ESRF	**Experiment title:** In-situ metrology of refractive X-ray lenses with a shearing interferometer	**Experiment number:** MI-753
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Report:

The **main objective** of this experiment was to use the wavefront-sensing capacities of hard X-ray grating interferometry (Weitkamp *et al.*, APL **86** (2005) 054101 and Opt. Express **13** (2005) 6296) for the **characterization of the phase profile and the corresponding aberrations of parabolic, rotationally symmetric X-ray refractive lenses** (RLs) made of light metals. These aberrations are difficult to measure with other techniques, yet their knowledge is essential for further improvement of the lens fabrication process, especially in the context of efforts to achieve ever smaller focal spot sizes (Schroer and Lengeler, PRL **94** (2005) 054802).

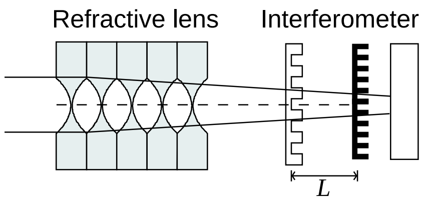


Figure 1: Setup for measurement of the phase profile of refractive lenses: the lens under test (single or compound RL) was placed just upstream of the interferometer, which consists of two linear transmission gratings — a silicon beam-splitter grating with a period of 4 μm and a gold absorption grating with a period of 2 μm — and an imaging detector. The distance between the two gratings was 69.7 mm.

Figure 1 shows the **setup of the experiment**, which was carried out using monochromatic X rays of a photon energy of 14.4 keV, i.e., within the range of energies in which RLs are typically used. We **tested both Al and Be single lenses** as well as **compound lenses** formed by stacking several single lenses in series. For all lenses, the diameter of the physical aperture was 0.9 mm, and the radius of curvature in the apex of each lens paraboloid 0.2 mm (design value). The field of view of the imaging detector, a CCD camera coupled to a thin single-crystal scintillator plate via a visible-light microscope optic, was chosen to be 1.4 mm (1024×1024 pixels of 1.4 μm size). It thus covered the entire lens aperture and part of the region outside the parabolic profile.

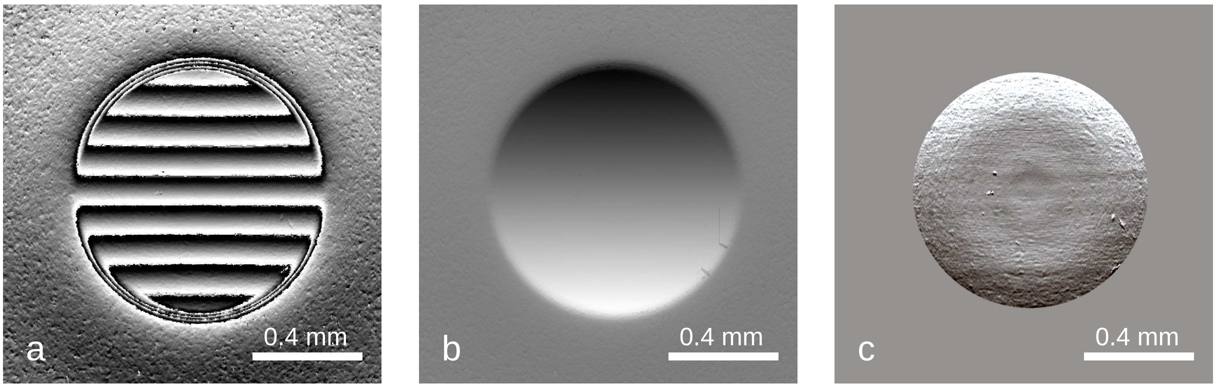
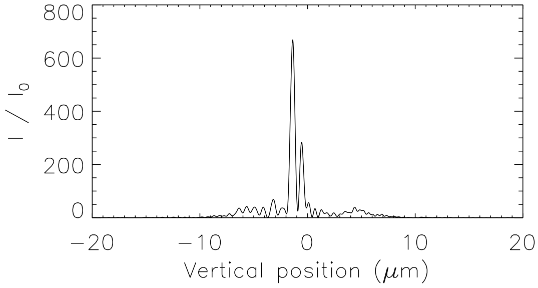


Figure 2: Phase-profile derivative of a compound refractive lens consisting of 16 single lenses. (a) Wrapped into the interval $[\pi,-\pi[$. (b) Phase derivative after unwrapping. (c) Deviations from perfect parabolic shape inside the aperture.

A total of **20 different lenses were measured** during the experiment. These covered both single and compound lenses. Figure 2 shows results for a compound lens made of 16 single beryllium lenses. The expected focal length for this lens was 3.80 m. The raw interferogram obtained by phase stepping (Fig. 2a) is proportional to the first derivative of the wavefront phase profile along the vertical direction, perpendicular to the grating lines. Since this signal has, in its turn, the nature of a phase, it is wrapped into an interval of width 2π. The unwrapping process in two dimensions is usually complicated and, if the phase gradient is too steep, it even becomes impossible. However, in the present case it is possible to use the *a priori* knowledge about the approximate shape of the lens to put additional constraints on the unwrapped phase, so that **an unwrapped first derivative of the wavefront phase can be obtained (Fig. 2b).** The derivative of the ideal parabolic profile of a spherical wave is an inclined plane. We can thus **fit a plane to the measured wavefront phase derivative and subtract it from the measured derivative.** The difference (Fig. 2c) gives a measure of any aberrations of the lens. In the case shown in Fig. 2, it can be seen that the lens has **substantial spherical aberrations:** its outermost parts have a longer focal length than the center. A quantitative analysis shows that the central part of the lens has an average focal length of 3.73 m, while the outermost part focuses at 3.85 m. The integration of the phase derivative shown in Fig. 2b yields the phase profile, which can then be used for propagation calculations to obtain a calculated spot profile. A vertical spot profile calculated in this way is shown in Fig. 3.

Figure 3: Spot profile calculated by propagating the retrieved phase profile of the lens to its focal plane. This preliminary calculation shows two central spot peaks, presumably caused by a misplacement of the two parabola branches with respect to each other, and the broad background caused by the spherical aberrations.



The information obtained in this experiment is new and provides valuable input for the further refinement of lens production. It could not be obtained with other methods available so far. The measurement technique can be used for optical elements of other types in the same way. The experiment is thus considered a full success.