SHORT PULSE RADIATION FROM AN ENERGY-CHIRPED ELECTRON BUNCH IN A SOFT X-RAY FEL

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Abstract

The production of short pulse radiation of 1fs or below would open up many new areas of research. Saldin et al recently proposed a scheme to generate such pulses, in which a laser pulse consisting of only a few optical cycles is used to give a short energy chirp to the electron bunch and uses a tapered undulator to compensate the chirped region. In this paper we study the application of this scheme to a soft x-ray free electron laser, including the results of full start to end simulations and an assessment of the sensitivity to jitter.

INTRODUCTION

The use of a few-cycle laser beam to modulate either the energy or trajectory of an electron beam when passing through an undulator forms the basis for many of the short-pulse generation schemes that have been proposed for high-gain free-electron lasers (FEL) [1-8]. By using only a few optical cycles, the perturbation given to the electron beam is confined to a short section of the bunch (typically 5-10fs long). The radiation emitted from this part of the bunch has different characteristics to that emitted by the remainder (either in wavelength or trajectory), meaning that this section can be preferentially selected for amplification in the main radiator undulator.

Saldin et al. recently proposed a variation of this principle which combines the time-dependant energy modulation (chirp) with a tapered undulator [5]. In this paper they demonstrated that the effects on the FEL gain of an energy chirp along the electron bunch is equivalent to an undulator taper on an un-chirped electron bunch. By combining these two results it is clear that if one can be made to compensate the other, confining the energy-chirp to a short section of the bunch will result in efficient FEL gain in just this part and hence only a short FEL pulse will develop. The undulator taper will lead to strong gain degradation for the rest of the bunch, resulting in an excellent contrast ratio between the short radiation pulse and background pedestal. A beneficial side effect is that the modulating laser pulse can also be used as a natural synchronisation trigger for pump-probe experiments.

In this paper we study the application of this scheme to a soft x-ray free electron laser, taking the UK's New Light Source (NLS) facility as a practical example [9]. We investigate the variation in FEL output as a function of modulating laser parameters and undulator taper depth, present results of start to end simulations for the optimised set-up and provide an assessment of the sensitivity of the scheme to realistic jitter sources.

SIMULATION DETAILS

The main components of the scheme are shown in Fig. 1 below. These are a source of high-brightness, high energy electron bunches, a few-cycle carrier-envelope phase (CEP) stabilised laser, a short undulator to act as energy modulator and a long radiator undulator.

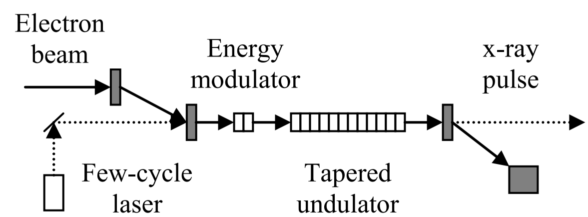

Figure 1: Main components of the tapered undulator scheme.

The electron bunch used for the simulations of the scheme is the same as the one optimised for standard NLS operation [9]. This electron bunch has an energy of 2.25GeV, a normalised slice emittance of 0.3mm.mrad and a slice energy spread of 160keV. The bunch charge is 0.2nC giving a peak current of 1120A, and is optimised to have constant slice parameters in a 50fs region of the bunch. This region of constant parameters is necessary in order to accommodate the anticipated timing jitter between electron bunch and modulating laser.

Studies of the scheme have been carried out using a combination of ASTRA [10], Elegant [11] and GENESIS [12]. A description of the injector and main linac can be found in [9]. The energy modulator consists of a two-period planar undulator with λ_m = 140mm and gap tuned to be resonant at the modulating laser wavelength. The main radiator modules are APPLE-II type undulators with λ_u = 32.2mm and are set to be resonant at 1keV photon energy. The radiator modules are interleaved in a FODO quadrupole lattice which provides the requisite transverse focussing.

The energy modulation given to the electron bunch by the combined laser-undulator interaction is calculated numerically in Elegant, in which the phase of the laser is set to $\pi/2$ in order to have maximum energy chirp at the centre of the modulated region. The resulting longitudinal phase space is shown in Fig. 2 for the case of an 800nm, 5fs FWHM, 0.4mJ laser pulse. The energy modulation has an approximately linear chirp at the centre of the bunch lasting less than 1fs.

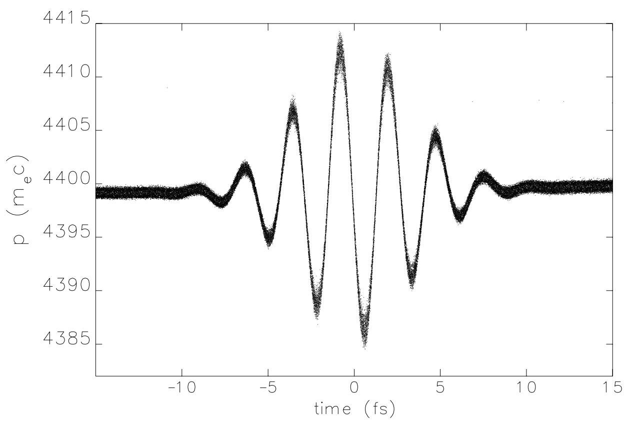

Figure 2: Longitudinal phase space of the electron beam after the energy modulator.

PERFORMANCE STUDIES

Parameter Selection

The general structure of the FEL output using this scheme is to have a short, single radiation spike at the centre of the FEL pulse with one or more satellite peaks on either side. The satellite peaks are located at points which are separated by the time period of the laser, but are reduced in amplitude due to the smaller gradient energy chirp and hence poorer match to the undulator taper. This structure can be altered within certain bounds by varying the modulating laser wavelength, duration and pulse energy along with the depth of undulator taper. In order to determine what the optimum set-up is, an empirical study was carried out investigating how each of these laser and undulator parameters affects the FEL output. The results of this study are summarised in Fig. 3.

Varying the laser wavelength was found to have the strongest influence on the final FEL output. For the scheme to work efficiently the length of the linear energy chirp should be well matched to the cooperation length of the FEL (i.e. about 1fs for the electron bunch investigated here). If it is too long then the FEL pulse will also be long, defeating the main goal of the scheme and potentially allowing more than one SASE radiation spike to develop. If it is too short then the FEL pulse will not develop properly, reducing the saturation power.

The main effect of altering the laser pulse duration is in changing the relative amplitude of the satellite peaks to the central one; the longer the laser pulse the larger the satellite peaks become. In the limit of a continuous modulating laser, a train of equi-spaced short radiation pulses will be produced.

The effect of altering the laser pulse energy appears to be more subtle. Increasing the energy leads to a larger energy chirp developing which in turn requires a stronger undulator taper to compensate. This then has the effect of improving the contrast ratio between the main peak and the background radiation (and also to the satellite peaks). The FEL pulse width is also marginally shortened and the line-width broadened. However, this comes at the expense of a decrease in saturation power.

From the results presented in [5] it is possible to calculate an 'exact' undulator taper in order to compensate for any given energy chirp. However, it was also noted that a mild positive energy chirp is actually beneficial to the SASE process, and that decreasing the taper depth can lead to higher power at saturation. The downside is that, by decreasing the taper depth, the match to the rest of the bunch is improved and so the contrast ratio is decreased.

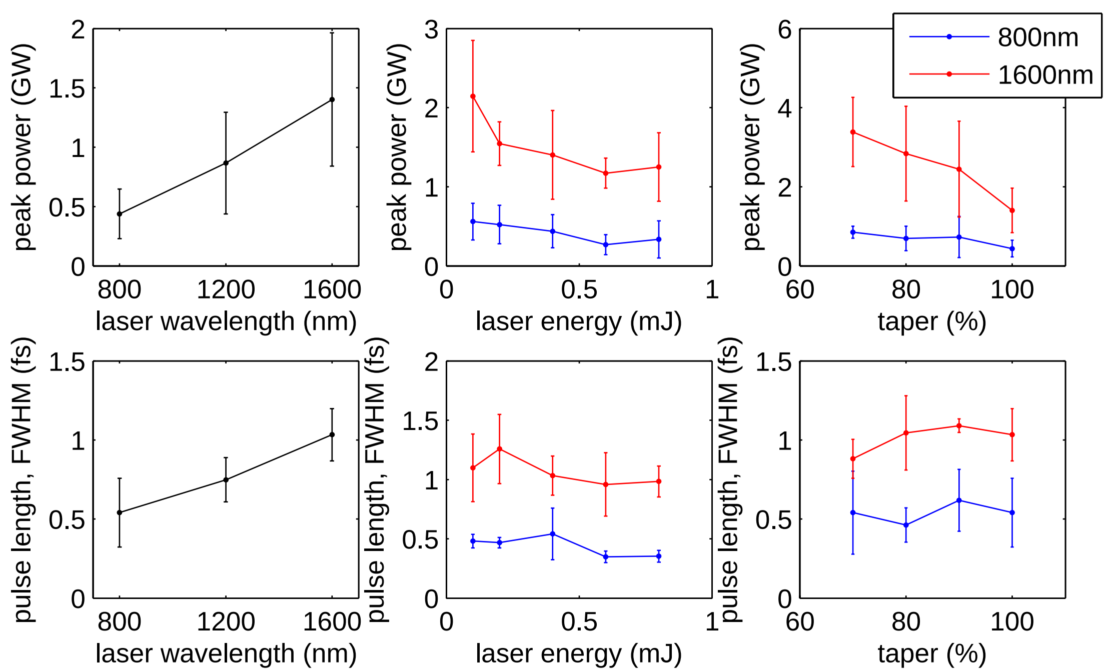

Figure 3: Summary of FEL pulse properties as a function of modulating laser parameters and undulator taper.

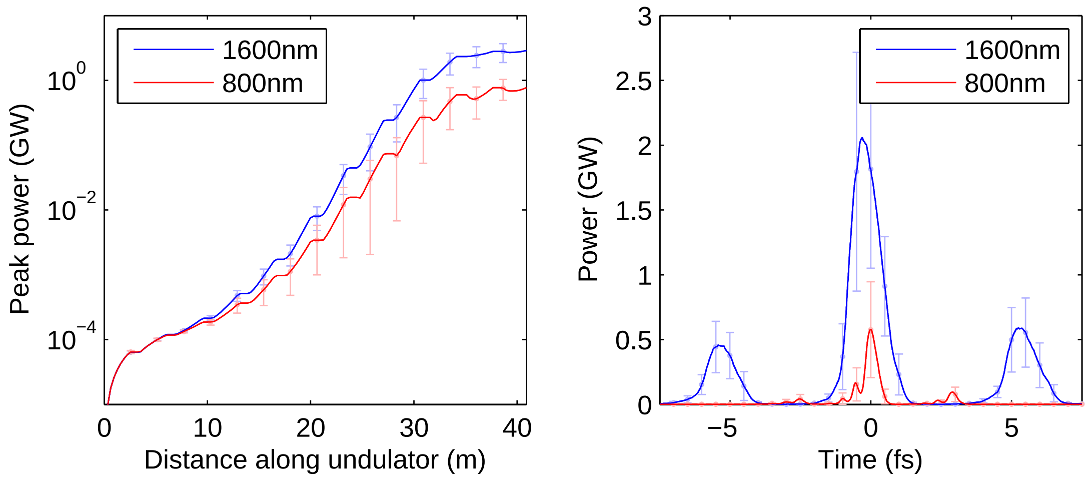

Figure 4: Peak power growth along the undulator (left) and power at saturation (right) for the 1600nm and 800nm modulating laser wavelength options. Values are calculated as averages over 100 shot-noise seeds.

Table 1: Summary of FEL pulse properties taken as averages over 100 shot-noise seeds

	1600nm laser	800nm laser	800nm laser + jitter sources
Peak power (GW)	2.31 ± 0.81	0.59 ± 0.36	0.66 ± 0.40
Pulse length, FWHM (fs)	1.07 ± 0.23	0.45 ± 0.12	0.52 ± 0.22
Linewidth (pm)	4.65 ± 1.74	8.8 ± 2.0	8.9 ± 2.5
Time-bandwidth product	0.96 ± 0.42	0.78 ± 0.31	0.91 ± 0.52
Radiation beamsize (μm)	38 ± 3	38 ± 5	44 ± 17
Arrival time jitter (fs)	0.23	0.06	0.11
Av. background power (MW)	7.5 ± 3.2	0.7 ± 0.1	1.9 ± 0.7

Performance of Optimised Set-up

The results of the parameter study identified two possible operating modes. The first solution is based around using a 1600nm, 10fs long laser pulse with 0.4mJ pulse energy. The second one uses an 800nm, 5fs laser pulse, again with a pulse energy of 0.4mJ. This second solution has the advantage that the laser is technically feasible with current technology [13-15], and produces FEL pulses with smaller FWHM on average. The laser pulse duration for the first option was selected in order to keep the relative bandwidth between the two lasers constant, and is assumed to be the minimum value that is practically achievable. In both cases, the optimum taper was judged to be 90% of the value found using the equations given in [5].

Shown in Fig. 4 is a comparison between the FEL outputs for the two options. Calculations were carried out based on a single start to end simulation for the electron bunch and averaging the FEL output over 100 different shot-noise seeds. Pulse properties are summarised in Table 1. On average, saturation is found to occur after 34.4m which corresponds to 25.1m of active undulator length.

From these results the benefits of using a longer modulating laser wavelength are clear; there is a four-fold increase in saturation power, which comes at the expense of an increase in FEL pulse duration. This increase in power is due to the 1600nm laser having a better match to the FEL cooperation length than the 800nm laser.

The temporal profile and spectrum at saturation for a single shot-noise seed using the 800nm option is shown in Figs. 5 and 6. The temporal profile shows that in this case, rather than consisting of a single spike, the central radiation peak is in fact a series of spikes. Each of these spikes is predominantly the emission from a short region of the electron pulse within a single undulator module and the spikes are therefore separated in time by the slippage that occurs between each module.

For both cases, the radiation spectrum shifts in wavelength due to the stepped taper; the larger the taper the further the wavelength shift [6]. Some fringing is also evident in the spectrum at saturation. This 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.

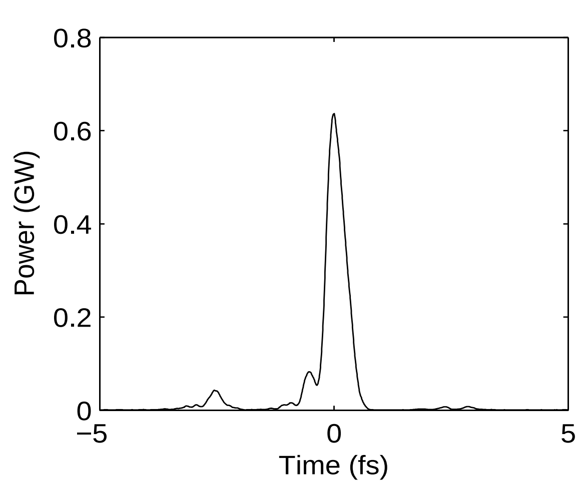

Figure 5: Typical temporal profile at saturation for the 800nm option.

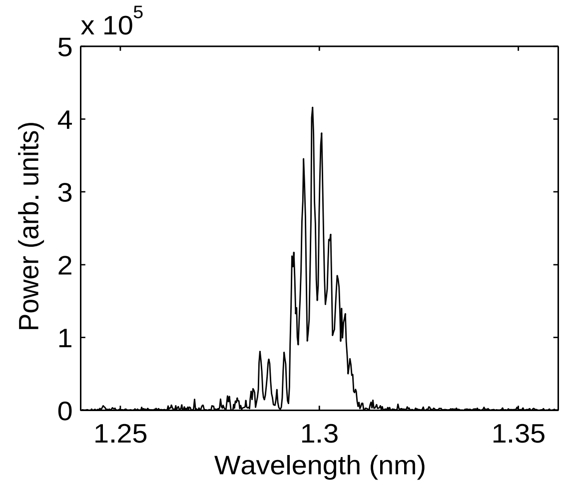

Figure 6: Typical spectrum at saturation for the 800nm option.

SENSITIVITY TO JITTER

On top of the intrinsic variation in FEL output due to the SASE process, the final radiation pulse properties are expected to suffer from shot-to-shot fluctuations in electron gun, linac and modulating laser parameters. This has been studied using 100 different start to end simulations for the 800nm modulating laser option, in each case applying Gaussian-distributed realistic errors to each component. In this study, the bunch compressor dipoles were assumed to be powered in series, and each RF cavity was modelled as being powered independently. The error distributions are listed in Table 2, and the resulting FEL pulse properties are summarised in Table 1.

The results of the jitter studies show that, whilst there is a small degradation in the majority of FEL pulse parameters, the power at saturation is largely unaffected by the introduction of realistic jitter sources and it is the shot-noise in the electron distribution that still dominates.

Table 2: Jitter sources included in the start to end tracking simulations (r.m.s. values)

Source	Value
Solenoid field	0.01%
Gun phase	0.1°
Gun voltage	0.1%
Charge	1%
Gun laser spot offset	0.025mm
Linac cavity phase	0.01°
Linac cavity relative voltage	10^{-4}
3rd harmonic cavity phase	0.03°
3rd harmonic cavity relative voltage	3×10^{-4}
Bunch compressor power supply	10^{-5}
Modulating laser phase	0.2rad

CONCLUSIONS

We have presented the results of start to end simulations for the tapered undulator short pulse generation scheme as applied to a soft x-ray FEL. A parameter study has highlighted the potential benefits (and drawbacks) of using a 1600nm laser compared to the commercially available Ti:Sa 800nm laser, and demonstrated the scheme is sufficiently robust to cope with realistic jitter sources. The use of an undulator taper helps to reduce the amplitude of background radiation pedestal compared to other schemes, and the scheme can be implemented with minimal hardware upgrades.

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