Performance of the 1-BM beamline optics

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Introduction

The overriding motivation for the construction of the Advanced Photon Source (APS) was to increase the availability of high-brilliance insertion device (ID) beamlines. A somewhat neglected fact, however, has been that APS bending magnets (BM) also offer high-quality x-ray beams suitable for a wide variety of experiments. In order to take full advantage of all the photons in a particular bandwidth provided by these bending-magnet sources, however, focusing of the beam is absolutely essential. Focusing the bending-magnet beam here at the APS poses some unique challenges, since the distances from the source are large, thereby requiring larger optics than those used previously at other synchrotrons. The rewards for using these optics are quite substantial, though, since focusing enhances the x-ray flux on the sample by several orders of magnitude, with the flux density at the focal spot approaching that of an unfocused insertion device. This report briefly reviews the design of the SRI-CAT 1-BM beamline, and the measured performance of the optics is compared with expected values. We limit the discussion to the properties of the fully focused x-ray beam in the 1-BM-C experimental enclosure.

Beamline 1-BM is a highly flexible beamline that has been used for a variety of experiments, such as diffraction, reflectivity, extended x-ray absorption fine structure (EXAFS), and high-energy scattering. The design of 1-BM [1] is a combination of several successful beamline designs used previously at second-generation synchrotrons [2, 3, 4]. The beamline consists of three stations, A, B, and C, with only the latter two used for experiments. The major optical components are two cylindrically bent mirrors and two alternately used focusing monochromators (Fig. 1).

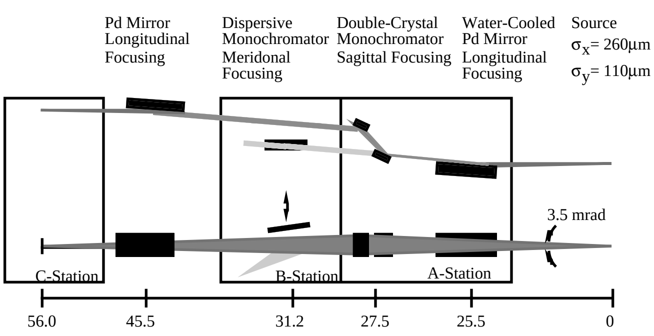

Figure 1: Top and side view schematic of the major optical components on the 1-BM beamline indicating their distance (meters) from the source and the location of the experiment stations. The size of the source is given in microns (FWHM).

The first optical component is a water-cooled 1.2 m long palladium-coated mirror located 25.5 m from the source. The x-ray beam is incident on this mirror at an angle of 2.8 mrad making the critical energy 24 keV. At this angle the mirror subtends 132 mrad vertically, thereby intercepting over 2/3 of total beam at 10 keV. This mirror is cylindrically bent in order to vertically "collimate" the beam (i.e., focus the beam at infinity). Collimating the beam allows the user to accept a larger portion of the vertical beam without sacrificing any energy resolution, because all the rays in the beam after the mirror will make a nearly identical angle with any vertically diffracting monochromator crystal further downstream. The collimating mirror is followed by the double-crystal monochromator (DCM). The second crystal in the DCM is a sagittally bent crystal, which provides horizontal focusing of the beam into the C station. Si(111), Si(220), and Si(400) crystals have been fabricated for this monochromator, which give it energy ranges of 4 – 25 keV, 6 – 39 keV, and 8 – 58 keV, respectively. If the first crystal of the DCM is translated out of the beam, the third optical component, a dispersive monochromator located in the B-station of the beamline, can be used. This monochromator horizontally diffracts and meridionally focuses the beam into this station providing a polychromatic beam used primarily for time-resolved dispersive EXAFS or diffraction measurements for energies between 5 and 20 keV. When passing the beam into the C station, the dispersive monochromator can be translated out of the beam. The last optical component in the beamline is a 1 m long palladium-coated cylindrical mirror located between the B and C stations. This mirror provides vertical focusing of the beam for the C station. The incident angle on this mirror is adjustable up to 5.6 mrad, although in normal operation it remains at 2.8 mrad in order to provide a horizontal beam into the C station.

Methods and Results

The energy bandwidth of the C station beam is determined by the cylindrical bend on the first beamline mirror and the first monochromator crystal of the DCM. To measure the mirror's effects on the beam divergence, a highly dispersive reflection from a Si crystal "analyzer" was placed after the DCM. The rocking curve width of this reflection is directly related to the bandpass of the monochromator and thus the divergence after the mirror. Measurements at 10 keV showed that, for a beam with a 109 µrad vertical divergence incident on the mirror, the bandwidth was reduced from 5.5 x 10^{-4} to 1.5 x 10^{-4} for Si(111) and from 3.6 x 10^{-4} to 8.1 x 10^{-5} for Si(220), when the mirror bend was changed from flat to collimating. The lower values on the energy resolution are 15% and 25% above the theoretical limit (i.e., perfect collimation, $\Omega \approx 0$) and indicate that the beam after the mirror had a minimum vertical divergence of ~10 µrad. Spherical aberrations from the mirror due to its nonellipsoidal shape (~1 µrad) and the finite extent of the source (~5 µrad) account for some of this residual divergence, but the predominant source was found to be slope errors in the figure of the mirror on the order of 10 μrad. This was confirmed by scanning the mirror through a small x-ray beam and noting the position of the analyzer crystal reflection. This measurement showed that, while the central 0.8 m of the mirror had only 2 – 3 μrad deviations from an ideal bend, both of the edges of the mirror were substantially overbent to the 10 μrad figure cited above.

The focal size of the beam in the C-station is determined by the sagittally focusing crystal in the DCM and the second focusing mirror. The combined performance of these two optics is illustrated in Figure 2, which shows a CCD image of a doubly focused 9.0 keV beam in the C-station using a Si(111) monochromator. This spot size was focused with a 2.20 mrad (H) x 0.09 mrad (V) beam incident on the monochromator. Profiles of this image give FWHM values of 0.25 mm vertical and 0.60 mm horizontal. These values are roughly twice as large as those obtained from ray tracing, assuming ideally shaped cylindrical focusing optics. The increase in the vertical spot size compared to that taken with flat-crystal optics is believed to be due to aberrations induced by a slight twisting in the sagittal crystal, while the increase in the horizontal focal size is thought to be due to nonuniformities in the thickness of the sagittal crystal. Another thing to note is that the focused beam has a long diffuse tail with ~5% of the peak intensity. Most of the contribution to these tails arises from the portions of the crystals near the legs of the sagittal crystal. If the incident beam is reduced to 1.75 mrad (H) this tail can be nearly eliminated.

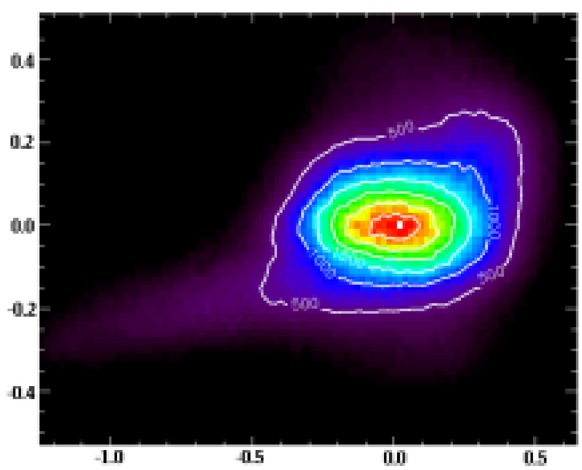

Figure 2: CCD image of the doubly focused beam in the C-station using both mirrors and a Si(111) monochromator crystal. Contours are arbitrary units corresponding to the number of counts in the CCD detector.

An indication of the combined performance of all the optical elements is given in Figure 3, which plots measured photon fluxes for the focused beam along with that achieved for the same size beam with flat crystals measured in the B-station and the flux expected from perfect crystal optics. Both the flat and bent crystal optics deviate from the ideal optics curve at higher energies. This is believed to be due strain or thermal effects in the DCM crystals, which are more prominent relative to the Darwin width of the monochromator crystals for higher energies. In the case of the flat crystal, the effects of thermal heating on the first crystal are probably the cause, while for the sagittal crystal the steeper drop off is probably due to the increasing strain of bending the crystal to the smaller bending radii required for increasing energy. We should note that, in principle, the optics can accept even larger beams, but we have given the flux for this size beam since it yielded a reasonable focus and bandwidth. If these factors are not critical to the experiment, the maximum beam size [3.00 mrad (H) x 0.13 mrad (V)] can be used to increase the expected flux to 2.5 x 10^{12} ph/s/100 mA at 10 keV. For this case, the focus assumes an irregular shape with most of the flux in a 0.3 mm vertical and 0.7 mm horizontal spot and a diffuse tail (~5% of peak intensity) extending for approximately 5 mm.

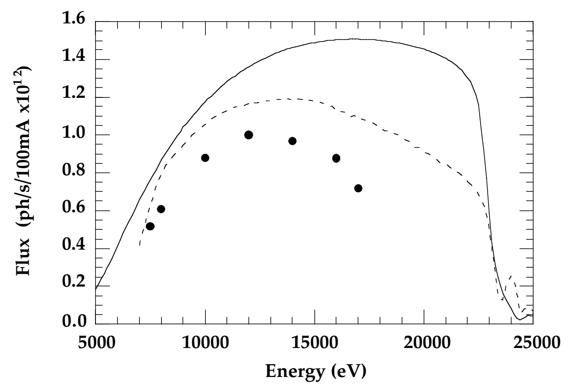

Figure 3: Theoretical flux (solid) flux for a 1.75 mrad (H) x 0.09 mrad (V) beam with a Si(111) monochromator and the observed flux with flat crystals (dash) and the fully focused sagittal crystal (circles).

Discussion

Comparing these values with those obtained from an ID beamline is informative. For instance, a 1.0 x 1.0 mm^2 unfocused beam 65 m from the source from a standard APS undulator A using a Si(111) monochromator would in theory yield 1.0 x 10^{13} ph/s/100 mA at 10 keV, only an order of magnitude above the observed flux on 1-BM into a well-defined focus. We should also note that, because of the collimation of the beam prior to the monochromator, the bandwidths on 1-BM are nearly the same as those seen on the ID beamlines. If focusing optics are used to collect the entire central cone of the undulator beam, this flux differential increases to a factor of 40. This comparison between a BM and ID source demonstrates that the great strength of ID devices is primarily the brilliance provided and not necessarily their overwhelming flux. Thus, for experiments that require only a large incident flux on the sample with relaxed conditions on the beam collimation, a BM beamline can be a viable alternative to an ID beamline.

Acknowledgments

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