Multiprism Lithium Refractive Optics for X-rays

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Introduction

The refraction of x-rays at the interface of solid materials is very small, quite like visible light going from cold to hot air. Even so, the minute refraction is easily seen in the scintillation of stars and the shimmering of light passing by a burning candle. On third-generation synchrotrons, the x-ray beams are so well collimated that even this small deflection is sufficient to manipulate the beam in a useful way. We do this with x-ray refractive elements made with metallic lithium [1-5]. In 2002, we showed how effective refraction can be in removing higher harmonics from the beam, and we obtained a 15-fold increase in intensity combined with a 50% throughput in 2-D focusing.

For x-rays, the complex index of refraction $n = 1 - \delta + i\beta$ is close to unity [6-7]. For 10-keV x-rays in lithium, δ is $\sim 10^{-6}$. The term $i\beta$ that describes x-ray absorption is about 2000 times smaller still and implies an attenuation length of around 60 mm.

A rectangular prism deflects x-rays over an angle $\alpha = 2\delta$ away from the prism's base. For 10-keV x-rays, the deflection is 2 μrad per prism, and for $N = \sim 100$ prisms in a row, the deflection is $2N\delta = \sim 0.2$ mrad. With this much deflection, an x-ray that started at the edge of a nominally 0.5-mm-wide x-ray beam crosses the beam's optical axis at a point 2.5 m downstream. When the multiprism is placed under an angle with the x-ray beam [8, 9], and when the x-rays at the edge go through N prisms while those in the center go through only a single prism, all the x-rays cross in a small region; thus, the beam is focused.

Our prism's top angle is 90°, the height is 0.5 mm, and the base is 1 mm. The average x-ray goes through the prisms at half-height. Lithium's 60-mm absorption length thus accommodates 120 prisms. The multiprism collimator here has 112 prisms.

Methods and Materials

At beamline 7-ID at the APS, the full width at half maximum (FWHM) source size for a 10-keV x-ray beam is 0.033 mm in the vertical and 0.8 mm in the horizontal. The beam's divergence makes the beam roughly 0.5-mm high and 1.75-mm wide at the entrance to the monochromator that is 30 m away. In front of the monochromator, the white beam is limited by a L5-20 slit that is typically set to 0.5 × 0.5 mm. The monochromator leaves the beam's divergence in the horizontal alone. In the vertical, however, the divergence can become slightly larger because of the thermal load, despite the best efforts to stabilize the vibrations induced by the double-crystal Si(111) cryogenically cooled monochromator [10].

The multiprism lens is housed in an evacuated chamber and sealed with two 0.125-mm-thick x-ray-transparent Be windows. Positioning and orientation of the lens with respect to the incident beam are handled by a four-axis positioner with computer-controlled stepper motors. A slit set to 0.5 mm typically limits the beam that goes into the lens. The principal beam diagnostic is a charge-coupled device (CCD)-based system that captures the visible light emitted by a thin, cerium-doped YAG crystal [5]. An ionization chamber right behind the lens measures the multiprism's x-ray transmission.

Results

At 2.4 m behind the lens, the x-rays focuses in the center of the original undeflected beam. Exactly how the prisms collimate [8, 9] will be analyzed in a forthcoming paper [11].

Figure 1 shows a vertical cross section through the center of the collimated region. The peak intensity is about 7.3 times larger than the uncollimated beam on the left side and is about 70 μm wide (the uncollimated beam is about 500-μm wide). The separation between the collimated and the uncollimated parts of the beam is poorly defined, but, within reason, the beam sizes and intensities are consistent with the x-ray transmission through the lithium in the lens.

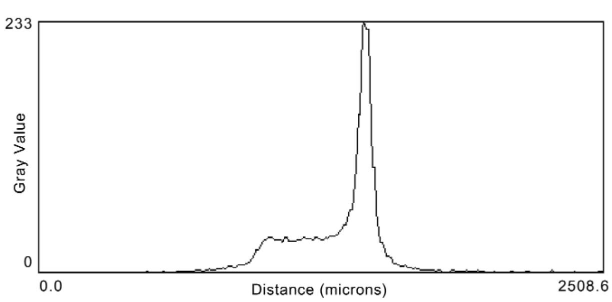

FIG. 1. Vertical cross section through the collimated beam 2.4 m behind the multiprism.

The x-ray transmission of the lithium lens is measured by shifting the lens's lithium in and out of the beam. With corrections for the undeflected beam and for the two 125-µm beryllium windows that seal the lithium lens inside its package, the gain G of a 1-D lithium multiprism at 10 keV is ~6.5. Adding a second multiprism (as envisioned by Cederstrom [8]) that steers the undeflected half of the beam to the same collimation region would give a gain G_2 of ~13.

Two properly angled multiprisms may double the gain of a single multiprism, but a single multiprism offers the additional flexibility to collimate at an arbitrary distance [11]. Two neighboring prisms at s and at $s + \Delta s$ under an angle with the x-ray beam intercept the beam at $h(s)$ and at $h(s + \Delta s) = h(s) + (\partial h/\partial s) \cdot \Delta s$. A beam slice that is $(\partial h/\partial s) \cdot \Delta s$ wide between the two prisms deflects in only one prism, over an angle 2δ (δ is the refractive index decrement). An x-ray in the center of this slice intersects a similar x-ray in the slice next to it at a local collimation distance $f(s)$ given by $(h/\delta)/(\partial h/\partial s)$, where the distance between two prisms $\Delta s = 2h$.

The multiprism's intercept with the beam $h(s)$ is equivalent to an angle $\Theta(s) = \partial h/\partial s$ between the multiprism and the beam, local to each point s along the multiprism. When the multiprism is bent, the collimation distance $f(s) = (h/d)/\Theta(s)$ varies along the prism, and collimation is poor. Collimation is optimal for a straight multiprism where the angle $\Theta(s) = \Theta$ is the same everywhere.

Clearly, the multiprism can collimate at any desired distance $f_\Theta = (h/\delta)/\Theta$ simply by changing Θ. The flexibility in collimation distance makes the single multiprism very useful. It can be located and finally aligned at some convenient position in the beam, then oriented such that the x-ray intensity is maximum at the location of the experiment. By moving the multiprism closer to the experiment, the collimation can improve still more, but often the extra work of aligning still another element in the beam is not worth the trouble. In addition, collimation of the fundamental x-ray energy away from the beam axis suppresses harmonics.

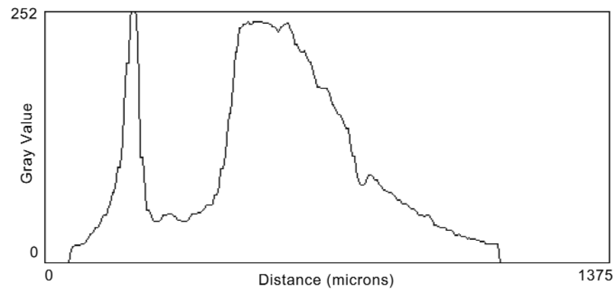

FIG. 2. Cross section of collimated and filtered x-rays 12 m behind the multiprism.

As an example, Fig. 2 is a cross section through the x-ray beam when it is collimated 12 m behind the multiprism and also filtered ~100 times to make the higher harmonics (at 30 keV, etc.) more prominent. The focused fundamental x-rays at 10 keV are indicated by the ~40-µm narrow peak to the figure's left, and the hump to the right is from the undeflected harmonics (without filtering, the harmonics are barely visible) [3].

Note that the fundamental x-rays separate spatially from the higher harmonics thanks to the chromaticity of the the index of refraction n. In other words, $1 - n = \delta$ varies with photon energy $h\nu$ as $\delta \propto 1/h\nu^2$. For certain experiments, the multiprism may be even more useful for its suppression of higher harmonics than for the intensity gain of the fundamental x-rays.

Two multiprisms perpendicular to each other

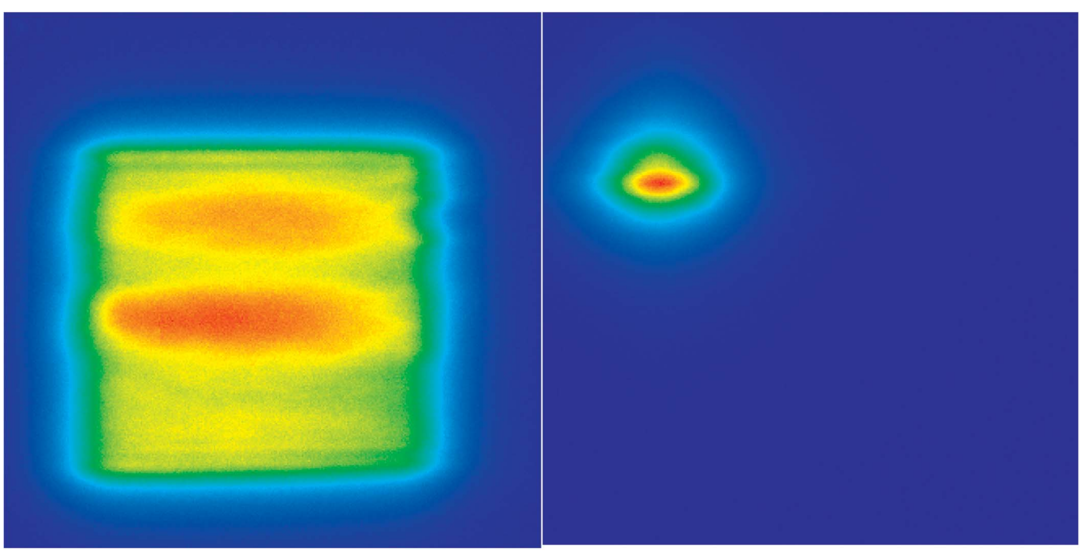

FIG. 3. Collimation in two dimensions.

collimate in two dimensions. Figure 3 compares the initial beam (left; the beam is limited by slits to a 500-μm^2 cross section) with the collimated spot size (right). The peak intensity in the collimated spot is ~15 times higher than in the uncollimated beam. This gain is satisfactory and very useful but much less than the 62-fold or 36-fold gain expected from the 6-fold gain in 1-D collimation in the vertical direction.

The lower gain is largely due to the lower gain achieved by collimating in the horizontal direction. The gain is inversely proportional to the width of the collimation region. In the vertical, this is substantially smaller than in the horizontal, where the gain is estimated as G = ~2.5. The 15-fold gain in 2-D focusing is consistent with a 2.5-fold gain in the horizontal and a 6.5-fold gain in the vertical. Small-angle scattering also widens the collimation region and reduces the gain.

Discussion

Using multiprism refractive optics made from lithium metal for x-rays is an excellent way to manipulate the insertion device (ID) beamlines on the APS and other third-generation synchrotrons. Cederstrom's original multiprism lens has two symmetrically placed multiprisms, but a single multiprism, as tested here, is also eminently usable. A multiprism made from lithium metal has a large enough aperture to accept an appreciable fraction (about equal to millimeter-size) of the x-ray beam. The multiprism collimates the x-rays at any desired distance, with (measured) gains in 1-D up to ~6.5 and in 2-D up to 15. Chromaticity of x-ray refraction $\delta \propto 1/(h\nu)^2$ with photon energy $h\nu$ causes spatial separation between the (collimated) 10-keV principal x-rays and the (uncollimated) higher harmonic x-rays at 30 keV and above.

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