Versatile focusing using a combination of toroidal and Kirkpatrick–Baez mirrors

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Toroidal mirrors can be used to efficiently focus synchrotron radiation for magnifications near 1. At the Pacific Northwest Consortium-Collaborative Access Team (PNC-CAT) insertion device beamline, a toroidal mirror is used to focus the entire undulator beam to a spot size of $400(H) \times 100(V)\ \mu m^2$. For large demagnifications, Kirkpatrick–Baez (KB) mirrors are a good choice. Spot sizes down to 1 μm have been achieved at PNC-CAT. However, these mirrors only collect a fraction of the undulator beam, and result in a highly divergent beam with a short working distance. To achieve an intermediate beam size with less divergence, the toroidal and KB mirrors can be combined. The toroidal mirror reduces the beam to match the entrance aperture of the KB mirrors. This combination can provide beam sizes below 100 μm while collecting the entire undulator beam and providing a convenient working distance. Thus, the beam size, working distance, and divergence can be tailored to the needs of the experiment.
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I. INTRODUCTION

The Pacific Northwest Consortium-Collaborative Access Team (PNC-CAT) undulator beamline at the Advanced Photon Source (APS) is designed to support a variety of experiments. These have wide ranging requirements for beam size and collimation. Microbeam imaging experiments generally need minimal spot sizes, but are insensitive to beam divergence. A good choice is the Kirkpatrick–Baez (KB)[1] arrangement of two mirrors individually focusing the vertical and horizontal directions. The KB arrangement allows the use of highly accurate spherical or elliptically bent flat mirrors, and can provide different demagnification in the horizontal and vertical for the highly asymmetric undulator source. At the PNC-CAT beamline, we have been employing a mirror system developed by the Consortium for Advanced Radiation Sources (CARS)-CAT[2,3] that provides focused beams as small as 1 μm. To achieve such large demagnification, the mirrors must directly image the source approximately 50 m away, and have a rather short working distance of 30 mm from the end of the last bender. The small size of the mirrors allows an entrance aperture of about $0.25 \times 0.25\ mm^2$. Since the unfocused undulator beam at the mirror position is about $1(V) \times 3(H)\ mm^2$, much of the beam is not focused.

To improve the efficiency for experiments that do not need such small beams, a larger set of KB mirrors has been built. These collect $0.6 \times 0.6\ mm^2$ and focus to about 3 μm. They also increase the working distance to 150 mm. This significantly improves the collection efficiency, but still does not utilize the majority of the beam available. In addition, both sets of KB mirrors result in beam divergences greater than 1 mrad, which can be detrimental to some diffraction or glancing angle experiments.

A toroidal mirror implemented as a bent cylinder can be used to focus the entire undulator output. Figure 1 shows the basic layout of the PNC-CAT ID beamline.[4] The toroidal mirror is located 34.3 m from the source, and can provide a slightly demagnified image of the source anywhere in the two experimental hutches. The mirror is dropped out of the beam when the KB mirrors are used. Since we use a bent cylindrical mirror,[5] the focal position in the horizontal can be controlled by adjusting the angle of the mirror, and in the vertical by the applied bend. Figure 2 shows the resulting focus as imaged by scanning a 10 μm pinhole. This focus is nearly ideal for the horizontal. In the vertical, the size is limited by the slope errors in the mirror [approximately 2 μrad root mean square (rms)]. Since the demagnification factor is close to 1, the divergence of the beam from the toroidal mirror is similar to that of the raw undulator beam (<100 μrad).

The focus from the toroidal mirror is smaller than the acceptance of the larger set of KB mirrors. This immediately suggested combining the two to achieve a smaller focus while still collecting the entire undulator output. In the rest of this article we describe results from this optical arrangement.

II. OPTICAL CONSIDERATIONS

There are two possible arrangements that can be used to combine the toroidal and KB mirrors. They are shown in Fig. 3. In Fig. 3(a) the KB mirror is used to focus a virtual image after the mirror. The ideal surface figure for this is a hyperbola. This arrangement is used when a focus in the 20-ID-B station is desired. The range over which the toroidal mirror focus can be adjusted is limited by Be windows at the end of the beamline. When focusing into the 20-ID-C station, the

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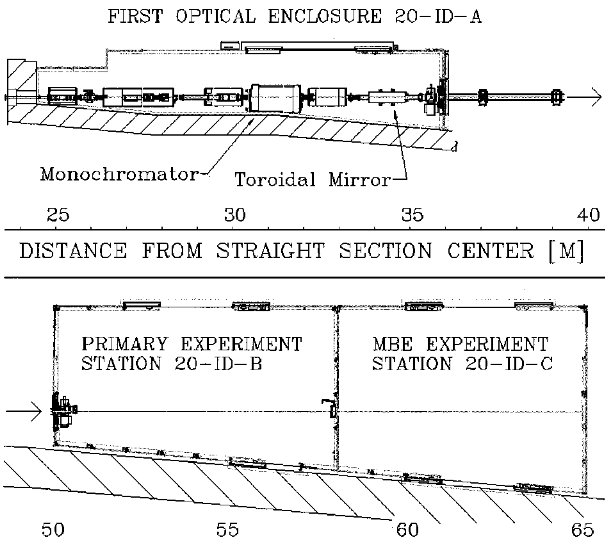

FIG. 1. Basic layout of the PNC-CAT ID beamline. The toroidal mirror is designed to focus anywhere in the two experimental hutches, 20-ID-B and C.

arrangement shown in Fig. 3(b) is used. The ideal surface figure is now an ellipse. However, it is a much different ellipse from the normal KB mirror configuration. In both cases an ideally configured mirror would reduce the toroidal mirror focus by $F3/F4$.

In the CARS design, the KB mirrors are configured by applying unequal bending moments to each end of a trapezoidal shaped flat mirror. The trapezoidal shape is optimized to produce the most accurate ellipse for the microbeam case. To produce other configurations the bending moments can be adjusted, but changing the shape would require a different mirror. Therefore, some figure errors can be expected, and there may be a limit on how much the toroidal focus can be reduced.

III. RESULTS AND DISCUSSIONS

As a test of the above ideas, the arrangement in Fig. 3(a) was used. The KB mirrors were positioned so that the center of the vertical focusing mirror was 51.75 m and the horizontally focusing mirror 52 m from the source. The toroidal mirror was adjusted to focus at 57 m, and the KB mirrors were optimized for best focus at 53 m. Ideally this should reduce the toroidal mirror focus by 5 in the horizontal and 4.2 in the vertical. The result is shown in Fig. 4.

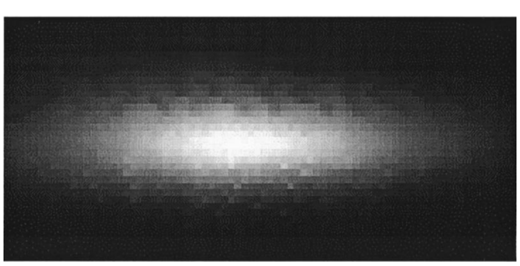

FIG. 2. Image of the focus from the toroidal mirror obtained by scanning a 10 μm pinhole over the focal spot. The full width at half maximum (FWHM) is $390(H)\times 94(V)$ μm.

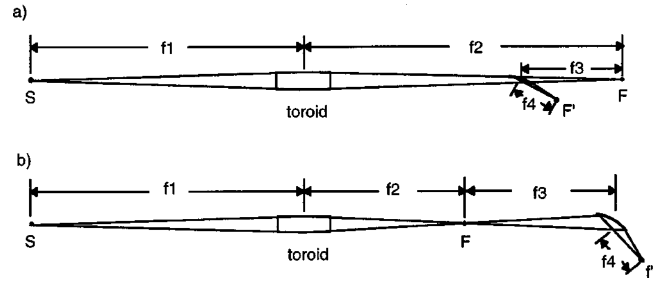

FIG. 3. Two possible geometries for combining a toriodal mirror with a KB mirror. At the PNC-CAT beamline $F1=34.3$ m, and $F2$ varies from 17 to 24 m.

The expected reduction is obtained in the horizontal size. The vertical reduction is less than expected. This is likely due to slope errors in bending to the proper hyperbolic shape. Such slope errors become more important as the focal spot becomes smaller, and ultimately set a lower limit on achievable spot sizes. In any case, the reduction in the horizontal is more important since it starts out much larger. The divergence was not directly measured, but based on the arrangement can be expected to be about 500 μrad horizontally and much less vertically. This type of beam is well suited to experiments like surface diffraction or glancing angle X-ray absorption fine structure (XAFS) in ultrahigh vacuum (UHV) conditions. The divergence is modest and the working distance is large enough to be compatible with large vacuum chambers or diffractometers. The measured flux normalized to 100 mA of beam current was 5×10^{12} at 8 keV using Si 111 crystals in the monochromator. This is close to the 1×10^{13} value obtained in the full unfocused beam.

The combination of these two types of mirrors is a versatile method for focusing. Beam sizes can be controlled independently in the vertical and horizontal from millimeters to microns. In many cases the vertical beam size from the toroidal mirror is already sufficiently small. Then only the horizontally focusing mirror from the KB setup can be used to provide an approximately symmetric 100 μm beam. Another example comes from an anomalous scattering experiment of solutions under pressure. This employed a large Rowland circle detector, and, therefore, was arranged with

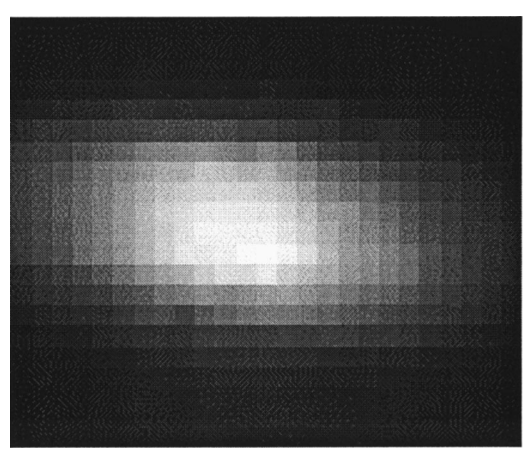

FIG. 4. Image of the focus obtained using the optical layout in Fig. 3(a). The image was measured by scanning a 10 μm pinhole. For the horizontal mirror $F3=5$ m and $F4=1$ m. The FWHM is $72\,(H)\times 39(V)$ μm.

the scattering in the horizontal plane. The sample cell diameter was approximately 100 μm, but to minimize radiation induced bubble formation in the solution, no focusing was desired in the vertical direction. A 100 μm $H \times 1$ mm V beam was provided by unbending the toroidal mirror and combining it with the horizontally focusing KB mirror.

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[5] Manufactured by SESO Inc.