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Characterisation of a novel super-polished bimorph mirror

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Abstract. A novel super-polished adaptive bimorph mirror has been developed, which provides variable focal distance and local figure control in the sub-nm range. The optic has the potential to generate distortion-free beams and enable dynamical focusing and wavefront control. We present results of this optic, including ex-situ characterisation of the surface topography using the Diamond-NOM, and in-situ investigation using synchrotron light at Diamond's B16 Test beamline. The wavefront properties of the mirror have also been studied using at-wavelength metrology methods based on X-ray speckle tracking.

1. Introduction

To transport and focus beams from modern third-generation synchrotron radiation (SR) sources, such as Diamond Light Source, X-ray optics of unprecedented quality are required. Of the various types of focusing optics employed in SR beamlines, reflective optics [1] are the most widely used because of several advantages, including: achromaticity; nearly 100% efficiency; and a range of working distances. In this work, a super-polished, adaptive mirror has been developed which provides variable focal distance and local figure control in the sub-nm range. This has been achieved by bringing two state-of-the-art technologies together: Elastic Emission Machining (EEM) [2] of an 8 channel, piezo bimorph mirror [3]. The bimorph electrodes enable the substrate to be bent to a large range of cylinders or ellipses (figuring) and provide at the same time fine local corrections to figure errors. Deterministic surface finishing of EEM provides an elliptical surface with exceptional mid spatial frequency errors. This yields a novel adaptive optic coupling variable focal distance and adaptive zonal control with a super-smooth surface that has a residual figure error of <1nm rms.

In-situ metrology is essential to achieve a well focused X-ray beam, not only to optimize the shape of the bimorph mirror and reduce figure errors, but also to correct and minimize the collective distortions of upstream optics (monochromator, windows, etc). Two different at-wavelength metrology methods were employed: pencil-beam scans [4, 5], and the X-ray Speckle Tracking Technique [6, 7]. Preliminary characterization of our EEM-bimorph mirror, mostly ex-situ using Diamond-NOM [8], was reported earlier [9]. Further characterization of the mirror, including extensive in-situ optimisation and characterisation using at-wavelength metrology with the SR beams, are presented in this paper.

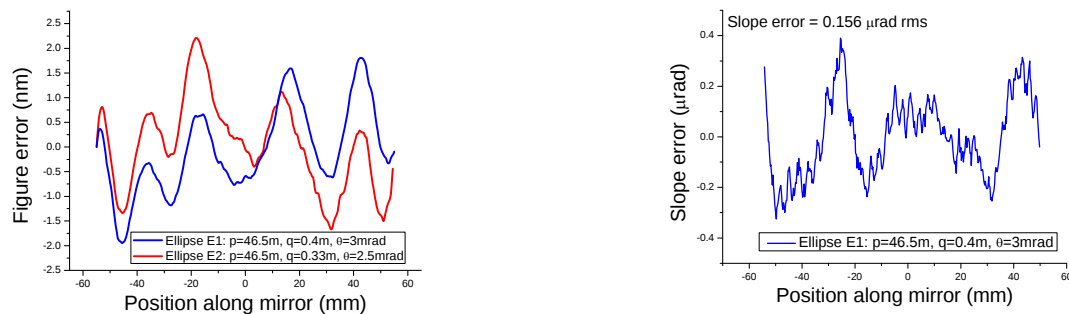


Figure 1. Measurements by Diamond-NOM: Figure error of the super-polished bimorph mirror for two very different ellipses E1 and E2 (left). Slope error = 0.156 μrad rms for the default ellipse E1 (right). See text for definitions of ellipses.

2. Experimental & Results

A 150mm long, bimorph mirror from Thales-SESO (France) was polished by JTEC (Japan) using EEM to be a tangential ellipse with: $p = 41.5\text{m}$ (source to image distance), $q = 0.4\text{m}$ (mirror to focal distance), and $\theta = 3\text{mrad}$ (nominal glancing angle of incidence). This geometry is typical of beamlines at Diamond and is pre-shaped into the mirror substrate, so that it is the "at rest" shape that the mirror has when no voltage is applied. The mirror provides 1-D focusing at high-demagnification, and could be used in a KB geometry for micro- and nano-focusing. Eight piezo electrodes enable the local curvature of the bimorph to be dynamically changed. The range of input voltages ($\pm 1500\text{V}$) allows the mirror to be used either at low glancing angles ($>2\text{mrad}$) to provide a short focal length, or at higher glancing angles ($<4\text{mrad}$) to achieve longer focal distance, while still retaining a large photon energy range of operation.

To determine the optimum voltages which minimize slope or height errors, the piezo response functions (PRF) of our multi-electrode bimorph mirror were determined (Figure 2-left) in the first instance using the Diamond-NOM, employing the procedure outlined in our earlier work [9]. This clearly shows sub-nanometer figure control is achievable using the EEM-bimorph mirror. A matrix method inverted the PRFs to calculate the interaction matrix. Using this data, voltages which minimize the figure error for any desired elliptical shape can then be computed and applied. Figure 1(left) shows the measurements for two very different ellipses E1 ($p=46.5\text{m}$, $q=0.40\text{m}$, $\theta=3\text{mrad}$) and E2 ($p=46.5\text{m}$, $q=0.33\text{m}$, $\theta=2.5\text{mrad}$), and after matrix corrections, both return similar residuals in figure error, which are less than 1nm rms. This clearly shows the sub-nanometer figure control that has been achieved for the EEM-bimorph mirror. The mirror shape can be further improved by increasing the number of electrodes. Figure 1 (right) show that the slope error measured by Diamond-NOM is $\sim 0.156\text{ }\mu\text{rad}$ rms for E1 after applying bimorph voltage corrections.

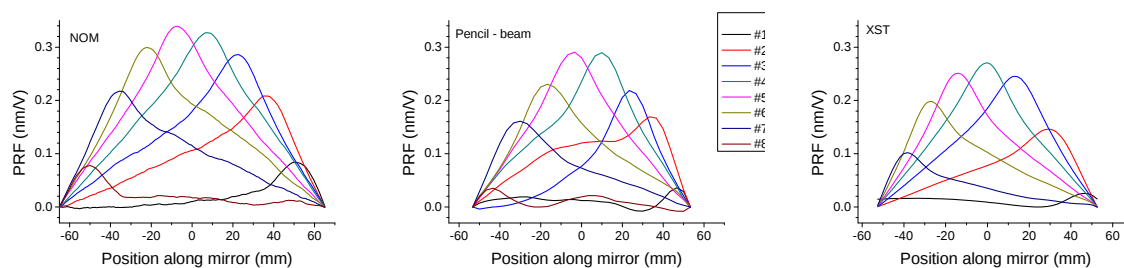


Figure 2. Piezo response function of the bimorph mirror, derived by (left) Diamond-NOM, (middle) pencil-beam method and (right) X-ray Speckle Technique.

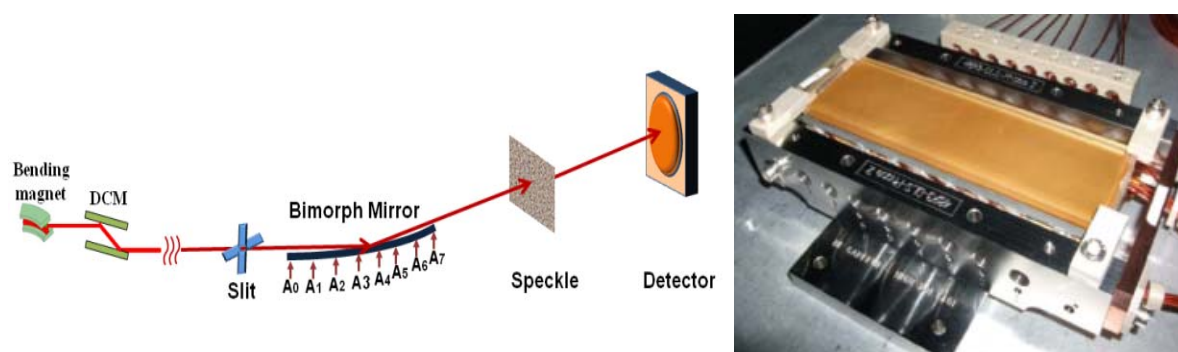


Figure 3. (left) a sketch of the measurement geometry on Diamond B16 beamline and, (right) a photograph of the EEM bimorph mirror.

X-ray tests and optimization of the EEM-bimorph mirror were performed on Diamond's B16 Test beamline [10] using a monochromatic X-ray beam of 8 keV. The theoretical FWHM photon source size in the vertical plane from the bending magnet source of Diamond is 56 μm , but in practice the effective source size is $\sim 70 \mu\text{m}$, increased by small perturbations and vibrations on the beamline. The EEM-bimorph mirror was installed at a distance of 46.5 m from the source on a versatile optics table in the experimental hutch of B16 (Figure 3). The size of the beam reflected from the bimorph mirror was measured using a high-resolution imaging detector, based on a PCO4000 CCD camera, equipped with multiple-objectives and a 5 μm thick Eu : LuAG scintillator. The detector has an effective pixel size of 0.45 or 0.9 μm , depending on whether a 10x or a 20x objective is used. To derive the beam size with higher accuracy, knife-edge scans with a 200 μm diameter gold wire were performed.

PRFs were determined using two at-wavelength methods: the pencil-beam scans; and the recently introduced X-ray Speckle Tracking (XST) technique [7]. Using two-dimensional speckle patterns, combined with digital image correlation algorithms, XST has the ability to acquire the two-dimensional first derivative of a beam wavefront distortion from only two X-ray images. From a conceptual perspective, XST measures the same quantity as the pencil beam scans: the full X-ray beam is dissociated into many beamlets, using slits with the pencil beam technique, and speckle pattern subsets with XST, to determine the change in trajectory of the X-rays when a piezo actuator is moved. These geometrical deflections, i.e. the measured X-ray wavefront gradient distortion, permit the recovery of the PRF. While the pencil beam technique uses a very simple setup, XST has the advantage of a spatial sampling resolution ten times better, combined with nanoradian accuracy. Further details about the XST method are given elsewhere in these proceedings [7]. The PRFs determined by the pencil-beam scan and XST are shown in Figure 2(middle) and (right) respectively. Excellent agreement is observed between the PRF acquired using ex-situ and in-situ methods.

To test the of the EEM-bimorph mirror's ability to provide different beam sizes, the interaction matrix was used to vary the focal size for a given ellipse E1($p=46.5\text{m}$, $q=0.40\text{m}$, $\theta=3 \text{ mrad}$). Figure 4(left) shows that an initially focused beam size of $\sim 1\mu\text{m}$ was defocused in a controlled way to 20 μm with negligible structures in the beam profile, and even up to 50 μm with acceptable structures. Figure 4(left) shows that even 20 times defocusing introduces structures of $<10\%$ in the flat-top intensity distribution of the beam. This is made possible by the extremely small figure error ($<1\text{nm rms}$) of the EEM-bimorph mirror. This compares extremely favourably to a typical X-ray focusing mirror where defocusing by a factor of two or three times the focal size produces unacceptable structures (50% or more ripple) in the beam intensity distribution.

Next, the ability of the EEM-bimorph to focus to different focal distances was tested. The mirror-to-focus distance was reduced from 400 mm to 330mm, and the piezo voltages on the mirror were set to the values derived from the PRFs determined by the XST technique. The measured focused beam size reduced from 0.77 μm for E1 (Figure 4-middle) to 0.52 μm for this new ellipse E2 (Figure 4-

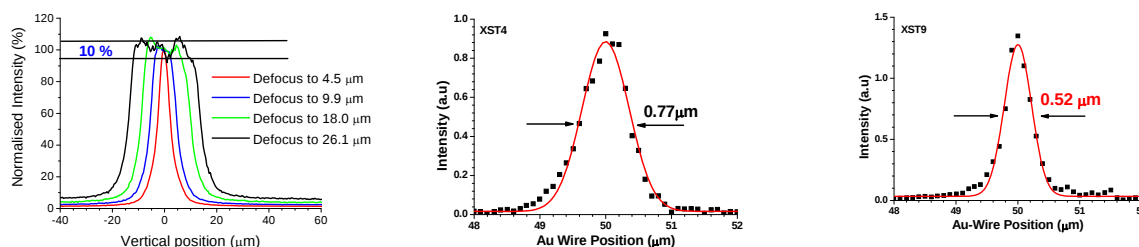


Figure 4. (left) Measurements of deliberate, but controlled, defocusing of the beam reflected from the bimorph mirror as shown by an imaging detector with a 20x objective. Wire scans with Gaussian fit of the focused beam for (centre) ellipse E1 and (right) E2.

right). This compares very well with the theoretical beam-size (0.71 μm and 0.58 μm , respectively) calculated from a convolution of the demagnified-source and the beam spread caused by a slope error of ~ 0.2 μrad rms.

For the present case of a strong elliptically shaped mirror (short mirror length and short focal distance), the pencil beam method suffers from a resolution limit as the whole beamlets measurement range collapses into an extremely small focal spot. A full 2D wavefront optimization, rather than a 1D pencil beam method, therefore has clear advantages, which would be even more apparent when the techniques are applied to diffraction-limited focusing.

3. Conclusions

The development and characterisation of a novel super-polished bimorph mirror has been presented. Detailed metrology characterization indicates excellent quality of the optic: sub-nm figure errors for a range of ellipses. In-situ characterisation with synchrotron radiation and optimisation with at-metrology X-ray methods demonstrates the adaptability of the optic to provide variable focal distance, variable beam sizes, and distortion-free beams. To the authors' knowledge, this is the first optic with a bendable ellipse with sub-nanometre figure errors.

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