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# THE DESIGN OF EEHG CASCADED HARMONIC LASING FOR SXFEL USER FACILITY*

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*Abstract*

The preliminary design and simulation results of EEHG cascaded harmonic lasing for SXFEL user facility have been presented in this paper. Using the basic seeded beamline of SXFEL user facility, the designed parameters are optimized to obtain full coherent FEL output at 90th harmonic of a 265 nm seed laser. According to the designed parameters and the layout of SXFEL user facility, the detailed simulations are carried out, the results show that the seeded beamline of SXFEL user facility can generate 2.93 nm full coherent radiation by the proposed method, which indicates that the method can extend the photon energy range of a seeded FEL and the method can be achieved at the SXFEL user facility.

## INTRODUCTION

SASE FEL has been the prior operation mode for most FEL facilities due to its remarkable FEL output [1-3]. Therefore, the temporal coherent of SASE FEL is generally poor since it arises from initial shot-noise. To obtain full coherent FEL pulses at short wavelength, seeded FELs with frequency up conversion technique are proposed, such as high gain harmonic generation [4-6]. The HGHG has limited frequency up-convention efficiency (generally h is less than 15) due to that the required amplitude of energy modulation is approximately linear correlated with the harmonic convention number h [5]. Among the external seeded FELs, echo-enable harmonic generation has the highest harmonic conversion efficiency, the EEHG employs two modulator-chicane sections to imprint the precise bunching at the high harmonics on the longitudinal phase space of electron beam by using two seed lasers [7-9]. The EEHG FEL was initially demonstrated by the early proof-of-principle EEHG experiment at the low harmonics (3th and 4th) of an infrared seed laser [8]. Recently, the high gain soft X-ray lasing of an EEHG FEL with the seed laser wavelength of 264 nm was demonstrated at 7.3 nm (h = 36) and 5.9 nm (h = 45), a coherent emission at the wavelength down to 2.6 nm (h = 101) was also considerable measured [9].

The EEHG FEL holds the promising abilities to generate intense, full coherence radiation at extreme ultraviolet and soft X-ray. However, the various three-dimensional effects of beam can smear out the fine structure in the longitudinal phase space for the EEHG. To generate full coherent FEL radiation at ultra-short wavelength, a novel technique of EEHG cascaded harmonic lasing method is proposed in Ref. [10] recently, which indicates that the proposed technique is a reliable method to obtain full coherent radiation and reduce the influence of various three-dimensional
effects of beam. Using a conventional seed laser at 265 nm, 225th harmonic radiation at 1.18 nm is demonstrated with a typical soft X-ray FEL parameters.

In this paper, a system design of EEHG cascaded harmonic lasing for SXFEL user facility is presented based on the simulation results. The SXFEL user facility is a typically soft X-ray user facility that has two undulator beamlines, one undulator beamline will operate at SASE mode, and the other undulator beamline will operate at EEHG or EEHG cascaded HGHG mode. The EEHG undulator beamlines consist two types undulator with two undulator period, U30 with a undulator period of 30 mm and U235 with a undulator period of 2.35 mm, which is suitable to achieve harmonic lasing.

## THE DESIGN OF EEHG CASCADED HARMONIC LASING

The layout of EEHG beamline at SXFEL user facility adopts a typical EEHG scheme with two type undulators. The beam energy of SXFEL can arrive 1.5 GeV, the relative beam energy spread is 0.01% and the normalized emittance is 1.5 mm.mrad. The principal layout of the EEHG cascaded harmonic lasering are presented in Fig. 1, where consist of two modulators, two dispersion sections, one reverse tapered undulator and one radiation undulator, the basic principle are described in Ref. [10]. For EEHG technique, the harmonic up-conversion efficiency can be qualified by the bunching factor, which can be calculated by

$$b_{n,m} = \left|e^{-1/2[nB_1+(Km+n)B_2]^2} J_m[-(Km+n)A_2B_2] \times J_n\{-A_1[nB_1+(Km+n)B_2]\}\right|. \quad (1)$$

According to the basic parameters of SXFEL user facility, the energy modulation amplitude $A_1$, $A_2$ and dispersion strength $B_1$, $B_2$ are optimized to obtain sufficient bunching at 30th harmonic (8.8 nm) of seed laser. Here, we consider a relatively small energy modulation amplitude. The optimized values of $B_1, B_2$ vary by using different combination of $n$ and $m$, Here, we adopt n = -1 and m = 1. The relations between bunching factor at 30th harmonic and $A_1$, $A_2$, $B_1$, $B_2$ are shown in Fig. 2. According to the results in Fig. 2, the EEHG parameters are optimized as $A_1$ = 1.5, $A_2$ = 1.5, $B_1$ = 23.2, $B_2$ = 0. The designed parameters are concluded in Table 1.Using the optimized parameters, the calculated bunching factors at different harmonics are presented in Fig. 3, the bunching factor at 30th harmonic is about 0.08, which is enough to generate the FEL pulse at 8.8 nm.

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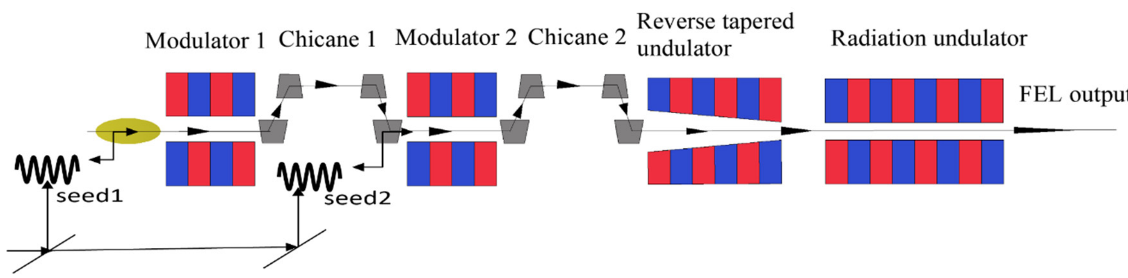


Figure 1: The side view of the proposed technique.

Table 1: The Designed Parameters of the EEHG Cascaded Harmonic Lasing Technique

| Parameter | Value |
|---|---|
| Beam energy | 1.3 GeV |
| Energy spread | 0.01% |
| Emittance | 1.5 mm.mrad |
| Peak current | 800A |
| Laser wavelength | 265 nm |
| Modulator amplitude | $A_1 = 1.5$, $A_2 = 1.5$ |
| Dispersion strength | $B_1 = 23.2$, $B_2 = 0.8$ |
| Undulator | U30, U235 |
| EEHG wavelength | 8.8 nm |
| Final wavelength | 2.93 nm |

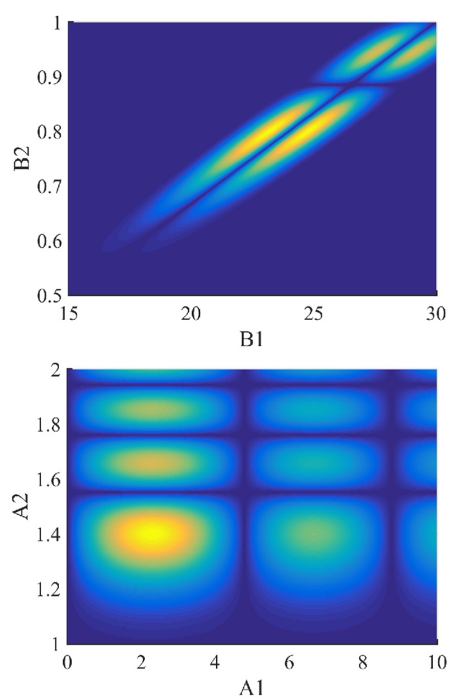


Figure 2: The relation between the bunching factor and $A_1$, $A_2$, $B_1$, $B_2$.

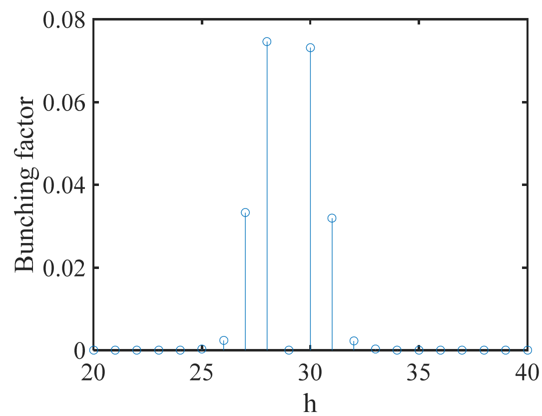


Figure 3: The bunching factor at different harmonics with $A_1 = 1.5$, $A_2 = 1.5$, $B_1 = 23.2$, $B_2 = 0.8$.

## THE SIMULATION RESULTS

Using the SXFEL parameters, 3D simulations with MATLAB and GENESIS are carried out. An electron beam with uniform current $I$, energy spread $\sigma_{E0}$ and emittance $\varepsilon$ in the longitudinal position is adopted in this simulation. Using the parameters in Table 1, the phase space as well as current profile before and after the modulators and dispersion sections with the optimized EEHG parameters are presented in Fig. 4.

The electron beam is then sent through the U30 undulator, where the resonant wavelength is tuned at the $30^{th}$ harmonic (8.8 nm). The bunching signal will be amplified at the undulator to produce FEL pulse of 8.8 nm. At the same time, the harmonic signal of 8.8 nm will also be amplified. To preserve the quality of electron beam, reverse tapered undulator [11-14] is introduced. The reverse taper strength of undulator need to be optimized to amplify the harmonic signal while preserve the beam quality. The relations between the energy spread, peak power and taper strength are shown in Fig. 5, where one can find the reverse tapered undulator can efficiently supress the radiation power and induced energy spread.

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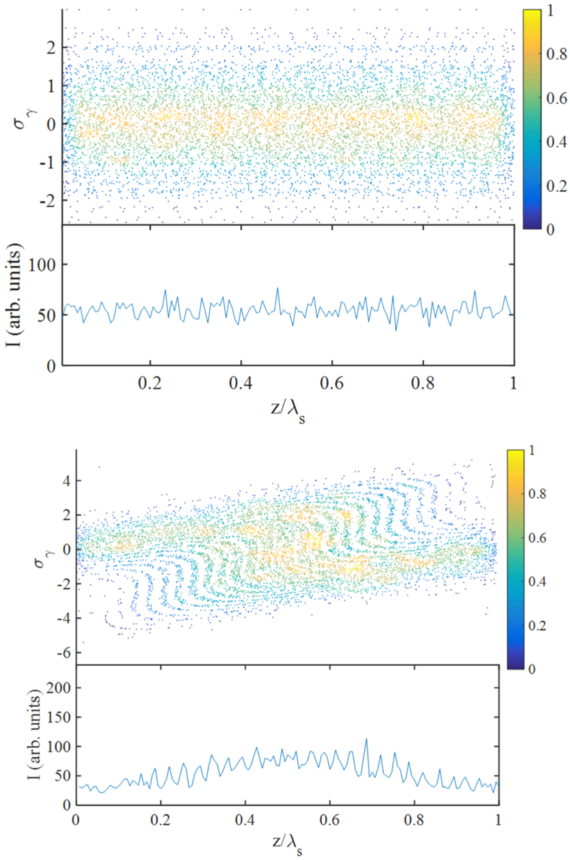


Figure 4: The phase space of electron beam before and after the modulators and dispersion sections.

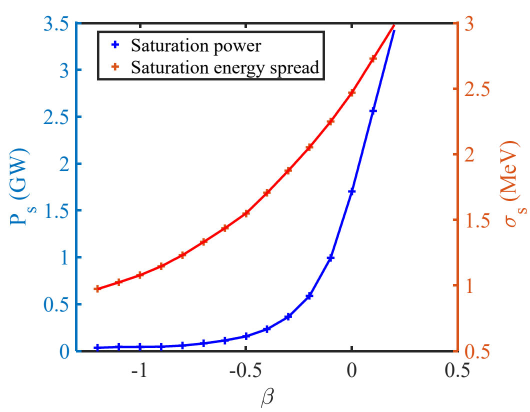


Figure 5: The relations between the energy spread, peak power and taper strength.

Here, we adopt a taper strength of -0.5, the peak power and the energy spread evolutions along the undulator are presented in Fig. 6. The electron beam is extracted from the reverse tapered undulator when the bunching factor at 2.93 nm arrives about 0.01, the undulator length is about 5 m. From Fig. 6, one can observe that the radiation power and the induced energy spread are significantly suppressed, which means that the quality of the electron beam will be well preserved. The electron beam can be used to produce FEL radiation at 8.8 nm.

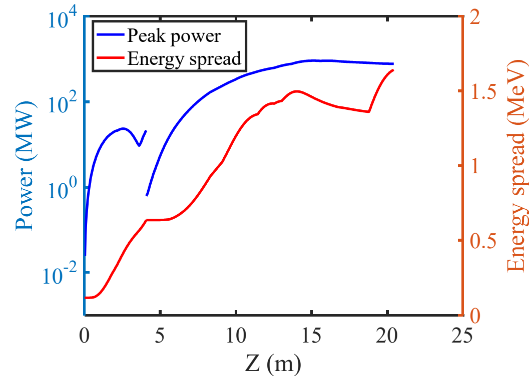


Figure 6: The peak power and the energy spread evolutions along the undulator.

The electron beam with bunching is lastly sent into the final radiator, which is tuned at the wavelength of 2.93 nm. The signal of bunching will be amplified in the radiator. The radiation peak power as well as the energy spread are also shown in Fig. 6. From Fig. 6, one can easily observe that the FEL radiation get saturation with a peak power of 300 MW at a distance of 10 m. Besides, the final spectrum is also shown in Fig. 7, where one can find that the spectrum has a smooth structure and the spectral bandwidth is near the Fourier transform limitation.

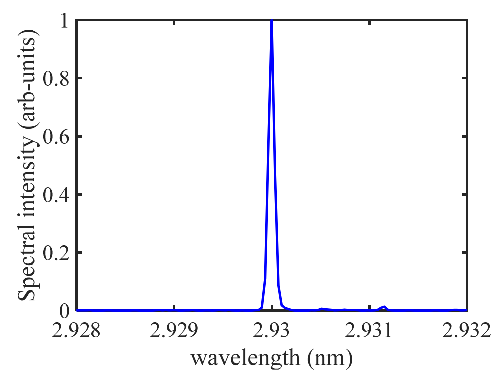


Figure 7: The final spectrum of the proposed technique.

## CONCLUSION

In this paper, the design of EEHG cascaded harmonic lasing for SXFEL user facility is preliminary studied and optimized. The simulations of the proposed technique are performed with the parameters of SXFEL user facility, the results show that the proposed technique can extend the frequency up-conversion efficiency of EEHG. As Ref. [10] mentioned, the technique can significantly reduce the various three-dimensional effects of beam by radiating at relatively lower harmonic of EEHG, it can furtherly extend the photon energy coverage to hard X-ray by increasing the harmonic number, and it also has a relatively simpler configure than two-stage seeded FEL while achieving similar FEL radiation. Most importantly, the technique can be easily achieved at SXFEL user facility consider that the EEHG undulator beamline has two type undulators with two undulator periods. Further works will focus on the experimental research of the EEHG cascaded harmonic lasing technique.

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## REFERENCES

[1] A. M. Kondratenko and E. L. Saldin, "Generation of Coherent Radiation by a Relativistic Electron Beam in an Ondulator", *Part. Accel.*, vol. 10, p. 207, 1980.

[2] R. Bonifacio, C. Pellegrini, and L. M. Narducci, "Collective Instabilities and High-gain Regime in a Free Electron Laser", *Opt. Commun.*, vol. 50, p. 373, 1984.

[3] J. Andruszkowet *et al.*, "First Observation of Self-Amplified Spontaneous Emission in a Free-Electron Laser at 109 nm Wavelength", *Phys. Rev. Lett.*, vol. 85, p. 3825, 2000. doi:10.1103/PhysRevLett.85.3825

[4] N. Huang *et al.*, "Features and futures of X-ray free-electron laser", *The Innovation*, vol. 2, p. 100097, 2021. doi:10.1016/j.xinn.2021.100097

[5] L. Yu *et al.*, "Generation of intense UV radiation by subharmonically seeded single-pass free-electron lasers", *Phys. Rev. Accel. Beams*, vol. 44, p. 5178, 1991.
doi:10.1103/PhysRevA.44.5178

[6] L. Yu *et al.*, "First Ultraviolet High-Gain Harmonic-Generation Free-Electron Laser", *Phys. Rev. Lett.*, vol. 91, p. 074801, 2003. doi:10.1103/PhysRevLett.91.074801

[7] D. Xiang and G. Stupakov, "Echo-enabled harmonic generation free electron laser", *Phys. Rev. Accel. Beams*, vol. 12, p. 030702, 2009. doi:10.1103/PhysRevSTAB.12.030702

[8] Z. T. Zhao *et al.*, "First lasing of an echo-enabled harmonic generation free-electron laser", *Nat. Photonics*, vol. 6, pp. 360-363, 2012. doi:10.1038/nphoton.2012.105

[9] P. R. Ribic *et al.*, "Coherent soft X-ray pulses from an echo-enabled harmonic generation free-electron laser", *Nat. Photonics*, vol. 13, pp. 555-561, 2019.
doi:10.1038/s41566-019-0427-1

[10] K. Zhang *et al.*, "Extending the photon energy coverage of a seeded free-electron laser via reverse taper enhanced harmonic cascade", *Photonics*, vol. 8, p. 44, 2021. doi:10.3390/photonics8020044

[11] E. L. Saldin, E. A. Schneidmiller, and M. V. Yurkov, "The features of an FEL oscillator with a tapered undulator", *Opt. Commun.*, vol. 103, pp. 297-306, 1993. doi:10.1016/0030-4018(93)90456-F

[12] E. L. Saldin, E. A. Schneidmiller, and M. V. Yurkov, "Self-amplified spontaneous emission FEL with energy-chirped electron beam and its application for generation of attosecond x-ray pulses", *Phys. Rev. Accel. Beams*, vol. 9, p. 050702, 2006. doi:10.1103/PhysRevSTAB.9.050702

[13] E. A. Schneidmiller and M. V. Yurkov, "Obtaining high degree of circular polarization at x-ray free electron lasers via a reverse undulator taper", *Phys. Rev. Accel. Beams*, vol. 16, p. 110702, 2013. doi:10.1103/PhysRevSTAB.16.110702

[14] A. A. Lutman *et al.*, "Polarization control in an X-ray free-electron laser", *Nat. Photonics*, vol. 10, pp. 468-472, 2016. doi:10.1038/nphoton.2016.79