Operating the SDUV-FEL with the echo-enabled harmonic generation scheme*

CHEN Jian-Hui(陈建辉)[1,2] DENG Hai-Xiao(邓海啸)[1,2] GU Qiang(顾强)[1] LI Dong-Guo(李冬国)[1] WANG Dong(王东)[1] ZHANG Meng(张猛)[1,2] ZHAO Zhen-Tang(赵振堂)[1;1)]

1 (Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China)
2 (Graduate University of Chinese Academy of Sciences, Beijing 100049, China)

Abstract Using the recently proposed echo-enabled harmonic generation (EEHG) free-electron laser (FEL) scheme, it is shown that operating the Shanghai deep ultraviolet FEL (SDUV-FEL) with single-stage to higher harmonics is very promising, with higher frequency up-conversion efficiency, higher harmonic selectivity and lower power requirement of the seed laser. The considerations on a proof-of-principle experiment and expected performance in SDUV-FEL are given.

Key words SDUV-FEL, HGHG, EEHG

PACS 41.60.Cr, 41.75.Ht, 42.65.Ky

1 Introduction

The free-electron laser (FEL) holds the promise to generate a short, high intense radiation pulse at a well-defined, tunable frequency. FELs can be operated in several different schemes. The most promising ones are based on self-amplified spontaneous emission (SASE)[1], and on high-gain harmonic generation (HGHG)[2—4]. A SASE source can produce very high brilliant X-ray pulses, but with poor temporal coherence and high intrinsic shot-to-shot fluctuations. In contrast, HGHG can deliver coherent optical pulses with tailored temporal and spectral profiles[3, 4]. Several projects are currently under development worldwide[5—7] with the aim of providing users with new bright and coherent light sources in the VUV and soft X-ray spectral regions. However the frequency up-conversion efficiency is limited to a small number due to the large energy modulation required and shot noise degradation[8, 9]. In recent years, there has been a growing interest in improving the up-frequency conversion efficiency, and a number of double modulator schemes are proposed[10—12], among which the echo enhanced harmonic generation (EEHG) scheme[12] has unprecedented up-frequency conversion efficiency and allows for the generation of ultrahigh harmonic with relatively smaller energy modulation.

The Shanghai deep ultraviolet FEL (SDUV-FEL) is an HGHG FEL user facility designed for generating coherent output with wavelength down to the deep UV region[5]. The SDUV-FEL is currently under construction. It is found that SDUV-FEL is well suited for the EEHG scheme with only minor modifications. In this paper, operating the SDUV-FEL with the EEHG is explored and the plan for proof-of-principle experiments is described with the expected performance outlined.

2 Principles of EEHG FEL

In contrast to the conventional HGHG FEL scheme, the EEHG FEL scheme is composed of two modulators, two dispersive sections (DS) and a radiator, as shown in Fig. 1. The frequencies of the first and second modulators can be different. The first dispersion section is chosen such that the energy modulation induced in the first modulator is macroscopically smeared out. At the same time, this smearing introduces a complicated fine structure into the phase

Received 31 December 2008

* Supported by Major State Basic Research Development Program of China (2002CB713600)

1) E-mail: zhaozt@ssrc.ac.cn

space of the beam. The echo then occurs as a recoherence effect caused by the mixing of the correlations between the modulation in the second modulator and the structures imprinted onto the phase space by the combined effect of the first modulator and the first dispersion section.

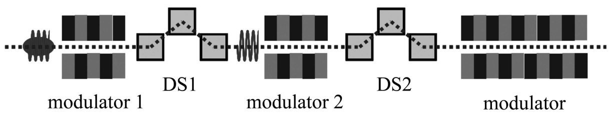

Fig. 1. Scheme of EEHG FEL.

Assuming an initial Gaussian beam energy distribution with variance σ_{E}^2, and using the variable $p=(E-E_0)/\sigma_{\mathrm{E}}$, the initial distribution function of the beam, normalized by unity, is

$$f_0(p)=\frac{N_0}{\sqrt{2\pi}}\exp\left(-\frac{p^2}{2}\right), \tag{1}$$

where N_0 is the number of particles per unit length.

After passing through the modulator and DS, we have,

$$p'=p+A\sin\kappa z\,, \tag{2}$$

$$z'=z+R_{56}p'\sigma_{\mathrm{E}}/E_0\,, \tag{3}$$

and the beam distribution becomes,

$$f(\zeta,p)=f_0(p-A\sin(\zeta-Bp)), \tag{4}$$

where $A=\Delta E/\sigma_{\mathrm{E}}$, $B=R_{56}\kappa\sigma_{\mathrm{E}}/E_0$, $\kappa=\omega/c$ and $\zeta=\kappa z$.

The final distribution function at the exit of the second dispersion section can be easily found by applying two consecutive transformations described by Eq. (2) and (3). The resulting final distribution function is,

$$f(\zeta,p)=\frac{N_0}{\sqrt{2\pi}}\exp\Big[-\frac{1}{2}\big(p-A_2\sin(K\zeta-KB_2p+\phi)- A_1\sin(\zeta-(B_1+B_2)p+ A_2B_1\sin(K\zeta-KB_2p+\phi))\big)^2\Big], \tag{5}$$

where now $\zeta=\kappa_1 z$, $B_1=R_{56}^{(1)}\kappa_1\sigma_{\mathrm{E}}/E_0$, $B_1=R_{56}^{(2)}\kappa_1\sigma_{\mathrm{E}}/E_0$ and $K=\kappa_2/\kappa_1$.

Integration of f over p gives the distribution of the beam density N as a function of the coordinate. For a practical case, with equal wavelength for both modulators, the bunching factor for the k-th harmonics reads[4],

$$b_k=2\left|\sum_{m=-\infty}^{\infty}\mathrm{e}^{\mathrm{i}m\phi}J_{-m-k}(A_1((m+k)B_1+kB_2)\times J_m(kA_2B_2)\mathrm{e}^{-\frac{1}{2}((m+k)B_1+kB_2)^2}\right|. \tag{6}$$

As an example, we show that the 24th harmonics of the seed laser can be generated with small energy modulation with dimensionless parameters: $A_1=3$, $A_2=1$, $B_1=26.8$, $B_2=1.14$.

The longitudinal phase space evolution in the EEHG scheme is shown in Fig. 2.

The density modulation before entering the radiator (i.e. (d) in Fig. 2) is shown in Fig. 3, with 24 peaks clearly shown.

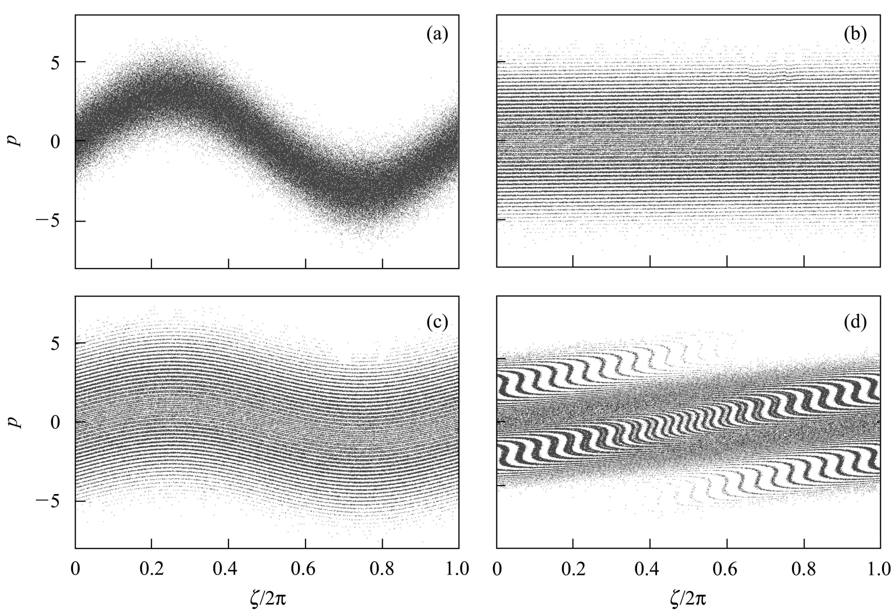

Fig. 2. Longitudinal phase space evolution: (a) after the first modulator; (b) after the first DS; (c) after the second modulator; and (d) after the second DS.

The bunching factor versus harmonic number from Fig. 3 is shown in Fig. 4, which agrees well with the prediction from Eq. (6).

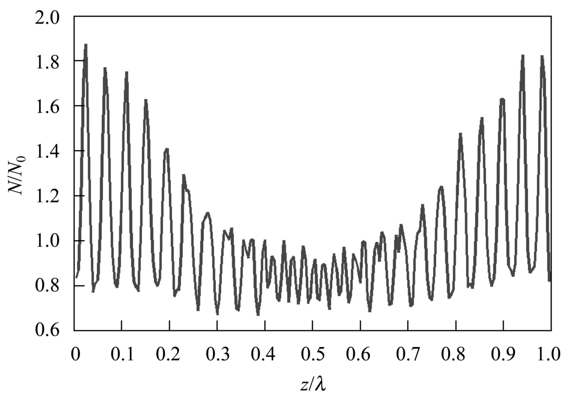

Fig. 3. Density modulation in one period of the seed laser.

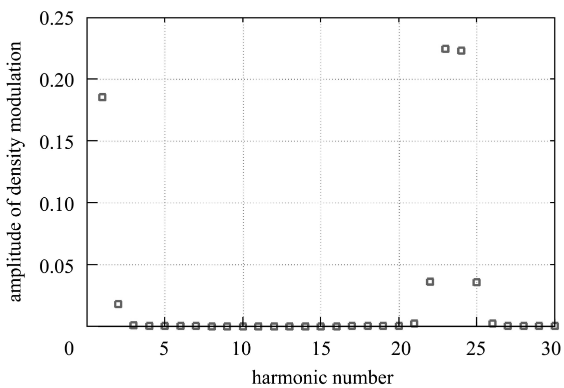

Fig. 4. Bunching factor vs. harmonic number.

In order to get more practical feelings of the bunching factor sensitivity to the machine parameters, we scan the DS parameters (B_1 and B_2). It is shown, in Fig. 5, that the 24th bunching factor remains within 10% deviation from 0.2 to 0.22 (relativity much higher than the conventional HGHG FEL scheme) even with 1% B_1 and/or B_2 deviation.

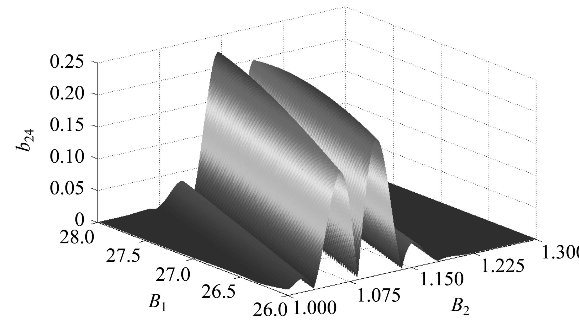

Fig. 5. Bunching factor sensitivity versus DS parameters.

3 SDUV-FEL with the EEHG scheme

With necessary modifications to the original design[5], it is possible to operate the SDUV-FEL with the EEHG scheme, as shown in Fig. 6. Another modulator is added. The original laser injection chicane is redesigned to produce larger R_{56}. The seed laser is split into two beams for the two modulators. One more laser injection port is added near the linac exit. In order to demonstrate well and characterize the EEHG scheme in comparison with the conventional HGHG scheme, it is determined to first operate both schemes in the same harmonics, i.e., the 4th harmonics of the seed laser.

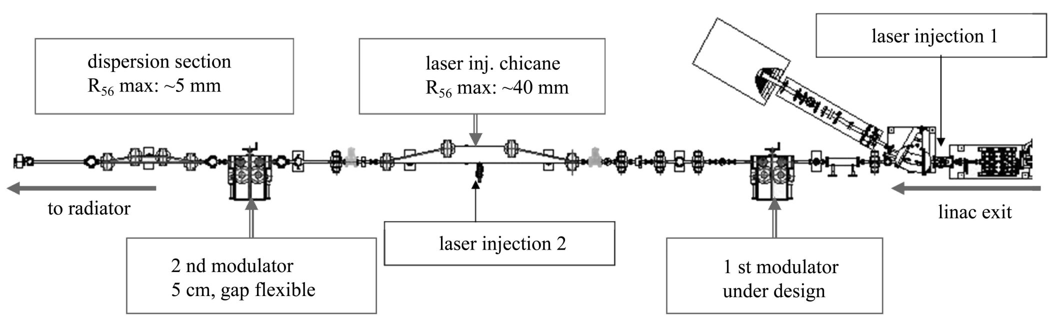

Fig. 6. Layout of the double modulator section of SDUV-FEL with the EEHG scheme.

The relevant machine parameters are listed in Table 1.

4 Performance simulations

In the previous sections, the analysis is based on simple one-dimensional models. However in practice three-dimensional effects should be taken into account, which includes coupling of transverse and longitudinal degrees of freedom, finite laser spot size, incoherent synchrotron radiation (ISR) and coherent harmonic generation (CSR) in DS, and many others. The expected performance under these circumferences is evaluated with intensive simulations with elegant[13] and Genesis[14]. With the parameters listed in Table 1, and the seed laser with peak power 2 MW and a waist radius of 1 mm, the longitudinal phase space after the two stages of energy modulation and the density modulation process is shown in Fig. 7, where the 4th harmonic pre-bunching before entering the radiator is clearly displayed.

Table 1. Machine parameters for SDUV-FEL with the EEHG scheme.

electron beam	
beam energy/MeV	160
slice energy spread (rms)/keV	32
normalized emittance/mm·mrad	5
length (rms)/ps	2—3
seed laser 1	
wavelength/nm	1047
pulse length/ps	8
peak power/MW	2
modulator 1	
period length/cm	5
number of periods	10
K	2.49
dispersive section 1	
total length/m	2
R_{56}/mm	6.011
dispersive section 2	
total length/m	1
R_{56}/mm	1.316
radiator	
period length/cm	2.5
length/segment/m	1.5
number of segments	6
K	1.45

Note: The parameter of Seed Laser 2 is identical to Seed Laser 1 and Modulator 2 is identical to Modulator 1

The FEL simulation is performed with the upgraded code Genesis[15] which consists of three parts of runs. In the first run, the energy modulation from the 1047 nm seed laser in the first modulator is simulated and the particle distribution is dumped at the exit of Modulator 1. The particle distribution is imported, transported through DS 1 and further sent to Modulator 2 for the other energy modulation. At the exit of Modulator 2, the particle distribution is dumped again. Finally, the particle distribution is re-imported for the third run and the undulator period of the radiator is tuned to the 4th harmonic of the seed laser, i.e. 262 nm. The significant enhancement of SDUV-FEL with the EEHG scheme is clearly seen in Fig. 8, where the peak power of the 4th harmonic exceeds 100 MW and the power saturates very quickly within 4 m. The large bunching factor favored by EEHG is responsible for the initial steep quadratic growth of power. Both advantages are attributed to the initial bunching factor and small energy modulation. In addition, the energy spread increasing is also relatively small compared to the conventional HGHG scheme. Similar phenomena and results are also reproduced with Ginger[16] and Simplex[17].

Time-dependent simulation is also performed with Genesis, and the radiation spectrum is shown in Fig. 9.

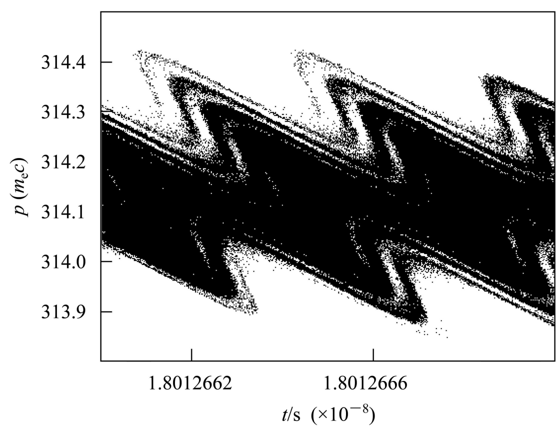

Fig. 7. Longitudinal phase space after DS2 from elegant.

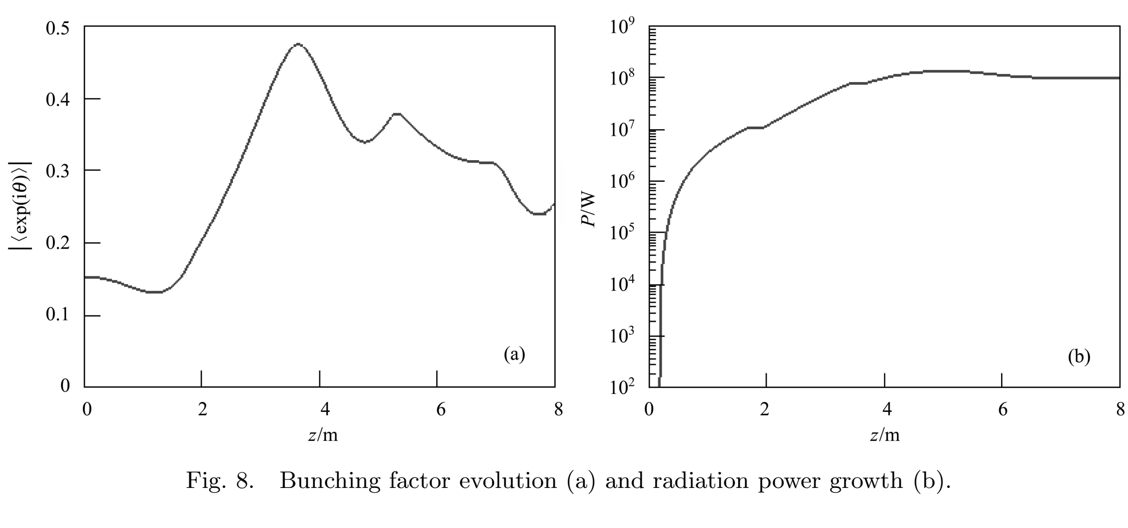

Fig. 8. Bunching factor evolution (a) and radiation power growth (b).

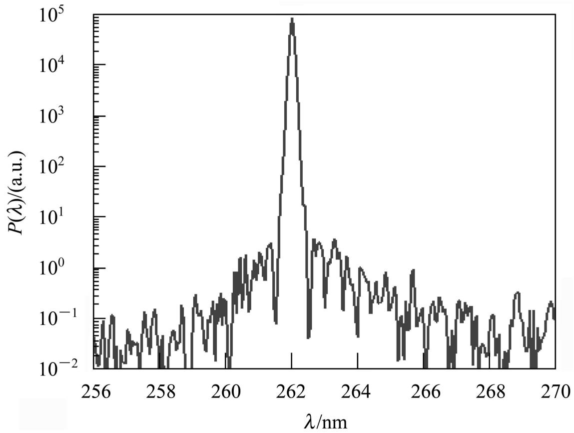

Fig. 9. Radiation spectrum from SDUV-FEL with the EEHG scheme.

5 Concluding remarks

The feasibility of operating SDUV-FEL with the EEHG scheme is presented. It is shown that the EEHG has a great potential as it allows for generating short wavelength radiation with much higher harmonics in the single stage of the harmonic generation FEL, therefore it may potentially reduce the number of stages of cascaded HGHG. It is worth stressing that this study is preliminary and there is still room for further improvement. It should also be noted that several effects such as incoherent and coherent synchrotron radiation existed in the dispersion section, which may induce the diffusion process; the longitudinal electron beam profile and so on, are not included in this study, which will be left for our subsequent reports.

The authors wish to thank Alex Chao (SLAC), Zhirong Huang (SLAC), Atoosa Meseck (BESSY), Dao Xiang (SLAC), Lihua Yu (BNL) and Sasha Zholents (LBNL) for helpful discussions.

References

1 Milton S et al. Science, 2001, **292**: 2037
2 YU L H. Phys. Rev. A, 1991, **44**: 5178
3 YU L H et al. Science, 2000, **289**: 932
4 YU L H et al. Phys. Rev. Lett., 2003, **91**: 074801
5 ZHAO Z T, DAI Z M, ZHAO X F et al. Nucl. Instrum. Methods A, 2004, **528**: 591
6 Bocchetta C et al. Proceedings FEL Conference. 2006
7 Meseck A et al. Proceedings FEL Conference. 2006
8 Saldin E L, Schneidmiller E A, Yurkov M Y. Opt. Commun., 2002, **202**: 169
9 HUANG Z. Proceedings FEL Conference 2006
10 Allaria E, De Ninno G. Phys. Rev. Lett., 2008, **99**: 014801
11 JIA Qika. Appl. Phys. Lett., 2008, **93**: 141102
12 Stupakov Gennady. slac-pub-13445, submitted to Physical Review Letters
13 Borland M. ANL Advanced Photon Source Report No. LS-287, 2000
14 Reiche S. Nucl. Instrum. Methods A, 1999, **429**: 243
15 Reiche S, Musumeci P, Goldammer K. PAC07
16 Fawley W M. LBNL Report LBNL-49625
17 Tanaka T. Proc. FEL2004, Trieste. 2004