Argonne NATIONAL LABORATORY

Phase Plate after CRL

--A promising way to get a cleaner focus

ARTICLE

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Perfect X-ray focusing via fitting corrective glasses to aberrated optics

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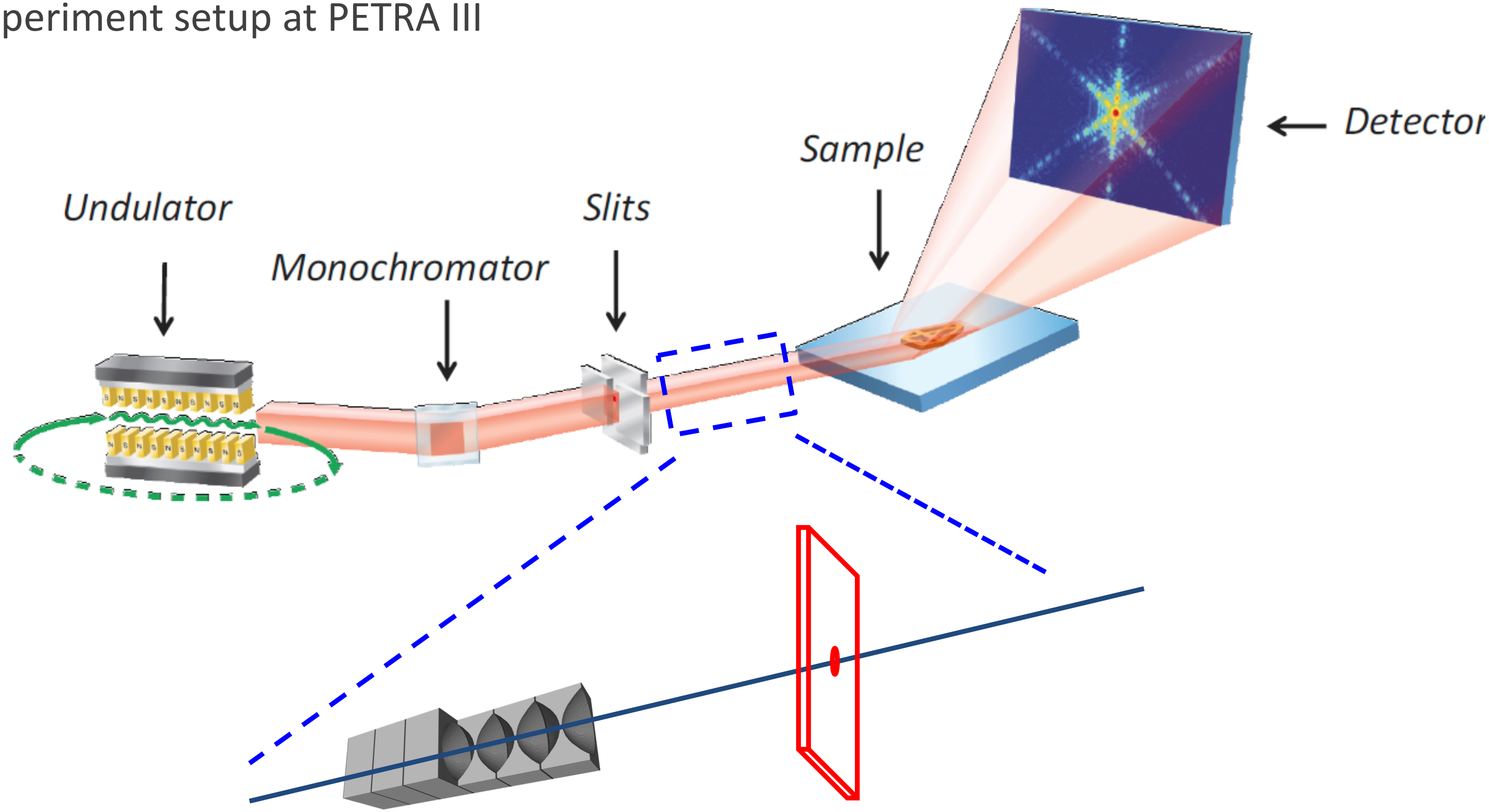
U.S. DEPARTMENT OF ENERGY

CSSI: coherent surface scattering imaging

- Experiment setup at PETRA III



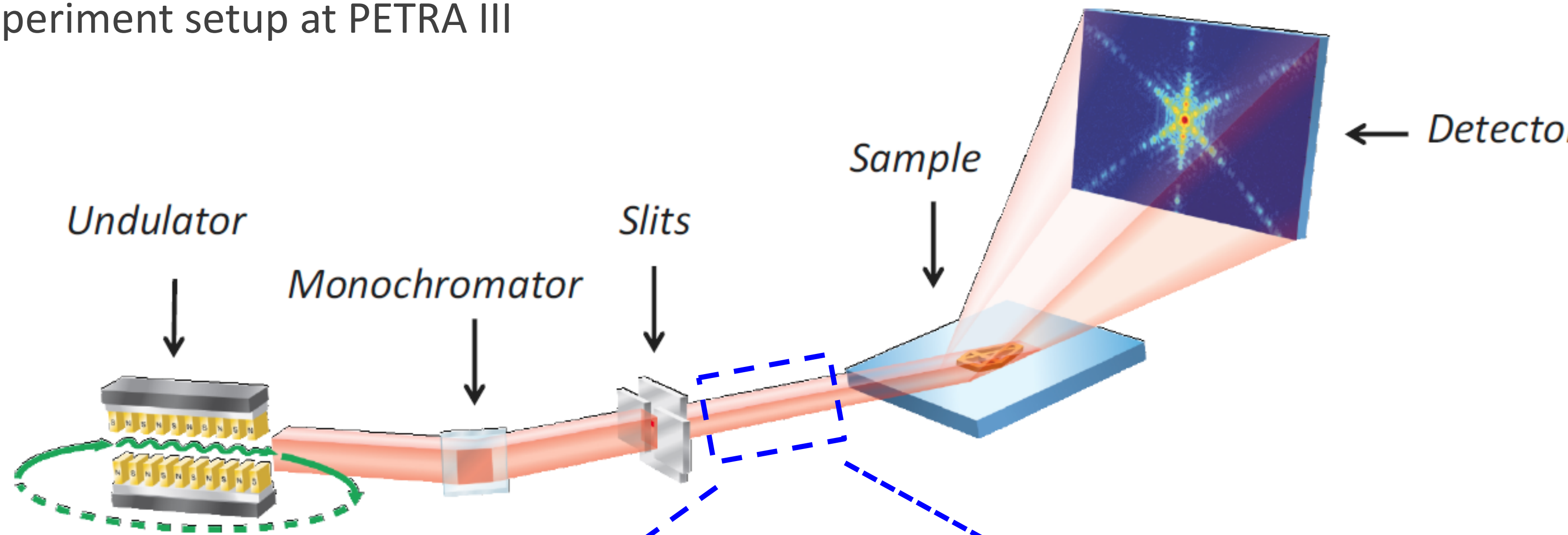
20 µm pinhole (September 2016)

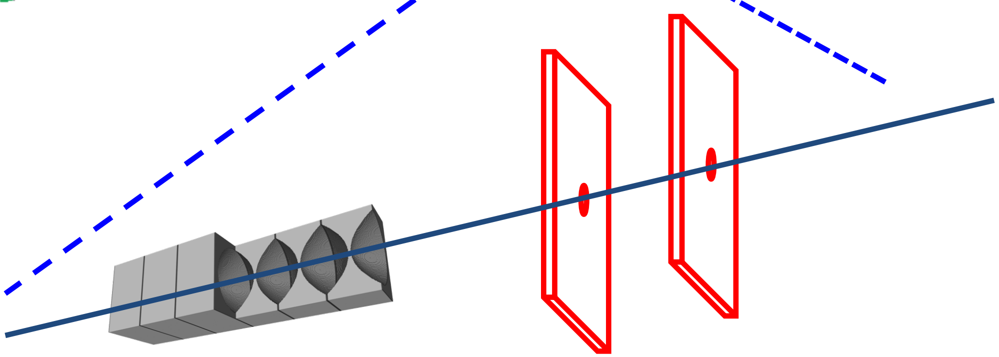
CRLs

Image from Jin Wang's APS-U talk, Nov. 2016

CSSI: coherent surface scattering imaging

- Experiment setup at PETRA III

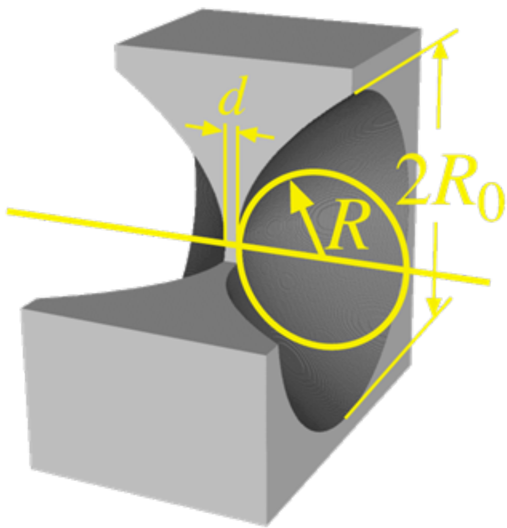


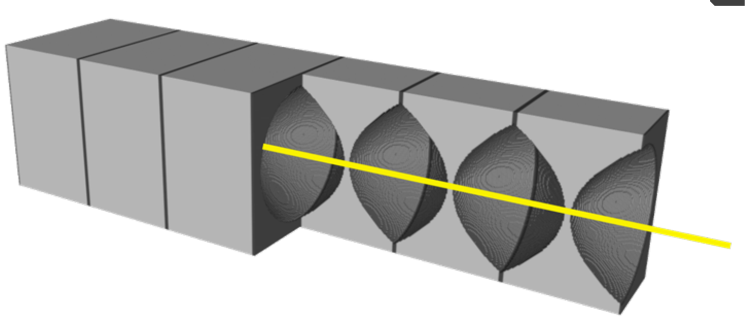


CRLs Pinhole1 Pinhole2 (August 2017)

Image from Jin Wang's APS-U talk, Nov. 2016

Compound Refractive Lens (CRLs)





Prof. Lengeler's Lecture 2012
Image from rxoptics.de

- ❑ Low z material, Be/Al/Ni
- ❑ Parabolic and biconcave profile
  - *"No optical aberration"*
  - *Focusing in whole plane*

- ❑ On-axis focusing element
- ❑ Compact
- ❑ High heat load

- ❑ Be CRLs are produced by powder metallurgy
  - Powder blending
    - Impurities, grain boundaries
  - *"Precision die"* compaction
  - Sintering

Small angle scattering
Aberration

Effect of the pinholes

Beam FWHM: 3.1µm(H), 1.8µm(V)
6σ width. 7.9µm(H), 4.6µm(V)

Knife edge scan
8.6µm pinhole
Detector-sample ~40cm

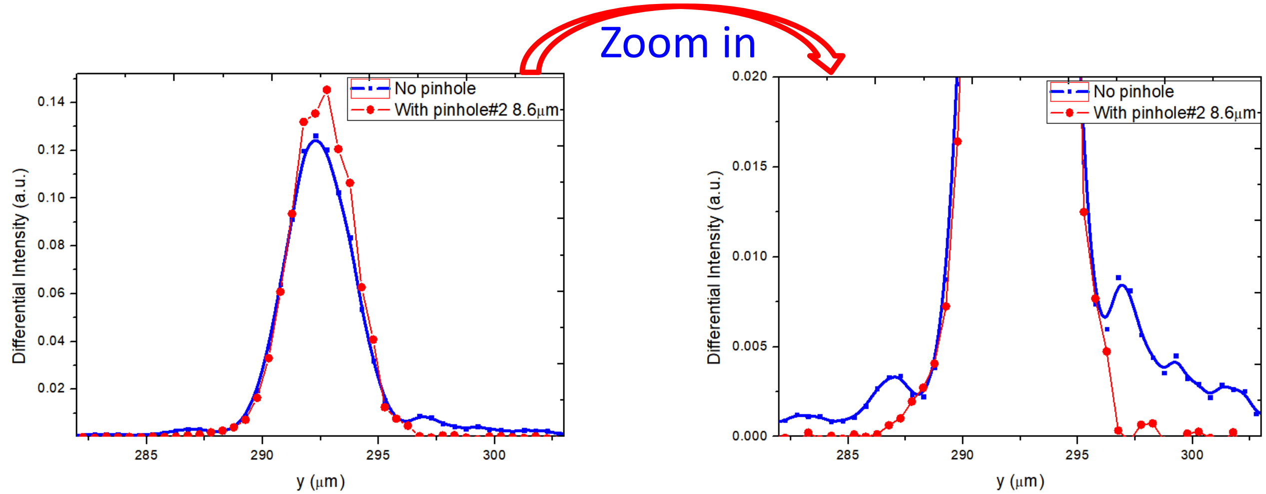
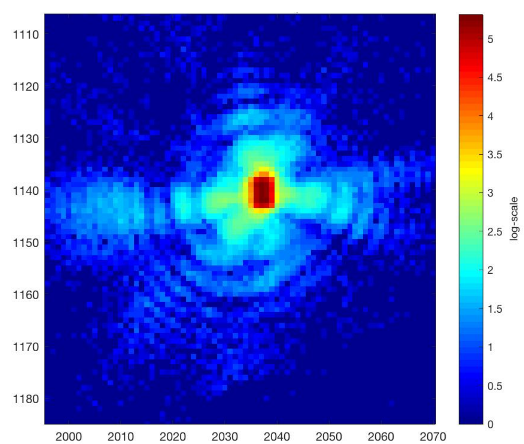
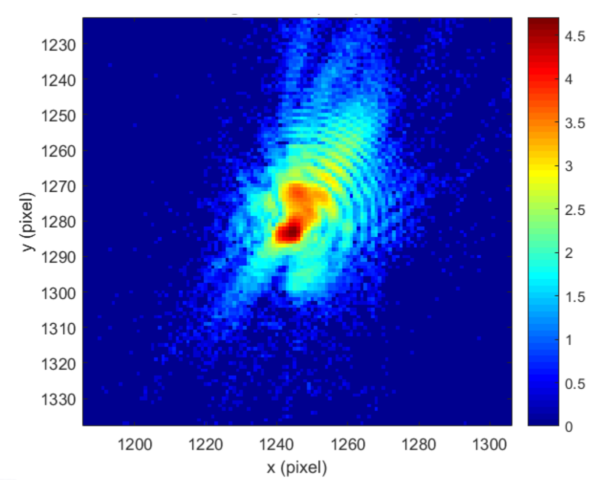


Image of the beam
Detector-sample ~5.0m

8.6/9.2µm pinhole



4.1/4.2µm pinhole



Test with gratings (gold stripes on silicon)

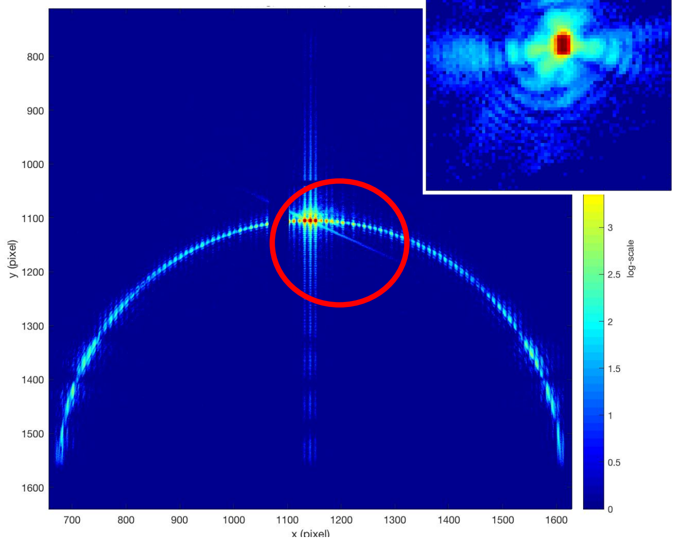
Energy=8keV

$\alpha_i = 0.400°$

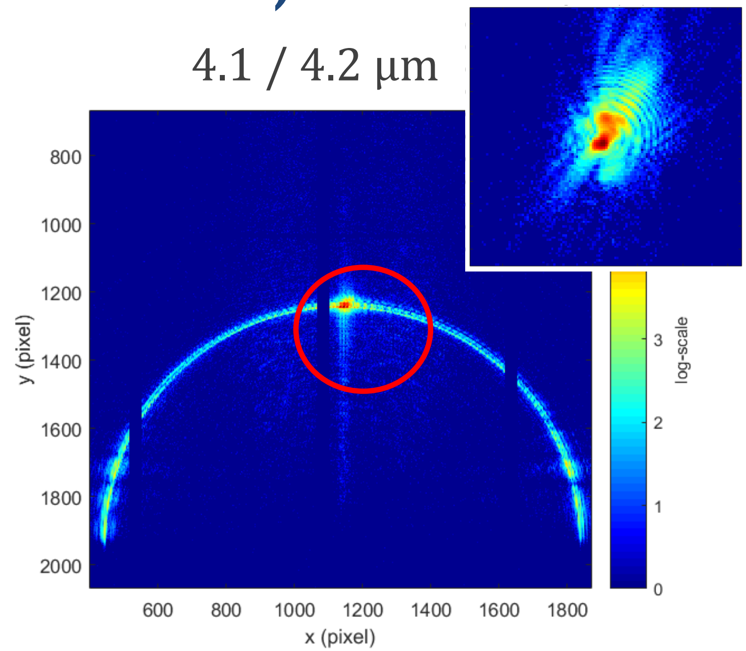
$\alpha_c[Au] = 0.406°$

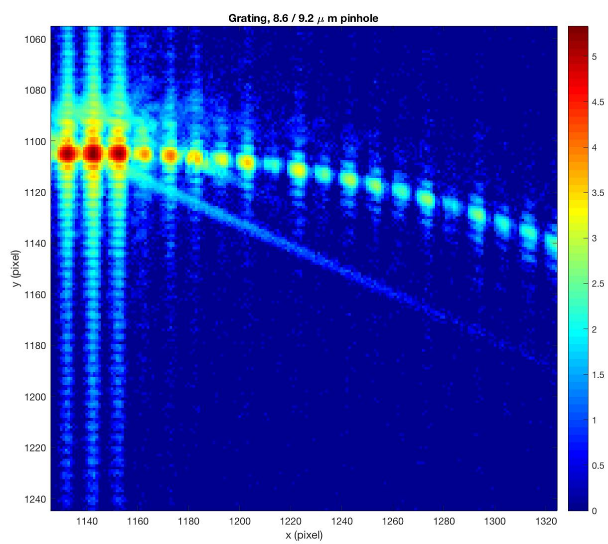
$\alpha_c[Si] = 0.157°$

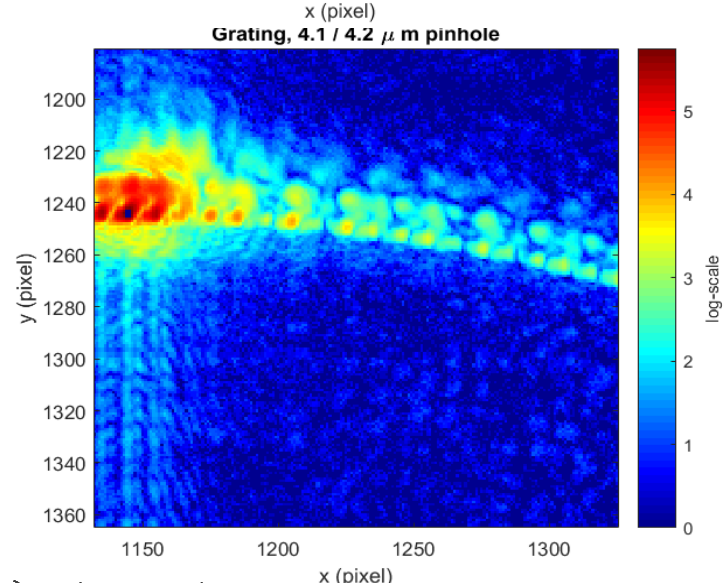
8.6 / 9.2 μm



4.1 / 4.2 μm

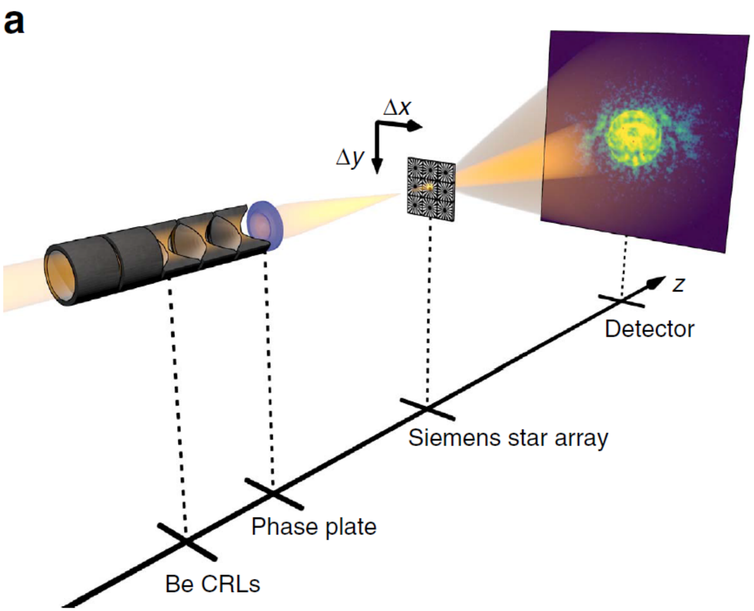




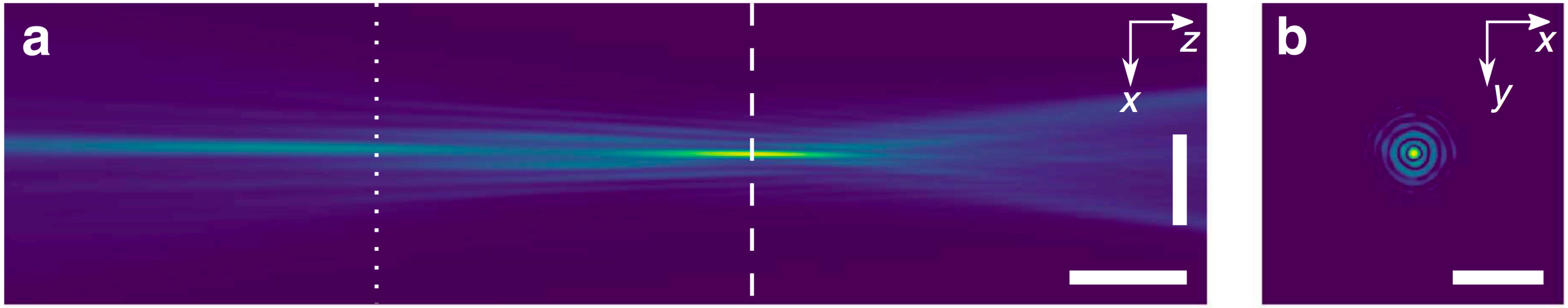


$$\psi(\boldsymbol{r}, \boldsymbol{R}) = O(\boldsymbol{r})P(\boldsymbol{r} - \boldsymbol{R})$$

Experimental setup



- Energy = 8.2 keV
- 20 sets of Be CRLs
  - R = 50 µm, D = 300 µm
- Sample: Standard Siemens stars with 50 nm smallest features structured in 1 mm thick tungsten on a diamond substrate
- The sample and the wavefield were reconstructed with a ptychographic algorithm.
- Propagate the wavefield back to the origin with the Fresnel–Kirchhoff diffraction integral



The wavefield at CRLs exit

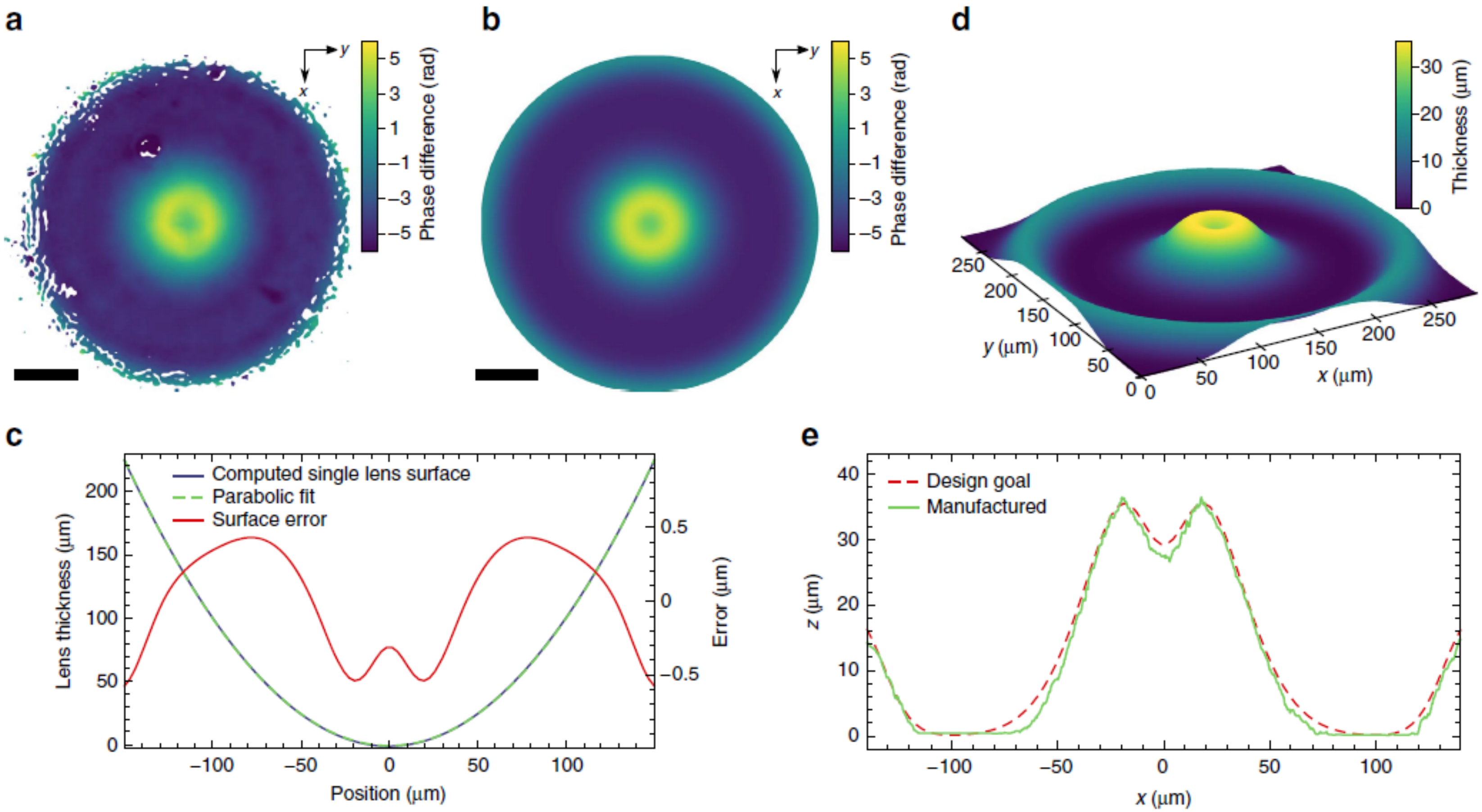
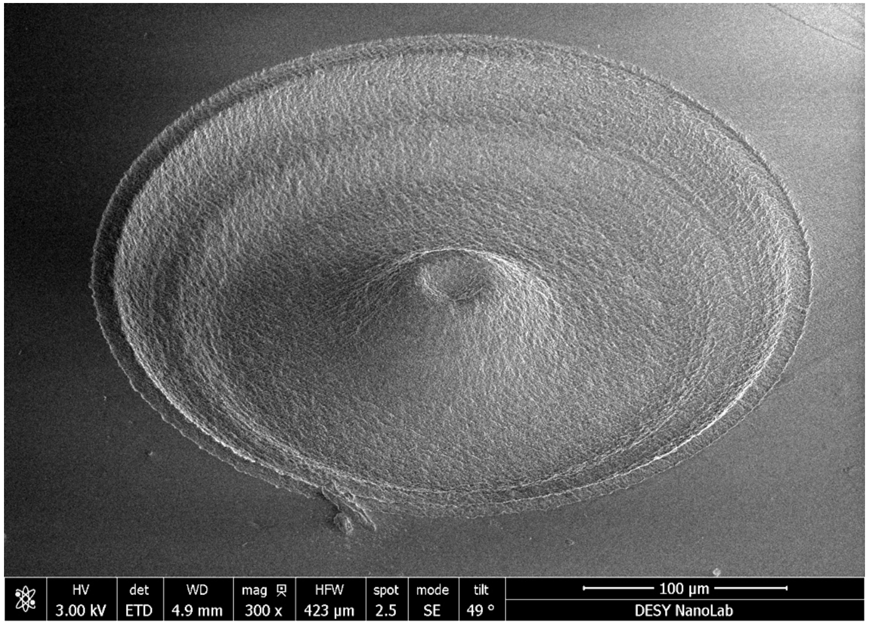


Figure 2 | Initial lens characterization and phase plate design. (**a**) Measured wavefront deformation at the lens exit compared to a spherical wave. (**b**) Phase error of a modelled lens stack at the lens exit. Scale bars in **a**,**b** correspond to 50 µm. (**c**) Deformation of every lens surface in the modelled stack of 20 beryllium compound refractive lenses used to generate **b**. The surface error (solid red line) is enhanced by the axis on the right side. (**d**) Model of the SiO_2 phase plate to correct for errors shown in **a**–**c**. (**e**) Surface profile of the manufactured corrective SiO_2 phase plate using ultrashort-pulse laser ablation compared with the design goal **d** as measured by a laser scanning microscope.

More about the phase plate



- Laser ablation (8ps @ 1030nm)
- Material: amorphous silicon oxide
  - Radiation hardness
  - Well know fabrication parameters
- X-ray transmission = 54% at 8.2keV
  - Can be increased to 95% if minimize the supporting SiO_2

http://photon-science.desy.de/news__events/news__highlights/scientists_develop_spectacles_for_x_ray_lasers/index_eng.html

Wavefield with/without phase plate

Without correction: 75% intensity in 800nm radius
With correction : 75% intensity in 125nm radius

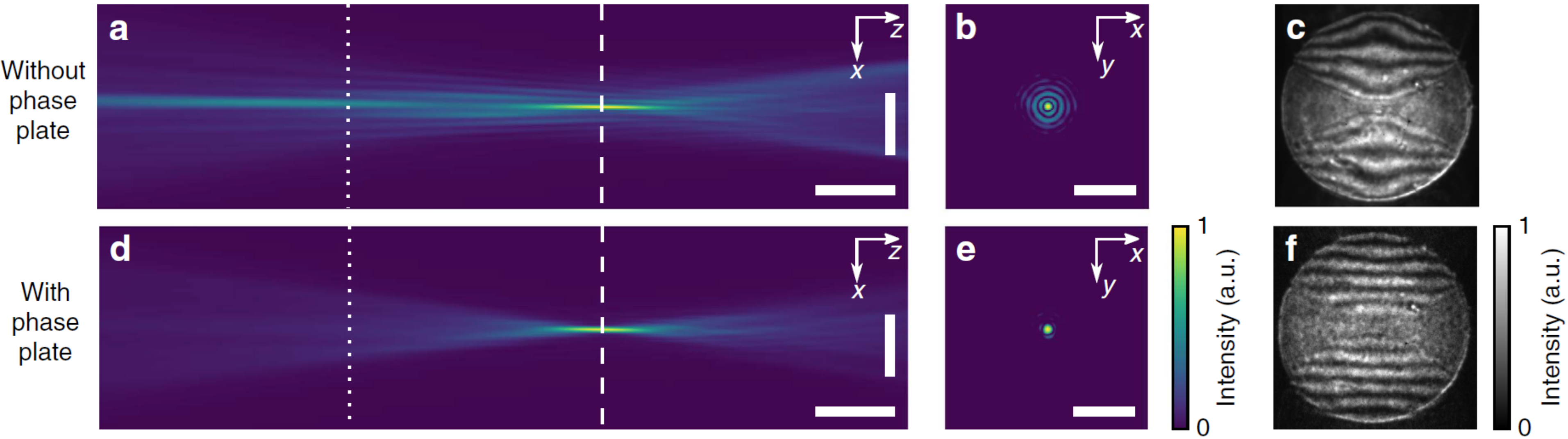


Figure 3 | Aberration correction by a corrective phase plate. (**a**) Beam caustic retrieved from the ptychographic reconstruction. Scale bars are 2 µm and 1 mm in *x* and *z* direction, respectively. (**b**) Logarithmic intensity distribution in the focal plane as marked by the dashed line in **a**. Scale bar represents 2 µm in *x* and *y* direction. (**c**) Ronchigram recorded at the dotted position in the beam caustic **a**. Insets **a–c** are without the phase plate. (**d**) Beam caustic retrieved from the ptychographic reconstruction. Scale bars identical to **a**. (**e**) Logarithmic intensity distribution in the focal plane as marked by the dashed line in **d**. Scale bar identical to **b**. (**f**) Ronchigram recorded at the dotted position in the beam caustic **d**. Insets **d–f** are with the phase plate installed. Insets **a**,**b**,**d**,**e** share the same colour bar as well as **c**,**f**.

Seiboth, Frank, et al. "Perfect X-ray focusing via fitting corrective glasses to aberrated optics." *Nature Communications* 8 (2017): 14623.

Focal spot characteristics

Logarithmic scale

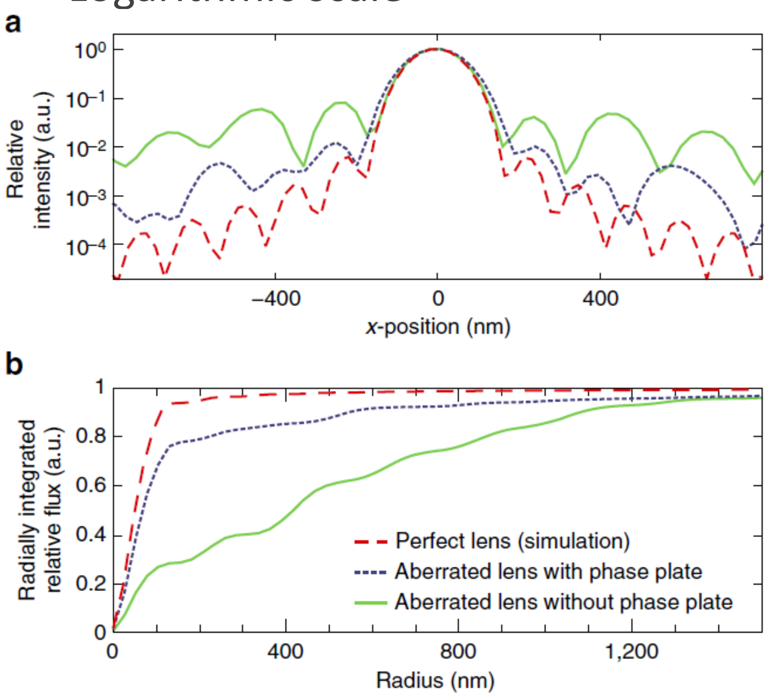
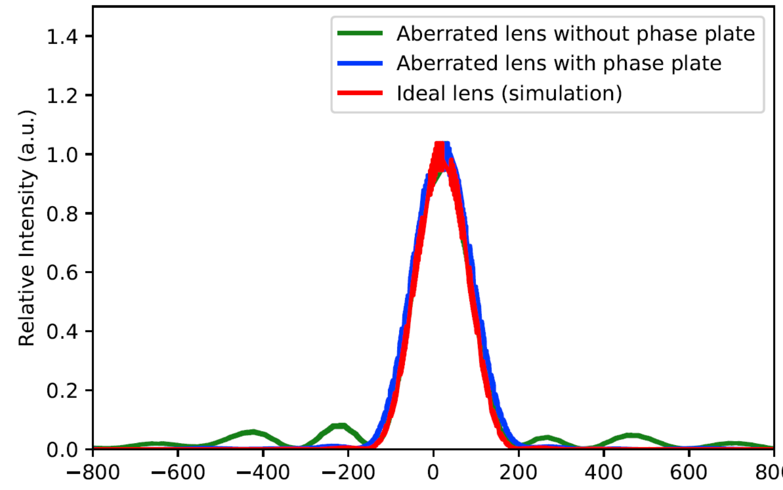
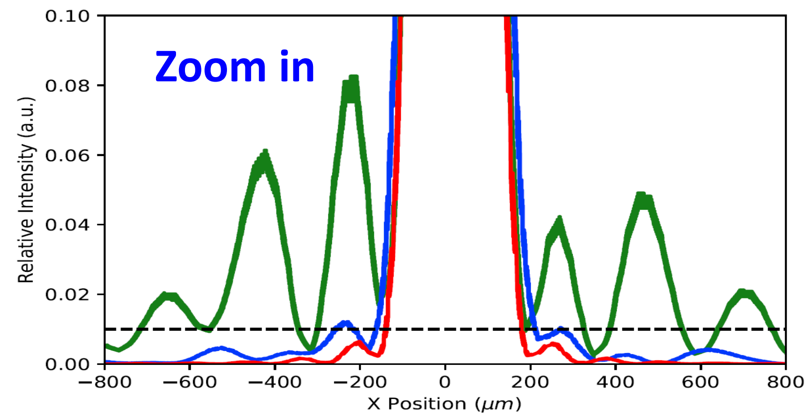


Figure 4 | Improved focal spot characteristics. (**a**) Horizontal slice (*x*-direction, logarithmic scale) through the focal plane depicted in Fig. 3b,e and for an ideal lens. (**b**) Radially integrated intensity distribution around the centre of the focal spot. The solid green line represents the results for the uncorrected lens (without the phase plate), the dotted blue line represents the phase plate corrected lens, and the dashed red line represents the modelled aberration-free lens in both **a**,**b**.

Linear scale





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Features

- In theory, this method also works for other focusing systems
  - KB, FZP, crystals/multilayers etc.
- Manufacturing challenges
  - Size ~10-100μm, tolerance ~0.1μm ?
  - 3D printing/laser/nanofabrication
  - Materials
    - Silicon oxide / metals / resists

2PP / ORMOCOMP

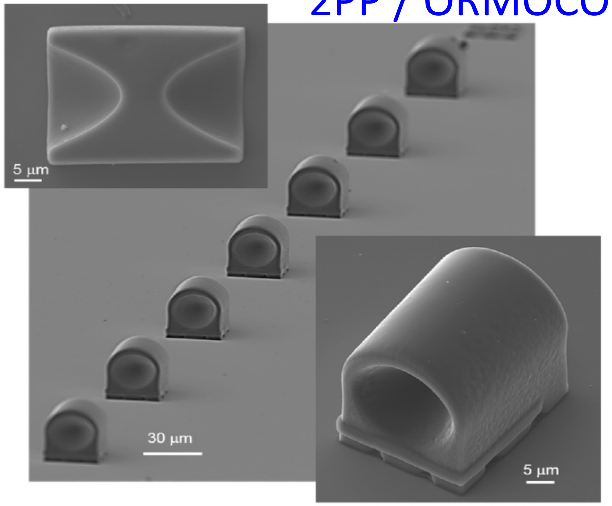

Fig. 2. SEM image of the fabricated polymer compound refractive lens. Upper insert shows the polymer lens in the cross-section. The insert in the bottom depicts individual refractive lens.

- The phase plate works over a large energy range.
  - Refractive index is almost material independent far from absorption edge
  - (But CRLs have strong chromatic aberration!)

Petrov, A. K., et al. "Polymer X-ray refractive nano-lenses fabricated by additive technology." *Optics Express* 25.13 (2017): 14173-14181.