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Submicrometer hard X-ray focusing using a single-bounce ellipsoidal capillary combined with a Fresnel zone plate

A. Snigirev,[a]* A. Bjeoumikhov,[b] A. Erko,[c] I. Snigireva,[a] M. Grigoriev,[d] V. Yunkin,[d] M. Erko[b] and S. Bjeoumikhova[e]

[a]European Synchrotron Radiation Facility, 6 rue Jules Horowitz, 38043 Grenoble, France, [b]IFG Institute for Scientific Instruments GbmH, Rudower Chaussee 29/31, 12489 Berlin, Germany, [c]BESSY GmbH, Albert-Einstein-Strasse 15, 12489 Berlin, Germany, [d]IMT RAS, 132432 Chernogolovka, Moscow Region, Russia, and [e]Bundesanstalt fur Materialforschung and Prufung, 12200 Berlin, Germany. E-mail: snigirev@esrf.fr

A single-bounce capillary with an ellipsoidal shape has been used for two-step focusing in combination with a Fresnel zone plate (FZP). The FZP serves as a first microfocusing element and produces a demagnified micrometer image of the source, before the elliptical capillary makes a last final compression of the beam. With 15 keV X-rays from the European Synchrotron Radiation Facility BM5 bending magnet, the two-step demagnification system produced a focus of about 250 nm with a gain of more than 1000. The use of an ellipsoidal capillary as a micro-mirror under off-axis illumination using micro-prefocusing optics might open up new opportunities in nanofocusing developments.

Keywords: hard X-ray focusing; single-bounce capillary; Fresnel zone plate.

As part of reflective optics, tapered glass capillaries were shown to have nanofocusing capabilities more than ten years ago (Bilderback *et al.*, 1994); however, no appreciable progress in using such simple devices for X-ray nanobeams has been made since. Problems consist of significant losses in the multireflection process and almost zero working distance, which substantially limits practical applications of tapered multi-bounce capillaries. However, the single-bounce capillaries proposed by Balaic *et al.* (1995) have a reasonable focal distance and high reflectivity (Balaic *et al.*, 1995; Huang & Bilderback, 2003, 2006; Bjeoumikhov *et al.*, 2005). In a typical process the pre-determined parabolic or elliptical capillary profile is achieved by pulling an originally straight glass tube with accurate control of mechanical movements and heating parameters. Owing to unavoidable inner-surface slope errors of the original glass tube, the best capillaries have 70 µrad slope errors (Huang & Bilderback, 2006), limiting the focusing performance to 10 µm.

To overcome these problems we propose to use a small elliptical capillary made from a bubble injected into the molten glass. We believe that this approach provides a better quality surface compared with the computer-controlled glass tube pulling process with variable speed. The final parameters of the ellipse are defined by the diameter of the bubble and pulling factor: major axis $2a$ = 95 mm and minor axis $2b$ = 50 µm. The capillary, of length 46.9 mm, has an entrance diameter of 50 µm and an output diameter of 8 µm, providing a working distance of 0.6 mm.

For best performance of the ellipsoidal capillary, we use a two-step focusing set-up where a Si Fresnel zone plate (FZP) (Snigireva *et al.*, 2007) serves as a first microfocusing element and produces a demagnified image of the source, before the elliptical capillary makes a last final compression of the beam down to a submicrometer spot (Fig. 1). Such a step-wise focusing set-up offers (i) non-aberrational focusing by the elliptical capillary, (ii) optimized overall acceptance of the optical system and (iii) selection of the proper fraction of the capillary reflecting surface, minimizing figure errors.

The two-step focusing set-up was tested at the micro-optics test bench located at ESRF beamline BM5 (http://www.esrf.fr/UsersAndScience/Experiments/Imaging/BM05/BeamlineGuide/EH2/MicroOpticsTest/). A 15 keV energy X-ray beam, after a double-crystal Si (111) monochromator, was focused by a Si FZP (Fig. 1). The main FZP parameters are: aperture A = 194 µm, outermost zone width Δr_n = 0.4 µm. The FZP focal distance at 15 keV was 950 mm. The height of the FZP structure was 16 µm, providing about 30% diffraction efficiency at 15 keV. The slits placed close to the FZP

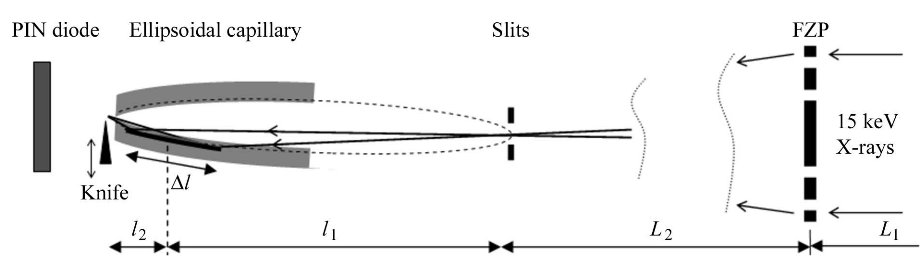

Figure 1
Two-step focusing experimental set-up. L_1 = 55 m is the distance from the bending-magnet source to the FZP position, L_2 = 0.95 m is the FZP image distance. Δl is the footprint of the beam impinging on the surface of one side of the capillary (thick curve). l_1 is the distance from the FZP focus to the mid-position of the beam footprint on the capillary surface, and l_2 is the distance from the mid-position of the footprint of the beam to the capillary focus.

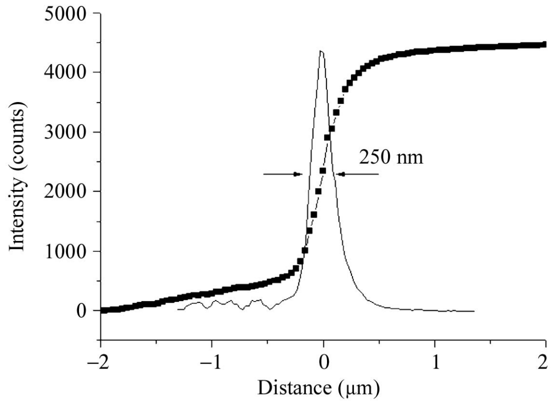

Figure 2
Vertical scan of a 200 μm Au wire as a knife-edge through the microbeam with extracted beam profile.

focus selected the first-order focusing and decreased the background from other orders. The secondary source produced by the FZP was 2.2 μm vertically and 5 μm horizontally [full width at half-maximum (FWHM)], corresponding to a demagnification factor of $M_1 = L_1/L_2 = 58$.

Taking advantage of the tiny focus beam generated by the FZP, we use an off-axis focusing geometry. For this we have tilted the capillary around the first focus point by approximately 0.1 mrad so that only a small part of the capillary side-wall is involved in the reflection. In fact, by changing the tilt angle we can vary the position of the beam on the capillary surface and therefore we can easily control the demagnification factor $M_2 = l_1/l_2$.

The best focal spot, of the order of 250 nm (FWHM), was measured for a capillary tilt angle of 0.08 mrad corresponding to a 5 mm footprint of the beam impinging on the surface of one side of the capillary (Fig. 2). Assuming that the measured focal spot is a convolution of the geometrically demagnified source size with slope errors, we estimate the slope errors to be better then 50 μrad. The overall gain of the two-step focusing system was higher than 1000 compared with a flat monochromatic beam. Applying the FZP, a flux enhancement by almost a factor of four in comparison with single capillary focusing was measured.

In general, the two-step focusing set-up provides three important benefits: it significantly improves the flux by increasing the overall acceptance of the optical system; it allows optimal aberration-free focusing by the elliptical capillary surface, and it considerably minimizes the influence of slope errors. For practical applications, off-axis illumination of the capillary by small pre-focused beam eliminates the beam transmitted through the exit aperture and makes for an easy implementation of a beam stop. By accurate scanning of the tiny beam along the capillary surface, one can control the demagnification factor and zoom the focal spot size.

The proposed approach allows a small capillary to be shortened further down to 5–10 mm, making it easy to align and operate. Use of short capillaries might open the possibility of coating the inside of capillaries with smooth films of desirable materials such as platinum or gold, thus making metal capillary optics appear very attractive (Hirsch, 2003). Finally, the single-bounce ellipsoidal capillaries are very appealing for X-ray nanobeam techniques because they are simple and have the potential to be reproduced inexpensively.

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