FEL Options for the Proposed UK Fourth Generation Light Source (4GLS)

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4GLS is a novel low energy light source proposed as a complementary facility to the DIAMOND x-ray project for the UK, and could probably replace the present SRS at Daresbury in about six years time. This facility will use a combination of three separate FELs, undulators and bending magnets to provide a unique source of high brightness continuous and pulsed radiation from the IR to XUV ($\sim$ 100 eV). Here we give a brief description of the proposed FELs in the IR and VUV followed by a pre-design parameter study of the more technically challenging XUV high gain FEL. The electron beam source for this FEL is a 600 MeV superconducting energy recovery linac with peak currents of a few kA, normalised rms emittance $\sim 3\,\pi$ mm mrad and rms energy spread $\sim 5 \times 10^{-4}$. Computer simulations using the 3-D FEL code GENESIS 1.3 are used to investigate a feasible undulator and beam focussing scheme, allowing estimates for achievable radiation power and saturation length to be made.

1. Introduction

The Fourth Generation Light Source (4GLS) [1] proposed for the UK's Daresbury Laboratory is designed to complement the DIAMOND facility currently being developed at the UK's Rutherford Appleton Laboratories [2]. 4GLS will provide users with a uniquely flexible source of ultra-high brightness continuous and pulsed radiation covering the FIR to XUV regions of the spectrum. This radiation will be generated by three FELs operating in the IR, VUV and XUV, supplemented by various spontaneous emission sources. The IR and VUV FELs are based on cavity oscillators and the XUV FEL will operate as a single pass SASE device. All are described in more detail below. A schematic of the 4GLS concept showing the FELs and other spontaneous emission insertion devices is shown in figure (1).

Two photo-injector driven superconducting linacs will generate the electron pulses that drive all the devices. The higher energy linac driving the VUV and XUV FELs will also operate as an Energy Recovery Linac (ERL) to allow efficient high average power modes of operation [3]. The spontaneous undulator and bending magnet radiation will generate photon energies of up to at least 500 eV with very high brightness. The design target for 4GLS radiation brightness as a function of photon energy is shown in figure (2). A major aim is to provide synchronised and simultaneous operation of all radiation sources to allow two-colour and pump-probe experiments. In what follows we give an outline of the preliminary design parameters of the ERL and the three FELs. The 3-D FEL code GENESIS 1.3 [4] is then used in a pre-design estimate of the performance that can be expected of the XUV FEL.

2. The 4GLS sources

The VUV and XUV FELs will be driven by an ERL based on five or six superconducting linac cryo-modules operating at 1.3 GHz and generating an electron beam energy of 600 MeV. A single cryo-module will drive the IR FEL with electron beam energy of $\sim$ 50 MeV. The linac module design and parameters have so far been based upon those from DESY's TESLA programme and its prototypes at TTF [5]. To satisfy the design aims of simultaneous operation of all devices and the operational requirements of the FELs, a mixed mode operation of the photo-injectors

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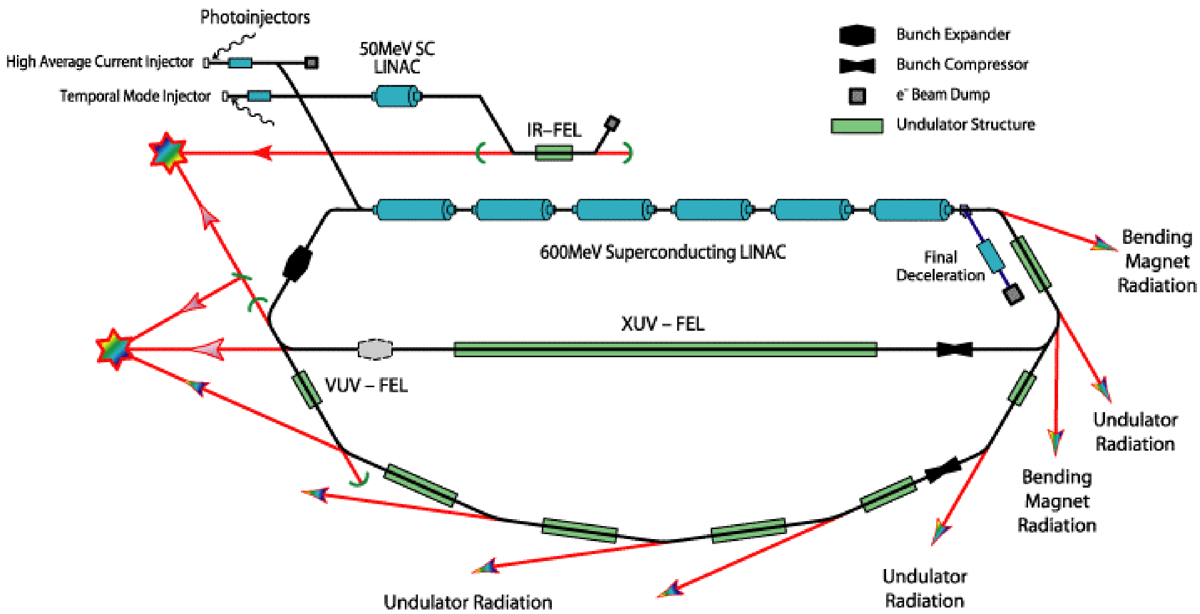

Figure 1. Concept schematic diagram for 4GLS

and linacs is required so that electron pulses with higher pulse charge/low rep-rate may be interleaved with lower pulse charge/higher rep-rate electron pulses. Two very different photo-injectors are therefore required. The first is a high average current (100 mA) 260 MHz mode-locked Ti-sapphire laser GaAs photo-injector providing a train of $\sim$ 20 ps pulses containing up to 100 pC of charge. This would source all devices except the XUV FEL which requires a higher bunch charge (typically $\lesssim 1$ nC) for SASE FEL operation. As SASE is a single shot process a high duty cycle is not required and potential problems associated with the high average power operation of the first photo-injector are not encountered. The gun would be similar to those under development for other SASE FEL experiments at present, but less demanding than for the x-ray ones. However the requirements of pulse interleaving and high average power are challenges that will require a significant programme of R&D in gun design.

The IR-FEL will be a multi-pass cavity designed to cover the spectral region $3 - 75$ μm. The high quality electron source (80 pC ; 0.2-1 ps at 10 MHz) means that short, high power radiation pulses (peak $\sim$ 100 MW) can be achieved. Although this FEL is not the most challenging part of the 4GLS project, the high quality electron beam will provide important advantages over several existing IR-FEL facilities, especially in delivery of high stability.

The proposed VUV-FEL is based on an optical klystron arrangement that has successfully operated at several storage ring facilities [6]. The 4GLS electron source (which will operate with a rep-rate of 6.25 MHz) has a significant advantage over storage rings in providing electron pulses with larger charges ($\sim$ 200 pC) and shorter lengths (0.2-1 ps) so increasing the gain by a large factor over that of storage ring FELs. The success of the storage ring FELs has relied upon the development of multi-layer mirror reflectivities of $\sim$ 95% [7] but currently limited to wavelengths $\gtrsim 190$ nm [8]. However, developments in pure-Al mirror technology confidently predicts extension of useful wavelength operation down to

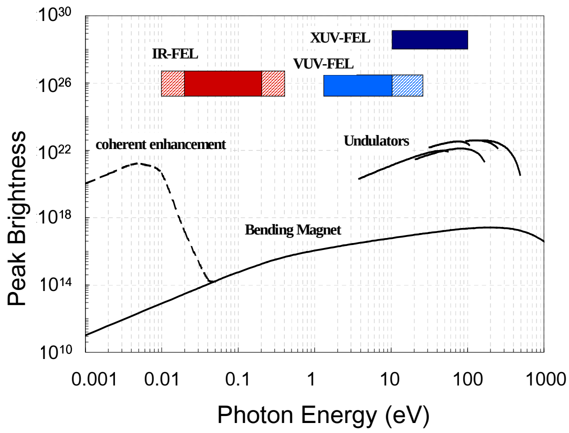

Figure 2. Peak Brightness (ph/s.0.1%.bp.mm^2.mrad^2) as a function of photon energy

120 nm [9]. For the proposed overall 7 m undulator of period $\lambda_u = 0.05$ m, electron pulse energy of 600 MeV and peak current $I_{pk} = 80$ A, the 4GLS VUV-FEL is expected to be tunable from the visible down to $\sim$ 120 nm. The peak output power estimate mid-tuning range is $\sim$ 12 MW.

The XUV-FEL is the most technically challenging of the 4GLS radiation sources and will operate in SASE mode down to fundamental radiation wavelengths of $\sim$ 10 nm. This requires electron pulses of high peak current, low emittance and low energy spread to achieve exponential radiation growth to saturation. Beam transport and pulse forming from photo-cathode to undulator entrance must minimise electron pulse degradation due to effects such as CSR and wakefield interactions. This will be of fundamental importance at the full design phase. The micropulse repetition rate will be 65 MHz with each macropulse containing approximately 650 micropulses of charge $\sim$ 1 nC. The macropulse repetition rate will be around 60 Hz. Micropulse durations are expected to be in the range 100 fs-1 ps. The following electron pulse parameters are an estimate of those thought achievable and are used henceforth: electron energy $E = 600$ MeV; peak current $I = 2$ kA; rms energy spread $\sigma_\gamma = 5 \times 10^{-4}$; normalised emittance $\epsilon_n = 3\,\pi$ mm mrad. Although the undulator will not be as demanding as those of shorter radiation wavelength FELs proposed for DESY and SLAC, it will still require manufacture to exacting high tolerances with advanced beam focusing and steering. For the pre-design study we choose an undulator and focussing similar to the DESY TTF project's 4MFU integrated focusing undulator [10] but differing in the undulator period and field strength which are $\lambda_u = 0.02$ m and $B_u = 0.5$ T respectively with FODO quadrupole strengths $Q = 20$ T/m, quadrupole lengths of $L_Q = 0.1$ m and period $\lambda_{FODO} = 0.7$ m.

Assuming no errors in the FODO lattice or wiggler alignment the following 1-D estimates for the FEL interaction are derived [11]: fundamental radiation wavelength $\lambda \approx 10.4$ nm; FEL parameter $\rho \approx 1.4 \times 10^{-3}$; nominal gain length $l_g \approx 1.15$ m; beam radius $r_b \approx 73\,\mu$m; Rayleigh range $Z_R \approx 1.61$ m; focussing β-function $\beta \approx 2.1$ m; shot-noise equivalent radiation power $P_{rad}(z = 0) \approx 12.4$ W; saturation length $z_{sat} \approx 13.9$ m; and saturation power $P_{sat} \approx 1.7$ GW. These parameters conform to the cold beam limit as $\sigma_{eff} \lesssim \rho$ where σ_{eff} is the effective beam energy spread due to both homogeneous energy spread and the equivalent energy spread due to emittance [12]. The gain length l_g is less than both the Rayleigh range and the β-function indicating that diffraction and betatron effects should not destroy the FEL interaction and that the 1-D estimates for the saturation length and power should be reasonable.

The numerical 3-D FEL code GENESIS 1.3 [4] has been used to conduct an initial study of the parameters of the previous section. Maximum gain was found in the steady-state at radiation wavelength $\lambda = 10.455$ nm with a saturation power $P_{sat} \approx 850$ MW and length $z_{sat} \approx 20.5$ m. Although the 1-D estimates are within a factor of two of the GENESIS simulation, the importance of the full 3-D simulation is evident in accurately determining the undulator length required to reach saturation. The effect of the FODO lattice quadrupole strength, Q on the saturation length, z_{sat}, and saturated radiation power, P_{sat}, is shown in figure (3). It is seen that the saturation length is optimised for $Q \approx 20$ T/m, as used in the calculations of the 1-D estimates of the previous section. Note however that this value of Q is not the optimum for the saturated power, which

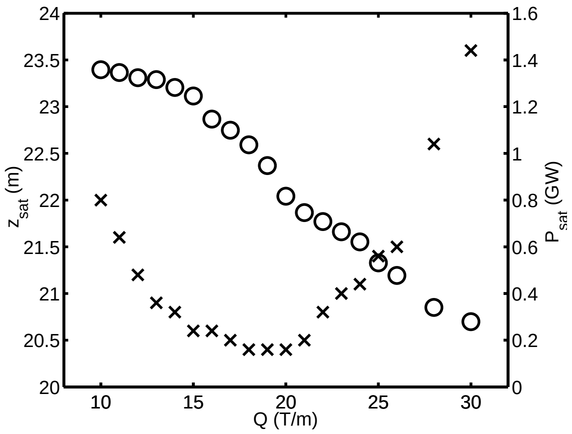

Figure 3. Saturation length z_{sat} ($\times$) and saturation power P_{sat} ($\circ$) as a function of FODO lattice quadrupole strength Q

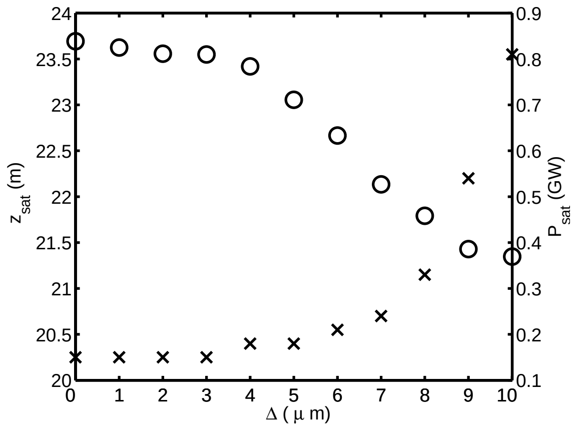

Figure 4. Saturation length z_{sat} ($\times$) and saturation power P_{sat} ($\circ$) as a function of FODO lattice quadrupole misalignment Δ

for $Q \approx 10\,\mathrm{T/m}$ is seen to approach the saturation power of $\approx 1.7\,\mathrm{GW}$ as predicted by 1-D theory. In figure (4) the effects of FODO quadrupole misalignment are show on the saturation length and saturated power for a FODO quadrupole strength $Q = 20\,\mathrm{T/m}$. Each quadrupole in the FODO lattice has been given a random uniform deviation in x and y between the limits $[-\Delta, \Delta]$ about the undulator axis. For these parameters, the figures indicate that quadrupole alignment to within 4 μm would be desirable. Such alignment requires a challanging but feasible Beam Position Monitoring resolution of $\sim 3\,\mu$m over a FODO period.

3. Conclusions

The basic feasibility of the 4GLS concept has been established, with its exciting future potential confirmed. A Scientific Case has already been accepted by the UK funding agencies and the next step is a full scale Design Study, probably starting in 2003 and lasting two years. In parallel a major R&D phase will be essential, covering the wide range of topics from electron beam dynamics through photo-gun and superconducting technology to user sensitive issues such as fs pulse synchronisation. FELs are at the heart of 4GLS and must work together successfully for much of the user exploitation highlights. The combination of FEL types is unusual at a single laboratory but provides attractive challenges. It is believed that 4GLS could be fully operational at a cost of about £100M (including buildings etc) by 2008.

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