Refractive optics to compensate X-ray mirror shape-errors

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ABSTRACT

Elliptically profiled mirrors operating at glancing angle are frequently used at X-ray synchrotron sources to focus X-rays into sub-micrometer sized spots. Mirror figure error, defined as the height difference function between the actual mirror surface and the ideal elliptical profile, causes a perturbation of the X-ray wavefront for X-rays reflecting from the mirror. This perturbation, when propagated to the focal plane results in an increase in the size of the focused beam. At Diamond Light Source we are developing refractive optics that can be used to locally cancel out the wavefront distortion caused by figure error from nano-focusing elliptical mirrors. These optics could be used to correct existing optical components on synchrotron radiation beamlines in order to give focused X-ray beam sizes approaching the theoretical diffraction limit. We present our latest results showing measurement of the X-ray wavefront error after reflection from X-ray mirrors and the translation of the measured wavefront into a design for refractive optical elements for correction of the X-ray wavefront. We show measurement of the focused beam with and without the corrective optics inserted showing reduction in the size of the focus resulting from the correction to the wavefront.

Keywords: Synchrotron radiation, modeling, wavefront correction, nano focusing

1. INTRODUCTION

A trend for modern synchrotron radiation sources is for smaller emittance electron beam sources that give increased transverse coherence of the X-rays and give the potential through strongly defocusing optics to achieve sub ten nanometre focal spots of hard X-rays. In order to achieve nanometre scale focal spot sizes requires specialized X-ray optics able to collect a large numerical aperture in order to reduce the diffraction limited focused beam size, designed to give a large magnification ratio and manufactured to introduce minimal distortion of the focused beam wave front.

The wavefront error introduced by reflection of X-rays from a mirror at glancing angle θ with a surface height error Δh is given by

$$\Delta z = 2\Delta h \sin \theta \qquad (1)$$

Simulations indicate that the maximum wavefront error should be of order $\lambda/100$ in order to not affect the diffraction limited focusing of an X-ray mirror. As the X-ray wavelength λ is typically of order 0.1 nm, this indicates that wavefront errors of order 1 pm will be required from future optics. X-ray mirrors operate at glancing angle of incidence with $\theta \sim 3$ mrad. being typical and Eq. 1 indicates that height errors on the mirror surface of 0.3 nm or better will be required. This is at the limit of the manufacturing capability for mirror surfaces. The low incidence angle of mirrors limits the achievable numerical aperture which determines the diffraction limited focal spot size. The diffraction limit can be increased by using larger glancing angles θ and this requires multilayer coating on the mirror surface. Working at lager angles however increases proportionally the figure error contribution to the focal spot size through Eq. 1. It is therefore likely that correction of the wavefront will be required to compensate for the aberration from the focusing optics in order to exploit future synchrotron radiation sources.

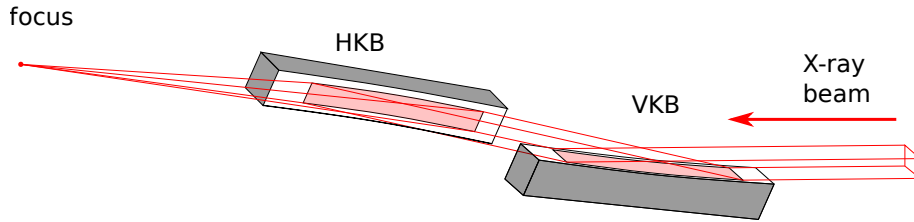Further author information: Send correspondence to DL, E-mail: david.laundy@diamond.ac.uk

Figure 1. Two dimensional focusing of X-rays by a Kirckpatrick-Baez mirror pair consisting of a vertical focusing mirror (VKB) and a horizontally focusing mirror (HKB). The HKB is placed after the VKB in order to achieve a larger demagnification factor

It is common for focusing to be implemented using a pair of elliptically profiled mirrors - one focusing vertically and the other horizontally as shown in Fig. 1. This arrangement allows the vertical and horizontal demagnification ratios to be chosen independently to match the differing sizes of the storage source in the horizontal and vertical directions. This optical arrangement of mirrors is known as a Kirkpatrick-Baez pair[1] often abbreviated as a KB pair. In this arrangement, the wavefront error can be decomposed into a vertically dependent component originating in the vertically focusing KB mirror and a horizontally dependent component originating in the horizontally focusing KB mirror. In 2016, we proposed and demonstrated using custom designed planar refractive optical elements to correct for wavefront error caused by the figure error of focusing elliptical mirrors (Sawhney et al[2]). The planar refractive optics were fabricated using Deep X-Ray Lithography (Becker et al[3]), also known as the LIGA process at beamline BL-07 at the Indus-2 electron synchrotron source[4]. The fabricated structures have high aspect ratios and highly vertical side walls with surface roughness in the range 10–20 nm. The finished structures are composed of the polymer SU-8 and are spin coated onto a silicon wafer substrate. SU-8 has a favorable ratio of refraction to absorption and also good stability and resistance to radiation damage.
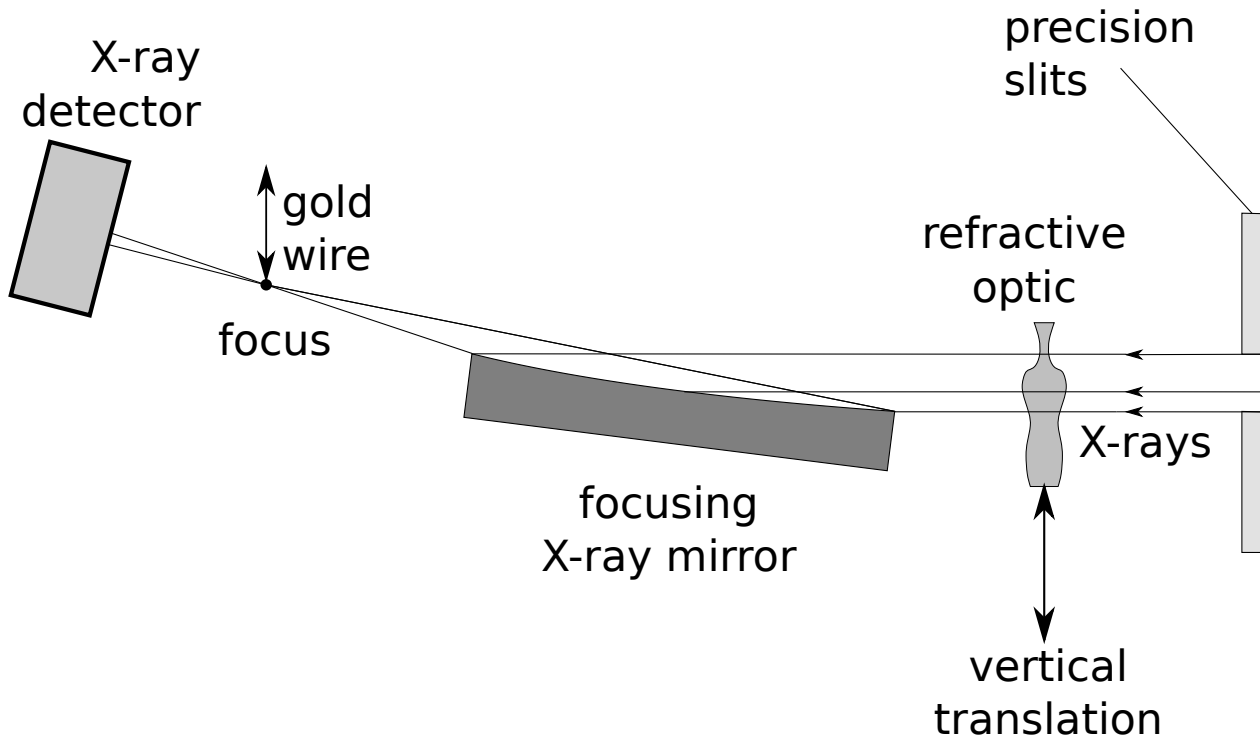

Figure 2. Experimental geometry for testing an X-ray mirror with wavefront correction refractive optics
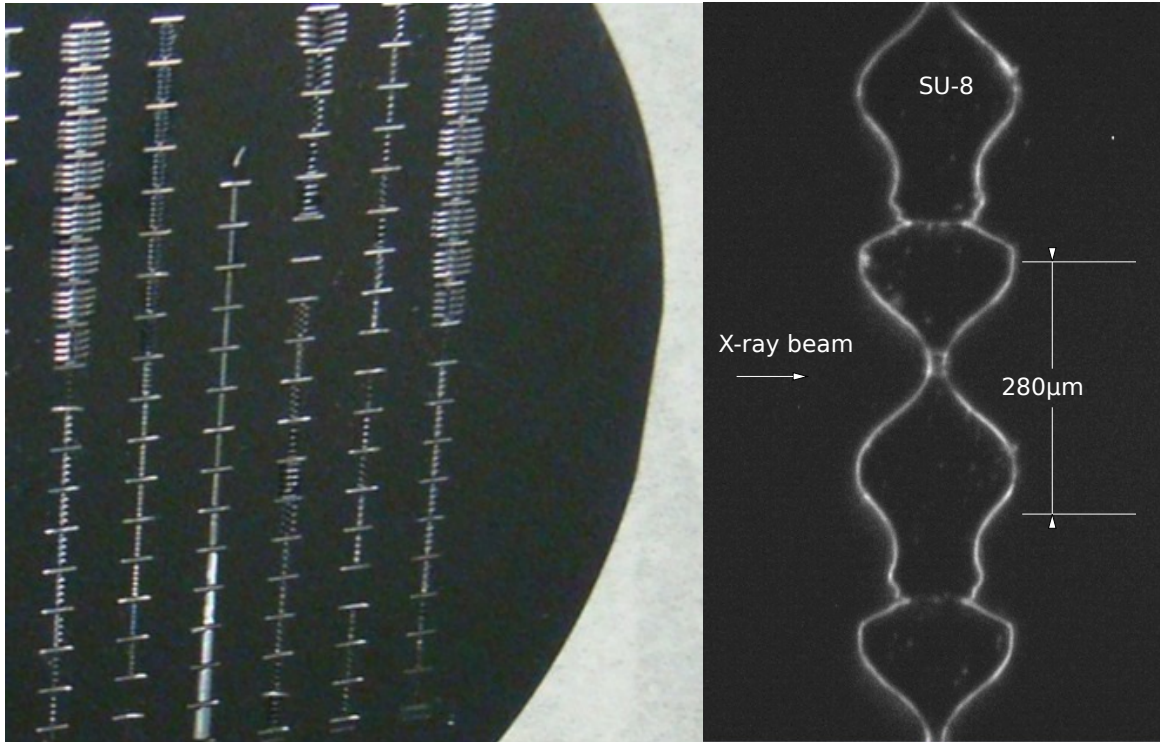
Figure 3. Left – a section of a wafer showing refractive structures laid down on the surface of the wafer in parallel rows. Right – a microscope image of a single refractive corrector

2. EXPERIMENTAL

The experimental layout for the measurements is shown in Fig. 2. The measurements were carried out on the Test Beamline at Diamond Light Source[5] with the X-ray mirror oriented to deflect and to focus the X-ray beam in the vertical direction. A monochromatic beam was selected by a double crystal silicon 111 monochromator. Precision four blade slits were used to select a section of the incident beam that completely filled the mirror surface. The beam profile was measured by scanning a gold wire (50 μm diameter) through the X-ray beam at the focal plane using a piezo actuator while measuring the intensity using a silicon PIPS detector. For measurements of the wavefront, the silicon PIPS was replaced by an X-ray area detector with pixel size of 6.5 μm. The refractive correcting optics were mounted on a goniometer at a distance of approximately 1m upstream of the optics being corrected with angular adjustments of the transverse tilt and rotation about a vertical axis and translational adjustment of the transverse position and the vertical position relative to the X-ray beam being provided. This allowed a large number of different structures to positioned in the beam. The most critical parameter for alignment is the vertical position of the structures with respect to the mirror being corrected and this alignment was performed by measuring the focus profile or the wavefront error as the structure position was stepped with a resolution of a few micrometers.

3. FABRICATION OF REFRACTIVE STRUCTURES

The thickness profile of the refractive corrective optics was determined from the mirror figure error measured by nano-metre optical metrology (NOM)[6] or from the wavefront error determined by at wavelength methods carried out on the Test Beamline. The measured error is projected using geometric optics across the mirror surface to the plane where the corrective optics is to be mounted. The wavefront error at this plane is then converted into the thickness profile of the corrective optics using the X-ray energy dependent refractive index of the material (the polymer SU-8 in this case). Using the refractor thickness function the structures were firstly drawn using CAD and then sent to a specialist company for production of an optical mask of size 50 mm × 50 mm. On each optical mask many hundreds of separate refractive structures could be drawn allowing fabrication of correctors
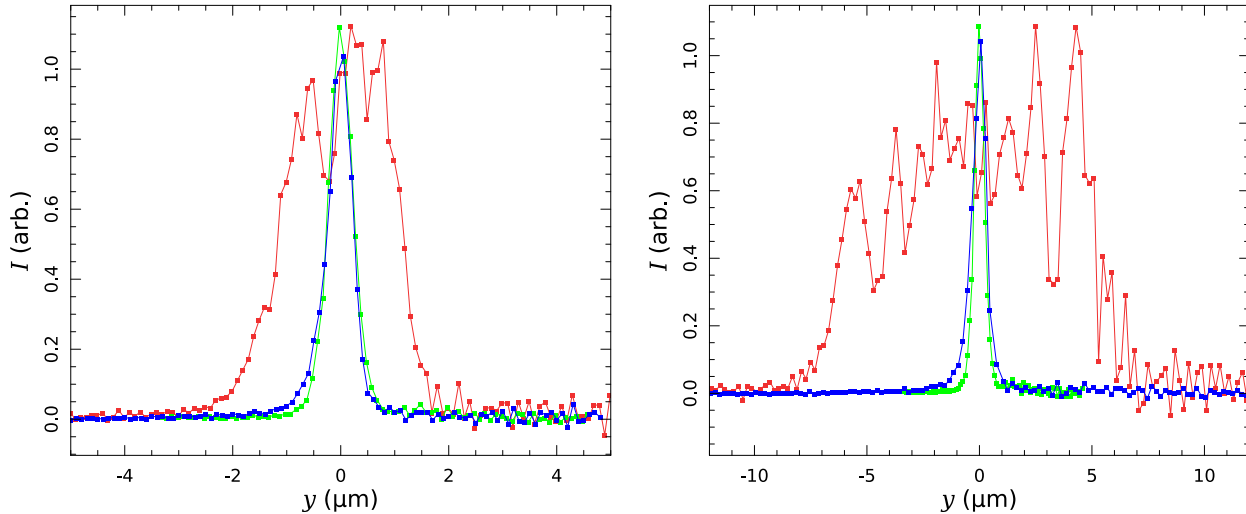
Figure 4. Focused beam profile for the three lane mirror. Red curves are for the bare mirror with no correction, blue shows the mirror with the corrective optics inserted. The green curve shows for comparison the profile obtained from lane 1 which had no artificial height profile added to the basic elliptical profile. The plot on the left shows the results for lane 2 (10 nm amplitude modulation) and the plot on the right shows the results for lane 3 (50 nm amplitude modulation)

for a variety of optical elements over a range of X-ray energies to be fabricated. In addition, to assist with alignment with the X-ray beam, fiducial structures were drawn at intervals. As part of the LIGA process, the optical mask is converted to a precision X-ray mask made from a $8\,\mu$m thick gold layer and the LIGA structures were produced using X-rays in the energy range 2.5 to 9 keV. After fabrication, the LIGA wafer was cut into 10 strips giving a sequence of structures that could be translated into the X-ray beam. The depth (transverse to
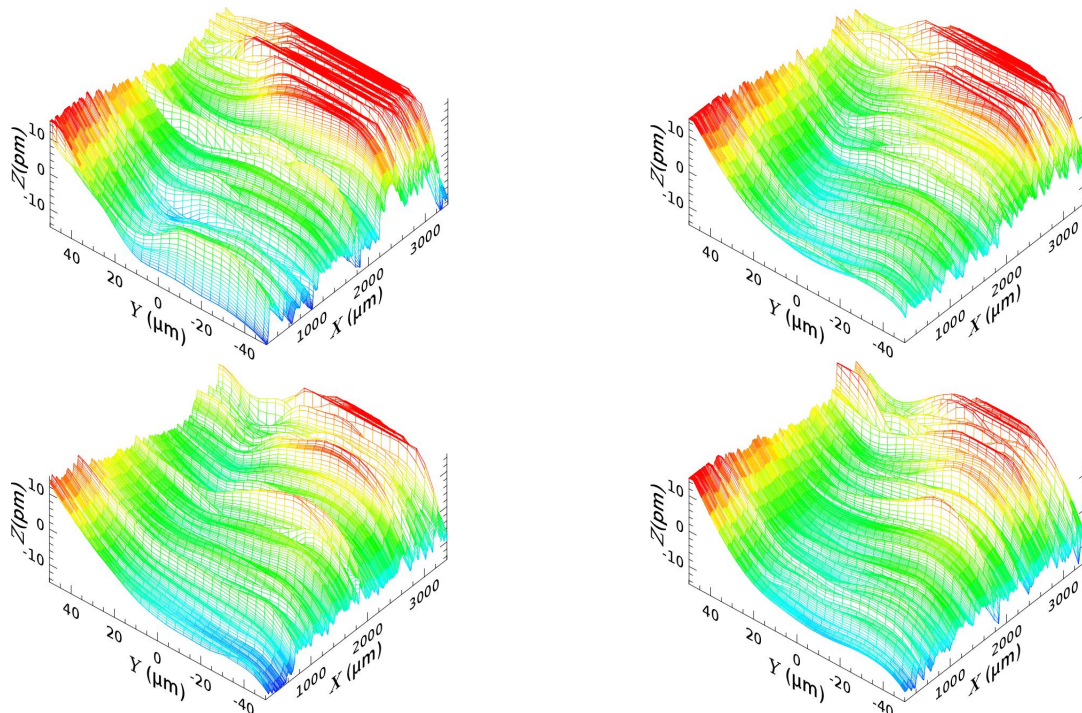

Figure 5. Measured wavefront error caused by insertion of the gold coated plane mirror for four different transverse positions of the mirror. The wavefront error is measured on a plane following the focusing mirror with X being horizontal position and Y vertical position in the plane.
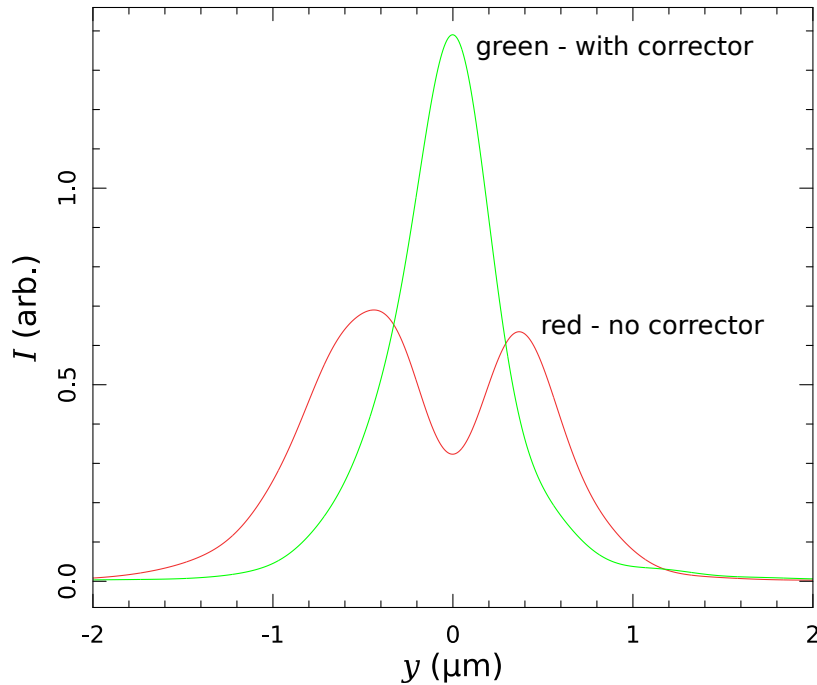
Figure 6. focus profile of the gold mirror

the X-ray beam) of the structures was of order $50\,\mu$m as measured by observing X-ray transmission contrast. A complete wafer and a structure that was used to correct a test mirror at an X-ray energy of 14 keV are shown in Fig. 3.

4. RESULTS

The technique was initially applied to a test mirror which had been manufactured with three distinct lanes running the length of the mirror. The first lane had a basic elliptical surface profile with $\theta = 3\,$mrad, $P = 45.0\,$m, $Q = 0.4\,$m and an active length of 90 mm. The second and third lanes had artificial profiles in addition to the elliptical profile. The maximum amplitudes of the artificial profiles were 10 nm for lane 2 and and 50 nm for lane 3. These profiles were characterised by NOM in the Diamond Optics and Metrology Laboratory.[7] Using the measured profiles, refractive correctors were designed and fabricated and the mirror focusing performance was measured on the Test Beamline without and then with the corrective optics inserted. The results are shown in Fig. 4. A maximum reduction in the focal spot sizes of a factor of over ten are observed.

The technique was then applied to an optical quality plane mirror with a gold coating which was inserted into the beam path before a high quality elliptical focusing mirror. The plane mirror introduced a significant modulation of the wavefront which was readily measured by at wavelength techniques at a plane immediately following the focusing mirror. The wavefront measured for four transverse positions of the plane mirror are shown in Fig. 5. This wavefront error was then used to design wavefront correctors which were then fabricated. Fig. 6 shows the resulting improvement in beam size.

5. CONCLUSIONS

These results demonstrate that hybrid optics consisting of a reflecting element with a refractive elements for correcting the wavefront for errors caused by figure error on the reflecting element can in some cases give an order of magnitude or more improvement in the size of a focal spot. The weak refraction of X-rays means that correction of the wavefront to better than $\lambda/100$ is easily achieved. While current state of the art microfocusing mirrors are capable of achieving diffraction limited spot sizes, with higher numerical aperture multilayer optics, the diffraction limited spot size will be reduced while due to the larger glancing angle of incidence, the wavefront
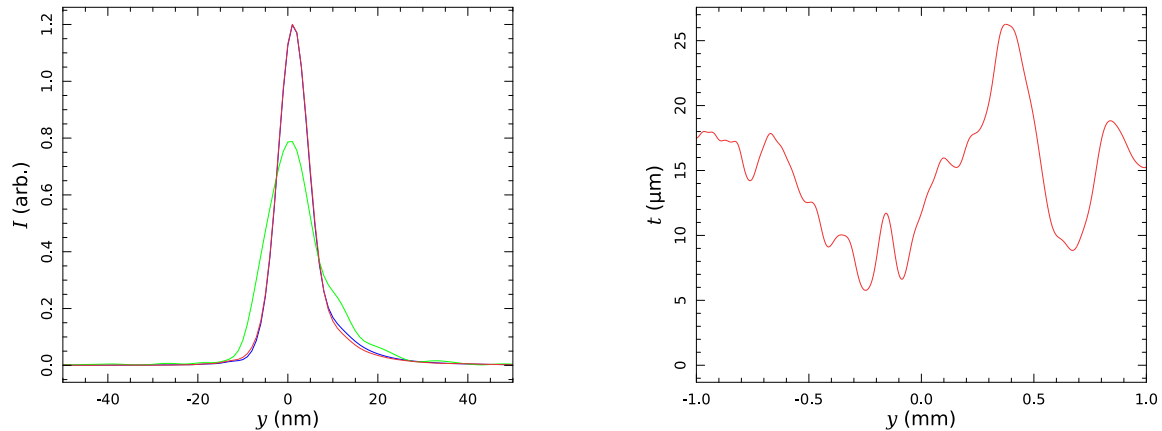
Figure 7. Left plot - simulated focus profile for an elliptical multilayer mirror with layer repeat distance 2 nm at 15 keV; green - mirror with no corrector, red - mirror with corrector, blue - a perfect mirror with zero figure error. Right plot - thickness profile of the SU-8 refractive optics corrector used in the simulation

error caused by figure error on the mirror will be magnified. In this situation, refractive corrector optics are able to correct the wavefront to allow the optics to achieve diffraction limited results. This is illustrated in Fig. 7 which shows the simulated focused beam profile for an elliptical multilayer mirror with layer spacing of 2 nm for X-rays for an X-ray energy of energy 15 keV with a refractive corrector. The figure error used for the multilayer was the figure error of the vertical KB mirror from the microfocus beamline (I14) at Diamond Light Source - the lowest figure error of any mirror at Diamond. The simulation used wave propagation to simulate the refractive corrector placed 0.5m before the multilayer mirror. The corrector reduces the focused beam size from 13 nm to 8 nm (fwhm).

6. ACKNOWLEDGMENTS

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