Characterization of InP nanowire with nano-focused coherent x-ray beam at P06 station at PETRAIII.

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Introduction

X-ray Bragg ptychography (XBP) and three-dimensional (3D) coherent x-ray diffraction imaging (CXDI) was applied to map the internal strain field of a single Indium Phosphide nanowire (NW) grown vertically on an InP substrate. The strain field induced in the InP NW by the Au particle on the top was retrieved. The results of the XBP reconstruction were compared with the results of the CXDI technique. The finite element method (FEM) analysis was performed to model the strain distribution within the NW after the growth procedure. The results of the experiment and FEM analysis show a good agreement with each other. XBP experiment was performed at nano-focusing end-station of P06 beamline at PETRA III.

Ptychographical experiment

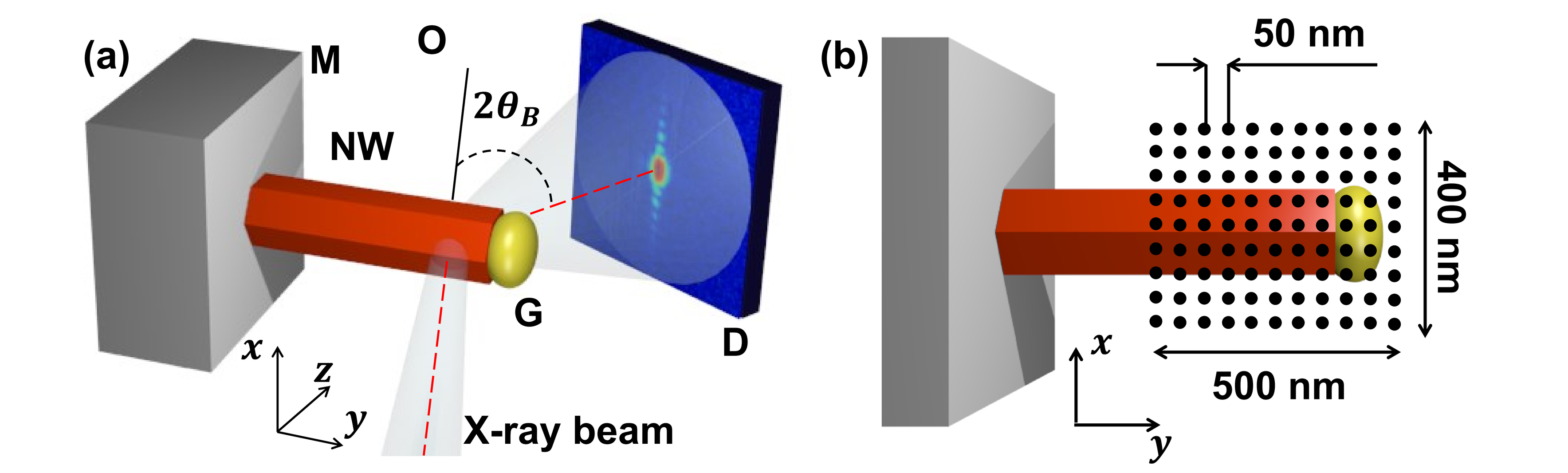

Figure 1. Experimental set-up for Bragg Ptychography experiment. (a) Single nanowire (NW) with gold particle on the top (G) was mounted on a moving stage (M) as a sample. Detector (D) was placed downstream to measure single Bragg peak at 14° degrees ($2\theta_B$) relative to optical axis of incoming beam (O). Fluorescence map also was recorded during scan; (b) Raster grid of ptychographical scan consist of 99 points with 50 nm step in between. Regions outside of the NW wasn't used in reconstruction.

Sample

Photonic applications of semiconductor nanowires (s-NWs) as a high-efficiency and cheap solar cells.

Growth of nanowire

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Metal organic vapor phase epitaxy (MOVPE)
Metal particle (Au) - catalyst

⇩

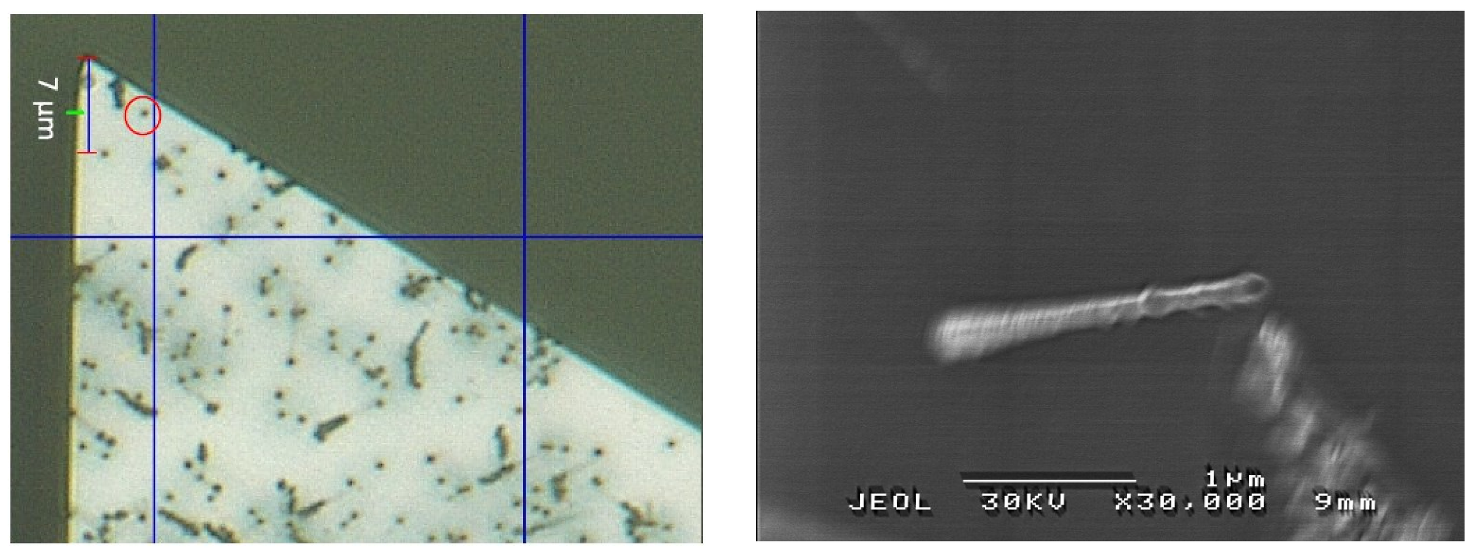


Figure 2. Images of investigated nanowires. (a) Optical microscope image of the forest of nanowires (red circle points our sample); (b) SEM image of the single InP nanowire. Sizes for these objects: diameter ~ $100\ nm$, length ~ $7.5\ \mu m$.

Measured data

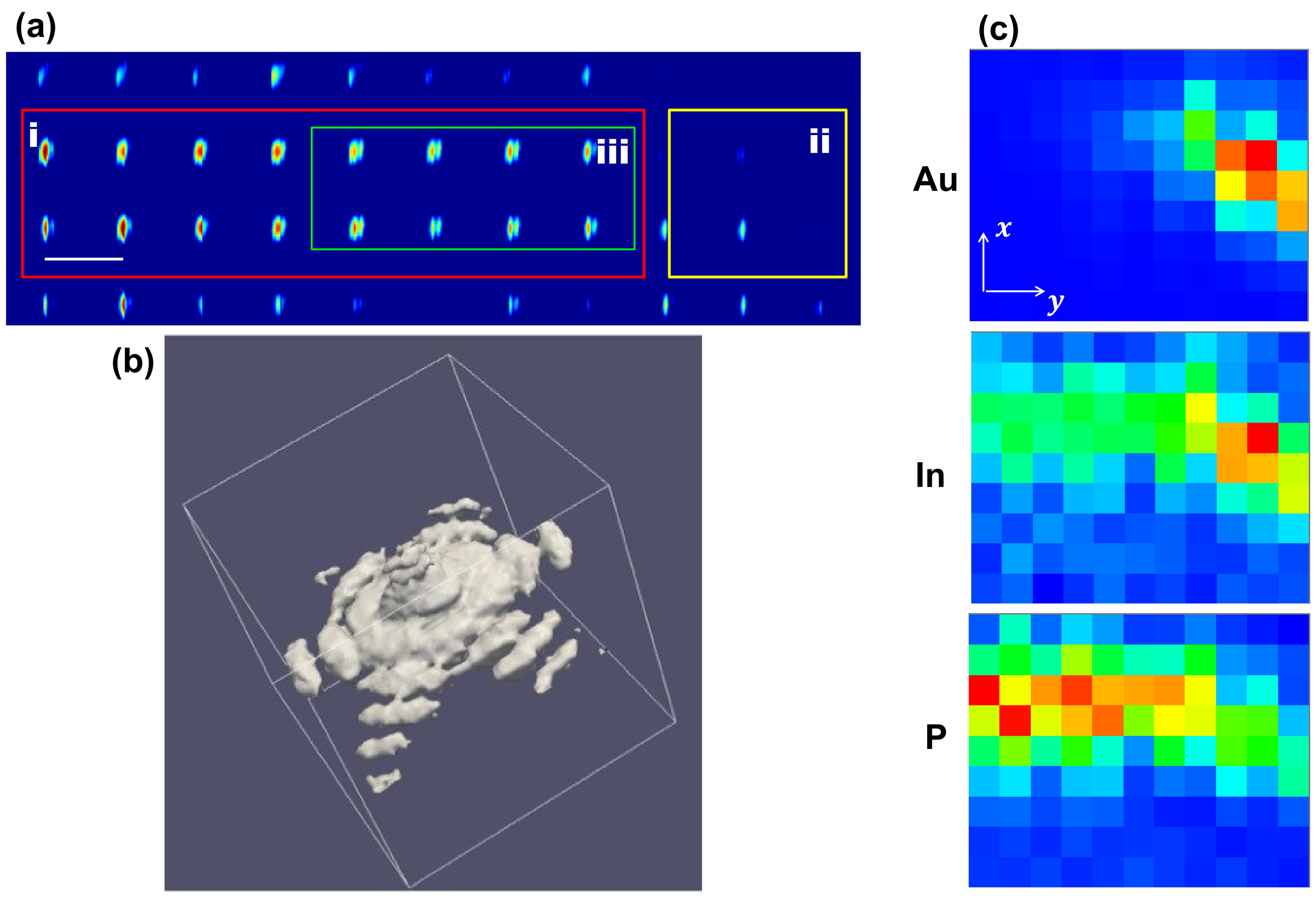
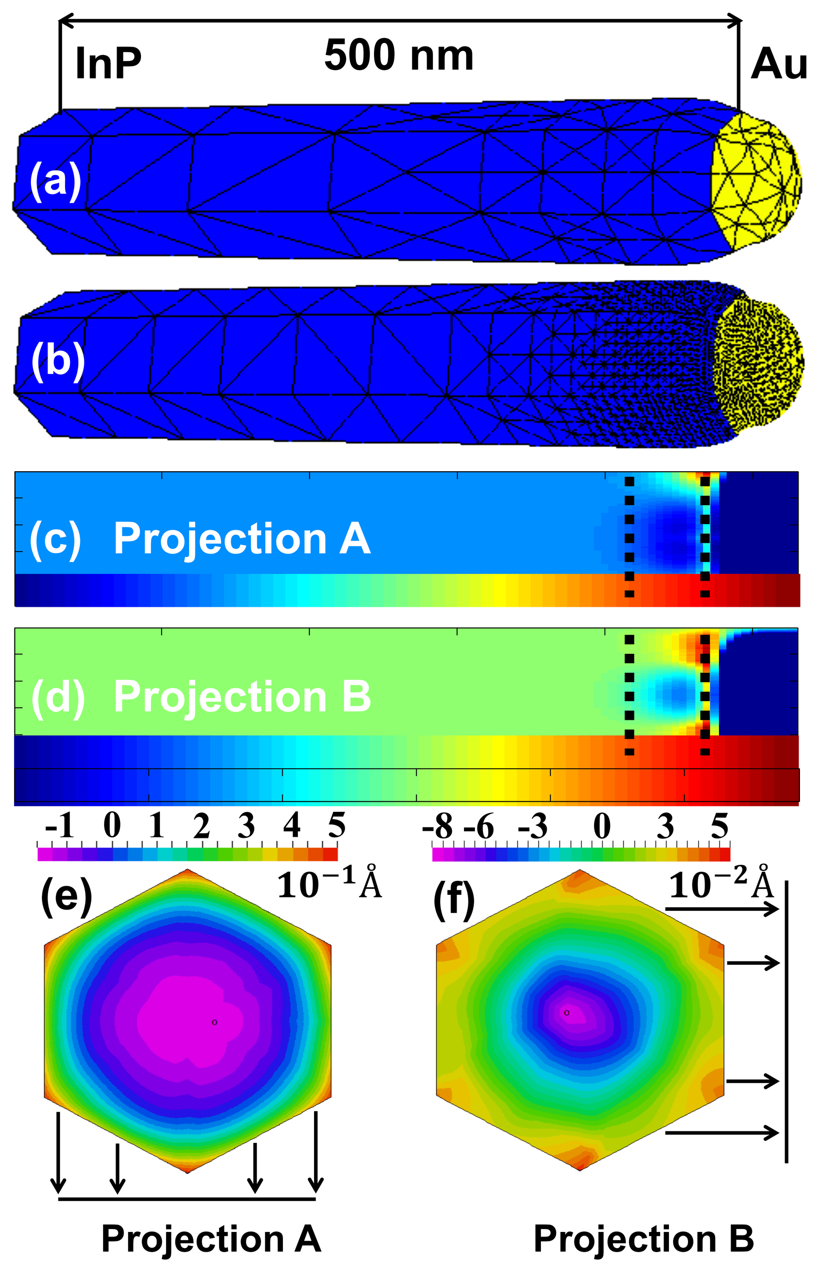


Figure 4. (a) Diffraction map of the raster scan: (i) region of the InP wire, (ii) region of the gold particle, (iii) region of the Bragg peak splitting. Scale bar is 50 nm. (b) 3D Bragg peak intensity from CXDI measurements at one position on the NW; (c) Fluorescence scans showing composition of InP nanowire with the gold particle on the top.

Finite Element Method



Additional strain appears at the interface between InP and Au due to the cooling during the growth process:

$$\delta\varepsilon = \alpha\Delta T,$$

α-thermal expansion coefficient

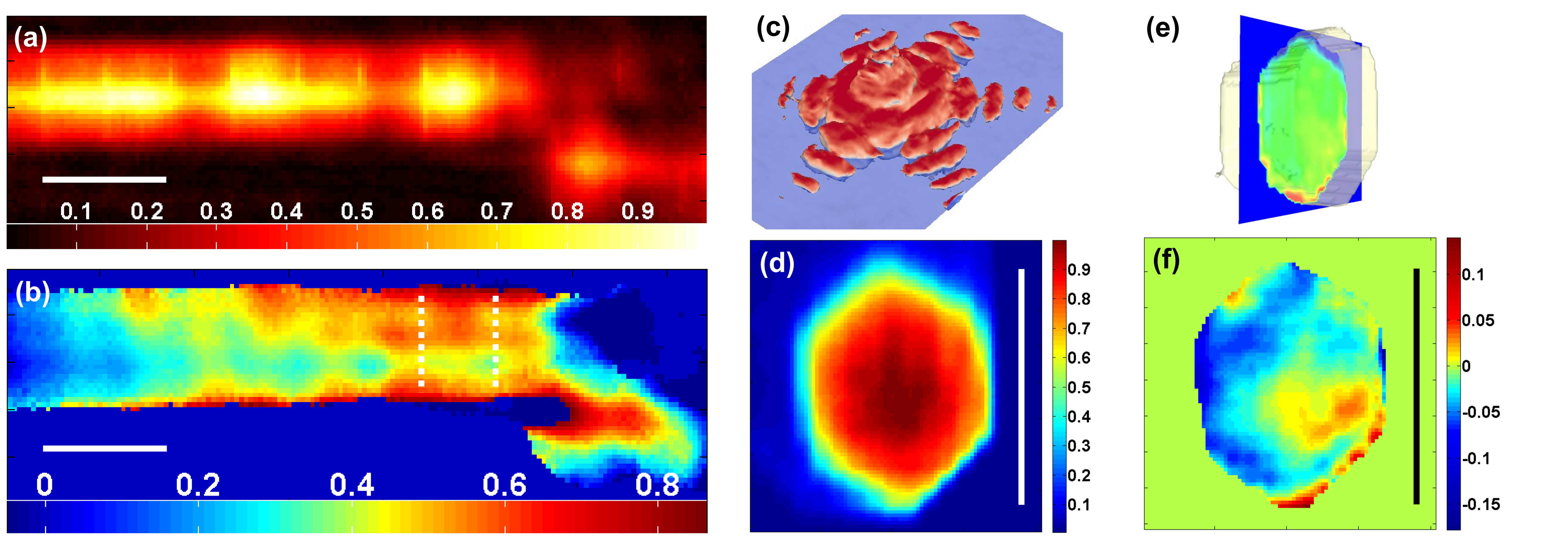
$\Delta T = 300°$

Free boundaries, no normal stress on the facets.

Zero values of displacement on the bottom (substrate).

Figure 5.
(a) Initial 3D model of the NW.
(b) Deformed NW after relaxation (all deformations are multiplied by 100).
(c) Projection A. Projection of the displacement field from edge to edge of the NW as shown in (e).
(d) Projection B. Projection of the displacement field from facet to facet of the NW as shown in (f).
(e) and (f) Transverse cuts of the displacement field u_y at the position 5 nm and 50 nm below the gold particle respectively.
Black dotted lines in (c) and (d) show where the cross sections were taken.

Reconstruction of InP NW



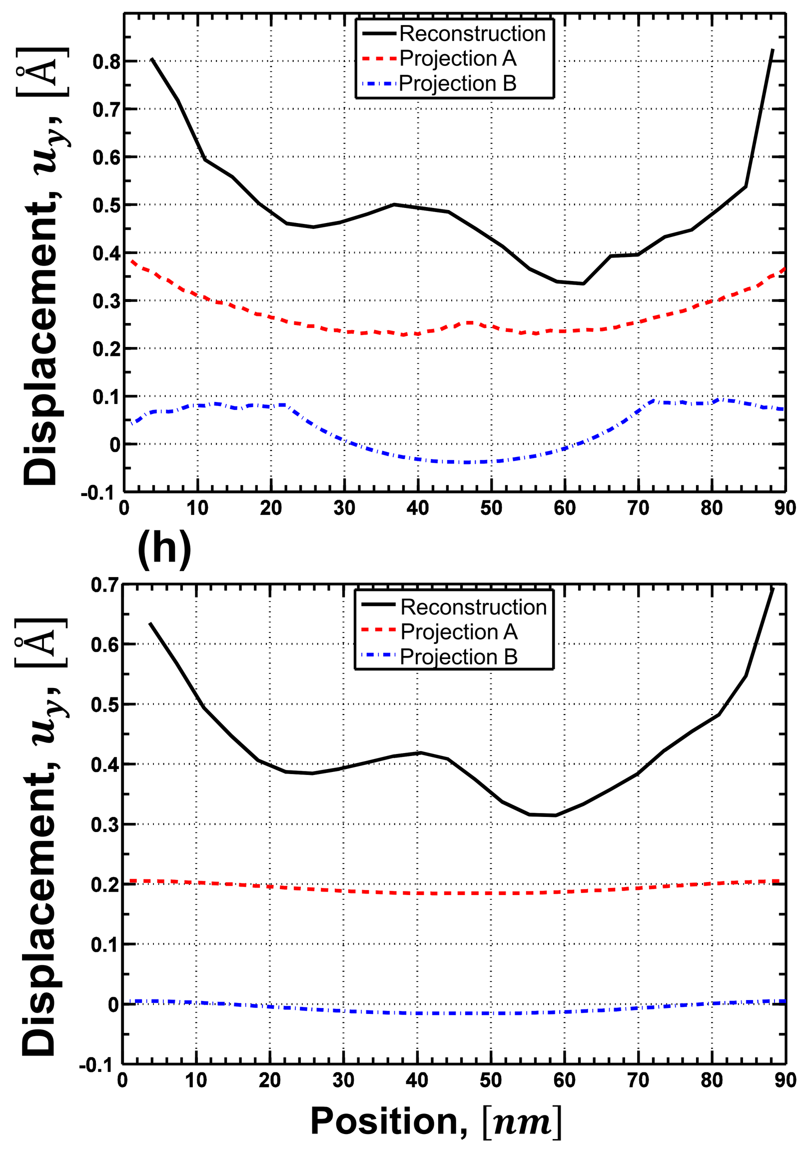


Figure 6. Results of Bragg Ptychography and CXDI reconstructions: (a) and (b) amplitude and reconstructed u_y component of the displacement field by XBP of the NW; (c) Blue plane cut shows the diffracted intensity signal, used for 2D CXDI reconstructions. (d) Reconstructed amplitude of the object. (e) 3D reconstruction of the object with the plane showing transverse distribution of the phase inside of the wire. (f) u_y component of the displacement vector field. Comparison of the displacement field obtained in XBP reconstruction and FEM model at different distances below Au particle, 5 nm (g) and 50 nm (h). Lines are shifted by 0.25 Å in (g) and by 0.2 Å in (h) for clarity. Scale bars are equal to 100 nm. Color bars show normalized values of the amplitude in (a) and (d) and lattice displacement in Å in (b) and (f).

Conclusions

We applied XBP and CXDI techniques to investigate the shape and internal structure of the single InP NW. The displacement field inside the NW was obtained after an inversion procedure by phase retrieval algorithms. Single free standing NW made of InP with Au particle on the top shows rather weak values of strain inside. The results of the reconstructions were compared with FEM calculations and show good agreement. Characterization of the InP NW confirms its high crystalline quality that opens a lot of possibilities for engineering applications. Paper in preparation.

Ptychographical imaging of the phase vortices in the X-ray beam formed by nano-focusing lenses.

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Introduction

We present the ptychographical reconstruction of the x-ray beam formed by nano-focusing lenses (NFLs) containing a number of phase singularities (vortices) in the vicinity of the focal plane. As a test object Siemens star pattern was used with the nest features of 50 nm for ptychographical measurements. The extended ptychographical iterative engine (ePIE) algorithm was applied to retrieve both complex illumination and object functions from the set of diffraction patterns. The reconstruction revealed the focus size of 91.4±1.1 nm in horizontal and 70±0.3 nm in vertical direction at full width at half maximum (FWHM). The complex probe function was propagated along the optical axis of the beam revealing the evolution of the phase singularities.

Ptychographical experiment

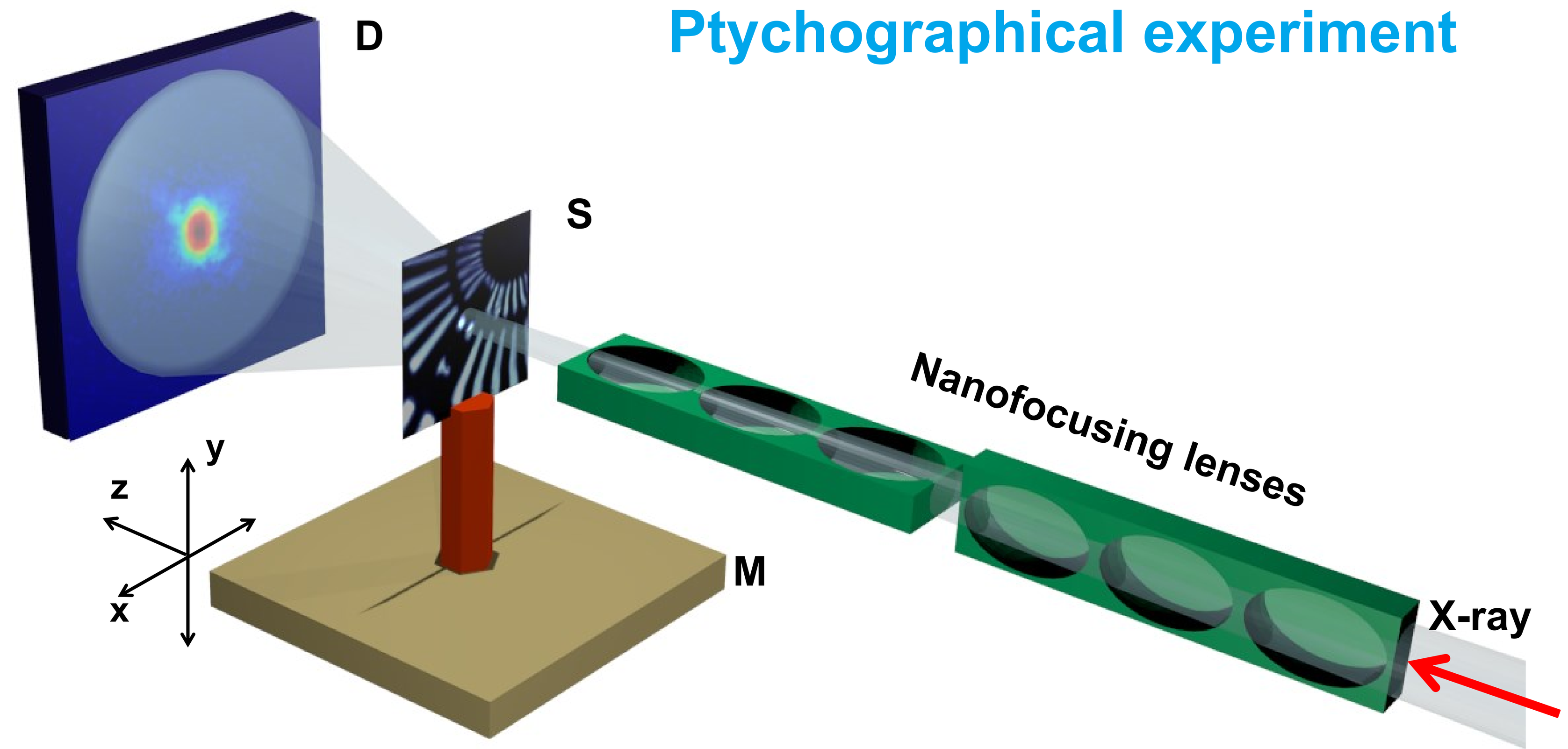
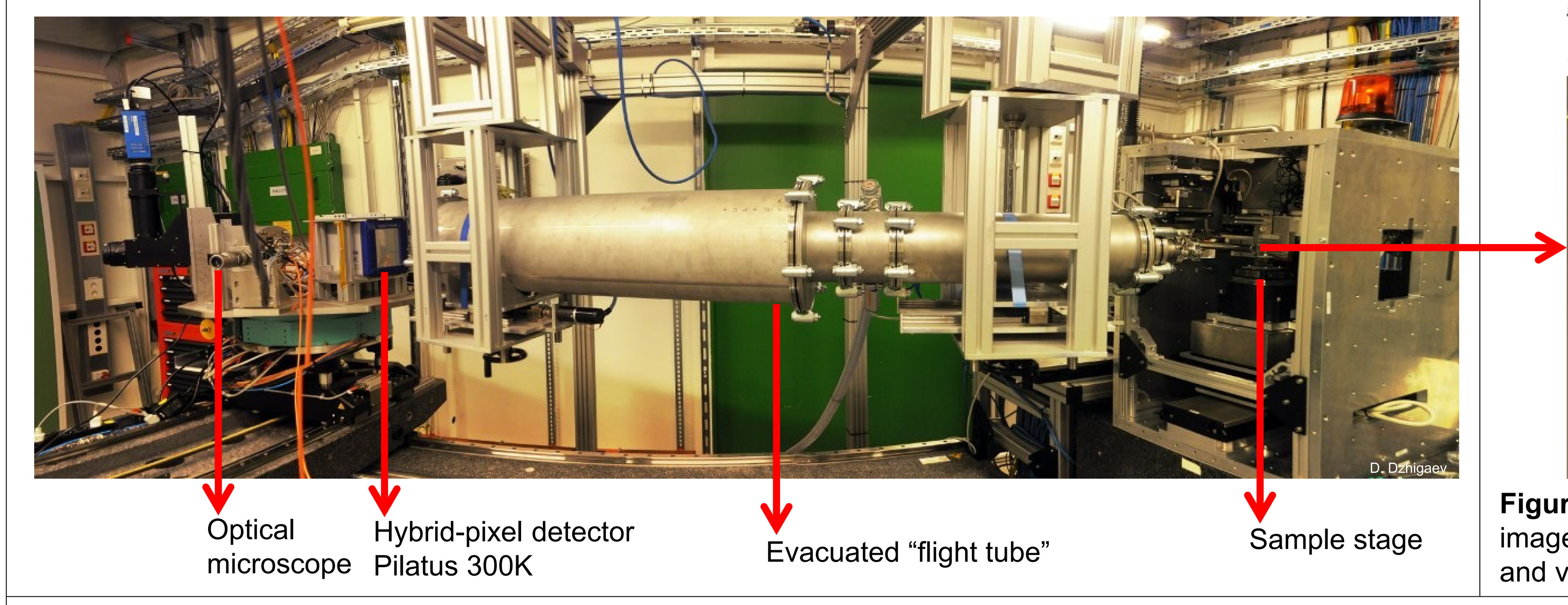


Figure 1. Experimental setup.
The incoming x-ray beam (red arrow) goes along the Z axis and is focused by a pair of perpendicularly positioned NFLs. The test sample (S) in the form of the Siemens star is mounted on the movable stage (M) and is illuminated at the positions of a raster grid. Diffraction patterns are collected by the detector (D) 2.1 m downstream.



The geometry of the experiment is shown in Fig. 1. Two perpendicularly positioned NFLs were used to obtain a nano-sized focus of the incident x-ray beam with 15.25 keV energy. The flux of the beam in the focus was 4×10^7 photons/sec. A Pilatus 300K hybrid-pixel detector (Dectris, Switzerland) with the pixel size of the $172 \times 172\ \mu m^2$ was used. The ptychographical scan was performed on a Cartesian grid with 50 nm step size and 41×41 scan positions, in the horizontal and vertical directions, perpendicular to the optical axis of the beam.

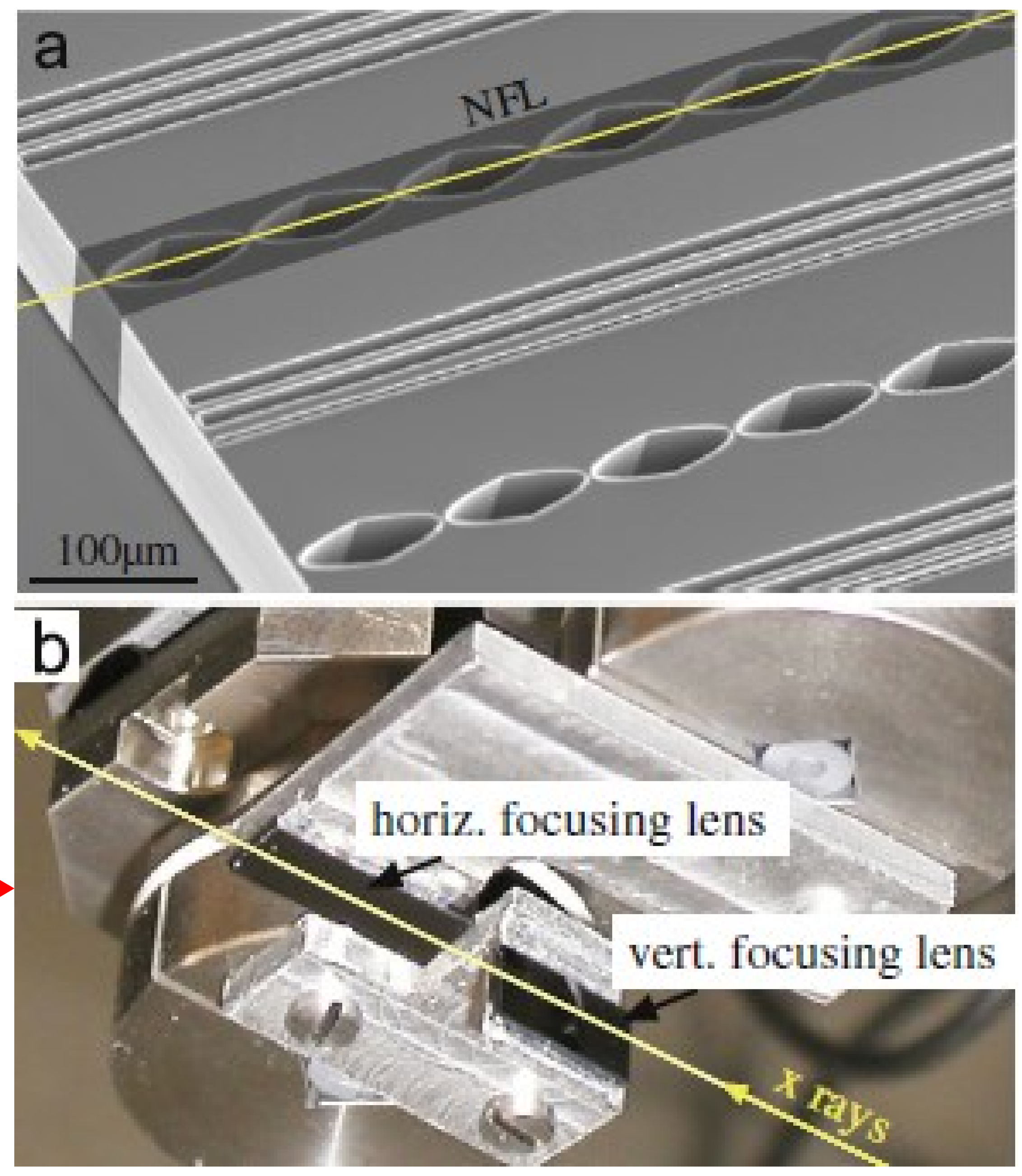


Figure 2. Nanofocusing lenses at P06 beamline at PETRA III [1]. (a) SEM image of an array of NFLs made of silicon. (b) Arrangement of the horizontal and vertical lenses at the beamline

Reconstruction

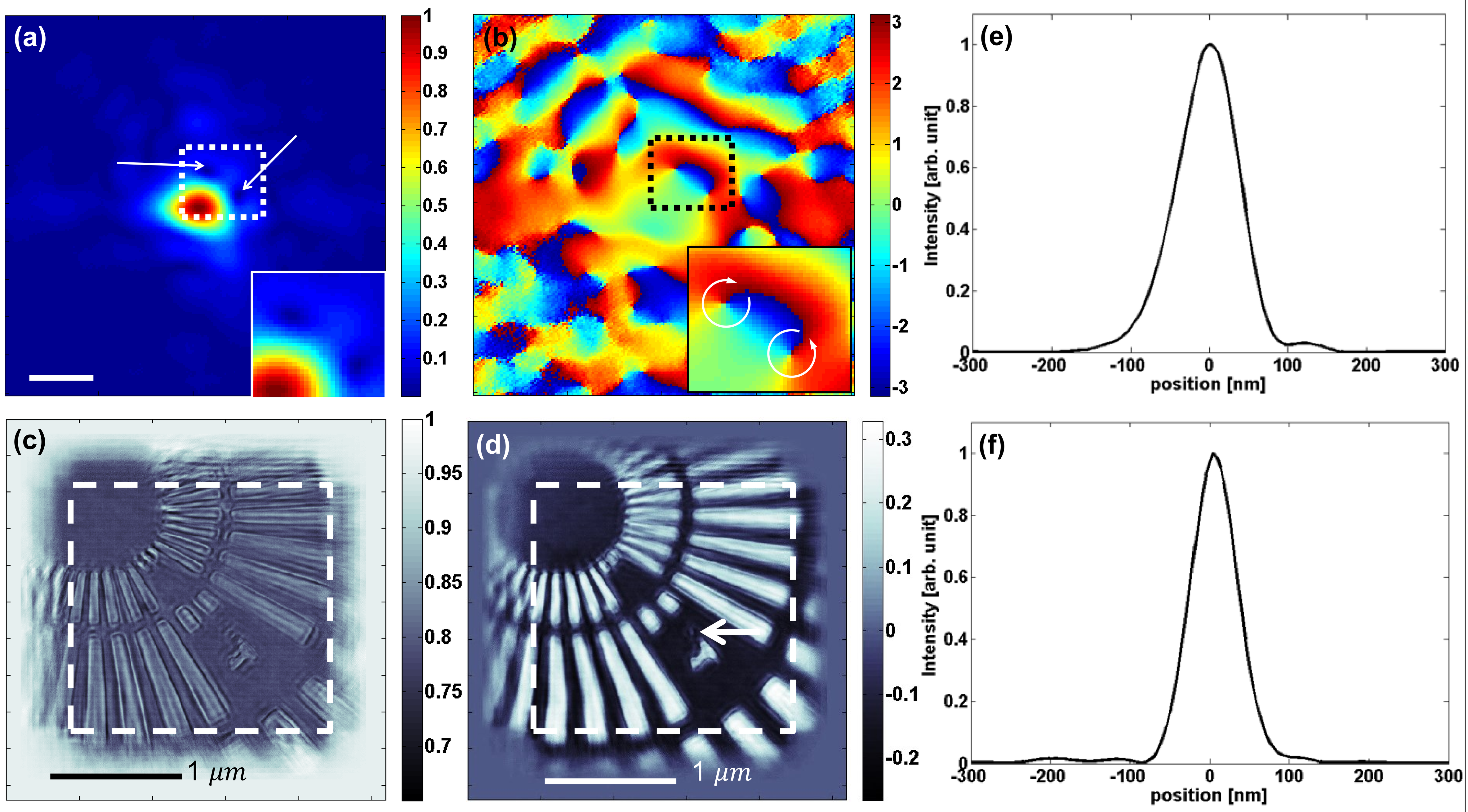


Figure 2. Results of ptychographical reconstruction at the sample plane. (a) Amplitude of the probe function. White arrows indicate two points of zero intensity corresponding to phase singularities (see inset for an enlarged view). (b) Phase of the probe function. In the inset an enlarged view of two singularities with opposite directions is shown. (c) Amplitude of the object function. (d) Phase of the object function. Smallest resolved feature is a dot that is 20 nm in diameter. It is shown by an arrow. The color bars in (a) and (c) show normalized values of the amplitude functions and in (b) and (d) values of the phase in radians. Region of the scan is outlined by white dashed lines in (c) and (d). (e) and (f) show horizontal and vertical profiles of the normalized intensity of the reconstructed probe function across the central maximum. Results are submitted in [2].

Evolution of the vortices

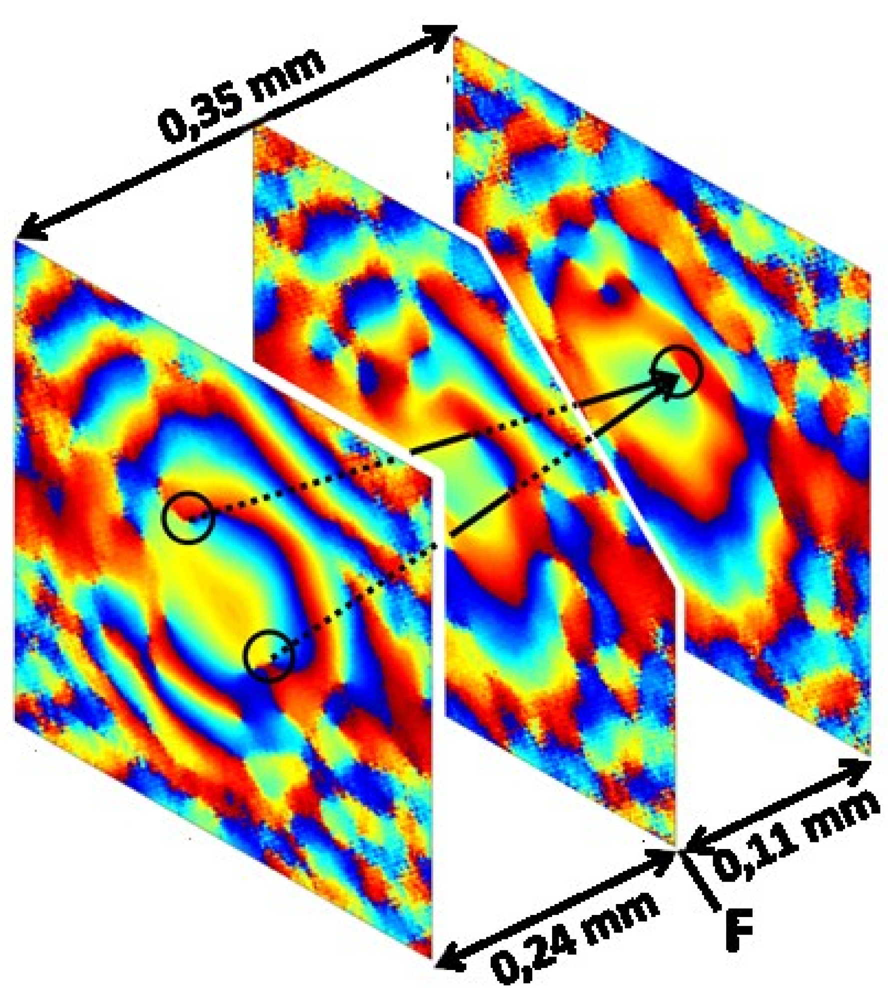


Figure 3. Propagation of the wave field. Three 2D cuts perpendicular to the beam propagation direction are shown: 0.24 mm in front of the focal plane (F), at the focal plane, and 0.11 mm behind the focal plane. At the first position the pair of vortices nucleate, at the last one they annihilate.

Results and discussion

We obtained the ptychographical reconstruction of the x-ray field focused by NFLs containing a number of phase vortices in the vicinity of the focal plane. After inversion procedure with the ePIE algorithm a complex wave field function was obtained. The pair of vortices closest to the central maximum of the beam with the topological charges ±1 were propagated from nucleation to annihilation plane. The length of the nodal line for these singularities was 0.35 mm in total. Appearance of the vortices in the focal region of the nano-focused beam could possibly affect the quality of the phase retrieval procedure and should betaken into account in future work.

References

1. C. Schroer, *et al.,* NIM A **616,** 93 (2010)
2. D. Dzhigaev, *et al.,* J. Phys. Conf. Series, see also: http://arxiv.org/abs/1311.1374 (2013)