ISBN: 978-3-95450-224-0 ISSN: 2673-7035 doi:10.18429/JACoW-FLS2023-TU4P12

INJECTION INTO XFELs, A REVIEW OF TRENDS AND CHALLENGES

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Abstract

In this contribution, we review the low-energy electron injectors for the existing X-ray Free-Electron Laser (XFEL) facilities, focusing on the buncher and booster sections. The technology choices are parallel to the increasing demand for stricter six-dimensional phase space quality. The current capabilities for beam parameters and future requirements are laid out, alongside a discussion on challenges and technological bottlenecks. In light of this review, preliminary results for a high-capability injector providing a high repetition rate and continuous wave emission are presented as an option for the UK XFEL.

INTRODUCTION

XFEL facilities are an unprecedented tool for probing matter at the atomic and molecular scales. The concept of the Free-Electron Laser (FEL) was introduced in the early 1970s [1], and since then developments in FEL technology led to the construction of XFEL facilities. The first lasing in the vacuum ultra-violet range was achieved in 2005 at the Deutsches Elektronen-Synchrotron (DESY) [2]. The FLASH user facility commenced operation in the same year and extended its capabilities into the soft X-ray range. A milestone was reached in 2009 when the Linac Coherent Light Source (LCLS) at the SLAC National Accelerator Laboratory achieved X-ray lasing, starting a new era of X-ray science [3]. Since then, ongoing efforts have focused on advancing XFEL capabilities with the exploration of different concepts such as multi- colour, two-pulse X-rays, variable polarisation states, high spectral purity X-rays, higher brightness X-rays, sub-femtosecond and attosecond X-ray pulses by manipulating the electron bunch before self-amplified spontaneous emission (SASE) takes place [4]. However, increasing demand in beam quality through expanding the scope of XFEL applications leads to upgrades of existing facilities [5, 6] and motivates the construction of new ones.

One such machine, the UK XFEL, is currently undergoing the Conceptual Design and Options Analysis phase based on the published science case [7]. An exhaustive science case for UK XFEL demonstrated a community preference for high repetition rate, photon energy, energy per pulse, and some additional features such as high repetition rate laser seeding, high spectral purity X-rays, attosecond pulses across all photon energies, combining X-rays with other advanced capabilities for EUV/gammas to have a unique X-ray light source [8].

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UK XFEL aims to operate across a large portion of the repetition rate-photon energy parameter space as shown in Fig. 1. In light of the science case requirements, UK XFEL has been proposed to operate at a 1 MHz repetition rate that will be likely driven by an 8 GeV beam generated using superconducting technologies. A more detailed discussion on the technologies proposed to be used based on the preliminary focus of the UK XFEL can be found in [7].

High brightness plays a central role in determining the ability of a light source to access new domains of ultra-fast X-ray science [9]. Therefore, the main design objective for the UK XFEL injector is to explore the minimum possible transverse slice emittance at the end of the injector.

The preliminary design of the UK XFEL proposes the use of a normal conducting very high frequency (VHF) gun operating either at the 6th or 7th subharmonic of the main linac RF frequency. The VHF gun will be followed by a single or 2-cell buncher operating at either harmonic or subharmonic of the main linac RF frequency to compress bunches to short lengths. Following that, a booster section will bring the beam to the emittance-dominated regime, where the energy of the beam reaches ~220 MeV after acceleration. A magnetic chicane will then perform the final bunch compression before the main linac. The design goal of the UK XFEL injector is preserving the transverse core slice emittance while compressing the bunch as much as possible and delivering it to the main linac at a high repetition rate.

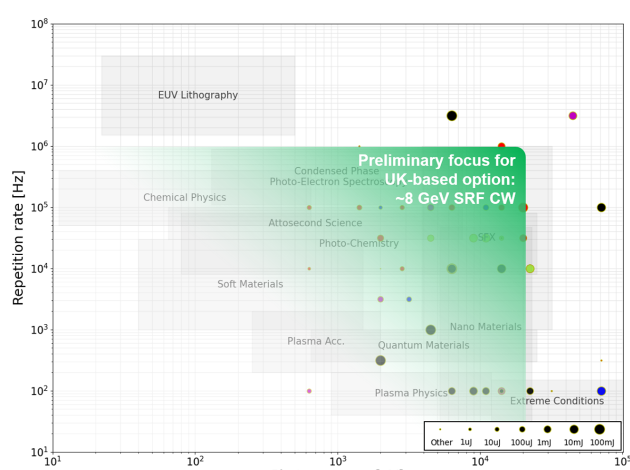

Figure 1: Research areas potentially covered by the UK XFEL, based on the preliminary repetition rate and photon energy capabilities. Figure courtesy of [7].

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OVERVIEW OF INJECTORS FOR XFELs

The performance and the components of the injectors employed in XFELs rely on the type of electron gun used. The electron bunch is typically generated using either photoemission or thermionic emission. In RF photo guns, the distribution of the bunch is controlled by the laser pulse that drives the photoemission process when illuminating the photocathode, while the resonant RF structures of the gun generate the accelerating field to extract the emitted electrons. RF photo-guns for XFELs are generally classed in two emission types as either high-field or medium to low-field, based on their cathode accelerating field, where the transverse brightness directly depends on the beam intensity [10].

A high-field RF photo-gun enables photoemission of high peak current however delivering a very low transverse emittance can be challenging due to the space charge defocusing. In this emission type, the bunch length, σ_z, is smaller than the transverse beam size, $\sigma_{x,y}$. The transverse emittance and brightness can be estimated using 'pancake' approximation [11]. Such an emission type can be obtained using high-frequency pulsed guns (>1 GHz) to reach high cathode fields up to $\sim$100 MV/m [12]. The beam is then matched into the main linac using solenoidal focusing as shown in Fig. 2(a). This ensures the compensation of the space charge effect and minimises the projected emittance.

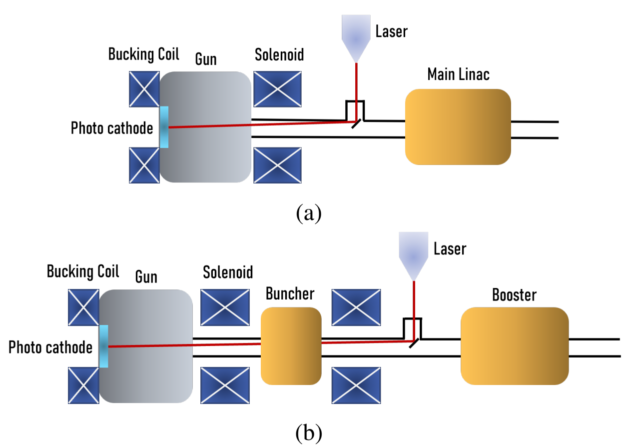

Figure 2: A simplified layout of (a) high (b) medium to low accelerating field RF photo-gun based electron injector.

Most operational XFEL facilities are based on pulsed RF photo-guns. The repetition rate is an engineering challenge and is limited by RF power dissipation on the walls of the cavity [10]. Therefore, the operation of an XFEL in Continuous Wave (CW) mode with high RF frequency and high RF field is not ideal. CW operation of normal conducting (NC) gun-based injectors can be performed either by reducing the field or the frequency, which is typically ~200 MHz [10].

An alternative technology is the superconducting RF (SRF) gun. In addition to their power efficiency, SRF guns have the advantage of reducing the migration of dislocations on the photocathode which can convert to dark current sources [13]. However, SRF gun technology is still in the development stage and faces some challenges. SRF cavities have poor compatibility with insertable photo cathodes due to the risk of contamination as a result of frequent photo cathode changes. In addition, the use of either cryogenic or room temperature solenoids far away from the gun cavity also poses challenges, due to Meissner field exclusion which can reduce the effect on the emittance compensation [12]. Since SRF guns can operate up to 50 MV/m (as demonstrated at KEK [14], with R&D studies pursuing higher gradients) with CW operation that is lower than the limits of high-frequency NC RF guns. Different groups at HZDR-ELBE, HZB-bERLinPro, DESY (for EU-XFEL), and KEK are working on the development of L-band SRF guns to achieve CW operation under high accelerating fields [10, 12, 14, 15].

The second type of emission involves lasing the photocathode to produce electrons in an elongated, 'cigar' like pattern to reach low emittance by reducing space charge. In this case, a longer laser pulse is used to emit the electrons, therefore the bunch length is much larger than the radius of the bunch in the transverse direction, where $\sigma_z >> \sigma_{x,y}$. The transverse emittance and brightness can be estimated using 'cigar' approximation [16]. Such an electron gun is typically operated at a subharmonic of the main linac (6th or 7th) that is sufficiently low frequency that allows to host a long bunch. The advantage of a low-frequency gun is to have negligibly small phase slippage, thus the emission field is almost the same as the cathode peak field. The long bunch is then matched (using a solenoid) into the buncher for ballistic compression before its acceleration in the booster as shown in Fig. 2(b). The UK XFEL injector is based on a VHF-band (185.7 MHz) NC CW gun to operate at 1 MHz repetition rate. Similar technology was demonstrated at LBNL for Advanced Photoinjector EXperiment (APEX) designed for the LCLS-II injector [17]. One should note that the APEX gun was then improved to the APEX2 design by increasing both the cathode launching field and the output energy to reduce RF heating and increase the cathode field [18].

There are currently two CW XFELs under construction, one is LCLS-II at SLAC, which improves the repetition rate from 120 Hz to 1 MHz compared to LCLS, and SHINE in China besides EU XFEL CW upgrade [5, 19, 20].

UK XFEL LOW ENERGY BEAM LINE

The proposed UK XFEL low energy beamline will generate a beam from a VHF gun bunched by a one or 2-cell buncher having harmonic or subharmonic of the main linac RF frequency followed by a booster linac to reach the emittance dominated regime at 220-250 MeV. The preliminary design presented here is based on a long electron bunch via 'cigar' emission, reaching slightly higher than 1 MeV energy level at the end of the gun and then compressing the bunch using a 2-cell harmonic buncher to ensure a linear longitudinal phase space before acceleration in the booster. A diagram of the injector beamline used in OPAL [21] simulations is shown in Fig. 3. This preliminary simulation study

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uses field maps constructed by cylindrical single-cell field distributions for VHF gun, buncher, and booster cavities with the parameters given in Table 1 to demonstrate a ballistic compression scheme while preserving the normalised core emittance below the target 1000 nm rad.

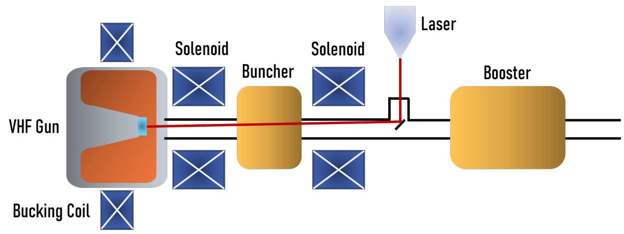

Figure 3: Diagram of the UK XFEL injector line showing the components used in the simulations. A half-cell VHF gun (operating at 185.7 MHz, 7th subharmonic of the linac RF), 2-cell 1.3 GHz buncher, and 2-cell 1.3 GHz linac (booster) were used along with the solenoids.

Table 1: OPAL simulation parameters used for the simulation study. The provided bunch parameters correspond to the initial flattop distribution.

	Parameter	**Value**	**Unit**
Bunch	Charge	300	pC
	Size	0.75	mm
	Length	150	ps
Gun	Phase	on crest	-
	Frequency	185.7	MHz
	Field	30.0	MV/m
Buncher	Phase	-90	degree
	Frequency	1300.0	MHz
	Field	10	MV/m
Booster	Phase	on crest	-
	Frequency	1300.0	MHz
	Field	100.0	MV/m

Figure 4 shows the RMS bunch length and energy spread of the electron bunch along the injector line. The ballistic bunching implemented aims to compress the bunch down to 10° of the RF frequency corresponding ~20 ps at the two-cell 1.3 GHz buncher. However, the energy spread increases in the buncher cavity due to a 90° phase shift relative to the gun phase where the energy of the tail of the bunch increases while it decreases at the head of the bunch. This is compensated in the booster during acceleration.

Normalised core emittance of the bunch (which refers to the emittance calculated using only the three slices at the center of the bunch out of 9 slices in total) was calculated along the beamline as shown in Fig. 5. The core emittance on the x- and y-axis at the end of the simulation window were found 588.5 and 576.57 nm rad, respectively. The studies of the low-energy injector will continue to investigate optimising the longitudinal phase space during the bunch compression as a function of the number of the cells, RF frequency, as well as the field in the buncher cavity; and preservation of the core emittance. The next steps include the demonstration of acceleration of the bunch using a full booster linac.

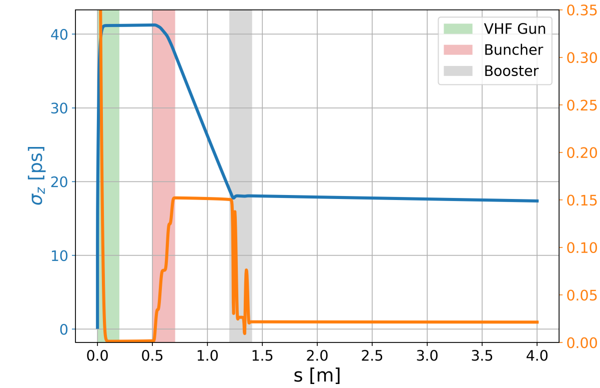

Figure 4: OPAL simulation results showing the RMS bunch length as well as the relative energy spread of the electron bunch along the beamline.

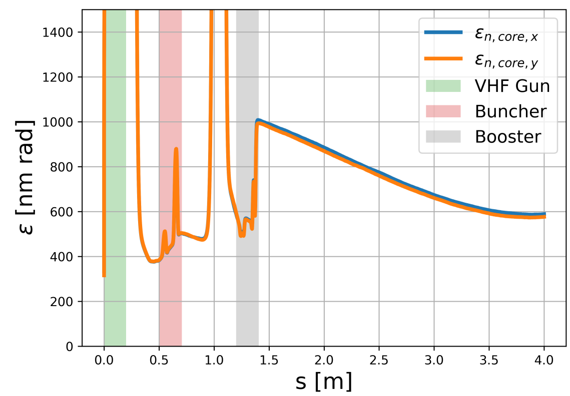

Figure 5: The variation of the normalized core emittance on the x- and y-axis along the beamline.

CONCLUSION

The UK XFEL conceptual design was initiated following a comprehensive science case study [7]. A possible low-energy injector design was studied to demonstrate the ballistic compression scheme using a 2-cell harmonic buncher and preserve the normalised core emittance. A single-cell buncher operating at the second subharmonic of the main linac RF frequency, along with various booster accelerating fields, is also under consideration for further simulations based on multi-objective optimisation.

ACKNOWLEDGEMENTS

The Authors would like to thank Alexander Malyzhenkov from CERN and Ben Hounsell from ASTeC for helpful discussions.

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