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RELATIVE TIMING JITTER EFFECTS ON TWO-STAGE SEEDED FEL AT SHINE

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Abstract

The synchronization between the ultrashort electron beam and external seed laser is essential for seeded FELs, especially for a multi-stage one. In this paper, we demonstrate a simple method to obtain the correlations between the pulse energy and relative timing jitter for evaluating the corresponding effects. In this method, the sensitivity of the output FEL performance against electron beam properties is demonstrated by scanning the electron beam and seed lasers, and the fitted curve is used to predict the pulse energy in different timing jitter by random sampling. The results indicate that the pulse energy of the first-stage EEHG is more stable than the second-stage HGHG. Meanwhile, the rise of bunch charge from 100 pC to 300 pC can reduce the timing control requirement by a factor of least 3 for the RMS timing jitter in our numerical simulations based on the parameters of Shanghai High-Repetition-Rate XFEL and Extreme Light Facility. The timing jitter study can demonstrate the feasibility of the EEHG-HGHG cascading scheme in different current profiles for generating Fourier transform-limited soft X-ray FEL.

INTRODUCTION

Free-electron lasers (FELs) have a wide application prospect to explore frontier scientific issues in physics, biology, chemistry, and material science, which can generate ultrashort wavelength radiation with high peak brilliance and ultrafast time structure [1]. XFEL facilities have been developed for the past decades, such as FLASH, LCLS, SACLA, PAL-XFEL, Swiss FEL, and European XFEL. The existing facilities are mostly based on self-amplified spontaneous emission (SASE) scheme, which is amplified from electronic noise. As a result, its radiation pulse and spectrum have several spikes and shot-to-shot fluctuations [2, 3]. To improve the longitudinal coherence, other FEL principles are proposed, such as self-seeding and external seeding schemes. The seeded FEL schemes are generally considered as high gain harmonic generation (HGHG), echo-enabled harmonic generation (EEHG), and phase-merging enhanced harmonic generation (PEHG) [4–6], etc.

In seeded FEL, the conventional laser is used to precisely tailor the longitudinal phase space of the electron beam. Therefore, the performance of seed lasers, such as transverse instability and relative timing jitter will significantly affect output FEL properties [7–9]. During the optimizing process of two-stage seeded FEL scheme at Shanghai High-Repetition-Rate XFEL and Extreme Light Facility (SHINE), it is indispensable for evaluating the impact of timing jitter on pulse energy fluctuations and spectrum degradation in two-stage seeded FEL.

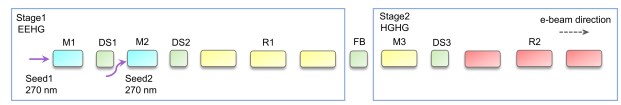

Figure 1: Schematic layout of two-stage EEHG-HGHG configuration for SHINE FEL-II line. Stage1 is composed of two modulators (M1, M2), two dispersion sections (DS1, DS2), and a long radiator (R1). For maintaining the laser-beam interaction in Stage2, the electron beam will be a delay in a magnet chicane (FB) with additional length. Then, Stage1 output will work as a seed laser in the Stage2 HGHG which is composed of one modulator (M3), one dispersion section (DS3), and a long radiator (R2).

In this work, a simple prediction method indicates that the pulse energy is a function of relative delay between the electron beam and seed lasers. The timing jitter study for SHINE clearly demonstrates the impact of relative timing jitter on two-stage FEL pulses performance and evaluates the tolerance of ultrashort electron beam with Gaussian profile. The next step to design and optimize electron beam parameters for two-stage seeded FEL is also discussed.

EEHG-HGHG CASCADING SCHEME

SHINE is the first high-repetition-rate hard X-ray FEL facility based on superconducting linac in China, and three FEL lines will be built, including FEL-I, FEL-II, and FEL-III. To meet the needs of users, we adopted the EEHG-HGHG cascading scheme with the "fresh bunch" technique in FEL-II [10]. The schematic layout of the FEL-II line is presented in Fig. 1. The first-stage EEHG will generate soft X-ray FEL with wavelength 5nm as harmonic conversion number is 54 of UV seed, then the second-stage HGHG can finally generate full coherent soft X-ray pulses with wavelength 1nm as harmonic up-conversion of 5. Owing to the limitation of the HGHG scheme, the seed laser power in the second stage cannot be too large, which means the length of R1 is shorter and the FEL output is not saturated in the first stage. The ideal longitudinal dispersion strength R_{56} of DS is also optimized by theoretical calculation. The parameters of different elements are listed in Table 1.

In our simulations, we adopted an 8 GeV Gaussian electron beam with a relative energy spread of 0.01%, the normalized emittance of 0.2 mm·mad, the peak current of 1500 A,

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and bunch length of 60 fs (FWHM). Besides, considering practical limitations for the length of DS, and the IBS effect decreasing the ideal bunching factor, we adopted the high-order operating mode that n = -3 in the EEHG scheme [11]. Meanwhile, to obtain maximum bunching factor at a wanted wavelength, we precisely optimized peak power of seed lasers of 8.5 GW and 13.5 GW and pulse duration of 20 fs to induce appropriate energy modulation. The main simulation parameters of FEL-II are shown in Table 2.

Table 1: Parameters of Different Elements

Elements	Value
Period of M1/M2	0.24 m
Period of M3/R1/R2	0.068 m
Length of M1	2.88 m
Length of M2	1.44 m
Length of M3	1.3 m
Length of R1	20 m
Length of R2	30 m
R_{56} of DS1	1.4 mm
R_{56} of DS2	80 µm
R_{56} of DS3	2 µm
R_{56} of FB	14 µm

Table 2: Main Simulation Parameters of SHINE FEL-II

Specifications	Electron Beam
Energy	8 GeV
Relative energy spread	0.01 %
Normalized emittance	0.2 mm·mrad
Peak current	1 500 A (Gaussian)
Bunch charge	100 pC/300 pC
Bunch length	60 fs/180 fs (FWHM)
Specifications	**Seed Laser**
Peak power of seed1	8.5 GW (Gaussian)
Peak power of seed2	13.5 GW (Gaussian)
Duration	20 fs (FWHM)
Wavelength	270 nm
Rayleigh length	3.52 m

TIMING JITTER STUDY

In the external seeding scheme, the synchronization of the electron beam and seed lasers in modulators is the key point to generate stable FEL output [12]. Seed1 and Seed2 can be split from one UV laser pulse system, so the timing jitter is neglectable. Meanwhile, we assume there is no arrival time jitter of each electron bunches. Thus, for the sake of simplicity, the relative timing jitter of the electron beam and seed lasers at the entrance of modulator only is considered, which helps us to analyze the FEL output properties due to electron beam variations along the longitudinal direction.

The two-stage seeded FEL numerical simulation results are shown in Fig. 2. The red lines represent the case with maximum pulse energy in two different stages. The FEL gain is sensitive to the current profile, which is proportional to $I^{1/3}$ [13]. Therefore, the final FEL spectrums are broadened with sidebands near the central wavelength, during the

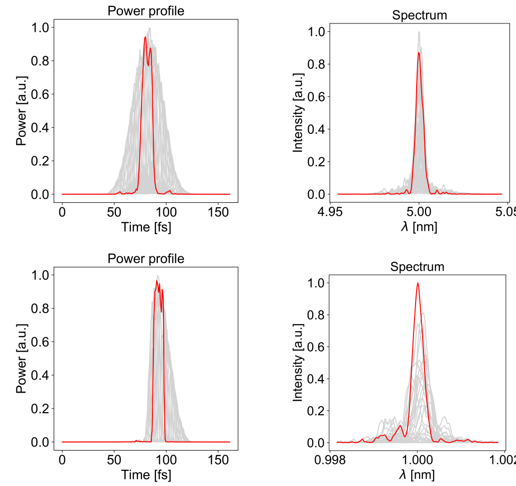

Figure 2: The temporal power profile and spectrum of the first-stage EEHG (upper) and the second-stage HGHG (bottom) FEL performance, respectively, by scanning the relative delay between the electron bunch and seed lasers of 70 fs.

scan of the electron beam and seed lasers. In principle, the FEL performance will be robust in seeded FEL, when seed lasers overlap the whole electron bunch in different modulators. However, the duration of seed lasers is shorter than the bunch length for cascading two stages with the "fresh bunch" technique. In our case, the bunch tail of 20 fs is manipulated by the Seed1 and Seed2 in the first-stage EEHG, while the magnetic chicane will make adequate time delay of 20 fs corresponding to R_{56} of 14 µm (see Table 2) to maintain the interaction of radiation pulse and bunch head in the second stage for generating fully coherent FEL pulses with wavelength 1 nm. However, there are only 20 fs for lasing in the second-stage HGHG, while the whole bunch length is 60 fs (FWHM). Additionally, the radiation easily slips to the bunch head or bunch tail due to the relative timing jitter, where the current is lower, so the incoherent radiation cannot be avoided. Under practical circumstances, the radiation pulse may not easily overlap with the electron bunch on the cascading scheme, especially for the following stage.

Furthermore, the sensitivity of FEL performance against electron beam properties is shown in Fig. 3 and indicates that the pulse energy is a function of the scan of 70 fs corresponding to the black fitted curves. The first stage performance shows a more stable response to timing jitter than the second stage, and pulse length of radiation from the first tends to be shorter than the duration of seed lasers due to pulse shorten effect in the seeded FEL. Numerical simulation results are shown that the spectrum is worse and the pulse energy significantly reduces at large relative timing jitter, where the reduced bunching factor at high harmonics becomes comparable to the spontaneous radiation. The delay is 0 means that the peak power of radiation from the first stage overlaps longitudinally the peak current of electron beam in M3, where it has the maximum pulse energy of 196.3 µJ for the second stage corresponding to the pulse energy of 119.6 µJ for the first stage. Although the first stage output as a seed laser with lower pulse energy cannot produce adequate en-

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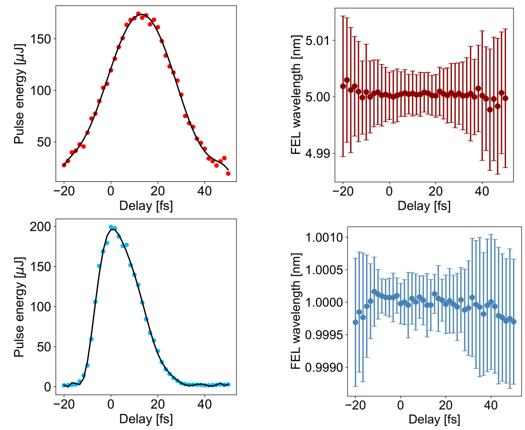

Figure 3: Sensitivity of the FEL performance against electron beam properties of the first-stage EEHG (upper) and the second-stage HGHG (bottom). The delay = 0 corresponds to the maximum final output FEL pulse energy. The black line is the fitted curve and the error bars indicate the RMS value of the spectrum.

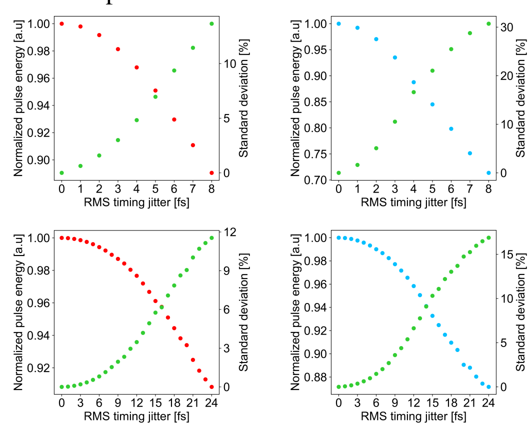

Figure 4: The correlations between the pulse energy normalized by mean pulse energy (without timing jitter) and RMS timing jitter in different cases with bunch charge of 100 pC (upper) and 300 pC (bottom). The red and blue dots represent mean pulse energy normalized by the without timing jitter for the first-stage EEHG and the second-stage HGHG, respectively. The green dots indicate the standard deviation normalized by the without timing jitter over 10000 samples.

ergy modulation, it exactly slips to the part with the peak current in M3 to obtain sufficient bunching factor because of slippage effect from the first stage and FB section.

We adopt the fitted curve (see Fig. 3) as a model that can predict FEL performance with a given RMS timing jitter. With this model, one can investigate timing jitter by sampling in more realistic cases, where the statistical timing jitter has Gaussian distribution with different RMS values. Therefore, the correlations between the normalized pulse energy and RMS timing jitter can be obtained by sampling. In this study, 10000 samples in each RMS value are obtained, while the bunch charge is 100 pC and 300 pC, which corresponds to the bunch length of 60 fs and 180 fs, respectively. As presented in Fig. 4, the RMS timing jitter is larger, which will lead to a larger reduction of mean pulse energy and larger deviations in 10000 samples. Furthermore, the FEL pulses energy of the first-stage EEHG is more stable than the second-stage HGHG. In addition, the final FEL output significantly reduces by 30% with a substantial standard deviation (±30%) in the case of 100 pC, when the RMS timing jitter is 8 fs. Based on our cases, one can obtain stable radiation pulses if the RMS timing jitter of seed lasers is less than 3 fs, corresponding to a pulse energy reduction of 7% and deviation of ±10%. Meanwhile, Fig. 4 shows that the final FEL output is slightly lower than the mean pulse energy (without timing jitter) by 3% with a small deviation (±2.5%) in the case of 300 pC, when seed lasers have the same RMS timing jitter of 8 fs. Compared with the final FEL performance with a bunch charge of 100 pC and 300 pC, increasing the bunch length by 3 times will relax the control requirement for the RMS timing jitter of seed lasers by least 3 times.

Although the bunch length can be increased to make the gaussian current profile more like a flat-top distribution to relax the requirement on RMS timing jitter, the seed laser will be relatively shorter than the electron beam and cannot suppress high-order harmonics, resulting in poor temporal coherence and a broad spectrum. Therefore, it is necessary to appropriately increase the seed laser duration while the bunch length increases.

CONCLUSION

In this paper, a simple method, which demonstrates the pulse energy is a function of relative delay between the electron beam and seed lasers, has been applied to predict the effects of relative timing jitter. The timing jitter study for SHINE demonstrates the impact of relative timing jitter on two-stage FEL pulses performance and evaluates the tolerance of ultrashort electron beam with Gaussian profile. The bunch length increases by 3 times will reduce the control requirement for RMS timing jitter by least 3 times.

The femtosecond seed lasers should precisely manipulate to tailor the ultrashort electron beam; however, it is a challenge to synchronize each other. From another perspective, the seed laser is relatively shorter and cannot avoid the incoherent radiation at high harmonics, when the bunch length increases. It is concluded that one should take the balance of the synchronization problem caused by the timing jitter, and the radiation spectrum degradation caused by short seed lasers into account, optimize the current profile, and finally realize the stable soft X-ray free-electron laser.

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