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Beryllium and aluminium refractive collimators for synchrotron radiation

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Be and Al refractive lenses with long focal lengths provide a simple and efficient method of collimating synchrotron radiation. The divergence of an undulator beam at SPring-8 is reduced from >11 μrad full width at half maximum without the collimators to <3 μrad downstream of the collimators. The Be collimators have almost no losses (~90% transmission) while the Al collimators reduce the flux by a factor of two (~45% transmission). Data are shown at 14.4 and 18.5 keV.

Keywords: X-ray optics; collimation; refraction; X-ray lens.

1. Introduction

Third-generation synchrotron X-ray sources make it possible to perform an ever-expanding variety of experiments. One of the major advantages of these sources over previous ones is that the X-ray beam divergence is relatively small (tens of μrad). However, the high brilliance of third-generation sources means that there is also a drive towards more ambitious experiments, many of which would significantly benefit from an even more collimated X-ray beam. Examples include high-energy resolution and high-**q**-resolution measurements and, in fact, any experiment making use of Bragg reflections in perfect crystals (*e.g.* for polarization control and analysis). Thus a simple and efficient method of further collimating the X-ray beam is both desirable and interesting. Here we demonstrate that metal refractive lenses with long focal lengths are suitable collimating elements.

Previously used methods of collimating X-ray beams include diffraction and reflection. In particular, asymmetric Bragg reflections in perfect crystals may be used to collimate an X-ray beam (Renninger, 1961).† The use of asymmetric diffraction, however, leads to an unavoidable increase in the X-ray beam size, as well as significantly changing the direction of propagation. Bragg reflections also require some care to align, and have limited energy acceptance. Reflection methods (see, for example, Mori & Sasaki, 1995), while having a large energy acceptance, are limited by the perfection of the bending of the mirror and the slope error of the mirror (even a 1 μrad r.m.s. slope error will lead to $1 \times 2.35 \times 2 = 4.7$ μrad divergence of the reflected beam). In addition, at higher energies, the critical angle for total external reflection becomes small, so one needs a large highly perfect surface to accept the whole X-ray beam. Reflection also changes the direction of propagation of the X-ray beam, by at least a few mrad.

Using a refractive lens for collimation avoids many of the difficulties mentioned above. The use of simple refractive lenses was discussed by Yang (1993) but it was really the introduction of a *compound* lens (Snigirev *et al.*, 1996) that can account for increased current interest. In general, recent work has concentrated on the use of compound lenses as focusing devices for making a small spot size (Snigirev *et al.*, 1996, 1998; Elleaume, 1998*a*,*b*; Smither *et al.*, 1997; Kohmura, Awaji *et al.*, 1998; Lengeler *et al.*, 1998), though Smither *et al.* (1997) also mentioned they might be used for collimation. That lenses are extremely well suited to collimating X-ray beams was demonstrated by Baron *et al.* (1999). Here we report results using Be and Al collimators, instead of the previously investigated plastic ones. The essential idea is that, by choosing the focal length of the lens to be the distance to the source, the lens collimates the transmitted radiation.

2. Collimator fabrication

The choice of material for a refractive X-ray lens is a compromise between several parameters [as discussed in detail by Yang (1993), Elleaume (1998*a*,*b*), Snigirev *et al.* (1998) and Lengeler *et al.* (1998)] and one important concern is the relative amount of refraction and absorption (*i.e.* the relative magnitudes of the real and imaginary parts of the index of refraction). One would prefer refraction with relatively little absorption and so, for medium-energy X-rays, elements with low atomic number are desirable, as

† For a review of dynamical diffraction in perfect crystals, including the effects of asymmetric reflection, see Batterman & Cole (1964), while some applications of highly asymmetric reflections may be found in, for example, Ishikawa *et al.* (1991).

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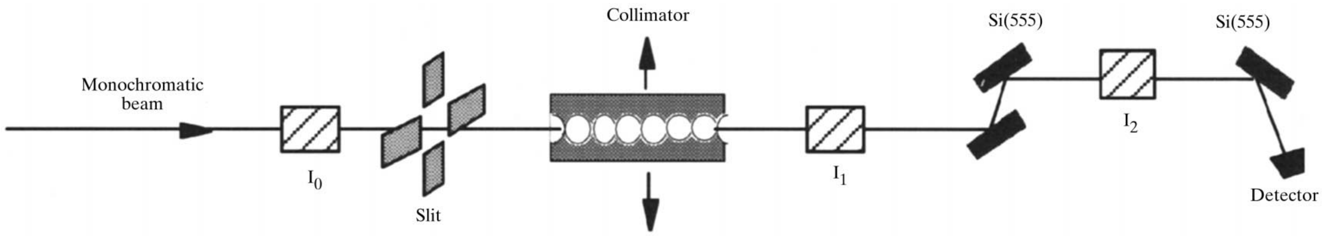

Figure 1
Experimental set-up. Diffraction (and collimation) occurs in the vertical. The distance from the source to the collimator is 44.5 m. I_0, I_1 and I_2 are beam intensity monitors.

they have lower photoelectric absorption per scattering electron. Thus Be is an interesting material. However, as Be is expensive, and difficult to machine, Al is a possible alternative, though it will tend to have lower transmission. Also, at higher energies where Compton scattering becomes more important, the performance of Be and Al refractive lenses should be similar (see, for example, Elleaume, 1998*a*). In comparison with plastic collimators, these metal collimators are expected to have better resistance to radiation damage.

The Be collimators were fabricated by Accel Instruments GMBH,† which has made some of the lenses investigated by other authors (Elleaume, 1998*a*,*b*; Snigirev *et al.*, 1998; Lengeler *et al.*, 1998). The material was Brush–Wellman beryllium S-65.‡ Two Be collimators were tested, both having 2.2 mm-diameter holes drilled about 4.5 mm deep. They had 7 and 13 interfaces of 100 µm, giving nominal focal lengths of 48 and 43 m at 14.4 and 18.5 keV, respectively.

The aluminium collimators (actually 'AlMg3'§) were fabricated in the workshop of the Institut für Experimentalphysik, Universität Hamburg, Germany. They had 2 mm-diameter holes with four and seven interfaces (∼50 µm each) for nominal focal lengths of 48 and 45 m at 14.4 and 18.5 keV, respectively. Note that, after drilling, the holes were finished with a fine polished reamer, while neighbouring holes were filled with metal cylinders to prevent any deformation of the interfaces.

3. Experimental set-up

The experimental arrangement for testing the collimators is shown in Fig. 1. All measurements were made at beamline 47XU (Kohmura, Suzuki & Ishikawa, 1998) of SPring-8. X-rays from the undulator were diffracted by an Si(111) monochromator and then passed through an ionization chamber and a motorized slit. The lens was mounted on a translation stage so it could be moved into or out of the beam. One important change from the previous work (Baron *et al.*, 1999) was the use of a cryogenically cooled Si monochromator (Mochizuki *et al.*, 1999) which could tolerate the full heat load from the undulator with small gap. Thus, all tests were performed at high flux, typically with a beam of $\sim 2 \times 10^{13}$ photons s^{-1} incident on the lens. The measured beam size was $\sim 0.6 \times 1.5$ mm (vertical × horizontal) full width at half maximum (FWHM) and was determined primarily by the natural divergence of the X-ray beam (the slit was much larger than the beam size).

The two 555 crystals in an energy-dispersive configuration serve to analyze the divergence of the radiation in the (vertical) scattering plane. If the first crystal is fixed and the second crystal is scanned, one obtains a map of the beam divergence incident on the pair with a 2:1 resolution (*e.g.* a measured rocking curve of 20 µrad corresponds to a beam divergence of 10 µrad). We note that, for small divergences, the finite Darwin width of the 555 reflections might affect the results. However, as calculations suggest it will make only a small (<15%) correction to our results, we neglect it here. Likewise, a small amount of strain in the crystals (broadening the non-dispersive rocking curve at 18.5 keV from the 1.14 µrad theory value to 1.4 µrad) is neglected.

4. Results and discussion

The effect of the Be collimators at 14.4 and 18.5 keV is shown in Fig. 2, which largely speaks for itself: there is a dramatic reduction in the divergence of the X-ray beam, with only a slight (∼10%) loss of intensity. At 14.4 keV the incident divergence was 14.0 µrad (FWHM), which was reduced to less than 2.8 µrad after the collimator. At 18.5 keV the incident divergence was 11.5 µrad and was also reduced to less than 2.8 µrad with the collimator. In fact, the broadening due to the finite rocking-curve width and the slight strain of the crystals means that the actual beam divergence after the collimator should be less than 2.5 µrad, in each case. The Al collimators (Fig. 3) show lower (∼45%) transmission, but comparable output divergence.

While the collimators are shown to perform extremely well, one should also consider some possible limitations on their performance. One important limitation is the finite source size, as the best achievable collimation is the source size over the focal length; thus ∼0.8 µrad (FWHM) in the

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‡ Maximum impurity content: 1% BeO, 0.06% Al, 0.1% C, 0.08% Fe, 0.06% Mg, 0.06% Si, and 0.04% other metals.
§ This is Al with ∼3% Mg. Composition: ∼95% Al, 2.6–3.6% Mg, 0.4% Si, 0.4% Fe, 0.1 Cu, 0.5% Mn, 0.3% Cr, 0.2% Zn, 0.15% Ti and <0.15% other.

vertical for this beamline [35 μm source size at 45 m (Tanaka *et al.*, 1999)]. Other factors include geometrical (spherical) aberration [contributing <0.3 μrad, see Baron *et al.* (1999)], the effect of not having the source point exactly in the focus of the collimator,† possible non-colinearity of the centres of the holes, and small-angle scattering within the collimator itself (Lengeler *et al.*, 1998). In addition, imperfections in beam transport (*e.g.* monochromator vibration, small-angle scattering from windows) may also reduce the final collimation of the beam. These factors will probably be increasingly important as one tries to achieve collimation better than the 2.8 (2.5) μrad demonstrated here.

No radiation damage effects were expected for these metal collimators, but we did test one of the Be collimators for 10 h in a beam of average flux $\sim 2 \times 10^{13}$ photons s^{-1} at 14.4 keV: no degradation in performance was observed. In contrast, a PMMA collimator performed poorly at high flux: after ~1 h in a beam of 2×10^{13} photons s^{-1} at 18.5 keV it showed significant degradation in response, including a reduction of the peak intensity by about a factor of two, an increase in the small-angle scattering and a noticeable yellowing of the material. At high fluxes, metal collimators are to be preferred.

We have shown that metal refractive lenses provide a convenient and effective method of collimating an X-ray beam. In particular, the Be collimators provide extremely good collimation with almost no losses, while the Al collimators lead to some reduction in flux but are relatively inexpensive. As compared with asymmetric Bragg reflections, these collimators have the important advantages of preserving the beam size, not requiring very careful alignment, and having larger energy acceptance (>~1%, though the exact value will depend on the maximum acceptable divergence). They also keep the direction of beam propagation fixed,‡ and therefore may be easier to use, both for one-dimensional and two-dimensional collimation. However, in contrast to diffraction methods, refractive collimators require a point-like source (with the best achievable collimation being the source size over the distance to the source) and thus are limited (at present generation machines with experimental hutches ~50 m from the source) to ~μrad in the vertical and ~10 μrad in the horizontal. To reduce the divergence below these levels, one might use a refractive collimator followed by an asymmetric Bragg reflection. Such a combined system still has the important advantage of reducing the output beam size by, for example, a factor of four, or more, for a given final divergence, relative to a scheme using only asymmetric diffraction.

† This will introduce a divergence of about $(\Delta L/F)\Delta\theta$, where ΔL is the displacement of the source from the focus of the lens and $\Delta\theta$ is the incident divergence. In our case the expected contributions for the Be (Al) collimators are about 1.0 (1.0) and 0.4 (0.1) μrad, at 14.4 and 18.5 keV, respectively.

‡ One notes that there can be a shift in propagation direction (~μrad) if the centre of the collimator is not exactly aligned to the beam centre.

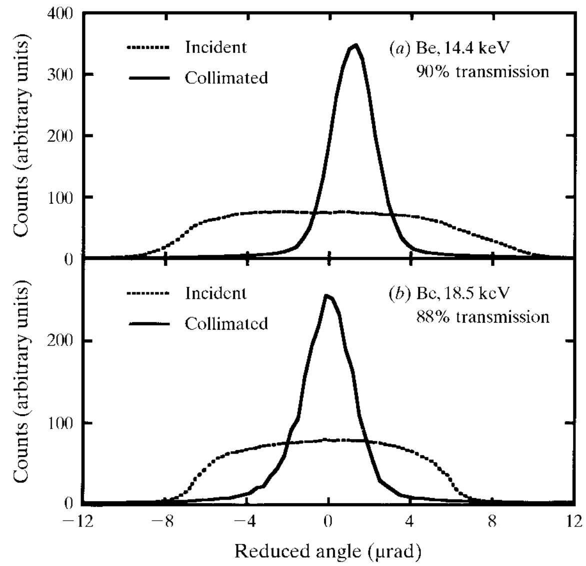

Figure 2
Effect of Be collimators at 14.4 and 18.5 keV. The 'reduced angle' is half the measured angle and corresponds to the incident beam divergence (see text).

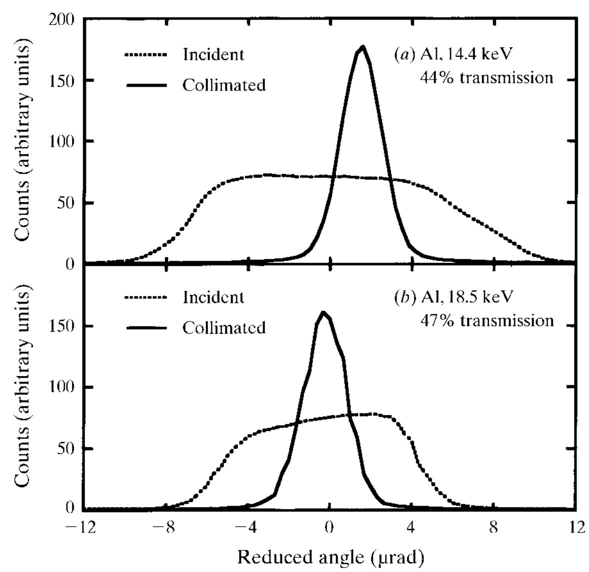

Figure 3
Effect of Al collimators at 14.4 and 18.5 keV. Note that in (*b*) the collimated response has been shifted by 3 μrad for convenience in display.

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