Efficient Optics for 50- to 100-keV Undulator Radiation by Using Crystals and Refractive Lenses

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Introduction

Compound refractive lenses (CRLs) are effective for collimating or focusing high-energy x-ray beams (50 to 100 keV) and can be used in conjunction with crystal optics in a variety of configurations, as demonstrated at the 1-ID undulator beamline at the APS. As a primary example, this report describes the quadrupling of the output flux when a collimating CRL, composed of cylindrical holes in aluminum, is inserted in between two successive monochromators — a modest-energy-resolution premonochromator followed by a high-resolution monochromator. The premonochromator is a cryogenically cooled, divergence-preserving, bent double-Laue Si(111) crystal device delivering an energy width $\Delta E/E$ of $\approx 10^{-3}$, sufficient for most experiments. The high-resolution monochromator is a four-reflection, flat Si(111) crystal system resembling two channel-cuts in a dispersive arrangement, reducing the bandwidth $\Delta E/E$ to $<10^{-4}$, as required for some applications. Tests with 65- to 90-keV photon energies show that the high-resolution monochromator, having a narrow angular acceptance of a few microrad (μrad), exhibits a fourfold throughput enhancement as a result of the insertion of a CRL that reduces the premonochromatized beam's vertical divergence from 29 μrad to a few μrad. The ability to focus high-energy x-rays with CRLs having long focal lengths (tens of meters) is also shown by creating a line focus of 70- to 90-μm beam height in the beamline end station with both the modest- and high-energy-resolution monochromatic x-rays.

Methods and Materials

A liquid-nitrogen-cooled monochromator for high-energy x-rays (50 to 200 keV), consisting of two bent Si(111) Laue crystals arranged to sequential Rowland conditions (Fig. 1), has been in operation for 3 years at the XOR sector 1 undulator beamline at the APS. In the routinely used energy range of 60 to 100 keV, it delivers over 10 times more flux than does a Si(111) flat-crystal monochromator, without any increase in energy width ($\Delta E/E$ of $\approx 10^{-3}$). Cryogenic cooling permits optimal flux, avoiding a sacrifice from the often-employed alternative technique of filtration — a technique less effective at sources like the 7-GeV APS, where considerable heat loads can be deposited by high-energy photons, especially at closed undulator gaps. The bent double-Laue optics are also characterized by a fully tunable fixed-exit beam with preserved source brilliance (divergence and size). Details on the design, properties, and performance of this instrument have been published [1]. The modest 10^{-3} level of energy spread is acceptable for numerous high-energy experiments currently performed at beamline 1-ID, such as pair-distribution function measurements [2-5], fluorescence spectroscopy [6, 7], powder diffraction [8, 9], material stress/texture determination [10], small-angle scattering [11], and diffuse scattering [12]. Nevertheless, applications that require better monochromaticity ($\Delta E/E$ of $\leq 10^{-4}$) exist. Examples include anomalous scattering with heavy elements, high-resolution stress/strain measurements with line-shape analysis, atomic physics spectroscopy, and excitation of nuclear resonances. The energy resolution of this monochromator can indeed be improved to 10^{-4} levels or better by careful choice of Laue crystal parameters, such as thickness, asymmetry, and reflection order. However, higher resolutions at high x-ray energies demand excellent mechanical stability, which is difficult to achieve at the white-beam optics stage, in which small angular instabilities or drifts $\delta\theta$ arising from thermal load and cooling get amplified into large energy

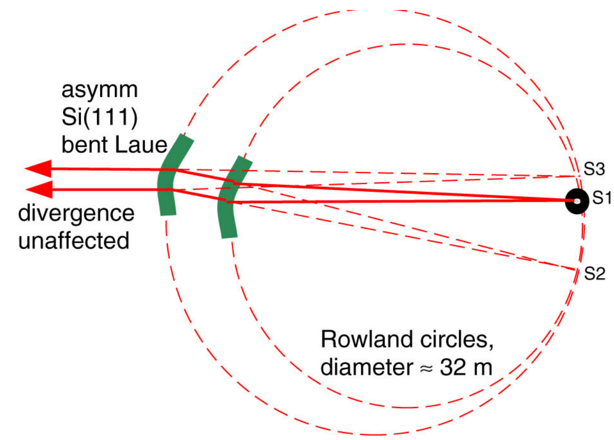

FIG. 1. Tunable, in-line, high-energy x-ray monochromator composed of two vertically diffracting, bent Laue crystals located about 32 m from undulator source S1. The two Rowland circles intersect tangentially at virtual source S2.

changes ($\Delta E = E \cot\theta\ \delta\theta$) as a result of the small Bragg angle θ and large energy E. So attaining narrower energy resolution might be best done alternatively, by using additional post-monochromatization optics after the broader-bandwidth, double-Laue system. This method keeps the white-beam optics invariant and relatively simple and permits the subsequent high-resolution system to operate without thermal load in a more amenable and accessible open-room environment, where it can be easily modified. Furthermore, the flexibility is present to return to the configuration that uses just the high-flux, modest-energy-resolution x-rays from the premonochromator by bypassing the post-monochromator. Hence, for its versatility, this approach was pursued. Specifically, CRLs were used to vertically collimate the exit beam from the double-Laue system to divergences comparable to the small angular acceptance of subsequent high-resolution, flat-crystal optics (Fig. 2). The effectiveness of such a method is enabled by a pre-monochromator that is brilliance preserving — a feature inherent in the bent double-Laue system but not, for example, in double mosaic crystal monochromators that are also used for high-energy x-rays.

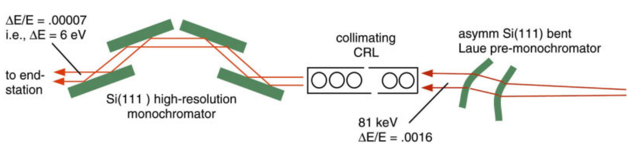

FIG. 2. High-resolution setup consisting of the bent Laue pre-monochromator, followed by a collimating CRL and the four-reflection, flat-crystal, high-resolution monochromator. The CRLs were obtained from Adelphi Technology, Inc., Palo Alto, California.

Results and Discussion

The performance of the arrangement depicted in Fig. 2 is described here for an energy of 81 keV. The bent double-Laue pre-monochromator delivers 4×10^{12} photons per second (ph/s) in a 1×1-mm^2 beam with an energy width $\Delta E/E$ of 1.6×10^{-3} and a vertical divergence of 29 μrad. The beam then passes through an aluminum CRL consisting of 86 cylindrical holes of 1-mm diameter, separated by 20- to 50-μm walls. These parameters give the device a 35-m focal length for 81-keV radiation, resulting in the desired collimating action, as it is placed 35 m from the undulator source. The collimated beam then Bragg-reflects through four symmetric Si(111) crystals in a (+--+) configuration implemented by two dispersive channel cuts. At 81 keV, a symmetric Si(111) Bragg crystal has energy and angular Darwin width acceptances of 1.4×10^{-4} and 3.5 μrad, respectively. So, ideally, one would expect this setup to monochromatize the beam to an $\Delta E/E$ of 1.4×10^{-4}, with a flux loss factor (relative to the pre-monochromator output) factor of about 23 (arising from one order of magnitude improvement in monochromaticity, compounded by a 50% attenuation loss through the CRL). In reality, a flux loss factor of about 50 was measured — a factor of two worse than expected. It could be attributed to imperfect CRL collimation due to cylindrical aberrations. However, it turns out that this imperfect collimation also results in the final energy resolution being two times better than expected (i.e., 7×10^{-5} instead of 1.4×10^{-4}). So the final 81-keV beam intensity is 8×10^{10} ph/s in a 1×0.5-mm^2 size (horizontal × vertical), with 6-eV energy resolution. This setup has been used for resonant powder diffraction studies near the Pb and Bi K edges at 88 to 91 keV [13]. That the CRL provides a fourfold enhancement was easily verified by measuring the output flux with the CRL removed from the beam.

To test focusing with CRLs at high energies, an aluminum CRL similar to the one described above, but with 215 holes, was used to vertically condense the 1×1-mm^2 beam from the bent Laue monochromator into the end station located 25 m beyond the CRL. This 1:0.7 distance ratio geometry produced a 1.7×0.089 mm^2 (horizontal × vertical) line focus with a CRL transmission of 27%. The 89-μm spot size is roughly twice that expected from the source size; the discrepancy is again most likely a result of cylindrical aberrations in the CRL. This arrangement has been used for high-energy x-ray small-angle scattering applications [11], where a 2-D detector is placed at the focal location. Similar focusing was also achieved in the high-energy-resolution mode. A full article on all this work will appear in the near future [14]. The elimination of cylindrical aberrations by using parabolic, as opposed to cylindrical, holes in the CRLs would improve performance in both the high-energy-resolution (collimating) optics and focusing optics.

Acknowledgments

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