OPTIONS ANALYSIS OF MHz INJECTORS FOR THE UK XFEL PROJECT

B. R. Hounsell*,[1] A. D. Brynes[1], L. S. Cowie[1], J. W. McKenzie[1], B. L. Militsyn[1], S. S. Percival[1], P. H. Williams[1], F. Yaman[1], ASTeC, STFC Daresbury Laboratory, Warrington, UK
C. Davut†,[1], O. Apsimon[1], University of Manchester, Manchester, UK
[1]also at Cockcroft Institute, Warrington, UK

Abstract

The UK XFEL conceptual design and options analysis process has recently been completed. The UK XFEL design proposes a superconducting linac operating with up to a 1 MHz repetition rate electron beam and demands beyond state of the art electron beam quality. This leads to strict requirements on the injector. The requirement for MHz repetition rates restricts the electron source technology to a number of options: DC guns, VHF guns, L-band SRF guns, VHF SRF guns and DC-SRF guns. Two of these injector technologies were investigated in detail: a VHF gun and a high field L-band SRF gun. In this proceeding the simulated beam dynamics performance and the technical readiness of the options will be compared and a number of conclusions will be drawn for the UK XFEL project.

INTRODUCTION

The conceptual design and options analysis (CDOA) of the proposed UK XFEL has recently been completed [1]. UK XFEL aims to achieve: near transform limited operation over photon energies from 0.1-20 keV; 6 or more simultaneous FELs at 100 kHz; widely-separated 2-color x-ray pump/x-ray probe. Two parallel injectors will feed a superconducting radio-frequency (SRF) 1.3 GHz L-band linac at bunch repetition rates from 0.1-1 MHz, distributed to the FELs by a spreader. A sketch can be seen in Fig. 1.

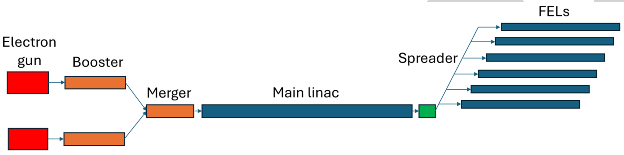

Figure 1: A schematic of UK XFEL showing two injectors and multiple FELs.

The design goals and choices made elsewhere impose requirements on the injector [1]; it must deliver high brightness with a full width (FW) duration <20 ps to match to the L-band main linac at two bunch charges (75 pC and 150 pC) simultaneously for the different FELs with an even spacing of 1 µs, at up to 1 MHz repetition rate. Also, it must be able to deliver two bunches in adjacent main linac buckets for the x-ray pump/x-ray probe mode.

MHz operation implies a limited number of gun options: direct current (DC), normal conducting radio-frequency (NCRF) VHF, SRF L-band, SRF-VHF or combined DC-SRF guns [2]. The choice requires balancing a number of factors: achievable cathode field, exit energy, compatibility with photocathode materials, beam dynamics complexity, and technical readiness. DC guns are the most technically mature option, having been used at several ERLs: JLAB FELs [3], CBETA [4], cERL [5] and ALICE [6]. However, they offer lower cathode fields (few MV/m) and exit beam energies (<500 keV); they have not been chosen for other XFEL facilities. NCRF VHF [7] is the next most mature, with higher cathode fields (< 27 MV/m) and exit energies (around 750 keV); LCLS-II [8] and SHINE [9] are both NCRF-VHF. EuXFEL is investigating a high-field L-band SRF gun with a field up to 50 MV/m [10] and LCLS-II HE an SRF-VHF gun with an exit energy of 1.6 MeV [11]. An SRF VHF gun/injector with parameters appropriate for an XFEL is also being investigated at BNL [12].

An analysis of existing injector designs, balancing technical risk against potential performance, led to these options being studied:

- Design-I: VHF gun with RF + magnetic compression
- Design-II: VHF gun with two-stage RF compression
- Design-III: L-band SRF gun without compression

Achieving low emittance from an injector requires balancing several factors including: cathode emittance; geometric and chromatic aberrations; and linear and non-linear space charge. Optimization was done using the genetic algorithm NSGA-II [13]; results are shown for the 150 pC case.

VHF GUN INJECTOR

Designs-I and II use a NCRF VHF gun [14]. The specifically designed 216.67 MHz gun has a 30 MV/m cathode field, a beam exit energy around 1.1 MeV field due to a longer front extrusion than typical, and a Cs_2Te photocathode. The design philosophy is to use the long RF wavelength to emit a long (>100 ps) bunch, allowing a smaller laser spot without space charge limited emission, to reduce the cathode emittance [15]. The bunch is then compressed in two stages. The benefits to the slice emittance can be seen in Fig. 2.

Each design uses a different two-stage compression scheme. Design-I uses an RF compression stage consisting of a NCRF 650 MHz linearizer and a NCRF 216.67 MHz buncher to compress to approximately 40 ps full width (FW); the bunch is then accelerated to the emittance-dominated regime by an SRF 650 MHz subharmonic booster. The second compression stage is a magnetic C-chicane with a

* ben.hounsell@stfc.ac.uk
† Now at Türkiye Enerji Nükleer ve Maden Araştırma Kurumu, Ankara, Türkiye

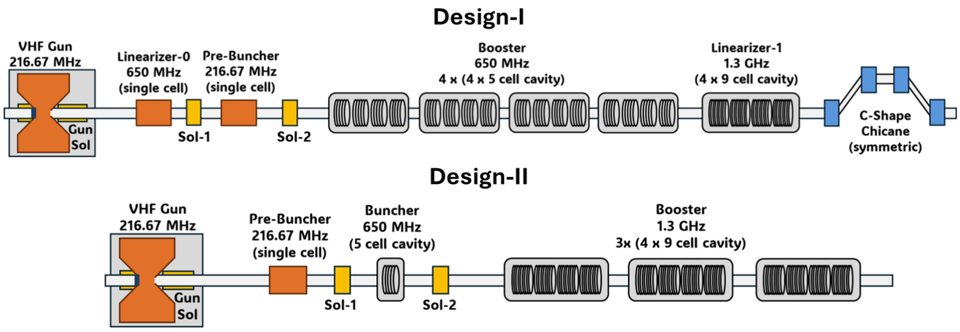

Figure 3: A schematic of Designs-I and II the VHF gun injectors.

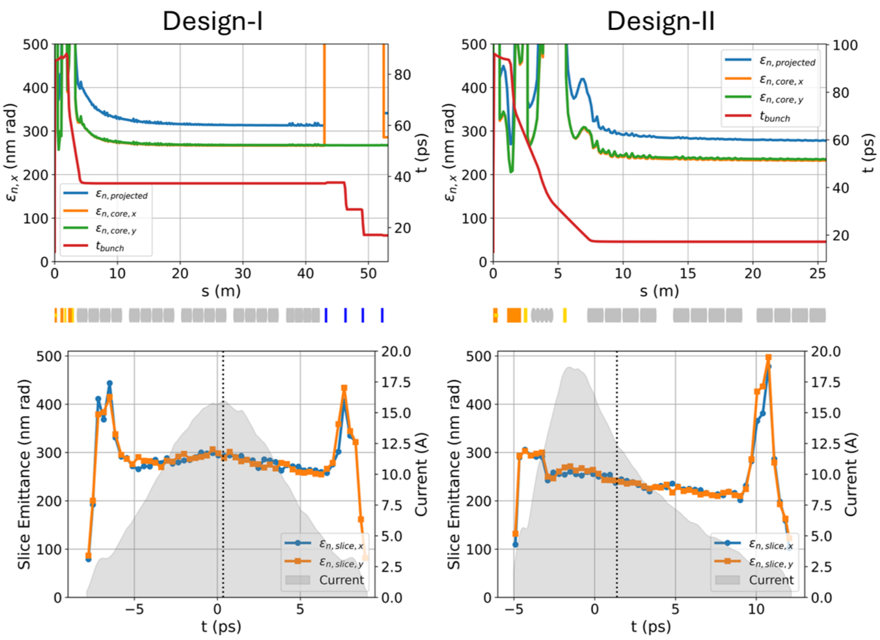

Figure 4: Transverse emittance, bunch length, slice emittance and current profiles for Design-I and Design-II.

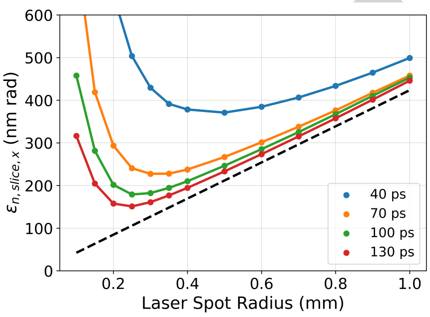

Figure 2: The effect of laser spot size and pulse duration on the slice emittance at the emittance compensation point after the VHF gun. The black dashed line indicates the theoretical minimum emittance from the cathode.

3.9 GHz SRF linearizer to compress to around 20 ps FW. Design-II uses two RF compression stages, the first a single-cell NCRF 216.67 MHz buncher, and the second a 5-cell SRF 650 MHz buncher-booster to accelerate and compress [16]. No linearization is used, to keep the energy as high as possible to minimize the space-charge induced emittance growth. Schematics are shown in Fig. 3.

The simulated beam parameters can be seen in Fig. 4. Design-II predicts a lower emittance of 235 nm rad compared to Design-I's value of 286 nm rad. However, due to the higher harmonic linearization of the compression stages, Design-I has a more linear longitudinal phase space with a more symmetric low skewness charge distribution.

L-BAND SRF GUN INJECTOR

Design-III uses a high-field 50 MV/m L-band SRF gun similar that of the EuXFEL upgrade [10] injecting directly into an L-band linac cryomodule, with no significant compression. A Cu photocathode is assumed as high-field SRF guns are not currently compatible with semiconductor photocathodes such as Cs_2Te. A schematic can be seen in Fig. 5.

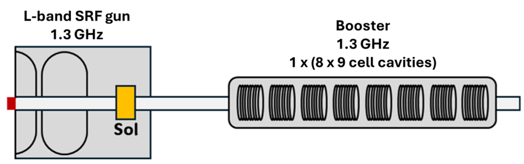

Figure 5: A schematic of the L-band SRF gun injector.

Table 1: Simulated Performance of the Three Injector Designs

Parameter	Design-I	Design-II	Design-III
Bunch charge [pC]	150	150	150
95% projected normalised horizontal emittance [nm rad]	286	232	122
95% projected normalised vertical emittance [nm rad]	267	235	122
Full width Bunch length [ps]	16.9	17.2	11.1
Skewness	0.08	0.7	0.07
Beamline length [m]	53.10	25.65	15.0

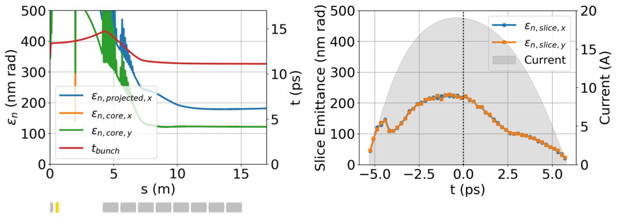

Figure 6: Transverse emittance, bunch length evolution, slice emittance and the current profile for Design-III.

The simulated beam parameters for Design-III can be seen in Fig 6. The bunch has a final emittance of 122 nm rad and the lack of compression means that the final charge distribution remains reasonably symmetric.

OPERATION WITH TWO INJECTORS AND MERGER

The requirement to deliver two different bunch charges simultaneously and to be able to locate two bunches in adjacent main linac buckets leads to the choice to have two injectors operating in parallel with a merging beamline. A diagram showing the two modes can be seen in Fig. 7. Each injector delivers a different bunch charge. An additional advantage of having two injectors is improved operational robustness: if one of them breaks, the other can still deliver beam and keep the facility operational.

A number of different approaches can be used for combining the bunches. These include: a fixed magnetic beamline, kickers or an SRF Transverse Deflecting Cavity (TDC). A fixed magnetic beamline uses low jitter mature technology but requires the injectors to deliver beams of different energies, leading to undesirable complexity in the downstream accelerator. Kickers that operate at a repetition rate of 1 MHz have been developed for LCLS-II [17] and SHINE [18]. Therefore, a kicker-based beamline could be used to deliver the 1 MHz evenly spaced bunches for operation of many simultaneous FELs. However, the requirement for the injector to deliver bunches in adjacent main linac buckets means that the combiner must be able to switch in around 770 ps, which is too fast for a kicker based system. An SRF TDC [19] operating at the first subharmonic of the main linac, 650 MHz, would be able to switch sufficiently quickly while still being able to combine the 1 MHz evenly spaced bunches. Consequently, an SRF TDC based merger is the preferred option for UK XFEL.

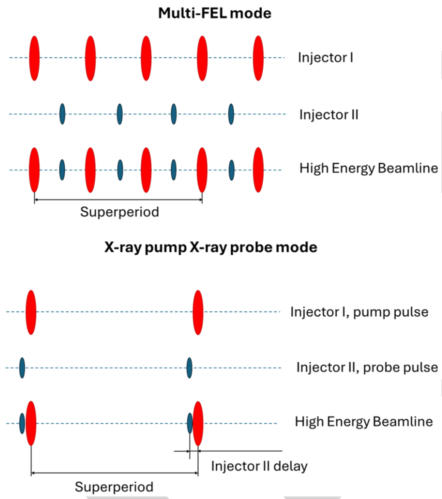

Figure 7: A diagram depicting the two operation modes for the two injectors. Ellipses of different sizes and colors are bunches originating from different injectors with different charges.

CONCLUSION & COMPARISON

UK XFEL is a proposed new XFEL which has recently completed its conceptual design and options analysis. Three injector designs were considered. Table 1 shows a comparison of the results of the beam dynamics studies; however, the choice needs to consider a range of factors. The preferred electron gun technology is a NCRF VHF gun due to its the higher technical readiness and the fact that the higher quantum efficiency (QE) of the Cs_2Te cathodes used in the VHF gun allow for 1 MHz operation with current laser technology. At present, the high-field SRF gun is limited to low QE metal photocathodes which would need to achieve optimistic QE values to deliver the required charge at the required repetition rate without excessive heating of the SRF cavity due to the photoinjector laser [20]. Consequently, Designs-I and II, are preferred over Design-III.

Of the two VHF gun based options, Design-I is preferred, as the improved longitudinal phase space leads to better 6D brightness and better performance at the end of the main linac [14]. Design-I also has the advantage that separation of functions between the emittance compensation and the two compression stages is better, so it should be easier to set up and operate. However, Design-II is a shorter beamline and does deliver better transverse emittance.

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