THREE DIMENSIONAL SIMULATION ON HARMONIC OPERATION OF SHANGHAI DEEP ULTRAVOILET FREE ELECTRON LASER*

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Abstract

With the right choice of the parameters in high gain harmonic generation (HGHG), the electron beam may be spatially bunched on the high harmonic of the radiator resonant frequency, instead of the fundamental frequency in the normal HGHG. Thus, the radiator is operated at harmonic mode and the harmonic power is expected to be significantly enhanced. Recently, the possibility of a proof-of-principle harmonic operation experiment based on Shanghai deep ultraviolet (SDUV) free electron laser (FEL) test facility has been studied. In this paper, the principle of harmonic operation, the numerical simulation approaches, and the detailed performances of harmonic operation of SDUV FEL are presented.

INTRODUCTION

An important goal of the FEL community is to reach the short-wavelength spectrum region with high coherent power. Self-amplified spontaneous emission (SASE) [1] and multi-stage HGHG [2] are two leading candidates for approaching hard x-ray region. However, limited by the practical difficulty in undulator manufacture technique, present undulator period is in the order of centimetres; what is more, the FEL gain falls off rapidly with the decreasing of the undulator period. Thus, it indicates that the FEL scheme require a high energy electron beam to achieve short-wavelength radiation.

High harmonics would be an alternative way to obtain short-wavelength instead of high energy electron beam. It have attributed to the development of intermediate energy synchrotron radiation (SR) light source [3]. Harmonic radiations also exist in the emission spectrum of FEL undulator operated at the fundamental mode. These kinds of harmonics, known as nonlinear harmonic radiation, have been theoretically analyzed [4] and experimentally measured [5]. It seems that the energy of the 3rd nonlinear harmonic radiation is about 1% of the fundamental level in conventional FEL.

HARMONIC OPERATION

Harmonic operation was firstly proposed by Latham [6] to obtain strong harmonic power. As seen in Scheme 1, Fig. 1, a signal at the harmonic frequency is injected into the undulator and amplified. The fundamental radiation is suppressed while the harmonic radiation is dominant in the undulator. However, the feasibility of Latham's scheme absolutely depends on the input signal. It will be useless in the short-wavelength spectral region for the lack of available input laser.

In order to make harmonic operation more practical, a linear harmonic operation based on HGHG was proposed by Dai [7], as seen in Scheme 2, Fig. 1. With the right choice of parameters for the modulator, the dispersive section, the radiator and the seed laser, the spatial bunching of the electron beam density distribution is corresponding to the harmonic radiation in the radiator, instead of the fundamental radiation in normal HGHG. In such a scheme, a seed laser with much longer wavelength than in Latham's proposal is employed.

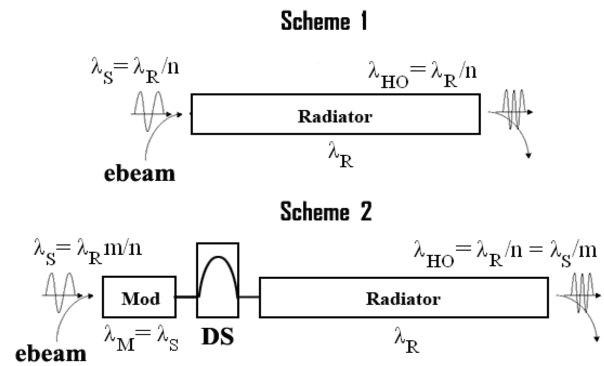

Figure 1: Layout of harmonic operation.

A good linear harmonic operation scheme is one where linear harmonic radiation is dominant in the radiator. So we can write the pendulum equation as follows,

$$\theta'' = -\frac{eK}{2k_w mc^2\gamma^2}[JJ]_n E_n e^{in\theta} + c.c. \qquad (1)$$

If we define $\phi = n\theta$, and then Eq. 1 can be rewritten as

$$\phi'' = \Omega_n{}^2 \sin(\phi + \varphi_n), \qquad (2)$$

where $\Omega_n{}^2 \propto nE_n[JJ]_n$. Given the growth rate of linear harmonic radiation $\sqrt{3}\rho_n\chi \propto \sqrt{3}\chi n^{1/3}[JJ]_n{}^{2/3}$, where $0 < \chi < 1$ is the factor due to three dimensional effects. Linear harmonic radiation reaches the condition of saturation when $\sqrt{3}\rho_n\chi = \Omega_n$. Thus, the solution for the saturation yields that

$$P_n = (\frac{1}{n}\frac{[JJ]_n}{[JJ]_1})^{2/3}\chi^4\rho_1 P_{beam}. \qquad (3)$$

Generally in linear harmonic operation, the saturation power of the 3rd harmonic is 5% level of fundamental saturation for $\chi \approx 0.70$. It indicates that the harmonic radiation powers are enhanced 5 times in linear harmonic

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operation. However, linear harmonic radiation performs very sensitive to the energy spread, peak current and emittance of electron beam. It seriously influences the performances of linear harmonic operation.

Another modification so-called superradiant harmonic operation was proposed by Giannessi [8]. A short pulse seed is introduced in the modulator, thus in the radiator, the quadratic growth of the superradiant radiation take the place of linear harmonic growth. When operated in superradiant regime, the energy exchange between the current and the laser field is proportional to the slippage length scaled with the fundamental resonant wavelength even if the radiation is amplified at the *n* times smaller harmonic. Thus, superradiant harmonic operation holds promising prospects performances.

NUMERICAL APPROACHES

In this section, we discuss some details of the numerical simulation approaches of harmonic operation.

General requirement of the FEL code

To accurately simulate the harmonic operation, a FEL code must satisfy the following requirements.

- Three dimensional descriptions of the electron beam distribution and the radiation distribution.
- Fully time-dependent simulation (Slippage effects is crucial for superradiant harmonic operation, in order to include it, time-dependent model is necessary.)
- Shot noise loading of SASE
- FODO structure and undulator segments
- Self-consistent model of harmonics (Typically the harmonics are driven by the nonlinear dynamics of the fundamental and the feed back of the harmonics on the electron beam can be neglected for the sake of faster calculation. However in harmonic operation, it is important to feed the coupling of the harmonic radiation back to the electron beam.)
- Publically free for source file (In order to properly study harmonic operation, current existing FEL code may need some modifications.)

According to the above, we choose GENESIS 2.0 [9] as the origin source.

Special attentions to phase loading

In harmonic operation, the fundamental and harmonic radiation competes with each other. However, whether in linear or superradiant harmonic operation, the harmonics grows much slower than fundamental radiation. Thus, the valid shot noise for the fundamental and the harmonic at the entrance of the radiator is crucial. The initial electron beam distribution must satisfy quiet start condition in both the modulator and the radiator. In order to satisfy this condition the particles have been distributed in $[0,2n\pi]$ in the modulator and $[0,2m\pi]$ in the radiator.

The most famous algorithms for shot noise are given by Penman [10] and Fawley [11]. However, both algorithms can not straightforward to set the shot noise consistently in the modulator and the radiator [8]. In order to load the right shot noise, a virtual pre-modulator with length of zero and resonant wavelength of *n* times of the seed laser wavelength is used. We load the initial phase of the electron beam in the pre-modulator. Then the seed laser, the fundamental and the harmonics in the radiator are all the high harmonics of the resonant frequency in the pre-modulator. Thus, it consistently assures valid shot noise. A group of shot noises at the beginning of the radiator with the seed laser off are listed in Table 1.

Table 1: The shot noise of the fundamental and harmonic if the seed laser is turn off in harmonic operation

	b1	**b3**	**Theory**
Quiet loading	2.28×10^{-6}	1.40×10^{-6}	3.91×10^{-4}
Penman loading	4.47×10^{-4}	1.48×10^{-3}	3.91×10^{-4}
Fawley loading	4.68×10^{-5}	3.57×10^{-4}	3.91×10^{-4}
Pre-loading	3.82×10^{-4}	3.75×10^{-4}	3.91×10^{-4}

Thus in order to properly model harmonic operation, modifying the parameter *convharm* in GENESIS 2.0 from integral type to real type data is enough.

PERFORMANCES OF SDUV FEL

Table 2: Parameters of harmonic operation of SDUV FEL

Parameters	**Value**
Seed laser wavelength	349 nm
Electron bema energy	160 MeV
Peak current	300 A
Normalized emittance	6 mm-mrad
Local energy spread	5×10^{-5}
Modulator period length	50 mm
Modulator length	0.80 m
Modulator gap	alterable
Radiator period length	25 mm
Radiator length	9.00 m
Radiator gap	10 mm
Radiator resonant wavelength	262 nm

SDUV FEL [12] is a 262 nm HGHG type FEL test facility. The design and the relevant R&D have been under way since 2000. Currently,

- A 40 MeV photocathode injector is commissioning. The injector will replace the existing 90 kV grid gun of the commissioned 100 MeV LINAC, and then the electron beam energy will be upgraded to 160 MeV.
- The fabrications of the bunch compressor chicane and the beam diagnostics have been achieved.
- First measurement of magnetic field of 6 segments fixed gap radiator is completed.
- The seed laser system with fundamental wavelength of 1047 nm is under commissioning.

- An alterable gap modulator is under fabrication.

In SDUV FEL, an alterable gap modulator and a fixed gap radiator shows great convenience for transferring to harmonic operation. If the 3rd harmonic of the 1047 nm seed laser is injected into the modulator, and adjust the modulator to resonant with the input signal, harmonic operation with $m = 4$ and $n = 3$ carries out. Now we study the performances of harmonic operation of SDUV FEL, and the main parameters are listed in Table 2.

Linear harmonic operation

As mentioned above, linear harmonic operation is very sensitive to the quality of the electron beam. To avoid bringing too large extra energy spread in electron beam at the entrance of the radiator, the seed laser power can't be too large in linear harmonic operation. On the other hand, the harmonic efficiency enhancement in linear harmonic operation is profited from the absence of the fundamental effects before saturation of the harmonic radiation. Thus strong harmonic bunching is necessary at the entrance of the radiator. In linear harmonic operation of SDUV FEL, a 10 ps, 1 MW, 393 nm laser which is the 3rd harmonic of the existing laser system is injected into the modulator, and the magnetic field of the dispersive section is 0.3 T.

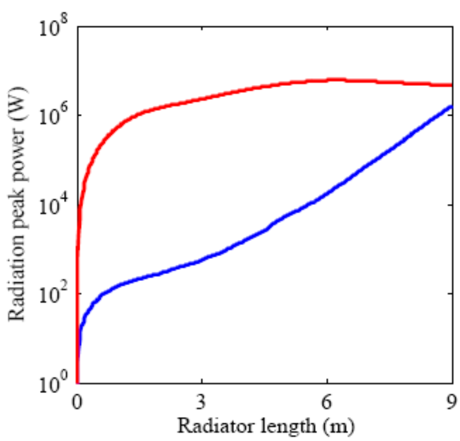

Figure 2: The peak power growth in linear harmonic operation of SDUV FEL. Red is the 3rd harmonic 87.3nm, and blue is the fundamental 262nm.

According to the simulation results, we obtain that the 3rd harmonic 87.3 nm starts with a strong spatial bunching and the fundamental 262 nm starts from shot noise. As the peak power growth shown in Fig. 2, the 3rd harmonic is amplified and dominant in the radiator, contrastively, the fundamental radiation performs as SASE FEL and can be neglected in the first 4 segments radiator, which are agree with what we have expected and would be an amazing character of harmonic operation. In more detail, we obtain a maximum power of 6.2 MW for the 87.3 nm radiation, which is 5% level of the fundamental saturation power in normal operation of SDUV FEL.

Fig. 3 shows us the output power and the FEL spectrum of the fundamental and the harmonics in linear harmonic operation of SDUV FEL. The output energy of 262 nm and 87.3 nm radiation is 8.36 nJ and 4.82 μJ, respectively. The 3rd harmonic 87.3 nm radiation has good longitudinal coherence.

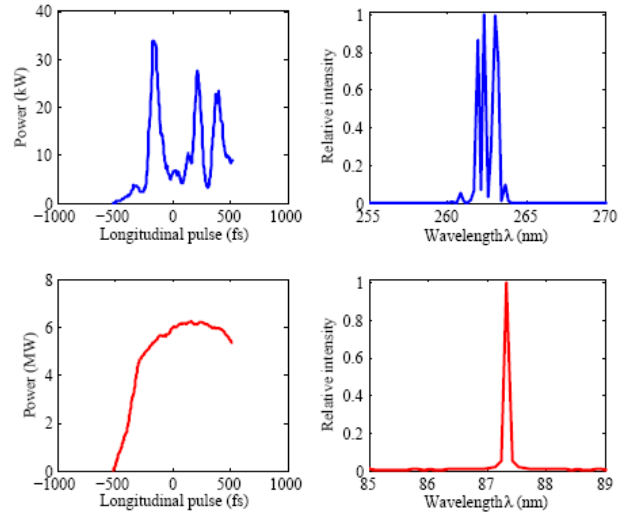

Figure 3: The output FEL performance after 4 segments radiator in linear harmonic operation of SDUV FEL.

Superradiant harmonic operation

Since strong slippage effect is involved in superradiant harmonic operation, the harmonic radiation is not very relevant to the modulated part of the electron bunch, but the fresh part of the electron bunch. For obtaining a strong harmonic bunching at the entrance of the radiator and a stable output performance, a 100 fs, 15 MW, 393 nm laser is expected to injected into the modulator in superradiant harmonic operation of SDUV FEL, and the magnetic field of the dispersive section is 0.15 T.

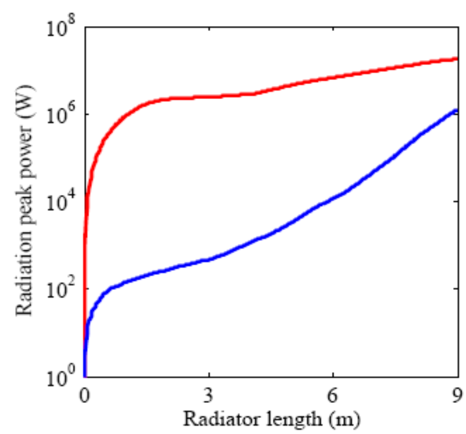

Figure 4: The peak power growth in superradiant harmonic operation of SDUV FEL. Red is the 3rd harmonic 87.3nm and blue is the fundamental 262nm.

According to the simulation results, we show the peak power growth in Fig. 4. The 3rd harmonic is amplified and dominant in the radiator. We obtain the maximum power of 18.5 MW for the 87.3nm radiation at the 6 segments of radiator, which is 15% level of the fundamental saturation power in normal operation of SDUV FEL. Further in a much longer radiator simulation, one may observe that the quadratic growth of the 3rd harmonic radiation still works until the growth of the fundamental stops the evolution of superradiant by ultimately spoiling the longitudinal phase space of the electrons.

Fig. 5 shows us the output power and the FEL spectrum of the fundamental and the harmonics in superradiant harmonic operation of SDUV FEL. The output energy of 262 nm and 87.3 nm radiation is 0.49 μJ and 1.82 μJ, respectively.

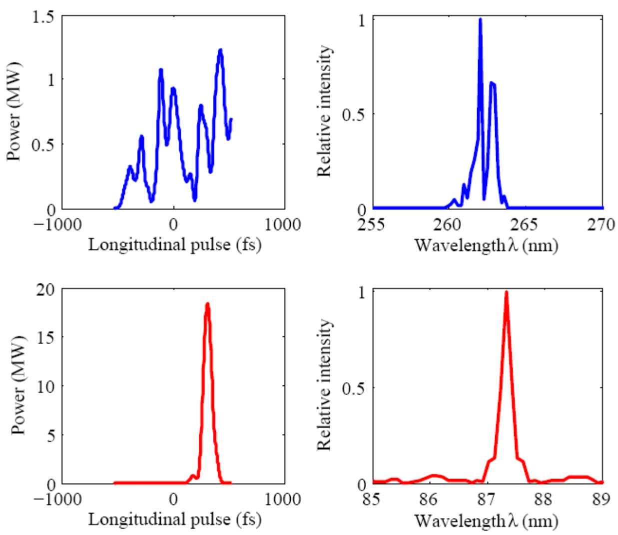

Figure 5: The final output performance in superradiant harmonic operation of SDUV FEL.

CONCLUSIONS

Compared with the conventional FEL operating at the fundamental frequency, harmonic operations significantly enhance the harmonic efficiency, and generate the short-wavelength radiation using a lower energy electron beam. It may attribute to miniaturization of FEL scheme. Since rigorous requirement over electron beam for ultra-short wavelength FEL, such as emittance, can't be satisfied at low energy, harmonic operation may work well in the region from ultraviolet down to soft x-ray wavelengths.

Since we are interested in the high harmonic radiation in harmonic operations, it is very sensitive to the strength of dispersive section. And we could advance or delay the saturation of the harmonic relative to the fundamental by adjusting the dispersive strength. As mentioned above, the harmonic radiation is dominant in a long distance where the fundamental could be negligible. Thus in the short-wavelength production by multi-stage HGHG [2], some stages could be replaced by such a scheme.

In this discussion, the linear and superradiant harmonic operations of SDUV FEL are studied. It indicates that linear harmonic radiation has a better spectrum and larger pulse energy, while superradiant harmonic operation may produce a stronger peak power. However, there are still many questions to be addressed before any before any detailed design or experiment can be carried out. The FEL performance of harmonic operation with measured field of SDUV undulator is under study.

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