THE PARAMETER STUDY FOR THE ENHANCED HIGH GAIN HARMONIC GENERATION SCHEME*

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Abstract

An easy-to-implement scheme called Enhanced High Gain Harmonic Generation (EHGHG) has been proposed. In this paper we investigate the effects of the system parameters in EHGHG scheme, such as the electron energy tuning, the dispersive strength, the seeding laser power, the electron beam energy spread, and amount of the phase shift. The numerical results from GENESIS (3D code) are presented, and show that: with the electron energy above the resonance, the efficiency is enhanced for both the new scheme and the existing scheme comparing with the resonant energy cases; the EHGHG scheme has acceptable parameters tolerance requirements and is no more or even less sensitive to the system parameters than that of the existing scheme.

BRIEF REVIEW OF THE EHGHG SCHEME

The high-gain harmonic generation (HGHG) [1] scheme is one of leading candidates for VUV to X-ray FELs. The EHGHG scheme [2] was proposed and shown to be able to significantly enhance the performance of traditional HGHG-FEL. An HGHG scheme is composed of two undulators separated by a dispersive section. In the EHGHG scheme, an energy spread suppression stage composed of a phase shifter and a short undulator is added after the dispersive stage of the HGHG scheme. A schematic of the EHGHG scheme is provided in Fig. 1.

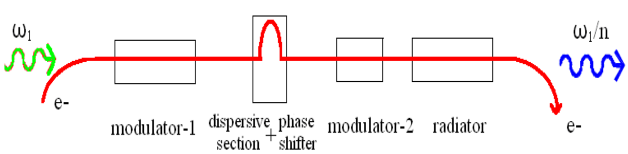

Figure 1: Schematic of the EHGHG scheme.

The whole physics processes sequence of this scheme is as follows: energy modulation → density modulation (bunching) → energy spread suppresion → 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. And 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 [3] to be 0.5. Finally the beam enters a third undulator (radiator) tuned in resonance to the harmonic wavelength of the seeding laser, to achieve the enhanced radiation.

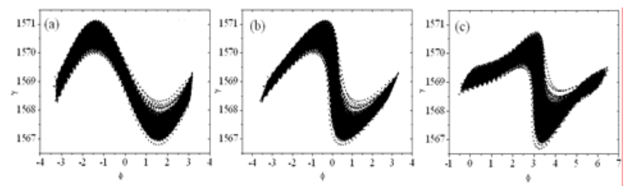

Figure 2: The electron beam phase space at the exit of (a)the first modulation section; (b)the dispersive section; (c)the second modulation section.

Figure 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. As shows in Reference [2], at the entrance of the gain section, the bunching factor of the EHGHG scheme increased for all harmonics comparing 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.

PARAMETER STUDY

The HGHG-FEL experiment involves lots of parameters, which are relevant to the magnet field, the electron beam and the seeding laser. Among them only few ones are tunable during the experiment. The seeding laser power and the strength of dispersive section are most important of all. To investigate the effects of the system parameters in the EHGHG scheme, the parameter set of Hefei soft X-ray FEL proposal [4] listed in Table 1 is used. We study the effects of energy tuning and the sensitivity of dispersive strength, seeding power, electron energy spread and phase shift over wide parameters region. The case that the gain section is tuned at 16th harmonic of the seeding laser is considered and numerical results from GENESIS [5] are presented and analyzed.

Energy Tuning

It has been known that detuning of the beam energy from the FEL resonance energy can increase the efficiency [6]. That the energy detuning gives efficiency enhancement can be explained as follows. For the electron energy above the resonance, but still in the phase

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space bucket, more energy can be extracted from the electron beam. For most of the electrons to be trapped in the phase space bucket, generally we require that the sum of the detuning and the total tuning spread must be smaller than the phase space bucket height, namely we have:

$$2k_u\left(\frac{\delta\gamma}{\gamma}+\sqrt{(\frac{\sigma_\gamma}{\gamma})^2+\frac{1}{2}(\frac{\Delta\gamma_m}{\gamma})^2}\right)<2\Omega \qquad (1)$$

where k_u is the wave number of the first undulator field, $\delta\gamma$ is the energy detuning, σ_γ is the initial energy spread (RMS), $\triangle\gamma_m$ is the maximum energy mudulation induced by seeding laser in the first modulator, and Ω means the height of the phase space bucket. Therefore, we have an upper limit for the energy tuning.

Table 1: Parameter set of the Hefei soft X-ray FEL proposal

Electron beam parameters:
γ : 1565.558 Peak current: 600A
Energy spread: 0.01%
Emittance: 2.0 mm·mrad
Seeding laser beam parameters:
Wavelength: 264 nm
Input power: 240 MW
Reileigh length: 3m
Magnet parameters:
Modulation section
Length: 0.864m
Undulator period: 5.4cm
Undulator parameter(a_u): 4.80318
Dispersive section
Induced dispersion(N_d): 60
Phase-reserved modulation section
Length: 0.324m
Undulator period: 5.4cm
Undulator parameter(a_u): 4.80318
Radiation section
Undulator period: 3.2cm
Undulator parameter(a_u): 1.23595

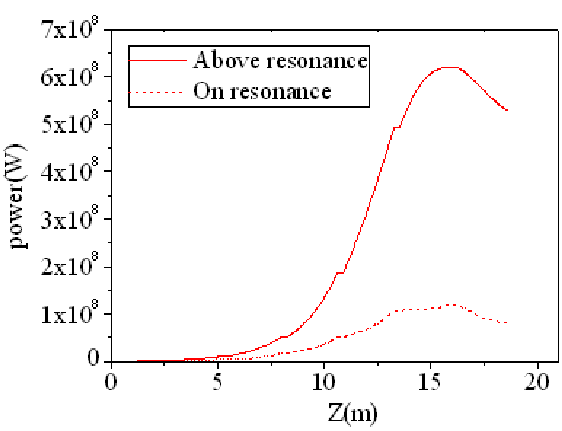

Figure 3: The radiation power in the gain section for different electron beam energy.

For the case here, the first term of the left hand side of above formula is ~0.510, the second term ~0.169, and the phase space bucket height 2Ω ~1.05. Fig. 3 shows the radiation power development in the gain section with the electron energy above resonance comparing with that on resonance. From the simulation result, the saturation power has grown by several times when we tuned the electron energy above the resonance energy.

The effect of Dispersive Strength

The sensitivity of radiation power to the dispersive strength is depicted in Fig. 4. The situation of HGHG scheme is also presented for comparison. The two curves have almost the same shape and cover the same wide range, but the curve of EHGHG scheme begins from a smaller N_d. This could be explained as the result of the bunching effect of the phase reversed modulation. Thus, in the subsequent study, we choose N_d=60 for EHGHG scheme and N_d=70 for HGHG scheme.

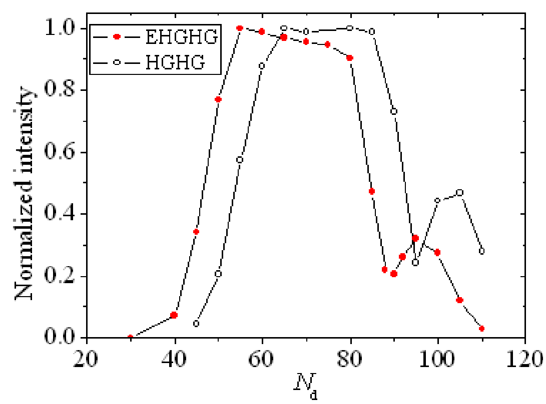

Figure 4: The variation of the normalized intensity with the dispersive strength.

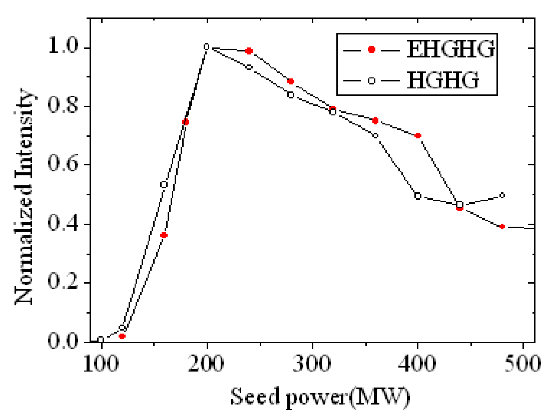

Figure 5: The variation of the normalized intensity as a function of the seed power at N_d=60 for EHGHG scheme and N_d=70 for HGHG scheme.

The Effect of Seeding Laser Power (P_0)

In harmonic generation FEL, the seeding laser interacts with the electron beam in the modulator to induce energy modulation. We need a large energy modulation for bunching, but on the other hand, the energy modulation acts as an additional energy spread that degrades the quality of the electron beam.

From Fig. 5, the maximum radiation power is obtained at P_0=240 MW. With increase of the input power, the radiation power drops slowly, but there is a sharp decline when the input power declines.

The Effect of Initial Energy Spread

The variation of the normalized intensity with the electron beam initial energy spread for EHGHG scheme and HGHG scheme is given in Fig. 6. It can be seen that the radiation power of EHGHG scheme has less sensitivity on initial energy spread than that of HGHG scheme. Namely, for the same output power, the new scheme has larger tolerance on the initial electron beam energy spread. It should be noticed that the radiation power is most sensitive to the initial electron beam energy spread comparing to other system parameters.

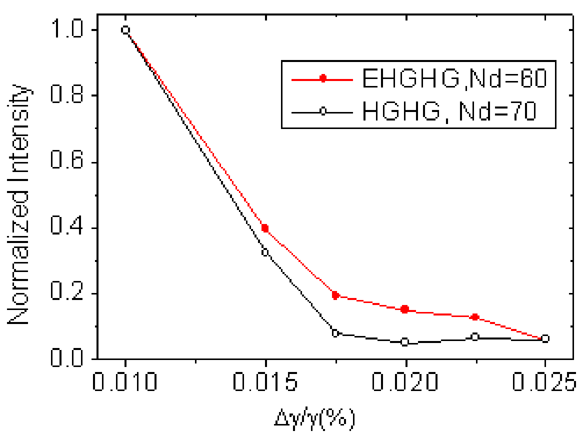

Figure 6: The variation of the normalized intensity as a function of the initial electron beam energy spread for EHGHG scheme (N_d=60) and HGHG scheme (N_d=70).

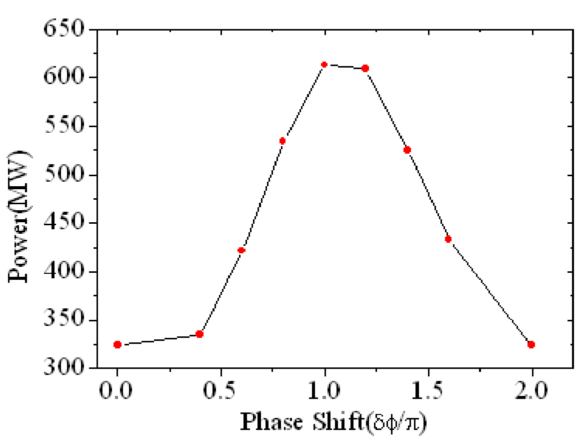

Figure 7: The variation of the normalized intensity as a function of the phase shift.

The Effect of the Phase Shift

Before the electron beam entering the second modulator, the phase of the electrons relative to the seeding laser is shifted for the energy spread suppressing. The sensitivity of output power of EHGHG scheme to the amount of phase shift is a key problem being very concerned. 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. We have numerical calculated the variation of output power with the shifting phase and shown it in Fig. 7. From the result, it is obvious that the π phase shift is the best case and the output power is not sensitivity to the phase shift. This is easy to be understood. Studying the phase space in modulator-2, only after π phase shift, the electrons already bunched will no more be modulated, and at the same time the energy spread of the other electrons will get the best suppressing. For $\triangle\Phi=\pi\pm\pi/4$ (N_d=0.6$\pm$1/8), over 80% intensity can be remained

Control the relative phase change between electrons and the ponderomotive wells should not be difficult to implement. 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.

CONCLUSIONS

The parameters of a new scheme intitled EHGHG is studied. First, we study the energy tuning and find that an appropriate energy detuning gives the emission power enhancement. Then the effect of dispersive strength, seeding laser power, initial electron energy spread and phase shift to the radiation power over wide parameters region is discussed and compared to the traditional HGHG scheme. We find that the new scheme has no more or less sensitivity to the parameters we studied than the traditional HGHG scheme. For the phase shift parameter, which do not exist in HGHG scheme, it has an acceptable tolerance on affecting the output power. For a future work, we will analysis the interaction of the parameters and find the optimized parameter settings.

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