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X-ray metrology and performance of a 45-cm long x-ray deformable mirror

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We describe experiments with a 45-cm long x-ray deformable mirror (XDM) that have been conducted in End Station 2, Beamline 5.3.1 at the Advanced Light Source. A detailed description of the hardware implementation is provided. We explain our one-dimensional Fresnel propagation code that correctly handles grazing incidence and includes a model of the XDM. This code is used to simulate and verify experimental results. Initial long trace profiler metrology of the XDM at 7.5 keV is presented. The ability to measure a large (150-nm amplitude) height change on the XDM is demonstrated. The results agree well with the simulated experiment at an error level of 1 μ rad RMS. Direct imaging of the x-ray beam also shows the expected change in intensity profile at the detector. Published by AIP Publishing. [<http://dx.doi.org/10.1063/1.4950739>]

I. INTRODUCTION

An x-ray deformable mirror (XDM) provides the capability to dynamically change or correct the electric field distribution in an x-ray experiment. Such a mirror has been used to correct for errors on itself or other optics, producing very high resolution.¹ A deformable optic also has the potential to provide customized beam shaping.² Piezoelectric bimorph mirrors were tested at ESRF as early as 1998.³ More recently, deformable optics have been tested at SOLEIL,⁴ SPring-8,⁵ Diamond Light Source,^{6,7} and Elettra.⁸ We have developed our own XDM,⁹ which to our knowledge is unique in having high actuator density on a long substrate and having internal metrology that is capable of monitoring the mirror's figure.

In this paper we describe initial experiments with our XDM at x-ray wavelengths. Although other deformable mirrors have been used routinely, our results represent an important validation of vacuum operation and x-ray use of this mirror and its technical approach. We have also learned some lessons; see Sections II D and II H. The x-ray metrology presented in this paper is not as precise as that done by other groups (e.g., grating interferometry has been used to measure a deformable optic by both Matsuyama *et al.*¹⁰ at SPring-8 and Marathe *et al.*¹¹ at APS). Our metrology, however, is complemented by detailed, diffraction-based simulations of both the XDM and the entire experiment. This allows us to assess that the measurements are what they should be and to determine the overall performance and limitations. Such a physics-based understanding of the XDM and metrology is a keystone of our approach to the long-term goal of developing a fully functional adaptive x-ray optics system.

II. EXPERIMENTAL SETUP

Our adaptive x-ray optics experiment is installed in the End Station 2 (ES2) vacuum chamber in Beamline 5.3.1 at the Advanced Light Source in Berkeley, California. The ES2 vacuum chamber is 2000 $\times$ 400 $\times$ 450 mm (l $\times$ w $\times$ h). Equipment is installed on a thermally isolated optical table, rendered in Figure 1. The items are controlled by connecting through a plethora of vacuum feedthroughs. The major optical items are listed in Table I and are described in detail below.

A. Incoming beam

The ALS storage ring operates in top-off mode at 500 mA in current and 1.9 GeV in electron energy. Beamline 5.3.1 is supplied with x rays from a 1.27 T bending magnet having a maximum flux density of about 1.4×10^{13} photons/(s/mrad² 0.1%BW) at 7.5 keV. Visible light is deflected away from the beam prior to low energy photons being stopped by a 10 μ m thick carbon filter to reduce the heat load downstream. A platinum-coated toroidal mirror at 5 mrad grazing angle focuses the beam 25 m away from the source at the entrance to ES2, while a cryogenically cooled double-crystal monochromator (DCM) at 22 m from the source selects the nominal operating energy of the experiment. The DCM is channel-cut Si(111) allowing detuning of the second crystal to suppress higher harmonics.

B. Pinhole

For operation at 7.5 keV, a variable slit unit is used to filter the incoming beam and provide a coherent, diverging beam for experimental use. The JJ X-ray AT-F7-AIR high-precision slit unit has an aperture size resolution of 0.813 μ m and a translation step size of 0.322 μ m, enabling detailed scanning with fixed, or varying, aperture across the incident beam. The

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FIG. 1. CAD layout of the XDM experiment showing major hardware elements.

2 mm thick tungsten carbide blades have a 2° knife-edge profile with aperture size adjustable from 7×7 mm to full overlap.

C. Slit

A slit unit identical to the one described above is used to control the diffracted beam emerging from the pinhole. This is primarily used to select a portion of the beam that impinges on the XDM for metrology experiments, as described in more detail in Section IV.

D. XDM

The XDM is used to modify the electric field of the x-ray beam. It is built with a monolithic, single-crystal silicon substrate that is 45 cm in length, 3 cm high, and 4 cm in width. Each of the 45 lead magnesium niobate (PbMnNb or PMN) actuators is 1 cm long, 3 cm high, and about 0.15 cm thick. The actuators are spaced evenly every 1 cm along the tangential axis of the mirror. This is illustrated in Figure 2. The actuators are epoxy bonded to the opposite side from the reflecting surface of the mirror while at mid-range in their operating voltage. This setup enables the mirror to bend both concave and convex. The location of 45 full bridge strain gauges is also shown in Figure 2. One half of each bridge is bonded to the back side of each actuator. The mating half-bridge is bonded to the top of the mirror, where strain is similar to that at the mirror's reflecting surface. The strain resolution of each gauge is about 10 parts per billion (commonly referred to as nanostrain). This corresponds to each gauge measuring surface figure changes to better than 1 nm between gauges. There are also eight Resistance Temperature Detectors (RTDs), one on each actuator block (see figure) and three on the top

FIG. 2. The XDM has 45 parallel actuators along the back surface, 45 full-bridge strain gauges at the top, and 8 temperature sensors. It is mounted with three flexure pads to isolate the XDM's motion. The mirror is mounted in horizontal-normal configuration with the reflective surface at back.

of the XDM. Please consult our previous work⁹ for further information.

The mirror is installed on a two-axis custom mount, allowing for rotations around the center of the mirror and translation horizontally in and out of the beam. Vacuum-rated Newport LTA precision motorized actuators drive both the translation and the rotation. The LTAs have 50 mm travel and encoders that ensure better than $\pm 1 \mu\text{m}$ repeatability. An iterative search using x rays determines when the mirror is nominally parallel with the incoming x-ray beam. From this position a $60 \mu\text{m}$ decrease in the rotation actuator results in a 1 mrad grazing incidence angle.

Extensive visible-light metrology has been conducted on the XDM, resulting in precise calibration of the response of the mirror to voltage. (See our previous work for details.^{9,12}) This allows us to take a given phase shape, within certain allowable spatial frequencies, and calculate the voltages necessary to apply to the XDM to create that shape.

All actuators commanded together can produce $7.4 \mu\text{m}$ peak-to-valley overall cylindrical figure in either direction (concave or convex). With the 45-cm length of the substrate, the resulting curvature is negligible; this XDM cannot work as a focusing optic. The overall stroke was chosen to ensure that the mirror could self-correct any polishing errors. Each actuator's influence function (aka response function) has been measured. An actuator near the center produces up to 300 nm height change peak-to-valley either up or down when commanded to maximum/minimum voltage around bias. These commands can produce large amounts of low-frequency shapes on the XDM surface: a two-cycle sine wave would have 750 nm peak-to-valley height while an eight-cycle sine wave would have 40 nm peak-to-valley height. (See Section 5.A of Poyneer *et al.*^{9,12} for more detail.) As demonstrated in Section IV B, this stroke range allows significant modulation of the electric field that results in beam structure changes as predicted by Fresnel propagation.

However there is significant uncertainty about the overall cylindrical figure of the XDM. Due to a bimorph effect between the PMN actuators and the silicon substrate, which have different coefficients of thermal expansion, the amount of cylinder changes with temperature.¹² As described in Section II H, the temperature rises quickly in vacuum. As

TABLE I. Locations of optics as implemented in the beamline experiment and simulation.

Item	z (cm)	Graze angle	Diameter
Pinhole	0.0	...	$1 \pm 0.5 \mu\text{m}$
Slit	61.0	...	Adjustable
XDM	103.5	$0.5 - 2$ mrad	45 cm
KB	150.5	8 mrad	12 cm
CCD	197.5	...	NA

such the XDM's temperature is different than in our visible-light metrology laboratory, and hence there is an uncalibrated amount of cylinder figure error.

E. KB

A Kirkpatrick-Baez (KB) optic can be used to focus the beam in this experiment. We use the existing horizontal KB optic in ES2. Here we give a brief description of the KB mirror; more details can be found in this reference.¹³ The mirror's length is 80 mm. It is designed for nominal use with a graze angle of 8 mrad, a distance from the object of 1.525 76 m and a distance to the image of 24.459 cm. This produces a radius of curvature of 52.7 m and an effective focal length of 21.08 cm. The KB is 150.5 cm from the pinhole, so the focused image of the pinhole should appear 24.5 cm downstream of the KB. The CCD (see below) is not at this focal plane, but instead 22.5 cm beyond it. This is to avoid damage and saturation and to have an appropriate sampling of the beam given the CCD's pixel size.

Because of this, the detector should not be viewed as imaging an out-of-focus spot, but rather as re-imaging a specific plane somewhere between the pinhole and the KB. Where f is the effective focal length and s_i is the distance from the center of the KB to the detector (47 cm, see Table I), the reimaged plane is located a distance $f s_i / (s_i - f)$ upstream of the KB. This distance is 38 cm; this is just 1 cm downstream from the center of the XDM. For the portion of the field that has already reflected off the upstream end of the XDM, the detector reimages the actual field at this location. For the portion of the field that reflects off the XDM after this distance, the detector reimages a virtual plane where the field has been back-propagated after reflection. Given that the optical layout of the experiment was strongly constrained by the differing aperture sizes of the KB and the XDM, as well as the size of the vacuum chamber, this reimaging phenomenon is something unavoidable that must be dealt with in experimental design and data analysis.

F. Detector

In the experiment, a detector takes images of the intensity of the electric field, which are used for a wide range of purposes including alignment, calibration and metrology. The detector is an Andor iKon-L SO, back-illuminated CCD. It has a 2048×2048 array of $13.5 \mu\text{m}$ pixels that directly detect x-ray photons. The CCD is mounted at the far end of the vacuum chamber on the optical axis. During operation the CCD controls a shutter upstream of ES2, resulting in a minimum exposure time of 5 ms.

The manufacturer's specification sheet gives a full-well depth of 100 000 electrons per pixel, and a conversion factor of 2100 photoelectrons per one received x-ray photon at 7.5 keV. Therefore the detector can record only about 46 x-ray photons per pixel before saturation. More photons can be recorded by accumulating multiple exposures. For a given number of x-ray photons available to the detector, the number of detected photons is obtained via multiplication by the quantum

efficiency of the CCD, which is approximately 23% at 7.5 keV based on the specification sheet.

G. Control software

Top-level operation of the XDM and experiments at the beamline is done with Matlab. Interaction with the hardware is done primarily in two modes. A specific set of hardware items can be commanded. These command actions include applying voltages to the XDM, moving the translation and angle of the XDM mount, selecting the attenuator film, setting the pinhole and slit sizes, and adjusting the translation and angle of the KB. A different set of hardware items can be measured. These measurable items are the RTD sensors and strain gauges on the XDM itself, a set of thermocouples located in the chamber and the CCD.

All commands and measurements are archived in HDF5 files. Through use of attributes, every measurement file also links to the most recent commands. Queries to the Beamline Control System (BCS) are used to record important parameters of the beamline state (the toroidal mirror tilt and bend, the nominal energy, etc.); these are also saved as attributes. This approach allows the entire state of the system to be recalled for any measurement of interest (e.g., CCD image).

An arbitrary sequence of measurements and commands can be executed in a specific order, forming what we term a "set." A single interface for setting up such scripts is provided and allows automation and consistency in the execution of tasks such as calibrating the attenuator films via transmitted flux, centering the pinhole on the incoming beam, and scanning the XDM mount through the beam for measurement (see Section IV A). Any set can be loaded in for later analysis. A set also provides a way to execute a simulation that matches the exact state and operations; see Section IV A 3, for an example.

H. Vacuum operation

In order to reduce carbon-based contamination of the mirror surface, operation under high vacuum is preferred. Vacuum operation also provides high transmission of x rays at our energies of interest. In addition to this, operating at $<50 \mu\text{Torr}$ pressure in the ES2 chamber allows for opening several upstream vacuum windows safeguarding the beamline and synchrotron vacuum, thereby significantly reducing the attenuation below 5 keV. The high vacuum is achieved using a turbomolecular pump backed by a mechanical roughing pump. The turbo pump has a capacity of 450 l/s and is capable of pumping down the chamber in less than an hour if it has not been at ambient for an extended period of time. After a lengthy period at ambient or major work inside the chamber, pump down can take 5–10 h.

It is important to note that the mirror is presently passively cooled. Under vacuum this poses a significant challenge as convective cooling is miniscule. Several heat sources create an appreciable ($0.1 \text{ }^\circ\text{C/h}$) temperature increase over tens of hours. This must be taken into account and monitored to ensure the mirror stays within its operating range of 15–25 $^\circ\text{C}$.

Significant heat sources were identified to be the mount actuators, the mirror itself, and the turbo inlet. Efforts to reduce the thermal load were made, including increasing thermal conductance between parts using copper braids, lowering the actuator power rating, and reducing the voltage applied to the strain gauges. Finally, a heat shield was installed to shelter the mirror casing from the thermal radiation emanating from the turbo inlet. These changes significantly reduced the thermal load on the system to the above-mentioned 0.1 °C/h. Additional plans are in the works to further reduce this and allow for longer continuous operation of the setup in vacuum.

III. SIMULATIONS

A key component of our integrated approach is having accurate, physics-based simulations of both the XDM and the entire x-ray experiment. This capability allows us to design our experiments properly and then to assess whether the experiments have performed as they should. In this section we describe in detail the necessary features of the simulation to capture the relevant physical effects. In Section IV we directly compare the experimental measurements with simulations.

Our simulations of the experiment are done in Matlab with custom codes that do Fresnel propagation for a one-dimensional field (x-only). These codes implement standard Fourier Transform techniques to solve Fresnel integrals, as is commonly done (e.g., in the IDL library PROPER¹⁴).

Most simulations of x-ray optics are done with ray tracing. This method is unsuitable for considering the XDM, as ray tracing does not capture diffractive effects. For example, placing a surface height ripple on the XDM surface will create a diffraction pattern just as a phase grating would. This behavior is not captured in a ray trace. As we will see below, other diffractive effects are also important.

When working in two dimensions (i.e., x and y, with a circular pupil such as a telescope), Fresnel codes work efficiently as long as the field can be adequately sampled relative to either a reference plane (in collimated space) or a reference sphere (converging or diverging space). When neither of these hold much more computationally intensive methods must be used to propagate the wavefront, such as in the case of highly aspheric optics.¹⁵

In the x-ray optics regime for light sources, focusing optics operate along one axis of the wavefront at a time. For example, to focus the beam in two dimensions two separate KBs are used. After the first KB mirror the field is not close to either a reference plane or a reference sphere. This prevents use of the standard approach described above. Though this complication has been considered in the literature,¹⁶ we have not developed such a code capability. This is because we have a single XDM that operates on one dimension only of the field, and we will use a single KB optic. This enables one-dimensional propagations with using reference to either a flat or cylindrical wavefront.

Propagations of x-ray optics differ from the visible light case in another way: the optics operate at grazing incidence.

One option is to ignore this and apply the effect of an x-ray optic (e.g., the phase change made by polishing errors to the surface) in a normal plane, such as was done for the LCLS HOMS and SOMS mirrors.¹⁷ However, in most cases of interest to us Talbot effects are present.¹⁸ In particular, the Talbot length can be comparable to the length of the x-ray optic in question. This means that phase errors on one end of the XDM will have propagated to amplitude errors at the other, so any simplification that ignores this is invalid.

In order to properly simulate the grazing incidence optics, we have implemented a modified version of an algorithm that calculates the electric field at a plane that is not normal to the axis of optical propagation.¹⁹ This allows us to propagate the field to the z-distance where the center of the field encounters the tilted optic. We then tilt the electric field so that it is parallel to the surface of the optic, apply any phase errors, and then tilt it back to normal. We have validated this approach as correctly modeling Talbot effects along the length of the optic that is at a shallow angle. The method is used all grazing incidence optics in the simulation.

Due to constraints set by sampling and the process of tilting the electric field, the one-dimensional field simulations require very long arrays. In a typical setup assuming a pinhole size of 0.5 μm and an energy of 7.5 keV, we require 4 096 samples across the uniform field at the pinhole. For proper calculation this must be padded by a factor of 2048 to produce a 8 380 416-element vector. This padding is vastly larger than is typically necessary in two-dimensional telescope simulations and is driven primarily by the tilting of the wavefront. For example, at the XDM plane, we want at least 1 mm pixel sampling on the surface, which is at least 450 samples across.

In addition to the above features, the simulation correctly models the reflection of the electric field off optics (which “flips” the field orientation) and tracks light that misses the ends of optics. Separate propagations are used for each portion of the beam to account for stray light and then combined at the final detector plane. As detailed below, this is used to produce images that behave in the same fashion as the actual beamline experiment.

As a final step, when the electric fields reach the detector plane the sampling is much finer than the pixel size of the real CCD. The intensity is calculated at full resolution then a frequency-domain filter is applied to correctly integrate the intensity given the pixel size. Finally the intensity signal is resampled at the pixel spacing using appropriate sized arrays and padding in the Fourier domain.

Using this set of codes we have implemented a complete simulation of the experiment. The actual response of the XDM (as measured with visible light metrology⁹) is incorporated in the code, along with translation and rotation of the mount. This enables us to conduct simulations of the same experimental scripts as are conducted in the beamline. These are used to verify the functionality of the experimental design (e.g., to check if the measurement sensitivity is what we expect from simple models) and to prototype algorithms for data analysis. In the sections below we will present various results obtained with the simulation.

IV. EXPERIMENTAL RESULTS

A. Long trace profiler measurements

1. Description

To directly measure the surface height of the XDM we use the technique of long trace profiling²⁰ (LTP). After the pinhole we use the aperture of the slit to select a portion of the beam. This sub-beam is then reflected off a small section of the XDM. The position of the spot on the detector then deviates from nominal as a function of the angle of the mirror's surface. LTP has the advantage of simplicity but has limits to its fundamental sensitivity set by the short distance from the XDM to the detector.

Despite the simplicity, the experimental setup posed a few challenges. First, the slit is just 20 cm in front of the near end of the XDM, and hence 65 cm from the far end. Given the diverging beam, the size of the beam on the XDM is a function of propagation distance. This means that the beam has a much smaller footprint on the near end of the XDM than on the far end. A larger footprint means a larger portion of the mirror is averaged when the beam is reflected.

Secondly, if the slit size is too small then diffraction will make the beam footprint much larger than it would be geometrically. A size that minimized diffraction effects and produced a well-sampled spot on the detector was selected. For these experiments the slit was commanded to a size of 25 μm . By the geometry given in Table I this should produce an image that is 6 pixels wide on the detector. In the measurements, however, the images of the slit seen by the detector are about 2 to 3 pixels wide. This is consistent with a smaller slit size in the range 10–13 μm . Reconciliation of this miscalibration of the slit size is left to future work; since the slit image is well-sampled and is significantly smaller than the spatial periods of the aberrations (see below), this has negligible effect on the experiment.

Finally, because the beam from the pinhole is non-uniform in the transverse direction, translating the slit will produce a continually varying beam profile on the XDM, which would potentially bias measurements of spot positions and require precise calibration. Instead we have chosen to translate the XDM on its stage through the beam. The processing algorithms can easily be adjusted for this geometry.

Finally, we did not use the KB optic for the long trace profile measurements. This is because the re-imaging behavior of the KB (discussed above in Section II E) gives an effective lever arm of zero near the center of the XDM.

2. Error budget

The fundamental sensitivity of the LTP depends on the ability to accurately measure small spot motions on the CCD. The surface angle θ that will move the spot one pixel Δ on the detector is $\theta = \Delta/(2z)$. In this case the distance z from the XDM center to the detector is 0.94 m. A surface angle on the XDM of 7.2 μrad will move the spot one pixel. Equivalently, a surface angle of 1 μrad will move the spot 0.14 pixels.

Accurate measurement of small spot motions is a fundamental and widely studied step in astronomical adaptive optics

(see, for example, this treatment of algorithm accuracy²¹). Assuming the spot is well-sampled on the detector, the major limitations in accuracy are the amount of light received and any confounding background scatter. The fewer photons received, the noisier the position estimate.

To test the fundamental sensitivity of the analysis algorithms and experimental setup, we conducted Monte Carlo simulations using a slit image modeled on experimental data. This model is of an 8-pixel vector with a Gaussian intensity profile with a standard deviation of one pixel. This profile is normalized to convert it to a probability distribution for an incoming x-ray being received at that particular location. Then a uniformly distributed random number is generated for each detected photon; its value from zero to one is used to place that photon along the profile. This generates a vector of the number of received x-ray photons p per pixel for this trial. For each pixel the actual detected number of photoelectrons is calculated as a Gaussian-distributed random number with mean pn , where n is the 2100 photoelectrons per one received x-ray photon conversion factor, and variance pnf , where f is 0.11 (the Fano factor²² for this type of detector).

This noisy realization of the slit profile on the detector is sent through analysis algorithms to generate an estimate of the spot position in pixels. This is done for hundreds of realizations of the detector image. The estimated error on the position estimate is the sample standard deviation of the estimate data. This Monte Carlo method was used for a several different numbers of incident x-ray photons. The RMS error follows the expected inverse relationship with the square-root of the number of photons, as it does for visible light. For this experimental setup, 25 000 incident x-ray photons results in 5750 photons converted to photoelectrons in the detector and a spot position error of 0.1 μrad RMS. This level of illumination requires about 2000 received x-ray photons per profile pixel, well above the saturation limit. This is achievable either by accumulating on order 50 frames at near-saturation while using a lineout on the CCD image or by integrating in a single image along the equivalent number of pixels along the slit's vertical axis.

Analysis with the Fresnel simulation indicates that the error from scattered light is 10 nrad RMS. The fundamental error of the spot-motion algorithm on Gaussian spots is 3 nrad RMS. Both of these are well below the photon noise limit. Other sources of error, such as mis-positioning of the mount, system drifts and temporal variability of the beam have not been evaluated. Given the above analysis, measurements of 0.1 μrad should be reasonably achievable considering only photon noise.

Our best flat measurement of the XDM is 0.7 nm RMS.⁹ If the residual figure error was due to the highest-frequency that we can control (2-cm period), it would have a 1-nm amplitude sinusoid of figure. This has a surface angle of 0.2 μrad , which should be achievable with the LTP. However if the error was due to a lower-frequency figure error (e.g., 20-cm period), this is not measurable accurately with this LTP. An improvement of a factor of ten would require one hundred times more photons and hence integration time. Unfortunately, these limits mean that the LTP approach in our experiment cannot measure the XDM at anywhere near the accuracy at which we can control

TABLE II. Experimental measurements.

	Set 336	Set 338
XDM voltages	Bias plus 150-nm amp., 18-cm period sinusoid	Bias
Direct image #	4944	5414
Date and time	2015-03-12 17:40:31	2015-03-12 18:06:21

it. That requires other metrology approaches, which are briefly discussed in Section V.

3. Results

Given the above analysis, the initial experimental characterization of the LTP was conducted with easily measurable XDM figures. Furthermore, due to the uncertainty with XDM cylinder from varying temperature, the initial LTP experiments are relative measurements. This temporarily obviates the issue of absolute calibration of the LTP. For any experiment two LTP scans are conducted—one with the XDM at uniform voltage and one with the XDM commanded to voltages that should make a known surface figure. Our experimental measurements are itemized in Table II.

One detector image is taken with the XDM moved completely out of the beam to measure the direct path. Then the XDM is stepped through the beam, in the advantageous direction given mount backlash. The detector images are processed with dark frames (which were taken just before the experiment). The slit images are summed along the long axis of the slit image to improve signal to noise. The precise location of the spot is determined with sub-pixel accuracy using the `xcorr` function in Matlab on this summed slit profile. Then the locations on the detector are converted to distances from the direct beam position, based on the initial frame of each experiment.

These distances are then converted to angles on the surface of the XDM by evaluating the geometry of the experiment. This requires knowledge of only the translations of the XDM mount (which were commanded), the distance from the center of the XDM mount to the detector (which has been measured), and the graze angle of the XDM.

As noted above, the exact same script of operations can be run on either the real hardware experiment or the simulation. During data analysis of any experiment we also run a full simulation of it and send the simulated data products through the same data reduction pipeline. This gives us a predicted measurement to compare to the actual experiment. These simulations are done at the nominal graze angle. Variation in the graze angle changes the compression/expansion of the surface figure along the length of the XDM, but not the magnitude surface angle. Because we make known shapes, this actually gives us a sensitive way to directly measure the graze angle of the XDM.

The results of an initial experiment measuring relative figure change are shown in Figure 3. Actual experimental data are shown in solid black with markers for each measurement; results of simulating the experiment are shown in dotted-

FIG. 3. Actual LTP measurements [black markers] agree well with the results of a full Fresnel simulation [dotted-dashed blue] of the experiment. Relative measurement of an 18-cm period, 150-nm amplitude sinusoidal height ripple on the XDM.

dashed blue. The best estimate of the graze angle was 1.15 mrad. Here we see that the experimental measurement tracks the simulated measurement quite well. All XDM actuators are functional and the applied voltages are producing the expected amount of stroke (more than a year after the visible light calibration of the actuator response was conducted). As this LTP measurement is on the surface of the XDM, we see the expected uniform sinusoid. Taking the difference from the real data and the simulated model at the measurement points provides an error signal with RMS value 1.0 μ rad.

Analysis of the recorded images and adjustment for the number of accumulations provide an assessment of the actual number of x-ray photons which were converted to photoelectrons. Assuming a camera gain of 0.65 photoelectrons per digital number, a typical slit image is the result of approximately 1725 converted x-ray photons. This is 3.3 times fewer than the case analyzed above and should result in a position error of 0.18 μ rad RMS due to photon noise. As our actual error is five times higher than this, there clearly are uncalibrated and unquantified errors in the system.

B. Direct imaging of beam

Before each LTP scan was executed, the slit was opened completely so that a direct image of the beam could be taken with the CCD. These images provide a secondary ability to measure the impact of the XDM surface height on the beam. In this case each recorded image was 10 $\times$ 50-ms, as executed by the detector's control software. The images, which have been dark subtracted, are shown in Figure 4. The XDM modulates the field along the horizontal direction. The exact source of the beam variability along the vertical direction is unknown but is assumed to originate from the toroidal mirror.

To compare these images first the sum is taken along the vertical direction to improve SNR. Then the image when the XDM is shaped is divided by the image with the XDM at bias. The resulting profile, shown in black in Figure 5, shows the

FIG. 4. Dark-subtracted images of the x-ray beam after reflection off the full XDM. [Left] XDM at uniform voltage. [Right] XDM with a 18-cm period, 150-nm amplitude sinusoidal height ripple.

same 2.5 cycles per aperture shape that was made by the XDM surface. Given the graze angle of 1.15 mrad and the distances in Table I, 73 pixels on the detector correspond to the full 45-cm aperture of the XDM.

To verify these measurements, simulations were run with a 0.5 μm pinhole at 7.5 keV and a graze angle of 1.15 mrad. Each simulation produces a single line along the horizontal axis. Simulations using commanded mirror voltages were run for both cases and the ratio taken. The resulting intensity ratio, shown in dashed blue in the figure, agrees very well with the measurements.

The simulation predicts a $\pm 20\%$ change in intensity due to the height ripple on the XDM surface. This intensity change emphasizes the importance of using a diffraction-based simulation. The nominal period of the height ripple on the XDM produces a phase ripple in the electric field of period 200 μm , which has a collimated Talbot length of 518 m. Given the diverging beam from the pinhole and the distance from the XDM to the CCD, the fractional Talbot length of the

propagation in the diverging beam²⁷ is 0.1%. However, the phase error in the field is large (about 13 rad) and these effects combine to produce the $\pm 20\%$ change in intensity. As the XDM can make sinusoids with nearly ten times more cycles across its diameter, modeling such Talbot effects correctly is essential.

This experiment is an excellent confirmation that using the XDM at grazing incidence in an expanding beam results in a non-linear mapping of the XDM surface into the beam's profile. The LTP data analysis directly reconstructs to the position on the XDM; Figure 3 clearly shows that a sinusoid of uniform frequency has been measured at the XDM surface. In contrast, the detector images the beam itself, and the resulting phase correction is compressed towards the side of the field which reflects off the downstream end of the XDM.

V. CONCLUSIONS AND FUTURE WORK

We have described in detail our adaptive x-ray optics experiment in ES2, Beamline 5.3.1 at the Advanced Light Source. The experiment is designed to test a 45-cm long, 45-actuator XDM. The experiments are complemented by detailed diffraction-based simulation codes that correctly capture both the XDM's influence functions and its grazing-incidence use. Initial at-wavelength, *in situ* metrology has been conducted at 7.5 keV. These include long trace profile measurements of relative changes in mirror figure and matched images of the full x-ray beam reflecting off the XDM. The LTP measurements have a noise level of around 1 μrad , which is about five times higher than what we would expect due to photon noise. Hence other uncalibrated errors exist. However, both the LTP scans and the ratio of the directly imaged intensities agree very well with full Fresnel simulations of the experiment.

Even when well-calibrated the LTP experiment is fundamentally not sensitive enough to measure the figure of the XDM when at flat (<1 nm RMS height error). Such high-precision measurements will require more sensitive approaches. For our next set of experiments, which are set

FIG. 5. The intensity ratio of actual data [black] agrees well with full Fresnel simulation [dashed blue] of the experiment. Detector images of full beam reflecting off of XDM with a 18-cm period, 150-nm amplitude sinusoidal height ripple. The non-uniform periods of the sinusoid are expected (see text).

to begin in early 2016, we will implement diffraction-based metrology that will be used in concert with the KB optic. We will install a scannable knife-edge at focus to directly interrogate the focused beam's spot size and features.

One metrology option is grating interferometry, which produces a fringe pattern that encodes the difference of sheared copies of the electric field phase. There are multiple recent demonstrations of this technique^{23,24} including two that measured local changes in a deformable optic.^{10,11} A second option to characterize optics is ptychography.^{25,26} We will use a target of known structure and estimate the unknown electric field in our system, and hence the shape of the XDM. Ptychography will require more measurements and more computation than grating interferometry. But it has the ability to estimate both the amplitude and phase of the electric field.

With the metrology in place we plan to exercise the XDM in two modes. First, we want to use the metrology make it very flat, potentially to the <1-nm surface height error that we have already demonstrated with visible metrology. Second, we want to shape the mirror to non-flat in specific ways to manipulate the beam shape. In both modes we will rely on precise calibration of the metrology and use our diffraction-based simulations to validate our experiments.

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