THE CONCEPTUAL DESIGN OF THE 4GLS XUV-FEL

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Abstract

The Conceptual Design Report for the 4th Generation Light Source (4GLS) at Daresbury Laboratory in the UK was published in Spring 2006 [1]. A key component of the proposal is an XUV-FEL amplifier directly seeded by a High Harmonic source and operating in the photon energy range 8-100eV. Numerical modelling shows the FEL may generate 50fs (FWHM) pulses of variably-polarised, temporally-coherent radiation with peak powers in the range 2-8 GW.

INTRODUCTION

Synchronised free-electron laser (FEL) sources which operate in the XUV, VUV and IR regions of the spectrum are fundamental components of the 4GLS design. These sources will deliver ultra-short pulses of temporally coherent photons with peak brightness at least 10^8 greater than that available from the best 3rd-generation light sources. 4GLS is intended to be a beyond state-of-the-art facility that must operate over extended periods, generating stable, synchronous and reproducible radiation pulses over the wide spectral range to end-user stations. In the conceptual design of 4GLS, therefore, the aim has been to create a robust design that does not overly stretch the specification of its individual components. This mildly cautious approach should minimise the risk in proceeding to the future design phase and enable further, more advanced, designs to be incorporated as technological progress permits. Here details mainly relating to the choice of undulator and electron focussing specifications and their relation to the FEL output are presented for the conceptual design of the XUV-FEL covering the 8-10eV photon energy range of the spectrum. The effects of FEL seeding by High Harmonic pulses are discussed in [2, 3] and the temporal seed/electron pulse offset due to jitter is discussed in [4].

GENERAL SPECIFICATION

The XUV-FEL baseline design will generate short, tunable, high-brightness pulses of 8-100 eV photons from an undulator system directly seeded by an external laser source. The radiation output will have good temporal and transverse coherence and also have variable polarisation. These specifications are expected to satisfy a wide range of current user requirements and also open up many new areas of science for exploration. It is also possible to utilise the exhaust electrons of the XUV-FEL in a spontaneous spent-beam undulator source, before the electron beam is dumped. The radiation from this source is then guaranteed to be synchronous with the XUV-FEL output for pump-probe type experiments. A schematic of the conceptual design for the 4GLS XUV-FEL is given in [3] of these conference proceedings.

Photon energy tuning in the XUV-FEL will be achieved by a combination of both undulator gap tuning and energy tuning of the electron bunches between 750 and 950 MeV. The electron bunches are assumed to have a rep-rate of 1-10 kHz, to be Gaussian of width $\sigma_t = 266$ fs and total charge of 1 nC giving a peak current of 1.5 kA, and with normalised emittance $\epsilon_n = 2$ mm mrad and fractional RMS energy spread of 0.1%. The FEL undulator will consist of a lattice of individual undulator modules allowing electron beam focusing elements and diagnostics to be placed in between. The final undulator modules of the FEL will be of APPLE-II design that will enable the generation of variable elliptically polarised radiation. Existing HHG laser systems can provide seed energies of 10 - 100 nJ with pulse widths of 30 fs FWHM over the photon energy range [2, 3]. The quality of XUV-FEL output can be expected to be similar to that of the input seed pulse which has a high degree of both spatial and temporal coherence [5]. The amplified pulse widths will also be only slightly longer than the seed pulse.

UNDULATOR AND FOCUSSING LATTICE

The design for the XUV-FEL undulator consists of a lattice of undulator modules containing both planar and variable polarisation undulator modules. For the planar undulators a relatively simple pure permanent magnet (PPM) was chosen and an APPLE-II design was chosen for the variable polarisation undulators. Each type of module will have a fixed period and a variable magnetic gap, g, that allows tuning of the RMS undulator parameter $\bar{a}_u$ via the undulator magnetic field. A minimum undulator magnetic gap is assumed for the design of both planar and variable undulators. Note that the gap between the vacuum vessel walls will be $(g - 3)$ mm, the 3 mm reduction from the magnetic gap being the estimated thickness of the vacuum vessel walls and the clearance between magnets and vacuum vessel. A schematic giving further detail of the undulator lattice and incorporating BPMs, phase matching devices and the focussing quadrupoles is shown in Fig. 1. The variable polarisation undulator sections, VU1..VU5, ensure that variably polarised photons may be generated across the full design spectrum. In practice, operation at higher photon energies will require a longer undulator

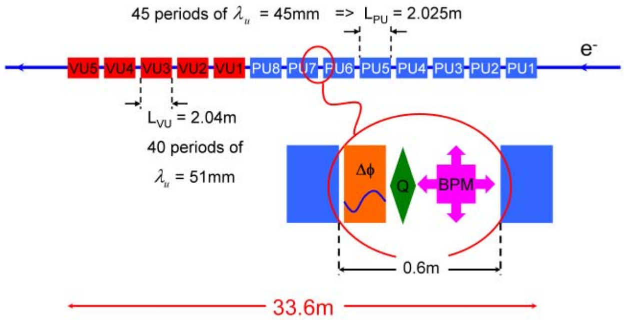

Figure 1: Schematic of the modular undulator system of the XUV-FEL. Undulator modules PU1..8 (blue) are planar undulators; VU1..5 (red) are variable polarisation undulators. The gap between undulator sections may contain a beam position monitor, quadrupole and radiation/electron phase matching unit.

length to achieve saturation. The effective undulator length may be varied by opening the magnetic gaps of individual undulator modules to their maximum. Those modules that have maximum magnetic gap generate only small on-axis magnetic fields and are effectively switched off for the purpose of the FEL interaction. For example, when operating for 100eV photon energy generation all undulator modules PU1..VU5 would be functional to achieve saturation, whereas for 50 eV operation only modules PU5..VU5 would need to be functional to achieve saturation, with PU1..PU4 gaps fully opened. This method of operation should allow a tapered vacuum vessel to be used along the undulator modules which will assist with reducing diffraction effects of HHG seed injection at lower photon energies [1, 3]. The minimum undulator parameter due to undulator gap tuning is taken to be $\bar{a}_u \approx 1$ to ensure sufficient FEL coupling. With this constraint then for a beam energy of 950 MeV the maximum planar undulator period that can achieve 100 eV FEL resonance is $\lambda_u \approx 45$ mm with a gap of $g \approx 28$ mm. At the lower beam energy of 750 MeV and for $\lambda_u \approx 45$ mm, the resonant photon energy is ≈ 10 eV for the minimum magnetic gap of $g \approx 10$ mm. The period of $\lambda_u \approx 45$ mm is then the optimum for the beam energy, magnetic gap and photon tuning range. A similar analysis for the variable polarisation APPLE-II undulators gives them an optimum period $\lambda_u \approx 51$ mm

A FODO focussing lattice has been chosen for the conceptual design. Other systems based upon quadrupole doublet and triplet focussing were investigated [5] and rejected. Although these latter designs allow longer, and therefore fewer, undulator modules of up to 4-5 m in length to be used, the quadrupole field strengths must be significantly greater by a factor of 3-4 than those required for a FODO lattice distributed between more modules. Tighter quadrupole alignment tolerances would therefore be required for the doublet and triplet positioning [6]. Monitoring of the electron beam transverse position, critical to the FEL interaction, would also be limited as would the ability to step-vary the full undulator length by opening the individual module gaps. For these reasons a simpler FODO focussing lattice of module length ≈ 2 m is the chosen design option.

In order to investigate the effect of β-function variation due to the discrete focussing quadrupoles of the FODO lattice, the 3-D code Genesis 1.3 [7] was used to determine both the saturation length L_{sat} and power P_{sat} as a function of average β-function. This was carried out for a planar undulator system of module length ≈ 2 m. The respective results are shown in Fig. 2. It is seen that $\beta \approx 3.5$

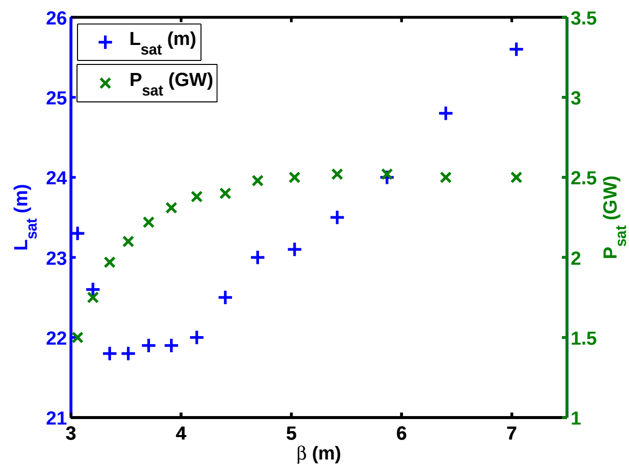

Figure 2: Genesis simulation of the saturation length,L_{sat}, and power, P_{sat}, as a function of the β-function in a FODO lattice for 100 eV operation.

m minimises the saturation length whereas $\beta \approx 5.5$ m maximises the output power. The nominal value of the β-function is chosen to be that which gives the maximum output power: β = 5.5 m. This is motivated by the fact that the planar modules PU1-PU8 produce a seed pulse (and pre-bunched beam) which will be amplified to saturation in the APPLE-II modules VU1-VU5, so maximising the power of the seed into the VU modules reduces the required length of the more technologically challenging APPLE-II modules. For the parameters used here a β-function of 5.5 m is satisfied by quadrupoles of magnetic length 0.09 m and of strength =13 T/m. The RMS electron beam radius may be calculated as $\sigma_b = \sqrt{\epsilon_n \beta/\gamma}$ = 77 μm for beam energy 950 MeV and the design normalised emittance $\epsilon_n = 2$ mm mrad.

UNDULATOR MODULE & GAP LENGTH

The modular construction of the combined undulator and FODO focussing lattice requires choice of the length of each undulator module, L_{PU} for planar and L_{VU} for variable undulators, and L_{gap} the spacing between modules. The FEL performance has a functional dependence on these parameters so optimisation is needed. The energy dispersion induced into the electron beam by the FEL interaction, and the natural homogeneous energy spread, are transformed into a spatial dispersion in proportion to the gap between undulator sections, L_{gap} which may disrupt the FEL bunching process. Furthermore, it is seen from Fig. 1 that the undulator module length and gap define the FODO focussing lattice period, $\lambda_{FODO} = 2(L_{PU} + L_{gap})$. In a FODO lattice, the β-function varies about its mean value by $\pm\lambda_{FODO}/2$ so affecting the electron beam radius via the relation above for σ_b. Thus if λ_{FODO} is too large (as determined principally by the module length) the electron beam radius variation may also adversely affect the FEL coupling. Alignment of the electron beam through the undulators is of critical importance to maintain the electron-radiation coupling. This requires both beam alignment between undulator modules and careful construction of the undulators to ensure that the beam wander due to magnetic field errors and pole alignment are minimised. Ideally, beam wander off the optical axis should be no greater than 20% of the electron/radiation beam radius.

Genesis 3-D simulations were carried out to simulate the FEL operating at 100 eV. Only the planar undulator modules were used with the nominal design parameters. Fig. 3 plots the results of Genesis steady-state simulations for the saturation power, P_{sat}, as a function of the gap between undulator modules, L_{gap}, for three different module lengths, L_{PU}. It is seen that the saturation power is nearly independent of the undulator module length and decreases almost linearly with the undulator gap. A gap of $L_{gap} = 0.6$ m is chosen for the design specification. This is the estimated minimum length into which the quadrupoles, BPMs and phase matching units can fit.

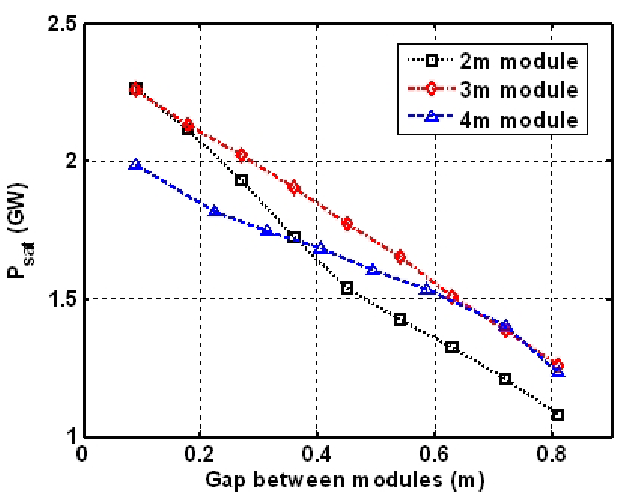

Figure 3: Simulation of the saturation power, P_{sat}, for XUV-FEL planar undulator operation at 100 eV as a function of the gap between undulator modules. The results are plotted for three module lengths: L_{PU}=2, 3 and 4 m.

Simulations of the saturation length L_{sat} of a seeded amplifier interaction, starting from a seed power of 30 kW at 100 eV, are shown in Fig. 4. For each length of undulator module L_{sat} is seen to increase with the module gap. However, there is a significant difference between each undulator module length, with the 4 m module having a saturation length longer than that of the 2 m module. This is attributed to the greater variation in the β-function for the longer module as discussed above. For this reason, and the greater opportunities for beam monitoring and control afforded by the greater number of undulator modules, the module lengths for the design specification are chosen to be $L_{VU} \approx L_{PU} \approx 2$ m. Hence, for the baseline design for 8 - 100 eV operation, each planar PPM undulator will have 45 periods of 45 mm giving a module length L_{PU} = 2.025 m and each variable undulator APPLE-II undulator will have 40 periods of 51 mm giving a length L_{VU} = 2.04 m.

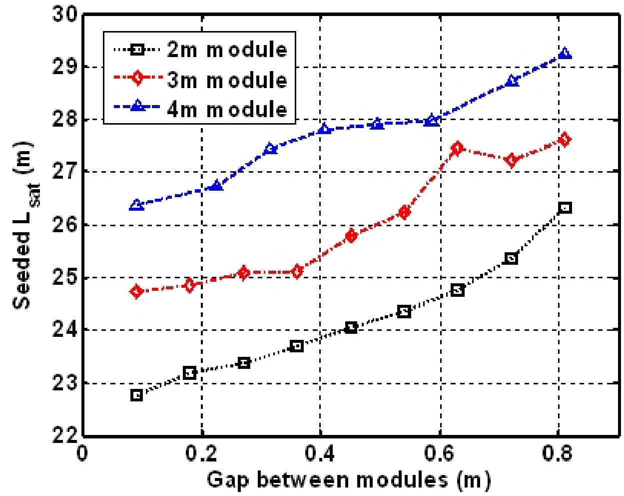

Figure 4: Simulation of the saturation length L_{sat} for XUV-FEL planar undulator operation at 100 eV as a function of the undulator module gap, L_{gap} for three module lengths: L_{PU}=2, 3 and 4 m. (The saturation length is the undulator length only: gaps between modules are not included.

3D STEADY-STATE SIMULATIONS

The design choices and optimisations discussed may be summarised by plotting both the saturation powers and lengths across the operating spectrum of the XUV-FEL. It has been assumed that the XUV-FEL is operating in an amplifier mode with a seed power equal to 10% of the peak power currently available from seed pulses as described in [2, 3]. The reduction in seed power by a factor of approximately ten conservatively estimates the power available following transmission and focussing losses from the seed laser into the undulator. The seed is focussed to the centre of the first in-use undulator module with Rayleigh length equal to half the module length. For seed pulses of 30 fs FWHM and of energy 3 nJ for 10 to 40 eV photons and 1 nJ for 40 to 100 eV give corresponding approximate peak powers of 100 kW and 30 kW. The saturation power over the operational spectral range as calculated by both Genesis (in steady state mode) and Xie formulae [8] are shown in Fig. 5. Both planar and helical mode results are shown.

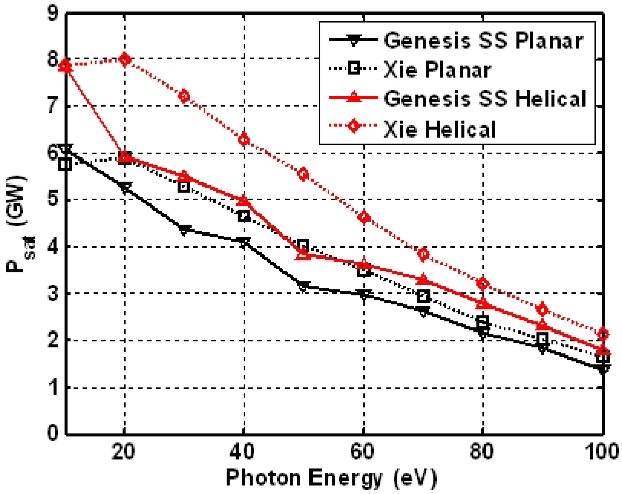

Figure 5: Summary of saturation power estimates for the XUV-FEL across its spectral operating range. 3-D Genesis steady-state (SS) simulations and the Xie formulae are in excellent agreement.

Note that the Xie design formulae cannot take into account mixed planar/helical undulators, so the 'Xie Helical' estimates assume a helical-only undulator for the equivalent length of the planar-helical combination. The Xie estimates also do not include the effects of gaps between undulator modules. These differences account for the small discrepancy of the 'Xie Helical' estimates from the other simulations, in the slightly higher saturation power estimation. Notwithstanding this, the 3-D numerical and Xie estimates are in excellent agreement. In Fig. 6, the length of undulator required for saturation is plotted as a function of photon energy. Note that the gaps between undulator modules are not included in this length and must be added on to obtain the total length of the combined undulator-focussing lattice.

CONCLUSIONS

A robust conceptual design for the XUV-FEL has been developed. Established FEL theory and state-of-the-art simulation codes predict this free-electron laser will generate 8-100 eV photon energies at giga-watt power levels and, as shown elsewhere [3], in pulses of duration 40-60 fs FWHM. The pulses will have very good temporal and spatial coherence with time-bandwidth products close to the Fourier transform limit for a Gaussian pulse [3, 5]. Unlike the SASE mode of operation, which effectively self-starts from intrinsic noise, the FEL interaction here is truly acting as a simple, bandwidth limited amplifier. So long as the radiation input seed pulses have sufficient spectral purity, the output radiation is very nearly a simple amplified version of the input. Recent advances in the High Harmonic seed sources of choice ensure that the seed requirements for the XUV-FEL already exist [2, 3]. Research in the next design phase will require full start-to-end simulations from the electron gun through to the end of the undulator. This will allow the modelling of the FEL interaction with more realistic electron pulses than that used here which assume a Gaussian variation of most variables. Investigation of tolerances, for example in quadrupole position and undulator field errors, will also be required, as will a more detailed study of the effects of relative electron-seed pulse jitter than the initial results presented at this conference [4]. Extension of the operational range down to 6eV photons may be possible and will be investigated further in the next design phase.

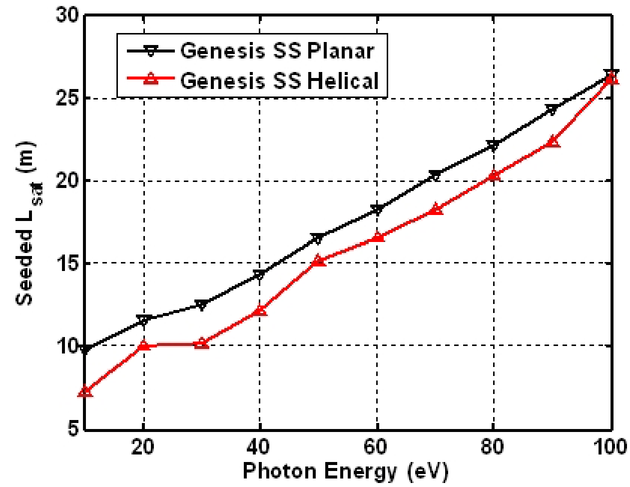

Figure 6: Summary of steady-state 3-D Genesis simulation estimates for the XUV-FEL undulator saturation length across the spectral operating range.

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