BIFOCAL MINIATURE TOROIDAL SHAPED X-RAY MIRRORS

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ABSTRACT

We have fabricated a bifocal miniature torodial mirror that horizontally and vertically focuses to two different locations to provide a smaller footprint of beam for grazing-incidence wide-angle scattering (GIWAXS), while at the same time focusing the beam in the horizontal direction on the detector to further enhance the angular resolution. At CHESS we traditionally use glass single-bounce monocapillary optics for a wide range of x-ray experiments to get a fine x-ray beam of 5 to 20 µm. This miniature toroidal mirror was prepared by designing and fabricating an x-ray focusing capillary, in which the sagittal and meridional focusing is decoupled, and only a quadrant of the accepted annulus is used for focusing the beam. The mirror produced a 120 µm horizontal by 25 µm vertical focus at 50 mm from the tip of the optic, and a 44 µm horizontal by 70 µm vertical focus at 150 mm from the tip of the optic.

INTRODUCTION

For a number of years the Cornell High Energy Synchrotron Source (CHESS) has been fabricating and using single-bounce monocapillary optics to produce x-ray microbeams [1,2]. With our current technology, these optics have achieved beam sizes of 5 to 50 µm, divergences of 2 to 10 mrad, and gains of 10 to 1000. The microbeams have been used in a large number of projects including protein crystallography [3], micro-small and micro-wide angle x-ray scattering (µSAXS and µWAXS) [2,4], microbeam Laue diffraction [2], micro-x-ray fluoresce (µXRF) [2,5], micro-x-ray diffraction (µXRD) [6], Confocal XRF [7], micro-x-ray absorption near edge structure (µXANES) [8] , and others. In almost every instance, the single-bounce monocapillary optic has an elliptically-shaped taper, with a number of different designs (Figure 1). Elliptic or parabolic optics are commonly used to obtain a common focus point x-ray focus in both the vertical and horizontal directions. The advantages of elliptically shaped optics have been known for some time [9].

However, there are instances where other shapes may be of interest for focusing x-rays as well. Using the glass optical pulling capabilities at CHESS, we have fabricated a miniature bifocal mirror of toroidal shape that horizontally and vertically focuses to two different locations. The toroidal mirror was designed to focus vertically at the sample position and horizontally at the detector position. This mirror was made to provide a smaller footprint of the beam on the sample for grazing incidence wide angle scattering (GIWAXS), while at the same time focusing the beam in the horizontal direction on the detector for better angular resolution in the horizontal direction. No other single-bounce monocapillary has been designed, to date, with a separate horizontal and vertical focal lengths.

MINIATURE TOROIDAL X-RAY MIRRORS

The toroidal monocapillary optic is very similar to an elliptical single-bounce monocapillary optic. It is made by the same optical pulling techniques [2]. Our original work while still maintaining a common focus was driven by microSAXS requirements to reduce the divergence in the microfocused beam, in order to achieve enough resolution for the samples studied [4].

The new miniature toroidal mirror was designed to decouple the sagittal and meridional focusing of the traditional single-bounce monocapillary optic (Figure 1). Essentially, the normal ellipsoidal shape is modified by increasing its inner diameter, changing the sagittal focus, and at the same time not modifying its meridional curvature, i.e. leaving the meridional focus unchanged.

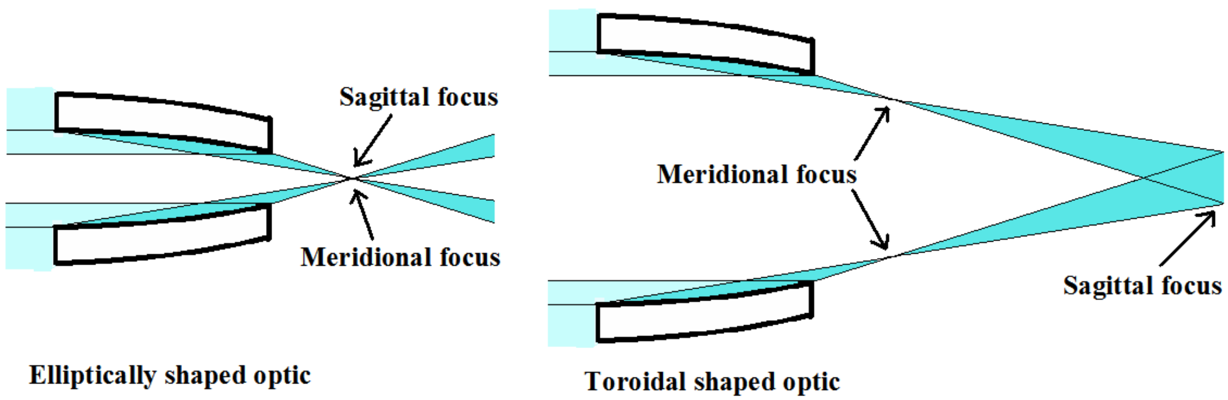

Figure 1 This sketch outlines the modification of a ellipsoidal shape (left) to a toroidal shape (right). The diameter of the optic is changed, thereby decoupling the sagittal and meridional focus. The meridional focus is unchanged, but the sagittal focusing is moved further from the tip of the optic.

Using the entire inner optical surface will not produce horizontal line focus at the sample position and a vertical line focus at the detector position. If the full surface of the optic is exposed to an x-ray beam, a narrow ring of intensity will be at the location of the meridional focus, and a semi large spot will be at the sagittal focus (Figure 2, top row of images). In order to define a line focus, only a section, around 10%, of the optic's inner surface is exposed to the x-ray beam. Slits are set upstream of the optic, which blocks the beam from reaching most of the optical surface except for a selected sector (Figure 2, bottom row of images).

Four test optics were made and two turned out to function correctly. The capillary length was 100 mm with an incident angle of reflection of 1.75 mrad (0.10º) at the tip of the optics, allowing the optic to work up to 17 keV. The mirror produced a 120(H)x25(V) μm^2 FWHM focus 50 mm from the tip of the optic, and a 44(H)x~70(V) μm^2 FWHM focus 150 mm from the tip of the optic at CHESS's D1 station (Figure 3). At the vertically focused position (50 mm from the tip), the focus was not exactly a straight line; it curved up on the sides slightly, giving a "smiley" shape. This is a typical feature of a sagitally focused beam away from the focal spot. From the center to the edges of the vertical focus, the peak intensity shifted by 20 µm.

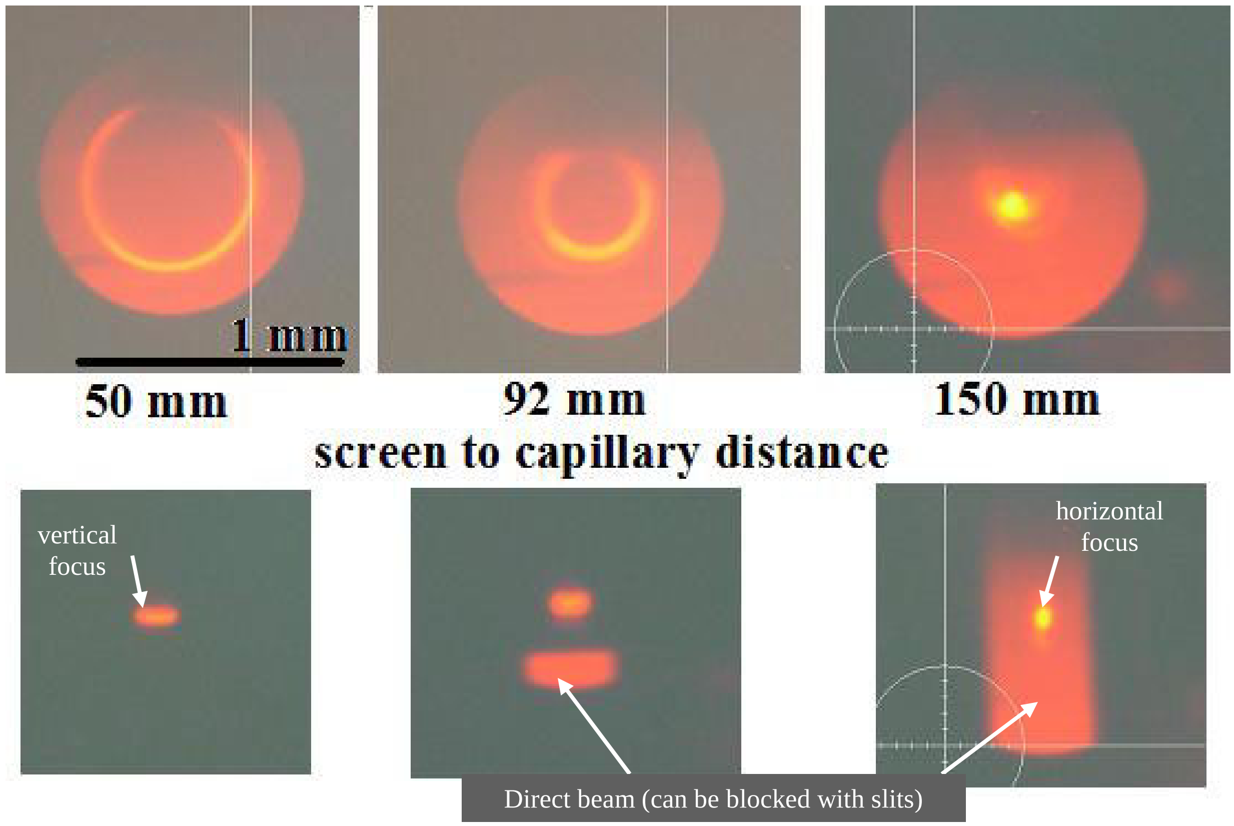

Figure 2 This is a set of x-ray images taken with the gadolinium gallium garnet fluorescent screen viewed by a microscope at various distances from the toroidal mirror's tip. The top row of images shows the effect of exposing the entire optic to the x-ray beam, while for the bottom images only a sector of the optic's inner surface was illuminated. The images on the left are at the meridional focus (50 mm from the tip of the optic), the images on the right are at the sagittal focus (150 mm from the tip), and the center images are between the two (at 92 mm from the tip). For reference, the background red fluorescence is from the direct beam going through the optic, and has a diameter of 1.0 mm in the top images.

In order to design the miniature toroidal mirror, the correct curvatures had to be made on the inner surface of the glass. The curvature of a reflection X-ray mirror in both the sagittal and meridional directions can be calculated from [10]:

$$\rho_{sagittal} = 2 f_v \sin\theta \qquad \rho_{meridional} = \frac{2 f_h}{\sin\theta}$$

Where '$\rho_{sagittal}$' and '$\rho_{meridional}$' are the sagittal and meridional radius of curvature, 'f_v' and 'f_h' are the vertical and horizontal focus locations from the optic, and 'θ' is the incident angle. These equations are meant to give the best approximate spherical curvature of an ellipsoidal shape. We get the correct ellipsoidal shape for the meridional focusing, using Rong Huang's elliptical monocapillary design program for designing ellipsoidal monocapillary shapes [11]. A capillary with a 50 mm focal length, and a 7 mrad tip divergence gives the correct meridional shape (left side of Figure 1). At this point, the meridional shape is set, and the sagittal radius of curvature will have to conform the best it can to the meridional shape. The sagittal curvature is always cylindrical, and hence can only have the ideal curvature at one point along the optic's length for a non-ellipsoidal shape, due to fabrication limits of the puller.

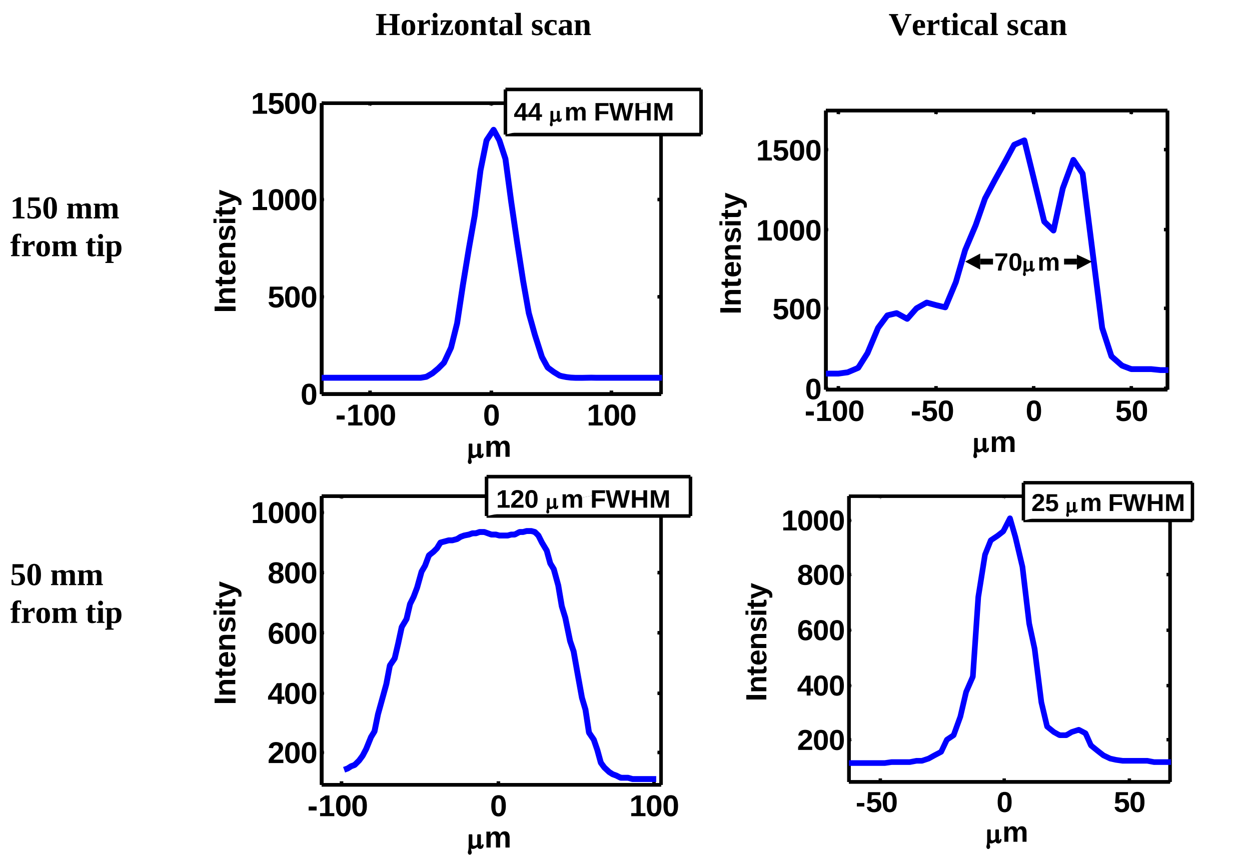

Figure 3 This shows the 5 μm pinhole scans across the bifocused beam at 150 mm (sagittal focus) and at 50 mm (meridional focus). The vertical scan of the beam at 150 mm has features, which are primarily caused by the slope errors along the optic, it has a full width of ~130 μm.

There are three 'natural' locations to set the correct sagittal radius; the tip, mid-point and the base of the ellipsoidal/meridional shape. Table 1 outlines these three options. When the tip, mid-point, or base are set to the correct diameter for the desired sagittal focal length of 150 mm from the tip, the other locations along the miniature toroidal optic have the incorrect diameter for putting the sagittal focal length at 150 mm from the optic's tip. The last column in Table 1 shows where the sagittal focal length ends up for both the base and the tip.

This first design of toroidal mirrors is based on the tip having the correct diameter for sagittal focusing, with a diameter offset of 700 μm from the base ellipsoidal shape. This design was chosen to make the meridional and sagittal focus correct for the GISAXS scattering geometry which requires a sample-to-detector distance of about 100 mm. For a first demonstration of the idea, maximizing the distance between the two focal lengths can more definitively show the optic's separation of vertical and horizontal focusing. For the present design, the tip focused at

150 mm from the optic's tip and the base focused at 220 mm from the optic's tip. In Figure 2, the sagittally focused spot has a halo of intensity around the central spot, in both the top and bottom image. We believe that this comes from the sagittal mis-focusing from the base of the toroidal optic.

	ID (for an ellipse) µm	X-ray incident angle (mrad)	sagittal focus length (mm)	ID for sagittal focusing (µm)	ID offset from ellipse shape (µm)	tip to base sagittal focal length (mm)
tip (50 mm to ellipse focus)	350 (at tip)	1.75 (at tip)	150 (at tip)	1050 (at tip)	700	150-220
mid. (100 mm to ellipse focus)	490 (at mid.)	1.23 (at mid.)	200 (at mid.)	984 (at mid.)	494	120-167
base (150 mm to ellipse focus)	610 (at base)	1.03 (at base)	250 (at base)	1030 (at base)	420	110-150

Table 1 This gives three options for the design of the miniature toroidal mirror, keyed from the tip, middle and base of the optic. The ellipsoidal shape sets the correct shape for meridional focusing. This makes the sagittal focus have a range of focal lengths along the length of the optic, which depends on the chosen design (last column).

We have tested the optic briefly for GIWAXS, but found a flaw in our thinking: at the sample, the beam is sagittally under-focused, and hence the spot shape has the typical "smiley" shape of sagittal focusing optics. The "smiley" get exaggerated due to the grazing-incidence with a typical incident angle of only 0.2deg. Hence there was an extended crescent on the sample instead of a well-defined short streak, and we did not get the improvement in GIWAXS resolution we had aimed for. Thus the reflections of a test sample on the CCD camera were still smeared out radially, as in an unfocused beam.

However, the basic idea of such a bifocal optics may still be revived by noticing that the "smiley" shape is only associated with the sagittal focus, but not with the meridional focus. Reversing the focal lengths so that the sagittal focus is on the sample while the meridional focus is on the detector may be a promising approach. In this case we would need to select a sector of the slit accepted annulus rotated by 90º from the original arrangement. A new design of a glass monocapillary would be needed to test this idea.

Nonetheless, the present bifocal optic may still be very useful for other types of samples or scattering geometries. For instance, diffraction or wide-angle scattering from single fibers or from microfluidic channels could benefit very much from focusing the beam only in one direction at the sample, while maintaining a good resolution in the perpendicular direction. Further tests, both with a redesigned optics for GISAXS and the present optics for fiber diffraction are planned.

CONCLUSIONS

We demonstrated a unique non-ellipsoidal shaped optic, and the first of its kind we have made at CHESS, with CHESS's monocapillary optic pulling technology. It worked as we expected, giving a separated horizontal and vertical focus. The torodial mirror concept opens up new optical design space for us to consider when we encounter experimental x-ray microfocusing problems. It is a shift in thinking that has lead us into some new parameter space for the design of x-ray optics which will prove to be useful in finding solutions for x-ray microbeam work.

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REFERENCES

[1] R. Huang and D. H. Bilderback, "Single-bounce monocapillaries for focusing synchrotron radiation: modeling, measurements and theoretical limits," J Synchrotron Radiat **13**, 74-84 (2006).

[2] Sterling Cornaby, "The Handbook or X-ray Single-Bounce Monocapillary Optics, Including Optical Design and Synchotron Applications," Dissertation, Cornell University (2008).

[3] Donald H. Bilderback, Alexander Kazimirov, Richard Gillilan, Sterling Cornaby, Arthur Woll, Chang-Sheng Zha, and Rong Huang, "Optimizing Monocapillary Optics for Synchrotron X-ray Diffraction, Fluorescence Imaging, and Spectroscopy Applications," AIP Conference Proceedings **879**, 758-763 (2007).

[4] J. S. Lamb, S. Cornaby, K. Andresen, L. Kwok, H. Y. Park, X. Y. Qiu, D. M. Smilgies, D. H. Bilderback, and L. Pollack, "Focusing capillary optics for use in solution small-angle X-ray scattering," J Appl Crystallogr **40**, 193-195 (2007).

[5] K. E. Limburg, R. Huang, and D. H. Bilderback, "Fish otolith trace element maps: new approaches with synchrotron microbeam x-ray fluorescence," X-Ray Spectrom **36** (5), 336-342 (2007).

[6] A. A. Sirenko, A. Kazimirov, S. Cornaby, D. H. Bilderback, B. Neubert, P. Bruckner, F. Scholz, V. Shneidman, and A. Ougazzaden, "Microbeam high angular resolution XRD in InGaN/GaN selective-area-grown ridge structures," Appl Phys Lett **89** (18), - (2006).

[7] A. R. Woll, J. Mass, C. Bisulca, R. Huang, D. H. Bilderback, S. Gruner, and N. Gao, "Development of confocal X-ray fluorescence (XRF) microscopy at the Cornell high energy synchrotron source," Appl Phys a-Mater **83** (2), 235-238 (2006).

[8] Raul A Barrea, Rong Huang, Sterling Cornaby, Don Bilderback, and Tom Irving, "High-flux, hard x-ray micro beam using a single-bounce capillary with doubly focused undulator beam," J Synchrotron Radiat (submitted in 2008).

[9] J. A. Howell and P. Horowitz, "Ellipsoidal and Bent Cylindrical Condensing Mirrors for Synchrotron Radiation," Nuclear Instruments & Methods **125** (2), 225-230 (1975).

[10] Jens Als-Nielson and Des McMorrow, *Elements of Modern X-Ray Physics*. (John Wiley & Sons Ltd, New York, 2001).

[11] Rong Haung, "http://glasscalc.chess.cornell.edu/ImageProf.html," (2004-2008).