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NUMERICAL SIMULATIONS FOR GENERATING FULLY COHERENT SOFT X-RAY FREE ELECTRON LASERS WITH ULTRA-SHORT WAVELENGTH

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Abstract

For the fully coherent, ultra-short and high power soft x-rays are becoming key instruments in many different research fields, such as biology, chemistry or physics. However, it's hard to generate this kind of advanced light source by the conventional lasers, especially for the soft x-rays with ultra-short wavelength because of no suitable reflectors. The external seeded free electron laser (FEL) is considered as one feasible method. Here, we give an example to generate highly temporal coherent soft x-rays with the wavelength 1nm by the two-stage cascaded schemes. The external seeded scheme EEHG is used as the first-stage while the HGHG scheme is used as the second-stage.

INTRODUCTION

The SASE scheme, external seeded scheme and self-seeding scheme are three important methods for the high-gain free electron lasers (FEL). The SASE scheme is now the main method to generate X-ray FEL which has been successfully used in many facilities [1, 2, 3], however, the SASE scheme use the local shot noise of the electron beam which will cause a few spikes in the output spectrum. The external seeded scheme use the fully coherent conventional laser as the seed to modulate the electron beam, if the power of the seed laser are large enough to suppress the shot noise of the electron beam, the output radiation pulse will be fully coherent in principle [4, 5]. Self-seeding scheme is another way to generate the fully coherent radiation pulse, this scheme uses crystals to filter the radiation pulse from the upstream sections to get monochromatic seeding pulse for the downstream sections, however, the output radiation power and central wavelength may have larger shot-to-shot fluctuations than SASE scheme according to the experiment [6].

China will build a high-repetition rate of 1MHz FEL facility (SHINE) based on superconducting LINAC technology. According to the requirements of the users, three beam lines will be built at the first time (FEL-I, FEL-II and FEL-III), one of them (FEL-II) is designed to generate highly temporal coherent soft x-rays with the central wavelength 1nm.

To generate this kind of advanced light source, the two-stage cascaded EEHG/HGHG scheme with fresh bunch technology is chosen as the baseline for FEL-II, it is comprised of two stages while the First-stage is EEHG and the second stage is HGHG. The principle of HGHG was proved in 1990s [7] and it is currently adopted in FERMI FEL user facility. EEHG scheme can work at high harmonics of seeding lasers which is successfully demonstrated by NLCTA, SDUV and FERMI recently [8, 9, 10, 11].

LAYOUT AND DESCRIPTION

The layout of the two-stage cascaded EEHG/HGHG scheme for FEL-II is shown in Figure 1.

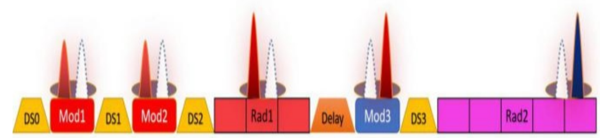

Figure 1: The layout of the two-stage cascaded scheme.

The first-stage EEHG is designed to generate 5nm fully coherent soft x-rays, the up-conversion harmonic number is 54 of 270nm seeding lasers, it has two modulators, two dispersion sections, and a long radiator. Then, the electron beam is delayed to interact with the radiation pulse from the first-stage, and the up-conversion harmonic number for the second-stage HGHG is 5, the second stage HGHG is comprised of one modulator, one dispersion section and a lone radiator. Finally, the highly temporal coherent 1nm soft x-ray is generated by the second long radiator.

The parameters of electron bunch from the output of LINAC for start-to-end simulations are given in Figure 2.

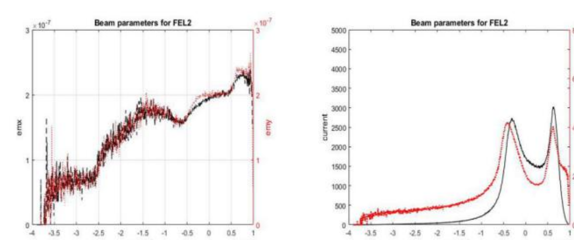

Figure 2: The emittance of x/y (left). The current and energy spread of electron bunch (right).

From Figure 2, one can find that the emittance for both sides x and y is lower than 0.3mm*mrad of the electron beam according to the first version from LINAC, and the peak current of the electron beam is larger than 1500A, besides , the energy of the electron beam is about 8GeV.

The lattice of the two-stage cascaded EEHG/HGHG scheme is given in Figure 3 based on the particle tracing program Elegant.

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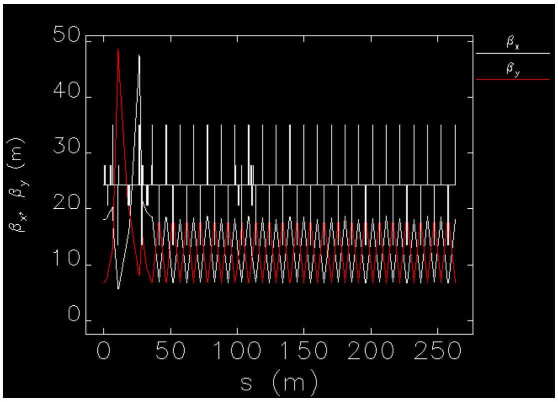

Figure 3: The lattice of two-stage cascaded EEHG/HGHG scheme.

Table 1: Length of the Different Parts of FEL-II

Element	Value	Unit
The first-stage EEHG		
DS0	5	m
Mod1	2.88	m
Mod2	1.44	m
DS1	15.3	m
DS2	7.2	m
Rad1	50	m
Delay chicane	5	m
The second-stage HGHG		
Mod3	5	m
DS3	5	m
Rad2	140	m

The length of the different element is shown in Table1. For the first-stage EEHG, the up-conversion harmonic number is 54, in order to get large enough bunching factor at the specified harmonic to suppress the shot noise of the electron beam and minimize the ISR effect causing by the two dispersion sections in EEHG scheme, we have choose the parameters $A_1 = 9$, $A_2 = 6$ (in units of the initial energy spread) and $n = -3$ (this parameter coming from the EEHG bunching factor b_{nm}) [12], the modulation deep for Mod1 and Mod2 is introduced by two seeding lasers, the parameters of them are listed in Table 2.

Table 2: The Main Parameters of Seed Laser

Seed laser		
Title	**value**	**unit**
Wavelength	~270	nm
Peak power1	18	GW
Peak power2	30	GW
Pulse length (FWHM)	~20	fs
Rayleigh length	~3.52	m

Table 2 shows that the peak power of the two seeding lasers is about 18GW and 30GW, respectively. However, the requirements of peak power can be lower if we increase the length of the two modulators, besides, the pulse length also can be longer than 20fs which depends on the input length of the electron bunch.

To optimize the maximum bunching factor at 54th of seeding lasers, we have scanned the strength of two dispersion sections which is shown in Figure 4.

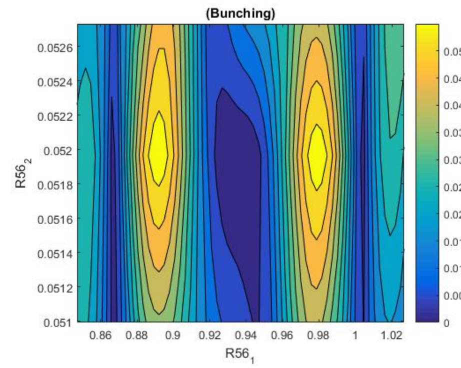

Figure 4: The optimized bunching factor for the first-stage EEHG.

Figure 4 shows that the ideal bunching factor at 54^{th} harmonic of seeding lasers is 0.06, the corresponding strength of the two dispersion sections is $R56_1 \approx 0.9mm$ and $R56_2 \approx 50\mu m$, respectively.

The parameters of the undulators in the different sections of FEL-II are listed in Table 3.

Table 3: Parameters of Undulators in Different Sections

Undulators		
Element	**Strength of K**	**Length of λ_u**
Mod1	33.3	24cm
Mod2	33.3	24cm
Mod3	8.4	6.8cm
Rad1	8.4	6.8cm
Rad2	3.5	6.8cm

The S2E simulation is performed by Genesis [13], the evolution of the EEHG phase space and the output bunching factor for the first-stage EEHG is shown in Figure 5.

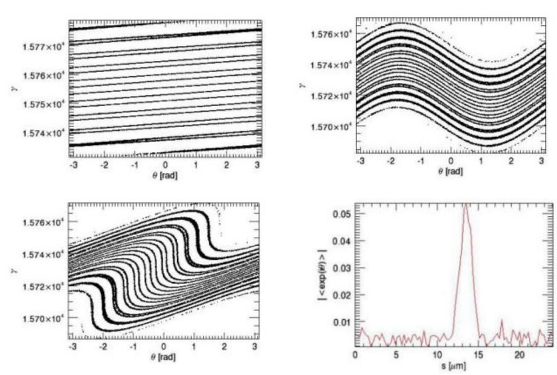

Figure 5: The evolution of EEHG phase space and bunching factor.

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From Figure 5 one can find that the bunching factor is about 0.05, the radiation power and spectrum of the first-stage is given in Figure 6.

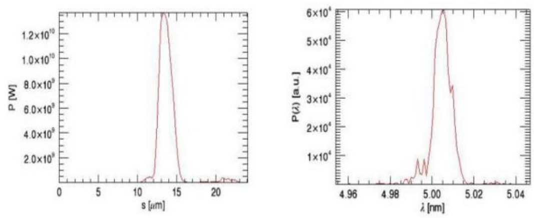

Figure 6: The output radiation power and spectrum from the first-stage EEHG.

Figure 6 shows that the output 5nm radiation power is about 12GW which is far away from saturation (about 25GW), however, it is enough to modulate the electron beam in second-stage, besides, the radiation power can be controlled by opening the gap of height variable undulators, after that, the radiation pulse is delayed to modulate a part of electron beam which is close to the head part, the HGHG bunching factor of the second-stage is given in Figure 7.

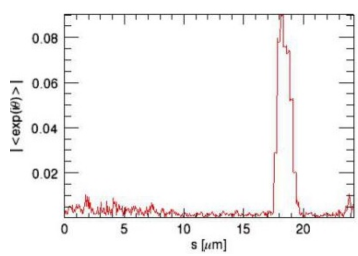

Figure 7: The bunching factor of the second-stage HGHG.

From Figure 7, we can find that the fifth harmonic bunching factor of the second-stage HGHG is about 0.08, and then the density modulated electron beam is sent to a long radiator to generate 1nm highly temporal coherent soft x-rays. The radiation power and spectrum of the second-stage is shown in Figure 8.

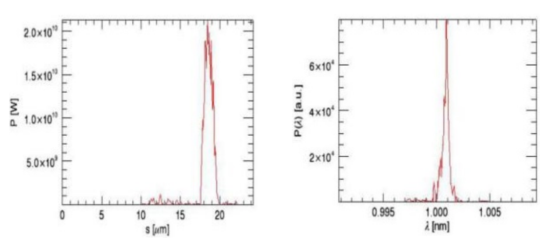

Figure 8: The radiation power and spectrum from the second-stage.

From Figure 8, one can find that the power of the 1nm highly temporal coherent radiation pulse is about 20GW.

CONCLUSION

The two-stage cascaded EEHG/HGHG scheme is recognized as a method to generate highly temporal coherent soft x-rays with ultra-short wavelength. In this paper, this scheme is designed to generate 1nm soft x-rays, and it is proved to work well at ultra-high harmonics of seeding lasers by the S2E simulation.

However, other effects may hinder the ability of this scheme to obtain this kind of soft x-rays with ultra-short wavelength and highly temporal coherence, such as IBS、CSR/ISR、MBI and phase error of the seeding lasers [14, 15, 16, 17], all these effects need to be carefully considered in the future optimization.

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REFERENCES

[1] P. Emma *et al.*, "First lasing and operation of an ångstrom-wavelength free-electron laser", *Nature Photonics*, vol. 4, 641 (2010), doi:10.1038/nphoton.2010.176

[2] T. Ishikawa *et al.*, "A compact X-ray free-electron laser emitting in the sub-ångstrom region", *Nature Photonics*, vol. 6, 540 (2012), doi:10.1038/nphoton.2012.141

[3] H. S. Kang *et al.*, "Hard X-ray free-electron laser with femtosecond-scale timing jitter", *Nature Photonics*, vol. 11, 708–713 (2017), doi:10.1038/s41566-017-0029-8

[4] L. H. Yu, "Generation of intense uv radiation by subharmonically seeded single-pass free-electron lasers", *Phys. Rev. A*, vol. 44, 5178 (1991), doi:10.1103/physreva.44.5178

[5] G. Stupakov, "Using the Beam-Echo Effect for Generation of Short-Wavelength Radiation", *Phys. Rev. Lett.*, vol. 102, 074801 (2009), doi:10.1103/PhysRevLett.102.074801

[6] J. Amann *et al.*, "Demonstration of self-seeding in a hard-X-ray free-electron laser", *Nature Photonics*, vol. 6, 693 (2012), doi:10.1038/nphoton.2012.180

[7] L.-H. Yu *et al.*, "High-Gain Harmonic-Generation Free-Electron Laser", *Science*, vol. 289, issue 5481, pp. 932-934, doi:10.1126/science.289.5481.932

[8] D. Xiang *et al.*, "Demonstration of the Echo-Enabled Harmonic Generation Technique for Short-Wavelength Seeded Free Electron Lasers", *Phys. Rev. Lett.*, vol. 105 (2010) 114801, doi:10.1103/PhysRevLett.105.114801

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

[10] E. Hemsing et al., "Echo-enabled harmonics up to the 75th order from precisely tailored electron beams", *Nature Photonics*, vol. 10, 512–515 (2016), doi:10.1038/nphoton.2016.101

[11] P. R. Ribič et al., "Coherent soft X-ray pulses from an echo-enabled harmonic generation free-electron laser", *Nature Photonics*, vol. 13 (2019) 555, doi:10.1038/s41566-019-0427-1

[12] K. Zhou, C. Feng, and D. Wang, "Feasibility study of generating ultra-high harmonic radiation with a single stage echo-enabled harmonic generation scheme", *Nucl. Instr. Meth. A*, vol. 834, 30 (2016), doi:10.1016/j.nima.2016.07.021

ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-TUP088

[13] S. Reiche, GENESIS 1.3: a fully 3D time-dependent FEL simulation code, *Nucl. Instr. Meth. A,* 429, 243 (1999). doi:10.1016/S0168-9002(99)00114-X

[14] A. Piwinski, in *Proc. 9th Int. Conf. on Hiqh Enerqy Accelerators*, SLAC Stanford, 1974, p. 405.

[15] Z. Huang, K. Kim, "Formulas for coherent synchrotron radiation microbunching in a bunch compressor chicane", *Phys. Rev. ST Accel. Beams*, vol. 5, 074401 (2002), doi:10.1103/PhysRevSTAB.5.129903

[16] D. Ratner, A. Fry, G. Stupakov, and W. White, "Laser phase errors in seeded free electron lasers", *Phys. Rev. ST Accel. Beams*, vol. 15, 030702 (2012), doi:10.1103/PhysRevSTAB.15.030702

[17] E. Hemsing *et al.*, "Seeding Experiments and Seeding Options for LCLS II", in *Proc. 38th Int. Free Electron Laser Conf. (FEL'17)*, Santa Fe, NM, USA, Aug. 2017, pp. 219-224, doi:10.18429/JACoW-FEL2017-TUB01