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OPTIMISATION OF AN HHG-SEEDED HARMONIC CASCADE FEL DESIGN FOR THE NLS PROJECT

D.J. Dunning and N.R. Thompson, ASTeC & CI, STFC Daresbury Laboratory, UK
B.W.J. McNeil, SUPA, University of Strathclyde, Scotland, UK
R. Bartolini, Diamond Light Source and John Adams Institute, University of Oxford, UK
Z. Huang and H. Geng, SLAC, Menlo Park, California, USA

Abstract

Optimisation studies of an HHG-seeded harmonic cascade FEL design for the UK's proposed New Light Source (NLS) facility [1] are presented. Three separate FELs are planned to meet the requirements for continuous coverage of the photon energy range 50-1000 eV with variable polarisation, 20 fs pulse widths and good temporal coherence. The design uses an HHG seed source tuneable from 50-100 eV to provide direct FEL seeding in this range, and one or two stage harmonic cascades to reach the higher photon energies. Studies have been carried out to optimise a harmonic cascade FEL operating at 1 keV; topics investigated include modulator configuration, seed power level and effects of the HHG seed structure. FEL simulations using realistic electron beam distributions are presented and tolerance to increased emittance has been considered.

INTRODUCTION

Three FELs have been proposed [2] to meet the requirements of the NLS science case [1], namely to provide continuous coverage of the photon energy range 50-1000 eV with variable polarisation, 20 fs pulse widths and good temporal coherence. The decision was made [1, 2] to seed the FELs with an HHG source, tuneable from 50-100 eV, with one or two stage harmonic casades to the required higher photon energies. Details of the undulator and gap choice and the consequent electron beam energy choice are given in [1, 3]. Details on the optimisation of the accelerator designs are given in [4, 5]. In this paper an optimisation study of the 430-1000 eV FEL ("FEL-3"), operating at its highest photon energy of 1 keV is presented. Presented elsewhere in these proceedings are an assessment of the performance of FEL-3 in the presence of realistic electron beam jitter sources and FEL intrinsic noise [6] and an assessment of polarization control using the crossed-planar undulator approach [7] applied to the FEL-3 design.

MODULATOR CONFIGURATION

Three alternative configurations considered for the modulator setup are shown schematically in Fig. 1. For each case the FEL performance was optimised through choice of modulator lengths, chicane strengths and beam matching, using the steady-state mode of Genesis 1.3 [8]. The results are given in Table 1.

Figure 1: Schematic of the three alternative modulator configurations considered for FEL-3.

Table 1: Comparison of FEL performance for the three modulator configurations, $|b_0|$ is the modulus of the bunching at the fundamental of the radiator and σ_γ is the energy spread (both at the entrance to the radiator).

Scheme	$\|b_0\|$	σ_γ	P_{sat} [GW]	L_{sat} [m]
(a)	0.059	2.21	2.07	21.5
(b)	0.050	2.31	1.74	23.0
(c)	0.060	1.65	2.48	20.0

Time-dependent simulations were carried out with a gaussian seed of peak power 400 kW and FWHM 20 fs, and the electron beam parameters were set to have no longitudinal variation. The results were found to match well with the steady-state and are shown in Fig. 2. Scheme (c), in which the second modulator length is twice that of the first modulator is found to give the best performance, with higher bunching and lower energy spread attained at the ra-

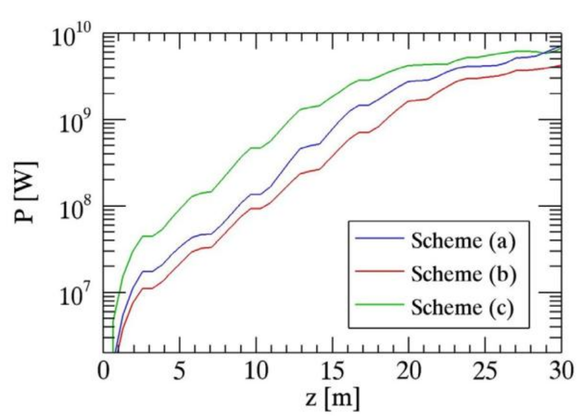

Figure 2: Radiation power as a function of distance through the radiator for time-dependent Genesis 1.3 simulations of the three modulator configurations

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diator entrance. The reason for this is thought to be that a higher degree of non-linearity in the beam is required in order to produce significant bunching at higher harmonic numbers. Since the first harmonic step is a factor of two, only a relatively short modulator-1 is required to give significant bunching, while a longer modulator-2 is needed to more effectively make the larger step to the fifth harmonic. Scheme (c) allows higher saturation power (P_{sat}) and shorter saturation distance (L_{sat}) and was hence selected for use in further optimisation studies.

START-TO-END SIMULATIONS

Time-dependent simulations were carried out for FEL-3 operating at 1 keV photon energy, using the tracked electron bunch of [4]. The results are shown in Fig. 3, at the point where the seeded part of the bunch reaches saturation (16.5 m into the radiator) - where the bandwidth of the radiation pulse is minimum.

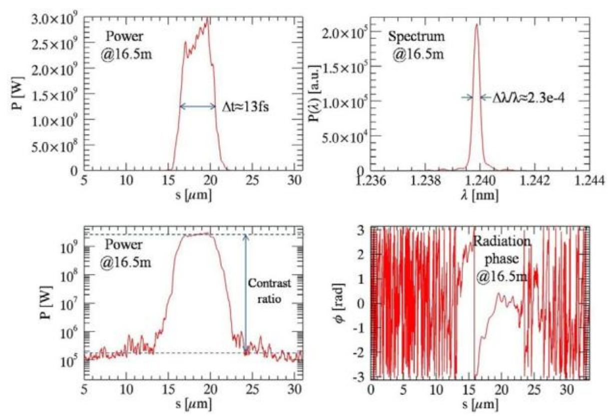

Figure 3: Start-to-end FEL simulation results for FEL-3 operating at 1 keV photon energy at saturation. Top left shows the longitudinal profile of the radiation power and top right shows the spectrum. Bottom left shows a log plot of the power profile to assess the contrast ratio and bottom right shows the radiation phase. The contrast ratio is ≈12500 and time bandwidth product $\Delta\nu\Delta t \approx 0.77$.

The longitudinal profile of the FEL radiation power shows improved smoothness and contrast ratio compared to previous simulation results [1, 2]. Several reasons for this have been identified, including the reduction of numerical noise in simulations, reduced energy spread of the electron bunch resulting from accelerator optimisation, and optimisation of the modulator configuration.

HHG FILTERING

It has been shown in simulations that the attosecond structure of an HHG seed washes out during amplification in an FEL amplifier [9], and that the FEL saturation distance is not significantly affected by filtering the seed to remove the structure [10]. Here the effect of the attosecond structure of the seed is assessed for the harmonic cascade scheme. Two cases were considered with different values of spectral filtering bandwidth being applied to the seed, as shown in Fig. 4. With the filter half-bandwidth set to

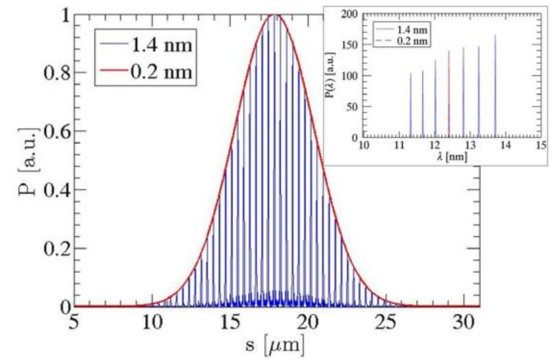

Figure 4: Normalised longitudinal profile, and spectrum (inset), of the input seed for the two cases of filtering.

0.2 nm only the resonant harmonic is retained such that the attosecond structure is fully removed, while at 1.4 nm, three harmonics either side of the resonant frequency are retained. The harmonics are assumed to be exactly phase-matched which is expected to be the worst case in terms of impact on FEL performance. Time-dependent simulations of FEL-3 operating at 1 keV were carried out for both cases, using the modulator configuration Scheme (c).

The evolution of the radiation profile with distance through the radiator and the bunching at the start of the radiator, are shown in Fig. 5 for both cases. The attosecond structure reduces through the modulators, however some

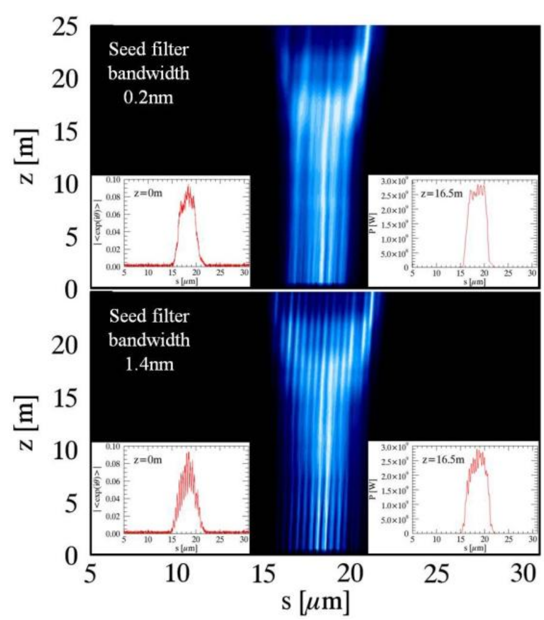

Figure 5: Evolution of the normalised longitudinal radiation profile with distance through the radiator. Also shown is the bunching at the start of the radiator (inset left), and radiation profile at saturation (inset right).

structure in the bunching remains at the start of the radiator, and is not entirely washed out during amplification. At saturation the radiation bandwidth is 0.025% for the 0.2 nm case, and 0.033% for the 1.4 nm case, indicating only a slight degradation in FEL performance. Further studies are required to assess whether the harmonic scheme can be optimised such that the attosecond structure is entirely washed out. In practice an unfiltered seed would have several advantages, allowing lower demands on seed power (since no losses through filtering), and avoiding increased complexity. The structure of the seed may also be reduced during transport to the undulator.

SEED POWER LEVEL

In the simulation results of Fig. 3, the temporal profile of the radiation output retains some noisy structure which is assumed to be a remnant of noise amplification in an harmonic system [11]. A study was carried out to determine whether the profile could be smoothed using a higher power seed. For direct seeding, this approach would be expected to have the desired effect, however in the proposed harmonic scheme the effect of a higher power seed on FEL performance is not obvious.

In [1, 2], criteria for the amplitude of the energy modulation applied to the beam in the modulators were used. The initial energy modulation generated, $\Delta\gamma$, must be greater than the natural RMS energy spread in the bunch σ_γ by a factor n, $\Delta\gamma > n\sigma_\gamma$, for there to be strong bunching up to the n^{th} harmonic of the seed laser wavelength. To radiate strongly in the radiator, the total energy spread due to the initial energy spread and imposed energy modulation must be small enough to satisfy: $\sigma_{\gamma,\mathrm{total}} = (\sigma_\gamma{}^2 + (\Delta\gamma/\sqrt{2})^2)^{\frac{1}{2}} < \rho\gamma$, where ρ is the fundamental FEL parameter [12]. In order to satisfy both conditions, the following criteria applies:

$$n\sigma_\gamma < \Delta\gamma < \sqrt{2(\rho^2\gamma^2 - \sigma_\gamma{}^2)} \qquad (1)$$

and is plotted in Fig. 6 as a function of harmonic number, assuming the nominal NLS electron bunch parameters. For FEL-3 where a step to the tenth harmonic is required, the range of appropriate energy modulation is $4 < \Delta\gamma < 6$, therefore an increase in seed power necessitates a reduction in modulator length. This has some advantages (less expensive undulator and less energy spread growth due to spontaneous emission) but it was found that even when increasing the seed power by a factor of 100 no improvement in pulse coherence or contrast ratio was obtained.

TOLERANCE STUDIES

The performance of FEL-3 at 1 keV was assessed assuming a larger normalised emittance of ε_n = 0.6 mm-mrad. The saturation power was found to reduce to 0.62 of its baseline value and the saturation length increased by a factor of 1.63, while the quality of the output pulse showed

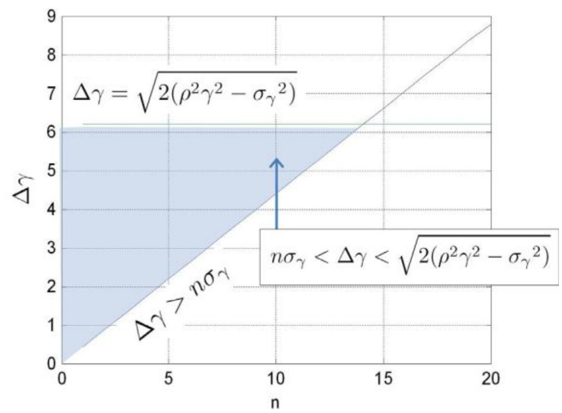

Figure 6: Energy modulation criteria for successful FEL operation, as a function of harmonic number.

the seeding scheme still to be effective. These relative changes are in extremely good agreement with the results of equivalent steady state simulations of the self-amplified spontaneous emission (SASE) power growth in the radiator only, for the two emittance values. The conclusion is made that the harmonic upconversion still works effectively at the higher emittance and the reduction in performance is only due to decreased FEL coupling in the radiator undulator.

Assessments of the tolerance of the FEL design to wakefields and seed/electron beam misalignment have been made and will be included in a future publication [13], together with results showing the properties of the radiation output at harmonics of the fundamental.

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