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THE STATUS OF A GRATING MONOCHROMATOR FOR SOFT X-RAY SELF-SEEDING EXPERIMENT AT SHINE*

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Abstract

The research status of a grating monochromator for soft X-ray self-seeding experiment at SHINE has been presented in this paper. The monochromator system includes the vacuum cavity, optical elements and mechanical movement device. Until now, the vacuum cavity has finished manufactured process completely, the optical mirrors have finished machining and measured by the longitudinal trace profiler (LTP) and atomic force microscope (AFM). To make sure the monochromator system can achieve an optical resolution of 1/10000 at the photon energy of 700-1300 eV, the system has been integrated and tested recently. In this year, the previous online experiment will be performed in the shanghai soft X-ray free-electron laser (FEL) user facility.

INTRODUCTION

To date, most X-ray free-electron laser (FEL) facilities under operation are based on the SASE (self-amplified self-emission) [1-3] mode, which can generate high peak power, ultra-short, transverse coherent radiation with tunable wavelength. However, SASE radiation arises from the initial shot-noise, it has poor longitudinal coherence and relative wider spectral bandwidth. To obtain fully coherent X-ray pulse, external seeding harmonic generation [4-7] are considered, where a conventional seed laser is generally required. While seeding FEL can produce fully coherent pulses, the shortest radiation wavelengths are generally at several nanometers due to the limitation of harmonic transfer efficiency. To generate fully coherent radiation at soft and hard X-ray wavelengths, self-seeding technique [8-12] is proposed, which has been proved that it can be used to produce both soft and hard X-ray pulses.

In the self-seeding technique, an optical monochromator is inserted between long undulator to generated fully coherent X-ray pulse, which is used as seed laser in the following FEL process. At the same time, a bypass chicane is utilized to smooth the previous micro-bunching. Compared with general FEL operation mode, a monochromator is required in the self-seeding technique and it can determine the performance of soft X-ray self-seeding. Until now, LCLS [10, 11], SACLA [12], PAL-FEL [13] have accomplished the hard X-ray self-seeding experiments, nevertheless only LCLS finished the soft X-ray self-seeding experiment. Self-seeding has been the basic operation mode of Shanghai high repetition rate XFEL and extreme light source (SHINE), the preliminary experiment study has been given in [14]. In this paper, we present the newest research status of a grating monochromator for soft X-ray self-seeding experiment at SHINE, meanly including the vacuum cavity, optical elements and mechanical movement device. The research of monochromator has been performed two years, most hardware have been manufactured and the monochromator system has been integrated and finished previous performance test, and some test results are presented in this paper. The shanghai soft X-ray free-electron laser (FEL) user facility is a user facility to generate soft X-ray down to 2 nm based on SASE and EEHG operation modes. In this year, the monochromator system will be installed at the SASE undulator beamline of SXFEL user facility and perform the online optical test.

THE VACUUM CAVITY

The optical design of monochromator system is presented in Fig. 1. The monochromator system includes four optical elements, a varied line space grating, a plane mirror and two cylindrical mirrors, this system is used to produce a coherent optical pulse with a spectral bandwidth of 1/10000.

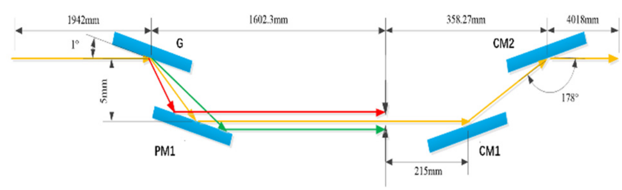

Figure 1: The layout of soft X-ray self-seeding monochromator.

In the monochromator system, there are two vacuum cavities, the grating and the plane mirror are installed in the first vacuum cavity, the two cylindrical mirrors are installed in the second vacuum cavity. To achieve a sufficient optical resolution, the mechanical section can be moved with a precision of 2 μm and a rotation precision of 8″. The cavities began to be manufactured from two years ago, the manufactured process has finished and the cavities have been integrated in this year and finished the factory acceptance. Figure 2 shows the outside view of the vacuum cavities, which can satisfy the requirement of self-seeding optical system. According to the measurement results, the degree of vacuum can arrive 5×10^{-8} Pa and the vacuum magnetic permittivity is lower than 1.05. Besides, the water-cooling systems are also considered in both vacuum cavities to increase the operated repetition rate of SHINE.

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Figure 2: The outside view of the vacuum cavities of soft X-ray self-seeding.

THE OPTICAL MIRRORS AND VLS GRATING

Based on the optical system design, there are four optical elements in the monochromator system, a cylindrical VLS grating, a plane mirror and two cylindrical mirrors. To get stable transfer efficiency in both photon energy, an optical coating of Au is used in both optical elements. Exceptionally, we also consider coatings with two material and substrate with a channel for the electron beam in the cylindrical VLS grating and the final cylindrical mirrors, Au and B_4C. According to the monochromator system design, the manufactured parameters are given in Table 1. To ensure the optical resolution of the monochromator, the RMS meridional slope error, sagittal slope error and surface microroughness need to be better than 0.5 µrad, 5 µrad and 0.5 nm separately.

Table 1: The Manufactured Parameters of Optical Elements

Parameter	Value
Grating	
Grooved area: L×W (mm^2)	Two Stripes (Au: 15×25, B_4C: 15×25)
Groove profile	Blazed
Line density	$N(x)=N_0(1+a_1w+a_2w^2+a_3w^3)$ N_0 = 1800 mm^{-1} (±0.2%) a_1= -1.204×10^{-3} mm^{-1} (±0.5%) a_2= 1.127×10^{-6} mm^{-2} (±0.5%)
Blaze angle (°)	1.8±0.1
Plane mirror	
Optical surface: L×W (mm^2)	25 (±0.5) × 50 (±0.5)
Cylindrical mirror 1	
Optical surface: L×W (mm^2)	25 (±0.5) × 25 (±0.5)
Radius-Sagittal (mm)	97.6 (±0.5%)
Cylindrical mirror 2	
Optical surface: L×W (mm^2)	B_4C: 11×25, Au: 11×25
Radius-Tangential (mm)	37695 (±0.5%)

Until now, all the optical elements have finished the manufactured process, Fig. 3 shows the picture of real VLS grating.

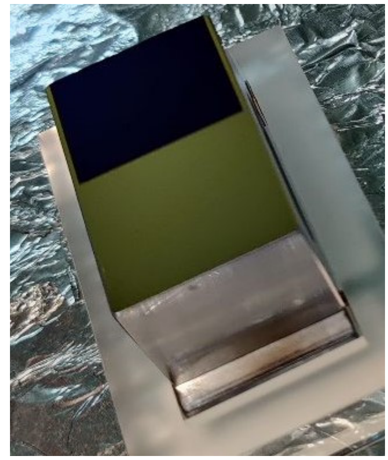

Figure 3: The picture of real VLS grating with two coating materials.

The parameters of these optical elements were measured recently. The basic grating parameters are measured by the atomic force microscope (AFM) of SSRF, the coatings of Au and B_4C were measured separately, the results are presented in Fig. 4. From Fig. 4, one can conclude that the grating line density is about 1800 lines/mm, the blazed angle is about 1.876°, which can satisfy the requirement of designed parameters.

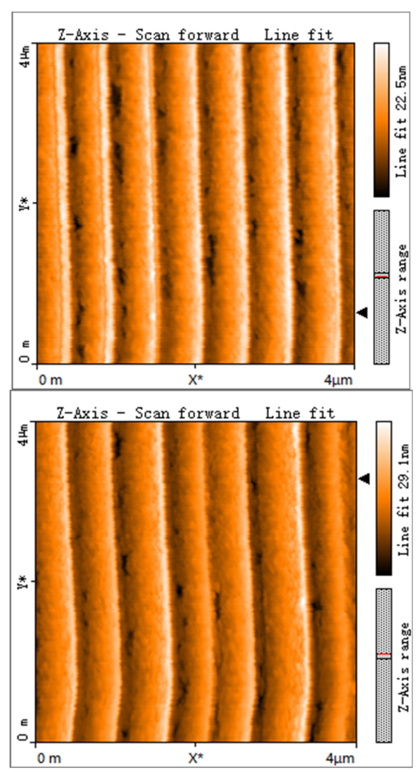

Figure 4: The measurement results of cylindrical VLS blazed grating.

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The processing difficulty of plane mirror is relative lower, the plane mirror has been measured by the longitudinal trace profiler (LTP) of SSRF, the results shows that the measured parameters can satisfy the requirement of designed parameters greatly. The cylindrical mirror 1 has relative smaller sagittal radius, which cannot be measured by LTP. The cylindrical mirror 2 has a relative lower weight due to a channel in the substrate, the vibration will have important impacts on the measurement process. The cylindrical mirror 2 were measured by the LTP of IHEP, the two coatings of different materials are measured separately. Taking the middle 25 mm, 20 mm, 17.5 mm as the clear length of optical surface for coating of B_4C, the tangential radiuses are 37.6 m, 37.4 m and 37.3 m separately, the meridional slope errors are 2 μrad, 1.8 μrad and 1.7 μrad. For the coating of Au, the measured tangential radius values are also similar, while the meridional slope errors are about 1.83 μrad, 1.39 μrad and 1.2 μrad. Figure 5 shows the LTP measurement results of taking 17.5 mm as the optical clear length for both two coatings. From the measurement results, one can find that the meridional slope errors are different when taking different optical clear length and the tangential radius can satisfy the requirement of monochromator system.

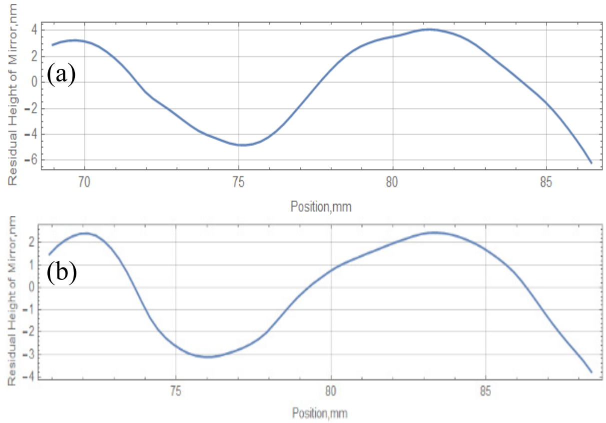

Figure 5: The measurement results of taking 17.5 mm as the optical clear length for two coatings: (a): B_4C, (b): Au.

According to the measurement results of CM2, the slope errors are larger than the designed parameters, which will have impact on the optical resolution. Here, we consider the case with an optical clear length of 17.5 mm, a slope error of 1.2 μrad, a radius error of 1% and a roughness of 0.9 nm. The monochromatic processes are simulated with SHADOW, three different photon energies are used in the simulation, 400 eV, 1000 eV and 1500 eV. The simulation results for these three photon energies are shown in Fig. 6. The simulated photon energies ranges are 400±0.04 eV, 1000±0.15 eV, 1000±0.15 eV.

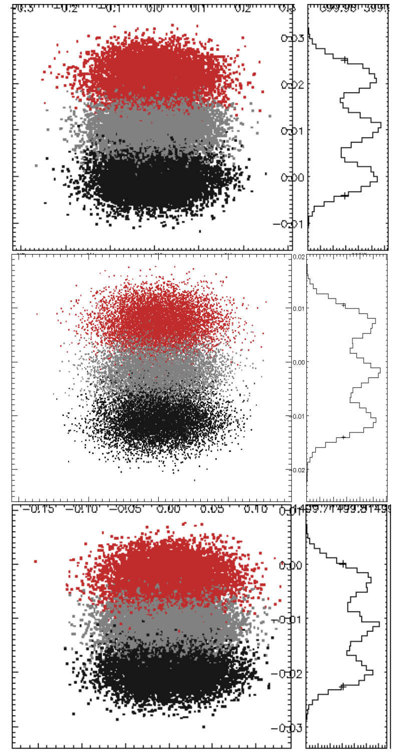

Figure 6: The resolution simulated results for three different photon energies, 400 eV, 1000 eV and 1500 eV.

From Fig. 6, one can easily find the optical resolutions are better than 1/5000 in both photon energy ranges. Therefore, the optical mirrors and grating can satisfy the requirement of the monochromatic system. The transfer efficiency of the monochromator is mainly influenced by the geometric loss of the exit slit, which is related to the roughness of the optical elements. According to the results, the optical elements can satisfy the requirement of the self-seeding monochromator system.

CONCLUSION

In this paper, the status of a grating monochromator system for soft X-ray self-seeding experiment at SHINE is presented. The manufactured process of the vacuum cavities in the monochromator system are firstly introduced. And then, the designed parameters of the optical elements are presented. Lastly, the manufactured optical elements and the measured results of these elements are presented, and the results shows that it can satisfy the requirements. In this year, the monochromator system will be installed at the optical beamline of the SXFEL user facility, the properties of the monochromator system will be tested. Further works will focus on the self-seeding online experiment and the optimization of the final self-seeding output characteristics.

REFERENCES

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

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-TUPAB072

[2] R. Bonifacio, C. Pellegrini, and L. M. Narducci, "Collective Instabilities and High-gain Regime in a Free Electron Laser", *Optics Communications*, 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", *Physical Reviews Letters*, vol. 85, p. 3825, 2000. doi.org/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", *Physical Review Accelerators and 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", *Physical Review Letters*, vol. 91, p. 074801, 2003.doi:10.1103/PhysRevLett.91.074801

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

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

[9] J. Feldhaus and E. L. Saldin, "Possible application of X-ray optical elements for reducing the spectral bandwidth of an X-ray SASE FEL", *Optical Communications*, vol. 140, p. 341, 1997. doi:10.1016/S0030-4018(97)00163-6

[10] J. Amann, W Berg, and V. Blank, "Demonstration of self-seeding in a hard-X-ray free-electron laser", *Nature Photonics*, vol. 6, pp. 693-698, 2012. doi:10.1038/nphoton.2012.180

[11] C. Emma *et al.*, "Experimental demonstration of fresh bunch self-seeding in an X-ray free electron laser," *Applied Physics Letters*, vol. 110, p. 154101, 2017. doi:10.1063/1.4980092

[12] I. Inoue *et al.*, "Generation of narrow-band X-ray free-electron laser via reflection self-seeding", *Nature photonics*, vol. 13, pp. 319-322, 2019. doi:10.1038/s41566-019-0365-y

[13] C. K. Min *et al.*, "Hard X-ray self-seeding commissioning at PAL-XFEL", *Journal of synchrotron radiation*, vol. 26, pp. 1101-1109, 2019. doi:10.1107/S1600577519005460

[14] K. Q. Zhang, C. Feng, D. Wang, and Z. T. Zhao, "The Preliminary Experiment Studies for Soft X-Ray Self-Seeding System Design of SCLF Facility", in *Proc. 9th Int. Particle Accelerator Conf. (IPAC'18)*, Vancouver, Canada, Apr.-May 2018, pp. 4481-4484. doi:10.18429/JACoW-IPAC2018-THPMK077