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A PROPOSAL FOR COHERENT HARD X-RAY GENERATION BASED ON TWO-STAGE EEHG

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Abstract

Generating stable and coherent short wavelength radiation is a great promise of the externally seeded free-electron laser. However, the frequency up-conversion efficiency is limited to a small number for a single stage configuration. Here we propose two schemes for producing fully coherent x-ray radiation based on two-stage EEHG setups. Electron bunches of quite different lengths are separately used in each stage of the cascaded EEHG and a monochromator is employed to purify the radiation from the first stage for seeding the second one. Theoretical analysis and 3D simulations show that proposed schemes hold the ability to generate fully coherent hard x-ray pulses directly from conventional UV seed lasers.

INTRODUCTION

Significant progress has been made in recent years in the free-electron laser (FEL) research and development. More x-ray FEL facilities have either been successfully operated or currently under constructions all over the world. Most of the presently existing or planned hard x-ray FEL facilities are based on the self-amplified spontaneous emission (SASE) principle, which can provide extremely high-intensity, ultra-short light pulses with good spatial coherence but poor temporal coherence and relatively large shot-to-shot fluctuations.

An effective way for significantly improving the temporal coherence and stability of high-gain FELs is employing external seeding schemes such as the high-gain harmonic generation [1] or the echo-enabled harmonic generation (EEHG) [2, 3], which generally relay on the electron beam longitudinal phase space manipulation techniques. Recent experiments at NLCTA at SLAC and SXFEL at SINAP have demonstrate the generation of coherent micro-bunching at VUV and x-ray wavelength ranges with a single stage EEHG [4-8], which shows the distinct advantages of EEHG at high frequency up-conversion efficiency and paves the way for coherent soft x-ray generation with a single stage setup. Analyses within the framework of idealized models also promisingly indicate the possibility of generating coherent radiation pulse at sub-nanometer wavelengths or even in the hard X-ray regime by using two-stages cascaded EEHG schemes, and the noise amplification problem may be solved by adding a soft x-ray monochromator between the two EEHG stages [9-11]. This cascading technique allows harmonic up-conversion numbers of a few thousand to be accessible that eventually enables the generation of hard x-ray radiation directly from a UV seed laser. Here we show two different schemes for coherent hard x-ray generation based on two-stage EEHG with either two linacs or two bunches from one linac and present a possible proposal for testing the scheme of two-stage EEHG at SXFEL.

TWO-LINAC BASED TWO-STAGE EEHG

There is a growing tendency these days to integrate the soft x-ray and hard x-ray FEL beamlines in one facility to cover both the soft x-ray and hard x-ray wavelength ranges for various FEL user experiments. The first scenario of the two-stage EEHG is based on this setup, as shown in Fig. 1(a). This scheme combines the EEHG technique with the fresh bunch technique. Two electron bunches with quite different beam properties are generated by two linacs and separately used in two stages for improving the FEL performance: the electron bunch used in the first stage is relative long (~500fs, 1kA) to provide a long seed laser pulse for the second stage; the electron bunch used in the second stage is very short (~80 fs, 3kA) to maintain low transverse emittance. There are mainly two apparent advantages of this setup with respect to the conventional fresh bunch technique: (i) the short electron bunch used in the second stage can be fully covered by the long seed laser pulse from the first stage EEHG, which will significantly reduce the timing jitter effects on the final output stability; (ii) the second stage can be operated with low charge mode, which can be used for the generation of high intensity ultra-short radiation pulses.

As shown in Fig. 1(a), the upper one is a hard x-ray FEL, which consists of a photocathode injector, a linac and an undulator beamline for EEHG operation. There are two bunch compressors in the linac to provide a few kilo-ampere peak current; the lower machine with total length much shorter than the upper one is used for soft x-ray FEL generation. Only one bunch compressor is need in this beam line to get a few hundreds of ampere peak current, and the undulator system is also designed for EEHG operation. The FEL pulse generated by the soft x-ray beam line can be either delivered to FEL experimental stations or be monochromized and used as seed lasers in the following EEHG beamline to configurate a two stages EEHG setup, which may allow a harmonic up-conversion number over a thousand or more to be achievable. It is worth to point out that one can also employ one linac to provide electron beams for both two FEL beamlines. A switch line with a fast kicker and a septum should be added before the second compressor of the linac for bunch-by-bunch switching for two bunch operation. A simultaneous operation is feasible for the soft x-ray and hard x-ray FEL beamlines with flexibility in control of bunch current and relative time delay by changing the bend angle of the second bunch compressor of the linac.

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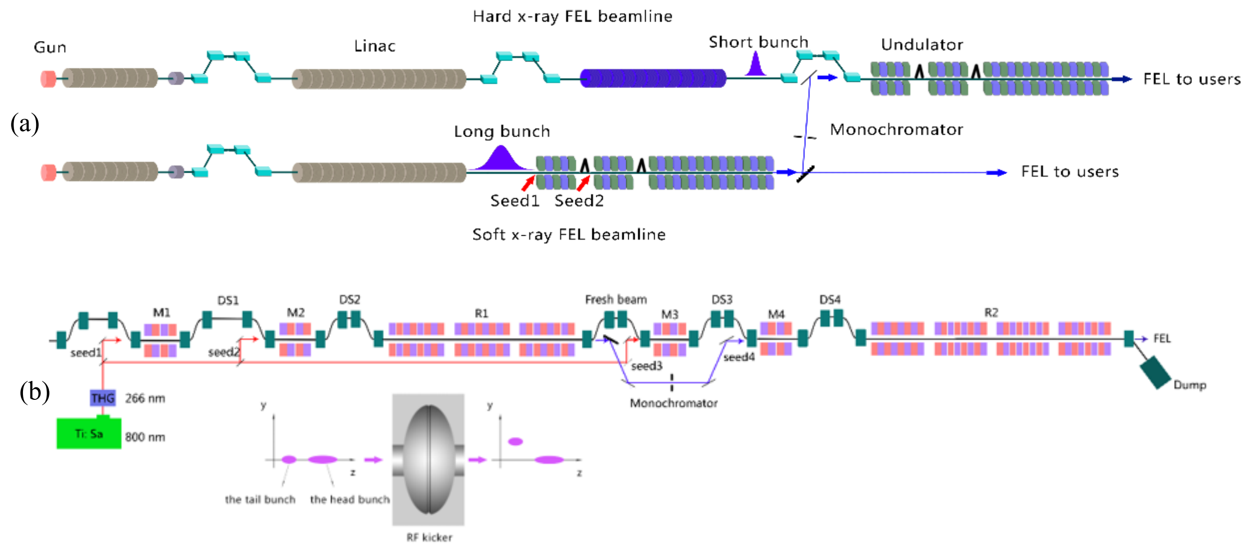

Figure 1: Layouts of two scenarios for the two-stage EEHG: (a) two-linac based two-stage EEHG, (b) double-bunch based two-stage EEHG.

One difficulty of EEHG is using two synchronized seed laser pulses to modulate the same electron beam in the two modulators. For the first stage EEHG in Fig. 1(a), the two seed lasers pulses can be simply obtained by splitting a single UV laser pulse by using optical methods. However, this becomes extremely complicated and a great challenge for the second stage due to the lack of suitable high-efficiency reflect materials at soft x-ray wavelength. To mitigate this problem, here we propose using a single seed laser pulse to modulate the electron bunch at two modulators in the second stage EEHG.

According to the basic theory of EEHG, if we assumed the first and second stage seed wavelengths equal, the optimized dispersion strength of the first chicane for kth harmonic generation can be estimated by [2, 3]

$$R_{56}^{(1)} = \frac{A_2\xi + m + 0.81m^{1/3}}{nA_2k_s\delta}, \tag{1}$$

The relative time delay induced by the chicane can be calculated by

$$\Delta t[ps] = \frac{5}{3}R_{56}^{(1)}[mm]\cdot \tag{2}$$

When the seed laser pulse duration is much longer than the time delay induced by the first chicane of EEHG setup, it is possible to modulate the electron bunch in the two modulators with the same seed laser pulse. For a soft x-ray EEHG seeding with UV lasers, the typical time delay induced by the first chicane is about ~10 ps, which is much longer than the accessible pulse length from a commercial Ti: Sapphire laser system. However, for a hard x-ray EEHG seeding with soft x-ray laser pulses, the required time delay is at sub-picosecond level, which makes it possible to seed the two modulation stages with a single picosecond seed laser pulse.

Here we perform S2E tracking of the electron beam, including all components of soft x-ray and hard x-ray beamlines. The main parameters used in the simulation are shown in Table. 1.

Table 1: Main Parameters Used in the Simulation for the First Scenario

Parameters	The soft x-ray beamline (1st stage)	The hard x-ray beamline (2nd stage)
Beam energy/GeV	1.6	6
Peak current/kA	1	3
Normal. emittance/μmrad	1	0.4
Slice energy spread	0.01%	0.01%
Bunch length/fs (FWHM)	500	80
Seed wavelength/nm	270	4.5
Seed powers/MW	200/500	800/800
Modulator period/cm	8	8
Modulator periods	20/10	15/10
Radiator period/cm	2.5	1.8
Radiator length/m	14	40

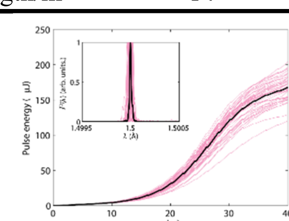

Figure 2: FEL gain curves in the radiator of the first stage (a) and the radiator of the second stage (b).

Figure 2 shows the FEL gain process in the radiators of the first and second stages. The power saturation of the first stage is achieved after about 14 m with saturation peak power over 2 GW. The output pulse energy fluctuation is about 3% (rms), which is mainly caused by the energy jitter of the electron beam. The corresponding spectrum at saturation for the first EEHG stage is also shown in Fig. 2(a). With a monochromator, the spectral noise is filtered, and the purified coherent signal is sent to the following

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EEHG stage as a seed laser. After the modulation process of the second stage EEHG, the maximal bunching factor at 30th harmonic of the seed exceeds 8%. With this large initial bunching factor, Fig. 2(b) shows the FEL gain process at 0.15 nm in the final radiator. The FEL output reaches saturation peak power of about 5 GW at around 35 m of the undulator.

TWO-BUNCH BASED TWO-STAGE EEHG

The schematic layout of the second scenario is shown in Fig. 1(b), consisting of two EEHG stages and a soft x-ray monochromatic and fresh beam section. Different from the conventional fresh bunch technique that utilizes only one electron bunch, in the proposed scheme, these two electron bunches are generated by two drive laser pulses, separated by one RF cycle. The two electron bunches are accelerated and compressed in the adjacent RF cycles in the linac to generate a high brightness two-bunch repeated electron beam. The bunch durations can be separately tuned by adjusting the durations of the two drive laser pulses. The proposed scheme is equivalent to having two separate concatenated seeded x-ray FELs. In order to maintain the electron beam quality and suppress the radiation noise in the radiators, an RF kicker (deflecting RF structure) can be added upstream of the undulator system to provide a transverse deflection. In the first EEHG stage, the head bunch (the longer one) passes through the undulators on axis to reach the saturation regime, generating a coherent soft x-ray radiation pulse, while the tail electron bunch (the short one) oscillates around the axis to significantly reduce the FEL gain and maintain the beam quality. The soft x-ray pulse generated from the first stage is filtered through a monochromator and delayed by one RF cycle to seed the tail electron bunch in the second EEHG stage, where the tail electron bunch is put on axis to generate coherent radiation at higher harmonics and the head electron bunch oscillates around the axis to avoid generating SASE noise in undulator R2.

Here we adopt a superconducting linac to drive the FEL. The superconducting linac can provide 8 GeV electron beam with peak current of about 3000 A and relative slice energy spread of about 0.01% at the end of the linac. As mentioned above, two electron bunches with different charges and bunch lengths are generated by the photo-cathode injector and accelerated in adjacent RF buckets in the linac. The head electron bunch used in the first EEHG stage is chosen to be about 300 fs in length to provide a relative long seed laser pulse for the second EEHG stage. The emittance is about 1 μmrad for this electron bunch. The tail electron bunch used in the second stage is chosen to be about 80 fs in length to maintain the low transverse emittance of about 0.4 μmrad. The tail electron bunch can be fully covered by the seed pulse from the first stage in the modulator of the second stage, which will significantly reduce the timing jitter effects on the stability of the final FEL output. The simulation results for the FEL gain processes in the two radiators and the spectra at saturation are shown in Fig. 3.

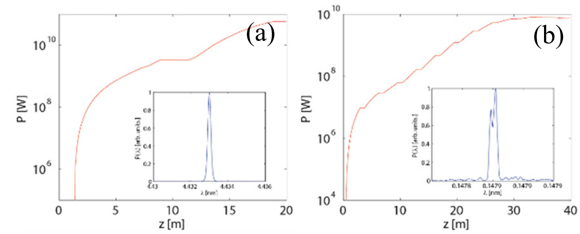

Figure 3: FEL gain curves in the radiator of the first stage (a) and the radiator of the second stage (b).

EXPERIMENT PROPOSAL AT SXFEL

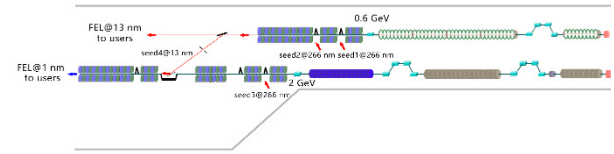

Figure 4: Proposal for testing the two-linac based two-stage EEHG at SXFEL.

In order to test the scheme and key techniques for two-stage EEHG, we propose using the existing SXFEL and an on newly developing CW-FEL test facility to construct a two-linac based two-stage EEHG, as shown in Fig. 4. As the R&D and a test facility for the Shanghai Coherent Light Facility [12], the CW-FEL can provide 600 MeV electron beam based on a SCRF linac with a pulse repetition rate up to 1MHz. By using a single stage EEHG, stable and coherent radiation pulses at ~13 nm can be achieved and serves as the seed laser for the second stage of SXFEL. The goal is to generate fully coherent radiation at 1-2 nm with EEHG-HGHG cascade or two-stage EEHG cascade.

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