Physics Considerations for a Plasma Booster Stage for the European XFEL

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Abstract

- The European XFEL linac accelerates high-quality electron bunches up to 17.5 GeV [1].
- These bunches lase in undulators at photon energies of up to 30 keV [2].
- A PWFA stage could increase the bunch energy cheaply and over a short distance [3].
- Simulations show the 5 kA current of EuXFEL bunches present challenges for a PWFA, mainly ion motion [4] & beam-induced ionisation [5]. We propose mitigation strategies.
- We developed models & performed beamtimes at the European XFEL to show whether a twin-bunch structure suitable for PWFA can be generated at the photocathode, then be accelerated and shaped in the linac sections and bunch compressors.

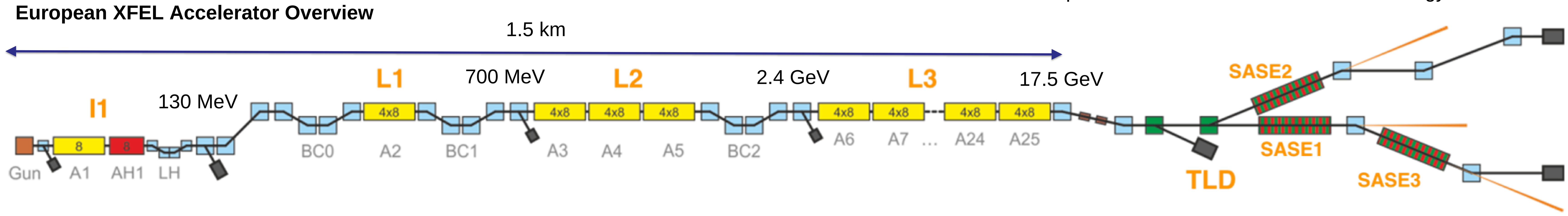
European XFEL parameters [2, 6]	
Energy (energy spread)	8 - 17.5 GeV (few MeV)
Charge (current)	250 pC (5 kA)
Normalised emittance	< 0.6 mm-mrad
Accelerator Length	1.5 km
Bunch train structure	27 kHz (10 Hz x 2700 bunches in 0.6 ms)

Project

Working towards a CDR for a plasma booster at EuXFEL. Two potential outcomes:

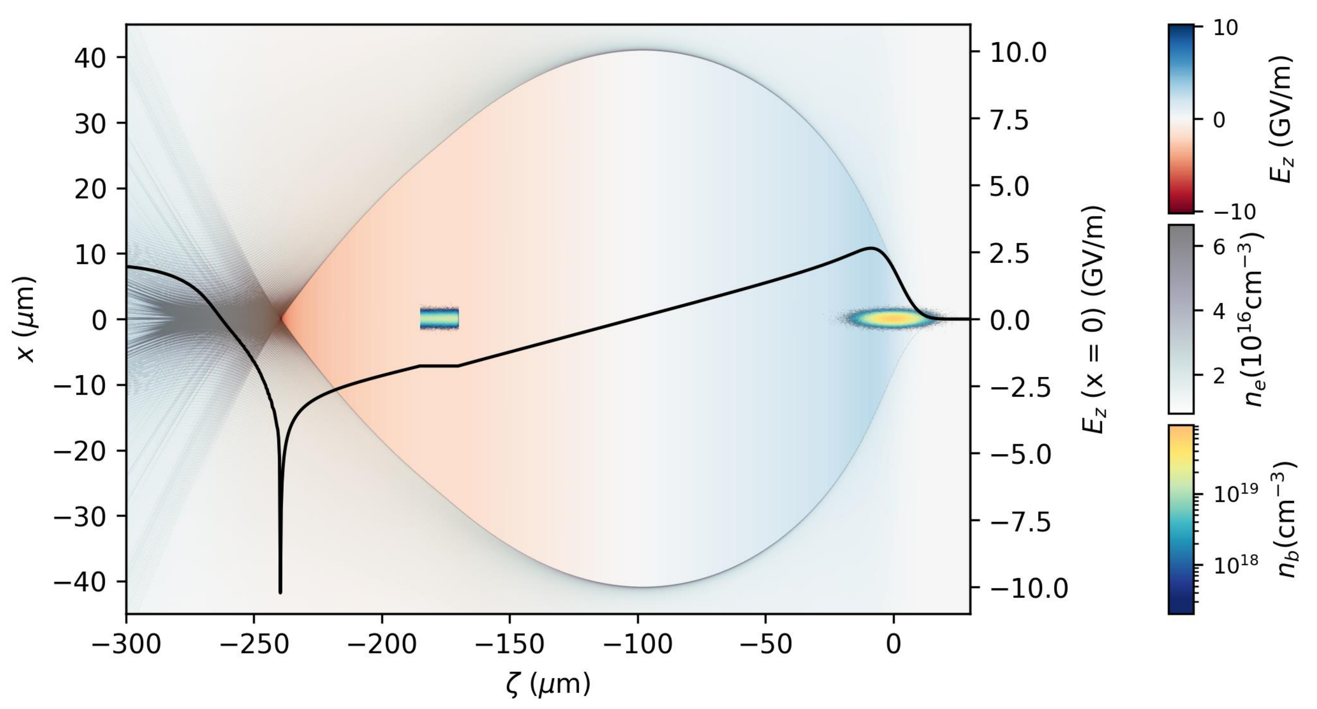
1. Provide > 30 GeV electron beams with current EuXFEL parameters
2. For a high-duty-cycle EuXFEL (100's kHz, 1 μs bunch spacing) the energy will be reduced to ~ 8 GeV. A plasma booster could retain current energy reach.

European XFEL Accelerator Overview



Principle, Beam and Plasma Parameters

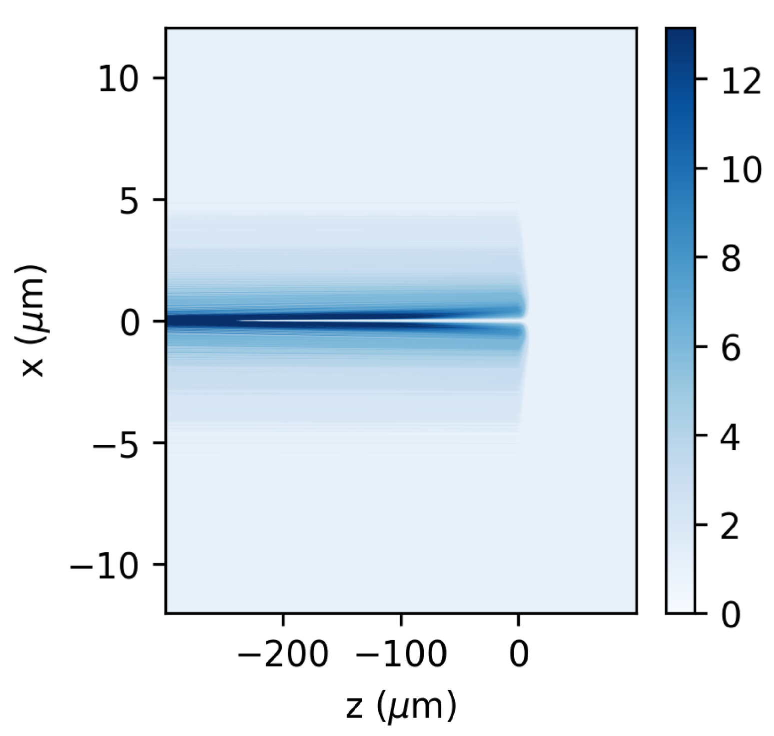
HiPACE++ simulation [7] of a 250 pC, 5 kA bunch driving a blown out wakefield.

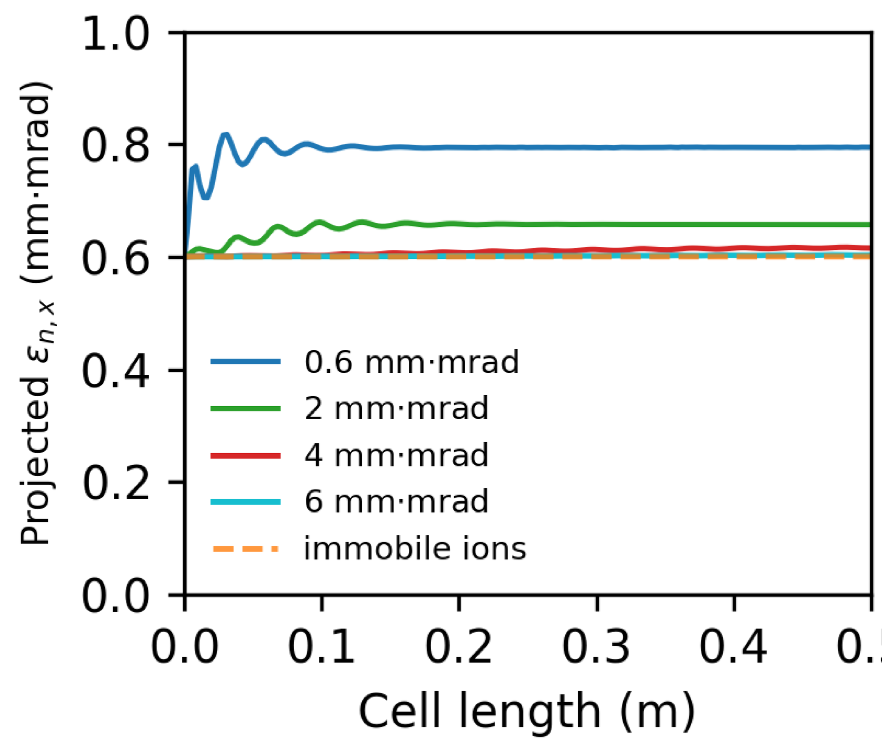


- The 54 pC, 1.2 kA witness beam is ideally shaped to flatten the wakefield [8,9], and gains energy at a rate of 2 GeV/m without increasing its energy spread.
- Our target density range is 1-6x10^{16} cm^{-3} with accelerating gradients of 2-9 GeV/m, plasma lengths of 8-2 m and charge (current) of 50-110 pC (1.2-2.8 kA).

PWFA Challenges

- High current, low emittance and low energy spread must be preserved for lasing.
- Radial E-field of matched EuXFEL beam is 600 GV/m. Ionises Ar^{8+}, N^{5+}, which a low-energy pre-ioniser will not. Disruptive for the wakefield. Li not usable (SRF vacuum).
- Need several metres of fully ionised Hydrogen: non-trivial.
- We find that most ion-motion driven effects come from the driver. Mitigation may be possible by using a larger emittance driver.





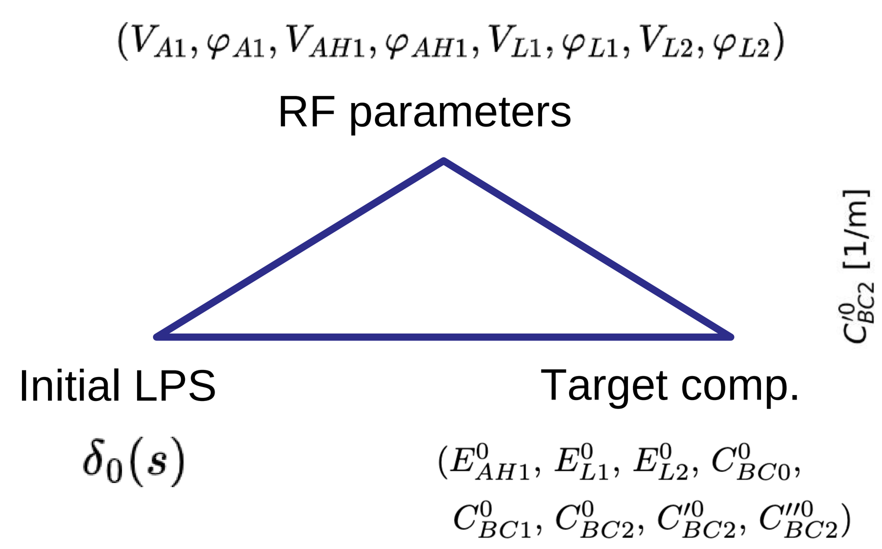
Left: Ion density after bunch interaction with an initially Ar^{+} plasma.
Right: emittance growth of the witness for varying driver emittances.

Possibilities of PWFA Experimentation

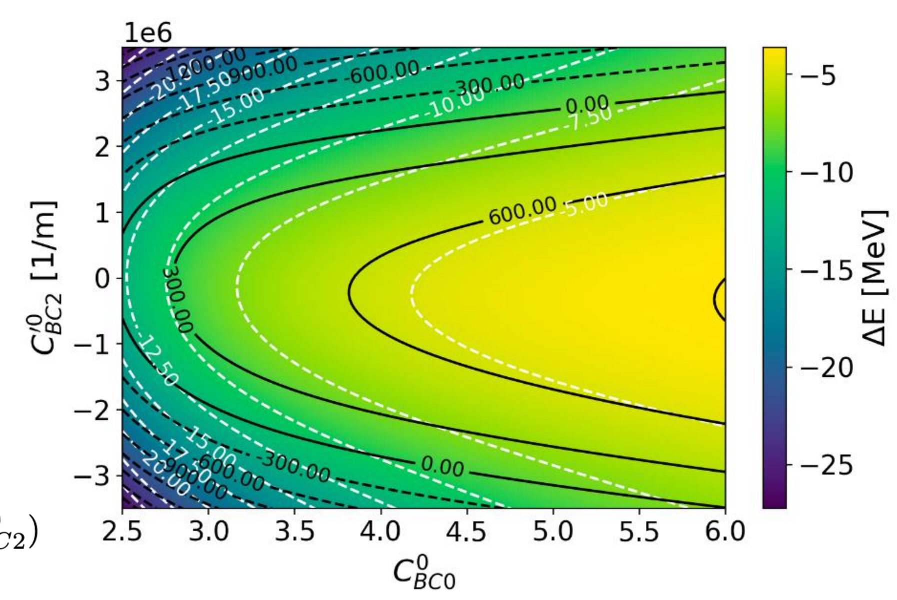
- EU funding "ELBEX" for the extraction of EuXFEL electron bunches into an empty tunnel for multiple use cases.
- We are exploring the possibility of including a PWFA stage, which may also benefit strong-field QED experimentation.

Twin Bunch Generation

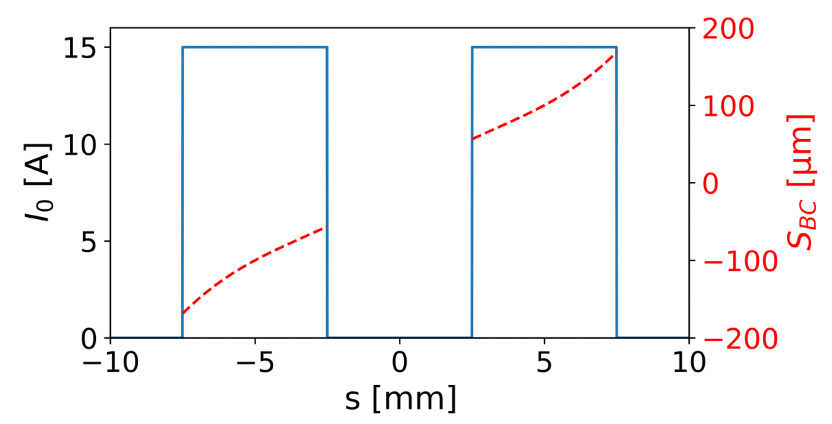
- We must generate the twin bunch structure cleanly i.e. at the photocathode.
- The witness must be properly shaped to prevent energy spread growth.
- We developed a semi-analytical model for tracking the longitudinal phase space of twin bunches with respect to a reference orbit [10]. It supports bunch shaping and, soon, collective effects (CSR, wakefields, space charge).

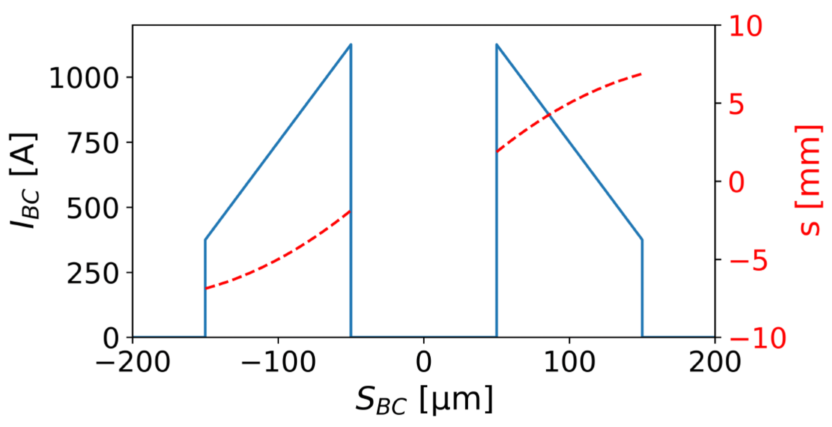


Given an initial LPS and a target compressed bunch profile, the required RF parameters are returned by the model.



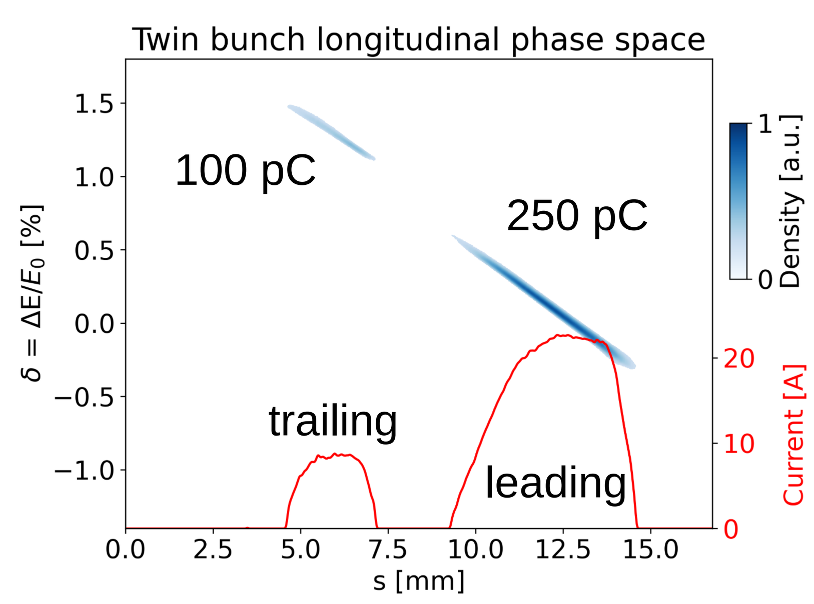
White: energy difference contour [MeV] *Black*: delay contour [μm]. Independent tuning of delay and energy difference may also have FEL applications.

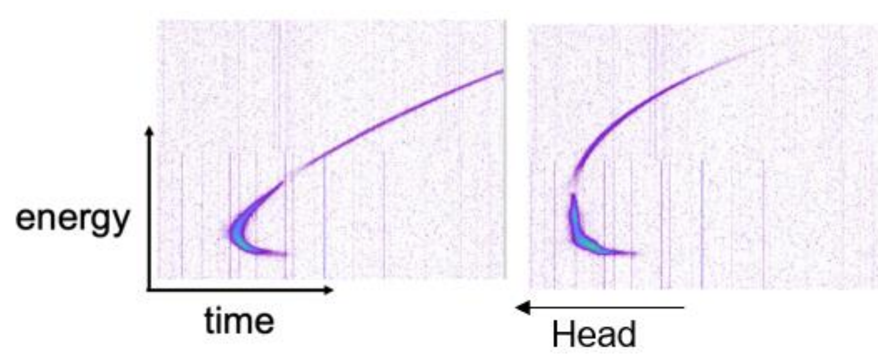




Initial top-hat bunches can be transformed into a bunch pair favourable for PWFA by adjusting amplitude, chirp and curvature in the accelerator.

Twin Bunch Experimentation at EuXFEL





- Generated a "driver-witness" pair at the photocathode & diagnosed it at the injector TDS (130 MeV).
- Matched both bunches to the design optics and transported them to the TDS after bunch compressor 2 (2.4 GeV)
- Measured the longitudinal phase space of the bunch pair. Optimal compression of both bunches not yet achieved.
- In future we will use an over-compression scheme, resulting in a time delay rather than energy offset.

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