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Hard X-ray nano-focusing with Montel mirror optics

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ABSTRACT

Kirkpatrick–Baez mirrors in the Montel (or nested) configuration were tested for hard X-ray nanoscale focusing at a third generation synchrotron beamline. In this scheme, two mirrors, mounted side-by-side and perpendicular to each other, provide for a more compact focusing system and a much higher demagnification and flux than the traditional sequential K–B mirror arrangement. They can accept up to a 120 μm × 120 μm incident X-ray beam with a long working distance of 40 mm and broad-bandpass of energies up to ∼30 keV. Initial test demonstrated a focal spot of about 150 nm in both horizontal and vertical directions with either polychromatic or monochromatic beam. Montel mirror optics is important and very appealing for achromatic X-ray nanoscale focusing in conventional non-extra-long synchrotron beamlines.

1. Introduction

Although traditional Kirkpatrick–Baez (K–B) mirrors [1] are widely used for synchrotron micro/nanofocusing, Montel (or nested K–B) mirror optics [2] are very appealing because of their compact design with stronger demagnification and the ability to collect larger divergences. Recent papers have described their advantages for neutron microfocusing [3] and for possible synchrotron applications [4,5]. With traditional K–B optics, X-rays are focused by sequential elliptical surfaces. Fabrication of ultra-precise mirror surfaces has been achieved to create the smallest doubly and singly focused beams to date [6,7]. With nested K–B optics however the two elliptical mirrors are positioned side-by-side and perpendicular to each other, as illustrated in Fig. 1. Some rays strike one mirror first while others strike the other mirror first. This geometry has important advantages compared with traditional sequential arrangement: the focal distance of the mirrors is much shorter than that for the primary mirror of a comparable sequential K–B system, which creates a greater geometrical demagnification of the source and reduces the effect of figure errors (in one direction), and the larger divergence allows for greater flux and/or a lower diffraction limit; the mirrors can be easily aligned to be orthogonal, which is critical for nanofocusing, and the mirror system is much more compact.

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2. Optical design and mirror fabrication

Many efforts have been made in recent years to use multilayer mirrors to increase the numerical aperture for lowering the diffraction limit [7–9]. However multilayer mirror optics typically has a restricted energy bandpass. To preserve achromatic focusing performance, total-external-reflection X-ray mirrors are still essential for applications such as diffraction experiments and extended X-ray absorption fine structure measurements. The prototype hard X-ray nanofocusing Montel system has been designed for Laue diffraction microscopy at the 34-ID-E station of the Advanced Photon Source (APS) [10]. The experimental station is located about 60 m from the source. A horizontal slit at 28 m was placed to control the total power in the beam and to reduce the horizontal source size to <100 μm; thus the slit also acts as a new effective object. In the vertical plane, the APS type-A undulator source, with FWHM of about 40 μm serves directly as the object [11].

In a Montel system, the mirror surfaces must come together at the corner of the mirror pair. Instead of cutting a prefigured mirror into two parts at a 45° angle to the surface at edges, we cut the edge of one mirror at slightly less than 90° at edge to "nest" against the companion mirror. The advantage of this approach is that only the edge of one mirror must be used, and the alignment is primarily one-dimensional at each end of the mirror pair. The two elliptical mirrors are both 40 mm long and coated with Pt to produce an identical focal length of 60 mm at 3 mrad incident angles. They can accept up to a 120 μm × 120 μm incident X-ray beam with a broad-bandpass of energies up to 30 keV.

The main challenge of nested mirror fabrication and assembly is to preserve the mirror surface quality at the reflecting edge. Two

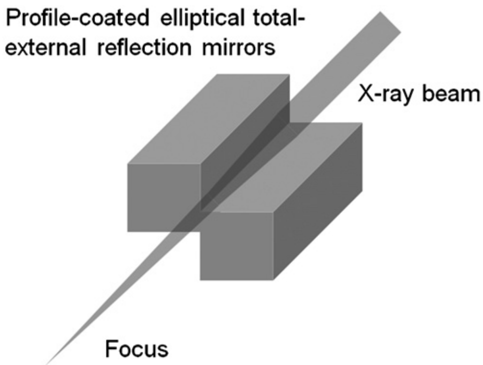

Fig. 1. Schematic of Montel mirror optics for a more compact focusing system.

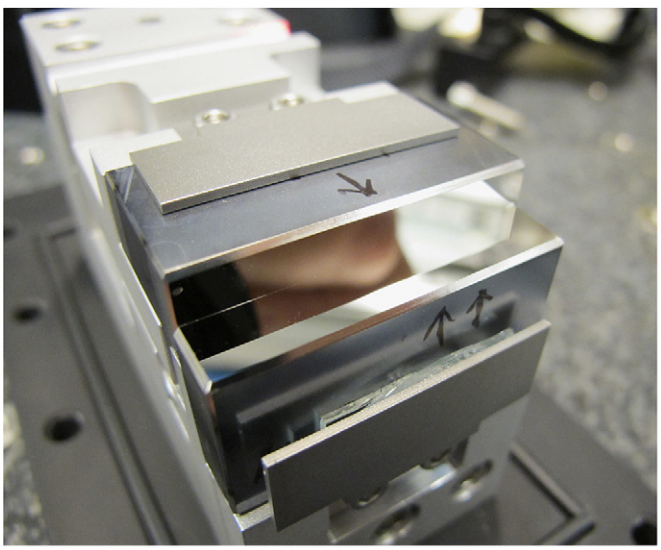

Fig. 2. Assembled mirror pair of the prototype Montel system. The mirror position and orthogonality were preset on a flexure based fixture with no motorized parts.

identical flat mirror substrates with dimensions of 40 mm (L) × 9 mm (W) × 20 mm (H) were chosen for producing the nested mirror pair. The quality of the mirror edge after polishing is expected to have roughness of about 0.1 nm rms and figure error of <1 nm P–V. However, chipping and micro-cracking at the edge were observed. A profile coating technique was used to convert inexpensive flat (or spherical) Si substrates into precise elliptical mirror surfaces [12]. The shape of the contour was calculated according to the desired elliptical profile of an ideal final mirror and from the measured shape of the original substrate surface. All the nested K–B mirrors were profile-coated with platinum. The metrology results using a stitching interferometer indicate that 0.76 nm rms height-error-accuracy remains in the horizontal mirror. However for the vertically deflecting mirror surface, the rms of the profile is about 3.0 nm after side-polishing. The increased rms values are due to chips at the edge, shown in the metrology measurement as sharp spikes.

The orthogonality of the mirror pair was checked by using a laser beam reflected from the corner where the two mirrors come together. There are typically two spots reflected by the alternative paths at the mirror joint. By adjusting the tilt, these spots are brought together and the mirror orthogonality is easily set at 100 μrad or less. A picture of the assembled mirror pair is shown in Fig. 2. The mirrors were mounted on a small fixture that allowed the horizontally deflecting mirror to be nested tight against the vertically deflecting mirror and rotated to make the two mirrors precisely orthogonal to each other. The gap of about 8 μm between the mirrors can be seen in the microscope, whereas with ideal positioning the gap should have been less than 5 μm for a straight line edge.

3. X-ray focusing performance and discussion

The mirror assembly was mounted on a six-axis hexapod stage for positioning and alignment of mirrors in both horizontal and vertical directions in the incident X-ray beam. A 6 ton granite optical table was used as the platform for focusing performance tests of the prototype Montel system. A removable small-displacement Si (1 1 1) double-crystal monochromator at the beamline allows rapid X-ray beam change between monochromatic and polychromatic modes. To measure the focal spot, a series of thin Au film stripes are scanned across the beam at glancing angle. Each stripe is equivalent to a ~20 nm wide pseudo-slit or reflector. Either Au fluorescence or the reflected intensity was collected for quickly locating and precisely measuring the focal spot [11].

A doubly focused spot of about 150 nm in both horizontal and vertical directions with either polychromatic or monochromatic beams was achieved. Fig. 3a shows 157 nm FWHM with monochromatic beam at 15 keV, and Fig. 3b shows a similar measurement made with polychromatic beam. The slightly smaller spot size of 151 nm indicates that there may be some focal blurring introduced by the monochromator. In the actual measurements, $50 \times 50\ \mu m^2$ beams were used with small adjustments in the mirror positions to search for the best part of the mirror surfaces and the mirror angles were adjusted to optimize the focal spot size. The transmission efficiency of the optics was checked by measuring the total flux in an ion chamber with or without the focusing mirrors. Measurements were performed at 11 keV to avoid the Pt L-absorption edges. Theoretically, one mirror should have reflectivity of 94%, while two mirrors should have a combined reflectivity of 89%. The measured reflectivity was 92% from the horizontal focusing mirror, which was close to theory. However, when the edge-polished vertical mirror was brought together with horizontal mirror, the overall reflectivity of the nested mirror system became 45%. This indicates significant losses of flux near the edge of the vertical mirror. When the edge of the mirror that is placed against the elliptical surface of its companion mirror is a straight line, intensity is lost from the doubly focused beam if either first or second

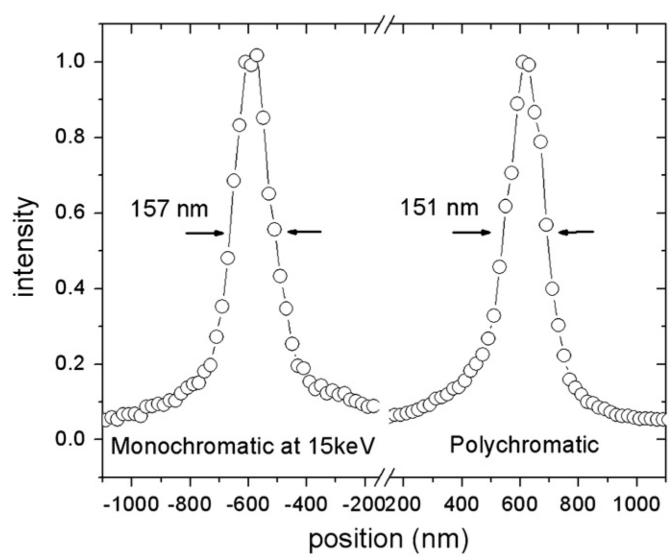

Fig. 3. Focal spots of a monochromatic beam at 15 keV and a polychromatic beam.

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reflections occur at the gap between the mirrors. The measured gap at mirror corner could explain up to a ~25% loss of flux. The additional losses are believed to be due to chipping of the edge.

In principle, perfect optics of the designed Montel focusing system can reach diffraction-limited two-dimensional focusing of ~40 nm in both directions. The current prototype is limited by several factors including mirror imperfection, beamline geometrical demagnification, vibrations of the optical system, and thermal beam instabilities. Improved thermal and mechanical stability of the focusing system, as well as mirror fabrication with higher performance are needed. New polishing procedures have since been developed to eliminate virtually all the edge chipping. Focusing efficiency is expected to significantly increase by side-polishing the mirror to make a simple cylindrical edge to reduce the missing portion of the mirror to below 1%. Better mirror control using a high-stiffness tip-tilting stage system with nanoradian-level multidimensional positioning resolution is also under development. Kirkpatrick–Baez mirrors in the Montel arrangement are important for non-dispersive nano-focusing of hard X-rays over a wide bandpass. It is particularly appealing to use in conventional (~60 m) synchrotron beamlines, which usually do not have sufficient geometrical demagnification to achieve sub-100 nm focal spot with a practical working distance.

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