The Ultra-high Spectral Resolving Power Soft X-ray Monochromator Design and the Its Key Techniques Development at HALF

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Abstract. Hefei Advanced Light Facility (HALF) is a diffraction limited synchrotron radiation (DLSR) light source. The Test Beamline (BL10) is dedicated to key techniques R&D for HALF beamline engineering with at-wavelength optical metrology, wavefront sensing, thermal deformation measurement, high stability mechanical parts tests. An ultra-high spectral resolving power ($E/\Delta E = 10^5$@1000 eV) monochromator with energy ranging from 250 eV to 2000 eV is designed for the beamline. This presentation will give the beamline optical design and the challenges for the ultra-high spectral resolving power monochromator construction. It gives the detailed specifications and requirements for optical components and monochromator's mechanical system.

1. Introduction

Hefei Advanced Light Facility (HALF) is a diffraction limit synchrotron radiation (DLSR) which is under construction. Its electron energy is 2.2 GeV and horizontal natural emittance is 86.3 pm•rad, providing high brightness and small source size in the soft X-ray range. It makes the experiments possible, which need photons with ultra-high spectral resolving power, high coherence or high spatial resolution. The beamline technique is challenging for DLSR beamlines. For example, high accuracy optical components and high accuracy mechanical movement with stable structure are necessary for the beamline. A test beamline (BL10) is under construction in HALF for the purpose of beamline techniques R&D, such as at-wavelength optical metrology, wavefront sensing, thermal deformation measurement, high stability mechanical parts test, etc. A collimated SX-700 monochromator covers 250 eV to 2000 eV photon energy range with spectral resolving power 10^5@1000 eV is designed for the beamline. This will pave the way for ultra-high spectral resolving power monochromator development. And the related techniques will be used for the high spatial resolution optics and high coherence optics system.

Shanghai Synchrotron Radiation facility (SSRF) has designed beamline with spectral resolving power of 4×10^4 at 1000 eV for the angle-resolved photoelectron spectroscopy (ARPES) experiment [1]. The Soft Inelastic X-ray Scattering (SIX) beamline in National Synchrotron Light Source II (NSLS-II) has constructed a beamline with resolving power of 10^5 at 1000 eV for the resonant inelastic X-ray scattering (RIXS) experiment [2]. MAX IV built the VERITAS beamline which was designed to reach a resolving power of 10^5 in at 1000 eV for RIXS[3].

This paper will give the beamline optical design and the requirements for optical components and wavelength scanning mechanical system.

2. The Test Beamline Optical Design and Performance

The optical layout of the 70 m-long beamline is shown in Figure 1. It utilizes a collimated SX-700 plane grating monochromator [4] which can be operated with high spectral resolving power, high flux and harmonics rejection modes.

The photon source for the beamline is the linearly-polarized undulator with 109 periods and period length 37.7mm. Its magnetic field is 1 T It covers the photon energy range of 250 – 2000 eV.

The undulator source size is small and is chose as the entrance slit for the monochromator. The first optical element M_1 of the beamline is positioned 32m from the middle of the undulator. It is a side-water-cooled toroidal mirror, which horizontally deflects the beam by 1.6 deg. M_1 collimates the beam vertically and focuses horizontally onto the exit slit which is 64 m from the source. The monochromator is 35m from the source. It consists of a side-water-cooled plane mirror and two side-water-cooled plane gratings. A cylindrical mirror M_2 is positioned 38m from the source, which focuses the beam vertically onto the exit slit. M_2 deflects the beam horizontally by 1.6 deg.

2.1 Spectral Resolving Power of the Monochromator

There are two interchangeable constant-line-spacing plane gratings with groove density of 600 l/mm and 2400 l/mm, covering the energy range of 250 – 1500 eV and 250 – 2000 eV, respectively. The beam incidents onto the plane mirror with grazing angle θ at photon energy E; the incident and diffraction angle of the grating are α and β, respectively. They satisfy the grating equation and the focusing relationship. For a collimated SX-700 monochromator, the fixed-focus constant $c_{ff} = \cos\beta/\cos\alpha$ keeps constant over the whole energy range, and can be set freely in operation. The beamline is designed to achieve the ultra-high spectral resolving power with 2400 l/mm blazing grating at $c_{ff} = 10$.

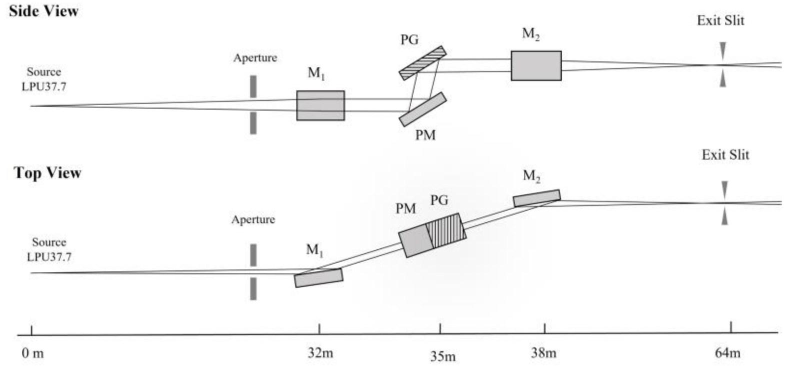

Figure 1. Optical design of the monochromator of BL10. PM: plane mirror; PG: plane grating.

In this optical system, the width of entrance slit (source size) and exit slit, the slope error of the optical elements, the diffraction limit of the grating and the non-uniformity of the grating spacing are the factors affecting the spectral resolving power.

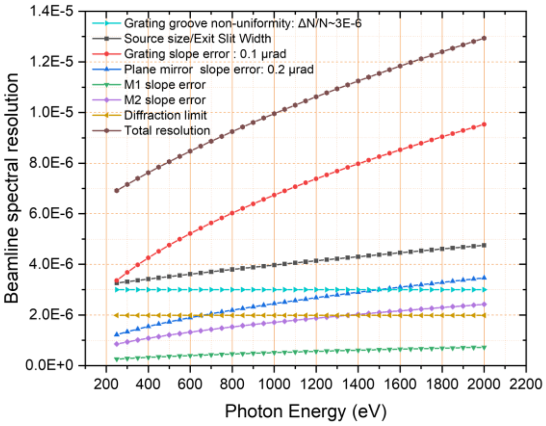

Figure 2. Different factors affecting the spectral resolution. The grating blazing angle is 1.5 deg.

Figure 2 shows the overall spectral resolving power and the grating slope error is the limiting factor. The grating slope error and the plane mirror slope error are 100 nrad and 200 nrad, respectively. The exit slit width varies with the energy, ranging from 3.3 - 6.7 μm. The source size has significant effect on the resolution.

The ray tracing result is shown in Figure 3. The monochromator can reach the spectral resolving power of 10^5 at 1000 eV. The detailed parameters of the optical elements are listed in Table 1.

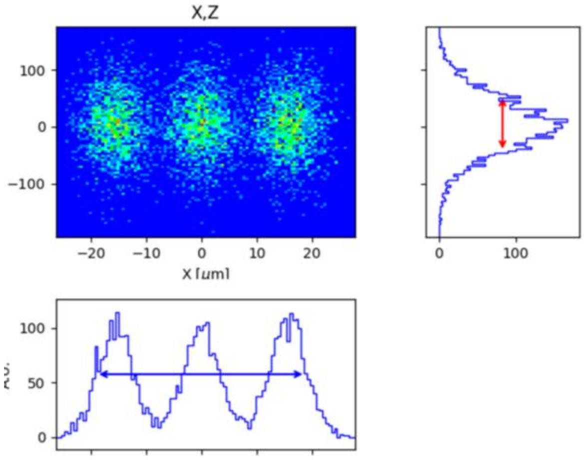

Figure 3. The ray tracing results by Shadow. The photon energies are 1000 ± 0.01 eV.

Table 1. The parameters of the optical elements

	M_1	PM	M_2	Grating
Dimensions (mm)`	400×50×50	400×40×50	400×50×50	200×40×50
Tangential radius	2,290 m	> 100 km	>100 km	> 100 km
Sagittal radius	894 mm	> 30 km	726 mm	> 30 km
Tangential slope error (μrad)	0.5	0.2	0.5	0.1
Sagittal slope error (μrad)	3	2	3	1
Grazing angle (deg)	0.8	1.7-5	0.8	0-1
Coating	Au	Au	Au	Au

2.2 Photon Flux

The transmission efficiency of the optical system includes the mirror (M_1, PM, PM) reflectance, grating diffraction efficiency and geometrical transmission efficiency. With the maximum source flux with harmonics, the flux at the exit slit is calculated and shown in Figure 4 corresponding to the spectral resolving power shown in Figure 2.

3. Key Techniques R&D for an Ultra-high Spectral Resolving Power monochromator

In order to reach the ultra-high spectral resolving power, several key techniques are under development. As shown in Section 2, the grating fabrication accuracy is significant: the grating groove density is required to be extremely uniform, and the grating total slope error should be better than 100 nrad. Moreover, the mechanical rotation resolution and its stability restricts the resolving power of the monochromator.

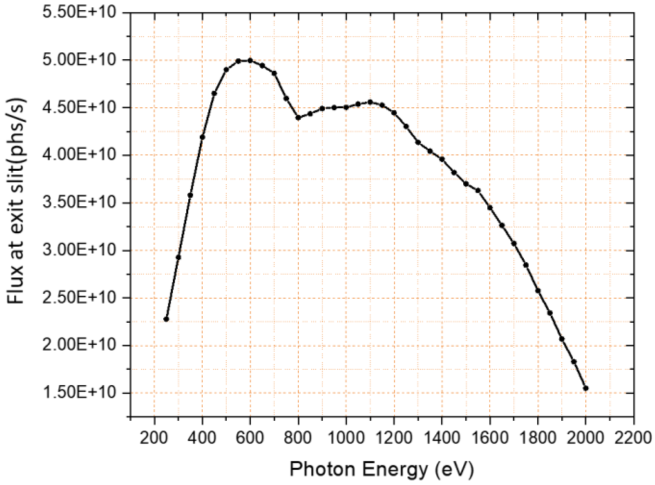

Figure 4. The calculated flux at high spectral resolution mode.

3.1 Grating groove density non-uniformity

According to the grating equation: sinα + sinβ = $Nm\lambda$. Here, N is the grating groove density, λ is the wavelength of light, m is the diffraction order of the grating, α and β are the incidence angle and the diffraction angle of the grating respectively. In order to evaluate how the grating groove density non-uniformity affects the spectral resolving power, the differential was taken on both sides of the grating equation and the following equation can be achieved:

$$Nd\lambda + \lambda dN = 0.$$

This equation shows that $d\lambda/\lambda \sim dN/N$. dN/N is the non-uniformity of the grating line spacing. The non-uniformity affects the spectral resolving power of the grating monochromator. The non-uniformity $dN/N \sim$ 3E-6 is needed. Therefore, the fabrication and measurement of a grating with groove density non-uniformity are critical for ultra-high spectral resolving power monochromator.

3.2 Surface error requirements of optical components

A high-quality optical surface is required with overall slope error of about 100 nrad (rms), which is challenging in fabrication, mounting, and cooling and measuring.

For fabrication, the state-of-art fabrication capability is around 50 nrad for slope error. The optical components mounting and clamping deformation and the gravity deformation should be controlled. The strain-free clamping method is adopted for the monochromator as shown in Figure 5. The slope error induced by clamping and gravity is around 15 nrad given by mechanical simulation.

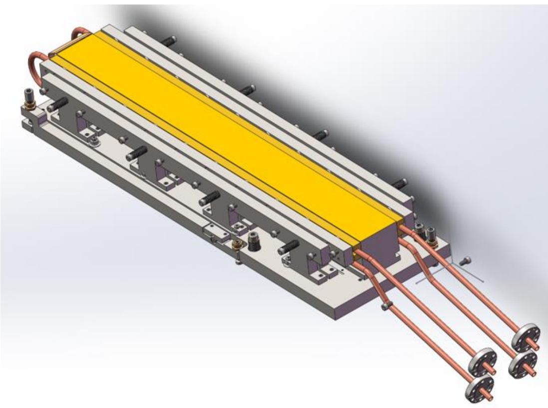

Figure 5. The clamping method for the pre-mirror in the monochromator

High heat power density absorbed by the optical elements will change the slope error. By calculating the source power density distribution and the transmission efficiency of the optical elements, the heat load of each element can be calculated precisely. We calculated the heat load at 250 eV of the first three optical elements. The precise heat load distribution on the mirrors M1, plane mirror and the grating are calculated precisely as shown in Figure 6[5], based on which the thermal distortion and cooling results are simulated. The thermal-induced residual slope error for the plane grating is around 30 nrad.

3.3 Mechanical resolution and stability requirement

High resolving power monochromator demands high mechanical resolution which can be calculated by grating equation and focusing condition. To reach the resolving power of 10^5@1000 eV, the mechanical rotation resolution should be better than 100 nrad and 50 nrad for the plane mirror and the grating, respectively. The requirement for stability is on the similar order of the rotation resolution.

3.4 A prototype monochromator mechanical performance

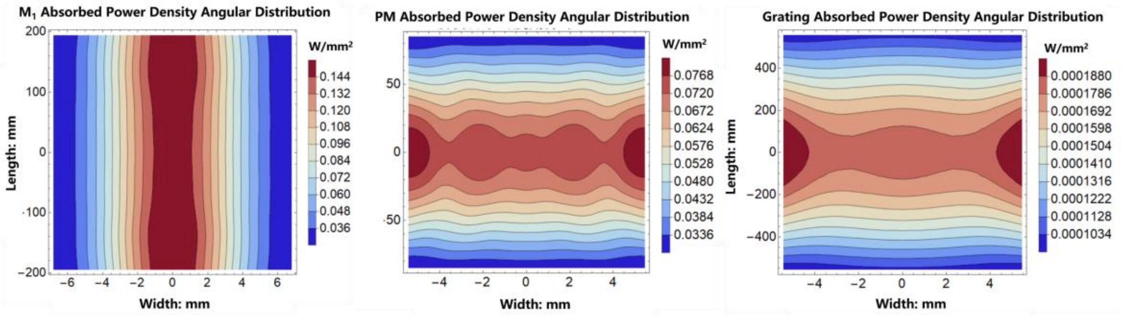

Figure 6. The precise heat load on the optical elements.

According to the optical specification, a prototype PGM has been built and tested [6]. The mechanical rotation resolution is about 50 nrad. The grating and the plane mirror angular stability in pitch direction at different flow rate of cooling water is tested. The angular stability is less than 30 nrad which meets the optical requirement.

4. Conclusion

An ultra-high spectral resolving power monochromator design is presented. Key factors affecting the spectral resolving power are listed. The prototype PGM is built and tested. The test results showed that the PGM performance is satisfactory and can be used for the HALF Test Beamline. The experience obtained will be utilized for both high spatial resolution and high coherence beamline construction.

Acknowledgements

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