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Eliminating the microbunching-instability-induced sideband in a soft x-ray self-seeding free-electron laser

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ABSTRACT

Soft x-ray self-seeding has been proved to be a feasible method to improve the longitudinal coherence of high gain free-electron laser. However, a pedestal-like sideband in the spectrum has been observed in the experiment, which generally limits the purity of the radiation pulse and the user's application. The previous theoretical study indicates that the pedestal-like sideband is mainly induced by microbunching instability generated from LINAC. In this paper, three dimensional simulations have been performed to confirm the analytical results and show the formation process of the spectral sideband. A probable method is proposed to eliminate the pedestal-like sideband by simply inserting a magnetic chicane before the self-seeding FEL undulator. Theoretical and numerical simulations have been performed and the results show that the proposed method can efficiently eliminate the microbunching-instability-induced sideband in a soft x-ray self-seeding FEL.

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1. Introduction

In the sub-nanometer wavelength, self-amplified spontaneous emission (SASE) [1–3] has been proved to be a reliable and superior scheme and becomes the main operation mode of most X-ray FEL facilities. However, considering SASE FEL initiates from the electron beam shot noise [4], the output bandwidth is typically on the order of 10^{-3} and the longitudinal coherence is poor. To improve this characteristic of SASE FEL, several techniques based on external seeding [5–11] and self-seeding [12–16] have been proposed and experimentally demonstrated in recent years. In the external seeding schemes, the short wavelength radiation can be achieved via the harmonic generation process [7–11]. Nevertheless, with the increase of the harmonic order, the properties of the output radiation deteriorate significantly. As a result, the output wavelength is restricted to the range of soft X-ray in the external seeding operation modes currently. Self-seeding schemes have been proved to be reliable methods for tandem X-ray and hard X-ray FEL generation with relatively simple setups [12–16]. However, the longitudinal coherence and stability still require further improvement.

Self-seeding FEL can be expressed as: a monochromator together with a bypass chicane implemented between separated undulators to get a monochromatic seed which is amplified by the same electron beam in the downstream undulator until saturation. Self-seeding FEL can be distinguished as soft and hard X-ray self-seeding depending on monochromator materials chosen for different photon energy ranges [13,14]. Under the ideal circumstance, the output bandwidth of the soft X-ray self-seeding scheme should approach the Fourier transform limit. However, recent spectral measurement results of the soft X-ray self-seeding experiment show that there is a pedestal-like sideband [15], which degrades the FEL longitudinal coherence and thus limits the user's applications [17,18]. Early research indicates that spectrum noise and monochromator optics are not the main inducements of this pedestal-like sideband. Recent analysis shows that the pedestal-like sideband may come from the modulation of electron beam's longitudinal phase space due to the space charge force during the acceleration and drift sections [19,20]. Similarly, a pedestal-like sideband is also observed in hard X-ray self-seeding FEL [16]. A theoretical analysis of sideband formation process is carried out in the Ref. [21], which indicates that this pedestal-like sideband is mainly caused by the long wavelength energy and density modulation driven by the microbunching instability effect in the LINAC.

In this paper, 3-D simulations have been performed to verify the theory prediction in the Ref [21]. The simulation results reveal that the long wavelength modulation induced by the microbunching instability will result in a symmetric sideband which will be amplified in the

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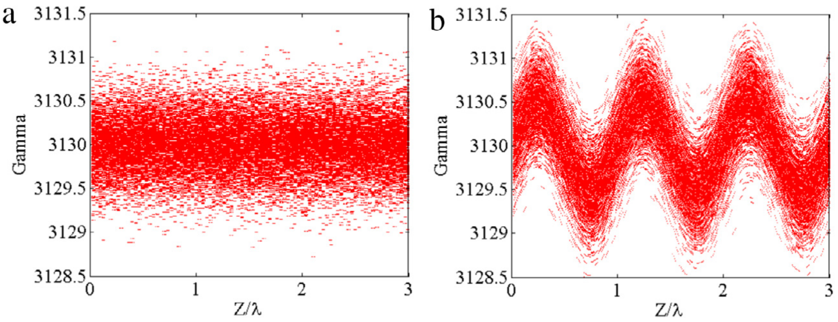

Fig. 1. The longitudinal phase space distributions before (a) and after (b) the single wavelength modulation.

following undulator in a soft X-ray self-seeding configuration. Moreover, an efficient and easy-to-implement method is proposed to possibly suppress the sideband by adding a magnetic chicane [22] before the self-seeding FEL undulator.

2. 3-D simulations for the sideband formation process

In order to study the evolution of the pedestal-like sideband and demonstrate the thesis in Ref. [21], we performed simulations for the self-seeding with initially energy modulated electron beams. Two cases have been considered: the first one, introduced in Ref. [21], uses an energy modulation with single frequency at ω_m; another more practical case utilizes a frequency chirped energy modulation with central frequency at ω_m. A monochromatic light with frequency of ω_{seed} is adopted to seed the electron beam at the entrance of the undulator for both cases.

For the first case, the initial beam energy modulation can be expressed as: $A(\xi) = A_m cos(k_m \xi)$, where ξ represents the longitudinal position along the electron beam, k_m is the wave number of the modulation and A_m is the amplitude of modulation. In this situation, the seed and sideband bunchings [23,24] are given by:

$$b_{seed} = \left\langle e^{-i\theta} \right\rangle, \tag{1}$$

$$b_{sideband} = \left\langle e^{-i\nu\theta} \right\rangle, \tag{2}$$

where θ is the electron ponderomotive phase and ν is the normalized frequency $\nu = 1 + \Delta\nu = \omega/\omega_{seed}$ [25,26]. Assuming the frequency shift is smaller than the FEL gain bandwidth in high gain regime, the power ratio between sideband and seed can be used to describe the forming process of sideband:

$$\frac{P_{sideband}(\hat{z})}{P_{seed}(\hat{z})} = \frac{\hat{A}^2}{9}\hat{z}^2 = \frac{4}{9}A_0^2 k_u^2 z^2, \tag{3}$$

where k_u is the wave number of the undulator and z is the position along the undulator. Eq. (3) indicates that the total power occupation ratio of sideband has a sustainable growth along the undulator and is proportional to the initial energy modulation intensity. The theoretical analysis of the sideband forming process is firstly elaborated in the Ref. [21]. A numerical solution of the 1-D FEL equation has been already executed in the previous theoretical analysis, suggesting that the given 1-D simulation conforms to the theory prediction. In this presented paper, a 3-D simulation is performed to prove the validity of this theoretical analysis. The nominal parameters of the Shanghai soft X-ray FEL (SXFEL) user facility [27], which are displayed in the Table 1, are adopted in our simulations.

Table 1
Main parameters for the simualtions.

Electron beam parameter	Value	Unit
Electron beam energy	1.6	GeV
Slice energy spread (RMS)	0.01%	–
Peak current	1.5	kA
Bunch length	40	fs
Normalized emittance	0.45	mm-mrad
Mono. Central energy	1.243	keV
Mono. Resolution power	1/10 000	–
Mono. Power Efficiency	0.03	–
Undulator period	0.0235	m
SASE undulator length	20	m
Seeded undulator length	20	m

A longitudinally uniform electron beam is used to study the basic physics of the spectral pedestal. The simulation is mainly performed with the code GENESIS [28] with several separate runs. The electron beam is firstly modulated with a modulation amplitude of 0.3 MeV (the relative modulation amplitude is 1.875) and modulation wavelength of 3.6 μm, which lies in the range of microbunching instability wavelengths observed in the experiments. The initial longitudinal phase space of the beam is shown in Fig. 1(a), after inducing the energy modulation, the longitudinal phase space evolves to Fig. 1(b).

The beam is then imported to carry out a self-seeding simulation: the beam is transported through a 15 m undulator to generate FEL radiation pulse before saturation, and further sending the FEL radiation pulse to a monochromator to obtain a relatively purified spectrum pulse. The electron beam is sent through a four-dipole chicane at the same time. At the exit of the chicane and monochromator, the beam and the purified radiation pulse are reimported to a 20 m long undulator to generate intense FEL pulse. The spectrum evolutions along the second undulator (radiator) are shown in Fig. 2. A symmetric distinguished sideband near the seed spectrum can be obviously observed, and the sideband increases sustainably along the undulator. For comparison, a conventional self-seeding spectrum and pulse distribution with the longitudinally uniform electron beam are presented in Fig. 3.

In order to illustrate the sideband formation process, the power ratio between the integrated sideband and the seed power at different distances of the second undulator are also calculated, as shown in Fig. 4. To compare the simulation outcomes with the theoretical results, the calculation results (based on Eq. (3)) are also presented. One can find that the simulation outcomes fit quite well with the calculated results. From the simulation and calculation results above, one can reasonably conclude as follows: 1. The initial energy modulation in the longitudinal phase space can result in symmetric sidebands near the seed spectrum. 2. The power ratio between sideband and seed has a sustainable growth along the second undulator. 3. 3-D simulations of the sideband evolution along the FEL undulator fit quite well the theoretical analysis in the high gain regime.

To illustrate the sideband formation process for an actual electron beam, one more practical case utilizing a frequency chirped energy modulation is also performed. According to the theoretical analysis, a frequency chirped initial energy modulation should result in a pedestal-like sideband, as that has been observed in the experiments. As shown in Fig. 5, the electron beam is modulated with a chirp at the wavelength

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