A 3D MODEL OF THE 4GLS VUV-FEL CONCEPTUAL DESIGN INCLUDING IMPROVED MODELLING OF THE OPTICAL CAVITY

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Abstract

The Conceptual Design Report (CDR) for the 4th Generation Light Source (4GLS) at Daresbury Laboratory in the UK was published in Spring 2006. The proposal includes a low-Q cavity (also called a regenerative amplifier) FEL to generate variably-polarised, temporally-coherent radiation in the photon energy range 3-10eV. A new simulation code has been developed that incorporates the 3D FEL code Genesis 1.3 and which simulates in 3D the optical components and radiation propagation within the non-amplifying sections of an optical cavity. This code is used to estimate the optimum low-Q cavity design and characterise the output from the 4GLS VUV-FEL.

INTRODUCTION

4GLS is a 4th Generation Light Source [1] proposed by CCLRC Daresbury Laboratory to meet the needs of the 'low photon energy' community. The Conceptual Design Report (CDR) was published in 2006 [2]. 4GLS will comprise synchrotron radiation sources, free-electron lasers and conventional lasers which will be combined synchronously to allow innovative pump-probe experiments.

A 600MeV high average current branch operating in energy recovery mode (80pC bunches at up to 1.3GHz) will feed spontaneous sources and a VUV-FEL. A 750-950MeV high peak current branch (1nC bunches at 1-10kHz) will feed a XUV-FEL[3]. There will also be an IR-FEL operating over 2.5–200μm.

This paper first summarises the VUV-FEL CDR design. The proposal is a low-Q cavity FEL, or Regenerative Amplifier FEL [4, 5], in which the high gain allows saturation to be reached in a few passes with mirrors of low reflectivity. It has been shown from 1D simulations [6] that the optimum outcoupling fraction is $\sim 75\%$ for mirrors of 60% reflectivity, using a hole for outcoupling. This fraction gives a near maximum output power but is a stable working point, such that the output power is relatively insensitive to small changes in outcoupling fraction or mirror reflectivity.

The next section presents 3D simulations of the CDR design, using Genesis 1.3 [7] and a new 3D optics simulation code developed at Twente University [8]. These simulations confirm the validity of the CDR design and the earlier 1D simulations which investigated the parameter space. The last section presents simulations to optimise the resonator.

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Table 1: Baseline VUV-FEL parameters, as presented in the 4GLS CDR.

UNDULATOR	
Undulator Period λ_w	60 mm
Periods per module	37
Number of modules	5
ELECTRON BEAM	
Electron Beam Energy	600 MeV
Relative Energy Spread (rms)	0.1%
Bunch Charge	80 pC
Peak Current	300 A
Normalised emittance	2 mm-mrad
OPTICAL CAVITY	
Cavity length L_{cav}	34.6 m
Upstream ROC r_1	12.85 m
Downstream ROC r_2	22.75 m
Rayleigh length z_r	2.8 m
Fundamental mode waist w_0	0.34 mm
Waist position (measured from US mirror)	12.2 m
Outcoupling hole radius	2 mm
Cavity stability $g_1 \times g_2$	0.88

CDR PARAMETERS

The VUV-FEL will produce radiation of variable polarisation using APPLE-II undulator modules. The minimum gap is 10mm and the undulator period 60mm. The photon energy range 3–10eV is covered by gap tuning from 10–19mm in helical mode and 12–25mm in planar mode. For high enough gain for RAFEL operation, the undulator length, expressed in the universal scaling of [9], must give $\bar{z} \equiv 4\pi\rho N_u \geq 4$ over all wavelengths and polarisations. The required length is then 11m, achieved with five 2.2m modules of 37 periods. The intermodule gap is 0.6m to allow space for a quadrupole, BPM and phase matching unit. A FODO lattice is used with quadrupoles of length 0.12m and strength 9T/m. The electron beam parameters have been derived using the FEL design formulae of Ming Xie [10].

The resonator parameters are derived from simple assumptions, with the expectation they will be revised after 3D optics modelling. The fundamental cold cavity mode is focussed to maximise the overlap between radiation and electron beam over the first two undulator modules. This is done with a waist at the end of the first module, 12m from the upstream (US) mirror as shown in Fig.1. The *optimum* Rayleigh length z_R (for maximum overlap) is then approximately one third the total length of the two modules plus

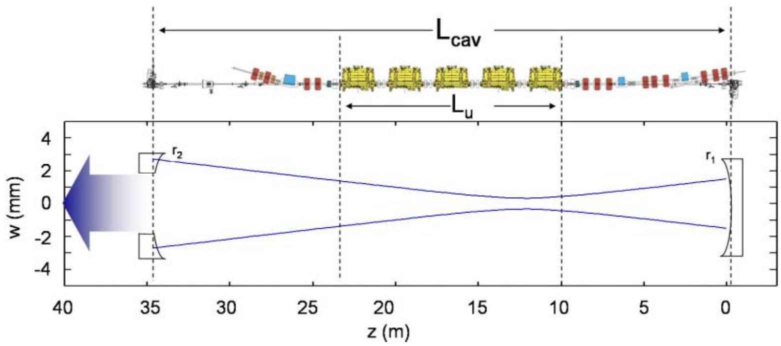


Figure 1: A schematic of the 4GLS VUV-FEL with the baseline CDR parameters. The fundamental cavity mode is shown on the same longitudinal scale as the engineering representation. The electron beam direction is right to left.

gap, i.e. around 1.7m. However, this z_R pushes the cavity geometry close to instability and gives an excessive spot size at the downstream mirror and some diffraction losses on the undulator aperture for the longer wavelengths. In addition the hole size on the downstream mirror is larger than the spot size of the spontaneous radiation emitted on the first pass and does not allow sufficient feedback. The Rayleigh length is therefore chosen so that the spot size of the fundamental cavity mode is the same as the estimated spot size of the spontaneous emission. This gives a Rayleigh length of 2.8m, somewhat larger than the value for maximum overlap.

The hole size is such that the outcoupling fraction of the fundamental cold cavity mode is 65%. This is slightly less than the optimum value (from 1D simulations) of 75% but the high gain FEL interaction is expected to guide the radiation reducing the spot size and increasing the outcoupling fraction towards its optimum value. The mirror material is protected aluminium with a reflectivity of 60% at 10eV. The CDR parameters are given in Table 1 and a schematic shown in Fig.1 where the fundamental cold cavity mode is shown on the same longitudinal scale as the machine layout.

3D SIMULATIONS

A new simulation code has been developed at Twente University that incorporates the 3D FEL code Genesis 1.3 and which simulates in 3D the optical components and radiation propagation within the non-amplifying sections of the optical cavity. Full details of the code are given elsewhere [8]. The code has been used to model the 4GLS VUV-FEL using Genesis 1.3 in steady-state mode. All the simulations presented here are for 10eV operation. Simulation results for 3eV will be presented in a later work.

Simulations of baseline design

The CDR parameters have been used for the initial simulations. The growth of output power and the measured outcoupling fraction, both as a function of pass number, are shown in Fig. 2. At saturation the output power is 350MW with a measured outcoupling fraction of 68%. The

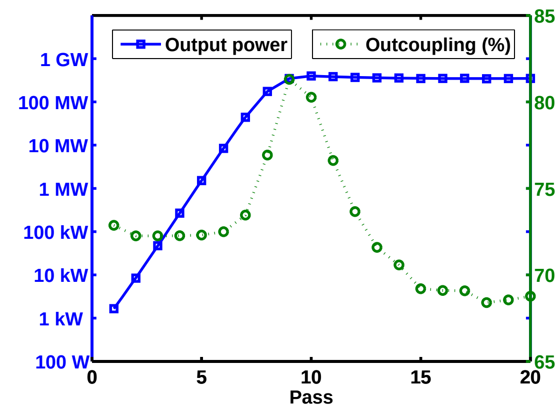


Figure 2: The growth of output power and the measured outcoupling fraction, both as a function of pass number, for the CDR parameters.

normalised power profiles at saturation, for different points within the optical cavity, are shown in Fig.3. A modal expansion algorithm is under development and will calculate the power distribution between the fundamental and higher order modes. It is clear however from Fig.3 that there is significant transverse HOM content in the radiation field. It is interesting to note that although the on-axis power of the radiation reflected from the downstream (DS) outcoupling mirror is zero, due to the large hole, by the time the radiation is reflected back off the upstream (US) mirror and back into the undulator the power is concentrated on-axis allowing good coupling with the electron beam for the next pass.

Cavity optimisation

Fig.4 shows the effect of varying the radius of the outcoupling hole and the mirror reflectivity on the output power after 20 passes (by which time the FEL has reached saturation for almost all parameter sets used here). The results show that the CDR working point (hole radius 2mm, reflectivity 60%) is satisfactory and stable—the output power is near optimum, yet small changes in hole size or reflectivity have a correspondingly small effect on the

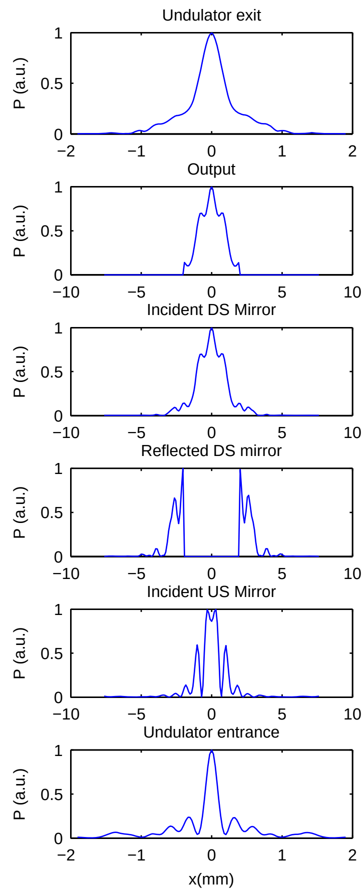


Figure 3: The normalised intensity cross sections at saturation, for different points within the optical cavity. The parameters are the CDR values (waist position 12 m, waist radius 0.34mm).

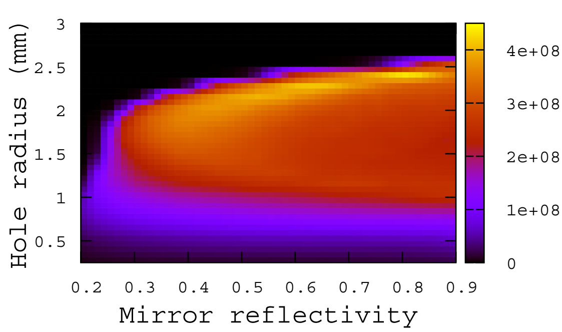


Figure 4: Output power (W) as a function of hole radius and mirror reflectivity. The CDR hole radius is 2mm and mirror reflectivity is 60%.

output power. In fact a reduction in reflectivity would cause a small increase in output power, as predicted by the earlier 1D simulations.

Different cavity configuration have been investigated by changing the ROC of the mirrors such that either waist size or waist position of the lowest order cold-cavity mode is kept constant and the other is varied. The dependence

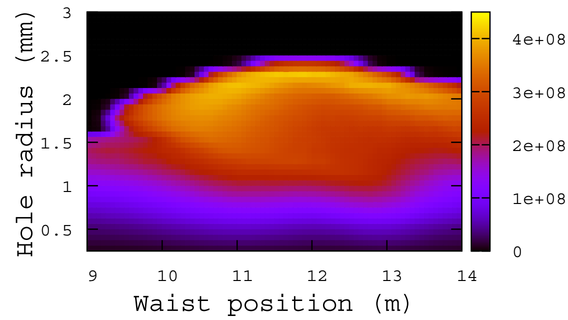


Figure 5: Output power (W) as a function of hole radius and waist position.

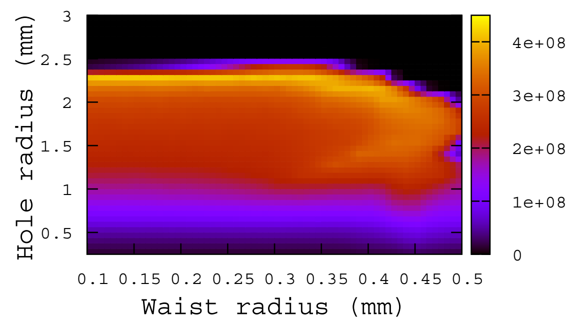


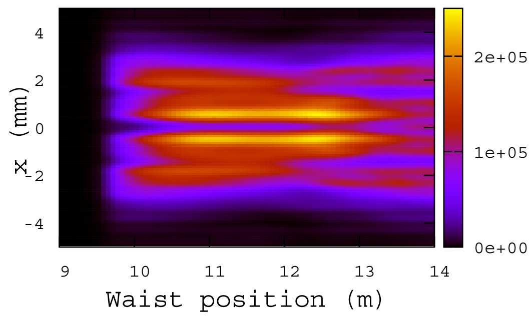
Figure 6: Output power (W) as a function of hole radius and waist size, for waist position 12.19m.

of the output power on hole radius and waist position is shown in Fig.5. It appears that moving the waist back 1m towards the undulator entrance (from 12m to 11m from the upstream mirror), i.e. to the centre of the first undulator module, gives a working point in a broader region of near maximum output power which would be beneficial.

The results of varying the waist radius from its CDR value of 0.34mm are shown in Fig.6 for a waist position of 12m where it is seen there is little dependence on waist radius even when the waist radius is 0.1mm which represents a cavity on the boundary of instability with $g_1 g_2 = 1.00$. Extensions of geometry into unstable resonator configurations will be investigated in the future. Similar results have been obtained for a waist position of 10.5m. These results demonstrate that considerations of cold cavity resonator modes are not very relevant to this design—the gain guiding of the high-gain FEL interaction strongly dominates.

This interpretation is supported by simulations investigating the effect of changes in waist position on the radiation profiles at different cavity positions. Shown in Fig. 7 are the far field intensity cross sections (calculated at 14m beyond the outcoupling hole, this being the position of the VUV-FEL optical diagnostic bench) and at the undulator entrance. The cross sections are displayed in arbitrary units. Again, the dependence on waist position is weak.

It is noted that the far field cross section in Fig.7 displays clear higher order transverse mode structure, with a



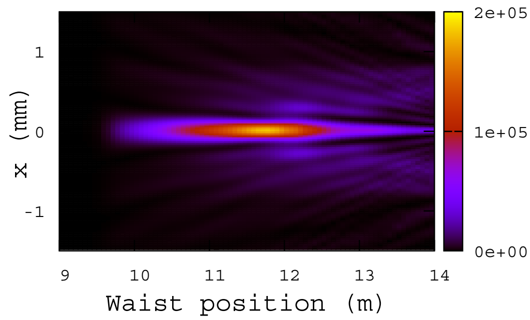


Figure 7: Intensity (a. u.) cross sections in the far field (top) and at the undulator entrance (bottom) as a function of the waist position of the cold-cavity fundamental mode of the resonator. The hole radius is 2mm.

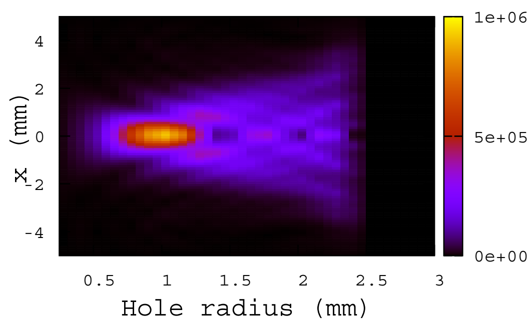


Figure 8: Intensity (a. u.) cross section in the far field as a function of hole radius, for waist position 12.19m.

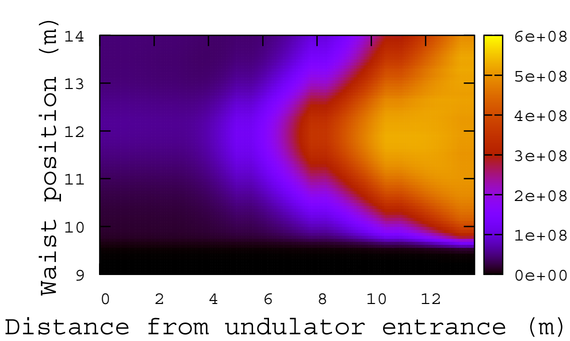


Figure 9: Power (W) growth along undulator as a function of waist position. The vertical bands are due to the gaps between the undulator sections.

minimum intensity on axis. A scan of the effect of hole radius on far-field cross section is shown in Fig.8 where it is seen that the far field cross section can be improved (i.e. brought closer to a fundamental gaussion mode) by reducing the hole radius. Further optimisation will now be done to maximise the output power while maintaining the optimum far-field cross section, including investigation of unstable resonators.

Finally, the total power within the undulator as a function of waist position is shown in Fig.9. The baseline waist position of 12m gives the strongest power growth.

CONCLUSION

Full 3D modelling of the VUV-FEL has been made possible with the new optics simulation package. The main conclusions are:

- The CDR parameters are close to the optimum values found with steady state simulations;
- The far field cross-section and total output power depend on hole radius but, for each hole radius, are otherwise relatively insensitive to the resonator configuration over a large range of ROC's around the CDR values;
- The high gain of the FEL ensures that optical guiding within the undulator and hole size are far more dominant in defining the radiation profile than the ROC of the mirrors.

These conclusions demonstrate that the VUV-FEL should be treated as a self-seeding amplifier FEL rather than as an oscillator FEL.

After 3eV simulations are complete it is expected that 3 mirror sets will be specified, one optimised for 10eV output, one for 3eV output and one for scanning over the full range.

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