A VUV-FEL FOR 4GLS: DESIGN CONCEPT AND SIMULATION RESULTS

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Abstract

A Free-Electron Laser operating in the photon energy range 3-10eV is a component of the 4th Generation Light Source (4GLS) proposal at Daresbury Laboratory in the UK. In this paper we present a current design proposal which is based on the Regenerative Amplifier Free-Electron Laser (RAFEL) concept. We also present simulation results which illustrate the potential performance of the device.

INTRODUCTION

4GLS is a 4th Generation Light Source [1] proposed by CCLRC Daresbury Laboratory in the United Kingdom to meet the needs of the 'low photon energy' community. There will be a suite of light sources—spontaneous 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 which is described in more detail elsewhere in these proceedings [2]. There will also be an IR FEL operating over 3–75μm.

This paper presents conceptual design work for the 4GLS VUV free-electron laser. This source is required to deliver intense sub-ps pulses of broadly tunable coherent radiation in the photon energy range 3–10eV (413–124nm).

PARAMETERS

The resonant undulator wavelength is given by $\lambda_r = \lambda_w/2\gamma^2\left(1+\bar{a}_w^2\right)$ where $\bar{a}_w$ is the *rms* undulator parameter given by $\bar{a}_w = 93.36 B_{rms}[\mathrm{T}]\lambda_w[\mathrm{m}]$, and for a typical PPM undulator with 4 blocks per period, a block height of half a period and a remanent field of 1.3T the on axis *rms* field is given by $B_{rms} = 1.584e^{-\pi g/\lambda_w}$. The minimum undulator gap is set at $g = 10$mm. This is only a first estimate of the gap required to minimise wakefield effects—the estimate may be revised after the results of ongoing analyses are available. The minimum gap defines the longest wavelength resonant in the undulator. Given a period of 54mm, the photon energy range 3–10eV can be covered by varying the gap from 10mm to 21mm. The undulator parameters are summarised in Table 1.

Table 1: VUV FEL parameters.

Undulator Period λ_w	54mm
Minimum gap (3eV photons)	10mm
Beam Energy	600 MeV
Relative Energy Spread (rms)	0.1 %
Bunch Charge	80 pC
Peak Current	300 A
Normalized emittance	2 πmm-mrad

The required electron beam parameters have been derived using the FEL design formulae of Ming Xie [3]. Iterative studies of gain length L_g and ρ parameter, using the undulator parameters previously given, enabled the nominal required beam parameters to be determined. These are given in Table 1.

DESIGN OPTIONS

Part of the conceptual design work has been the assessment of different FEL options to deliver the required photon output. The Self-Amplified Spontaneous Emission (SASE) option does not promise the high quality pulse characteristics required, in terms of coherence and pulse-to-pulse reproducibility. Genesis 1.3 [4] simulations for 10eV output, using the parameters given in Table 1, are shown in Figure 1. The predicted pulse shape exhibits the characteristic spiky SASE profile and the output radiation is not Fourier transform limited. The bandwidth is 0.8% (FWHM) and the SASE saturation length is more than 30m.

An alternative option to reduce undulator length and improve pulse quality is to seed directly into an amplifier. However, the VUV FEL is fed by the high average current electron beam with up to GHz repetition rate, and it is not thought that seed sources close to these repetition rates will be available in the 4GLS timescales.

The logical alternative is a self-seeding scheme. This has led to the investigation of the Regenerative Amplifier FEL (RAFEL).

REGENERATIVE AMPLIFIER CONCEPT

The RAFEL is a high gain amplifier FEL in which a small fraction of the output radiation is fed back as a seed for the following pulse [5, 6]. The device starts up from electron beam shot noise, and due to the high gain, saturation can be reached in a few passes (<20) using mirrors of

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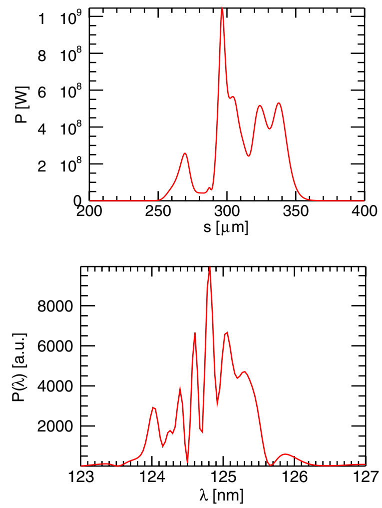

Figure 1: Genesis 1.3 simulation results showing SASE pulse profile and spectrum at saturation for 10eV photons. The estimated bandwidth is 0.8% (FWHM).

low reflectivity. It is anticipated that over the wavelength range required a broadband reflectivity of 60% can be obtained using Al mirrors with a fluoride coating [7].

There are several expected advantages of the RAFEL over a low gain oscillator FEL. The RAFEL can operate with low reflectivity mirrors in a region where high reflectivity is not available. The RAFEL should be less sensitive to radiation-induced mirror degradation, and the small number of passes required to reach saturation should relax the longitudinal alignment tolerances. The optical feedback allows the undulator length to be reduced significantly compared to a SASE device, and it is expected that a RAFEL source can deliver higher quality and more stable pulses than a SASE FEL.

1D steady-state simulations

The RAFEL takes advantage of the fact that if the gain is high enough the intracavity saturation intensity can be increased by *increasing* the total cavity loss. The results of 1D steady-state simulations are seen in Figure 2: for a gain parameter $G = 4\pi\rho N_w = 4$, the intracavity intensity increases as the cavity loss is increased from 60% and peaks at a loss of 97%.

Figure 3 shows the optimised output intensity (the maximum output intensity that can be obtained by scanning the outcoupling fraction) as a function of gain parameter G for a range of mirror reflectivities. It is seen that at $G = 4$ the output intensity is insensitive to the mirror reflectivity—the intensity using 60% reflectivity mirrors is only 5% lower than the intensity using 95% reflectivity mirrors.

It is interesting to examine the scans performed over the outcoupling fraction, for different reflectivities. A subset of these scans are shown in Figure 4 for the case $G = 4$.

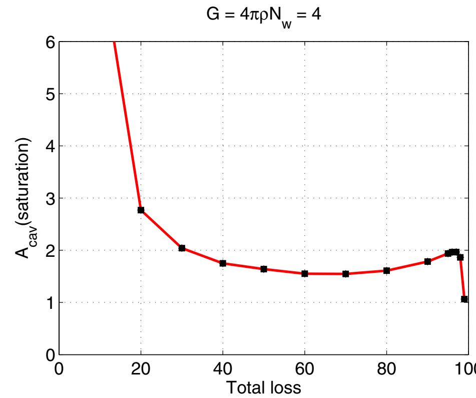

Figure 2: Intracavity saturation intensity as a function of total cavity loss, for a gain parameter $G = 4\pi\rho N_w = 4$. The data is from 1D steady state oscillator simulations.

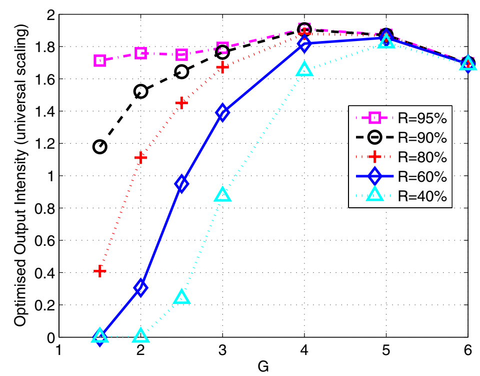

Figure 3: The optimised output intensity as a function of gain parameter G for a range of mirror reflectivities.

For $R = 60\%$ the optimised outcoupling fraction is 92%. A small increase above 92% would prevent lasing. It is not practical to operate an FEL with hole outcoupling and control the outcoupling fraction to within a few percent. Minor electron beam instabilities or fluctuations in the transverse optical mode would change the outcoupling. It would be sensible to operate at a lower outcoupling of, for example, 75%. This would slightly limit the output power, but as shown from Figure 4 would also be a more stable operating point. It is interesting that for $G = 4$, with a fixed outcoupling of 75%, the output power *increases* as the mirror reflectivity *decreases*. This has the practical advantage that mirror degradation actually enhances the FEL performance.

3D steady-state simulations

Genesis 1.3 has been used in steady-state mode to confirm the main results of the 1D simulations. An oscillator was simulated by reducing the output power after each pass to account for reflectivity and outcoupling (via a hole or

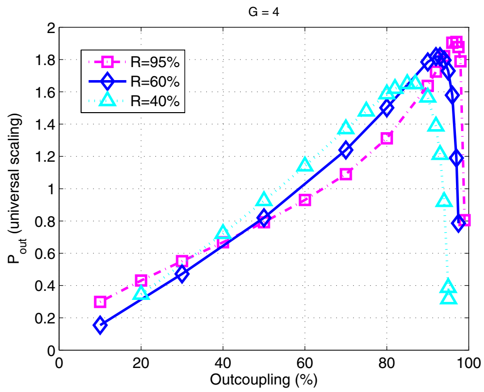

Figure 4: Output power as a function of outcoupling fraction, for different mirror reflectivities and $G = 4$. The curve for 60% reflectivity is in blue.

annulus), then using the result as a seed power for the next pass. A fixed outcoupling of 75% was used, with reflectivities of 40%, 80% and 95%. The input parameters were as in Table 1. The gain length L_g was calculated using the formulae from [3], then the undulator length L_w required to achieve $G = 4$ (9.3m) was calculated using $L_w = G\sqrt{3}L_g$. The evolution of the output power is shown in Figure 5. The predicted output power at saturation is 400MW for 80% and 95% reflectivity but increases to 430MW when the reflectivity is decreased to 40%. This is explained by Figure 5 which shows the evolution of the intracavity intensity over one pass at saturation. For 95% reflectivity the FEL is oversaturating (full saturation occurs at around 8m), whereas for 40% reflectivity the intracavity power at the start of the pass is the correct amount to give full saturation at the end of the undulator (9.3m). By changing the cavity loss we are tuning the seed power at the start of the following pass to enable the FEL to saturate optimally.

3D TIME-DEPENDENT SIMULATIONS

3D time-dependent simulations have been done to investigate the photon pulse quality that can be expected and whether the low level of cavity feedback (just a few percent) is sufficient to enable the longitudinal coherence of the photon pulse to develop before saturation.

The parallel MPI implementation of Genesis 1.3 was used (this code is in its beta-testing phase). The machine used for the parallel runs was a 1024-processor IBM computer [8] and we found speed-ups of up to 100 times when using up to 256 processors. The speed of computation made it possible to simulate the RAFEL to saturation, in time dependent mode, using little more than 1 hour computing time.

A reflectivity R of 60% was used and hole outcoupling α of 75% giving a feedback fraction of $(1-\alpha)R^2 = 0.09$. The radiation feedback included no modelling of optical propagation through cavity elements. The feedback was modelled by reducing the power of the output radiation pulse by the feedback factor across all transverse points of the grid and using this modified pulse as the input radiation field for the next pass.

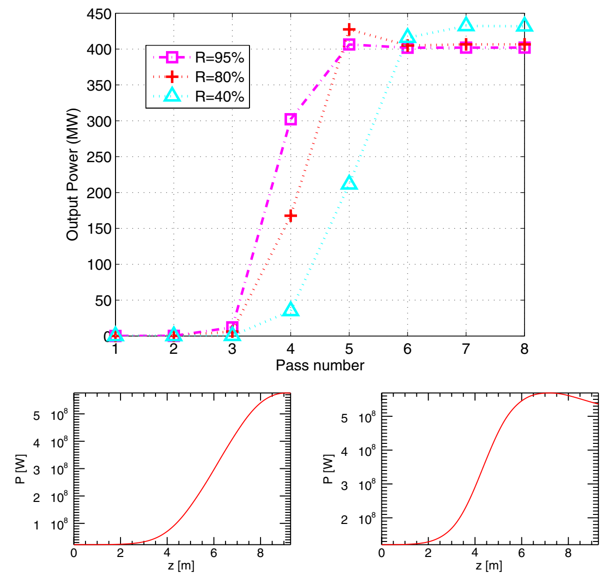

Figure 5: **Top**: pass to pass evolution from steady state Genesis 1.3 simulations. **Lower left**: evolution of intracavity intensity during pass 7 for 40% reflectivity mirrors. **Lower right**: evolution of intracavity intensity during pass 7 for 95% reflectivity mirrors.

Figure 6 shows the evolution of the intracavity pulse profile for the case where the cavity length is detuned by $\sim 12\mu$m. A smooth pulse profile develops after only 3 passes. Saturation occurs after 8 passes where the intracavity peak power is 290MW, equivalent to an output power of $290 \times 0.75 = 218$MW. At saturation the bandwidth is 0.26% (FWHM)—the spectrum at saturation is shown in Figure 7.

At the synchronous cavity length the pulse profile at saturation is unstable and spiky, but the peak intracavity power is higher at 870MW, equivalent to an output power of 650MW. The spectrum shows sidebands and the FWHM bandwidth is slightly narrower than for the detuned case, at 0.2%. The RAFEL parameters are summarised in Table 2.

More simulations are needed to cover the full cavity detuning length, but these results indicate that at the synchronous cavity length the output power can be increased at the expense of pulse to pulse stability, and that by detuning the cavity length the pulse quality and stability can be improved at the expense of output power. It is illustrative to compare the RAFEL pulse profiles and spectrums at saturation with the SASE pulse profile and spectrum shown in Figure 1—the low level of feedback is sufficient to enhance the spectral and temporal characteristics of the output compared to SASE.

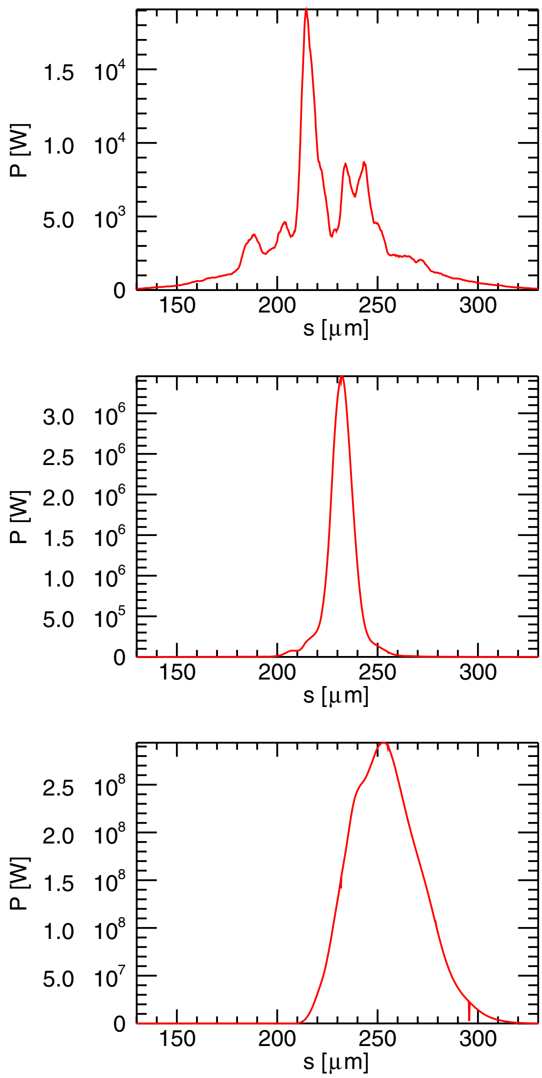

Figure 6: Detuned cavity length: From top to bottom are shown Genesis 1.3 simulations of pulse profiles after 1 pass, 3 passes and at saturation (after 8 passes).

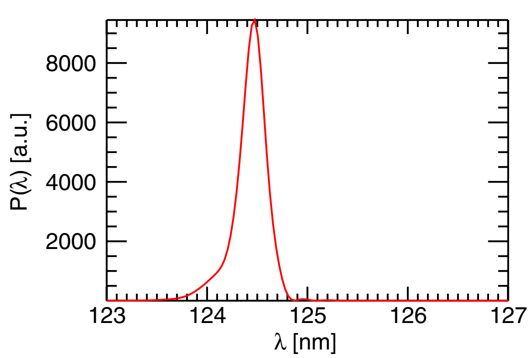

Figure 7: Detuned cavity length: Genesis 1.3 simulation radiation spectrum at saturation (after 8 passes).

Table 2: RAFEL cavity parameters and output predictions.

Mirror material	Al with fluoride protection
Reflectivity	60%
Outcoupling fraction	75%
Output peak power	220–650MW
Bandwidth (FWHM)	0.2–0.3%

CONCLUSION AND OUTLOOK

The RAFEL is a promising design for fulfilling the 4GLS VUV FEL requirements. One-dimensional simulations have been used to determine suitable design parameters and a regime has been identified where the performance of the device is relatively insensitive to (and can even be enhanced by) changes in mirror reflectivity due to surface degradation. Time dependent simulations of the evolution of the radiation output indicate that the RAFEL design promises high quality photon pulse output appropriate to the requirements of 4GLS. In comparison with a low gain oscillator FEL, the work done demonstrates that the RAFEL can reach saturation in far fewer passes with mirrors of far lower reflectivity.

Further work needs to be done on the assessment of mirror reflectivities in this wavelength range. There are plans to expose samples to high intensity SR using a VUV beamline on the Synchrotron Radiation Source at Daresbury. The method of outcoupling has not been decided—the simulations done so far are independent of this choice. Options to be considered are hole outcoupling and annular outcoupling, with either a straight or a ring cavity. Full 3D optics modelling is planned and will be incorporated into the time dependent Genesis model. The aim is to develop a fully three-dimensional time-dependent start-to-end simulation of the RAFEL from its start up from shot noise to its saturation.

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