A COMPARISON STUDY OF HIGH HARMONIC CHARACTERIZATIONS IN EEHG OPERATION OF SDUV-FEL

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Abstract

With a relatively small energy modulation, the echo-enabled harmonic generation (EEHG) scheme promises a remarkable efficiency for high harmonic microbunching generation. Recently, a proof-of-principle experiment of EEHG scheme has been carried out at Shanghai deep ultraviolet (SDUV) free electron laser (FEL), where the 2nd harmonic of the 1047 nm seed laser was observed with EEHG mechanism. Moreover, to explore the advantage of EEHG scheme, higher order harmonics up to 7~15th are seriously under consideration in SDUV-FEL. In this paper, we consider on the potential methods for measuring the higher order harmonic microbunching. It shows that, in comparison with the coherent transition radiation (CTR) and the coherent synchrotron radiation (CSR) based diagnostics, the coherent undulator radiation (CUR) is a more feasible way to characterize the high order harmonic microbunching in EEHG operation of SDUV-FEL.

INTRODUCTION

On the way to compact and fully temporal coherent radiation sources in the short-wavelength spectral region, in free electron laser (FEL) community, various seeded FEL schemes were proposed. Among them, echo-enabled harmonic generation (EEHG) [1] mechanism predicts an unprecedented frequency up-conversion efficiency and allows for the generation of ultra-high harmonic with relatively small energy modulation. It is found that the Shanghai deep ultraviolet (SDUV) [2] FEL is well suited for EEHG scheme with only minor modifications. Thus, a proof-of-principle experiment of EEHG was proposed [3] and carried out at SDUV-FEL.

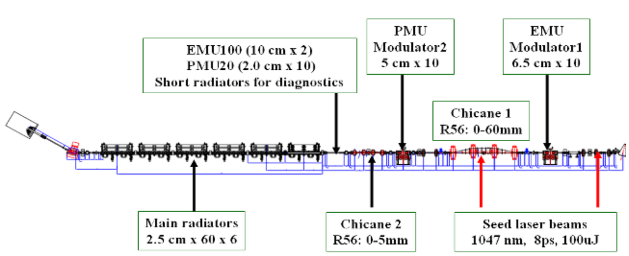

Figure 1: The double modulator section of SDUV-FEL.

The layout of the double modulator section of SDUV-FEL is illustrated in Figure 1. The original laser injection chicane is redesigned to produce larger R_{56} and one more laser injection port is added near the linac exit. The seed laser is split into two beams for the two modulators. For obtaining a strong radiation signal, in the experiment, a 2 periods, 0.2 m long undulator is set to be resonant at the 2nd harmonic of the seed. In our first experiment [4-5], the 2nd harmonic microbunching with EEHG mechanism was successfully demonstrated.

However, the most attractive feature of EEHG scheme is efficient generation of high harmonic microbunching. And intensive study [6] indicates that for lower harmonic generation in SDUV-FEL, EEHG scheme results in a similar performance when compared with other seeded schemes. Thus, in order to explore the promising ability of EEHG mechanism at high harmonic microbunching, the characterization of the 7~15th harmonic is taken to be the next step in EEHG commissioning at SDUV-FEL. Since the typical electron beam in SDUV-FEL operation is 135 MeV, one can not easily find a resonant radiator for such high harmonics of the seed laser. And these high harmonics may not be amplified to saturation in SDUV-FEL. It seems that, high harmonic microbunching can only be measured at the exit of the second chicane by some conventional longitudinal diagnoses, i.e., coherent transition radiation (CTR) and coherent synchrotron radiation (CSR) based method. Moreover, a novel method based on coherent harmonic radiation of an undulator was proposed [7] to picture the high harmonic microbunching of the electron beam in EEHG operation of SDUV-FEL.

In this paper, an intensive comparison between these 3 methods mentioned above is presented in the frame of theory and numerical simulation. And on the basis of the results, an experimental setup is described.

PARAMETERS & OPTIMIZATION

Table 1: Parameters of SDUV-FEL with EEHG setup.

Parameters	Value
Electron bema energy	135 MeV
Peak current	100 A
Normalized emittance	10 μm-rad
Local energy spread	1×10^{-4}
Transverse beam size	200 μm
Seed laser wavelength	1047 nm
Seed laser duration FWHM	2 ps
Seed laser waist	1 mm
Seed laser 1 power	10 MW
Seed laser 2 power	5 MW
$R_{56}^{(1)}$	5.50 mm
$R_{56}^{(2)}$	0.52 mm
Modulator 1 period length	65 mm
Modulator 1 periods	10
Modulator 2 period length	50 mm
Modulator 2 periods	10

We consider the 9th harmonic of the 1047 nm seed laser (i.e., 116.3 nm) as an example. With the parameters listed in Table 1, the longitudinal beam density modulation is optimized at the 9th harmonic of the seed laser when the electron beam passes through the second dispersion. The bunching factor versus harmonic number is illustrated in

Figure 2, where b_9 exceeds 0.10 is clearly displayed. Meanwhile, $b_1 = 0.15$ and $b_3 = 0.02$ are observed.

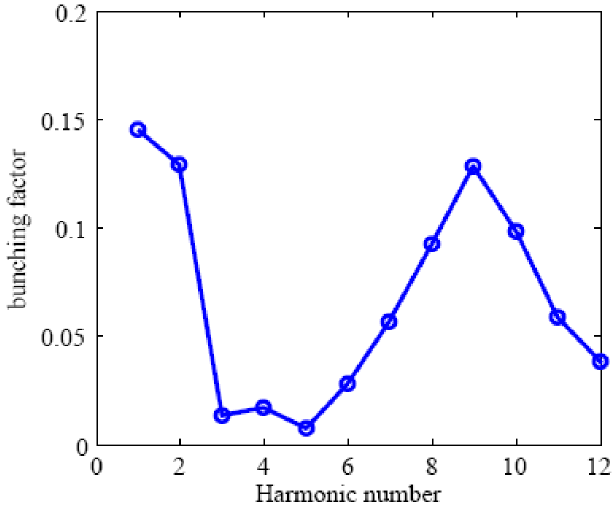

Figure 2: The bunching factor versus harmonic number.

A COMPARATIVE ANALYSIS ON POTENTIAL DIAGNOSTICS

Since the electron beam in SDUV-FEL is typically 135 MeV, there is no suitable undulator which is resonant at 9th and even higher harmonic of the seed laser. Thus high harmonics may not be amplified to saturation by typical FEL process. Here, we study the performance of potential diagnostics for the 9th harmonic microbunching.

Coherent Transition Radiation (CTR)

One of the most popular longitudinal beam diagnoses is the CTR-based method, which relies on the fact that the coherent radiation spectrum emitted by the electron beam as it passes a transition foil is essentially the Fourier transform of the longitudinal beam distribution. It has been widely used in diagnosing macrobunches at the picosecond level [8-9]. In recent years, the CTR-based method was dramatically driven by FEL applications. It has been successfully used to measure the electron beam microbunching in FEL [10-12] and inverse FEL process [13-15]. If the microbunched beam is taken to be

$$f(x,y,z) = \frac{N_b}{(2\pi)^{3/2}\sigma_x\sigma_y\sigma_z} e^{-\frac{x^2}{2\sigma_x^2}-\frac{y^2}{2\sigma_y^2}-\frac{z^2}{2\sigma_z^2}} \times [1+\sum_{n=1}^{\infty} b_n \sin(nk_r z)], \quad (1)$$

where N_b is the number of electrons in the bunch, $\sigma_{x,y,z}$ are the transverse (x, y) and longitudinal (z) beam sizes, respectively, k_r is the radiation wave number (and thus the beam modulation wave number), n is the harmonic number, and b_n is the microbunching factor for the n^{th} harmonic. If one assumes that the microbunching period in the beam's rest frame is much smaller than the transverse beam size, i.e., $k_r\sigma_{x,y} / \gamma >>1$, which is indeed the case for FEL, the n^{th} harmonic CTR energy emitted when the electron beam strikes a conducting surface can be given as follows [10]

$$U_n = \frac{nhc\alpha(N_b b_n)^2}{8(\pi)^{3/2}\sigma_z}\left(\frac{\gamma}{nk_r}\right)^4\left(\frac{\sigma_x^2+\sigma_y^2}{\sigma_x^3\sigma_y^3}\right), \quad (2)$$

where α is the fine structure constant, h is the Planck constant, c is the speed of light in vacuum and γ is the mean electron beam energy in unit of m_0c^2. It is noted that higher charge intensities, higher microbunching and smaller beam size would enhance CTR production.

In SDUV case, the CTR energy from the 9th harmonic is only 19 fJ. According to Eq. (2), the CTR energy at different harmonics of the seed laser is given in Figure 3. CTR has a broad spectrum, especially at each harmonic of the seed laser. We can see that, the fundamental and the lower harmonics of the seed laser frequency have much larger radiation energy in respect with the concerned 9th harmonic of the seed laser.

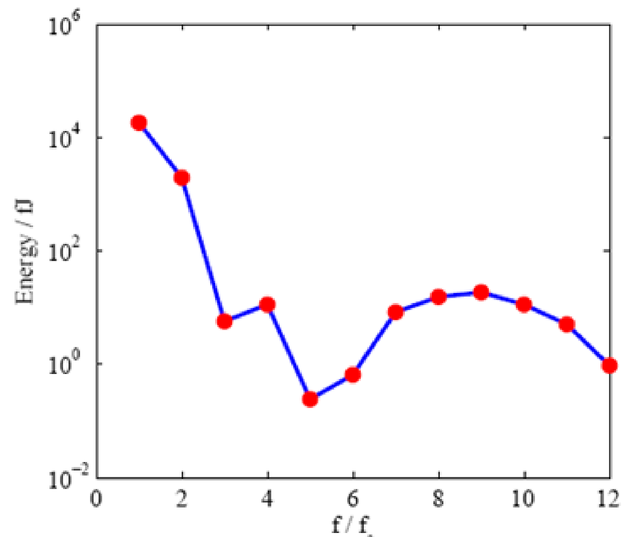

Figure 3: The CTR energy at each harmonics of the seed laser frequency.

Coherent Synchrotron Radiation (CSR)

CSR can occur at wavelengths equal to or longer than the bunch length. In this particular case the electrons emit coherently and the intensity is rather proportional to the square of the number of electrons in the bunch N^2 than to N. Considering the large electron number in an electron bunch, the intensity gain for CSR compared to incoherent synchrotron radiation is huge. CSR has been widely used in the electron bunch length measurement. In recent years, the CSR has been successfully used to observe the microbunching instability in high gain FEL.

From the fundamental of the electrodynamics, in time domain, the CSR signal radiates in the last dipole of the second dispersion chicane in EEHG setup of SDUV-FEL was calculated. Figure 4 shows the CSR spectrum, where the radiation patterns from the electron bunch length, the seed laser and the 9th harmonic are clearly observed.

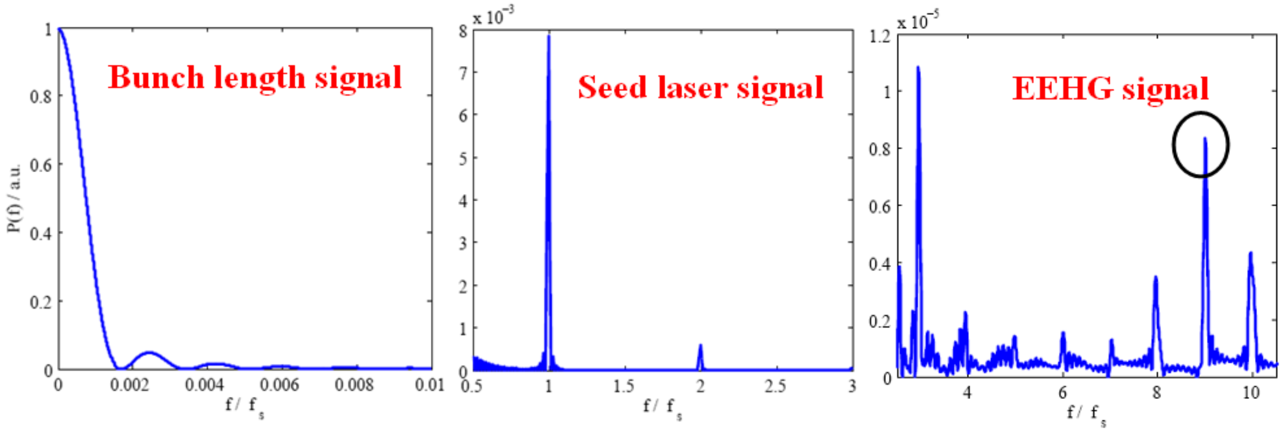

Figure 4: The CSR spectrum radiates from the last dipole of the second dispersive chicane.

According to the Parseval's theorem,

$$\int P(t)dt = \frac{1}{2\pi}\int P(\omega)d\omega\,, \tag{3}$$

we can figure out each component energy in frequency domain. While the component from the electron bunch length dominates in CSR, the 9th harmonic of the seed laser is about 85 pJ.

Coherent Undulator Radiation (CUR)

High harmonics of the undulator radiation is regarded as a natural extension to short wavelengths [16-18], and of great interest. According to FEL physics, harmonic evolution in an undulator can be written down

$$\frac{\partial}{\partial z}E_m(z) = \frac{eK[JJ]_m}{4\gamma m_0 c^2}b_m(z)\,, \tag{4}$$

where m is the harmonic order of undulator radiation; E_m is the slowly varying envelope of the radiation field; e is the charge of a single electron; K is the dimensionless undulator parameter and $[JJ]_m$ is the polarization factor for planar undulator.

For a microbunched electron beam as Eq. (1) describes, the CUR power of the m^{th} harmonic radiation of the radiator reads

$$P_m = \frac{\int |E_m(r)|^2\, d^2r}{2Z_0} = \frac{Z_0(IKb_m[JJ]_m l)^2}{12\pi(\sigma_x{}^2+\sigma_y{}^2)\gamma^2}\,. \tag{5}$$

And the CUR energy of the m^{th} harmonic radiation yields

$$U_m = \frac{Z_0(IKb_m[JJ]_m l)^2\sigma_z}{5\pi(\sigma_x{}^2+\sigma_y{}^2)\gamma^2 c}\,, \tag{6}$$

where I is the peak current of the electron beam and l is the passed radiator length.

In the EEHG scheme, by adjusting the seed laser and the dispersion of chicanes, the electron beam density can be efficiently modulated on arbitrary harmonic of the seed laser. In other words, EEHG scheme shows a significant microbunching for the interested harmonic, while other harmonics still preserve the small level. Thus, if the longitudinal density modulation of the electron beam is optimized at the n^{th} harmonic of the seed laser in EEHG operation, and the optimized harmonic is the m^{th} harmonic of a radiator undulator, strong CUR would be observed at the beginning of the radiator. For SDUV-FEL case, the 9th harmonic of the seed laser could be the 3rd harmonic of the planar radiator.

Figure 5 shows the GENESIS [19] simulated peak power in SDUV-FEL radiator. As seen in Figure 5, the 9th harmonic of the seed laser is clearly enhanced by an initial large bunching factor. Finally, at the end of 1.5m long radiator, the 3rd harmonic CUR 116.3 nm energy exceeds 64 nJ while the fundamental CUR 349 nm radiation energy is 8 nJ.

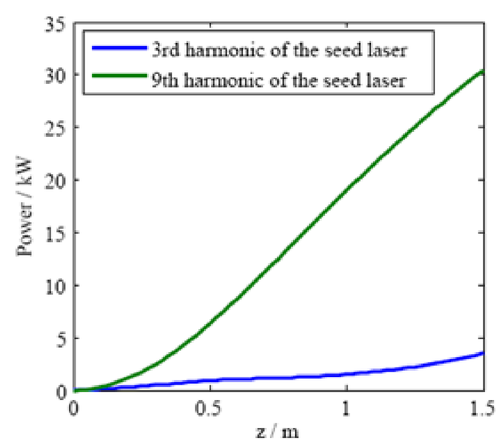

Figure 5: The peak power growth of the CUR in one segment of SDUV radiator.

Table 2: CUR energy from theory and simulation

	The 3rd harmonic	The 9th harmonic
Theory	9 nJ	120 nJ
Simulation	8 nJ	64 nJ

Table 2 shows the theoretical estimate and simulation results of the CUR. If we take the numerical errors, the transverse effects in simulation and the microbunching variation in the radiator into accounts, the simulation results is prettily consistent with the analytical estimation.

Finally, the performances between the three methods mentioned above are listed in Table 3 for comparison and summary.

Table 3: A short performance comparison between CTR, CSR and CUR based method.

	Radiation source	Signal	Signal energy	Noises	Noise energy	SNR
CTR	Aluminum foil	116.3 nm	19fJ	THz	100uJ	$\sim 10^{-10}$
				IR	20pJ	$\sim 10^{-3}$
CSR	Dipole	116.3 nm	85pJ	THz	10uJ	$\sim 10^{-7}$
				IR	80nJ	$\sim 10^{-3}$
CUR	SDUV radiator	116.3 nm	64nJ	UV~VIS	8nJ	$\sim 10^{1}$
				SE	5nJ	$\sim 10^{1}$

PROPOSED MEASURMENT

In comparison with the CTR and CSR based method for measuring high harmonic microbunching in EEHG operation of SDUV-FEL, the following prospects arisen from the CUR-based method.

- The radiation energy of CUR is much larger than that of CTR and CSR. It significantly reduces the required resolution of the detectors.
- The spectrum of CUR is much purer than that of CTR and CSR. Radiation spectrum from CUR only appears at the first several harmonics of the radiator radiation and dominates in the interested harmonic. It means that in the diagnosis, the radiation source from CUR has better signal noise ratio than that of CTR and CSR.

The CUR-based method can be extended to arbitrary harmonics of the seed laser with a harmonic operation technique [20]. Thus, by setting different values to m and n, arbitrary coherent harmonic radiation with EEHG is expected to be investigated in SDUV-FEL. In reality, up to 20th harmonic can be realized by using a flexible gap radiator.

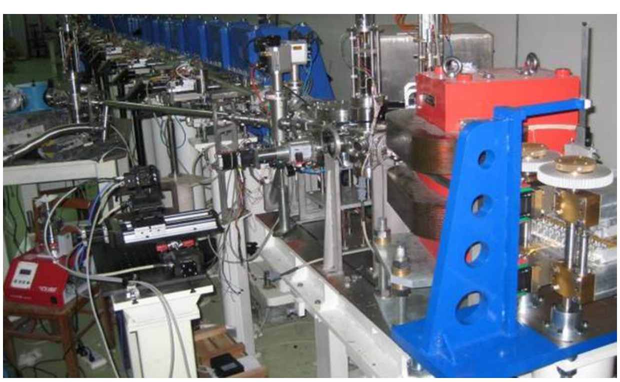

Figure 6: Proposed high harmonic measurement setup in EEHG operation of SDUV-FEL.

Figure 6 shows the current setup for high harmonic measurement, where a flexible gap, 20 mm period, 0.2m long radiator is followed by a VUV spectrometer with response range from 300 to 30 nm. With such a layout, harmonics up to 20th order can be characterized by CUR in EEHG operation of SDUV-FEL.

CONCLUSION

The 2nd harmonic bunching with EEHG mechanism has been successfully demonstrated in SDUV-FEL. So far, the experimental results agree well with theoretical predictions. However, higher harmonic microbunching with EEHG is of great interest. In comparison with the CTR and the CSR-based diagnoses, the CUR-based one shows extremely strong radiation energy and high signal-noise-ratio, it will be prettily helpful in improving the diagnoses in high harmonic microbunching. Based on the results of the comparative studies, corresponding setup and measurement for high harmonic characterization is under way in EEHG operation of SDUV-FEL.

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