DESIGN STUDY FOR THE PEHG EXPERIMENT AT SDUV-FEL*

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Abstract

In this paper, design studies for the proof-of-principle experiment of the recently proposed phase-merging enhanced harmonic generation (PEHG) mechanism are presented. A dogleg and a new designed transverse gradient undulator should be added in the undulator system of SDUV-FEL to perform the phase-merging effect. With the help of 3D simulation codes, we show the possible performance of PEHG with the realistic parameters of SDUV-FEL.

INTRODUCTION

High-gain seeded FEL schemes have been developed for producing stable and fully temporal coherence laser pulse from deep UV down to the x-ray regime. The most famous frequency up-conversion scheme is so called the high-gain harmonic generation (HGHG) [1], which uses an external laser pulse to interact with the electron bunch for the generation of coherent micro-bunching. The property of HGHG output is a direct map of the seed laser's attributes, which ensures high degree of temporal coherence and small pulse energy fluctuations with respect to self-amplified spontaneous emission (SASE) [2]. However, significant bunching at higher harmonics usually needs to strengthen the energy modulation in HGHG, which will result in a degradation of the amplification process of FEL. Thus the requirement of FEL amplification on the beam energy spread prevents the possibility of reaching short wavelength in a single stage HGHG.

Recently, a novel seeded FEL scheme termed phase-merging enhanced harmonic generation (PEHG) [3, 4], has been proposed for significantly improving the frequency up-conversion efficiency of harmonic generation FELs. Generally, a transversely dispersed electron beam and a transverse gradient undulator (TGU) [5] are needed in PEHG for performing the phase-merging effect purpose: when the transversely dispersed electrons passage through the TGU, around the zero-crossing of the energy modulation, electrons with the same energy will merge into a same longitudinal phase.

Several ways have been proposed [3, 4, 6] for performing the phase-merging effect as shown in Fig. 1, where doglegs are added before modulators for transversely dispersing the electron bunch. Fig. 1(a) shows the initial proposed PEHG scheme, where a short TGU is used for the energy modulation and to precisely manipulate the electrons in the horizontal dimension. It is found later that these two functions of TGU can be separately performed by employing a modified design, as shown in Fig. 1 (b). In this scheme, a normal modulator is used for the energy modulation, and the TGU is responsible only for transverse manipulation of the electrons, a design that will be much more flexible for practical operation. Fig. 1(c) shows a much simpler scheme that adopts a normal modulator and a wave-front tilted seed laser pulse to realize the phase-merging effect. Analytical and numerical investigations indicate that all these three schemes have the potential of generating ultra-high harmonic bunching factor with a relatively small energy modulation. To demonstrate these theoretical predictions, a proof-of-principle experiment for PEHG has been planned at Shanghai deep ultraviolet free-electron laser facility (SDUV-FEL) [7, 8]. In this paper, we present the design studies for this experiment.

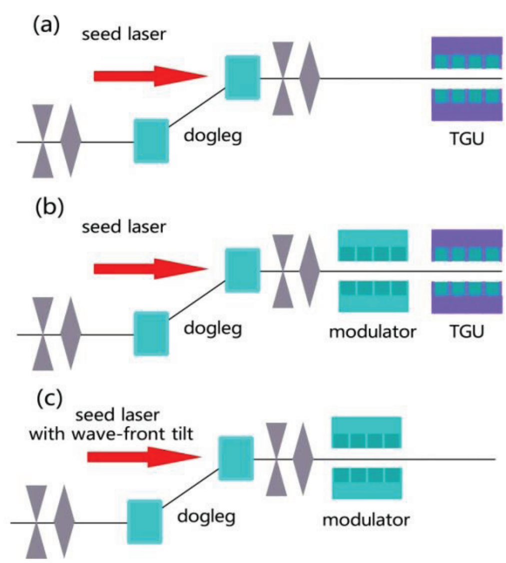

Figure 1: Modulation schemes for PEHG.

LAYOUT AND MAIN PARAMETERS

The SDUV-FEL is an integrated multi-purpose test facility for seeded FEL principles, capable of testing various seeded FEL working modes. A new beam line will be added after the linac of SDUV-FEL for the PEHG and Thomson scattering experiments in this year. The layout of the PEHG experiment is shown in Fig. 2. A dogleg is adopted for switching the electron bunch and introducing a large transverse dispersion into the electron beam. After that, a conventional modulator and a new designed TGU, as shown in Fig. 3, are employed for energy modulation and manipulating the electron beam. The energy modulation will be converted to density modulation by the dispersion section (DS). Then the coherently bunched beam is sent through the radiator for high harmonic radiation.

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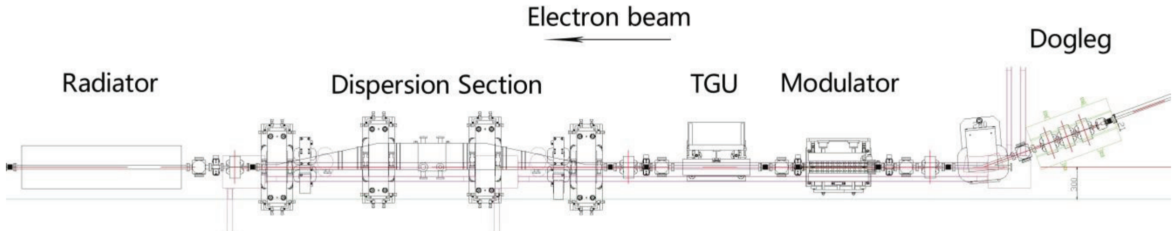

Figure 2: Layout for the PEHG experiment at SDUV-FEL.

One can find that the undulator beam line in Fig. 2 is suitable for testing all the three modulation schemes in Fig. 1. Here we only present the design and simulation results for the second scheme (Fig. 1(b)), which is the most flexible scheme for PEHG.

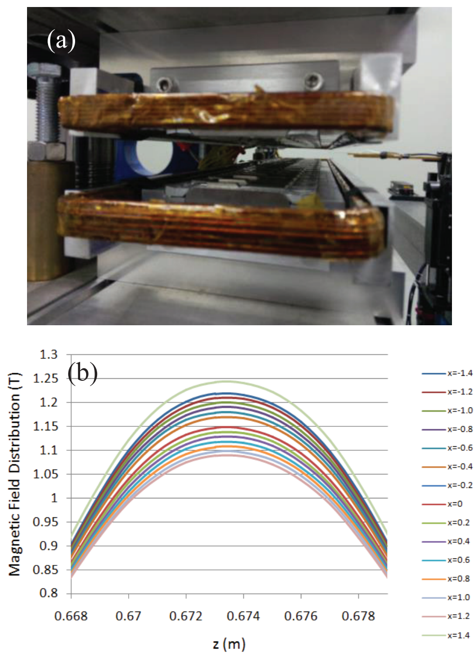

Figure 3: (a) The TGU for PEHG experiment. (b) Measurement results of magnetic field distributions for different transverse position of TGU.

To roughly estimate the optimal parameters of the PEHG experiment, here we adopt the 4-dimensional linear beam transport matrix in the *x-z* plane, i.e., (x, x', z, δ) is used in the following. The 4×4 beam transport matrix for the dogleg is

$$\boldsymbol{R}_D = \begin{pmatrix} 1 & L_D & 0 & \eta \\ 0 & 1 & 0 & 0 \\ 0 & \eta & 1 & \xi_D \\ 0 & 0 & 0 & 1 \end{pmatrix}, \quad (1)$$

where L_D is the length of the dogleg, η and ξ_D are, respectively, the dispersion and the momentum compaction generated in the dogleg. We ignore the effects of ξ_D hereafter.

When an electron beam with central beam energy γ_0 is sent through a TGU with total length L_T, transverse gradient α and central undulator parameter K_0, the transport matrix of the short TGU approximately reads:

$$\boldsymbol{R}_T \approx \begin{pmatrix} 1 & L_T & 0 & 0 \\ 0 & 1 & 0 & -\tau \\ \tau & \tau L_T/2 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}, \quad (2)$$

where $\tau = L_T K_0^2 \alpha / 2\gamma_0^2$ is the transverse gradient parameter of the TGU. Then the transport matrix for the whole beam line including all components shown in Fig. 1(b) can be written as

$$\boldsymbol{R} = \begin{pmatrix} k_1 & k_2 & 0 & a_2\eta \\ k_3 & k_4 & -h\tau & c_2\eta - \tau \\ k_1\tau + c_1\eta(1+h\xi_c) & k_2\tau + d_1\eta(1+h\xi_c) & 1+h\xi_c & \xi_c + a_2\eta\tau \\ c_1 h\eta & d_1 h\eta & h & 1 \end{pmatrix}, \quad (3)$$

where a, b, c, d are beam matching parameters, $k_1 = a_1 a_2 + b_2 c_1$, $k_2 = a_2 b_1 + b_2 d_1$, $k_3 = a_1 c_2 + c_1 d_2 - c_1 h\eta\tau$, $k_4 = b_1 c_2 + d_1 d_2 - d_1 h\eta\tau$, $a_1 d_1 - b_1 c_1 = 1$, $a_2 d_2 - b_2 c_2 = 1$, h is the seed laser induced energy chirp around the zero-crossing of the energy modulation and ξ_c is the momentum compaction of the DS. For simplify, we choose $a_1 = a_2 = d_1 = d_2 = 1$ and $b_1 = b_2 = c_1 = c_2 = 0$ here, then the Eq. (3) can be re-written as

$$\boldsymbol{R} = \begin{pmatrix} 1 & 0 & 0 & \eta \\ 0 & 1-h\eta\tau & -h\tau & -\tau \\ \tau & \eta(1+h\xi_c) & 1+h\xi_c & \xi_c + \eta\tau \\ 0 & h\eta & h & 1 \end{pmatrix}, \quad (4)$$

The density modulation of a high harmonic generation scheme is an optical-scale micro-bunch compression process. To maximize the high harmonic bunching factor, $1 + h\xi_c = 0$ should be satisfied first, and the optimized condition for the phase-merging effect is $\xi_c + \eta\tau = 0$. Under these optimized conditions, the bunching factor will be only affected by the product of τ and the initial horizontal beam size σ_x according to Eq. (4). From Eq. (3), one can also find that the required value of η and τ for performing the phase-merging effect can be significantly reduced by changing the values of a_1 and a_2. The optimal parameters for the PEHG experiment are summarized in Table 1.

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Table 1: Main Parameters for PEHG Experiment

Parameters	Value
Beam energy	160 MeV
Slice energy spread	48 keV
Normalized emittance	3 μmrad
Bunch charge	300 pC
Peak current	100 A
η of dogleg	1 m
Seed wavelength	2500 nm (from OPA)
Seed pulse length	1 ps (FWHM)
Period of TGU	60 mm
L_T of TGU	0.6 m
α of TGU	-43.5 m^{-1}
K_0 of TGU	5
ξ_c of DS	1 mm
Radiation wavelength	250 nm
Period of radiator	25 mm
Length of radiator	1.5 m

SIMULATIONS

With parameters shown in Table 1, we carried out 3D simulations for the PEHG experiment. ASTRA [9] is used for tracking the particle from the cathode to the injection point to the linac. Then the electron beam is tracked through the main accelerator with help of ELEGANT [10] taking into account of the CSR and the space charge effects. The energy of the electron beam is around 160 MeV at the exist of the linac, the peak current after bunch compression is about 100 A, and the slice energy spread in the central part of the electron beam is around 2 keV. This kind of small energy spread will result in a large bunching factor at low harmonic numbers for both HGHG and PEHG.

The key advantage of the PEHG is that it can generate very high harmonics with harmonic number much larger than the ratio of energy modulation to energy spread. This makes it possible to generate very high frequency bunching while simultaneously keeping the beam energy spread small. However, limited by the beam energy and period length of the radiator, generation of ultra-high harmonic radiation is not possible at SDUV-FEL. An alternative way to demonstrate the superiority of PEHG over HGHG is to increase the initial slice energy spread. In this design, we adopt a Nd:YLF laser at 1047 nm to heat the electron beam energy spread before the dogleg. After this laser heater, the slice energy spread is increased to about 48 keV.

The energy and density modulation processes are tracked with a modified version of GENESIS [11]. For comparison purpose, we carried out simulations for both HGHG and PEHG. The only difference for these two simulations is set $\alpha = 0$ or $\alpha = -43.5m^{-1}$. The longitudinal phase space distributions in a small fragment of the electron bunch are shown in Fig. 4. Different from a conventional HGHG, most of the electrons are compressed into a small region around the zero-phase in PEHG, which indicates that the density modulation has been significantly enhanced for high harmonics, as shown in Fig. 5. The 10th harmonic bunching factor of HGHG is at the shot noise level.

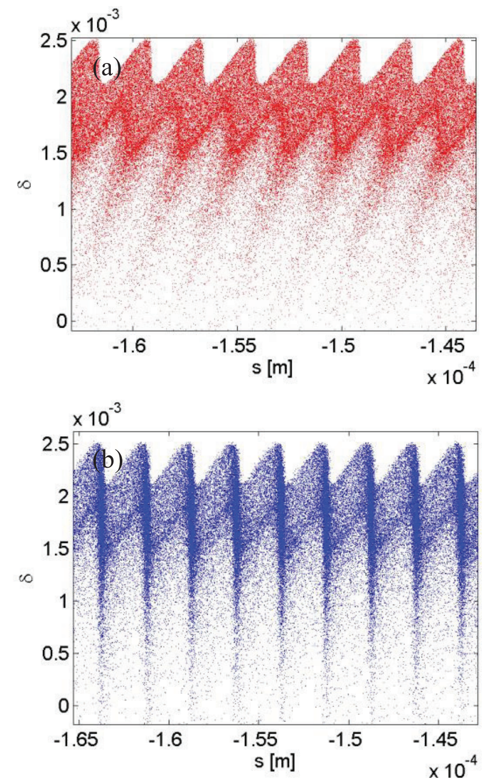

Figure 4: Phase space distributions in the central part of electron beam for (a) HGHG and (b) PEHG.

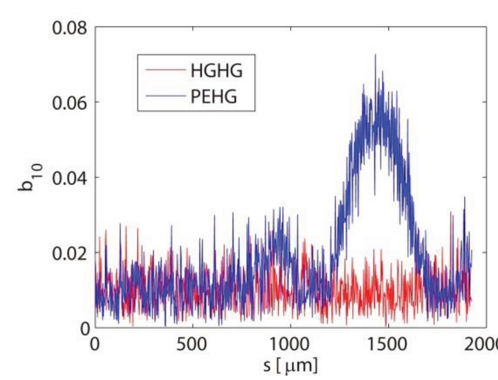

Figure 5: Comparison of 10th harmonic bunching factor distributions along the electron bunch for HGHG and PEHG.

The bunched electron beams are then sent through a short radiator resonant at 250 nm for the generation of coherent signals at 10th harmonic of the seed. Simulations results of the radiation pulses and single-shot spectra for HGHG and PEHG are shown in Fig. 6. The output pulse

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energy of PEHG is much higher than HGHG at 10th harmonic and the spectrum bandwidth of PEHG is quite close to the transform limit.

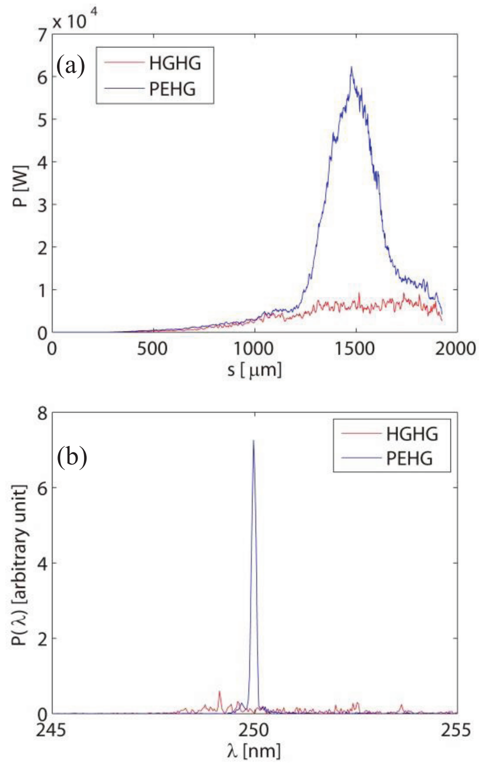

Figure 6: Comparisons of 10th harmonic radiation pulses (a) and spectra (b) for HGHG and PEHG.

CONCLUSION

In conclusion, we present design studies of a proof-of-principle experiment for PEHG based on the upgraded SDUV-FEL. With a new designed dogleg and a TGU, all the three modulation schemes for PEHG can be demonstrated at SDUV-FEL. Theoretical analysis and numerical simulations are given to shown the parameter optimization method and possible performance of PEHG. The coherent signal of PEHG at 250 nm with pulse energy much larger than HGHG can be obtain by properly choosing the parameters of the machine. The upgrade of SDUV-FEL will be finished in this year and the commissioning of PEHG will be started in the next year.

REFERENCES

[1] L.H. Yu, Phys. Rev. A, 44 , 5178 (1991).
[2] A. M. Kondratenko, E. L. Saldin, Part Accel. 10, 207 (1980).
[3] H. Deng, C. Feng, Phys. Rev. Lett. 111, 084801 (2013).
[4] C. Feng, H. Deng, D. Wang, Z. Zhao, New J. Phys. 16, 043021 (2014).
[5] Z. Huang, Y. Ding, C.B. Schroeder, Phys. Rev. Lett. 109 204801 (2013).
[6] C. Feng, T. Zhang, H. Deng, Z. Zhao Phys. Rev. ST Accel. Beams 17, 070701 (2014).
[7] Z. Zhao, *et al*. Nucl Instr Meth A, 528, 591 (2004).
[8] H. Deng, Nucl. Sci. Tech. 25, 010101 (2014).
[9] K. Floettmann, ASTRA User's Manual.
[10] M. Borland, Phys. Rev. STAccel. Beams 4, 070701 (2001).
[11] S. Reiche, Nucl Instr Meth A, 429, 243−248 (1999).

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