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D12.2

Prototype of corrected CRL nanofocusing unit for user experiments

Due date

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D – 12.2	Prototype of corrected CRL nanofocusing unit for user experiments

DELIVERABLE DESCRIPTION

We report on the implementation of a demonstrator for aberration correction of X-ray nanobeams generated by compound refractive lenses (CRLs) at beamline P06 of PETRA III at DESY. The aberrations are compensated by a tailor-made optical phase plate that needs to be positioned with respect to the CRLs in order to effectively compensate shape errors. The demonstrator combines the CRL mount and phase plate mount into a single device, allowing for a combined alignment. A novel piezo-driven positioning system allows for a one-off alignment of the phase plate relative to the CRL and freeze the alignment. In subsequent uses, the device can be operated by non-expert users.

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NATURE

☐ R - Report

☒ P - Prototype

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INTRODUCTION

Compound refractive lenses (CRLs) are widely used at synchrotron radiation facilities for X-ray beam shaping [1, 2] and focusing [3]. They are made by pressing a parabolic lens profile into a thin foil of aluminum or beryllium via a coining process. Their focusing capability depends on the manufacturing quality of the stamp and mechanical alignment during the coining process, both of which are limited by today's technology [4]. Recently, diamond CRLs made by laser ablation and mechanical polishing emerged, which exhibit similar shape errors [5].

It has been shown that each lens shows a typical shape deviation of 500 nm from an ideal paraboloid of rotation [3]. When many of these lenses are stacked in order to create sub-micrometer X-ray beams, these shape errors add up and lead to spherical aberration, impacting the resolution and imaging capabilities of X-ray microscopes.

A solution to overcome these challenges is the correction of aberration by an additional optical element, called a refractive phase plate [6]. It is tailor-made for the specific lens configuration and needs to be aligned with respect to the optical axis to within a few micrometers, requiring a motorization within a plane perpendicular to the optical axis.

Here, we present the development of a new CRL lens holder with an integrated mechanism to align a phase plate and keep the aligned position over time and in between experimental campaigns in order to enable usability by non-expert users and to provide aberration-corrected nanobeams with CRLs within the NFFA catalogue for end users.

PROTOTYPE FOR LENS POSITIONING

For strong X-ray focusing with spot sizes in the sub-micrometer range many tens of CRLs are typically combined within a lens stack. A high-precision prism is used to place individual CRLs along a common optical axis with a lateral positioning accuracy of roughly 10 µm. When an X-ray beam propagates through the lens stack shape errors in each lens introduce deformations to the wavefront, causing aberration. The positioning and rotational alignment of each single lens within this stack can influence the resulting aberration pattern. Thus, a completely assembled lens stack is often characterized at once and a phase plate for the specific configuration is manufactured. The created phase plate is specific to the stack and needs a higher lateral alignment accuracy of < 2 µm with respect to the optical axis. As this is mechanically not feasible, the phase plate is often mounted and aligned with a sperate stack of linear stages, placing the phase plate downstream of the assembled CRL stack [7]. This approach leads to a very good fit of the phase plate to the X-ray beam aberration, as the phase plate shape can be computed very well at this position. However, it requires realignment with a change of X-ray energy, as the focal distance changes.

Here, we are developing two improvements of the concept to increase usability by non-expert users: First, the phase plate mounting and fine positioning has been integrated within the CRL prism via piezo actuators that can keep their position even without an applied voltage. This allows to keep the phase plate alignment between measurements campaigns. Second, the phase plate

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position was shifted upstream of the CRL stack to the beam entrance side. While the phase plate shape will not match perfectly due to unknown error profiles for individual CRLs, the benefit is a lifted requirement on the longitudinal placement of the phase plate along the optical axis. This allows to change X-ray energies over a broad range of several keV without the need to realign the device.

Piezo positioning kinematic

The phase plate positioning device is realized with two flexures actuated by piezo elements for decoupled motion in two directions perpendicular to the optical axis. We are using a newly developed piezo actuator from Physik Instrumente called "PIrest". It operates in the remanent strain regime of the actuator, exploiting domain switching processes [8]. While conventional piezo elements work in a polarized state of the ceramic, using the piezoelectric effect at high electrical fields of several kV/mm, as shown in Fig. 1a), the new PIrest ceramic operates by polarizing and depolarizing domains in a soft piezoelectric ceramic, as shown in Fig. 1b). The piezo element adjusts between statistically oriented domains due to thermal depolarization (S_0 in Fig. 1b) and remanent strain S_{rem} (strain remaining after switching off a high electrical field after reaching S_{max}) by short voltage pulses.

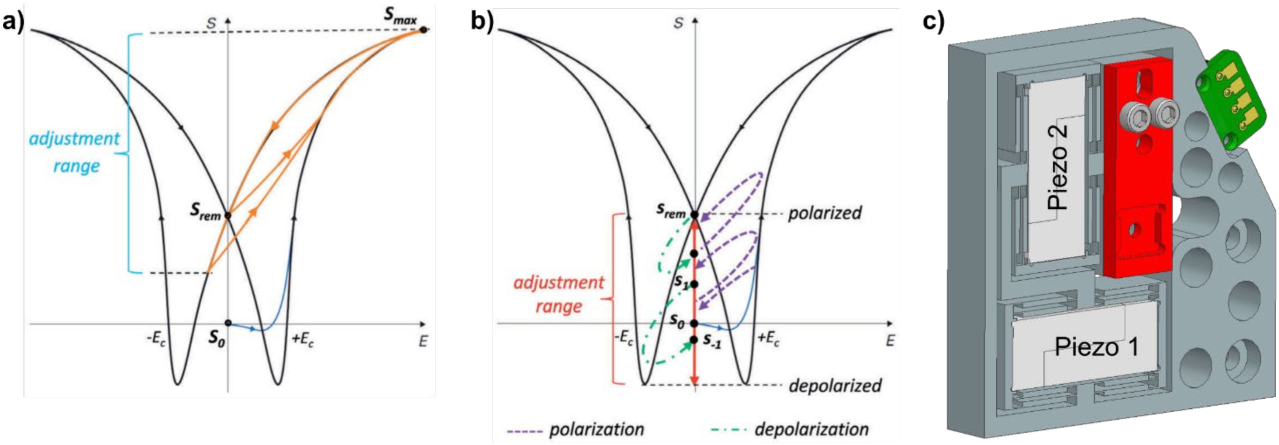

Figure 1: a) Operation regime of a conventional piezo element (taken from [8]). B) Operation range of the PIrest actuators (taken from [8]). c) CAD model of the prototype flexure device with two mounted piezo elements and the phase plate mounting plate (red).

Here, we are using a piezo element that can nominally be elongated by 6 µm, leading to a designed range of motion of 40 µm for the phase plate. The phase plate itself is printed on the red holder, shown in Fig. 1c), with an accuracy of 10 µm with respect to the optical axis. The metrology to determine the position is done offline in a mechanical lab on an alignment jig.

Implementation at beamline P06, PETRA III, DESY

The device was implemented and tested at the microhutch endstation of beamline P06 at PETRA III, DESY. A CAD model of the CRL tank is shown in Fig. 2a). An upstream view with the phase plate positioning device and a mounted phase plate is shown in Fig. 2b). The CRL tank is mounted on a hexapod, shown in Fig. 2c), to provide alignment in 6 degrees of freedom for the CRL system to the beamline optical axis. The hexapod is mounted on a long travel stage along the optical axis to accommodate for CRL tanks with focal lengths ranging from 100 mm up to 800 mm.

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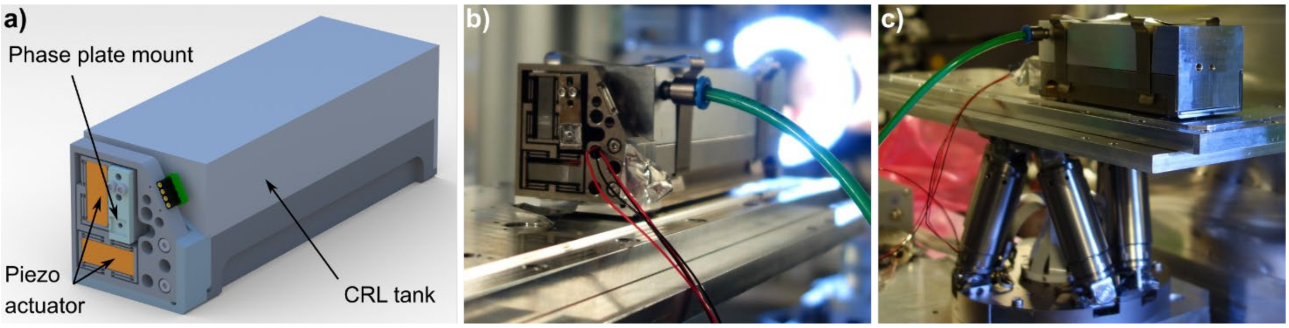

Figure 2: a) CAD model of the CRL tank with attached phase plate positioning device. b) View from upstream (beam entrance) of the CRL tank with attached phase plate device. c) View from downstream (beam exit) of the CRL tank mounted on a hexapod for alignment.

RESULTS

For demonstration purposes a lens stack comprising of 20 individual beryllium lenses was mounted in the tank, yielding a nominal focal length of 250 mm and a diffraction-limited spot size of 130 nm at an X-ray photon energy of 8.2 keV. The alignment procedure with the build-in alignment guide of the prism as well as the straightness of the CRL mounting prism were tested and confirmed by reaching the nominal focusing parameters, which were determined via ptychographic phase retrieval of the focused wavefield. Details about the focusing and aberration-correction results can be found in the report for MS 16 in WP 12.

The phase plate kinematic was evaluated by mounting a 3D-printed polymer phase plate (see report for D12.1) and manipulating its position with the piezo actuators in the X-ray beam. We observed a reduced maximum travel range of 25 µm in both axis perpendicular to the optical axis, which is about 60 % of the designed 40 µm. We address this reduction to machining tolerances of the thin flexures. Here, a change in wall thickness can impact the kinematic properties. The reached minimum step size of the system was found to be low enough to position the phase plate with a precision < 1 µm, suitable for accurate alignment. When switching off the piezo controller no movement or meaningful drift of the phase plate could be observed over several hours.

A further improvement of the piezo kinematic is foreseen to provide larger travel ranges. In addition, long-term stability and drift tests will be performed once the device is in active use over many weeks at beamline P06.

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