Plasma Booster Status Report

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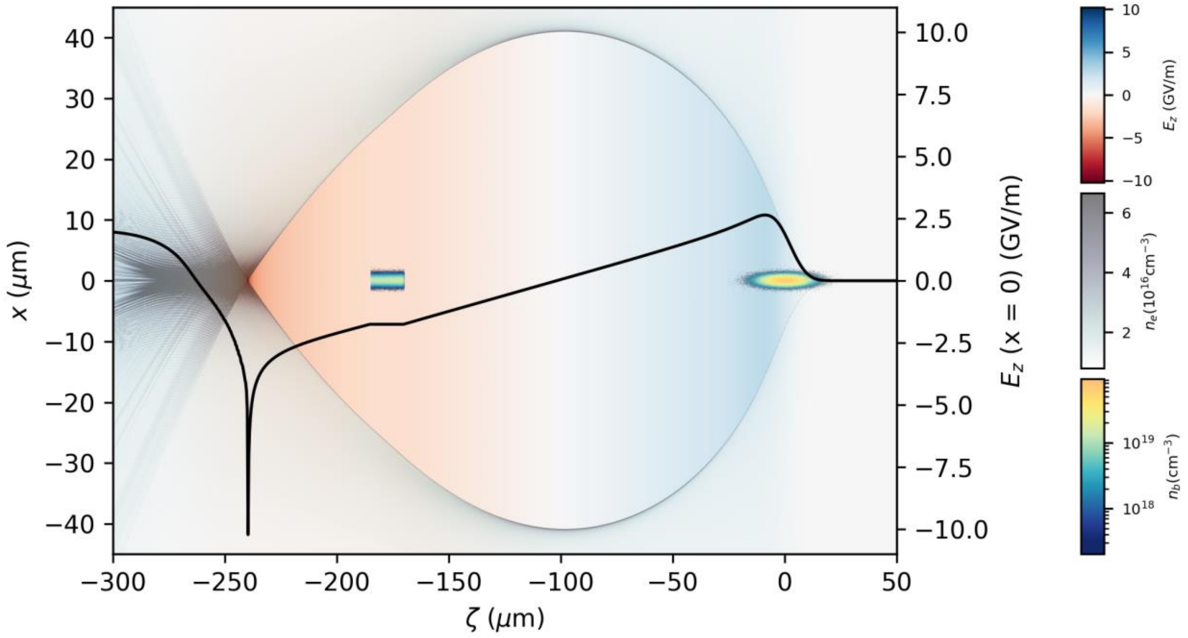
XFEL Accelerator R&D Status 2025

HELMHOLTZ

DESY.

Plasma Booster Concept

- A high current, short electron bunch is focussed into a plasma.
- Its space charge force drives plasma electrons off axis, the ions move relatively little on this timescale.
- The bubble of positive charge is accelerating and focussing for electrons at multi-GV/m strengths.
- The longitudinal field can be flattened by a shaped trailing bunch for energy-spread-preserving acceleration [1-3].
- The bubble has linear focussing fields to preserve emittance [4].



Questions:

- Can a plasma booster double the XFEL bunch energy in a cheap and compact manner?
- Can it preserve the quality of the bunches?
- Can this be done with bunch trains to enable future user applications?

We can also begin to answer many of these questions at FLASHForward.

[1] W. Lu et al., Phys. Rev. Lett. **96**, 165002 (2006)
[2] M. Tzoufras et al., Phys. Rev. Lett. **101**, 145002 (2008)
[3] C. A. Lindstrøm et al., Phys. Rev. Lett. **126**, 014801 (2021)
[4], C. A. Lindstrøm et al., Nat Commun **15**, 6097 (2024).

Project Organisation

Pillar 1

Technologies for a high-energy-gain plasma booster

Twin bunch acceleration from the photocathode

High energy gain acceleration at FLASHForward

Pillar 2

Technologies for a high-repetition-rate plasma booster

Production, testing and use of fast plasma sources

Pillar 3

High-average-power plasma boosters

Temperature measurements of plasma sources

Cooled plasma sources

Incoupling & outcoupling of electron bunches

Diagnostics for MHz plasma boosters

Pillar 4

Concept for a plasma booster at XFEL

Linac simulations for driver-witness pair acceleration

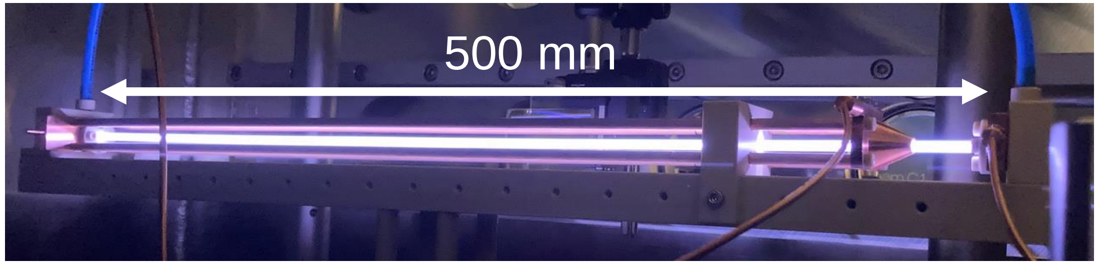
PIC simulations to determine plasma source requirements

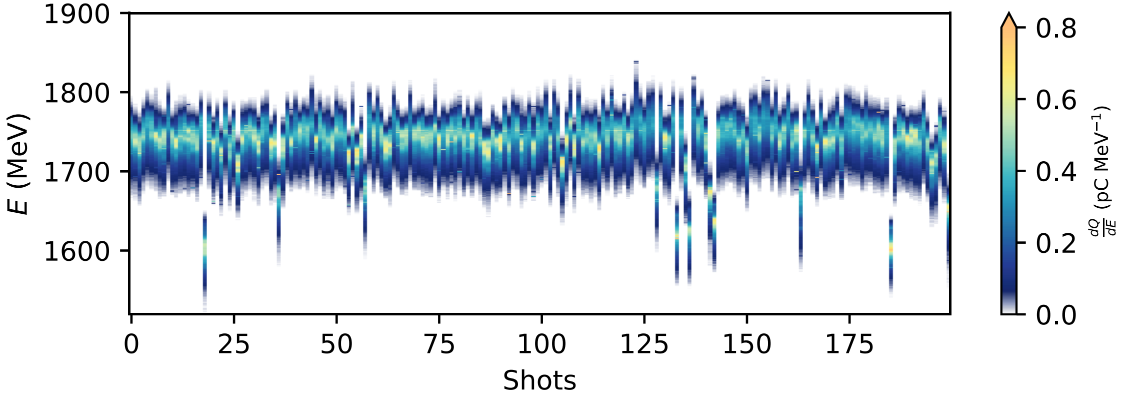
Beamline design

High Energy Gain & High-Rep-Rate Acceleration at FLASHForward

High energy gain

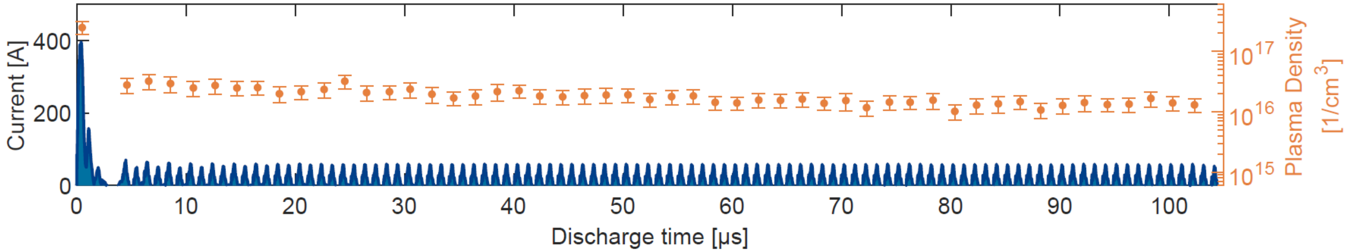
- Developed 500 mm discharge plasma source & performed first tests at FLASHForward, accelerating bunches from 1.2 to 1.75 GeV.
- The overall energy transfer efficiency was ~ 3%. We aim to exceed 10% in the near future by increasing charge coupling to previously achieved levels.

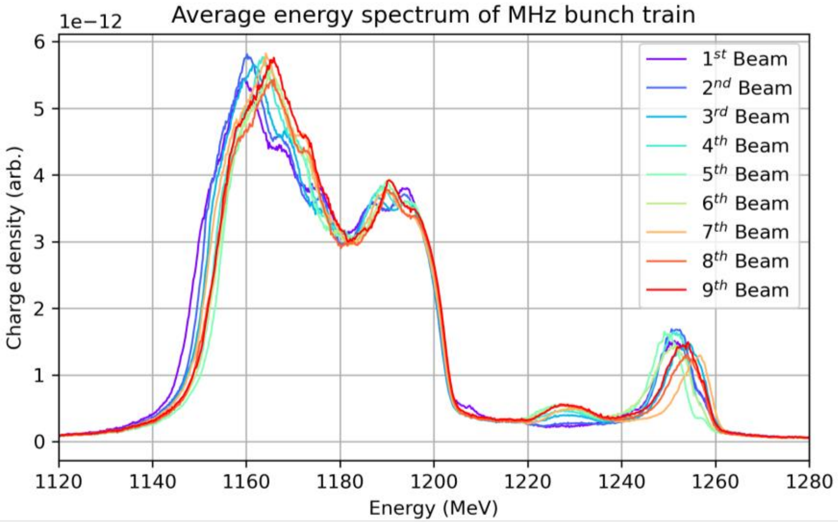




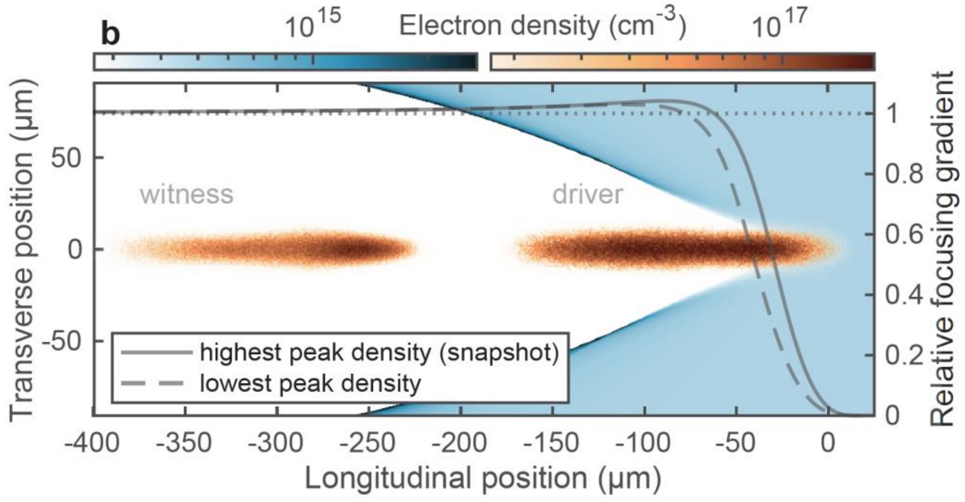
MHz repetition rate

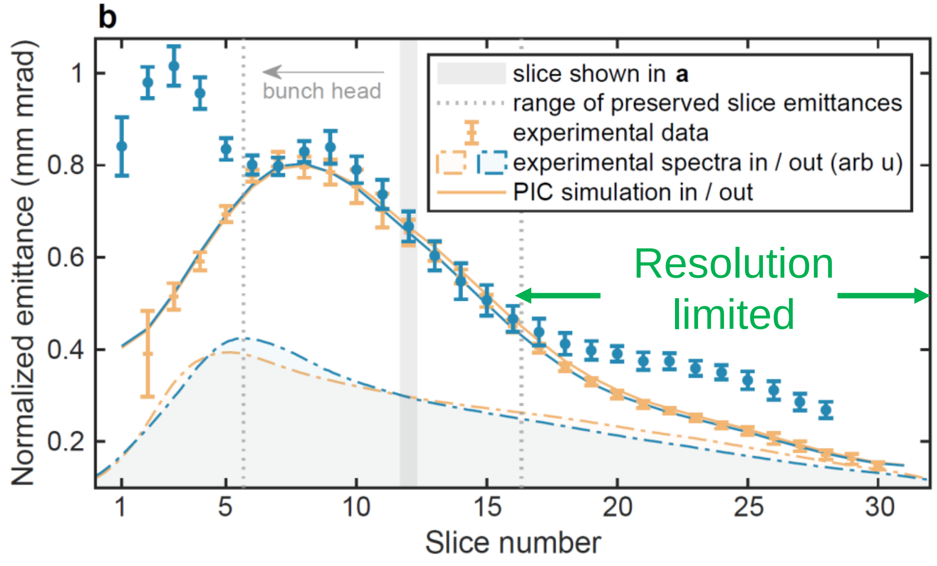
- Developed MHz-rep-rate discharge system capable of 100 pulses in 100 μs.
- Produces > required peak plasma density every time.
- Deployed at FLASHForward to demonstrate acceleration of ~ 10 bunches at 1 MHz by > 50 MeV.
- Developing timing system to allow independent timing adjustments for hundreds of pulses.





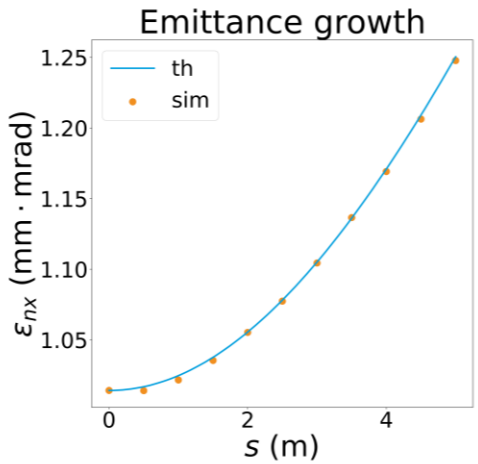
Incoupling & Outcoupling Developments

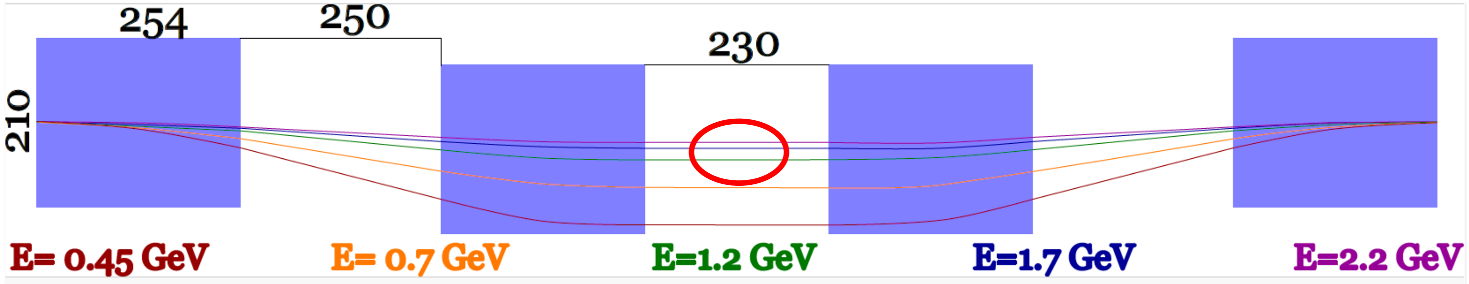




- We experimented with a passive plasma lens to symmetrically focus a witness to β-functions suitable for plasma acceleration (10-20 mm)
- The emittance of many slices was preserved.
- Tighter & tunable focussing possible.
- The driver is almost entirely focussed in this scheme- ideal for PWFA incoupling.

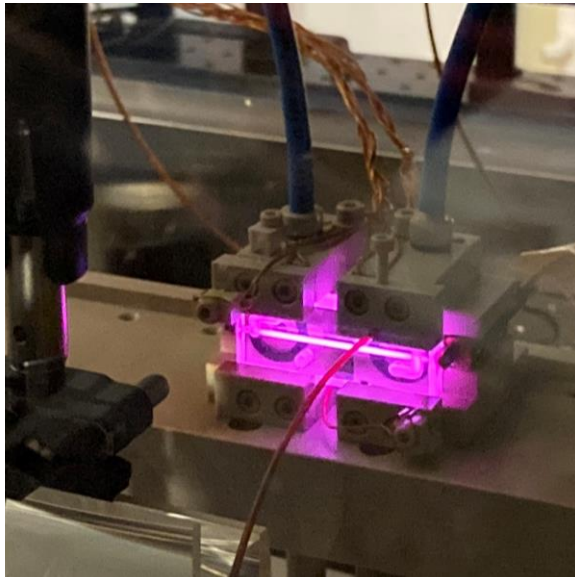
- For outcoupling at FLASHForward we are optimising a driver-witness separation chicane for energy +50% & +100% energy gain cases.
- Short chicane ~ 2m- small but tolerable emittance growth. Need a safe dump scheme.

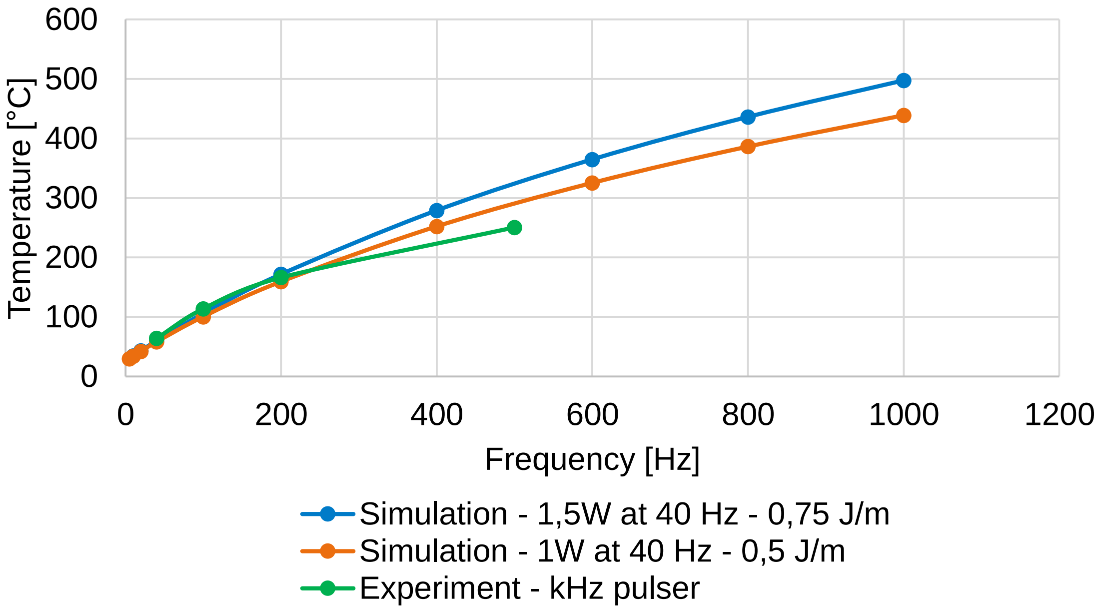


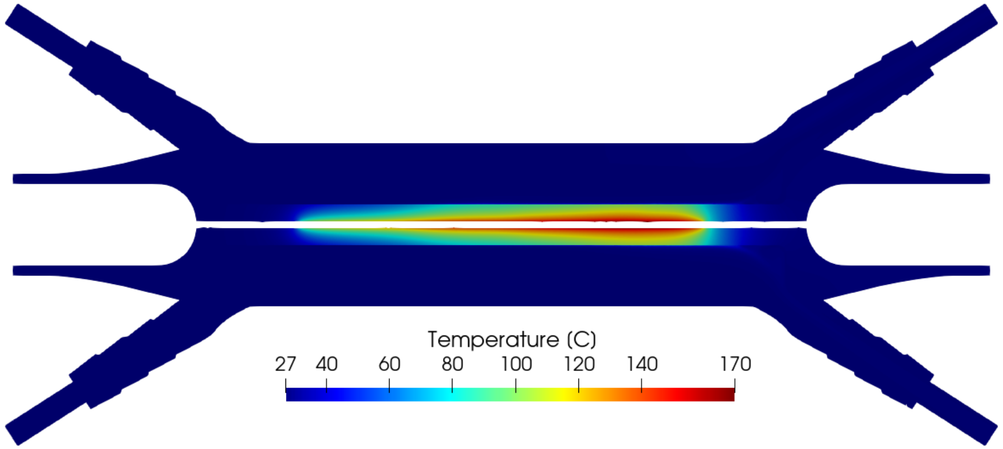


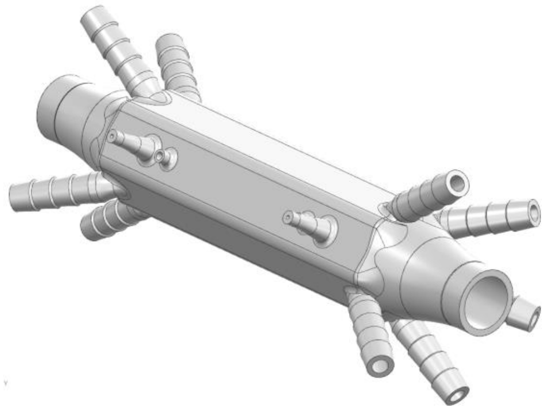
Plasma Sources for High-Average-Power Operation

- Measured the temperature of the surface of our plasma source during operation.
- Used these to benchmark ANSYS simulations of heating from equivalent constant heating source.
- Designed water-cooled 100 mm long plasma cell based on this model.
- It is being 3D printed from aluminium oxide and will be tested soon with wire heating then 1 kHz discharge plasma creation.
- Should support > 5 kHz FLASHForward-like operation.



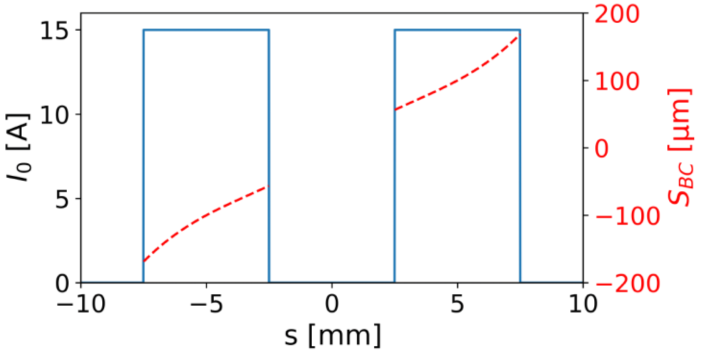


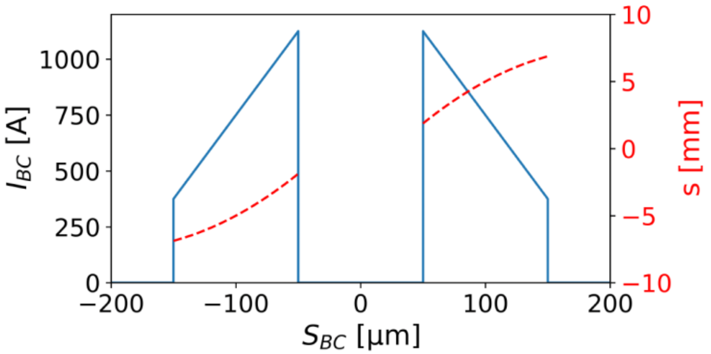




Twin Bunch Modelling at XFEL & FLASH

- Semianalytical, 3rd order model developed. Provides RF parameters from initial longitudinal phase space and defined target compression.
- Capable of supporting current profile shaping, delay and energy difference tuning. Collective effects to be included soon
- Initial current profile with flattop shape is preferred for bunch temporal shaping





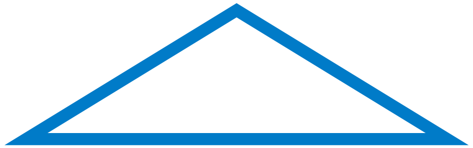
Upper: initial current profile

Lower: current profile after compression

$$C_{\mathrm{BC}} = \frac{1}{Z_{BC}} = \frac{1}{\frac{\partial S_{BC}}{\partial s}} = C_0 + C_1(S_{BC} - S^0_{BC}) + \frac{1}{2}C_2(S_{BC} - S^0_{BC})^2 \qquad I_{\mathrm{BC}}(S_{\mathrm{BC}}) = I_0 \cdot C_{\mathrm{BC}}(S_{\mathrm{BC}})$$

$$(V_{A1}, \varphi_{A1}, V_{AH1}, \varphi_{AH1}, V_{L1}, \varphi_{L1}, V_{L2}, \varphi_{L2})$$

RF parameters

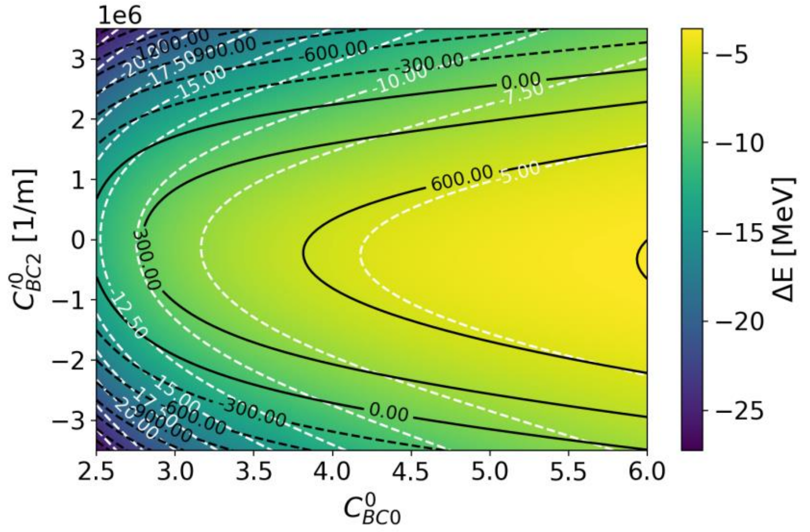


Initial LPS

$$\delta_0(s)$$

Target compression

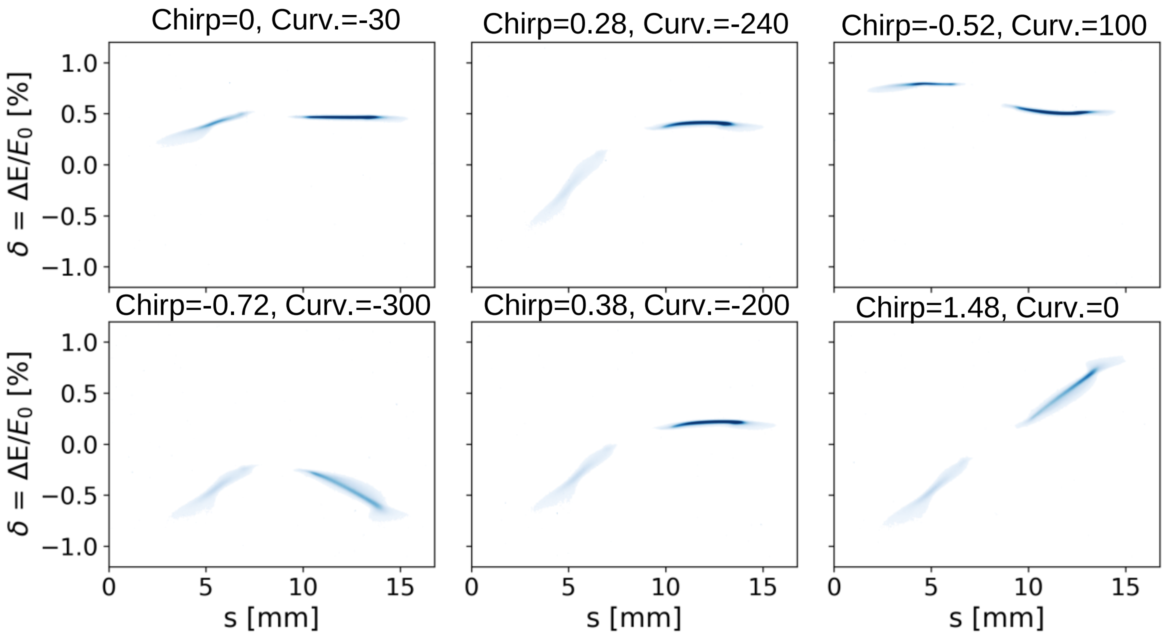
$$(E^0_{AH1}, E^0_{L1}, E^0_{L2}, C^0_{BC0}, C^0_{BC1}, C^0_{BC2}, C'^0_{BC2}, C''^0_{BC2})$$



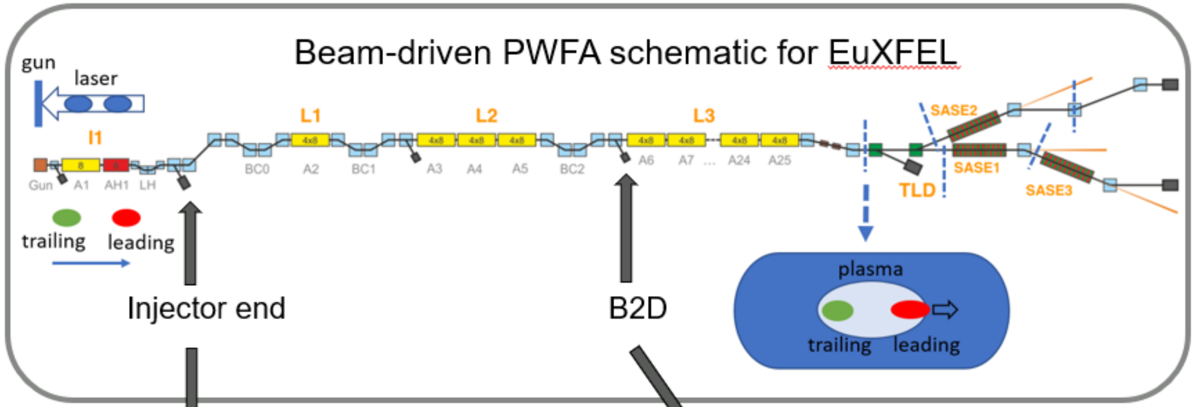
White curve: energy difference contour [MeV]
Black curve: delay contour [µm]

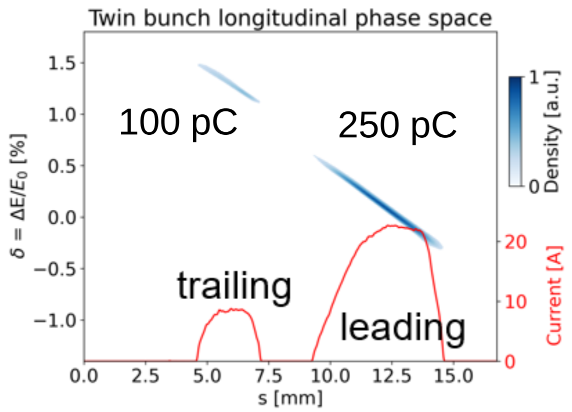
Twin Bunch Experimentation at XFEL

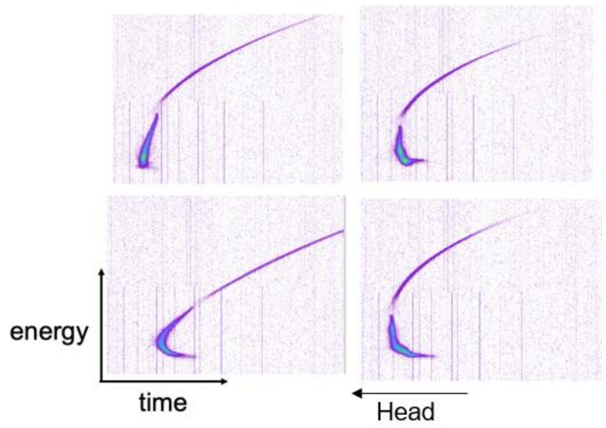
- Twin-bunch generation at injector with photocathode laser shaping for the trailing bunch
- Matching and orbit optimization at injector
- Twin-bunch transport to B2D with 100% transmission (only the leading bunch was compressed)



Independent tuning of the driver-witness LPS at the XFEL injector TDS

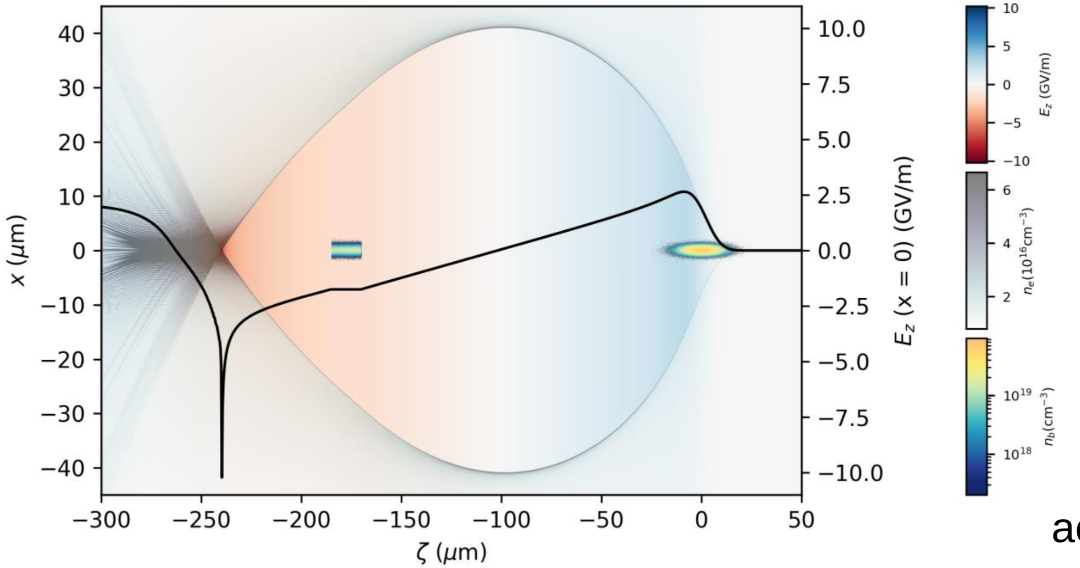


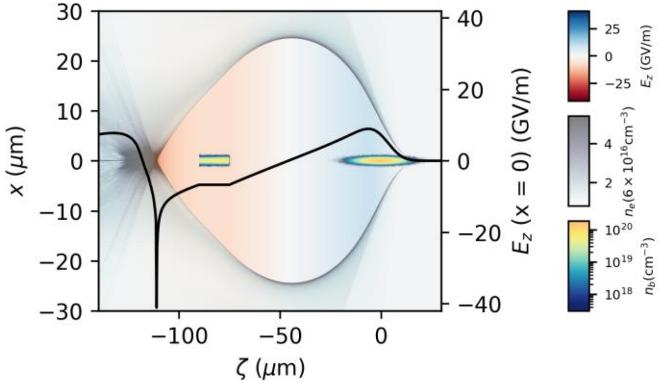




PIC Simulations of a Plasma Booster for XFEL

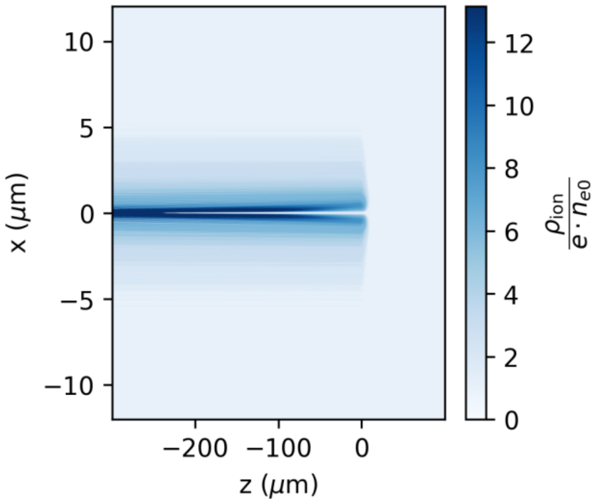
- Performed PIC simulations with 5 kA driver bunches and idealised trailing bunches.
- 250 pC driver accelerates 50-110 pC at 2-9 GeV/m, with Q inversely proportional to gradient.
- Implies plasma lengths of ~ 1-8 m.

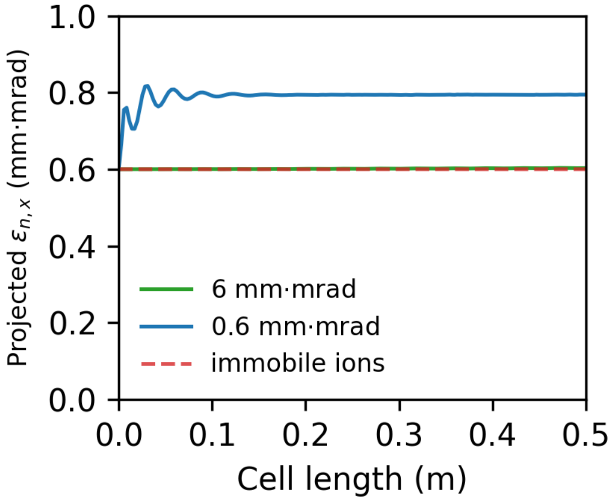




PWFA at 1x10^{16} and 6x10^{16} cm^{-3}, illustrating the trade-off between accelerating gradient and tolerances

- Identified 2 major issues with high-current drivers: beam induced ionisation and emittance growth from in-bubble ion motion.
- Ionisation implies the use of fully ionised Hydrogen.
- Emittance growth from in-bubble ion motion is then ~ 30%, but can be mitigated e.g. by using a larger driver emittance.





Conclusions and Next Steps

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- Larger energy gains at FLASHForward (1.2 → 1.75 GeV)
- MHz-repetition rate plasma accelerator sources demonstrated.
- Passive plasma lenses are an excellent option for in- and outcoupling for PWFA stages.
- Initial design for a driver-witness separation scheme.
- Model-supported design of a capillary for multi-kHz operation.
- Developed a twin-bunch acceleration model for shaped bunches with controllable energy difference and delay.
- Performed beamtimes using two NEPAL lasers at XFEL, accelerating (shaped) bunches in one RF bucket.
- Determining promising plasma working points for XFEL-type bunches.

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Next steps

- > 10% overall efficiency acceleration.
- 10’s bunches accelerated at MHz frequency & study plasma evolution with PWFA interaction.
- Iterate design for a driver-witness separation scheme & design dump.
- Production and testing of cooled plasma capillaries.
- Twin bunch creation & transport at FLASH, followed by PWFA experimentation.
- Final plasma source requirements & beamline design for an XFEL plasma booster.