Latest Results from the FLASHForward Experiment

1. PWFA results
2. Plasma source development
3. Applications to other experiments

J. C. Wood, J. Beinortaitė, J. Björklund Svensson, L. Boulton, G. Boyle, P. Burghart, J. Cowley, R. D'Arcy, J. P. Díaz, A. Ferran Pousa, B. Foster, M. J. Garland, P. González-Caminal, M. Hohmann, M. Huck, H. Jones, A. Kanekar, O. Kornilov, A. Křivková, C. A. Lindstrøm, G. Loisch, T. Long, A. Maier, S. M. Mewes, L. Müller, I. Najmudin, J. Osterhoff, T. Parikh, F. Peña, D. Samoilenko, S. Schröder, I. Schultess & the LUXE Collaboration, B. Schütte, E. Svirplys, M. Thévenet, J. Thomas, M. J. J. Vrakking, S. Wesch, M. Wing

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Experiment Goals & Facility

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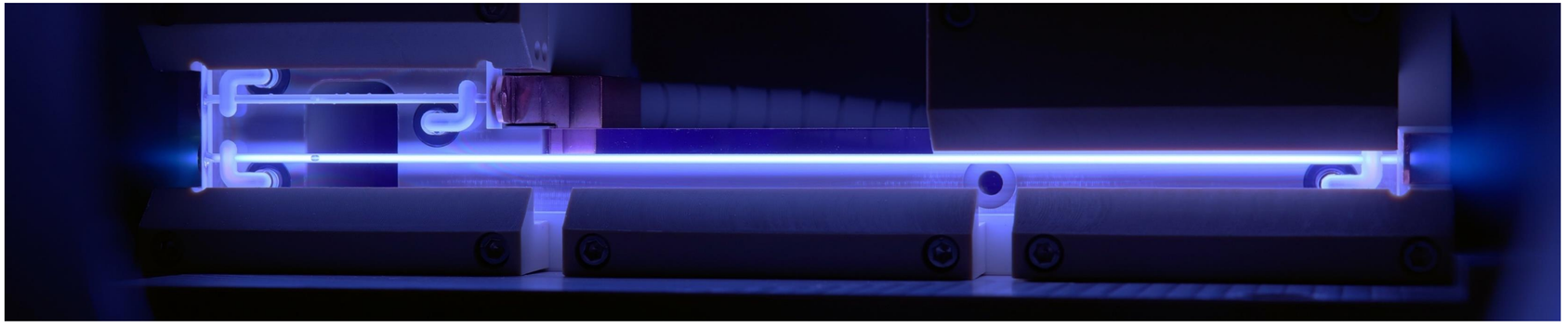
FLASHForward Goals

A beam-quality-preserving plasma booster stage at high repetition rate



Bunch-quality-preserving acceleration

- Energy spread preservation
- Emittance preservation
- Brightness preservation

High energy gain and efficiency

- Towards energy doubling
- High overall efficiency (witness energy gain / driver energy loss)

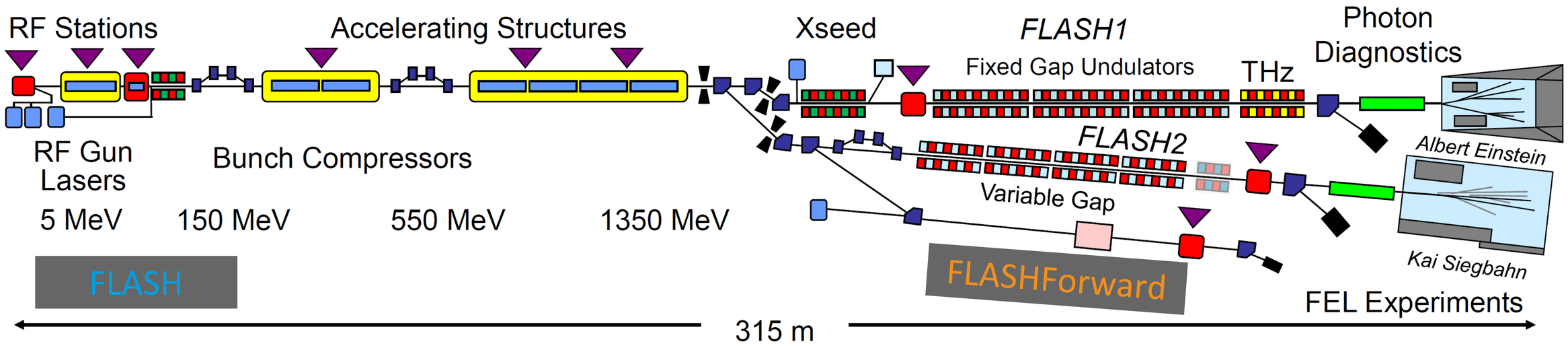
High-repetition-rate acceleration

- Plasma evolution studies
- Acceleration of bunch trains
- Then: high average power

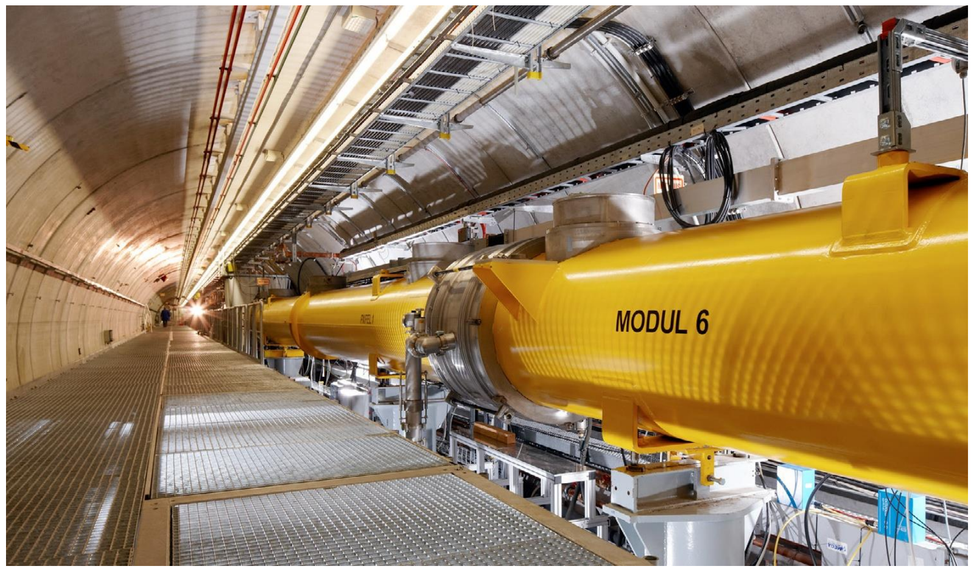
Simultaneously!

FLASH Overview

A linac accelerating high-quality electron bunches for EUV & soft x-ray free electron lasing



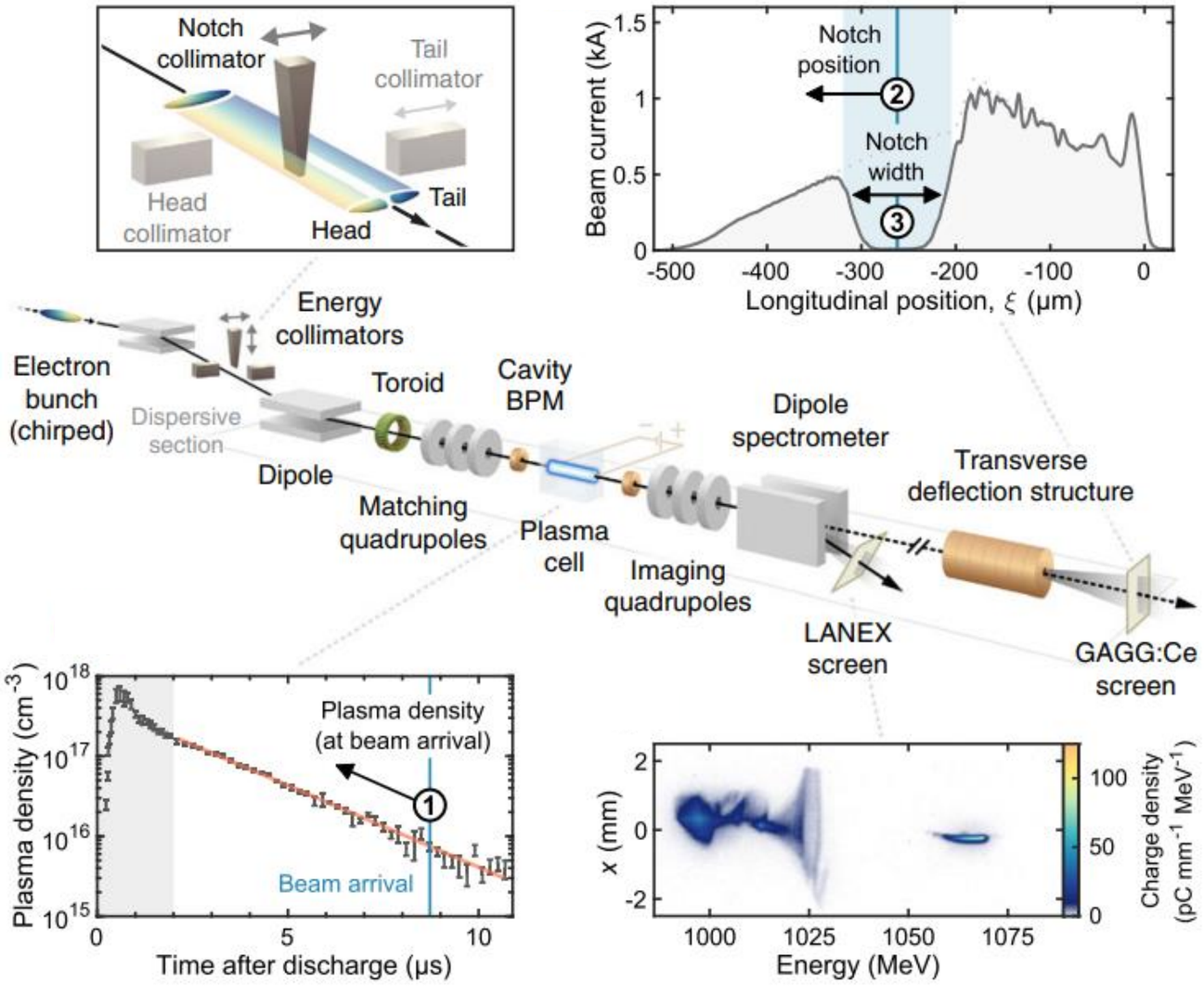
- SRF linac delivering trains of high-quality bunches for XUV & soft x-ray FEL beamlines, and the FLASHForward plasma-accelerator beamline.
- Machine has been shutdown since June 2024 to upgrade FLASH1. Restarted recently, commissioning shifts last week.



https://flash.desy.de/
B. Faatz at al., NJP, 2016, 10.1088/1367-2630/18/6/062002

FLASHForward Overview

DESY´s PWFA Experiment



C. A. Lindstrøm et al., Phys. Rev. Lett.**126**, 014801 (2021)

Our Typical PWFA Setup

- 1-1.2 GeV bunches with ~ 1 nC, 1 ps, linear LPS & ramped current profile.
- Bisect the bunch in a dispersive section to form a driver-witness pair
- 400 pC, 1 kA driver. 40 pC witness.
- Discharge ionised plasma, timed so $n_e \approx 1 \times 10^{16}$ cm^{-3} at beam arrival time.
- Establish an optimally beam loaded working point by varying notch position, notch width and n_e.
- Main diagnostics:
  - Two imaging spectrometers (low res. with large field of view, and high res.)
  - X-band transverse deflection structure

Quality Preserving Acceleration and Focussing

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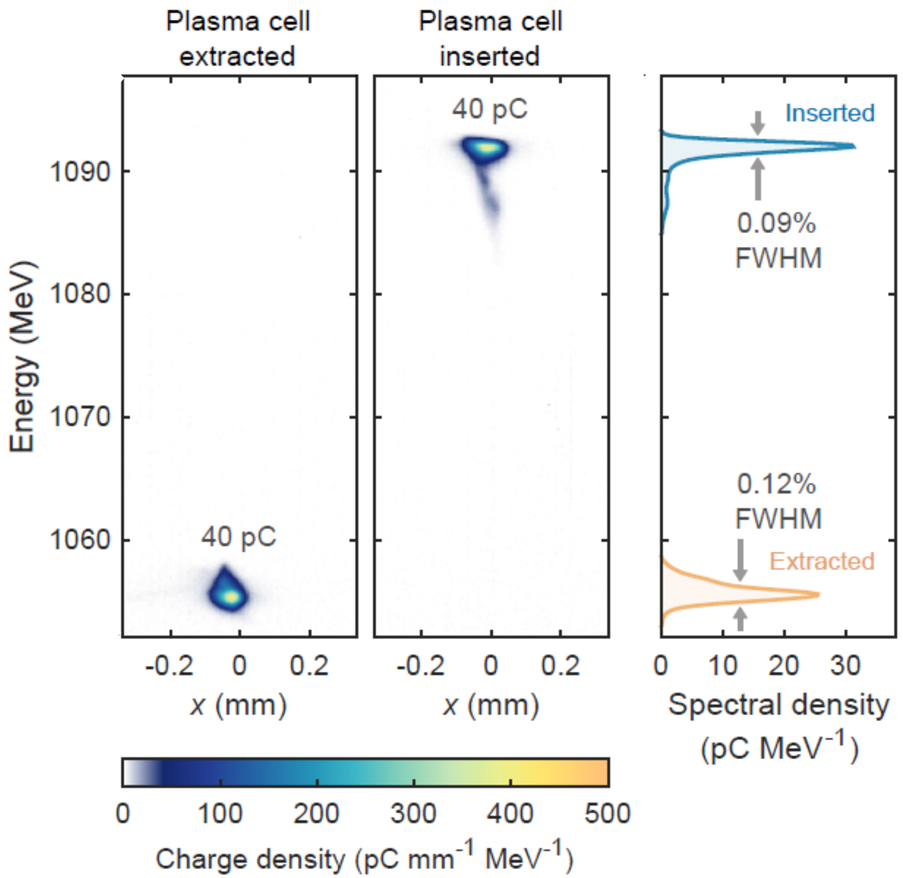
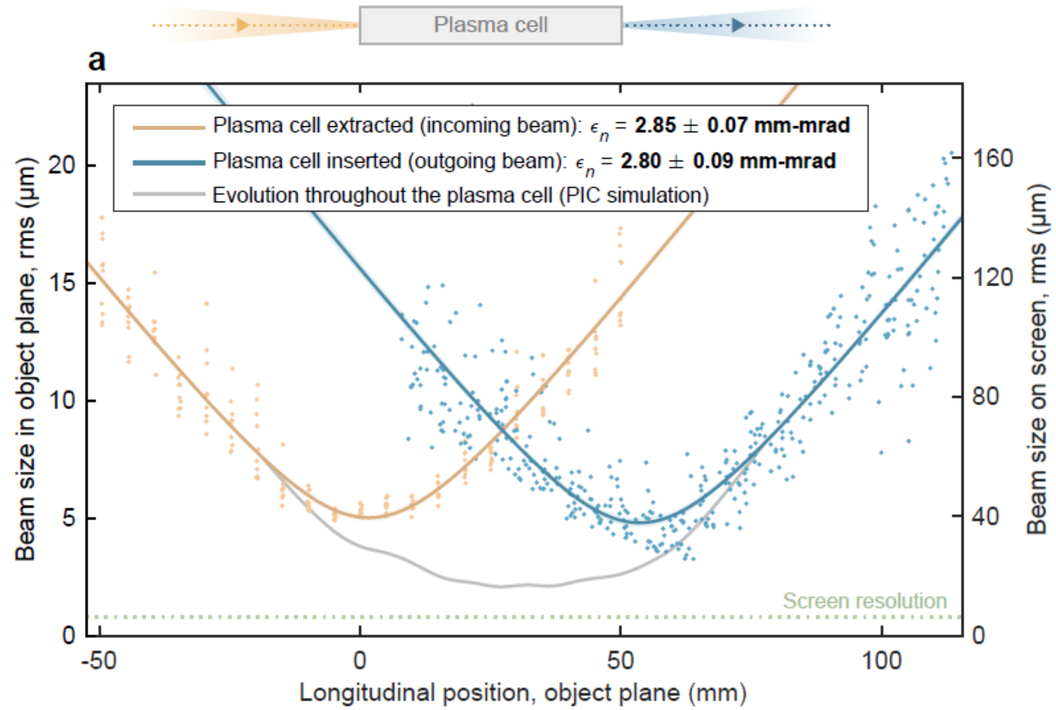
Emittance Preservation in PWFA

Emittance preserved at 2.8 mm-mrad after plasma acceleration by 40 MeV



40 pC accelerated by 40 MeV in a 50 mm plasma, 0.1% energy spread.

- Object plane scans for non-interacted and accelerated bunches show the same emittance.
- $\varepsilon_{n,x}$ preserved at 2.8 mm-mrad within 3% uncertainty.



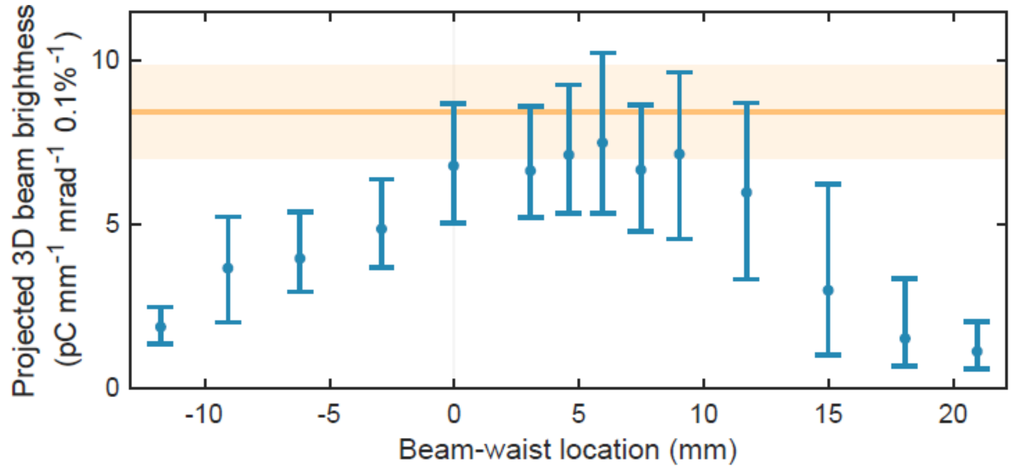
C. A. Lindstrøm, Nat. Comms., **15**, 6097 (2024), https://www.nature.com/articles/s41467-024-50320-1

3D Brightness Preservation in PWFA

Minimising tilts and focal plane control are key

- **Angular alignment tolerance:** < 0.5 mrad offset required for 50 mm plasma.
- Simulations show < 0.1 mrad offset needed for ε_n a 500 mm plasma.

- **Focal position tolerance:** Trade-off between focussing before the plasma (mismatching) and too far in to the plasma (charge loss).
- Regime with many instances (~40%) of 3D brightness preservation (charge, energy spread & ε_n).



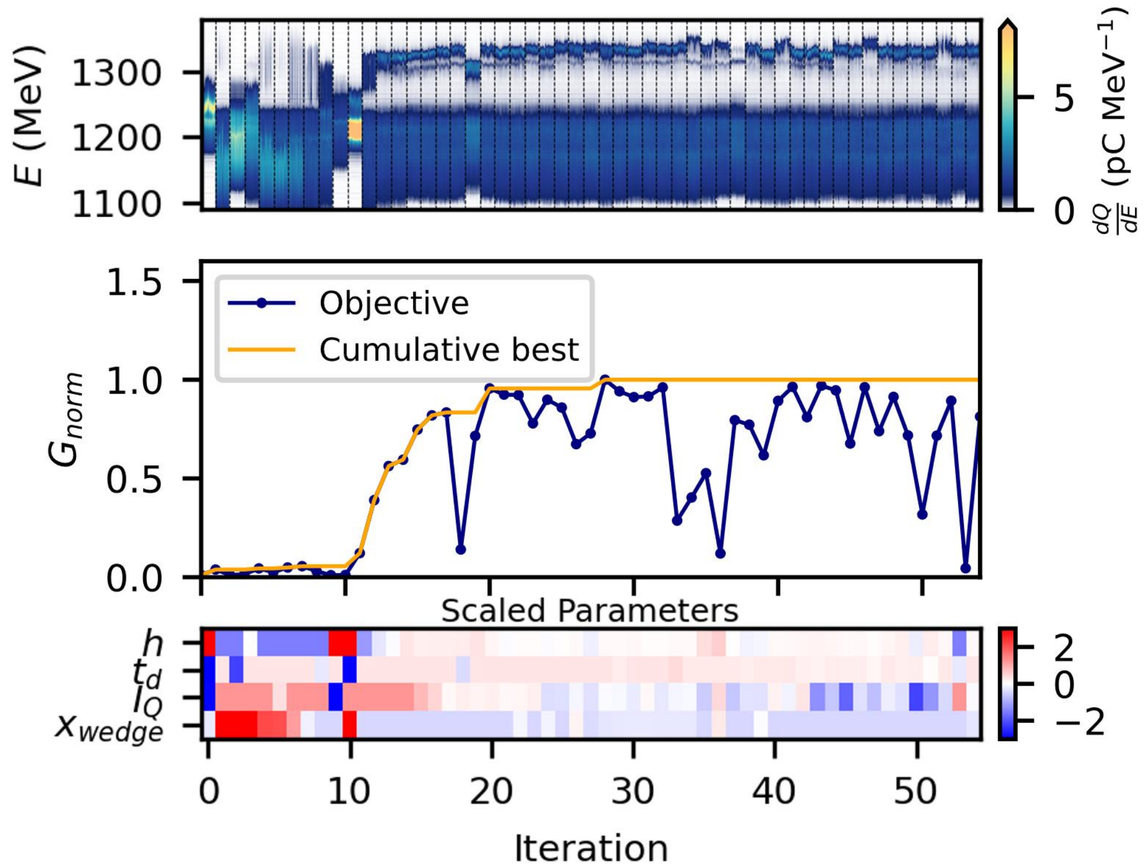
C. A. Lindstrøm, Nat. Comms., **15**, 6097 (2024), https://www.nature.com/articles/s41467-024-50320-1

Bayesian Optimisation

Producing an optimally beam loaded working point quickly *(L. Boulton talk, 23.09)*

- Finding an optimally-beam-loaded working point, required for all levels of quality preservation, is time consuming (3D grid scan after initial setup).
- Can Bayesian optimisation rapidly find such a working point?

$$G = (\Delta E)^2 \left(\frac{\mathrm{d}Q}{\mathrm{d}E}\right)_{max}$$



- Starting from ~ noise, converged on a solution in 28 iterations (< 40 mins) to:
  - (34 ± 2) pC accelerated charge
  - (103 ± 1) MeV energy gain in 50 mm (2.1 GV/m)

A. Ferran Pousa et al., PRAB, 2023, 10.1103/PhysRevAccelBeams.26.084601

J. C. Wood et al., Proc. 15th IPAC, 2024, doi: 10.18429/JACoW-IPAC2024-MOPR40

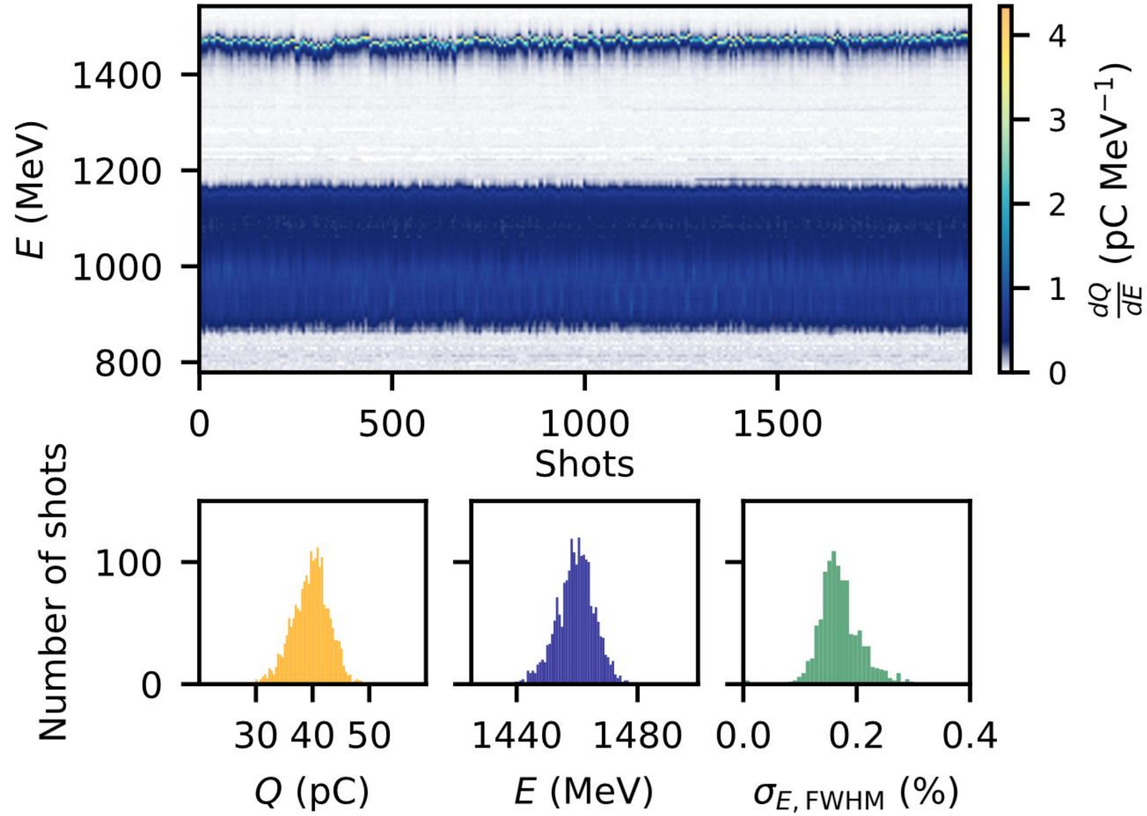
Towards High Energy Efficiency

For FF≫: Need to accelerate many 10‘s pC by a large fraction of a GeV

- Bunch compression limits our acceleration gradients- longer acceleration distances required.
- Switched 50 mm capillary for a 195 mm capillary.
- Made small changes from 50 mm cell working point, and from 2000 consecutive shots achieved, at 1.3 GeV/m:

Q (pC)	ΔE (MeV)	$\sigma_{E,FWHM}$ (%)	Efficiency (%)
40 ± 3	**250 ± 6**	**0.17 ± 0.04**	**3.6 ± 0.3**

- Efficiency = witness energy gain ÷ driver energy in



J. C. Wood et al., Proc. 15th IPAC, 2024, doi: 10.18429/JACoW-IPAC2024-MOPR40

Towards High Energy Efficiency

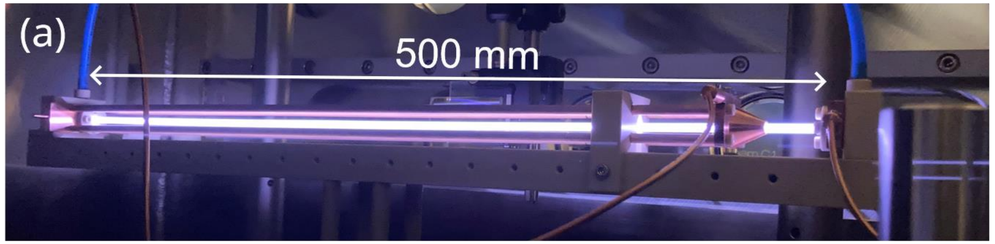
For FF≫: Need to accelerate many 10‘s pC by large fraction of a GeV

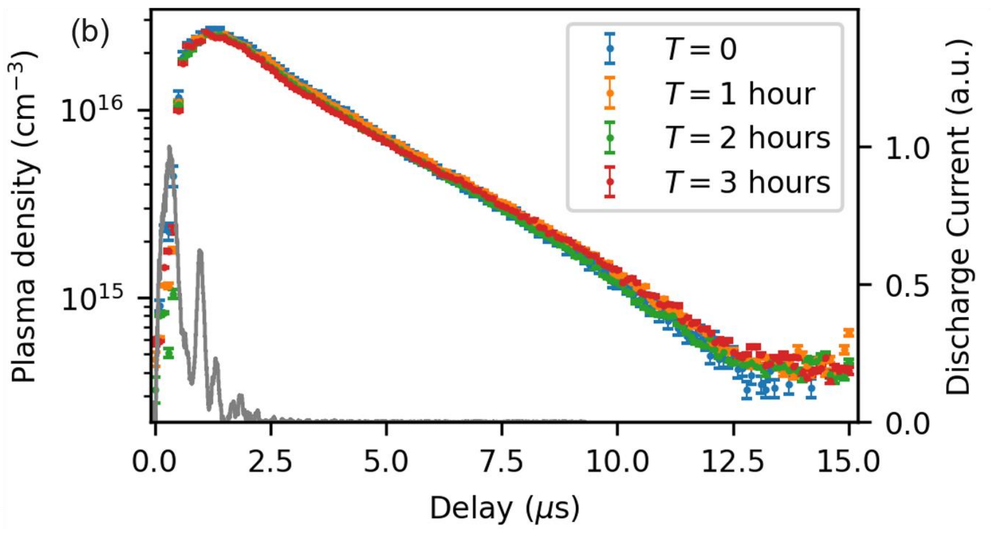
Cell Design

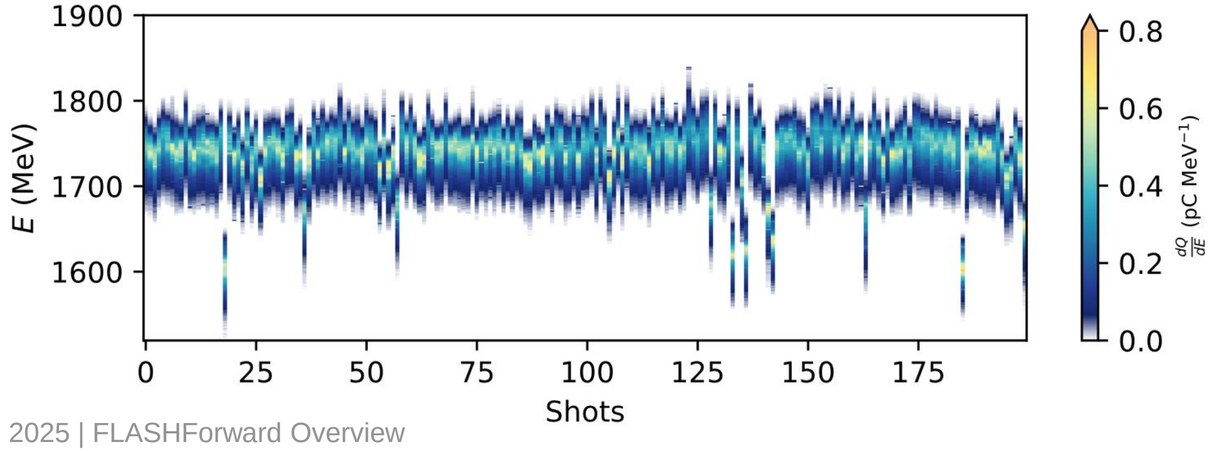
- Aim for 0.5 GeV gain at 1 GV/m: 500 mm plasma at ~ 1×10^{16} cm^{-3}.
- Glow discharge required for stable discharges.
- Reliably produces required density over long periods.

Electron Acceleration Data

- First data taking, demonstration acceleration from 1.2 → 1.75 GeV.
- 18.5 pC, 1.6% FWHM energy spread.
- The overall energy transfer efficiency was ~ 3%. Further beamtimes will focus on better charge incoupling.





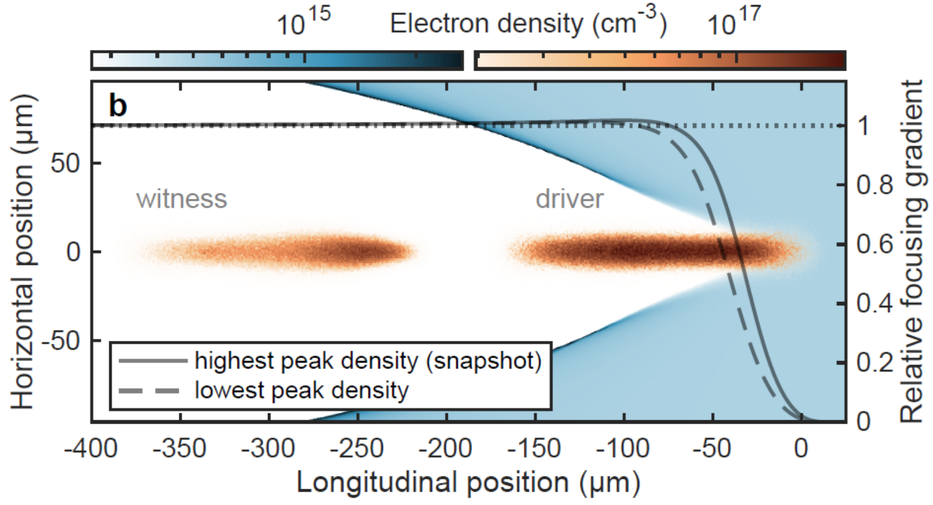


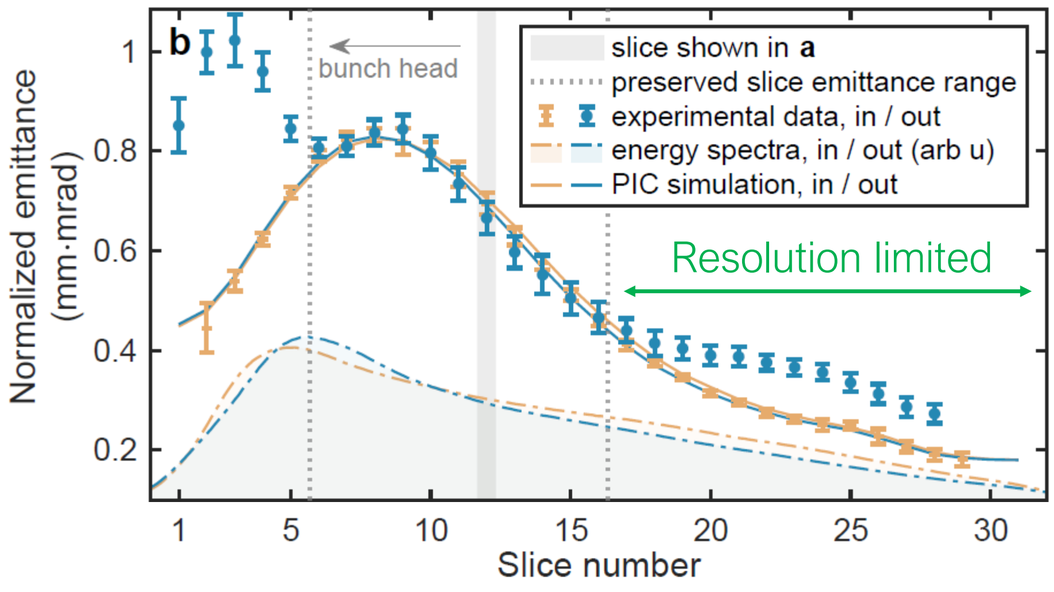
Plasma Lenses for High Quality Beams

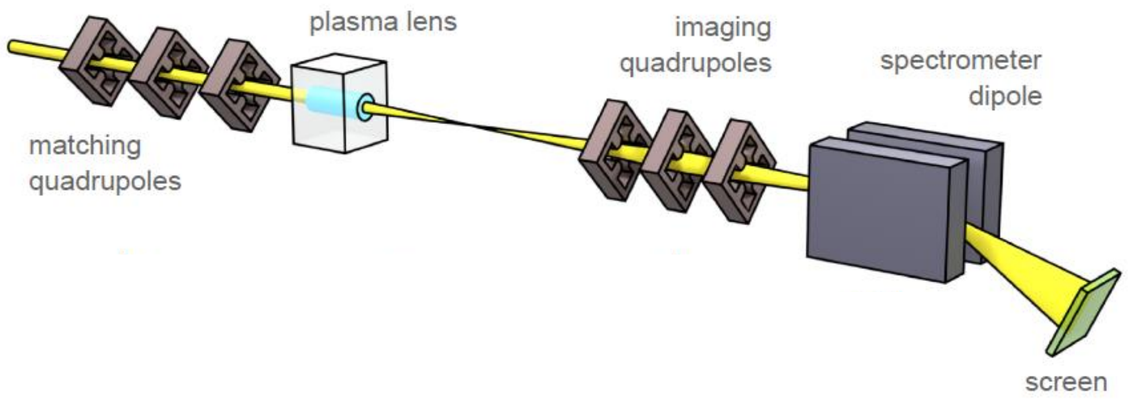
Compact, symmetric, low chromaticity focussing with emittance preservation

(J. Björklund Svensson talk, PS1, 25.09 @ 16:40)

- PPL: use the focussing force of a wakefield in a ~ 10^{14} cm^{-3} plasma as a lens. Symmetric focussing, less chromatic than quadrupoles (short focal length). Requires a driver, but most of it is also focussed.
- A low-chromaticity solution to in/out-coupling for PWFAs (v. small β function) is to set a soft focus with quads then focus tightly with a PPL.
- We showed this can be done while preserving $\varepsilon_{n,x}$ for many beam slices
- Waist β function & focal length simultaneously tuned via n_e. 5 mm (expt., res. limited)/ 2 mm (PIC) β functions shown. Tightest focus with quads is ~ 10 mm.







J. Björklund Svensson et al., arxiv.org/abs/2509.08420 (2025) Under review at PRL.

Understanding Plasmas and Sources

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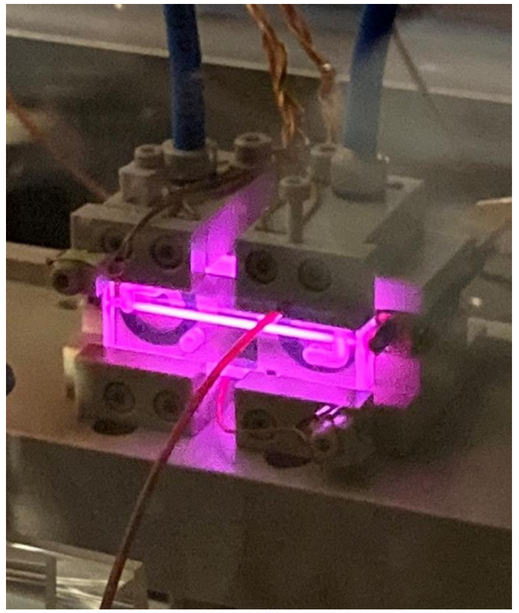
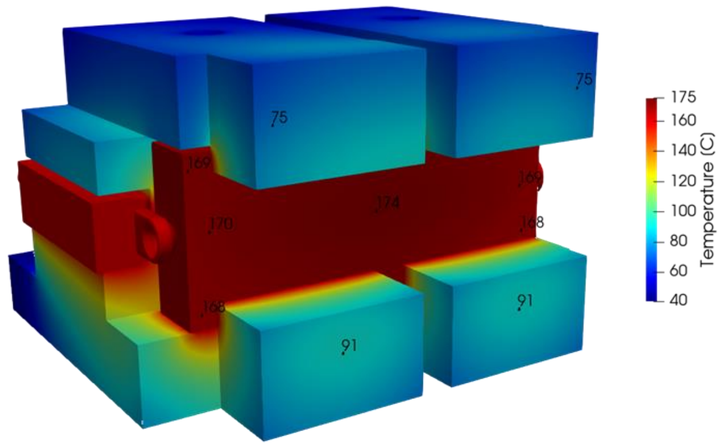
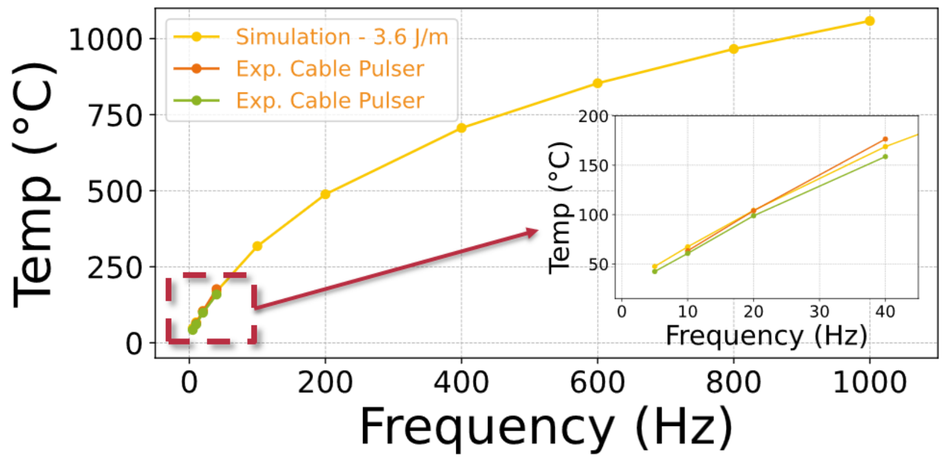
Heating Effects on Plasma Capillaries for PWFA

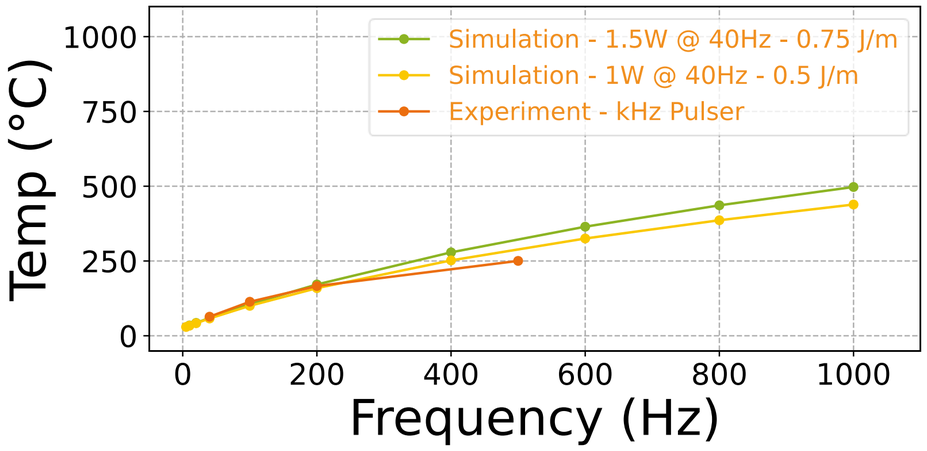
Effects of high heating loads on plasma sources must be understood *(J. P. Díaz poster, 22.09)*

- Sources for plasma boosters need up to 10 kHz rep rate.
- At FF>> we deposit ~ 1 J/m from the wakefield and 3.6 J/m (@ 25 kV) or ~ 0.5 J/m (@ 8 kV) from plasma creation with a discharge.
- We benchmarked ANSYS simulations at both voltages by probing the surface temperature of the capillary.
- Extended model to kHz repetition rates, reaching temperatures of 500 and 1000 C.
- Next step: design active cooling systems.







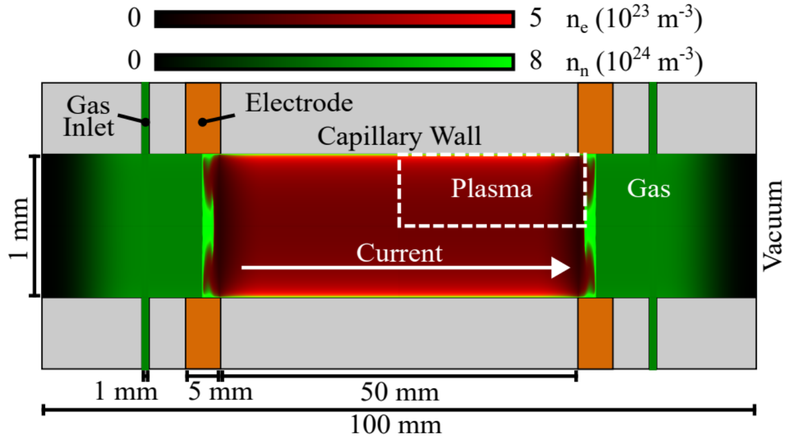


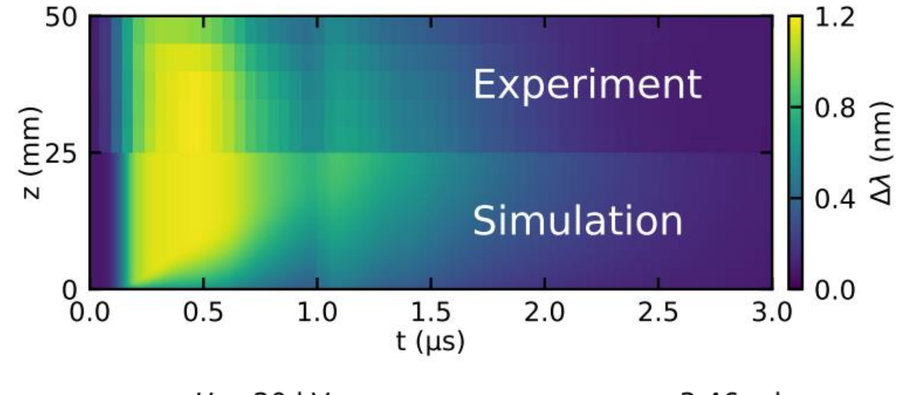
Benchmarked Modelling of Discharge-Ionised Plasmas

To compare to spectroscopy measurements, simulations require emission models

- We perform hydrodynamic simulations of our discharge capillaries to learn about our plasmas.

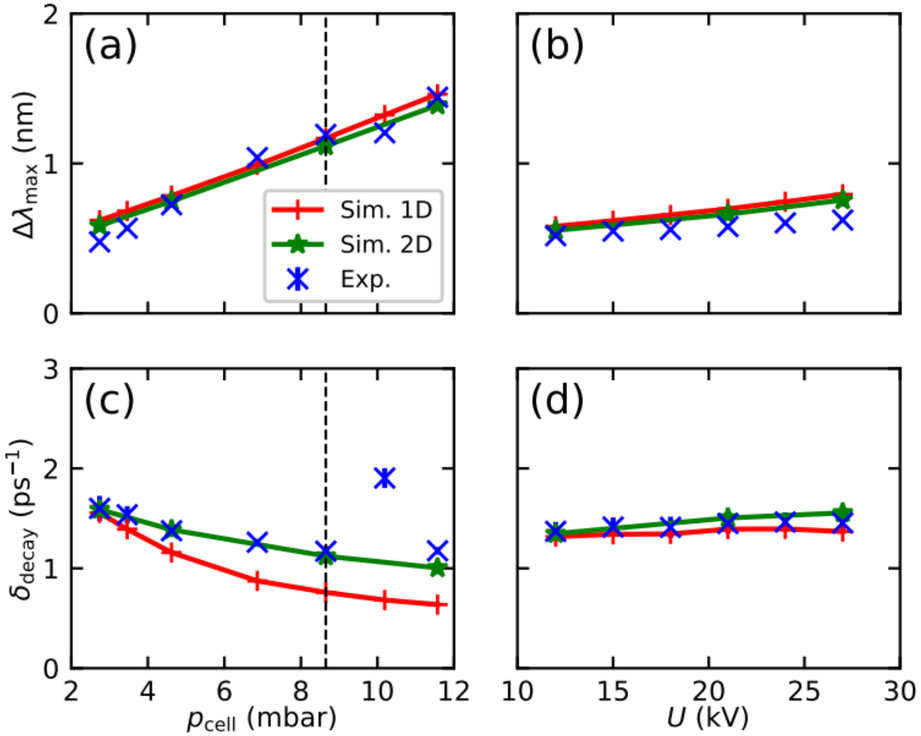
  S. M. Mewes et al., Phys. Rev. Res. **5**, 033112 (2023)





- Model benchmarking required for verification so it can inform future designs.
- In the lab we measure n_e via the pressure broadening of the H_α line.
- We incorporated an emission model into the simulation. Very good agreement between the maximum and decay time of the line width.
- It is clear that from the simulation that the measured line width is the sum of many lines of different widths (e.g. from radially varying plasma n_e and T).
- The simulation is required to extract the true density.

S. M. Mewes et al., arxiv.org/pdf/2506.16192 (2025).
Under review at PRR



Applications Beyond Accelerators

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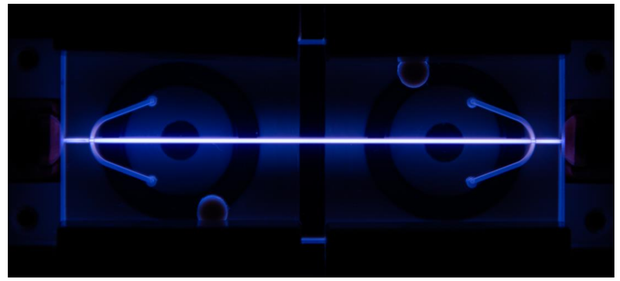
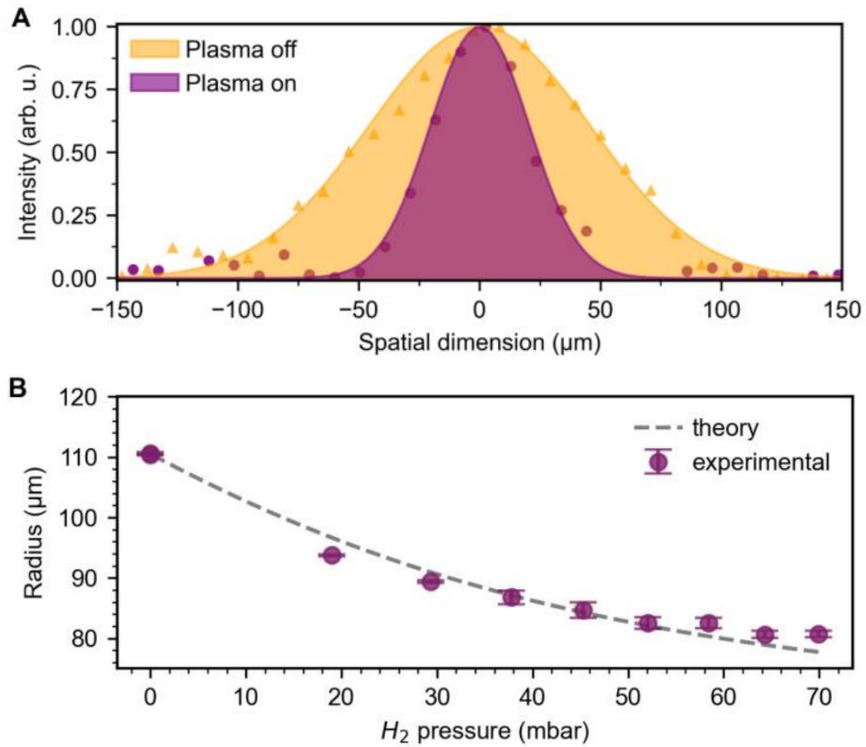
Plasma Lenses for Attosecond UV Radiation

Plasma lenses can focus many 10‘s eV attosecond light with low absorption

- Sub-100 attosecond UV light from HHG is difficult to focus. Refractive optics are absorbative & dispersive, reflective optics have low reflectivity.
- A highly transmissive lens would be of great value to photon-hungry experiments on time-resolved electron dynamics.
- A parabolic n_e profile from a discharge can be used to focus light. A collaboration with MBI Berlin experimentally demonstrated this.
- A – Pulse focussing from 97±2 µm to 40±2 µm.
- B – The focal spot size (and focal length) was varied for by changing the gas pressure in the capillary. Beamline transmission of 80%.
- Simulations showed very minor pulse stretching (<10 %), & compression is possible.



$$\eta = \sqrt{1 - n_e(r)/n_c}$$



E. Svirplys et al. arxiv.org/pdf/2504.11272 (2025). Accepted by Nature Photonics

A Beam Dump Calorimeter for LUXE

Successful tests of a gamma-beam calorimeter for strong-field QED experiments

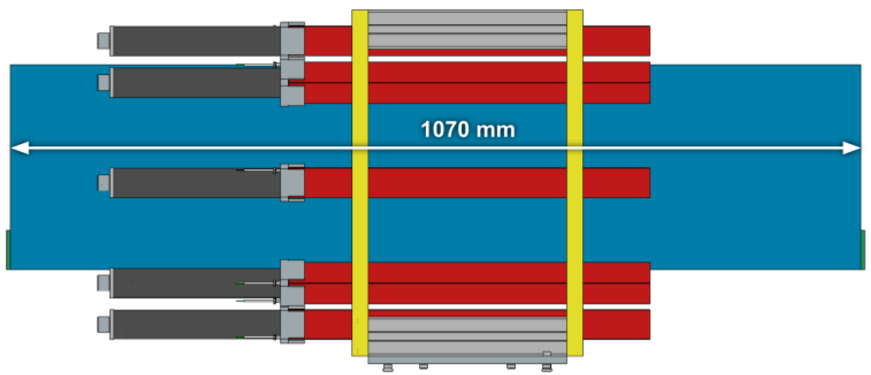
- The LUXE experiment proposes to collide the ~ 17 GeV electron bunches from EuXFEL with a high-intensity laser to study strong-field QED.

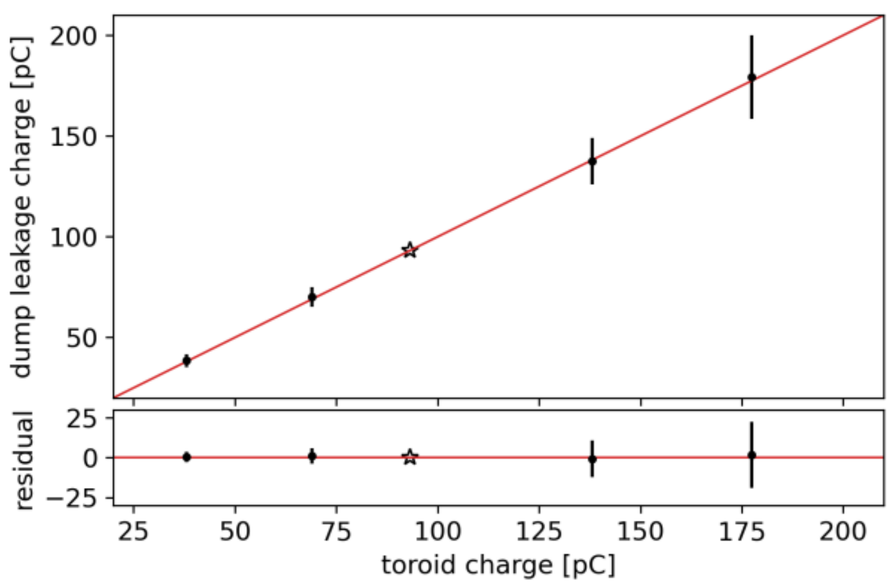
- A γ-flux monitor is required. It is possible to use the electromagnetic shower created in the beam dump for this.

- Cerenkov light is produced in Pb-glass bars, signal is read out by PMTs.

- We have tested this concept with GeV electrons in the FF≫ beam dump.

- The calibrated signal from the detectors matches the charge from a toroid. Differential signal level between PMTs provide beam position information.





I. Schultess et al., arxiv.org/abs/2508.17991 Submitted to JINST.
LUXE TDR: https://link.springer.com/article/10.1140/epjs/s11734-024-01164-9

Acknowledgements

The DESY Plasma Group

See our webpage at plasma.desy.de
for a full list of teams and activities.

Fig: Marta Mayer (DESY)

Conclusions

Beam Quality Preservation

> Emittance preservation in PWFAs and passive plasma lenses demonstrated, working on Bayesian optimisation implementation to speed up the process.

Energy transfer efficiency

> Developed 500 mm discharge plasma cell and showed acceleration of a < 2% energy spread bunch from 1.2 to 1.75 GeV.

Repetition rate concerns

> Benchmarked model of cell heating to guide design of cooled systems for high average power.

Aiding advances in other fields

> Successful benchmarking of MHD code for discharge capillary simulations.

> Leveraged our plasma cells and beamline for focussing of as UV light & calorimeters for strong-field QED experiments.