Bent Double-Laue Crystal Monochromator for High-Energy X-Rays (50–200 keV)

S. D. Shastri, A. Mashayekhi, K. Fezzaa, W.-K. Lee, P. B. Fernandez, G. C. Tajiri, D. A. Ferguson, and P. L. Lee
SRI-CAT, Advanced Photon Source, Argonne National Laboratory, Argonne, Illinois 60439

Introduction

The standard double-crystal monochromator consisting of two flat, perfect, parallel crystals (e.g., Si(111)) in a nondispersive setting is ideal for most low-energy experiments (below 30 keV), but not for high energies (above 60 keV). Although this approach fundamentally still works, it does not extract and deliver photons from the white beam in an efficient manner, as clarified below. In this report, an alternate monochromator optics scheme, composed of two bent Laue crystals, is described that efficiently extracts monochromatized high-energy synchrotron radiation. Such optics has been tested in the 60–100 keV range and delivers over ten times more flux in the *same* monochromatic output energy width as flat Bragg crystals.

The inefficiency of a flat Si(111) double-crystal monochromator set for 100 keV in an APS undulator A white beam is explained by the Dumond representation in Fig. 1. The steep, narrow slice arising from the small Bragg angle and narrow Darwin width results in a fairly large energy width in the monochromatized beam ($\Delta E/E \approx 2.5 \times 10^{-3}$) without the benefit of maximum flux. Over 90% of the radiation in the white beam within that energy width does *not* pass through the optics. In addition to the Si(111) reflection properties at 100 keV, this inefficient performance is also due to the enlarged vertical divergence (53 μrad) from the source at high energies and closed-gap operating conditions. Unlike at lower energies (below 50 keV), where the divergence is governed by the particle beam's small emittance ($\sigma_{y'} \approx 5$ μrad), at high energies the insertion device field errors and particle beam energy spread give rise to somewhat wiggler-like behavior and hence larger divergences. [1]

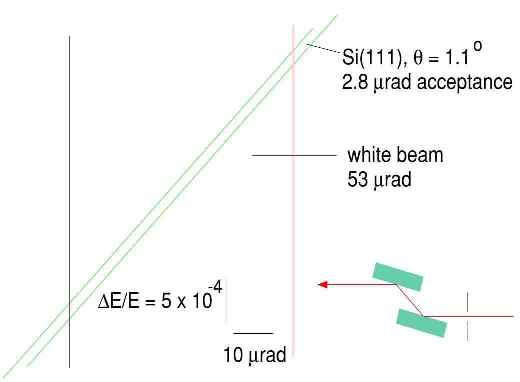

Figure 1: Dumond diagram representation of a flat Si(111) monochromator set for 100 keV in an APS undulator A white beam.

Bent Double-Laue Monochromator Geometry

To improve upon the optics just discussed, one could attempt to develop a scheme that leaves the monochromatized energy width unchanged, but enhances flux by over a factor of 10 by passing through all the photons from the source within that $\Delta E/E \approx 2.5 \times 10^{-3}$ bandwidth. Such a bandwidth is acceptable for numerous high-energy experiments currently performed at sector 1 of the SRI-CAT, such as powder diffraction, residual stress determination, pair distribution function measurements, and fluorescence spectroscopy. This desired improvement in output was accomplished using the optics sketched in Fig. 2. The white beam is incident on the first Laue crystal, cylindrically bent to a Rowland circle going through the source S1. The singly diffracted beam emerges as if emanating directly from a virtual source S2, also located on the first Rowland circle. The second crystal is also bent, but to a Rowland circle going through the virtual source S2. The doubly diffracted beam propagates as if coming from the virtual source S3 located on the second Rowland circle and close to the original source S1.

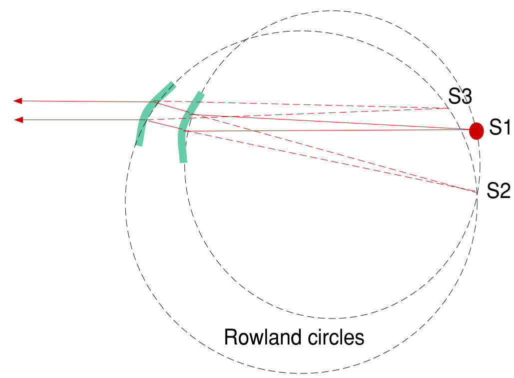

Figure 2: Tunable, in-line monochromator of two bent Laue crystals at about 32 m from the source S1.

The over ten-fold flux increase results from the bending strain-induced broadening of the crystal reflection's angular acceptance [2], as shown in Fig. 3. The intrinsic acceptance $\Delta\theta_{acc}$ changes from 3 μrad in the flat Bragg case to 40 μrad in the bent Laue case, thereby enabling efficient monochromatization. But despite this broadening, one does not experience any additional detrimental energy width because the spread of angles of incidence $\Delta\theta_{inc}$ with respect to the crystal lattice decreases from 53 μrad in the flat Bragg case to 1.6 μrad in the bent Laue case. This near vanishing of $\Delta\theta_{inc}$ is characteristic of the Rowland geometry, which makes all rays from

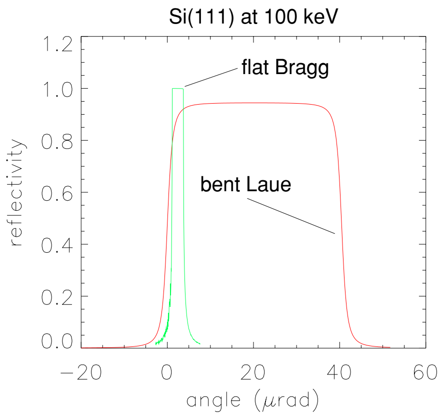

Figure 3: Dynamical diffraction calculations of intrinsic reflectivities for the flat, symmetric Bragg and bent, asymmetric Laue cases. The latter case assumes a 32 m bend radius, 10° asymmetry, and 2.5 mm thickness.

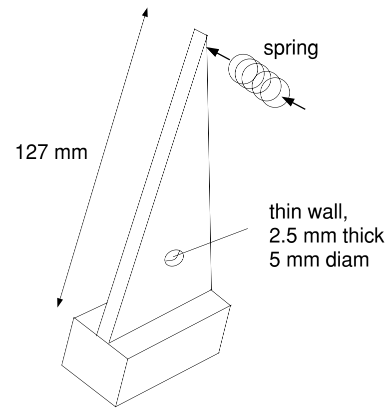

Figure 4: Shape of silicon Laue crystals. The beam diffracts through the thin wall section.

any given point within the source impinge at the same angle onto the bent crystal lattice, leaving only a small source size contribution. The net result leaves the energy spread $\Delta E/E = \cot\theta\sqrt{\Delta\theta_{acc}^2 + \Delta\theta_{inc}^2}$ essentially unchanged from 2.5×10^{-3} to 2.0×10^{-3} in going from flat Bragg to bent Laue geometries at 100 keV.

Performance Results

The bent Laue Si(111) optics was tested at three energies: 67, 75, and 100 keV. The monochromatic flux delivered in a beam defined by a 1×1 mm^2 white beam aperture placed 27 m from the source ranged from 1.2×10^{13} ph/s (at 67 keV) to 6.3×10^{12} ph/s (at 100 keV) for 100 mA ring current and 11.0 mm undulator gap. The measured energy spreads $\Delta E/E$ at 67, 75, and 100 keV were 1.4, 1.6, and 2.0×10^{-3}, respectively, in exact agreement with calculations, and actually slightly less than what flat Si(111) optics would give (1.7, 1.9, and 2.5×10^{-3}, respectively) at less than one-tenth the flux under the same operating conditions of current, gap, and slits.

Although the two-crystal system specifically shown here provides monochromaticity at the 10^{-3} levels, it is important to realize that levels of 10^{-4} or better in monochromaticity are achievable by careful choice of the crystals' reflection order, asymmetrical cut, thickness, and bend radius.

Bending with Heat Load and Cryogenic Cooling

The technical challenge of implementing the bent double-Laue monochromator optics is achieving fine control and stability of the bend radii of the two crystals. The first crystal, in particular, poses additional difficulty due to the presence of harsh nonequilibrium conditions of closed undulator gap heat load and cryogenic (liquid N_2) cooling. Crystal benders allowing excellent mechanical control and stability were developed, which operate by inducing the cylindrical bending deflection of a stiff triangular crystal by pushing indirectly on its tip through a weak spring, as sketched in Fig. 4. This arrangement leaves the crystals' bend radii insensitive to thermal or mechanical perturbations and drifts anywhere in the system.The cryogenic cooling for the first crystal is accomplished by flowing liquid N_2 through the copper blocks clamping the large base. Details of the bender, crystal, and cooling designs will be presented elsewhere.

Summary

The bent double-Laue monochromator optics described here is a tunable, fixed-offset, in-line system that extracts intense, high-energy monochromatic beams. In addition to being an order of magnitude more efficient than flat, perfect crystal optics, it is also superior to imperfect crystal optics, which are not phase-space (brilliance) preserving and behave unpredictably in double-reflection geometries due to mosaicity mismatches.

The next development under way is replacement of the second Laue crystal by a bent Bragg crystal in a Johann geometry with its Rowland circle going through point S2 in Fig. 2. This will vertically focus the beam at an experiment located downstream.

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References

[1] S.D. Shastri, R.J. Dejus, and D.R. Haeffner, "Experimental Characterization of APS Undulator A at High Photon Energies," J. Synchrotron Rad. **5**, 67–71 (1998)

[2] P. Suortti and C. Schulze, "Fixed-Exit Monochromators for High-Energy Synchrotron Radiation," J. Synchrotron Rad. **2**, 6–12 (1995)