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Development of *in situ*, at-wavelength metrology for soft X-ray nano-focusing

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ABSTRACT

At the Advanced Light Source (ALS), we are developing broadly applicable, high-accuracy, *in situ*, at-wavelength wavefront slope measurement techniques for Kirkpatrick–Baez (KB) mirror nano-focusing. We describe here details of the metrology beamline endstation, the at-wavelength tests, and an original alignment method that have already allowed us to precisely set a bendable KB mirror to achieve a FWHM focused spot size of ∼120 nm, at 1 nm soft X-ray wavelength.

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1. Introduction

The comprehensive realization of exciting advantages of new third- and fourth-generation synchrotron radiation light sources requires concomitant development of reflecting and diffractive X-ray optics capable of micro- and nano-focusing, brightness preservation, and super-high resolution. The fabrication, tuning, and alignment of the optics are impossible without adequate metrology instrumentation, methods, and techniques [1]. While the accuracy of *ex situ* optical metrology at the Advanced Light Source (ALS) has reached a state-of-the-art level [2–4], wavefront control on beamlines is often limited by environmental and systematic alignment factors, and inadequate *in situ* feedback.

At ALS beamline 5.3.1, we are developing broadly applicable, high-accuracy, *in situ* at-wavelength wavefront measurement techniques to surpass 100 nrad slope measurement accuracy for Kirkpatrick–Baez (KB) mirrors [5]. The at-wavelength methodology we are developing relies on a series of tests with increasing accuracy and sensitivity. Scanning slits tests, performed with a scanning illuminated sub-aperture, determine the wavefront slope across the full mirror aperture [6]. Shearing interferometry techniques use coherent illumination and provide higher sensitivity wavefront and slope measurements [7]. Combining these techniques with high precision optical metrology and experimental methods enables us to provide *in situ* setting and alignment of bendable X-ray optics to realize diffraction-limited, sub-50 nm focusing at beamlines.

We describe here details of the metrology beamline endstation, the at-wavelength tests, and original experimental techniques that have already allowed us to precisely set a bendable KB mirror to achieve a FWHM focused spot size of ∼120 nm, at 1 nm soft X-ray wavelength.

2. Metrology beamline and the test mirror

Metrology beamline 5.3.1 at ALS has a versatile design with a broad energy range from 30 eV to 12 keV, and a long optical bench suitable for metrology development. As detailed elsewhere [8], X-rays from an ALS bend magnet are focused by a 1:1 toroidal mirror, M1, and pass through a monochromator, comprised of a pair of W/B_4C multilayer mirrors with 4 nm period, which select the wavelength to be about 1 nm. The M1 toroidal mirror focuses the incident X-rays 12 m downstream. This focus is formed inside a 2 m long vacuum chamber of a dedicated experimental endstation. Since mechanical vibration can degrade focusing performance, vibration isolation was a primary consideration in the endstation design [8]. The interior optical breadboard, which supports the KB test mirror assembly and the optical components in both conjugate planes, is rigidly supported by the main optical table, and is thereby decoupled from vibrations of the vacuum chamber.

The experiments described here were conducted with a single, bendable, KB test mirror prepared at the ALS Optical Metrology Laboratory (OML). The mirror substrate is made of crystal silicon and is 102 mm in length and 4 mm in thickness. The substrate is side-profiled to enable it to achieve the desired elliptical shape when optimally bent. Before installation at the beamline, the mirror is optimally bent at OML to the desired shape, as described

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Table 1
Specifications of the KB mirror.

Soft X-ray wavelength	Object distance	Image distance	Central-ray grazing angle	Numerical aperture	Residual RMS slope error[a]
1 nm	1600 mm	120 mm	8.0 mrad	3 mrad	0.4 μrad

[a] RMS slope error is measured *ex situ* using long trace profilometry.

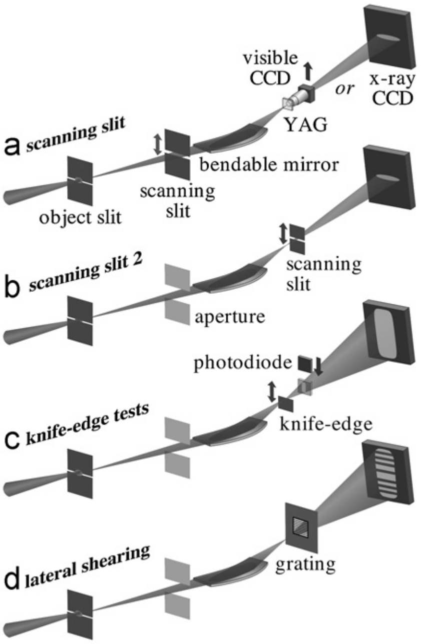

Fig. 1. *In situ*, at-wavelength tests: a series of tests with increasing accuracy and sensitivity.

in Table 1 [8]. In order to mitigate the environmental temperature sensitivity of the mirror shape, a Peltier temperature-stabilization system is attached to the KB mirror-bender assembly [9]. Molybdenum glue-blocks are attached to the ends of the mirror to improve thermal conductivity between the mirror and the bending mechanism. Using this system, we have previously reported that temperature stabilization of the mirror–bender assembly effectively stabilizes the mirror shape [9].

3. At-wavelength testing methodology

Fig. 1 shows a series of at-wavelength tests currently under development at ALS [8]. The tests are performed repeatedly during *in situ* alignment and tuning as the system approaches an optimized condition. The scanning-slit test and the knife-edge test were used to characterize and optimize the alignment, respectively, of the single KB mirror used (Table 1). This one-dimensional focusing enables us to isolate and study the performance of various testing methods without the complication of two mirror reflections, yet the methods can be easily extended to two-dimensional focusing. All of the tests rely on well-conditioned illumination from a small slit in the object plane of the test mirror. ALS beamline 5.3.1 provides a monochromatic beam ($E/\Delta E = 500$) focused to a 150 μm (vertical) × 300 μm (horizontal) spot. To generate a cylindrical beam for one-dimensional focusing tests, a nanofabricated entrance-slit spatial filter was placed in the object plane of the KB mirror.

The simplest and most widely used at-wavelength technique for X-ray mirror alignment and tuning is the scanning-slit test [6]. A movable slit placed before the mirror (Fig. 1a) restricts the illuminated portion of the mirror in steps and the lateral position of the line-focus on the YAG plane is measured as a function of beam position along the mirror's clear aperture. Owing to the mirror's elliptical shape and oblique angle of incidence, there is a non-linear relationship between scanning-slit position and beam position on the mirror surface, and accurate interpretation of the results as wavefront slope measurements requires a coordinate transformation. The scanning-slit test has another variation (also Fig. 1a) that records the transmitted beam on an X-ray CCD camera; the additional detector distance enables greater precision in slope measurements but requires careful systematic error correction to compensate for the non-linear mapping. Fig. 1b shows a geometry with the scanning-slit placed downstream of the focus. The interpretation of this test is very similar to that of the well-known Hartmann test.

The knife-edge test (Fig. 1c), performed with an opaque, nanofabricated edge, reveals the size of the focal spot determined by all perturbations, including diffraction, mirror shape error, misalignment, vibration, etc. When placed close to the plane of best focus, the knife-edge is moved in steps that are smaller than the diffraction-limited beam focal spot. In the knife-edge test described in this report, intensity is measured with a large area photodiode placed beyond the knife-edge. A second version of the knife-edge test (Fig. 1c) records a series of diffraction patterns using the downstream X-ray CCD camera. Such measurements enable us to quantitatively extract wavefront slope information across the pupil.

For *in situ* wavefront slope measurements, lateral shearing interferometry offers additional sensitivity [7], speed, and analysis simplicity. A relatively coarse grating (4–8 μm pitch) is used to maximize the overlap of various diffraction orders in the CCD plane. The fringe pattern can be analyzed to reveal the wavefront slope in the direction of the shear.

4. Original procedures for precise *in situ* mirror alignment

To install an optimally pre-bent KB mirror at a beamline, there are two critical first-order alignment parameters: the mirror tilt (pitch) angle and the longitudinal focal plane position. In this section we demonstrate that the method of characteristic functions, originally developed for the optimal setting of bendable optics [4] with two free parameters, can be extended to systematically optimize the alignment of a single KB mirror *in situ*.

It can be shown [4] that due to the near linearity of the bending problem, the minimum set of data necessary for tuning two bending couples consist of three slope traces measured before and after a single adjustment of each bending couple. From the measurements, the experimental characteristic functions of the benders, which describe the response of the mirror surface shape to a unit change of bender couples, are found. An efficient algorithm used for finding optimal bender settings is based on linear regression analysis using the measured characteristic functions of the benders [4].

In the case of mirror alignment, we have found that an analogous characteristic functions measurement technique is

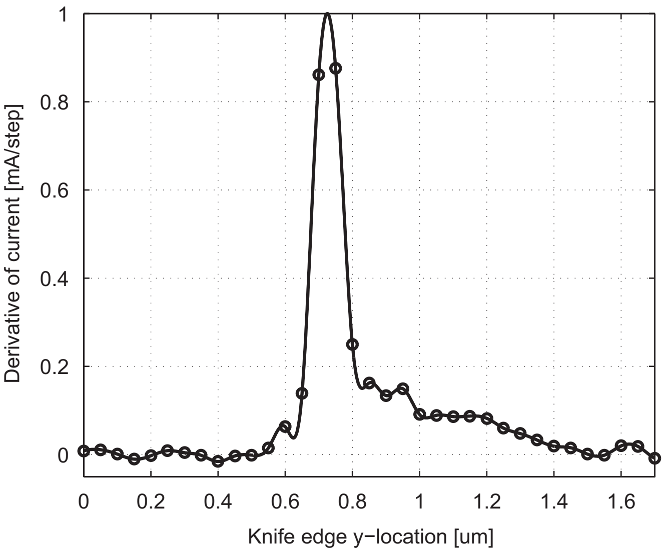

Fig. 2. Focal spot size measured with a photodiode and a scanning knife-edge, in the focal plane. The round spots are experimental data and the solid curve is its interpolation. Focal spot FWHM size is estimated as ~120 nm.

applicable to the KB mirror alignment, using the KB mirror tilt and the focal plane position as the two free parameters; this procedure is described in Ref. [8]. The alignment method using characteristic functions was performed repeatedly from different initial alignment positions with similar results. We observed that for our mirror, in as few as two to three iterations, the alignment converges to the settings with geometrical ray error on the order of 100 nm RMS, consistent with the RMS geometric spot size expected from the mirror slope error measured *ex situ* (Table 1).

After precise *in situ* mirror alignment, a knife-edge test was performed to measure the physical focal spot size. The knife was translated in small steps using a translation stage with 42 nm resolution. As the edge scans through the beam, the photodiode current reveals the sharpness of the focus and its derivative provides a measurement of the spot's width. The knife-edge scan step size was 50 nm, and the signal derivative is shown in Fig. 2. By interpolation, we estimate that the FWHM of the focal spot size is approximately 120 nm. In this configuration, the beam had a noticeable tail on one side of focus, which indicates possible residual coma in the mirror surface figure, together with possible asymmetrical scattering on mirror surface; these effects are currently under investigation.

After this initial alignment the mirror is aligned well enough for lateral shearing interferometry (Fig. 1d) to perform *in situ* mirror fine tuning [10–12] and to surpass 100 nrad slope measurement accuracy; this will be described in future work.

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