STUDY OF AN HHG-SEEDED HARMONIC CASCADE FEL FOR THE UK'S NEW LIGHT SOURCE

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Abstract

The New Light Source (NLS) project was launched in April 2008 by the UK Science and Technology Facilities Council (STFC) to consider the scientific case and develop a conceptual design for a possible next generation light source based on a combination of synchronised conventional laser and free-electron laser sources. The requirement identified for the FELs was continuous coverage of the photon energy range 50-1000eV with variable polarisation, 20fs pulse widths and good temporal coherence to as high a photon energy as possible. This paper presents a design study of three separate FELs which in combination satisfy these requirements. It is proposed to use an HHG seed source tunable from 50-100eV giving direct seeding at the fundamental FEL wavelength up to 100eV, then one or two stages of harmonic upconversion within the FEL to reach the higher photon energies. FEL simulations using realistic electron beam distributions tracked from the gun to the FEL are presented, illustrating the predicted coherence properties of the FEL output.

INTRODUCTION

The objective of The New Light Source (NLS) project is to consider the scientific case and develop a conceptual design for a possible next generation light source based on a combination of synchronised conventional lasers and free-electron laser sources. The requirement identified for the FELs was continuous coverage of the photon energy range 50-1000eV with variable polarisation, 20fs pulse widths, good temporal coherence and 1 kHz repetition rate. Dialogue between the NLS Science Coordinators and accelerator and FEL design teams established that the full wavelength range 50–1000eV should be covered by three separate free electron lasers, with FEL-1 tuning from 50–300 eV (24.8–4.13 nm), FEL-2 tuning from 250–850 eV (4.96–1.46 nm) and FEL-3 tuning from 430–1000 eV (2.88–1.24 nm). With the assumption that APPLE-II undulators would be used to provide the full required polarisation control, that the minimum magnet gap is 8 mm and that the rms undulator parameter $\bar{a}_w$ should always satisfy $\bar{a}_w \geq 0.7$ the electron beam energy could be set to 2.25 GeV. Further details of the undulator and gap choice and optimisation of the electron beam energy and accelerator design are given elsewhere in these proceedings [1, 2].

In this paper a design study of the three NLS FELs is presented, with a particular emphasis on the design and performance of FEL-3 at its highest photon energy of 1000 eV. The chosen seeding strategy is explained, followed by numerical simulation results used to optimise the FEL performance and predict the temporal and spectral properties of the FEL output.

SEEDING

The NLS Science Case specifies temporally coherent FEL pulses with durations of the order of 20 fs. Such a specification cannot be met by a SASE FEL [3]. The theory of the spectral and temporal characteristics of SASE FEL output is well understood [4] and confirmed by experimental observation [5]. The device starts up from the spontaneous emission from the electron bunch, which is noisy due to sub-radiation-wavelength phase noise in the electron distribution (the shot noise), and this spontaneous emission is amplified to saturation via the exponential FEL instability. The output pulse comprises a sequence of phase-uncorrelated spikes separated by at least $2\pi l_c$ where $l_c = \lambda_r/4\pi\rho$ is the FEL cooperation length defining the intrinsic coherence length of the FEL interaction and ρ is the FEL parameter [3] with typical value 10^{-3} for soft X-Ray FELs. The temporal profile of the output pulse varies randomly shot-to-shot, and the spectrum is similarly noisy with bandwidth $|\Delta_\lambda/\lambda|_{FWHM} \simeq 2\rho$. The FEL pulse length is given approximately by the length of the lasing part of the electron bunch, the region of high enough beam quality, i.e. high peak current, low emittance and small energy spread.

However, if a temporally coherent radiation pulse is injected into the FEL undulator to co-propagate with the electron bunch, with a wavelength matched to the resonant wavelength of the undulator, and with a power level greater than the spontaneous emission generated by the electron beam shot noise, then this coherent 'seed' pulse dominates the spontaneous emission and is amplified to saturation in the FEL while retaining its coherence. Furthermore, the pulse length of the amplified pulse is close to that of the injected seed pulse which can be considerably shorter than the electron bunch length. Finally, the shot-to-shot stability of the FEL output pulse is much improved. This is the principle of seeding which has been adopted by the NLS project in order to meet the requirements for pulse length and coherence stated in the Science Case.

The time-bandwidth product $\Delta\nu\Delta t = (1/\lambda)(\Delta\lambda/\lambda)\Delta z$ is adaopted as a quantitative measure of output pulse coherence. In the given definition $\Delta\lambda$ is the FWHM bandwidth and Δz is the FWHM pulse length. As an example, for a SASE FEL, with $\rho = 10^{-3}$, resonant at 1000 eV (1.24 nm) and driven by a 100 fs section of electron beam, $\Delta z = c\Delta t = 30\mu$m and $|\Delta\lambda/\lambda|_{FWHM} \simeq 2\rho = 2 \times 10^{-3}$ giving $\Delta\nu\Delta t_{\rm SASE} \approx 50$. If however the same FEL is seeded the time-bandwidth product is expected to be close to that of a transform limited Gaussian pulse with constant phase, i.e. $\Delta\nu\Delta t_{\rm seeded} \approx 0.5$. The effect of the seeding is thus illustrated: the temporal coherence of the FEL pulse is increased by two orders of magnitude.

Direct seeding at the resonant wavelength of the FEL is only possible if a seed source of sufficient power is available at the required wavelength. The NLS FELs are required to operate at up to 1000eV where no such seed source exists. In this case subharmonic seeding is possible—the FEL is seeded at a subharmonic of the required photon energy, then harmonic up-conversion is done within the FEL to reach the required output energy while retaining the temporal coherence of the seed.

CHOICE OF SEED AND FEL SCHEME

Laser Seeded HGHG Cascade FEL

Two options for a seed source are a conventional laser system or a source based on HHG in gases. The assumptions made when choosing the FEL scheme for NLS were that the minimum wavelength accessible by a high power conventional laser system is 250 nm, based on design work for the FERMI@Elettra project [6], and that the available power at that wavelength is approximately 100 MW. For HHG systems, it is considered that it will be feasible within $\sim$5 years to deliver 400 kW of peak power to the FEL undulator at a photon energy of 100 eV (or wavelength 12.4 nm) and repetition rate 1 kHz.

The decision was made to base the FEL design on an HHG seed source. In order to justify this decision the next sections first present the principle and operation of an FEL scheme based on a High Gain Harmonic Generation (HGHG) Cascade seeded by a conventional laser, and then present the alternative, and simpler, HHG-seeded approach that has been adopted for NLS.

A FEL scheme based on harmonic up-conversion of a high power laser seed was proposed many years ago [7]. A variation of this scheme, known as High Gain Harmonic Generation (HGHG) was proposed later [8, 9]. Single harmonic up-conversions using the HGHG principle have been successfully demonstrated [10]. A schematic of the scheme is shown in the top of Fig. 1. The principle is that the high power seed laser interacts with the electron beam within a short modulator undulator tuned to be resonant with the laser seed. The interaction generates a sinusoidal energy modulation along the electron bunch with period equal to the seed laser wavelength. The electron bunch is then passed through a magnetic chicane which is longitudinally dispersive, such that electrons with a higher energy take a shorter path through the chicane and catch up with the lower energy electrons. The effect is that the initial sinusoidal energy modulation is converted into a periodic density modulation, or bunching. As long as the initial energy modulation $\Delta\gamma$ is greater than the natural RMS energy spread in the bunch σ_γ by a factor n, i.e. satisfying

$$\Delta\gamma > n\sigma_\gamma \tag{1}$$

then a Fourier transform of the bunch density shows that there is also strong bunching at higher harmonics of the seed laser wavelength, up to harmonic n. The bunch then propagates into a radiator undulator tuned to one of these higher harmonics and due to the pre-bunching in the beam at that higher harmonic the bunch radiates strongly and coherently at this harmonic. The initial growth of radiation power is initially quadratic with distance through the radiator undulator, with coherent power $P_{\rm coh}$ over the first two gain lengths proportional to the square of the bunching parameter: $P_{\rm coh} \propto |b|^2$ where $b \equiv \langle e^{i\theta}\rangle$ and θ is the electron ponderomotive phase. If the total energy spread due to the initial energy spread and imposed energy modulation is small enough and satisfies

$$\sigma_{\gamma,\rm total} = \sqrt{\sigma_\gamma^2 + \left(\frac{\Delta\gamma}{\sqrt{2}}\right)^2} < \rho\gamma \tag{2}$$

this initial coherent power burst is amplified exponentially to saturation.

To up-convert from the seed laser wavelength of 250 nm to a final output of 1.24 nm requires a total harmonic up-conversion of n $\sim$200, so approximating that each harmonic up-conversion has a harmonic factor of 5 this would require a total of four harmonic up-conversions in series. Such a scheme, termed a harmonic cascade, was proposed for the BESSY-FEL [11] and an example is under construction at FERMI@Elettra [6]. In these schemes the radiator undulator of the first stage is made just long enough that the radiation power is sufficient to act as a seed pulse for the second stage, and the radiator output of the second stage is then used to seed the third stage, and so on, until the desired output wavelength is reached in the final radiator, which is made long enough for the FEL to reach saturation.

Due to the high gain FEL interaction in the first radiator however the energy spread in the electron bunch has grown significantly such that the condition of (1) cannot easily be satisfied in the modulator of the second stage. To counter this problem, the 'fresh bunch' scheme has been proposed [12] in which an additional chicane before the second stage modulator delays the electron bunch with respect to the radiation pulse such that in the second stage modulator the new seed pulse overlaps with a section of the bunch that did not interact with the seed in the first stage, and so consequently has not suffered the energy spread degradation of the seeded part of the bunch. A consequence of the fresh bunch scheme is that the electron bunch must be made long

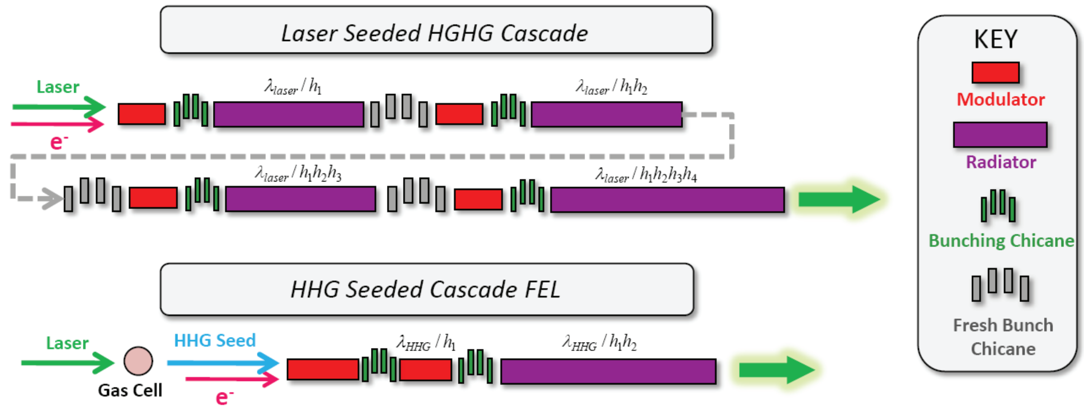

Figure 1: Schematic comparing the layout of two FEL schemes—the Laser Seeded HGHG Cascade FEL (top) and the HHG Seeded Cascade FEL (bottom).

enough that for each stage in the cascade there is a fresh part of the bunch available in front of the previously seeded part. For a given bunch charge, making the bunch longer reduces the peak current and because the FEL output power scales with peak current as $P \propto I^{4/3}$, and the gain length scales as $L_g \propto I^{-1/3}$, the performance of the FEL is degraded and the total length (and hence cost) increased.

HHG-Seeded Cascade FEL

The scheme proposed for NLS uses a HHG seed rather than a laser seed, in common with a recent proposal by the University of Wisconsin [13]. An immediate advantage of this scheme is that as the HHG seed can reach the shorter wavelength of 12.4 nm, compared to 250 nm with the laser seed, the total harmonic ratio between seed and final output at 1.24 nm is reduced from 200 to 10. This means that the maximum number of harmonic up-conversions is reduced from four to two. Furthermore, although a single stage of harmonic upconversion is done in a very similar way to the HGHG scheme described previously, the way the stages are cascaded is more simple.

The scheme is illustrated schematically in the lower part of Fig. 1. For the first stage the main difference from the HGHG scheme is that the power available from the 12.4 nm HHG seed is far lower than that available from a 250nm laser, so the first modulator undulator must be somewhat longer to achieve the required energy modulation $\Delta\gamma$. The collective FEL interaction can then be used within the first modulator to amplify the seed pulse and increase the amplitude of the energy modulation. Due to the FEL interaction the energy modulation starts to develop into a density modulation within the modulator itself, such that the chicane before the radiator is not required to produce the density modulation (as in the HGHG scheme) but rather to enhance and optimize it. Once again this density modulation, or bunching, contains higher harmonic components, and after the chicane the electron bunch propagates into another undulator tuned to one of these higher harmonics of wavelength $\lambda_{\mathrm{HHG}}/h_1$. Again there is an initial burst of coherent radiation, but now instead of extending this undulator to allow this radiation to grow near to saturation so that it can be used as a seed for the next stage, the undulator is only made long enough to modulate the beam at *its* resonant wavelength $\lambda_{\mathrm{HHG}}/h_1$—this undulator is another modulator, not a radiator. A second chicane is then used to optimize the higher harmonic bunching at the final radiation wavelength $\lambda_{\mathrm{HHG}}/h_1h_2$ and finally the electron bunch enters the radiator resonant at $\lambda_{\mathrm{HHG}}/h_1h_2$, at the start of which strong coherent emission is generated and amplified exponentially to saturation. Because the radiation power is never allowed to grow near to its saturation value within the first and second modulators, the energy spread growth within the seeded part of the bunch is constrained to a modest value such that exponential growth in the radiator is possible. There is thus no need for a fresh bunch chicane.

Comparison of the generic layouts of the two schemes illustrated in Fig. 1 clarifies the simplification in layout and reduction of number of components afforded by the adoption of the FEL scheme based on HHG seeding.

SEED POWER REQUIREMENT

For the seeding to be effective, such that the temporal coherence and pulse length of the seed are retained in the FEL output, the seed power P_{seed} must be much higher than $P_{\mathrm{rad}}(0)$, the power of the spontaneous emission due to the electron beam shot noise (or the shot noise power). For direct seeding, where the output wavelength of the FEL is the same as the seed wavelength, so that no harmonic up-conversions are required, simulations [14] and experiment [15] have shown that typically the seed power must satisfy $P_{\mathrm{seed}} \gtrsim 100 \times P_{\mathrm{rad}}(0)$. For harmonic up-conversion schemes there is an additional factor of n^2 required due to the degradation of the signal-to-noise ratio from input to final output [16]. In this case the requirement is approximately $P_{\text{seed}} \gtrsim 100 \times n^2 \times P_{\text{rad}}(0)$ where n is the harmonic ratio between seed and final output.

The shot noise power is given by the approximate expression [17]

$$P_{\text{rad}}(0) \approx \frac{6\sqrt{\pi}}{N_\lambda \sqrt{\ln(N_\lambda/\rho)}} \rho^2 P_{\text{beam}} \qquad (3)$$

where N_λ is the number of electrons per radiation wavelength. From this it is seen that at shorter wavelengths, where N_λ becomes smaller, the shot noise power increases placing greater demands on the seed source. Assuming that the undulator parameter a_w = 1.0, the undulator period λ_w = 30 mm, the normalized emittance ε_n = 1 mm-mrad and the peak current I_{pk}=2 kA (these are all typical values for the NLS FELs) then at the minimum wavelength of the HHG seed, 12.4 nm, the shot noise power is approximately 35 W. From the previous discussion this means that the seed power required for direct seeding at 12.4 nm (100eV) is P_{seed} = 3.5 kW and for a harmonic FEL scheme seeded at 100 eV and up-converting to 1000eV the required seed power is 350 kW. On this basis the 400 kW which is foreseen to be available from the HHG seed source at the FEL is sufficient to assure longitudinal coherence of the FEL output.

SEED TUNING AND HARMONIC CONVERSIONS

In order to cover the entire tuning ranges of FEL-1, FEL-2 and FEL-3 the required tuning range of the HHG seed and the required combinations of harmonic up-conversions were studied. As before, the total harmonic ratio between seed and FEL output is n. For two harmonic up-conversions, with ratios $h_1 = [1, 2, 3, 4, 5, \ldots]$ and $h_2 = [2, 3, 4, 5, \ldots]$ the total harmonic number must be $n = h_1 h_2 = [2, 3, 4, 5, 6, 8, 9, 10, 12 \ldots]$. The criterion was applied that $h_1 \leq h_2$ because bunching develops more strongly at lower harmonics. This keeps the first modulator as short as possible and minimizes energy spread growth before the first harmonic conversion.

The results of the study were that for uninterrupted wavelength coverage in FEL-3 and FEL-2 the HHG seed must tune from 75-100 eV, whereas for FEL-1 the seed must tune from 50-100 eV. The required harmonic up-conversions to give uninterrupted wavelength coverage over the design tuning ranges of the three FELs are illustrated schematically in Fig. 2.

DESIGN OPTIMISATION

The FEL scheme has been simulated with the standard three-dimensional FEL code Genesis 1.3 [18]. In order to allow rapid progress in the optimization of the design parameters the code was firstly used in steady state mode. Here only a single slice of the electron beam, of length one radiation wavelength, is used in the simulation and the

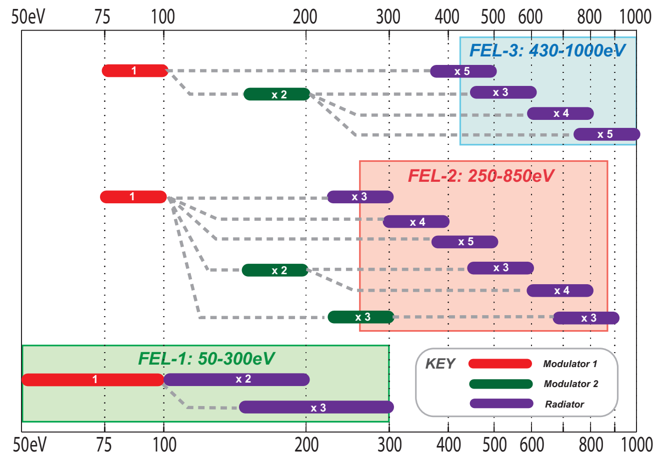

Figure 2: Undulator tunings and combinations of harmonic upconversions to give uninterrupted wavelength coverage for FEL-3, FEL-2 and FEL-1.

electron beam parameters for that slice are chosen to be representative of the average parameters within that part of the real electron bunch which will be aligned with the HHG seed pulse. In this mode of simulation the boundary conditions of the electron beam phase space are periodic over the wavelength slice—the effect is of simulating an infinitely long electron bunch and co-propagating radiation pulse and for this reason the steady-state simulation can give no information about the spectral properties of the FEL pulse. Neither can any information about the growth of the shot noise emission be obtained because this grows from the slice-to-slice variation of sub-wavelength phase noise in the electron distribution so cannot be modelled using only a single slice. Information about the spectral and temporal properties of the output pulses can therefore only be obtained from time-dependent simulations in which the whole electron bunch is simulated but these simulations are thousands of times more CPU intensive and thus inappropriate for initial optimization studies.

The generic layout for a two stage harmonic upconversion, such as that required to seed at 100 eV and produce output at 1000 eV, is shown in the lower part of Fig. 1. For the given HHG seed power of 400 kW, Modulator 1 was made long enough that (1) was satisfied, yet also short enough that (2) was simultaneously satisfied at the start of Modulator 2 and at the start of the Radiator. The strength of the magnetic chicane before Modulator 2, the length of Modulator 2 and the strength of the chicane before the Radiator, were chosen to optimize the harmonic bunching at the end of Modulator 2, equivalent to optimising the bunching at the resonant wavelength of the final Radiator. The coherent emission over the first two gain lengths in the radiator is the signal which is amplified to saturation in the radiator. Because the power of this coherent signal is proportional to the square of the bunching parameter, the bunching must be strong enough that the coherent signal dominates the shot noise power ensuring good temporal coher-

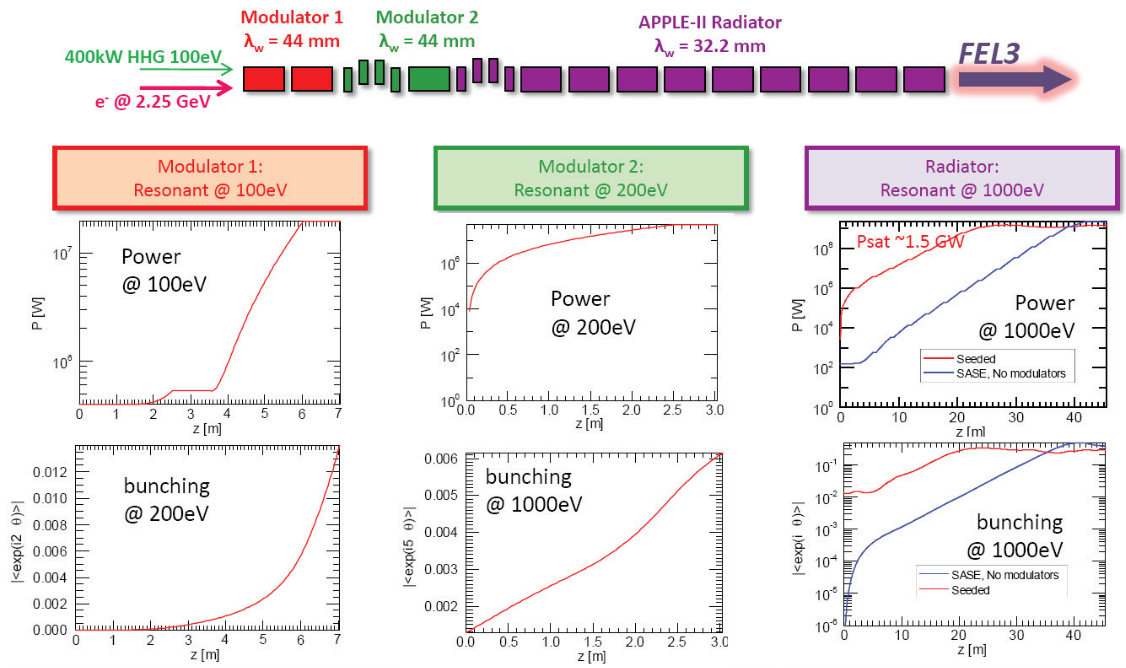

Figure 3: Steady state Genesis 1.3 simulations for FEL-3 at 1000 eV photon energy. The blue curve is for the equivalent SASE case.

ence in the output. The criterion applied was that $|b| > 1\%$ is sufficient for retention of temporal coherence, and this was confirmed in later time-dependent simulations.

This optimization was carried out for a number of different output wavelengths for FEL-3, FEL-2 and FEL-1. The assumed electron beam slice parameters were those of a tracked 200 pC electron bunch with $E = 2.25$ GeV, $I_{\rm pk} = 1200$ A, $\sigma_\gamma = 10^{-4}$ and $\varepsilon_n = 0.4$ mm-mrad. For the cases where only one harmonic up-conversion was required the optimization followed a similar philosophy, but was somewhat more straightforward. In all cases the undulators are composed of 2.5 m sections and placed within a FODO focussing structure with a gap between undulator sections of 1 m, a realistic space for the insertion of quadrupole, diagnostics station, phase shifter, corrector, BPM, vacuum pump and flanges. The strength of the FODO lattice quadrupoles was adjusted to minimize the gain length within the radiator at 1000 eV resonance. At the optimum the mean electron beam β-function was found to be 7 m.

An example of the simulation results is presented in Fig. 3, for the 1000 eV photon output of FEL-3. The HHG seed, at photon energy 100 eV with peak power 400 kW, is injected into Modulator 1. The growth of the seed power and corresponding growth of bunching at the 2nd harmonic is shown. Modulator 2 is resonant at 200 eV. The strong emission of radiation at 200 eV due to the pre-bunching of the beam is clear, and this drives the development of bunching at the fifth harmonic of 200 eV. Finally in the Radiator the initial bunching at 1000 eV is just over 1% and the coherent power grows quickly to 1 MW within the first 2.5 m undulator section. This coherent power is then amplified exponentially to a saturation level of 1.5 GW at a saturation length of 30 m in the Radiator.

A comparison 'equivalent' SASE case is shown where the electron beam is not pre-bunched by modulators but injected directly into the radiator undulator. Here the initial power is set to the shot noise power level. It is seen that there is no initial coherent power burst, but after a lethargy distance of around 3 m the FEL exponential growth regime is entered and the power saturates after 40 m. The growth rate of the SASE case is slightly greater than the seeded case—this is because of the energy spread growth within the modulators of the seeded scheme, although this energy spread growth is not sufficient to prohibit exponential amplification within the radiator.

Following this programme of design optimization it was possible to ascertain the required undulator lengths for the three NLS FELs. The resulting schematic layout is shown in Fig. 4.

PERFORMANCE SUMMARY

The performance estimates of the NLS FELs, as calculated from steady-state Genesis 1.3 simulations, are summarized in Table 1. The calculations for pulse energy and number of photons per pulse assume a 20 fs FWHM photon pulse. All figures are for the APPLE-II undulators in horizontal polarization. The power levels in circular polarization mode will be somewhat higher.

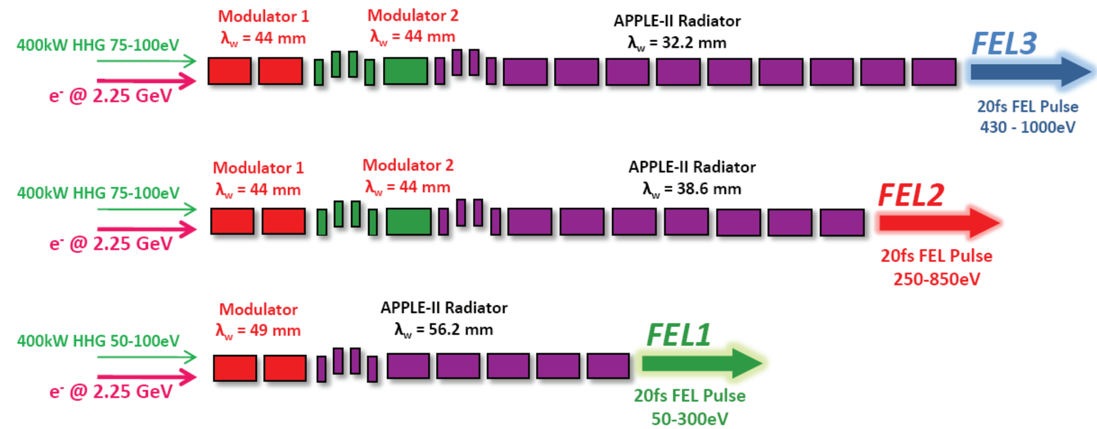

Figure 4: Schematic layout of the three NLS FELs. Each undulator section is 2.5 m long, with gaps between modules 1.0 m

Table 1: Calculated output performance of NLS FELs, based on the results of Genesis 1.3 steady state simulations. The pulse lengths are estimated as 20 fs FWHM for all photon energies.

FEL	Photon Energy	Output Power	Pulse Energy	Photons/pulse	Peak Brightness
	eV	GW	μJ		#ph/s/mm^2/mrad^2/0.1%bw
FEL-1	50	12.6	252	3.1×10^{13}	3.3×10^{30}
	300	6.1	121	2.5×10^{12}	5.8×10^{31}
FEL-2	250	4.7	93	2.3×10^{12}	3.1×10^{31}
	850	1.7	34	2.5×10^{11}	1.3×10^{32}
FEL-3	500	4.0	80	1.0×10^{12}	1.1×10^{32}
	1000	1.5	31	1.9×10^{11}	1.6×10^{32}

TIME DEPENDENT SIMULATIONS

Time dependent Genesis 1.3 simulations have been performed to test the results of the steady state optimization and to provide information regarding spectral and temporal properties of the FEL output, including the effects of shot noise. Initially, an 'ideal' bunch is assumed. The electron bunch properties at the entrance to the FEL are estimated from electron tracking simulation results and are set in the simulation to be constant longitudinally along the bunch. In this way the influence of the growing SASE background on the properties of the output pulse can be analysed independently of any effects due to longitudinal variations in the electron bunch properties. Then the reults using the full tracked electron bunch provided by the NLS accelerator [2] are shown.

FEL-3 at 1000 eV: Ideal Bunch

The results of time-dependent simulations of FEL-3 operating at 1000 eV photon energy, using an 'ideal' electron bunch are shown in Fig. 5 approximately at the point where the seeded part of the bunch reaches saturation (18.7 m into the radiator). The time-bandwidth product is very close to transform limited ($\Delta\nu\Delta t = 0.5$) and there are no significant discontinuities in the radiation phase in the seeded region. The contrast ratio, defined here as the ratio between the peak power of the pulse and the average power of the surrounding SASE background, is approximately 50. The longitudinal profile of the FEL radiation power retains remnants of the SASE noise.

FEL-3 at 1000 eV: Tracked Bunch

Time-dependent simulations of FEL-3 at 1000 eV photon energy have been done using the tracked electron bunch [2] for two cases: with and without laser heating. Current profiles of the simulated part of the electron bunch are shown in Fig. 6. The results of time-dependent simulations for the case with no laser heater are shown in Fig. 7, 16.1 m into the radiator. It is seen that the current spikes due to microbunching of the electron beam translate into spikes in the longitudinal profile of the FEL pulse. Higher radiation power is attained in a shorter undulator distance compared to the ideal case, however the temporal and spectral properties of the output are significantly degraded. As a consequence of this, a laser heater was incorporated into the accelerator design [2] to provide smoothing of the current spikes. The results using the tracked electron bunch operating with a laser heater are shown in Fig. 8. It is seen that the radiation power profile and spectrum are significantly improved from the case with no laser heater. The time-bandwidth product is close to transform limited ($\Delta\nu\Delta t \simeq 1.0$) and the contrast ratio is approximately 40.

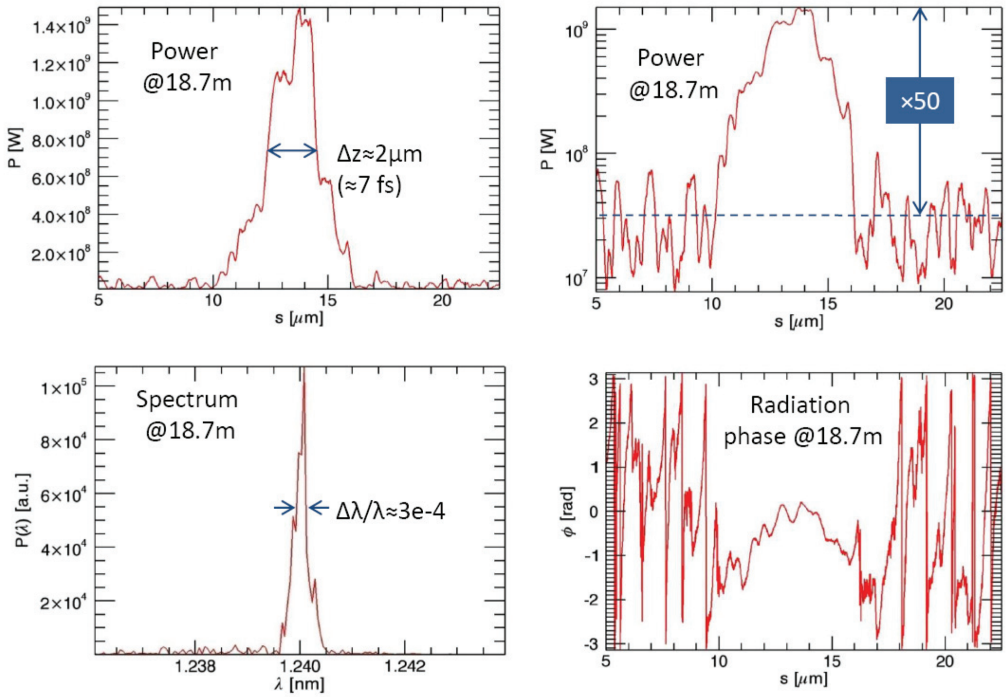

Figure 5: Genesis 1.3 simulation results of FEL-3 operating at 1000 eV, using the 'ideal' electron bunch. Top left shows the output pulse temporal profile, top right shows the pulse profile on a log scale to assess the contrast ratio, bottom left shows the pulse spectrum and bottom right shows the radiation phase. The contrast ratio is $\simeq$50 and time bandwith product $\Delta\nu\Delta t \simeq 0.5$.

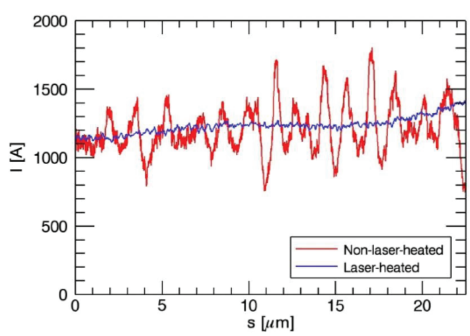

Figure 6: Current profile of the tracked electron bunch, with and without laser heating.

CONCLUSION

Designs for the three New Light Source project FELs have been produced and full start-to-end simulation results indicate that the FEL output will exhibit the good temporal coherence and sub 20 fs pulse lengths specified in the NLS Science Case. The decision has been made to seed the FELs with an HHG source, operarating at up to a photon energy of 100 eV, then upconvert this coherent seed to the required higher photon energies with one or two stages of harmonic generation within the FELs. The seed source is required to deliver up to 400 kW of peak power to the

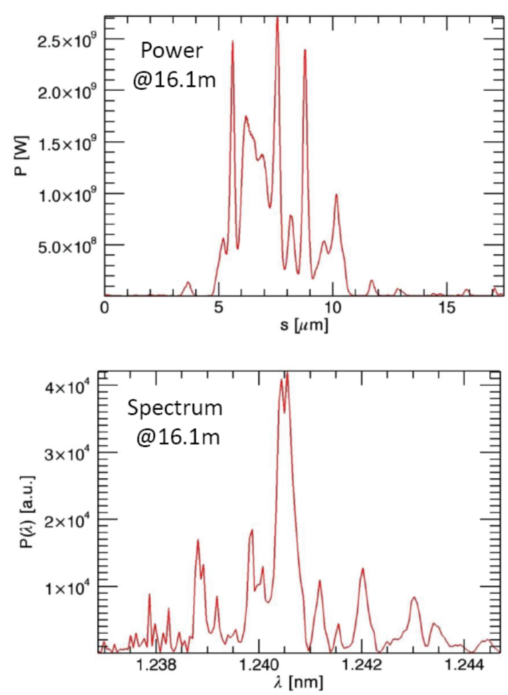

Figure 7: Genesis 1.3 simulation results of FEL-3 operating at 1000 eV, using the tracked electron bunch without a laser heater.

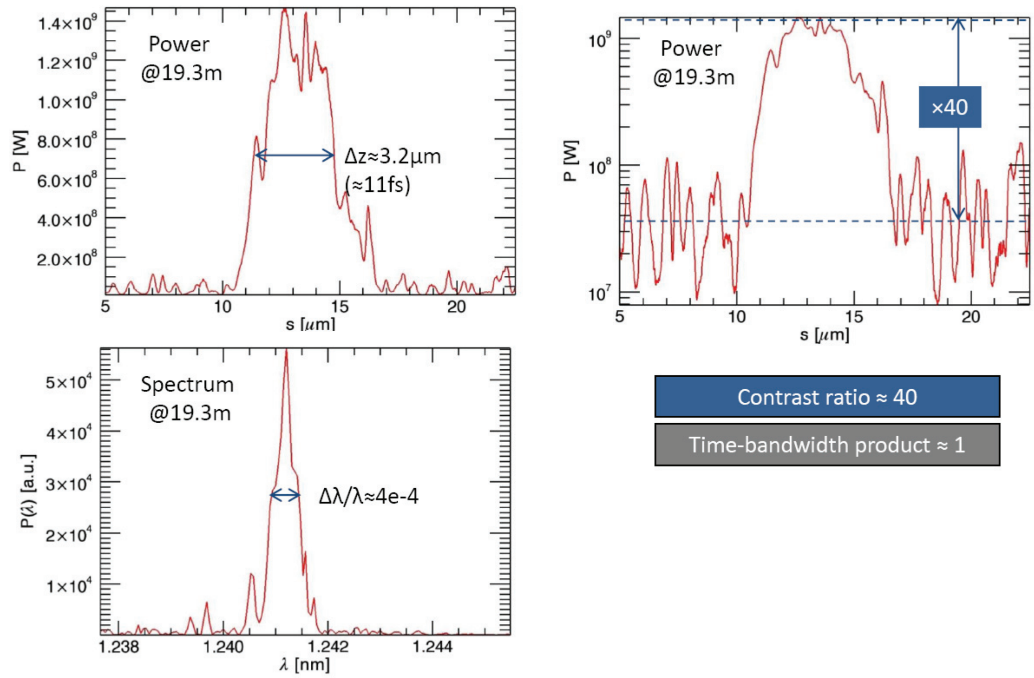

Figure 8: Genesis 1.3 simulation results of FEL-3 operating at 1000 eV, using the tracked electron bunch with a laser heater. Top left shows the output pulse temporal profile, top right shows the pulse profile on a log scale to assess the contrast ratio and bottom left shows the pulse spectrum. Compared to the results using the ideal bunch, the contrast ratio has decreased slightly to $\simeq$40 and time bandwith product has increased to $\Delta\nu\Delta t \simeq 1.0$.

FEL undulator—the current assessment of the NLS team, based on the rapid progress being made in this area, is that within the next $\sim$5 years it will be possible to deliver HHG pulses with this level of peak power, with 1 kHz repetition rate, tunable over the range 50–100 eV.

Ideas are currently under consideration for the improvement of the contrast ratio, such as tapering to match the energy drop in the seeded part of the electron bunch, or techniques for distinguishing between the narrow bandwith seeded radiation and the broader bandwidth SASE background, and will be reported on in the future. Additional time-dependent simulations at other wavelengths in FEL-1, FEL-2 and FEL-3 are also underway to extend the dataset of output pulse properties available to potential NLS users.

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