Focus characterization of a Beryllium CRL by ptychographic imaging

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The nanoprobe endstation at PETRA III P06 [1] provides the possibility to change the optics unit in the scanner frame shown in Figure 1(b). This feature allows one to study and characterize all kind of different nanofocusing optics such as FZPs, MLLs, NFLs, and CRLs. The latter were used in this experiment to demonstrate the feasibility of coherent imaging techniques using this kind of optic. We used 36 single lenses made of beryllium with a biconcave shape, a radius of curvature $R$ at the apex of a lens of $R = 50 \mu m$, and a housing thickness of $W = 2 mm$. Combining these we build a $72 mm$ thick lens with a nominal focal length of $f = 143.2 mm$ for the used photon energy of $E = 8.0 keV$ ($\lambda = 1.55 \AA$). The maximum geometrical aperture of the lens is given by the thickness of the beryllium foils used. With a thickness of $l = 1 mm$, the aperture $D_{geo}$ is given with $440 \mu m$. Further experiments in late 2010 showed, that small-angle scattering in the lens is an issue for coherent imaging techniques. To resolve this problem we only illuminated the inner part of the CRL using a double slit system in front of them as depicted in Figure 1(a). For an initial experiment we used a slit opening of $80 \times 80 \mu m^2$, reducing the geometrical aperture $D_{geo}$. This results in a smaller numerical aperture $NA$, which is half of the opening angle of the optic and for small angles given as $NA = D_{geo}/(2f)$, and thus a larger size $d_t$ of the diffraction limited beam.

Figure 1: (a) Experimental setup for ptychographic imaging. (b) View of the scanner frame with the CRL lens holder and alignment axis. The probe (c) as well as the illuminated object (d) are reconstructed from the recorded diffraction patterns by a ptychographic algorithm [2].

To fully characterize the focused CRL beam, we performed a ptychographic scan with a siemensstar test sample of $500 nm$ thick tantalum to provide a strong scatterer. Moving the sample with $50 nm$ step size trough the focused hard x-ray beam, we scanned an area of $2.5 \times 2.5 \mu m^2$. At each scan point we recorded a far-field diffraction pattern, using a Pilatus 300k detector at a distance of $2063 mm$. We used a ptychographic algorithm as proposed by Maiden and Rodenburg [2] to
reconstruct both the wavefield probing the sample (Figure 1(c)) as well as the illuminated object (Figure 1(d)). The phase of the wavefield is encoded in color, the amplitude in hue, respectively. For the reconstructed object the Phasshift is shown, reaching nearly the theoretical value of 0.8 rad. The wavefield is reconstructed in the plane of the scanned object. To retrieve a complete intensity distribution along the optical axis of the focused beam (caustic) we numerically propagate the wavefield around the object plane [3]. This method allows one to characterize the used optic [4] and determine fabrication errors or misalignments [5].

Combining knife-edge techniques with ptychography, we first determined the exact position of the focal plane. We noted, that the focal distance was only \( f = 134.9 \text{ mm} \), resulting in a corrected radius of curvature \( R = 46.8 \mu \text{m} \) due to fabrication errors.

In the present example, we also measured both the size of the diffraction limited beam \( d_t \) as well as the depth-of-focus \( d_l \) as a function of the geometrical aperture. Knowing the exact size and shape of the used beam is crucial for many experiments involving scanning microscopy or tomography. The lateral focus size of a diffraction limited beam is given by \( d_t = \zeta \cdot \lambda/(2NA) \), where the factor \( \zeta \) depends on the aperture shape. With the double slits in front of the lenses and negligible attenuation inside the lens, the shape is roughly a box, leading to \( \zeta \) of about 0.89. For a slit opening of \( 80 \times 80 \mu \text{m}^2 \) the numerical aperture \( NA \) becomes \( 2.89 \cdot 10^{-4} \). The analytically calculated focus size of \( d_t = 237 \text{ nm} \) fits well with the measured one of \( 243 \text{ nm} \). The intensity along the optical axis is shown in Figure 2 for different geometrical apertures ranging from \( 40 \mu \text{m} \) to \( 120 \mu \text{m} \).

![Image](image.png)

**Figure 2:** Numerically calculated intensity profiles (caustics) along the optical axis from a ptychographic reconstruction of the wavefield. Shown are beam profiles for different geometrical apertures \( D_{geo} \), ranging from \( 40 \mu \text{m} \) (a) to \( 120 \mu \text{m} \) (e). This results in a different \( NA \) of the optic, while keeping the focal distance \( f \) constant. A higher \( NA \) decreases the lateral focal size \( d_t \) while at the same time reducing the depth-of-focus \( d_l \), which scale like \( \propto NA^{-1} \) and \( \propto NA^{-2} \), respectively.

Note that the focal distance is a constant throughout the experiment, thus we only vary \( NA \) with the geometrical aperture \( D_{geo} \) through the double slits, enabling us to produce different beam shapes as shown in Figure 2. The depth-of-focus \( d_l \), with the definition of \( d_t(0 \pm d_t/2) = \sqrt{2}d_t \), is given by \( d_t = (2/\ln 2)^{1/2} d_t/NA \). While we decrease the lateral focus size \( d_t \) by increasing \( NA \), since \( d_t \propto NA^{-1} \), we simultaneously decrease \( d_l \), which is \( \propto NA^{-2} \). The numerically retrieved values from the caustics in Figure 2(a)-(e) are in good agreement with analytically calculated ones.

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**References**