IMPROVED TEMPORAL COHERENCE IN SASE FELS

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Abstract

A method for attosecond pulse train generation in FEL amplifiers was recently proposed. The method uses periodic equal temporal delays between the electron bunch and co-propagating radiation to generate a modal structure in the radiation field. The modes may be phase-locked via an energy modulation in the electron beam. As a consequence of the radiation/electron delays, the relative slippage of the radiation with respect to the electron bunch is also increased and results in a longer cooperation length which improves the temporal coherence. Simulations presented here demonstrate that the longer cooperation length increases the temporal coherence. In particular, it is shown that a SASE FEL can operate in single-spike mode with longer, higher charge electron bunches than previously thought possible.

INTRODUCTION

In a self-amplified spontaneous emission (SASE) FEL a relativistic electron beam propagates at mean velocity $v_z < c$ along an undulator and amplifies the initial spontaneous emission (noise) via the exponential FEL instability with a gain length $l_g = \lambda_u/4\pi\rho$, where ρ is the dimensionless FEL parameter [1]. The coherence of the SASE output is restricted as a radiation wavefront may propagate through only a fraction of a typical electron bunch as $v_z < c$. Thus many autonomous regions of the radiation/electron interaction will be uncorrelated in phase. The temporal output power is chaotic, comprising phase-uncorrelated regions that contain 'spikes' separated by $\lesssim 2\pi l_c$, where the cooperation length $l_c = \lambda_r/4\pi\rho$ is the relative slippage between a radiation wavefront and the electron bunch in one gain length through the undulator [2]. The 'Long Pulse Regime' is defined when the electron bunch length $l_b \gg 2\pi l_c$ and the number of SASE spikes in the output pulse is $n_{\text{spikes}} \simeq l_b/2\pi l_c$. Conversely, in the 'Short Pulse Regime', or 'single-spike SASE' mode, $l_b \lesssim 2\pi l_c$ and $n_{\text{spikes}} \simeq 1$.

In a scheme proposed for generating attosecond pulse trains in SASE FELs [3], periodic delays of the electron bunch are introduced using magnetic chicanes placed between undulator modules. The delays, of duration δ, generate a set of axial radiation modes in frequency space with spacing $\Delta\omega = 2\pi c/s$ where $s = l + \delta$ is the total slippage in one undulator/chicane module. The equally spaced modes corresponds to a temporal pulse train with spacing s/c. This pulse train is modulated by the envelope of SASE spikes. However, as discussed in [1] the enhanced slippage leads to an increased cooperation length $\hat{l}_c \simeq l_c S_e$ where $S_e = (l + \delta)/l$ is termed the 'slippage enhancement factor' and for N periods per undulator module, $l = N\lambda_r$ (the case $S_e = 1$ occurs when $\delta = 0$ i.e. no chicane delays). Thus, the phase correlated regions of the individual SASE spikes are extended over a greater range $\simeq 2\pi l_c S_e$ and the mean SASE spike spacing is increased by $\simeq S_e$. In the short pulse single spike regime this means that the electron bunch length may be longer by a factor $\simeq S_e$. In this paper we do not consider any electron beam modulation at the mode spacing which can lock the modes to generate well defined pulse trains [1]. Instead, the 'Mode-Coupled' regime of [1] is adapted to demonstrate the improved temporal coherence that may be possible as suggested above.

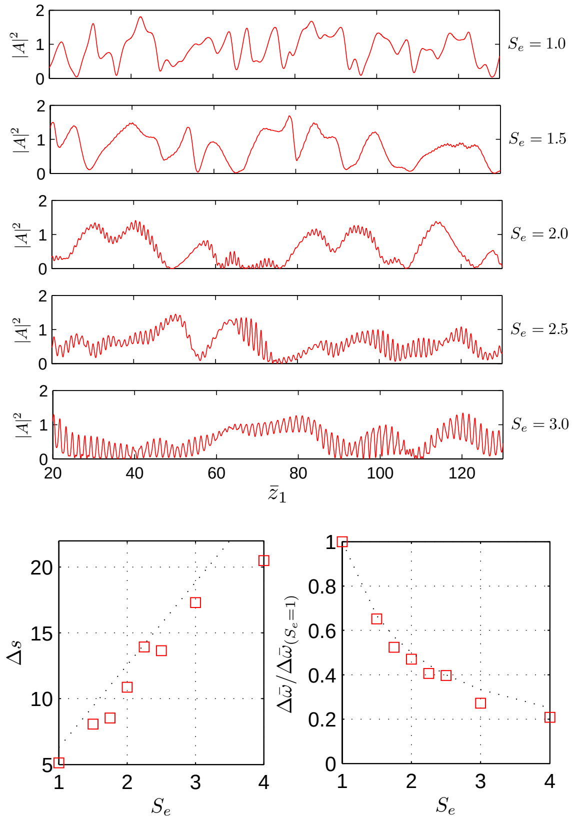

Figure 1: Long Pulse Regime. **Top**: Scaled power at saturation for $S_e = 1.0$ to $S_e = 3.0$. **Bottom Left**: Mean SASE spike spacing. **Bottom right**: Radiation bandwidth scaled to the bandwidth at $S_e = 1.0$.

NUMERICAL SIMULATIONS

The system is modelled using a 1D FEL code that solves the universally scaled FEL equations [1, 4, 5]. The propagation distance through the undulator is scaled by the gain length, $\bar{z} = z/l_g$, and the distance within the electron bunch is scaled by the cooperation length, $\bar{z}_1 = (z - c\bar{\beta}_z t)/l_c$. The slippage terms are scaled by l_c, so that $\bar{l} = l/l_c$, $\bar{\delta} = \delta/l_c$, $\bar{s} = \bar{l} + \bar{\delta}$ and $S_e = \bar{s}/\bar{l}$. A scaled frequency is defined as $\bar{\omega} = (\omega - \omega_r)/2\rho\omega_r$ so the resonant frequency $\bar{\omega}_r = 0$ and the axial modes occur at $\pm 2\pi n/\bar{s}$ for integer n.

As discussed in [1], the delay chicanes may also introduce longitudinal energy dispersion as parameterised by $D = R_{56}/2l_c$ [6, 7]. However, here we begin by considering isochronous chicanes with $D = 0$. Results for $D \neq 0$ are included at the end of the paper, however further optimisation of the parameters is required.

Long Pulse Regime

An undulator module length of $\bar{z} = 0.5$ was chosen with a rectangular current profile electron pulse of length $\bar{L}_e = 250$ and FEL parameter $\rho = 0.002$. The slippage enhancement was varied from $S_e = 1.0$ to $S_e = 4.0$. Sections of the output pulses at saturation ($\bar{z} = 13.0$) for $S_e \leq 3$ are shown in Figure 1 (top). The mean spacing of the SASE spikes increases with S_e and for $S_e \geq 2$ smaller scale oscillations due to the axial modes begin to appear. Figure 1 (bottom left) shows Δs, the mean distance between the SASE *envelope* spikes as a function of S_e (red squares), indicating good agreement with the function $\Delta s = 2\pi l_c S_e = 2\pi \hat{l}_c$ (black dotted line). Figure 1 (bottom right) shows the full radiation bandwidth, normalised to the bandwidth for the $S_e = 1$ case, as a function of S_e. Here the black dashed line represents the function $\Delta\bar{\omega}/\Delta\bar{\omega}_{S_e=1} = 1/S_e$. It is clear that the SASE spike spacing is proportional to S_e while the bandwidth is inversely proportionally to S_e. The total pulse length is independent of S_e, so the time bandwidth product $\Delta\nu\Delta t$ is therefore also inversely proportional to S_e The chicane enhanced electron bunch/radiation slippage therefore improves the temporal coherence of the radiation.

The shorter period oscillations of the SASE envelope occur due to the axial mode generation of [1]. Two methods are presented which are used to remove these oscillations while retaining the improved coherence. The first method stops the chicane delays a few gain lengths before saturation so that the modes either side of the resonant frequency are no longer amplified and the oscillations become washed out. The second method varies the delay δ of each chicane so that a modal structure is not allowed to develop and be amplified. In Figure 2(a) the same $S_e = 1$ case is shown as in Figure 1. Also shown are the radiation phase ϕ (with the plot colour correlated to the radiation intensity) and the radiation spectrum. Figure 2(b) is for the case S_e=3, with regular repeated delays to saturation. It is clear that here the radiation phase varies more slowly along the pulse and is indicative of the increased temporal coherence. The spectrum shows the axial modes at $\bar{\omega} = \pm 2\pi/\bar{s} = \pm 4.18$. In Figure 2(c) a combination of the two techniques described above has been used—random errors have been added to the delays (with phase matching maintained), of maximum amplitude $\Delta\bar{\delta} = 0.5$ about a mean delay of $\bar{\delta} = 1.0$, and the delays have then been terminated for $\bar{z} > 9.0$. The axial modes, and hence the short period modulations to the SASE envelope are no longer visible, while the benefits of improved temporal coherence are retained.

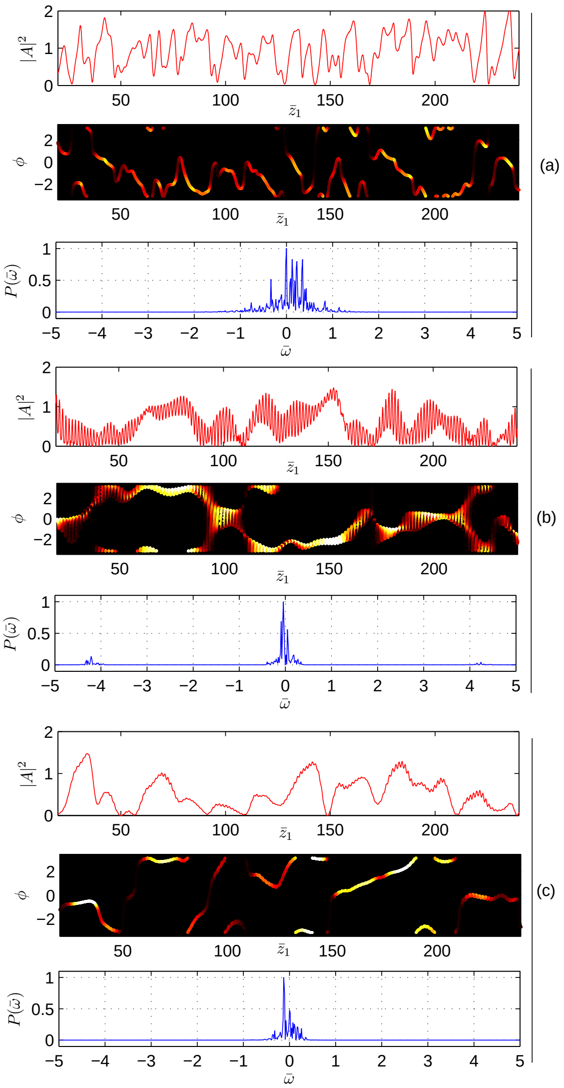

Figure 2: Long Pulse Regime: Scaled power, radiation phase and spectrum for (a) $S_e = 1.0$, (b) $S_e = 3.0$ and (c) $S_e = 3$ with delays randomised and terminated prior to saturation.

Short Pulse/Single Spike Regime SASE

The methods above are now applied to the short pulse regime. Five simulations of gaussian electron bunches with FWHM bunch length $\bar{L}_b = 23.5$ starting from different intitial shot noise conditions were carried out for $S_e = 1.0$. The pulses at saturation ($\bar{z} = 14$) are shown in Figure 3(a). For this electron bunch length, the average number of spikes expected for $S_e = 1$ is $L_b/2\pi l_c = 3.7$—the sim-

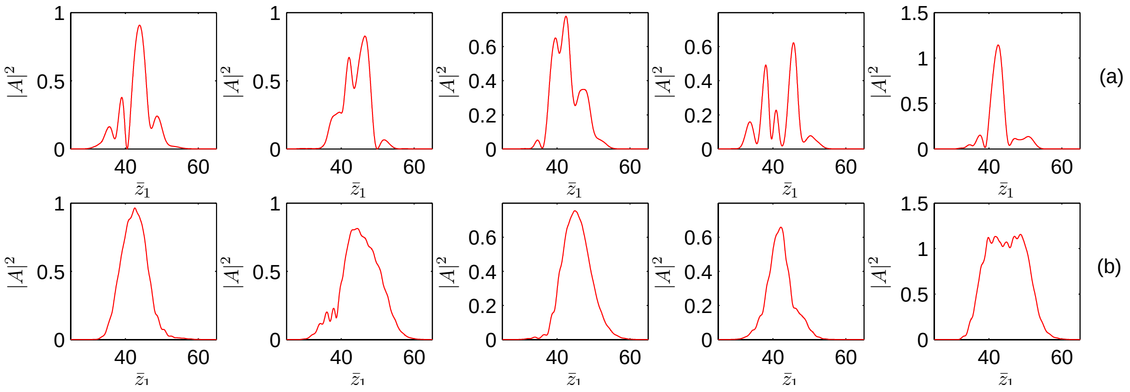

Figure 3: Short Pulse Regime: Scaled power pulse profiles at saturation for (a) $S_e = 1.0$ and (b) $S_e = 4$ with delays randomised and terminated prior to saturation.

ulations show an average of 3.8 spikes in good agreement. In Figure 3(b) randomised delays of amplitude $\Delta\bar{\delta} < 0.5$ have been applied up to $\bar{z} = 9$ with mean $S_e = 4$. Here the pulses take longer to reach saturation and are shown at $\bar{z} = 16$, however the number of spikes is reduced to approximately one. The time bandwidth product was calculated for each pulse, using the definition $\Delta\nu\Delta t = \Delta\bar{\omega}\Delta\bar{z}_1/2\pi$ (where the width used is $\Delta x = 2\sqrt{2\ln 2} \times \sigma_x$ so that a transform limited gaussian intensity pulse would have $\Delta\nu\Delta t \simeq 0.44$). For $S_e = 1.0$ the time bandwidth product varies from 1.36 to 2.62 with a mean value of 1.91, whereas for $S_e = 4$ it varies from 0.65 to 0.99 with a mean of 0.83. Thus on average $\Delta\nu\Delta t$ is reduced by a factor of 2.35 by using the delay chicanes.

Finally two similar cases for $S_e = 3$ are shown in Figure 4, where the longitudinal dispersion due to the chicanes is included. This has an additional effect of enhancing the bunching (and is the principle behind the Distributed Optical Klystron (DOK) FEL amplifier [8, 9, 10]) so that saturation is reached earlier at $\bar{z} = 10$. Again, single SASE spikes are seen, with $\Delta\nu\Delta t = 0.80$ for the left hand pulse and $\Delta\nu\Delta t = 1.11$ for the right hand pulse. Including the chicane dispersion appears to result in more shot-to-shot variation in the output properties than the cases where dispersion is not included, and appear to limit the successful application of the technique to the range $S_e \lesssim 3$. A more comprehensive investigation of parameter space may be able to overcome this apparent limit.

CONCLUSION

It has been shown in 1D simulations that the Mode-Coupled FEL can be modified to improve the longitudinal coherence of SASE FELs. The spacing of the SASE spikes appears proportional to, and the radiation bandwidth inversely proportional to, the slippage enhancement S_e in accordance with the simple analysis. Using these methods, the electron bunch duration can thus be extended to operate in single spike mode. Examples were shown where for normal SASE an electron bunch would normally generate an output pulse comprising up to 4 SASE spikes, whereas with the technique applied single spike output can be obtained with a time bandwidth product only approximately twice that of a transform limited gaussian pulse.

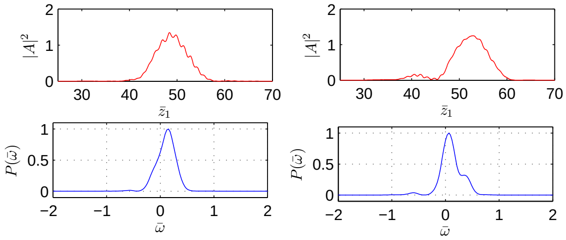

Figure 4: Short Pulse Regime: Scaled power pulse profiles where longitudinal dispersion of chicanes is included for $S_e = 3$.

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