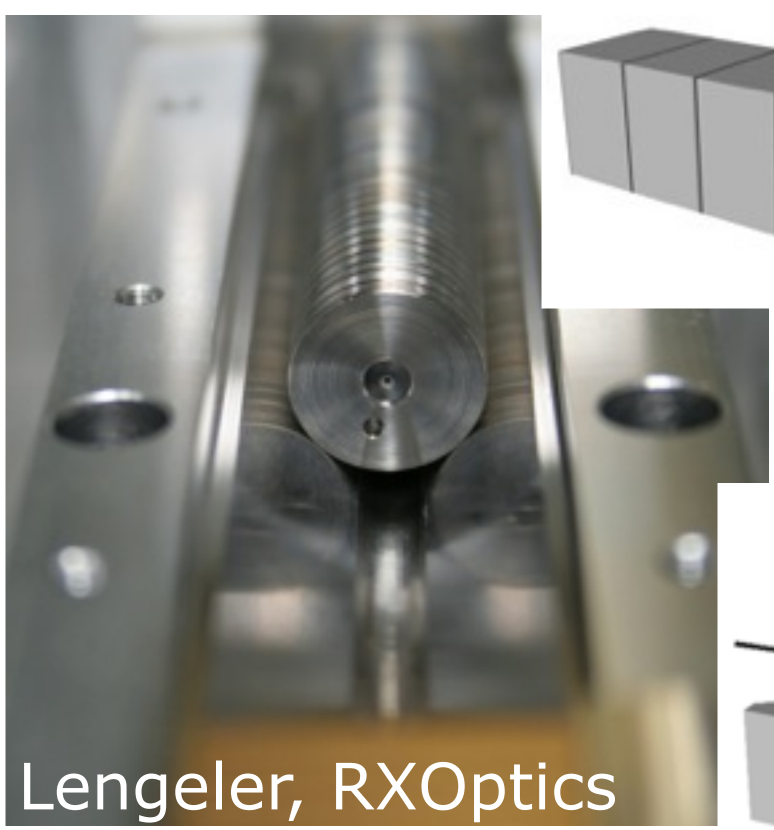
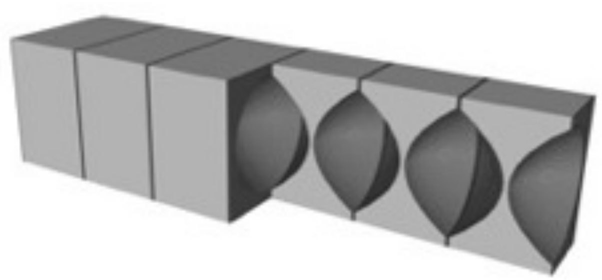
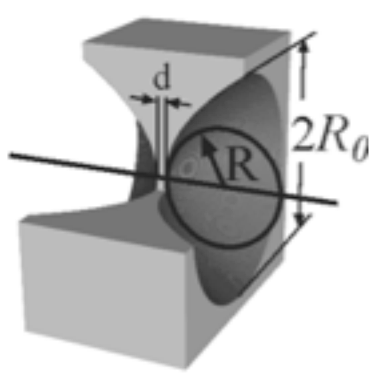
Refractive X-Ray Lenses

- first realized in 1996 (Snigirev et al.)
- a variety of refractive lenses have been developed since
- applied in full-field imaging and scanning microscopy
- most important to achieve optimal performance:

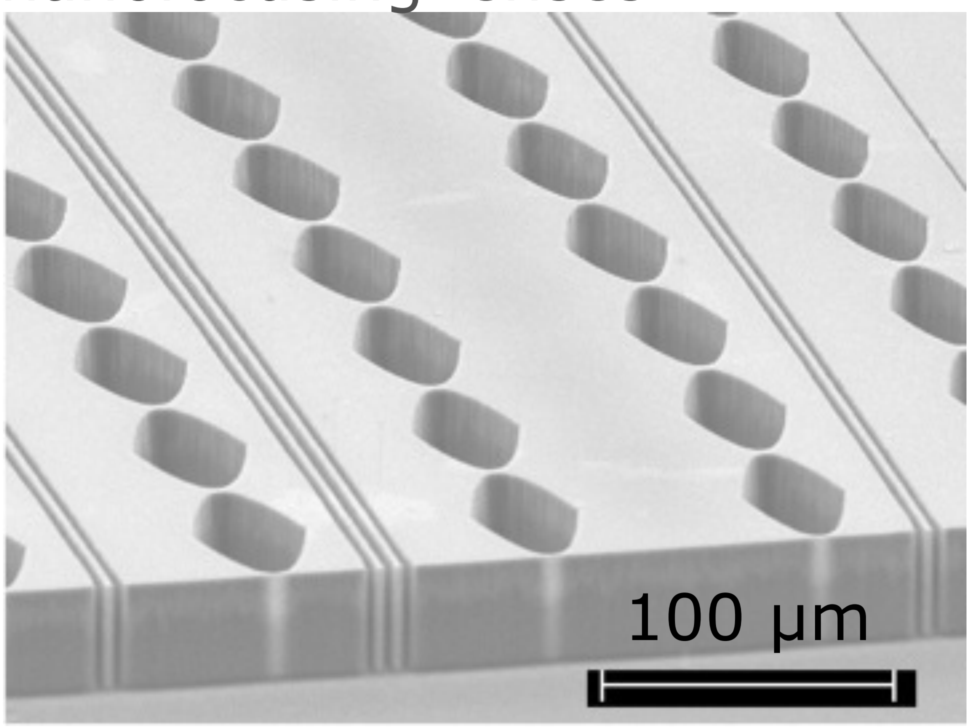
parabolic lens shape







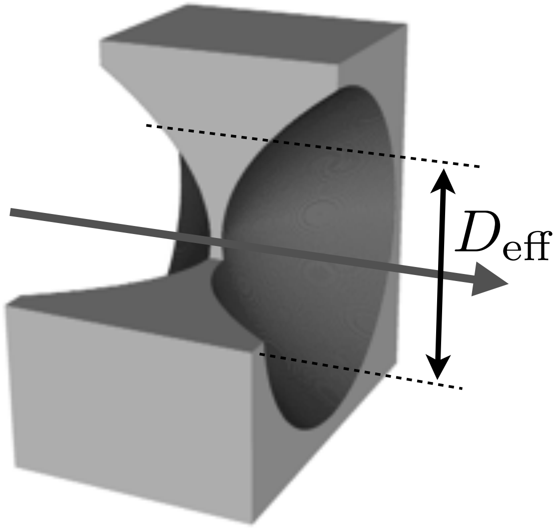
nanofocusing lenses



Nanofocus

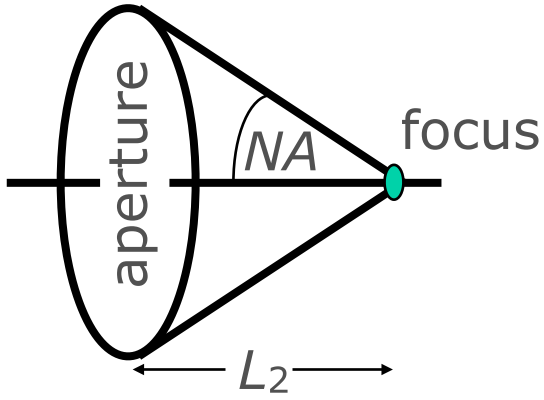
large focal length *f*: aperture limited by absorption

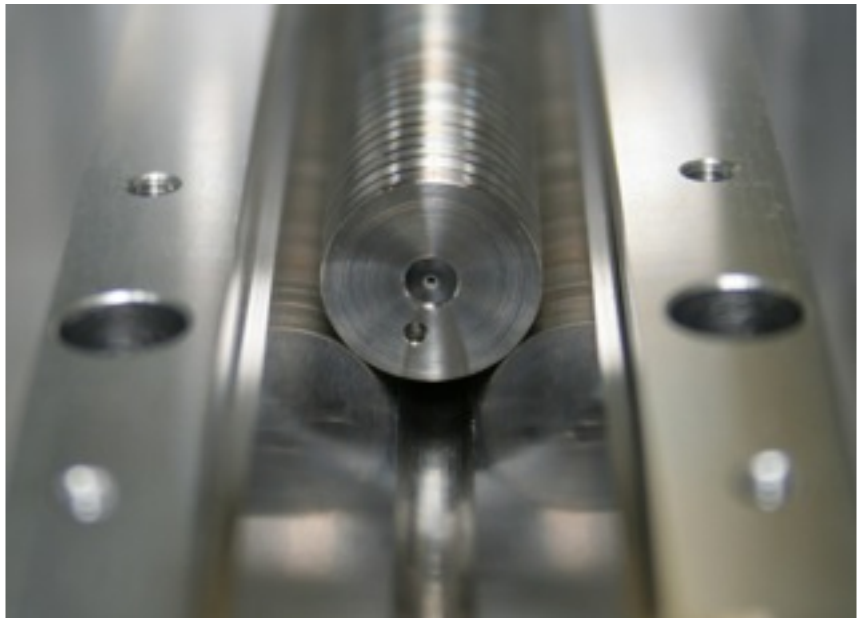
$$D_{\mathrm{eff}} = 4\sqrt{\frac{f\delta}{\mu}} \propto \sqrt{f \cdot E}$$



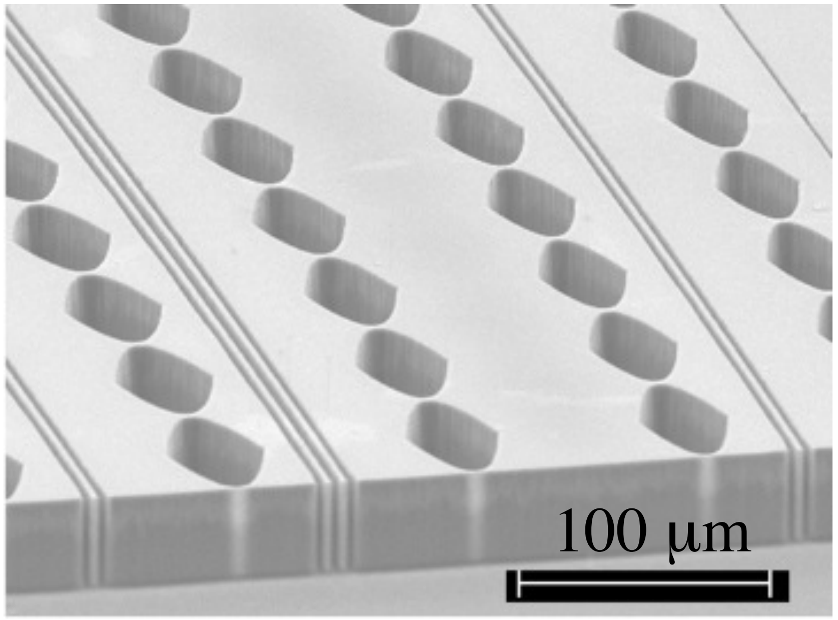
→ minimize μ/δ (⇒ small atomic number Z)

→ $NA = \frac{D_{\mathrm{eff}}}{2f} \propto \sqrt{\frac{E}{f}}$ (⇒ minimize focal length *f*)

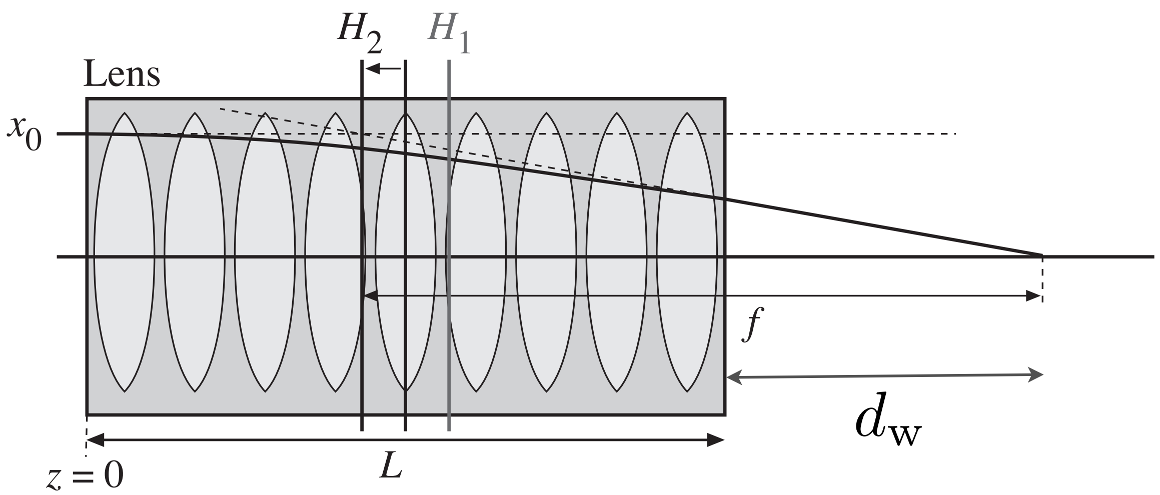




transition to nanofocusing lenses (NFLs) →



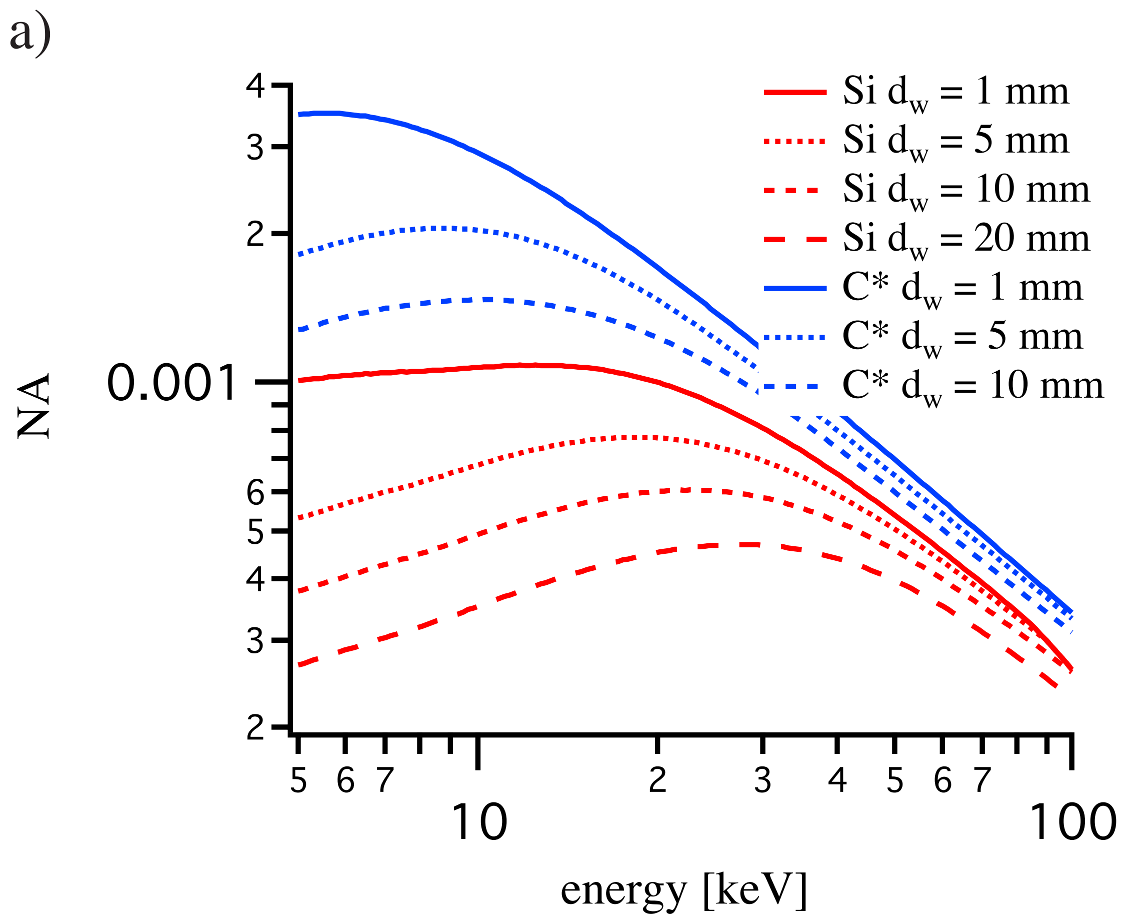
Diffraction Limit

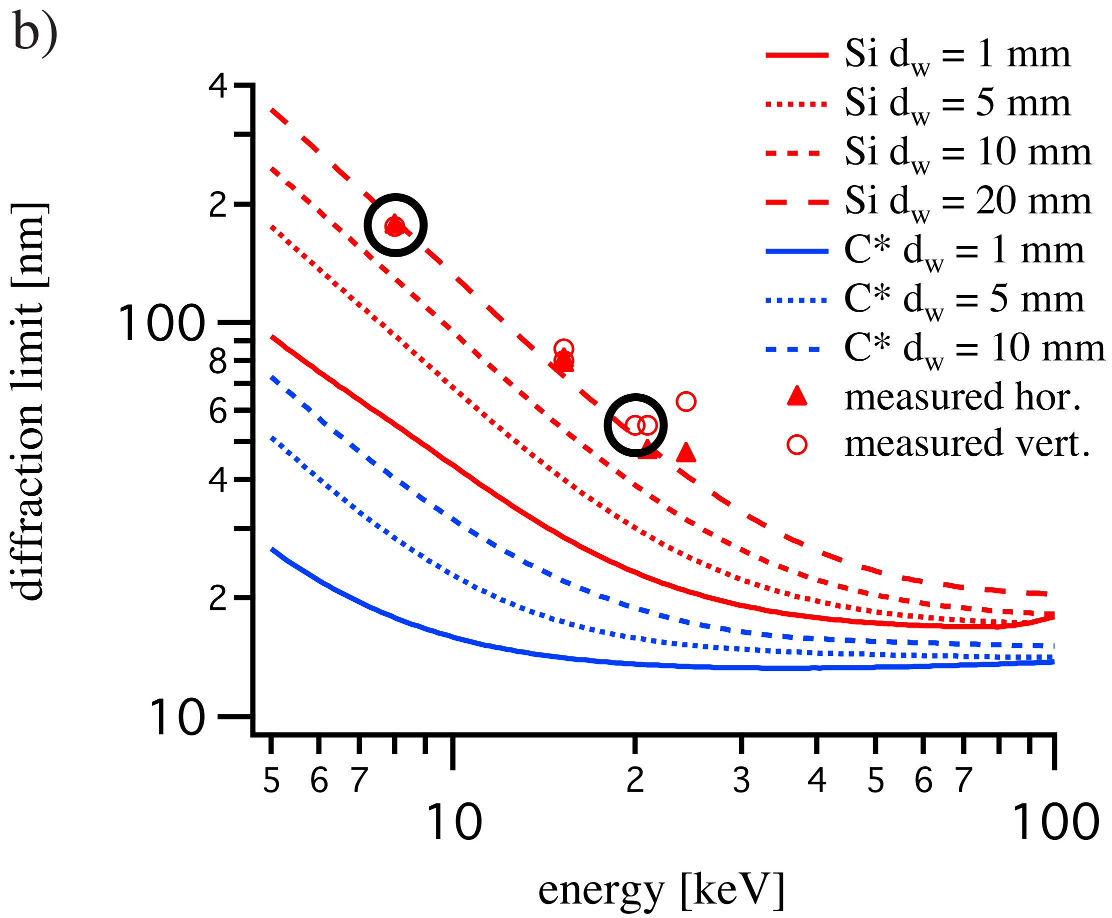


diffraction limited focusing (Abbe):

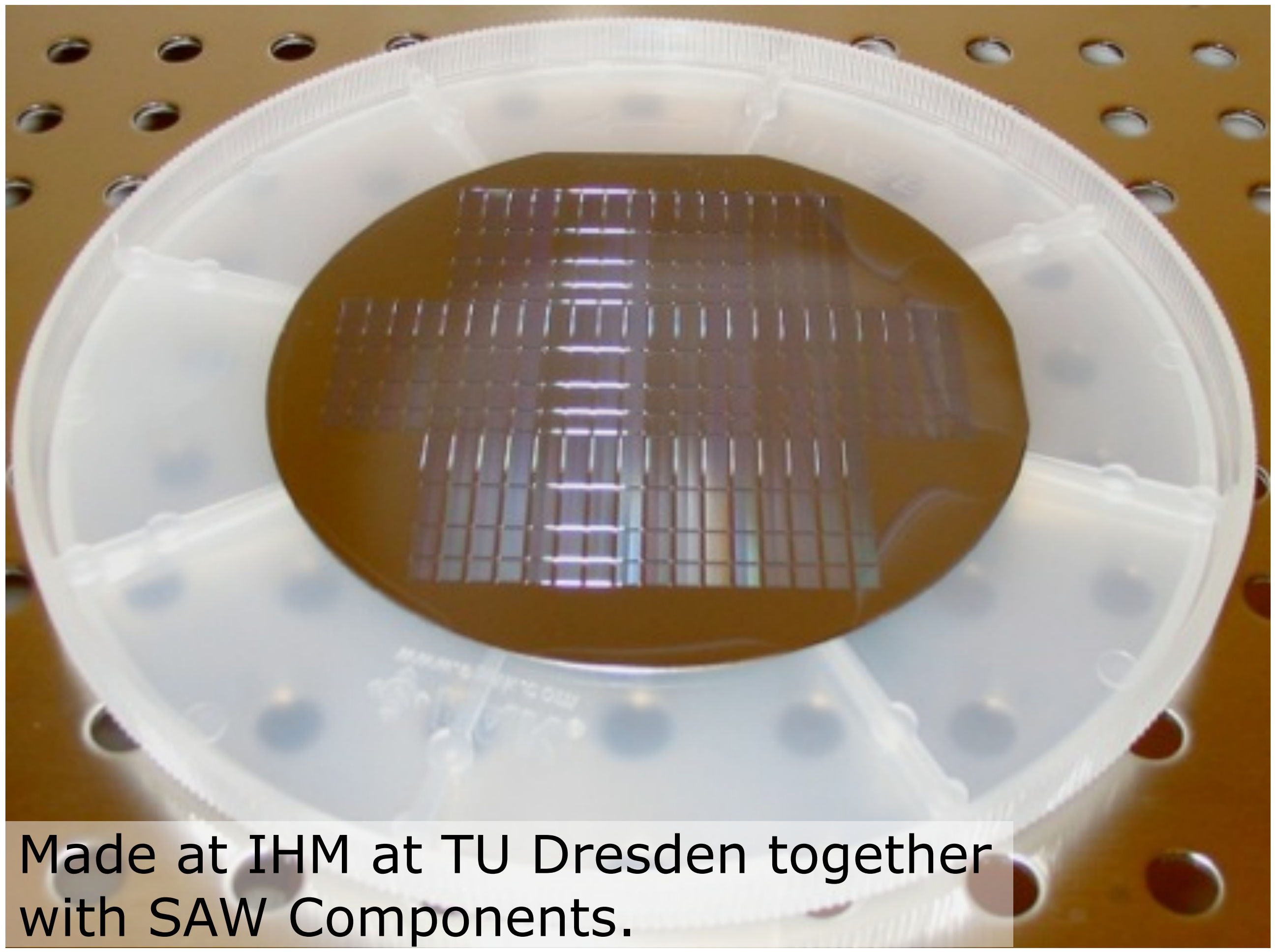
$$d_t = 0.75 \cdot \frac{\lambda}{2NA}$$

$$> 0.75 \cdot \frac{\lambda}{2\sqrt{2\delta}} \propto \frac{1}{\sqrt{\rho}}$$

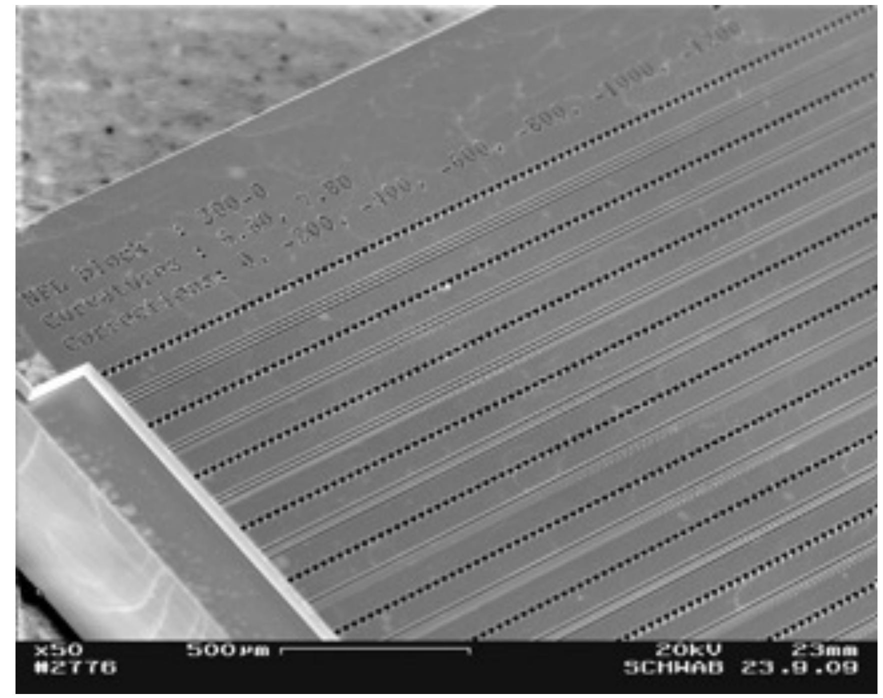


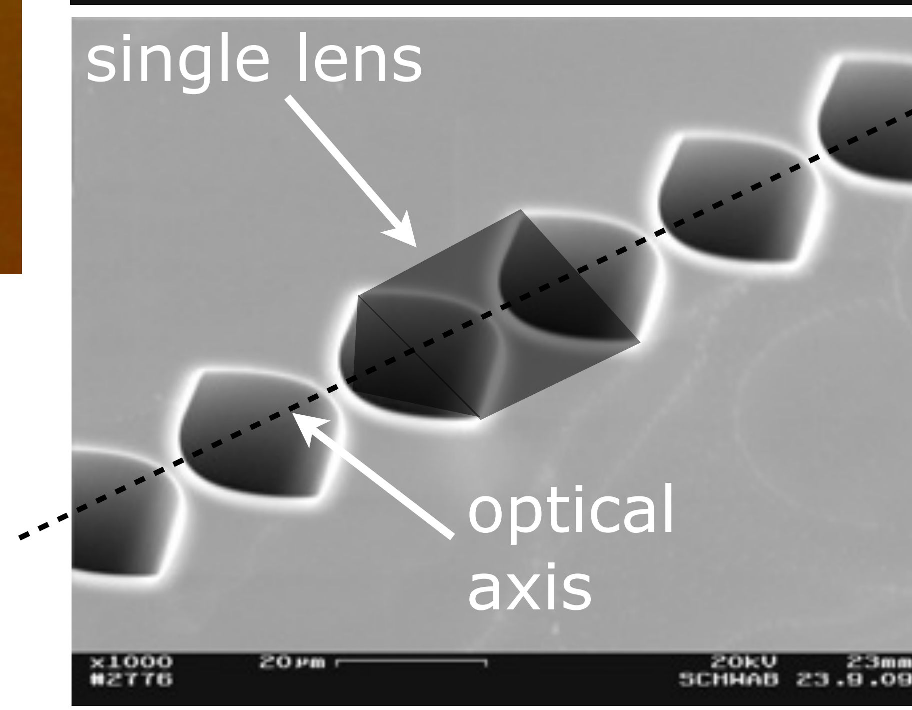


Nanofocusing Lenses (NFLs) Made of Silicon



Made at IHM at TU Dresden together with SAW Components.





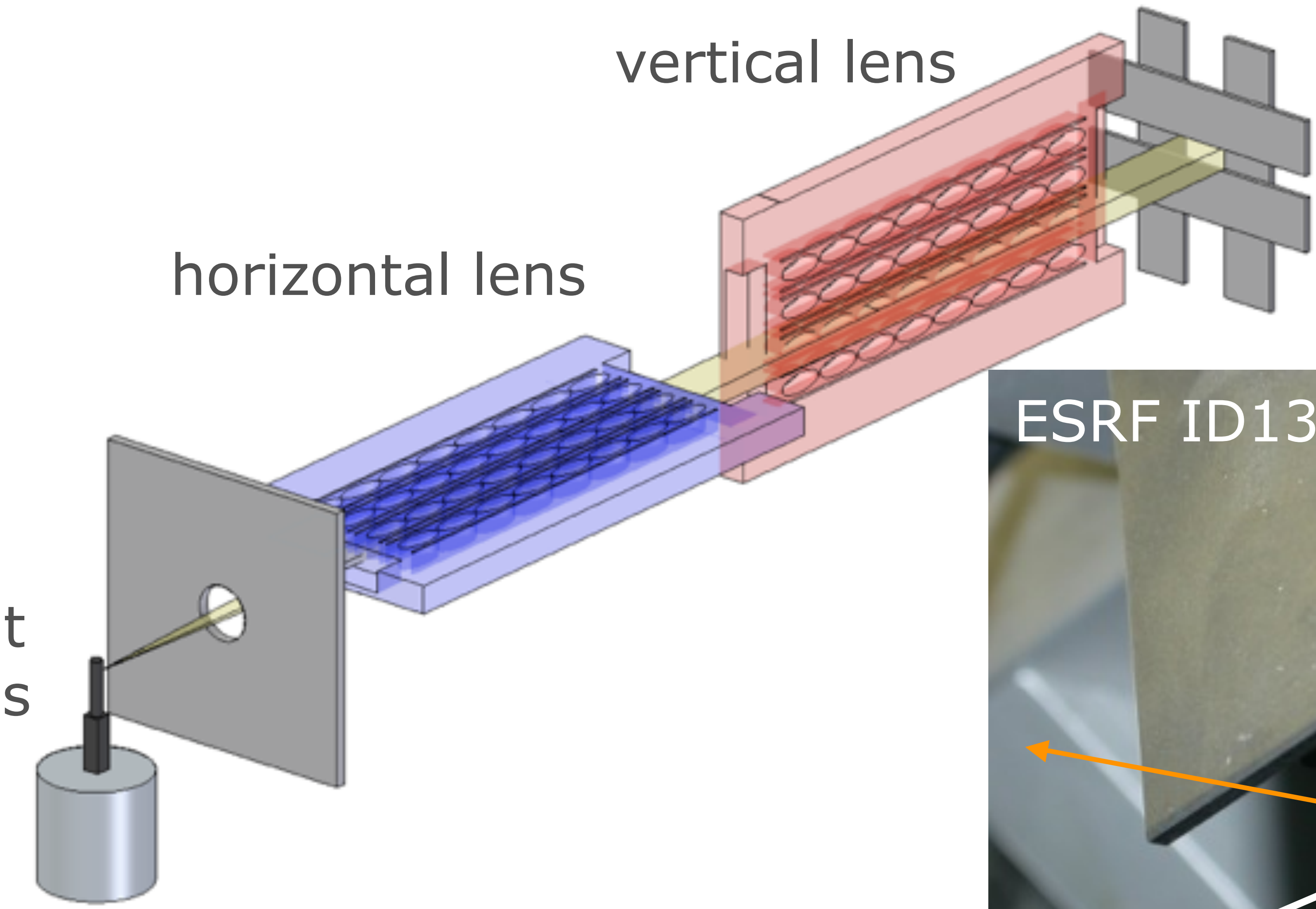
APL **82**, 1485 (2003)

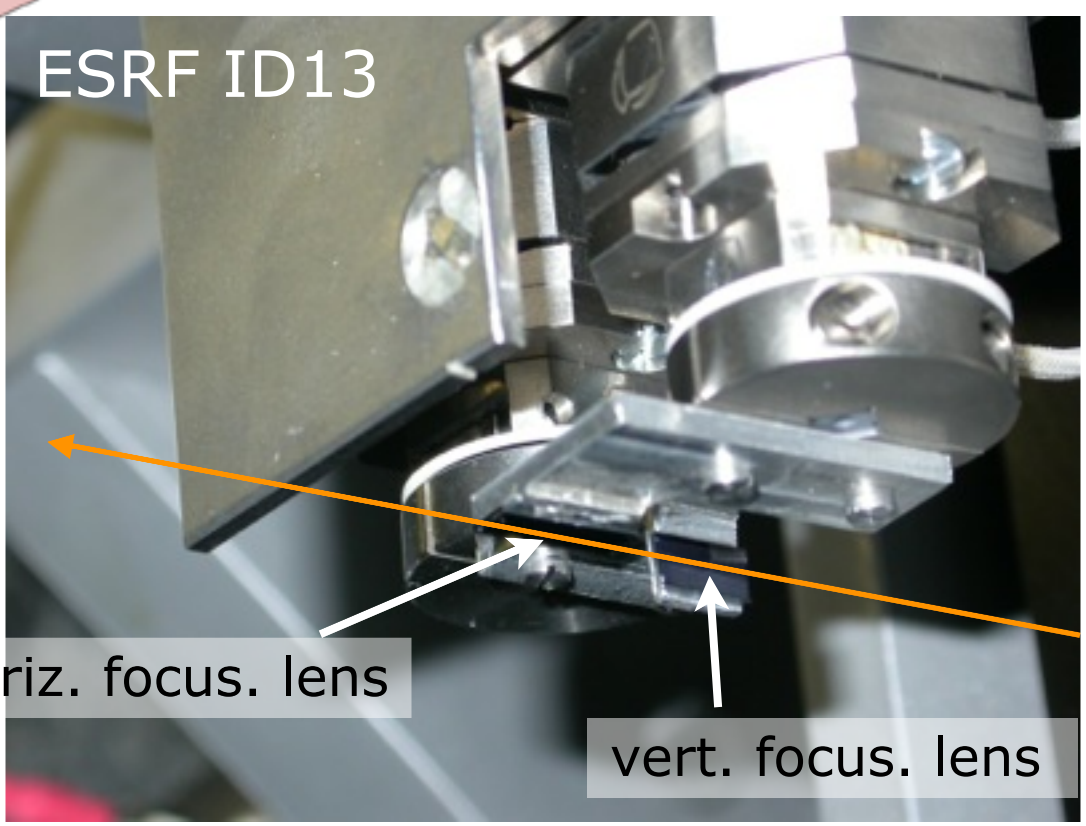
3136 NFLs on wafer!
about 600000 single lenses!

→ high accuracy, reproducibility

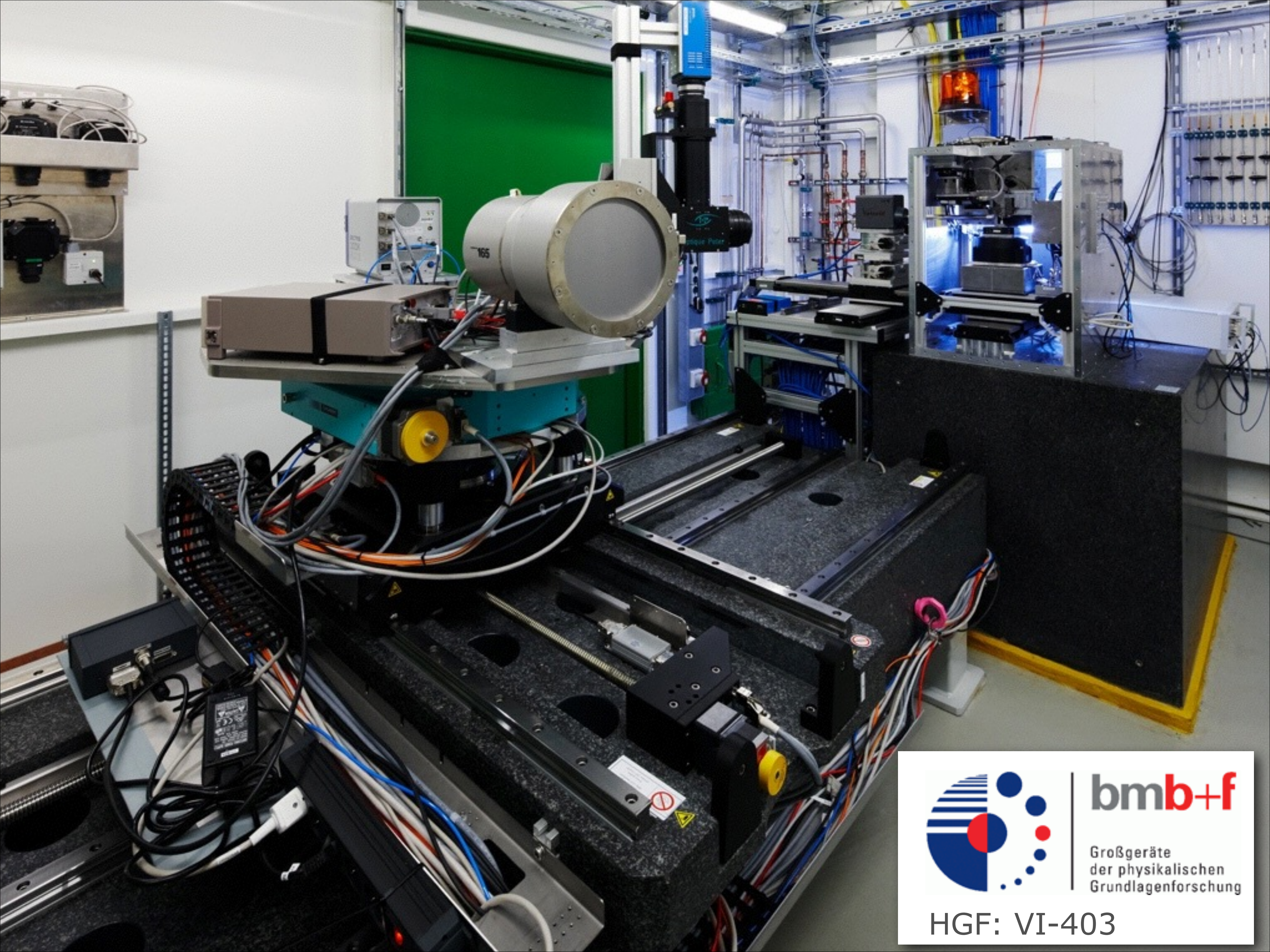
Nanofocusing Lenses (NFLs)

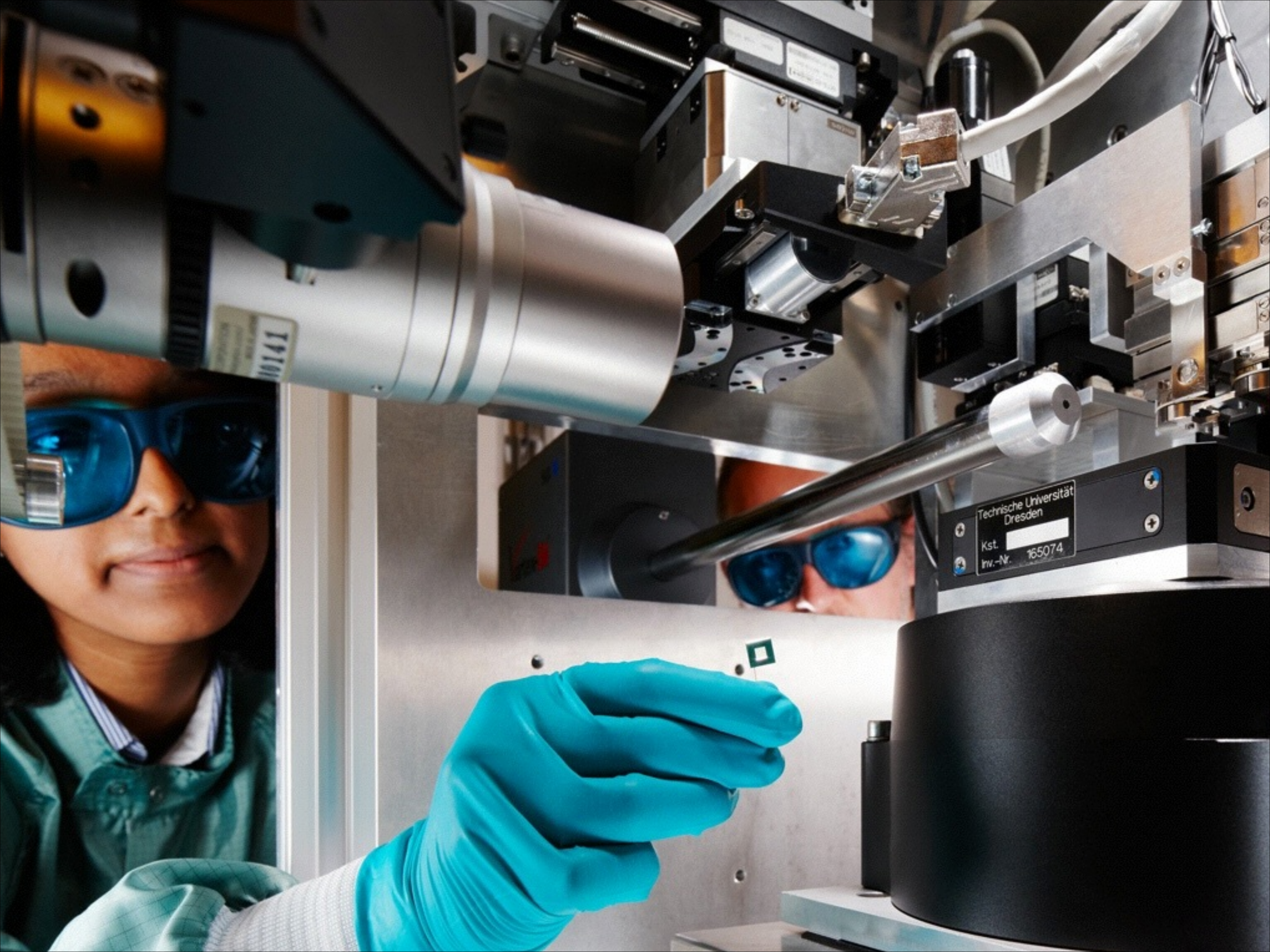
point focus requires two lenses in crossed geometry





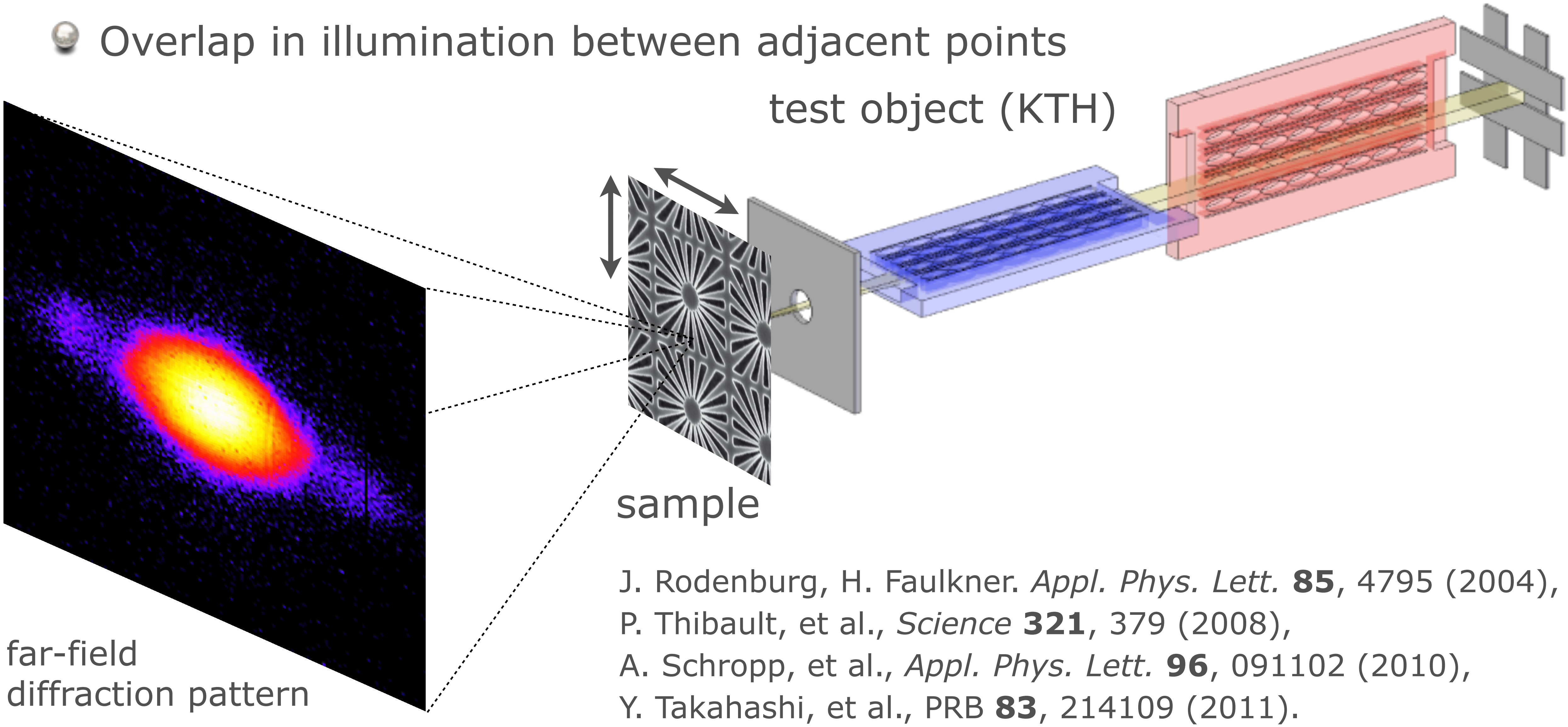
Hard X-ray Scanning Microscopy at PETRA III


bmb+f
Großgeräte
der physikalischen
Grundlagenforschung
HGF: VI-403


Technische Universität
Dresden
Kst.
Inv.-Nr. 165074

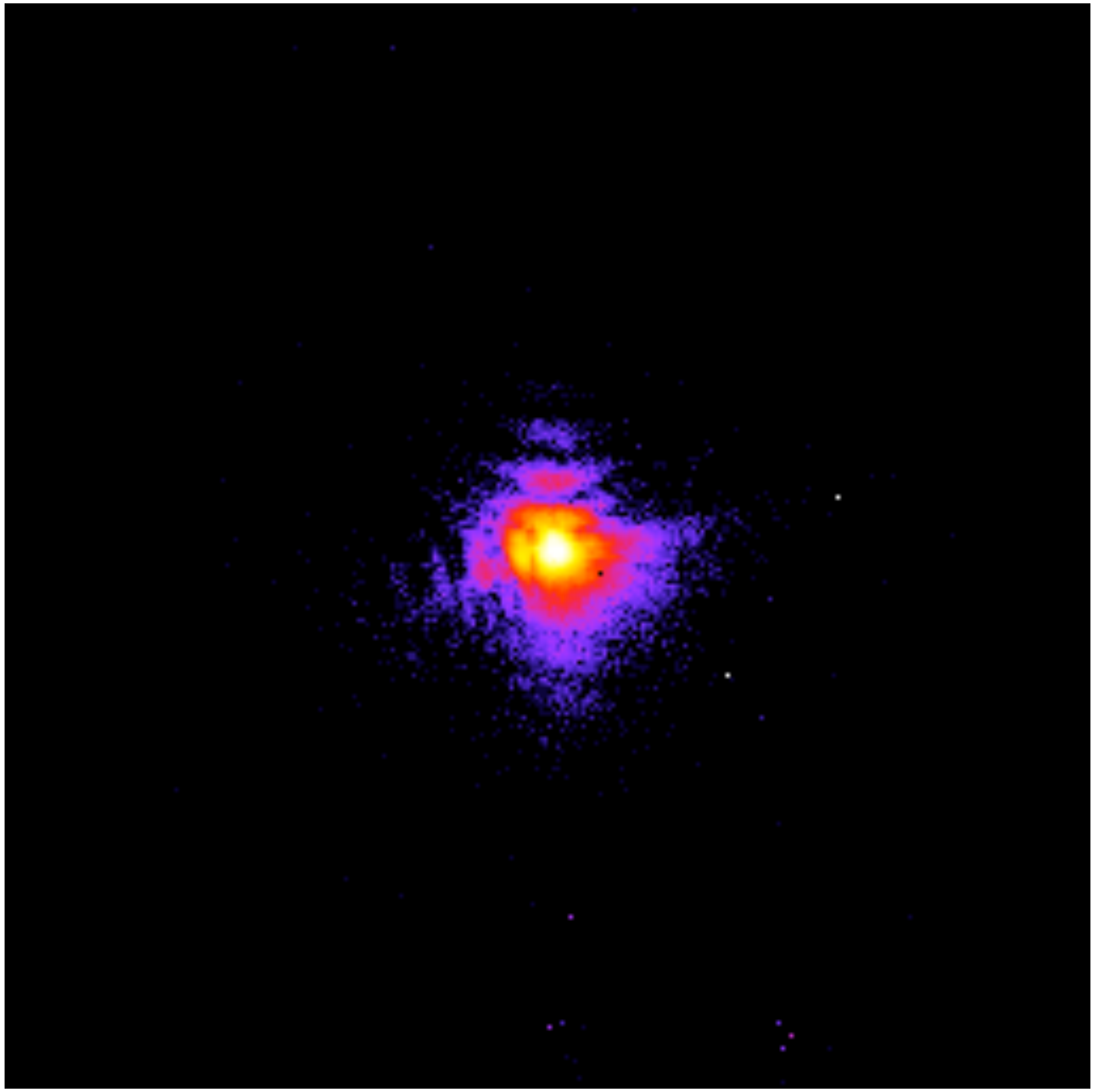
Scanning Coherent X-Ray Diffraction Imaging: Ptychography

- Sample is raster scanned through confined beam
- At each position of scan: diffraction pattern is recorded
- Overlap in illumination between adjacent points



J. Rodenburg, H. Faulkner. *Appl. Phys. Lett.* **85**, 4795 (2004),
P. Thibault, et al., *Science* **321**, 379 (2008),
A. Schropp, et al., *Appl. Phys. Lett.* **96**, 091102 (2010),
Y. Takahashi, et al., PRB **83**, 214109 (2011).

Ptychographic Microscopy



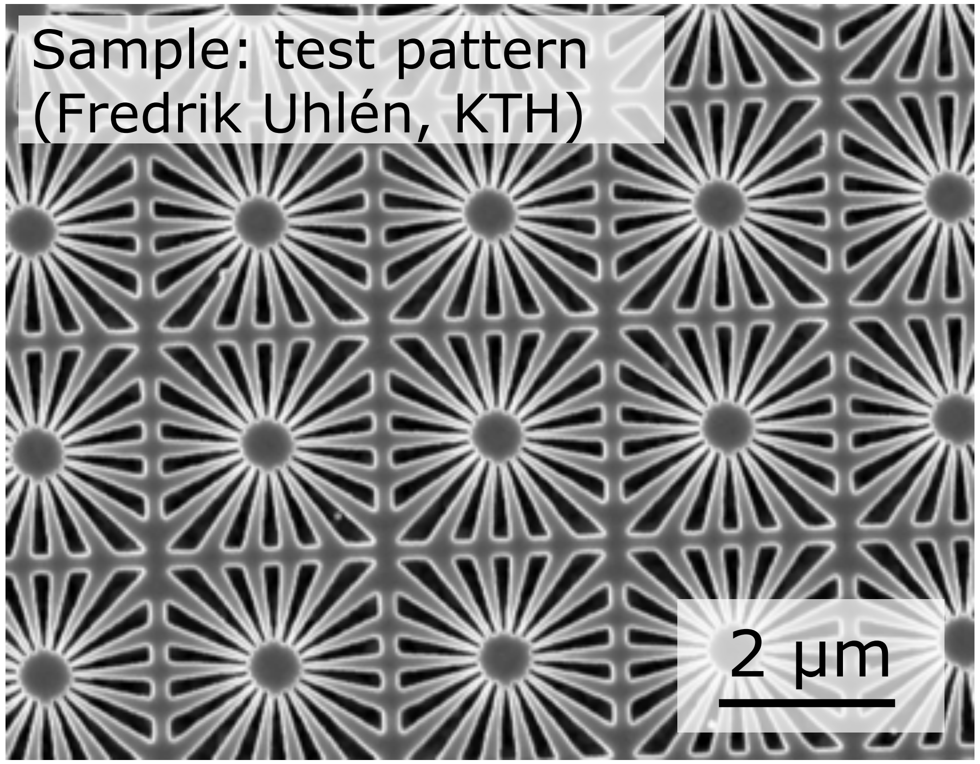
A. Schropp, et al., *Appl. Phys. Lett.* **96**, 091102 (2010).

Experiment at P06:

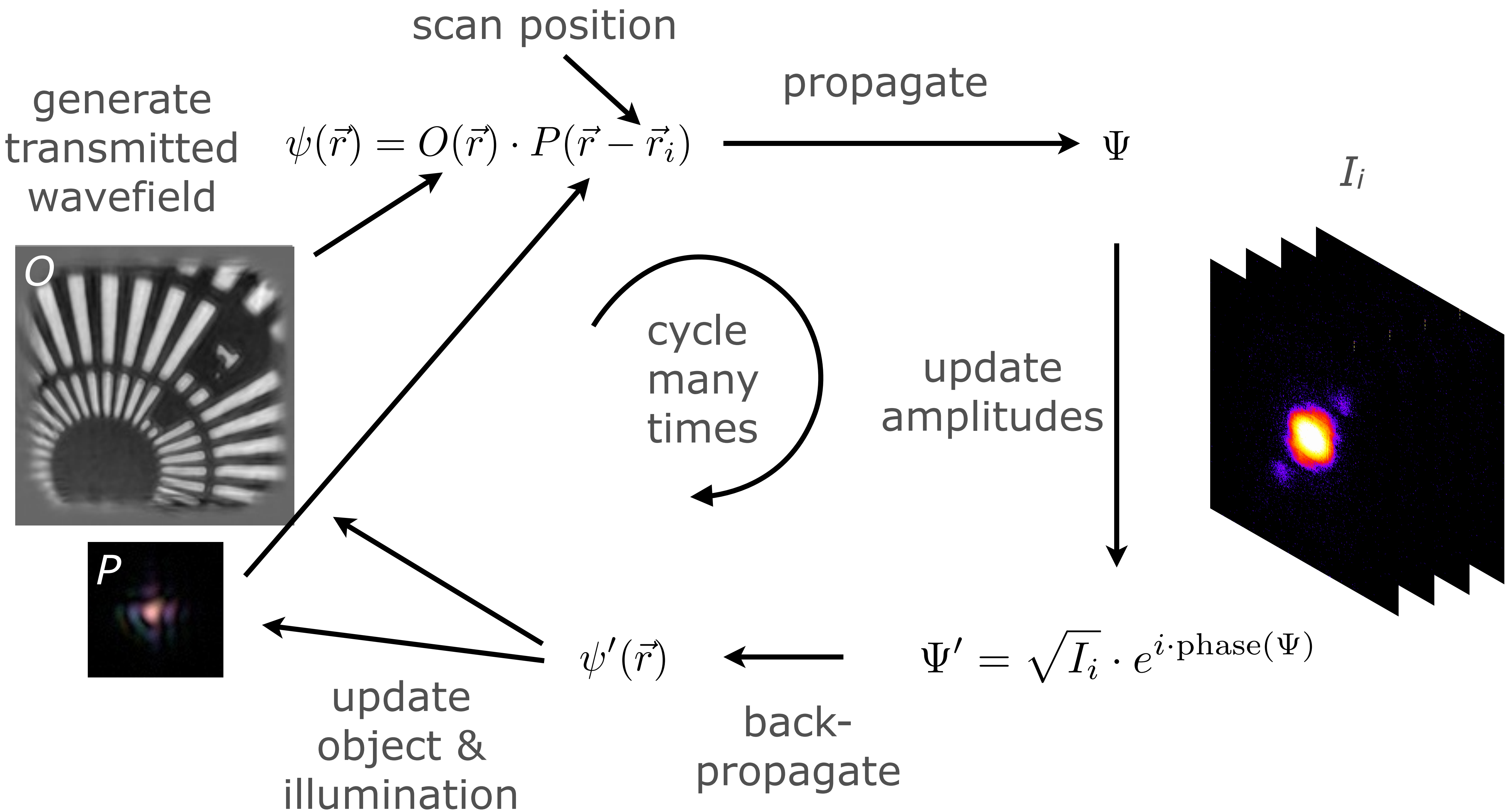
detector:
Pilatus 300k (172μm pixel size)

sample-detector distance:
2080 mm

exposure time:
1.0 s per point

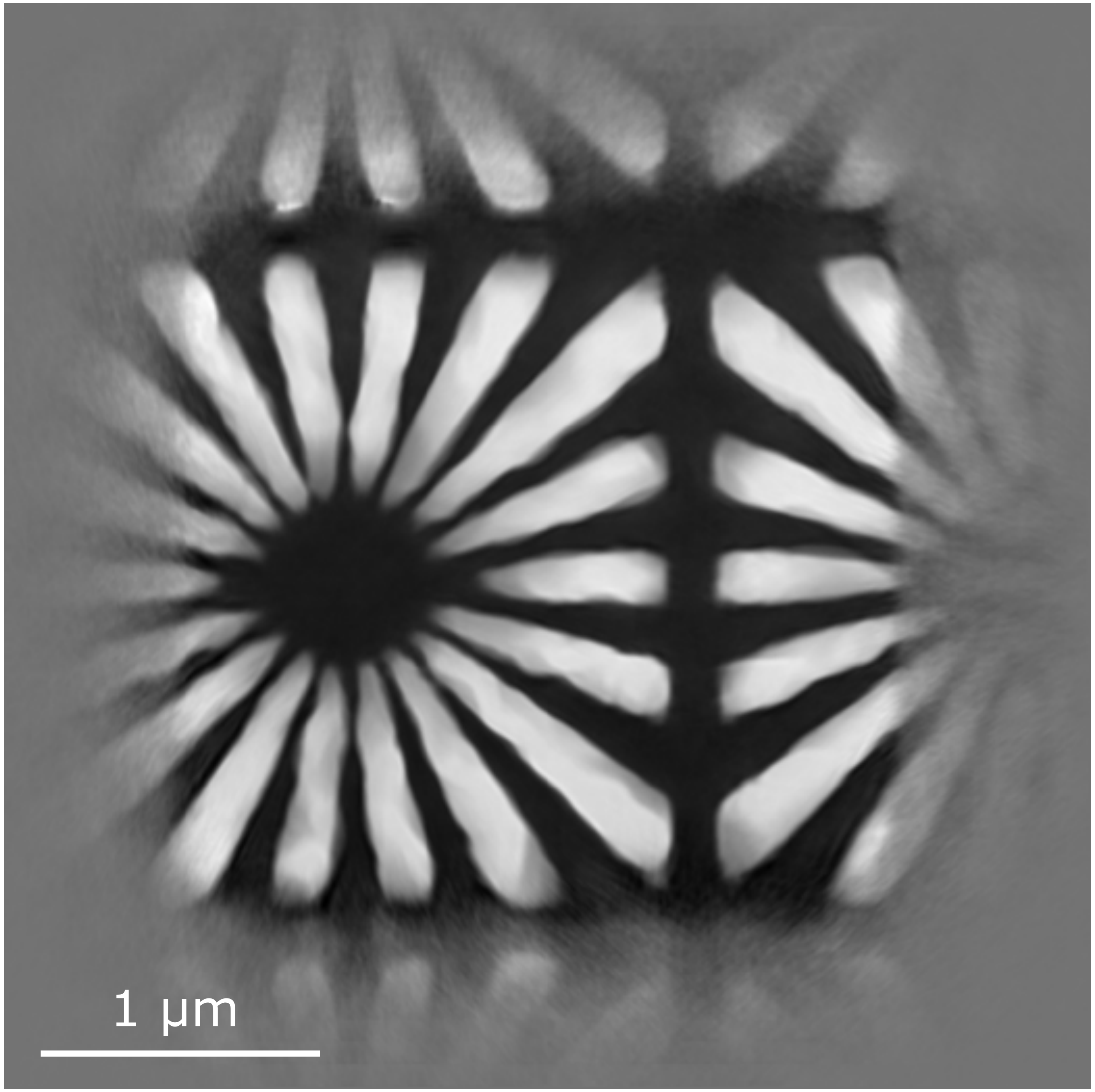


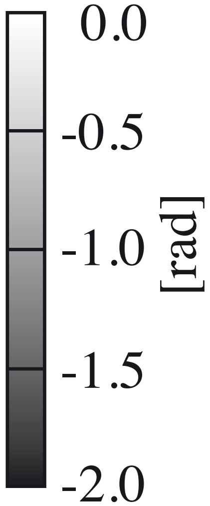
Ptychography: Reconstruction

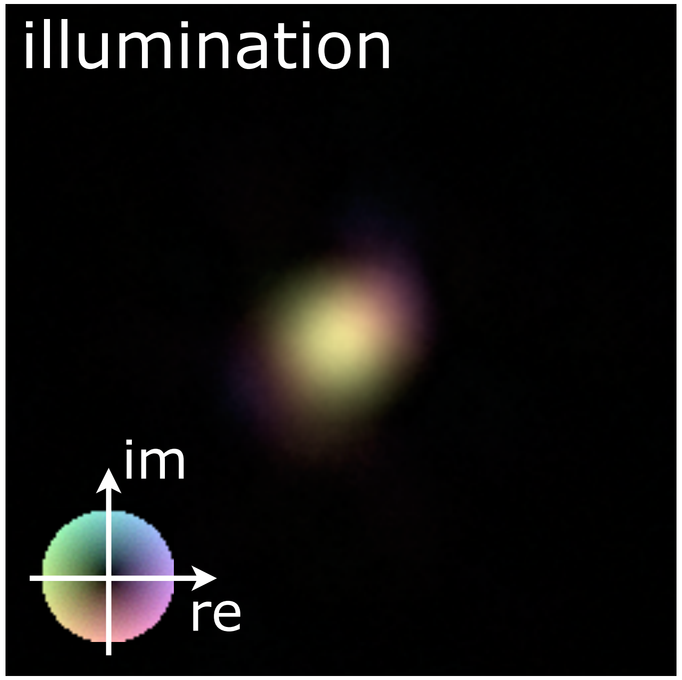


Maiden & Rodenburg, Ultramicroscopy **109**, 1256 (2009).

Scanning Microscopy: Ptychography





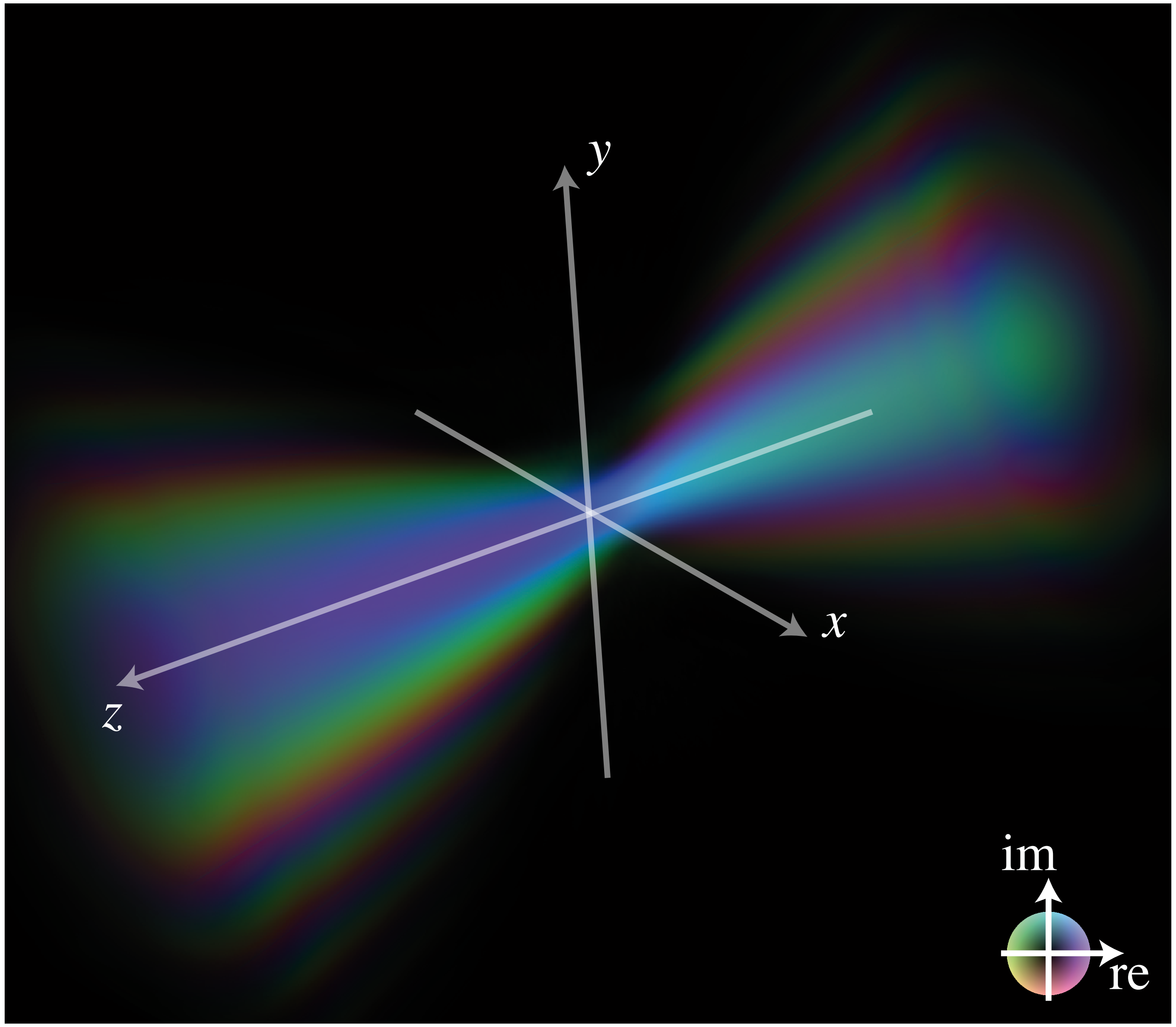


Full state (solution of Helmholtz equation)

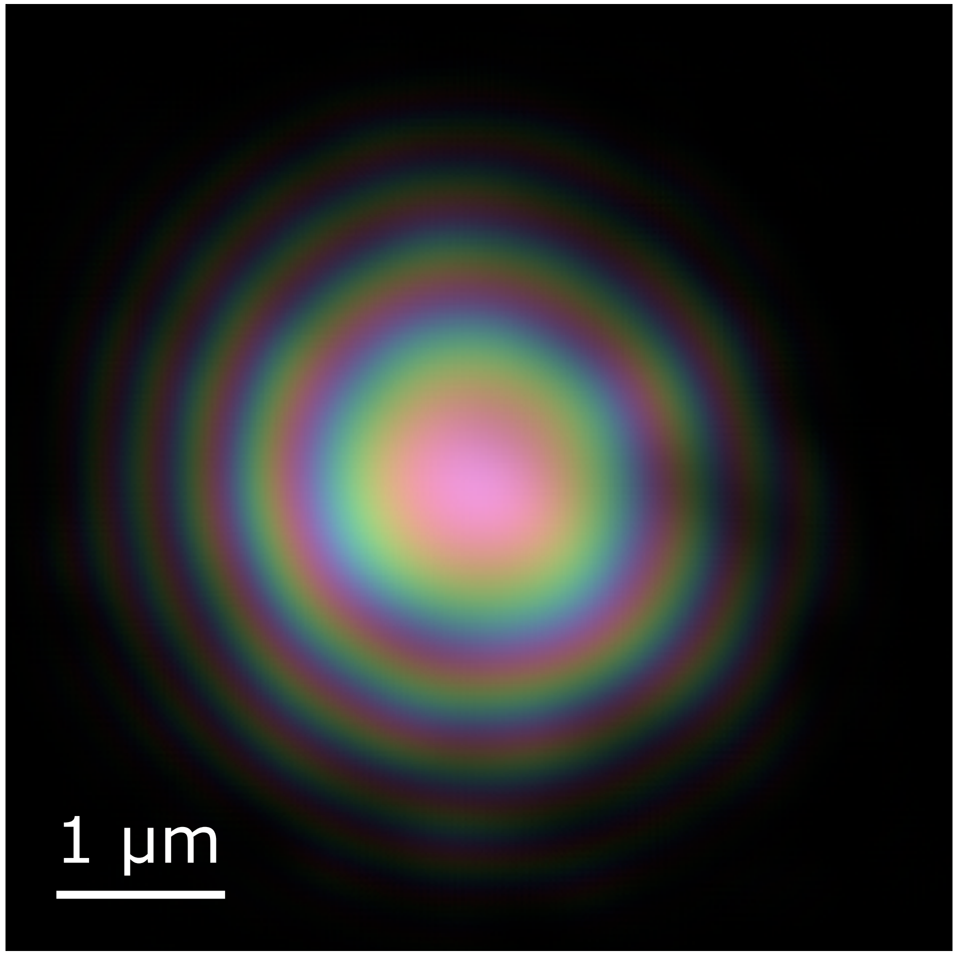
E = 8.0 keV
25 x 25 steps of 80 x 80 nm^2
2 x 2 µm^2 FOV
exposure: 1.0 s per point
detected fluence: 120 ph/nm^2

A. Schropp, et al., APL **96**, 091102 (2010).

Evaluation of Complex Wavefield



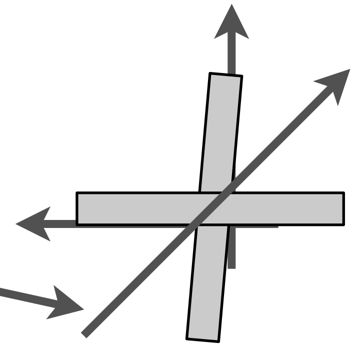
Caustic: -4 mm to 4 mm



Slight astigmatism:

improper lens alignment:

more strongly focusing direction



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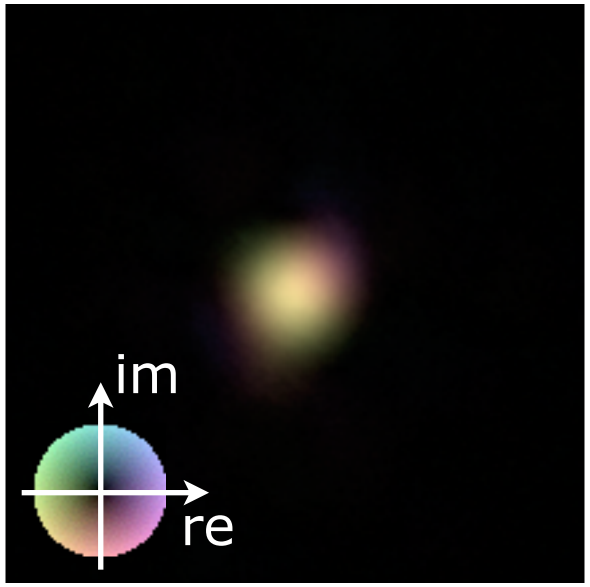
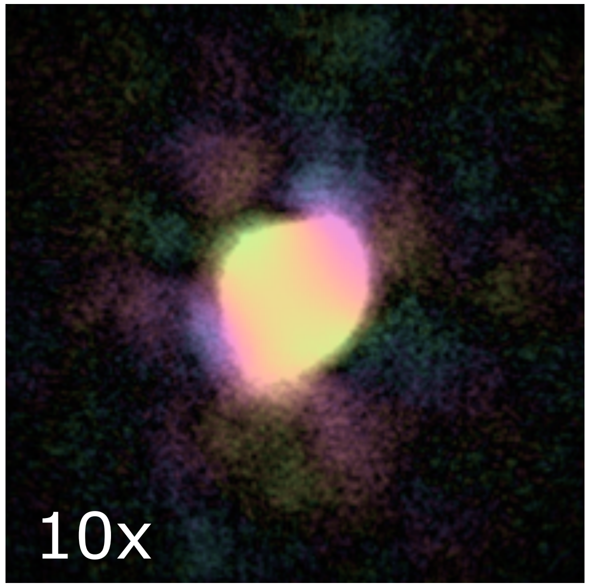
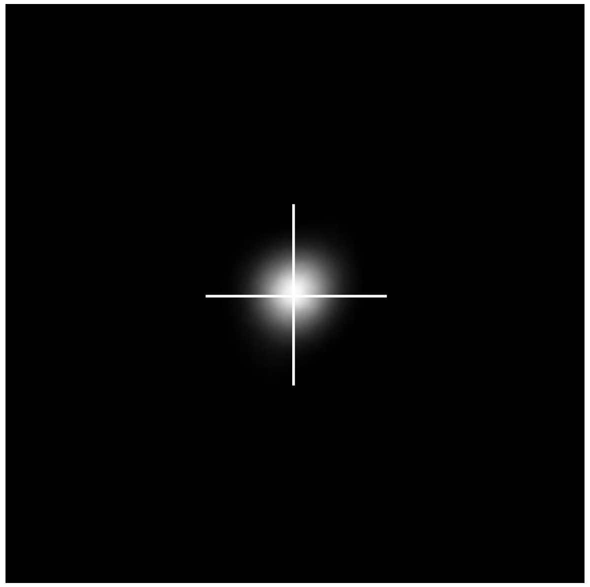
Evaluation of Complex Wavefield

complex amplitude:

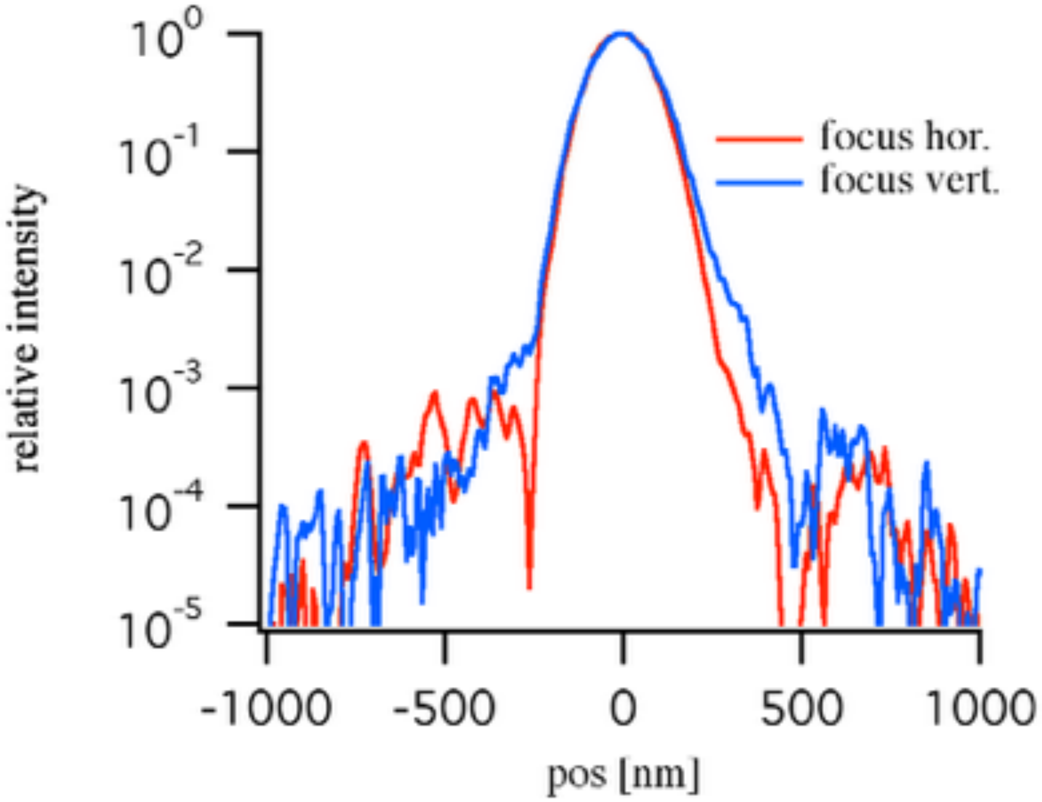




intensity:



$1/\sqrt{2}\times$ width of amplitude



ideal focus: 155 x 175 nm^2

A. Schropp, et al., APL **96**, 091102 (2010), S. Hönig, et al., Opt. Express 19, 16324 (2011).

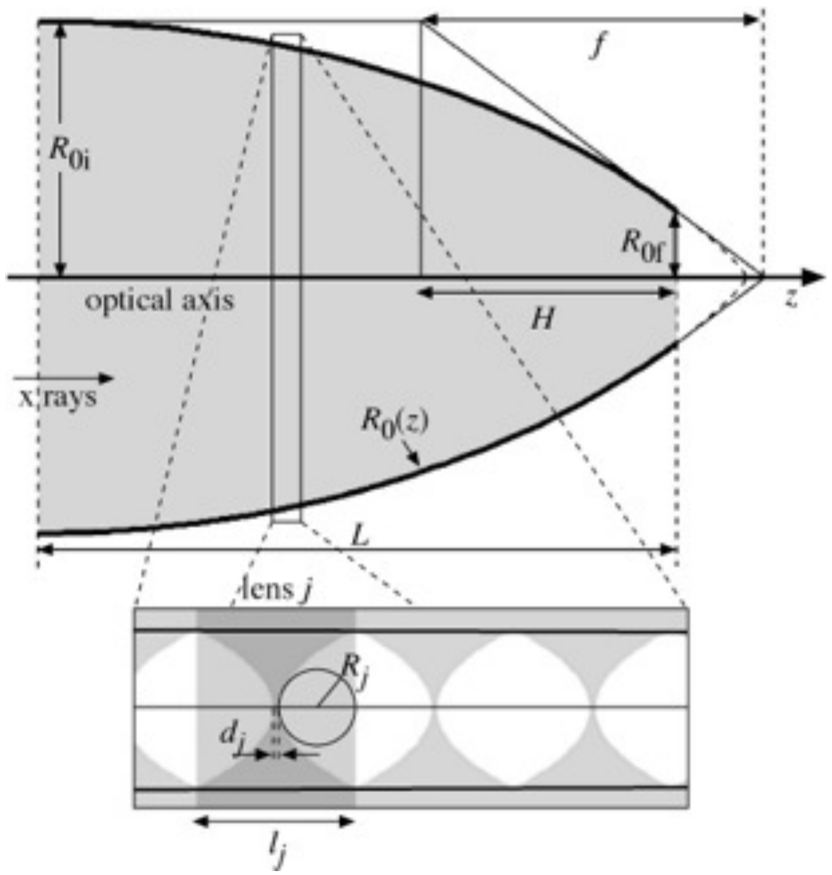
Adiabatically Focusing Lenses

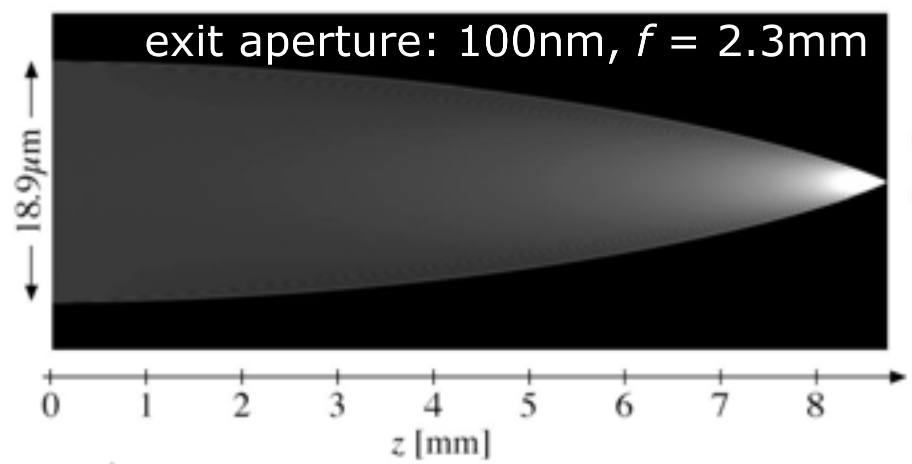
Adjust aperture to follow converging beam:

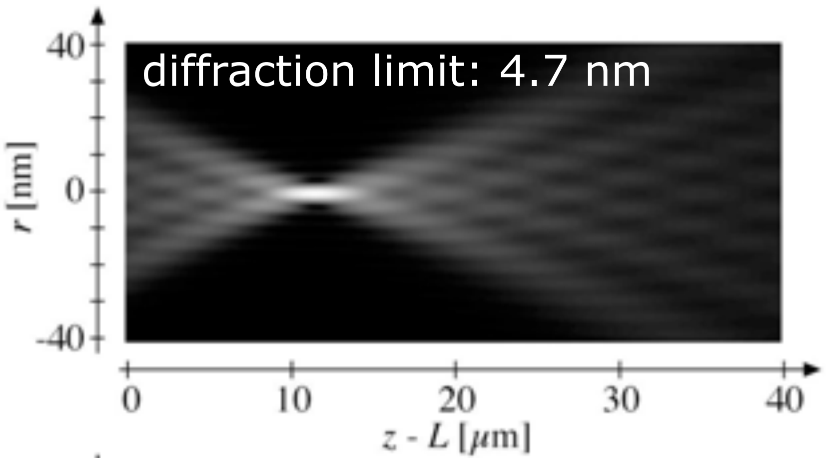
- increased refractive power per unit length
- numerical aperture diverges logarithmically
- performance limited by feature size

Theoretical considerations:

- numerical aperture should exceed critical angle to total reflection: $NA > \sqrt{2\delta}$





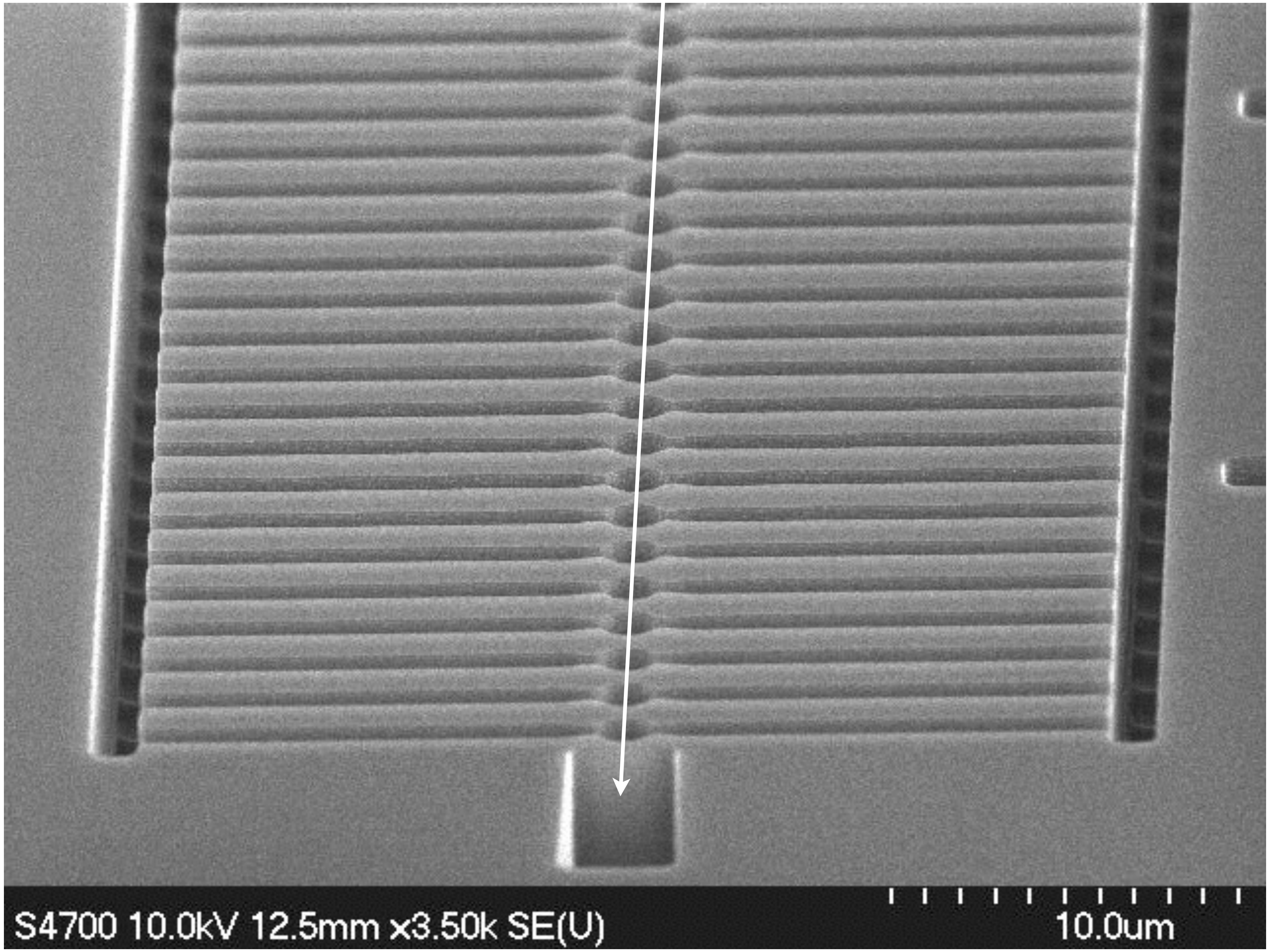


Extreme focusing:

example: diamond AFL

PRL **94**, 054802 (2005)

AFL Made of Silicon



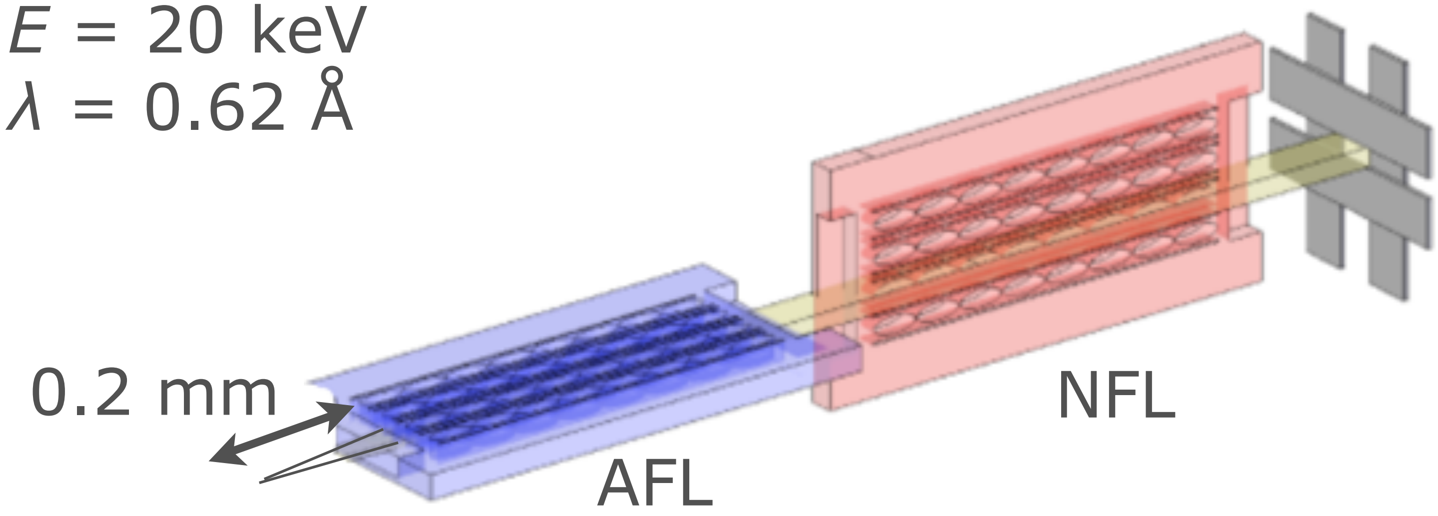
SEM image
near the exit
of the lens.

$$R_{0f} \approx 500 \text{ nm}$$

20 keV:
L = 2.889 mm
N = 535

Characterizing AFLs by Ptychographic Imaging

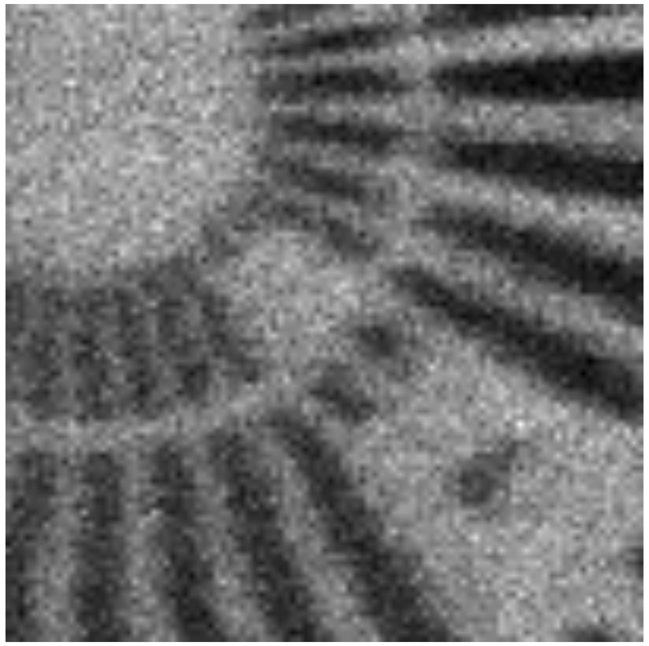
E = 20 keV
λ = 0.62 Å



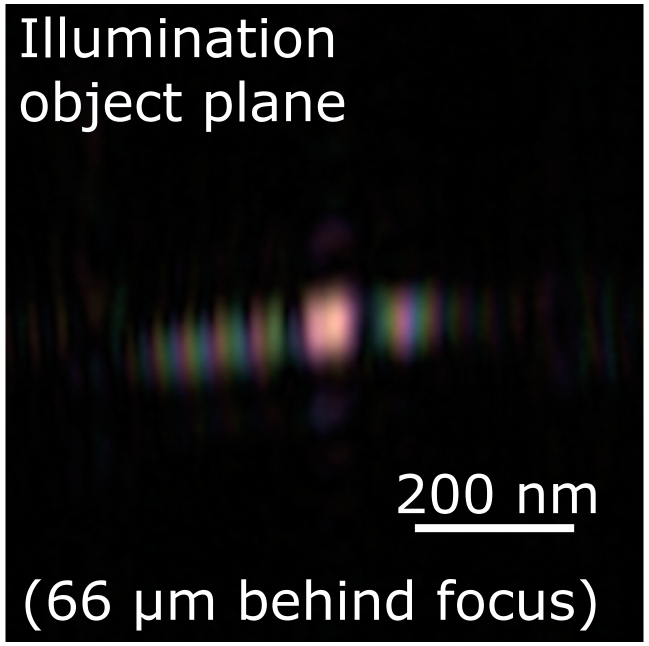
ptychogram:

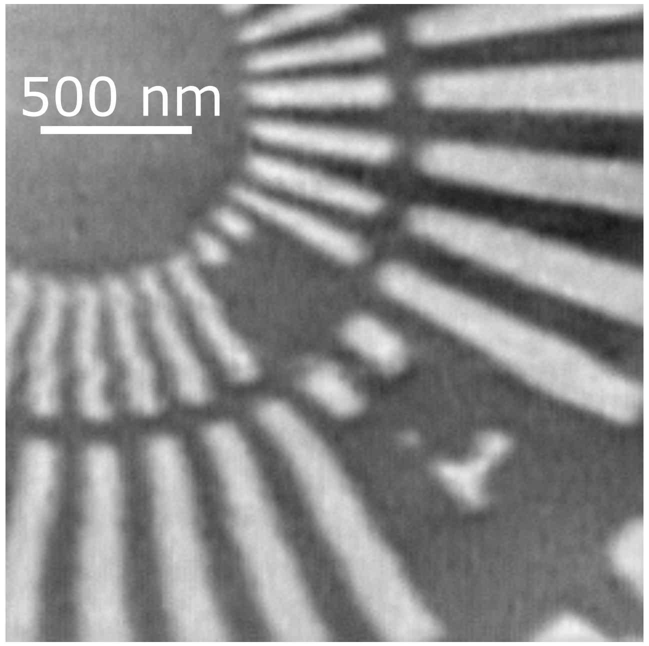
100 x 100 steps
20 x 20 nm^2 step size

Ta fluorescence



reconstruction:





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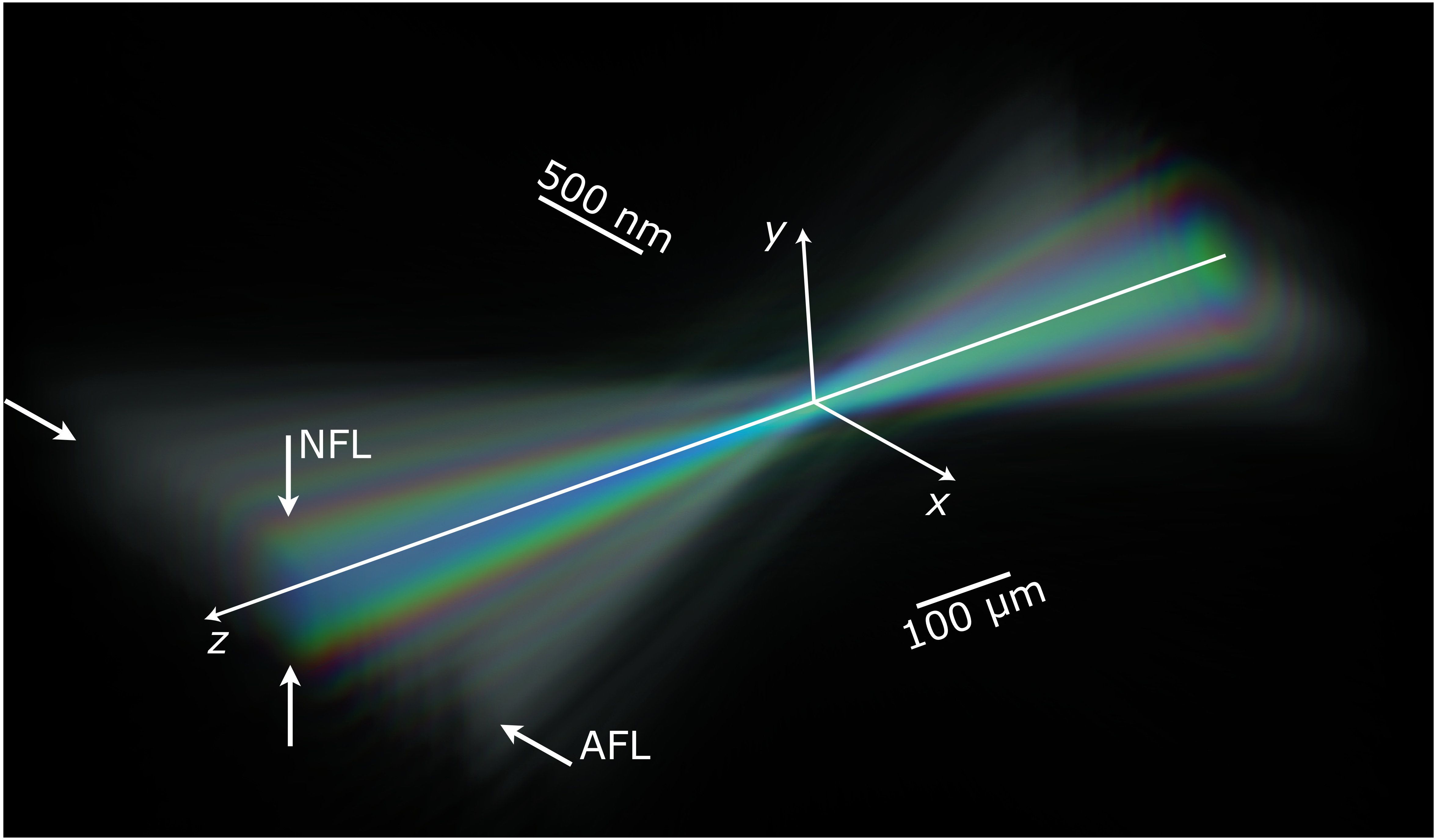

500 nm
y
NFL
x
z
100 µm
AFL

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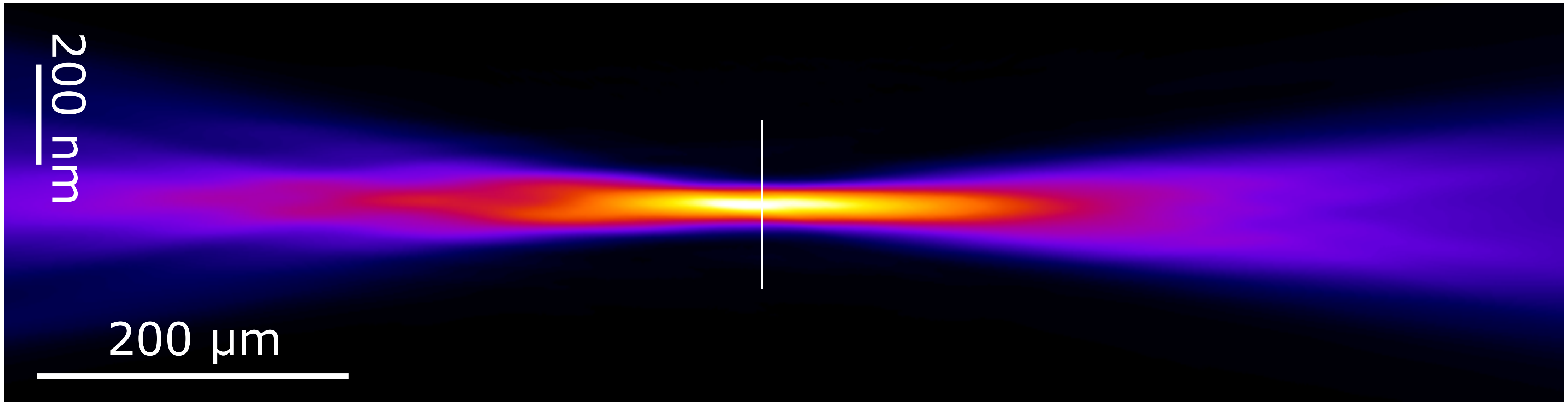
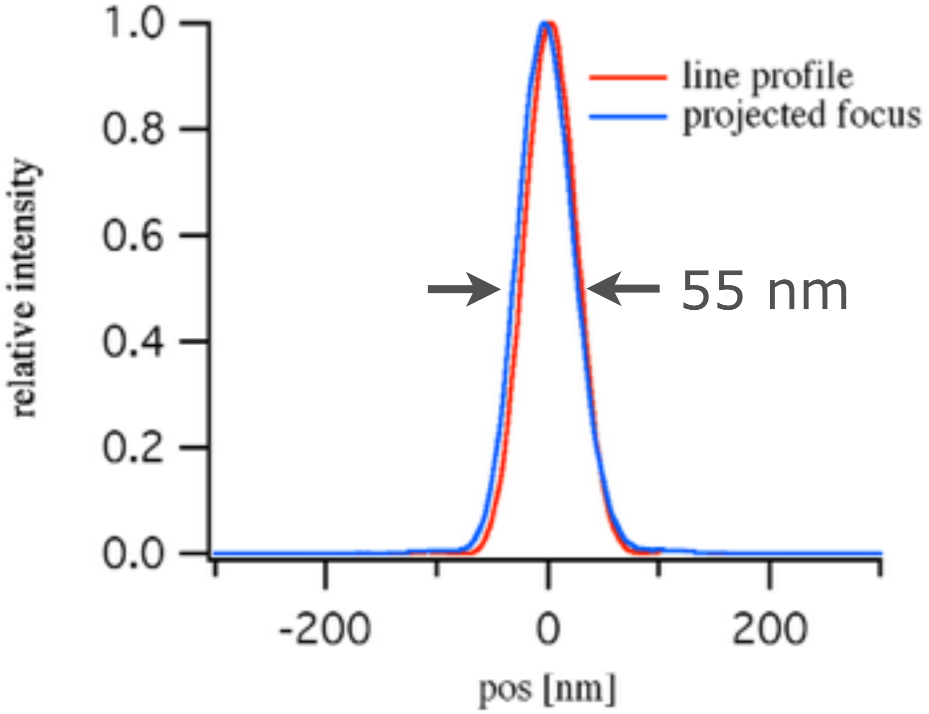
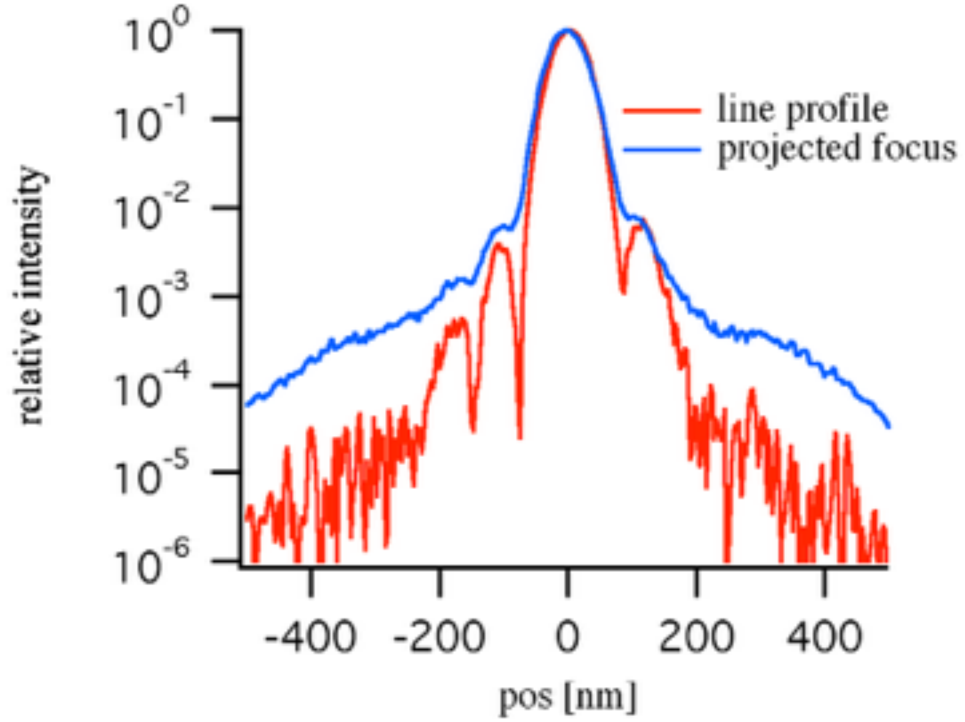
NFL Focus



Nearly Gaussian diffraction-limited beam:





interval ±25 nm:

66 % of radiation

interval ±50 nm:

94 % of radiation