STUDY OF THE ENERGY CHIRP EFFECTS ON SEEDED FEL SCHEMES AT SDUV-FEL

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Abstract

In this paper, theoretical and simulation study of the energy chirp effects on the HGHG and EEHG schemes are present. It is found that the central wavelength and output bandwidth of EEHG can be nearly immune to the beam energy chirp by properly setting the strengths of the chicanes. Experimental studies for both these two schemes have been carried out at the SDUV-FEL to demonstrate the theoretical predictions.

INTRODUCTION

High-gain seeded FEL schemes have been developed for producing stable and fully temporal coherence laser pulse from deep UV down to the x-ray regime. Both high-gain harmonic generation (HGHG) [1] and recent proposed echo-enabled harmonic generation (EEHG) [2, 3] are promising candidates for short wavelength FEL. Recently, these two schemes have been operated and tested at the Shanghai deep ultra-violent FEL (SDUV-FEL). The HGHG FEL at 347nm has reached saturation in later 2010 [4] and the EEHG signal at 350nm has been successfully amplified by the long radiator in early 2011 [5].

It is anticipated that seeded FEL schemes can be used for generation of transform-limited radiation pulse, which usually requires a uniform electron beam with constant current and energy. However, it is found that the energy profile of the electron bunch coming into the undulator usually has an initial energy chirp and an energy curvature due to the radio frequency curvature and wakefield effects in the accelerator. Sometimes this energy chirped electron beam may be useful to overcome the sensitivity of the output power to the electron beam energy jitters. However, the energy chirp in the electron beam will also impact the FEL process in the undulator and result in a broader output bandwidth. In this paper, the FEL performance of HGHG and EEHG with an energy chirped electron beam is studied both theoretically and experimentally at the SDUV-FEL. It is found that the central wavelength and bandwidth of the radiation generated by the EEHG scheme can be nearly immune to the beam energy chirp by properly setting the strengths of the two chicanes. This feature may be useful for generating of fully coherent short wavelength radiation.

PRINCIPLE

According to the basic theory of EEHG, the central wavelength of the EEHG radiation should be [3]

$$\lambda_{\mathrm{EEHG}} = 1/[\frac{n}{\lambda_{s1}} + \frac{m}{\lambda_{s2}}], \quad (1)$$

Where m and n are integers, λ_{s1} and λ_{s1} are the wavelengths of the seed lasers. The central wavelengths of the HGHG and the EEHG have a quite different dependence on the energy chirp [6]:

$$\lambda'_{\mathrm{HGHG}} = \lambda_s(1+HB)/k, \quad (2)$$

$$\lambda'_{\mathrm{EEHG}} = [1+H(B_1+B_2)]\Big/[\frac{n}{\lambda_{s1}} + (1+HB_1)\frac{m}{\lambda_{s2}}], \quad (3)$$

where $H = hE_0\lambda_{s1}/2\pi\sigma_E$ is the dimensionless chirp factor, E_0 is the beam central energy, σ_E is the initial energy spread, h is the energy chirp factor, $R_{56}^{(1)}$ and $R_{56}^{(2)}$ are strengths of DSs and $k = n + mK$ is the harmonic number of HGHG, $K = \lambda_{s1}/\lambda_{s2}$. Here, we define the wavelength shift factor $a = \lambda'_{\mathrm{EEHG}}/\lambda_{\mathrm{EEHG}}$. From Eq. (3), one can get

$$a = 1 + CH, \quad (4)$$

where $C = B_1 + B_2 - \lambda'_{\mathrm{EEHG}}\, mB_1/\lambda_{s2}$. From Eq. (1), it is found that the output wavelength will immune to the energy chirp (C=0) when the relation between the two DS strengths satisfies

$$B_2 = -\frac{n}{k}B_1. \quad (5)$$

The optimized relationship between the strengths of the two DSs for EEHG operation is [3]

$$B_2 = -\frac{n}{k}B_1 + \frac{\xi}{k}, \quad (6)$$

Where ξ is the solution of

$$A_1\left[J_{n-1}(A_1\xi) - J_{n+1}(A_1\xi)\right] = 2\xi J_n(A_1\xi), \quad (7)$$

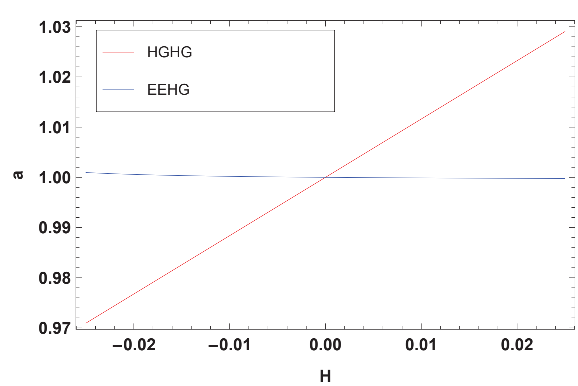

Figure 1: wavelength shift factor as a function of energy chirp in the electron beam.

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Generally, for a given B_1, the difference between the optimized values calculated by Eq. (5) and Eq. (6) can be turned to be much smaller than B_2 by increasing A_1 and k, which means that the EEHG scheme with optimized condition will be insensitive to the energy chirp at high harmonics.

Figure 1 shows wavelength shift factors as a function of the energy chirp for both HGHG and EEHG. The parameters of EEHG used here are $A_1 = 6$, $A_2 = 1$, $B_1 = 23.53$, $B_2 = 1.16$ and K=1, which are optimized for the 20th harmonic of the seed. The strengths of the DSs are quite close to the requirement of Eq. (5). It is found in Fig. 2 that the wavelength shift factor of EEHG nearly has no response to the energy chirp.

ENERGY CHIRP EFFECTS AT SDUV-FEL

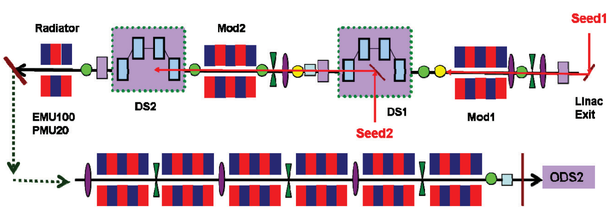

Figure 2: Layout of the experiment area of SDUV-FEL.

The SDUV FEL is a seeded FEL test facility designed for generating coherent radiation with wavelength down to the Ultraviolet region. The schematic layout of the undulator system, as well as their main components, is shown in Fig. 1. Main parameters used during the experiment can be found in Table 1. The undulator system consists of two modulators, two dispersion sections and two radiators. The second modulator and dispersion section are used for HGHG experiment. The first modulator and dispersion section are added for the EEHG experiment. The gap of the short radiator is flexible and can be adjusted for generating harmonic signal of HGHG or EEHG. The long radiator with fixed gap is used for the amplification of these signals.

Table 1: Main Parameters of SDUV–FEL

Electron beam		
Beam energy [MeV]	135.4	
Global energy spread [MeV]	0.2	
Charge [pC]	100~300	
Emittance [mm-mrad]	4	
Pulse length (FWHM) [ps]	8	
Seeding laser	**1 (for EEHG)**	**2 (for HGHG and EEHG)**
Wavelength [nm]	1047	1047
Energy [μJ]	0 ~ 60	0~60
Pulse length (FWHM) [ps]	8.7	8.7
Modulator	**1 (for EEHG)**	**2 (for HGHG and EEHG)**
Period length [mm]	65	50
Period number	10	10
K	1.6	2.0
Radiator		
Period length [mm]	50	
Period number	10	
K	1.4	
Disperation	**1 (for EEHG)**	**2 (for HGHG)**
R56 [mm]	7	1.9

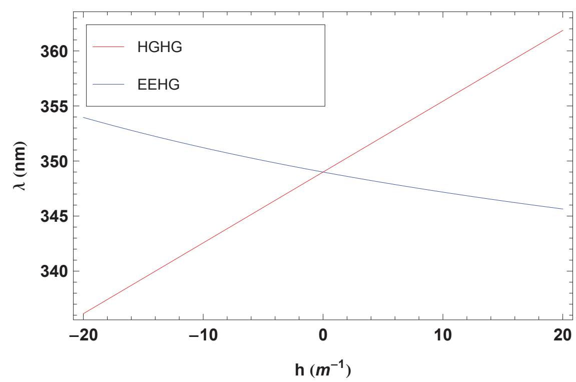

Figure 3: Central wavelength as a function of the energy chirp in the electron beam.

Besides the parameters shown in Table 1, several important parameters like local energy spread and energy modulation amplitudes induced by the seed lasers should also be determined. In our experiment, these parameters are accurately measured by the CHG based method [7]. The measurement results show that the local energy spread is about 2.6keV at the exit of the linac when the electron beam is compressed by a factor of about 2. The maximal energy modulation amplitudes induced by the seed lasers are measured to be about 25.6 keV for seed 1 and about 21.4keV for seed 2. The energy modulation amplitudes are calculated to be $A_1 = 9.85$ and $A_2 = 8.23$ .The strengths of the two DSs are set to be $R_{56}^{(1)} = 7mm$ and $R_{56}^{(2)} = 1.9mm$ to optimise the EEHG performance at 3rd harmonic of the seed for m=4, n=-1 [3].

As the harmonic numbers for both HGHG and EEHG are only 3, the central wavelength of EEHG is not immune to the energy chirp, as Fig. 3 shows. It is clear that the central wavelengths of HGHG and EEHG present opposite variations with respect to the energy chirp, and the wavelength of EEHG is less sensitive to the energy chirp than that of HGHG.

The central wavelengths of the HGHG and EEHG radiation are determined by the electron bunching. Figure 4 shows the phase spaces at the entrance to the radiator of EEHG for the electron beam with a linear energy chirp ($h = -6m^{-1}$). One can find that the liner chirp is changed

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to step configuration chirp after the DS2 of EEHG. In each step the energy chirp is different from the initial energy chirp and can be turned to different values by changing the strengths of the DSs.

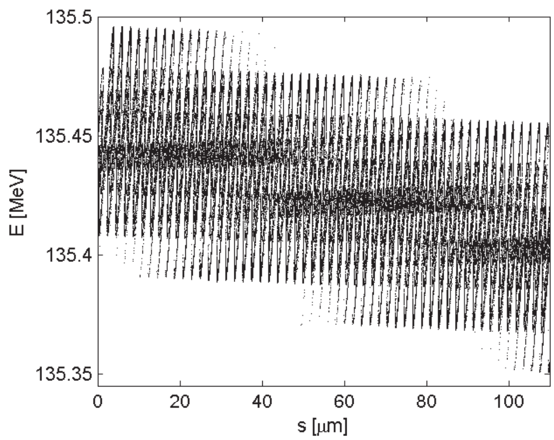

Figure 4: Phase space of the electron beam at the entrance of the radiator of EEHG.

There is always a nonlinear energy chirp in the electron beam due to the radio frequency curvature and wakefield effects in the accelerator, which will result in a frequency chirp in the FEL radiation and increase the bandwidth of the output. It is found in Fig. 5 that the effect of nonlinear energy chirp on the bandwidth increase of the EEHG FEL is smaller than the HGHG FEL, which means that the coherence of EEHG will be better than HGHG under our experiment condition.

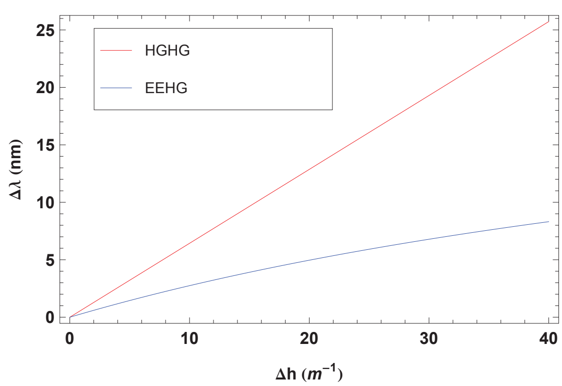

Figure 5: Spectral bandwidth increase as a function of total energy chirps in the electron beam.

To verify the theoretical prediction, HGHG and EEHG experiments have been carried out at the SDUV-FEL. The electron beam is chirped by adjusting the phase of the accelerator tank and overbunched by a compressor. The HGHG and EEHG signals generated by the chirped electron beam are amplified by the long radiator and the spectrum of the radiation is recorded by a spectrometer. The measurement results are shown in Fig. 6. The central wavelength of HGHG FEL shifts from 349nm (3rd harmonic of the seed) to a shorter wavelength of about 345nm due to the large energy chirp, and the central wavelength of EEHG FEL shits to a longer wavelength of about 350nm. The FWHM spectral bandwidth of EEHG is about 0.7nm, which is 2 times smaller than HGHG.

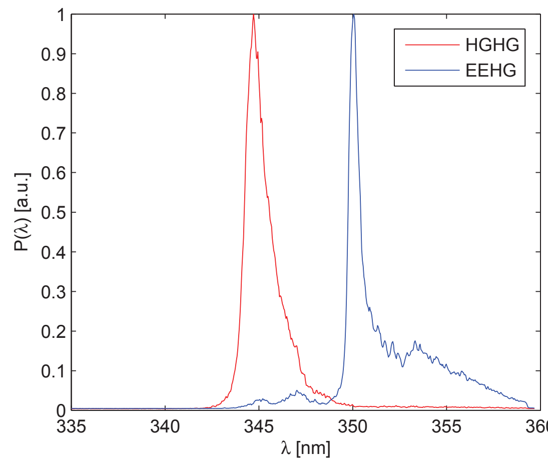

Figure 6: Measurement spectra of FEL radiation generated by HGHG and EEHG.

CONCLUSION

The performances of the HGHG and EEHG have a quite different dependence on the energy chirp in the electron beam. The EEHG with optimized condition can be nearly immune to the energy chirp at high harmonics and insensitive to the energy chirp at low harmonics. Thus, the central wavelength of the EEHG will not change much from the 3rd harmonic of the seed laser and the coherence of the radiation produced by EEHG is better than HGHG in our experiment. The experimental results confirm the theoretical prediction at the SDUV-FEL. This information may be useful for the design of an EEHG based FEL in the future.

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