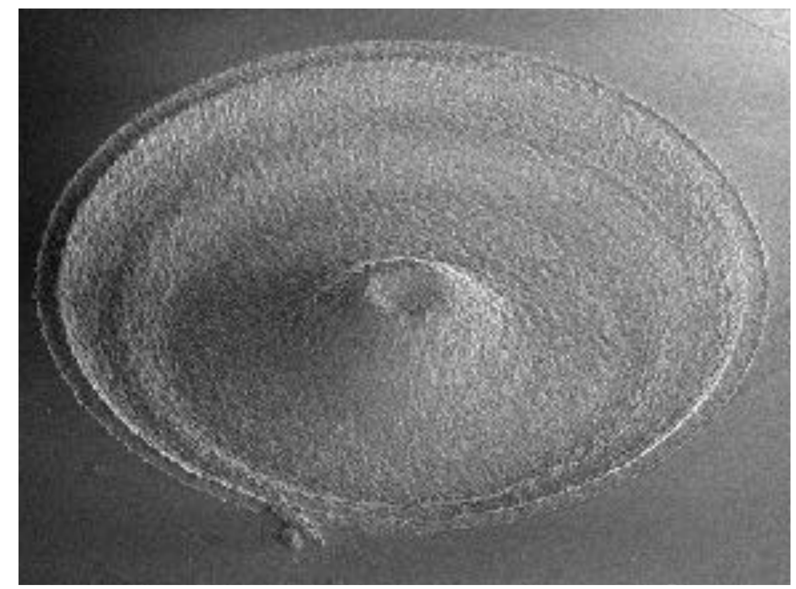
Diffraction-Limited Nano-Focusing with Refractive X-Ray Optics

PHANGS-Workshop 2017



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

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HELMHOLTZ
RESEARCH FOR GRAND CHALLENGES

DESY

X-Ray Nanoscience and X-Ray Optics

Prof. Dr. Christian G. Schroer (DESY and Universität Hamburg)

Dr. Gerald Falkenberg (DESY - P06 beamline responsible)

S. Alizadehfanaloo, S. Botta, D. Brückner, J. Bulda, R. Döhrmann, J. Garrevoet, L. Grote, R. Hoppe, M. Kahnt, H. Lindemann, M. Lyubomirskiy, M. Scholz, A. Schropp, W. Schröder, F. Seiboth, M. Seyrich, K. Spiers, F. Wittwer, X. Yang, Y. Zhang

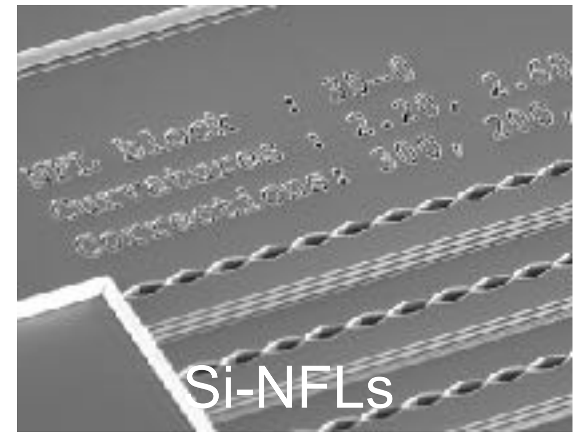
Scanning coherent X-ray micoscopy, using fluorescence (XRF), diffraction (SAXS, WAXS), absorption (XAS) and ptychographic (CXDI) contrast.

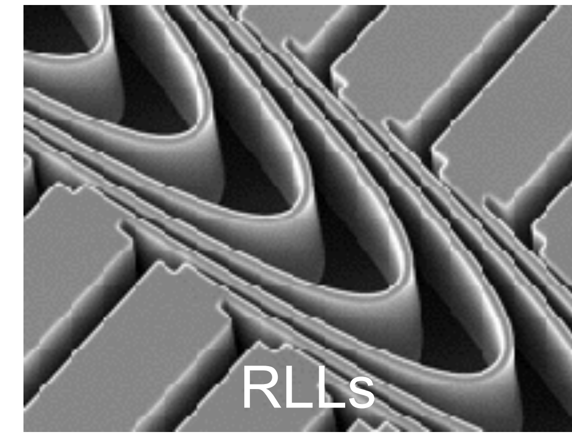
PETRA III (DESY, Hamburg)

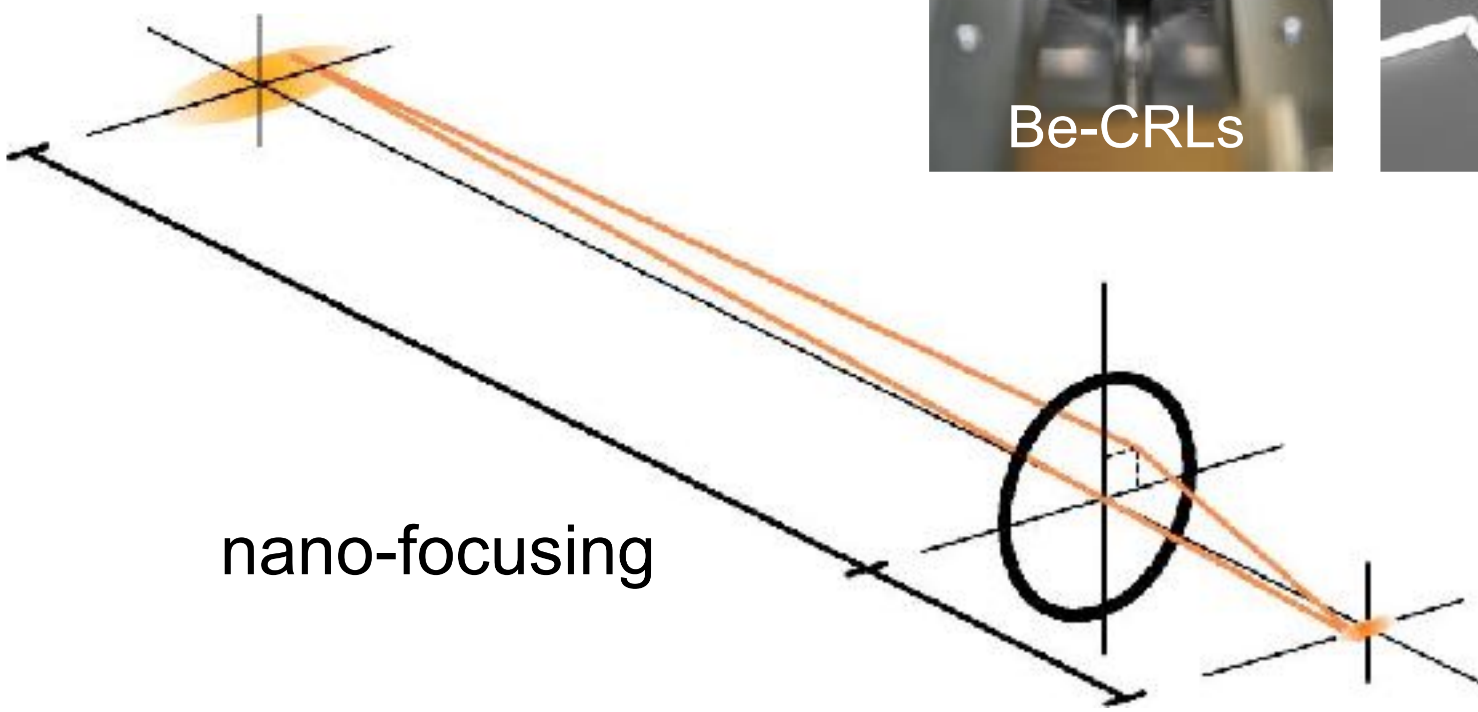
ESRF (Grenoble)

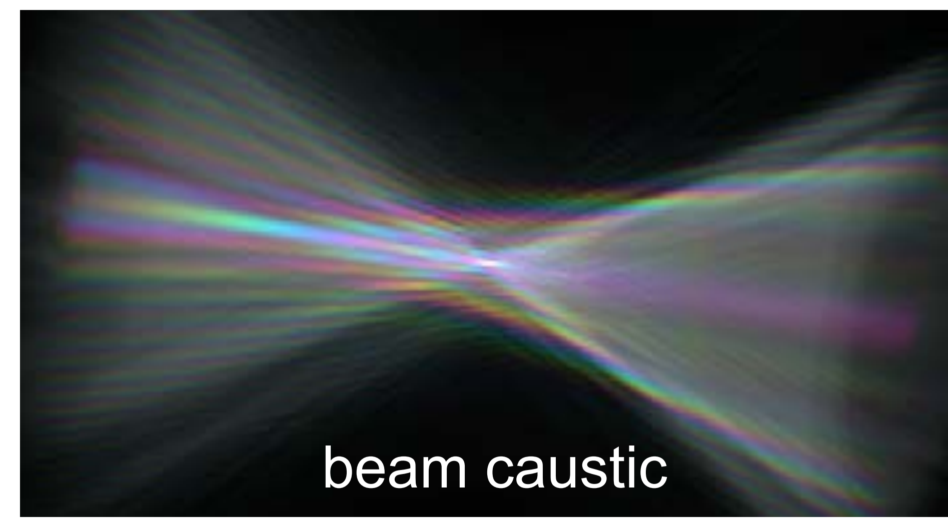
LCLS (SLAC, Menlo Park)

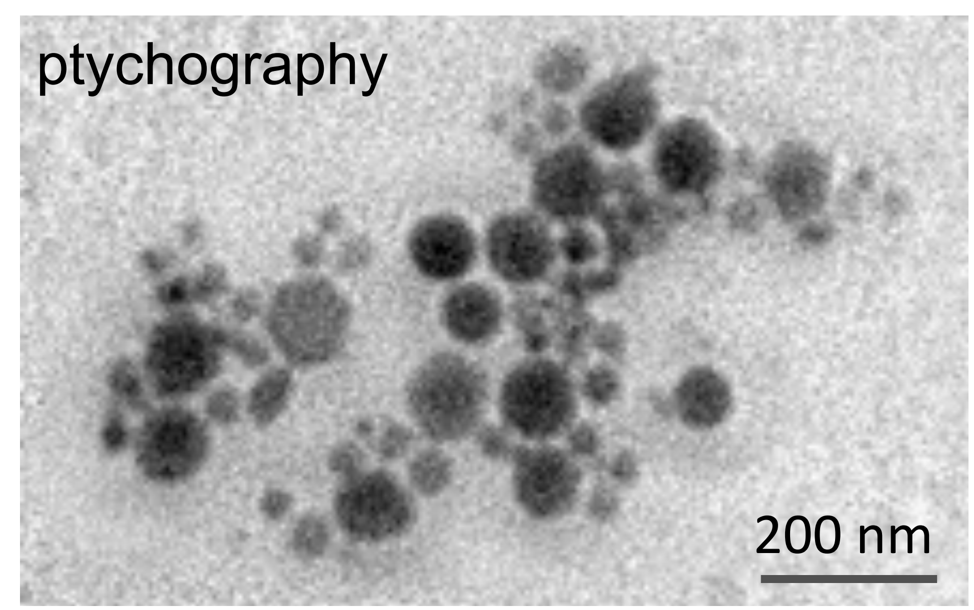
Overview









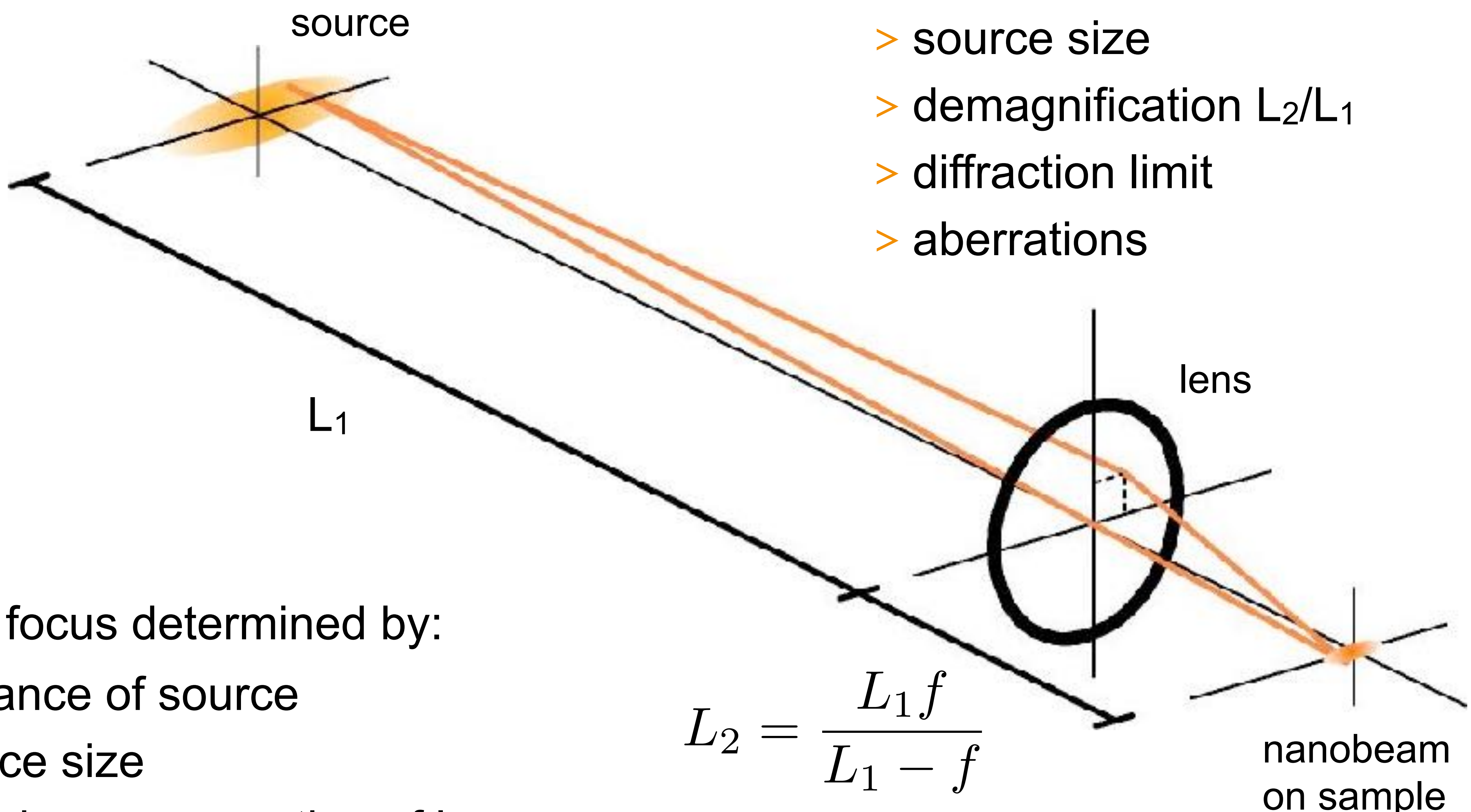


- X-ray optics
- X-ray nanobeam characterization
- New nanoprobe setup at beamline P06: **PtyNAMi**
- Scanning coherent X-ray microscopy (pytchography)

Generating Hard X-Ray Nanobeams

Focus size and shape determined by:

- > source size
- > demagnification L_2/L_1
- > diffraction limit
- > aberrations



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

Flux in focus determined by:

- > brilliance of source
- > source size
- > focusing cross section of lens

X-Ray Optics

external total reflection

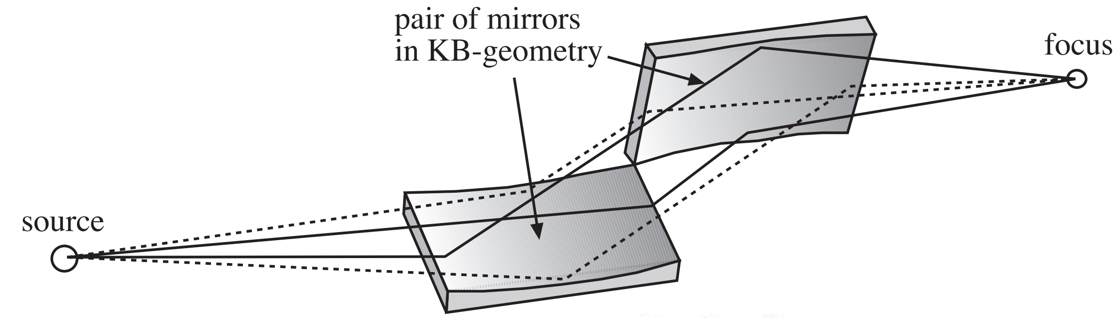
> mirrors (25 nm)

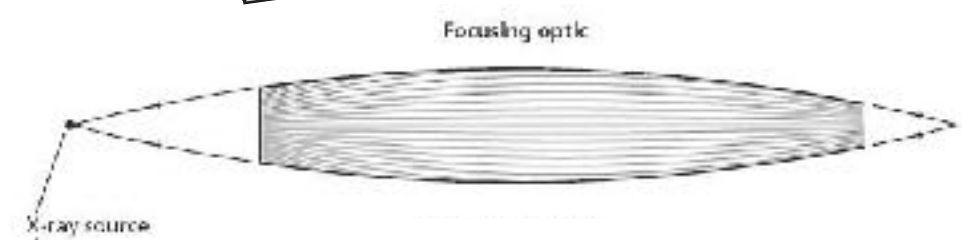
H. Mimura, *et al.*, APL **90**, 051903 (2007)

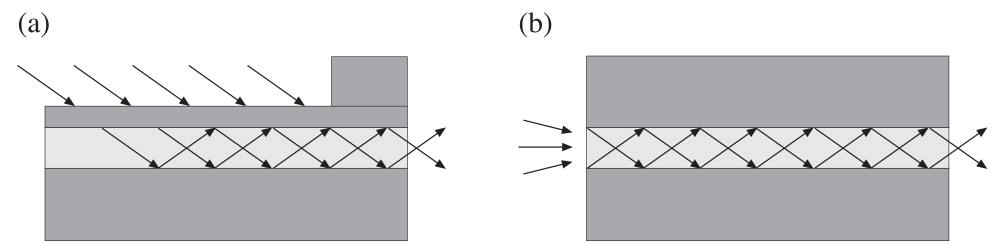
> capillaries

> waveguides (≈ 10 nm)

S. P. Krüger, *et al.*, J. Synchrotron Rad. **19**, 227 (2012)







diffraction

> Fresnel zone plate (< 10 nm)

J. Vila-Comamala, *et al.*, Ultramic. **109**, 1360 (2009)

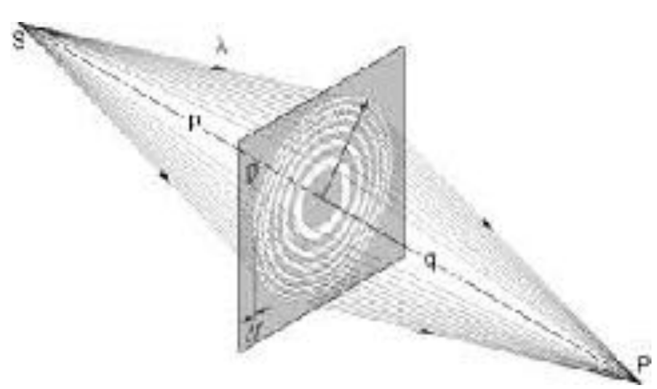
> multilayer mirror (7 nm)

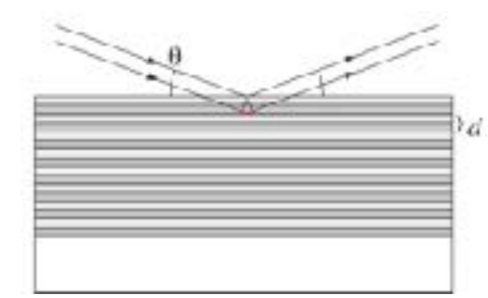
H. Mimura, *et al.*, Nat. Phys. **6**, 122 (2010)

> multilayer Laue lenses (8 nm)

A. Morgan, *et al.*, Sci. Rep. **5**, 09892 (2015)

> bent crystal



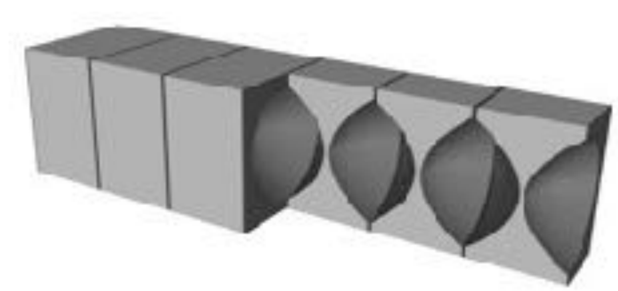


refraction

> refractive lenses (43 nm, 18 nm)

C. G. Schroer, *et al.*, AIP Conf. Ser. **1365**, 227 (2011)

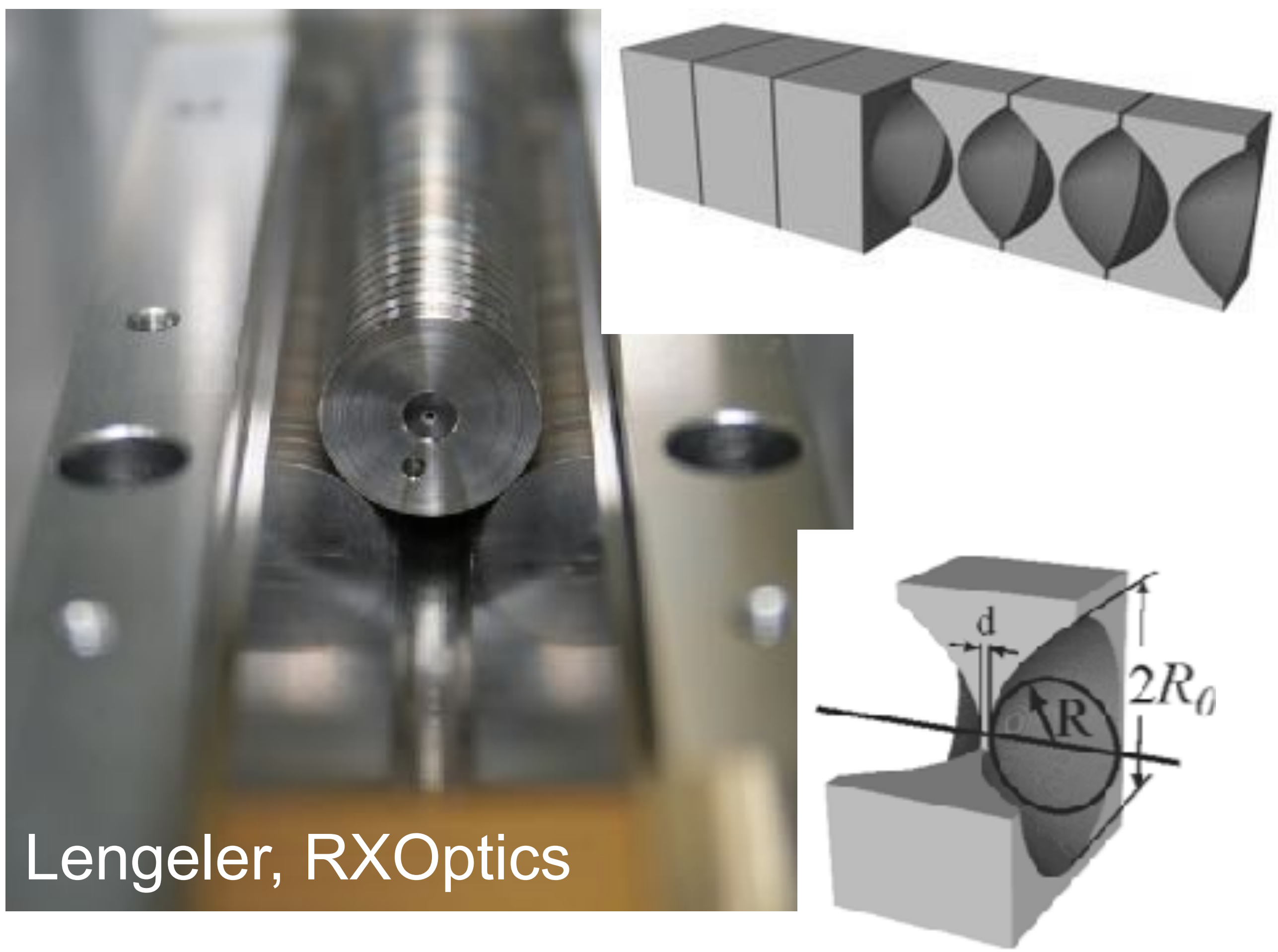
J. Patommel, *et al.*, APL **110**, 101103 (2017)



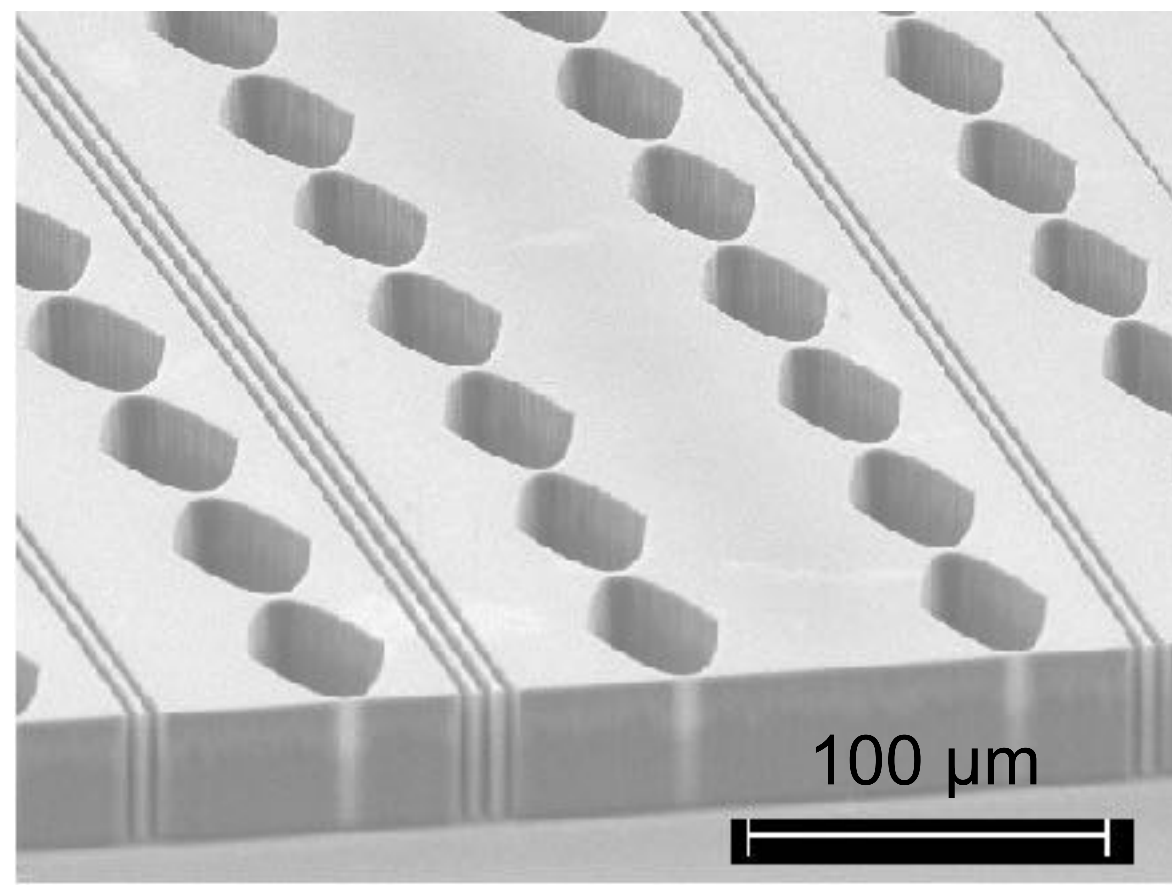
Beryllium Compound Refractive X-Ray Lenses

- first realized in 1996 (Snigirev, *et al.*)
- various new developments exist today
- applied in full-field imaging and scanning microscopy
- most important to achieve optimal performance: parabolic lens shape

Beryllium compound refractive lenses (Be-CRLs)

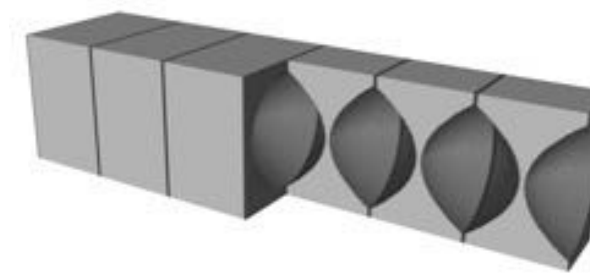


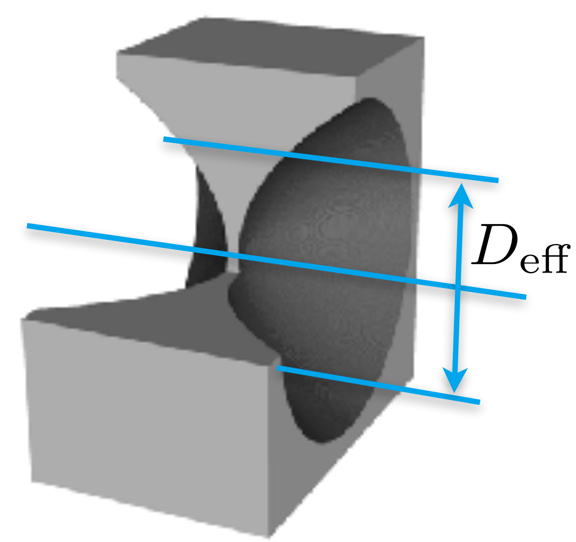
Silicon-nanofocusing lenses (NFLs)



Be CRLs — Parameters

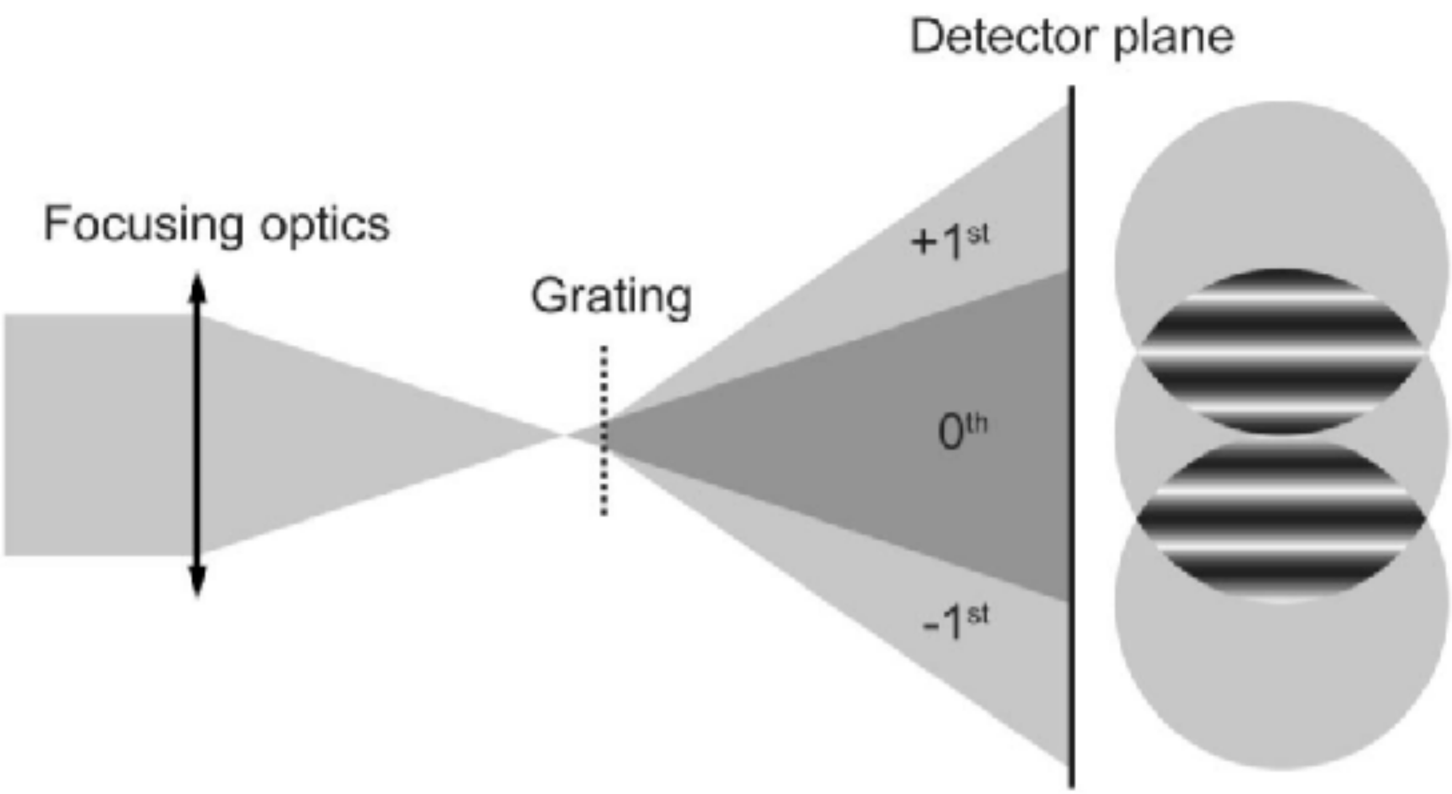
E [keV]	f [mm]	N	NA [mrad]	d_t [nm]	wd [mm]	T_p [%]	gain
	100	52	0.91	64	71	15	$3.1 \cdot 10^6$
8.0	200	24	0.58	100	187	35	$2.9 \cdot 10^6$
	300	16	0.42	137	288	47	$2.1 \cdot 10^6$
	400	12	0.33	174	388	56	$1.5 \cdot 10^6$
	200	56	0.59	65	168	37	$6.4 \cdot 10^6$
12.0	300	36	0.43	91	281	51	$4.5 \cdot 10^6$
	400	27	0.34	116	383	59	$3.2 \cdot 10^6$
	200	138	0.55	48	119	27	$7.8 \cdot 10^6$
18.0	300	84	0.41	63	252	42	$6.3 \cdot 10^6$
	400	61	0.32	80	368	52	$4.7 \cdot 10^6$
	300	173	0.37	51	202	28	$5.4 \cdot 10^6$
25.0	400	122	0.30	62	331	38	$4.6 \cdot 10^6$
	500	95	0.25	75	449	46	$3.7 \cdot 10^6$

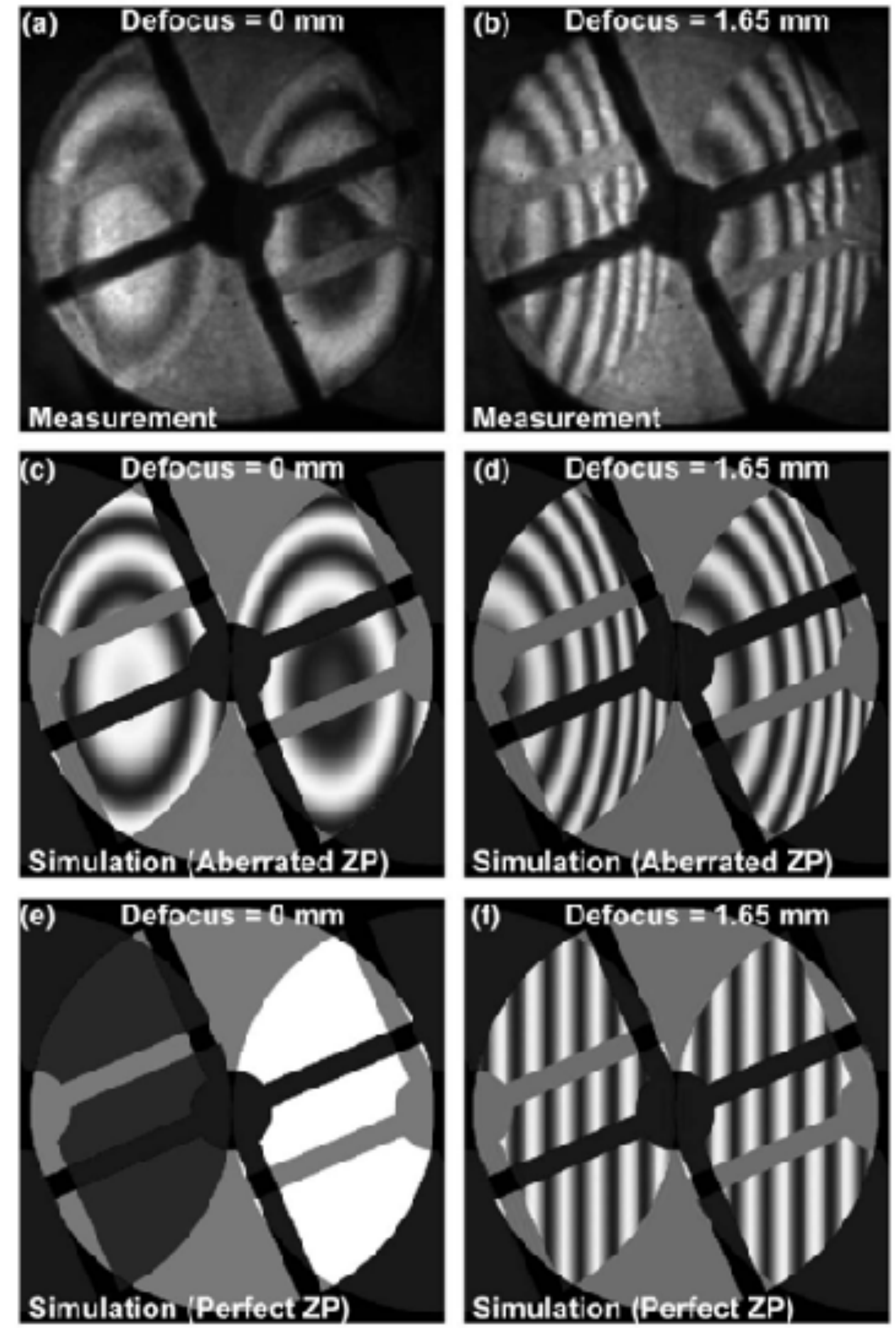




diffraction limited focal focus with a size
of about 100nm (FWHM)

Nanobeam Characterization by Ronchi-Interferometry

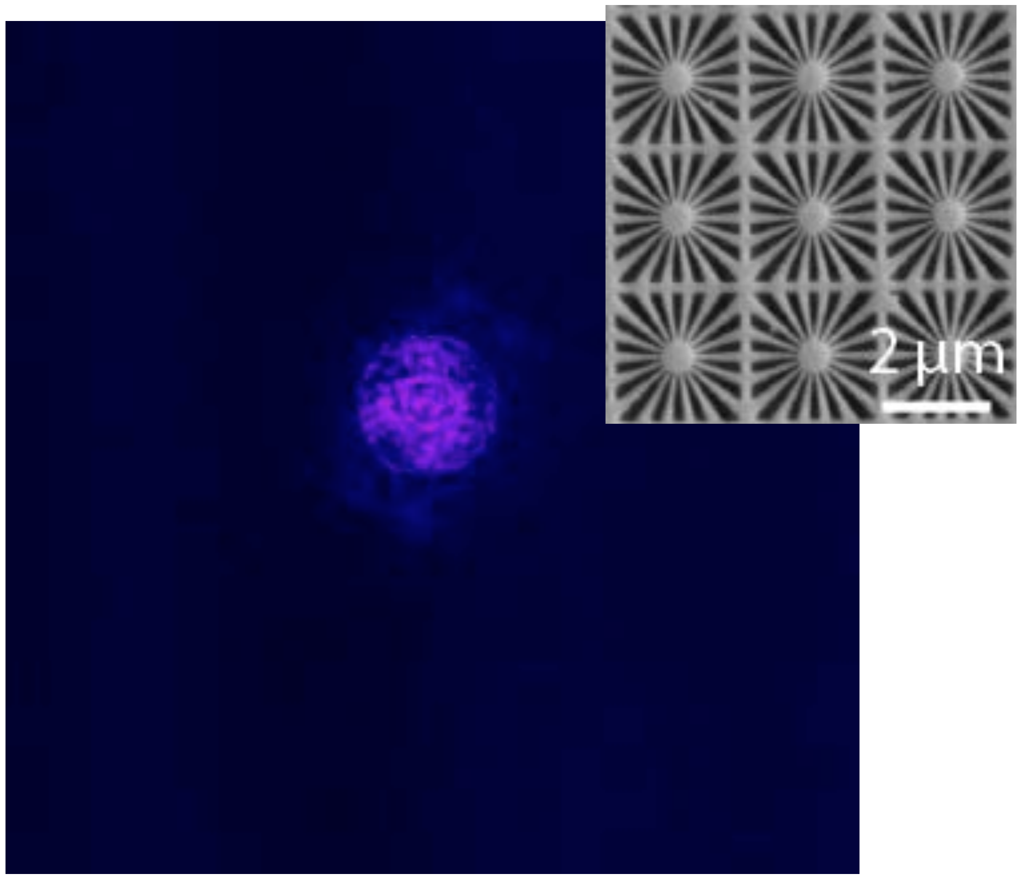




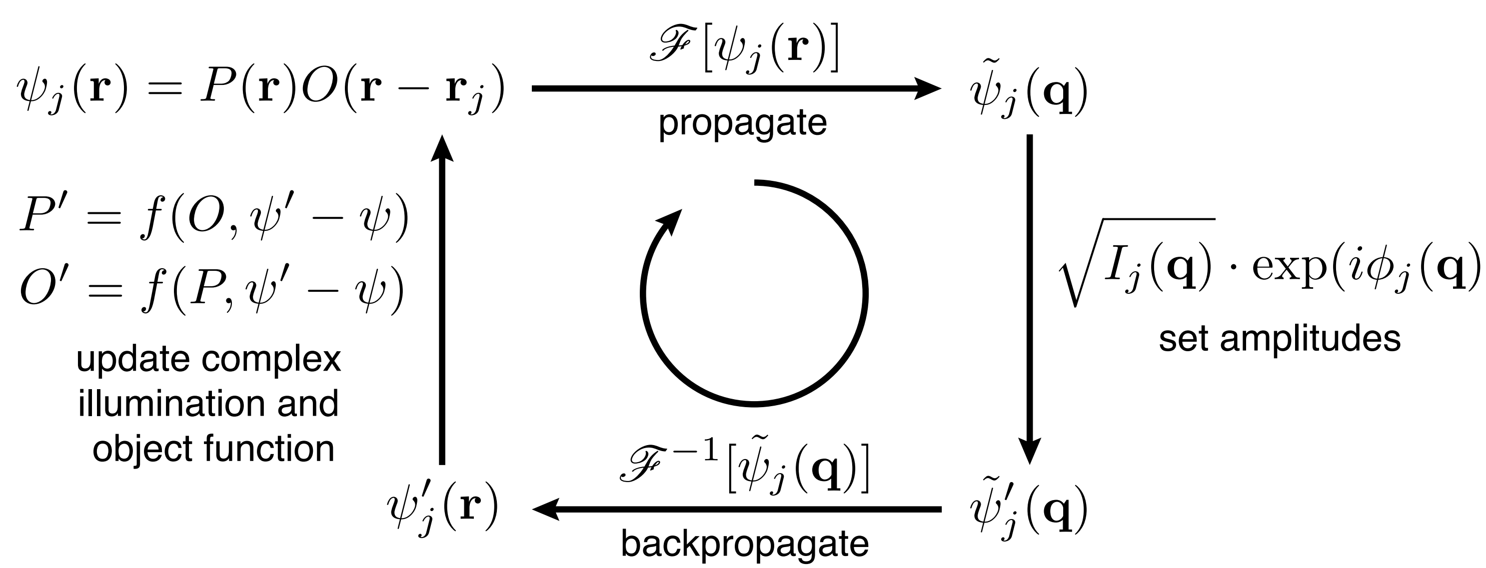
V. Ronchi, "Forty Years of History of a Grating Interferometer", Applied Optics 3, 437 (1964)

D. Nilsson, et al., "Ronchi test for characterization of nanofocusing optics at a hard x-ray free-electron laser", Optics Letters 37, 5046 (2012)

Nanobeam Characterization by Ptychography



diffraction patterns measured
on a nano-structured sample



iterative phase retrieval algorithm

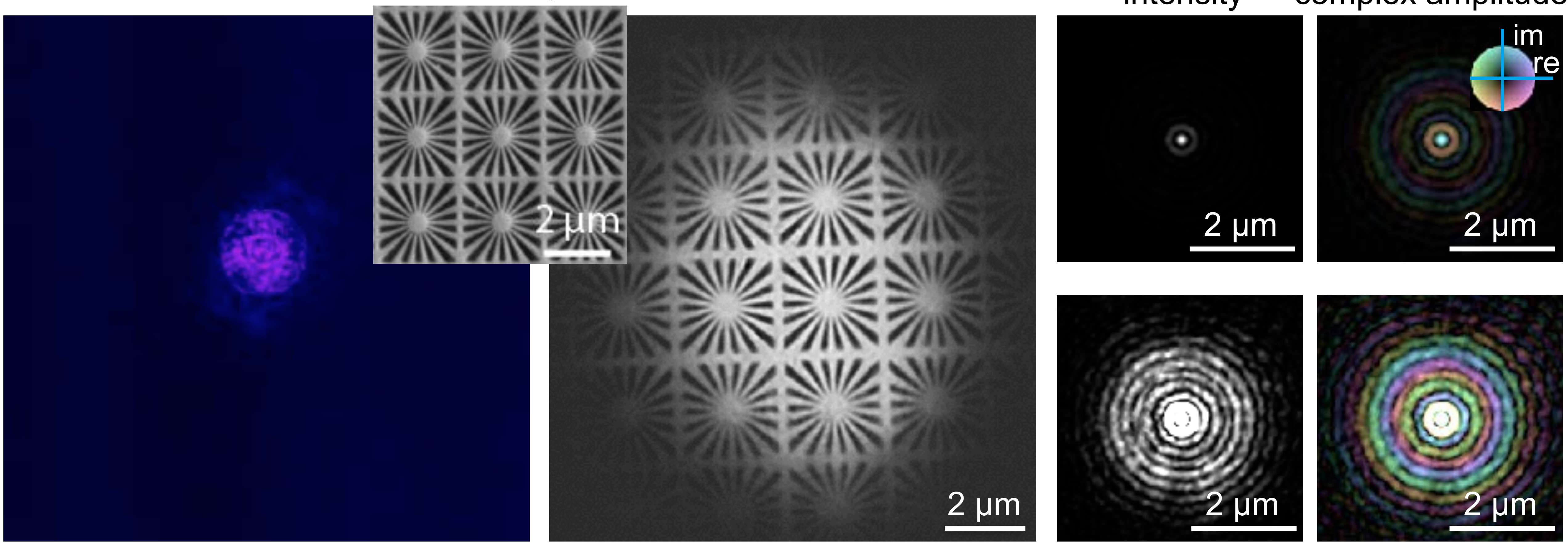
- 125 nm (FWHM) central peak
- spherical aberration present, producing a series of side maxima
- important information required to improve the optics

Schropp, A. et al., Full spatial characterization of a nanofocused x-ray free-electron laser beam by ptychographic imaging, Sci. Rep. 3, 1633 (2013)

Nanobeam Characterization by Ptychography

SEM-image

intensity complex amplitude



diffraction patterns measured on a nano-structured sample

numerically retrieved object

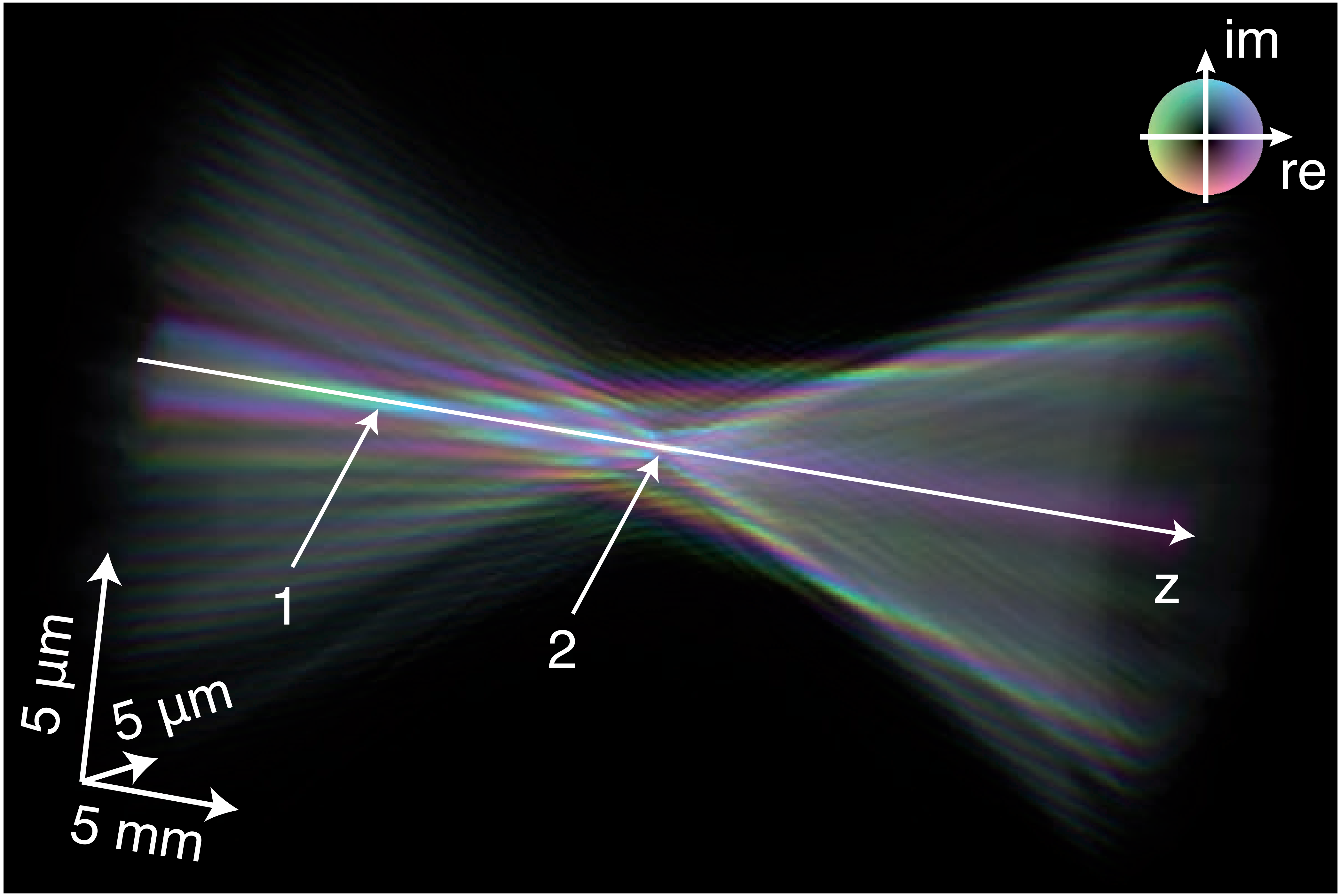
intensity complex amplitude

> 125 nm (FWHM) central peak
> spherical aberration present, producing a series of side maxima
> important information required to improve the optics

Schropp, A. et al., Full spatial characterization of a nanofocused x-ray free-electron laser beam by ptychographic imaging, Sci. Rep. 3, 1633 (2013)

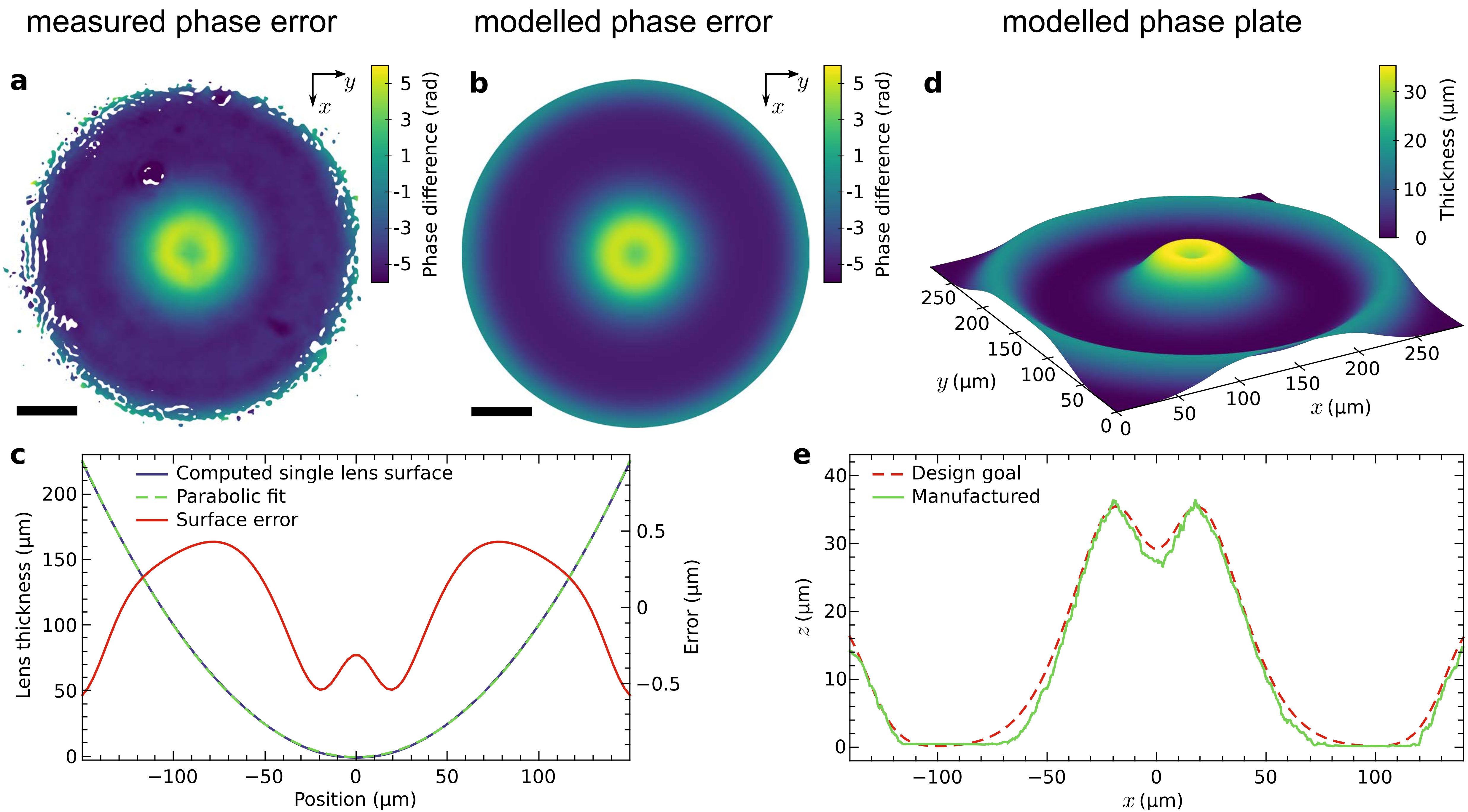
Nano-Focused Beamprofile

Paul-Peter-Ewald Fellowship (Volkswagenstiftung):
“Focusing X-ray free-electron laser beams for imaging and creating extreme conditions in matter”



A. Schropp, *et al.*, Sci. Rep. **3**, 1633 (2013).

Determination of Lens Shape and Errors

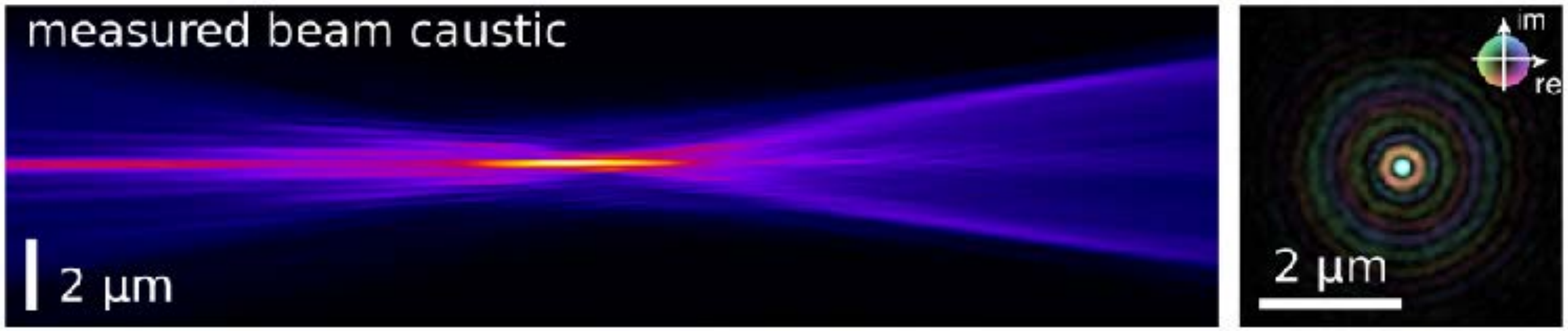


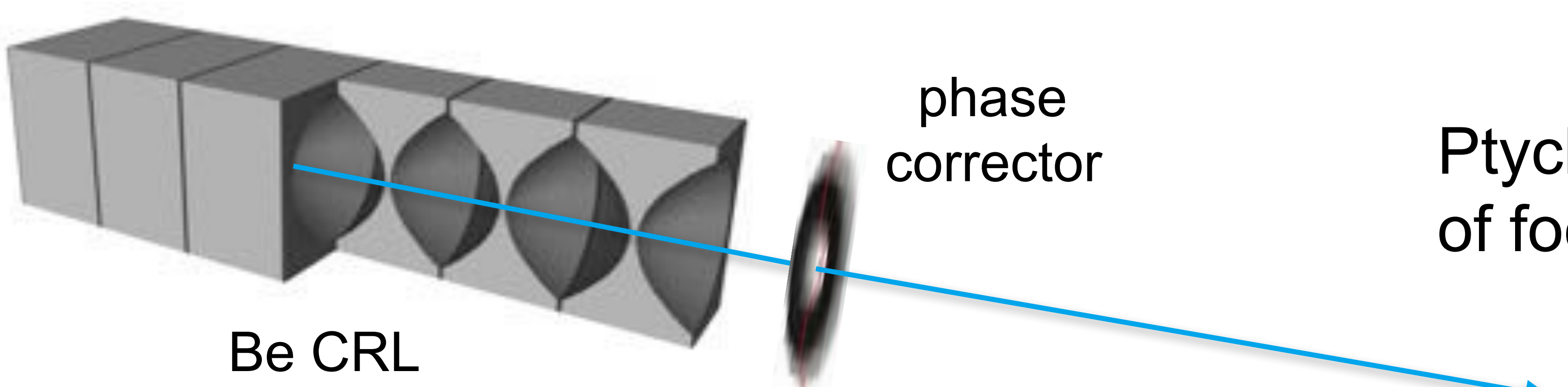
> Shape errors of single Be-CRLs are smaller than 500 nm! Very challenging to improve!

> Phase plate for whole stack of lenses is easier to fabricate.

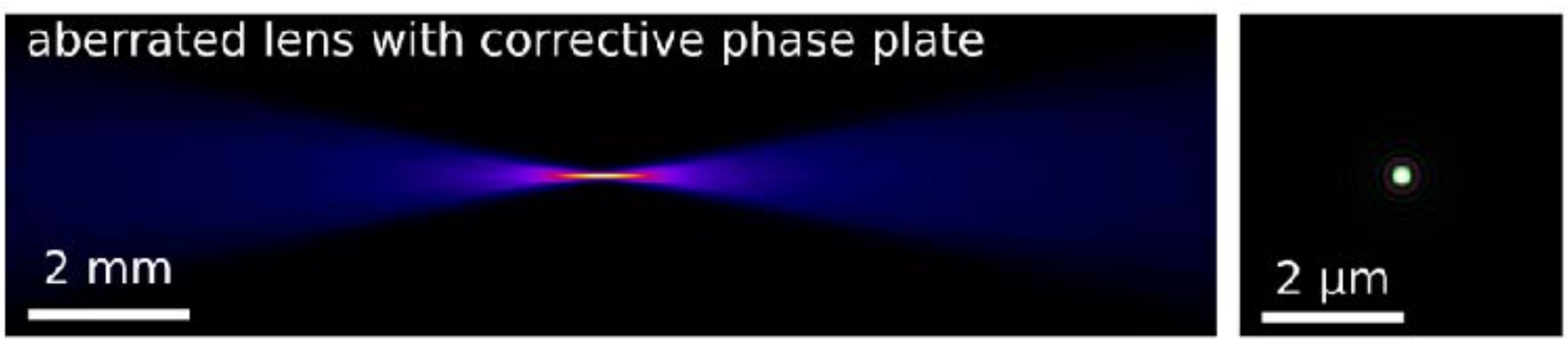
F. Seiboth, *et al.*, Nat. Commun. **8**, 14623 (2017).

Experimental Verification



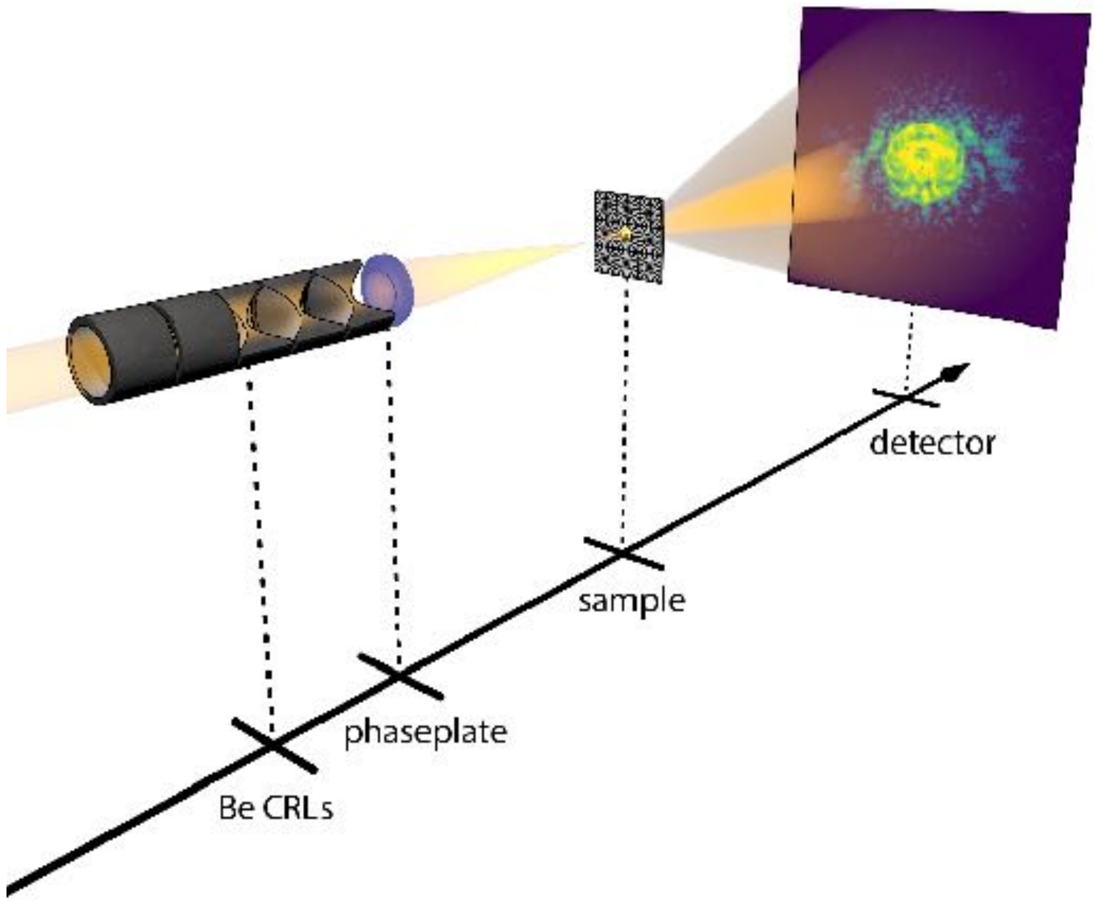


Ptychographic verification of focusing properties



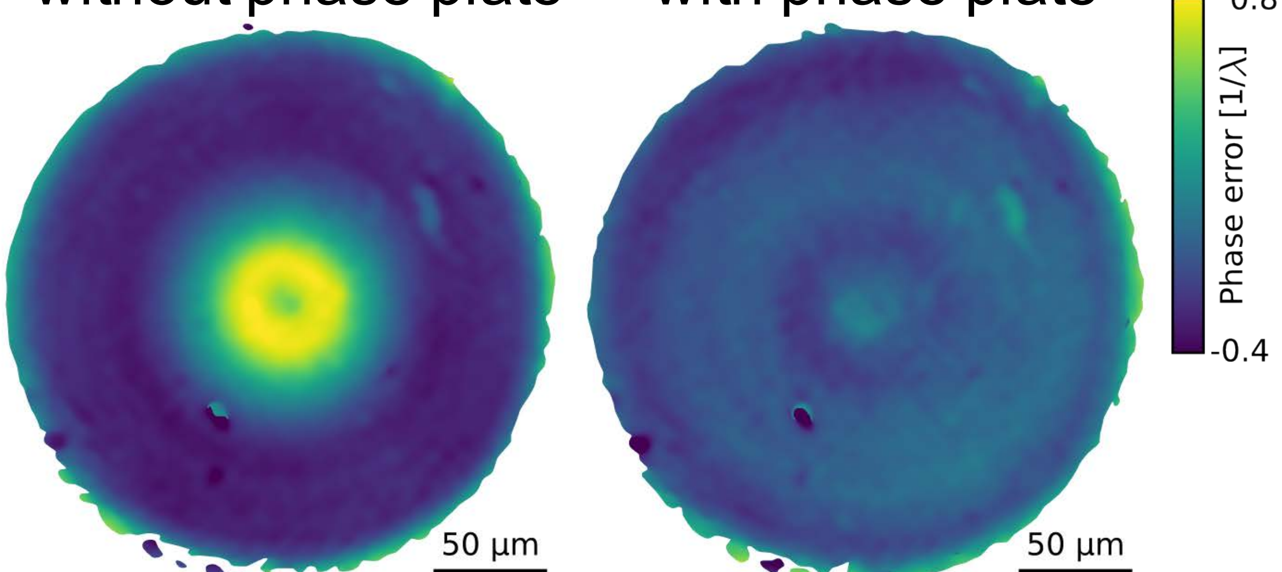
Aberrations: Quantification

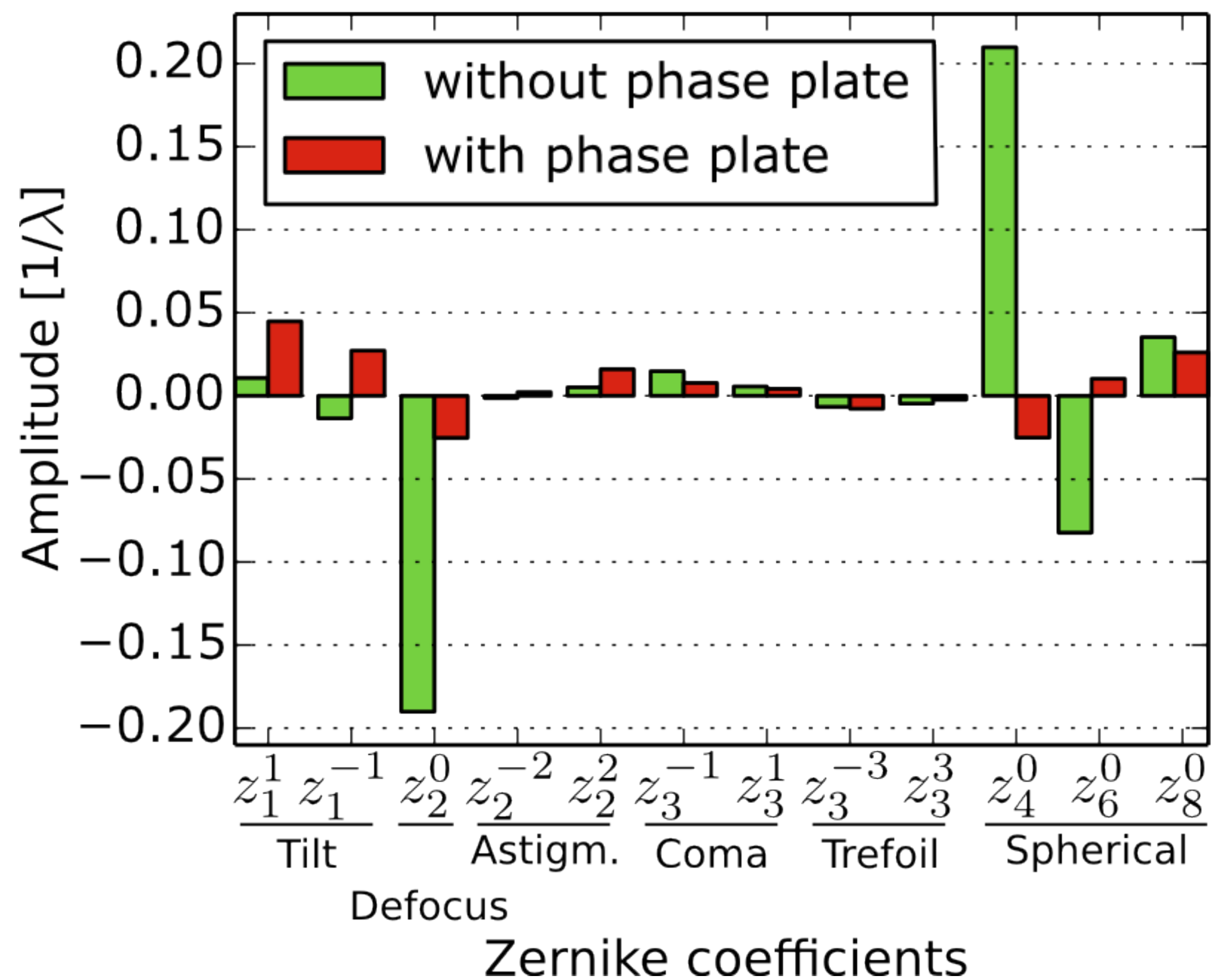
RMS wavefront error improves from 0.23λ to 0.06λ!



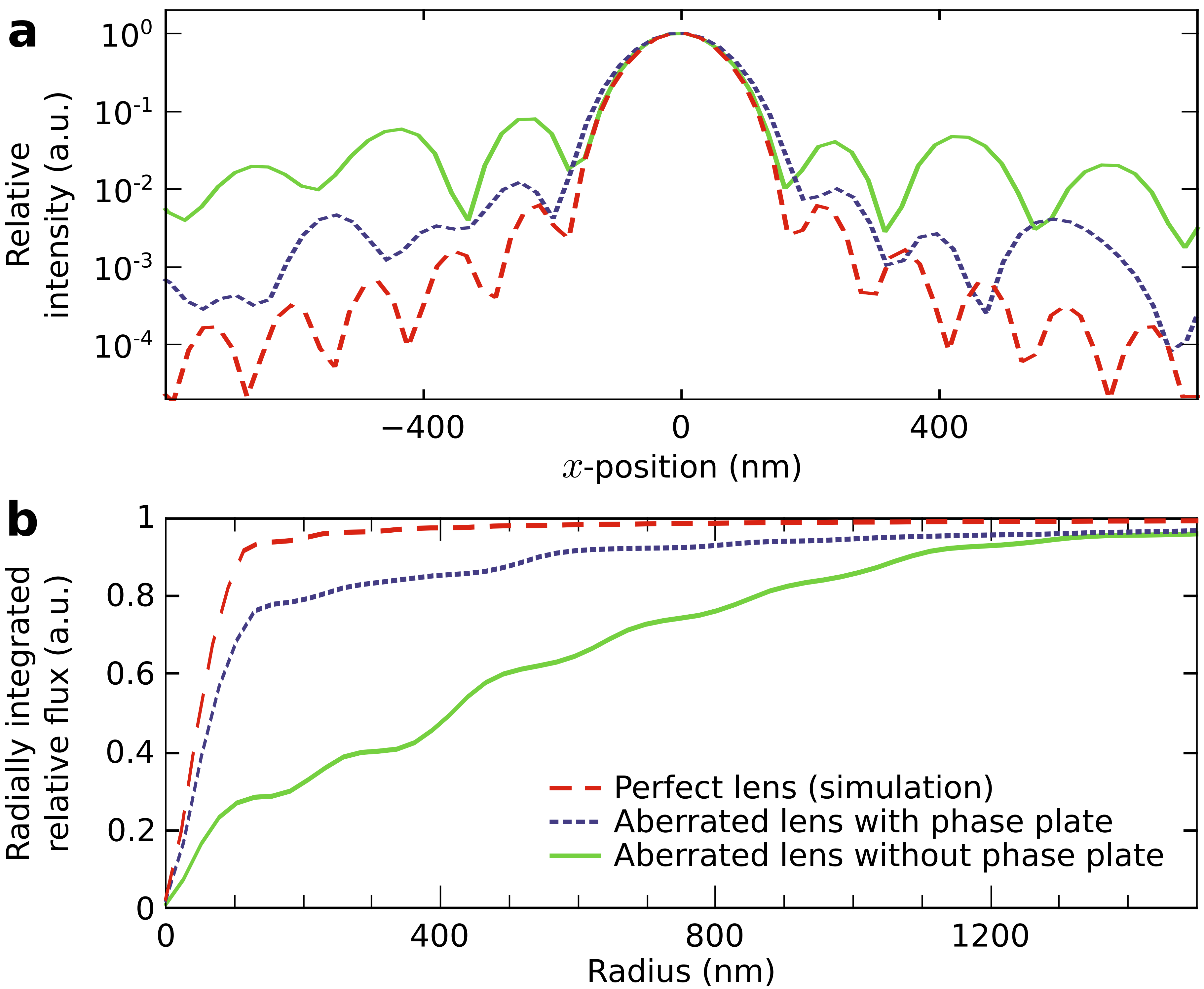
without phase plate

with phase plate





Diffraction-Limited Nano-Focusing



Lens with
Strehl ratio > 0.8!

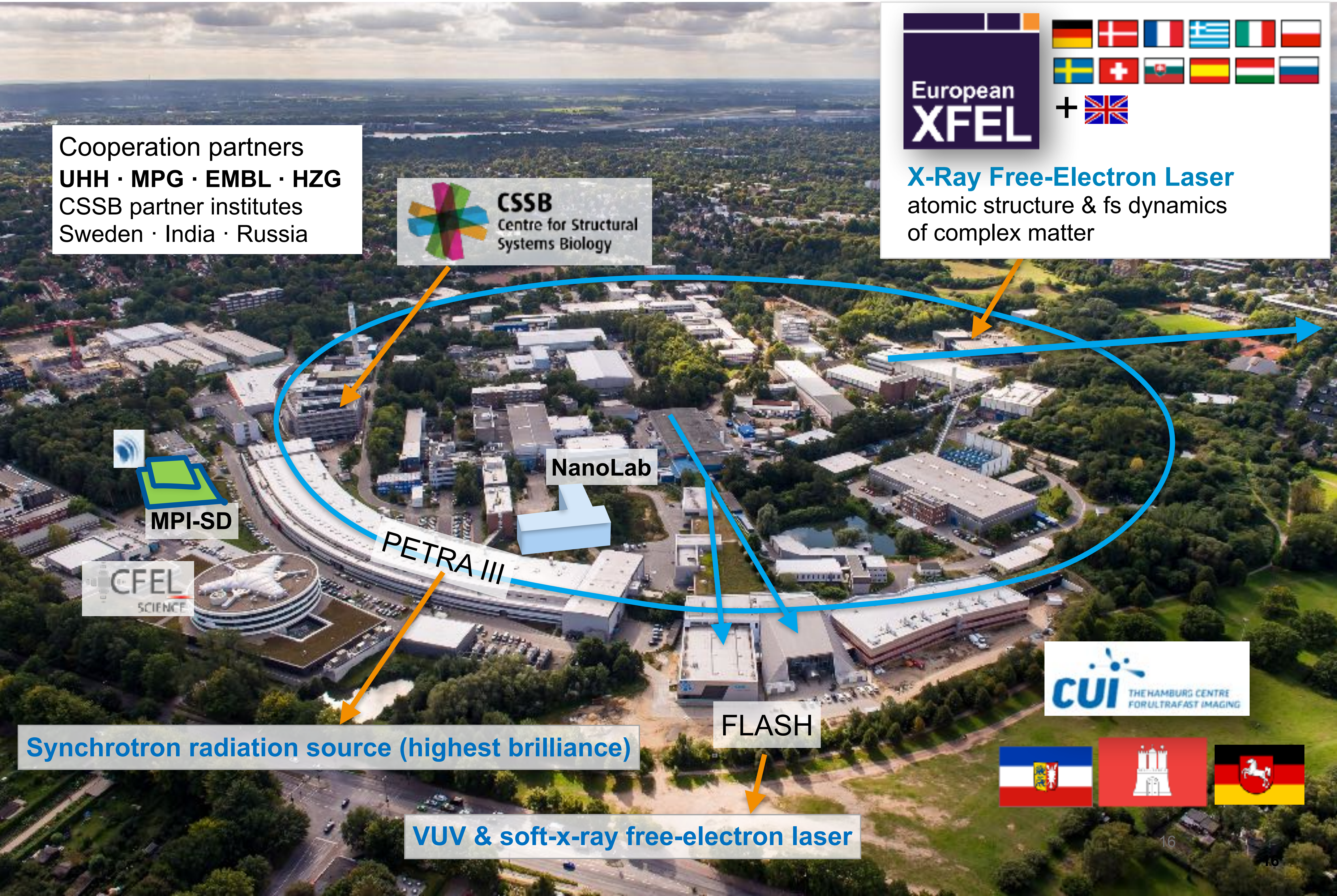
75 % of the radiation is concentrated in the central speckle!

↓

Focus full beam!

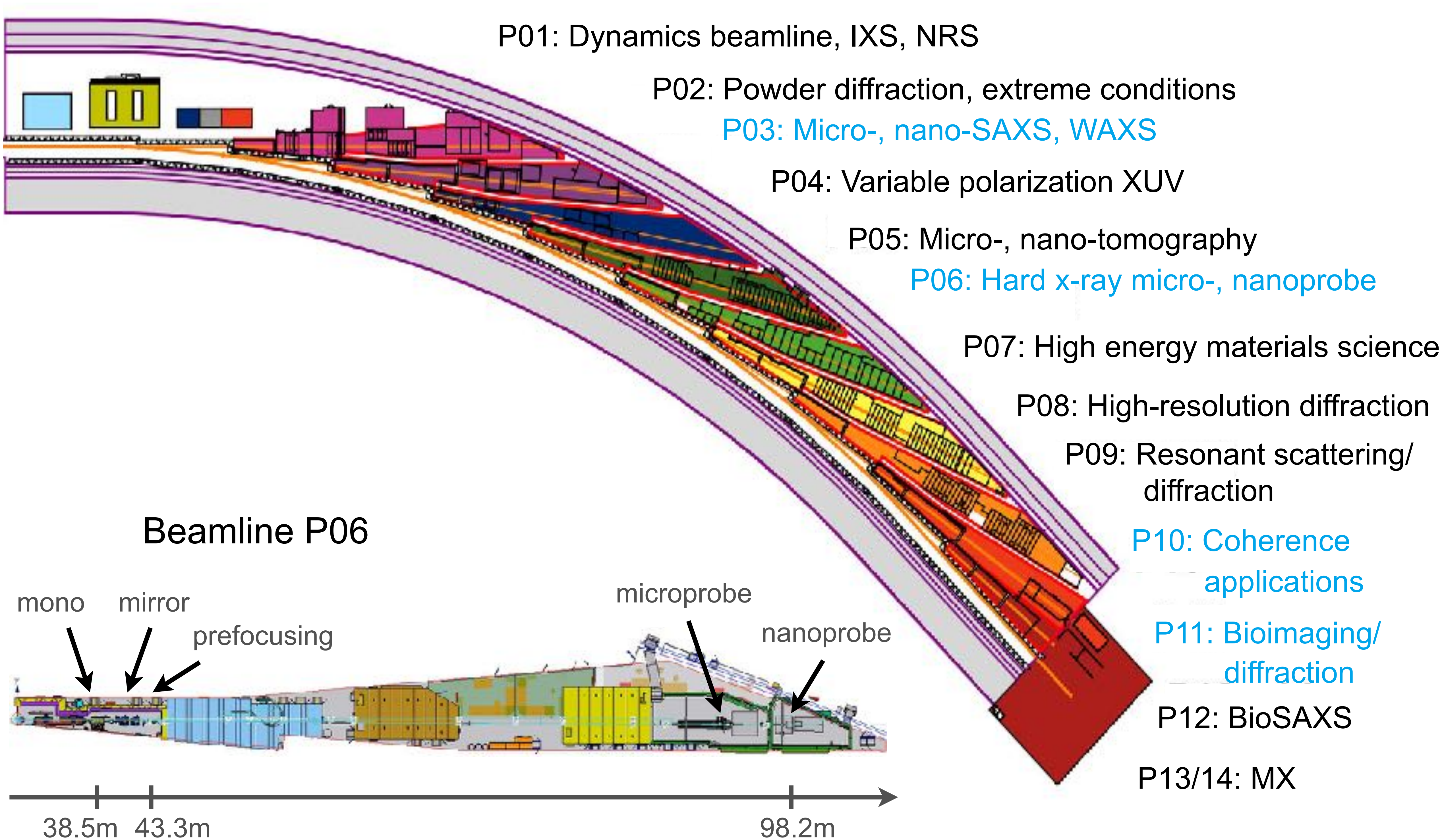
F. Seiboth, *et al.*, Nat. Commun. **8**, 14623 (2017).

DESY Campus Hamburg-Bahrenfeld

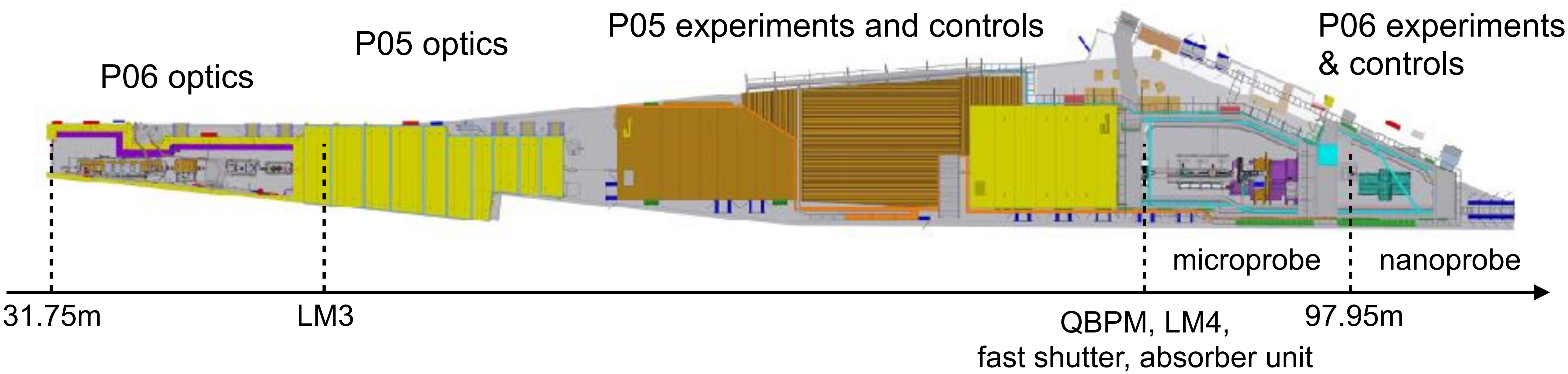


PETRA III — Max von Laue Hall

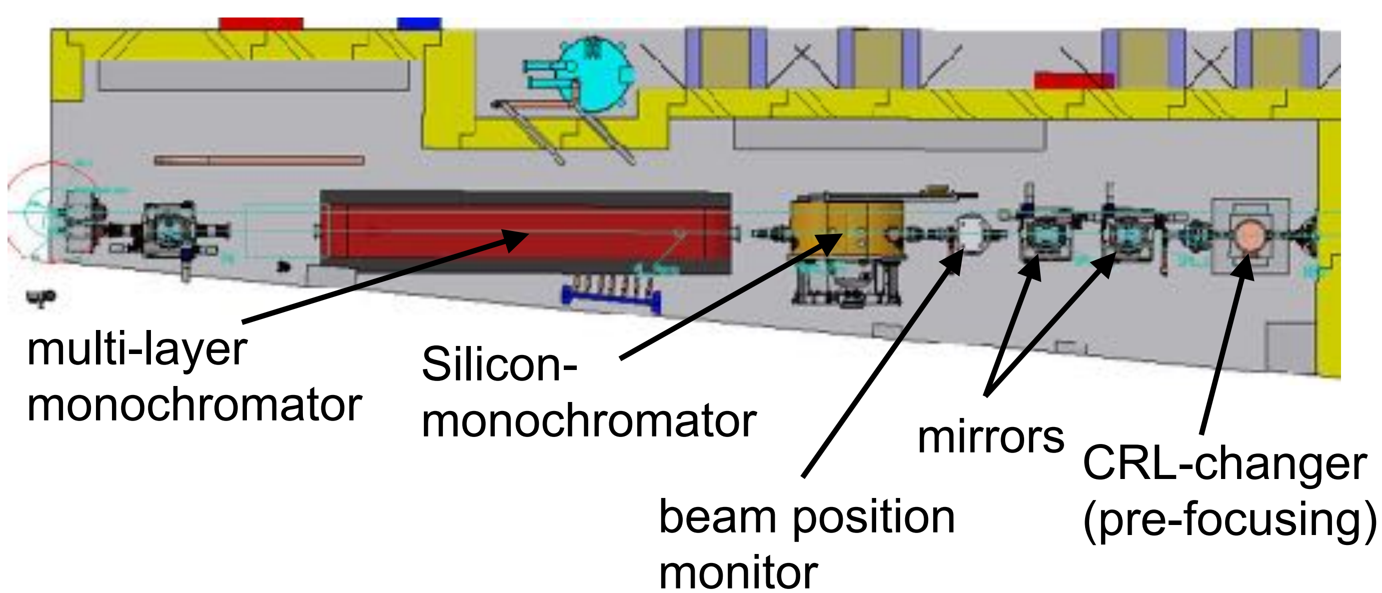
9 Sectors — 14 Beamlines

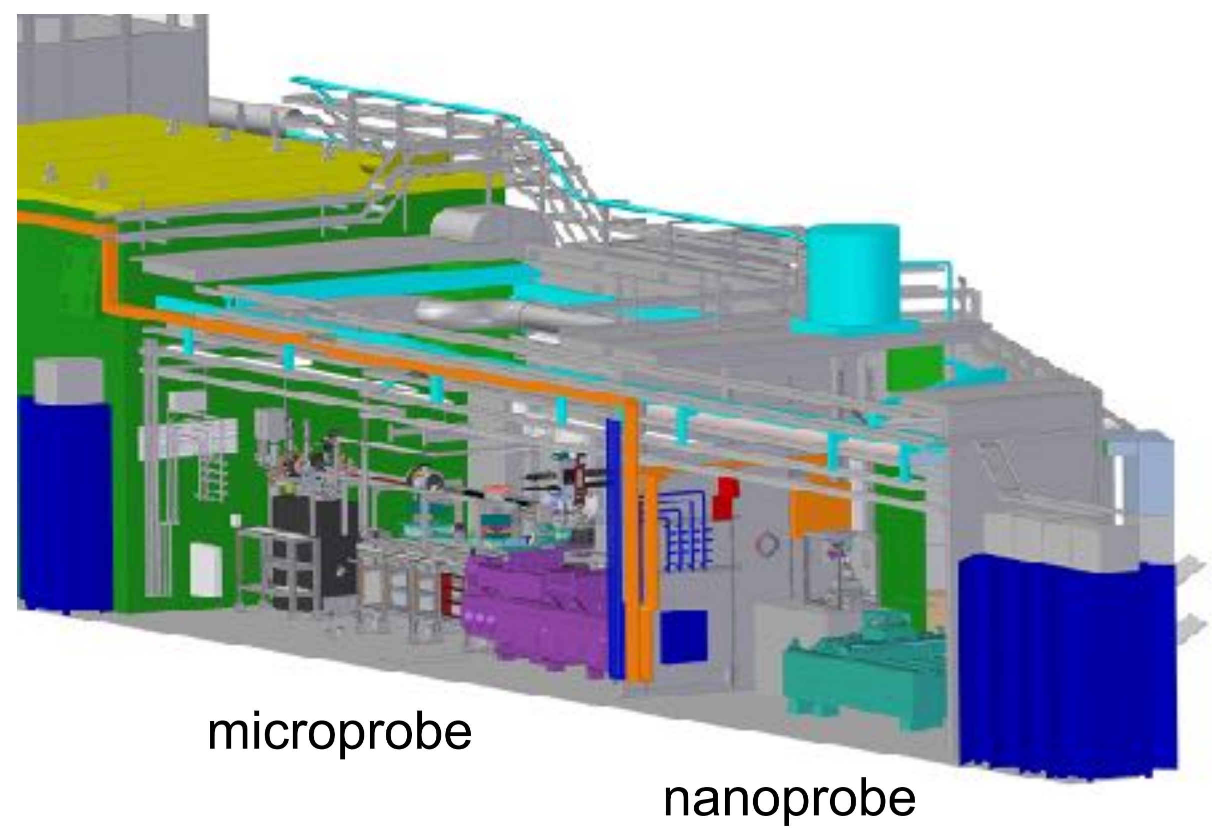


PETRA III — Beamline P06

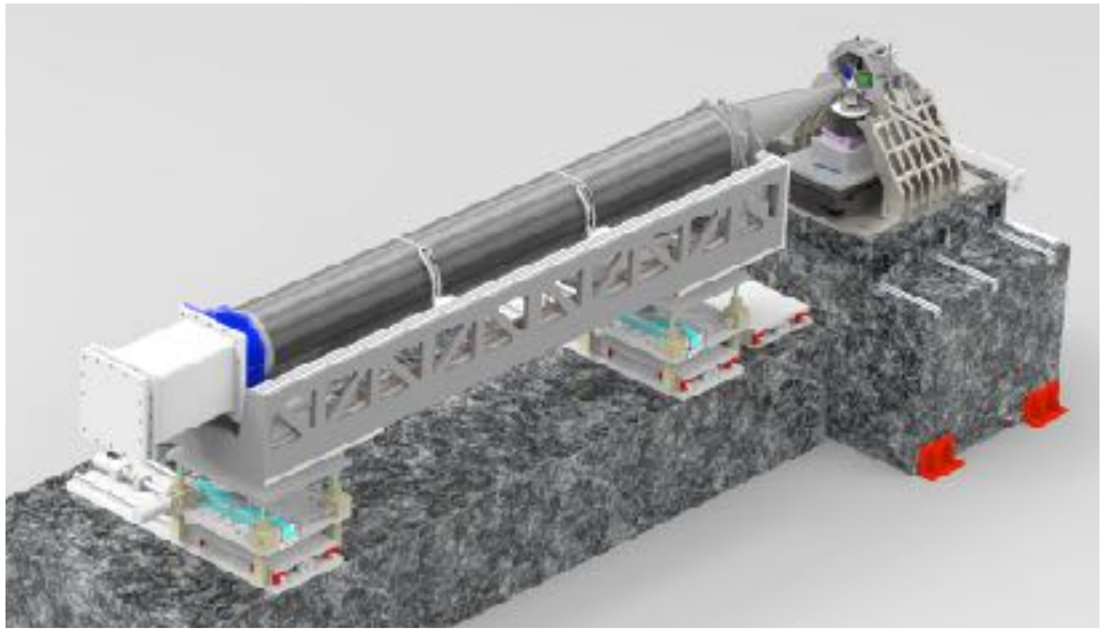


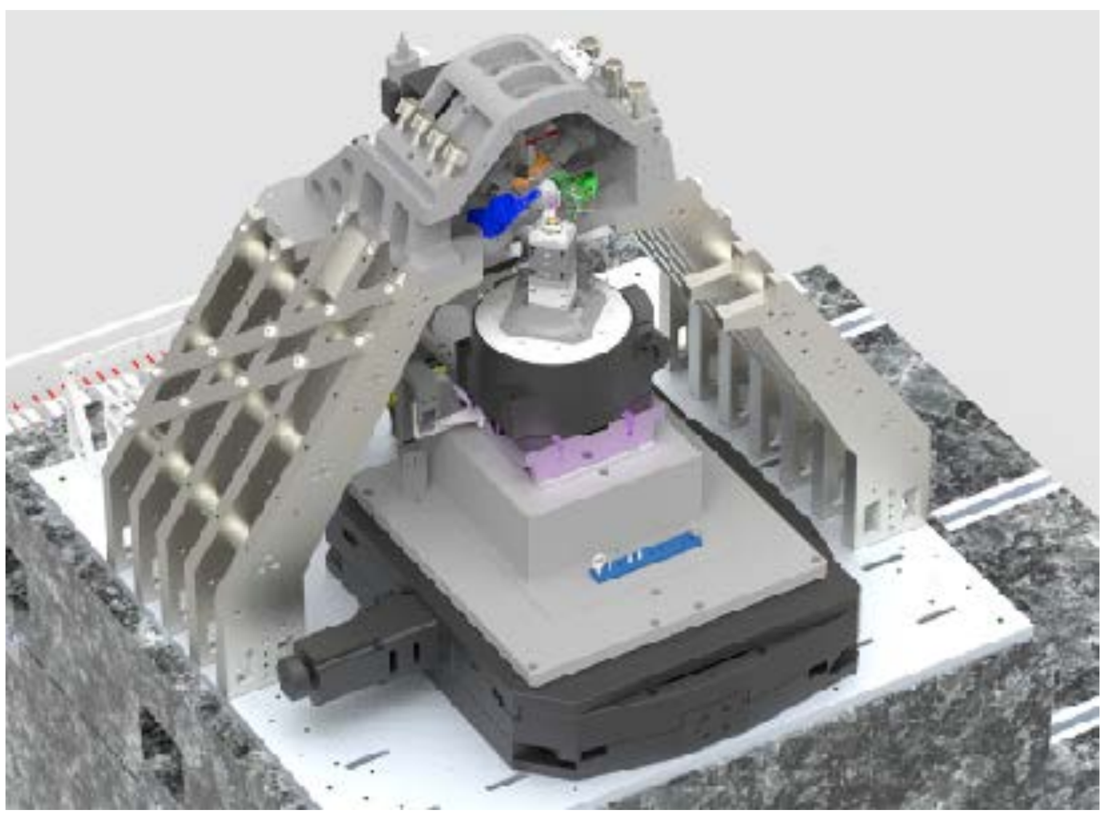
P06 optics hutch



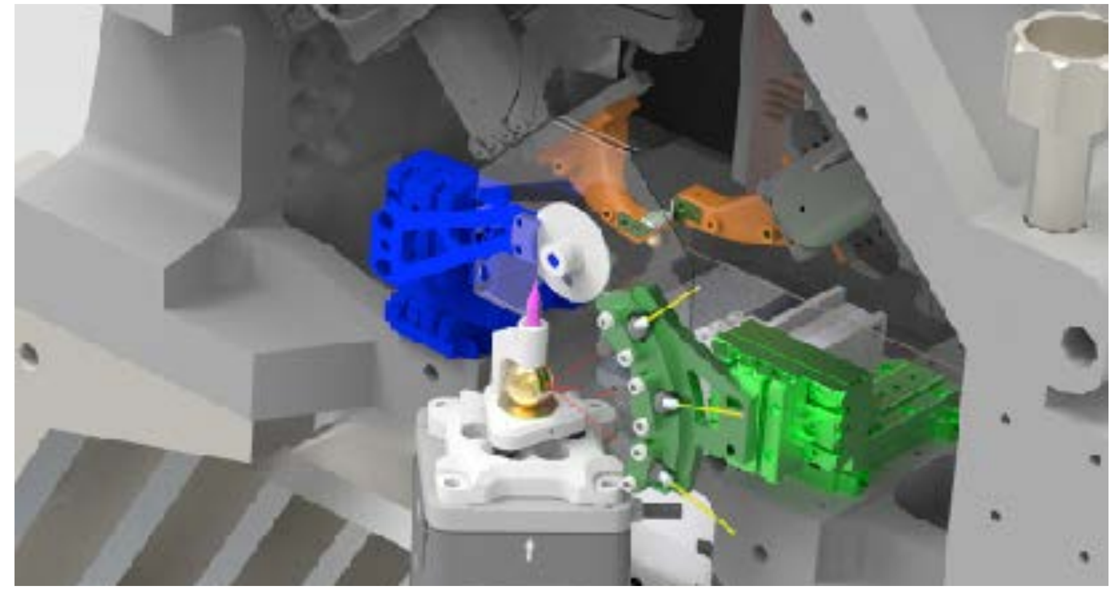


PtyNAMi: Ptychographic Nano-Analytical Microscope





R. Döhrmann, S. Botta, H. Lindemann *et al.*



Goals:

> high spatial resolution
> high sensitivity
> 2D and 3D imaging
> *in situ* & *operando*

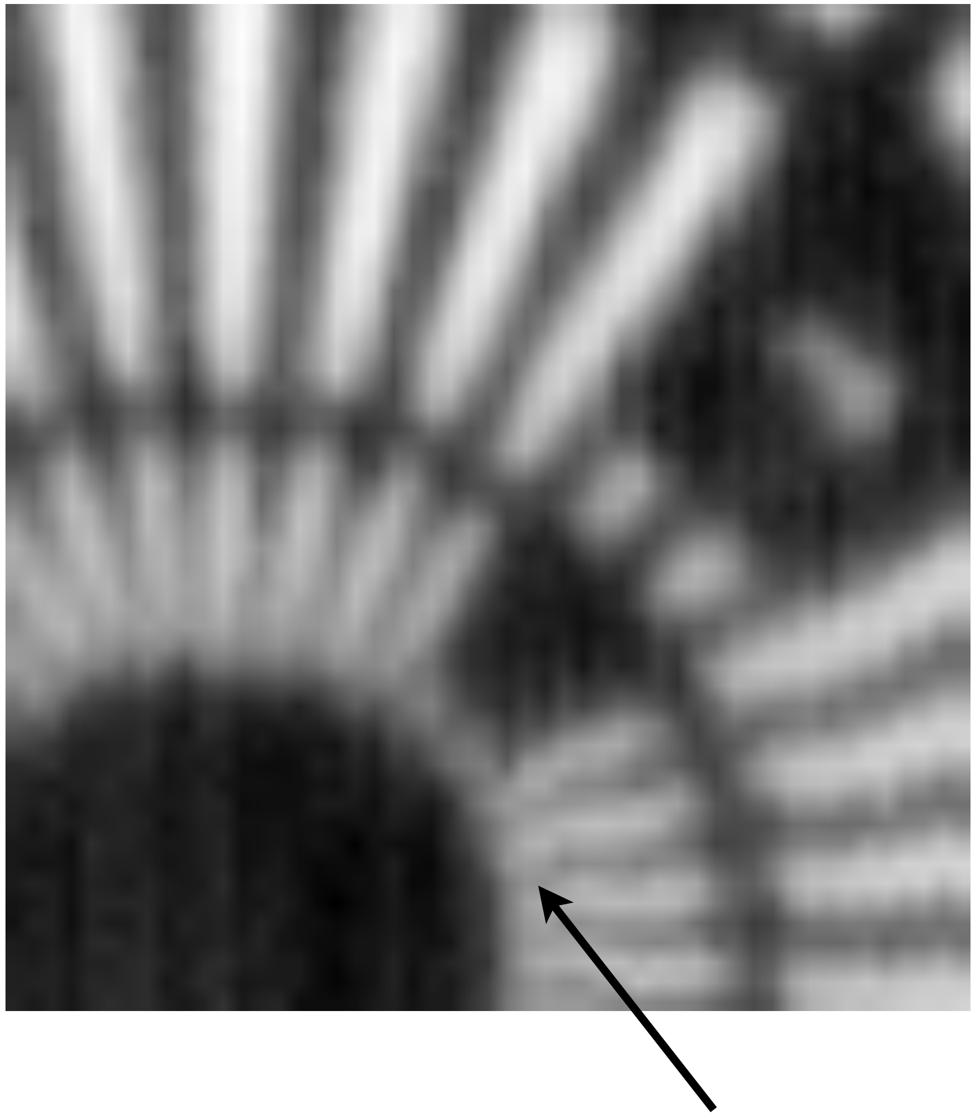
Experimental requirements:

> optimized coherent flux with pre-focusing
> high performance optics
> high mechanical stability and control
> low background

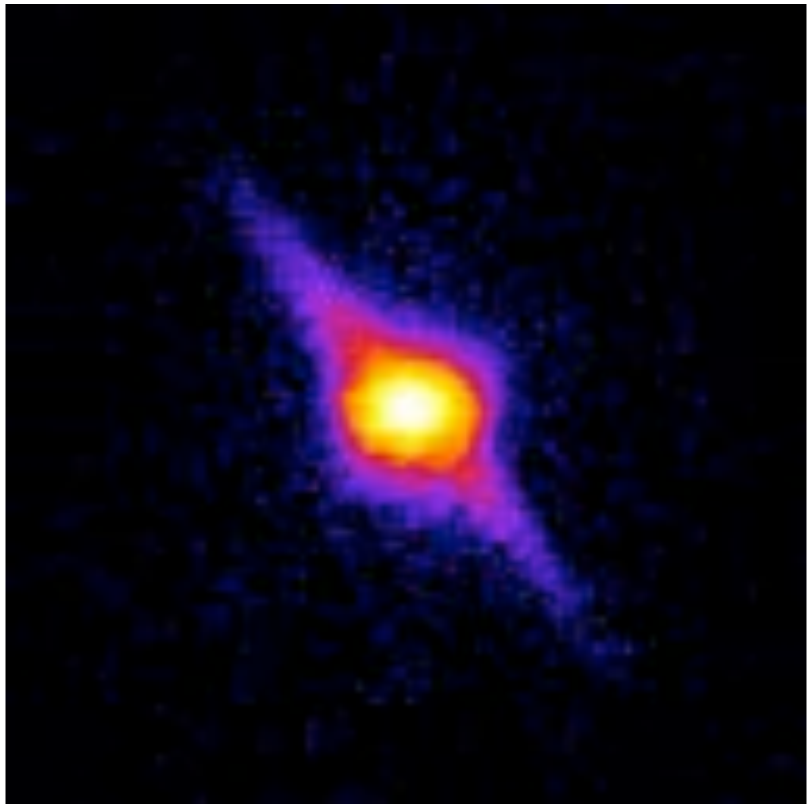
Ptychography

Scanning Coherent X-Ray Microscopy

Ta L_α fluorescence



50 nm lines and spaces



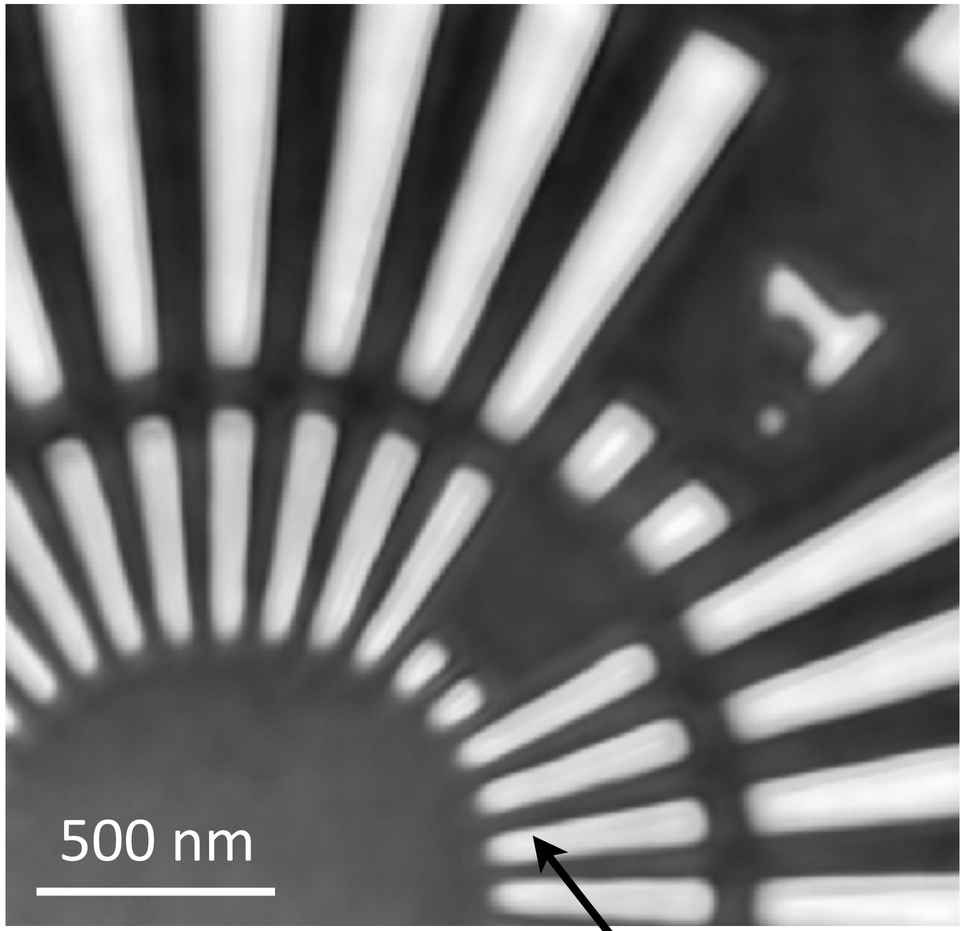
E = 15.25 keV
50 x 50 steps of 40 x 40 nm^2
2 x 2 μm^2 FOV
exposure: 0.3 s per point

dose: ≈ 20000 $photons/nm^2$
resolution: ≈ 10 nm

Ptychography

Scanning Coherent X-Ray Microscopy

ptychography (phase shift)



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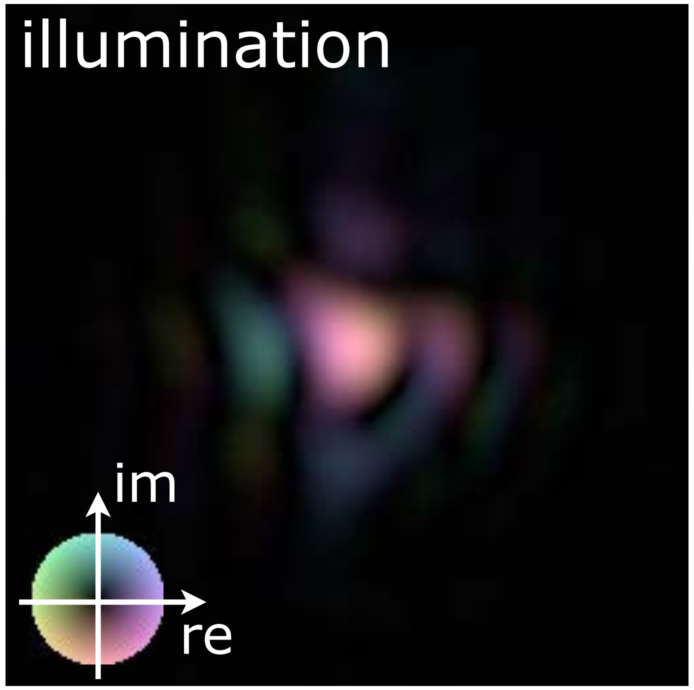

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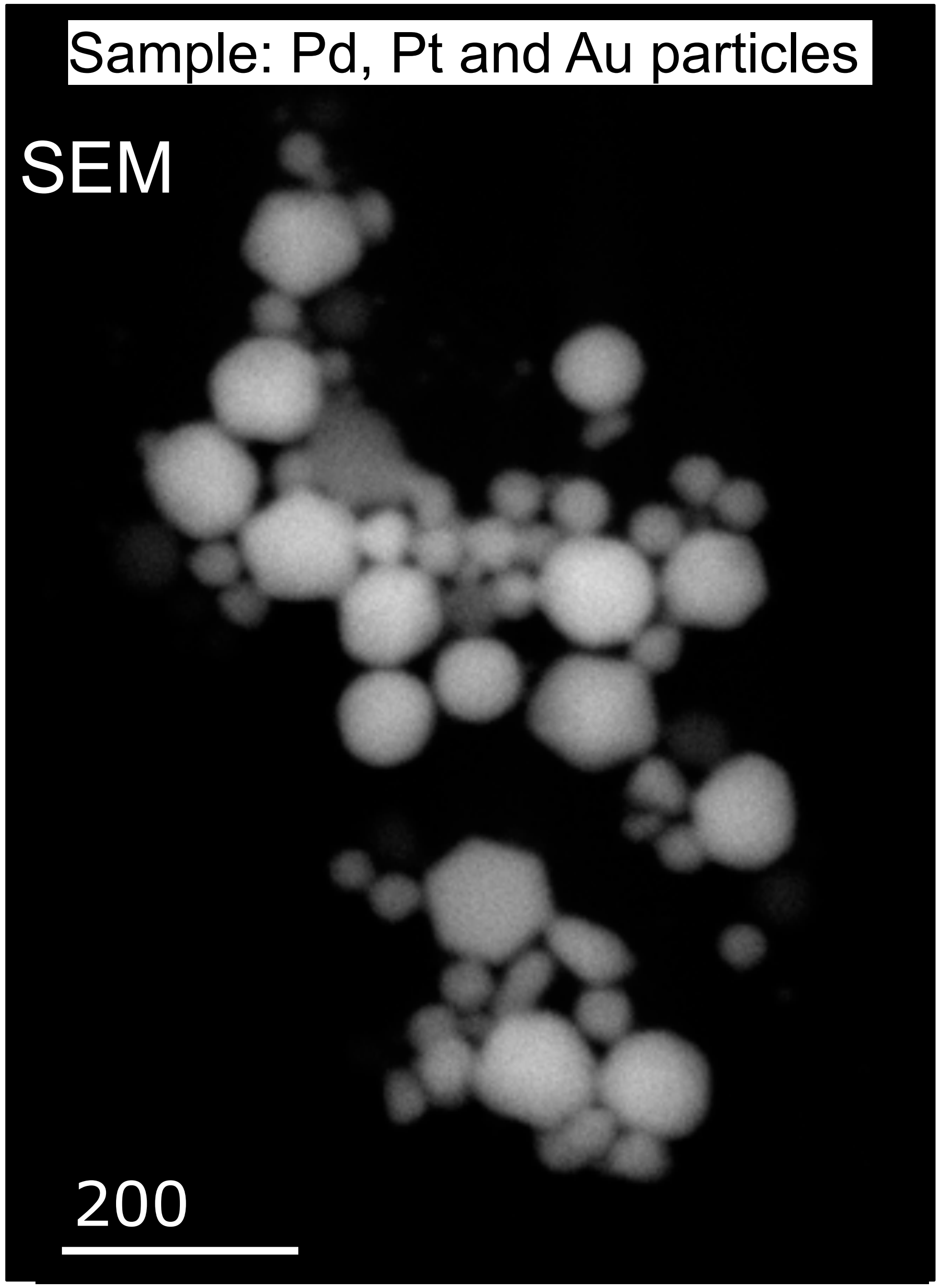
High-Resolution Ptychography

Juliane Reinhardt, *et al.*, “Beamstop-based low-background ptychography to image weakly scattering objects”, Ultramicroscopy **173**, 52 (2017)



Collaboration with J. D. Grunwaldt, Karlsruhe and C. Damsgaard, Copenhagen

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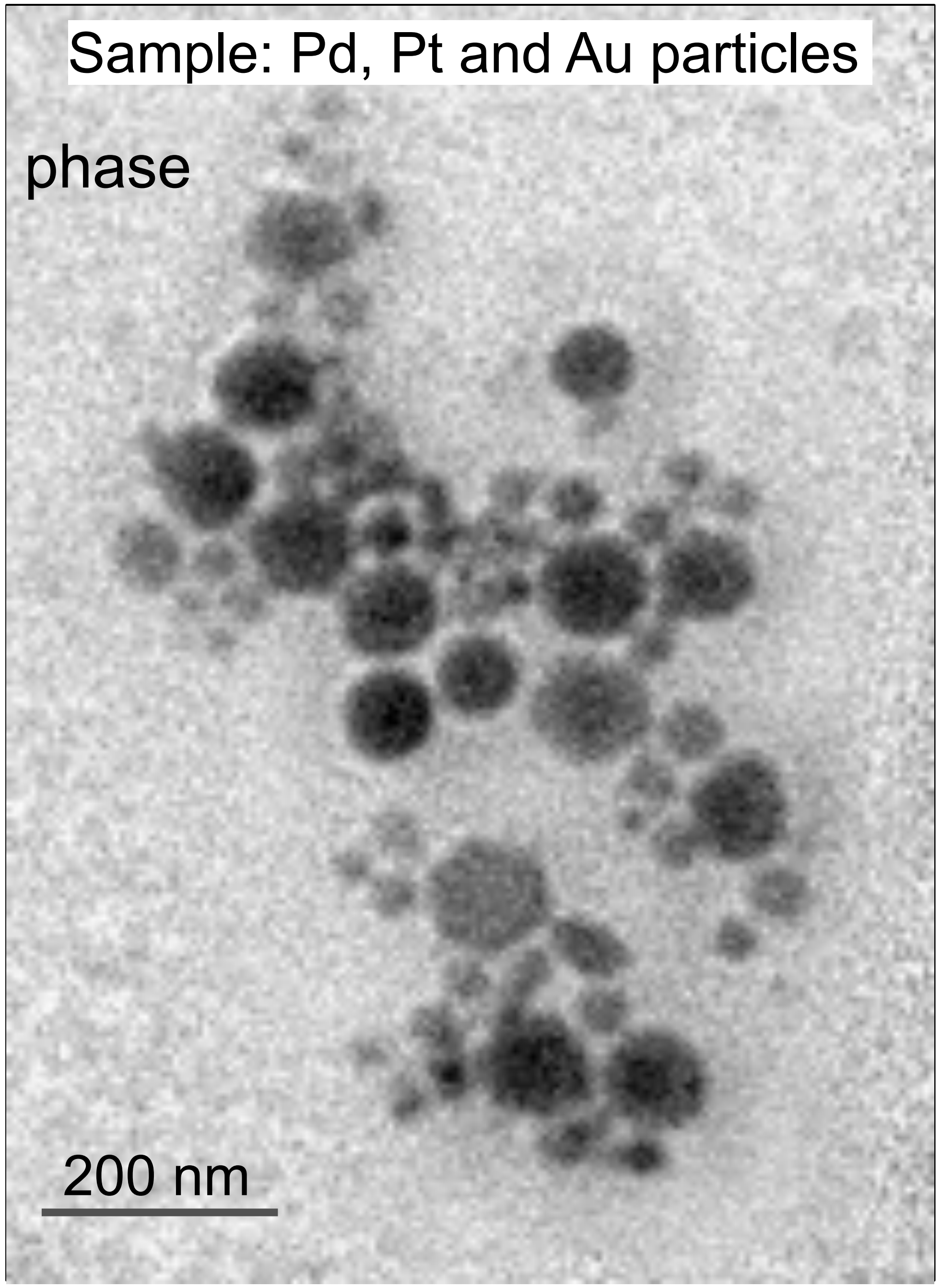

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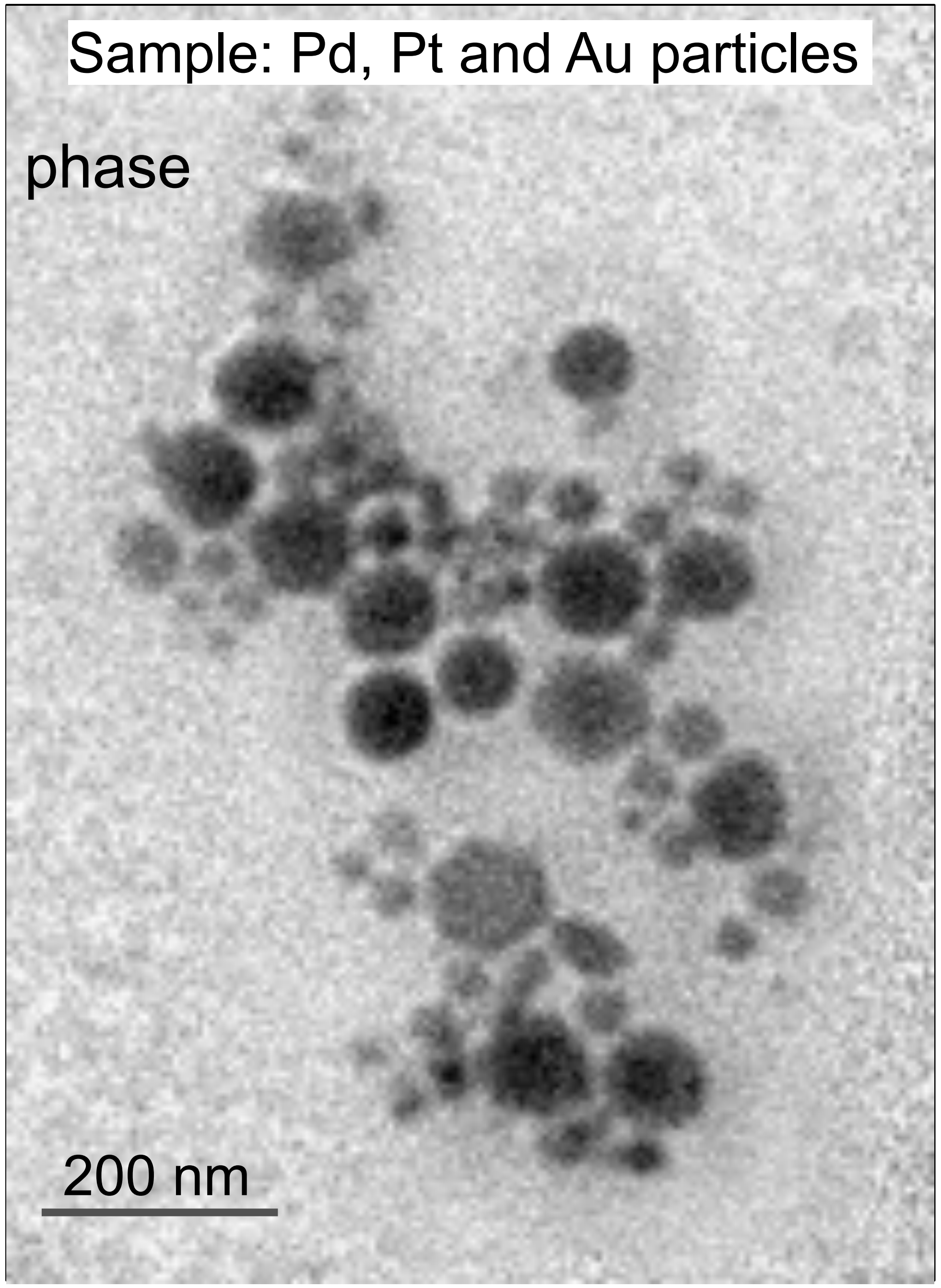

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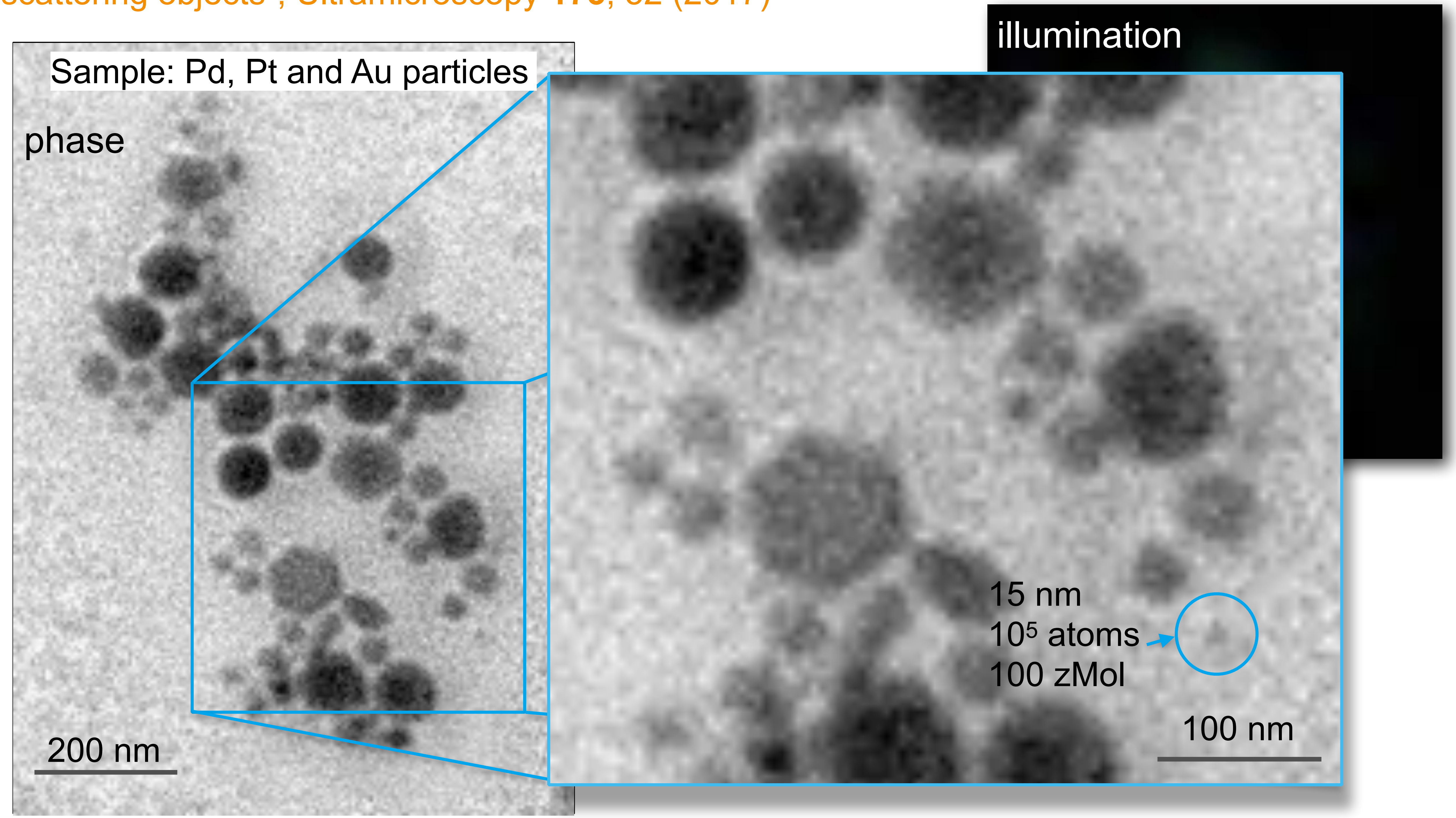
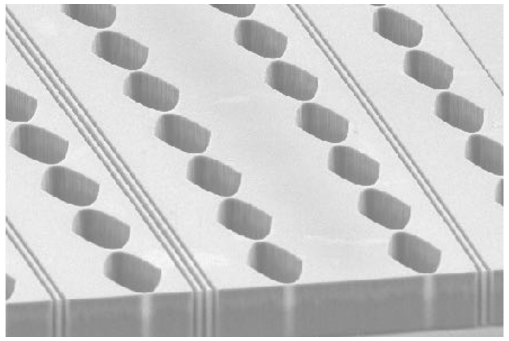


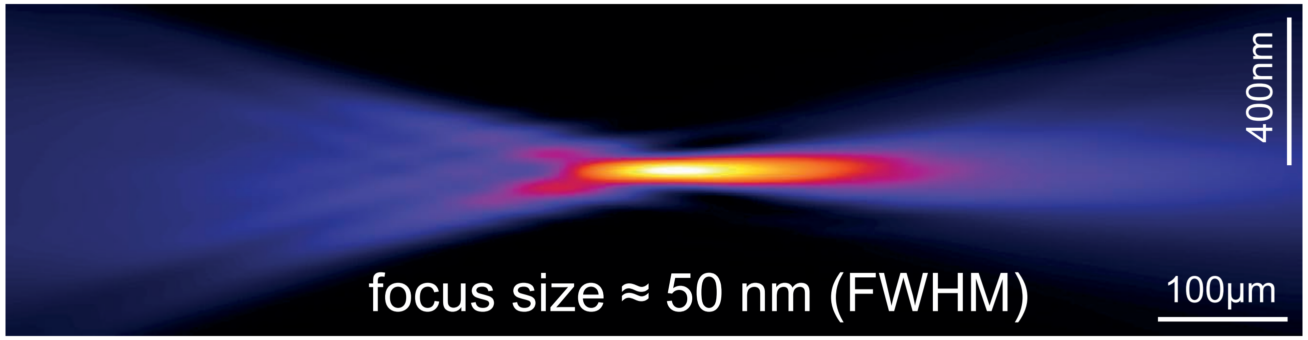
Collaboration with J. D. Grunwaldt, Karlsruhe and C. Damsgaard, Copenhagen

Further Optics Developments

Nanofocusing Lenses (NFLs)

> C. G. Schroer, *et al.*, AIP Conf. Ser. **1365**, 227 (2011)

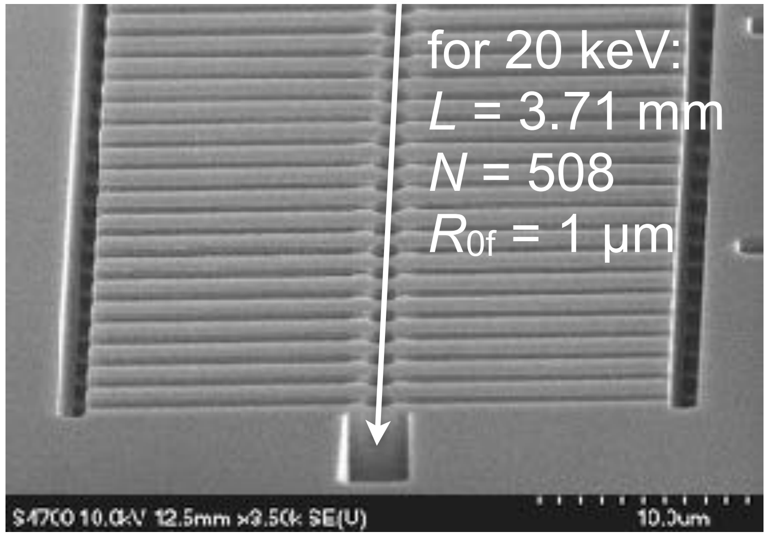




Adiabatically Focusing Lenses (AFLs)

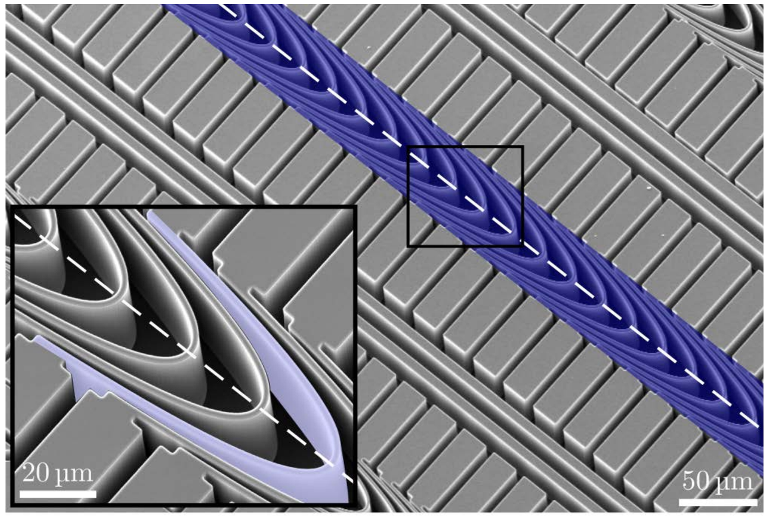
> C. G. Schroer and B. Lengeler, “Focusing Hard X Rays to Nanometer Dimensions by Adiabatically Focusing Lenses”, PRL **94**, 054802 (2005)

> J. Patommel *et al.*, “Focusing hard x rays beyond the critical angle of total reflection by adiabatically focusing lenses”, APL **110**, 101103 (2017)



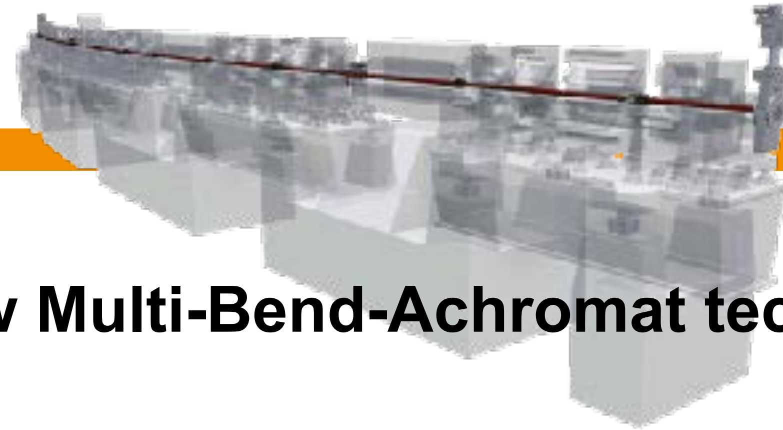
Refractive Lamellar Lenses (RLLs)

> F. Seiboth *et al.*, “Hard x-ray nanofocusing by refractive lenses of constant thickness”, APL **105**, 131110 (2014)



PETRA IV Project — Design of a New Source

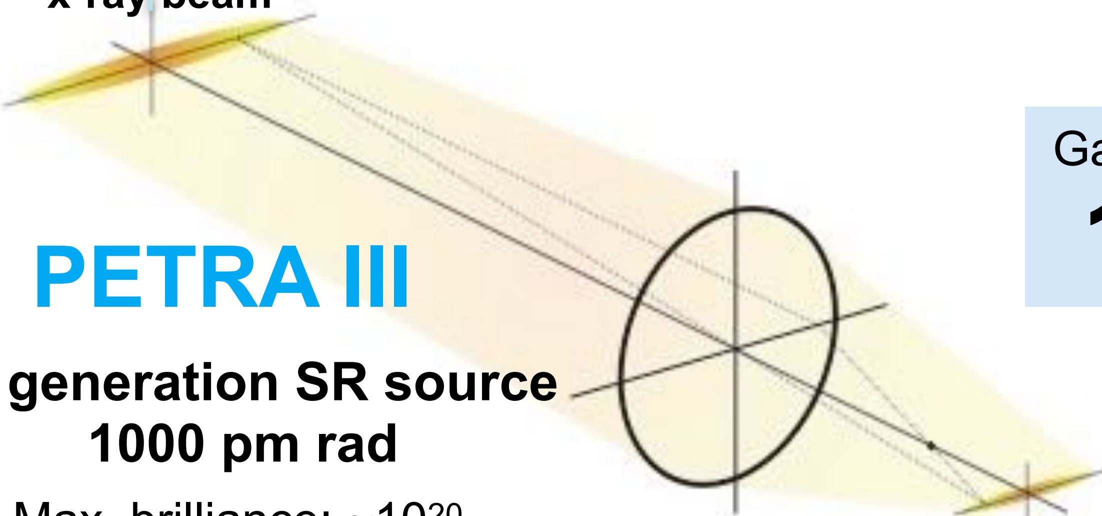
source size:
140 µm x 6 µm



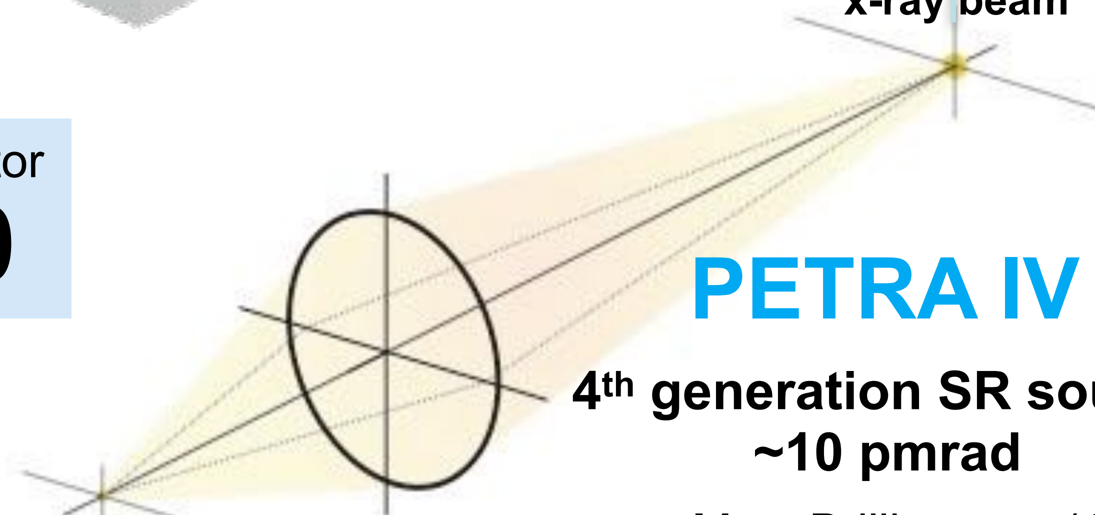
source size:
6 µm x 6 µm

New Multi-Bend-Achromat technology

asymmetrical x-ray beam



round x-ray beam



Gain factor
100

PETRA III

3rd generation SR source
1000 pm rad

Max. brilliance: ~10^{20}
coherence: ~0.1-1%

nanometer focusing

PETRA IV

4th generation SR source
~10 pmrad

Max. Brilliance: >10^{22}
Coherence: > 25%

PETRA IV

> new multi-bend-achromat (MBA) technology +

> 2.3 km circumference (largest SR source)
emittance scales as 1/(circumference)^3

→ diffraction limited down to a wavelength of 1 Å (ultimate storage ring)

Qualitative step in synchrotron analytics

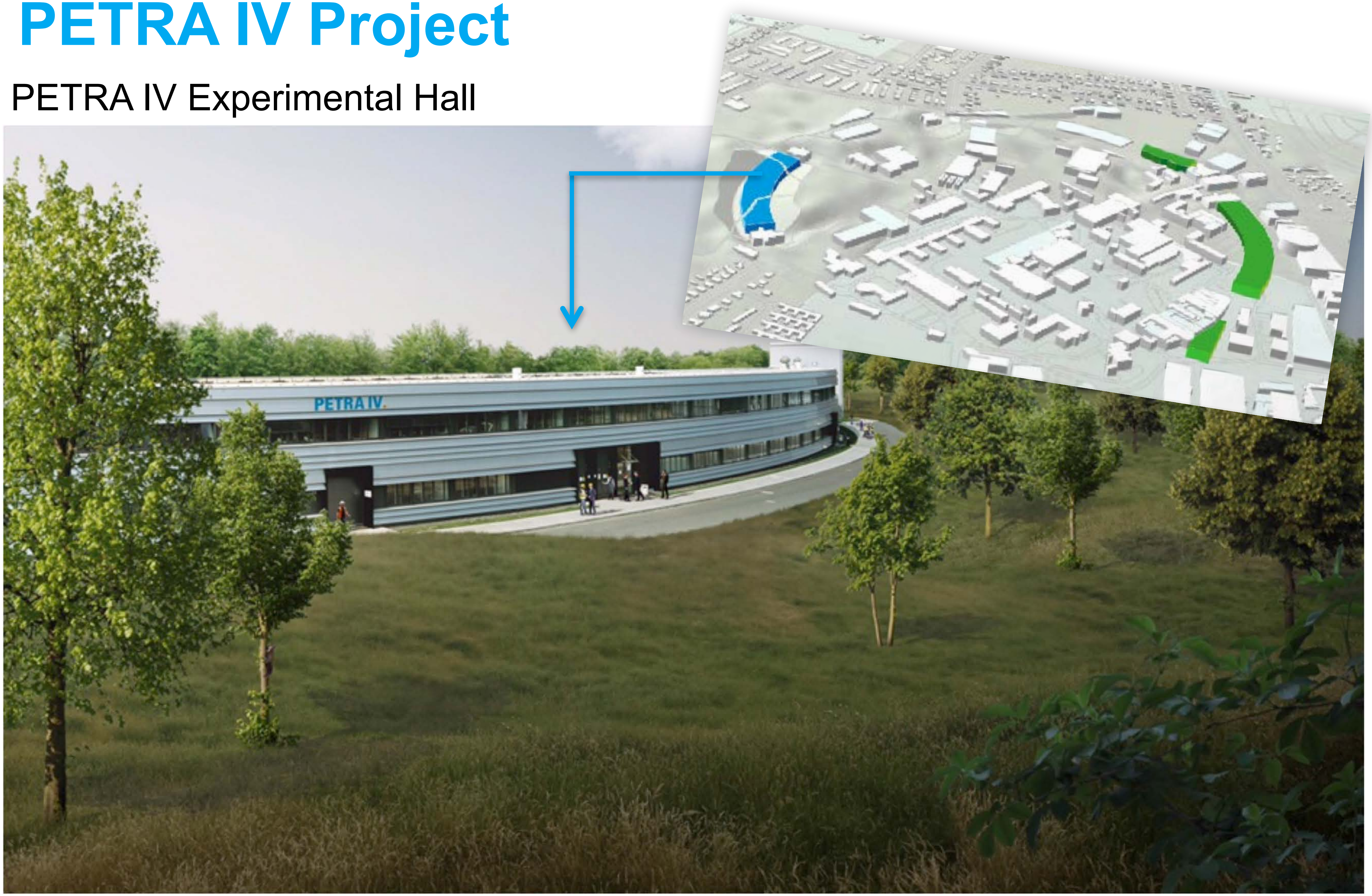
In-situ 3D-microscopy on nanometer scale

Operando nanoimaging of

> structure, chemistry
> electronic and magnetic properties
> dynamics on the sub-nanosecond scale

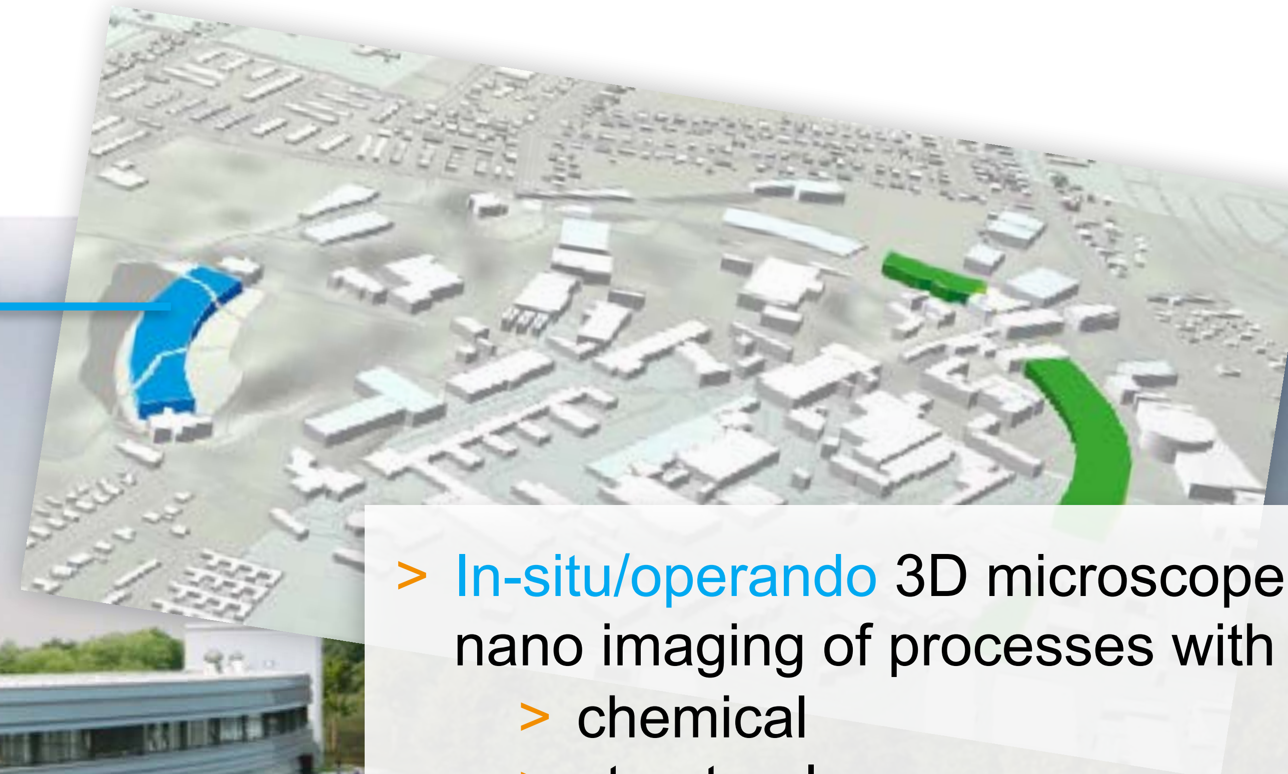
PETRA IV Project

PETRA IV Experimental Hall



PETRA IV Project

PETRA IV Experimental Hall

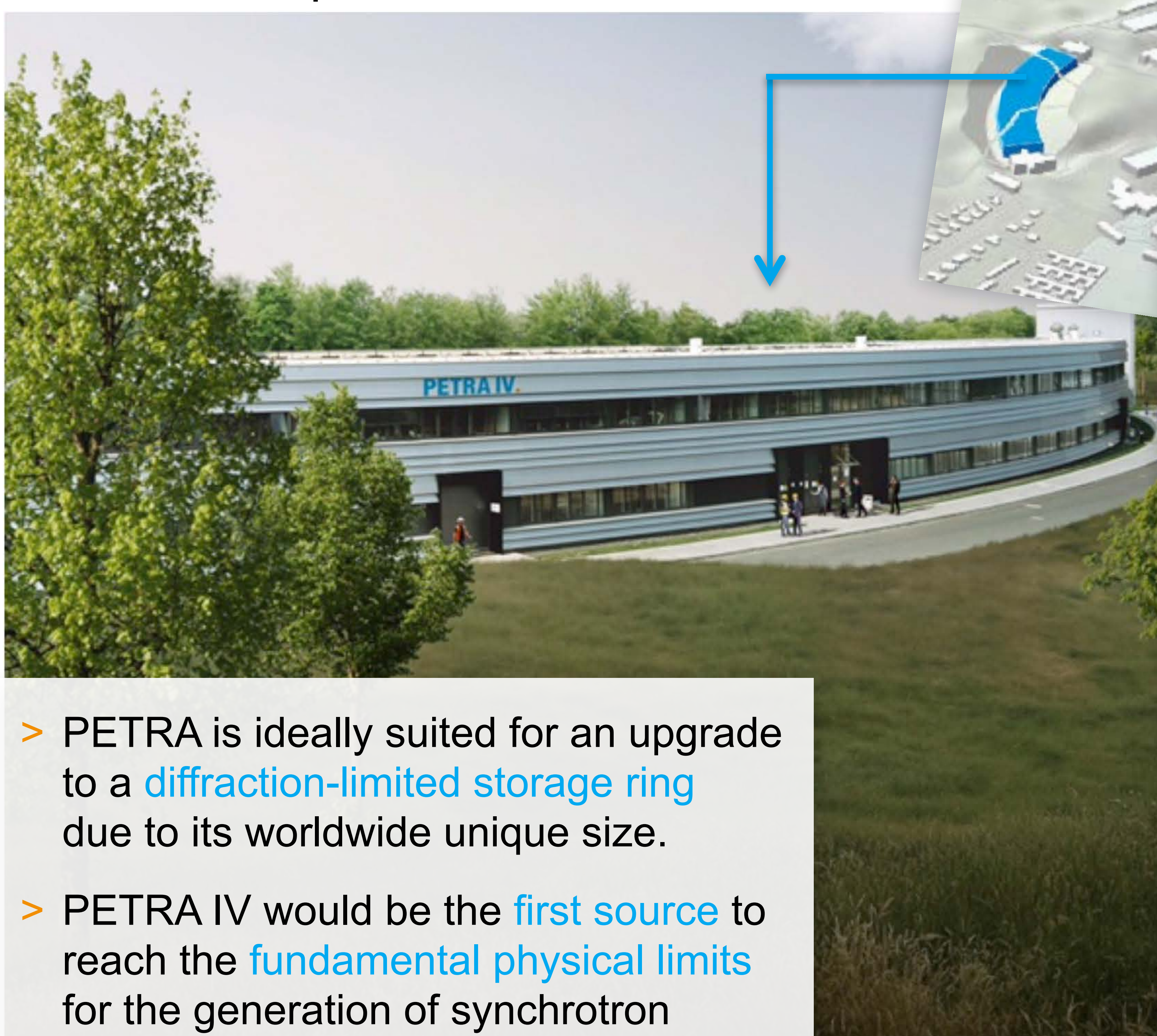


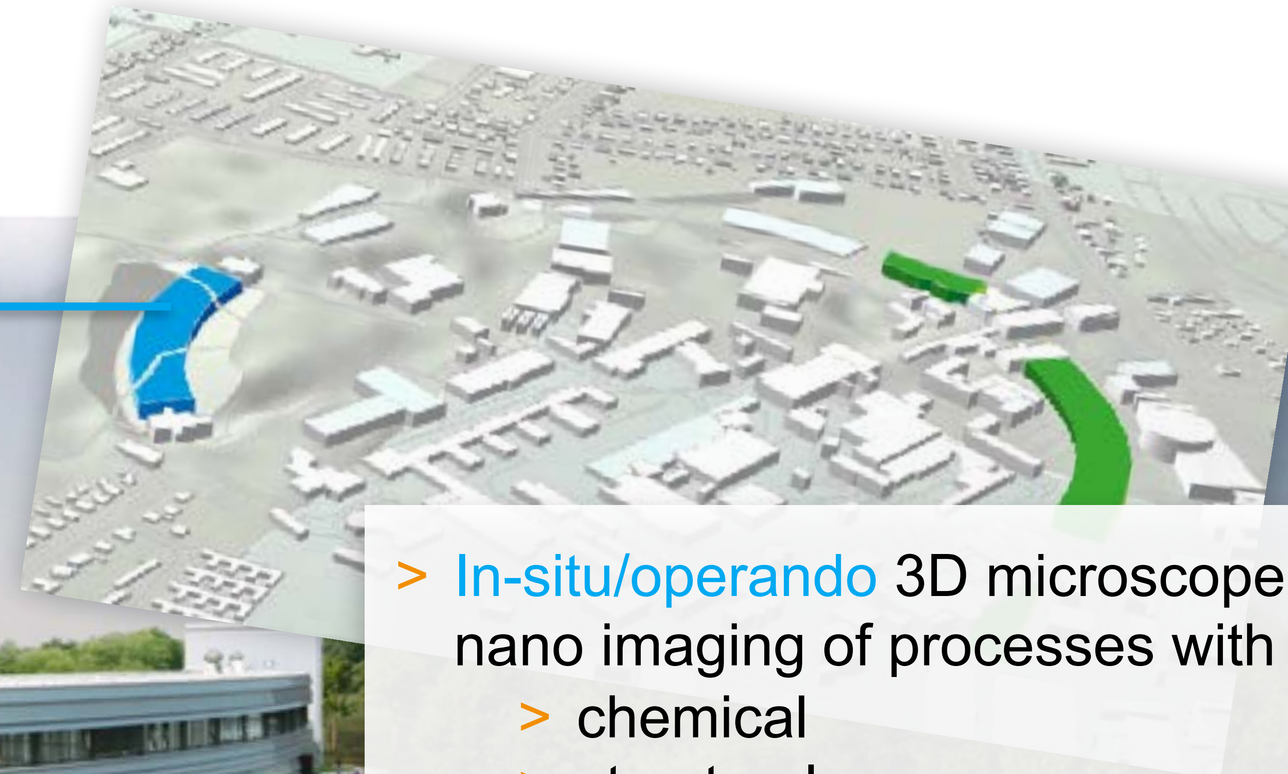
- In-situ/operando 3D microscope nano imaging of processes with
  - chemical
  - structural
  - electronic
  - magnetic
  - …

  contrast on all relevant length and (slower) time scales (≈ ns)
- Novel contributions:
  - health
  - energy
  - mobility/transport
  - IT/communication
  - earth and environment

PETRA IV Project

PETRA IV Experimental Hall





- PETRA is ideally suited for an upgrade to a diffraction-limited storage ring due to its worldwide unique size.
- PETRA IV would be the first source to reach the fundamental physical limits for the generation of synchrotron radiation at 1 Å wave length.

- In-situ/operando 3D microscope nano imaging of processes with
  - chemical
  - structural
  - electronic
  - magnetic
  - …

  contrast on all relevant length and (slower) time scales (≈ ns)
- Novel contributions:
  - health
  - energy
  - mobility/transport
  - IT/communication
  - earth and environment

Summary

Development of refractive optics

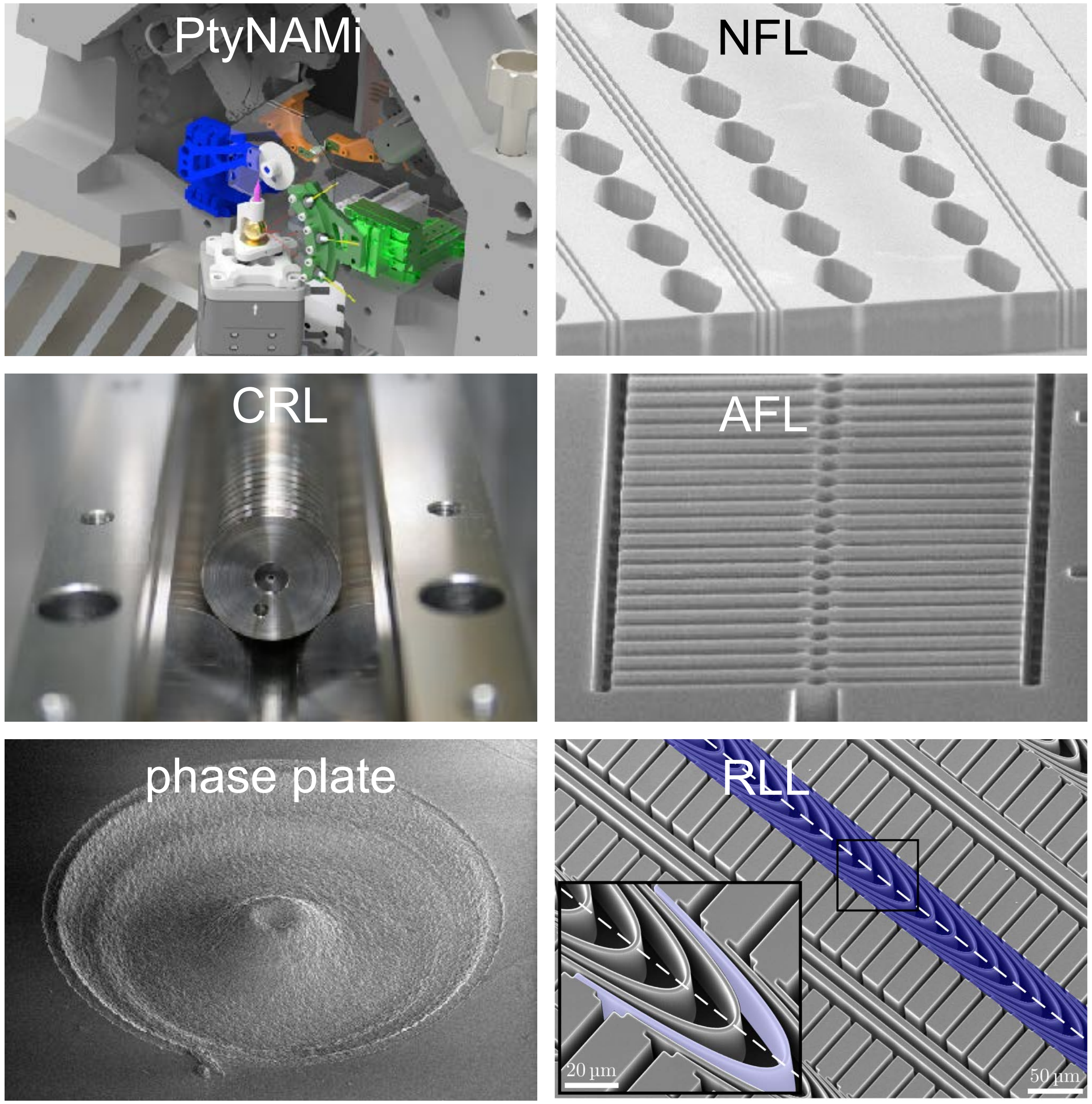
- NFL: Almost optimal performance
- AFL: $NA > \sqrt{2\delta}$
- CRL: diffraction-limited nano-focusing enabled by an additional phase plate.
- RLL: New design of refractive optics enabling us to use different materials.

PtyNAMi

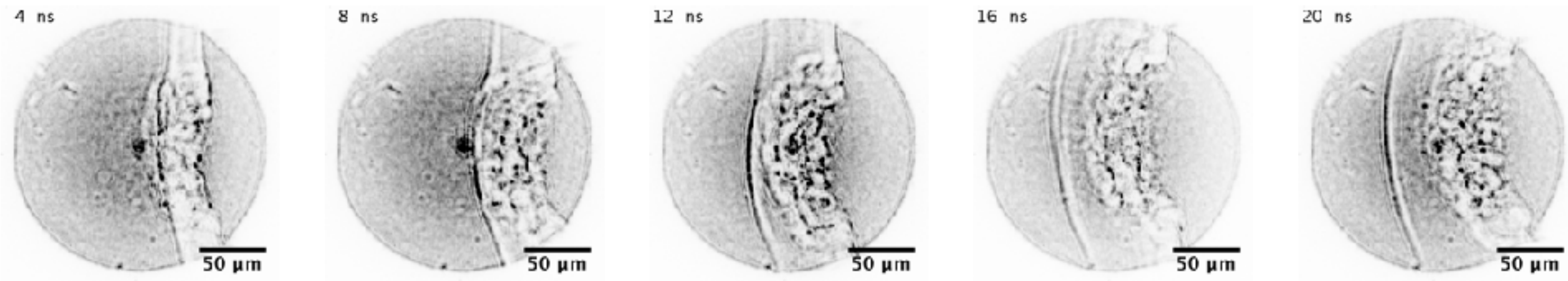
- New microscope being developed for beamline P06 at PETRA III.

Relevant for applications at synchrotron radiation sources and XFELs

- scanning coherent X-ray microscopy
- aberration-free direct X-ray imaging
- heating of matter with strongly focused XFEL-beams



Acknowledgements



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Scanning coherent X-ray micoscopy, using fluorescence (XRF), diffraction (SAXS, WAXS), absorption (XAS) and ptychographic (CXDI) contrast.

PETRA III (DESY, Hamburg)

ESRF (Grenoble)

LCLS (SLAC, Menlo Park)