GENERATION OF LONGITUDINALLY COHERENT ULTRA HIGH POWER X-RAY FEL PULSES BY PHASE AND AMPLITUDE MIXING*

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Abstract

We study an improved SASE (iSASE) scheme to generate narrow bandwidth X- ray FEL pulses by introducing repeating delays of the electron beam respect to the radiation field, thus mixing the spikes phase and amplitude, increasing the cooperation length and generating a bandwidth much smaller than in the SASE case. The improved longitudinal coherence is used, in combination with a tapered undulator, to increase the efficiency of energy transfer to the radiation and generate ultra-high peak power. We report results of theoretical and simulations studies for a hard X-ray iSASE FEL at 0.15 nm, using an LCLS-II undulator to generate X-ray pulses with peak power between 0.1 and 1 TW. The analysis is carried out using a time dependent 1-dimensional model and with GENESIS numerical simulation including 3-dimensional effects.

INTRODUCTION

The Linac Coherent Light Source (LCLS), the most powerful operating source of transversely coherent, few to hundred femtosecond pulse duration, X ray Free Electron Laser (FEL) [1], offers novel ways to study the structure and dynamics of atomic and molecular system. LCLS could become even more useful by increasing its longitudinal coherence and peak power. Its line width, about 5×10^{-4}-10^{-3}, is determined by the temporal spikes [2] characteristic of the Self-Amplified Spontaneous Emission (SASE) process [3]. The peak power at saturation is limited to 30-50 GW.

Much attention has been given recently to overcome these limitations, by using seeding, self-seeding and tapered undulators [4-6]. In this paper we consider an alternative method, that we call improved SASE (iSASE), to achieve both objectives using phase and amplitude mixing between spikes.

The spiking and longitudinal coherence of an X-ray SASE FEL is limited by the radiation-electron slippage. Only electrons within one cooperation length interact through their emitted radiation field [2]. The cooperation length L_c, is related to the power gain length L_G by the relationship $L_c = 2L_G \lambda/\lambda_u$, where λ and λ_u are the radiation wavelength and the undulator period. The length of each spike is of the order of L_c. An electron bunch shorter than the cooperation length generates a transform limited X-ray pulse [9]. The FEL bandwidth for a longer bunch is determined by the single spike length and is larger than the transform limit.

In this paper we study a method to effectively increase the cooperation length using an iSASE FEL. The concept is to introduce in the FEL undulator, divided in modules separated by a break, additional slippage (i.e. localized shifts of the electron bunch respect to the radiation field) by repeated delays of the electron beam respect to the radiation field. The shifts are introduced with small magnetic chicanes at the end of each module, as in Fig. 1.

A delay of the order of the cooperation length introduces a correlation between the electromagnetic field phases and amplitudes of the spikes, in effect increasing the slippage length and the longitudinal coherence. The most important parameters in the mixing process are the electron delay, δ, the cooperation length L_c, the number of delays introduced and the gain in each module. This concept has been studied before, in one case to increase the FEL power output [10], in another case to introduce mode locking in the radiation field [11] or improve its temporal coherence [12].

This paper extends the previous work to include 3-dimensional effects, a more general sequence of delays to minimize the line width, and using a tapered undulator to increase the peak power. We show that a choice of delays increasing geometrically along the undulator can yield a line width about ten times smaller than what can be achieved by the constant delay considered in Ref. [12]. When using a tapered undulator we compare iSASE with a SASE and a self-seeded FEL. Recent work on self-seeding [7] has demonstrated the feasibility but also the limitations of this method, including expected large intensity fluctuations associated with shot to shot changes in electron beam energy and current distribution [8]. We show in this paper that iSASE is not sensitive to electron beam energy fluctuations.

THE UNIVERSAL 1-D MODEL AND BANDWIDTH REDUCTION

We use a universal 1-D model to study the dependence of the line width on the choice of the delays and of the gain of each undulator module.

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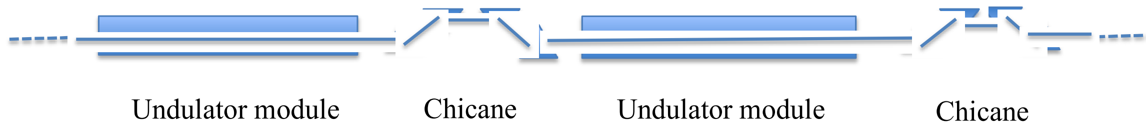

Figure 1: An undulator section showing two modules and chicanes to delay the electrons. The number and strength of the chicanes, and the number and length of modules, is determined by optimizing the iSASE FEL power and bandwidth.

A SASE FEL starts from noise in the initial bunching distribution. The radiation field establishes a correlation between different electrons only within one cooperation length, $Lc \approx \lambda/4\pi\rho$ where ρ is the FEL parameter [3] proportional to the bandwitdth $\Delta\omega/\omega \approx \rho$.

The effect was first discussed in Ref. [2] using a 1-D universal model, valid in the linear FEL regime, with one normalized field variable, A, and two collective electron variables, B and P, to describe the electron bunching and energy modulation. The equations are.

$$\frac{\partial A(\xi,\zeta)}{\partial z} + \frac{\partial A(\xi,\zeta)}{\partial \zeta} = B(\xi,\zeta),$$

$$\frac{\partial B(\xi,\zeta)}{\partial \xi} = P(,\zeta),$$

$$\frac{\partial P(\xi,\zeta)}{\partial \xi} = iA(\xi,\zeta)$$

where, $\xi = z/L_G$ is the scaled position along the undulator axis, $\zeta = c(z/v_z - t)/Lc$ is the scaled position along the electron bunch, v_z is the electron velocity along the z-axis. We consider only the case of zero initial energy spread and a bunch length much larger than the cooperation length.

Introducing the Fourier transform respect to the bunch variable we have.

$$\frac{\partial \bar{A}(\xi,\Delta)}{\partial \xi} - i\Delta\bar{A}(\xi,\Delta) = \bar{B}(\xi,\Delta),$$

$$\frac{\partial}{\partial z}\bar{P}(\xi,\Delta) = i\bar{A}(\xi,\Delta),$$

$$\frac{\partial}{\partial z}\bar{B}(\xi,\Delta) = \bar{P}(\xi,\Delta)$$

with $\Delta = (\lambda_r - \lambda)/(\rho\lambda_r)$ is the detuning normalized to ρ and $\lambda_r = \lambda_u(1+K^2)/(2\gamma^2)$. The solutions are.

$$\bar{A}(\xi,\Delta) = \sum_{n=1}^{3} a_n(\mu_n,\Delta)\exp(i\mu_n(\Delta)\xi),$$

$$\bar{B}(\xi,\Delta) = \sum_{n=1}^{3} \frac{a_n(\mu_n,\Delta)}{i\mu_n(\Delta)^2}\exp(i\mu_n(\Delta)\xi),$$

$$\bar{P}(\xi,\Delta) = \sum_{n=1}^{3} \frac{a_n(\mu_n,\Delta)}{\mu_n(\Delta)}\exp(i\mu_n(\Delta)\xi)$$

where μ_n are the solution of the cubic equation

$$\mu^3 - \Delta\mu^2 + 1 = 0$$

A delay δ of the electrons between undulator modules introduces a phase factor in the bunching at the next module entrance modifying the equation for the field as

$$\frac{\partial \bar{A}(\xi,\Delta)}{\partial \xi} - i\Delta\bar{A}(\xi,\Delta) = \exp(i\Delta\delta)\bar{B}(\xi,\Delta)$$

The delay is equivalent to applying a filter between modules, thus modifying the spectrum. We evaluate the 1-D model for a case with eight undulator modules, each with a power gain length equal to 3, and 7 chicanes. The bunch length is 200 times the cooperation length. The spectra obtained in three cases, with different choices of the delay, are shown in Figure 2, where we compare the spectra for: a) a SASE case, $\delta=0$, with a bandwidth, in units of the FEL parameter ρ, of about one; b) constant delay $\delta=3$, bandwidth reduced to 0.2 in agreement with Ref. [12]; c) a delay increasing geometrically, $\delta=1, 2, 4,\ldots 64$, line width reduced to about 0.02. For a bunch of 200 cooperation length, the transform limited bandwidth is 0.015 ρ, so approaching that in the geometric case.

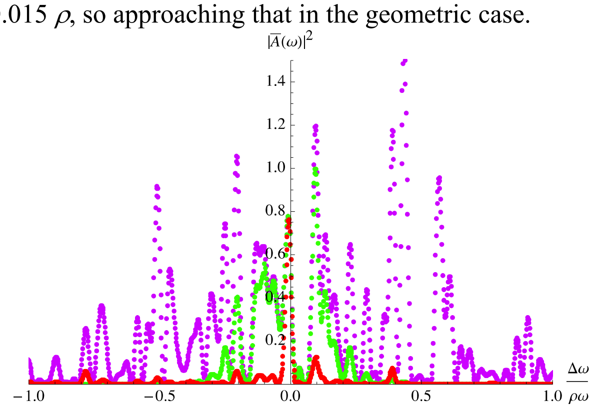

Figure 2: Spectra comparison for three cases: δ =0, SASE, purple, line width about 1; δ =3, 3, 3, 3, 3, 3, 3, green, line width about 0.2; δ=1, 2, 4, 8, 16, 32, 64, red, line width about 0.02.

The difference between the constant and the geometrical delay can be explained as follows: at each delay stage, the effective correlation length is improved at most by a factor 2, since a delay larger than the existing coherence length would leave a fraction of the electron beam unaffected by the increased slippage. Starting with a delay of one cooperation length and doubling at each stage yields a final correlation length $L_{coh} = L_{coop}\, 2^N$, N being the number of delay stages. In contrast, a constant delay introduces a total correlation length $L_{coh} = (N+1)\, L_{coop}$. For the geometrical delays the field intensity at the undulator exit is however smaller than in the other cases.

The output radiation intensity and spectrum is not sensitive to beam energy fluctuations, in contrast to the self-seeding case. A change in beam energy only moves the iSASE central frequency. Compared to self-seeding or seeding it gives a similar line width but the intensity does

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not fluctuate with the electron beam energy. There is also no problem associated with crystal heating or vibration when using a high repetition rate of electron bunches with a superconducting linac.

iSASE FOR LCLS-II

In this section we consider using the iSASE scheme for LCLS-II, to reduce the bandwidth and prepare a seed for a tapered undulator. We consider an LCLS-II type variable gap undulator and electron beam parameters. The analysis is done numerically using GENESIS including time dependent and 3-dimensional effects. The electron beam parameters are: Energy, 13.5 GeV; Emittance, 0.3 μm-rad; slice energy spread, 1.3 MeV; peak current, 4 kA with 60 pC flattop current distribution of 15 fs duration; β-function, 15 m. The photon wavelength is 0.15 nm.

The undulator is composed of modules 3.4 m long, with period of 3.2 cm, and break sections 1 m long. In each break there is a 5 optical wavelength slippage delay between the optical pulse and the electron bunch. The power gain length is about the length of a module and the cooperation length is about 230 wavelengths or 35 nm.

We use the geometrical delay pattern, starting with a delay of 415 optical periods after the first three modules, followed by an additional 800 optical periods after the 6-th undulator module, and 1600 optical periods after the 9-th undulator module. At this point the FEL power is already large, so we add only one undulator segment the 10-th, before an additional 3200 optical period's shift is introduced to complete preparing the seed for the tapered undulator. The iSASE seed is then amplified to above 0.6 TW in the next 22 undulator modules.

The iSASE, blue, and SASE, red, spectra after the tenth module are shown in Figure 3. The iSASE spectrum is dominated by a single line with a FWHM bandwidth of 5.1E-05, close to transform limit. The SASE spectrum has a FWHM of 1.5E-03. iSASE effectively shrinks the spectral width by a factor of 30, compared to 50 in the 1-D theory for a different delay sequence. The power after 10 undulator modules is lower in the iSASE case. The FEL temporal profile is shown in Figure 4.

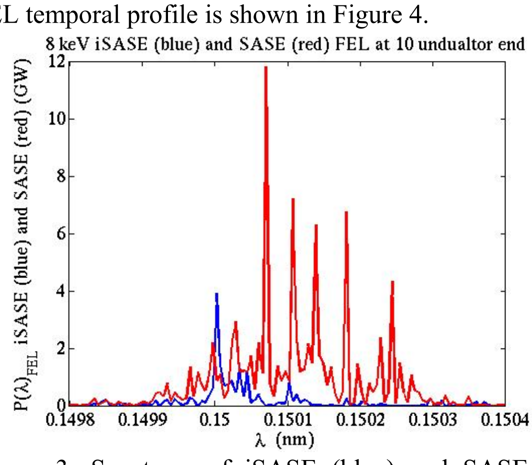

Figure 3: Spectrum of iSASE (blue) and SASE (red) radiation after 10 undulator modules. iSASE FWHM bandwidth is 5.1E-05, compared to 1.5E-03 for SASE.

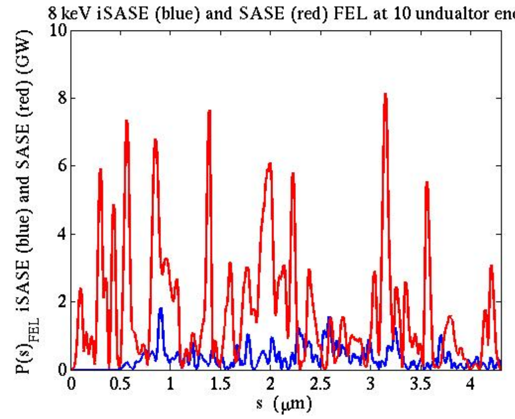

Figure 4: Temporal profile of the iSASE seed (blue) after 10 undulator segments compared to SASE (red).

iSASE TAPERED FEL

The efficiency of a tapered undulator FEL depends strongly on the longitudinal coherence of the input seed [13]. In this section we evaluate and compare the efficiency for SASE, iSASE and self-seeding.

Self-seeding to generate a coherent seed has been demonstrated at LCLS. However large FEL intensity fluctuations are observed. With an ideal crystal, there can be 5 MW seed into the second undulator. Optimizing the undulator taper we obtain the result shown by the black dashed curve in Figure 5 reaching TW. In the same Figure 5, we also show the power gain curve for a SASE (black dash-dotted) and for an iSASE (black solid) FEL with optimized tapers and seed prepared with 10 undulator modules, as discussed before.

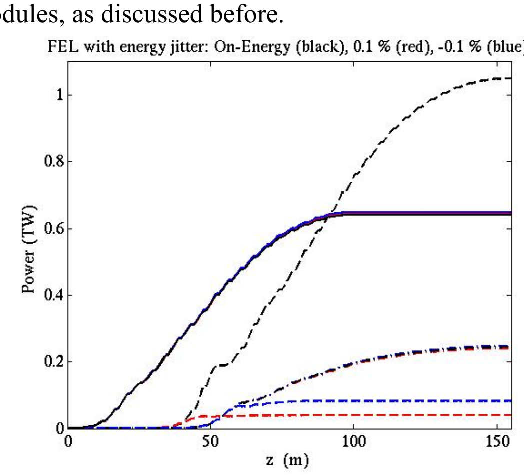

Figure 5: FEL power gain curve variation for a ±0.1 % energy jitter: on-energy (black), 0.1 % (red), and -0.1 % (blue), and SASE (dash-dotted), iSASE (solid), and Self-seeding (dashed).

Notice that, for the iSASE, since the bunching is well developed, it starts quickly in the tapered undulator; while for the Self-seeding or the SASE, they need to go through the exponential growth in a much longer distance.

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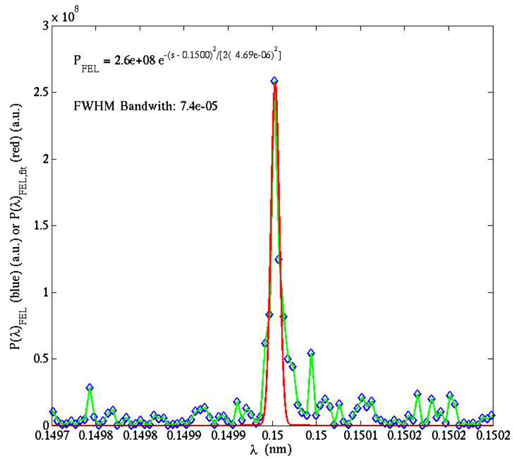

Figure 6: iSASE spectrum, tapered undulator end, bandwith close to transform limit. Red curve is a fitting to the raw data (blue diamond connected by green line).

With a tapered undulator to bring the FEL power to above 0.6 TW in the iSASE example, the FEL narrow bandwidth is nicely preserved as shown in Figure 6.

EFFECT OF ENERGY JITTER

Large FEL intensity fluctuation is observed in the self-seeding experiment, mainly caused by electron beam energy jitter. Here we simulate how iSASE, SASE, and Self-seeding intensities change for a 0.1 % electron beam centroid energy variation.

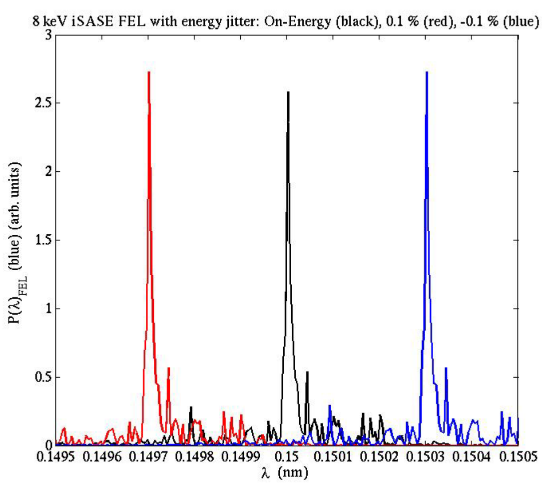

Figure 7: iSASE FEL spectrum change for a ±0.1 % energy jitter: on-energy (black), 0.1 % (red), and -0.1 % (blue).

As in Figure 7, the centroid energy jitter causes a change in the FEL central wavelength. The bandwidth however remains narrow in all three cases. Figure 5 shows that, while the wavelength moves with the beam energy, the FEL power is essentially unchanged as the set of solid curves. In contrast to the iSASE stable power, in the self-seeding case the FEL power fluctuates by 100 % as in Figure 5 as the set of dashed curves. To complete the comparison we simulate also a tapered SASE system with a ± 0.1 % energy jitter. The results in Figure 5 show that the tapered SASE system is also stable as the set of dash-dotted curves.

CONCLUSIONS

The results obtained show that iSASE is an effective method to improve the longitudinal coherence of an X-ray FEL, and that it can be used to generate X-ray pulses in a tapered undulator FEL with peak power much larger than in the SASE case. In the case studied the iSASE peak power is less than in the self-seeded case. However the output intensity is much less sensitive to beam energy fluctuations.

The results presented here are based on a designed LCLS-II undulator. We intend to continue the iSASE exploration considering undulator/delay designs optimizing both the longitudinal coherence and the efficiency. Additional work will also be done to fully evaluate the system tolerances, all sources of fluctuations, and perform a proof of principle experiment on an existing FEL.

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