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AN OVERVIEW OF THE T20 BEAMLINE FOR THE LUXE EXPERIMENT AT THE EUROPEAN XFEL

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Abstract

The Laser Und XFEL Experiment (LUXE) at the EuXFEL aims to explore hitherto unprobed regions of quantum electrodynamics characterised by both high-energy and high-intensity. This will be accomplished by leveraging the electron beam provided by the EuXFEL and an intensely-focused laser to study electron-photon and photon-photon interactions. The LUXE experiment will be placed in the empty XTD20 tunnel and to this end a new beamline, T20, will need to be installed to deliver one bunch per bunch train to LUXE. The T20 beamline feature a total bend angle of 6.7°, which, combined with the very short bunches provided by the EuXFEL raises concerns regarding the deleterious impact of coherent synchrotron radiation (CSR) on the bunch emittances. As the LUXE experiment has specific beam size requirements at its IP, these effects and the limits on the focus must be characterised. In this paper the T20 beamline design and its final focus are outlined. Furthermore, the impact of collective effects on the beam quality at the LUXE IP are discussed, and finally a means to mitigate the impact of these effects and improve the beam quality at the LUXE IP is shown.

INTRODUCTION

The European X-Ray Free Electron Laser (EuXFEL) [1] in Hamburg, Germany, is a 3.1 km-long multi-user facility capable of providing hard and soft x-rays to various experiments and has been operating successfully since 2018. To maximise the number of operable experiments using the electron beam, the main accelerating linac branches into two beamlines at the 2 km mark, to a hard x-ray undulator to the left (SASE2), and to hard and soft x-ray undulators straight ahead from the main linac (SASE1 and SASE3, respectively). Further installations of undulators are planned in the future, firstly hard x-ray undulators in the left branch after SASE2 [2], and then construction of an entire new branch to the right in 2029 (requiring a new tunnel to be drilled). However, as a small section (≈ 50 m) of this new tunnel has already been dug, there is a period of opportunity before 2029 where this tunnel section (called XTD20) may house an experiment which uses the high-quality electron beam provided by the EuXFEL for novel particle physics searches. This is how the LUXE experiment [3] fits into the broader EuXFEL programme.

The LUXE experiment will operate parasitically off the main XFEL linac in the XTD20 tunnel, taking one electron bunch per bunch train (out of 2700 bunches per train) and collide it with an intensely-focused laser. As the future installation of undulators in a whole new branch from the linac has long been planned, the beamline arc, called T20, which transfers the beamline to the XTD20 tunnel has already undergone considerable development during the main EuXFEL design process [4–6].

The extreme bunch conditions at the EuXFEL present challenges at LUXE. Specifically, the electron bunches at the end of the linac will generally be very short ($\sigma_z \approx 5\,\mu$m) due to requirements in the downstream undulators. At these short bunch lengths and high energies (14 GeV to 17.5 GeV) the bunch will radiate partially coherently in all typical EuXFEL bending magnets likely to be used in any T20 arc design [7]. Furthermore, the overtaking criterion, shown in Eqn. 1, is satisfied in these same magnets at these bunch lengths, meaning that steady state CSR fields will dominate and that the projected and slice emittances are liable to be diluted due to these self-fields.

$$L_s = \frac{R\varphi^3}{24} > \sigma_z \tag{1}$$

In this paper, recent developments in the T20 beamline design and its use for LUXE are presented and discussed. Specifically, this involves integrating the arc into the current switchyard design and the design of the final focus system, as well as beam dynamics simulations featuring full collective effects, with particular focus on the impact of CSR on the focus spot size. Finally, an alternative compression scheme in the main linac is discussed as a means to achieve the required focus at the LUXE IP.

T20 BEAMLINE AND FINAL FOCUS SYSTEM FOR LUXE

The Switchyard

The switchyard featuring both T20 and LUXE and its relation to the other beamlines is shown in Fig. 1. The extraction system will employ a Lambertson septum-kicker pair to extract the beam from the main linac. Although only one bunch per train will be used by the LUXE experiment, the rise time of the extraction kicker, at 2 µs, mandates that an additional ten bunches must be dumped upstream of the switchyard.

The Final Focus

The final focus system for LUXE will use four quadrupoles making up the inner triplet and two quadrupoles for the matching section. The vertical and horizontal dispersions are brought to zero at the end of the arc and before the matching section. Two possible focuses are considered assuming

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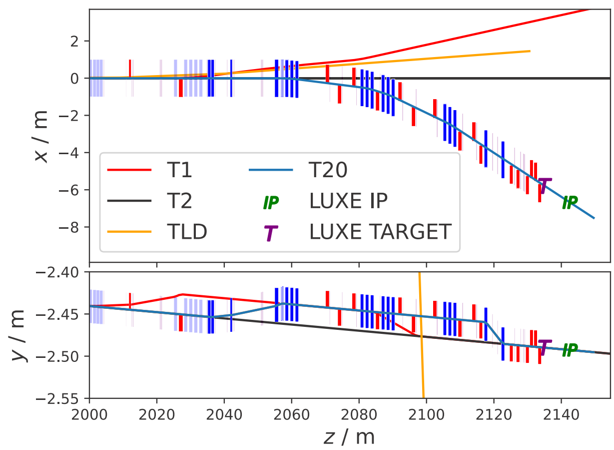

Figure 1: The horizontal and vertical views of the switchyard. For clarity, only magnets leading up to the LUXE experiment are shown. Dipoles and quadrupoles are shown in blue and red, respectively. Unpowered magnets are shown translucent.

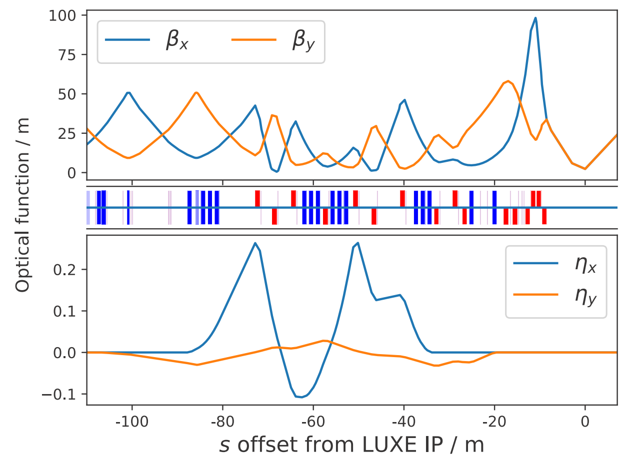

Figure 2: The betatron and dispersion functions for the T20 and LUXE beamline for the $\beta^* = 2.3$ m case and the focus at the IP. The lattice is displayed in between the two plots, with dipoles in blue and quadrupoles in red.

an emittance of 1.4 mm mrad (the assumed emittance as outlined in the LUXE CDR [3]), one corresponding to a spot size of 5 µm (the original expected focus size at the IP) and another corresponding to 10 µm. The reason for this is that the smaller β^* requires more quadrupole tuning upstream of the final focus quadrupoles and matching section into the arc. Consequently, $\beta^* = 2.3$ m, which corresponds to the 10 µm focus is instead now considered to be the benchmark case due to its relative simplicity. The decrease in the luminosity as a result of this larger spot size is projected to have an acceptable impact on the interaction rates at the IP.

Finally, the LUXE experiment will operate in two modes, one where the electron beam is focused at the IP (electron-photon collisions), and another where the electron beam is focused at a tungsten target 8.5 m upstream of the IP (photon-photon collisions) [3]. The LUXE final focus design supports both configurations, with the optical configuration corresponding to the focus at the IP shown in Fig. 2.

The beam properties assumed at the IP for the sake of the final focus design are shown in Table 1. Although the beam energy is assumed to be 16.5 GeV, the arc and final focus design has sufficient redundancy built into it that the beam can be transported to the IP from the linac with the required IP spot size at a beam energy of up to 20 GeV, although it should be mentioned that the beam energy at the EuXFEL is unlikely to reach 20 GeV during the expected lifespan of LUXE.

BEAM DYNAMICS SIMULATIONS FOR LUXE

To date the electron beam at the LUXE experiment has been assumed to be Gaussian in all six dimensions of phase space. However, in reality the beam transverse and longitudinal profiles will differ from this ideal considerably due to collective effects upstream of the experiment. Therefore, to

Table 1: Expected Beam Properties at the LUXE IP

Parameter	Symbol	Value	Unit
Beam energy	E	11.5 to 17.5	GeV
Bunch charge	q	250	pC
Spot size	σ	5 to 10	µm
Beta function	β^*	0.58 to 2.3	m
Distance to IP	L^*	8.5	m
Bunch length	σ_z	40	µm
Emittance	ε	1.4	mm mrad

sufficiently determine the beam's expected shape and size at the IP, one must simulate the electron beam across the 2.1 km from the gun to the LUXE IP, accounting for all collective effects. Furthermore, as shown in Table 1, the emittance transmitted to the IP from the linac has been assumed to be 1.4 mm mrad, however to accurately determine the actual beam size attainable at the IP, the final emittance at the IP must be calculated.

One code typically used for simulating the full length of the EuXFEL, often referred to as *start to end* simulations, is OCELOT [8]. The application of OCELOT to EuXFEL beam dynamics simulations is outlined in more detail in [9]. For simplicity the same simulation configuration as described in that paper is also used here [10], modified only to add the T20 arc and LUXE to the beamline ($\beta^* = 2.3$ m) to match the LUXE CDR [3]. This configuration is typical of the sort used for generating ultra-short bunches for lasing in the undulators.

The phase space at the IP is shown in Fig. 3, which shows that for a typical EuXFEL bunch, the transverse emittances at the LUXE IP are larger than expected and the spot size will be larger than 10 µm. As this increase in the emittance is most likely due to CSR, lengthening the bunch can mitigate this effect and help to preserve the transverse emittances.

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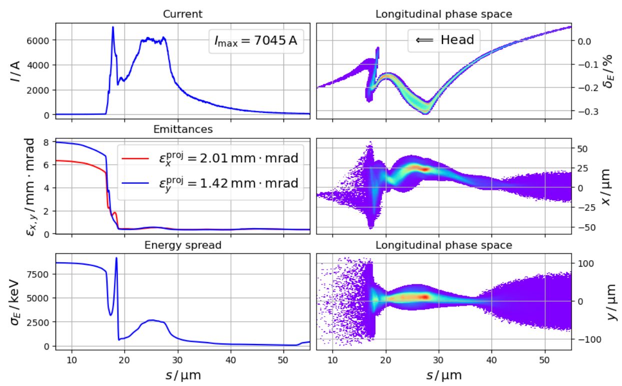

Figure 3: The phase space distribution at the LUXE IP at 16.5 GeV using a similar radio frequency working point (i.e., bunch compression) as for lasing.

This can be done by adjusting the radio frequency (RF) parameters in the upstream accelerating modules to reduce the chirp and subsequent post-chicane bunch length.

The transition time between two RF phases (whilst maintaining the same final central energy) is given by

$$t = \frac{v_1 \sin(\varphi_1 - \varphi_2)}{\rho \cos \varphi_2}, \tag{2}$$

where v_1 is the initial voltage, φ_1 and φ_2 are the initial and final phases, respectively, and ρ is the *vec limit*, which defines how much time transitioning between two RF working points takes. At the EuXFEL $\rho = 0.5\,\mathrm{MV\,\mu s^{-1}}$ and is defined per RF station, where there are four accelerating modules per station.

A full semi-analytical treatment of RF configurations for bunch compression is outlined in [11]. Here, however, a simplified model is used where the known good RF configuration is simply adjusted by reducing the chirp in L1 and L2 by reducing the phase by up to 1.03° and 0.5°. These two values correspond to slightly more than the maximum $\Delta\varphi$ achievable in 2 μs, the rise time of the kicker, and were calculated using Eqn. 2. A range of RF configurations up to these values were simulated in start to end simulations using OCELOT. The subsequent emittances at the LUXE IP are shown in Fig. 4, and whilst there is some periodic behaviour also impacting the emittances, it is clear that the 2 μs for the kicker to rise is ample time to reduce the compression to adequately preserve the beam emittance at the LUXE IP.

The transverse phase space projections for the fully compressed beam are shown alongside those of the partially decompressed beam in Fig. 5. The reduced transverse emittances approach those at the switchyard. Assuming the smallest plausibly achievable β^* (0.58 m) at the IP, an emittance of 0.6 mm mrad in the switchyard, and a maximum energy of 17.5 GeV, the focus size can perhaps be brought down to as low as 3.2 μm, far below the LUXE CDR value of 10 μm [3].

CONCLUSION

In this paper the lattice design for the T20 arc and LUXE final focus were described. Simulated beam properties were presented and it has been shown that using the decompression scheme it should be possible to satisfy the requirements laid out in the LUXE CDR, in particular a spot size lower than the minimum required will likely be achievable. This may enable the experiment to benefit from a brighter luminosity or enable more longitudinal space for the experiment. Regardless, the simulated IP beam distributions will be used for Monte Carlo LUXE detector simulations. Future work primarily involves validating this decompression scheme in the EuXFEL, specifically that such decompression can indeed be achieved within the 2 μs of the kicker rise time.

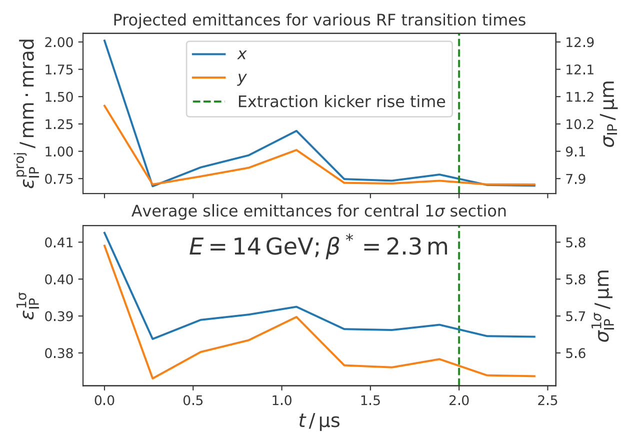

Figure 4: The relationship between time spent reducing the chirp with the RF in L1 and L2 and the simulated emittance at the LUXE IP. The chosen larger β^* and smaller energy are used to present a reasonable worst-case scenario.

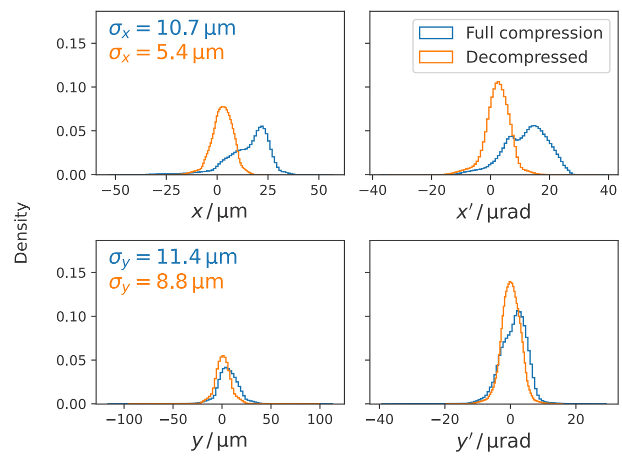

Figure 5: The transverse phase space projections at the LUXE IP with and without decompression, using one of the optimal working point shown in Fig. 4. The beam sizes are simply the standard deviations of the coordinates, whereas the projected emittance in Fig. 3 is the RMS emittance.

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