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Enhanced high gain harmonic generation scheme with negative dispersion [*]

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Abstract: The enhanced high gain harmonic generation (EHGHG) scheme has been proposed and shown to be able to significantly enhance the performance of HGHG FEL. In this paper we investigate the EHGHG scheme with negative dispersion. The bunching factor at the entrance of the radiator is analyzed, which indicates that the scheme with negative dispersion can further weaken the negative effect of the dispersive strength on the energy spread correction factor. The numerical results from GENESIS (3D-code) are presented, and are in good agreement with our analysis. Then we comparatively study the effects of the initial beam energy spread and the relative phase shift on the radiation power. The results show that the EHGHG scheme with negative dispersion has a larger tolerance on the initial beam energy spread and a nearly equal wide good region of the relative phase shift compared with the case of positive dispersion.

Key words: negative dispersion, bunching factor, energy spread, relative phase shift

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1 Introduction

The high-gain harmonic-generation (HGHG) scheme [1] is one of the leading candidates for approaching the vacuum ultraviolet to hard X-ray free-electron lasers (FELs). It has the advantages of a shorter undulator and much better longitudinal coherence of the FEL pulse, compared with another high-gain FEL scheme called self-amplified spontaneous emission (SASE) [2]. However, it is difficult to reach the hard X-ray region with a normal seeding laser as the frequency up-conversion efficiency is small. Therefore, more complicated cascaded HGHG with "fresh bunch technique" [3] and high-order harmonic generation (HHG) [4, 5] seeded HGHG schemes are proposed.

In recent years, some novel schemes based on HGHG such as enhanced HGHG (EHGHG) [6] and echo-enabled harmonic generation (EEHG) [7] have been put forward to enhance the bunching factor of higher harmonics and extend the FEL wavelength to shorter region. The EEHG scheme can generate ultrahigh harmonics with relatively small energy modulation. The analytical calculations and numerical simulations imply that a single-stage EEHG FEL is able to generate high power soft X-ray radiation directly from a UV seeding laser [8, 9]. However, the facility of EEHG FEL is complicated and the radiation is very sensitive to some system parameters [10]; the strength of the two dispersive sections, for instance. The EHGHG scheme can also significantly enhance HGHG performance, but is less advanced in increasing the up-conversion efficiency than EEHG. Nevertheless, it is easy to be implemented, especially for an existing HGHG facility; a small modification can enhance the FEL distinctly.

We have studied the effects of system parameters in the EHGHG scheme and compared them with those of the HGHG scheme [11]. It has been shown that the EHGHG scheme has an acceptable tolerance of system parameters while increasing the efficiency. In Ref. [12], a chicane with a negative momentum compaction factor was used, and we are thinking of using a negative dispersive section in the EHGHG scheme. Normally, a 4-dipole chicane has a positive dispersion. We can achieve the negative dispersion by adding a quadrupole between the middle two dipoles [13, 14]. In this paper, we investigate the EHGHG FEL with negative dispersion and compare its performance with the positive case.

2 EHGHG with negative dispersion

The EHGHG scheme is composed of a normal HGHG configuration and a short modulator added after the dispersive section for suppressing the electron beam energy spread and increasing the harmonic bunching factor.

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One key point for the EHGHG scheme is that the fractional part of the dispersive strength (N_d) [15] should be carefully tuned to be 0.5; so that the electron beam can have a phase seperation of π with the seeding laser before entering the second modulator, where the electron beam will be modulated for energy spread suppression. Here the suppression process mainly works on the non-bunched electrons. In addition, the suppression section has a bunching effect when the electron beam is under-bunched before entering it. Therefore, 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.

The density modulation can be measured by using the bunching factor. For the HGHG scheme, the initial bunching factor of the nth harmonic in the radiation section is given by

$$b_n \simeq \sum_{j+k=n} (-1)^j J_j\left(nD_1\frac{\Delta\gamma_{m1}}{\gamma}\right) J_k\left(nD_2\frac{\Delta\gamma_{m2}}{\gamma}\right) \times \exp\left\{-\frac{1}{2}[(\mathrm{j}D_1+kD_2)\sigma_\gamma/\gamma]^2\right\}, \quad (1)$$

where J_n is the nth order Bessel function, $D_1=4\pi(N_\mathrm{d}+N_2+N_1/2)$, $D_2=2\pi N_2$, N_1 and N_2 are the number of periods of the first and the second modulator, respectively. N_d is the scale parameter of the dispersive strength, γ is the electron energy, σ_γ is the initial energy spread of electrons, and $\Delta\gamma_{m1}$ and $\Delta\gamma_{m2}$ are the energy modulation induced by the seeding laser in the first and second modulator, respectively.

If we set the dispersive strength to a negative value, it seems to us that the negative effect of the dispersive strength N_d on the energy spread correction factor is further weakened. Thus, a larger absolute value of N_d may be used, and a larger energy modulation may be allowed to generate higher bunching. And the FEL performance may be further enhanced.

To validate our analysis, numerical simulations were done by using 3D code GENESIS [16]. As an example, the simulations were based on the parameter set of Hefei soft X-ray proposal [17], which is listed in Table 1. In these simulations, we adopt the electron energy detuning above resonance to generate more powerful radiation.

Table 1. The main parameters of the Hefei soft X-ray proposal.

beam energy	800 MeV
beam energy spread	0.01%
beam peak current	600 A
beam transverse emittance	2.0 mm·mrad
average beta function	4.21 m
modulator period length	5.4 cm
modulator parameter (a_u)	4.8014
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)	−85
radiator period length	3.2 cm
radiator undulator parameter	1.23595
radiator resonant wavelength	16.5 nm
radiator length	15.936 m

Figures 1(a)–(c) shows the evolution of the electron beam longitudinal phase space of the EHGHG with negative dispersion from the end of the first modulator to the entrance of the radiator. It can be found that the range of the electron energy of the whole beam decreases. However, the energy spread is still suppressed mainly for the non-bunched electrons.

In Ref. [11], we have investigated the normal EHGHG with positive dispersion with the same parameters as those in this paper, and the seeding power and dispersive strength for that were optimized to be P_0=240 MW and N_d=60, respectively. The dependence of the saturation power and length on the seeding power and negative dispersive strength studied here is given in Fig. 2. It is obvious that the optimized parameters for the EHGHG

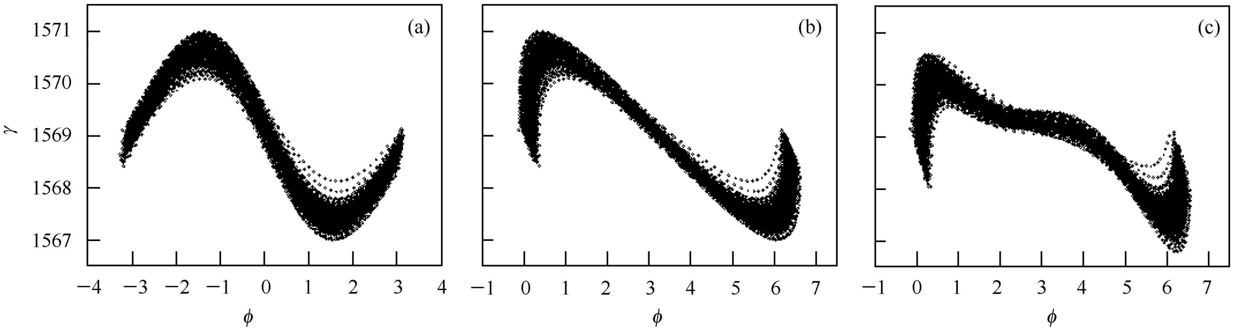

Fig. 1. The electron beam longitudinal phase space at the exit of: (a) the first modulation section; (b) the dispersive section; and (c) the second modulation section.

with positive dispersion are not fitted here. A larger absolute value of N_d is needed, and simultaneously a more powerful seeding laser can be accepted. For the parameter set of P_0=320 MW and $N_\mathrm{d}=-85$, the saturation power and length are P_sat=497 MW and L_sat=13.28 m, respectively. Compared with the best case of the EHGHG with positive dispersion, the saturation length decreases a lot and one section of undulator (2.4 m) can be saved. Meanwhile, only a little of the saturation power is lost.

To reveal the characteristic of the EHGHG with negative dispersion, we compare the EHGHG with negative and positive dispersion at the same seeding power of 240 MW. The result is exhibited in Fig. 3. From the illustration, it can be clearly found that the scheme of negative N_d suffers a larger absolute value of N_d. When N_d is equal to -100, it has the shortest saturation length of 14.272 m, which is smaller than the minimum value of the scheme with positive N_d while the saturation powers are comparative.

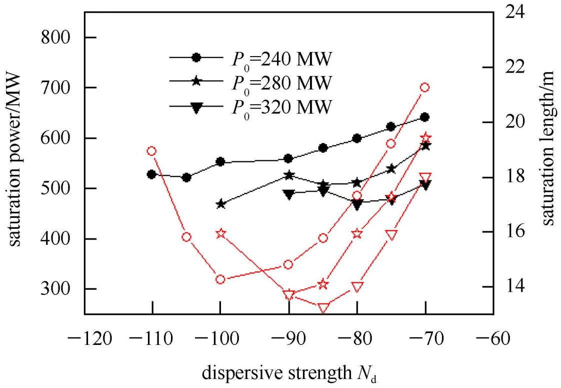

Fig. 2. The variation of saturation power and length of the EHGHG with negative dispersion with different dispersive strength (N_d) and seeding power (P_0). The solid black icons are for the saturation power and the open red ones are for the saturation length.

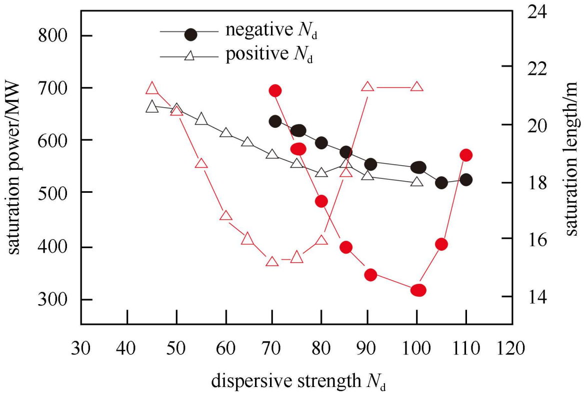

Fig. 3. The comparison of the EHGHG with negative and positive dispersive strength at the equal seeding power of P_0=240 MW. Black: saturation power; red: saturation length.

Now we fix the seeding power to be 240 MW, and choose N_d to be 70 and -100 for comparative study. Fig. 4 shows the electron energy distribution at the entrance of the radiator, in which one can find that the scheme with negative N_d has a more concentrated electron energy distribution and its energy spread is smaller. Furthermore, the bunching factor of the negative N_d case at the entrance of the radiator is a little higher, as shown in Fig. 5.

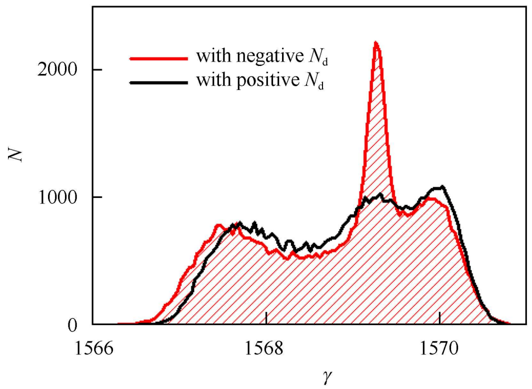

Fig. 4. The electron energy distribution at the entrance of the radiation section of the EHGHG with N_d=−100 (the red shadow region) and N_d=70 (the black line) at P_0=240 MW.

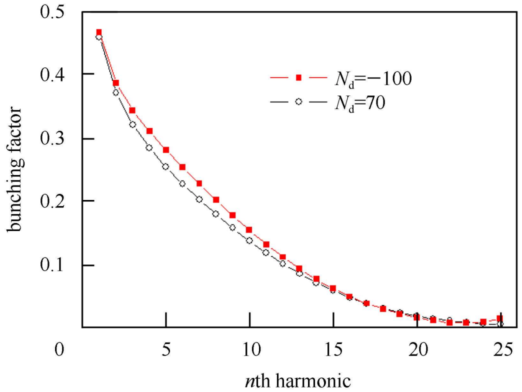

Fig. 5. The bunching factor at the entrance of the radiation section for N_d=−100 (the black block) and N_d=70 (the red circle) at P_0=240 MW.

Next, we investigate the parameter tolerance of the schemes with different signs of N_d, such as the initial electron energy spread and the relative phase shift between the seeding laser and electron beam. The radiator length is set to be 14.272 m. The radiation intensities at the end of the radiator as functions of the initial electron energy spread and the relative phase shift are given in Fig. 6 and Fig. 7, respectively, which are compared between the EHGHG with $N_\mathrm{d}=-100$ and N_d=70. Obviously, the scheme with negative N_d has a larger tolerance on the initial energy spread. This coincides with our analysis mentioned above. For the relative phase shift, the two cases have almost an equal width of good region. But the good region center of the negative N_d case locates in the left of π while the positive N_d case is a little larger than π. This is because the negative N_d case bunches the electrons at the phase of $2n\pi$ while the positive N_d case is at $(2n+1)\pi$, where n is an integer. However, the two schemes both have an acceptable tolerance on the relative phase shift, which makes it easy to be implemented for the EHGHG scheme as controlling the relative phase change between the electrons and the ponderomotive wells is a key problem and is rather difficult to be exactly accurate.

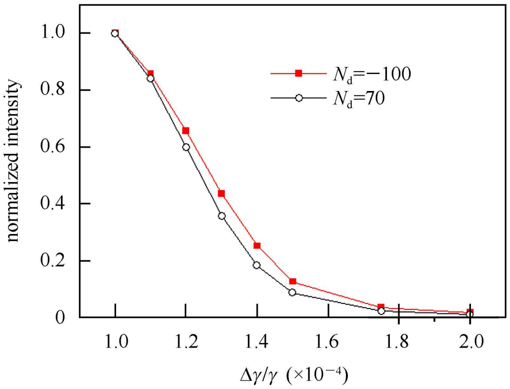

Fig. 6. The normalized radiation intensity at $z=$ 14.272 m as a function of the initial electron energy spread.

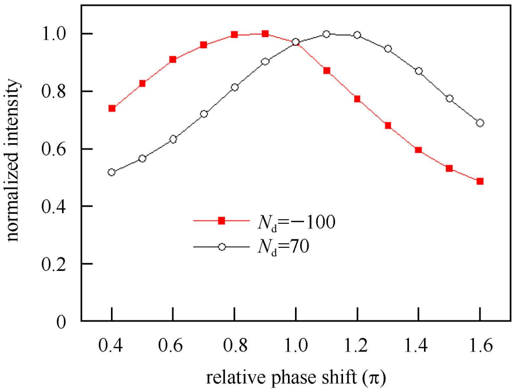

Fig. 7. The normalized radiation intensity at $z=$ 14.272 m as a function of the relative phase shift.

3 Conclusions

The EHGHG scheme with negative dispersion has been investigated. We analyzed the bunching factor of the EHGHG scheme. Then the numerical simulations were done and compared with the positive N_d case. The results demonstrate that the negative dispersion can further weaken the negative effect on the energy spread correction factor and a larger absolute value of N_d can be accepted. The comparative studies indicate that the negative N_d case can suppress the beam energy spread to a smaller value, bunch the electrons a little higher, and have a larger tolerance on the initial energy spread and an almost equal wide good phase shift region.

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