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TAPER-ENHANCED HIGH-BRIGHTNESS SASE FOR STABLE TEMPORALLY COHERENT HXR FEL PULSES

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Abstract

High-Brightness Self-Amplified Spontaneous Emission (HB-SASE) is a proposed method for improving the temporal coherence of SASE FEL pulses using magnetic electron beam delay chicanes along the undulator. Isochronous chicanes, which include high-strength quadrupoles, could deliver the greatest improvement in temporal coherence but it is more convenient if the delay chicanes comprise only dipoles. This paper presents a simulation study of a FEL operating at 25 keV, driven by a low charge electron bunch, in which HB-SASE is implemented with dipole-only chicanes to generate temporally coherent FEL pulses. Post-saturation tapering of the undulator field is used to further amplify the FEL pulse while maintaining its temporal coherence. The scheme is predicted to produce coherent, mJ pulse energy FEL pulses with few-femtosecond duration and excellent shot-to-shot stability of wavelength, pulse energy and pulse profile—as such it is a candidate for implementation on a future UK-XFEL.

INTRODUCTION

Next generation XFELs will likely be defined by their ability to produce X-ray pulses of the highest quality at high repetition rates. For example, the Science Case for an XFEL in the UK identified a need for temporally coherent pulses at photon energies from 0.1-20 keV with pulse durations ranging from 1-100 fs and repetition rates up to 1 MHz [1]. A number of FEL techniques will be required to cover this large parameter space, from seeding and harmonic generation schemes such as Echo-Enabled Harmonic Generation [2] at the lower photon energies to self-seeding [3] and cavity based XFELs [4] at the higher photon energies. One technique being studied as a possible option is High-Brightness SASE (HB-SASE) [5]. This is an optics free technique that is thus applicable at any wavelength and repetition rate and is independent of any constraints due to material properties or thermal loadings. This paper presents a simulation study of HB-SASE operating at 25 keV, implemented using a low charge electron bunch and compact dipole-only delay chicanes in combination with post saturation tapering. The simulations predict fully coherent few-femtosecond output pulses with mJ-level pulse energies and good shot-to-shot stability.

HIGH-BRIGHTNESS SASE

To implement HB-SASE electron beam delay chicanes are inserted between the individual modules of a long undulator beamline. These delay chicanes have additional uses besides HB-SASE—for example they can be used to operate the FEL in an optical klystron mode, as demonstrated at SwissFEL, in which the gain length is reduced by up to 30 % [6]. In HB-SASE the purpose of the chicanes is to delay the electron bunches with respect to the co-propagating, exponentially growing, radiation pulses. The FEL coherence length is proportional to the rate of slippage between electrons and radiation, so by artificially increasing the slippage rate the longitudinal coherence of a SASE FEL pulse can be increased. The delay added by each chicane must be unique—this prohibits the build-up of axial modes (as required by the technique of Mode-Locking) which would otherwise cause a strong unwanted modulation in the temporal profile of the FEL pulse [5].

HB-SASE using isochronous chicanes, which necessarily include high-strength quadrupoles [7], promises to deliver the greatest improvement in coherence length over SASE with a potential 100-fold increase. However it is more practical if the delay chicanes comprise only dipoles because they can then be more compact and their alignment tolerances are less stringent. Unfortunately this limits the performance because to achieve long coherence lengths the delays must be large and the longitudinal dispersion, which is proportional to the delay, then completely smears out the FEL microbunching. In studies so far the coherence length increase of HB-SASE using dipole-only chicanes is approximately a factor of 15 [8]. Given that the intrinsic saturation length of SASE at 25 keV is about 0.3 fs, this implies temporally coherent pulses of duration 3-5 fs can be produced at this photon energy if the electron bunch duration is similarly short. The low charge of course limits the FEL saturation pulse energy, but because the HB-SASE FEL pulse at saturation has good temporal coherence tapering the undulator parameter is an effective method for further amplifying the pulse.

THE SIMULATED SYSTEM

In this study the bunch charge was set to 15 pC with a Gaussian profile of FWHM duration approximately 15 times the intrinsic SASE coherence length. The system was simulated in Genesis 1.3 (v4) [9]. The parameters are shown in Table 1. Initially the sequence of delays was optimised to maximise the coherence length $l_{\mathrm{coh}} = \int_{-\infty}^{+\infty} |g(\tau)|^2 d\tau$, where $g(\tau) = \langle E^*(s)E(s+\tau)\rangle / \langle E^*(s)E(s)\rangle$, with E the electric field, s the distance coordinate along the FEL pulse and τ the dummy integration variable. This was done by simulating multiple random delay sequences.

With the optimum delay sequence found, a taper was optimised to maximise the FEL pulse energy, with no constraint on total undulator length. The taper was set to be

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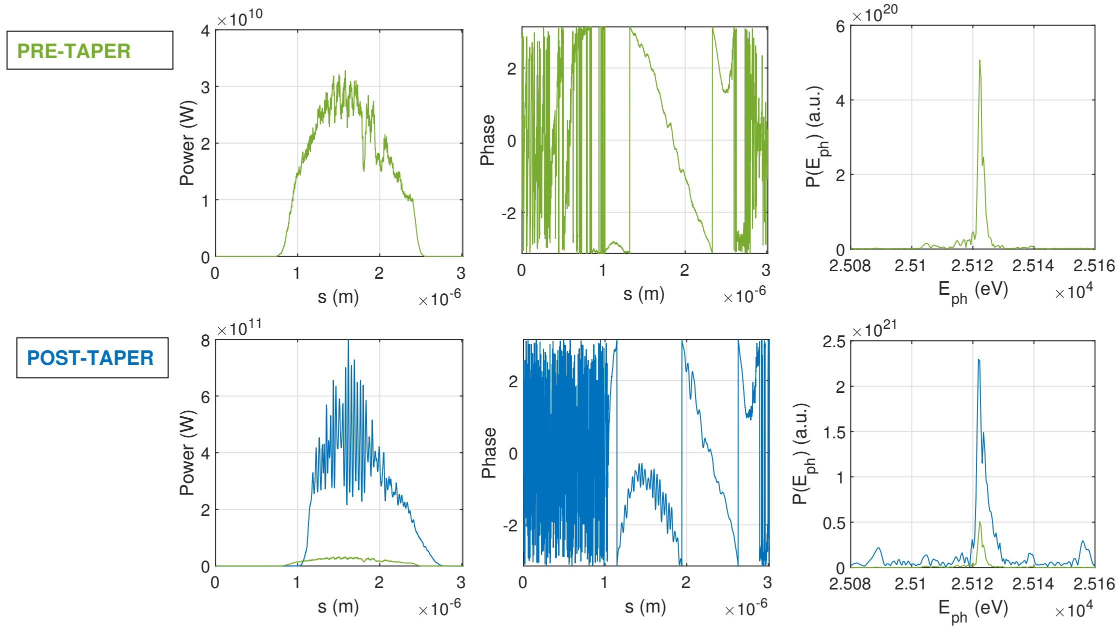

Figure 1: Top row: example of HB-SASE pulse profile (left), far field phase (centre) and spectrum (right) after the electron beam delays (pre-taper) at z = 35 m through the undulator. Bottom row: same, but at z = 140 m after the optimised taper, with the pre-taper pulse profile and spectrum also shown on the same scales in green.

quadratic initially and then linear, varying stepwise per undulator module. It was parameterised by a, the undulator module at which the quadratic taper begins, b, the undulator module at which the quadratic taper changes to a linear taper, and d, the total reduction in the undulator parameter a_w at the transition from quadratic to linear. In addition the gradient of the taper was set to be matched at the transition points a and b. This form of taper was chosen because past empirical studies have shown it to be more effective than either a pure quadratic or pure linear taper, and in fact the form is in agreement with the universal taper law of Ref. [10].

To compare the HB-SASE performance with SASE, the same taper optimisation process was carried for an equivalent SASE system i.e., all the parameters were identical except the delay chicanes were all set to have zero delay. With both HB-SASE and control SASE optimised, sets of simulations were done using different electron beam shot noise seeds to enable analysis of the shot-to-shot performances.

Table 1: System Parameters.

Electron Bunch	
Energy E	10 GeV
Bunch charge Q	15 pC
Peak current I	3 kA
Bunch duration σ_t	2 fs
Normalised emittance ε_n	0.14 mm–mrad
Undulator	
Type	Delta (circular mode)
Period λ_w	15 mm
Undulator parameter a_w	1.23
Resonant photon energy E_{ph}	25 keV

SIMULATION RESULTS

Figure 1 shows an example of HB-SASE pulses pre- and post-tapering, at $z = 35$m and $z = 140$m through the undulator respectively. Before the tapering begins the pulse peak power is 30 GW with a FWHM pulse duration of $\Delta t = 3.9$ fs and FWHM bandwidth $\Delta\lambda/\lambda_0 = 5.7 \times 10^{-5}$. The radiation phase is seen to evolve smoothly over the pulse. The corresponding time-bandwidth product $\Delta\nu\Delta t = (1/\lambda_0)(\Delta\lambda/\lambda_0)\Delta s$ is then found to be $\Delta\nu\Delta t = 1.35$, approximately 3 times that of a transform limited Gaussian pulse.

After the taper the pulse peak power has increased by a factor of 20 to approximately 600 GW. The pulse has shortened to $\Delta t = 2.6$ fs and the bandwidth increased to $\Delta\lambda/\lambda_0 = 2.8 \times 10^{-4}$ giving time-bandwidth product $\Delta\nu\Delta t = 4.35$. The radiation phase now evolves more rapidly through the pulse indicating a shorter coherence length which is calculated as $l_{coh} = 1.0$ fs. The spectrum shows sidebands that were not visible pre-taper. These are typical of strongly tapered systems and are attributable to the electrons performing synchrotron oscillations in the ponderomotive buckets [11]. In the temporal domain the sidebands are responsible for the fast modulations in the pulse profile. Future work will apply the alternative phase jump method

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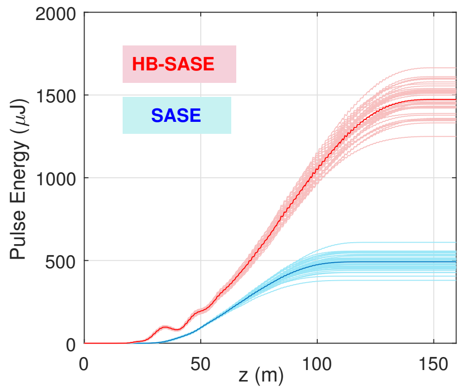

Figure 2: Pulse energy growth for HB-SASE and SASE control. The bold lines are the averages over the 100 individual noise realisations which are shown in the fainter colours.

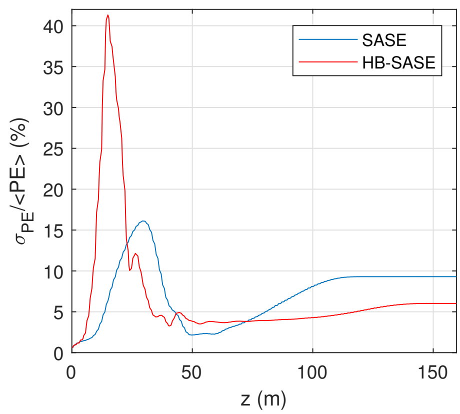

Figure 3: The rms variation in pulse energy, as a function of distance through the undulator.

for efficiency enhancement [12]—this has been shown to be effective at suppressing the sidebands so has the potential to smooth the pulse temporal profile, reduce the bandwidth and increase l_{coh}.

The performance of the tapered HB-SASE system and the optimised control SASE system is shown in Figs. 2, 3 and 4. Figure 2 shows the growth of pulse energy—the mean HB-SASE pulse energy is 1.5 mJ compared to 0.5 mJ for SASE. The rms variation in pulse energy, as a function of distance through the undulator, is shown in Fig. 3—at maximum pulse energy the HB-SASE pulse energy fluctuation is 6.0 % and for SASE it is 9.1 %. Figure 3 shows the spectra, both averaged and single shot. The FWHM width of the HB-SASE averaged spectra is 2.2×10^{-4} which is less than the width of a single shot spectra, indicating that the shot to shot wavelength stability is better than 0.02 %. Note that any fluctuation in this data is due only to electron beam shot noise and that in a real system fluctuations in electron beam energy, for example, will degrade this wavelength stability.

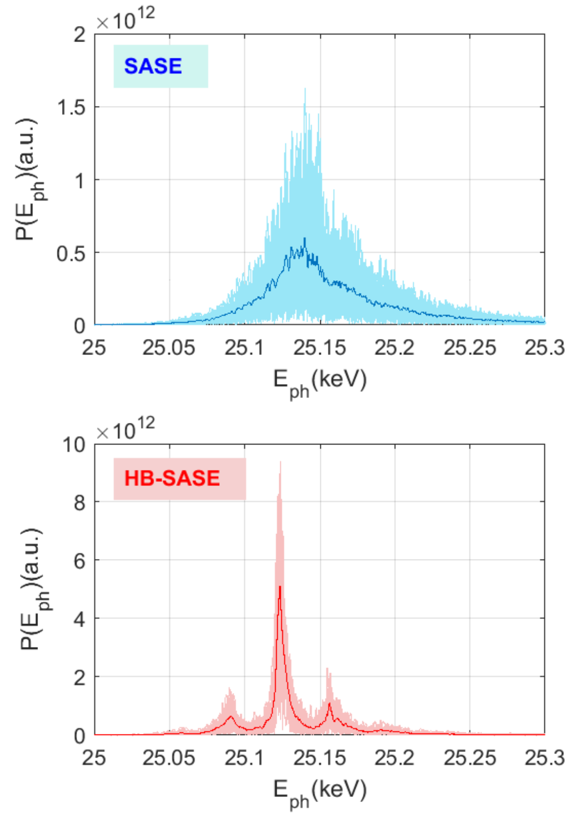

Figure 4: Averaged (bold) and single shot (faint) spectra.

CONCLUSION

A simulation study was done of a HB-SASE FEL operating at 25 keV photon energy and driven by a 15 pC 10 GeV electron bunch. The electron beam delay chicanes comprise only dipoles. Post saturation tapering was applied. The output pulses have FWHM duration 2.6 fs with peak power approximately 600 GW, pulse energy approximately 1.5 mJ and FWHM bandwidth $< 3 \times 10^{-4}$. The shot-to-shot stability of the pulse energy is 6 % rms and the full variation of the central photon energy is less than 0.02 %.

This mode of operation is being studied further for potential implementation on a future XFEL in the UK. One adaptation under study is a hybrid HB-SASE scheme where one or two of the dipole-only chicanes are replaced with less compact, but isochronous, chicanes which apply the longer delays. Work so far has indicated coherence lengths of up to 7 fs at 25 keV can be obtained. This would allow HB-SASE to cover a sub-section of the required output parameter space, but it is not considered feasible to generate 100 fs coherent pulses at the highest photon energies without the use of exclusively isochronous chicanes.

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