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NUMERICAL SIMULATION OF PHASE SHIFT METHOD FOR FEL POWER ENHANCEMENT IN PAL-XFEL*

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Abstract

Recently the phase jump method for efficiency enhancement in free-electron laser (FEL) was proposed [1]. One of the unique features of PAL-XFEL with phase shifters may be taken for the demonstration of this phase jump scheme. In this paper we numerically investigate the scheme using the three-dimensional numerical simulation code GENESIS [2]. The physical parameters are based on the hard x-ray line of PAL-XFEL [3]. The preliminary simulation results indicate that this phase jump scheme can enhance about four times the FEL output power performance for the untapered case at 4 keV. Combination of this scheme with undulator tapering is also discussed in this paper.

INTRODUCTION

Generating an intense high-power x-ray free electron laser (FEL) can be of great interest, e.g., the peak power at the level of terawatt (TW) or sub-TW, since such power level of output radiation has stimulated numerous experiments in various scientific areas. The output characteristics of FEL are determined by its operation modes. In the x-ray wavelength regime a single-pass high-gain FEL can work either in the Self-Amplified Spontaneous Emission (SASE) or seeded mode (or self-seeding). Up to the end of exponential growth in the short-wavelength single-pass FEL, the power efficiency is about ρ (the Pierce or FEL parameter, usually smaller than 1×10^{-3} for x-ray FELs), indicating that the output peak power can be only $P_{\rm rad} \approx \rho P_{\rm beam}$ (with $P_{\rm beam}$ the electron beam power) ~25 GW for an electron beam with a typical peak current ~5 kA and the nominal energy of several GeV in a ~100-m-long untapered undulator. There is still a factor of 20-40 before reaching the aforementioned sub-TW or TW power level. Dedicated undulator taperings are a typical technique for power enhancement [4] and recently the efficiency enhancement based on a phase jump method is also proposed [1, 5]. In this paper we will investigate the latter based on the hard x-ray line of Pohang Accelerator Laboratory x-ray FEL (PAL-XFEL) [3]. One of the unique features of PAL-XFEL is its phase shifters within every undulator breaks. Such an advantage may be taken for the demonstration of this phase jump scheme.

CONCEPT OF PHASE JUMP METHOD

Recently the phase shift method for efficiency enhancement in the post-saturation regime of a single-pass untapered free-electron laser (FEL) was proposed [1]. The working principle is to utilize the phase shifters, located between undulator segments, to fine tune the phase space or ponderomotive bucket center to point the microbunched electron beam (or the barycenter of the electron phase space density distribution) towards the deceleration quadrant. Then in the subsequent undulator segment the electron beam energy can transfer to the radiation field and the field energy continues to grow. The starting location of the phase shift method should be initiated where the bunching factor peaks, usually at the first or initial saturation location. The optimized output performance may be obtained by fine adjusting the location of the initial phase shift at different photon energies. The interested readers are referred to Ref. [1] for more details.

From the above argument we assume that between two consecutive phase shifters the microbunched electron synchrotron motion (or a macroparticle rotating in the phase space) should not exceed a quarter of the full cycle. Specifically it should not cross from the second quadrant to the third one, according to the convention made in Ref. [1]. Therefore such a scheme is limited by the electron synchrotron motion in the phase space. The electron synchrotron motion, corresponding to the rotation in the longitudinal phase space, is driven or trapped by the joint potential due to the external undulator magnetic field and the radiation field. The small-amplitude synchrotron oscillation frequency can be related to the amplitude of the radiation field as follows [1]

$$\Omega_{\rm syn} \approx \sqrt{\frac{e\,|E_0|\,K[JJ]k_U}{\gamma_0^2 mc^2}} \tag{1}$$

where e and m are the magnitude of the electron charge and rest mass, E_0 is the amplitude of the instantaneous radiation field, K is the peak undulator parameter, $[JJ]$ is the coupling factor (1 for the helical undulator and $J_0(\xi) - J_1(\xi)$ with $\xi = K^2/(4 + 2K^2)$ for the planar undulator), $k_U = 2\pi/\lambda_U$ is the undulator wavenumber, and γ_0 is the Lorentz relativistic factor of the electron beam.

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From Eq. (1) it can be seen that as the field gains energy the growing field amplitude leads to faster and faster electron synchrotron motion. Within a fixed length of the undulator segment, the accumulated electron phase (with respect to the radiation field) becomes larger as the radiation field grows and may enter the undesired acceleration regime, where the electron beam gains energy from the radiation field. Therefore for the phase shift method to be effective we require the length of the undulator segment should be shorter than that corresponding to a quarter of the synchrotron oscillation period. That is,

$$L_{\rm segm} < L_{\rm sync}(z)/4 \tag{2}$$

Before ending this section we note that the dependence of $\Omega_{\rm syn}$ also goes to $\sqrt{K}$ and inversely to γ_0.

NUMERICAL RESULTS

In this section we will use the three-dimensional numerical simulation code GENESIS [2] to investigate the phase shift scheme. We take PAL-XFEL beam and undulator system [3] as an example. Table 1 summarizes the relevant beam, undulator and radiation parameters. The FEL operation mode can be SASE or seeded (self-seeding). The current undulator system consists of 20 planar undulators, with 4.94 m for each undulator segment and made with variable gaps. The variable undulator gaps enable the undulator tapering up to 15%. Here we only utilize a total ratio of 7% (quadratic) tapering throughout the undulator system. Phase shifters are installed between two consecutive undulator segments in the hard x-ray line. For simplicity, we only consider the steady state in this paper. It is straightforward to implement the phase shift scheme in the numerical simulation. At every phase shift section (or drift section) the phase difference between the electron beam and the radiation field can be fine tuned by adjusting its equivalent K value by noting the relation below

$$\frac{1+K^2_{\rm AD,rms}(z)}{1+K^2_{\rm AW,rms}(z)} k_U L^{PS} = m\pi,\ 0 \leqslant m \leqslant 2 \tag{3}$$

where $K_{\rm AW,rms}$ and $K_{\rm AD,rms}$ are the rms K values of the undulator and the drift sections used in GENESIS ($K_{rms} = K\big/\sqrt{2}$), $L^{\rm PS}$ is the length of the phase shifter, and m is an integer between 0 and 2.

It is found that, in the presence of a single phase shifter, as the phase difference changes from 0 to 2π, the output radiation power exhibits a sinusoidal dependence. This can be expected because the electron beam may undergo a complete cycle from a deceleration phase to acceleration phase, and vice versa. The simulation results confirm the sinusoidal dependence and are shown in Fig. 1.

Let us first consider the SASE untapered case. The output power performance, after a proper arrangement of phase shifters, exhibits a factor of 4 enhancement, as shown in Fig. 2. In the figure the light-red curve is obtained with all the phase shifters set to 0 (or 2π) phase difference between the electron beam and the radiation field, while the light-blue curve represents the case with optimized phase shifters. For the seeded case, we find that the results do not make much difference except for earlier occurrence of initial saturation. The factor of 4 power enhancement will be further discussed later in this section.

Table 1: Electron beam and undulator parameters used in the simulation. These numbers are largely based on PAL-XFEL hard x-ray line.

Name	Value	Unit
Electron beam energy	5.885	GeV
RMS fractional energy spread	1.74×10^{-4}	
Peak current	4	kA
Normalized emittance	0.4	μm
Average beta function	11.5	m
Undulator parameter K_0 (peak)	2.08	
Undulator period	2.6	cm
Undulator section length	$190\lambda_u \approx 4.94$	m
Input seed power	500	kW
Resonance wavelength	3.1/4	Å/keV
First saturation power	~20	GW
Pierce parameter	1×10^{-3}	

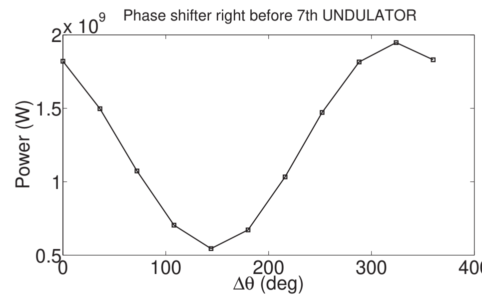

Figure 1: Sinusoidal dependence of the resultant FEL peak power as a function of phase difference between electron beam and the radiation field.

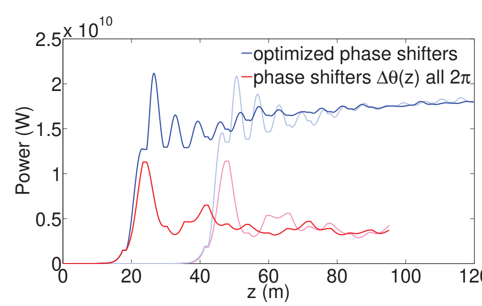

Figure 2: The output peak power as a function of z. The blue and red curves correspond to the optimized and all-2π cases, respectively.

Let us now consider application of the phase shift method in the tapered case. We begin from a pre-determined taper profile. The taper profile is obtained based on Y. Jiao et al. [6] algorithm. Optimization of the phase shifter elements was not incorporated. Given the taper profile we fine tune

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the phase shifters in the drift sections after $z = 20$ m and the resultant power gain curves are shown in Fig. 3. In the figure we find that the enhancement of the total power is significant (350 GW) compared with the untapered case (about 18 GW). However the improvement appears limited compared with the mere undulator tapering; only a factor of 1.17 power enhancement for blue and red curves shown in Fig. 3. It is still pending to conclude that the main contribution of the total power enhancement can be undulator tapering over the phase shift scheme since the provided taper profile is not optimized in the presence of both undulator tapering and the phase shifters.

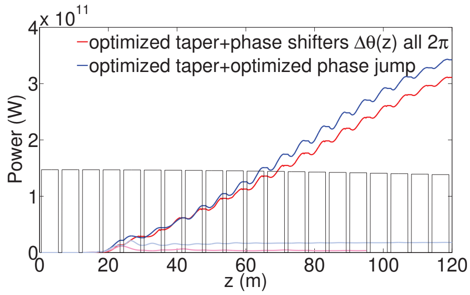

Figure 3: The output peak power as a function of z for the tapered case. Total taper ratio (7%) is obtained via multidimensional optimization algorithm according to Ref. [6].

Having taken a closer look at the power gain curves in Fig. 3, one might wonder that the output power may not be properly optimized, because of the presence of dip structures along z. After careful aligning the dip structure with the undulator segments, we find that the power dips occur within the undulator segments, instead of the drift sections. In fact one can see that within the phase shifter sections the corresponding z evolution of the power is flat. This should be expected because of the absence of beam-wave interaction in the drift sections.

Now let us come to discussion of the validity of such a phase shift scheme, i.e., Eq. (2). The amplitude of the radiation field at initial saturation location can be estimated by the following expression

$$|E_0| \approx \frac{\sqrt{120 P_{\text{sat}}[W]}}{\sigma_{x,e}} \approx \frac{\sqrt{120 \times 15GW}}{20\ \mu\text{m}} \approx 6.7 \times 10^{10} \frac{V}{m} \tag{4}$$

where we assume the electron beam and the radiation field are matched in the transverse extent. The initial saturation power is assumed to be 15 GW (see Fig. 2). Then we can estimate the synchrotron oscillation frequency by Eq. (1) and the corresponding synchrotron period

$$\Omega_{\text{syn}} \approx \sqrt{\frac{6.7 \times 10^{10} \frac{\text{eV}}{m} (2.08)(0.8025)\left(\frac{2\pi}{0.026}\right)}{5885\text{MeV} \times 11516.7}} \approx 0.63\ \text{m}^{-1} \tag{5}$$

Note that the estimated synchrotron period here can be the longest one. Therefore the estimate may be optimistic. From Eq. (2) we find that the undulator segment length should be within 2.5 m for such a phase shift scheme to be effective. To verify we presume the undulator segment length be halved throughout the whole undulator line, assuming other parameters remain the same. The focusing-defocusing quadrupoles within every undulator segment are rematched to the comparable level. Figure 4 illustrates a further improved output power performance for the halved undulator segment length. The results shown in the figure are not optimized because a better starting location of the phase shifter method may have changed and shall be adjusted. For the moment we have only done for one particular photon energy (4 keV) for the phase shift scheme. To end this section we comment that for such a scheme to enhance the FEL output power, a more comprehensive study shall be done for the photon energy spectrum that the hard x-ray line shall cover.

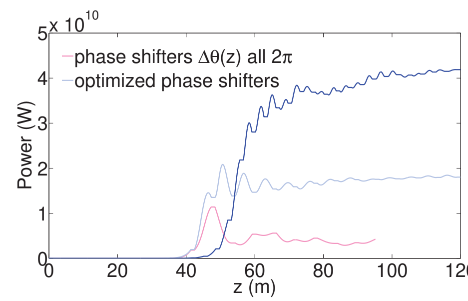

Figure 4: The output peak power as a function of z. The light-blue and light-red curves are identical to those shown in Fig. 2. The deep-blue curve represents the case with halved undulator segment length.

SUMMARY AND CONCLUSION

In this paper we have investigated the phase shift scheme explored recently in Refs. [1, 5] and applied to the PAL-XFEL hard x-ray line with a specific set of electron beam and undulator parameters. From the numerical simulation results we find that for untaperd case the output power can be enhanced by a factor of 4 for both SASE and seeded case, with the difference that the latter saturates at an earlier stage. We have also studied this scheme for a given taper profile and found that the major contribution to the total power is mainly from the undulator tapering. However the taper profile was optimized when the phase shifters set to 2π.

In terms of the effectiveness of the phase shift method, i.e., Eq. (2), it can be related to the electron synchrotron oscillation frequency, which depends on the amplitude of the (growing) radiation field. When the undulator segment length is relatively longer (than the corresponding synchrotron period) or the field amplitude gets larger, such a scheme shall become ineffective. Finally we note the above study is specific for 4 keV photon energy based on the phase shift scheme. We comment that for such a scheme to enhance the FEL output power, a more comprehensive study should be done for the photon energy spectrum that the hard x-ray line shall cover.

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