ELECTRON BEAM DELAYS FOR IMPROVED TEMPORAL COHERENCE AND SHORT PULSE GENERATION AT SWISSFEL

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Abstract

Proposals have been made for the introduction of magnetic electron beam delays in between the undulator modules of a long sectional FEL undulator - these can be used for the generation of trains of FEL pulses which can individually be shorter than the FEL cooperation time [1] or to greatly improve the temporal coherence of the FEL output compared to the nominal SASE configuration [2–4]. This paper comprises a feasibility study of the application of these techniques to a future SwissFEL hard X-Ray beamline. Three-dimensional simulations are used to investigate the potential photon output.

INTRODUCTION

SwissFEL, the X-ray free electron laser at the Paul Scherrer Institut, is currently under construction with planned operation from the end of 2016. The facility comprises a FEL named Aramis operating from 1–7Å and a second FEL named Athos operating from 7–70Å. Both FELs will operate in SASE and self-seeding modes. Space is reserved in the undulator hall for the future addition of a second hard X-ray FEL. In this paper we investigate the potential performance of two proposed novel FEL schemes, the Mode-Locked Amplifier FEL [1] and the High-Brightness SASE FEL [2–4] if implemented on this future beamline. The two schemes are considered together because they utilise common hardware.

The Mode-Locked Amplifier FEL

In the Mode-Locked Amplifier FEL electron beam delay chicanes are introduced between the modules of a long FEL undulator. By delaying the electrons, the emission from each undulator module is delayed with respect to the emission from the previous undulator module. If the undulator modules are relatively short, such that the electron bunch microstructure does not evolve much from one undulator module to the next, the total field builds up as a series of delayed, overlapped, fields of similar phase and amplitude leading to interference. In the frequency domain the field comprises a spectral comb centred on the resonant wavelength $\lambda_r = \lambda_w(1+\bar{a}_w^2)/2\gamma^2$ with an overall envelope given by the spontaneous emission spectrum of a single undulator module with FWHM bandwidth $\Delta\lambda/\lambda \approx 1/N_w$. Here λ_w is the undulator period, $\bar{a}_w$ is the rms undulator deflection parameter, γ is the electron relativistic factor and N_w is the number of periods in one undulator module. The wavelength spacing between the sideband modes is given by $\Delta\lambda = \lambda_r^2/s$ where $s = \delta + N_w\lambda_r$ is the total slippage between radiation and electrons in one combined undulator+delay module with δ the applied delay in the chicane and $N_w\lambda_r$ the slippage in one undulator module. The spectrum is equivalent to that of a laser ring cavity of length s—in effect a very short laser cavity has been synthesised via the use of the macroscopic electron beam delays. Viewed in the temporal domain the radiation intensity builds up into a sequence of non-identical spikes of separation s modulated by the normal SASE envelope, which due to the increased slippage itself becomes stretched temporally by the slippage enhancement factor $S_e = s/N_w\lambda_r$. The shape of the spikes evolves along the pulse because the radiation sideband modes are not phase locked. To lock the modes a technique analogous to that used in conventional lasers cavity is adopted—a modulation is added to the system with a frequency equal to the mode spacing, or equivalently a period of s. In the FEL this is done by adding a modulation of period s to the electron beam energy. In the time domain the FEL pulse is then seen to comprise a series of cleanly separated, similar radiation spikes where the length of each spike is approximately equal to the slippage $N_w\lambda_r$ in each undulator module.

The mode-locked amplifier FEL is thus a method for producing a train of separated ultrashort radiation pulses. In addition, because the bandwidth is inversely proportional to the module length when the modules are shorter than a gain length it is possible, by using very short undulators, to produce radiation output pulses with a bandwidth significantly broader than that of a SASE FEL.

The High Brightness SASE FEL

The High Brightness SASE (HB-SASE) FEL utilises the same hardware. The SASE radiation coherence length is artificially extended by using electron beam delays to increase the relative slippage between radiation and electrons. For equal delays s a modal structure is created in the radiation spectrum, as in the Mode-Locked FEL. In the time domain this gives a pulse strongly modulated with period s. It has been found that in this case the increase in radiation coherence length is limited. However, because the mode spacing depends on the delay s then by making all the delays different it can be arranged that the sideband modes are unique for every delay s_i so that there are no modes which are continually amplified. Only the central resonant mode reaches saturation, giving a narrow bandwidth pulse with a smooth temporal structure. For the simulations in this paper the delays are based on prime number sequences [4], but good results have been observed in other studies using delays which are random [2] or steadily increasing by a common factor [3]. Studies of the evolution of the radiation coherence length l_{coh} through the system show that it grows exponentially for a distance of several gain lengths through the undulator and at saturation, for both prime number and

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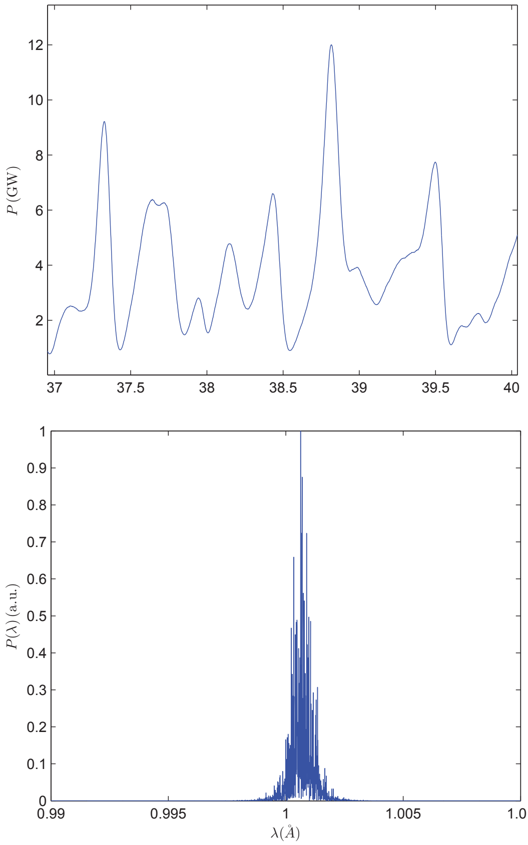

Figure 1: SASE control case for Long Pulse parameters. A 3 fs section of the radiation pulse and spectrum of the whole pulse are shown, at saturation which occurs at 37 m.

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random delays, $l_{\text{coh}} \approx 0.35S$ where $S = \sum s_i$ is the total slippage between radiation and electrons.

OUTLINE OF SIMULATION STUDIES

Both schemes were studied using version 3.0 of the 3D simulation code Genesis 1.3 [5] and the results compared with control simulations of standard SASE, the results of which are shown in Figure 1. The parameters were based on the nominal parameters for the SwissFEL accelerator operating in Long Pulse mode at a resonant wavelength of 0.1 nm, and are given in Table 1. The approach taken was to determine the minimum changes required to the standard lattice, as utilised in the Aramis beamline, in order for the two schemes to demonstrate effective performance. The nominal undulator length for Aramis is $N_w = 265$ periods—this was used as a starting point then the length reduced to 130 periods, then 65 periods. The intra-undulator gap length of 0.6 m was kept constant and the FODO quadrupole gradient also kept constant to maintain the same average β-function. For each undulator length the schemes were simulated with standard 4-dipole chicanes, in which the appropriate R_{56} term corresponding to the delay was calculated (and implemented via the `itram56` input parameter in Genesis 1.3), then also with ischochronous chicanes ($R_{56} = 0$). For the studies of Mode-Locking the full amplitude of the applied energy modulation $\Delta\gamma/\gamma$ was varied between 3.8×10^{-4} ($\simeq \rho$) to 14.8×10^{-4} ($\simeq 4\rho$), and slippage enhancement factors of $S_e = 3.0$ and $S_e = 6.0$ were used. For HB-SASE no energy modulation is required because the modes are suppressed and do not therefore require locking.

Table 1: Electron Beam and Undulator Parameters Used for Simulations

Parameter	**Value**
Beam Energy E	5.8 Gev
Peak Current I	3 kA
Normalised Emittance ε_n	0.3 mm-mrad
Energy Spread σ_γ/γ	6×10^{-5}
Undulator Period λ_w	15 mm
Undulator parameter $\bar{a}_w$	0.848

Results for Mode-Locking

It was found that for $N_w = 265$ it was not possible to produce a clean temporal or spectral structure, for any combination of energy modulation, slippage enhancement factor or chicane type. The best results for this undulator length (not shown) were for $R_{56} = 0$, $S_e = 6$ and $\Delta\gamma/\gamma = 3.8\times10^{-4}$ for which there was observed a strong regular modulation in the pulse profile and clear spectral modes, but neither the temporal spikes or modes were clearly separated.

However, far improved results were obtained for shorter undulator modules—-the cleanest pulse profiles and spectra results for the four permutations of $N_w = 130$, $N_w = 65$, $R_{56} = 0$ and $R_{56} \neq 0$ are shown in Figures 2-5. The caption for each plot gives the parameters and N_{mod} is the undulator module after which the results are shown. The ranges on the x-axes of these plots are the same as the SASE control case shown in Figure 1 to allow easy comparison with the SASE case. For $N_w = 130$ the FWHM duration of the temporal spikes is ≃70 as and this reduces to ≃30 as for $N_w = 65$. It is also seen that the full bandwidths of the mode-locked output are significantly broader than the SASE control—for SASE $(\Delta\lambda)_{\text{FULL}} \sim 0.003$ Å which approximately doubles for $N_w = 130$ to ∼ 0.007 Å and doubles again to ∼ 0.014 Å for $N_w = 65$. Comparison of the results using standard and isochronous chicanes shows that the spectra are less well defined for standard chicanes but that the temporal structures are comparable. It should also be noted that using standard chicanes the required number of undulator modules is nearly halved, due to the enhancement of the FEL bunching in the chicanes.

Results for HB-SASE

Summary results for HB-SASE are encapsulated in Figure 6 which shows, for $N_w = 265$, $N_w = 130$ and $N_w = 65$ the rms bandwidth, normalised to that of the SASE control, for $R_{56} = 0$ and $R_{56} \neq 0$, as a function of the slippage enhancement S_e. Also shown in the figure, for reference, is the reciprocal of the slippage enhancement factor S_e. Here S_e is defined slightly differently because each delay is dif-

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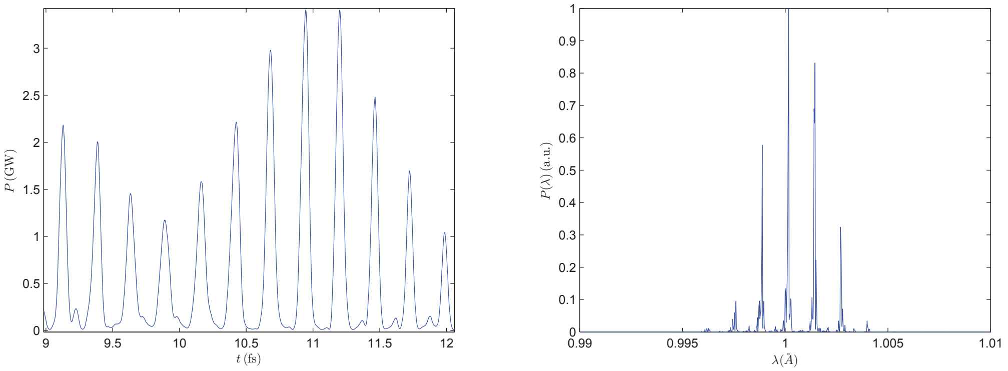

Figure 2: $N_w = 130$, $R_{56} = 0$, $\Delta\gamma/\gamma = 7.4 \times 10^{-4}$, $N_{\text{mod}} = 14$.

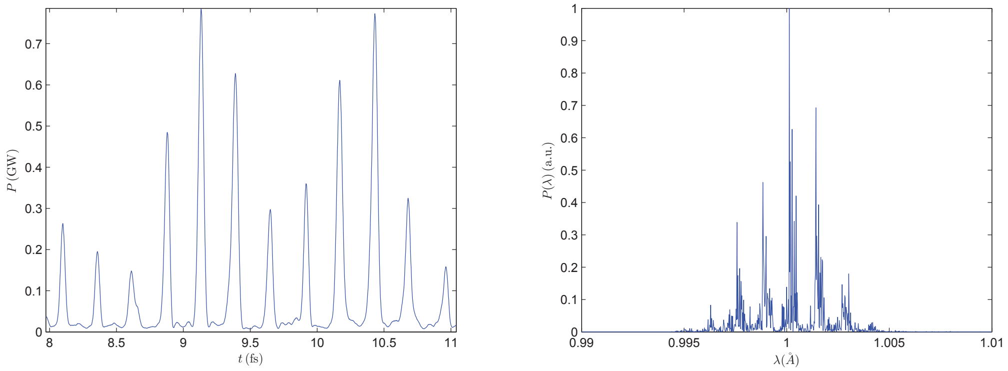

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Figure 3: $N_w = 130$, $R_{56} \neq 0$, $\Delta\gamma/\gamma = 3.8 \times 10^{-4}$, $N_{\text{mod}} = 8$.

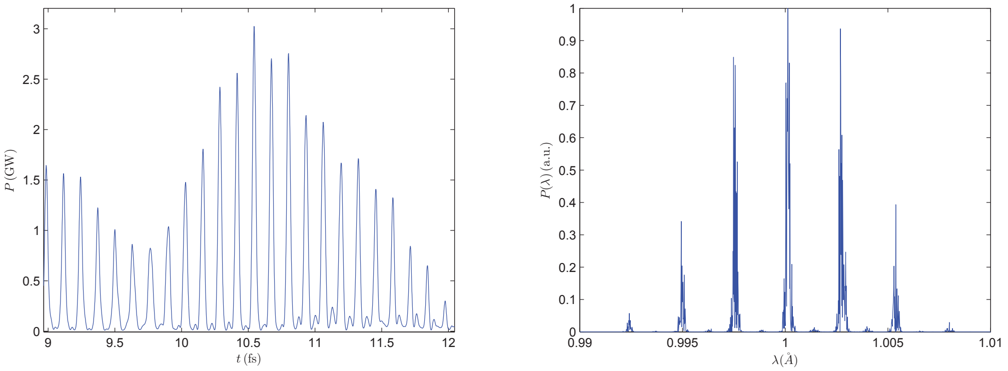

Figure 4: $N_w = 65$, $R_{56} = 0$, $\Delta\gamma/\gamma = 7.4 \times 10^{-4}$, $N_{\text{mod}} = 28$.

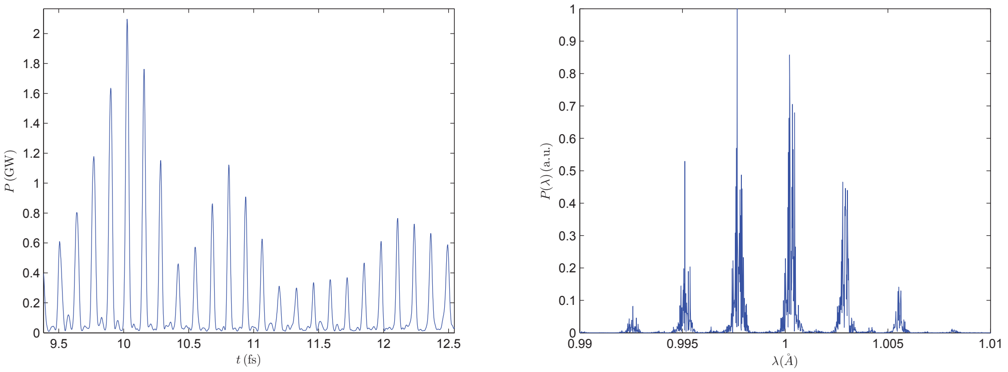

Figure 5: $N_w = 65$, $R_{56} \neq 0$, $\Delta\gamma/\gamma = 3.8 \times 10^{-4}$, $N_{\text{mod}} = 19$.

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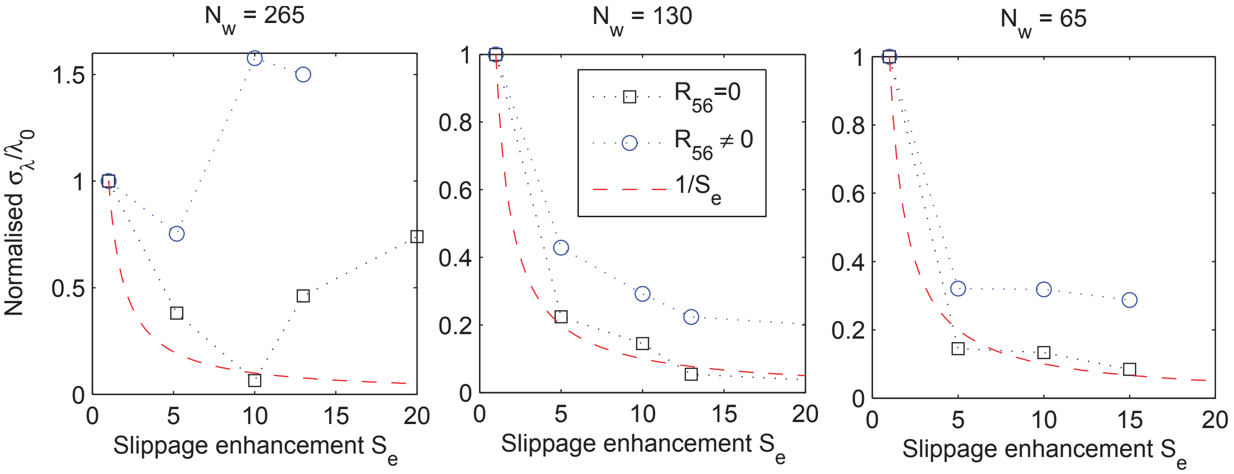

Figure 6: Summary of HB-SASE results, showing for $N_w = 265$, $N_w = 130$ and $N_w = 65$ the rms bandwidth, normalised to that of the SASE control, for $R_{56} = 0$ and $R_{56} \neq 0$, as a function of the slippage enhancement S_e.

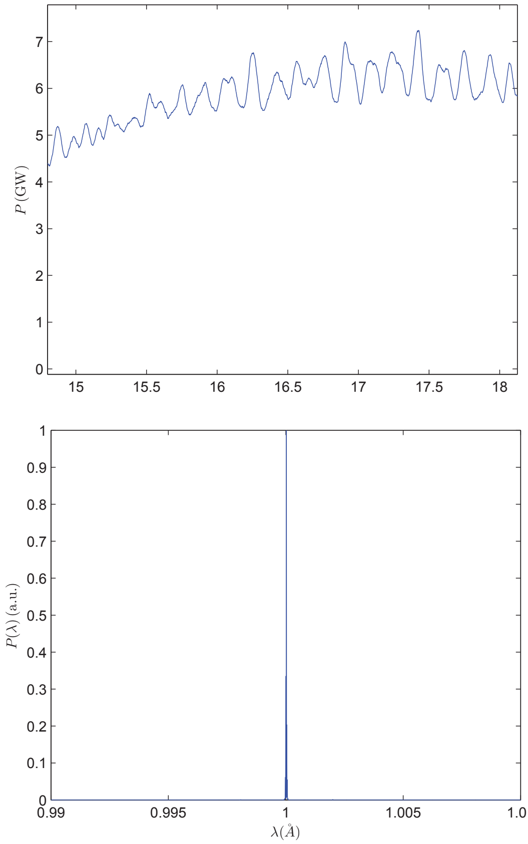

Figure 7: Example HB-SASE result, with $N_w = 130$, $S_e = 21$, $N_{\text{mod}} = 17$.

ferent, so $S_e = (\sum_{i=1}^{n} s_i)/nN_w\lambda_r$ is the total accumulated slippage divided by the total slippage within the undulator modules. The results show that for $N_w = 265$ the bandwidth, compared to SASE, can be reduced by a factor of 15 using isochronous chicanes, but no reduction is possible with standard chicanes. For the shorter undulator modules a bandwidth reduction of up to a factor of 5 can be achieved using standard chicanes, and a reduction of a factor of 30 can be achieved with isochronous chicanes. Further reduction may be possible for larger values of S_e. Comparison of the measured bandwidths with $1/S_e$ shows that for isochronous delays, and the shorter undulators, the bandwidth reduction is approximately proportional to S_e. Example output is shown in Figure 7 in which the axes scalings are the same as previously. The parameters for this example are $N_w = 130$, $S_e = 21$, $N_{\text{mod}} = 17$ and the rms bandwidth of the pulse is $\sigma_\lambda/\lambda_0 = 1.6 \times 10^{-5}$.

CONCLUSION

It was found that for Mode-Locking the undulator modules should have length shorter than $N_w = 130$ periods and the beam delays could be implemented as dipole only chicanes. To extend the output bandwidth further than the factor of four enhancement demonstrated here the undulator modules should be reduced to even shorter than $N_w = 65$. Future work will push this limit as far as possible to determine the broadest possible bandwidth.

For HB-SASE it was found that for $N_w = 265$ the bandwidth can be reduced by a factor of 10 using isochronous chicanes, but not at all with standard chicanes. Shorter undulator modules are required to see an effect using standard chicanes but for significant bandwidth reduction isochronous chicanes are needed. A factor of 30 reduction is already observed, which is sufficient to generate transform limited output for the 10pC mode of operation of the SwissFEL accelerator—first results for this option confirm this, but space restrictions in this paper do not permit them to be included. In future the HB-SASE work will be extended to higher slippage enhancement factors. It may also be possible to use delay sequences using mostly standard chicanes, but bring forward to earlier in the sequence some of the larger delays and implement these with special chicanes with an R_{56} of the *opposite sign* to cancel the R_{56} accumulated to that point. These delays would require more space and require the use of quadrupoles, so diffraction issues may be relevant, but this will be another interesting topic for future study.

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