

HALHF@CLARA

Summary of first experimental run



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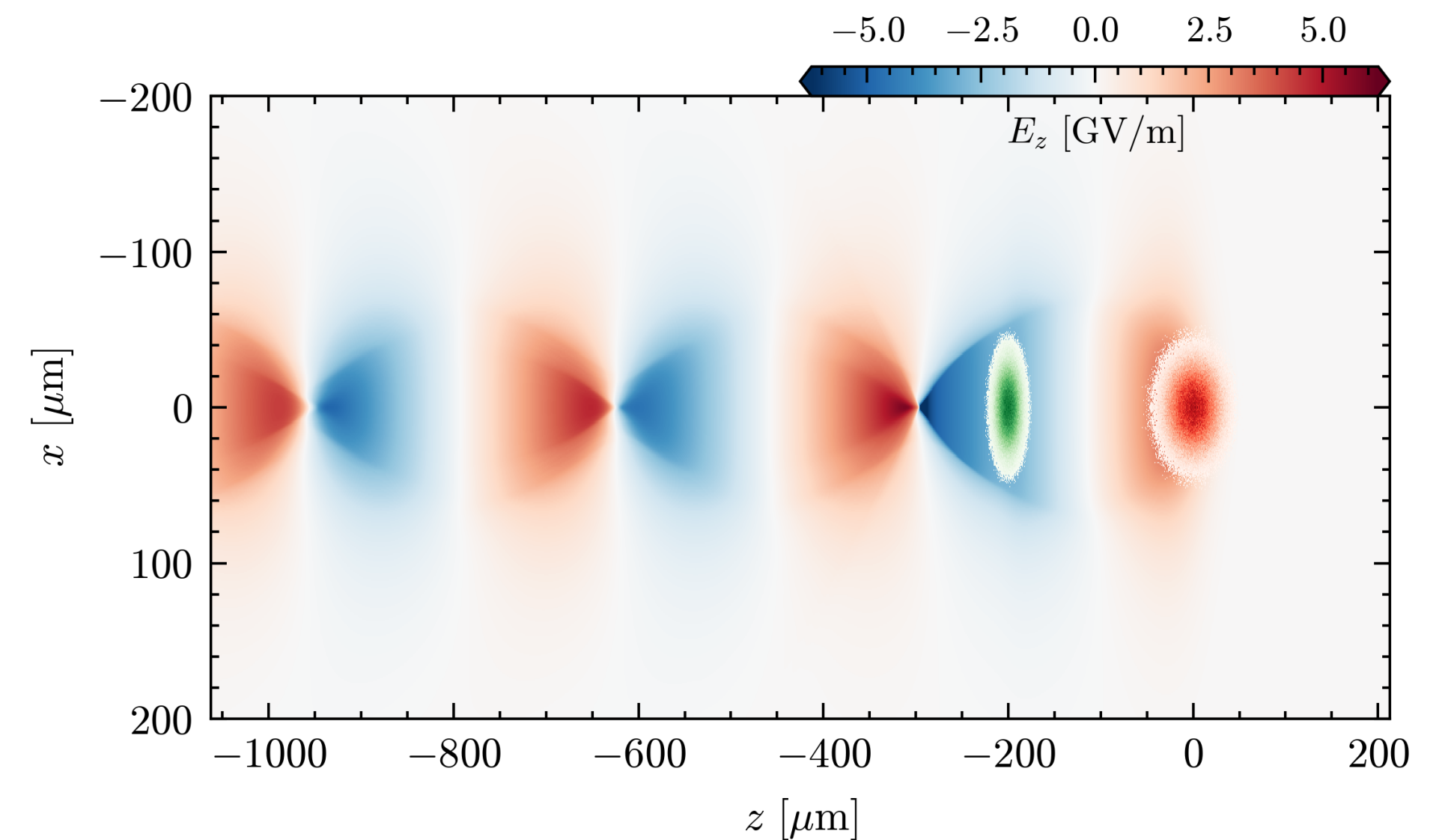
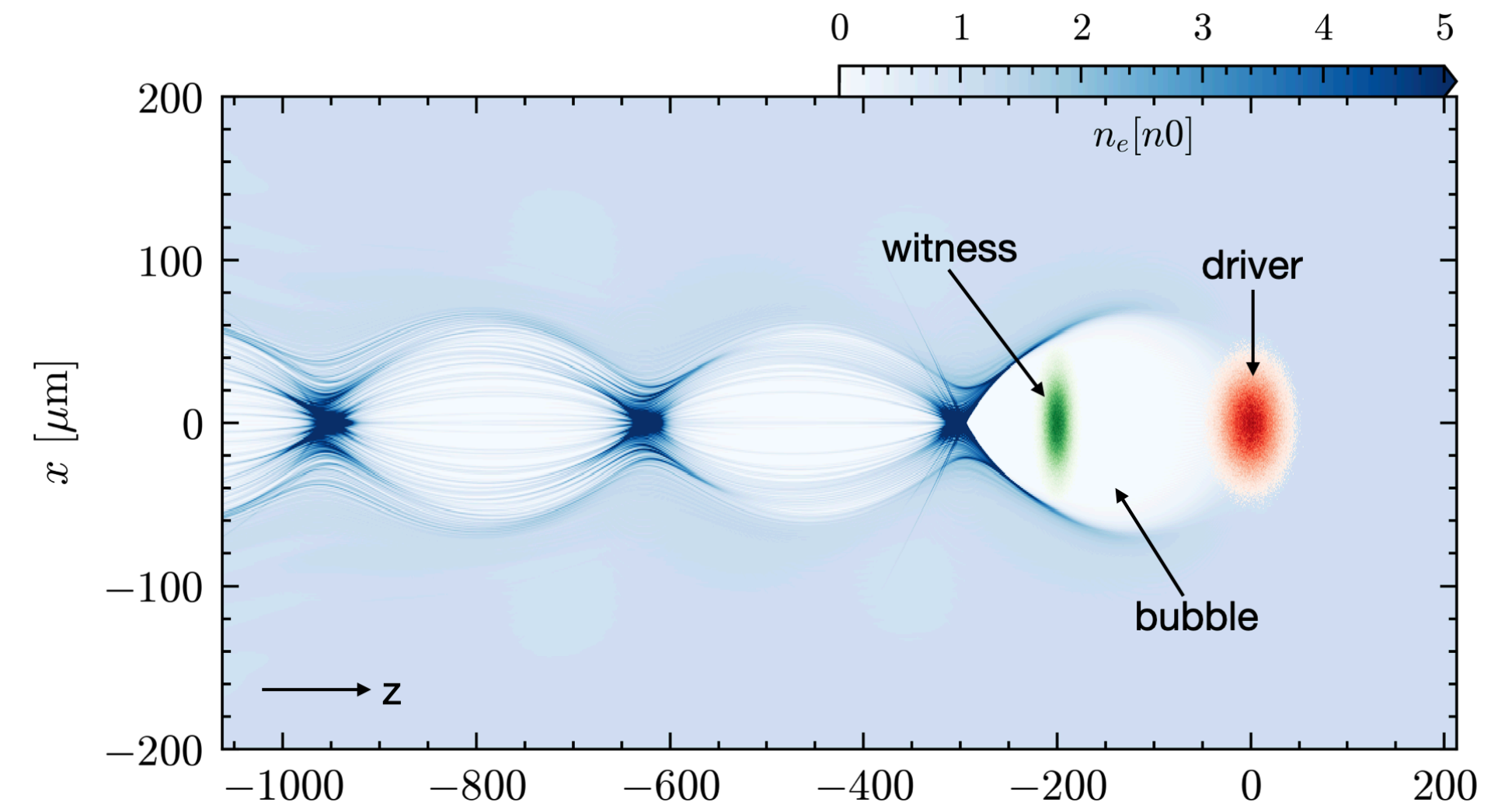
The University of Manchester

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A. Ellingsen⁵, J. Jones⁴, C. A. Lindstrom⁵, I. Najmudin¹, K. N. Sjøbæk⁵, T. Overton⁴, T.
Pacey⁴, E. Shackleton⁴, S. Wen², J. Wood³, G. Xia², R. D'Arcy¹

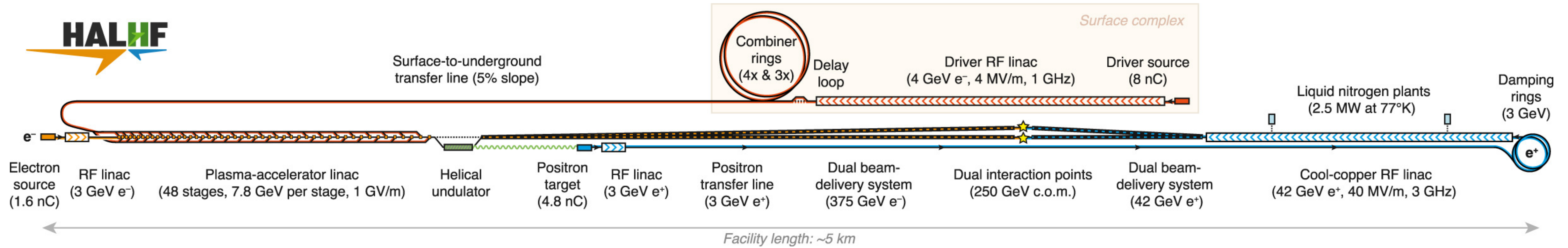
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Why plasma-wakefield acceleration?

- > Significantly higher fields achievable than RF (limited by cavity breakdown)
- > ‘Driver’ electron bunch repels plasma electrons → charge separation behind the bunch
- > Strong electric fields (~ 10 GV/m)
- > Electrons pulled back on-axis by ions → plasma wake
- > ‘Witness’ bunch surfs the wake and accelerates



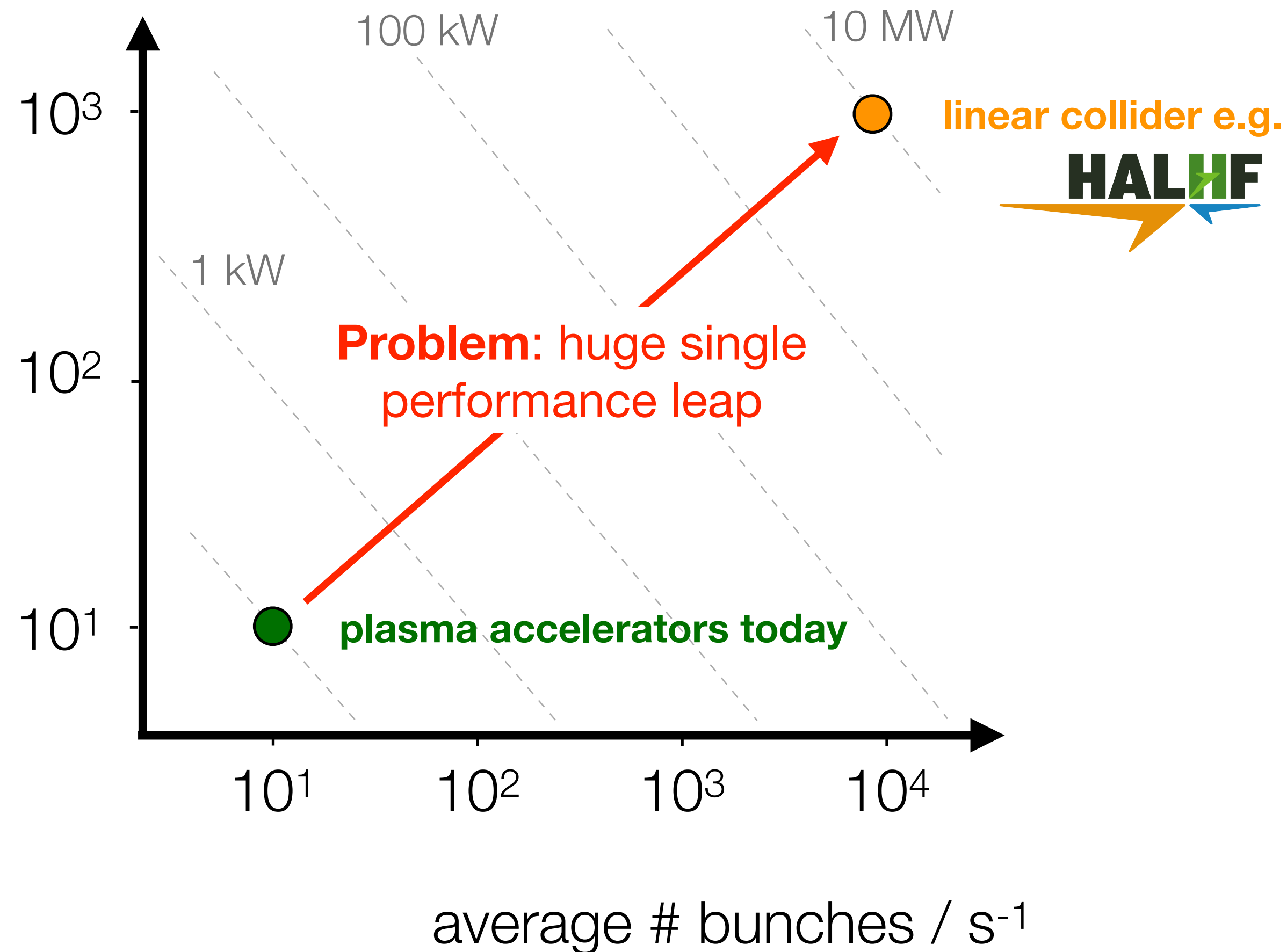
HALHF: A hybrid asymmetric linear Higgs factory



- > Plasma accelerator for electron acceleration
- > Positron acceleration is much more complicated...
- > Conventional RF linac for positron acceleration (31 GeV)
- > 500 GeV electrons (for asymmetric-energy collisions)

Challenge: HALHF requirements are far beyond the state of the art

E / GeV



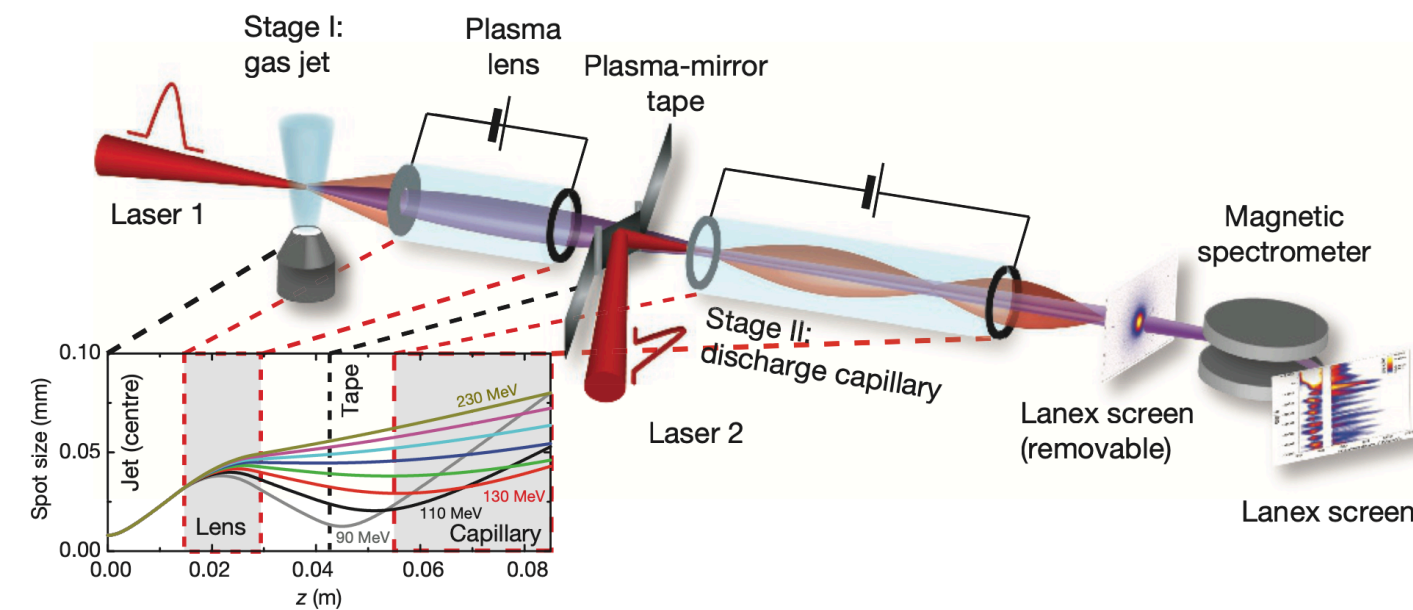
- > Require staging to get to higher energies
- > 8 m long plasma stages
- > 48 stages
- > 100% charge coupling and quality preservation
- > 100 Hz macro-pulse repetition rate
- > 16 ns (62.5 MHz) bunch separation
- > 25 MW drive-beam power

Courtesy: Richard D'Arcy

State-of-the-art and required direction of travel

> Staging state of the art

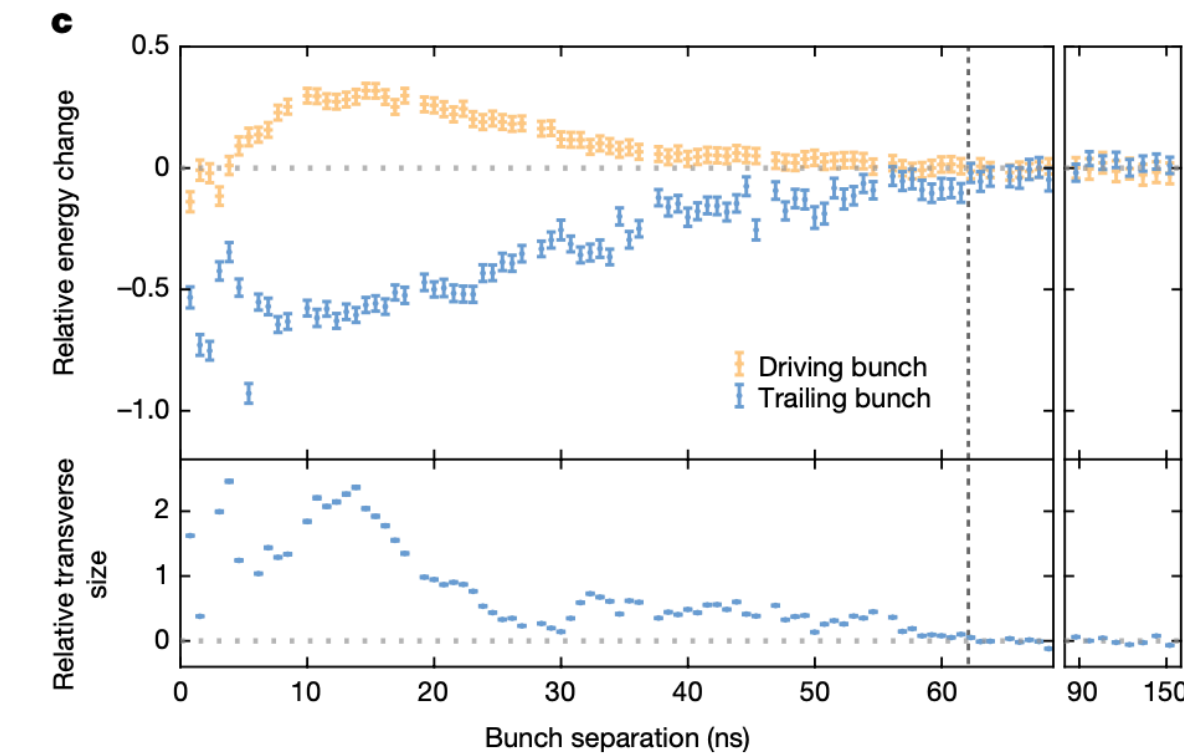
- > Two LWFA stages (gas jet + capillary)



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

> Repetition rate state of the art

- > 10 Hz*



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

*but 10 MHz achievable in principle

> Challenges

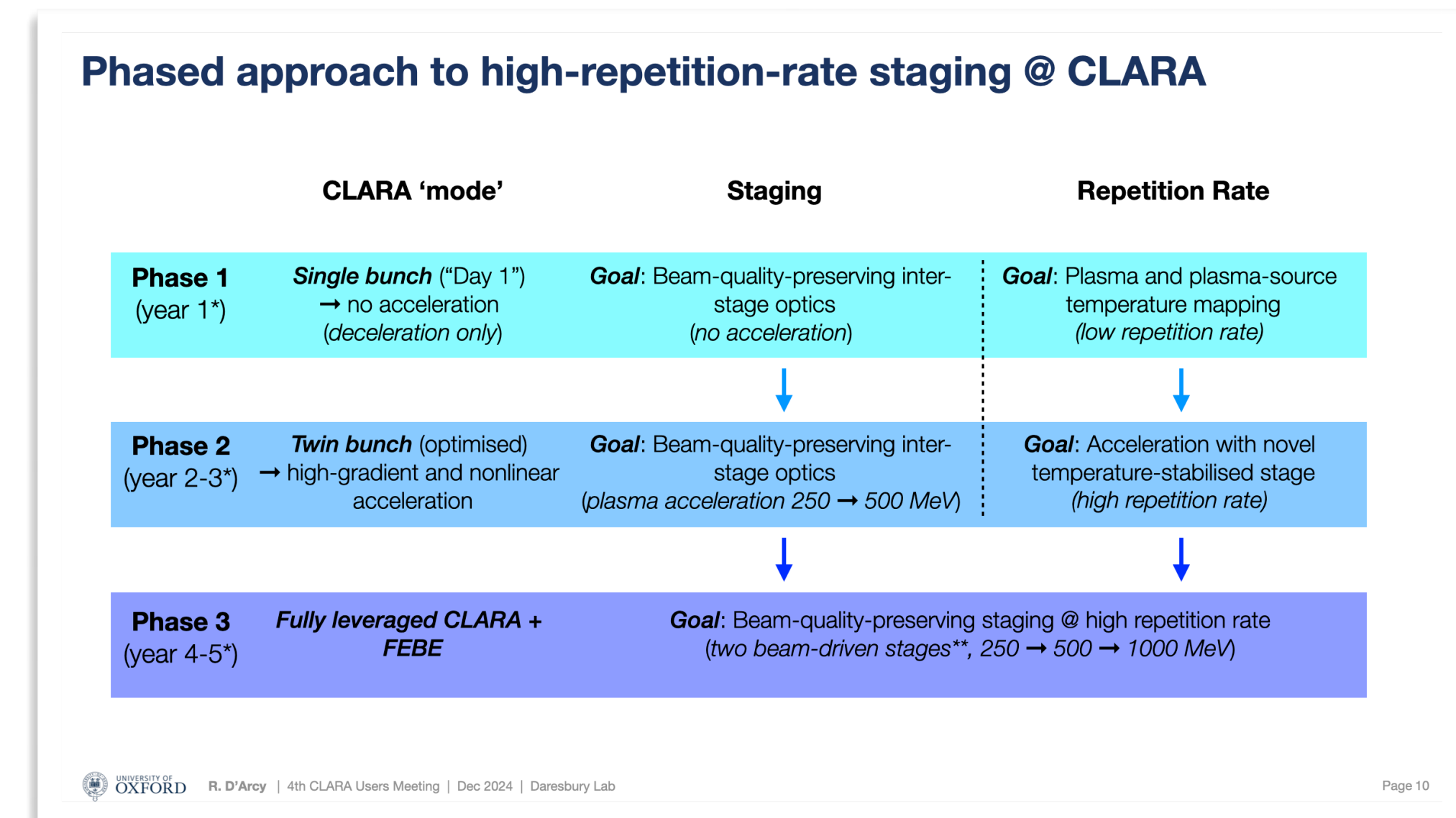
- > Coupling between stages (3.5% charge transfer in the proof-of-principle result)
- > Lack of energy-scalable schemes

> Challenges

- > Unknown temperature increase (due to higher average power)
- > Only low-repetition-rate plasma sources

Multi-year programmatic approach at CLARA

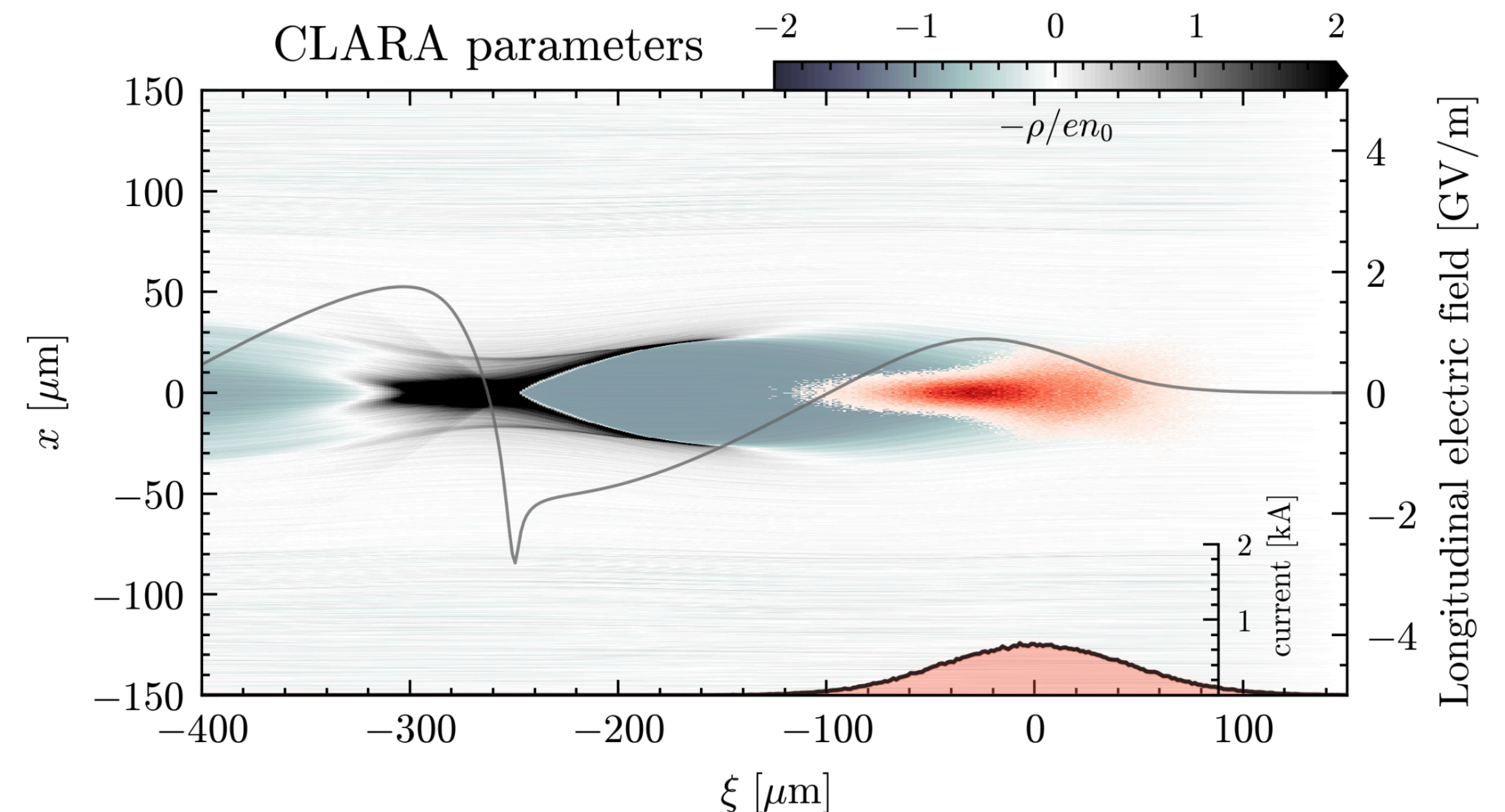
- > Utilise CLARA to make substantial progress towards HALHF over multiple years:
 - > **Staging** (*250 MeV beams means staging can be explored in a more compact way at CLARA than other FEL-quality facilities with higher energies*)
 - > Transversely nonlinear plasma lenses
 - > Beam-quality-preserving inter-stage scheme
 - > *Two-stage demonstrator*
 - > **Repetition rate** (*CLARA linac at 100 Hz*)
 - > Energy-transport channels (temperature evolution)
 - > Bunch-train studies (100 Hz, ~10 ns separation)
 - > *Temperature-stabilised plasma sources*



Detailed phased approach presented at the first CLARA users' meeting (2024)

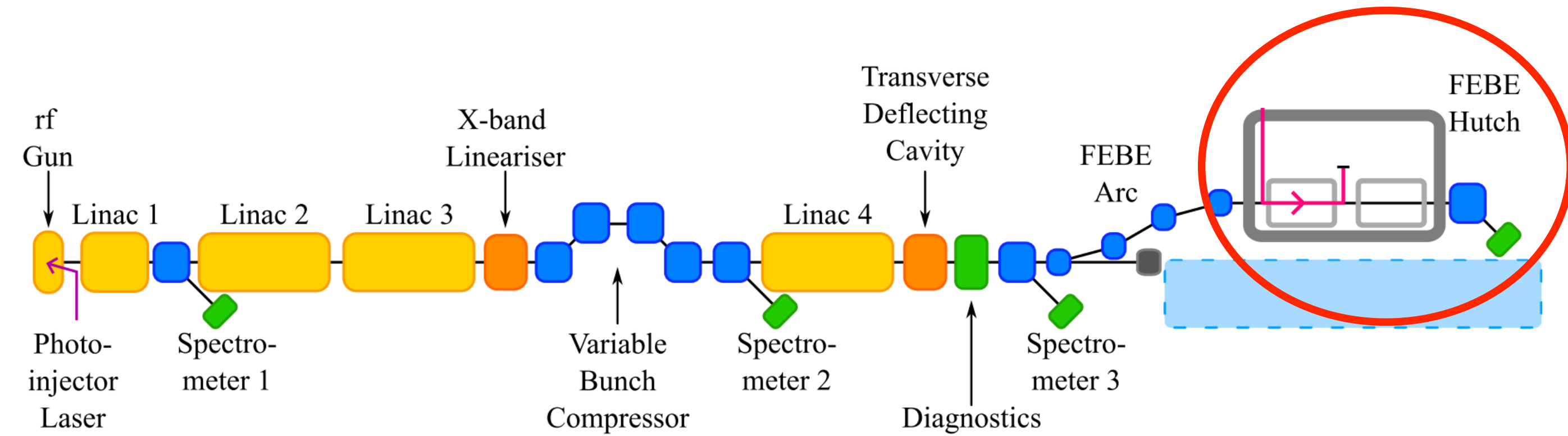
Phase 0 objectives

- > Install necessary plasma infrastructure → *based around the Oslo plasma lens + Manchester HV*
- > Integrate with CLARA → *gas, discharge, plasma, diagnostics, synchronisation*
- > Demonstrate strong beam-plasma interaction (drive bunch only) → **Stretch goal: GV/m fields**
- > Show plasma-based focussing → **Stretch goal: emittance preservation (in argon)**

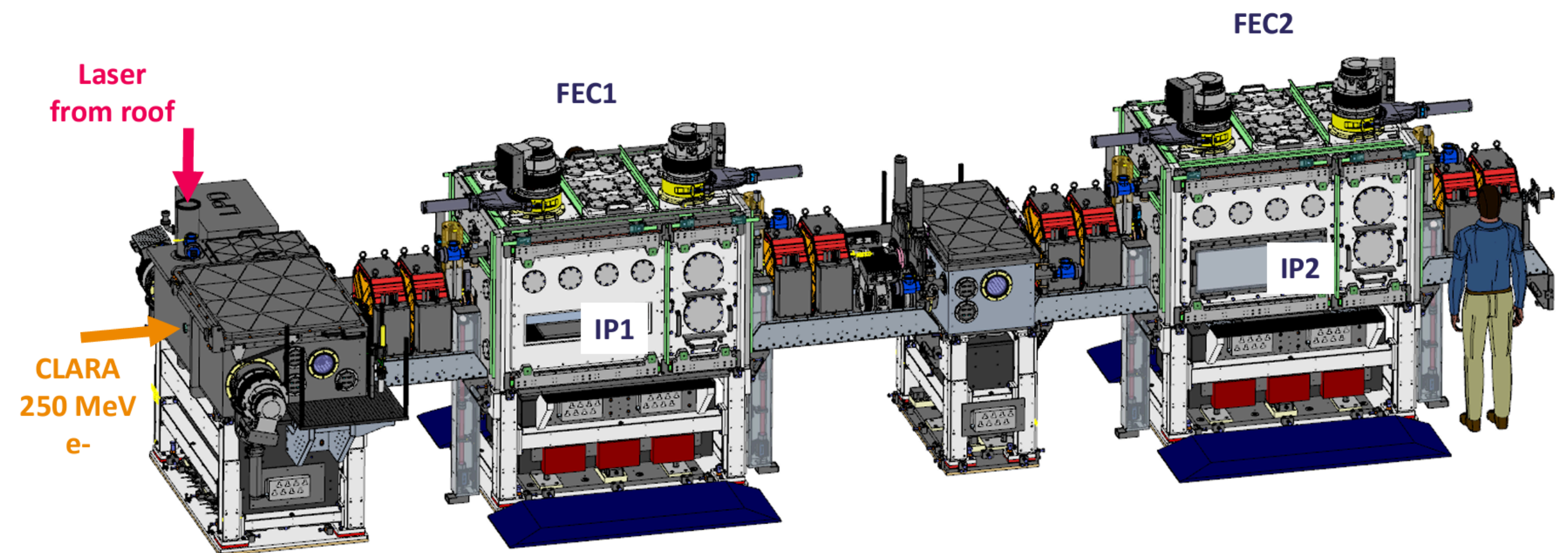


CLARA/FEBE overview

- > 250 MeV beams
- > 100 pC and 250 pC working points
- > Beam prepared by CLARA personnel and delivered to FEC1
- > Plasma source to be housed in FEC1
- > Capture and propagation to ESPEC (beyond FEC2)
- > Five weeks of experimental allocation
- > Last experiment in friendly user run (as most taxing on the machine)

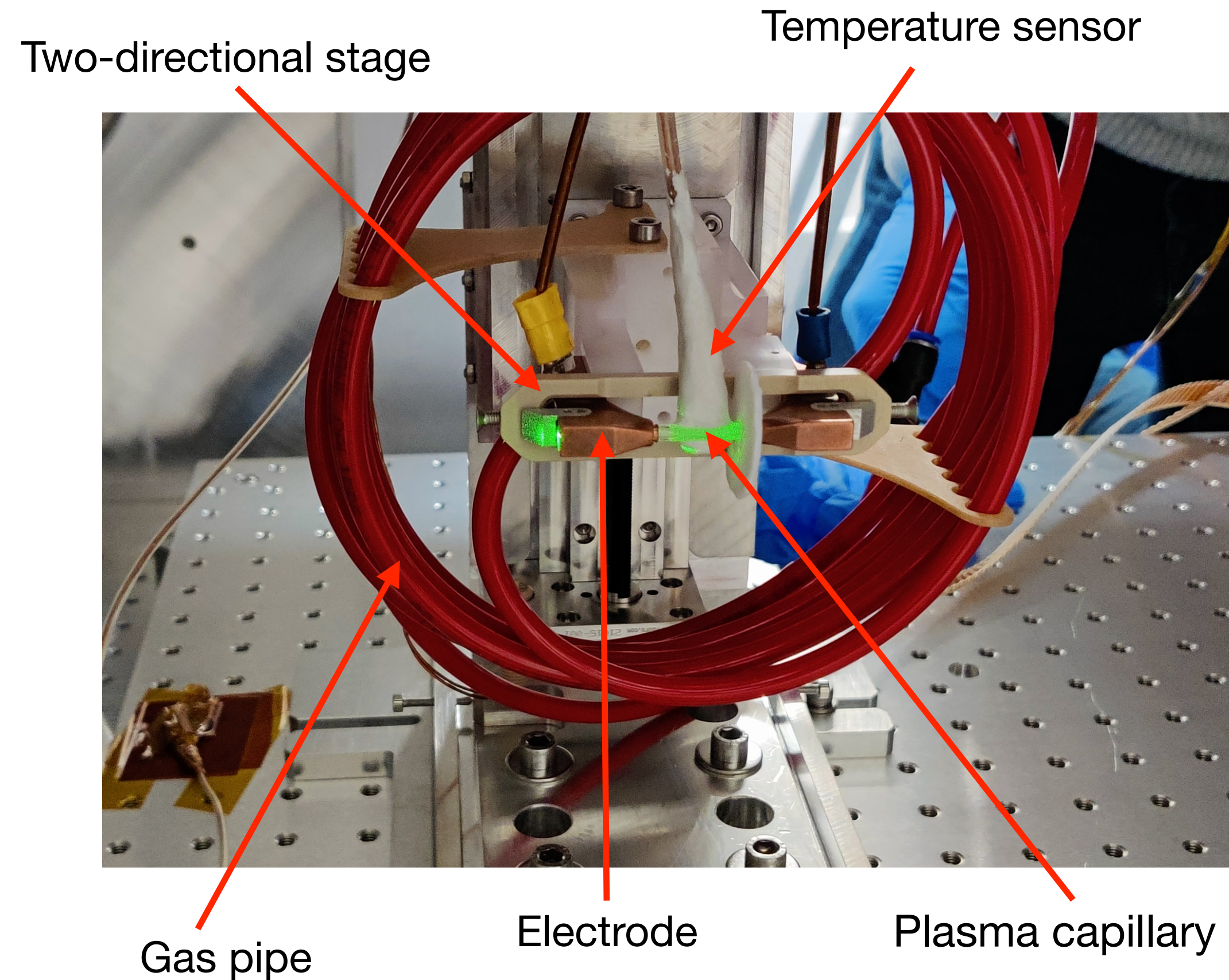


CLARA Beamline. E. W. Snedden et al. Phys. Rev. Accel. Beams 27, 041602 (2024)

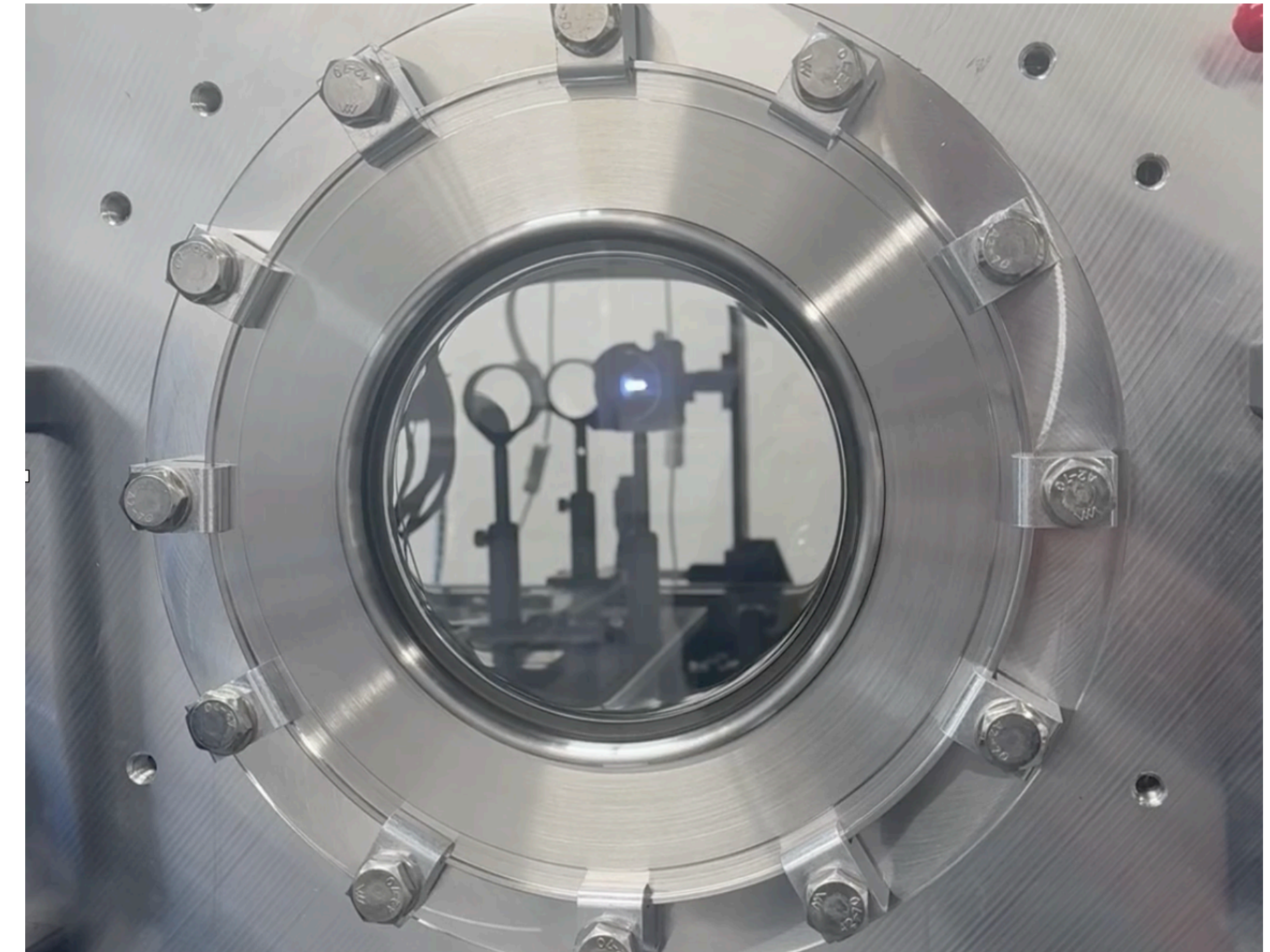


FEBE Hutch Beamline (graphical rendering). Credit: **Tom Pacey**

Experimental Setup



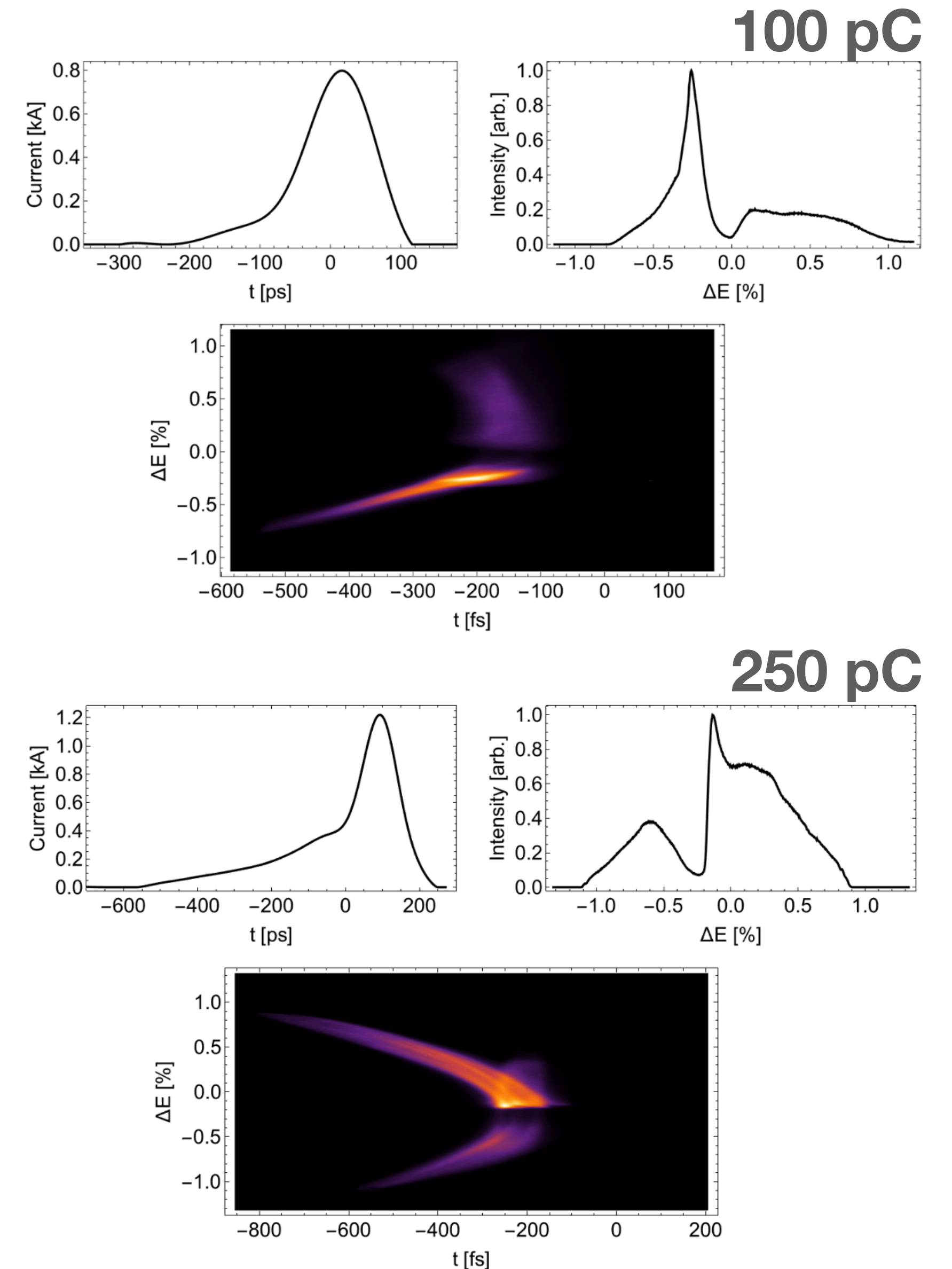
- > 12 mbar Ar in capillary
- > High-voltage system connected



- > First plasma generation in argon
- > No precise knowledge of the plasma density

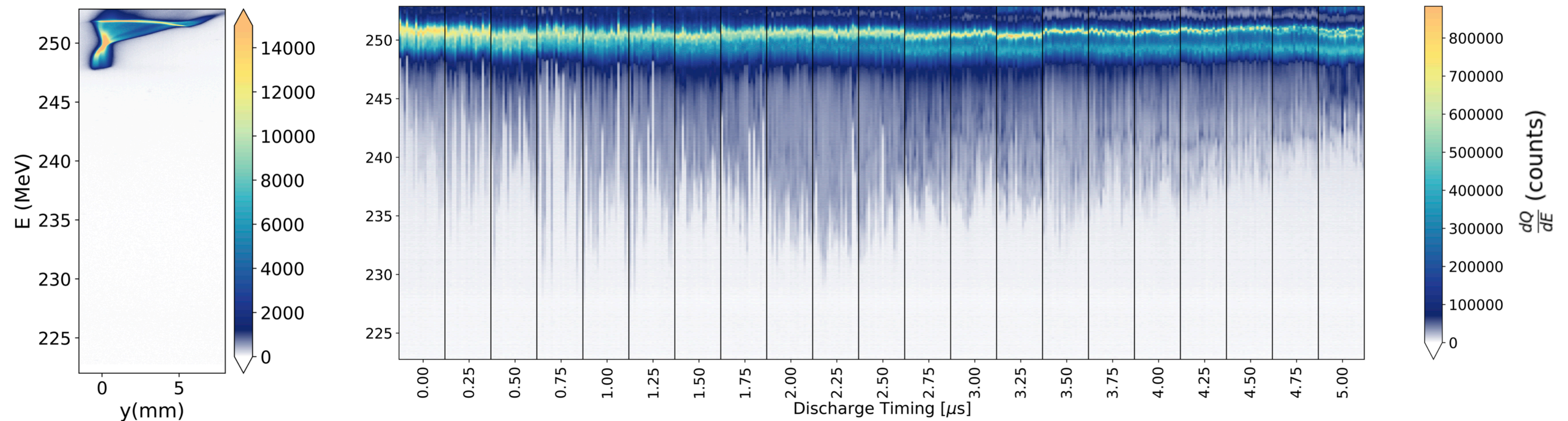
Beam Parameters

- > Spent the majority of the beam time with a 100 pC beam due to a number of advantages
 - > *Reduced space charge effects* → *similar LPS to that measured upstream*
 - > *Lower emittance* → *easier to focus at IP*
- > Used this beam to establish a nice (<0.5 GV/m) interaction
- > Moved to the 250 pC beam on the last day to push towards higher decelerating gradients



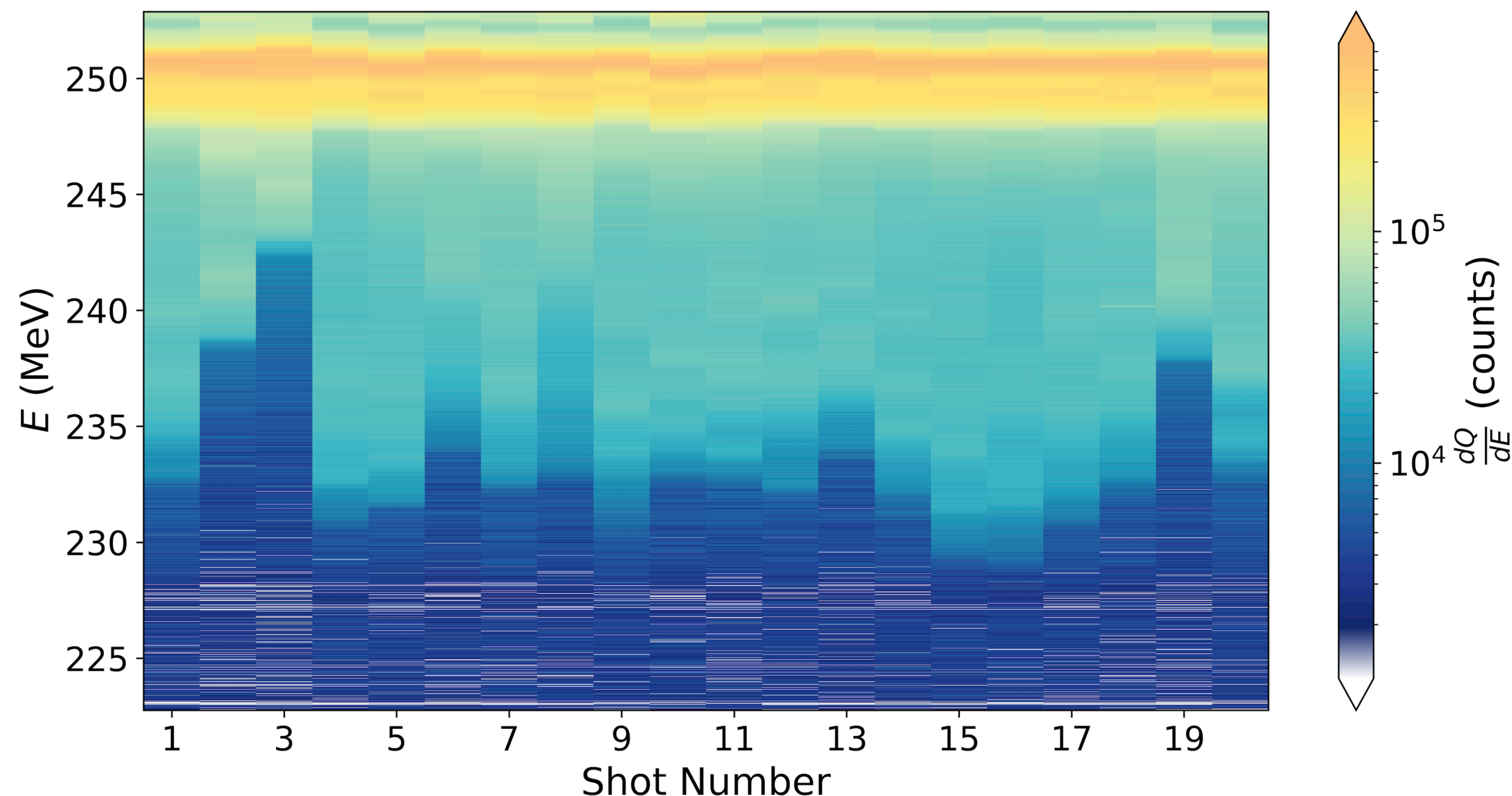
Discharge timing scan results

- > Established a nice working point relatively quickly with 250 pC beam
 - > ~ 1 kA (*TDS + arc effects*)
 - > $\sim 20 \times 20$ μm at the IP (*mini-OTR*)
- > Some (*but very few*) shots show >20 MeV energy loss in <20 mm of plasma $\rightarrow$ **$>\text{GV/m}$ fields!**



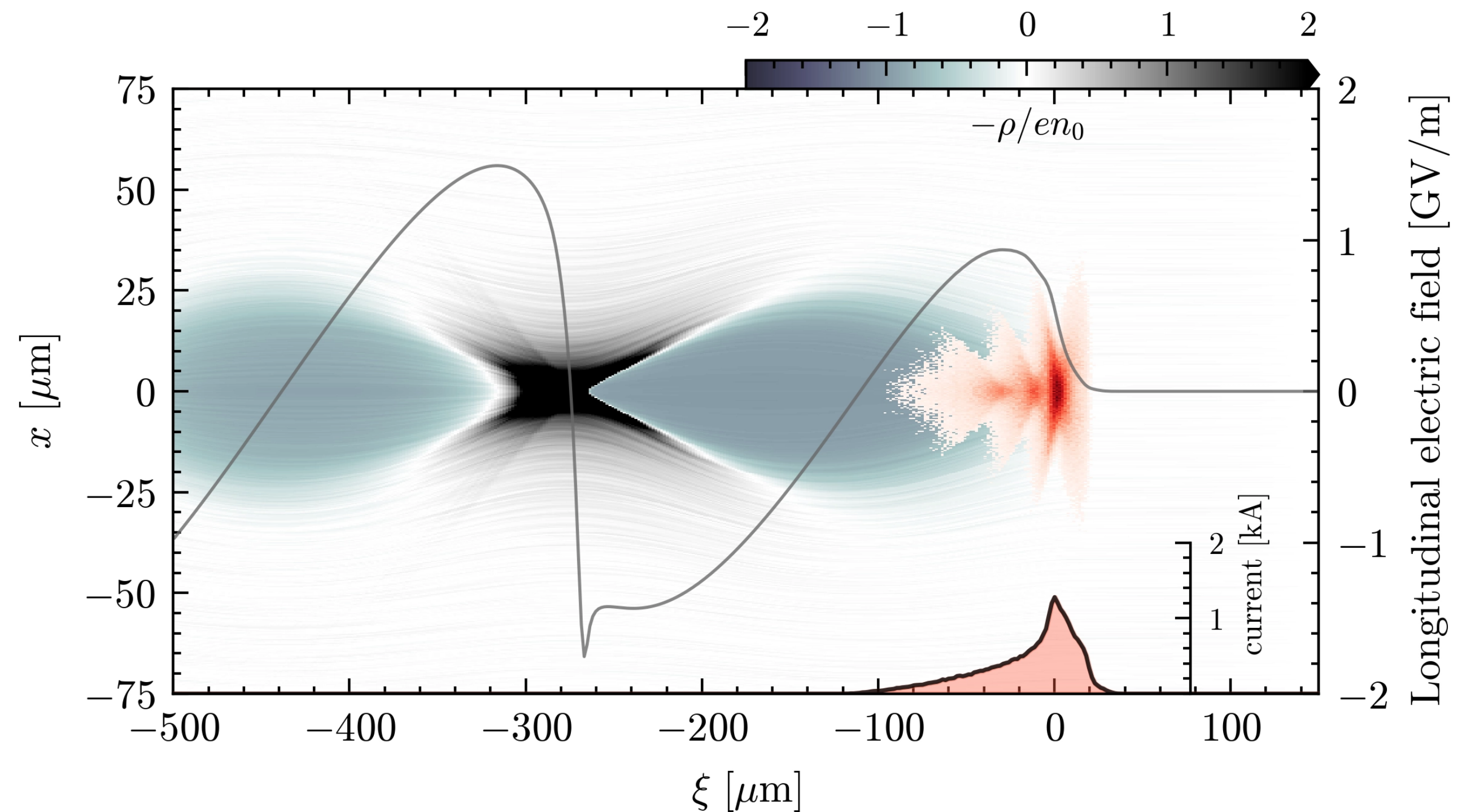
Drive beam samples GV/m decelerating fields

- > Analysis of the 20 taken 2.25 μ s after discharge (timing with the smallest minimum beam energy)
- > Average minimum beam energy:
 233.4 ± 2.6 MeV
- > ~ 0.83 GV/m decelerating fields
- > 2.25 μ s after discharge $\rightarrow$ *flat top very likely much less than 20 mm* $\rightarrow$ higher decelerating gradients likely
- > Transformer ratio needed to determine accelerating field
- > Need simulation to determine transformer ratio, plasma and beam parameters...



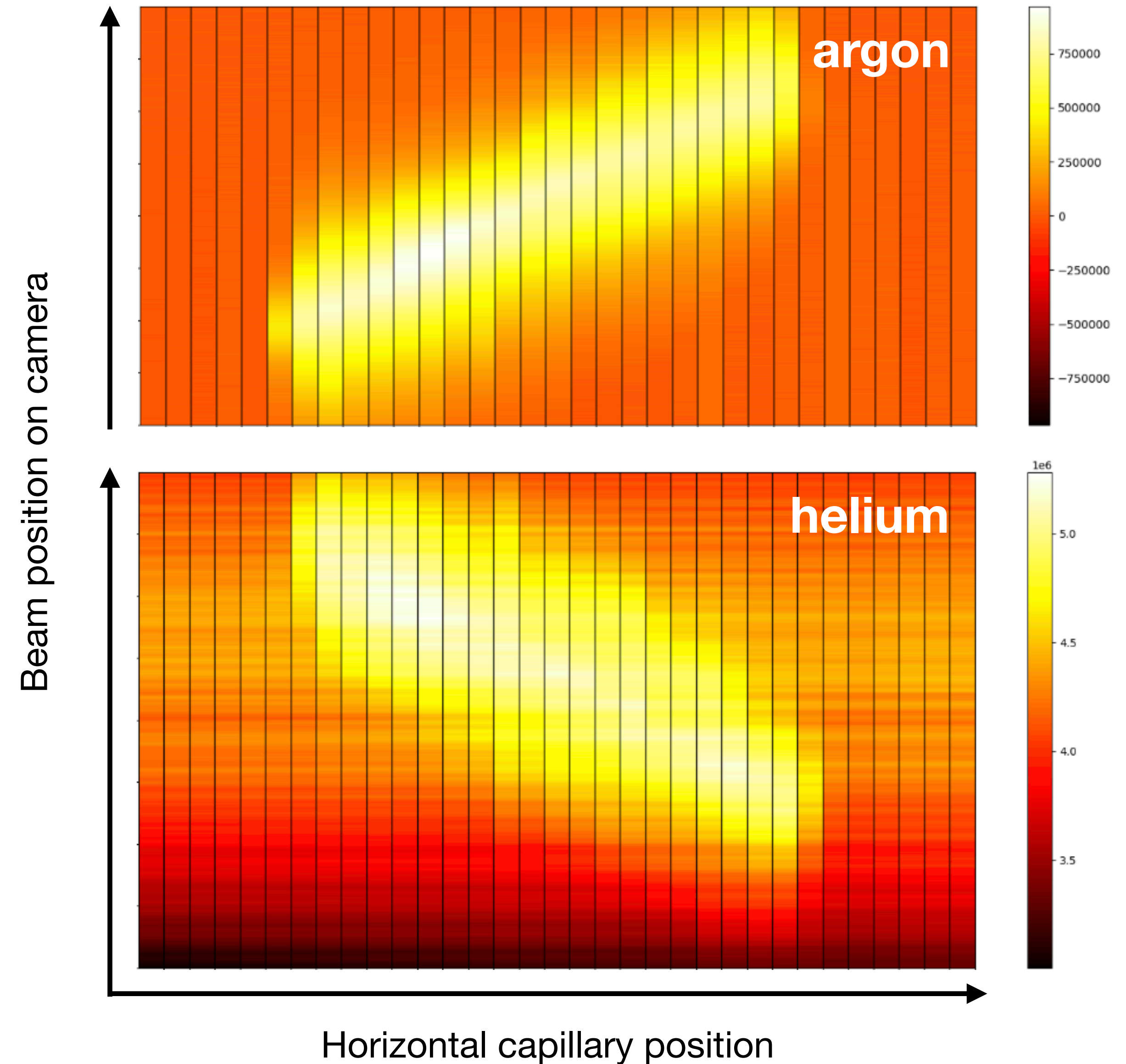
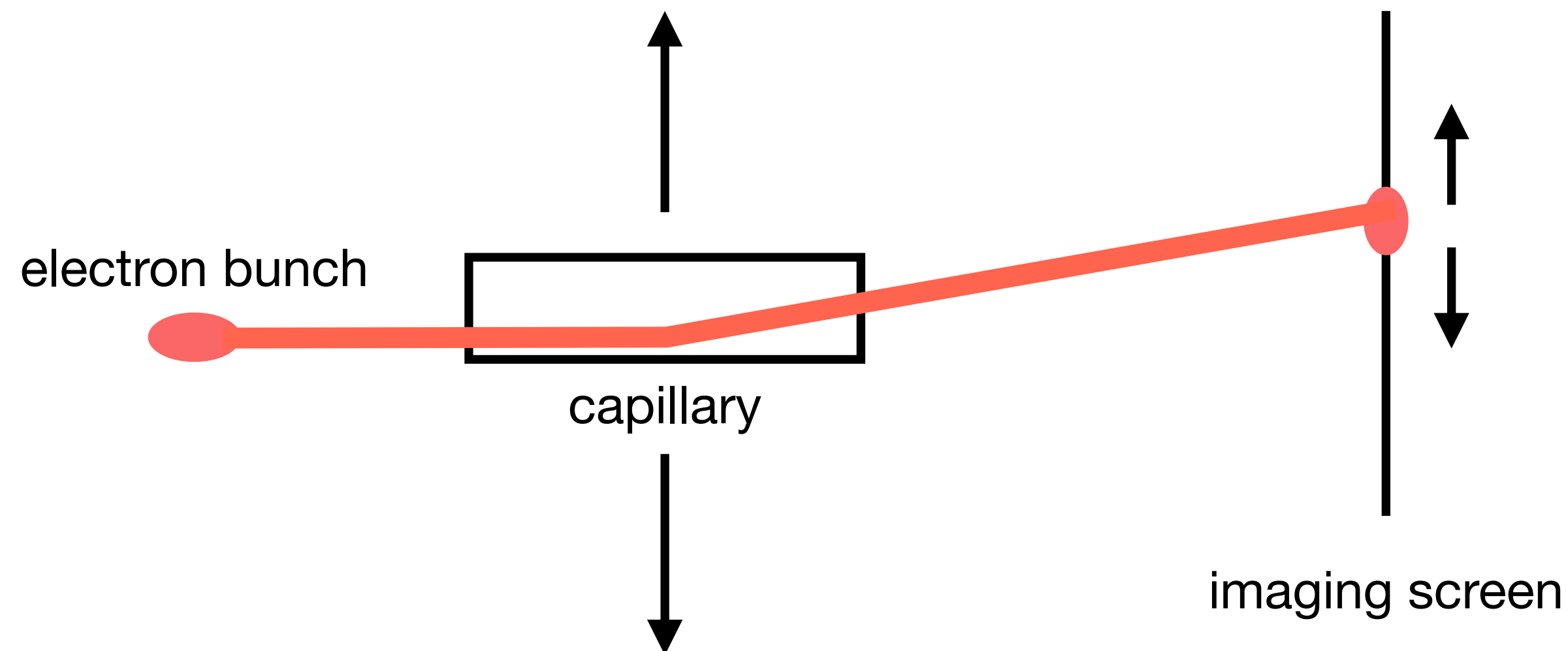
Outlook — *matching experiment with simulation*

- > Better understand the high-gradient working point with PIC simulations
- > Already found a reasonable working point by hand → 10^{16} cm^{-3} plasma density, 20 mm flat top, **measured** longitudinal current from the TDS with added compression factor
- > *Many unknowns:*
 - > Flat-top length
 - > Plasma density
 - > Bunch longitudinal phase space
 - > Bunch size and emittance
 - > etc.
- > Bayesian Optimisation?



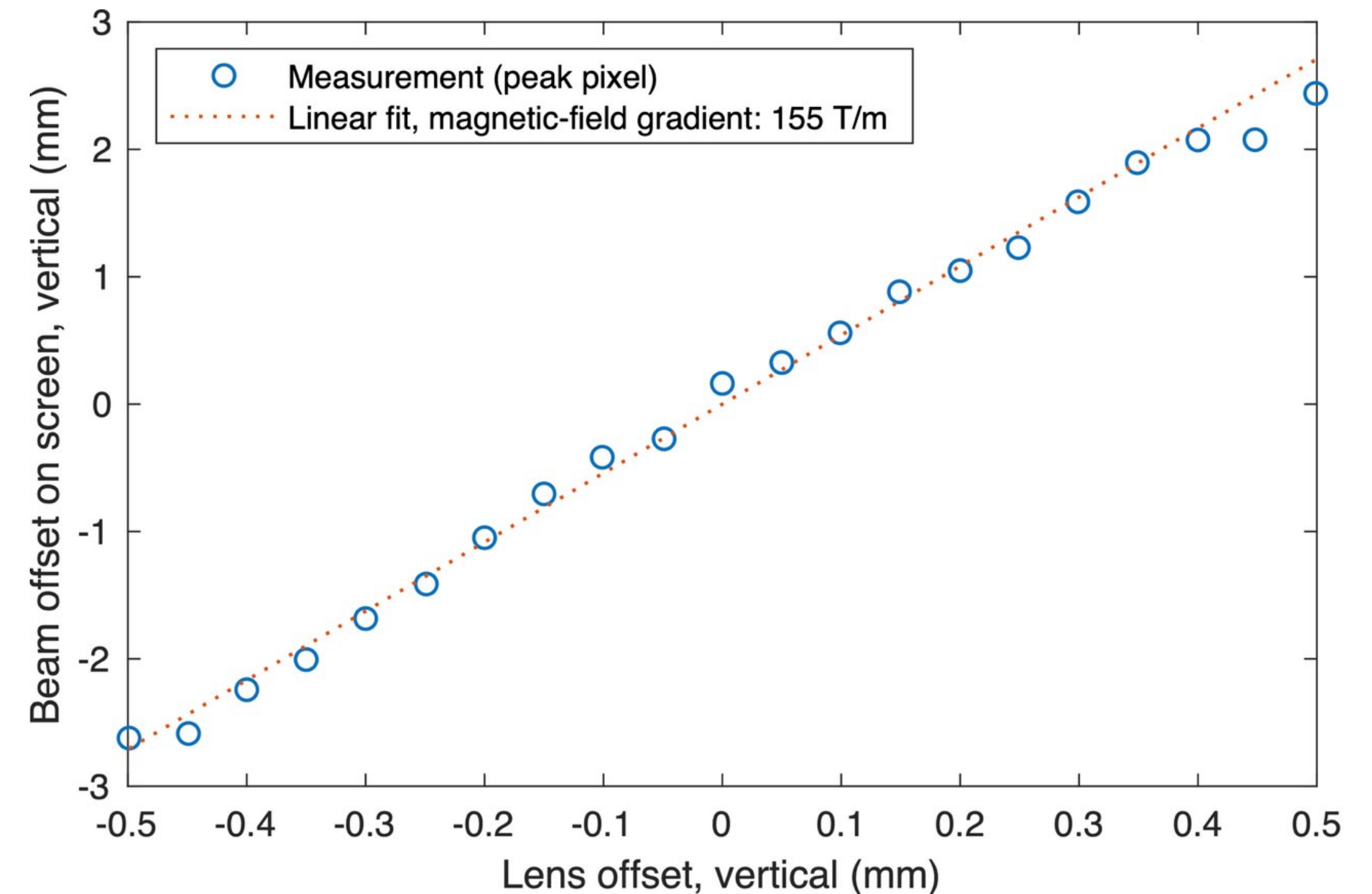
Plasma lensing demonstration

- > Low charge (30 pC)
- > Minimal compression (~ 1 ps)
- > Established operation in Ar
- > Linearity scans in both Ar and He
- > Off-axis lens acts like transversely displaced quadrupole



Aberration-free plasma lensing?

- > 150 T/m magnetic fields achieved
- > Linear fit $\rightarrow$ aberration free lens?
- > Next steps with remaining recorded data:
 - > Confirm emittance preservation (in argon) with quad scans
 - > Repeat process (expecting emittance spoiling due to nonlinearities) in helium



Courtesy: C.A. Lindstrøm

Summary — *from zero to state-of-the-art in 5 weeks*

- > First beam-driven plasma *accelerator* in the UK established(!) and first active plasma lensing at CLARA(!)
- > Plasma infrastructure successfully installed at CLARA
- > GV/m fields achieved
- > Clean lensing data taken
- > Required an international collaboration of 19 scientists to achieve → huge thank you to everyone involved
- > Next major steps will be to better understand the 250 pC CLARA working point + plasma
- > Hoping to kick off *Phase 1* in a beam time later this year...

physicsworld

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HALHF is going all in on plasma acceleration

16 Jun 2026

Backup Slides

Multi-year programmatic approach

High energy / Staging

High luminosity / Repetition rate

Phase 1

Inter-stage optics demonstrator

Beam-quality preservation with nonlinear lenses

Energy-transport studies

Plasma and plasma source temperature mapping

Phase 2

Quality-preserving plasma acceleration

Bunch pairs

Novel sources/plasma ramps

High-repetition-rate acceleration

100 Hz acceleration

Bunch trains

Phase 3

Driver generation and in-/out-coupling

Multi-driver generation at photocathode

Coupling in and out of chicane

'High'-average-power acceleration

Temperature-stabilised plasma sources

Phase 4

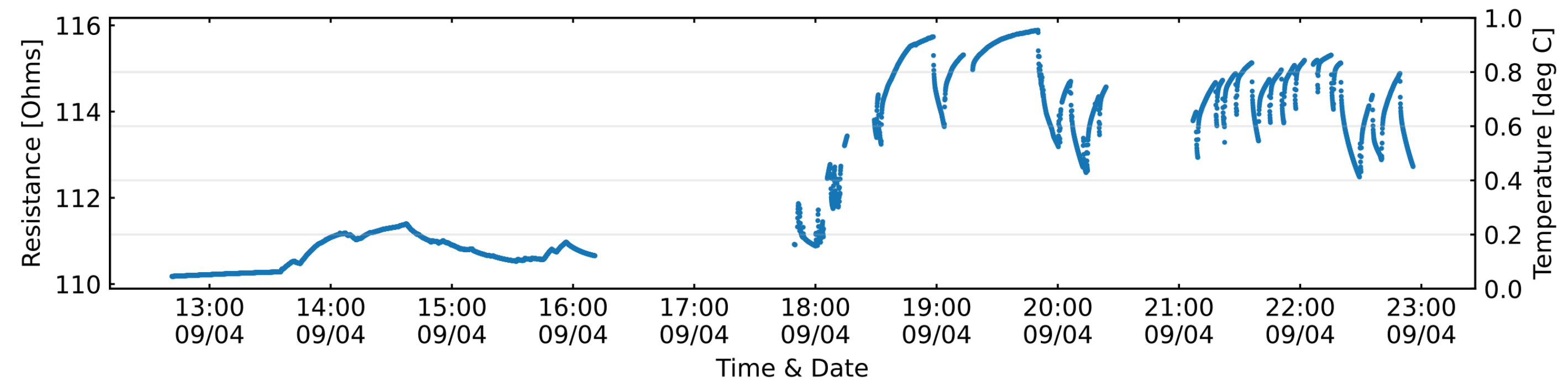
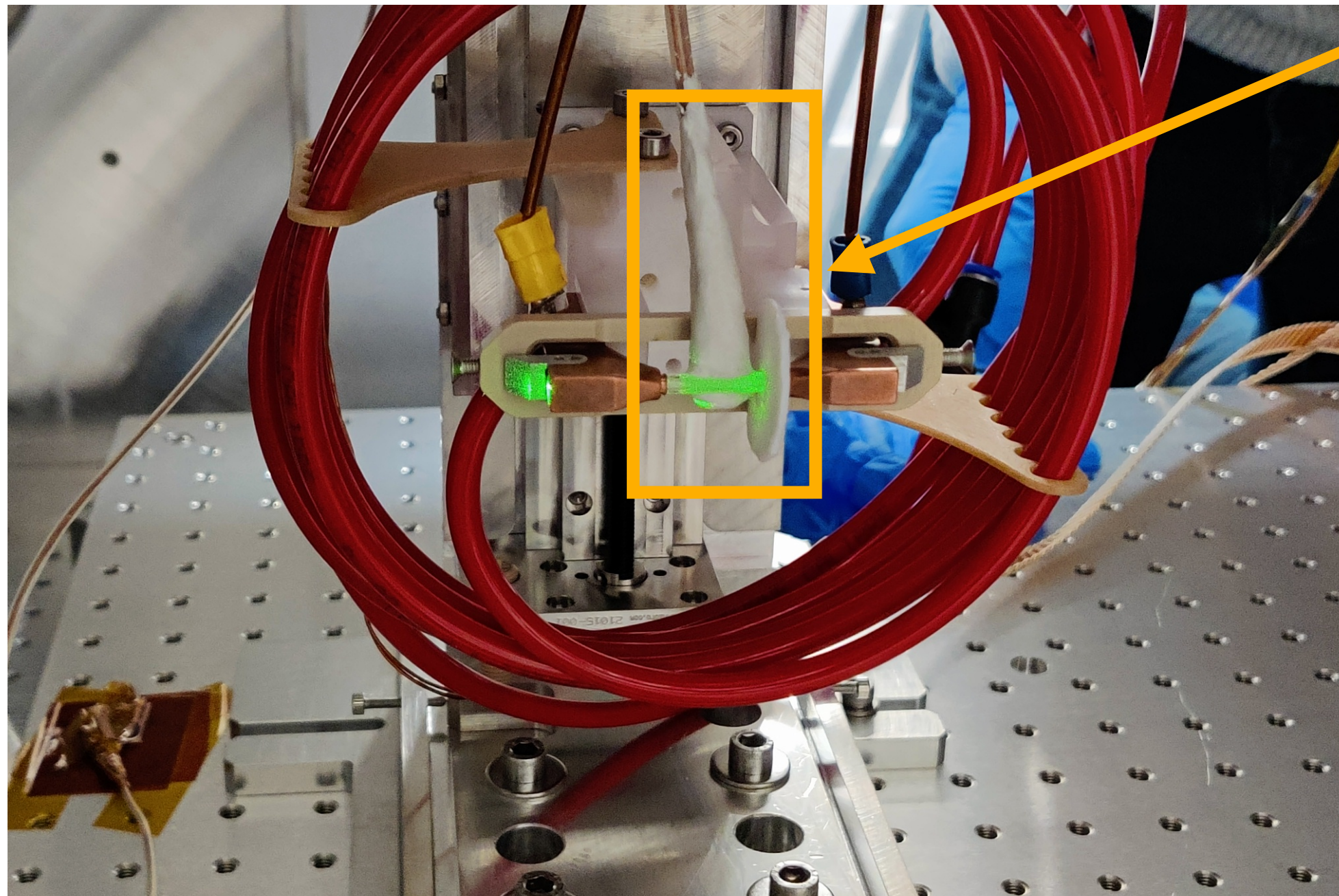
Two-stage demonstrator @ high average power

Multi-year programmatic approach

Phase 0	<i>Plasma infrastructure implementation and first tests</i> ~GV/m fields ~kT/m fields	
Phase 1	<i>Inter-stage optics demonstrator</i> Beam-quality preservation with nonlinear lenses	<i>Energy-transport studies</i> Plasma and plasma source temperature mapping
Phase 2	<i>Quality-preserving plasma acceleration</i> Bunch pairs Novel sources/plasma ramps	<i>High-repetition-rate acceleration</i> 100 Hz acceleration Bunch trains
Phase 3	<i>Driver generation and in-/out-coupling</i> Multi-driver generation at photocathode Coupling in and out of chicane	<i>‘High’-average-power acceleration</i> Temperature-stabilised plasma sources
Phase 4	<i>Two-stage demonstrator @ high average power</i>	

Cell temperature measurement

- > Also have cell temperature information (*with beam!*) from a PT100 temperature attached to the capillary
- > To be used alongside plasma temperature diagnostics in future runs



Courtesy: Ibrahim Najmudin

Simulation limitations

- > Not able to recreate long tail at low energy
- > LPS measured at TDS but compression and R56 before IP
- > Potential to use Bayesian Optimisation but many inputs poorly known
 - > Bunch length/current profile
 - > Plasma density
 - > Flat-top length
 - > Beam transverse size
 - > ...

