Hard X-ray Scanning Nanoprobe: coherent nanobeam optics limits; refractive lenses

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bmb+f
Großgeräte
der physikalischen
Grundlagenforschung

HGF: VI-203, VI-403

Hard X-Ray Nanoprobe and Scanning Microscopy

Highest resolution:

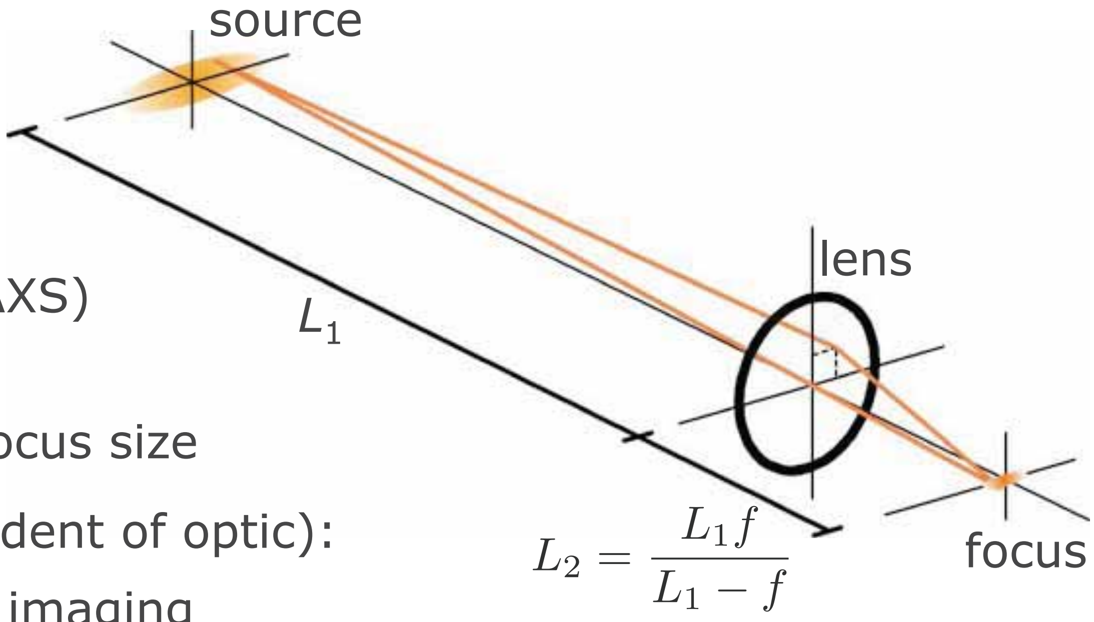
- diffraction limited imaging of source onto sample
- flux on sample given by coherent flux F_c and efficiency T of optic

Scanning microscopy:

- different contrasts:

  fluorescence
  absorption (XAS)
  diffraction (SAXS & WAXS)
  ...

  Resolution limited by focus size

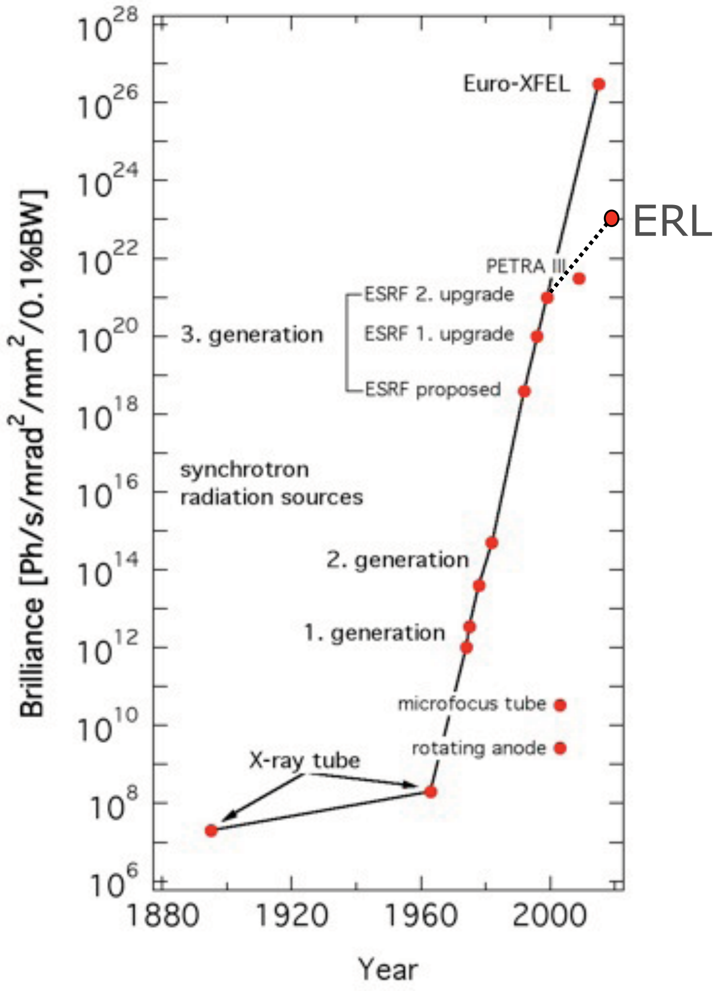


$$L_2 = \frac{L_1 f}{L_1 - f}$$

Improve resolution (independent of optic):

coherent x-ray diffraction imaging
combined with nanofocusing

Brilliance and coherent dose density



Coherent flux:

$$F_{\mathrm{c}} = Br \cdot \lambda^2 \cdot \frac{\Delta E}{E}$$

Diffraction limited beam:

coherent flux is focused!

Defines SNR for all contrast mechanisms in scanning microscopy

Beyond nanobeam resolution:

CXDI: resolution limited by dose density

$$I_{\mathrm{c}} \Delta t = \frac{F_{\mathrm{c}}}{A} \Delta t$$

Schropp, Schroer, NJP **12**, 035016 (2010) (cf. poster)

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Optimal Nanofocusing: Optimize Coherent Flux Density

Assume optimal adaptation of aperture to coherence length

focused flux:

$F = F_\mathrm{c} \cdot T$ *T*: efficiency of optic $F_\mathrm{c} = Br \cdot \lambda^2 \cdot \frac{\Delta E}{E}$

diffraction limit: focal spot area:

$$d_t = \alpha \frac{\lambda}{2NA} \propto \frac{\lambda}{NA} \quad \longrightarrow \quad A \propto d_t^2 \propto \frac{\lambda^2}{NA^2}$$

Coherent dose density:

$$I_\mathrm{c} \Delta t = \frac{F_\mathrm{c}}{A} \Delta t \propto \underbrace{Br} \cdot \underbrace{NA^2 \cdot T} \cdot \frac{\Delta E}{E} \cdot \Delta t$$

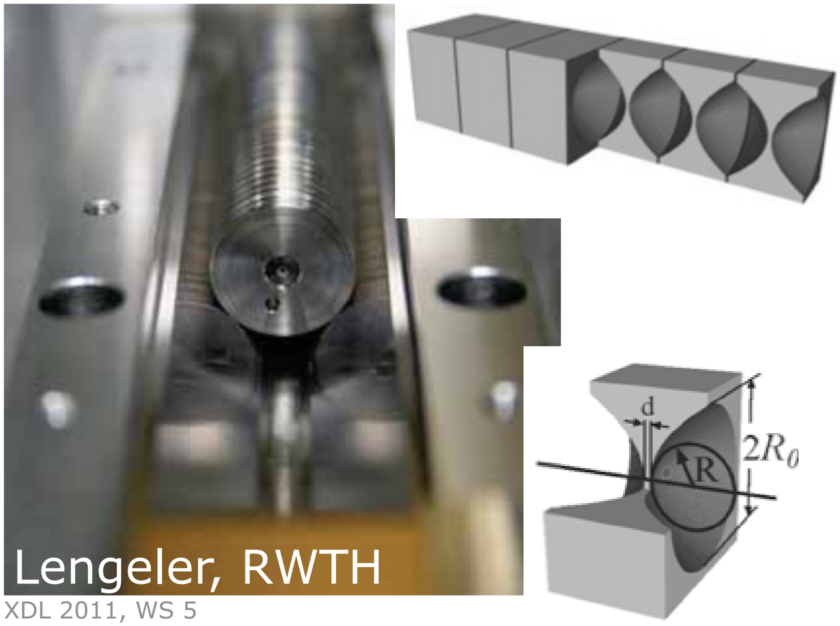
Δt: exposure time

source   figure of merit for optic   limited by sample

Refractive X-Ray Lenses

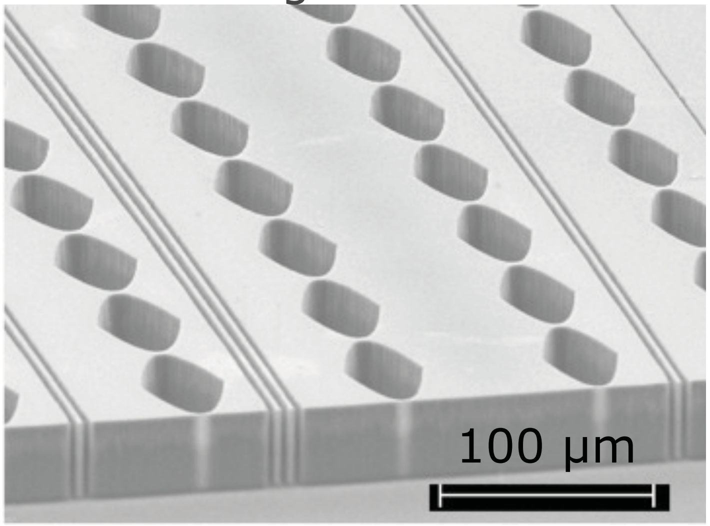
- first realized in 1996 (Snigirev et al.)
- a variety of refractive lenses have been developed since
- applied in full-field imaging and scanning microscopy
- most important to achieve optimal performance:

parabolic lens shape

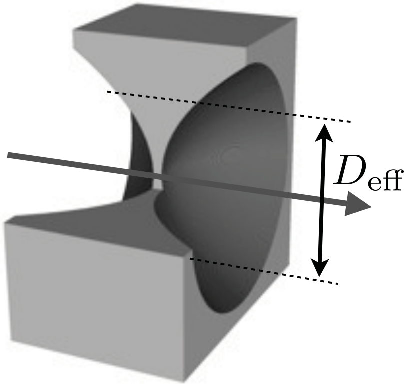


Lengeler, RWTH

nanofocusing lenses

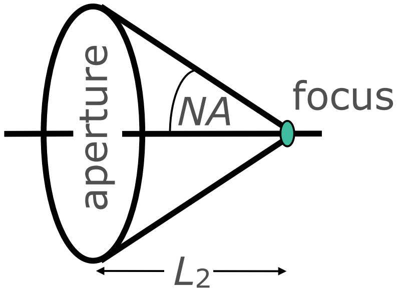


Nanofocus



large focal length *f*: aperture limited by absorption

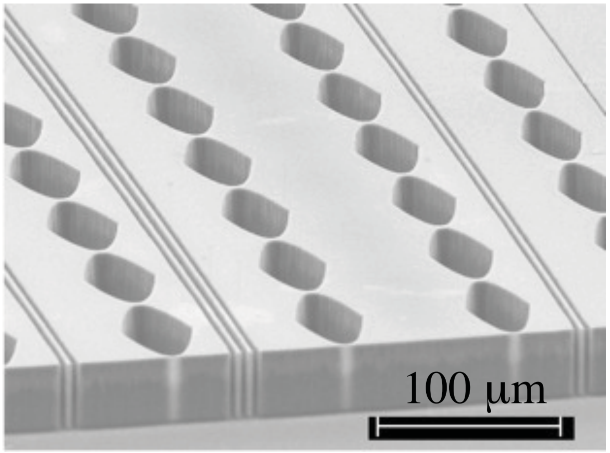
$$D_{\mathrm{eff}} = 4\sqrt{\frac{f\delta}{\mu}} \propto \sqrt{f}$$



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

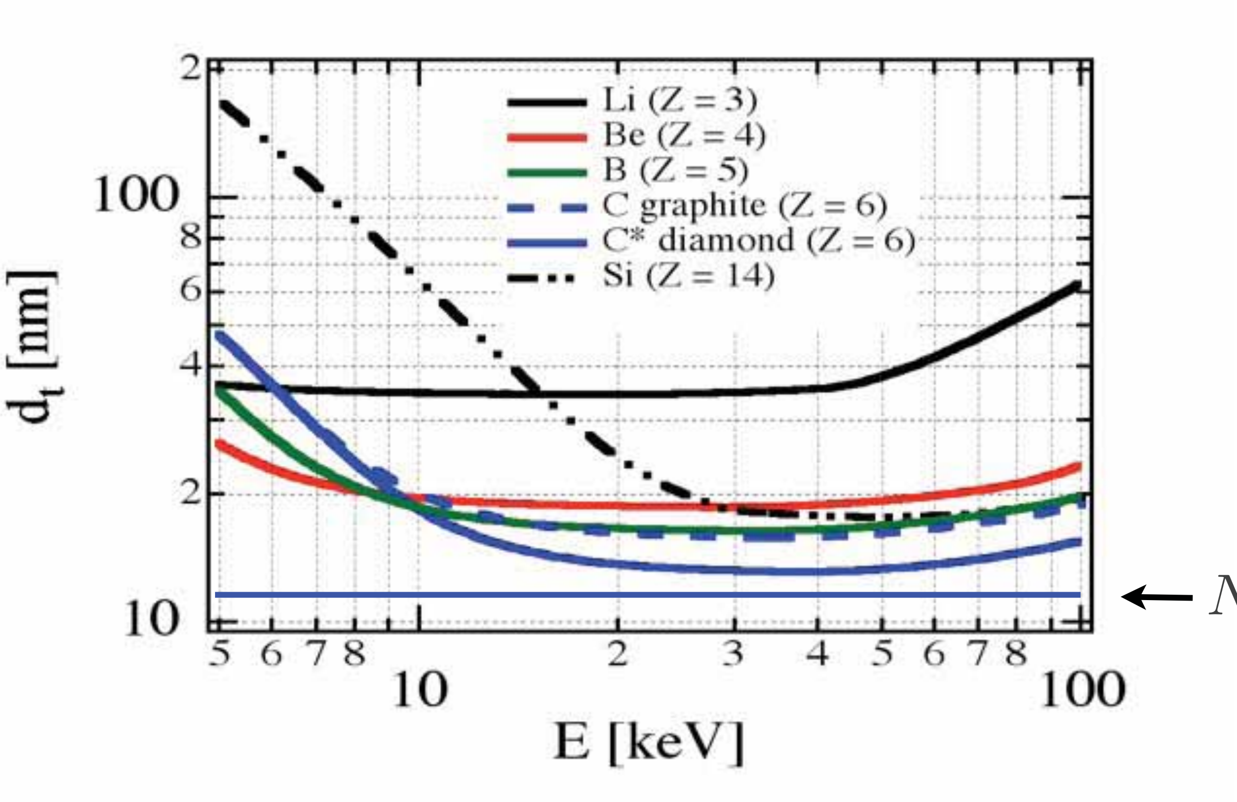
→ $NA = \frac{D_{\mathrm{eff}}}{2f} \propto \frac{1}{\sqrt{f}}$ (⇒ minimize focal length *f*)

transition to
nanofocusing
lenses (NFLs)
→



Nanofocusing Lenses

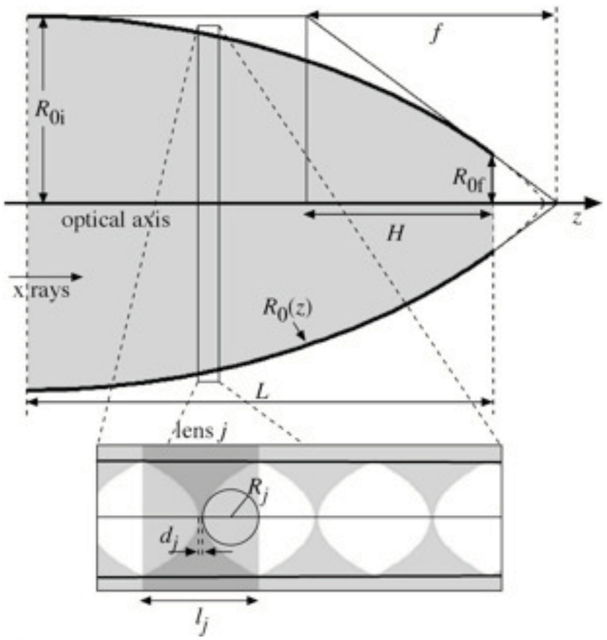
Optimal diffraction limit (at shortest focal length):



$$\leftarrow NA_{\max} = \sqrt{2\delta}$$

for focal point 1 mm behind horiz. lens

Adiabatically Focusing Lenses

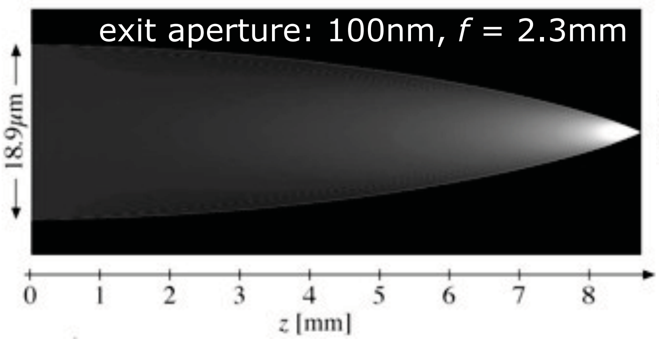


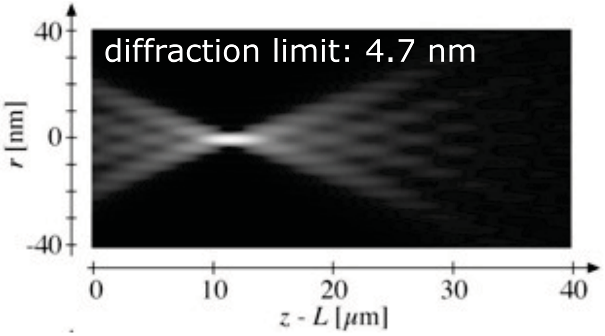
Adjust aperture to follow converging beam:

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

Example: Diamond

- low Z high density ρ

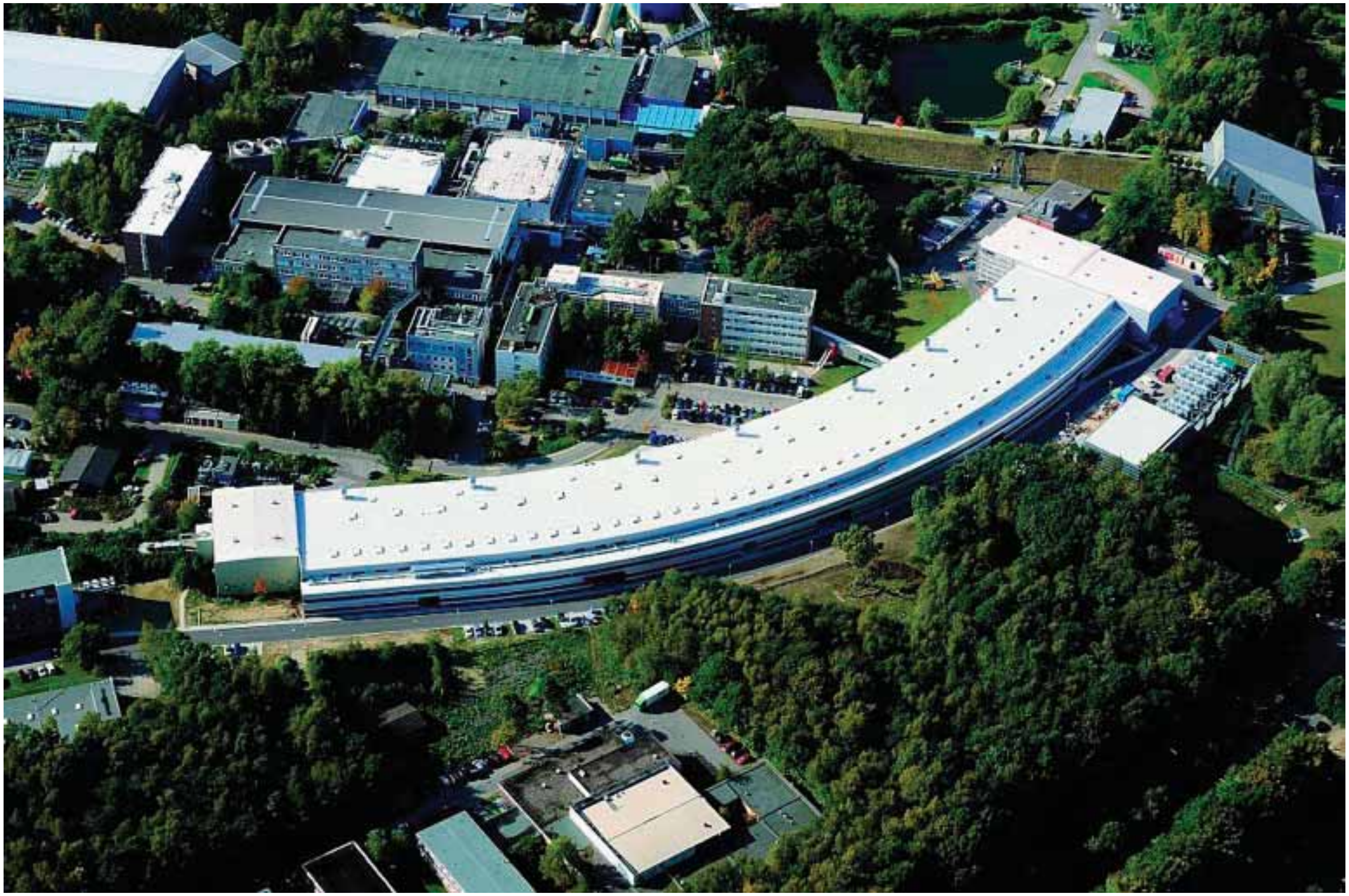

exit aperture: 100nm, *f* = 2.3mm

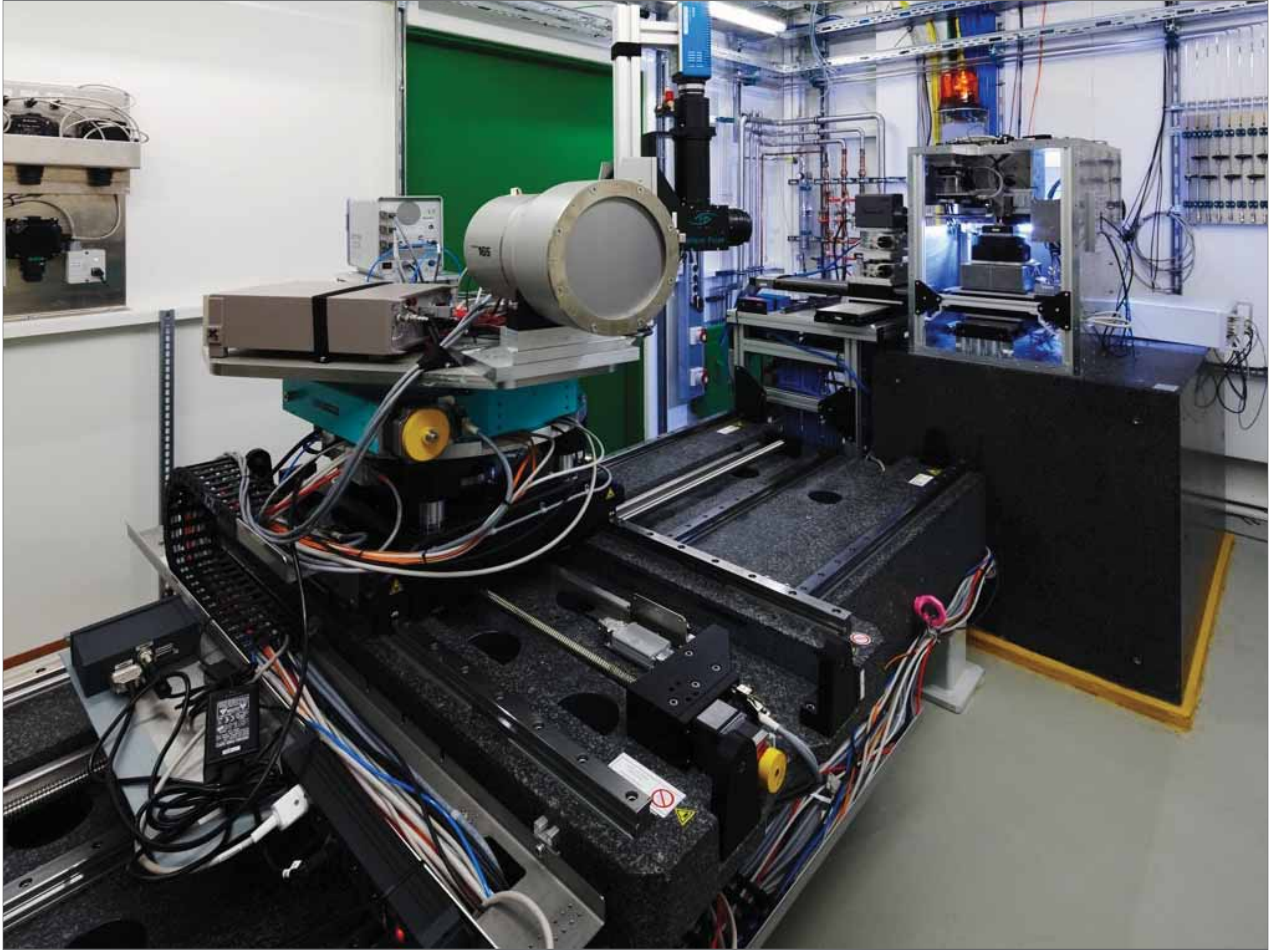

diffraction limit: 4.7 nm

no sharp fundamental limit: limit given by fabrication

PRL **94**, 054802 (2005)

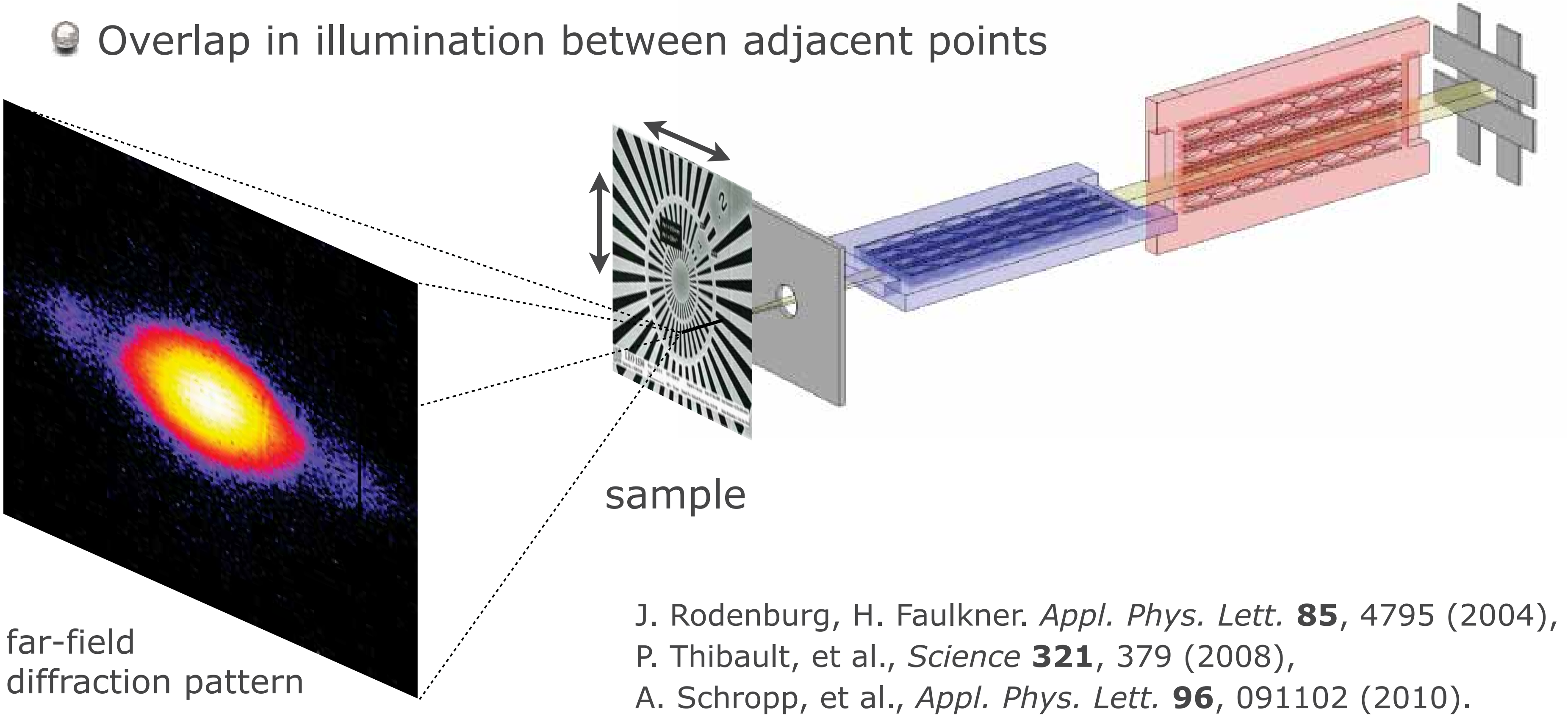
Hard X-ray Scanning Microscopy at PETRA III





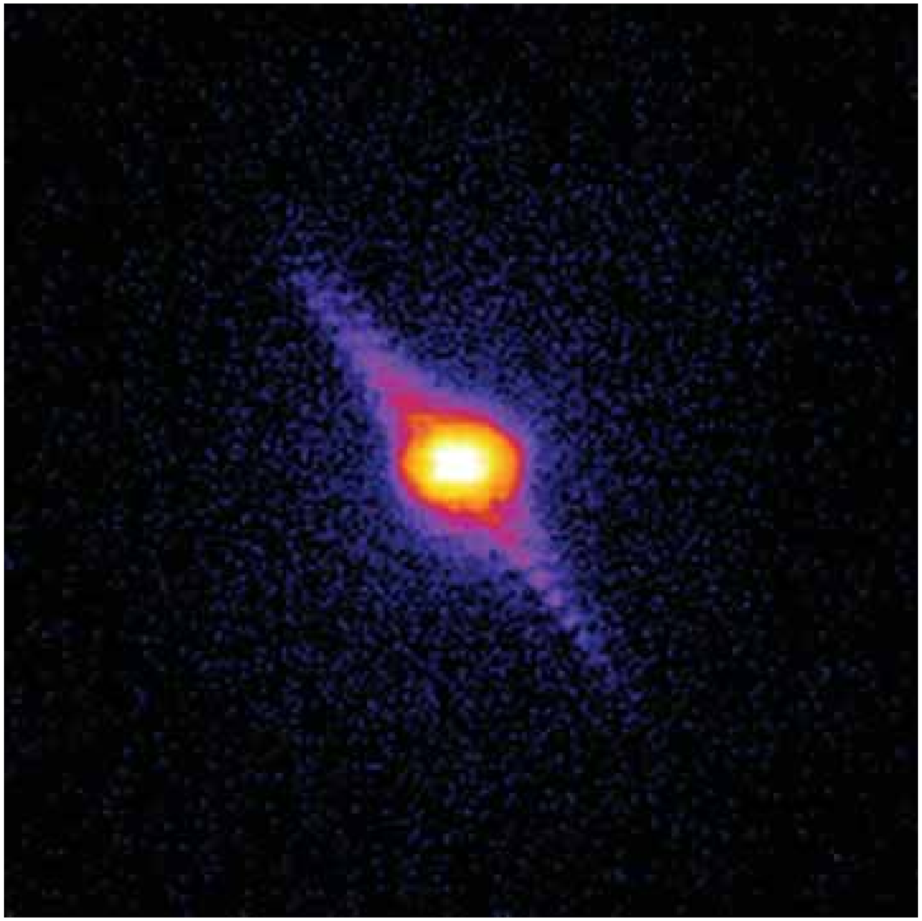
Scanning Coherent X-Ray Diffraction Imaging: Ptychography

- 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).

Ptychographic Microscopy



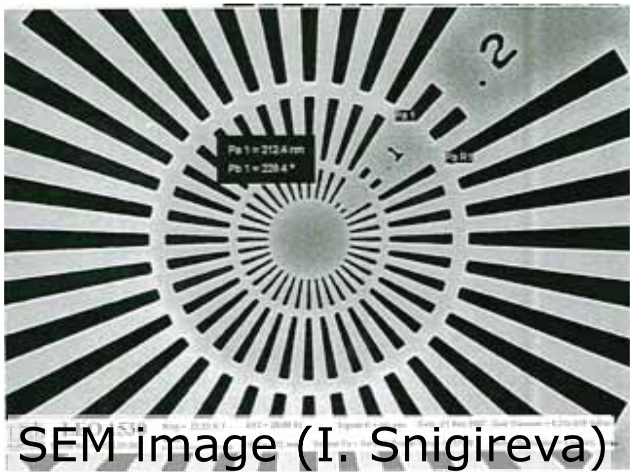
Experiment at P06:

detector:
Pilatus 300k (172μm pixel size)

sample-detector distance:
2080 mm

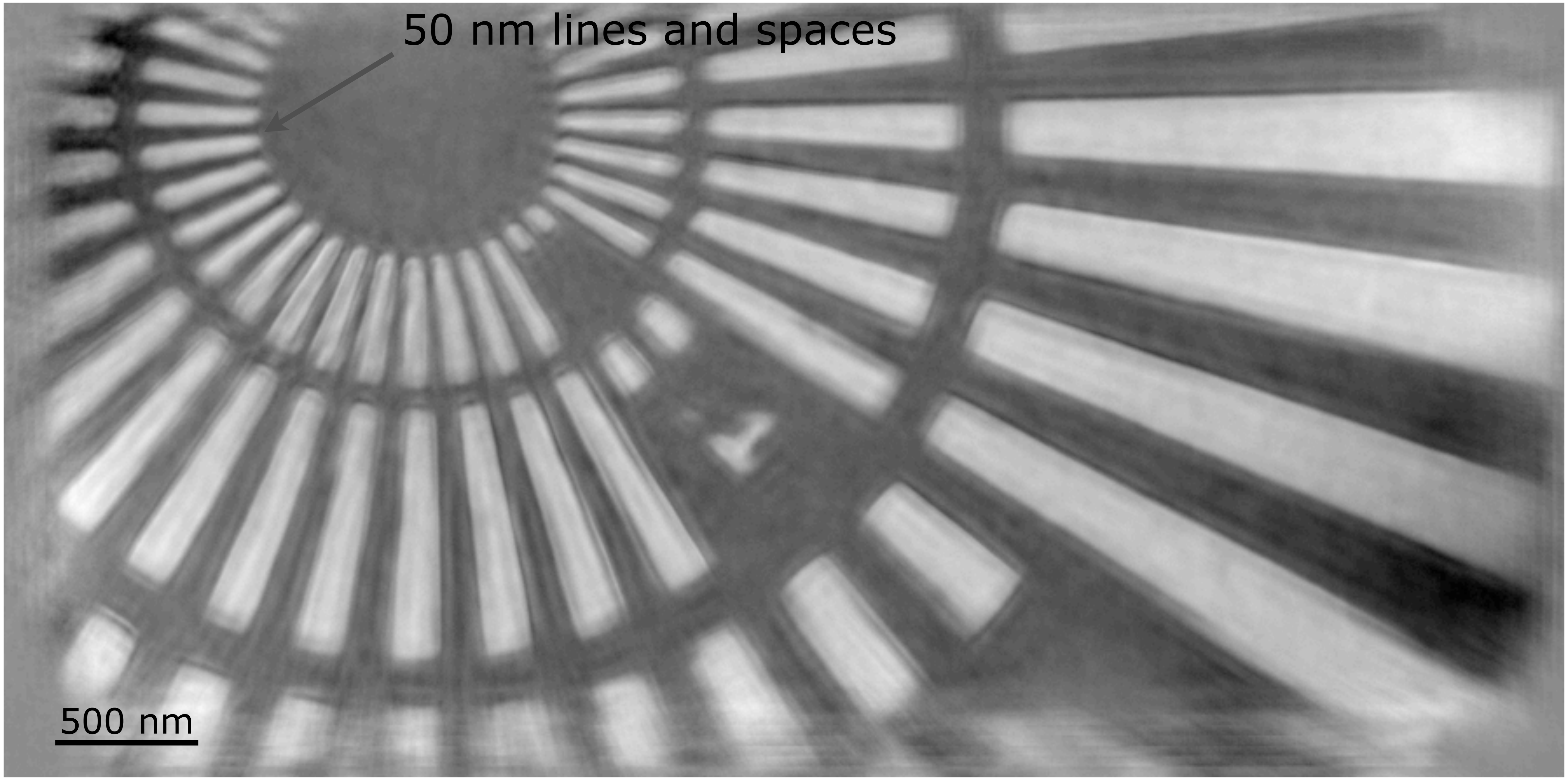
exposure time:
1.5 s per point

Sample: NTT AT test pattern



SEM image (I. Snigireva)

Scanning Microscopy: Ptychography



E = 15.25 keV, 125 x 62 steps of 40 x 40 nm^2: 5 x 2.48 μm^2 FOV
exposure: 0.3 s per point

Nanofocusing Lenses with High Numerical Aperture

E = 24.3 keV

Lens made of Si becomes nearly transparent

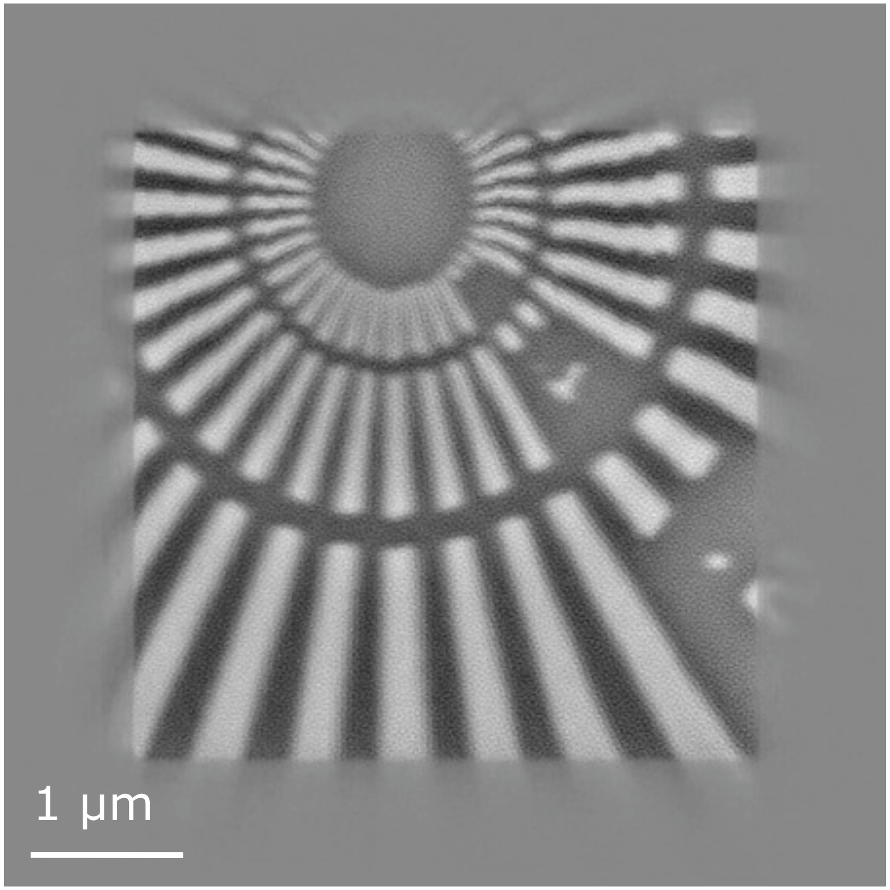
Expected focus: 43 x 52 nm^2 (diffraction limited)

Ptychographic scan:

- 101x101 scan points
- 40 nm step size
- 0.5 s exposure time

Artifact: Graininess

Compton scattering generates background



Schropp, et al., APL **96**, 091102 (2010), Schroer, et al., Proc. XRM 2010

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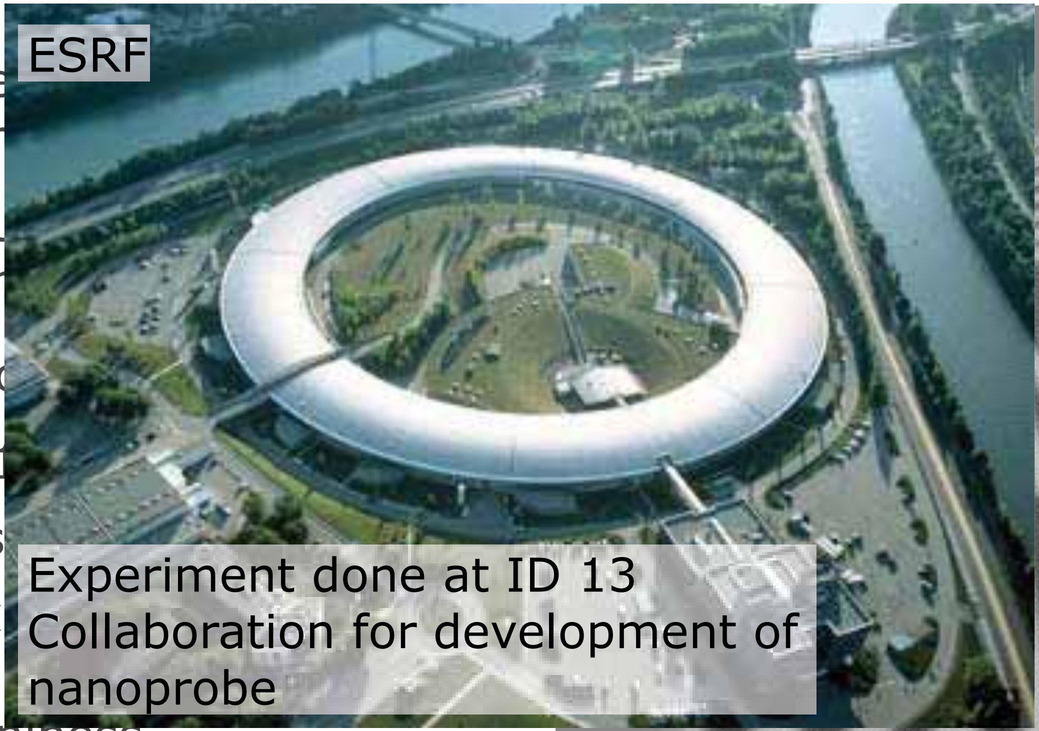
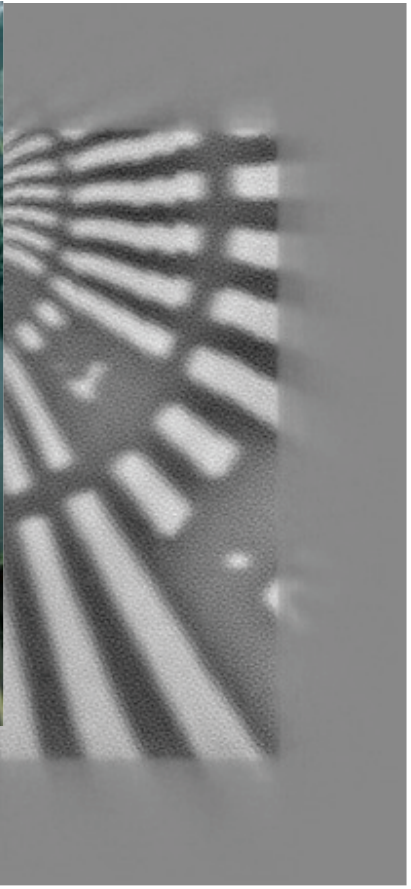


ESRF

Experiment done at ID 13
Collaboration for development of nanoprobe



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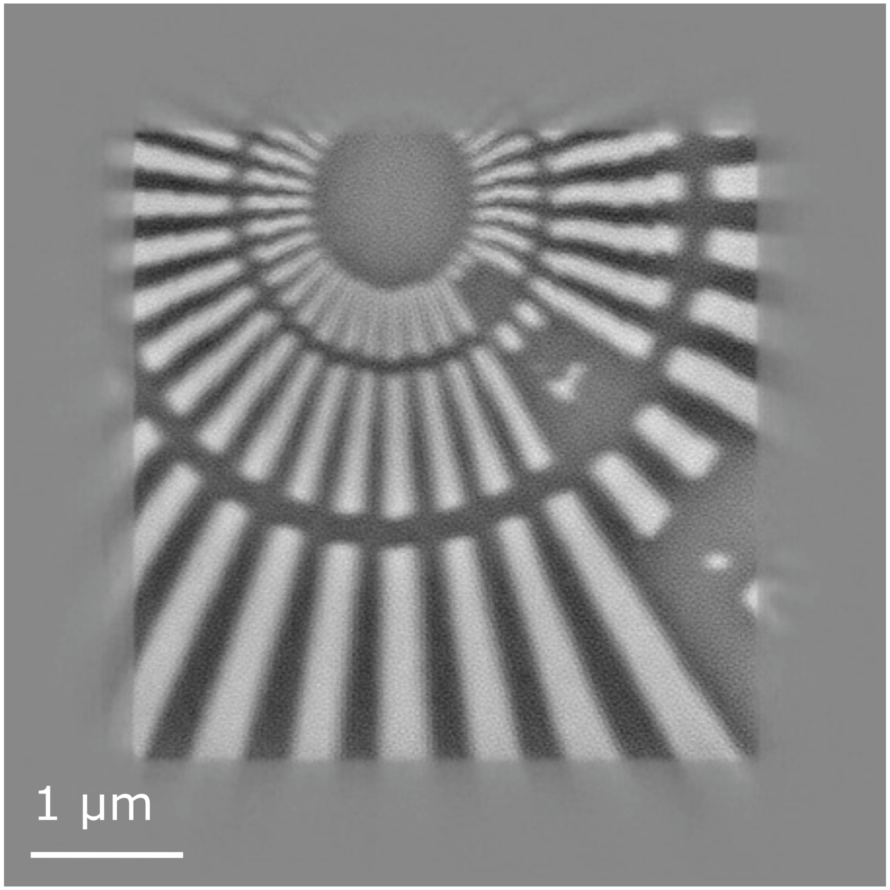

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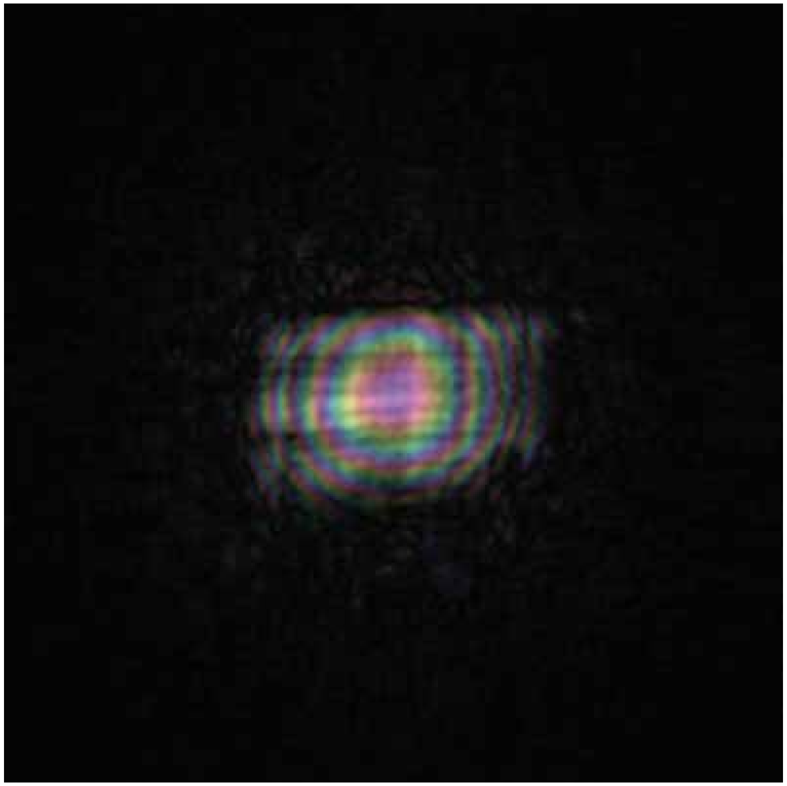
Focus: astigmatism

lenses not perfectly mutually orthogonal

Reconstructed focus



Schropp, et al., APL **96**, 091102 (2010), Schroer, et al., Proc. XRM 2010

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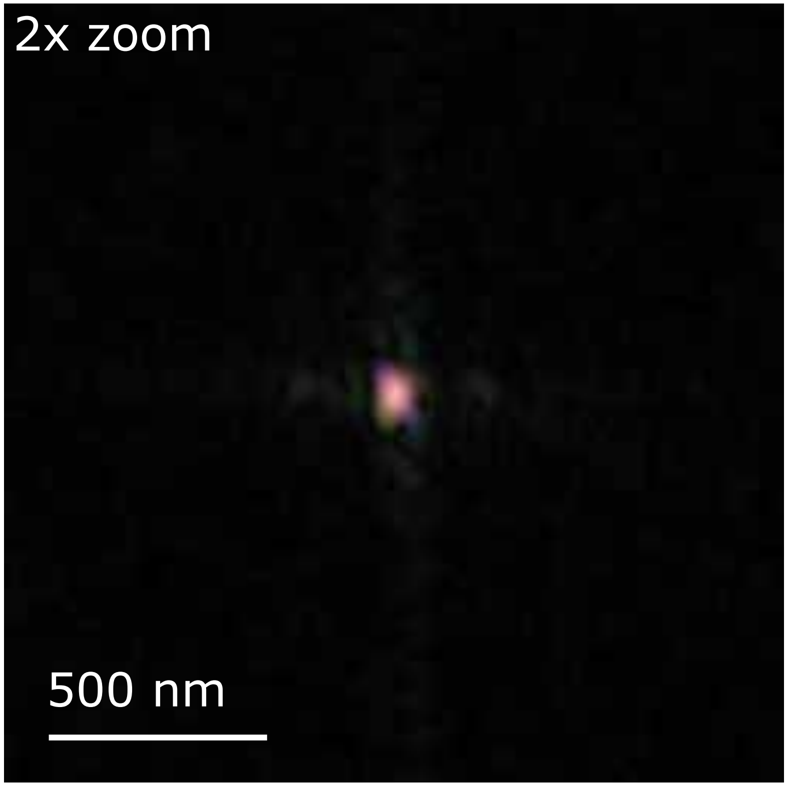

Schropp, et al., APL **96**, 091102 (2010), Schroer, et al., Proc. XRM 2010

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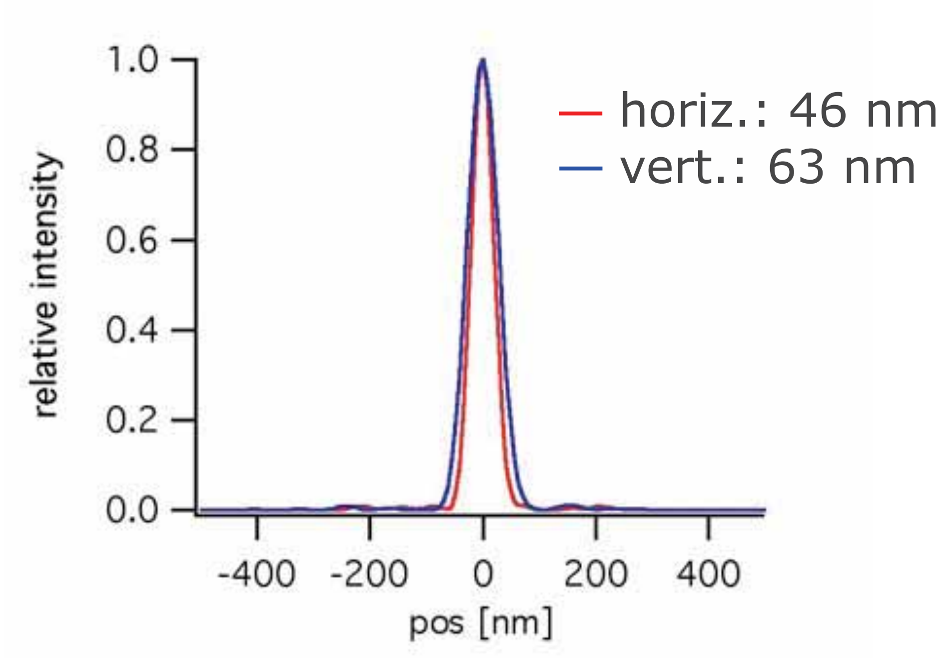

Focus: astigmatism

lenses not perfectly mutually orthogonal

Main advantage of Gaussian aperture:

relatively clean Gaussian Beam

Schropp, et al., APL **96**, 091102 (2010), Schroer, et al., Proc. XRM 2010

Focus at High Numerical Aperture

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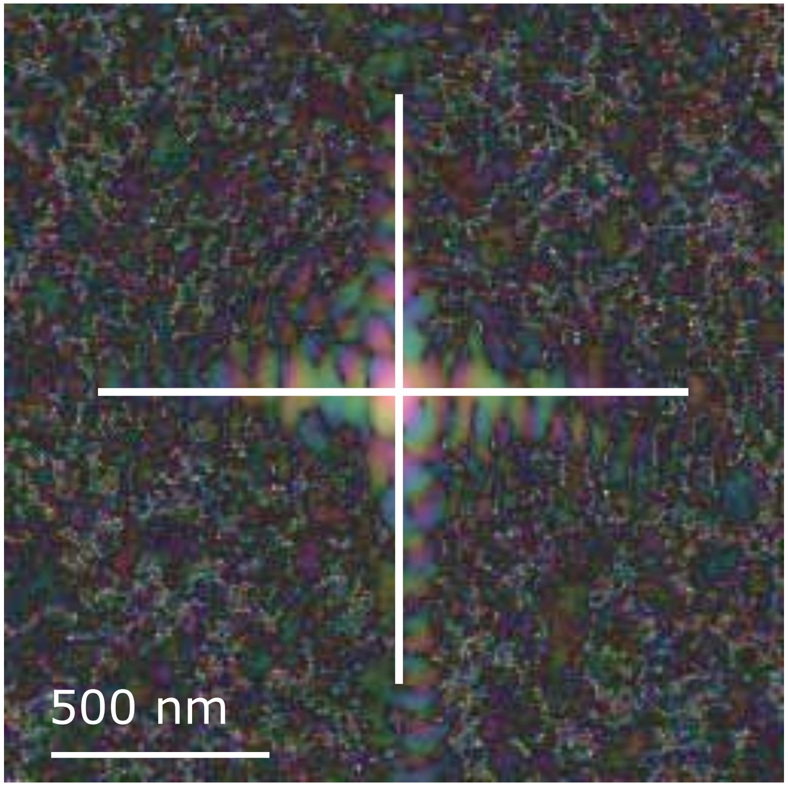

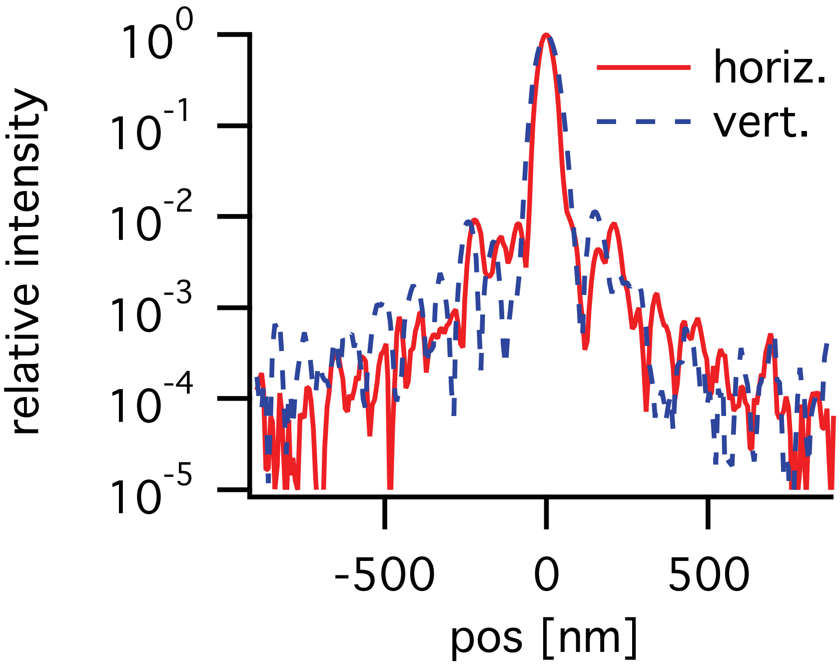

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Schroer et al., Proc. XRM 2010

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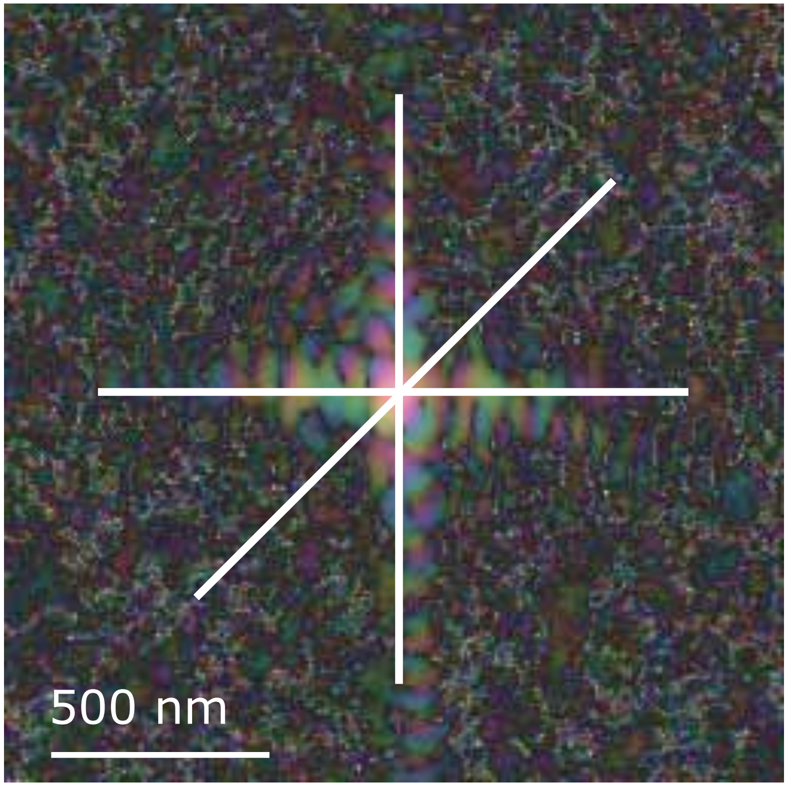
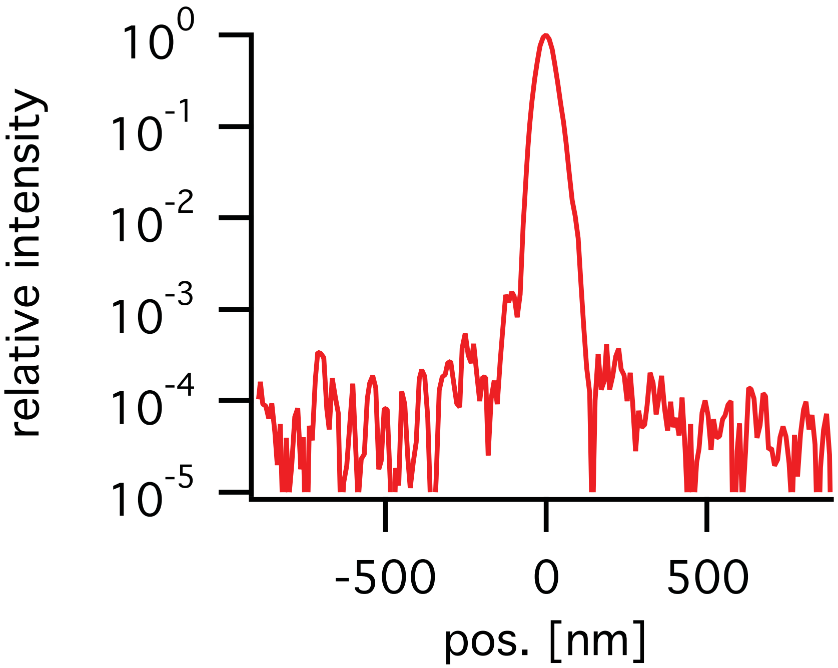
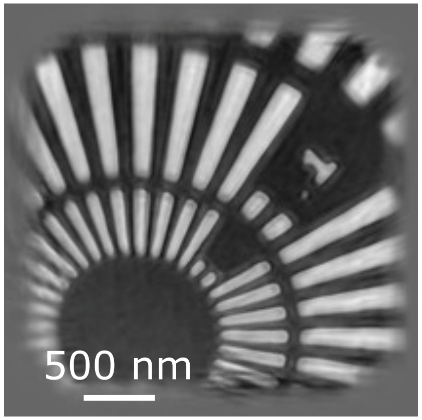
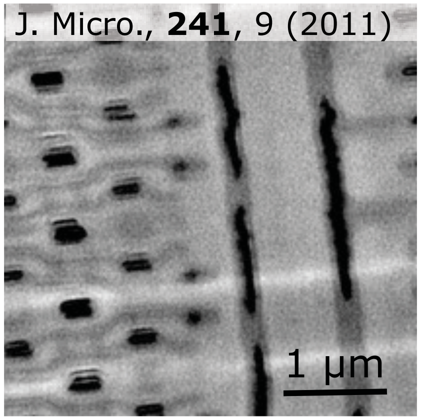


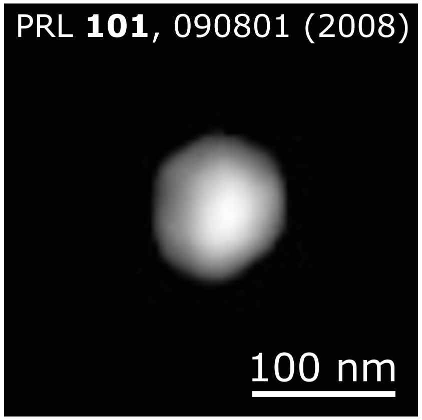


Schroer et al., Proc. XRM 2010

Compare Resolution and Dose Density

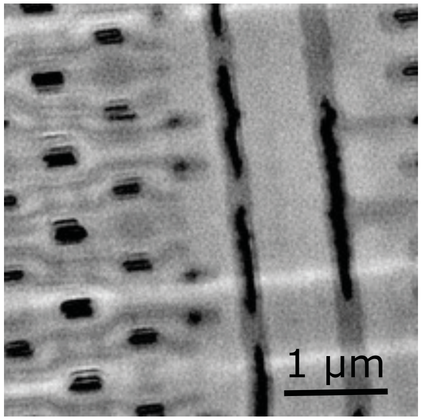



J. Micro., **241**, 9 (2011)


PRL **101**, 090801 (2008)

	siemens star ptychography	microchip ptychography	gold particle CXDI
dose density [ph/nm^2]	100000	800	1500000
measured resolution	10 nm	40 nm	5 nm
dose density ratio	1:15	1:1875	1:1
expected resolution ratio	$1 : \sqrt[4]{15} \approx 1 : 1.96$	$1 : \sqrt[4]{1875} \approx 1 : 6.6$	1:1
expected resolution	$\approx 10\ \mathrm{nm}$	$\approx 33\ \mathrm{nm}$	5 nm

Current Results and Optimized Experiment at ERL



$$I_\mathrm{c}\Delta t \propto Br \cdot NA^2 \cdot T \cdot \Delta t$$

Match coherence with aperture of optic:

- increase in flux: > 20 x

ERL: increase brilliance by about 500 x

- increase in flux: ~ 500 x

Optic: diamond NFL

- increase transmission: >10 x
- increase NA: ~3 x

Imaging radiation hard object:

$$I_{\mathrm{c}_\mathrm{ideal}}\Delta t \approx 20 \times 500 \times 10 \times \cdot I_{\mathrm{c}_\mathrm{today}}\Delta t \approx 10^6 \cdot I_{\mathrm{c}_\mathrm{today}}\Delta t$$

→ gain about 1.5 orders of magnitude in resolution

→ ~ 0.3 nm resolution (NTT test pattern), ~ 1 nm for C based object