# PULSE - A HIGH-REPETITION-RATE LINAC DRIVER FOR X-RAY FELS

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*Abstract*

We describe a staged concept for a linac-based free-electron laser providing coherent tuneable VUV and soft X-ray output with pulse lengths down to 10 fs or less. Use of 1.3 GHz cryomodules operated with CW RF will allow flexible pulse patterns at potentially very high repetition rates up to 1 MHz. We consider the options for FELs that may be included in a facility of this type.

## INTRODUCTION

The UK New Light Source is a project to deliver world class photon output across a wide range of wavelengths to satisfy experimental users from a variety of science areas, based on a combination of advanced conventional lasers and accelerator-based sources. Key science drivers that will determine the specification of this facility are under consideration by a number of science working groups, covering ultra-fast electron dynamics, attosecond science, high energy densities, condensed matter, and chemical and life sciences [1]. Several options are being considered for the accelerator source in a collaboration between UK labs and universities, which will eventually incorporate one or more free-electron lasers (FELs). In this paper we consider a high-repetition-rate short bunch source (PULSE) based on superconducting L-band cavities. A companion paper considers an alternative scheme based on S-band structures [4].

## SOURCE LAYOUT

There is significant interest in using L-band technology - developed for XFEL - at high repetition rates for light sources. In particular, both the University of Wisconsin and Lawrence Berkeley Laboratory have proposals for L-band accelerators operating up to 1 MHz repetition rate [2, 3]. We consider a similar scheme, in which we provide flexible compression for different FEL schemes, and the possibility to provide electron bunches at a variety of energies. This latter aspect allows the facility to be constructed in stages, starting with longer wavelength FELs and then adding cryomodules later. An initial start-to-end design has examined the ability to generate ultra-short bunches of length around 10 fs, with reasonable emittance and energy spread, using an adapted PITZ-type RF injector at 1 kHz repetition rate [5]. Injector options for higher repetition rate are considered below.

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## HIGH-REPETITION-RATE INJECTOR

High repetition rates of up to 1MHz do not allow for usage of S- and L-band photoinjectors which are considered to be standard in modern FELs. These injectors at high duty factors require extremely high (MW) RF power and do not provide a low enough emittance. The possible normal-conducting (NC) options are therefore:

- Grid modulated thermionic injector: A disadvantage of this is relatively high emittance.
- DC photocathode injector: Disadvantages include relatively high emittance because of low cathode field and the requirement for a very high voltage.
- VHF photoinjector. The emittance is better than from a DC gun, but still not ideal because of the low cathode voltage ([6].

A common problem of all NC injectors is the requirement for a complex bunching scheme in order to stabilise the buncher phase. This is important because it dominates the arrival time jitter of the bunch at the FEL. An alternative solution is a superconducting RF injector, in which high cathode fields can be achieved to enable the production of beams with low emittance; they are also able to deliver high charge bunches at a high repetition rate. Good vacuum in the gun cavity extends the quantum efficiency lifetime of alkali photocathodes: strong magnetic fields are restricted around the gun which makes it difficult to realise the classic emittance compensation scheme: several alternative schemes are under development but practical results have not yet been reported. Also, the maximum power of the gun beam is restricted by the RF coupler used. At L-band this does not exceed 50kW. For a practical $1.5$-cell $5$ MeV gun design this restricts the gun average current to $10$ mA: at a bunch charge of $200$ pC this provides an upper bound on the repetition rate of $\leq 5$ MHz. It may be possible to extend this using amulti-coupler scheme. Finally, consideration should be given to the dissipation of spent photocathode laser power in the superconducting cavity; for 1 MHz repetition rate this power will not exceed $0.5$ W.

## STAGED SUPERCONDUCTING DESIGN

One of the key goals of the accelerator design is to allow staged construction and therefore costs. The first stage of PULSE delivers an electron energy of 735 MeV which allows FEL operation down to around 10 nm, the approximate cutoff point for HHG seeding. Depending on the science case requirements, additional acceleration can be pro-

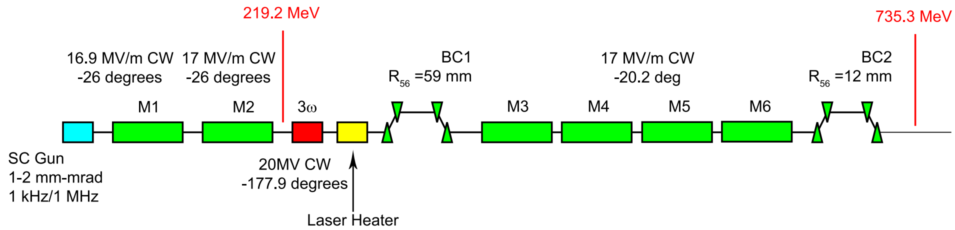


Figure 1: Layout of the first stage, showing the two-stage compression design for short bunch operation.

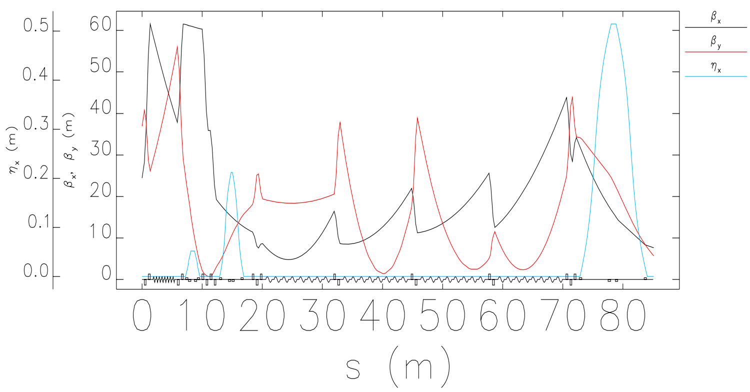


Figure 2: Transverse optical functions up to BC2.

vided to give beam extraction at multiple higher energies, enabling for example multi-frequency pump-probe experiments. The 735 MeV design utilises a two-stage compression system, and TESLA-type 1.3 GHz superconducting modules (9 cells per cavity, 8 cavities per cryomodule). Daresbury Laboratory has experience in this technology deriving from ALICE (formerly ERLP), and the now terminated $4^{\text{th}}$ Generation Light Source project [7]. Superconducting cavities allow CW operation, providing flexible pulse patterns and high repetition rates limited by the injector and by the parasitic beam loss in the accelerator. The conceptual layout is shown in Figure 1. The two superconducting modules after the gun have independently powered cavities to provide matching of the invariant envelope, followed by a third-harmonic (3.9 GHz) module for linearisation of the longitudinal phase space which delivers a mean energy of 220 MeV. Space is allocated for a laser modulator followed by a bunch compressor (BC1) with $R_{56}$ of 58.9 mm. Four further cryomodules operating at an average gradient of 17 MV/m increase the energy to 735 MeV, followed by a second bunch compressor (BC2) with an $R_{56}$ of 11.9 mm. In short bunch mode, the generated electron bunch has a FWHM length of 10 fs, a slice energy spread of 0.25 % and a transverse slice emittance of 1.33 mm mrad in the central 5 fs slice. By utilising a lower bunch charge of 200 pC, and by allowing a slightly larger transverse emittance and energy spread, a relatively high peak current can be delivered, with half (100 pC) of the charge delivered within a 10 fs central slice, corresponding to an effective peak current of over 10 kA (see Figure 3). The full electron beam parameters are summarised in Table 1.

Table 1: Parameters of the short-bunch design.

| **Parameter** | **Value** |
|---|---|
| Bunch charge | 200 pC |
| Average bunch rate | 1 kHz → 1 MHz |
| 1.3 GHz gradient | 17 MV/m |
| 3.9 GHz total voltage | 20 MV |
| Linac 1 Phase | $-26.0°$ |
| Energy at BC1 | 220 MeV |
| BC1 $R_{56}$ | 58.98 mm |
| Linac 2 Phase | $-20.0°$ |
| Final energy | 735 MeV |
| BC2 $R_{56}$ | 11.90 mm |
| Bunch length (FWHM) | 10 fs |
| Projected energy spread | 0.56 % |
| Slice energy spread (5 fs) | 0.29 % |
| Slice Emittance (5 fs norm.) | 1.43 mm mrad |
| Peak Current (5 fs) | 11.5 kA |
| FEL Resonant Wavelength | 40 → 10 nm |
| Accelerator Length | 110 m |

## FREE-ELECTRON LASERS

The typical minimum wavelength of a FEL, as a function of electron beam energy, is obtained from the FEL resonance condition $\lambda_r = \lambda_u(1 + a_w^2)/2\gamma^2$, where $\lambda_r$ is the resonant wavelength, $\lambda_u$ is the undulator period, $a_w$ is the rms undulator parameter and $\gamma$ is the electron energy in units of electron rest mass. The assumptions are made that for sufficient magnetic flux on the beam axis the undulator period-to-gap ratio must satisfy $\lambda_u/g \geq 2$ and for

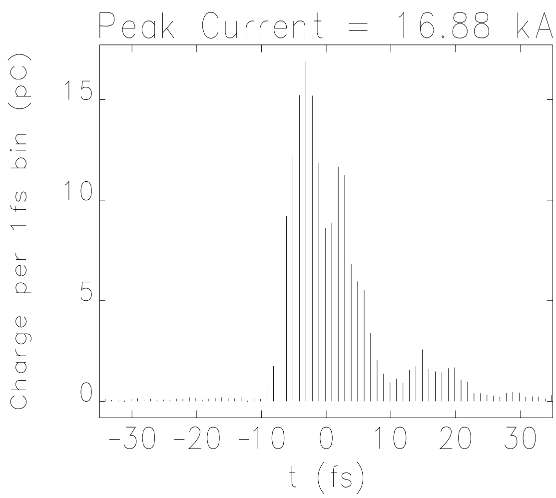


Figure 3: Current profile after BC2 at 735 MeV, in 1 fs bins.

sufficient FEL coupling the undulator parameter must satisfy $a_w \geq 0.7$. Under these assumptions the resonance condition can be expressed as $\lambda_r \geq 2g/\gamma^2$. For a $10$ mm magnetic gap this gives $\lambda_r \geq 1/(50\gamma^2)$ and for a $5$ mm gap $\lambda_r \geq 1/(100\gamma^2)$. The first inequality is satisfied by all FELs known to the authors, except the SCSS Prototype which uses in-vacuum undulators with a $4$ mm magnetic gap.

For the PULSE first stage the beam energy is $735$ MeV so we can expect a minimum FEL wavelength of $\sim 10$ nm. The electron bunch length $T_b$ is $10$ fs (FWHM) and the FEL cooperation time is $t_c = \lambda_r/(4\pi\rho c) \simeq 1.3$ fs (where $\rho$ is the FEL or Pierce parameter, assumed here to be $0.002$). The number of temporal spikes in a Self-Amplified Spontaneous Emission (SASE) FEL is $n_{spikes} \simeq T_b/(2\pi t_c)$ [8] giving $n_{spikes} \simeq 1.2$ for these parameters: this indicates that a possible mode of operation may be weak superradiance where single-spike temporally-coherent output is obtained naturally from a SASE FEL. The disadvantage of this scheme is that the pulse-to-pulse stability is too poor for many applications. However, sufficient power at wavelengths down to $10$ nm is available from Higher Harmonic Generation (HHG) sources to allow seeding of the FEL at its fundamental resonant wavelength. This would provide improved temporal coherence and pulse-to-pulse stability over SASE as well as reduced saturation length. In this case the electron bunch should be about an order of magnitude longer to allow synchronisation with the HHG seed pulse of width around $30$ fs. The corresponding reduction in peak current, which reduces the FEL coupling, would be offset by a reduction in energy spread, assuming the conservation of longitudinal emittance: such a scheme is currently being studied.

For the higher-energy stages of PULSE, the resonant wavelength will fall below $10$ nm so that direct seeding at the fundamental using HHG will not be possible: temporal coherence, if required, can only be obtained using a staged harmonic FEL concept such as a harmonic optical klystron.

Further attractive possibilities for inclusion within the NLS proposal, if identified as important science drivers, are schemes to generate attosecond X-ray FEL pulses, either as isolated pulses of widths $\geq 100$ as as predicted by various slicing or gain modulation schemes [9, 10, 11, 12, 13, 14, 15, 16, 17] or as trains of $\geq 20$ as pulses as predicted recently by a scheme to mode-lock an amplifier FEL [17]. The technology to implement many of these schemes is relatively straightforward, typically utilising a long wavelength laser and a short undulator to impose an energy modulation on the electron beam, and one or more dipole chicanes to convert energy modulation into spatial modulation or act as electron delays. Such schemes are currently being considered.

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