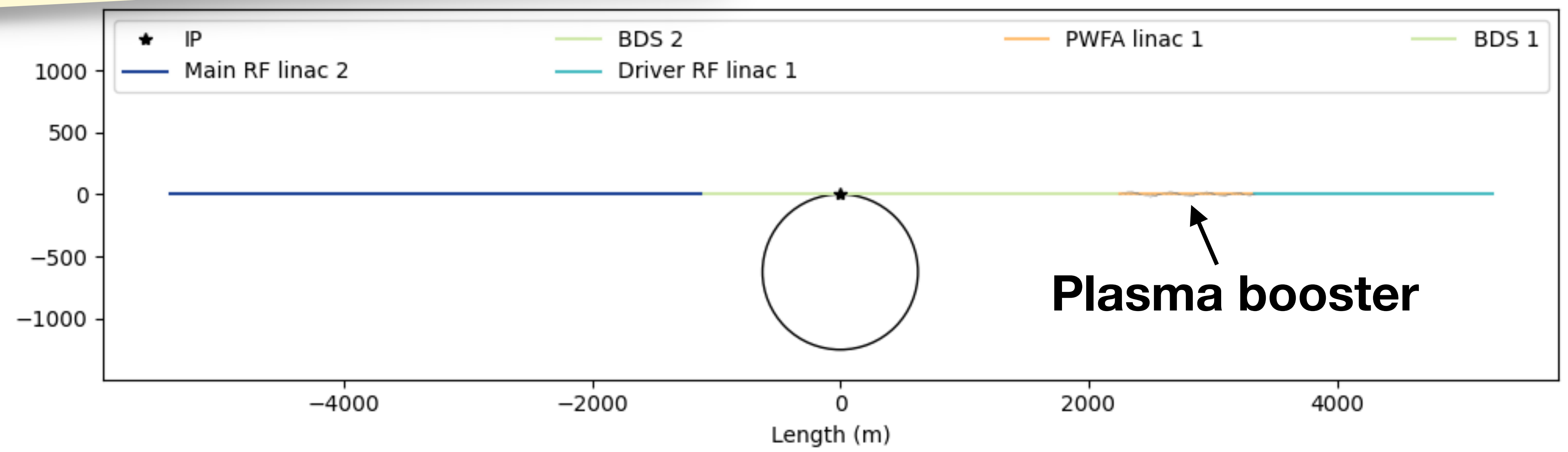
A cost-effective increase in energy reach of an existing linear collider

- 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 Ge*
- Additional cost of ord
  (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).*



C-like collider at 250 GeV

LCWS2024 Talk
— B. Foster (Oxford, DESY), July 8th, 16:00



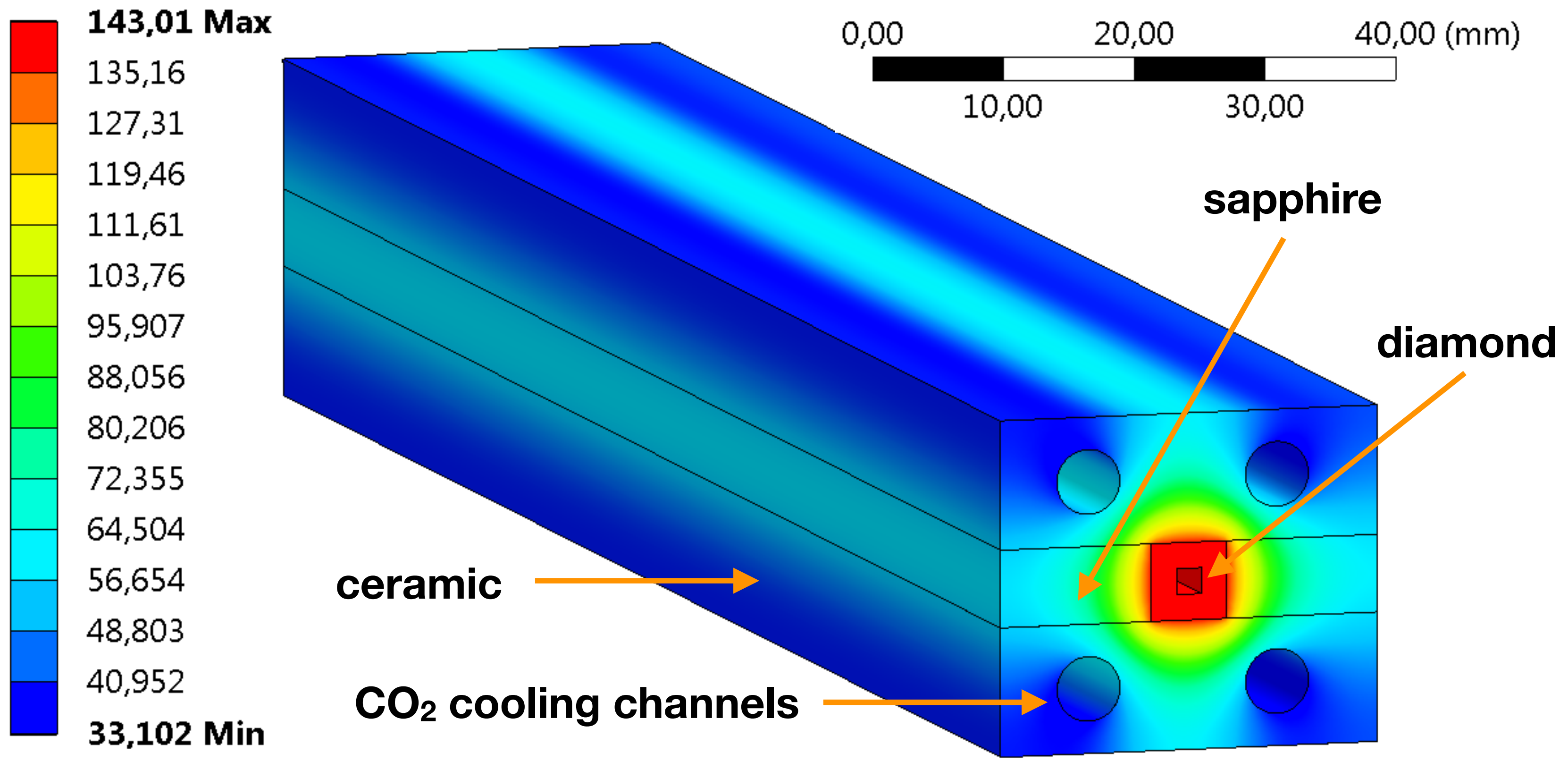
Plasma-boosted ILC-like collider at 500 GeV

Outlook and plans

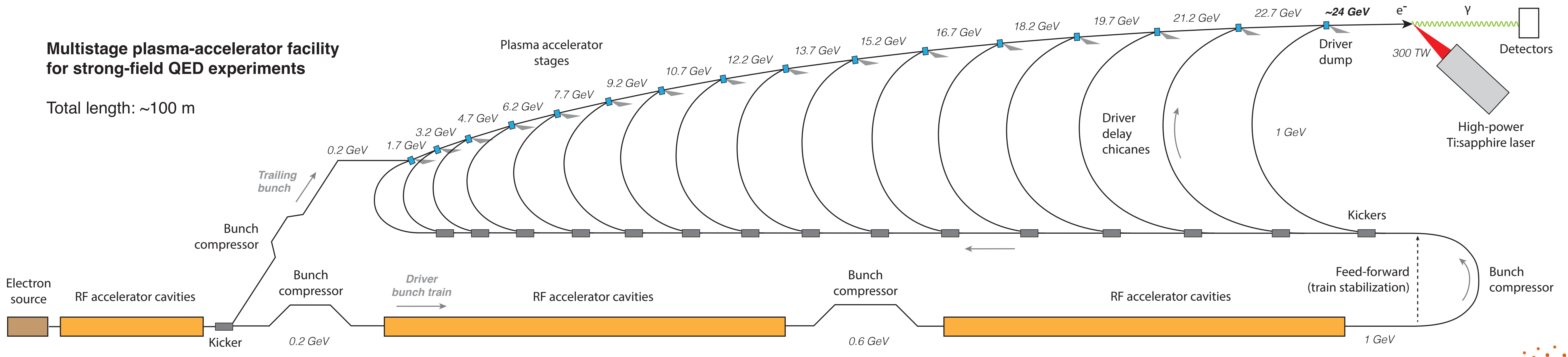
Mid-term outlook and R&D

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

European Strategy Update

‘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**