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Nonlinear harmonic generation in Shanghai deep ultraviolet FEL*

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Abstract: High powers of the harmonics can be achieved through nonlinear harmonic generation in high gain single pass FEL, which may be used to get shorter wavelengths or to relax some stringent requirements on the electron beam quality for the 4th generation light source. In this paper, the 3rd nonlinear harmonic generation in Shanghai Deep Ultraviolet Free Electron Laser source is investigated by a 3D simulation code, including the sensitivity of nonlinear harmonic generation to several crucial parameters of the FEL system. The results show that the power of the 3rd nonlinear harmonic radiation can be as high as 2% of the fundamental power. In addition, the experiment and measurement of the 3rd harmonic radiation is proposed.

Key words: Nonlinear harmonic generation; FEL; High gain harmonic generation; Measurement

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Free electron lasers(FELs) are devices using the relativistic electron beams passing through a transverse periodic magnetic field to generate coherent radiation[1]. An important goal of the FEL community is to reach the hard X-ray spectral region with high coherent powers. In recent years, taking self-amplified spontaneous emission(SASE)[2] and high gain harmonic generation(HGHG)[3] as two leading candidates, high gain single pass FELs have become the most potential way for approaching the hard X-ray region. As it is known, one of the characteristics of high gain single pass FEL is the nonlinear harmonic generation[4], which is driven by the fundamental and grows at a rate faster than the fundamental. The nonlinear harmonic generation occurs in the high gain and saturation regime. Meanwhile, at the end of the undulator system, most current high gain FEL is in deep saturation regime[5]. FEL theory and simulation predict that the output power of the 3rd nonlinear harmonic generation is about 1% of the fundamental level[6], which is 8 orders of magnitude brighter than that of the current 3rd generation synchrotron radiation light sources[7]. Thus, the nonlinear harmonic generation is significant and regarded as the natural extension to shorter wavelengths. In this paper, a detailed investigation of the nonlinear harmonic generation in Shanghai Deep Ultraviolet(SDUV) FEL[8] is presented.

1 Harmonic radiations in high gain, single pass FEL

In the FEL spectrum of a high gain undulator operated at the fundamental frequency, an important and natural character is the existence of coherent harmonic radiation. Generally, due to the low coupling coefficient and its sensitivity to the "warm-beam" effects, the gain of the linear harmonic is much smaller than that of the fundamental frequency. However, the nonlinear harmonic grows much more rapidly than the fundamental when electron beam is strongly bunched by the field of the undulator and the fundamental radiation, which holds great promise as an intense coherent harmonic source. Such harmonic performance may be clearly illustrated by one dimensional(1D) FEL theory. The coupled Maxwell-Vlasov equations[3] can be written as

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$$\left(\frac{\partial}{\partial\tau}+\frac{\partial}{\partial\theta}\right)E_n \propto \int F_n \mathrm{d}\gamma \tag{1}$$

and

$$\left(\frac{\partial}{\partial\tau}+2n\frac{\gamma-\gamma_0}{\gamma_0}i\right)F_n \propto \sum_{u=1}^{u+v=n} D_u E_u \frac{\partial F_v}{\partial\gamma} \cong D_1 E_1 \frac{\partial F_{n-1}}{\partial\gamma}+D_n E_n \frac{\partial F_0}{\partial\gamma} \tag{2}$$

where E_n is the slowly varying electric field envelope function of the n-th harmonic radiation, F_n represents the corresponding bunching which will contribute to the growth of the n-th harmonic radiation significantly, the scaling parameter D is a measure of the coupling coefficient. $\tau=k_\omega z$ and $\theta=k_\omega z+k_s z-\omega_s t$ are the well known dimensionless variables in FEL. On the right hand side of equation(2), the first term describes the nonlinear harmonic interaction and the second describes the linear harmonic generation. As mentioned above, the nonlinear term is driven by the bunching of the fundamental, and we can rewrite the Maxwell's equation to the lowest order as

$$\left(\frac{\partial}{\partial\tau}+\frac{\partial}{\partial\theta}\right)E_n \propto \begin{cases} E_1^n & (\text{strongly bunched}) \\ E_n & (\text{initial distribution}) \end{cases} \tag{3}$$

Therefore, if the fundamental laser bunches the electron beam strongly, the nonlinear harmonics will grow faster than the fundamental. Actually the gain length scales inversely with the harmonic number[6].

In a planar undulator employed high gain FEL, FEL theories and FEL simulations[9] indicate that the electron beam motion causes significant powers of the first few odd harmonics in the forward direction due to the existence of the nonlinear harmonic interaction process.

2 Status of SDUV FEL

SDUV FEL is underway at Shanghai Institute of Applied Physics(SINAP), China. As indicated in Figure 1, SDUV FEL is a 262 nm HGHG type FEL test facility. Relevant R&D has been under way since 2000. For the time being, a photocathode injector consisting of an RF gun and a 3 m SLAC type accelerating tube is developed to generate a 40 MeV electron bunch with a charge of 1 nC in 8 ps and a normalized emittance less than 6 mm-mrad. This injector is expected to replace the existing 90 kV nanosecond grid gun and a 15 MeV buncher. Meanwhile, the four-dipole magnetic chicane bunch compressor, the radiator undulator, the seed laser system and beam diagnostics have been designed and fabricated. Moreover, SASE operation is considered in the design of SDUV FEL. The nominal parameters of SDUV FEL are listed in Table 1.

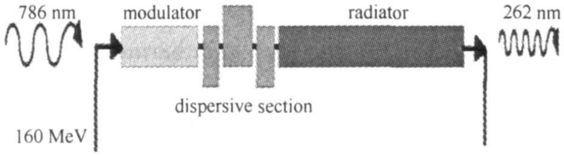

Fig. 1 Layout of 262 nm SDUV HGHG FEL

Table 1 Nominal parameters of SDUV FEL

	seed laser parameters			electron beam parameters			
	λ_s/nm	Z_R/m	P_s/MW	E/MeV	I_p/A	ε/(μm·rad)	(σ_γ/γ)/%
SASE	786	0.8	0	160	300	6	0.01
HGHG	786	0.8	15	160	300	6	0.01
	modulator undulator			dispersive section and radiator undulator			
	λ_u/mm	K	L/m	$\partial\psi/\partial\gamma$	β/m	λ_u/mm	K
SASE	50	2.01	0.8	0	3	25	1.41
HGHG	50	2.01	0.8	3	3	25	1.41

3 Simulation results of harmonic performance

Upgraded from TDA[10] simulation code, TDA-H[11] is competent for 3D harmonic calculation. It is applied to study nonlinear harmonic generation in SDUV FEL. In all the simulations described below, a signal of 1 W at the fundamental wavelength 262 nm is assumed at the beginning of the radiator undulator.

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In HGHG operation of SDUV FEL, as listed in Table 1, the design value of dispersive strength $\partial\psi/\partial\gamma$ is 3 and the seed laser power P_s is 15 MW. However, it seems that the 3rd harmonic radiation performs more preferably for a dispersive strength of 12 and an input seed laser power of 0. 5 MW. The powers as a function of the radiator length are shown in Figure 2, where the optimal values for harmonic radiation is employed for simulation. The fundamental 262 nm radiation saturates at 6. 2 m with saturated power of 93. 4 MW. The 3rd harmonic 87. 3 nm radiation saturates at 7. 4 m with saturated power of 2. 35 MW, which is 2. 52% of the fundamental power.

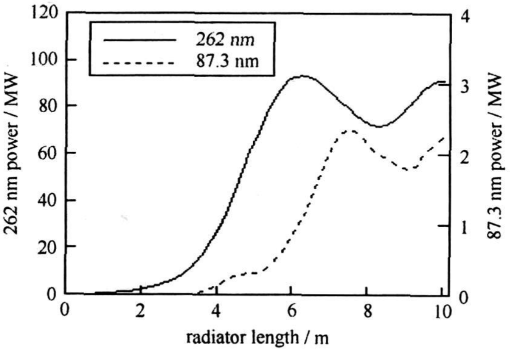

Fig. 2 Simulated power growth of the fundamental and the 3rd harmonic radiation in HGHG operation of SDUV FEL *vs* radiator length

More detailedly, Figure 3 plots the sensitivities of the saturated power and saturation length of the fundamental and the 3rd harmonic radiation to the peak current of the electron beam. The saturated power fluctuation factors of the 262 nm and 87. 3 nm radiation are 2 and 3 respectively when I_p changes from 200 A to 350 A. However, the saturation length of two modes decreases by 30%. In addition, we have calculated the sensitivities of the fundamental and the 3rd harmonic radiation to the local energy spread and the normalized emittance. For the initial local energy spread, when σ_γ/γ increases to about 0. 06%, the saturated power of the two modes decrease monotonically to about 50% of that produced by an electron beam with the nominal parameters, and the saturation length increases by 60%. For the normalized emittance, when ε decreases from 8 μm · mrad to 4 μm · mrad, the saturated power of the 262 nm radiation increases from 64 MW to about 120 MW, yet there exists a fluctuation in saturated power of the 87. 3 nm radiation, and the saturation length of two modes decreases monotonically.

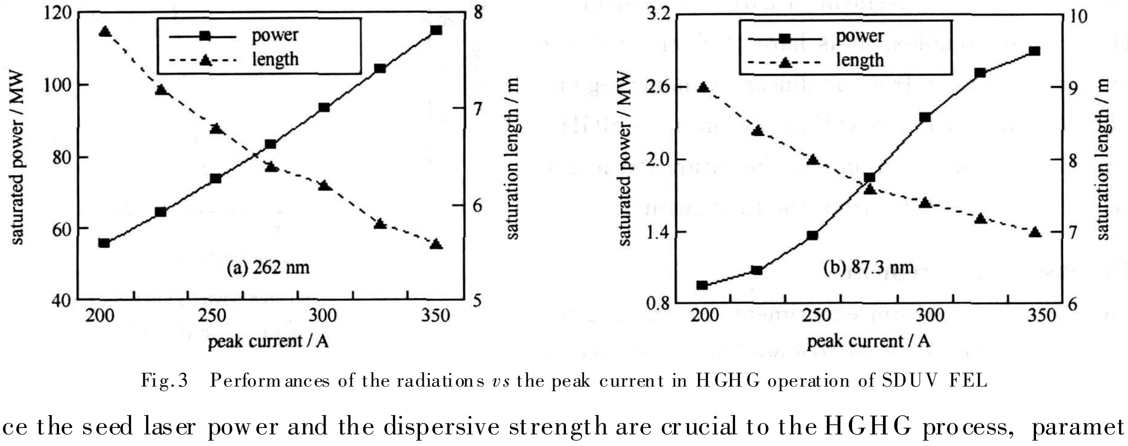

Fig.3 Performances of the radiations *vs* the peak current in HGHG operation of SDUV FEL

Since the seed laser power and the dispersive strength are crucial to the HGHG process, parameters scan was performed by varying the seed laser power and the dispersive strength. The results are shown in Figure 4 and 5 respectively, which validate our choice of $\partial\psi/\partial\gamma = 12$ and $P_s = 0.5$ MW for good harmonic performance.

In HGHG operation of SDUV FEL, when we take away the seed laser and make $\partial\psi/\partial\gamma = 0$, the bunching of the electron beam would be so small that the radiator undulator operates as a SASE FEL. The simulation was performed and the growth of the fundamental and the 3rd harmonic radiation in SASE operation of SDUV FEL are shown in Figure 6. We have found the 262 nm radiation saturated at 14. 2 m with saturated power of 103 MW and the 87. 3 nm radiation saturated at 17. 2 m with saturated power of 2. 09 MW which is 2. 03% of the fundamental. The 262 nm radiation grew exponentially with a gain length of 0. 66 m in close agreement with the linear theory[2,6]. The 87. 3 nm radiation started from the linear amplification with a gain length of 2. 11 m, and ended with the nonlinear harmonic interactions of the 2nd nonlinear harmonics and the fundamental radiation, where the gain length was 0. 22 m. Indeed, we observed that the gain length of 3rd

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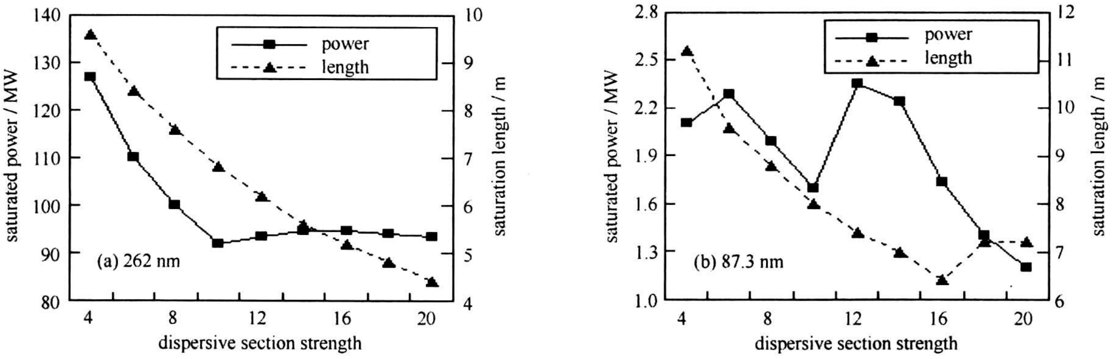

Fig. 4 Performances of the radiations *vs* the dispersive strength in HGHG operation of SDUV FEL

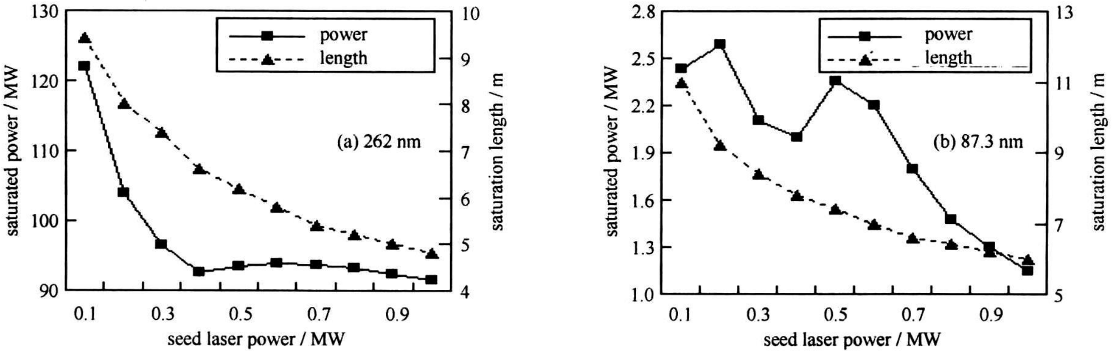

Fig. 5 Performances of the radiations *vs* the seed laser power in HGHG operation of SDUV FEL

nonlinear harmonic scales was 1/3 times the fundamental gain length. Compared with SASE operation, the field evolvement of harmonic contents in HGHG is more complex. It is hard to distinguish the linear harmonic region from nonlinear harmonic region. In summary, whether in SASE operation or in HGHG operation, the field evolution and the saturation length of the 3rd harmonic differ from the fundamental.

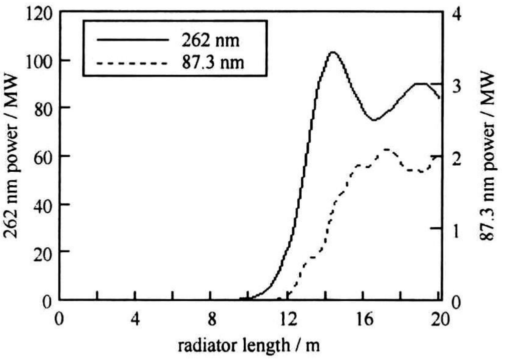

Fig. 6 Simulated power growth of the fundamental radiation and the 3rd harmonic radiation in SASE operation of SDUV FEL

4 Proposed measurement

We intend to perform experiments on the 262 nm fundamental and the 87.3 nm 3rd nonlinear harmonic of SDUV FEL. Since the 87.3 nm radiation is in the vacuum ultraviolet spectral region and the diagnostic pop-in systems for the fundamental measurement have been under manufacture, an in-vacuum system at the exit of the radiator undulator is proposed to measure the 3rd nonlinear harmonic radiation. As shown in Figure 7, the FEL output is split to three parts. We attempt to measure the energy, the spectrum and the facular distribution of the 3rd harmonic radiation. Since the output energy of the 3rd harmonic radiation is about several uJ, we plan to use a commercially available photodiode detector that responds from the infrared to X-ray spectral region to measure the output energy. The second part of the beam enters in a spectrometer, formed

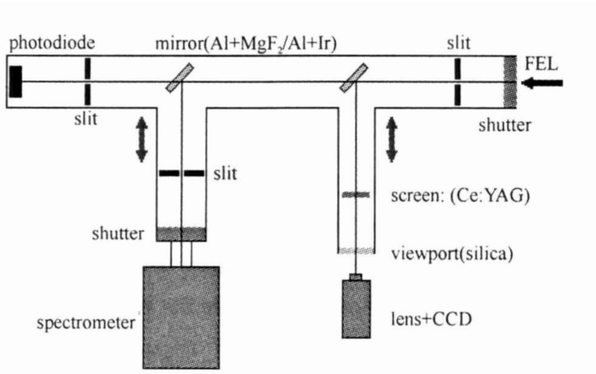

Fig. 7 Proposed measurement system of the 3rd harmonic radiation of SDUV FEL

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by a sphere grating and a charge coupled device(CCD), where the spectrum of the 3rd harmonic radiation is obtained by single shot method. The last part of the beam is used to examine the facular distribution of the 3rd harmonic radiation indirectly. As the Ce: YAG screen has a high radiation efficiency of 2×10^4 photons per MeV, a fast radiation attenuation of 88 ns/300 ns and an excellent physical characters with a radiation peak value of 550 nm, a visible light CCD is enough to observe the facular image, actually the facular distribution of the 3rd harmonic radiation, on the Ce: YAG screen.

5 Conclusion

Nonlinear harmonic generation of high gain FEL is the natural extension to short wavelength. Employing a 3D simulation code, we have studied the radiation power of the 3rd nonlinear harmonic generation in SDUV FEL and examined the sensitivity of the saturated power and saturation length to variations in electron beam peak current, initial local energy spread, transverse emittance, seed laser power and strength of the dispersive section. Together with the 262 nm radiation of 100 MW saturated power, an 87.3 nm radiation with a high power of 2 MW was achieved. Such a vacuum ultraviolet harmonic radiation is proposed to measure at the exit of the undulator system.

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上海深紫外自由电子激光的非线性谐波辐射研究

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摘 要: 自由电子激光中的非线性谐波辐射能达到较高的谐波功率,可以用来得到短波长辐射或者降低第4代先进光源对电子束团品质的严厉要求。基于3维自由电子激光软件,深入详细地研究了上海深紫外自由电子激光装置的非线性谐波辐射,并且提出了谐波辐射实验和测量建议。研究表明上海深紫外自由电子激光装置3次非线性谐波辐射的功率可以达到基波功率的2%水平。

关键词: 非线性谐波; 自由电子激光; 高增益高次谐波发生器; 自放大自发辐射

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