SHORT PULSE OPTIONS FOR THE UK'S NEW LIGHT SOURCE PROJECT

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Abstract

The New Light Source project aims to construct a suite of seeded free-electron lasers driven by a 2.25GeV cw super conducting linac. As part of the upgrade path, a number of options are being considered for generating ultra short (<1fs) soft x-ray pulses, with low-charge 'single-spike' operation and bunch slicing like approaches of particular interest, including as a possible extension to echo-enhanced harmonic generation. In this paper we present the status of this work, including recent results from fully start to end simulations.

INTRODUCTION

The production of coherent, soft x-ray radiation lasting 1fs or below is expected to have a transformative effect in many areas of science, with free-electron lasers (FELs) emerging as prime candidates for the generation of such pulses. The UK's New Light Source project (NLS) was initiated with the aim of meeting the needs of these science communities [1].

Several schemes have been proposed for generating short pulse radiation in high-gain FELs, the majority of which rely on either selectively manipulating the electron bunch distribution or the FEL pulse after saturation. These schemes can be summarised as emittance spoiling [2], laser slicing methods [3-8] or FEL pulse manipulation [9]. One further scheme relies on having an ultra-short electron bunch to pass through the FEL [10]. In this paper we present the application of two of these schemes to the NLS, namely the single spike operation [10] and energy-chirp with tapered undulators [7].

SINGLE SPIKE OPERATION

One method which does not rely on manipulating either the electron bunch or the FEL pulse is the so-called single-spike operation. In this scheme the electron bunch length L_e is tailored to satisfy the condition

$$L_e \le 2\pi L_c \qquad (1)$$

where the cooperation length (L_c) is defined as

$$L_c = \frac{\lambda_r}{4\pi\sqrt{3}\rho} \qquad (2)$$

and ρ is the Pierce parameter. In the case of the NLS this requires the electron bunch length to be below 1fs. If this condition can be met, the FEL output will consist of a single self-amplified spontaneous emission (SASE) radiation spike with good transverse and temporal coherence [11]. This level of bunch compression is best achieved at very low bunch charges (below 10pC), when the impacts of collective effects are much reduced and a very high beam quality can be maintained from the RF gun and transported through the linac to the entrance of the undulators.

The main benefits of this mode of operation are simplicity of implementation, the lack of background radiation pedestal and the high-degree of longitudinal coherence which are produced. However, since the FEL process is initiated by the SASE mechanism it suffers from large shot-to-shot fluctuations in the output power and the FEL output is not synchronised to an external laser, meaning any jitter in the arrival time of the electron beam will be transferred directly to timing jitter in the FEL output (typically 10-15fs rms). One further drawback with this mode of operation is that machine diagnostics are very difficult to operate at such low bunch charges.

Simulation Results

The performance of the scheme has been studied with start-to-end simulations using a combination of ASTRA [12], Elegant [13] and Genesis [14]. The gun, linac and FEL models used were as described in [15], with the exception that the gun charge was reduced to 2pC and the linac working point re-optimised using the maximum peak current and electron bunch FWHM as target parameters. Limits were placed on the maximum chicane magnet bend angles and accelerating cavity phases in order to keep timing jitter as low as possible and to minimise the final energy chirp on the electron bunch. The current profiles and longitudinal phase space distributions for the electron bunch at the entrance to the FEL are shown in figure 1. The compression in the main linac takes the electron bunch from a peak current of 0.55A and 3.8ps FWHM at the exit of the injector to a peak current of 1.9kA and 0.8fs FWHM at the undulator entrance.

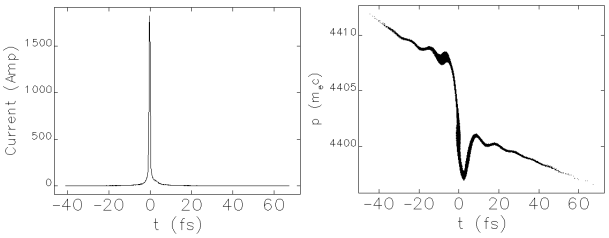

Figure 1: Current distribution and longitudinal phase space distribution at undulator entrance.

The x-ray pulse profile and spectrum at saturation calculated using time-dependent Genesis simulations are given in figure 2 below. Calculations were made using a single electron bunch distribution for 10 different shot-noise seeds. In all but 1 case, the radiation shows a clear single spike in both the temporal and spectral domains, with the FEL reaching saturation after 15.3m of active undulator length. The peak power at saturation for the 10 seeds was 2.3±1.1GW, the line width was 6.7±2.4pm and pulse duration was 0.45±0.07fs FWHM. The time-bandwidth product for the radiation pulses is 0.6±0.3 (compared to 0.44 for a Gaussian pulse), indicating excellent temporal coherence.

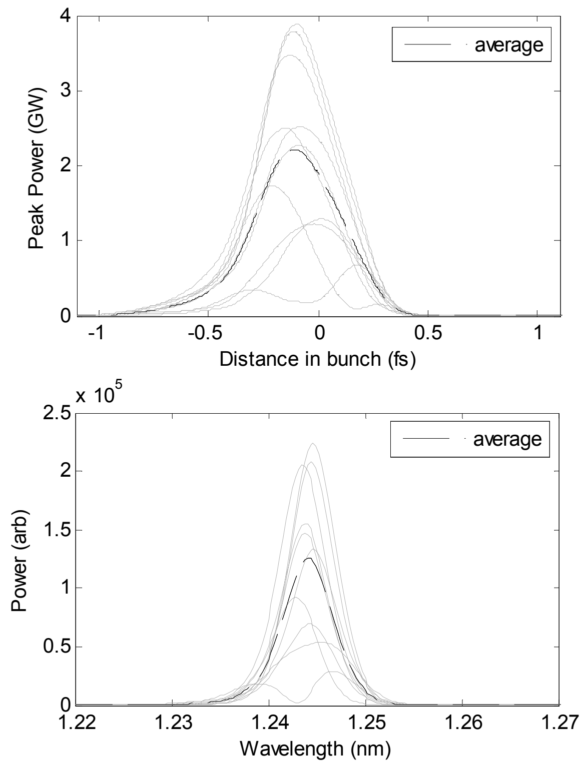

Figure 2: Power (top) and spectrum (bottom) at saturation for 10 different shot-noise seeds.

ENERGY-CHIRP WITH TAPERED UNDULATORS

The major drawbacks of the single spike operation are the lack of tight synchronisation control and the low-charge electron bunch. The slicing scheme proposed by Saldin et al. [7] avoids both these potential problems. The scheme is based around using a laser pulse consisting of only a few optical cycles to modulate the electron bunch energy at the laser wavelength, and by tapering the undulator gap to compensate the chirped region. Since only a small part of the electron bunch will have the required gradient of energy chirp to be matched to the undulator taper, only this section of the bunch will experience high gain. The remainder of the bunch will suffer from strong gain degradation, resulting in an excellent contrast ratio between the short pulse radiation and radiation background. In this method, the FEL radiation pulse is naturally synchronised to the modulating laser pulse.

The main components of the scheme are shown in figure 3 below.

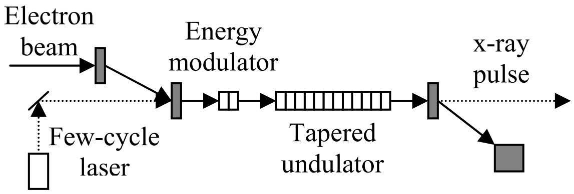

Figure 3: Main components of the short-pulse scheme.

The modulating laser is focussed in the centre of the short (two period) undulator resonant at the external laser wavelength. If this laser pulse is timed to coincide with the arrival of the electron bunch, the electrons in the centre of the bunch will be modulated in energy. By setting the phase of the laser to $\pi/2$ (sine mode), a large approximately linear energy chirp can be applied to a short section of the bunch lasting less than 1fs, as shown in figure 4.

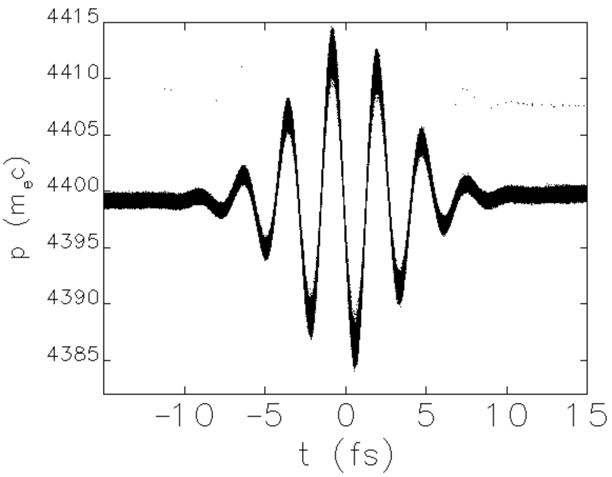

Figure 4: Energy modulation given to the electron bunch by the combined undulator – laser interaction.

Simulation Results

The electron bunch used as the basis for this investigation is the same as the one presented in [15]. An investigation into the optimum modulating laser parameters for this bunch concluded an 800nm, 5fs FWHM laser with 0.4mJ pulse energy should be used, with the optimum taper for the radiator undulator found to be 90% of the value found from the equations given in [7]. Plots showing the temporal profile and spectrum at saturation for 10 shot-noise seeds are given in figure 5. As for the single spike investigation, the same electron distribution was used for each seed.

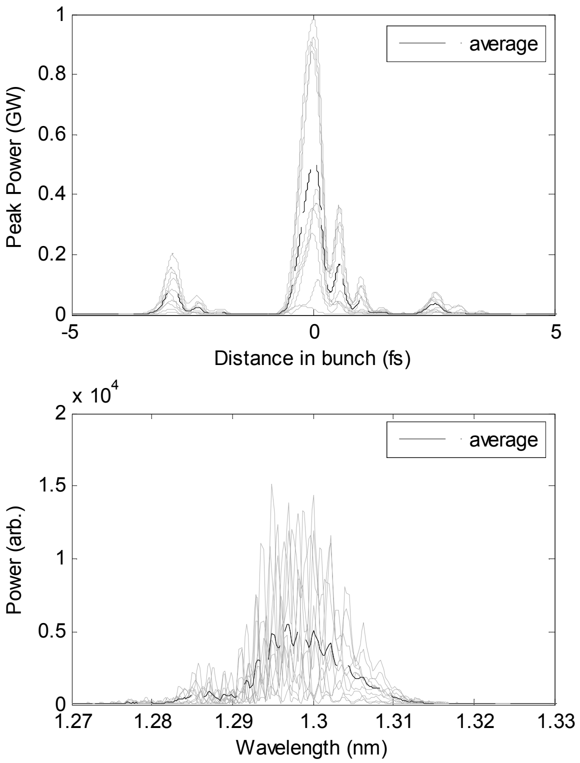

Figure 5: X-ray pulse power (top left) and spectrum (top right) at saturation for 10 different shot-noise seeds.

The radiation consists of a dominant central radiation spike, with two, smaller satellite spikes located at ±2.7fs with respect to the central peak. The satellite peaks are located at adjacent laser wavelengths from the central peak, and appear reduced in amplitude due to the lower gradient energy chirp at these locations which are not properly matched to the undulator taper. This temporal profile is characteristic of all results obtained using this scheme, with only the number of satellite peaks, relative amplitude with respect to the main peak and temporal separation found to vary with modulating laser parameters and undulator taper depth.

The radiation spectrum at saturation exhibits some fringing. This effect is due to interference between the radiation emitted by the main peak and that emitted by the satellite peaks, with the separation of the fringes given by

$$\Delta\lambda = \frac{\lambda^2}{\Delta t}\frac{1}{c}$$

where Δt is the time separation between central and satellite radiation peaks and λ is the FEL radiation wavelength. To remove these fringes from the spectrum, the modulating laser would need to consist of a true single cycle, or the amplitude of the satellite FEL radiation peaks would need to be negligibly small.

On average, 25.1m of active undulator length is required to reach saturation. Calculated over 100 shot-noise seeds the peak power at saturation is 0.6±0.4GW, the line width is 8.8±2.2pm the pulse duration is 0.45±0.12fs FWHM and the time-bandwidth product is 0.8±0.3. The contrast ratio is 11.6±11.3 for the satellite peaks and 870±542 compared to the background from the main bunch.

The modulating laser parameters used as the basis for these studies appears to be feasible with current technology [16-18]. However, as is evident in the temporal pulse profile at saturation this wavelength of laser is too short for the FEL to lase efficiently. The central radiation peak consists of a series of spikes with each growing in amplitude until saturation occurs. This is understood to be due to the length of the linear energy chirp given to the electron bunch by the modulating laser being shorter than 2π times the cooperation length of the FEL, and the FEL pulse slipping out of the taper-matched section of the bunch after each undulator module. A modulating laser wavelength of 1600nm would be required in order for the linear energy chirp given to the electron bunch to be well matched to the cooperation length of the FEL. However, studies have shown the x-ray radiation produced with this type of laser would have a larger FWHM and reduced contrast ratio to the background radiation for a given laser pulse energy.

CONCLUSIONS

We have investigated two complimentary short pulse generation schemes applied to a soft x-ray FEL. Both schemes are able to produce sub-fs, GW-level pulses with a high degree of longitudinal coherence. However, both schemes have potential drawbacks, namely the lack of tight synchronisation control for the single spike scheme and the existence of satellite peaks and background radiation pedestal for the energy-chirp with tapered undulator scheme.

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