RESEARCH ON PULSE ENERGY FLUCTUATION OF A CASCADED HIGH GAIN HARMONIC GENERATION FREE ELECTRON LASER

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Abstract

Shot-to-shot pulse energy fluctuation is one of the most critical issues for two-stage cascaded high gain harmonic generation (HGHG) free electron lasers (FELs). In this paper, we study the effects of various electron parameters jitters on the output pulse energy fluctuations based on the Shanghai Soft X-ray free electron laser facility (SXFEL). The results show that the relative timing jitter between the electron beam and the seed laser is proved to be the most sensitive factor. The energy jitter and charge jitter make some contributions and are non-ignorable as well. Some comparisons between our facility and FERMI have been made and we hope the conclusions draw from this study would be a reference for the optimization of future seeded FEL facilities based on cascading stages of HGHG.

INTRODUCTION

Free electron lasers (FELs) [1] capable of generating coherent x-ray radiation with high brightness and ultra-fast time structures, have been recognized as one type of the 4th generation light sources and witnessed an impressive research and development worldwide in the last decade [2]. For nowadays, most shot-wavelength FEL facilities, such as FLASH [3] in Germany, LCLS [4] in US, SACLA [5, 6] in Japan, make use of the self-amplified spontaneous emission (SASE) scheme [7, 8], which can provide extremely high-intensity, ultra-short pulses with stable output pulse energy (~5% level, saturation) and good spatial coherence. However, the temporal coherence of SASE scheme is poor (comparing to the "Fourier transform limit") due to its starting from the shot noise. Recently, the "self-seeding" scheme has been proposed and demonstrated at LCLS to show a great improvement in temporal coherence while the final output radiation pulse energy of self-seeding scheme still suffer from the intrinsic chaotic properties of SASE and at the same time, the self-seeding scheme is very sensitive to the electron beam energy jitter, which lead to a large output intensity fluctuations [9-11].

Alternatively, in order to improve the FEL performance and generate fully coherent radiation pulses, various seeded FEL schemes, such as the high gain harmonic generation (HGHG) [12, 13], the echo-enabled harmonic generation (EEHG) [14-16] and the phase-merging enhance harmonic generation (PEHG) [17, 18] etc., have been proposed and studied around the world. In the HGHG scheme, an external seed laser is used to modulate the electron beam for generating coherent components at high harmonics of the seed laser. Inheriting the properties of the seed laser, the output radiation ensures high degree of temporal coherence with respect to SASE. Unfortunately, suffering an essential drawback, a single-stage standard HGHG frequency conversion allows only a limited frequency multiplication factor, which prevents the possibility of reaching X-ray wavelength in a single-stage HGHG. To overcome this problem, cascading multi-stage HGHG with 'fresh-bunch' technology was proposed [19, 20]. Recently, a great success has been achieved at FERMI, the first user facility based on cascaded HGHG principle, for providing coherent soft X-ray with the central wavelength from 100 to 4 nm [21, 22].

In a two-stage cascaded HGHG, a part of the electron beam is modulated by the seed laser and used to generate high harmonic coherent radiation in the first stage. The output radiation in the first stage is shifted to a fresh part of the electron beam for modulating the bean and generating higher harmonic radiation in the second stage. Experimental results at FERMI have shown good output pulse energy stability (about 10%, rms) for a single stage HGHG (FEL1) and (about 25%, rms) the cascaded HGHG (FEL2) in the long wavelength range. However, the stability becomes worst when going to the shortest spectral range (4 nm) and increases up to about 40% (rms) [23], which are obviously serious problems for the FEL users.

The goal of this article is to analyze the output pulse energy fluctuation with various linac errors (timing jitter of the drive laser and the seed laser, the charge jitter and the energy jitter) taking into account. 3D start-to-end simulations have been carried out to show the contributions of each parameter jitter to the output fluctuations.

I: STANDARD TWO-STAGE CASCADED HGHG AT SXFEL

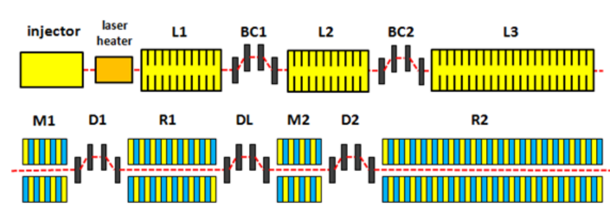

Figure 1: Layout of the SXFEL facility. The upside of the figure is the linac part and the downside is the FEL part.

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ISBN 978-3-95450-147-2

The SXFEL is a test facility based on two-stage cascaded HGHG, aiming to provide 8.8 nm radiation, as shown in Fig.1. The linac of SXFEL consists of an injector, a laser heater system, main accelerator (L1, L2 and L3) and compression system (BC1 and BC2). The electron beam with pulse length of 8 ps, charge of 500 pC in the injector will be accelerated to 840 MeV and compressed to 600 A at the end of the linac with the pulse length of 800 fs. The main parameters of the SXFEL facility are listed in table I.

Table 1: Main Parameters of SXFEL

Electron beam	
Electron beam energy (MeV)	840
Slice energy spread (keV)	200
Peak current (A)	600
Charge (pC)	500
Bunch length (FWHM, fs)	800
Transverse beam size (rms, mm)	0.1
Linear accelerator	
R_{56} in BC1(mm)	48
R_{56} in BC2(mm)	20
Compression ratio in BC1	5
Compression ratio in BC2	2
Seed laser	
wavelength (nm)	264
pulse length (FWHM, fs)	140
Peak power (GW)	4.5
Rayleigh length (m)	15
Undulator	
Period of M1 (cm)	8
Period of R1 & M2 (cm)	4
Period of R2 (cm)	2.5
Undulator parameter K of M1	5.802
Undulator parameter K of R1 & M2	3.139
Undulator parameter K of R2	1.340
Undulator length of R1 (m)	6
Undulator length of R2 (m)	18
Radiation wavelength at the 2^{nd} stage (nm)	8.8

3D start-to end simulation of the electron beam with all components of SXFEL has been carried out based on three-dimensional tracking code ASTRA [24] (for the simulations in the injector), ELEGANT [25] (for the simulations for the remainder of the linac) and GENESIS [26] (for the simulations of FEL performance). From the simulation results of the linac, one can find that electron beam is with high quality maintains in an approximately 600 fs wide with the peak current over 500 A, the slice energy spread of 200keV and the normalized emittance of 0.7 mm mrad.

After the acceleration and compression in the linac, the high-quality electron beam is send to the undulator to generate FEL radiation. In the first stage of HGHG scheme, a moderate energy modulation of 1.15 MeV is chosen in the first modulator (M1). The bunching factor at 6^{th} harmonic of the seed laser is about 10% at the entrance of the radiator (R1) and the 44 nm FEL radiation pulse with peak power of about 800 MW is generated at the end of the radiator. A matching section including the delay line (DL) is located after the first stage in order to provide adjustable beta-matching, diffusion of FEL spot and smear out the electron beam microbunching generated in the first stage. Similarly, the energy modulation amplitude for the second stage is 0.62 MeV and the 5^{th} harmonic bunching factor is about 9%. The FEL radiation is generated by the fresh part saturates with a peak power of 300 MW after about 16 m long radiator undulator (R2). The bandwidth of the 8.8 nm radiation is about 0.05%, which agrees with the FERMI's experiment results. The noisy spikes and little FEL spectrum broaden are mainly caused by the amplification of intrinsic shot noise and the non-linear energy chirp in the electron beam. The simulation results are shown in Fig. 2.

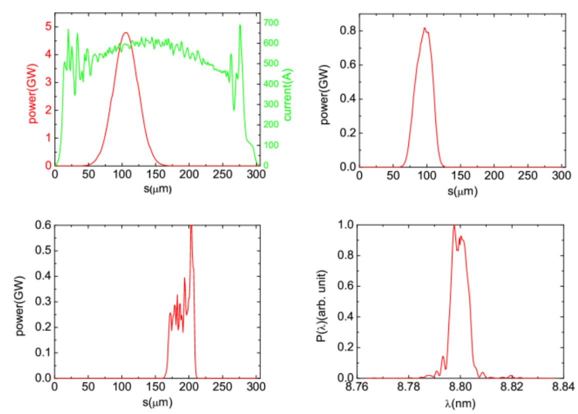

Figure 2: Simulation results for the SXFEL: (top left) relative position of the seed laser (red line) and the beam current (green line) in the first modulator; (top right) Output pulse of the first stage HGHG; (bottom left) Output pulse of the second stage HGHG; (bottom right) final output spectrum.

II: OUTPUT PULSE ENERGY FLUCTUATION WITH LINAC ERRORS

Table 2: Main Errors in the Simulations

Charge error (rms)	5%
Timing jitter of drive laser (rms, fs)	200
Phase error in the linac(rms, degree)	0.1
Voltage error in the linac(rms)	0.1%
Beam timing jitter at the end of linac(rms, fs)	<100
Timing jitter of seed laser (rms, fs)	50

It is easy to find out that the saturation power of the FEL output P_{sat} is quite sensitive to the peak current, transverse emittance and the central energy of the electron beam. The electron beam sensitivity of the linac is investigated by summing the uncorrelated random effects of SXFEL, as shown in table 2. With these linac errors, Fig.4 summarizes various parameters distributions along the electron bunch for 350 shots of linac output, from which one can find that the transverse emittance of the electron beam is very stable, while the fluctuations of the electron beam energy and current could be very large.

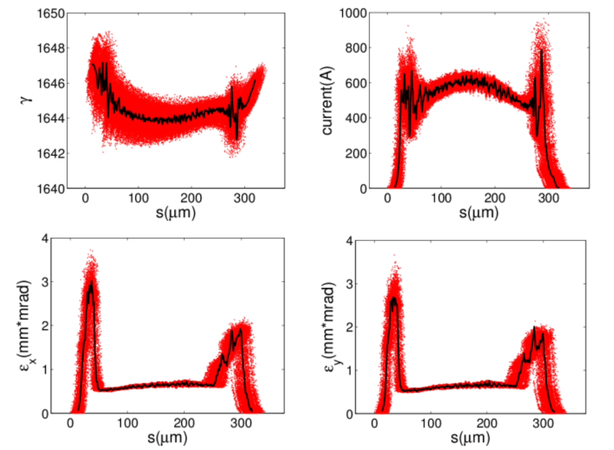

Figure 3: Shot-to-shot jitters of various electron beam parameters: (top left) slice energy; (top right) current and (bottom) transverse emittance.

We first concentrate on the contributions of the energy jitter and the charge jitter of the electron beam to the FEL output fluctuations. The timing jitter between the electron beam and the seed laser is ignored temporarily. The shot-to-shot output pulse energy fluctuations for two HGHG stages are shown in Fig. 4, indicating about (rms) 5.8% and 5.9% pulse energy fluctuations for each stage. The effects of central energy and bunch charge jitters on the FEL output fluctuations are summarized in Fig. 5 and Fig. 6. It is easy to calculate that the shot-to-shot pulse energy fluctuations for two stages would be reduced to 5.1% and 4.1% when the energy jitter is removed, indicating a stronger dependence on the energy jitter in the second stage than that in the first stage. Similarly, one can calculate the shot-to-shot pulse energy fluctuations of the two stages would be reduce to 3.2% and 5.3% without charge jitter taking into account.

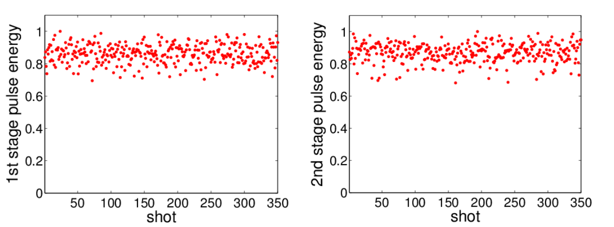

Figure 4: Shot-to-shot pulse energy fluctuations in the first stage (left) and the second stage (right) without timing jitter taking into account. The maximum pulse energy of each stage is 93.8 μJ and 45.6 μJ.

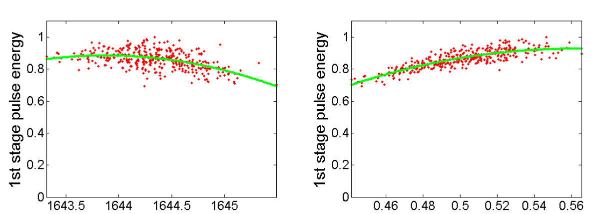

Figure 5: The correlation between the first-stage output pulse energy and the central energy (left) and charge bunch (right).

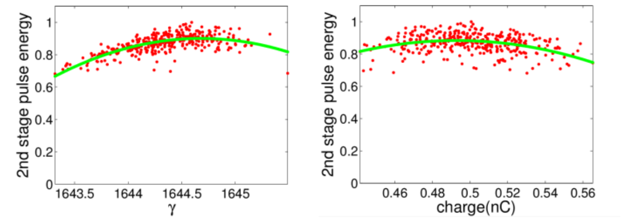

Figure 6: The correlation between the second-stage output pulse energy and the central energy (left) and charge bunch (right).

The timing jitter of the electron beam at the end of the linac is less than 100fs (rms) for SXFEL, while the timing jitter of the seed laser is about 50fs. For simplicity, we assume that the relative timing jitter between the electron beam and seed laser is 100fs. Shot-to-shot pulse energy fluctuations with such a large timing jitter demonstrate a terrible fluctuation in both stages. The peak-to-peak pulse energy fluctuation is almost 100%, which is unacceptable for FEL users. The correlations between the timing jitter and the output pulse energy for two stages are given in Fig. 7, showing that different work point and timing jitter lead to different pulse energy fluctuations in each stage. This is because the high-quality part of the electron beam is about 600fs, which is comparable to the timing jitter. This increases a higher possibility of modulating the electron beam with bad quality, leading to a significant reduce of the output radiation.

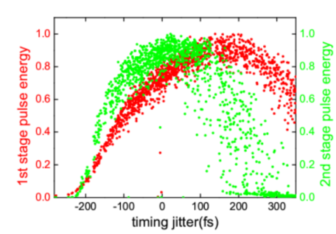

Figure 7: The correlation between the pulse energy and the timing jitter in both stages. The maximum pulse energy of each stage is 109.9 μJ and 44.7 μJ, respectively.

CONCLUSIONS

In this paper, we analyze the shot-to-shot output pulse energy fluctuations of two-stage cascading HGHG with linac errors taking into account based on SXFEL. The simulation results show the large timing jitter between the seed laser and the electron beam will lead to a 100% shot-to-shot pulse energy fluctuation in the existing two-stage HGHG scheme. The energy jitter and the charge jitter of the electron beam also make some contributions. We hope that the conclusions draw from this study would be a reference for the optimization of future seeded FEL facilities based on cascading stages of HGHG.

ISBN 978-3-95450-147-2

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