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Enhanced harmonic generation for high-repetition-rate soft x-ray free-electron laser

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Abstract. Externally seeded free-electron lasers are promising for generating intense, stable, and fully coherent soft X-ray pulses. An earlier study demonstrates that high brightness and coherent soft X-ray radiation can be produced based on coherent harmonic generation and superradiant principles, termed high-brightness high-gain harmonic generation (HB-HGHG). However, the seed laser at the ultraviolet region cannot induce sufficient energy modulation at high repetition rates due to state-of-the-art laser system limitations. A recently suggested self-modulation scheme shows that the peak power requirement of a seed laser can be reduced by around one order of magnitude in an HGHG setup. In this paper, we present start-to-end simulation results to estimate the feasibility of the self-modulation-enhanced HB-HGHG scheme.

1. Introduction

X-ray free electron lasers (XFEL) can produce high-brightness, fully coherent ultrashort radiation pulses, immensely contributing to various research fields, such as biology, medicine, and materials science. However, phase-related experiments, e.g., time-resolved pump-probe, require X-ray radiation pulses with high repetition rates and full coherence to enhance experimental efficiency [1].

Most modern XFEL facilities worldwide are operated in the self-amplified spontaneous emission (SASE) scheme [2], which lacks intensity stability and longitudinal coherence due to the amplification process originating the inherent shot noise of the electron beam. The self-seeding schemes can improve the longitudinal coherence but still suffer from shot-to-shot fluctuations. Externally seeding schemes, such as high gain harmonic generation (HGHG) [3], echo-enabled harmonic generation (EEHG) [4], and phase-merging harmonic generation (PEHG) [5], inherit the properties of the seed laser, enabling to generate fully coherent radiation pulses at the extreme ultraviolet and soft X-ray region.

With the development of superconductivity, continuous-wave (CW) XFEL facilities have become an ongoing construction priority, stimulating widespread interest in the FEL community. The earlier proposed high-brightness high gain harmonic generation (HB-HGHG) scheme [6] can generate highly coherent and high brightness soft x-ray FEL radiation pulses based on coherent harmonic generation (CHG) and superradiant principles, which requires ultra-large energy modulation to reach the water window region. However, due to state-of-the-art laser system limitations, the ultraviolet (UV) seed laser is challenging to induce sufficient energy modulation with high repetition rates. Recently, the self-modulation scheme experimentally demonstrated that the peak power requirement of a seed laser could be reduced by around one order of magnitude in an HGHG setup [7, 8]. In this paper, start-to-end simulations of the self-modulation-enhanced HB-HGHG scheme [9] are conducted with realistic electron beam parameters of the SXFEL user facility.

2. Schematic layout and description

The standard HB-HGHG requires an intense UV seed laser to modulate the electron beam delivering fully coherent soft X-ray radiation pulses. The required laser-induced energy modulation amplitude is nearly 38 times the slice energy spread in one short modulator, which is challenging for the present laser system as well as such high repetition rates.

Figure 1 illustrates the schematic layout of the self-modulation-enhanced HB-HGHG scheme. Firstly, an ultrashort UV seed laser is adopted to modulate the tail part of the electron beam in modulator 1. Then the initial energy modulation is converted into density modulation by chicane 1. The coherent radiation from a pre-bunched beam can further enhance the laser-induced energy modulation in the self-modulator. The enhanced energy modulation of the tail part is transformed into an associated density modulation by a small chicane 2. The electron beam is sent into a radiator to generate a coherent signal at the tail part. After that, the electron beam will be delayed through the chicane 3, and the coherent signal can reseed the fresh part of the electron beam in the following amplifier modules via superradiant process.

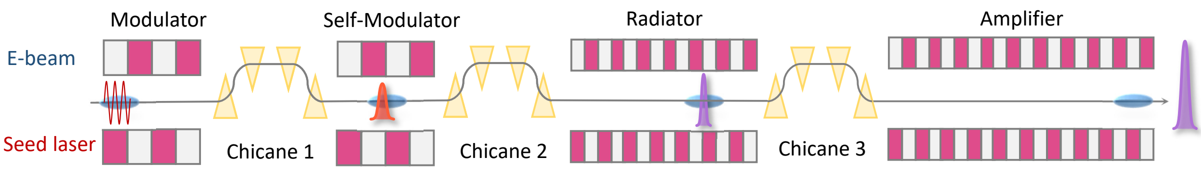

Figure 1. The schematic layout of the self-modulation-enhanced HB-HGHG scheme.

3. Start-to-end simulations

The SXFEL user facility initially aims to generate fully coherent soft X-ray radiation pulses by a two-stage cascaded HGHG or EEHG scheme consisting of enough modulators and dispersion sections. It is compatible with the self-modulation-enhanced HB-HGHG scheme. Start-to-end simulations are conducted to verify the feasibility of this scheme utilizing the nominal parameters of the SXFEL user facility listed in Table 1. The real electron beam was obtained using the particle tracking codes ASTRA and ELEGANT with single-stage bunch compressor chicane. The longitudinal phase space of the electron beam, current distribution, and slice emittance profile are shown in Fig. 2. The peak current is around 580 A at the end of the linac. The normalized slice emittance is 0.8 mm·mrad, and the slice energy spread is about 50 keV, consistent with the experimental measurement [10].

The FEL simulations were performed with GENESIS [11]. The main parameters of the seed laser and undulators are listed in Table 1. The self-modulator and radiator are operated in the superradiant region, similar to the superradiant cascade setup [12, 13], where the evolution of the pulse profile is determined by both the slippage length and the seed laser duration. Pulse splitting occurs when the seed laser duration is comparable to the slippage length, and thus shorter seed lasers are favorable to produce ultrashort FEL pulses [14]. In addition, the seed

Table 1. Main Simulation Parameters of SXFEL User Facility

Electron beam	**Value**	**Unit**
Energy	1.4	GeV
Slice energy spread	50	keV
Normalized emittance	0.8	mm·mrad
Peak current (Flat-top)	580	A
Bunch charge	500	pC
Seed laser	**Value**	**Unit**
Peak power of seed	10	MW
Duration	30	fs
Wavelength	265	nm
Rayleigh length	2.96	m
Undulator	**Value**	**Unit**
Period of Modulators	0.08	m
Length of Modulators	2	m
Period of Radiator	0.05	m
Length of Radiator	7	m
Period of Amplifier	0.05	m
Length of Amplifier	20	m

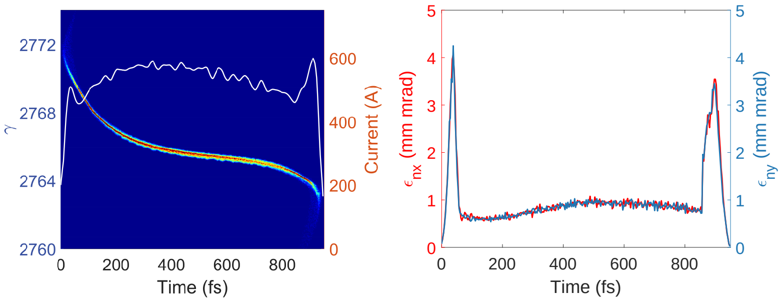

Figure 2. The longitudinal phase space of the electron beam and current distribution (the left), and slice emittance profile (the right).

laser imperfection can be significantly smoothed in the modulator when the slippage length is comparable to the seed laser duration [15]. Therefore, in our case, a UV seed laser with a peak power of 10 MW and pulse duration of 30 fs (FWHM) is used to modulate the electron beam in modulator 1. The initial laser-induced energy modulation is around 325 keV, corresponding to 6.5 times the slice energy spread. The enhanced energy modulation after the self-modulation is 46.4 times the slice energy spread, which represents a sevenfold increase in energy modulation, i.e., nearly fifty-fold reduction in the peak power requirement of the seed laser.

Figure 3 illustrates the 30th harmonic bunching factor at the entrance of the radiator and the output radiation power profile. The maximum bunching factor at the 30th harmonic of the seed laser is about 9%, corresponding to R^1_{56} and R^2_{56} of 0.32 mm and 17 μm, respectively. The pulse leading edge has a high-power spike because the pulse can slip over the fresh part of the electron beam. Moreover, the coherent radiation signal can be shifted to the fresh part by chicane 3 with

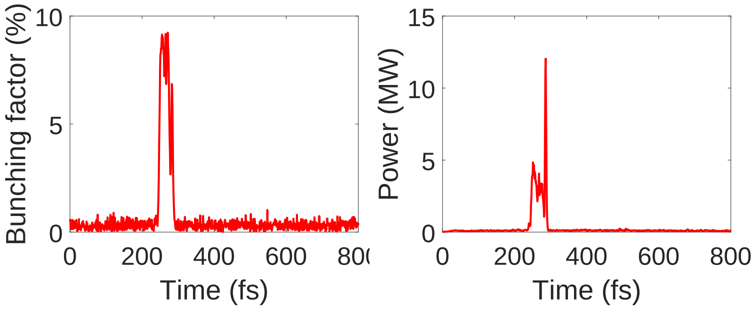

Figure 3. The 30th harmonic bunching factor at the entrance of the radiator (the left) and the output radiation power profile at the exit of the radiator (the right).

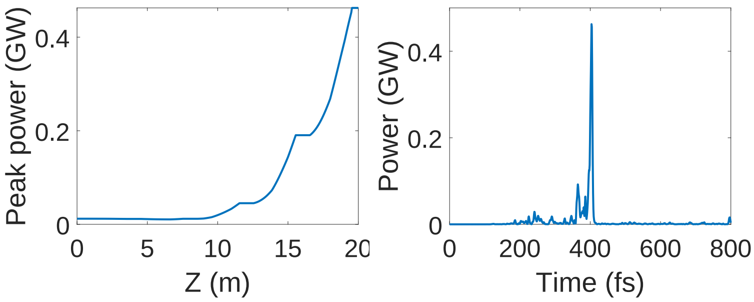

Figure 4. The FEL gain curve along the amplifier (the left) and the final output FEL power profile (the right).

R_{56}^3 of 60 μm, which can also smear out the harmonic bunching factor in the former modules. Figure 4 shows the final output FEL gain curve and power profile, respectively, where the FEL works in the CHG regime. The FEL peak power grows quadratically along the amplifier, as shown in Fig. 4. The FEL peak power reaches 462 MW, the FWHM pulse length is about 6.2 fs, and the FWHM spectral bandwidth is about 2.6×10^{-3}, corresponding to a time-bandwidth product of 0.55, approaching the Fourier-transform limit.

4. Conclusion

In this paper, we present numerical start-to-end simulation results of the self-modulation-enhanced HB-HGHG scheme. The feasibility of this scheme for generating high-repetition-rate and fully coherent soft X-ray radiation pulses with a few-femtosecond timescale has been demonstrated. The final output power can be further enhanced by using more amplifier modules. In addition, the generation of ultra-high harmonics requires a detailed study of practical issues such as microbunching instability and shot noise of the electron beam.

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