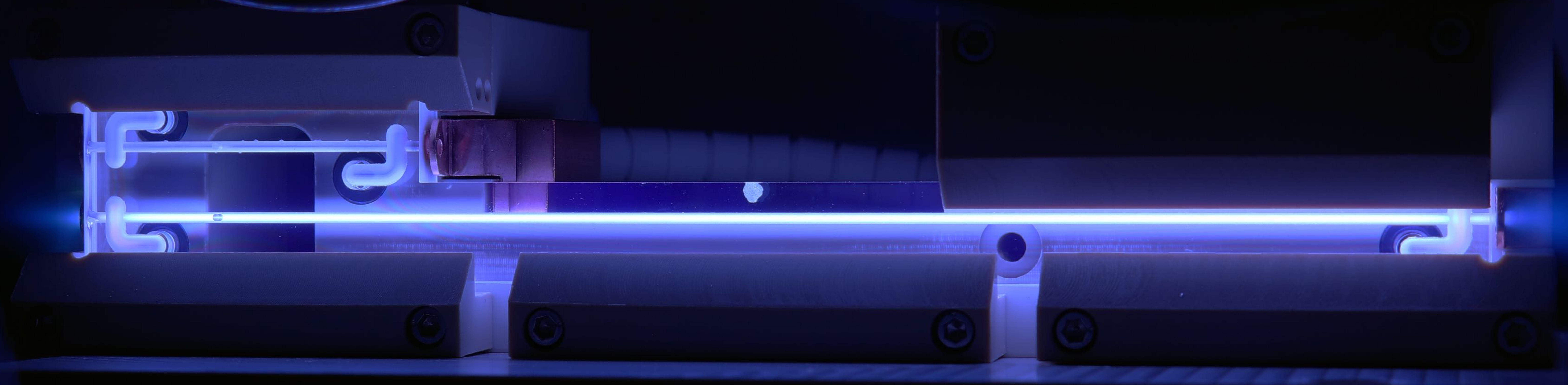
Advanced Acceleration:
Particle-Beam Drivers



Richard D'Arcy

John Adams Institute, University of Oxford

UNIVERSITY OF OXFORD

John Adams Institute for Accelerator Science

16th April 2026 | JAI Advisory Board Meeting | University of Oxford

Strong effort in advanced acceleration across the JAI

- ***Imperial***:
  - Ken Long, Stuart Mangles, Zulfikar Najmudin, Jaroslaw Pasternak, Steve Rose
- ***Oxford***:
  - Phil Burrows, Richard D'Arcy, Simon Hooker, Peter Norreys
    - *Emeriti*: Brian Foster, Roman Walczak
- ***Royal Holloway***:
  - Pavel Karataev

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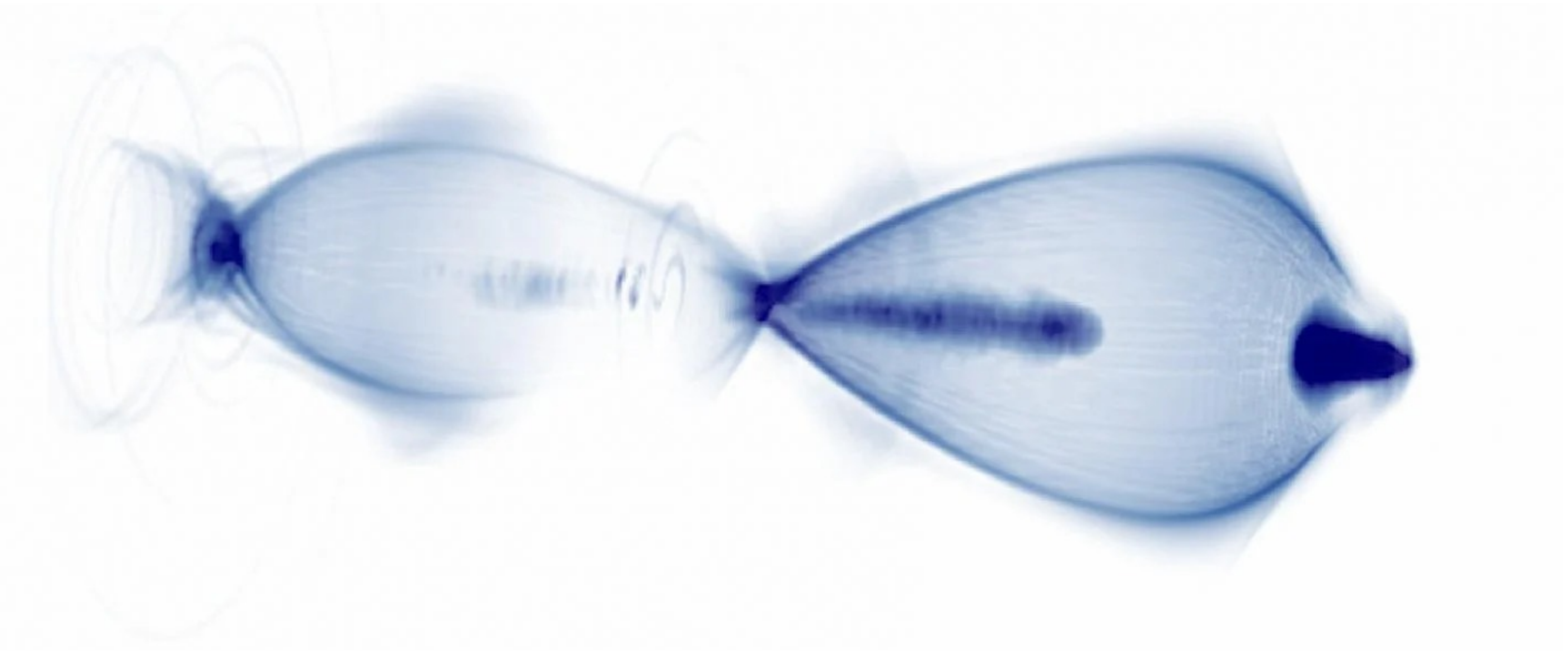
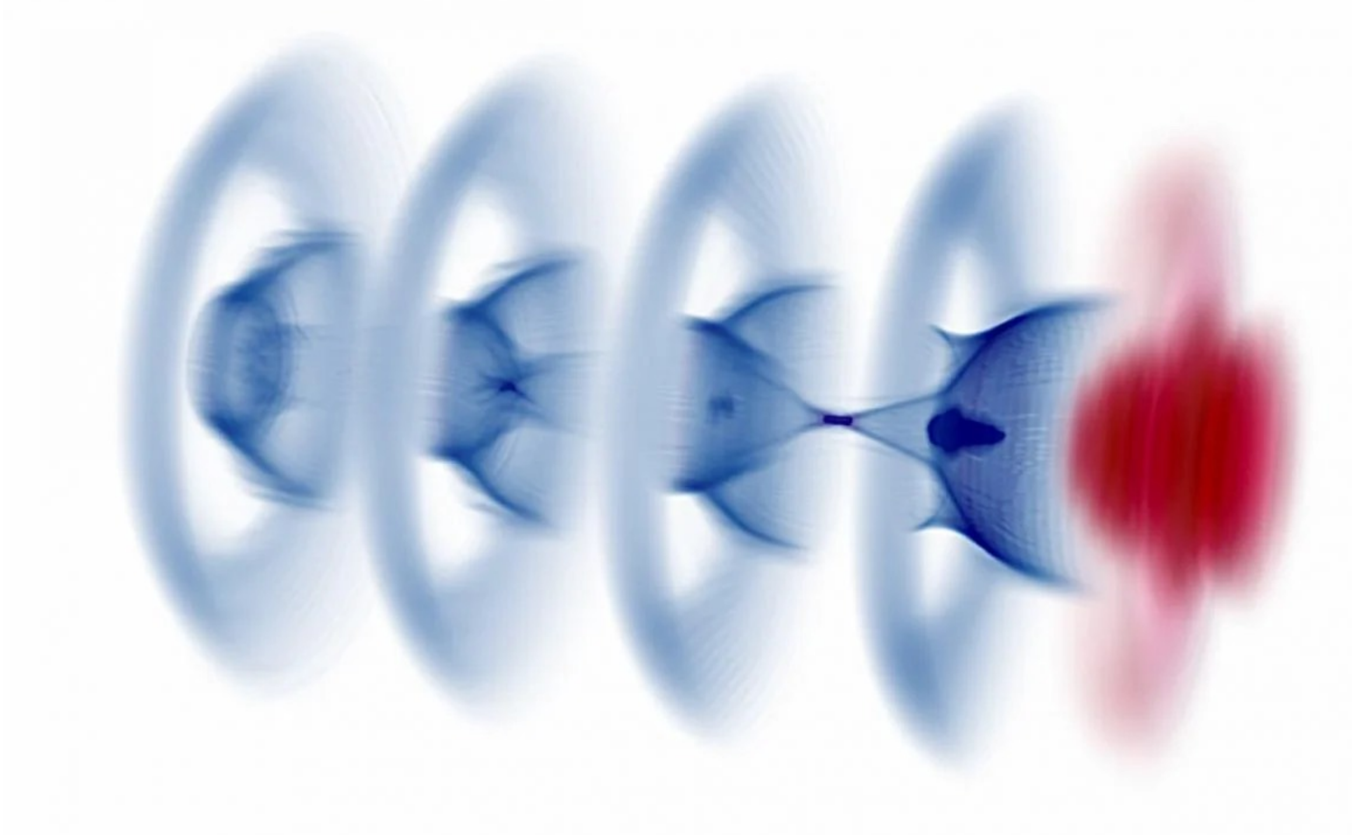
Beam-Driven



- Electron-driven (*HALHF, FLASHForward, CLARA, FACET-II*)
- Proton-driven (*AWAKE*)

Laser-Driven



- See Simon's presentation next

Plasma accelerators as a source of affordable high-energy beams

- Very **high gradients** sustainable in plasma accelerators (1-100 GV/m) could make **future machines smaller, cheaper, and greener**
  - Very recent results from LBNL showed 10 GeV energy gain in 30 cm
  - Energy is comparable with modern **free-electron lasers** but achieved in a fraction (~0.1%) of the length
- Most economic impact is expected in discovery machines requiring the highest energy e.g. **particle colliders**

- Such applications also require ***high luminosity*** **→ beam quality (<u>brightness</u>), energy efficiency,** and **<u>repetition rate</u>**
- Results from the last year from FLASHFORWARD▸▸ show further promise for acceleration of electrons in plasma…

High repetition rate

High energy efficiency

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

Low energy spread
(luminosity spectrum, final focusing)

Low emittance

Bright electron bunches from a plasma-wakefield accelerator (FF▸▸)

- **High brightness beams** are required for photon science and particle physics
- We don't care about the drive-beam quality ➞ Can we use a **poor-quality drive beam** to generate a high-quality witness?
- 'Low-quality' FLASH drive beams (>20 um emittance) transformed in to high quality witness bunches
  - 1.2 um emittance
  - 1.3% energy spread
  - 14 pC/MeV spectral density
  - High reproducibility
- 3D brightness boost (measured) of ~4x over the driver
- 6D brightness boost (simulated) of >1000x

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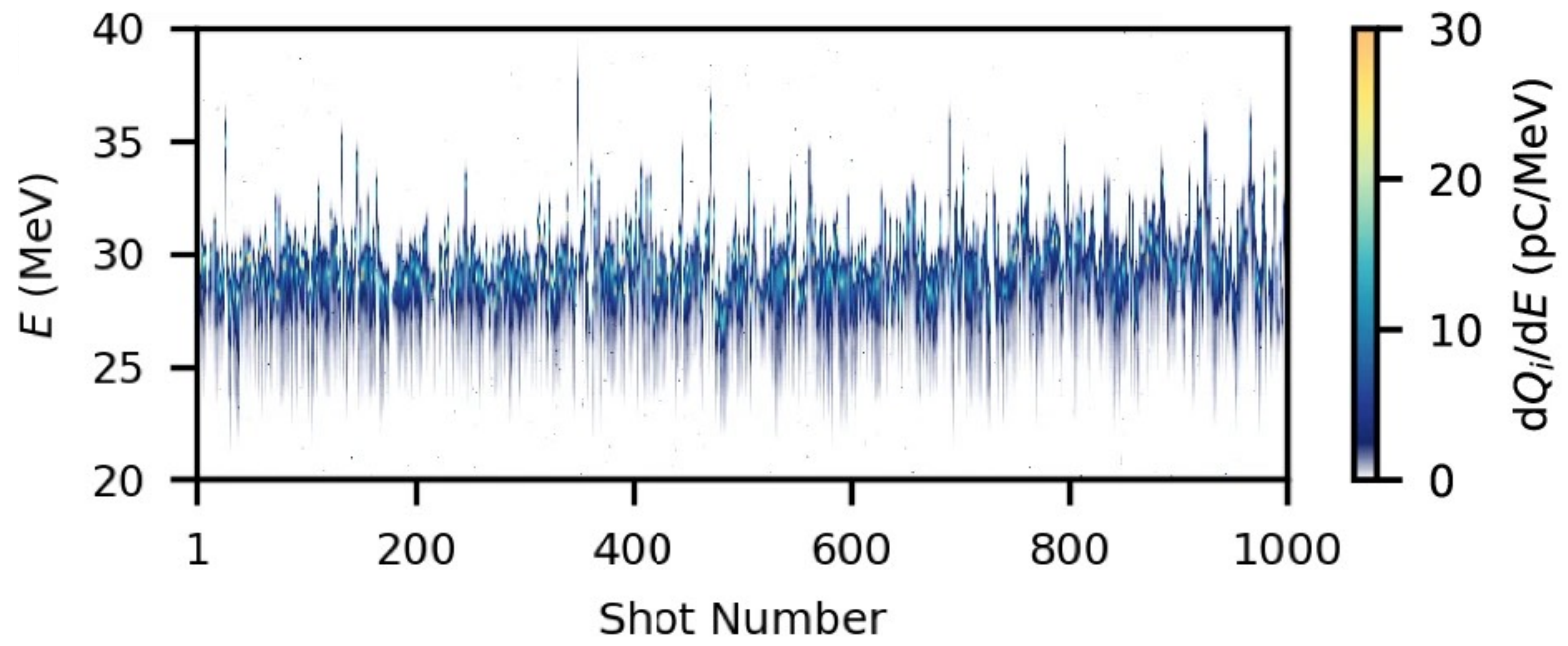
Article | Open access | Published: 11 February 2026

Bright electron bunches from a plasma-wakefield accelerator with a steep density down-ramp

J. C. Wood, L. Boulton, J. Beinortaitė, J. Björklund Svensson, S. Bohlen, G. Boyle, J. M. Garland, P. Gonzalez Caminal, C. A. Lindstrøm, G. Loisch, S. M. Mewes, T. Parikh, F. Peña, K. Põder, S. Schröder, M. Thévenet, S. Wesch, J. Osterhoff & R. D'Arcy

Nature Communications **17**, Article number: 1588 (2026) | Cite this article

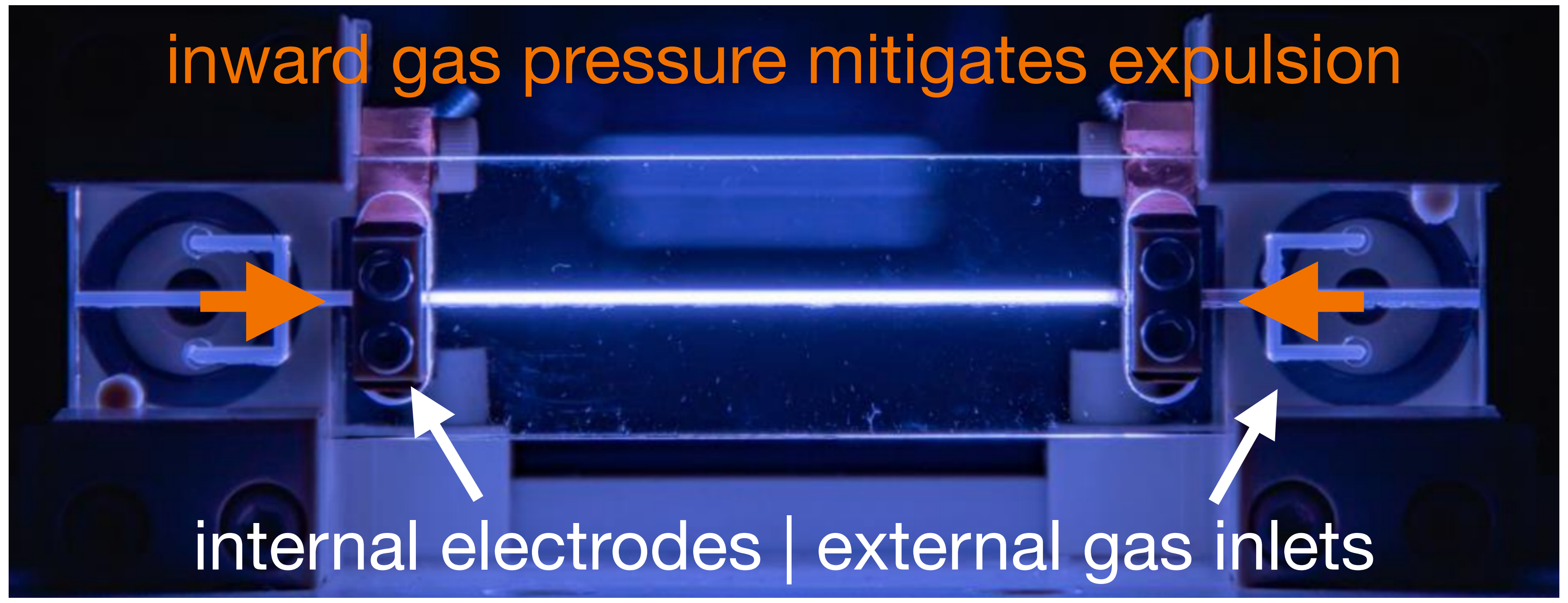


MHz repetition rate acceleration in plasma wakefields (FF▸▸)

> State of the art in repetition rate in plasma is ~Hz-level but FLASH is capable of MHz repetition rates

> **Missing piece** — a plasma source capable of sustaining similar plasma density over many μs

> Novel design to mitigate expulsion of plasma in to vacuum and regenerate plasma at MHz rates

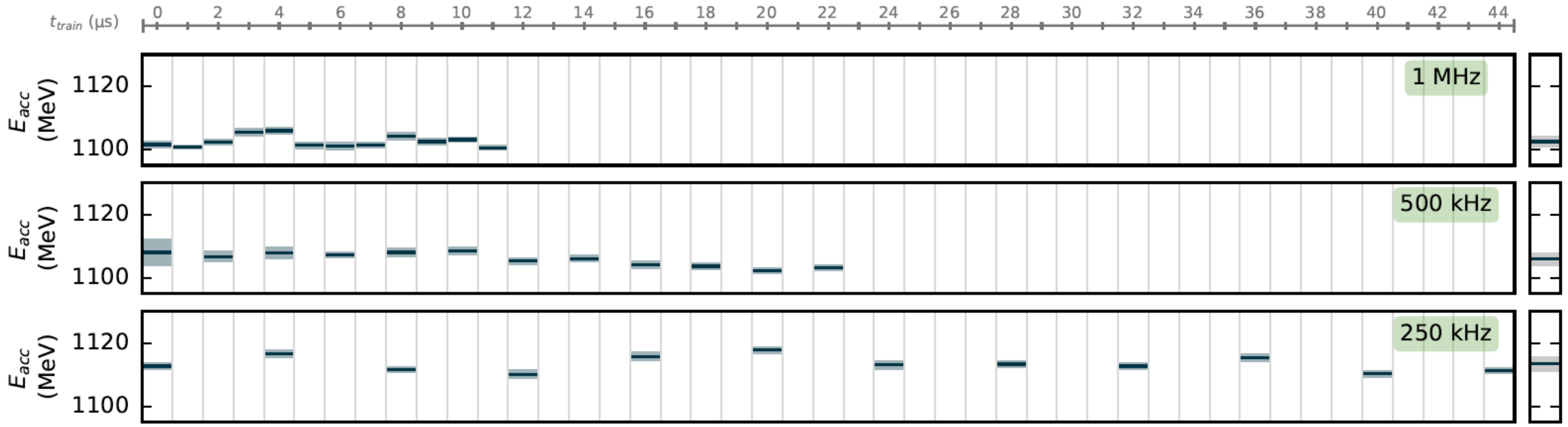


> Proof-of-principle results show **acceleration** of short trains (12 bunches) at **0.25, 0.5, and 1 MHz repetition rate**

> Builds on the promise of the recovery time result (~10 MHz)

→ D'Arcy *et al.*, Nature **603** (2022)

> First steps towards scaling up to high average power

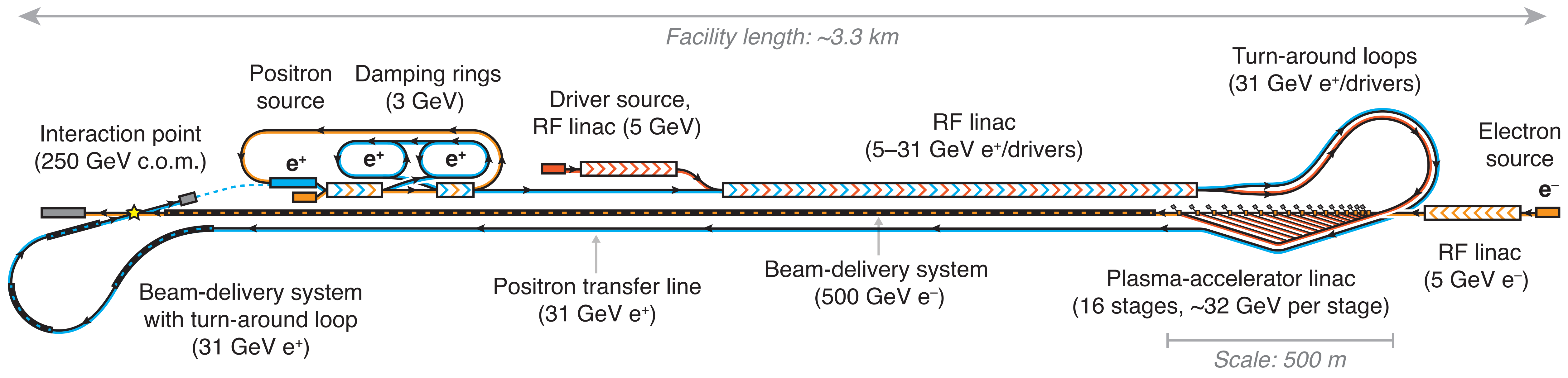


G. Loisch *et al.*, Nature (under review)

HALHF — a hybrid, asymmetric, linear Higgs factory

> Continued strong progress in plasma acceleration (of electrons) further motivates HALHF

> Original concept proposed in 2023 ➞ Foster, D'Arcy, & Lindstrøm, New J. Phys. **25** (2023)

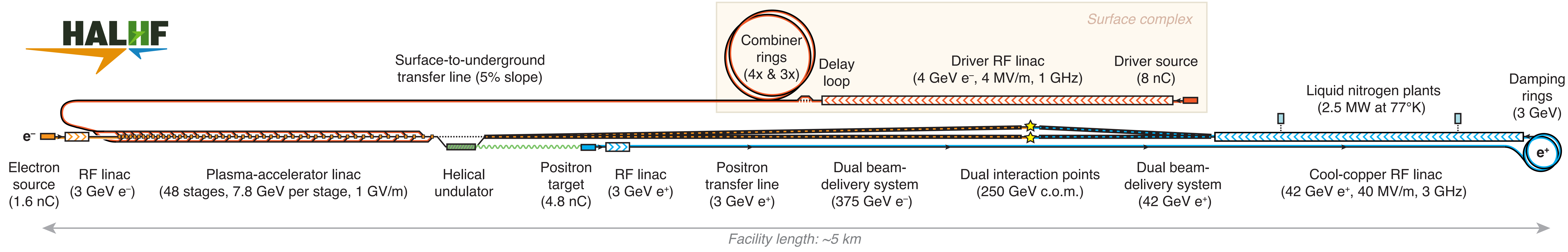


Source: Foster, D'Arcy & Lindstrøm, New. J. Phys. 25, 093037 (2023)

> Engagement with the community led to iteration and refinement of the design

> Developed a cost model (all collider subsystems scaled from ILC/CLIC) and optimised for 'Full Programme Cost' using Bayesian optimisation

HALHF 2.0 — an updated baseline design (2025)



Source: Foster et al., Phys. Open 23, 100261 (2025)

> Separate RF linacs for e- drivers (high I_{avg}, low E_z) and e^+ beams (low I_{avg}, high E_z)

> Reducing the driver energy (compatible with CLIC tech)

> Lower plasma density (lower E_z but better tolerances)

> Many more plasma stages (48 in total)

> Polarised e^- and e^+ (ILC-like helical undulator source)

> Combiner rings to decrease I_{peak} in the driver linac, and shorten the e^+ bunch train

> Two interaction points/detectors

Optimised for cost: **3.8B CHF →** ~40% of ILC, ~60% of CLIC

HALHF — ESPPU and next steps

- New baseline, costings, required resources, staged R&D plan, and subsystem TRLs submitted to the ESPPU
- Over 50 signatories
- Also part of the LCVision Process

arXiv > physics > arXiv:2503.19880

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Physics > Accelerator Physics

[Submitted on 25 Mar 2025 (v1), last revised 30 Mar 2025 (this version, v2)]

HALHF: a hybrid, asymmetric, linear Higgs factory using plasma- and RF-based acceleration

Erik Adli, Joshua Appleby, Timothy L. Barklow, Marica Biagini, Jonas Björklund Svensson, Mikael Berggren, Simone Bettoni, Stewart Boogert, Philip Burrows, Allen Caldwell, Jian Bin Ben Chen, Vera Cilento, Laura Corner, Richard D'Arcy, Steffen Doebert, Wang Dou, Pierre Drobniak, Calvin Dyson, Sinead Farrington, John Farmer, Angeles Faus-Golfe, Manuel Formela, Arianne Formenti, Louis Forrester, Brian Foster, Jie Gao, Spencer Gessner, Niclas Hamann, Alexander Harrison, Mark J. Hogan, Eir Eline Hørlyk, Daniel Kalvik, Antoine Laudrain, Reme Lehe, Wim Leemans, Carl A. Lindstrøm, Benno List, Jenny List, Xueying Lu, Edward Mactavish, Vasyl Maslov, Emilio Nanni, John Osborne, Jens Osterhoff, Felipe Peña, Gudrid Moortgat Pick, Kristjan Põder, Jurgen Reuter, Dmitrii Samoilenko, Nela Sedlackova, Andrei Seryi, Kyrre Sjobak, Terry Sloan, Steinar Stapnes, Rogelio Tomas Garcia, Maxim Titov, Malte Trautwein, Maxence Thévenet, Nicholas J. Walker, Marc Wenskat, Matthew Wing, Jonathan Wood

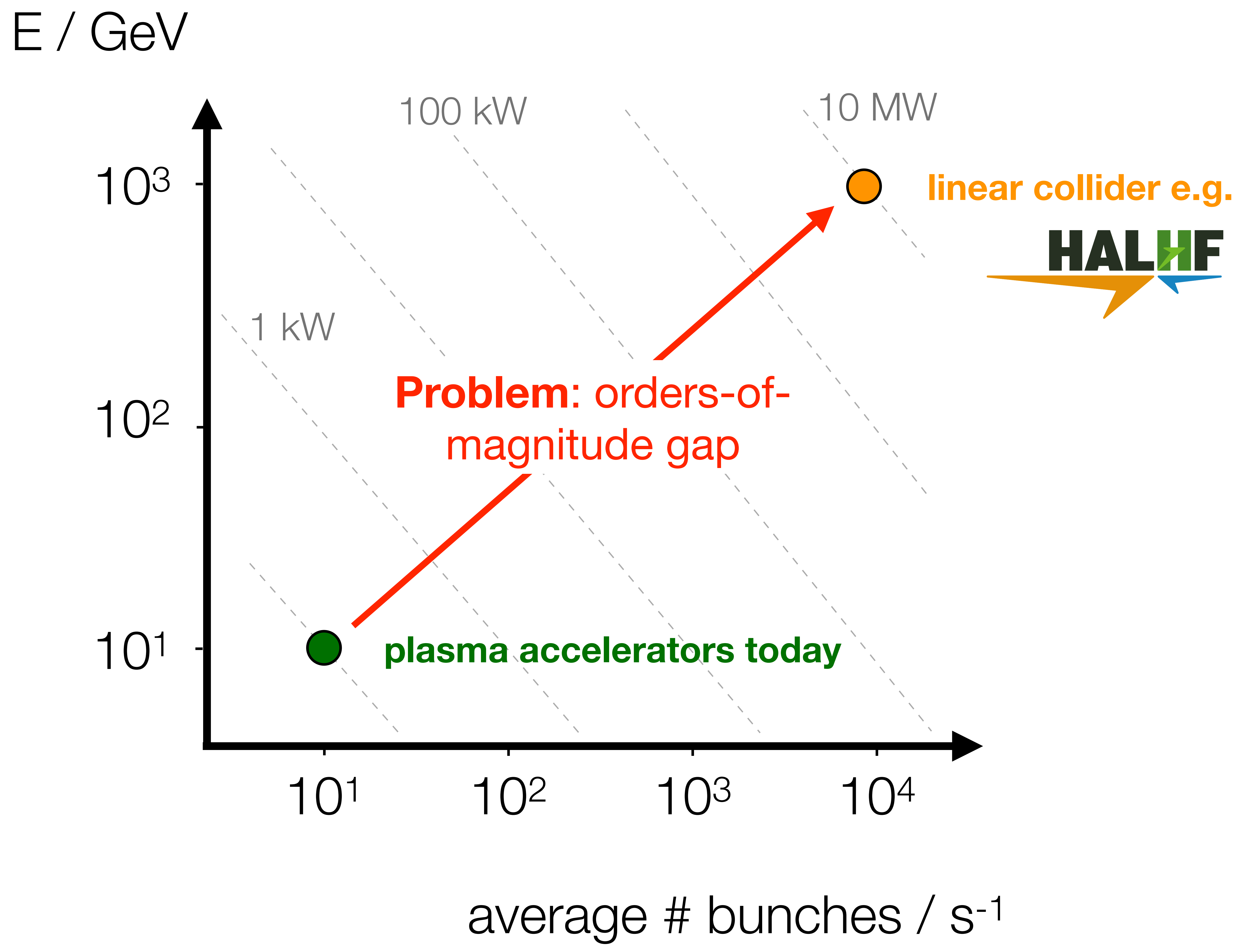
HALHF is a hybrid linear collider that uses electron-driven plasma-wakefield acceleration to accelerate electrons to high energy while using radio-frequency cavity technology to accelerate positrons. The most cost-effective solution collides low-energy positrons with high-energy electrons, producing a boost to the final state in the electron direction with $\gamma = 1.67$. The current HALHF baseline design produces a luminosity comparable to that of the baseline ILC but with a greatly reduced construction and carbon footprint and hence much lower cost than the mature linear-collider designs ILC and CLIC. Costs for HALHF are evaluated, together with that for the approximate 15-year R\&D programme necessary to realise HALHF. Time scales and cost for the R\&D are estimated. Upgrade paths for HALHF technology from a 250~GeV Higgs factory, through 380 and 550~GeV, up to 10~TeV are sketched.

Comments: Submitted to the European Strategy for Particle Physics, 2026 Update
Subjects: Accelerator Physics (physics.acc-ph)
Cite as: arXiv:2503.19880 [physics.acc-ph]
(or arXiv:2503.19880v2 [physics.acc-ph] for this version)
https://doi.org/10.48550/arXiv.2503.19880

ESPPU submission document for HALHF

- ***Next step***
  - Finalise first stage of conceptual design in a pre-CDR document (summer 2026)

Energy and luminosity requirements for HEP require new concepts



- **High energy** (staging*)
  - **1)** Novel inter-stage optics schemes
- **High repetition rate** (luminosity)
  - **2)** Long-timescale (*fs-μs*) plasma simulations
  - **3)** Temperature-based energy mapping

✱ Large energy gain can be achieved in a single stage using a highly energetic proton driver

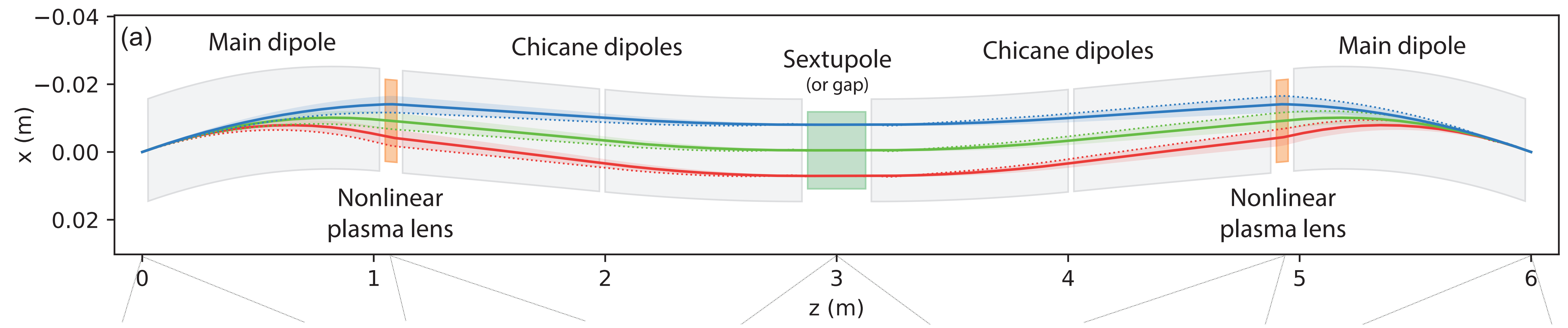
→ will be covered in the AWAKE section later in the talk

1) Novel inter-stage optics schemes

UNIVERSITY OF OSLO · UNIVERSITY OF OXFORD

> The combination of large energy spread and high divergence (exiting the plasma stage) necessitates achromatic optics

> New achromatic solution proposed, based on local chromaticity correction (with ***nonlinear*** plasma lenses) in a chicane

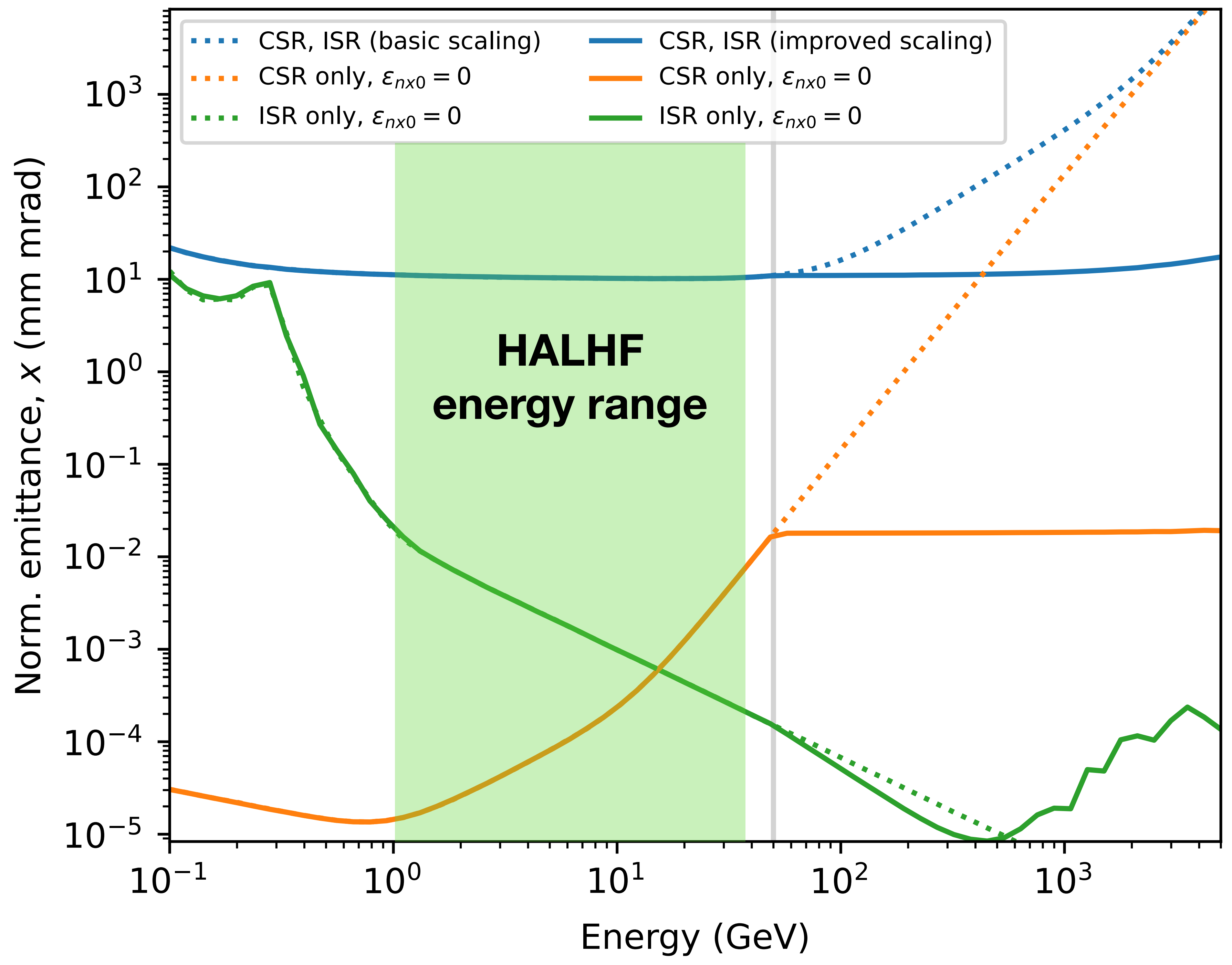


> Staging solution simulated in ImpactX to investigate energy scalability ➞ *emittance preserving over HAHLF energy range*

> CSR causes emittance growth at low energies (<0.5 GeV)

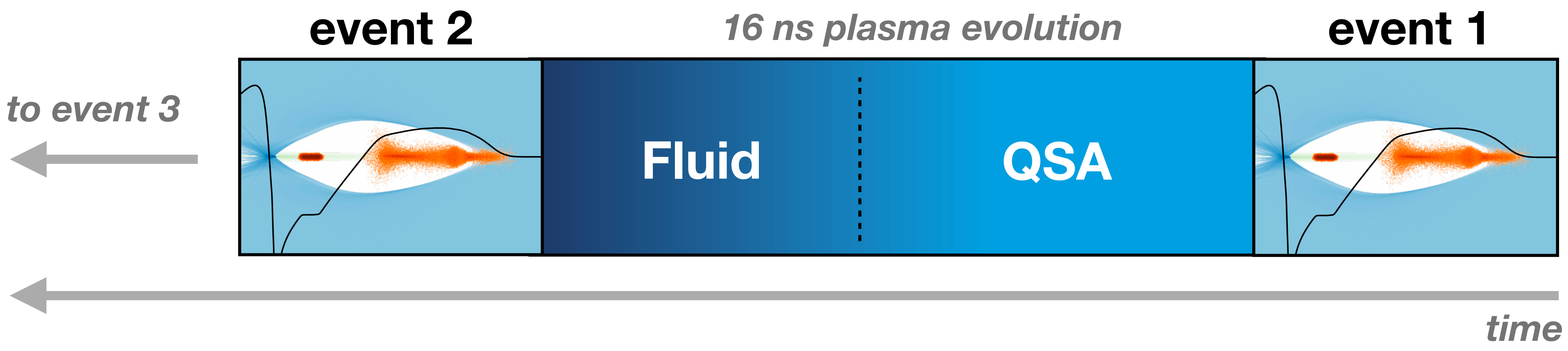
> ISR disruptive at high energies (>500 GeV)

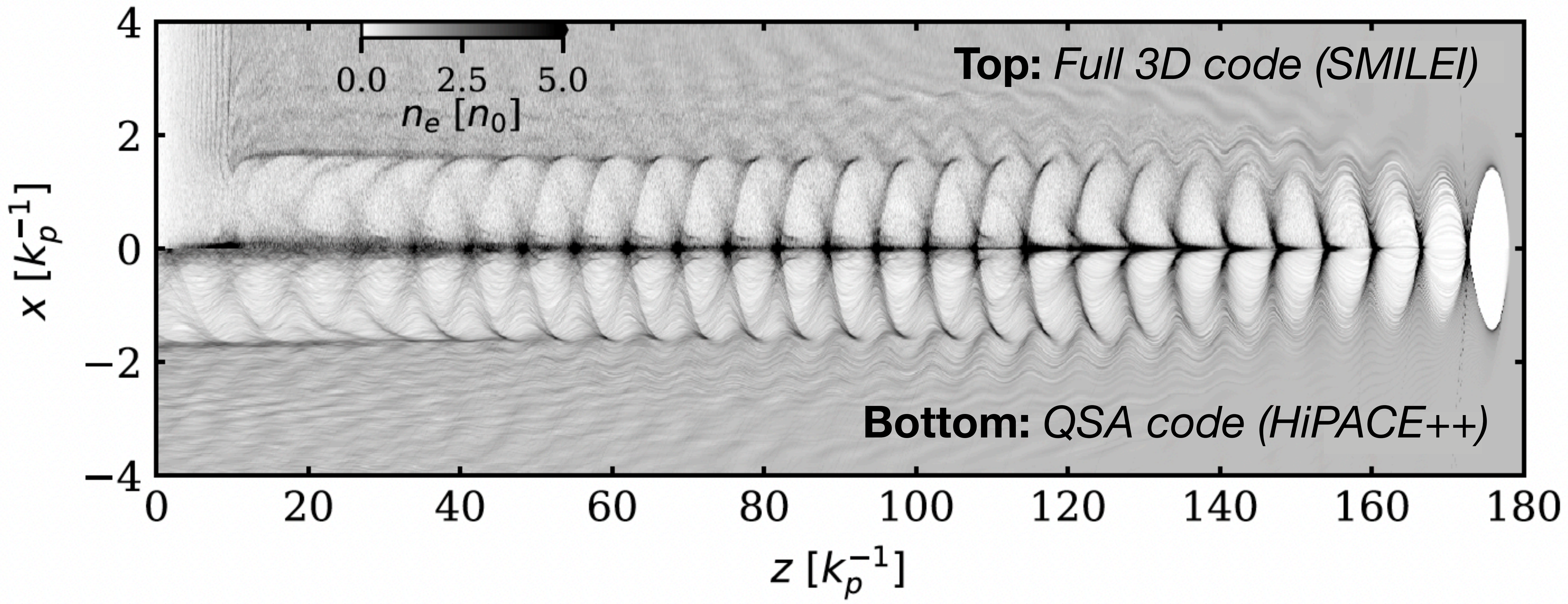
> **Next**: Build prototype and test at (plasma-)accelerator facility



2) Plasma simulations of high-rate bunch trains

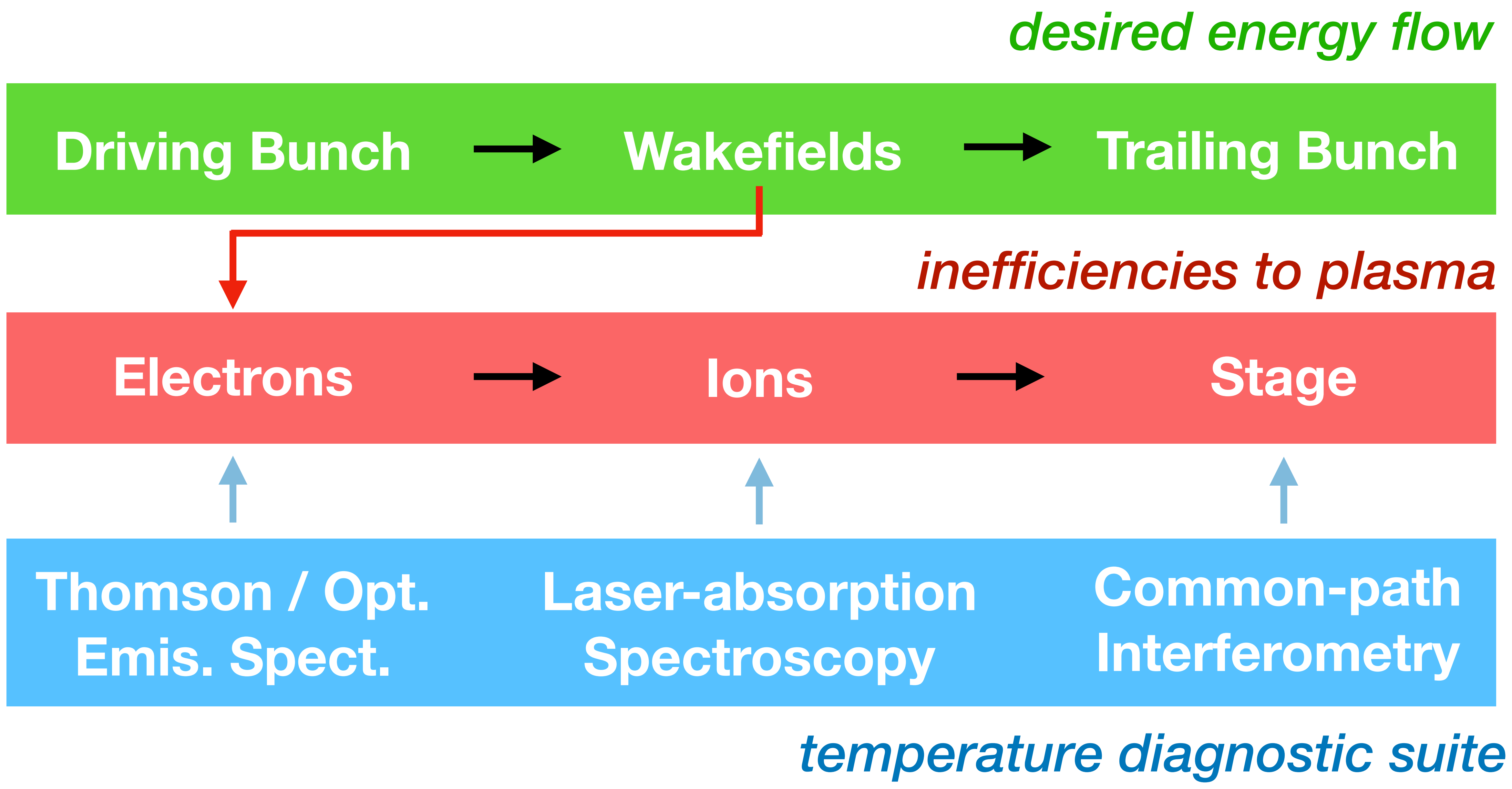
- Need self-consistent simulations of plasma evolution between acceleration events (*16 ns at HALHF*)
  - Temporal analogue of two plasma stages
  - Computationally prohibitive
- New fast/cheap scheme based on quasi-static PIC + Fluid
- Recently benchmarked against 3D PIC over short timescales →
- **Next**: Complete the simulation pipeline and benchmark against results from plasma-accelerator facilities

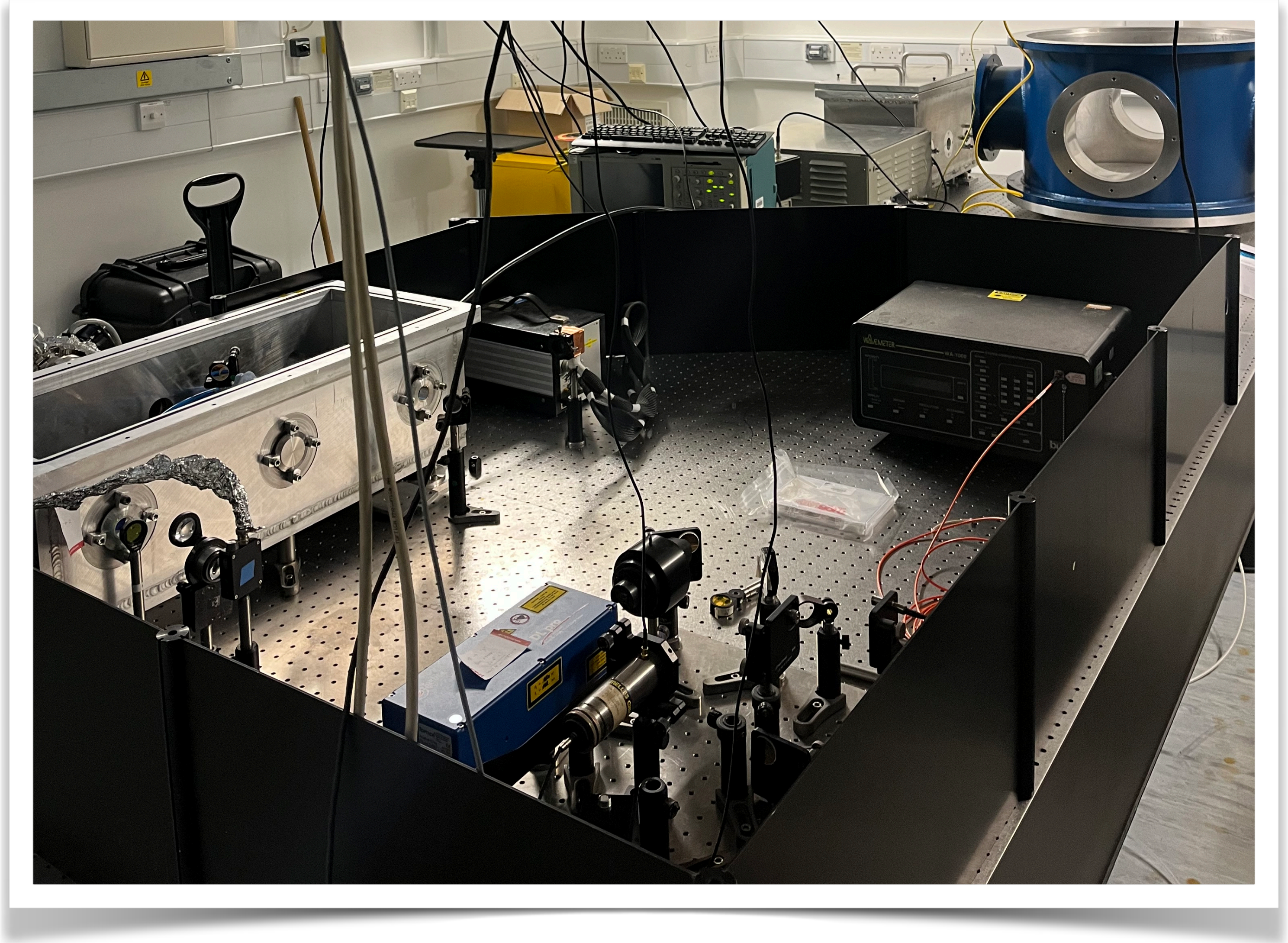




3) Direct diagnostics for plasma (and stage) heating

- Each HALHF bunch train will deposit **1.6 kJ in the plasma in ~2 μs** (*due to inefficiencies in the wakefield process*)
- Open Questions — Where does this energy go? How does it affect the wakefield process? Can we manage the thermal load?
- Developing an all-optical diagnostic suite to track the thermal evolution of the energy in the plasma accelerator
- Dedicated Oxford Physics lab for benchmarking with a discharge capillary
  - Preliminary results taken with all individual diagnostics
- **Next**: Implement at plasma-accelerator facilities





HALHF@CLARA

> CLARA completed full-energy commissioning end of 2025

> Currently at the end of a ‘Friendly User’ run (Jan-Apr 2026)

> HALHF@CLARA the final experiment (currently in fifth week of a five-week experimental period)

> **Experimental goals** (*this beam time*):

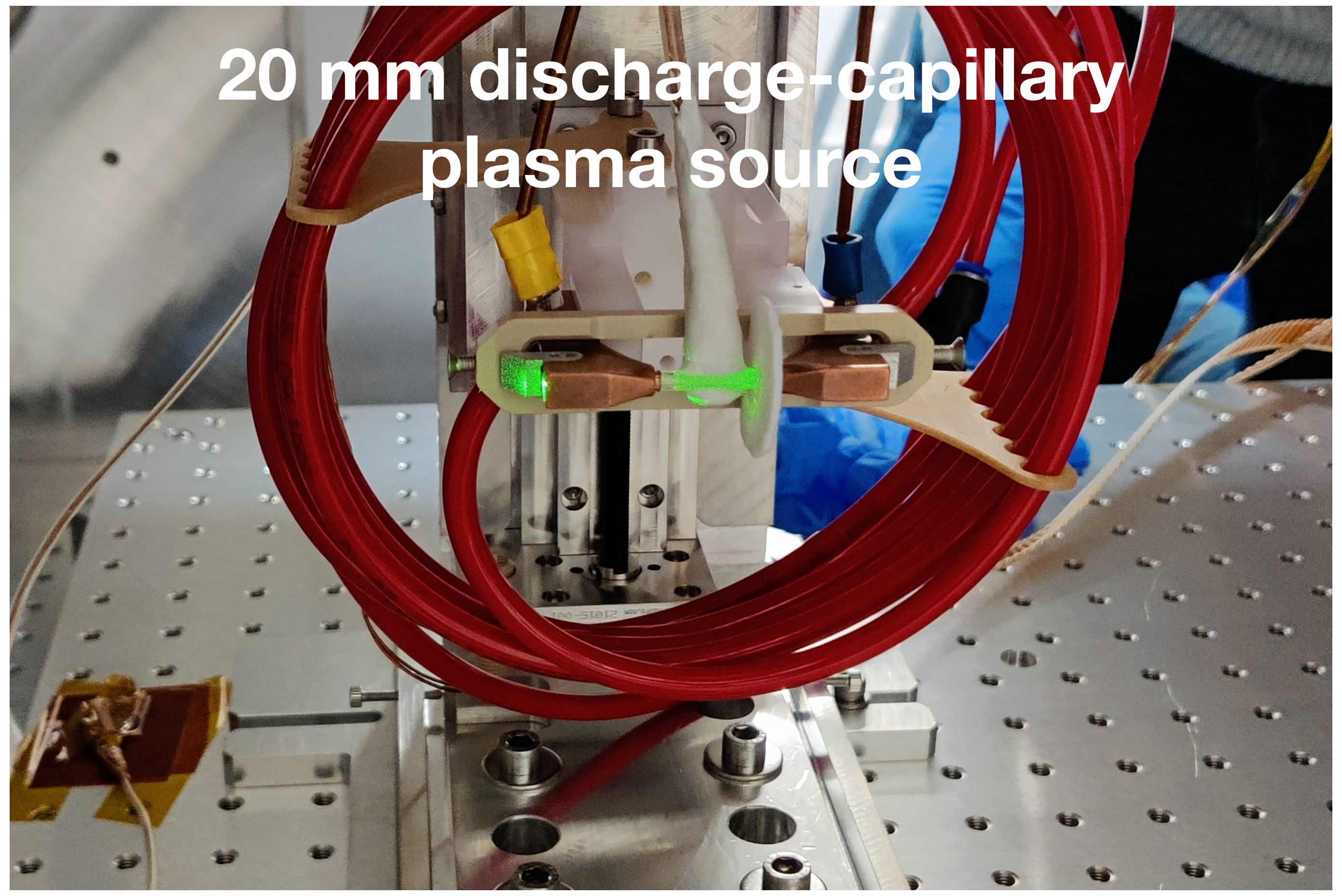
> > Install plasma-accelerator infrastructure at CLARA

> > First generation of plasma at CLARA with a discharge capillary (technology pioneered by Hooker *et al.*)

> > Drive a plasma wake with a CLARA beam

> > > **Stretch goal**: Generate GV/m (decelerating) gradients

> > Demonstrate plasma lensing with emittance preservation



HALHF@CLARA

UNIVERSITY OF OXFORD | UNIVERSITY OF OSLO | MANCHESTER 1824 The University of Manchester | UKRI Science and Technology Facilities Council ASTeC

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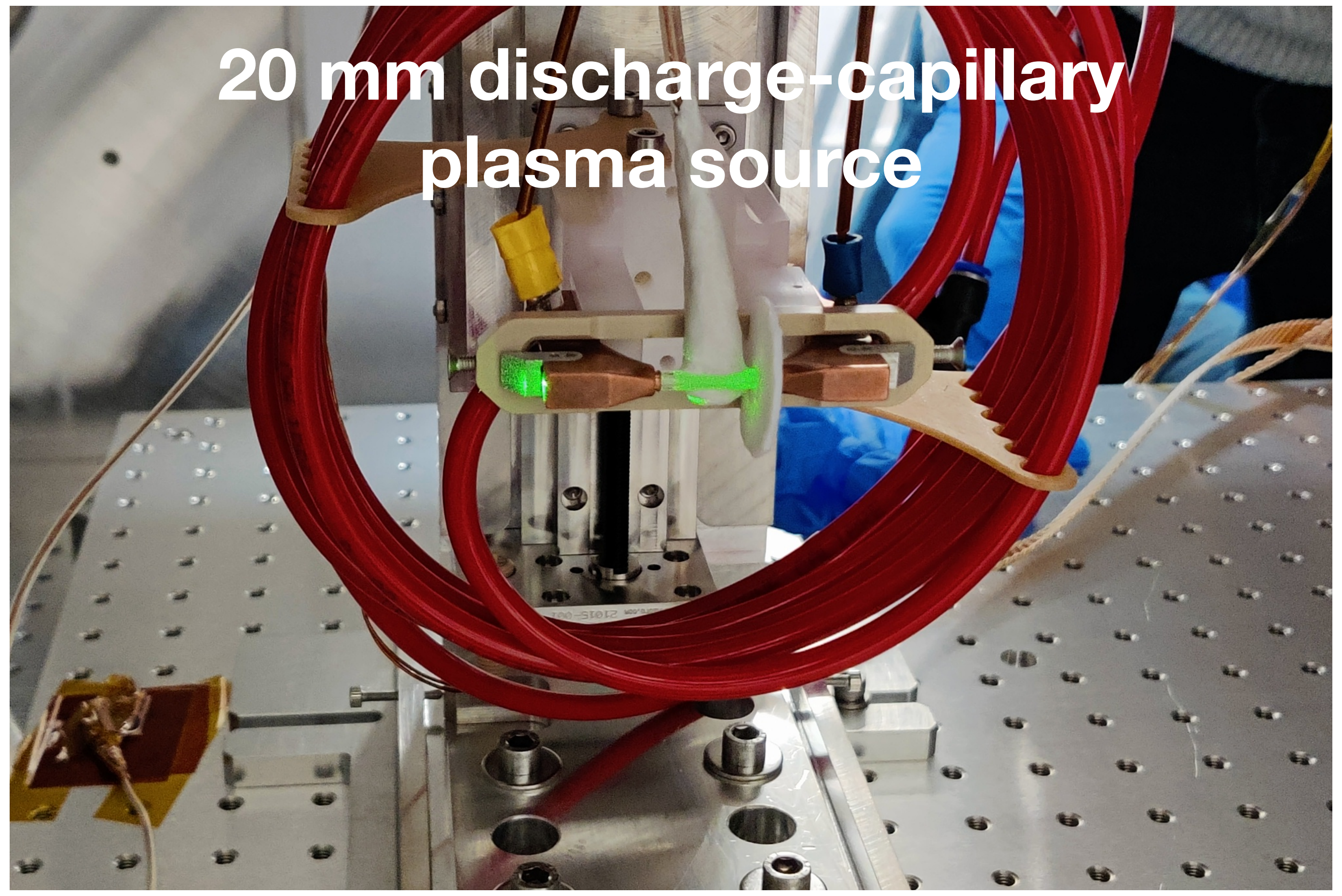

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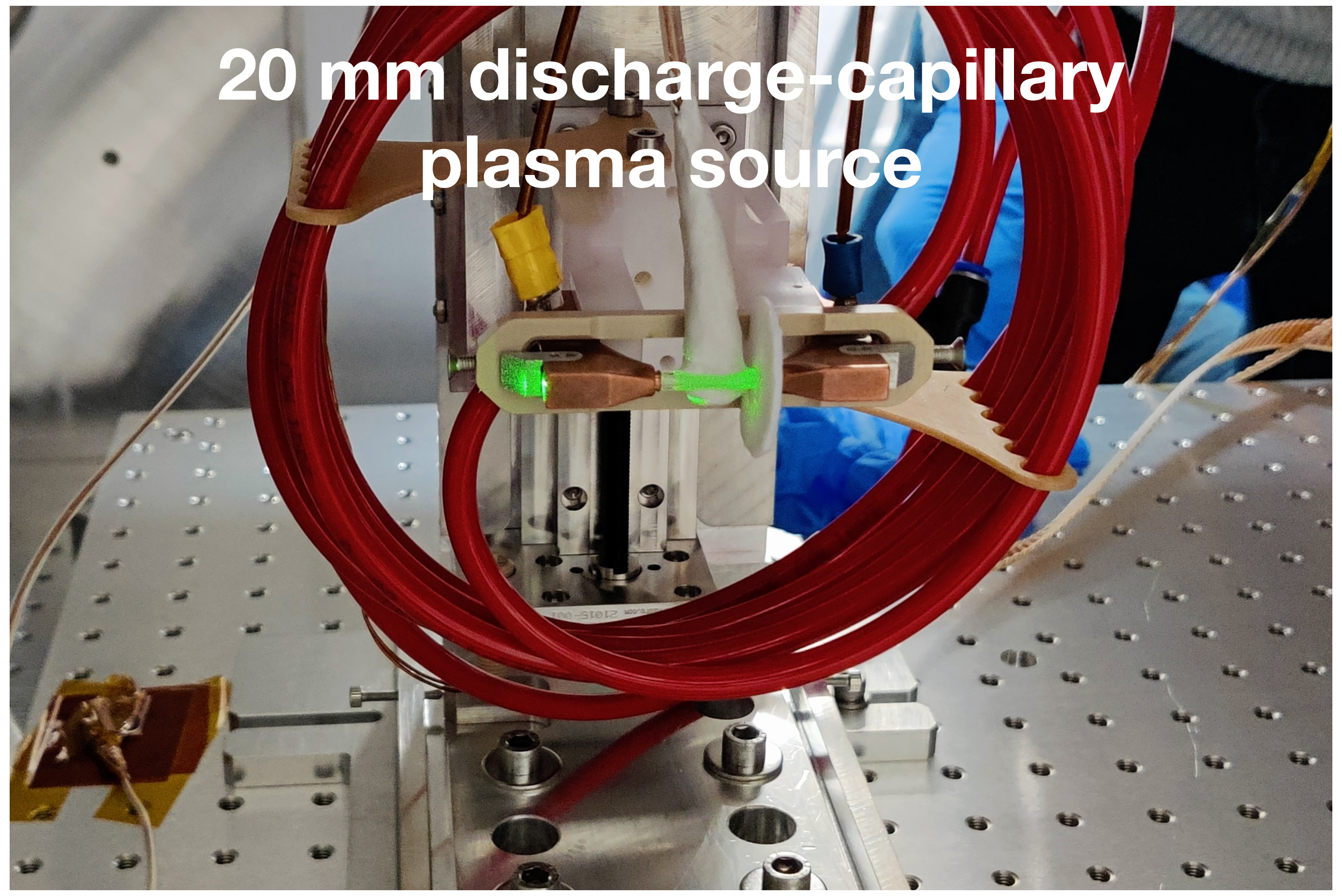

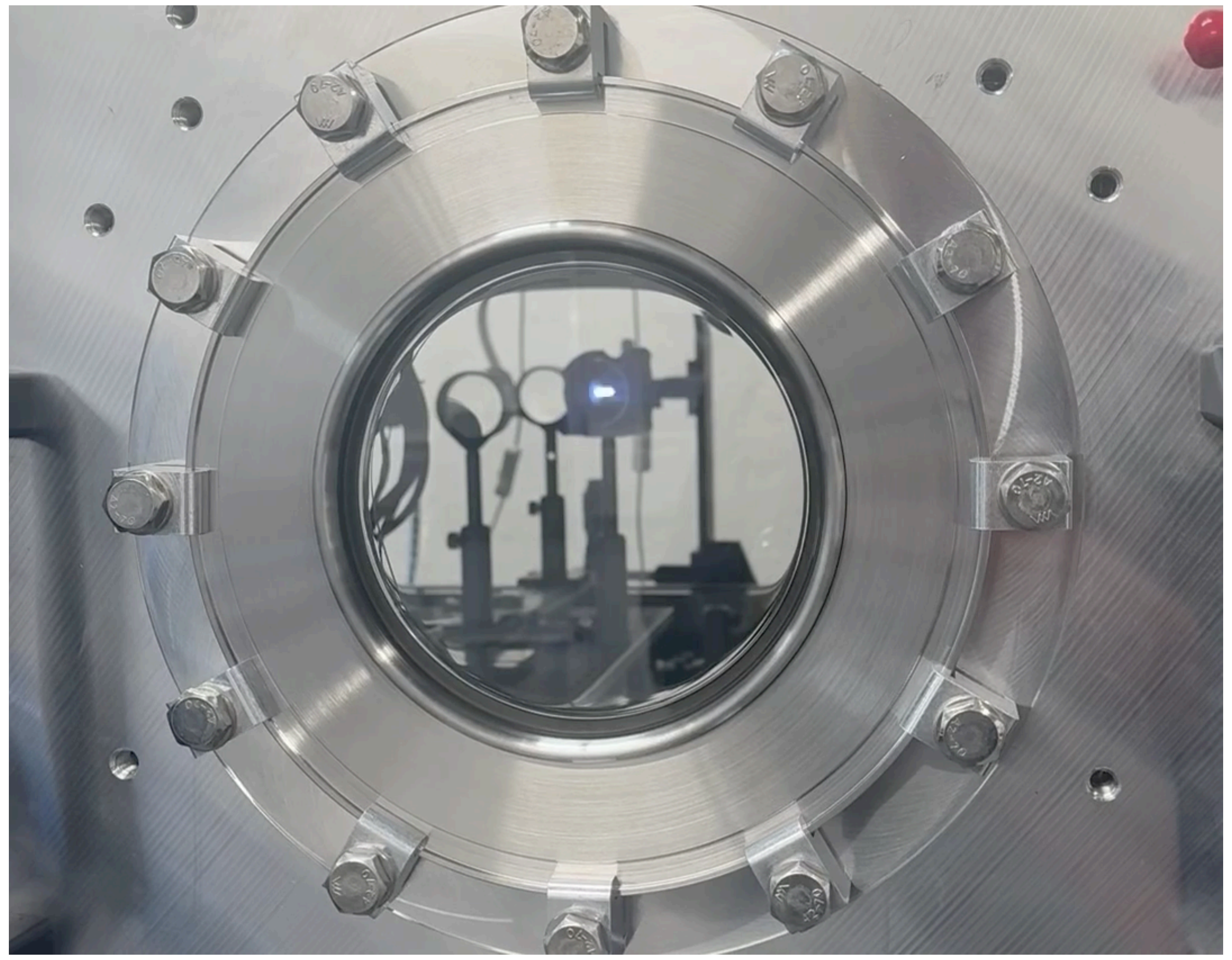

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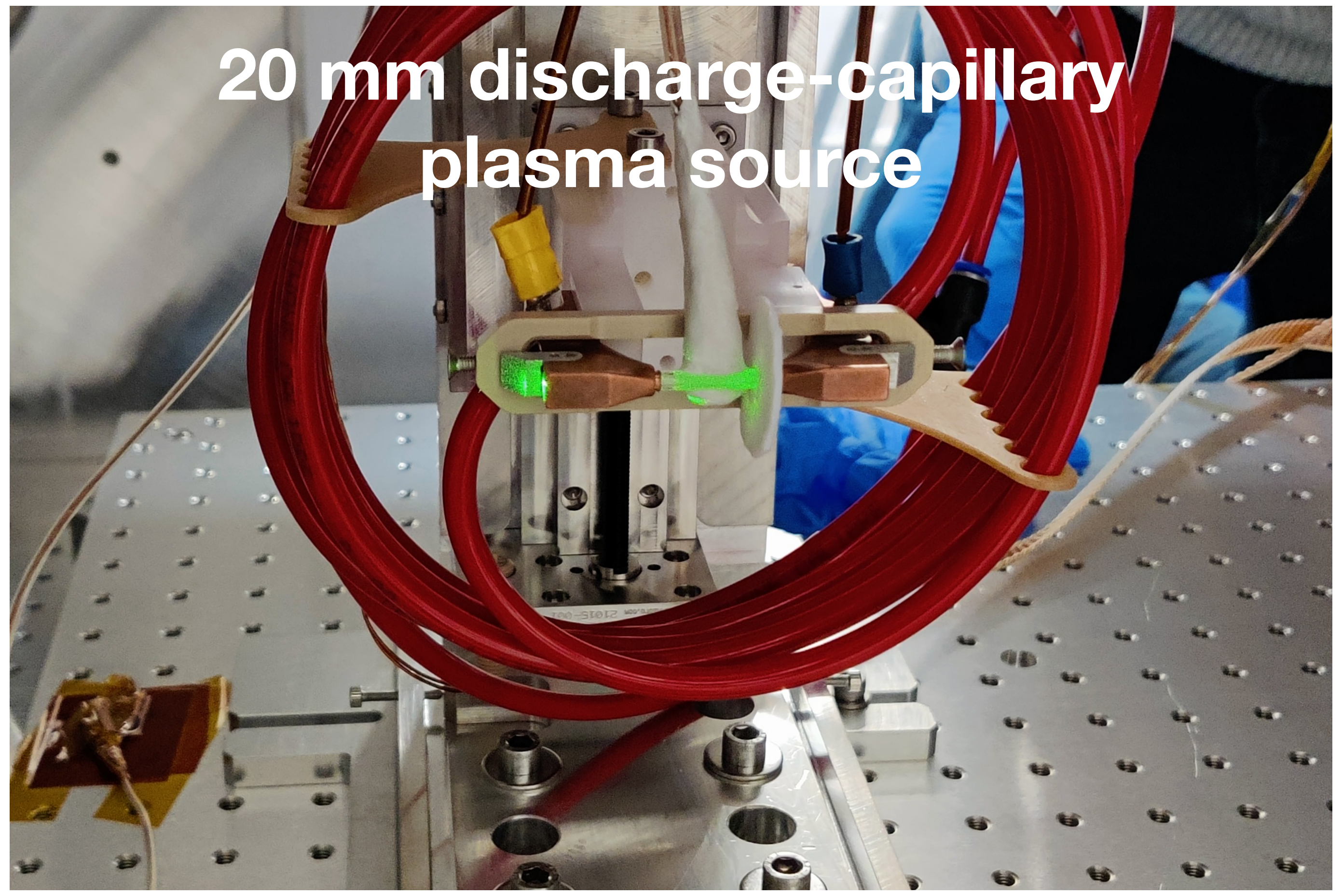
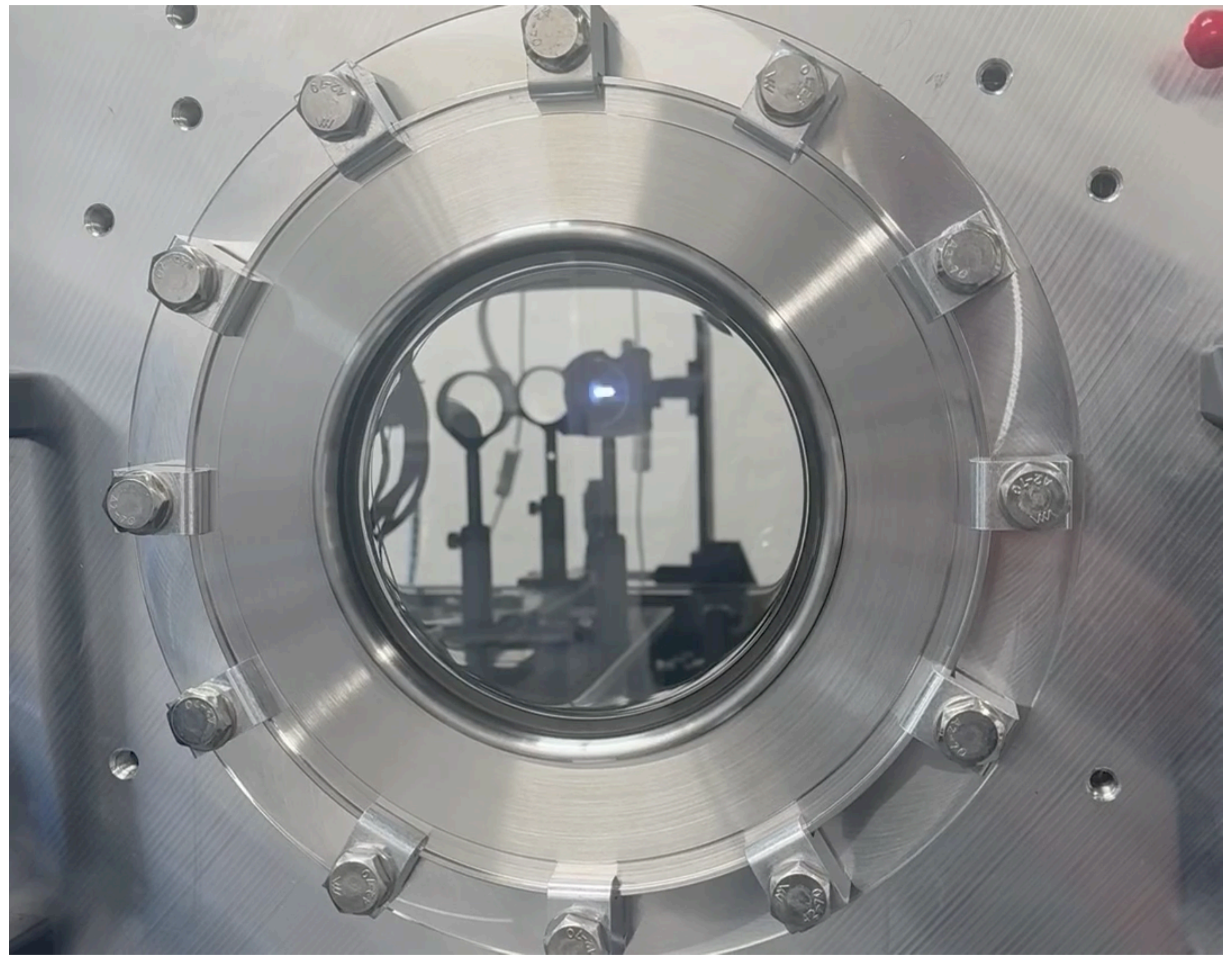
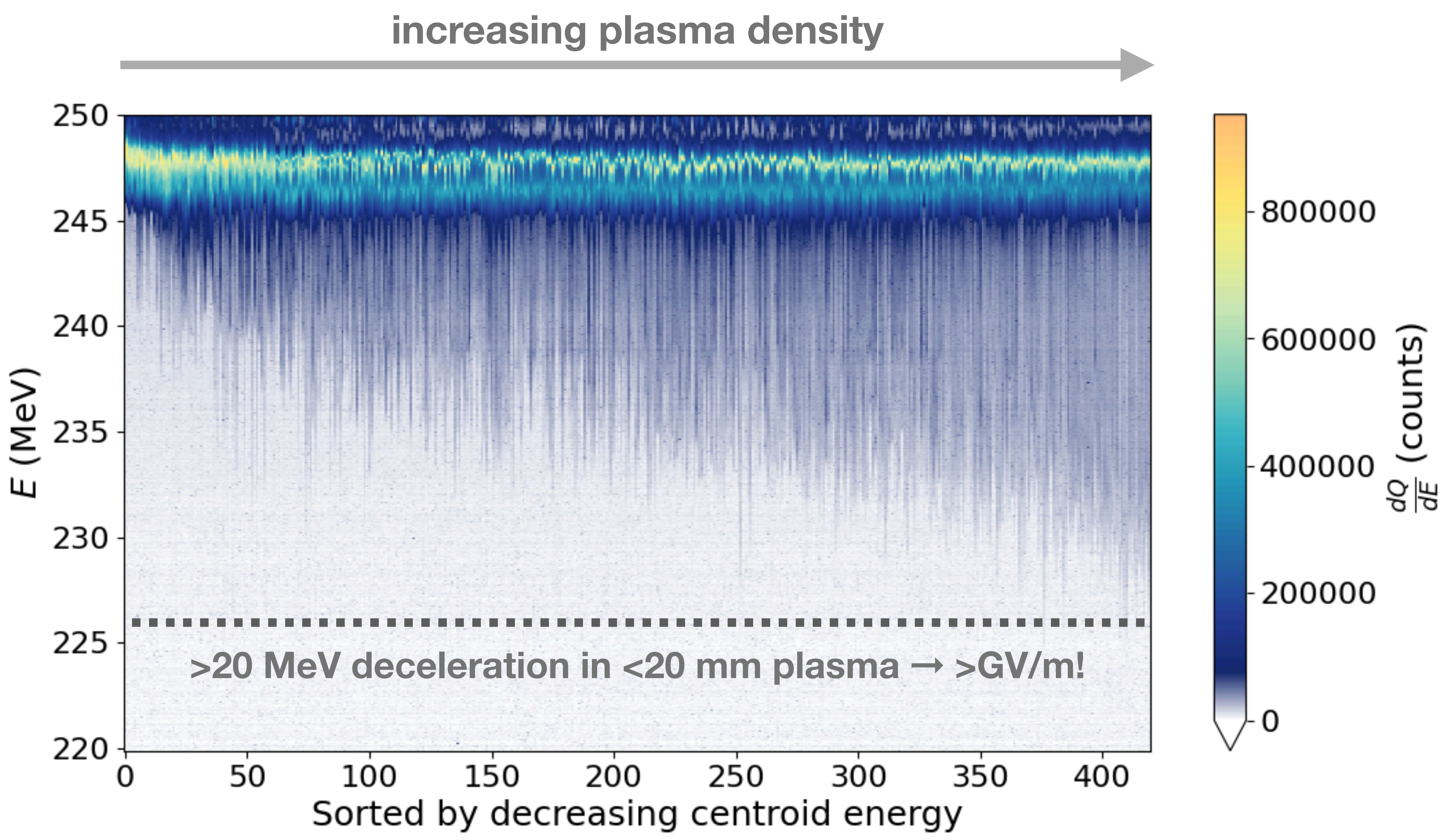




HALHF@CLARA

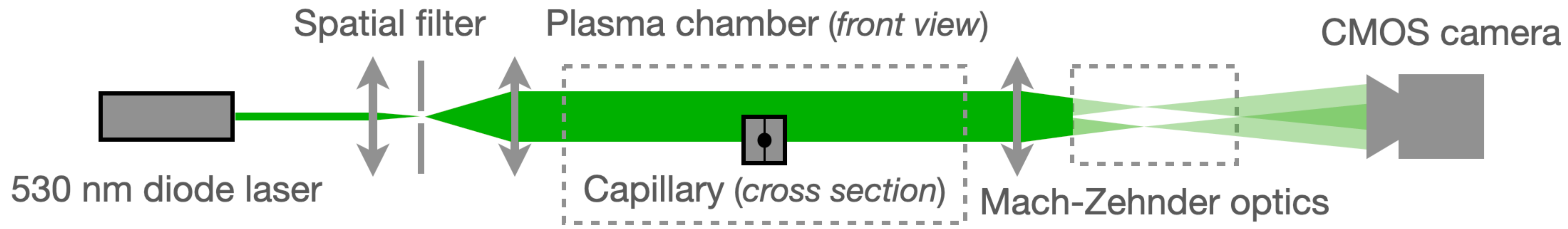
- > **GV/m gradients achieved** on the final day of plasma-wakefield experimentation the first beam time
- > First beam-driven plasma *accelerator* in UK

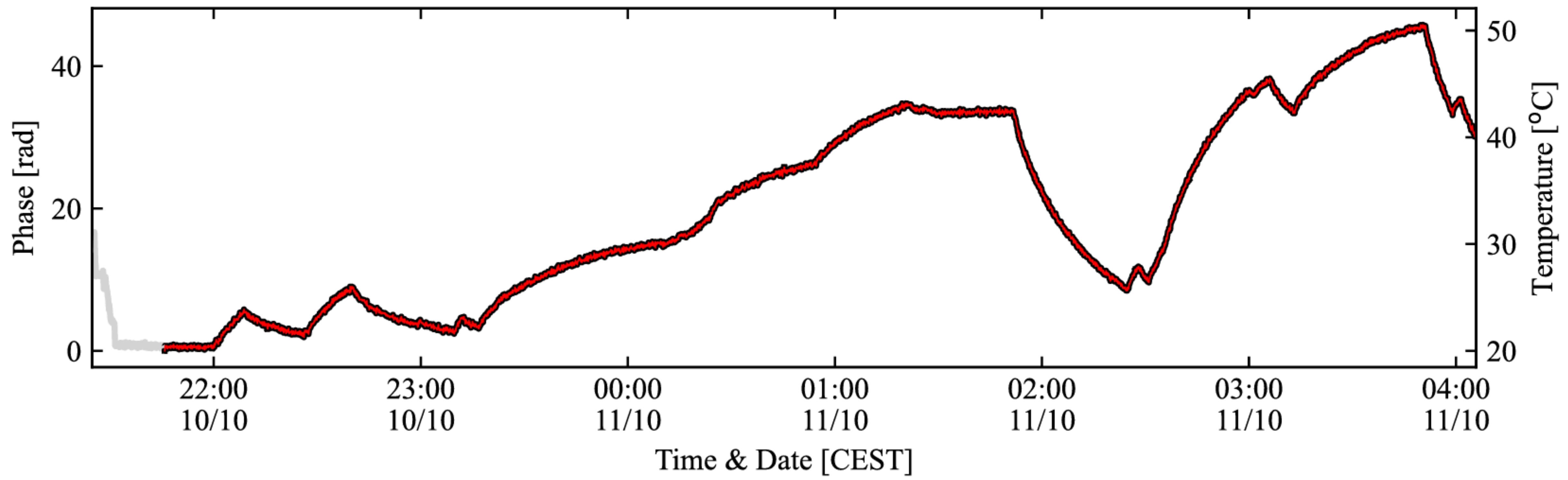
- > **Next steps** (in subsequent beam times):
  - > Staging of wakefield-accelerated beams (*with novel interstage optics scheme*)
  - > Plasma acceleration of bunch trains with HALHF properties (*~10 ns separation, 100 Hz*)
  - > Energy-mapping studies (*using temperature diagnostic suite*) and high-average-power plasma sources



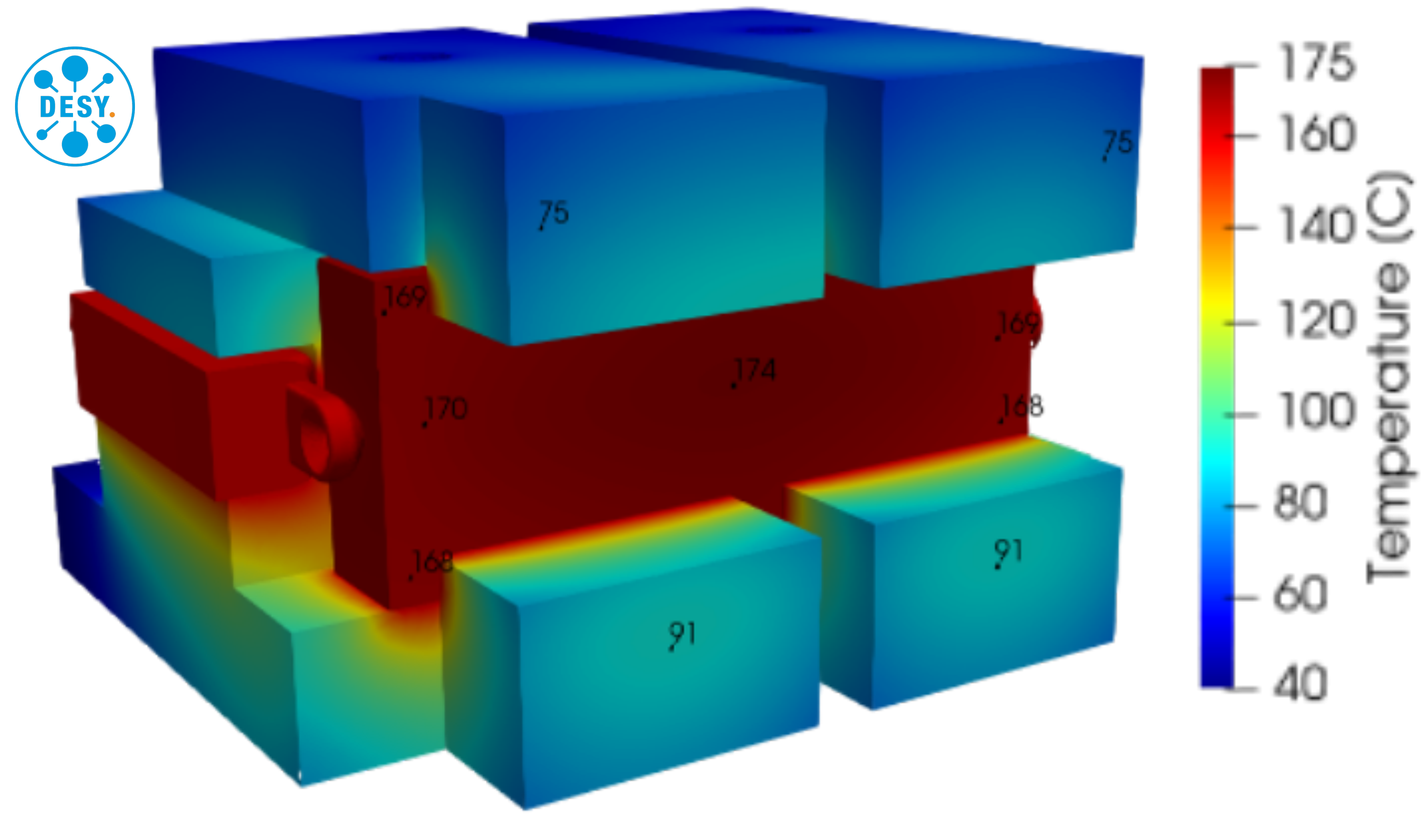
HALHF@FLASHForward

- Synergistic goals of JAI (Oxford) and FLASHForward in high-repetition-rate and high-average-power plasma acceleration
- Novel plasma-stage temperature diagnostic (Oxford) was implemented at FLASHForward in late 2025
  - Measures temperature-induced phase shift of laser propagation through sapphire stage
- First results show successful operation measuring temperature increase/decrease over many hours





- **Next step**: Correlate temperature increase with the energy deposited in the plasma
- First step towards designing high-average-power plasma stages for FLASH/EuXFEL and HALHF



HALHF@FACET-II

> Mutual interest in implementing discharge-capillary plasma stages at FACET-II (*process just successfully completed at CLARA*)

> Electron beams at FACET-II are closest (in existence) to those desired for HALHF ➞ *synergistic goals with **Eu-XFEL plasma-booster project** and **AWAKE***

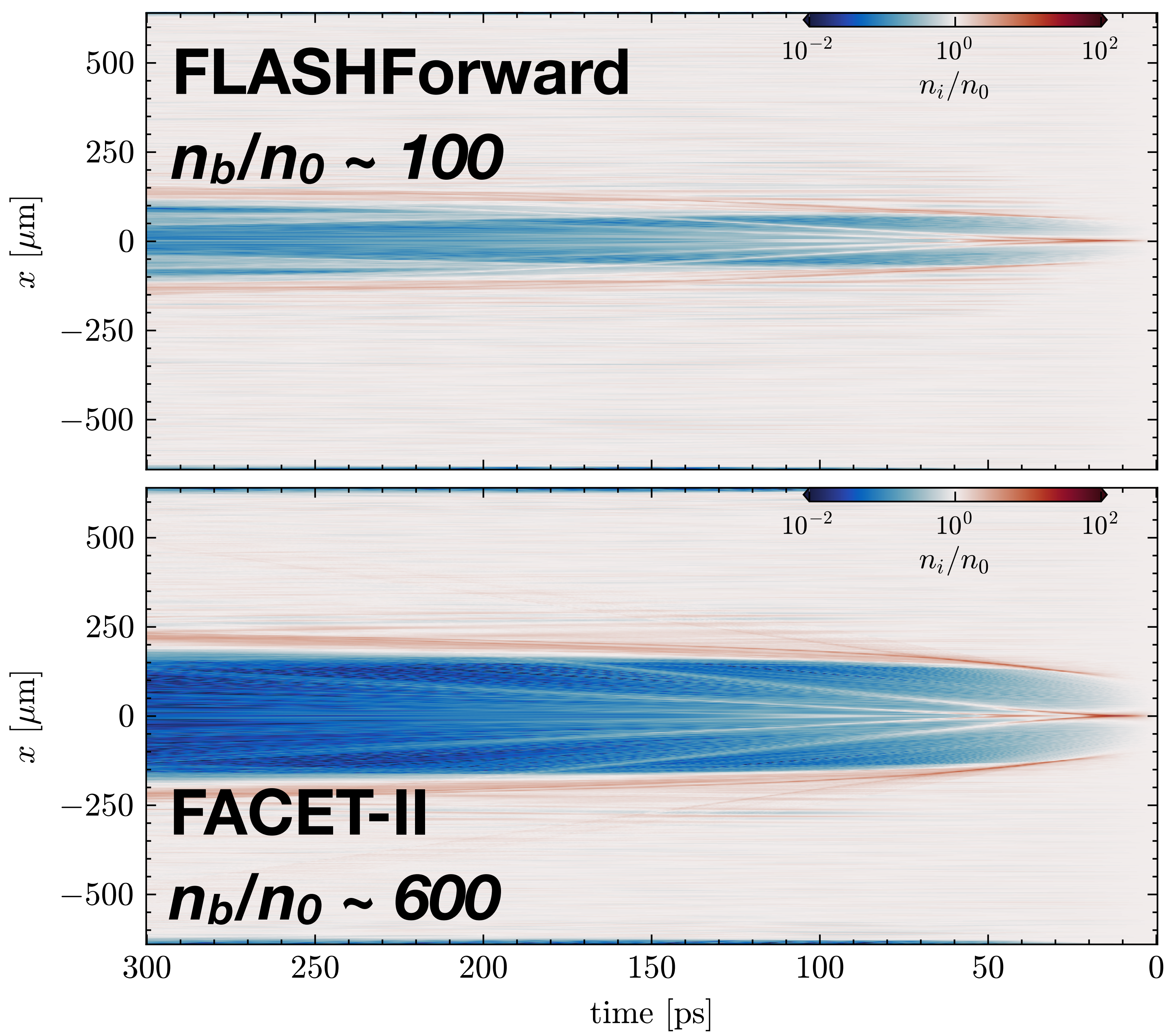
  > Extreme intensities (~100 kA) results in HAHLF-like perturbation to the plasma (*essential for simulation benchmarking*)

  > Plasma- and plasma-stage-temperature monitoring

  > Beam-induced ionisation

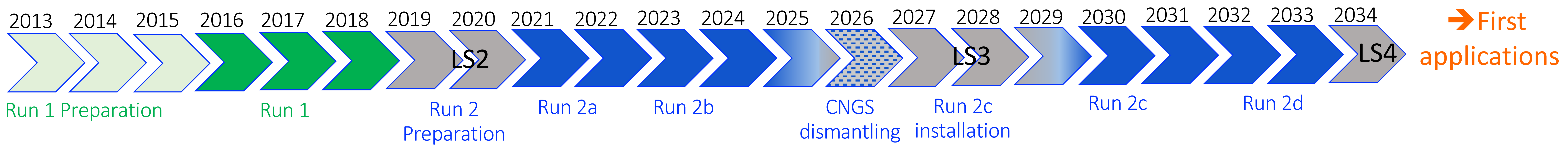
  > Cell development (large diameter, longitudinal and radial magnetic confinement, cooling, etc.)

> **First beam time in Autumn 2026** *(experiment runs until end of 2027)*



More violent plasma perturbation with FACET-II beams

AWAKE — Using energetic proton beams to achieve extremely large energy gain in a single stage



AWAKE Run 1 (2016-2018): Proof of Concept ➞ Adli *et al.*, Nature **561** (2018)

AWAKE Run 2 (2021-2034): Towards an Accelerator

> Run 2a) [2021–22]: Electron seeding of self-modulation ➞ Batsch *et al.*, PRL **126** (2021)

> Run 2b) [2023–25]: Micro-bunch stabilisation with a density step ➞ Clairembaud *et al.*, PRL (under review)

> Run 2c) [2025–]: Demonstrate electron acceleration and emittance preservation (full data taking 2029 onwards)

1. Demonstrate **scalable plasma source** technology ➞ **Imperial**
2. Accelerate electron beam to **high energy**
3. While controlling electron **beam quality** ➞ **Oxford**

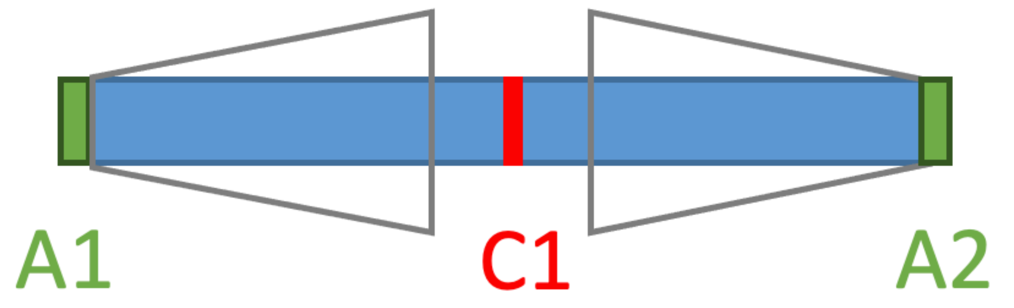
Claudia Cobo, Zulfikar Najmudin

Metre-scale discharge capillaries (scalable plasmas)

Challenge:

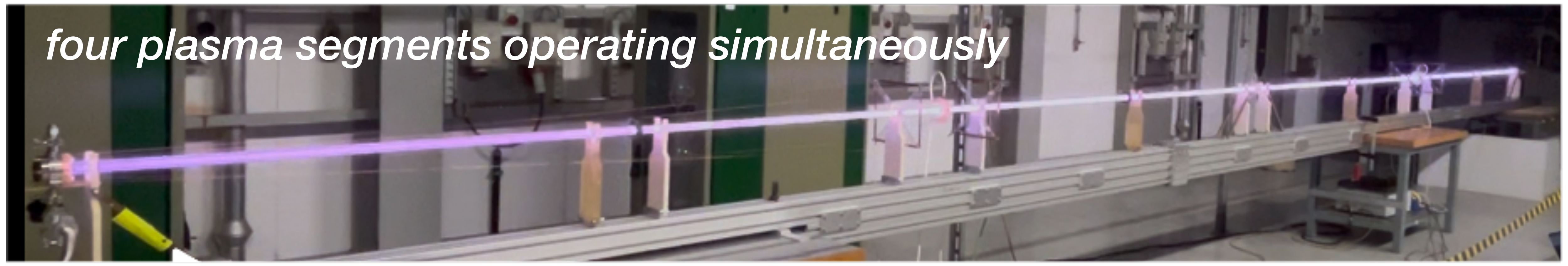
> Stable acceleration to multi-GeV energy requires sub-%-level plasma density uniformity across ~10 m of plasma

sketch of one plasma segment



Scalable plasma source R&D (tests @ CERN)

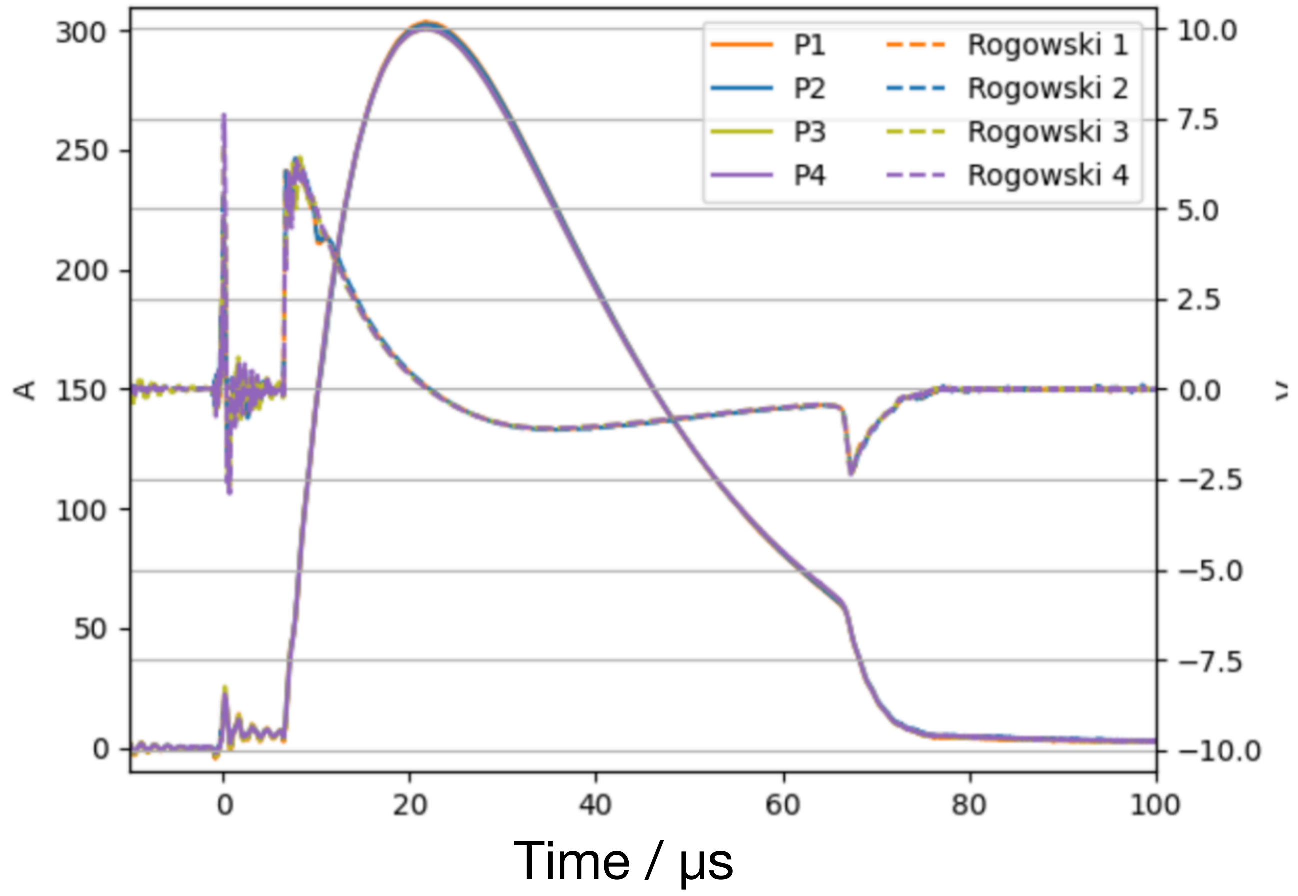
> Requires segmentation of the capillary for ease of manufacture
> Four 3m plasma segments with common cathode tested

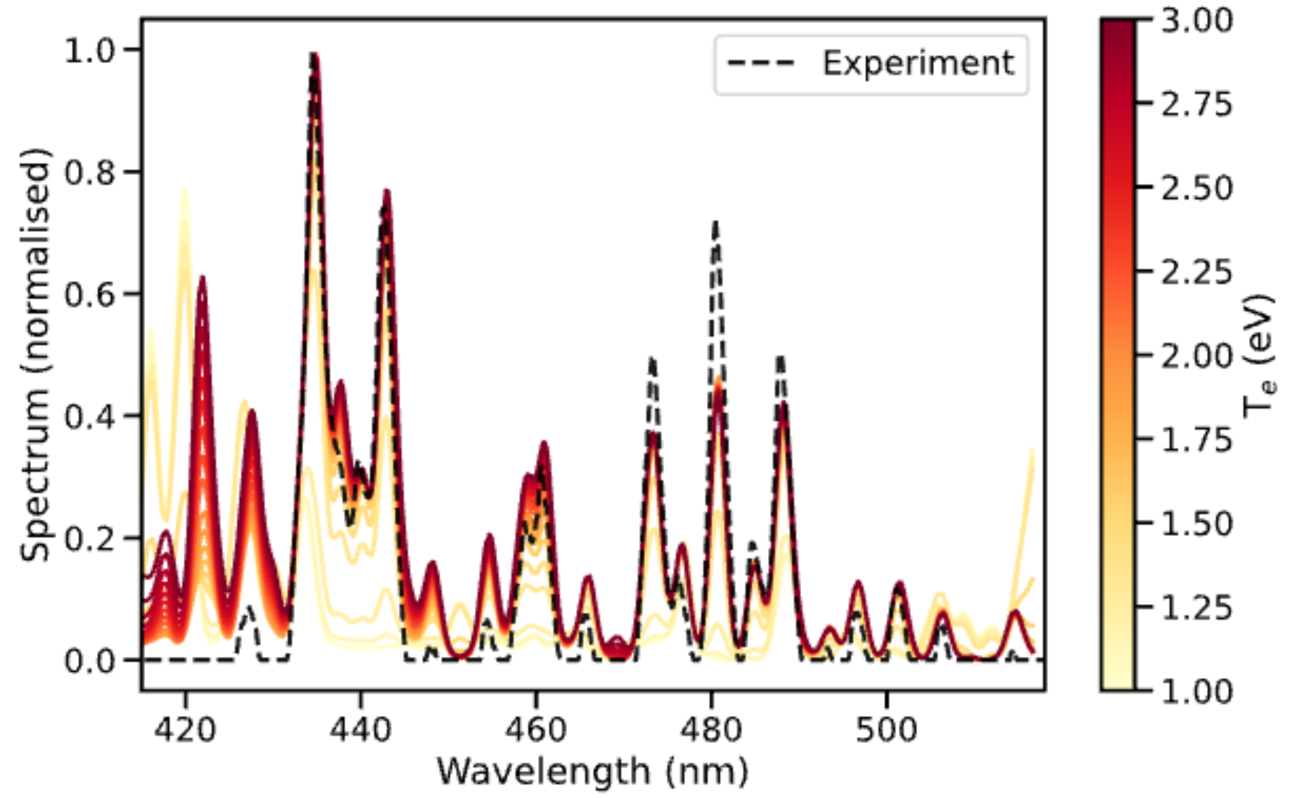


Stable and consistent plasma generation

> Plasma-generating current profile the same for all four segment to within <1%
> Collisional-radiative spectral analysis code used to determine temperature and density
>> Needed to ascertain consistent plasma properties across segments

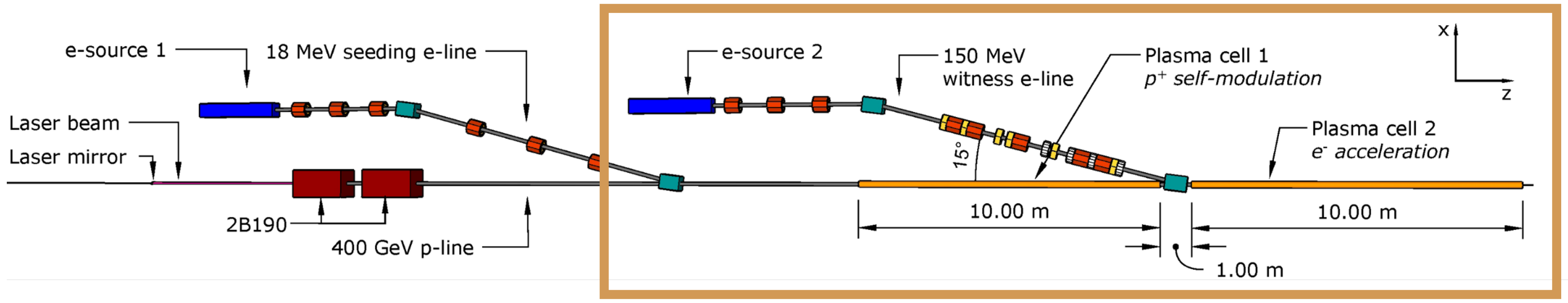
Courtesy of C. Amoedo





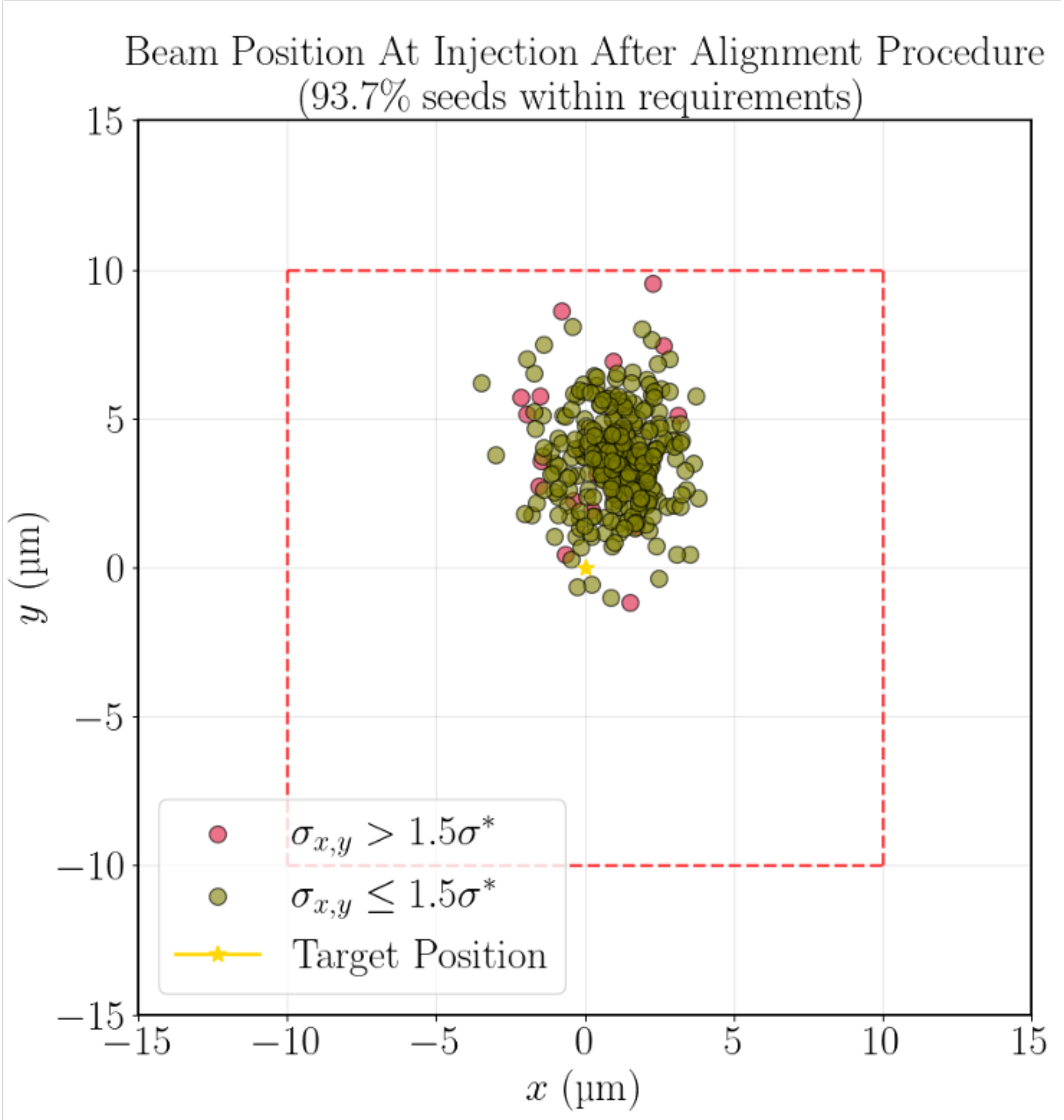
S2E proton and electron beamline design (beam quality)

- ***Challenge***: New beamline for 150 MeV witness beam has challenging matching constraints ($\sigma_{x,y}$ = 5.75-8.6 um)
  - Complex (linear and nonlinear) optics design required
  - Micrometer-level radial alignment required



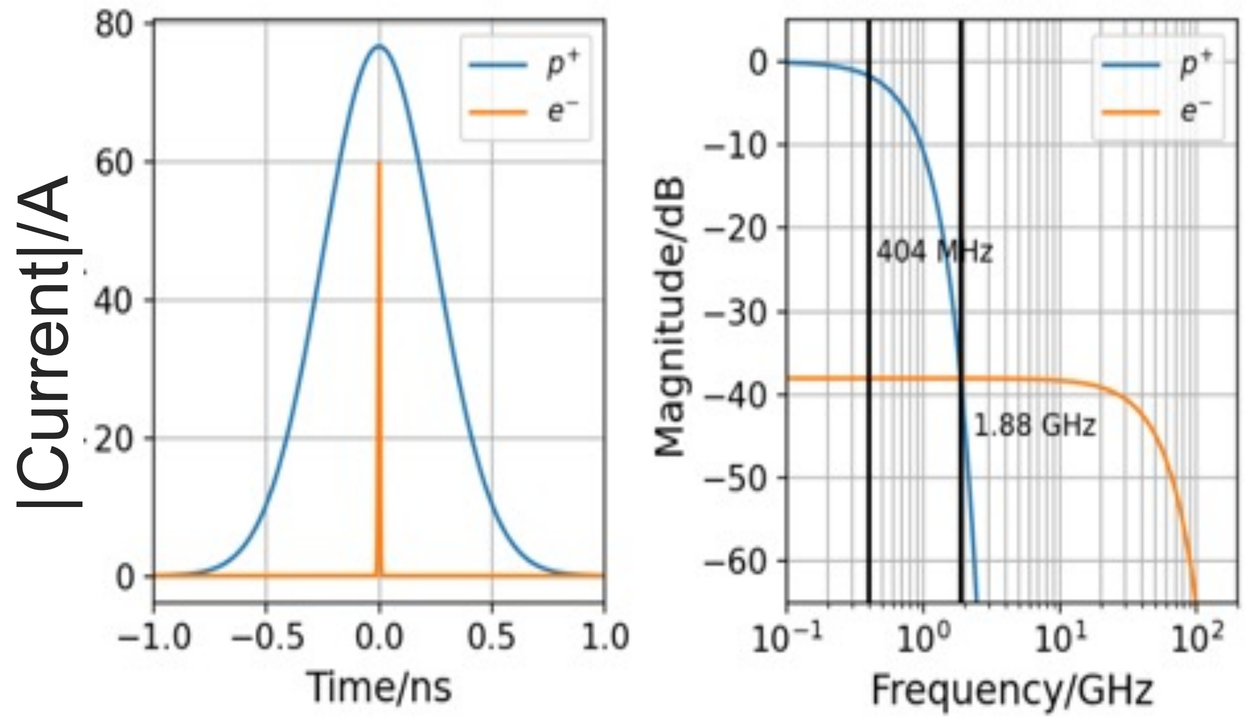
- ***New optics design***:
  - Tracking results (XSuite + external optimiser) generate beams of transverse size $\sigma_x^* = 5.67$ µm, $\sigma_y^* = 6.07$ µm
  - **Within experimental specifications (without errors)**

- ***Errors and alignment***:
  - Magnets need to be installed on movers to reach beam size/ pointing in presence of errors
  - Active alignment procedure simulated for 300 bunches ➞ 94% within requirement
  - **Studies allowed 'freezing' of beamline design such that technical procurement could begin**



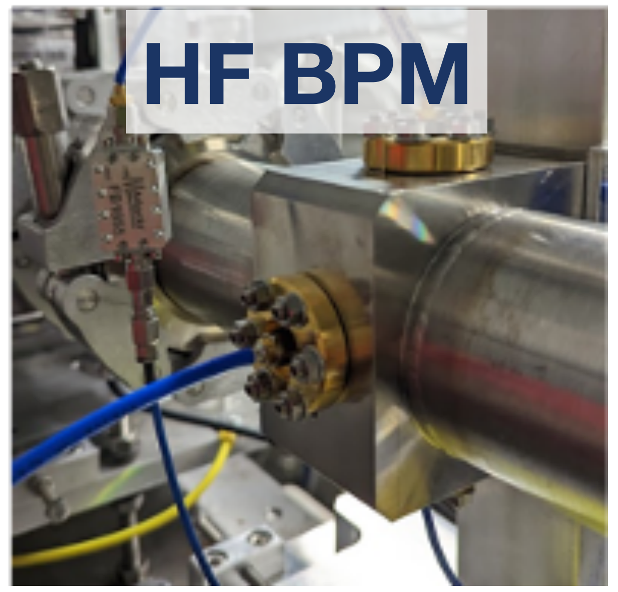
Bethany Spear, Phil Burrows

Novel high-frequency BPMs (beam quality)

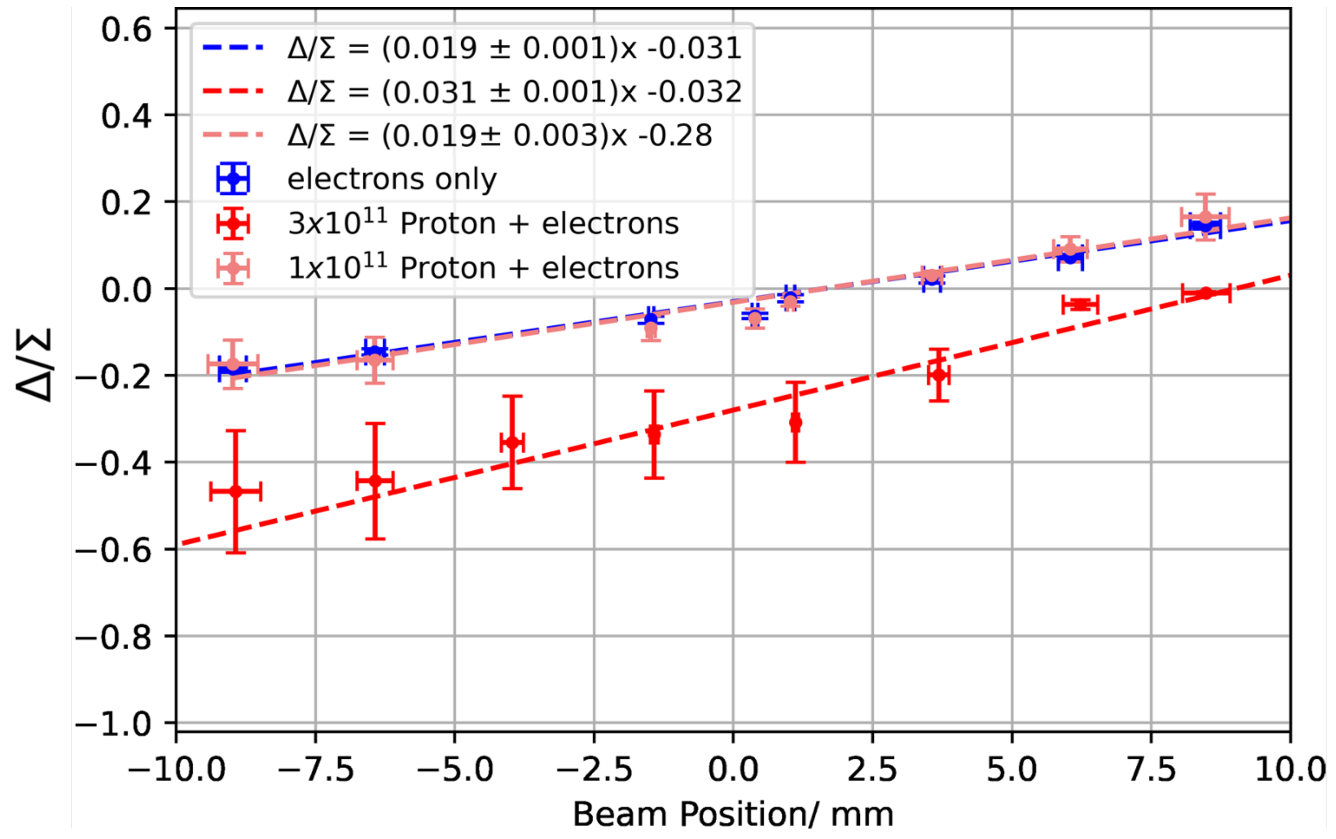


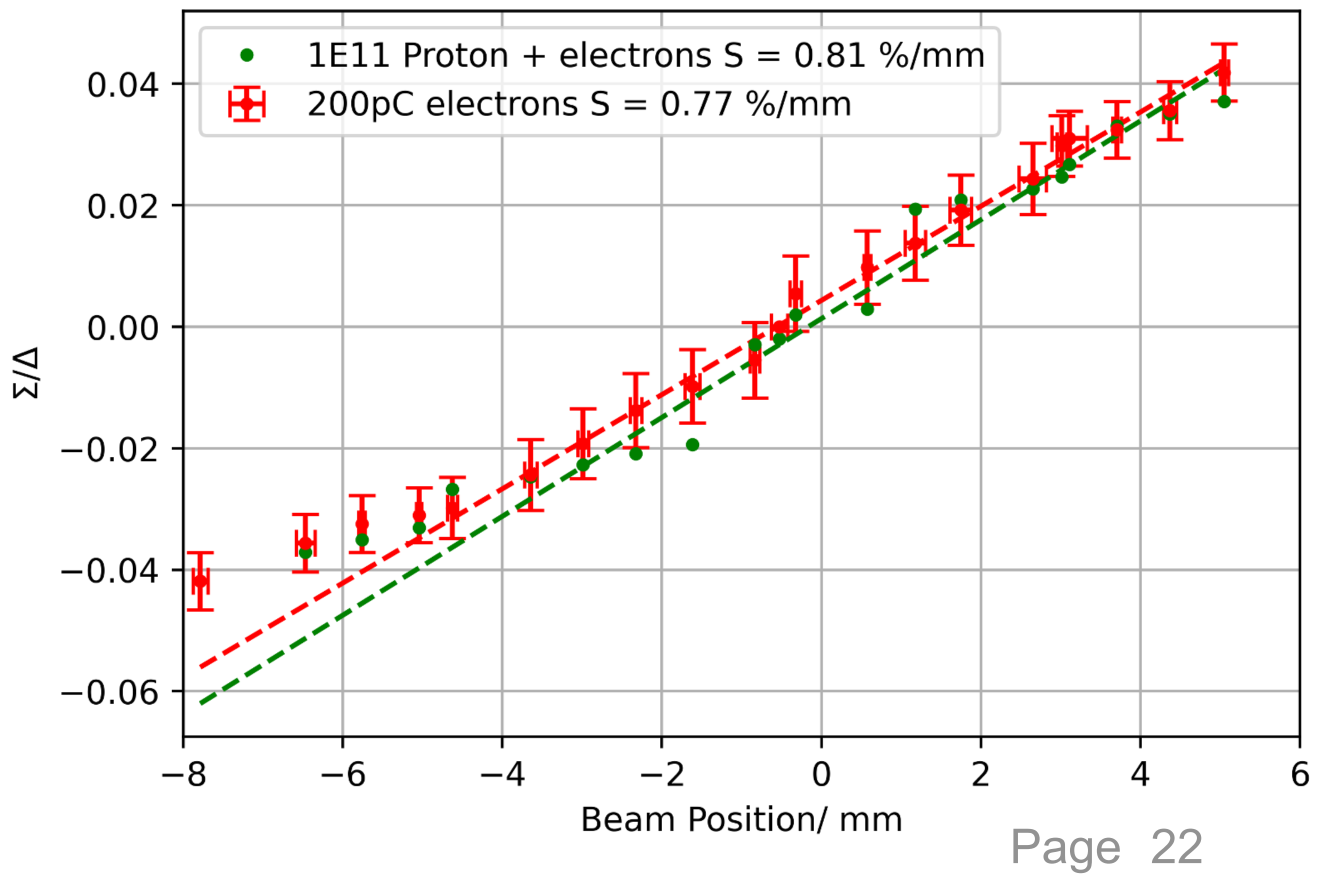
- ***Challenge***: Proton bunches are longer (~250ps vs. ~1-5ps) and higher charge (48 nC vs. 0.6 nC) than electron bunches
  - At 404 MHz signal dominated by protons
  - Current stripline BPMs unable to measure beam position when protons are present
  - Inability to optimise horizontal offset, necessary to mitigate hosing (**beam quality**)

- ***Two options are being explored:***
  1. Cherenkov-diffraction-based BPM
  2. High-frequency button BPM



- ***First tests with beam (30 GHz TRIUMF electronics)***
  - At low proton intensities successful discrimination of the proton signal observed for both types
  - Sensitivity to the electron signal is **~2%/mm** for the ChDR BPM and ~**0.8%/mm** for the HF Button





Bethany Spear, Phil Burrows

Novel high-frequency BPMs (beam quality)

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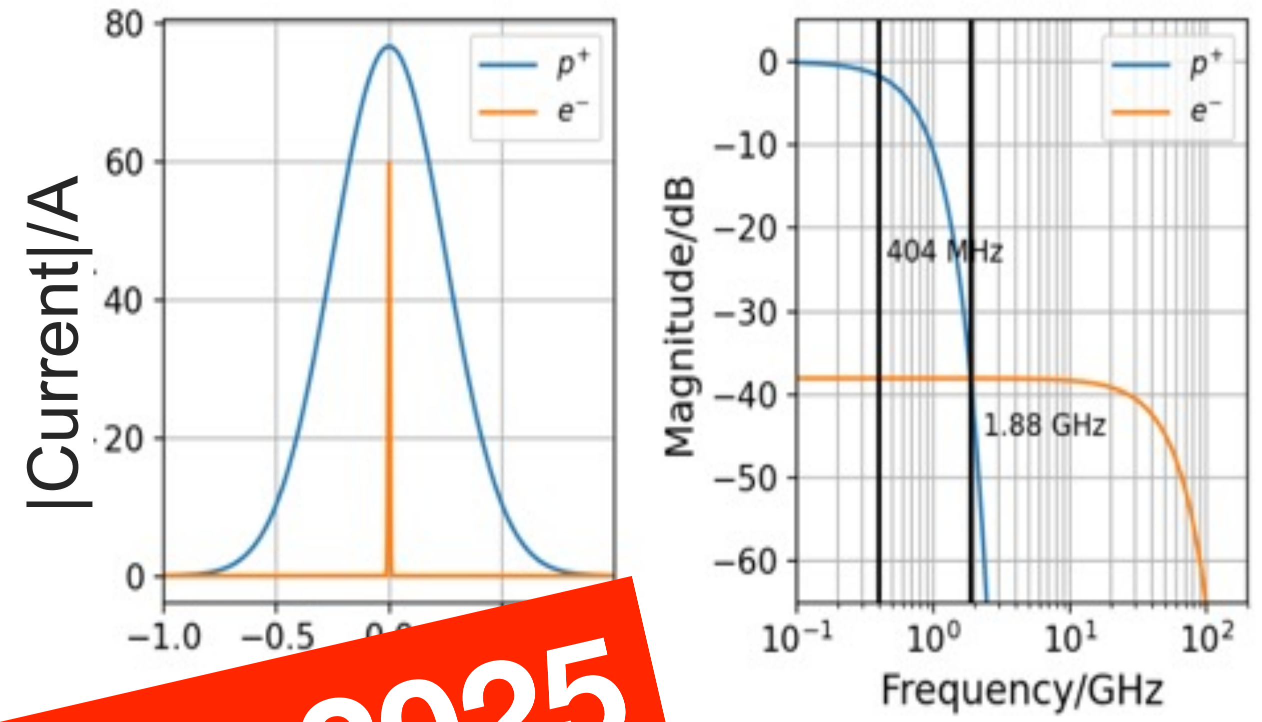

Beth successfully defended her PhD in October 2025

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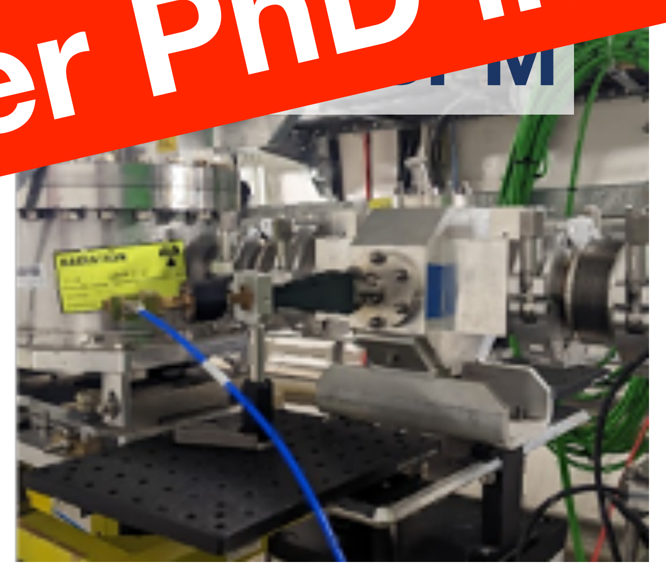

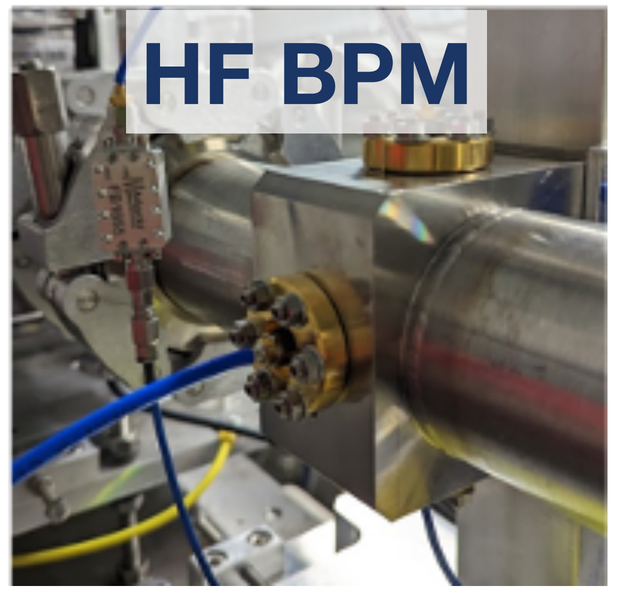

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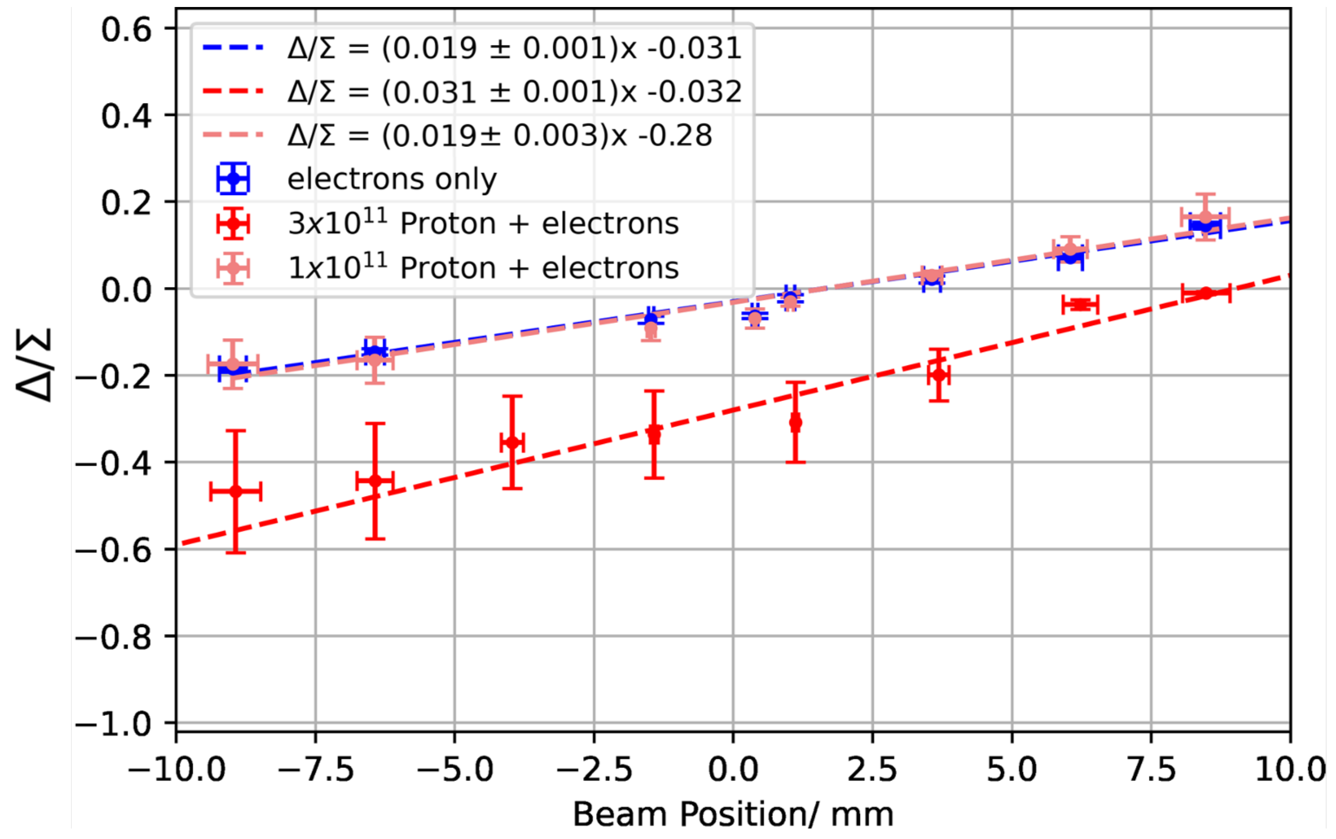
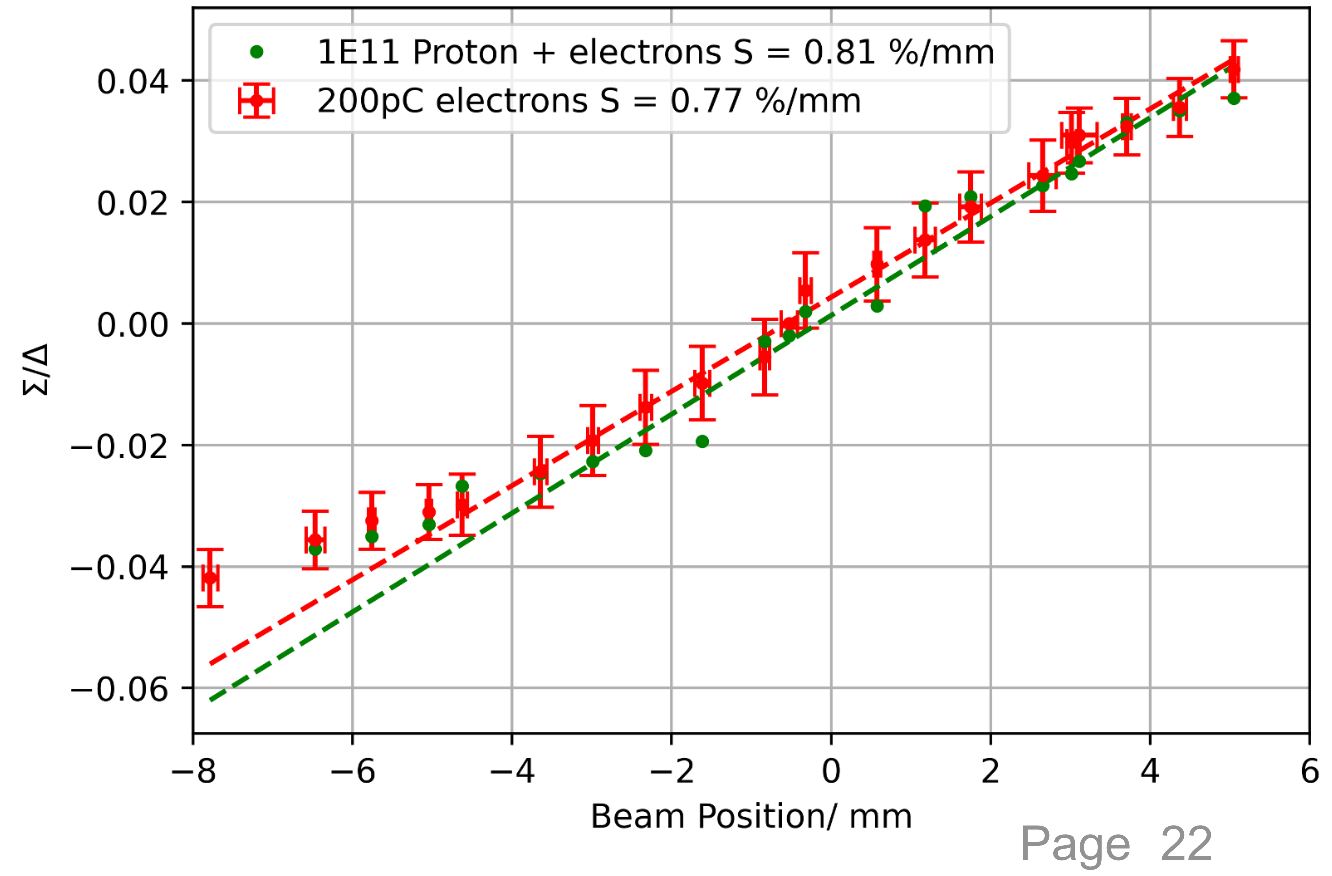




Advanced beam-driven acceleration at the JAI

Summary and outlook

- Continued success from collaboration with FLASHForward
  - Key milestones for the project and field continue to be reached
- HALHF progressing towards conceptual-design readiness
  - Official collaboration (>50 members) continues to refine the HALHF design
  - Pre-CDR document being prepared for summer 2026 (in line with LDG roadmap timeline)
- Key R&D goals from HALHF take their first experimental steps
  - Novel beamline, simulation, and diagnostic tools being developed by the JAI and Oslo
  - First tests at diversified facilities (CLARA, FLASHForward, and FACET-II) are already in motion
- Strong contributions to AWAKE continue
  - Essential JAI input enabled Run1 success
  - JAI contributions to plasma sources, beamline design, and diagnostics are already proving key to Run2 success

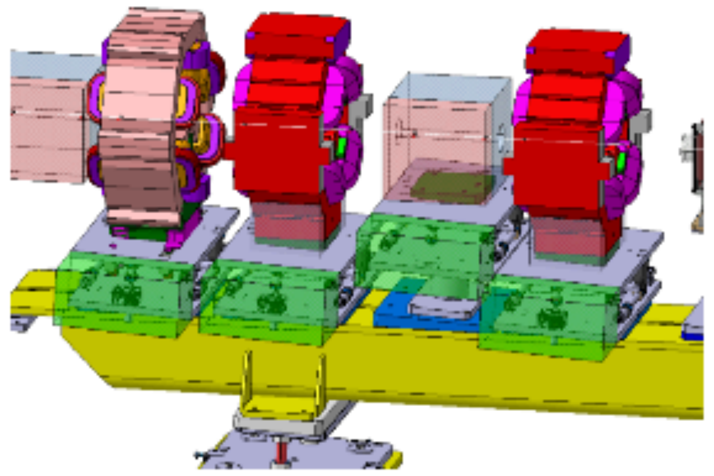
Backup slides

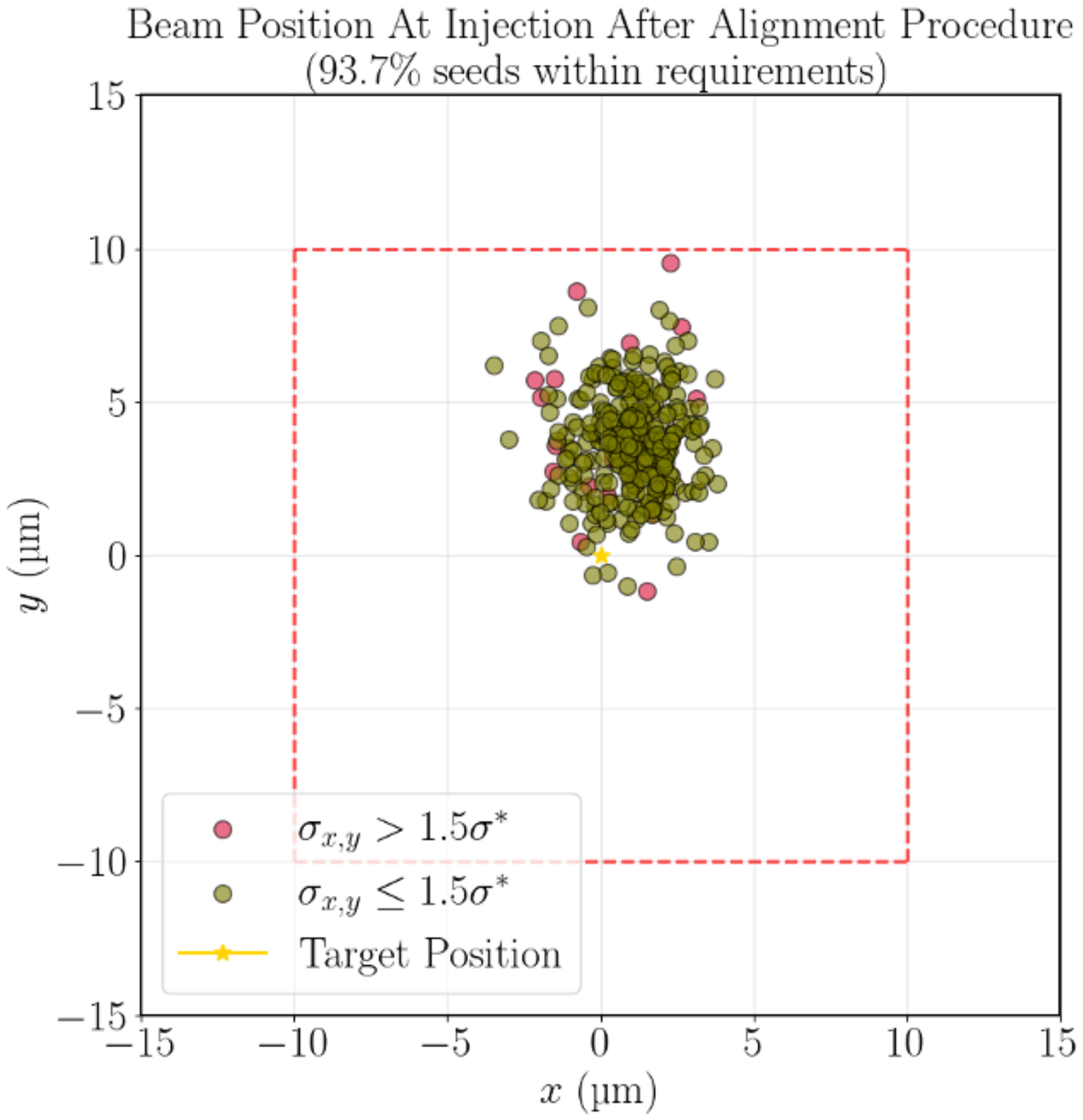
Hea

Errors and alignment procedure

- **To reach beam size and pointing specifications in presence of errors**, magnets need to be installed on **movers** (vertical and radial adjustment at um-level)
- **Active alignment procedure**
  - **Quadrupole shunt:** centre quadrupoles w.r.t. beam orbit
    - Change quad strength Δk and measure Δx_{BPM}
    - Compute quad-beam offset Δx_{QUAD}
    - Move quadrupole of - Δx_{QUAD}
  - **DFS:** minimize parasitic dispersion and orbit
    - Change beam energy and measure Δx_{BPM}
    - Use correctors to minimise beam offset
  - **Numerical optimisation**
    - Align sextupoles and octupoles by minimizing σ_{inj} (BTV)
- Alignment procedure simulated for 300 seeds
  - Gaussian distributions of errors with the following RMS:

Parameter	Error (RMS)
BTV resolution	1 µm
BPM resolution	10 µm
Magnets misalignment	100 µm
Power converters ripple	0.1%
Input beam position jitter	10 µm
Input beam angle jitter	1 µrad





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