ISASE STUDY

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Abstract

Improved Self Amplified Spontaneous Emission (iSASE) is a scheme that reduces FEL bandwidth by increasing phase slippage between the electron bunch and radiation field. This is achieved by repeatedly delaying electrons using phase shifters between undulator sections. Genesis 1.3 [1] is modified to facilitate this simulation. With this simulation code, the iSASE bandwidth reduction mechanism is studied in detail. A Temporal correlation function is introduced to describe the similarity between the new grown field from bunching factor and the amplified shifted field. This correlation function indicates the efficiency of iSASE process.

INTRODUCTION

Improved Self Amplified Spontaneous Emission (iSASE) [2, 3]is capable of improving spectrum by increasing cooperation length, and may have the potential to serve as a self-seeding scheme. With several phase shifters installed along the FEL lattice, optical field can be shifted and connection is built up between electrons that separated by several spikes width away. Then with proper interference between new grown field and optical field, bandwidth can be reduced.

Similar idea, known as phase locking of longitudinal spikes in SASE process, is first introduced by A. Gover [4]. Then phase locking FEL amplifier is studied to generate attosecond xray pulse trains by repeatedly delay electron bunch [5]. Similar configuration is then used to improve temporal correlation of SASE FEL [6, 7].

ISASE MECHANISM

SASE mode, radiation field slips one wave length after every undulator period. Slippage field stimulates electrons to radiate in the same phase. Coherent length is built up as electron bunch and radiation field interact through the undulator. One way to improve the temporal coherence is to provide additional slippage to the radiation field. As it's in the SASE mode, slippage field will stimulate electron bunch to generate similar wave package. Therefore it may improves the correlation function and potentially increase coherence length.

Phase shifters are installed after a few gain length. After phase shifters, radiation field is shifted by ϕ, here ϕ is in pondermotive phase. Shifted radiation field stimulates local electron bunch to radiate in similar pattern. Electron bunch, on the other hand, has its own energy and density modulation will also generate radiation field accordingly. iSASE mechanism can be understood by viewing optical field as superposition of new grown field from bunching factor and amplified optical field,

$$E_1(\theta; z) = E_0(\theta; z) + aE_0(\theta + \phi; z). \qquad (1)$$

Here θ is the pondermotive phase, z is the location along the undulator, $E_0(\theta; z)$ represents new grown field from electron bunch distribution, and $aE_0(\theta + \phi; z)$ is the amplified shifted radiation field, with a to be complex amplitude describing the amplitude and angle difference between these two field. The phase difference can come from radiation field propagation or electron bunch relative drift.

Then the power spectrum is

$$P(\nu; z) = |\tilde{E}_0(\nu; z)|^2 T(\nu, \phi, a), \qquad (2)$$

where $\nu = \omega/\omega_s$ and

$$T(\nu, \phi, a) = 1 + |a|^2 + 2|a| \cos(\nu\phi + \varphi), \qquad (3)$$

with φ to be the angle of complex amplitude a. Power spectrum is modulated by $T(\nu, \phi, a)$. Modulation of the original power spectrum $|\tilde{E}_0(\nu)|^2$ has potential to reduce bandwidth. The interference term can be written as $2|a| \cos(\Delta\nu\phi + x + \varphi)$, with $\Delta\nu = \nu - 1$ and x is the fractional phase of ϕ. Modulation function has the period determined by relative shift ϕ in frequency domain. The modulation period in frequency domain is $\frac{2\pi}{\phi}$.

The fractional phase x and complex amplitude phase φ contribute as a detuning factor $(x + \varphi)/\phi$ to the modulation since it shifts the modulation function. In order to maintain FEL power, we can choose $T(\nu, \phi, a)$ peak has to overlap with $|E_0(\nu)|^2$ center where the power is maximal. When the delay ϕ is small, then the modulation function is almost uniform across the FEL spectrum. Therefore the bandwidth is almost unchanged. When the modulation period $\frac{2\pi}{\phi}$ is comparable to the FEL bandwidth, modulation to the FEL spectrum becomes more obvious. Yet if the modulation period is too small, multi harmonics may occur in the spectrum. Choosing $\frac{2\pi}{\phi}$ to be close to the FEL bandwidth, modulated power spectrum may have maximal reduction.

Figure 1,2 shows the power spectrum at two different locations from Genesis simulation. To exclude possible contribution from fractional phase, a unbreaked undulator is used. This guarantees no phase evolution in the radiation field. Slippage is assumed to be multiple number of wavelength. Effect of a phase shifter is like a modulation function to the power spectrum (Eq. 2). At $z = 20m$ (Fig. 1),

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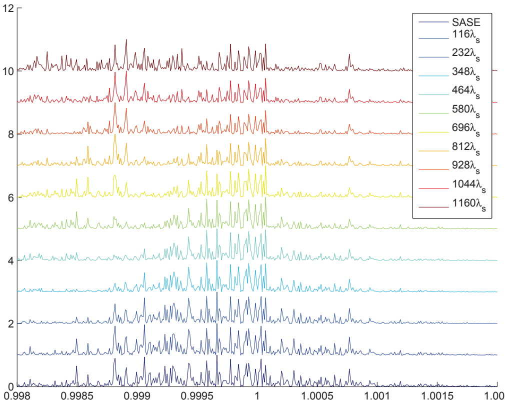

Figure 1: Figure plots the power spectrum at $z = 20m$ for different phase shifter strength. The phase shifter locates at $7m$.

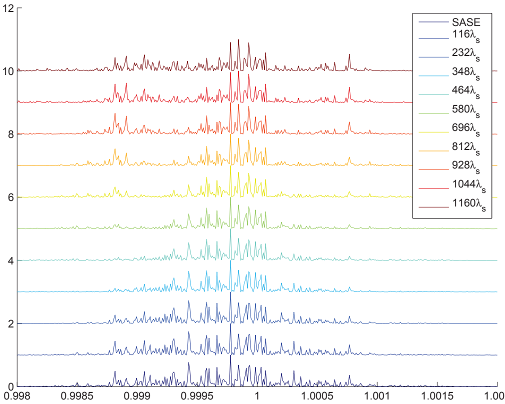

Figure 2: Figure plots the power spectrum at $z = 30m$ for different phase shifter strength. The phase shifter locates at $7m$.

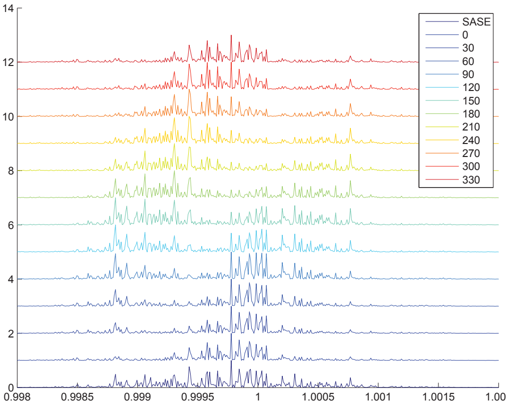

Figure 3: Figure plots the power spectrum at $z = 30m$ for phase shifters with different fractional phase. The phase shift slippage is $580\lambda_s$.

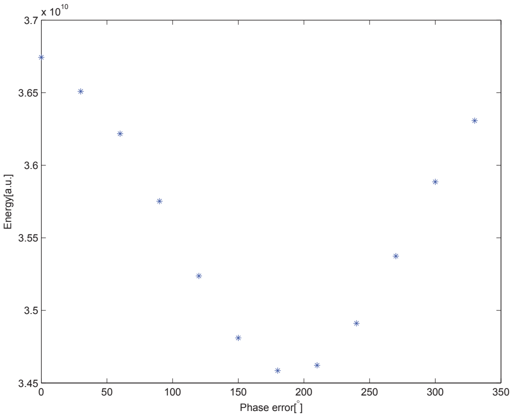

Figure 4: Figure plots the power at $z = 30m$ for phase shifters with different fractional phase. The phase shift slippage is $580\lambda_s$.

the power spectrum is noisy (see SASE spectrum). Phase slippage $\phi = 348\lambda_s$ is able to clean up the skirt of SASE spectrum, and provide the quietest spectrum among all the cases. For those cases where $\phi > 348\lambda_s$, modulation period becomes smaller. Therefore several humps occur in these cases. At $z = 30m$ (Fig. 2), FEL bandwidth reduces due to FEL interaction. Phase slippage $\phi = 580\lambda_s$ gives the quietest spectrum in this case. $\phi = 348\lambda_s$ on the contrary has a slightly mild modulation across the SASE bandwidth, therefore less bandwidth reduction at this location. Again, side band occurs as phase slippage increases.

The effect of the fractional phase slippage can be translated into detuning in the modulation function. As the modulation function center shifts, different frequency will be amplified. Figure 3 plots the power spectrum at $z = 30m$ with one phase shifter locates at $z = 10m$. Phase error varies from 0° to 360°. As phase error increases, the modulation function starts to blue shift. As a result, some higher frequency signal get amplified. Moreover, since the modulation function is a periodic function, some lower frequency signals are also amplified. When the phase slippage is 180° out of phase, the valley of the modulation function locates at the center of the SASE spectrum, and resulting in two humps with almost equal power in the spectrum. Figure 4 plots correspondingly the power with different phase shifter errors. When the modulation function peaks at the center of FEL natural gain band, FEL power is maximal corresponding to zero fractional phase error. FEL power is minimal if the valley of the modulation function coincides with the center of FEL natural gain band.

CORRELATION FUNCTION

A necessary condition for iSASE to have interference and then modulate the power spectrum is that the new grown radiation field and amplified slipped radiation field have similar distribution. The distribution of new grown field is determined by the prebunched beam. Therefore maintaining the electron bunching factor is essential. Phase shifters are usually dispersive, thus electrons are inevitably rotated in the longitudinal phase space.

To illustrate the interference mechanism, we force electron bunch to maintain its bunching factor distribution through the phase shifter. Figure 5 shows the field envelope

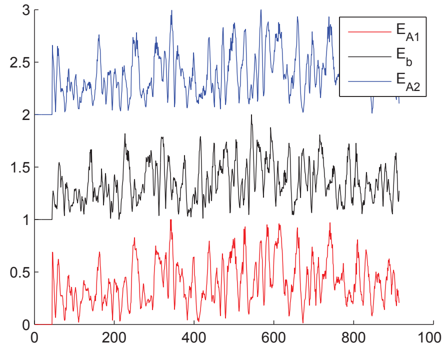

Figure 5: Temporal distribution of E_{A1},E_b,E_{A2}.

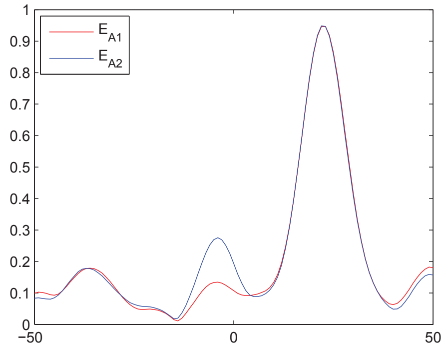

Figure 6: Correlation function between new grown field E_b and shifted field E_A.

for new grown field and amplified field are similar. The new grown field E_b is obtained by setting the radiation field to zero after passing phase shifter. Effectively this is equivalent to seeding the next undulator section with a prebunched electron bunch. The amplified field $E_A^{(1,2)}$, on the other hand, can be computed in two ways. The first way it's to keep both prebunched beam and shifted radiation field after phase shifter and simulate through the second undulator section. Subtracting E_b from the radiation field in the second section we obtain the amplified field $E_A^{(1)}$. The $E_A^{(2)}$ can be computed by smearing density modulation after passing the phase shifter. This is achieved by resampling macro particles as a fresh beam. Then the electron bunch are uniformly distributed within a wavelength.

Correlation function is used to quantify the similarity between the new grown field and amplified field,

$$g(\phi) = \frac{\langle E_\alpha(\theta) E_\beta^*(\theta + \phi)\rangle}{\sqrt{\langle |E_\alpha(\theta)|^2\rangle \langle |E_\beta(\theta)|^2\rangle}}. \tag{4}$$

Figure 6 plots the correlation between the new grown field and the amplified field, i.e. correlation between E_b and $E_A^{(1,2)}$. The peak center denotes the relative shift, while height of the peak depicts the similarity. Correlation length can be deduced from the width of the peak. Having a strong correlation between $E_A(\theta)$ and $E_b(\theta)$ is a necessary condition for them to interference.

CONCLUSION

In this paper, we study the iSASE mechanism with Genesis 1.3 simulation code. Phase shift is translated into a filter function to the power spectrum. Any phase difference between shifted field and new grown field generate a detuned filter function, and may amplify slightly different frequency. A correlation function is introduced to describe the correlation between new grown field and shifted field.

APPENDIX

A new package is being developed to facilitate Genesis to simulate insertion devices like phase shifters. An new element, insertion, is added to the element list. In this element electron bunch and optical field are processed independently. Electrons can be processed by a transfer map. Optical field will be processed according to the optical elements. Then the relative slippage between optical field and electron bunch is taken into account by swapping field.

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