Available online at www.sciencedirect.com
ScienceDirect

NUCLEAR SCIENCE AND TECHNIQUES

Nuclear Science and Techniques 19 (2008) 7–12

On harmonic operation of Shanghai deep UV free electron laser

DENG Haixiao[1,2] DAI Zhimin[1,*]

[1] Shanghai Institute of Applied Physics, Chinese Academy of Sciences, Shanghai 201800, China

[2] Graduate University of the Chinese Academy of Sciences, Beijing 100049, China

Abstract By choosing parameters in the modulator, the dispersive section and the seed laser, the spatial bunching of the electron beam can be correlated to the *n*-th harmonic of the radiator radiation, instead of the fundamental radiation in conventional high-gain harmonic generation (HGHG). Thus, the radiator undulator is operated at high harmonic mode. In this paper, the possibility of harmonic operation of Shanghai deep ultraviolet (SDUV) free electron laser (FEL) is studied. Discussions on the principle of harmonic operation, the simulation code development, the simulation results, and the proposed experimental procedure for verification of harmonic operation at the SDUV FEL are also presented.

Key words Harmonic, FEL, HGHG, Efficiency

CLC number TN248.6

1 Introduction

In recent years, people are increasingly interested in the short-wavelength free electron laser (FEL) when taking self-amplified spontaneous emission (SASE)[1] and high-gain harmonic generation (HGHG)[2-4] as two leading candidates for approaching hard X-ray region. However, presently the undulator period of FEL is in the order of centimeters[5-7], due to difficulties in placing strong and small magnets together into an alternating array. And because the FEL gain decreases rapidly with the undulator period, short-wavelength FEL must be achieved with high energy electron beam, which means enormous machines, substantive costs, and time and efforts consuming.

On the other hand, according to the resonant relationship of an undulator, the radiation frequency scales as the harmonic number[8]. Therefore, high-order harmonics show an alternative way to obtain short-wavelength instead of high energy electron beam. High-order harmonics in undulator have been attributed to the development of intermediate energy synchrotron radiation (SR) light source[9]. In large scale high energy SR light sources, such as ESRF, APS and Spring-8, high brightness hard X-ray radiations are generated by insertion devices operating at the fundamental and low odd harmonics (3rd or 5th). But these are expensive SR facilities. An intermediate energy SR light source operating at high-order harmonics, which can be built and operated with a far less cost, is able to provide comparable performance in the X-ray of 10~20 keV[10].

Harmonic radiations, the natural extension to short-wavelengths, also exist in the emission spectrum of FEL undulator operated at the fundamental mode. These harmonic radiations are nonlinear and weak. They were studied by theoretical analyses[11,12], numerical simulations[13] and experimental measurements[14]. The output power of the 3rd nonlinear harmonic radiation is about 1% of the fundamental in a conventional FEL. And for obtaining stronger harmonic powers, Latham[15] proposed a novel harmonic amplifier, i.e. harmonic operation (HO) FEL, in which a signal at the harmonic frequency is injected

Partially supported by the Key Project for Promoting Fundamental Research in China (Grant No. 2002CB713600)

* Corresponding author. *E-mail address:* daizhimin@sinap.ac.cn

Received date: 2007-10-10

into the entrance of the undulator to enhance the harmonic radiation. But Latham's scheme is not practical in short-wavelength region, because of the lack of suitable lasers to input signals in this region.

However, the HO scheme may be easily extended in HGHG FEL. By choosing suitable parameters of the modulator, the dispersive section and the seed laser, the spatial bunching of electron beam density distribution can be correlated to the harmonic radiation in the radiator, instead of the fundamental radiation in a conventional HGHG FEL. A seed laser with much longer wavelength than the Latham's scheme is employed in HO of a HGHG FEL to generate output radiation of a given wavelength.

In this paper, the possibility of HO of Shanghai deep ultraviolet (SDUV) FEL source[16] is studied. The principle of the HO of HGHG is described briefly in Section 2. In Section 3, the status of SDUV FEL is reported. The 3rd, 5th and 7th order HO of SDUV FEL are numerically simulated in Section 4. And in Section 5, a proof of the principle experiment of HO is suggested on the basis of SDUV FEL.

2 Harmonic operation (HO) of HGHG

A conventional HGHG FEL (see Scheme 1 in Fig.1) consists of a modulator, a dispersive section and a radiator. The electron beam enters the modulator and travels together with the seed laser, which modulates energy of the electron beam. The energy-modulated E-beam passes through the dispersive section, where the energy modulation is converted to the spatial modulation, with abundant harmonics bunching in the electron beam density distribution. Finally, when the spatially modulated E-beam enters the radiator, which is designed to be resonant to one of the harmonics of the seed laser, rapid coherent emission at this resonant harmonic is produced. The harmonic is further amplified exponentially until saturation.

As Scheme 2 in Fig.1 indicates, the wavelength of the seed laser is not in integer times of wavelength of the resonant radiation in the radiator but integer times of wavelength of the n-th harmonic radiation. When the energy-modulated E-beam enters the radiator with abundant harmonic bunching, the n-th coherent harmonic radiation (which is the m-th harmonic of the seed laser) is rapidly produced and amplified exponentially until saturation. Meanwhile, the fundamental radiation of the radiator, in wavelength of n/m of the seed laser, is expected to start from shot noise.

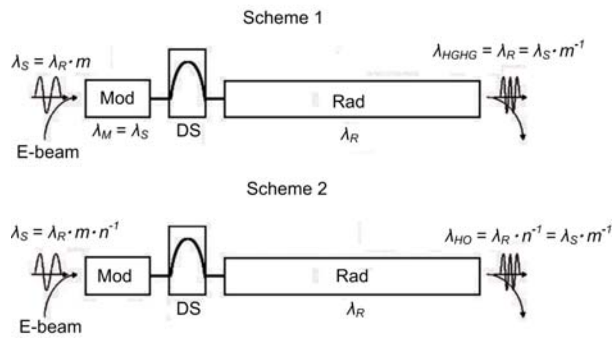

Fig.1 Schematic of HGHG FEL and HO of HGHG FEL

In comparison to the conventional FEL, the promising prospects with HO of HGHG FEL are as follows.

1) Before saturation of the harmonic radiation, the fundamental radiation is so small that nonlinear effects could be neglected. Thus, linear harmonic radiation is dominant in the radiator undulator of a good HO of HGHG FEL. In such a scheme, the efficiency of harmonic radiation is approximately ρ_n/n[17], where ρ_n is the pierce parameter corresponding to the harmonic radiation. The value can be estimated by assuming that dynamics of the electron phase space is only forced by the harmonic radiation. The power-conversion efficiency of the harmonic radiation in HO of HGHG can be enhanced significantly.

2) The required E-beam energy in HO of HGHG for generating a radiation in interested wavelength, as decided by the resonant relation, is much lower.

3) The harmonic radiation in HO of HGHG has the advantage of HGHG FEL, such as full longitudinal coherence, high stability of the central wavelength and pure spectrum.

Therefore, HO of HGHG is of great interests.

3 SDUV FEL

Shanghai deep UV (SDUV) FEL at Shanghai Institute of Applied Physics is a test facility of 262 nm HGHG FEL. The project was started in 2000 when a 100 MeV linac was built. A photocathode injector consisting of an RF gun and a 3 m SLAC type accelerating tube was developed to generate 40 MeV electron bunch of 1 nC in 8 ps with normalized emittance of less than 6 mm-mrad. The injector is to replace the 90 kV nanosecond grid gun and 15 MeV buncher of the linac, and the E-beam energy will be upgraded to 160 MeV. Meanwhile, efforts have been made in developing the four-dipole magnetic chicane bunch compressor, the radiator undulator, the seed laser system and beam diagnostics. The nominal parameters of the scheme are listed in Table 1.

Table 1 The nominal parameters of SDUV FEL

Parameters	Values
Seed laser wavelength λ_S / nm	1047
Electron beam energy E / MeV	160
Peak current I_P / A	300
Normalized emittance ε / mm-mrad	6
Local energy spread σ_γ / γ	1×10^{-4}
Modulator period length λ_{UM} / cm	5.0
Modulator length L_M / m	0.8
Modulator undulator parameter K_M	0.5~3
Resonant wavelength λ_R / nm	262
Radiator period length λ_{UR} / cm	2.5
Radiator undulator parameter K_R	1.41
FEL pierce parameter ρ	0.0026

4 Harmonic operation (HO) of SDUV FEL

In a conventional FEL scheme, the E-beam is driven by the fundamental radiation and nonlinear effect is important. Usually the famous pendulum equation is employed to describe the longitudinal dynamic, and it is valid when the harmonic radiation does not contribute significantly to the electron dynamics. In an HO of HGHG FEL, however, the simplification does not work correctly. An n-th order HO of HGHG FEL is mainly driven by the n-th harmonic radiation itself. Hence the introduction of self-consistent, multi-frequency, pendulum-like longitudinal dynamics is necessary. Another important issue is the initial electron phase loading. To satisfy the quiet start in the modulator undulator, the electron phase should be in integer times of 2π. Due to the non-integer number of harmonic up-conversion, the initial electron phase should be loaded between 0 and $2n\pi$ to satisfy the quiet start of the fundamental radiation in the radiator undulator[18].

Since harmonic radiations and special attentions in initialization of the phase space of the E-beam are refereed in HO of HGHG, the 3D FEL code currently available (such as GENESIS1.3[19] and TDA3D[20]) can not deal with HO of HGHG suitably. Thus, a code based on solving 1D FEL equations[21] was developed to investigate the process of HO. The electron phase is loaded by the “mirroring” method used in GENESIS1.3 to remove the effect of finite electron numbers. The gain reduction due to the transverse emittance effect is equivalent to an external initial energy spread[20]. FEL equations including the 1st, the 3rd, the 5th and the 7th harmonic radiation components are integrated.

Since the fundamental radiation starts from zero, the main optimization step of HO of HGHG is making the harmonic radiation saturate earlier than the fundamental so as to avoid the nonlinear effects of fundamental radiation. It can be achieved by adjusting the seed laser power and the dispersive strength. HO of SDUV FEL is optimized and simulated by the code. The main parameters are listed in Table 2.

Table 2 Parameters of harmonic operation of SDUV FEL

Parameters	Values		
Harmonic operation order n	3	5	7
Seed laser parameter m	4	7	10
Seed laser wavelength λ_S / nm	1047	1047	1047
Harmonic wavelength λ_{HO} / nm	262	150	105
Electron beam energy E / MeV	91.0	93.3	94.2
Seed laser power P_S / MW	1.5	0.2	0.2
Dispersive strength $\partial\theta / \partial\gamma$	3.50	20.0	21.0
Sat-harmonic power P_{HO} / MW	46.5	12.8	2.4
Sat-fundamental power P_{1S} / MW	127	109	139
Opt-fundamental power P_{1O} / MW	249	250	251
P_{HO} / P_{1O} (%)	18.8	5.12	0.96

4.1 The 3rd order harmonic operation

The 3rd order harmonic operation means that the radiator undulator is operated at the 3rd harmonic frequency. Thus, n=3 and m=4 were chosen for the investigation. Fig.2 shows the simulated bunching factors corresponding to the fundamental and the 3rd harmonic radiation in the radiator undulator. The 3rd harmonic radiation starts with a strong spatial bunching and the fundamental starts from a zero bunching. As the simulated power grows (Fig.3), the 3rd harmonic is amplified coherently and dominant in the radiator undulator. Contrastively, the fundamental radiation performs as SASE FEL and can be neglected in the first 7 m of the radiator undulator. This is, as we expected, an amazing character of HO of HGHG FEL.

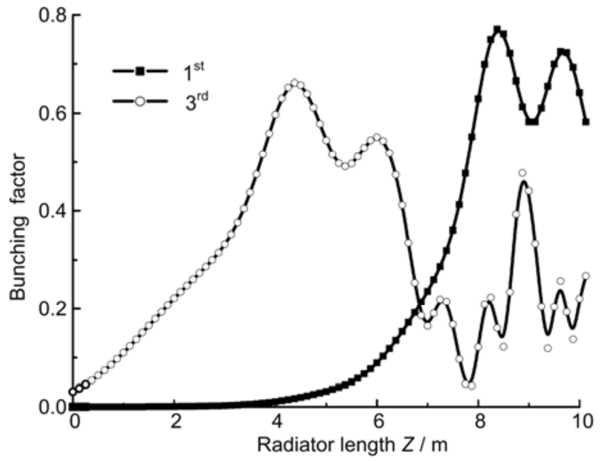

Fig.2 Simulated bunching factors in the 3rd order harmonic operation of SDUV FEL, m = 4.

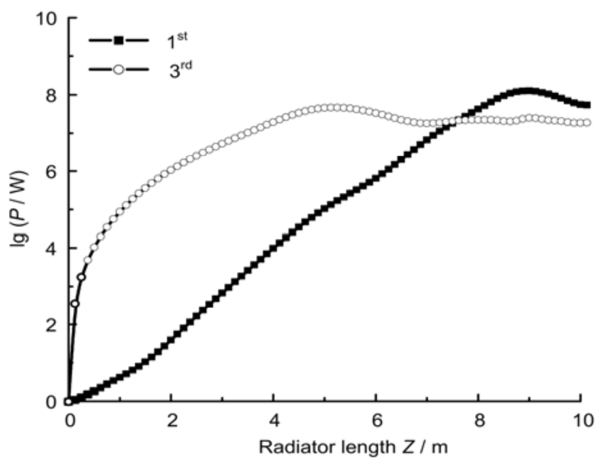

Fig.3 Simulated radiation powers in the 3rd order harmonic operation of SDUV FEL, m = 4.

The output powers of the fundamental 786 nm radiation and the 3rd harmonic 262 nm radiation should be concerned in the 3rd order HO of SDUV FEL. The energy of the E-beam with optimum performance at the fundamental and at the 3rd linear harmonic radiation is 91.2 MeV and 91.06 MeV, respectively. By adjusting the electron energy to 91.06 MeV the optimal 262 nm radiation with saturation power of 46.5 MW and 786 nm radiation with saturation power of 127 MW were obtained. Thus the saturation power ratio of the 3rd harmonic radiation to the fundamental is mainly 36.6%. However, because of the 0.14 MeV energy deviation (from 91.2 MeV) and the existence of significant power at the 3rd harmonic, the fundamental radiation was not at its optimum. Later we found less 262 nm radiation with the beam energy at 91.2 MeV but there was the 786 nm radiation with saturation power of 249 MW. Then the optimum power ratio of the 3rd harmonic radiation to the fundamental is 18.8%, which is consistent with the estimated value of 15.8%. Therefore, the 3rd harmonic radiation efficiency is enhanced from 1~2% to 18.8% of the fundamental level, which testifies the most attractive aspects of HO of HGHG.

4.2 The 5th order harmonic operation

In the 5th order harmonic operation, which has promising prospects in HO of SDUV FEL, m = 7 was chosen for numerical investigation. The 5th harmonic radiation efficiency could be enhanced to 5.12% of the fundamental level, which is consistent with 5.78% obtained from our estimation. The power growth of the fundamental and the 5th harmonic radiation in the 5th order HO of SDUV FEL is given in Fig.4.

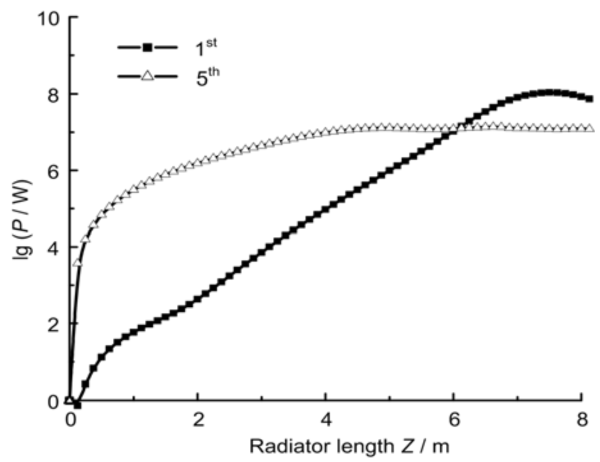

Fig.4 Simulated radiation powers in the 5th order harmonic operation of SDUV FEL, m = 7.

4.3 The 7th order harmonic operation

In the 7th order harmonic operation, m=10 was chosen for numerical investigation. The 7th harmonic radiation also holds promising prospects in the 7th order HO of SDUV FEL. The power growth of the fundamental and the 7th harmonic radiation in the 7th order HO of SDUV FEL is illustrated in Fig.5.

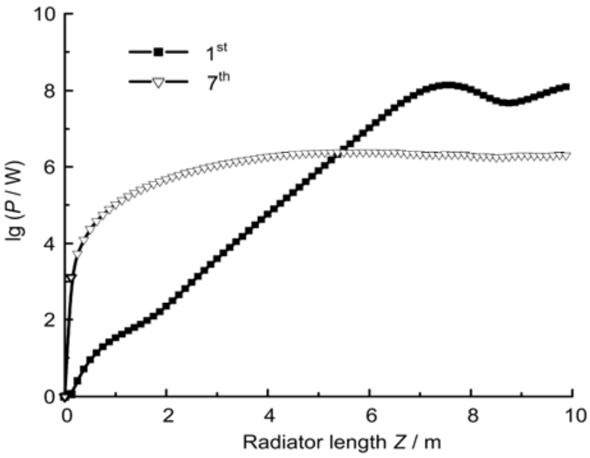

Fig.5 Simulated radiation powers in the 7th order harmonic operation of SDUV FEL, m=10.

The 7th harmonic radiation efficiency is enhanced to 0.96% of the fundamental level, but it is much lower than 2.78% from analytical estimation. This can be explained as follows. On one hand, the 7th harmonic radiation is very sensitive to quality of the electron beam referring to the linear harmonic radiation in HO of HGHG. To have an allowable energy spread of the electron beam at the entrance of the radiator undulator, the seed laser power can not be too large in high order HO of HGHG FEL. On the other hand, an efficiency enhancement of the harmonic radiation in HO of HGHG is mainly profited from the absence of the fundamental radiation effects before the saturation of harmonic radiation. In order to obtain strong spatial bunching at the entrance of the radiator undulator, the power of the seed laser should be large enough in high order HO of HGHG FEL. Therefore, high order HO of HGHG becomes unserviceable while the FEL stability and FEL efficiency of harmonic radiation is degraded in the 7th order HO of SDUV FEL.

5 Proposed experimental verification

In this section, a preliminary design of HO of HGHG on the basis of SDUV FEL is presented. For the reason of significant power generation in experimental verification, the 3rd order HO of HGHG was chosen. SDUV FEL is to generate 262nm HGHG radiation by a 160 MeV beam with a 1047 nm Nd: YLF seed laser. The seed laser system and the diagnostics system are in construction. Then m=4 was chosen for simplification, thus the diagnostics systems can be used in HO of SDUV FEL to measure the 3rd harmonic operation.

According to the resonant relation, in HO of HGHG as scheme 2 in Fig.1, parameters of the modulator and radiator must satisfy

$$\frac{n}{m} = \left(\frac{\lambda_{\mathrm{UR}}}{\lambda_{\mathrm{UM}}}\right)\frac{(1+K_{\mathrm{R}}^{\;2}/2)}{(1+K_{\mathrm{M}}^{\;2}/2)} \tag{1}$$

In SDUV FEL, for convenience of the HO of HGHG, a modulator undulator with alterable gap and a radiator undulator with fixed gap are employed. To operate SDUV FEL at the 3rd order HO of HGHG, we have K_{R}=1.41and K_{M}=0.81. By adjusting the gap of the modulator undulator and reducing the E-beam energy to 91.06 MeV, resonance at 786 nm can be established in the radiator, and the 3rd harmonic 262 nm radiation with significant power can be observed.

6 Concluding remarks

Using harmonics in FEL, HO of HGHG produces significant power. Compared with conventional FEL the short-wavelength radiation using a lower energy electron beam, would contribute to miniaturization of FEL scheme. Rigorous requirement over electron beam for ultra-short wavelength FEL, such as emittance, cannot be satisfied at low energy. So HO of HGHG may work well in the region from ultraviolet down to soft x-ray wavelengths. In this paper, detailed study on HO of SDUV FEL is given which indicates that the efficiency of the n-th harmonic radiation in n-th order HO of SDUV FEL is 18.8%, 5.12% and 0.96% of the fundamental level when n=3, 5, and 7 respectively. This is the most attractive feature of HO of HGHG FEL. And a proof of principle experiment is preliminarily proposed based on SDUV FEL. However, there are still many questions to be addressed before detailed design or experiment being carried out.

References

1 Murphy J, Pellegrint C, Bonifacio R. Opt Commun, 1985, **53**: 197-202.

2 Yu L H. Phys Rev A, 1991, **44**: 5178-5193.

3 Bonifacio R, de Salvo L, Poerini P, *et al*. Nucl Instrum Methods Phys Res A, 1990, **296**: 787-790.

4 Yu L H, Babzien M, Ben Z I, *et al.* Nucl Instrum Methods Phys Res A, 2000, **445**: 301-306.

5 Trskhtenberg E, Tcheskidov V, Vasserman I, *et al*. Nucl Instrum Methods Phys Res A, 2005, **543**: 42-46.

6 Abo B M, Hartrott M, Knobloch J, *et al*. Nucl Instrum Methods Phys Res A, 2005, **528**: 476-480.

7 Oh J S, Kim D E, Kim E S, *et al*. Nucl Instrum Methods Phys Res A, 2004, **528**: 582-585.

8 Closon W B. IEEE J Quantum Electron, 1981, **17**: 1417-1427.

9 Zhao Z T. Nucl Sci Tech, 2003, **14**: 1-8.

10 Kitamura H. J Synch Radiat, 2000, **7**: 121-130.

11 Huang Z, Kim K. J Phys Rev E, 2000, **62**: 7295-7305.

12 Jia Q K. IEEE J Quantum Electron, 2007, **43**: 833-837

13 Biedron S G, Freund H P, Milton S V, *et al*. Nucl Instrum Methods Phys Res A, 2001, **475**: 118-126.

14 Tremaine A, Wang X J, Babzien M, *et al*. Nucl Instrum Methods Phys Res A, 2003, **507**: 445.

15 Latham P E, Levush B, Antonsen T M, *et al*. Phys Rev Lett, 1991, **66**: 1442-1445.

16 Zhao Z T, Dai Z M, Zhao X F, *et al*. Nucl Instrum Methods Phys Res A, 2004, **528**: 591-594.

17 Zhang J S, Dai Z M, Ren Z X. J Phys D: Appl Phys, 2000, **33**: 1798-1802

18 Bonifacio R, Corsini R, Pierini P. Phys Rev A, 1992, **45**: 4091-4096.

19 Reiche S. Nucl Instrum Methods Phys Res A, 1999, **429**: 243-248.

20 Tran T M, Wurtele J S. Comput Phys Commun, 1989, **54**: 263-272.

21 Bonifacio R, Narducci L M, Pellegrini C. Opt Commun, 1984, **50**: 373-378.