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A NOVEL METHOD FOR GENERATING HIGH-REPETITION-RATE AND FULLY COHERENT EUV FREE-ELECTRON LASER

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Abstract

High-brightness extreme ultraviolet (EUV) light source is strongly required for high-resolution photoelectron spectroscopy, imaging experiments, and EUV lithography. In this work, the self-modulation technique is introduced into seeded FELs, such as high-gain harmonic generation (HGHG), to significantly reduce the requirement of the seed laser power by enhancing coherent energy modulation. Numerical simulations demonstrated that the modified HGHG configuration with the self-modulation technique could generate high-repetition-rate, fully coherent, stable, and kilowatt-scale EUV pulses at a more compact linac-based light source.

INTRODUCTION

High-brightness extreme ultraviolet (EUV) light source is a prerequisite for fundamental science. In terms of EUV high-resolution photoelectron spectroscopy and imaging experiments, high brightness and full coherence characteristics are essential. In terms of EUV lithography (EUVL), high average power (higher than 1 kW) and high stability characteristics are more critical. A high-power, fully coherent, and stable EUV light source is urgently required. Over the past decades, synchrotron radiation (SR) has been supplied as a standard tool for advanced research [1]. The SR light source's limitations are the longitudinally incoherent and the order of tens of picoseconds of pulse duration. With accelerator and undulator technology advancements, free-electron lasers (FELs) with high-intense and ultra-fast characteristics have made enormous progress in cutting-edge applications [2], which is the most promising high-power EUV light source.

Generation of high-brightness EUV radiation pulses requires the combination of a high-repetition-rate electron beam and various operating mechanisms. The steady-state microbunching mechanism-based photon source and storage-ring-based FEL are promising EUV light sources because the electron beam repetition rate in the storage ring can easily reach 100 MHz [3, 4]. However, the drawbacks of the electron beam in the storage ring are the low peak current, the induced energy spread that can limit the FEL extracted power, and the multiple turns stability remains experimentally demonstrated. Besides, the energy recovery linac (ERL) based light source with the self-amplified spontaneous emission (SASE) scheme [5, 6] is another method to produce kW-scale EUV pulses [7]. However, generating high-quality electron beams with high beam energy and high peak current is challenging. The total length of the ERL-FEL typically reaches over 100 m to improve the efficiency of extracted radiation power. Moreover, SASE FEL suffers from longitudinally incoherent and significant shot-to-shot jitter due to the initial shot noise of the electron beam.

Currently, most FEL facilities are based on linac that can produce electron beams with small energy spread, high peak current, and low emittance, thus achieving high single-pass FEL gain. The challenge of producing high average power kW scale EUV from single-pass FEL sources is the demand for high-repetition-rate electron beam or high beam energy. With the advanced superconducting radiofrequency technology, continuous-wave electron beam generation and FEL light source becomes feasible. Seeded FELs inherit the characteristics of the external seed laser, which can generate fully coherent and stable FEL pulses [8–10]. To generate high-repetition-rate EUV pulses in seeded FELs, such as high-gain harmonic generation (HGHG) [8], a UV seed laser of several MHz is required, challenging for state-of-the-art laser technology. Recently, the self-modulation technique has been demonstrated theoretically and experimentally in seeded FELs to reduce the power requirement of the seed laser at least two orders of magnitude by amplifying coherent energy modulation [11]. Thus, externally seeded FELs introducing the self-modulation technique have excellent potential to produce high-repetition-rate, fully coherent, and stable EUV pulses.

In this work, we demonstrate the feasibility of the single-pass FEL facilities to produce high-repetition-rate, fully coherent, and stable kW-scale EUV generation, with its potential application to EUVL. After upgrading the linac and laser systems, this modified HGHG configuration with the self-modulation technique is compatible with existing seeding beamlines.

PHYSICAL DESIGN

In a standard HGHG, an external seed laser interacts with the electron beam in a modulator undulator and imprints a sinusoidal energy modulation. After a dispersion section, the energy modulation is transferred into a density modulation and radiators resonate at the target harmonic of the seed laser. Typically, the energy modulation amplitude is proportional to the harmonic number n. For amplifying the FEL

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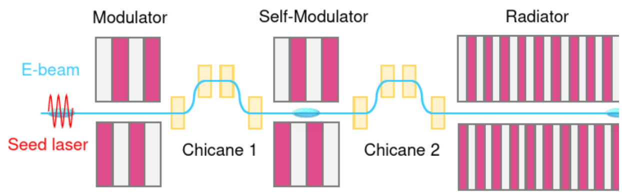

Figure 1: The schematic layout of the self-modulation HGHG configuration. A UV seed laser with lower intensity modulates the energy beam in the modulator. Then, the electron beam is compressed longitudinally by a four-dipole magnetic chicane 1 to enhance the coherent radiation in the self-modulator resonating at the fundamental wavelength of the seed laser. Through the precisely optimized magnetic chicane 2, the electron beam can generate high harmonic radiation toward the EUV region in the following radiator.

radiation in the EUV range, the energy modulation should be increased. The self-modulation technique is employed to the standard HGHG to enhance a larger energy modulation extending to the spectrum wavelength of the EUV. Meanwhile, the seed laser power is significantly lower than that of the standard HGHG, which means the conventional externally seeding scheme HGHG can generate the high-repetition-rate EUV radiation.

The schematic illustration of the self-modulation HGHG is shown in Fig. 1. Compared to the standard HGHG, this configuration introduces one additional self-modulator to generate coherent energy modulation. Generally, the power of the coherent radiation is given by

$$P_{\mathrm{coh}} = \frac{Z_0 \left(K[JJ]_1 L I b_n\right)^2}{32\pi\sigma_x^2\gamma^2} \tag{1}$$

where $Z_0 = 377\ \Omega$ is the vacuum impedance, K is the undulator parameter, $[JJ]_1$ is the planar undulator Bessel factor, L is the self-modulator length, b_n is the n-th bunching factor, I is the peak current, and σ_x is the transverse beam size. Here, the coherent radiation intensity can be further enhanced by precisely optimizing the beam size, the peak current, and the self-modulator length, thus relaxing the requirement of the seed laser system.

To verify the feasibility of the self-modulation HGHG to generate EUV pulses with high average power, the nominal parameters of the SXFEL user facility are adopted, as shown in Table 1, to present some physical design and optimization. The SXFEL user facility was initially designed to generate coherent soft x-ray pulses using externally seeding schemes, such as cascaded HGHG or EEHG. The baseline design is fully compatible with the self-modulation HGHG configuration. The electron beam, seed laser, and undulator parameters are listed in Table 1, the FEL pierce parameter is calculated to 7×10^{-3}, corresponding to the gain length is 0.5 m. The 1.6 m long self-modulator corresponds to a gain length of 3.2 times. Due to the 3-fold gain length being critical for quadratic growth and FEL exponential growth, the coherent energy modulation in the self-modulator is significantly enhanced, producing significant harmonic bunching

Table 1: Main Simulation Parameters of SXFEL User Facility

Specifications	**Electron beam**
Energy	1.4 GeV
Slice energy spread	50 keV
Normalized emittance	1 mm·mrad
Peak current	700 A (Flat-top)
Bunch charge	600 pC
Specifications	**Seed laser**
Peak power	400 kW (Gaussian)
Duration	1 ps (FWHM)
Wavelength	266 nm
Rayleigh length	5 m
Specifications	**Undulator**
Period of Modulators	0.08 m
Length of Modulators	1.6 m
Period of Radiator	0.05 m
Length of Radiator	16 m

in the wavelength of EUV and broadening the HGHG operating range. By obtaining the same harmonic bunching factor, the self-modulation HGHG introduces an additional energy spread compared to standard HGHG. However, the seed laser power can be reduced by nearly two orders of magnitude, with great potential for high repetition rate operation.

SIMULATION RESULTS

To analyze the feasibility of the self-modulation HGHG, the simulations were carried out with GENESIS [12]. We first introduced a UV seed laser with a peak power of 400 kW, as shown in Table 1, producing an initial weak energy modulation of about 65 keV, corresponding to 1.3 times the slice energy spread. The steady-state simulation is performed to fast optimize the working points of R_{56}s of chicane 1 and chicane 2, as shown in Fig. 2. The maximum bunching factor at the 20th harmonic of the seed laser is about 0.07, with one of the optimal R_{56}^1 and R_{56}^2 of 0.86 mm and 0.043 mm, respectively.

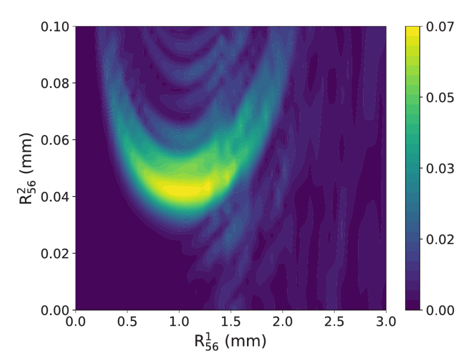

Figure 2: Optimization results of the optimal area of R_{56}s at the 20th harmonic bunching factor, corresponding to EUV wavelength.

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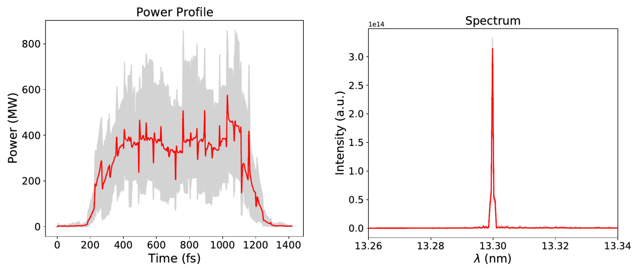

Figure 3: The 100-shot EUV FEL performance using the self-modulation technique after a 4 modules radiator of 16 m. Each grey plot corresponds to a single-shot simulation. The red plot corresponds to the average of all 100 shots.

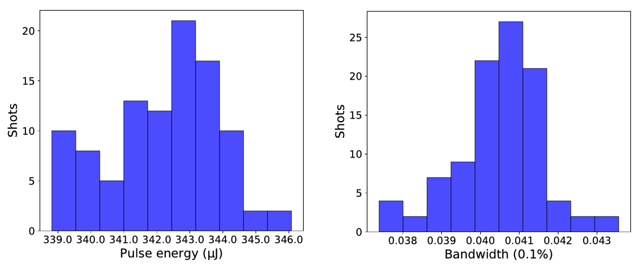

Figure 4: The statistical properties of 100 shots output EUV FEL performance.

FEL Performance

The time-dependent simulations were performed by further precisely optimizing the beam orbit, beam size, and undulator parameters, as shown in Fig. 3. The average EUV pulse energy reaches 342.2 μJ, and the rms pulse energy jitter is 1.7 μJ. The number of photons per pulse is about 2.3×10^{13} Due to the slippage of the self-modulator and shot noise effects, there are several spikes on the power profile. The average FWHM pulse length is about 646.0 fs. The average FWHM bandwidth is about 4.0×10^{-5}, corresponding to a time-bandwidth product of 0.58, approaching the Fourier transform limit. Besides, as shown in Fig. 4, the shot-to-shot pulse energy and relative bandwidth fluctuation is 0.49% and 2.8%, respectively. The enhanced energy modulation amplitude is about 24.5 leading to a lower saturation pulse energy. Based on the self-modulation technique, the seed laser power is only 400 kW, corresponding to the average power of 1.2 W, promising to reach a 3 MHz repetition rate with the existing seed laser system. Assuming that the electron beam generated by the linac can achieve a 3 MHz repetition rate corresponding to an average current of 1.8 mA, the average power of the fully coherent EUV FEL can reach 1 kW. It is worthy that a tapering undulator can be used to extract additional power from the electron beam, which can further increase the average power by a factor of 3 to 5.

Stability Analysis

More numerical simulations were performed to investigate further whether the stability of the output FEL properties is sensitive to the seed laser power. Here, we assumed that the maximum power jitter of the seed laser is ± 6%, corresponding to between 376 kW to 424 kW when the dispersion strength of chicanes is constant. As shown in Fig. 5, a slight increase in the seed laser power can improve the harmonic bunching factor because of a range of working points, such as R_{56} of chicane 2. Besides, according to Fig. 6, both the pulse energy deviation and time-bandwidth product of output spectra as a function of the seed laser power. When the seed laser power is as low as 370 kW, the pulse energy is instead increased while the longitudinal coherence is significantly decreased. Because the introduced seed laser is weak, resulting in a pedestal on the power profile, the SASE background from the shot noise eventually leads to a lower signal-to-noise ratio. Therefore, the shot noise effects need further analysis to verify the self-modulation technique toward shorter wavelength FEL.

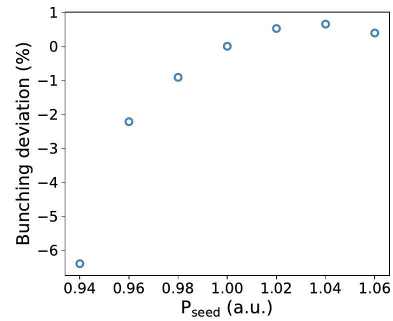

Figure 5: The 20th harmonic bunching deviation versus the seed laser power. The power is normalized by the nominal case of that of 400 kW.

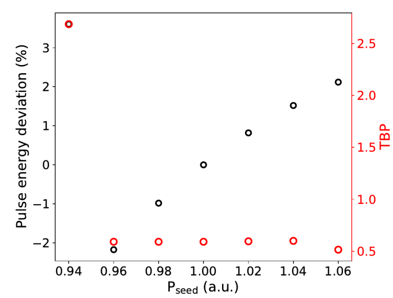

Figure 6: The EUV pulse energy deviation and the time-bandwidth product of output spectra versus the seed laser power. The power is normalized by the nominal case of that of 400 kW.

DISCUSSION

In this work, a novel method for generating high-repetition-rate, fully coherent, stable, and compact EUV FEL is demonstrated by numerical simulations. By reasonably optimizing the working points, one can obtain fully coherent EUV pulses with an average power of 1 kW utilizing a 3 MHz electron beam and a seed laser with an average power of only 1.2 W, significantly improving the efficiency of the EUV spectroscopic experiments. It should be noted that the output EUV pulse intensity can be further enhanced by increasing the electron beam repetition rate and combining it with the fresh bunch technique [13, 14], with the

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potential to achieve kW-scale EUV-FEL. In addition, the sensitivity analysis of the novel method to the seed laser power shows that shot noise effects are essential at high harmonic up-conversion numbers. The degradation of FEL coherence should be considered during the optimization of the seed laser, which can be further investigated in future work.

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REFERENCES

[1] Z.T. Zhao, "Storage Ring Light Sources", *Reviews of Accelerator Science and Technology*, vol. 03, no. 01, p. 57-76, 2010. doi:10.1142/S1793626810000361

[2] N. Huang, H. Deng, B. Liu, D.Wang, and Z. Zhao, "Features and futures of X-ray free-electron lasers Features and futures of X-ray free-electron lasers", *The Innovation*, vol. 2, no. 2, p. 100097, 2021. doi:10.1016/j.xinn.2021.100097

[3] X. Deng *et al.*, "Experimental demonstration of the mechanism of steady-state microbunching", *Nature*, vol. 590, no. 7847, pp. 576-579, 2021. doi:10.1038/s41586-021-03203-0

[4] J. Lee *et al.*, "Demonstration of a ring-FEL as an EUV lithography tool", *Journal of Synchrotron Radiation*, vol. 27, no. 4, pp. 864-869, 2020. doi:10.1107/S1600577520005676

[5] A. Kondratenko and E. Saldin, "Generating of coherent radiation by a relativistic electron beam in an ondulator", *Part. Accel.*, vol. 10, pp. 207–216, 1980. http://cds.cern.ch/record/1107977/files/p207.pdf

[6] R. Bonifacio, C. Pellegrini, and L. Narducci, "Collective instabilities and high-gain regime in a free electron laser", *Optics Communications*, vol. 50, no. 6, pp. 373–378, 1984. doi:10.1016/0030-4018(84)90105-6

[7] N. Nakamura *et al.*, "Demonstration of proof of concept of the EUV-FEL for future lithography", *Proc. of SPIE*, vol. 11854, 2021. doi:10.1117/12.2600782

[8] L. H. Yu, "Generation of intense uv radiation by subharmonically seeded single-pass free-electron lasers", *Physical Review A*, vol. 44, no. 8, pp. 5178–5193, 1991. doi:10.1103/PhysRevA.44.5178

[9] G. Stupakov, "Using the beam-echo effect for generation of short-wavelength radiation", *Physical Review Letters*, vol. 102, no. 7, pp. 1–4, 2009. doi:10.1103/PhysRevLett.102.074801

[10] H. Deng and C. Feng, "Using off-resonance laser modulation for beam-energy-spread cooling in generation of shortwavelength radiation", *Physical Review Letters*, vol. 111, no. 8, pp. 1–5, 2013. doi:10.1103/PhysRevLett.111.084801

[11] J. Yan *et al.*, "Self-amplification of coherent energy modulation in seeded free-Electron Lasers", *Physical Review Letters*, vol. 126, no. 8, pp. 84801, 2021. doi:10.1103/PhysRevLett.126.084801

[12] S. Reiche, "GENESIS 1.3: a fully 3D time-dependent FEL simulation code", *Physical Review Accelerators and Beams*, vol. 429, no. 1, pp. 243-248, 1999. doi:10.1016/S0168-9002(99)00114-X

[13] L. Hua Yu and I. Ben-Zvi, "High-gain harmonic generation of soft X-rays with the "fresh bunch" technique", *Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 393, no. 1-3, pp. 96-99, 1997. doi:10.1016/S0168-9002(97)00435-X

[14] K. Zhou *et al.*, "Generating high-brightness and coherent soft x-ray pulses in the water window with a seeded free-electron laser", *Physical Review Accelerators and Beams*, vol. 20, no. 1, pp. 010702, 2017. doi:10.1103/PhysRevAccelBeams.20.010702