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Study of the output pulse stability of a cascaded high-gain harmonic generation free-electron laser

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ABSTRACT

Cascading stages of high-gain harmonic generation (HGHG) have been demonstrated to be a promising candidate for producing fully coherent soft X-ray radiation directly from UV seed sources. However, the large shot-to-shot output pulse energy fluctuation may still be a serious problem for its user applications. In this paper, we study the effects of various electron beam parameters jitters on the output pulse energy fluctuations of a two-stage HGHG. Theoretical calculations and intensive simulations have been performed and the results demonstrate that the relative timing jitter between the electron bunch and the seed laser pulse is mainly responsible for the large output pulse energy fluctuation. Several methods that may be helpful to improve the FEL stability have also been discussed.

1. Introduction

Free electron lasers [1] 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 short-wavelength (vacuum ultraviolet, soft and hard X-ray) FEL facilities around the world, such as FLASH [3], LCLS [4] and SACLA [5,6], are based on the self-amplified spontaneous emission (SASE) principle [7,8], which can provide extremely high-intensity, ultra-short light pulses with stable output pulse energy (∼5% level, saturation) and good spatial coherence but limited temporal coherence due to its starting from electron beam shot noise. Recently, the "self-seeding" scheme has been demonstrated at LCLS to show a great improvement in temporal coherence while the final output radiation pulses of self-seeding scheme still suffer from the intrinsic chaotic properties of SASE and at the same time, the self-seeding is very sensitive to electron beam energy jitter, which lead to 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 high gain harmonic generation (HGHG) [12,13], echo-enabled harmonic generation (EEHG) [14–16] and phase-merging enhanced harmonic generation (PEHG) [17,18] etc., have been proposed and studied around the world. In the standard HGHG scheme, an external laser source is used to modulate the electron beam for inducing coherent components at high harmonics of the seed. The output radiation inherits the properties of the seed laser, which 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 multistage stages of HGHG with 'fresh-bunch' technology were proposed [19,20]. Recently, a great success has been achieved at FERMI@Elettra, the first user facility based on cascaded HGHG principle, for providing coherent soft X-ray with the central wavelength from 100 to 4 nm [21–24].

In a two stages cascaded HGHG, a part of electron beam is modulated by an external seed laser and used to generate high harmonic coherent radiation in the first stage. The output radiation from the first stage is shifted to modulate a fresh part of the electron beam for higher harmonic generation in the second stage. Experimental results at FERMI have shown good output pulse energy stability (about 10%, rms) for a single stage HGHG (FEL-1) and (about 25%, rms) the cascaded HGHG (FEL-2) 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) [25], which are obviously serious problems for FEL users.

The goal of this article is to analyze the output fluctuation with various linac errors (timing jitter of the drive laser and seed laser, charge jitter of the injector, phase and voltage jitter of the accelerator) taking into account. 3D start-to-end simulations have been

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performed to show the contribution of each parameter jitter to the output fluctuations (similar work in Ref. [26]).

This article is organized as follows. First we will introduce the results of start-to-end simulations based on two-stage cascading HGHG with main parameters of the Shanghai soft X-ray FEL facility (SXFEL) in Section 2. Linac errors are introduced and the output pulse energy fluctuations are shown in Section 3. Some discussion and comparisons are given in this section as well. Summaries and conclusions are given in Section 4.

2. Standard two-stage cascaded HGHG at SXFEL

The SXFEL is a test facility based on two-stage cascaded HGHG, as shown in Fig. 1. The linac of SXFEL consists of an injector (1.6 cell S-band photocathode RF gun, to provide initial electron beam with length of 8 ps, charge of 500 pC and peak current of 60 A), a laser heater system, main accelerator L1 (S-band, accelerate the electron beam to 210 MeV), L2 (S-band, accelerate the beam to 420 MeV), L3 (C-band with about 30% larger radius of the iris aperture to suppress longitudinal wakefield, accelerate the beam to 840 MeV), and two bunch compressor chicanes BC1 (compress the beam by 5 times) and BC2 (compress the beam twice further). The electron beam, after generated in the RF gun and accelerated in the linac, with the total length of 800 fs and peak current of 600 A, is finally sent into the undulator system for soft X-ray FEL generation.

3D start-to-end tracking of the electron beam with all components of SXFEL has been carried out based on main parameters listed in Table 1. The electron beam dynamics in photo-injector was simulated with ASTRA [27] to take into account of space-charge effects and ELEGANT [28] was then used for the simulation in the remainder of the linac, including the longitudinal space charge effect (LSC), coherent synchrotron radiation effect (CSR) and longitudinal wakefield. The longitudinal phase space, beam current and slice energy spread distribution at the exit of the linac are summarized in Fig. 2, where one can find that electron beam with high quality maintains in an approximately 600 fs wide with current over 500 A, slice energy spread of 200 keV and normalized emittance of 0.7 μm-rad.

The universal FEL simulating code GENESIS [29] was utilized to calculate the FEL performances based on the output of ELEGANT. To obtain realistic simulation results, the whole electron beam was tracked through the first stage to the second stage HGHG. The simulation results are illustrated in Fig. 3. In view of the tradeoff between the seed laser induced energy spread and the available bunching factor, a moderate energy modulation of 1.15 MeV is chosen in the first modulator (M1). The bunching factor at 6th harmonic of the seed is about 10% (achieved in the dispersion, D1)

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 2nd stage (nm)	8.8

at the entrance of the first radiator (R1). As shown in Fig. 3, the 44 nm FEL radiation pulse with peak of about 800 MW was 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 e-beam microbunching generated in the first stage. The energy modulation amplitude for the second stage is 0.62 MeV (in the modulator, M2) and the 5th harmonic bunching factor is around 9% (achieved in the dispersion section, D2). The FEL radiation generated by the fresh part saturates with a peak power of 300 MW after about 16 m long radiator undulator (R2). Operating a two stage FEL beyond saturation power (∼400 MW) may accentuate the sensitivity to electron beam parameters and deteriorate the coherence properties for the power oscillation and the increasing energy spread. The bandwidth of the 8.8 nm radiation is about 0.05%, which agrees with the FERMI's experiment results [25]. 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 FEL spike at the head of the pulse could be related to a superradiance effect.

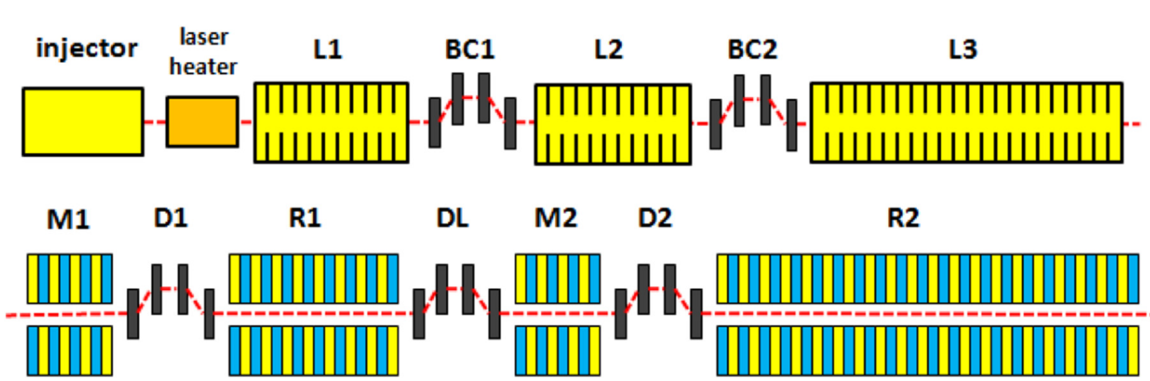

Fig. 1. Layout of the SXFEL facility. The upside of the figure is the linac part and the downside is the FEL part (L: accelerator structure, BC: bunch compressor, M: modulator, D: dispersion section, DL: delay line, R: radiator).