PERFORMANCE COMPARISON OF SEVERAL DOUBLE-MODULATOR HARMONIC GENERATION SCHEMES ON SDUV-FEL

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Abstract

High-gain Harmonic Generation (HGHG) FEL is one of the two main approaches to reach extremely short wavelength. Recently, some novel operation modes such as G. De Ninno's double-modulator scheme, Enhanced HGHG (EHGHG) and Echo-enabled Harmonic Generation (EEHG) have been put forward to enhance the bunching factor of higher harmonics in HGHG FEL. Currently a new modulator and a new chicane with large dispersion strength are suggested to be employed in Shanghai Deep Ultraviolet FEL (SDUV-FEL) so that it will be capable of undertaking these new FEL experiments. We simulated and compared the performance of these three operation modes based on the SDUV-FEL parameters.

INTRODUCTION

Due to its high brightness, short wavelength, short pulse duration and excellent coherence, Free-electron Laser (FEL) has been commonly considered the 4th generation light source. Nowadays self-amplified spontaneous emission (SASE) [1] and high-gain harmonic generation (HGHG) [2, 3, 4] are the two main approaches to reach x-ray region. Compared to SASE FEL, HGHG FEL is more compact in terms of its whole size and its radiation has much better temporal coherence. However, HGHG FEL needs seeding lasers and its up-frequency conversion efficiency is always limited by many factors such as energy spread and shot noise of electron bunches. Therefore, whether HGHG FEL could reach hard x-ray region is always a hot issue discussed for many years.

Recently, many novel ideas have been put forward to enhance the up-frequency conversion efficiency of HGHG FEL. For instance, G. De Ninno suggested a double-modulator scheme [5] to limit the electron bunch's extra energy spread caused by the energy modulation with a seeding laser while keep its bunching at a high value. Then Qika Jia put forward another scheme with two modulators, which is called EHGHG [6] to obtain a relatively high bunching factor compared to classical HGHG scheme. Currently, EEHG [7, 8] perhaps is the most fascinating idea for generating extremely high harmonics FEL radiation, which needs two modulators with very low seeding power and two magnetic chicanes, one of which needs large dispersion strength.

As a test facility for modern FEL R&D, recently SDUV-FEL has been equipped a new modulator and a new magnetic chicane with extremely large dispersion strength. Besides the conventional SASE and HGHG experiments, such a double-modulator and double-chicane device will be capable of doing proof-of-principle experiments of all the novel ideas mentioned above. In this paper, we applied these three schemes on SDUV-FEL and showed some simulation results, from which we compared their performance in terms of the saturation power and saturation length of the generated harmonics.

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PRINCIPLE

N. De Ninno's Double-Modulator Scheme

In the first modulator, the electron beam obtains a large energy modulation by a seeding laser with large power. Meanwhile, the bunching of fundamental and higher harmonics develops greatly due to its large energy spread in this section. Then e- beam experiences a π phase shift and enters the second modulator, in which it interacts with another seeding laser whose phase is the same as that in the first modulator and thus is π different from that of the current e- beam. Therefore, e- beam's energy spread will be effectively suppressed, while its bunching will still increase due to the existing energy spread. Finally, it passes a dispersion section which induces a larger bunching. The whole process could be seen from Fig. 2.

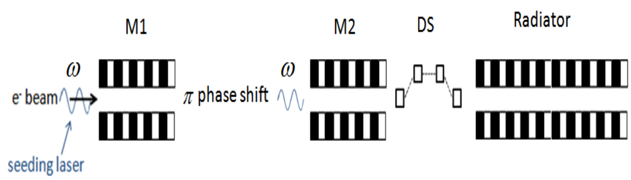

Figure 1: Scheme of the double-modulator device.

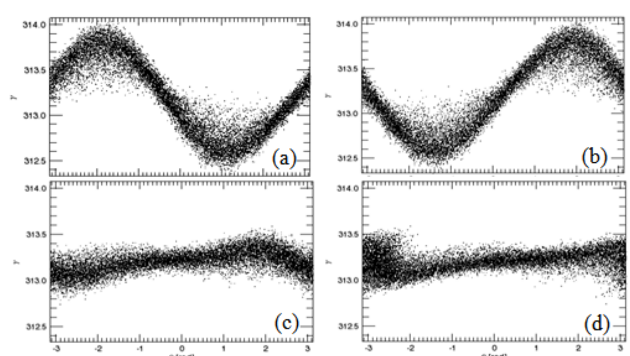

Figure 2: Electrons' phase space when passing the scheme described in Fig. 1 (a) at the end of the first modulator (b) at the entrance of the second modulator (c) at the end of the second modulator (d) at the end of the dispersion section.

EHGHG

This scheme is similar to the one described above. The only difference is that in this one, after passing the first modulator, the e- beam is first compressed by a dispersion section and then passes a so-called de-modulator. However, thanks to this difference, the seeding power does not need to reach a very high level as the first scheme requires. Because the key of the first scheme is to use a powerful laser, the order of whose power is ~GW, to generate a high bunching in the first modulator and then to suppress e- beam's energy spread using the second modulator. While in EHGHG scheme, the bunching enhancement is mainly realized in the dispersion section, so it don't require a high seeding power. Fig. 4 shows the development of the electrons' phase space in this scheme.

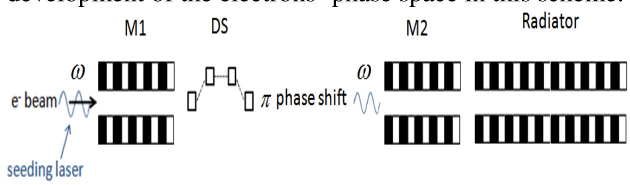

Figure 3: Scheme of EHGHG.

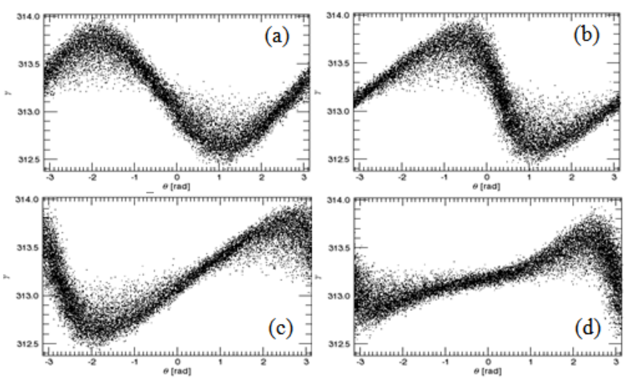

Figure 4: Electrons' phase space when passing the scheme described in Fig. 3 (a) at the end of the first modulator (b) at the end of the dispersion section (c) at the beginning of the second modulator (d) at the end of the second modulator.

EEHG

In EEHG, the e- beam experiences a very small energy modulation and then goes through a dispersion section with extremely large R56, which shreds the e- beam into many small pieces along the longitudinal direction as shown in Fig. 6(b). Then these pieces obtain a small energy modulation again in the second modulator and finally are bunched at very small scale. (See Fig. 6(c)(d).) By adjusting the power of two seeding lasers and R56 of two magnetic chicanes, we could maximize the bunching factor of a certain harmonic, while suppress that of the other ones.

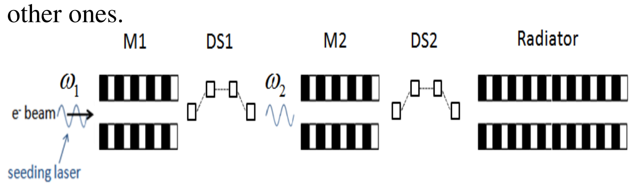

Figure 5: Scheme of EEHG.

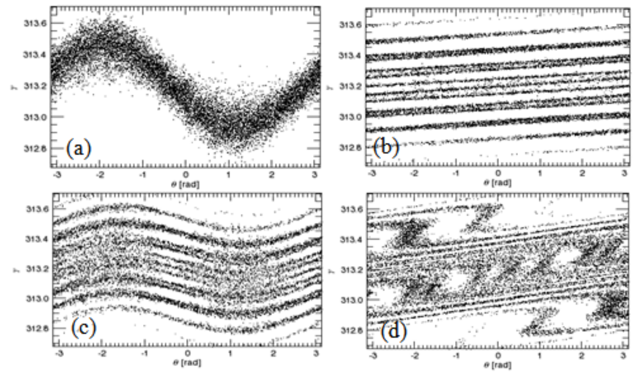

Figure 6: Electrons' phase space when passing the scheme described in Fig. 5 (a) at the end of the first modulator (b) at the end of the first dispersion section (c) at the end of the second modulator (d) at the end of the second dispersion section.

SIMULATION AND ANALYSIS

The layout and parameters of SDUV-FEL are shown in Fig. 7 and Table 1, respectively. Note that there are two sets of parameters for Radiator. The former set and the latter one respectively correspond to the 4th and 10th harmonic amplification. Furthermore, we have only one seeding laser, which requires us to split the laser power into two parts for the two modulators. All the following simulations were performed with 3D code Genesis [9, 10].

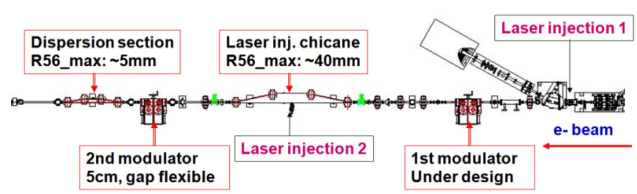

Figure 7: Layout of SDUV-FEL.

Table 1: Parameters of SDUV-FEL

Electron beam	
Beam energy [MeV]	160
Slice energy spread [keV]	32
Peak current [A]	300
Emittance [mm-mrad]	6
Pulse length [ps]	2 ~ 3
Seeding laser	
Wavelength [nm]	1047
Peak power [MW]	0 ~ 50
Pulse length [ps]	8
Modulator 1	
Period length [mm]	65
Period number	10
K	2.08
Modulator 2	
Period length [mm]	50

Period number	10
K	2.49
Chicane 1	
R56 [mm]	0 ~ 40
Chicane 2	
R56 [mm]	0 ~ 5
Radiator	
Period length [mm]	25 / 18
Length / segment [m]	1.5 / 1.08
Number of segments	6
K	1.45 / 0.53

From Fig. 8, we could see that for the 4th harmonic, the performance of the three novel schemes is very close and a little better than that of classical HGHG scheme. The two keys determined to the saturation power and saturation length of FEL radiation are the e- beam's bunching and energy spread. Fig. 9 shows the relationship between bunching (energy spread) at the entrance of Radiator and seeding power for the first double-modulator scheme and EHGHG. P1 and P2 are the seeding power in Modulator 1 and Modulator 2, respectively. In Fig. 9, we assume P1 + P2 = 50MW to maximize the utility of the seeding laser. We find that for the first double-modulator scheme, the bunching is small, but meanwhile the energy spread is also small. We should note again that the characteristic of this scheme is to employ an extremely powerful laser (~GW) to induce large bunching in two modulators. However, in our case, the seeding laser is too small (~MW) to induce strong bunching. On the other hand, for EHGHG, although the bunching is relatively large, the energy spread is large too. As shown in Fig. 10, after passing the chicane, most electrons will be bunched where the seeding laser field is almost zero, which makes these electrons not affected by the seeding laser. Therefore, for EHGHG, although the bunching could be quite strong due to the function of the chicane after Modulator 1, its energy spread suppression is not effective compared to the first double-modulator scheme.

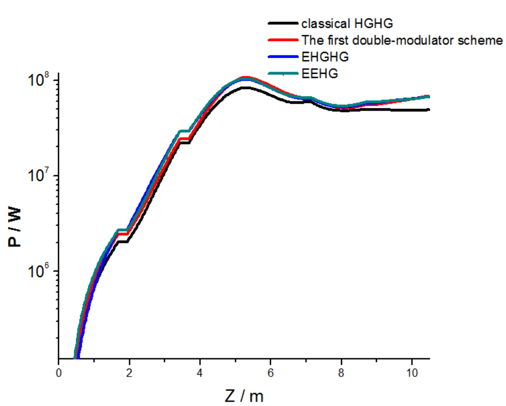

Figure 8: The optimized power gain curve of the 4th harmonic (262nm) in Radiator.

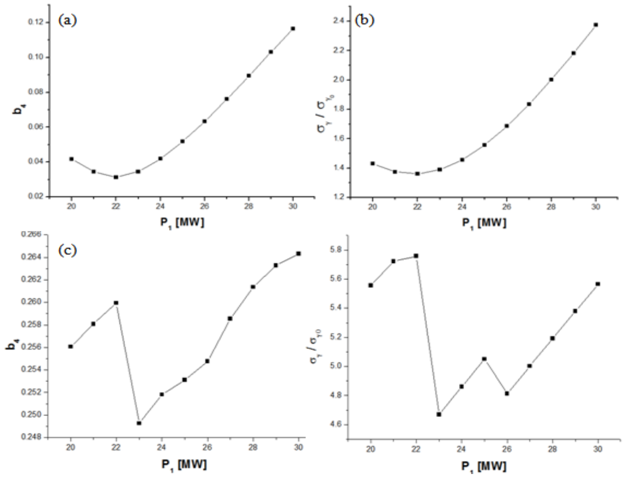

Figure 9: (a) bunching VS P1 for the first double-modulator scheme (b) energy spread VS P1 for the first double-modulator scheme (c) bunching VS P1 for EHGHG (b) energy spread VS P1 for EHGHG.

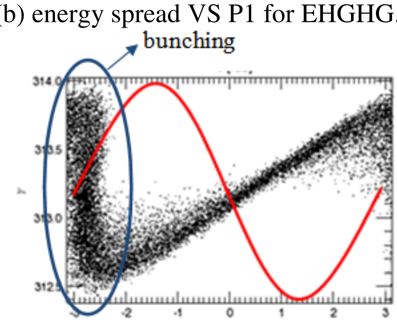

Figure 10: e- beam's phase space at the entrance of Modulator 2 for EHGHG, the red line represents the phase of seeding laser in Modulator 2.

From Fig. 8, perhaps we cannot see which scheme is superior to the others for the low harmonic numbers. However, with the increasing harmonic number, the advantage of EEHG is gradually obvious. Shown in Fig. 11, for 10th harmonic, EEHG undoubtedly performs best, which verifies its capability to reach extremely high harmonic number. Also, at high harmonic number, the difference between the first double-modulator scheme and EHGHG appears. In our case, the latter works better than the former. In fact, for the first double-modulator scheme, at the end of Radiator the 10th harmonic has not been saturated due to its small bunching and small energy spread at the entrance of Radiator.

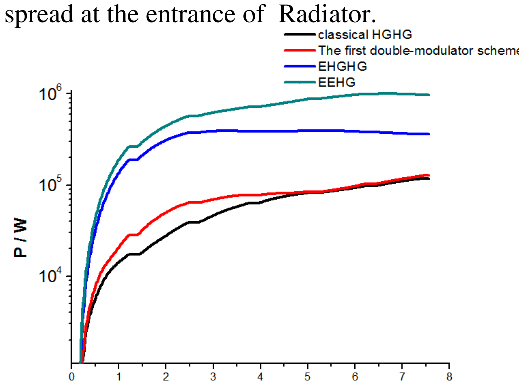

Figure 11: The optimized power gain curve of the 10th harmonic (104.7nm) in Radiator.

CONCLUSION

We simulated several novel ideas which will be experimented on SDUV-FEL in the near future. We concluded that for low harmonic numbers, the three novel schemes have the similar performance which is better than that of the classical HGHG scheme. While for high harmonic numbers, EEHG shows its unique status due to its large bunching but small energy spread. Additionally, for high harmonic numbers, EHGHG has a better performance than the first double-modulator scheme does. In fact, these two schemes possess their own advantages. Compared with the first double-modulator scheme, EHGHG could obtain stronger bunching while its second modulator has the less energy spread suppression effect.

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