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High-resolution spherical grating monochromator for the undulator beamline (BL-16B) at the Photon Factory

Eiji Shigemasa,[a]* Akio Toyoshima,[a] Yonglian Yan,[b] Tatsuji Hayaishi,[c] Koichi Soejima,[d] Takanori Kiyokura[e] and Akira Yagishita[a]

[a]Photon Factory, IMSS, Oho 1-1, Tsukuba, Ibaraki 305, Japan, [b]BSRL, Beijing 100039, People's Republic of China, [c]Tsukuba University, Ibaraki 305, Japan, [d]Niigata University, Niigata 950-21, Japan, and [e]NTT-BRL, Kanagawa 243-01, Japan. E-mail: sigemasa@kekvax.kek.jp

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The design and performance of a 24 m high-resolution spherical grating monochromator (H-SGM) for the undulator beamline (BL-16B) at the Photon Factory are described. With three interchangeable gratings of 400, 900 and 2000 lines mm^{-1}, the H-SGM is designed to cover the photon energy range 40–600 eV. With a resolving power of approximately 2000 in the photon energy range 40–530 eV, more than 10^{11} photons s^{-1} have been measured. The best resolutions obtained so far, at a substantially lower photon flux, are greater than 10 000 at 250 eV and 8000 at 400 eV

Keywords: spherical grating monochromators; undulator radiation; VUV and soft X-ray regions.

1. Introduction

Reconstruction of the undulator beamline BL-16B of the Photon Factory has recently taken place. In 1988, a 2 m grazing incidence monochromator (GIM) was installed at BL-16. The design of this monochromator was very complicated, using an entrance-slitless configuration and an aberration-corrected focusing system to achieve high resolution combined with high throughput (Muramatsu & Maezawa, 1989). Although the 2 m GIM provided intense photon flux (> 10^{11} photons s^{-1}) with reasonable energy resolution (Muramatsu *et al.*, 1992), the total performance did not live up to expectations. This was mainly due to an imperfection in the complex scanning mechanism. Moreover, the energy resolution was not good enough to meet the recently increasing demands for higher resolution in advanced experiments. The main purpose of the present reconstruction was to improve the resolving power significantly while maintaining as high a throughput as possible over the entire energy range. Drawing on the lessons learned from the previous monochromator, a simple scanning mechanism was preferred. To fulfil all these conditions, the Dragon-type monochromator (Chen, 1987) was adopted in the present design. In this type of monochromator, there is only one optical element, *i.e.* the grating, between the entrance and the exit slits. This is very favourable for high-resolution operation. Furthermore, the scanning mechanism realized by sine-bar rotation is very simple and reliable, which is exactly what is required.

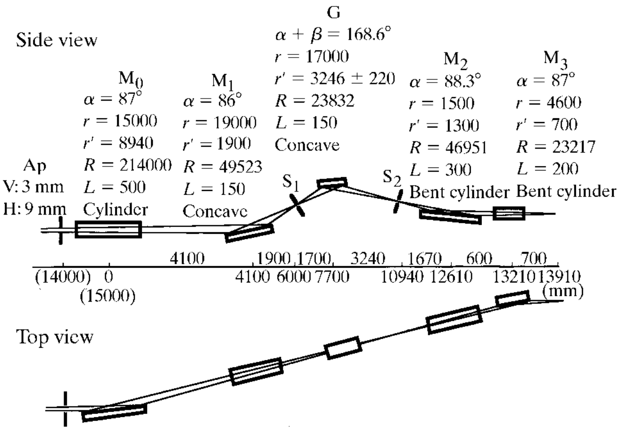

Figure 1
A schematic layout of the 24 m H-SGM at BL-16B of the Photon Factory.

2. Layout

The optical arrangement of the 24 m high-resolution spherical grating monochromator (H-SGM) is schematically shown in Fig. 1. In front of all the optical elements, there is an aperture which consists of two independent, directly water-cooled copper blocks, located 14 m from the centre of a 26 period multipole wiggler/undulator. The usual setting of this aperture is 3 mm (V) × 9 mm (H), which limits the half acceptance angle to 0.11 mrad (V) × 0.32 mrad (H). The undulator radiation is deflected horizontally by a cylindrical mirror M_0 coated with Pt, which is located 15 m from the source. M_0 also serves as a horizontal focusing mirror with a focal length of 8.94 m. A spherical mirror M_1 is located 4 m behind M_0, and focuses the radiation vertically onto a water-cooled entrance slit S_1 with a demagnification of 10:1. M_0 and M_1 (SiC substrates) are cooled from both sides by water-cooled copper blocks coated with Ni. These mirrors are in thermal contact with the blocks through liquid In–Ga interfaces. Three holographically ruled laminar-profile spherical gratings with SiC substrates are designed to cover the energy range 40–600 eV, which includes a tunable range of the first harmonic of the undulator radiation. The gratings with groove densities of 400, 900 and 2000 lines mm^{-1} cover the spectral ranges 40–120, 90–270 and 200–600 eV, respectively, and are interchangeable without breaking the vacuum. The including angle of the gratings is 168.6° and the fixed entrance-slit arm length is 1.7 m. The exit slit S_2 travels ±220 mm along the photon-beam axis, with a centre position at 3246 mm from the grating. Two refocusing mirrors M_2 and M_3 are bent cylinders, made of fused quartz. The incidence angle of the vertical focusing mirror M_2 is 88.3° to make the exit beam horizontal. M_3 deflects the beam by 6° horizontally with a demagnification of 6.6:1. The total demagnification of this beamline in the horizontal direction is 11:1. The refocusing mirrors can make an image with a horizontal length of about 0.5 mm and a vertical length corresponding to the vertical size of the exit-slit opening. The 2000 lines mm^{-1} grating is coated with Ni. The other gratings and the mirrors M_1, M_2 and M_3 are coated with Au. All the mirrors and grating blanks were fabricated by Canon Inc., and holographically ruled laminar gratings were fabricated by Shimazu Co.

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3. Performance

3.1. *Photon flux and linear polarization factor*

Photon flux is an important quantity in measuring the performance of monochromators. The absolute photon flux for each grating has been measured using a Si photodiode supplied by IRD Inc. With both entrance- and exit-slit openings set at 100 µm, the photocurrent from the photodiode was measured after the sample position and converted into the absolute photon flux, taking account of the quantum efficiency of the photodiode. In this case, the resolving power in the regular spectral region for each grating is 1000–3000. The results are normalized to a stored positron ring current of 300 mA. More than 10^{11} photons s^{-1} have been measured in the photon energy range 40–530 eV. However, the flux measured is at least one order of magnitude lower than the calculated values (Shigemasa *et al.*, 1995). This discrepancy is probably attributable to an error in the focal length of the second mirror M_1, an overly optimistic estimation of the grating efficiencies in the calculations (Shigemasa *et al.*, 1995), and carbon and oxygen contamination of the optical elements.

Evaluation of the degree of the linear polarization of the monochromated radiation is also a major concern. In order to accomplish this, the angular distributions of photoelectrons from He atoms have been measured, since the asymmetry parameter of the 1*s* photoionization in He is known to be 2 (Derenbach *et al.*, 1983). Fig. 2 shows results of the measurements at the photon energy of 73 eV. Using the formula for the angular distributions of the He 1*s* photoelectrons as shown in Fig. 2, the degree of linear polarization has been estimated to be around 99%. This value is good enough to perform various kinds of polarization-dependent experiments.

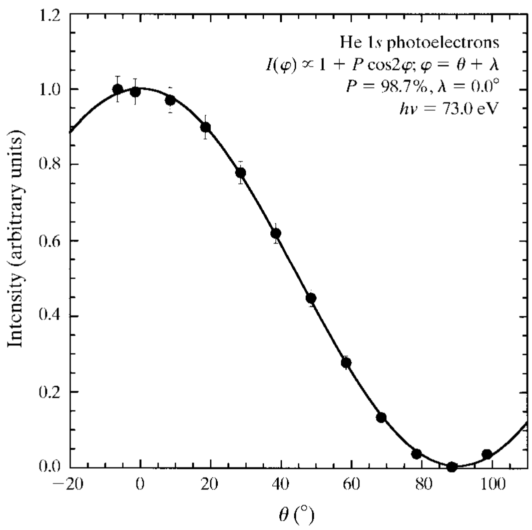

Figure 2
The angular distribution of photoelectrons from He at the photon energy of 73 eV. The filled circles with error bars denote the experimental data points and the solid line shows the fitting result based on the inserted equation. θ is the angle of the ejected photoelectron relative to the horizontal axis, λ is the angle of tilt between the major axis of the polarization ellipse and the horizontal axis, and P is the degree of linear polarization.

3.2. *Resolution*

Resolution is also an important index for measuring the performance of monochromators. In order to demonstrate the instrumental resolution, the inner-shell photoabsorption spectra of Ar were measured with the grating of 2000 lines mm^{-1}. Fig. 3 shows the photoabsorption spectrum in the vicinity of the 2*p* ionization thresholds of Ar. This spectrum was recorded monitoring the total ion yields with slit openings of 10 µm. The Ar 2*p* → *nd* Rydberg series up to $n = 7$ is clearly seen in Fig. 3. The Ar $2p_{3/2}$ → 4*s* resonance corresponding to the lowest energy peak in Fig. 3 stands isolated and therefore has been widely used for evaluating the instrumental resolution. The instrumental resolution was evaluated utilizing the deconvolution procedure used in our previous work (Masui *et al.*, 1992). The Lorentzian width for the Ar $2p_{3/2}$ → 4*s* excitation has been reported to be 116 (3) meV using electron energy-loss spectroscopy by Shaw *et al.* (1982). In the deconvolution procedure, the Lorentzian width for the Ar $2p_{3/2}$ → 4*s* resonance was fixed to 113 meV, because it had already been suggested that this width might be slightly less than 116 meV (Aksela *et al.*, 1992). The recent result by Watanabe *et al.* (1997) also supports the value of 113 meV for the natural width for Ar $2p_{3/2}$ → 4*s* excitation, which has been deduced on the basis of curve-fitting results with Voigt functions. The full width at half-maximum (FWHM) of the transmission function obtained is 24.2 meV. This corresponds to a resolving power of about 10 000

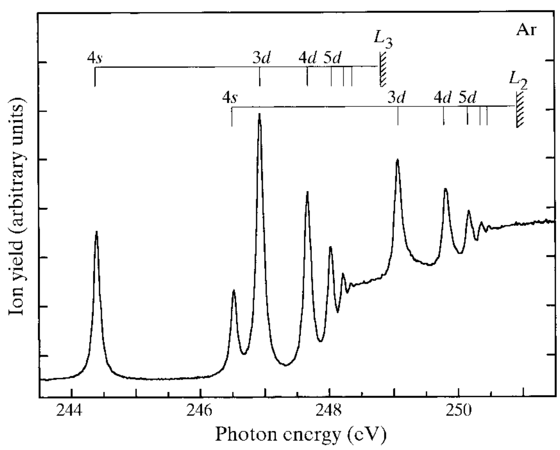

Figure 3
The photoabsorption spectrum in the vicinity of the 2*p* ionization thresholds of Ar.

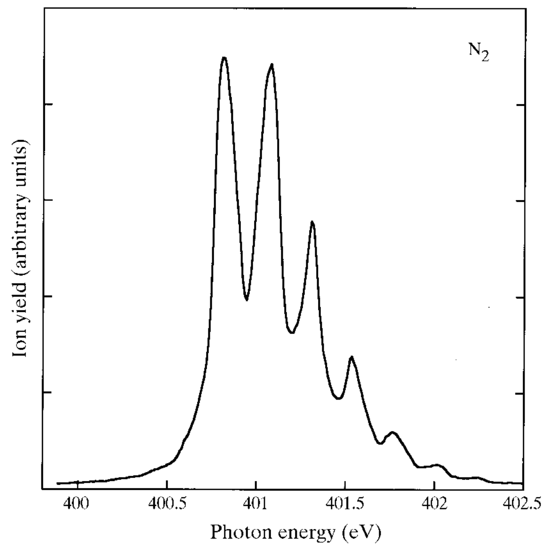

Figure 4
The photoabsorption spectrum of N_2 at the N 1*s* → π^* resonance.

and is in accord with the theoretically predicted value of 23.0 meV (Shigemasa *et al.*, 1995).

The *K*-shell photoabsorption spectrum of N_2 at the N 1*s* → π^* resonance is presented in Fig. 4, which was recorded by monitoring the total ion yield. Both entrance and exit slits were set for maximum resolution at 5 µm. In contrast to the case of Ar, it is difficult to determine the transmission function with the N 1*s* → π^* excitation of N_2, because the natural line width is not well established. This is due to the existence of several nearly overlapping vibrational bands. However, a comparison with the recent data for the N 1*s* → π^* resonance in N_2 offered by Watanabe *et al.* (1997) suggests that the energy resolution might be around 50 meV at 400 eV, which corresponds to a resolving power of about 8000.

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