OPERATING CASCADED HIGH-GAIN HARMONIC GENERATION WITH DOUBLE-PULSE ELECTRON BEAMS

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Abstract

Cascading stages of high-gain harmonic generation (HGHG) is a promising candidate for the generation of fully coherent x-ray radiation. However, fluctuation of the output pulse energy is still a critical issue for a realistic facility with cascaded HGHG scheme. In this paper, we proposed using double-pulse electron beams to drive two stages cascaded HGHG, which will be helpful for increasing the stability of the output pulse energy against the arriving timing jitter in the second stage. Methods to generate the required double-pulse electron beams are introduced in the paper and three-dimensional simulations are carried out to show the significantly improvement of the FEL stability comparison with the standard cascaded HGHG by using this technique.

INTRODUCTION

Free electron lasers (FELs) hold great promise for the generation of coherent x-ray radiation with high brightness and ultra-fast time structures which will enable scientists in physics, chemistry, biology and medicine to study nature down to the molecular and atomic level at a time-scale that fits this resolution [1]. For nowadays, self-amplified spontaneous emission (SASE) FEL [2] is still the primary candidate for nanometer and sub-nanometer wavelength FEL generation. As the world's first hard x-ray FEL facilities, the Linac Coherent Light Source (LCLS) and the Spring-8 Angstrom Compact Free Electron Laser (SACLA) have demonstrated x-ray FEL technology in an impressive fashion [3-5]. However, SASE FEL suffers from the limited temporal coherence and large statistical fluctuations as the initial radiation starts from the electron beam shot noise.

To improve the FEL performance, frequency up-conversion schemes, such as high-gain harmonic generation (HGHG) [6,7], echo-enabled harmonic generation (EEHG) [8-10] and phase-merging enhanced harmonic generation (PEHG) [11,12], etc., have been proposed to manipulate the electron beam phase space with external coherent laser sources. In the standard HGHG, coherent micro-bunching is formed in the electron beam after energy modulation and density modulation. The output radiation, which inherits the properties of the seed laser, can have a high degree of temporal coherence and much stable central wavelength and output pulse energy compared to SASE. These properties of HGHG FEL have already been demonstrated

in several single-stage HGHG experiments. However, the need to limit the growth of the energy spread prevents the possibility of reaching X-ray wavelength in a single-stage HGHG. To overcome this problem, cascading multiple stages of HGHG with 'fresh-bunch' technology have been proposed [13] and recently realized at FERMI for coherent soft X-ray generation at the wavelength of 20 to 4 nm [14-17]. The experimental results at FERMI show great output stability for the first stage HGHG but large pulse energy fluctuation up to 50-60% (FWHM) in the second stage [18], which may be a quite serious problem for FEL users. Such a critical energy fluctuation may primarily originates from the interplay of timing jitter between the relative arrival times of the electron beam and seed lasers, together with variations of the electron beam of properties along the longitudinal direction: for different shots, seed laser pulses in the modulator of the second stage will interact with parts of electron beam with quite different beam qualities.

In this paper, we propose using double-pulse electron beam to significantly improve the output stability of a two stages HGHG. The two pulses are separately used for producing of high harmonic radiation pulses in two stages. With the first bunch length much longer than the second one, the radiation pulse from the first stage can cover the whole bunch length in the second stage. Thus makes the power output much less sensitive to the small relative arrival timing jitter in the second stage. We first show the simulation results of a standard two stages HGHG. Then, we will introduce methods to generate two-pulse electron beams that fit the requirement. Summaries and conclusions are given in the last.

STANDARD CASCADED HGHG WITH A SINGLE-BUNCH ELECTRON BEAM

The Shanghai Soft x-ray FEL facility (SXFEL) is a test facility based on two-stage cascaded HGHG, as shown in Fig. 1. The linac of SXFEL consists of an injector, a laser heater system, a main accelerator (L1, L2 and L3) and two bunch compressors (BC1 and BC2). The electron beam is generated in a 1.6-cell S-band photocathode RF gun with initial bunch length of 8 ps, bunch change of around 500pC and peak current of 50A. Then the electron beam is boosted to 210MeV in L1 (S-band) and compressed by 5 times in the first bunch compressor (BC1). After that, the beam is boosted again to about 420MeV in L2 (S-band) and compressed twice further in the second bunch compressor (BC2). Finally, L3 (C-band) is used to future accelerate the electron beam to 840 MeV

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at the end of the linac and send to the FEL part for soft x-ray generation.
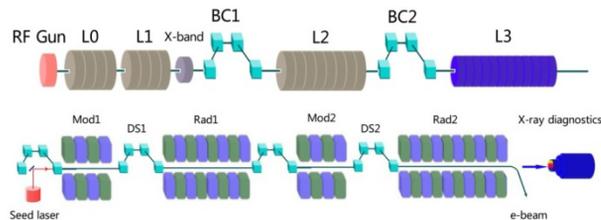

Figure 1: Layout of SXFEL facility.

Start-to-end tracking of the electron beam, including all components of SXFEL, has been carried out based on main parameters shown in Table 1. ASTRA [19] was used to simulate the injector part, considering the space charge effect. ELEGANT [20] was then used for the simulation in the remainder of the linac, with LSC, CSR effects taking into account. The longitudinal phase space and slice parameter distributions along the electron beam at the end of the linac are summarized in Fig. 2. One can find a constant profile is maintained in an approximately 500 fs wide and over 500 A region, while the normalized emittance and slice energy spread in this part is about 0.65 μm-rad and 200 keV, respectively.
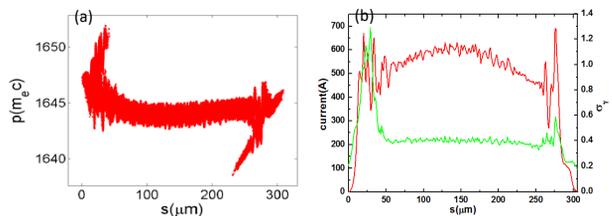

Figure 2: (a) Longitudinal phase space of the electron beam. (b) Beam current (red line) and slice energy spread (green line) distribution.

Table 1: Main Parameters of SXFEL

Electron beam energy (MeV)	840
Slice energy spread (keV)	200
Peak current (A)	600
Charge (pC)	500
Bunch length (FWHM, fs)	800
Seed laser wavelength (nm)	264
Seed laser pulse length (FWHM, fs)	140
Seed laser power in 1st stage (GW)	5
Seed laser waist size (mm)	1.1
R_{56} in D1 (mm)	0.015
R_{56} in D2 (mm)	0.008
Period of M1 (cm)	8
Period of R1 & M2 (cm)	4
Period of R2 (cm)	2.5
Radiation wavelength at 2nd stage (nm)	8.8

Simulations for FEL performance were performed with GENESIS [21] based on the output of ELEGANT. The simulation results are shown in Fig. 3 and Fig. 4. The electron beam is energy modulated by a 265 nm seed laser with pulse length of about 140 fs in the first modulator (Mod1), as shown in Fig. 3a. The energy

modulation is then converted to density modulation when the beam passes through the first dispersion section (DS1). The bunching factor at 6th harmonic of the seed is close to 0.1. This bunched electron beam is sent through the first radiator (Rad1) for the generation of intense high harmonic radiation at 44 nm. The output power of the first stage HGHG is over 500 MW, which is sufficient for seeding the second stage HGHG. The following delay line (DL) section is used to shift the radiation to a 'fresh' part of the electron beam, which is called 'fresh-bunch' technology. The shift length of the radiation is 120μm. The simulation results for the second stage are shown in Fig. 4. The Final output wavelength is 8.8 nm and the output peak power is over 300 MW.
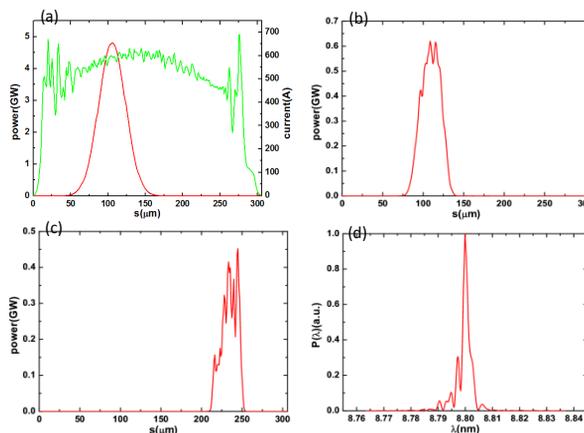

Figure 3: (a) relative position of the seed laser pulse (red line) and the electron beam (green line) in the first modulator; (b) Output pulse of the first stage HGHG; (c) Output pulse of the second stage HGHG; (d) corresponding radiation spectrum.
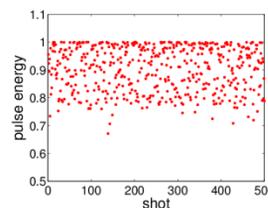

Figure 4: The output pulse energies at various shots for a fluctuating relative arriving time between the seed laser pulse and the electron beam in the second stage for a standard cascaded HGHG.

As we mentioned above, the output pulse energy of cascaded HGHG is quite sensitive to the relative arrive timing jitters between the seed laser pulses and the electron beams. Experiments have demonstrated that the output pulse energy for a single-stage HGHG is quite stable. So we deduce that most of the output fluctuations are coming from the timing jitter in the second stage. The sensitivity of the output pulse energy to the timing jitter has been studied by introducing random shot-to-shot fluctuations of the relative arriving time of the seed laser pulse in the second stage. The resulting 500 shots of the fluctuations of the output pulse energy are shown in Fig. 5. One can find that, with 30 fs (rms) relative timing jitter

on the second seed laser pulse, the fluctuations of the output pulse energy will be over 7.93% (standard deviation), which is at a comparable level to the experiment measurement results at FERMI [18].

DOUBLE-PULSE GENERATION BASED ON EMITTANCE-SPOILER

The emittance spoiler technique is initially proposed for the generation of ultra-short X-ray radiation pulses [22]. By adding an emittance spoiler foil with vertically oriented narrow slots in the central of the bunch compressor chicane, the emittance of most of the electron beam will be spoiled while leaving only short unspoiled parts to produce radiation pulses much shorter than the total electron bunch. It is found later that double-slot foil is quite suitable for the generation of double-pulse FEL with different colors and variable durations [23,24]. Thus this technique provides us a relative simple method for the generation of double-pulse electron beams.

In our scheme, a double-slot foil (3μm Aluminum foil with one slot 0.9mm and the other 2mm, the distance of double slots: 1mm) is placed in the middle of the second bunch compressor chicane, aiming to generate two unspoiled parts (140fs and 300fs respectively in the simulation) in the electron beam.The longitudinal phase space of the electron beam at the exit of the linac is shown in Figure 5. One can change the width and the distance of those two pulses by changing the width and the position of slots on the foil. As shown in Figure 6, we used a long seed laser (140 fs,rms) to modulate the long pulse to generate a long radiation pulse which could cover the whole short pulse. The short pulse is almost as long as the radiation part of the electron beam in the second stage in the last section, so that the pulse length and the pulse energy of the radiation in those two situations are almost the same. Figure 6 shows the FEL performance. The pulse length of the radiation in the first stage (about 300fs) is much longer compared to the radiation in the last section (140fs). The peak power is about 500MW in the first stage and 300 MW in the second stage, which is similar with that of a standard cascaded HGHG. Figure 7 shows the output pulse energy fluctuations for the timing jitter of rms 30fs, from which one can find the fluctuation is reduced to about 2.90% (standard deviation), over 2 times smaller than that of a standard HGHG.
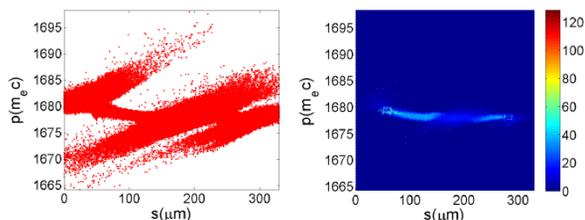

Figure 5: Longitudinal phase space of the electron beam at the exit of the linac. Some spoiled parts in the electron beam (in the head and tail) are cut for the convenience of the simulation, since those parts make little contribution to the radiation.
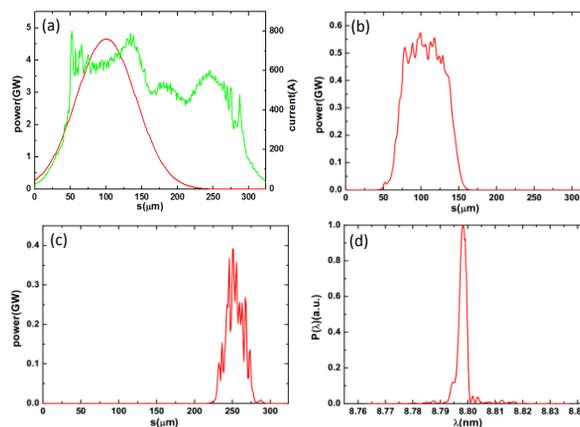

Figure 6: (a) relative position of the seed laser pulse (red line) and the electron beam (green line) in the first modulator. (b) Output pulse of the first stage HGHG. (c) Output pulse of the second stage HGHG, and (d) corresponding radiation spectrum.
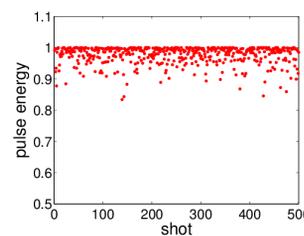

Figure 7: The output pulse energies at various shots for a fluctuating relative arriving time between the seed laser pulse and the electron beam in the second stage for the emittance spoiler case.

CONCLUSIONS

In summary, operating cascaded HGHG with double-pulse electron beam has been proposed for improve the stability of the output pulse energy. Simulation results demonstrated that with a 30 fs rms timing jitter, double-pulse schemes can increase stability of the pulse energy by over 2 times. The double-pulse electron beam can be generated by inserting a double-slot foil in the linac. Scheme based on double-slot foil seems quite simple to be applied on existing cascaded HGHG FEL facility.

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