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Focusing of X-rays by Total External Reflection from a Paraboloidally Tapered Glass Capillary

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The first observation of a true geometrical focus of X-rays well beyond the exit of a paraboloidally tapered glass monocapillary is reported. An intensity gain of 250 ± 20 into a $6 \times 9\,\mu$m pinhole for 8 keV X-rays and transmission efficiencies of more than 90% below 20 keV were observed.

Keywords: capillary focusing; paraboloidal capillaries.

1. Introduction

Single-capillary X-ray optics have been the subject of considerable work in recent years. The principal aim of this work is the development of a simple optic capable of concentrating X-rays with a range of energies into a very small spot, thereby producing a substantial intensity increase over a small area. Thiel, Bilderback & Lewis (1993) have reported very significant intensity gains into spots as small as 0.3 µm in diameter. However, the transmission efficiency of these devices, defined as the fraction of the radiation entering the capillary that exits from the exit aperture, is very small. Also, the X-rays make multiple reflections within these devices so that no true focal point exists and the beam expands uniformly past the exit aperture (Attaelmanan, Voglis, Rindby, Larsson & Engström, 1995; Engström, Fiedler & Riekel, 1995). This fact limits these capillaries to applications where very short working distances are acceptable. A superior capillary design would provide a region of maximum X-ray intensity well removed from the capillary tip, with the position of this intensity maximum ideally independent of X-ray energy. The paraboloidal and ellipsoidal taper profiles offer these features by producing a region of maximum X-ray intensity at their focal points for suitable X-ray source geometries. Grazing-incidence optics have previously been used successfully for soft X-ray focusing (Pearlman & Benjamin, 1977; Hasegawa, Taira, Harada, Aoki & Ninomiya, 1994). These optics utilize similar geometries at larger scales to accomplish X-ray beam focusing into large focal areas and with low collection efficiencies.

The reflectivity of the capillary glass surface is approximately a step function with respect to glancing-incident angle, with the position of the sudden drop in reflectivity being termed the critical angle (Henke, Gullikson & Davis, 1993; Stern, Kalman, Lewis & Lieberman, 1988). For glancing angles of incidence below the critical angle, essentially all incident X-rays at the surface are specularly reflected if the surface is sufficiently smooth. The capillaries also have sufficient wall thickness to render X-ray transmission through the glass negligible. Balaic & Nugent (1995) have recently presented a general theoretical model demonstrating that the approximately conical capillary profiles that have been investigated are inevitably of very limited efficiency. It is found that the efficiency of capillary devices can be drastically improved by limiting the number of reflections a photon must undergo, and decreasing the incident angle at each of these reflections. A capillary with a paraboloidal taper profile is of particular interest because it offers a true geometrical point focus for well collimated axially incident X-rays (Welford & Winston, 1978). Such a capillary constitutes a small parabolically curved X-ray mirror with cylindrical symmetry.

For an ideal optic the resolution of this focal point is diffraction-limited. Further, the paraboloidal capillary can be truncated short of the position of this focus to provide an unobstructed focal plane for experimental use. The position of this focus will not change with X-ray energy and may therefore be used with either monochromatic or white-beam synchrotron radiation. The potential for very high reflection efficiency also suggests that these devices may in fact be uniquely suited for focusing high-intensity white synchrotron radiation. In contrast, previously reported capillary experiments (Attaelmanan *et al.*, 1995; Engström, Larsson & Rindby, 1991; Engström *et al.*, 1995; Hoffmann, Thiel & Bilderback, 1994; Thiel *et al.*, 1993) and simulations (Voss, Kim, Stern, Brown & Heald, 1994) demonstrate beam condensing rather than focusing, with the narrowest cross section in the condensed beam being observed at the exit aperture of the capillary.

2. Experimental procedure

In this paper we present the first demonstration of a paraboloidally tapered X-ray focusing capillary which exhibits substantial intensity gains into a rather large focus combined with a very high transmission efficiency. The capillary was produced by a novel technique that enables us to draw a predetermined capillary profile with considerable precision. This technique will be described in a further publication. Fig. 1 shows the experimentally determined profile of a capillary drawn to a paraboloidal shape. This capillary has an entrance diameter of 800 μm and was cut so as to have an output diameter of 300 μm. With this capillary, parallel axially incident X-rays are brought to a focus smaller than the exit aperture and located well beyond it. The capillary was designed to produce an X-ray focus nominally 39 mm beyond the end of the capillary. The size of the focus is determined by the accuracy of the taper profile, which is in turn determined by the accuracy of the drawing procedure.

The capillary was investigated on beamline 20B (the Australian National Beamline Facility) of the Photon Factory synchrotron in Tsukuba, Japan. The capillary was aligned with the aid of a pair of motorized *xy* translation stages placed perpendicularly to the beam propagation direction at each end of the capillary. These stages aligned the capillary coaxially with an X-ray beam monochromatized by a channel-cut silicon crystal (Fig. 2). The incident beam was collimated down to 1 × 1 mm in cross section by a crossed-slit arrangement placed at the capillary entrance. Observation of the beam issuing from the capillary with a phosphor screen placed 60 cm from the exit aperture showed an intense spot surrounded by an annulus of comparable intensity. The annulus was slightly asymmetrically displaced with respect to the central spot for the best alignment of the capillary, indicating a slight bend in the capillary. The annulus could be moved with small translations of the capillary tip. The central spot remained stationary during these translations. We therefore concluded that the central spot consisted of X-rays that had not been reflected by the capillary walls and was produced by the straight-through collimated beam. The surrounding annulus corresponded to the focal rays diverging past the focal plane. A further motorized translation stage was then used to deflect the capillary in the direction opposite to the observed bend indicated by the asymmetry of the annulus. This had the effect of both centring the annulus about the central collimated-beam spot and increasing the observed focal intensity. The X-rays issuing from the capillary were scanned using a knife-edge and a 6 × 9 μm crossed-slit aperture mounted on an *xyz* translation stage with the *z* axis directed along the beam path. As a reference, incident beam intensity measurements were also taken through a 0.75 mm reference pinhole. Intensities were measured using an ionization chamber containing air.

By translating a knife-edge laterally through the beam issuing from the capillary at 5 mm intervals from its exit aperture and observing the beam intensity as a function of knife-edge position, an optimal focal region was found. The rate of change of the observed intensity with respect to the position of the knife-edge was calculated and the full width at half maximum intensity found. Fig. 3 shows both the FWHM and peak intensity deduced from this data. The smallest observed beam width indicates the position of the focus in the beam. The optimal focus was thus found to be located 25 mm from the exit aperture of the capillary. This compares with the designed position of 39 mm. The discrepancy between the expected and observed focal plane positions is attributable to figure error in the taper profile of the capillary.

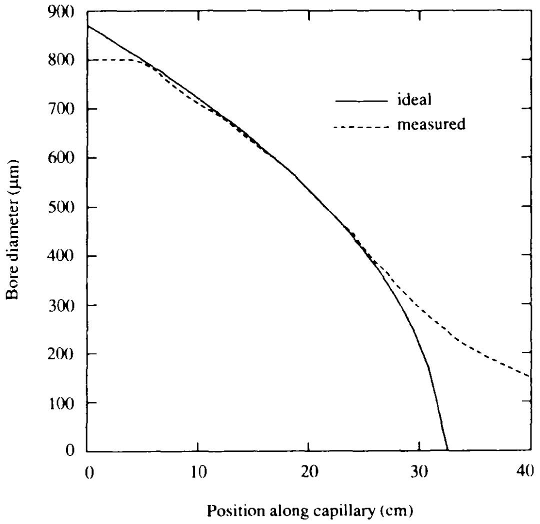

Figure 1
Measured capillary taper profile compared with ideal paraboloid taper. The capillary was subsequently truncated at 5 and 29 cm.

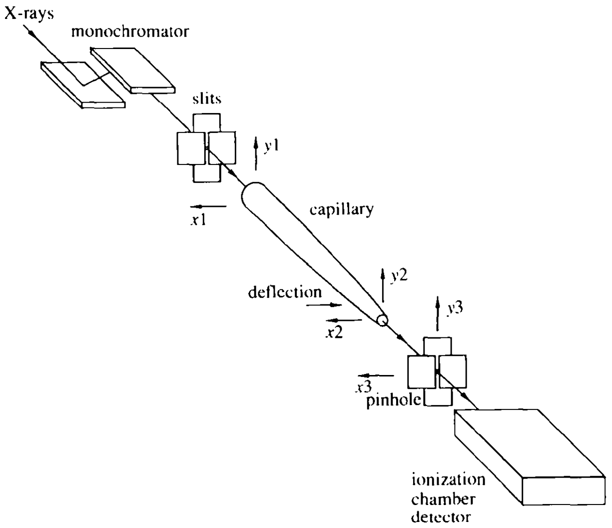

Figure 2
Experimental arrangement for the capillary focusing experiments.

A raster scan was then performed using the crossed-slit aperture in the focal plane in front of the ion chamber, using 8 keV X-rays. The resulting intensity distribution is shown in Fig. 4 as a function of the position coordinates *x* and *y* perpendicular to the beam axis. The figure shows a circular disk of low intensity of approximately 300 µm diameter that corresponds to the straight-through beam which undergoes no reflections in the capillary. Superimposed on this disk is a peak of 40 ± 5 µm FWHM, corresponding to the focal spot of the focused beam. By measuring the intensity through the pinhole at the position of the intensity maximum in the focal plane and comparing it with the raw intensity in the incident beam at the same position (found by removing the capillary from the experiment), we measured an intensity gain of 250 ± 20 at 8 keV into an area of 6 × 9 µm.

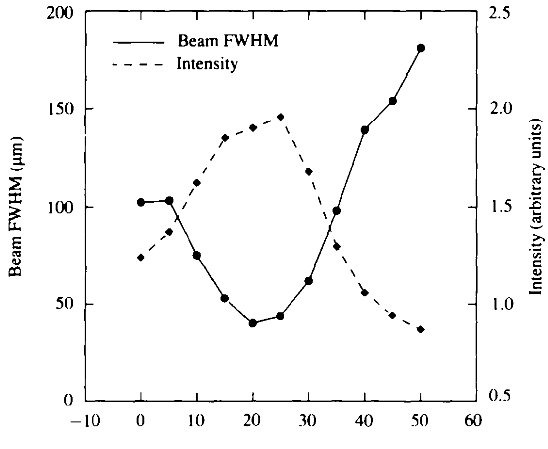

Figure 3
Capillary beam FWHM intensity and observed peak intensity *versus* distance from the exit aperture of the capillary for 8 keV X-rays.

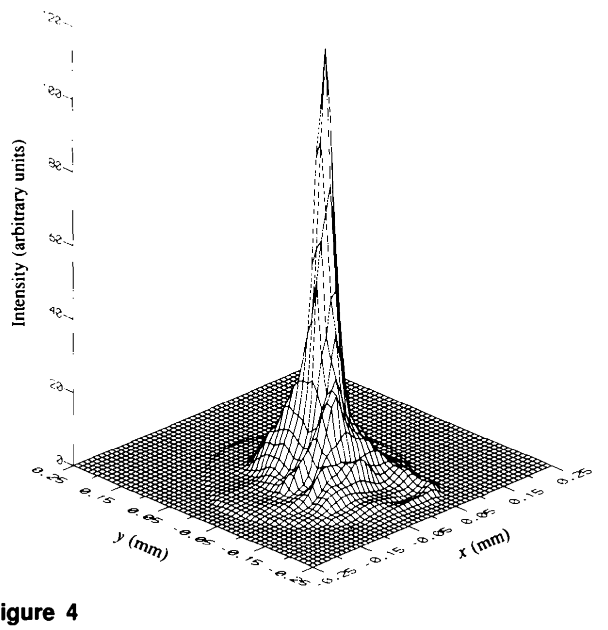

Figure 4
Focal plane intensity distribution for 8 keV X-rays at a distance of 25 mm from the capillary exit. In this plot, the straight-through beam can be clearly seen as a circular disk of low intensity.

We subsequently measured the transmission efficiency of the capillary as a function of X-ray energy by sweeping the monochromator from 5 to 20 keV with the capillary in place and performing the same experiment with a 0.75 mm lead pinhole in place of the capillary. The intensity transmitted through the capillary as a function of X-ray energy was divided by the intensity observed as a function of X-ray energy through the 0.75 mm pinhole, corrected for the entrance aperture area. This experiment showed that below 7 keV the capillary is essentially 100% efficient (although a maximum of 83% of the incident flux is actually focused by this capillary). That is, within measurement error, none of the radiation entering the capillary is absorbed by the optic. This is to be expected because the reflectivity of borosilicate glass is almost 100% for glancing angles of incidence below the critical angle, and the steepest taper present in the capillary (nearest the exit aperture) is much less than the critical angle of 4 mrad for 7 keV X-rays. Above this energy, the efficiency begins to drop to a lowest measured value of 90% at 20 keV. This decrease in focused intensity remains within the confidence limits given above for the observed intensity gain.

3. Conclusions

We have reported the first demonstration of a focused X-ray beam from a capillary optic. Exceptionally high throughput into a focal region well removed from the tip of the capillary has been observed. This overcomes a major disadvantage of capillary optics: the very short working distance. The focal spot we observed is relatively large; however, with further development, we are confident that smaller diameter foci may be achieved. In any case, we found that the intensity gain at the peak of the focus exceeds two orders of magnitude for a range of X-ray energies.

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