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POSSIBLE METHOD FOR THE CONTROL OF SASE FLUCTUATIONS

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Abstract

It is well known that because the SASE FEL starts up from the intrinsic electron beam shot noise, there are corresponding fluctuations in the useful properties of the output pulses which restrict their usability for many applications. In this paper, we discuss a possible new method for controlling the level of fluctuations in the output pulses.

INTRODUCTION

The output of a Self-Amplified Spontaneous Emission (SASE) Free-Electron Laser [1, 2] exhibits fluctuations in the temporal and spectral domains [3] because the FEL interaction grows from an initial bunching b_0 due to the intrinsic random shot noise in the electron beam. The fluctuations can be problematic for FEL applications, although if the FEL pulse properties are recorded on a shot-by-shot basis the experimental output data can often be appropriately normalised as a mitigation strategy. This paper presents a first examination of a proposed new method for damping shot-to-shot instability. One or more dispersive chicanes are added in between the undulator modules of a SASE FEL. The longitudinal dispersion of the chicane can be set to change the amount of bunching in the electron beam in a way that is anti-correlated with the energy spread. Because the FEL-induced energy spread is itself directly correlated to the FEL power this allows a simple, passive mechanism for single pass feedback and stabilisation.

DESCRIPTION OF METHOD

Following previous work optical on klystron enhancement to SASE FELs [4] it is useful to take into account the analytical treatment originally derived for HGHG [5] to provide a simple model for the method. The bunching factor at the nth harmonic after the dispersive section in HGHG is given by

$$b_n = \left| \exp\left(-\frac{1}{2}n^2\sigma_b^2 k_r^2 R_{56}^2\right) J_n\left(n\frac{\Delta\gamma}{\gamma_0}k_r R_{56}\right)\right| \qquad (1)$$

where σ_b is the intrinsic relative energy spread, $k_r = 2\pi/\lambda_r$ is the resonant wavenumber, R_{56} is the dispersive strength of the chicane, J_n is the nth order of the Bessel function of the first kind and $\Delta\gamma$ is the energy modulation induced by the FEL prior to the chicane.

This function is plotted in Figure 1 for $\sigma_b = 1\times10^{-4}$, $\lambda_r = 2\pi/k_r = 100$ nm, $n = 1$, and $R_{56} = 60\,\mu$m. The important point to note is that there are values of $\Delta\gamma/\gamma_0$ where the gradient of this plot is negative—these are highlighted in blue. The method for SASE stabilisation takes advantage of this negative gradient to introduce a feedback into the

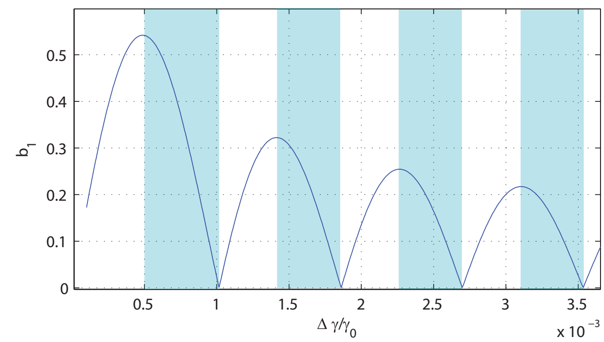

Figure 1: Plot b_n vs $\Delta\gamma/\gamma_0$ using Equation (1), for $\sigma_b = 1\times10^{-4}$, $\lambda_r = 2\pi/k_r = 100$ nm, $n = 1$, and $R_{56} = 60\,\mu$m. The blue shading highlights regions where the gradient of the function is negative.

FEL growth. For example, if at the entrance to the chicane the initial bunching is small and the average induced energy spread over a number of SASE pulses is in the blue shaded region where $0.5\times10^{-3} \le \Delta\gamma/\gamma_0 \le 1\times10^{-3}$, then those pulses which had grown more strongly than average would have an induced energy spread higher than the average and would therefore acquire bunching after the chicane that was lower than average. Conversely, those pulses growing more weakly than average would have their bunching enhanced more than average. Overall, all the pulses would have their bunching increased in the chicane, giving stronger growth, but crucially, the weaker pulses would be boosted *more* than the stronger pulses, hence damping the shot-to-shot variation.

NUMERICAL RESULTS

The method was simulated using the three-dimensional FEL code `Genesis 1.3`. Two of the 240 MeV electron beam modes for the CLARA test facility [6] were used: ULTRASHORT mode which is a low charge velocity bunched mode intended to produce electron bunches suitable for lasing at 100 nm in single spike SASE regime; SHORT mode which is the default 250 pC mode for 100 nm SASE with peak current 400 A. For both modes the energy spread was set to $\sigma_b = 1\times10^{-4}$ and the dispersive strengths of the chicanes were within the design ranges of the facility.

ULTRASHORT Mode

The parameters of the method were empirically optimised to obtain the best stabilisation performance. The results are shown in Figure 2, which shows the pulse energy growth for a control SASE case, with 8 different shot noise seeds, and the results with the same seeds where chicanes are applied

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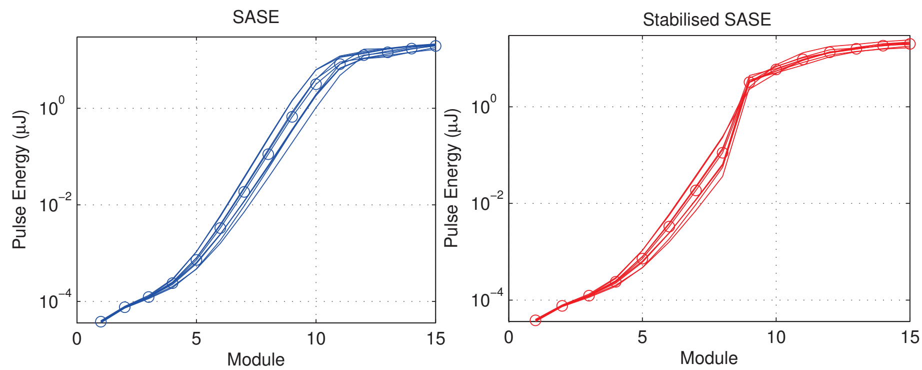

Figure 2: ULTRASHORT mode stabilisation. Top left shows the pulse energy growth for a control SASE case, with 8 different shot noise seeds. The circles mark the average. Top right shows the results where chicanes are applied before undulator modules 9, 10 and 11, with R_{56} values empirically optimised to 60 µm, 20 µm and 5 µm.

before undulator modules 9, 10 and 11, with R_{56} values 60 µm, 20 µm and 5 µm. It is seen that in undulator module 9 the variation in pulse energy over the different seeds is damped because the pulse energy plots clearly converge. After module 9 the RMS variation is reduced compared to SASE by a factor of 5.

Examination of the simulation data shows that at the entrance to undulator module 9, where the applied chicane dispersion is 60 µm, the average peak energy modulation in the electron bunch over the 8 seeds is $\Delta\gamma/\gamma_0 = 0.9 \times 10^{-3}$. From Figure 1 this means that the system is operating in the required region of negative gradient, in agreement with the simple theory.

SHORT Mode

In SHORT mode the output pulses are longer, each comprising on average 7 SASE spikes. In this case the stabilisation would be expected to work locally within the pulse, (i.e. reducing the variation in the peak powers over all the SASE spikes in each pulse) as well as over many pulses (reducing the variation in pulse energy from shot-to-shot).

Results are shown for an empirically optimised case, where chicanes are applied before undulator modules 6 to 11 inclusive, with R_{56} values 50 µm, 60 µm, 20 µm, 10 µm, 2 µm and 1 µm. This example was optimised to extend the stabilisation over as many modules as possible. In this case the number of random seeds was increased to 24 to reduce any statistical error. Figure 3 shows the RMS variation of the pulse energy over the 24 different seeds for the stabilised case, normalised to the SASE control case. The reduction in the RMS is a factor of 5 after 9 modules. It should be noted however that for the stabilised case the applied dispersion gives a reduction in the saturation length. For the SASE control, saturation (defined as the point where the radiation bandwidth and transverse size are minimised) occurs after 11 undulator modules. Here the average pulse energy is 80 µJ and the RMS variation over all seeds is 11.1%. For the stabilised case, an average pulse energy of 80 µJ is reached after only 9 undulator modules where the RMS variation is 4.6%. Therefore, if comparing output at the pulse energy

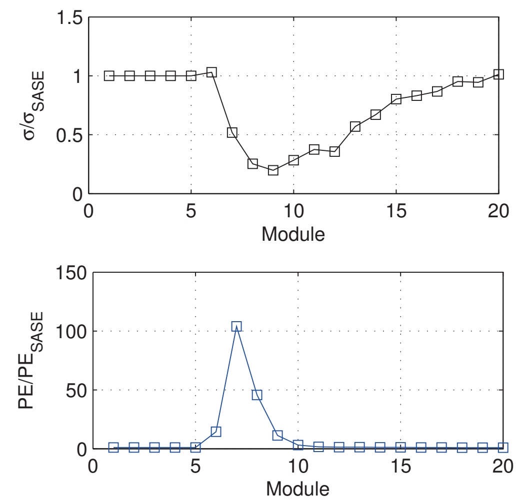

Figure 3: SHORT mode stabilisation. Top shows the RMS variation of the pulse energy over the 24 different seeds for the stabilised case, normalised to the SASE control case, and bottom right shows the normalised average pulse energy growth

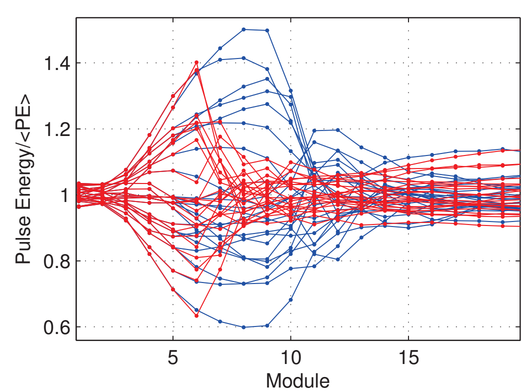

Figure 4: SHORT mode stabilisation. The blue plots show the 24 individual SASE cases, where the pulse energy at each module is normalised to the mean SASE pulse energy at that module. The red plots are for the 24 stabilised SASE cases.

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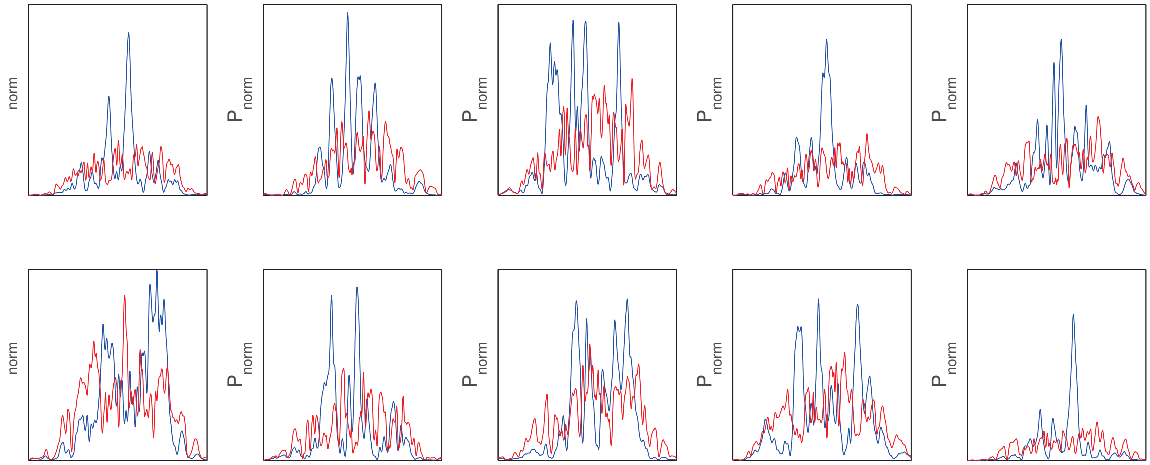

Figure 5: SHORT mode stabilisation: 10 randomly chosen examples from the 24 different shot noise seeds, showing the SASE (blue) and stabilised (red) pulse profiles at the exit of the 8th undulator module. Each pulse is normalised such that the pulse energy is unity.

of SASE saturation the improvement in stability is only a factor of 2.4.

Figure 4 shows (in blue) the 24 individual SASE cases, where the pulse energy at each module is normalised to the mean SASE pulse energy at that module, and (in red) the 24 stabilised SASE cases. It is seen that at module 7, for the stabilised cases, the pulses with higher than average pulse energy are damped (relative to the average) and those with lower pulse energy are boosted.

Finally, Figure 5 shows 10 randomly chosen examples from the 24 different shot noise seeds, with SASE (blue) and stabilised (red) pulse at the exit of the 8th undulator module. All pulses are normalised to have unity pulse energy. It is seen that with the stabilisation applied the strongest SASE spikes are damped (relatively) and the weakest SASE spikes are amplified, showing that the stabilisation method does act locally within the individual pulse as well as over many pulses.

Examination of the electron bunch data at the entrance to the 7th undulator module, where the chicane applies an R_{56} of 60 µm, shows that over the whole bunch the relative energy spread varies over the range $3 \times 10^{-4} \leq \Delta\gamma/\gamma_0 \leq 1 \times 10^{-3}$. Comparing this to Figure 1 shows that this range falls mostly within the region of negative gradient and is therefore consistent with the analytic model.

CONCLUSION

A method has been proposed to stabilise the shot-to-shot variation intrinsic to SASE FELs. A simple analytic justification for the method has been given and the first simulation results are consistent with this. Two cases have been studied using the parameters of the CLARA FEL test facility: for single spike SASE operation the method is shown to reduce pulse energy fluctuations by up to a factor of five. For SASE with longer electron bunches, in which each output pulse comprises a number of SASE spikes, the method is seen to reduce the shot-to-shot pulse energy fluctuations by a factor of five at equivalent undulator length as well as damp the variation in peak intensity for SASE spikes within an individual pulse. Comparison of the stability at equivalent pulse energy (in this case the pulse energy for SASE saturation) shows the improvement in stability is not as good - it is a factor of 2.4. Further study will fully characterise the output pulse quality of the stabilised case to compare with SASE and attempt to fully optimise the scheme to determine the stabilisation limits. The parameters used in the simulations are within the specified ranges of the parameters of the CLARA FEL Test Facility currently under construction at Daresbury Laboratory in the UK, making experimental testing of the scheme feasible in the near future.

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