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Parameter study for enhanced high gain harmonic generation scheme

JIA Qi-Ka(贾启卡) LI He-Ting(李和廷)

National Synchrotron Radiation Laboratory, University of Sicence and Technology of China, Hefei 230029, China

Abstract: An easy-to-implement scheme called Enhanced High Gain Harmonic Generation is expected to be able to significantly enhance the performance of HG-FEL. In this paper we investigate the effects of the system parameters in the new scheme, including the electron energy detuning, initial electron-beam energy spread, seeding laser power, dispersive field strength and amount of the phase shift, etc. The numerical results from GENESIS (3D-code) are presented and show that the new scheme has acceptable parameters tolerance requirements and is no more or even less sensitive to the system parameters than that of the existing scheme; With the electron energy above the resonance, the efficiency is enhanced for both the new scheme and the existing scheme compared with the resonant energy case.

Key words: harmonic generation, bunching factor, radiation power

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1 Introduction

Self-Amplified Spontaneous Emission (SASE) [1] and High-Gain Harmonic Generation (HGHG) [2] have become two leading candidates for approaching the vacuum ultraviolet to hard X-ray free-electron lasers (FELs). Benefiting from the high quality seeding laser, HGHG provides radiations with a high degree of stability whereas the central wavelength, bandwidth and pulse duration can be controlled. These theoretical predictions have been demonstrated in the first HGHG proof of principle experiment [3].

For very high harmonics, the wavelength conversion efficiency of one-stage HGHG becomes very low. Therefore the proposals of future X-ray light sources relying on HG-FEL were based on the more complicated cascaded HGHG configuration [3, 4]. Recently, some novel schemes such as enhanced high gain harmonic generation (EHGHG) [5] and echo-enabled harmonic generation (EEHG) [6, 7] that allow a HG-FEL to operate at shorter wavelengths and radiate more powerfully has been proposed. Comparing the two novel schemes, the EEHG has more advanced performance on harmonic generation, but the EHGHG scheme can be easier to be implemented, especially for the existing HGHG facility, a small modification can give the FEL a distinct improvement. We have studied the main parameters sensitivities in EEHG scheme [8]. In this letter, the effects of system parameters in EHGHG scheme have been studied and compared with the effects in the existing HGHG scheme.

2 Brief review of the EHGHG scheme

The EHGHG scheme was proposed and shown to be able to significantly enhance the performance of traditional HGHG-FEL [5]. The HGHG scheme is composed of two undulators separated by a dispersive section. In the EHGHG scheme, an energy spread

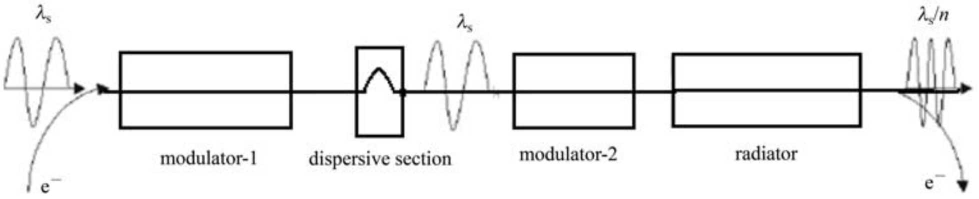

Fig. 1. Scheme of the EHGHG.

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suppression stage composed of a phase shifter and a short modulator is added after the dispersive stage of the HGHG scheme. The schematic of the EHGHG scheme is provided in Fig. 1.

The whole physics processes sequence of this scheme is as follows: energy modulation → density modulation (bunching) → energy spread suppression → radiation enhancement. In the first undulator (Modulator-1), the electron beam interacts with a resonant seeding laser to produce energy modulation. Then the beam travels through a dispersive section to transform the energy modulation into density modulation. Next, the beam energy spread is suppressed in a short phase reversed undulator (Modulator-2) with the same seeding laser as in Modulator-1. In this section, the π phase shift can be achieved by carefully tuning the dispersive field strength to let the fractional part of N_d [9] to be 0.5. Finally the beam enters the third undulator (radiator) tuned in resonance to the harmonic wavelength of the seeding laser, to achieve the enhanced radiation power.

Figures 2(a)–(c) show the evolution of the electrons distribution in phase space from the entrance of dispersive section to the exit of the phase reversed modulator. It can be found that the beam energy spread is reduced after passing through the second modulator, but is suppressed mainly for the non-bunched electrons. In addition, the phase reversed modulator has some bunching effect when the electron beam is under-bunched before entering it. As shown in Ref. [5], at the entrance of the gain section, the bunching factor of the EHGHG scheme increased for all harmonics compared with the case of HGHG scheme. Thus, with the EHGHG scheme an electron-beam with smaller energy spread and stronger bunching can be provided, so that more powerful higher harmonic radiation can be generated.

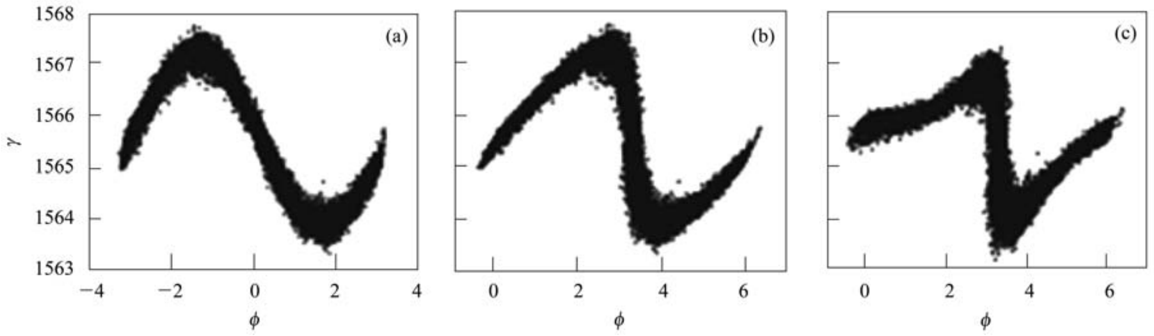

Fig. 2. The electron beam phase space at the exit of (a) the first modulation section; (b) the dispersive section; (c) the second modulation section.

3 Parameter study

The HGHG-FEL experiment involves lots of parameters, which are relevant to the electron beam, the seeding laser and the magnet field. Among them only a few parameters are tunable during the experiment. The seeding laser power and the strength of dispersive section are most important of all. We study the effects of the energy detuning and the sensitivity of the initial electron-beam energy spread, the seeding laser power, the dispersive field strength and the phase shift over wide parameters region. To investigate the effects of the system parameters in the EHGHG scheme, numerical simulations were done by using the 3D code GENESIS [10] and when the effect of variation of a parameter is studied, we keep the others steady.

The main parameters for the simulations are listed in Table 1. They are based on the parameters of

Table 1. The main parameters for the EHGHG scheme.

beam energy	800 MeV
beam energy spread	0.01%
beam peak current	300 A
beam transverse emittance	2.0 mm·mrad
average beta function	4.21 m
modulator period length	5.4 cm
modulator parameter (K)	4.80318
modulator-1 period number	16
modulator-2 period number	6
modulator resonant wavelength	264 nm
peak seeding laser power	240 MW
dispersive strength (N_d)	60
radiator period length	3.2 cm
radiator undulator parameter	1.23595
radiator resonant wavelength	16.5 nm
radiator length	15.936 m

the Hefei Soft X-ray FEL Proposal [11], but the gain section is tuned at the 16th harmonic of the seeding laser. The peak seeding laser power ($P_{\rm seed}$=240 MW) and dispersive field strength ($N_{\rm d}$=60) are optimized for the 16th harmonic. For comparison, the case of the HGHG scheme is also simulated. The parameters are mostly the same as the parameters of the EHGHG scheme except the peak seeding laser power and dispersive field strength, which are optimized to be $P_{\rm seed}$=200 MW and $N_{\rm d}$=75.

3.1 Electron energy detuning

It has been known that detuning of the beam energy from the resonance can enhance the FEL efficiency [12]. That can be explained as follows. For the electrons with energy above the resonance but still in the bucket of the phase space, more energy can be extracted from the electron beam. To trap most of the electrons into the phase space bucket, generally we require that the sum of the detuning and the total beam energy spread is smaller than the phase space bucket height, namely we have:

$$2k_{\rm u}\left(\frac{\delta\gamma}{\gamma}+\sqrt{\left(\frac{\sigma_\gamma}{\gamma}\right)^2+\frac{1}{2}\left(\frac{\Delta\gamma_{\rm m}}{\gamma}\right)^2}\right)<2\varOmega \qquad (1)$$

where $k_{\rm u}$ is the wave number of the first undulator field, $\delta\gamma$ is the energy detuning, σ_γ is the initial energy spread (RMS), $\Delta\gamma_{\rm m}$ is the maximum energy modulation induced by seeding laser in the first modulator and $2\varOmega$ means the height of the phase space bucket. Therefore, we have an upper limit for the beam energy detuning.

For the case here, the first term of the left hand side of the above formula is ~0.510, the second term ~0.169 and the bucket height of the phase space $2\varOmega$ ~1.05. The development of the radiation power in the gain section of the EHGHG scheme with the beam energy above resonance compared with that on resonance is given in Fig. 3. From the simulation result, the saturation power has grown by several times when the electron energy is detuned above the resonance.

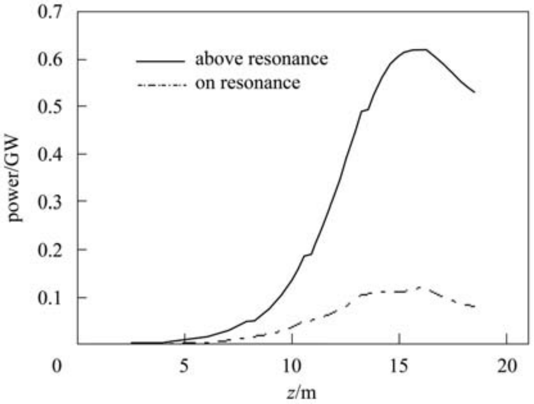

Fig. 3. The radiation power in the gain section of the EHGHG scheme for different electron beam energy.

3.2 Initial electron-beam energy spread

The radiation intensity at the end of the radiation section as a function of the initial electron-beam energy spread for EHGHG scheme and HGHG scheme is given in Fig. 4 respectively. It can be seen that the radiation power of the EHGHG scheme at the end of the radiation section declines slower than that of the HGHG scheme as the initial electron-beam energy spread grows. If over 90% intensity is required to remain, the initial relative beam energy spread should be smaller than 1.22×10^{-4} for the EHGHG scheme and 1.13×10^{-4} for the HGHG scheme. Apparently, the suppression of the beam energy spread, which is the principal advantage of the EHGHG scheme, results in that the new scheme has a larger tolerance requirement on the initial electron-beam energy spread.

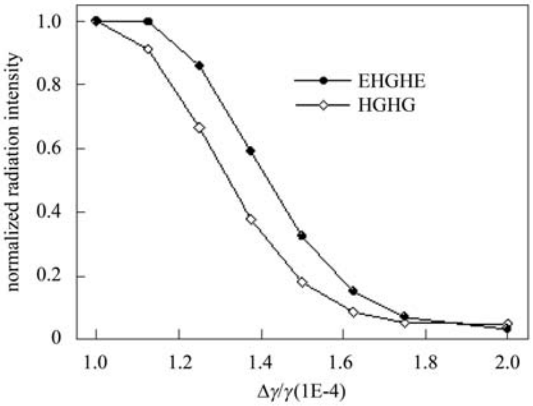

Fig. 4. Normalized radiation intensity at the end of the radiation section as a function of the initial electron-beam energy spread.

3.3 Seeding laser power

In harmonic generation FEL, the seeding laser interacts with the electron beam in the modulator to induce energy modulation. A sufficient energy modulation is needed for bunching, but on the other hand, it acts as an additional energy spread that degrades the quality of the electron beam. So, there must be an optimal seeding power that the energy modulation and the beam quality can be in the best balance. The effect of the variation of seeding power on the bunching factor and output power has been numerically simulated. The result (Fig. 5) shows that the dependence of output power on the seeding power is similar for the EHGHG and HGHG schemes. The output power grows fast with the seeding power before reaching its peak value and then declines slowly. For the seeding power we chose, $P_{\rm seed}$ =240 MW of EHGHG and $P_{\rm seed}$ =200 MW of HGHG, if we require the fluctuation of output power is no more than 10%, the two schemes have an equal wide good region of peak seeding power (about 60 MW). This is an acceptable tolerance for the technology of seeding laser.

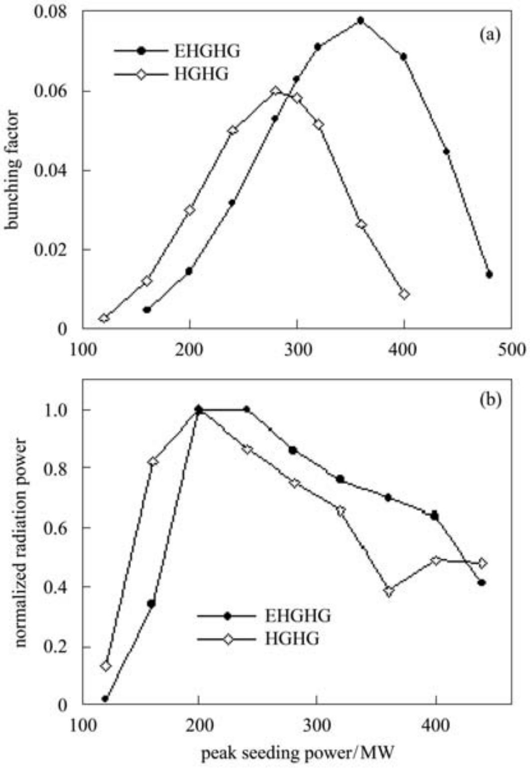

Fig. 5. (a) Bunching factor at the entrance of radiator as a function of the peak seeding power; (b) Normalized radiation power at the end of the radiation section as a function of the peak seeding power.

In addition, it should be noticed that the best seeding power for the output power is less than that for the bunching factor for both the two schemes. There could be two reasons responsible for this. First, when the seeding power is too large, the additional energy spread induced by energy modulation degrades the electron beam quality and depresses the output power. Second, in the radiator the electron beam will continue to be bunched, so it may be overbunched when the beam is highly bunched at the entrance of the radiator.

3.4 Dispersive field strength

The bunching factor at the entrance of the radiator and the radiation power at the end of the radiator as a function of dispersive field strength are depicted in Fig. 6. The situation of the HGHG scheme is also presented.

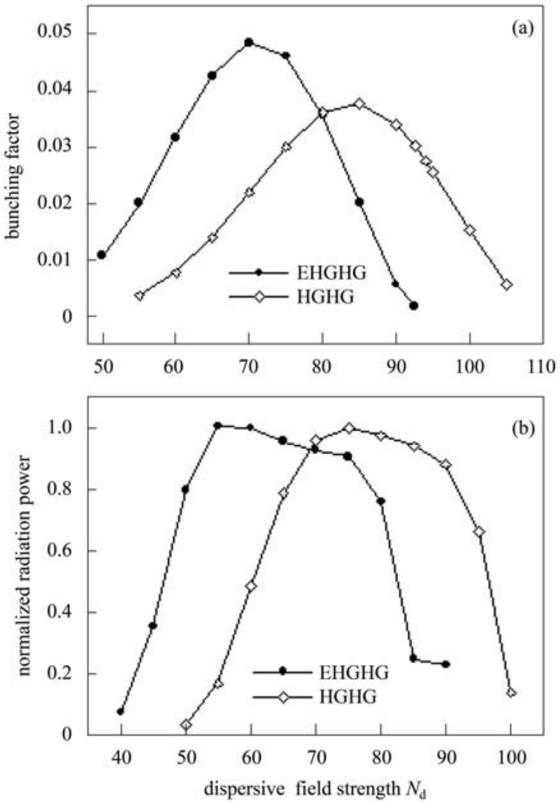

Fig. 6. (a) Bunching factor at the entrance of radiator as a function of the dispersive field strength; (b) Normalized radiation intensity at the end of the radiation section as a function of the dispersive field strength.

From the results, both the two schemes have a good wide region of dispersive field strength for the radiation power. However, the good region of the EHGHG scheme starts from a smaller value of $N_{\rm d}$. This could be explained from two aspects. The main reason is that the phase reversed modulation also has some bunching effect on the under-bunched electron beam, thus the EHGHG scheme can bunch less in the dispersive section. Besides, that the optimized seeding power for EHGHG (240 MW) is large than that for HGHG (200 MW) also makes the optimal dispersive field strength for the EHGHG scheme smaller than that for the HGHG scheme, because generally the maximum bunching is achieved when the dispersive field strength and seeding power satisfy:

$$4\pi N_{\rm d}\frac{\Delta\gamma_{\rm m}}{\gamma}\sim\frac{\pi}{2}.$$

Being same with the case of seeding laser power, for both the two schemes, when the dispersive field strength is the best for the output power, the electron beam is under-bunched at the entrance to the radiator. As mentioned previously, it is because the electron beam continues to be bunched in the radiator.

3.5 Phase shift

In the EHGHG scheme, for the beam energy spread suppressing, the phase of the electrons relative to the seeding laser is shifted π before the electron beam enters the second modulator. It has been mentioned that we can tune the fractional part of the dispersive field strength (N_d) to achieve the phase shift we want. The sensitivity of output power to the amount of phase shift is the key problem. The variation of radiation power with the phase shift has been numerically calculated and shown in Fig. 7. From the result, obviously the π phase shift is the best case and the radiation intensity has an acceptable tolerance on the phase shift. If over 90% intensity is expected, we should require $0.85\pi \leqslant \Delta\phi \leqslant 1.3\pi$, namely, the fluctuation of the fractional part of N_d should be smaller than 0.075.

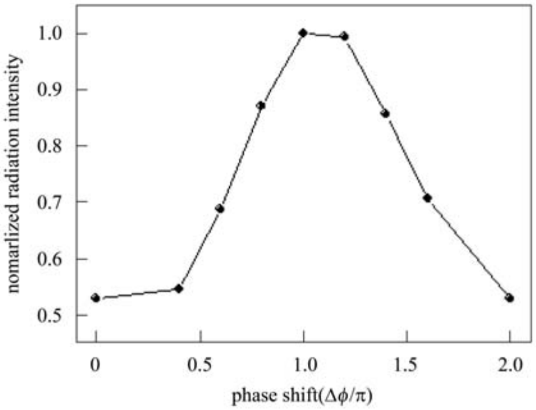

Fig. 7. Normalized radiation intensity at the end of the radiation section as a function of the phase shift.

Controlling the relative phase change between electrons and the ponderomotive wells should not be difficult. In particular, for VU to X-ray FELs, which require long interaction lengths and employ many undulator sections, the phase shifters are needed to exactly match the phase between individual segments so that constructive superposition of the emitted light occurs, especially for the undulator systems with variable magnet gap.

4 Conclusions

The parameters of a new scheme intitled EHGHG are studied. First, we study the energy detuning and find that an appropriate energy detuning gives the emission power enhancement. Then the effect of initial electron-beam energy spread, seeding laser power, dispersive field strength and amount of phase shift to the radiation power over wide parameters region is discussed and compared with that of the traditional HGHG scheme. We find that the new scheme has less or no more sensitivities on the parameters we studied than the HGHG scheme. In detail, the new scheme has a larger tolerance requirement on the initial electron beam energy spread than the HGHG scheme, and the two schemes both have wide good regions of the seeding power and dispersive field strength. For the phase shift parameter, which does not exist in the HGHG scheme, it has a realizable tolerance on affecting the output power.

In this paper, we give a primary study on the parameters tolerance of the EHGHG scheme. For a specific design using the EHGHG scheme, more detailed parameters tolerance study should be done with exact parameters optimization and more complicated parameters interaction should be considered at the same time.

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