LONG-SCALE MODULATION OF ELECTRON BEAM ENERGY IN FREE ELECTRON LASERS

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Abstract

The effects of pre-conditioned electron beams on free electron laser (FEL) behaviour are considered in simulations. Under consideration is modulation of the electron beam energy, using long-scale modulation period relative to the resonant FEL wavelength. Structure can be generated in the radiation field and electron beam with extent of significantly less than the FEL co-operation length, without applying spatio-temporal shifts between the radiation and electron beam [1].

INTRODUCTION

Numerous schemes have been proposed to generate short radiation pulses from an FEL amplifier (see e.g. [2, 3, 4] and references therein). Typically single pulses are generated with widths of the order of the coherence length $l_{coh} \approx l_c$, where $l_c = \lambda_r / 4\pi\rho$ is the co-operation length of the interaction [5]. A recent proposal [6], allows a single isolated pulse of significantly less than the coherence length to be generated through beam manipulation using the echo-enabled harmonic generation technique, but with lower peak power than typical FEL saturation level. In [1] a scheme (termed "mode-locked") was proposed to deliver a train of radiation pulses significantly shorter than l_c with peak power comparable to FEL saturation. In this scheme, the electron beam is periodically delayed relative to the radiation in a modular undulator-chicane system, and an energy modulation with period equal to the total slippage in one undulator-chicane module is applied to allow a train of equally spaced, short, high power pulses to develop.

In this paper, the role of such an energy modulation, with a long-scale period (relative to the resonant FEL wavelength) in an FEL amplifier (i.e. no delays) is assessed in simulations. A scheme has been devised to deliver radiation output with similar temporal properties to the mode-locked FEL scheme (i.e. a train of few-cycle radiation pulses), without the requirement for a bespoke undulator-chicane system but with reduced peak output power. Some limitations of the modelling method, and proposals for future development are discussed.

EFFECT OF ENERGY MODULATION

Simulations have been carried out to assess the effect of an energy modulated electron beam, with long-scale modulation period relative to the resonant FEL wavelength, on a SASE FEL. A resonant FEL wavelength of λ_r =1.24 nm was chosen for the simulations, and a modulation period of $\approx 30\lambda_r$ was used, since this is a typical value used in mode-locked FEL simulations. Undulator and electron beam parameters similar to those of the UK New Light Source design [7] were used, with more details given in the next section. The FEL code Genesis 1.3 [8] was used. For simplicity, the beam modulation step was not modelled; instead a sinusoidal energy variation was applied to the electron beam distribution. There was assumed to be no other longitudinal variation in electron beam parameters. The amplitude of the modulation was varied and the effect on FEL behaviour observed.

In Fig. 1, the maximum power in the simulated window is plotted against distance through the undulator, for several different values of the initial energy modulation amplitude (0.01 %, 0.05 %, 0.1 % and 0.5 %).

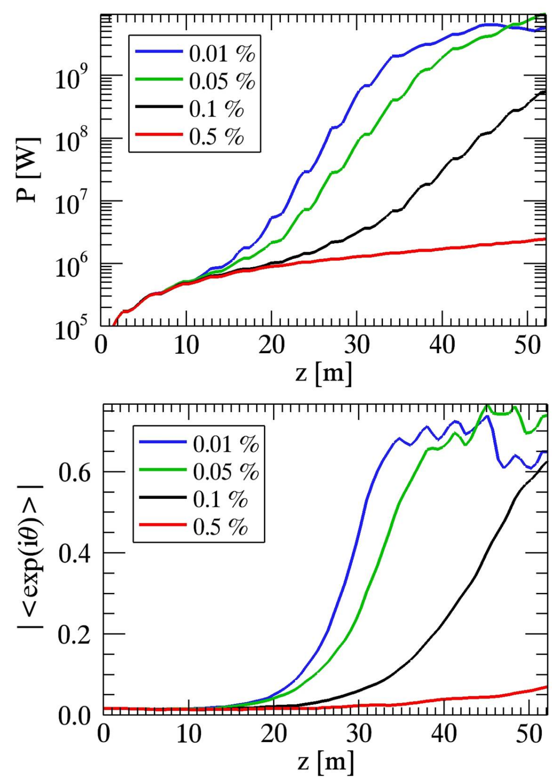

Figure 1: Maximum power (top) and maximum bunching (bottom) in the simulated window plotted against distance through the undulator, for different values of initial energy modulation amplitude.

For an energy modulation amplitude of 0.01 % the peak power and saturation distance are not significantly different to the case with no energy modulation. As the energy

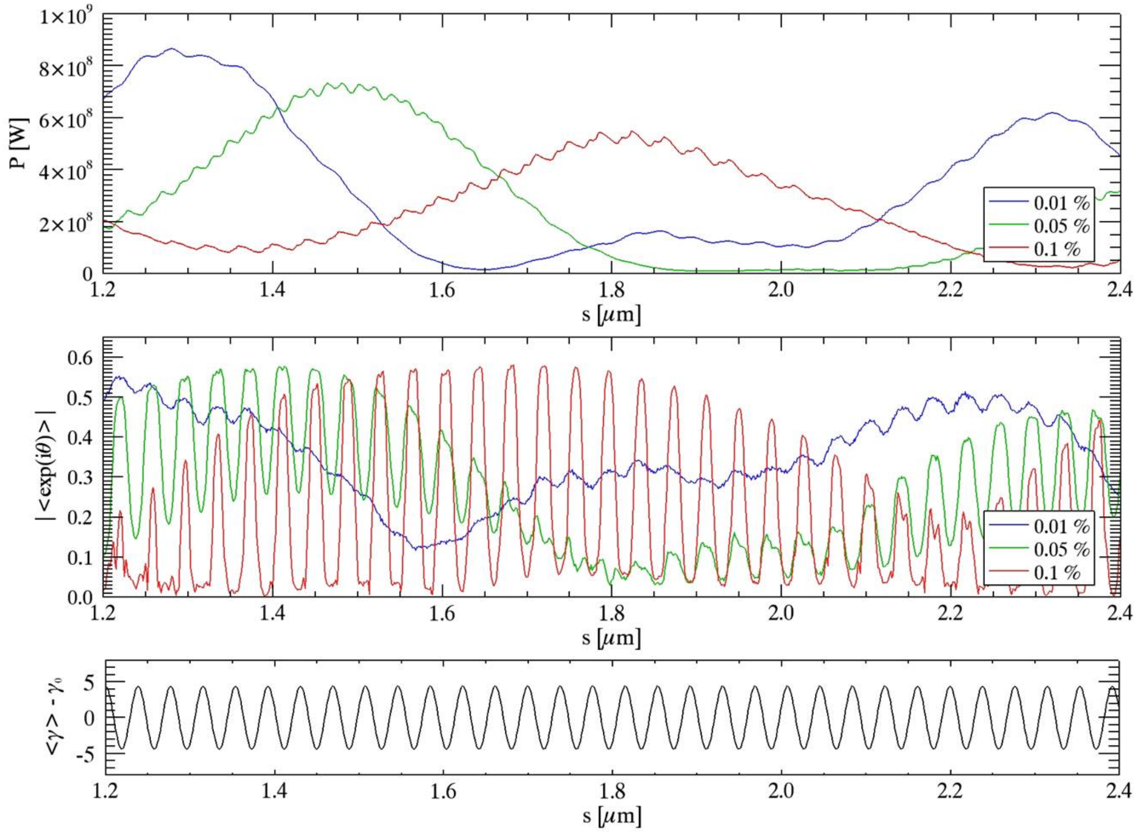

Figure 2: Longitudinal profile of the radiation power (top) and that of the electron beam bunching (middle) are shown for different values of the initial energy modulation amplitude. For each case the plotted data is near to FEL saturation. The beam energy at the entrance to the FEL is shown for the 0.1 % energy modulation case (below), to show the position of the bunching peaks relative to the modulation phase.

modulation amplitude is increased, the gain length of the FEL is increased. Also shown in Fig. 1, is the maximum of the bunching ($b = \langle e^{i\theta} \rangle$) in the simulated window plotted against distance through the undulator.

Figure 2 shows the longitudinal profile of the radiation power and that of the electron beam bunching for the different values of initial energy modulation amplitude. For each case the plotted data is near to FEL saturation (the 0.5 % energy modulation case is not shown since saturation was not reached in the simulated undulator distance). For an energy modulation of 0.1 %, there is significant pulse-train structure observed in the bunching profile. This structure is also evident to a lesser extent at 0.05 % energy modulation, and to a much lesser extent at 0.01 %. The peaks of the bunching profile occur at the positions of minimum electron beam energy. Detuning the central energy of the sinusoid has no effect on the position of the peaks, indicating that it is the energy gradient which determines the position of the peaks, rather than the absolute value of the energy. Also, previous work on the mode-locked FEL has shown that both the maximum and minimum energy positions of the sinusoid preferentially support the FEL interaction relative to the intervening regions. Further work is required to establish why the peaks at the minimum energy positions dominate here.

It is noted that since it is the variation in energy gradient that determines the bunching structure, the modulation period is also significant. The modulation amplitude optimisation carried out is therefore only applicable for a specific modulation period. Similarities to results in [2] have been noted, in which a tapered undulator is used to preferentially support a short region of electron beam with a specific energy chirp. Here, the strength of the FEL interaction is degraded in the regions of the beam with significant chirp.

The radiation profile does not exhibit a similar structure to the bunching profile, even when there is significant structure in the bunching profile. Instead the radiation profile characteristics are similar to typical SASE output with a relatively small undulation on the scale of the bunching structure. This is to be expected since the radiation slips forward relative to the electrons, so that any structure is washed out.

SHORT PULSE GENERATION

A scheme is proposed to utilise the bunching structure shown in the previous section to deliver radiation output

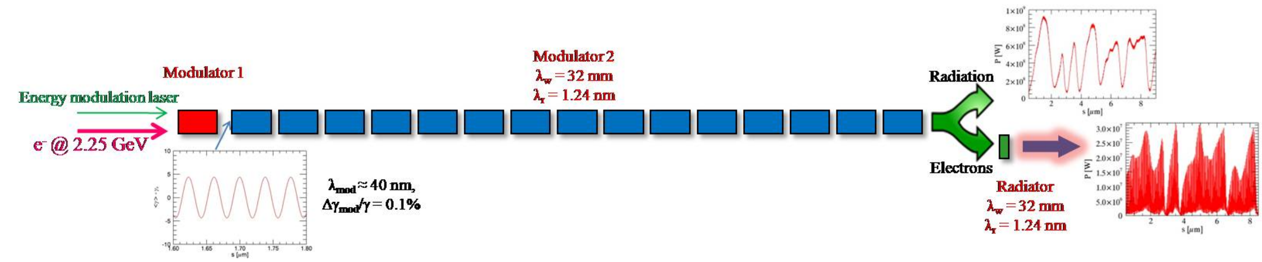

Figure 3: Schematic of the proposed scheme. A short modulator section (Modulator 1) is used to apply an energy modulation to the beam with long-scale period relative to the resonant FEL wavelength. This energy-modulated beam then enters a long undulator section (Modulator 2), in which the FEL interaction proceeds to near to saturation. A fine structure is generated in the bunching while the radiation temporal profile has only small ripples corresponding to this fine-structure since it slips across both the highly bunched and less bunched regions. The radiation and electrons are separated at this point and the electrons are passed through a very short undulator (10 periods) to emit radiation with fine structure corresponding to the bunching.

with similar temporal properties.

The layout of the proposed scheme is shown in Fig. 3, including details of the parameters used in simulations. A short modulator section (Modulator 1) is used to apply an energy modulation to the beam with long-scale period relative to the resonant FEL wavelength. This energy-modulated beam then enters a long undulator section (Modulator 2), in which the FEL interaction proceeds to near to saturation. As described in the previous section, a fine structure is generated in the bunching with peaks corresponding to the minimum energy gradient positions. However the radiation temporal profile has only small ripples corresponding to this fine-structure since it slips across both the highly bunched and less bunched regions. When the bunching is maximised (near saturation) the radiation and electrons are separated and the electrons are passed through a very short undulator (10 periods) to emit radiation with fine structure corresponding to the bunching. It is emphasised that no additional slippage (as applied in [1]) is required.

This method has some similarities to a recent proposal [6], in which an extension of the echo-enable harmonic generation method is used to manipulate an electron beam to generate significant bunching in a short region of the beam such that a single isolated pulse of significantly less than the coherence length (20 as FWHM at λ_r=1 nm) is generated upon passing through a short (12 period) undulator.

Simulations of the scheme shown in Fig. 3 have been carried out using a 0.1 % amplitude energy modulation. Bunching structure develops as shown in Fig. 2 with a maximum bunching factor of ≈ 0.6. In the radiator section a pulse train structure develops with $\sim$30 as FWHM radiation pulses at $\sim$30 MW peak power after 10 undulator periods. A short region of the radiation power profile and spectrum at this point are shown in Fig. 4. The spectrum shows several discrete frequencies. Figure 5 shows the radiation phase and power over a longer time window. The envelope of the pulse train shows fluctuations typical of SASE, with phase correlation between radiation pulses over a co-operation length.

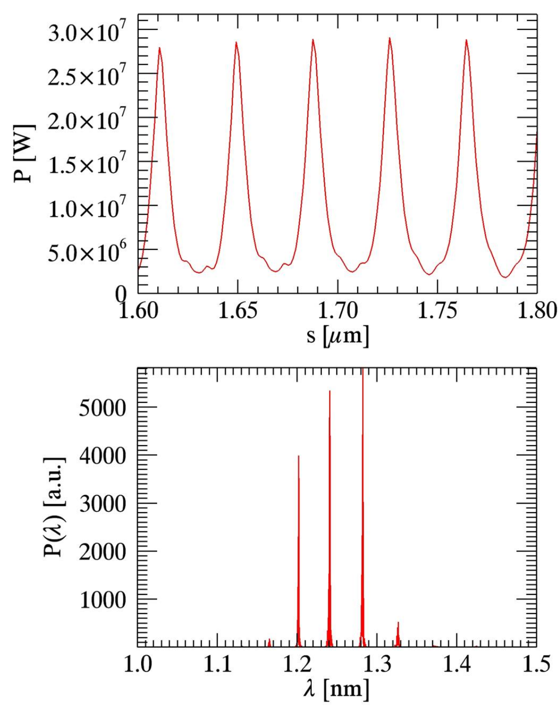

Figure 4: Radiation power profile and spectrum in the radiator after 10 undulator periods.

Only a basic optimisation has been carried out to demonstrate the principles of the scheme, and improved output would be expected with further optimisation, however peak powers are not expected to reach FEL saturation levels (as achieved in simulations of the mode-locked FEL scheme).

Future Work

This scheme could be a precursor to a full mode-locked FEL experiment, since it could be attempted on an existing

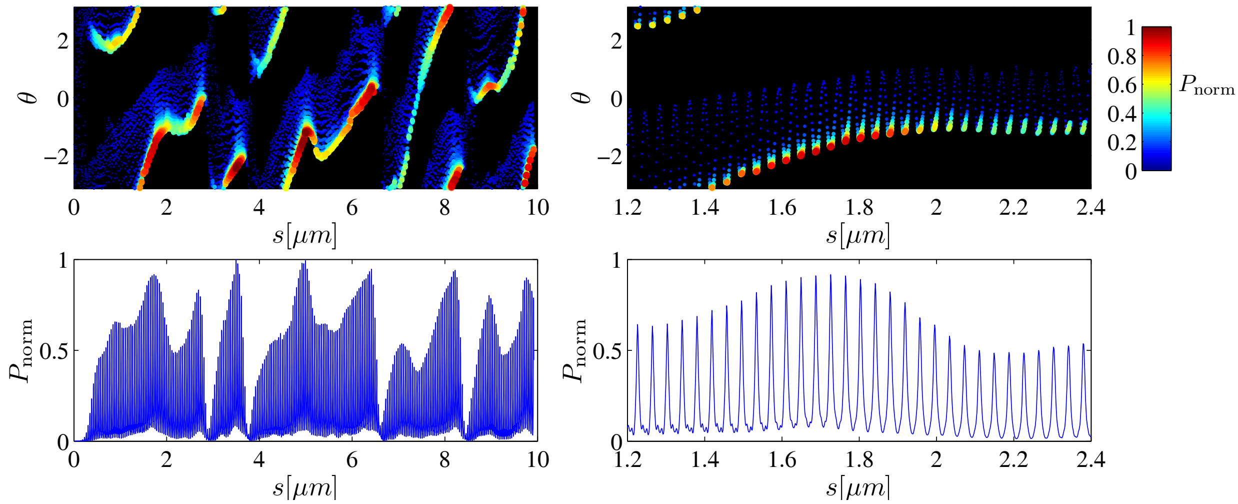

Figure 5: Radiation phase (with plot colour correlated to radiation intensity) and normalised power profile in the radiator after 10 undulator periods, for the simulated 30 fs time window (left), and zoomed to show a 4 fs region (right). The phase is continuous on the scale of a co-operation length.

machine without requiring the construction of a dedicated undulator-chicane system. It would allow principles related to the mode-locked FEL mechanism to be tested, engender the development of appropriate diagnostics and potentially test the utility of the pulse-train structure for experiments. The scheme could potentially be a useful source in its own right. As an additional benefit, the radiation pulse train would be naturally synchronised to the FEL radiation that is separated from the electrons before the final radiator

Further simulation work could investigate topics such as using seeding to control the envelope of the pulse train, harmonic up-conversion in the radiator, and modelling of the beam modulation step. A limitation of the simulation method used is that the long-scale energy modulation does not rotate in phase-space as shown in Fig. 6 since the particles are confined to their initial ponderomotive wells. In a real system, this effect could potentially affect the behaviour of the proposed scheme, hence investigation in a code such as [9] is suggested.

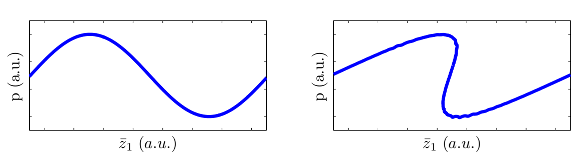

Figure 6: Energy modulation evolution in simulation codes. In the code used, electrons are confined to their initial buckets - density modulation (right) due to an initial sinusoidal modulation (left) is possible on the scale of the radiation wavelength but not on the longer scale of the modulation period.

CONCLUSIONS

The effect of an energy modulation with a long-scale period (relative to the resonant FEL wavelength) in an FEL amplifier has been assessed in simulations. For an optimised value of energy modulation amplitude, there is development of significant pulse-train structure in the bunching profile. A scheme has been devised to deliver radiation output with similar temporal properties to the mode-locked FEL scheme (i.e. a train of few-cycle radiation pulses), without the requirement for a bespoke undulator-chicane system but with reduced peak output power. Several interesting topics for future development of the scheme have been proposed, and limitations of the modelling method should be addressed in future work.

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