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A new water-cooled and doubly bent crystal monochromator for Compton scattering experiments

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The design and performance of a new water-cooled and doubly bent crystal monochromator for Compton scattering experiments are described. Its mechanical system is similar to that of a usual bent cylindrical X-ray mirror. A monolithic Si (111) crystal is mounted on a water-cooled and cylindrically polished copper crystal holder with liquid Ga–In alloy between them in order to obtain good thermal and mechanical contact. The sagittal bending radius of the holder, R_s, is 508 mm. The holder is mounted on a mechanical bender making a meridian radius, R_m, of 596 m. The performance of the monochromator, which has been installed at the Photon Factory Accumulator Ring beamline NE1, is as follows. The focused beam size, flux and energy resolution for 60 keV X-rays are 0.5 mm in height and 2.0 mm in width, 5×10^{12} photons s^{-1} and about 60 eV, respectively. The new monochromator gives one order higher brightness at the sample position and also better energy resolution than the previous monochromator. The overall momentum resolution for high-resolution Compton scattering experiments becomes 0.08 atomic units, and the background can be reduced by a third, because it is possible to insert a fine slit after the analyser crystal without losing any Compton scattering signal.

Keywords: X-ray monochromators; Compton scattering.

1. Introduction

A new doubly bent monolithic (DBM) crystal monochromator has been installed at beamline AR-NE1A1 (Kawata *et al.*, 1989) which is the dedicated beamline for Compton scattering experiments. The previous monochromator for this beamline was a quasi-doubly bent (QDB) crystal monochromator (Kawata *et al.*, 1991) which comprised an array of 20 pieces of singly bent crystal. It produced a focused X-ray beam at 60 keV of size 2 mm height × 8 mm width, whose energy resolution and flux were about 90 eV and 6×10^{12} photons s^{-1}, respectively; various Compton scattering experiments (*e.g.* Sakai, 1996; Shiotani *et al.*, 1993; Sakurai *et al.*, 1995) were successfully performed by using this monochromator.

Recently, however, sophisticated Compton scattering experiments have needed much better focusing at the sample position and higher energy resolution without losing any flux in order to observe Compton scattering from small samples, to reduce the background of the signal, and to obtain higher momentum space resolution. The focused beam size and energy resolution at the previous QDB crystal monochromator did not correspond to the ideal values but were broadened by the misalignment of 20 pieces of singly bent crystal. In order to improve the beam size and energy resolution, a new doubly bent monolithic (DBM) crystal monochromator has been designed and installed into the beamline.

In this article, we describe the commissioning of the monochromator. Details of the design are described in §2, and the performance, focused beam size, flux, energy resolution and the overall resolution for Compton scattering experiments are given in §3. In the final section we discuss some possible improvements.

2. Design of the DBM crystal monochromator

For Compton scattering experiments, as mentioned in a previous paper (Kawata *et al.*, 1991), it is not necessary to obtain an extremely collimated monochromatic beam, so that the concept of a doubly bent crystal monochromator is still one of the solutions for Compton scattering experiments. The difference between the DBM and QDB crystal monochromators is whether the doubly bent crystal system is realized by a monolithic crystal or not. Fig. 1(*a*) shows a schematic view of the monochromator. Its mechanical system is similar to that of a usual bent cylindrical X-ray mirror. The monolithic Si (111) crystal is mounted on a water-cooled and cylindrically polished copper crystal holder with liquid Ga–In alloy between them in order to obtain good thermal and also mechanical contact. The sagittal bending radius of the holder, R_s, is 508 mm and the surface is coated by a thin Ni layer to avoid damage by the Ga–In alloy. Then the holder is mounted on a bender making a meridian radius, R_m, of 596 m, as shown in Fig. 1(*a*). Fig. 1(*b*) shows a side view of the bender. At each side of the

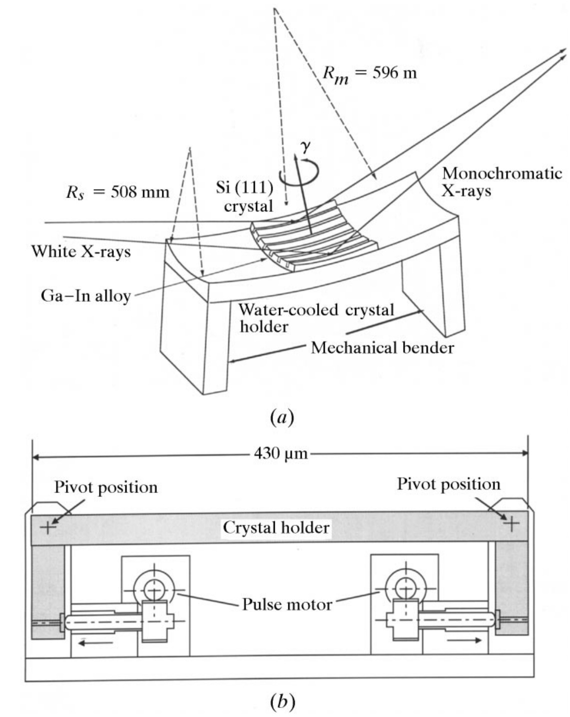

Figure 1
(*a*) Schematic view of the monochromator. The monolithic Si (111) crystal is mounted on a water-cooled cylindrically polished copper crystal holder with liquid Ga–In alloy between them. (*b*) Side view of the bender used to make a meridian curvature of the above crystal holder.

crystal holder there is a pulse motor which pushes a lever to adjust the meridian bending radius. The γ-rotation of the crystal holder, shown in Fig. 1(a), can also be adjusted by another pulse motor.

Fig. 2 shows a drawing of the crystal. The crystal is made of an Si (111) plate, whose size is 3 × 74 × 200 mm (thickness × width × length). There are 36 grooved channels (0.6 mm width and 2.7 mm depth) with an interval of 1.8 mm at the surface in order to realize the sagittal bending. Therefore, the width of the remaining rib, which is used for X-ray monochromatization, is 1.2 mm, and the thickness of the weak linkage is 0.3 mm. The thickness of 3 mm at the remaining rib is important for avoiding crystal strain which is introduced by contact with the crystal holder. At the back surface we also cut 39 channels (0.5 mm width and 0.5 mm depth), with 5 mm intervals, perpendicular to the channels at the open surface. The channel at the back surface is also important for realizing the sagittal bending. Let us consider an anticlastic bending which is always produced by the sagittal bending deformation at the weak linkage. If there are no grooved channels on the back of the crystal, any anticlastic bending would not be allowed even at the part of the weak linkage because of the large asymmetrical ratio between the crystal length and the width (200 mm × 0.6 mm). The stress, which does not allow the anticlastic bending, will make the crystal itself crack easily. In our design, the channels on the back work to separate the several small weak linkage parts of size 5 mm × 0.6 mm, and may reduce the stress, so that a sagittal curvature of 508 mm can be realized.

3. Performance of the monochromator

3.1. *Focusing, flux and energy resolution*

The monochromator is located at a point 26150 mm from the light source and the beam size just before the monochromator is limited by slits of 3 mm height and 20 mm width. Figs. 3(a) and 3(b) show the image of the monochromated 60 keV X-rays at 34000 mm from the source (under the focusing point) and at 37700 mm from the source (the focusing point), respectively. Figs. 3(c) and 3(d) show the intensity profiles at the focusing point, which were measured by scanning a fine slit (0.05 mm width) along the horizontal and vertical directions, respectively. The focused beam size is 0.5 mm in height and 2.0 mm in width. The flux of the above focused beam was measured by a free air ion chamber. The obtained flux is about 5×10^{12} photons s^{-1}. The energy resolution of the monochromator was estimated by the FWHM of the derivative curve of the Tm K-absorption-edge spectrum, whose energy and intrinsic energy spread are 59.38 keV and 29.16 eV (Leisi *et al.*, 1961), respectively. The energy spread of the DBM crystal monochromator is estimated to be about 60 eV.

If we assume that the crystal is perfect, values of the flux and energy resolution can be calculated from source parameters (flux density and vertical source size), the attenuation of a 7 mm-thick aluminium absorber, and the monochromator bandpass, which is limited by the Darwin width (4.4 µrad) for Si (111) at 60 keV. The calculated values of flux and energy resolution at the above condition are 1.5×10^{12} photons s^{-1} and 30 eV, respectively. The discrepancy between the obtained and calculated values indicates that the real monochromator crystal is not perfect, but the acceptance of the beam divergence is almost three times wider than that of the perfect crystal. If we assume that the acceptance is 15 µrad, the calculated values of flux and energy resolution are 5×10^{12} photons s^{-1} and 50 eV, respectively, and these are in good agreement with obtained values.

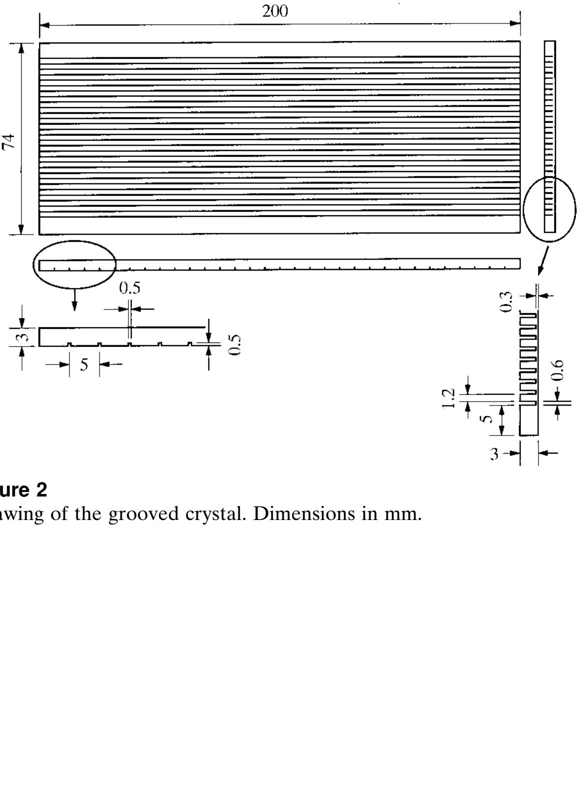

Figure 2
Drawing of the grooved crystal. Dimensions in mm.

3.2. *Overall performance for high-resolution Compton scattering experiments*

The DBM crystal monochromator gives one order higher flux density at the sample position and also better energy resolution than those of the previous monochromator. Fig. 4 shows a comparison between the raw spectra of the high-resolution Compton scattering from Cu, which were obtained by using the previous and new monochromators. There are two remarkable differences between them. One is the reduction of the background level. The fine-focused beam size makes it possible to insert a fine slit after the analyser crystal of the high-resolution Compton spectrometer without losing any Compton scattering signal. Then, the background can be reduced to a third of that of the previous experiments. Another is the higher peak intensity of the elastic-scattering X-rays because of the improvement of the energy resolution. The inserted figure shows an enlargement of the spectra around the elastic scattering. Black dots (open circles) correspond to the data obtained by the new (previous) mono-

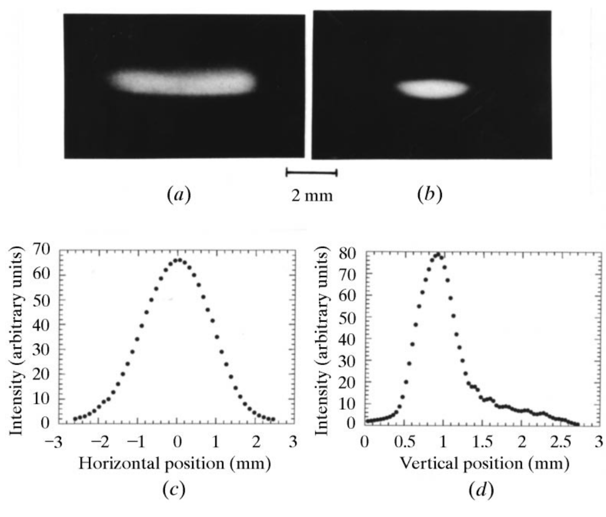

Figure 3
Image of the monochromated 60 keV X-rays (a) under the focusing point and (b) just at the focusing point. (c) and (d) show the intensity profiles at the focusing point along the horizontal and vertical directions, respectively. The focused beam size is 0.5 mm in height and 2.0 mm in width.

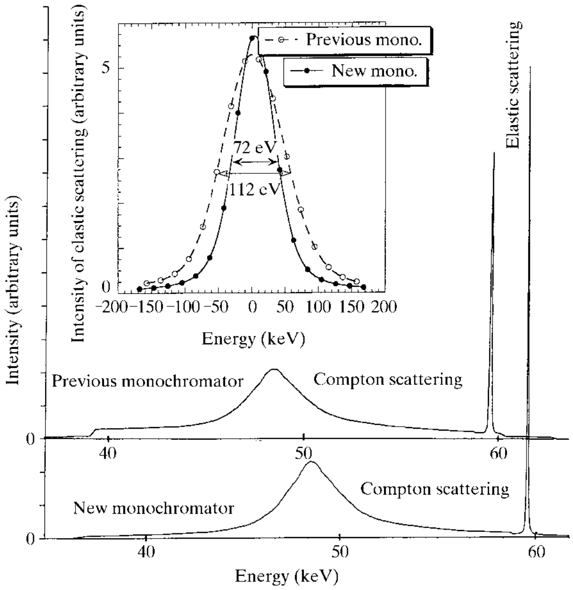

Figure 4
Comparison between the raw spectra of the high-resolution Compton scattering from Cu, which were obtained by using the previous QDB and new DBM crystal monochromators. The inserted figure shows the spectra around the elastic scattering. Black dots (open circles) correspond to the data obtained by the new (previous) monochromator. The corresponding momentum space resolution by using the new monochromator is estimated to be 0.08 atomic units.

chromator. The overall energy resolutions can be estimated by these FWHM as 72 and 112 eV, respectively. The corresponding momentum space resolution of 0.08 atomic units can be achieved by using the DBM crystal monochromator.

4. Discussion

There is an Al heat absorber of thickness 7 mm in front of the monochromator, and the total power, which the monochromator must withstand, can be reduced to 200 W by the aperture (3 mm in height and 20 mm in width). There is no deterioration of the energy resolution and no change of focused beam size under the above condition. This indicates that the cooling system is sufficient for the above heat load. If we opened the slits completely (total power of 500 W), however, we observed the deterioration of the energy resolution. In the present design, the cooling system for the crystal holder is a water-cooling system and the cooled channels are just five holes of diameter 6 mm. Under a finite-element analysis (ANSYS), we recognize that the deformation caused by the heat load of 500 W can be reduced by designing a cooling system based on microchannels at the holder; this will be the next improvement for the monochromator.

Another improvement planned for the monochromator is to mount two Si crystals whose directions of the surface normal are $\langle 111 \rangle$ and $\langle 100 \rangle$ in order to cover the following energy ranges of the monochromated X-rays: 40–70 keV by Si (111) and 90–160 keV by Si (400). The higher energy range of the monochromated X-rays will be used for magnetic Compton scattering experiments to enhance the magnetic effect and also for (X, eX) coincidence experiments (*e.g.* Bell *et al.*, 1990; Itou *et al.*, 1998) to reduce the multiple scattering of the recoiled electrons.

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