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Parameter optimization and start-to-end simulation for the phase-merging enhanced harmonic generation free electron laser

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ABSTRACT

Recently, a novel scheme called the phase-merging enhanced harmonic generation (PEHG) free-electron laser (FEL) has been developed to achieve higher harmonic bunching in a single stage set up. However, previous studies of the PEHG mechanism ignored the practical lattice configuration, leaving out the impact of the intrinsic beam divergence on the phase-merging effect. In this paper, a new method based on the beam transport matrix is proposed to comprehensively study the optimization conditions of the harmonic generation FELs. On the basis of this method, the new optimization conditions of the PEHG are obtained by taking into account both the intrinsic horizontal beam size and the intrinsic horizontal beam divergence. The parameter optimization and three dimensional start-to-end simulations are carried out using the typical beam parameters of the Shanghai Soft X-ray Free Electron Laser user facility. The simulation results are in agreement with the theoretical analysis and demonstrate the validity of the PEHG-FEL.

1. Introduction

High-gain free electron lasers (FELs) have made great progresses in recent years [1–3], which enables the cutting-edge research in many scientific frontiers [4,5]. Among them the seeded FELs, for example, the high gain harmonic generation (HGHG) [6,7] FEL and the echo-enabled harmonic generation (EEHG) [8] FEL, are very promising to produce fully coherent laser pulses from the deep ultraviolet down to the X-ray regime. At present, the experiments at FERMI based on the HGHG are quite successful [9]. As for the EEHG, the third, fourth, seventh and up to 75th harmonics of the seed laser have been demonstrated [10–13]. Typically, due to the seed laser's attribution in a seeded FEL, a smaller power fluctuation and a more stable output laser spectrum can be obtained with respect to the self-amplified spontaneous emission (SASE) FEL [14]. For seeded FELs, the HGHG scheme is relatively mature, in which an external seed laser is used to modulate the electron beam to generate the coherent micro-bunch and then initiate the emission process. Generally, in order to achieve a higher harmonic radiation in the HGHG, the energy modulation depth needs to be strengthened, which may result in the increase of the slice energy spread, and hence degrade the amplification process of FEL. Therefore it is hard to reach very short wavelengths in a single stage set up.

Recently, a novel scheme called the phase-merging enhanced harmonic generation (PEHG) was proposed to achieve higher harmonic bunching in seeded FELs [15,16]. In the PEHG, an electron beam with transverse dispersion passes through a transverse gradient undulator (TGU) [17], suffering different undulator K values. The electrons with different energy around the zero-crossing phase of the seed laser will gradually catch up with each other and merge into the same longitudinal position. The principle takes advantage of the transverse–longitudinal coupling of the electron beam, and it holds the promise of achieving higher harmonics bunching with no need of large energy modulation.

Generally a dogleg with dispersion η and a TGU with transverse gradient α are required to perform the phase-merging effect. The schematic layout of the initially proposed PEHG-FEL is shown in Fig. 1(a), consisting of a dogleg, a typical HGHG configuration and a TGU. The dogleg is used to introduce the transverse dispersion into the electron beam. The short TGU is needed for energy modulation and horizontal manipulation of the electron beam. A modified design shown in Fig. 1(b) is given later to perform these two functions separately by a normal modulator and a TGU, which would be much more flexible in practical operation [16]. In addition, two other schemes are proposed to achieve the "phase-merging" effect by modifying the dogleg and the dispersion section (DS) or by exploiting the natural field gradient of a

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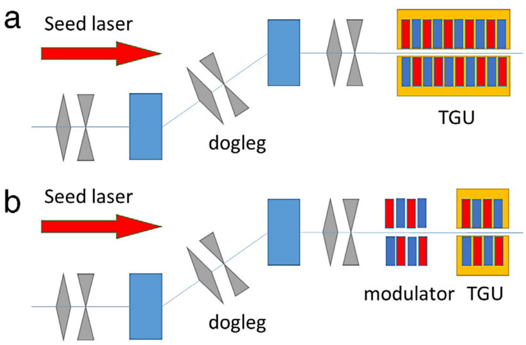

Fig. 1. (a) The initially proposed PEHG scheme with a TGU for both energy modulation and horizontal manipulation of the electron beam; (b) The modified PEHG scheme with a normal modulator and a TGU to perform these two functions separately.

normal undulator in the vertical direction [18,19]. Our studies in this paper are based on the scheme shown in Fig. 1(b).

Previous studies of the PEHG demonstrate that it is possible to reach very high harmonics in a single stage set up, meanwhile the slice energy spread of the electron beam can be kept relatively small. The results are based on the assumption that only the inherent beam size matters to the final phase-merging effects. However, the intrinsic beam divergence should also be taken into consideration since the length of all components in a practical FEL facility cannot be ignored. In this paper, we will give a comprehensive study of the principle of the PEHG-FEL.

The paper is organized as follows: Section 2 presents the theoretical analysis of the principle of the PEHG-FEL. The numerical simulations are carried out using the typical beam parameters of the Shanghai Soft X-ray Free Electron Laser user facility (SXFEL) [20,21]. The lattice configuration and the typical parameters of the SXFEL user facility are shown in Section 3, and the simulation results are discussed in Section 4. Finally a conclusion is given in Section 5.

2. Principle

To briefly demonstrate the principle of the PEHG-FEL, we adopt the simplified 4×4 dimensional linear beam transport matrix in $x - z$ plane, i.e.(x, x', z, p), in the following discussions. Here $p = (\gamma - \gamma_0)/\sigma_\gamma$ is the dimensionless energy deviation, and σ_γ is the energy spread. The transport matrix of dogleg is

$$R_D = \begin{bmatrix} 1 & L_d & 0 & \eta \\ 0 & 1 & 0 & 0 \\ 0 & \eta & 1 & \xi_d \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

where L_d represents R_{12} in the matrix, η and ξ_d are respectively the dispersion and the momentum compaction generated by the dogleg. The energy modulation with an amplitude $A = \Delta_\gamma/\sigma_\gamma$ is generally $p_1 = p_0 + A\sin(k_s z)$, where Δ_γ is the energy deviation introduced in the modulator. Considering that within one seed wavelength range, the electrons near the zero-crossing phase gets a quasi-linear energy chirp $h = k_s A$, thus the energy of these electrons can be simply written as $p_1 = p_0 + hz$. Then the corresponding transport matrix for this part of electron beam can be derived as

$$R_M = \begin{bmatrix} 1 & L_m & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & h & 1 \end{bmatrix} \quad (2)$$

with a total length L_T, a transverse gradient α and a central undulator parameter K_0, the transport matrix of a TGU can be approximately given by

$$R_{TGU} \approx \begin{bmatrix} 1 & L_T & 0 & \tau L_T/2 \\ 0 & 1 & 0 & \tau \\ \tau & \tau L_T/2 & 1 & \tau^2 L_T/6 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

where $\tau = \alpha L_T K_0^2/2\gamma_0^2$ is the transverse gradient parameter of the TGU with the central energy γ_0 the electron beam. Besides, the transport matrix of the dispersion section (DS) with length L_c and momentum compaction factor ξ_c is typically

$$R_C = \begin{bmatrix} 1 & L_c & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & \xi_c \\ 0 & 0 & 0 & 1 \end{bmatrix}. \quad (4)$$

The transport matrix for the whole beam line shown in Fig. 1(b) is

$$M = R_C.R_{TGU}.R_M.R_D \quad (5)$$

which can be written as

$$\begin{bmatrix} 1 & L_d + L_m + L_T + L_c + h\eta\tau(L_T/2 + L_c) & h\tau(L_T/2 + L_c) & \eta + \tau(L_T/2 + L_c)(1 + h\xi_d) \\ 0 & 1 + h\eta\tau & h\tau & \tau(1 + h\xi_d) \\ \tau & \eta(1 + h\xi_c) + \tau(L_d + L_m + L_T/2) & 1 + h\xi_c & \xi_c + \eta\tau + \xi_d(1 + h\xi_c) \\ 0 & h\eta & h & 1 + h\xi_d \end{bmatrix}. \quad (6)$$

To enhance the high harmonic bunching, the electrons should merge into the same longitudinal position as well as possible, which means the items in the third row of Eq. (6) should be as small as possible. Therefor we can obtain the optimization conditions of the PEHG-FEL

$$\begin{cases} 1 + h\xi_c = 0 \\ \xi_c + \eta\tau = 0 \end{cases} \quad (7)$$

then the whole transport matrix becomes

$$\begin{bmatrix} 1 & L + L_T + 2L_c & L_T/2h\tau & \eta + \tau L_0(1 + h\xi_d) \\ 0 & 2 & h\tau & \tau(1 + h\xi_d) \\ \tau & \tau L & 0 & 0 \\ 0 & h\eta & h & 1 + h\xi_d \end{bmatrix} \quad (8)$$

where

$$\begin{cases} L = L_d + L_m + L_T/2 \\ L_0 = L_T/2 + L_c \end{cases}. \quad (9)$$

The drift spaces between components are ignored for simplicity.

Under the optimization conditions, one can find that the bunching factor of the PEHG-FEL is eventually determined by two parts: one is the product of τ and the initial horizontal beam size σ_x, and another is the product of τ and the initial horizontal beam divergence $\sigma_{x'}$ together with the length L. According to the analysis above and the preliminary studies (see Ref. [16]), the bunching factor of the PEHG-FEL at the nth harmonic becomes

$$b_n = J_n[nAB]e^{-(1/2)n^2(T_1^2+T_2^2)} \quad (10)$$

with

$$\begin{cases} A = \dfrac{\Delta\gamma}{\sigma_\gamma} \\ B = \dfrac{\xi_c k_s \sigma_\gamma}{\gamma_0} \\ T_1 = k_s \tau \sigma_x \\ T_2 = k_s \tau L \sigma_{x'} \end{cases} \quad (11)$$

where A is the energy modulation depth, B is the dimensionless strength of the dispersion section (DS) and k_s is the wave number of the seed laser. The bunching factor b_n given in Eq. (10) is quite different from the initial one in Ref. [16]. And it will reduce to the original formula when $L = 0$.

According to Eqs. (10) and (11), for a given electron beam with an initial horizontal emittance ϵ_x, ignoring the correlation of $x - x'$, the