BERYLLIUM PARABOLIC REFRACTIVE X-RAY LENSES

B. Lengeler, C. Schroer

M. Kuhlmann, B. Benner, T. F. Günzler, O.Kurapova

II. Physikalisches Institut B, Aachen University, Germany

A. Snigirev, I. Snigireva

ESRF Grenoble

e-mail: lengeler@physik.rwth-aachen.de

Collaboration

ESRF in Grenoble

M. Drakopoulos, A. Simionovici (ID22)

Wuppertal University

M. Richwin, B. Griesebock, R. Frahm

Advanced Photon Source

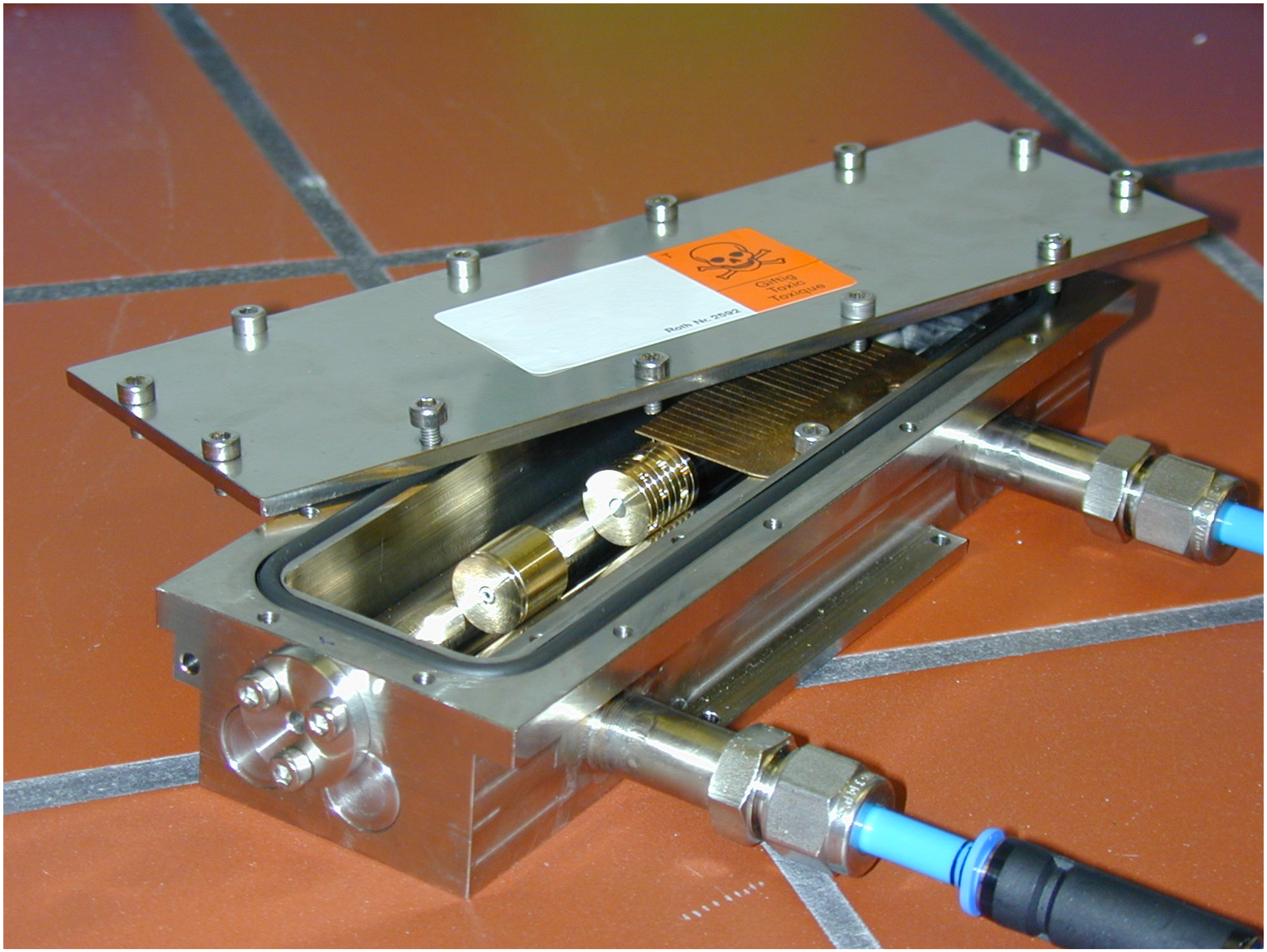
D. R. Haeffner, A. Mashayekhi

Financial Support

Bundesministerium fuer Bildung und Forschung

DESY-HS

Beryllium Lenses



A. PARABOLIC REFRACTIVE X-RAY LENSES

- novel optical components for hard x-rays (6 to 120 keV)
- focuses in both directions
- **can be used like glass lenses for visible light,**
  but Numerical Aperture is small (10^{-3} ... 10^{-4})
- compact and robust, easy to align and to operate
- Applications in
  - micro- and nanofocusing
  - imaging in absorption & phase contrast
  - imaging in fluorescence mode
  - microtomography
  - coherent x-ray scattering: speckle spectroscopy

The problem

index of refraction $n = 1 - \delta + i\beta$ $\delta, \beta \sim 10^{-6} > 0$

- refraction is weak
- absorption is strong $\beta = \lambda\mu/4\pi$
- focal length is long

„ There are no refractive lenses for x-rays!“ W.C.Roentgen

- focusing lens must be concave

But **refraction is not zero**

absorption is not infinite

Strategy for refractive x-ray lenses

- small radius of curvature R: $f = R / 2\delta$
- stacking of many lenses in a row: $f = R / 2N\delta$
- low Z lens material: $\mu / \rho \sim Z^3 / E^3$

  candidates: **Be**, B, C, Al, Si
- profile must be parabolic: no spherical aberration
- refractive x-ray lenses are by far less sensitive to surface roughness than mirrors are! (=> easier to manufacture)

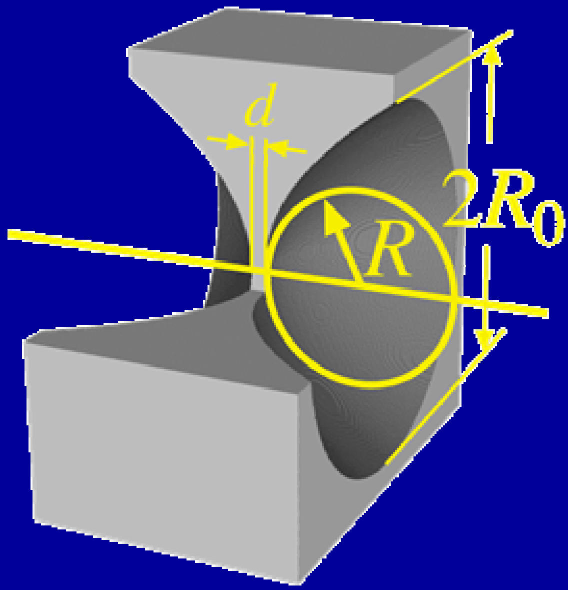
PARABOLIC REFRACTIVE X-RAY LENSES

DESIGNED & MADE AT AACHEN UNIVERSITY

Parabolic Refractive Lenses

Lens surfaces are paraboloids of rotation

single lens



parameters for Be lenses:

$R \quad = 200\mu m$

$2R_0 = 1mm$

$d \quad = 50\mu m$

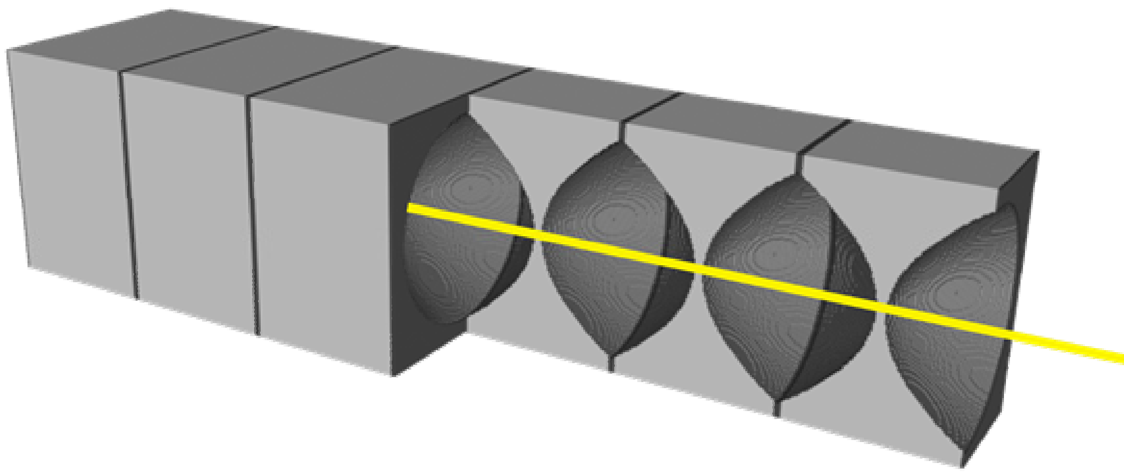
parabolic profile: no spherical aberration

focusing in full plane

=> excellent imaging optics

Parabolic Refractive Lenses

stack of lenses: $f = R / 2N\delta$ typical: 0.3m - 2m

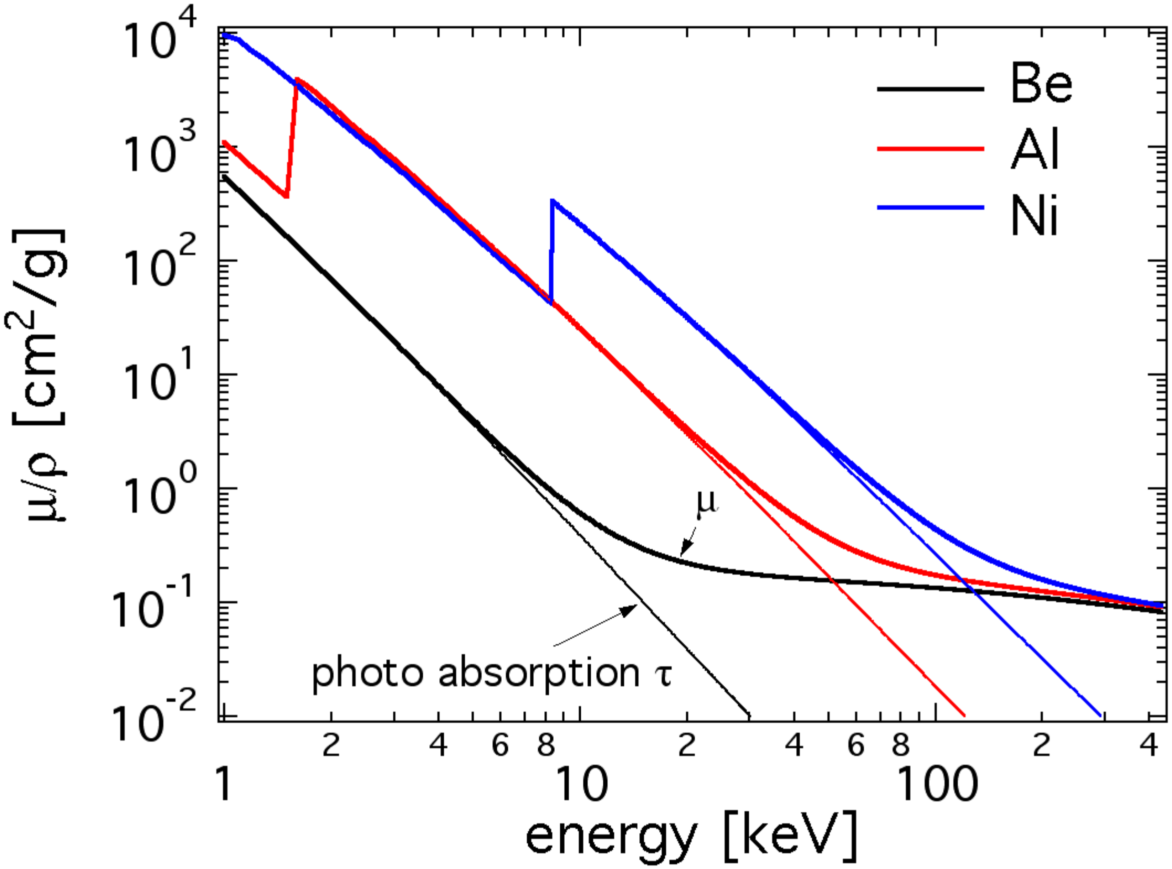


variable number of lenses : 1 to about 300

Focal distance can be adjusted to fit experimental equirements

Attenuation of X-Rays in Matter

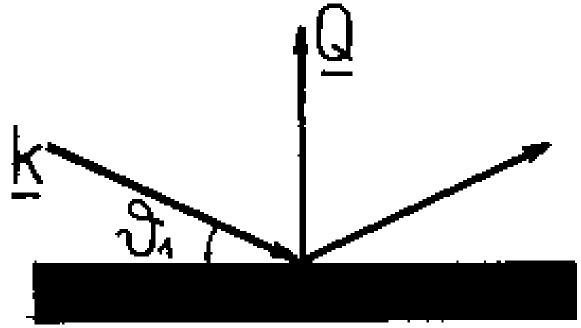
attenuation coefficient: $\mu = \tau + \mu_{\text{compton}}$

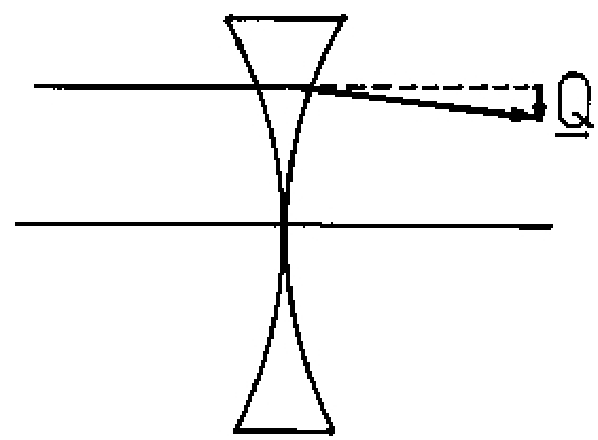


- photo absorption: $\tau \sim Z^3/E^3$
- Compton scattering dominates at high x-ray energies

Influence of surface roughness

mirror **lens**





Damping ~ $\exp[-Q^2 \sigma^2]$

momentum transfer $Q = 2k \sin \theta_1 = 2k\, \theta_1$

Mirror $Q = 7\ 10^{-2}\ A^{-1}$ @ $\theta_1 \sim 0.3°$ & $\lambda = 1A$

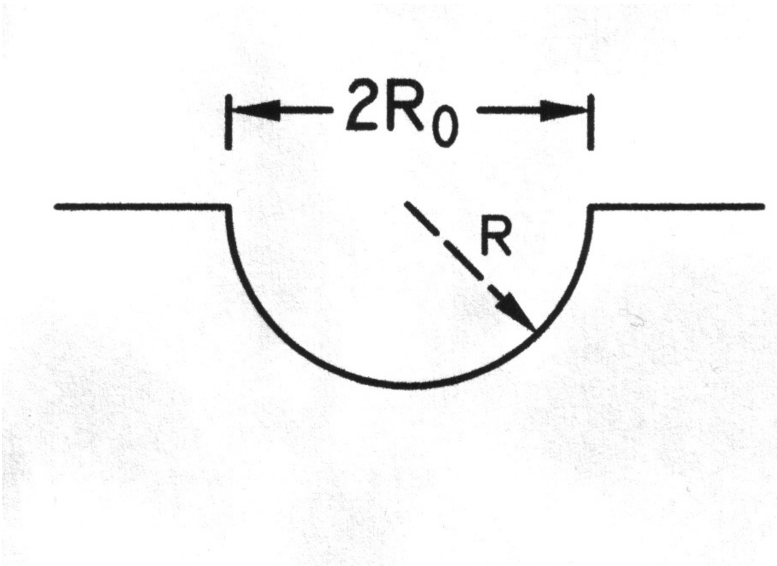
lens stack $Q = N^{1/2}\, k\, \delta = 1.4\ 10^{-4}\ A^{-1}$ @ $N = 100$ & $\lambda = 1A$

a lens is about a factor of 500 less sensitive to surface roughness!

Parabolic Refractive Lenses

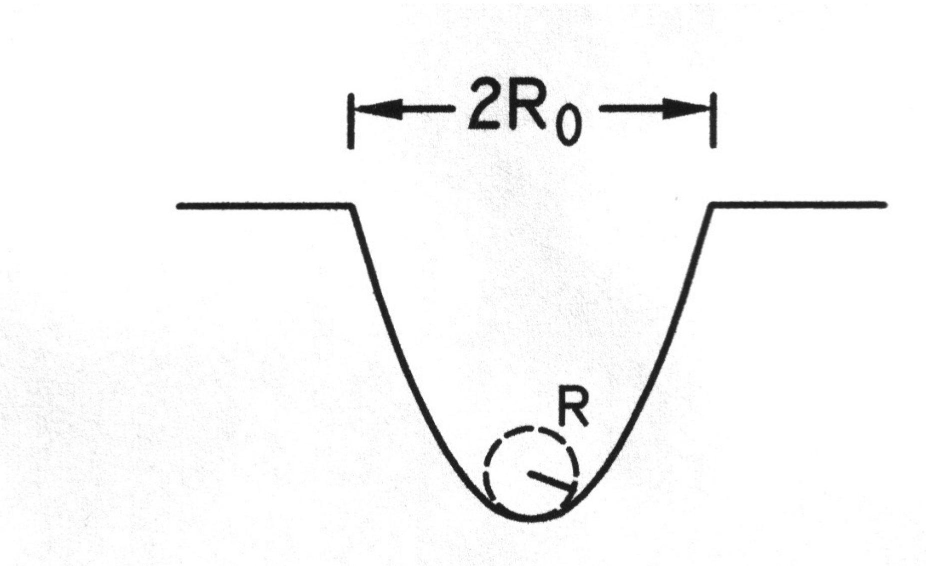
Advantage: aperture is independent of radius of curvature

spherical lens:



$R_0 \leq R$

parabolic lens:

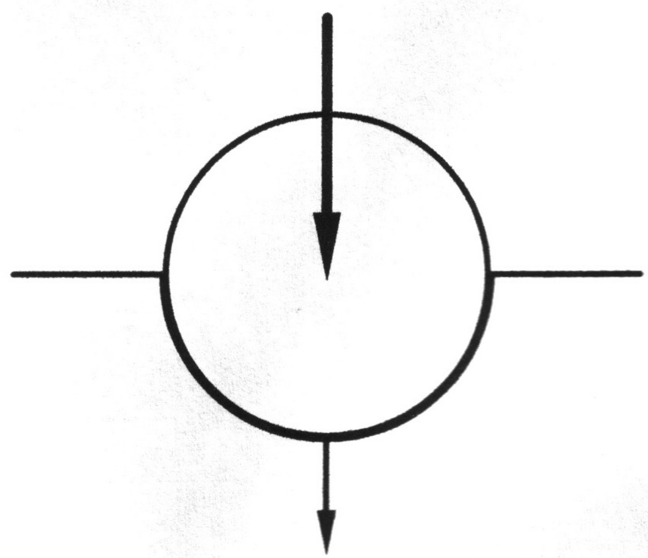


R_0 and R independent

Parabolic Refractive Lenses

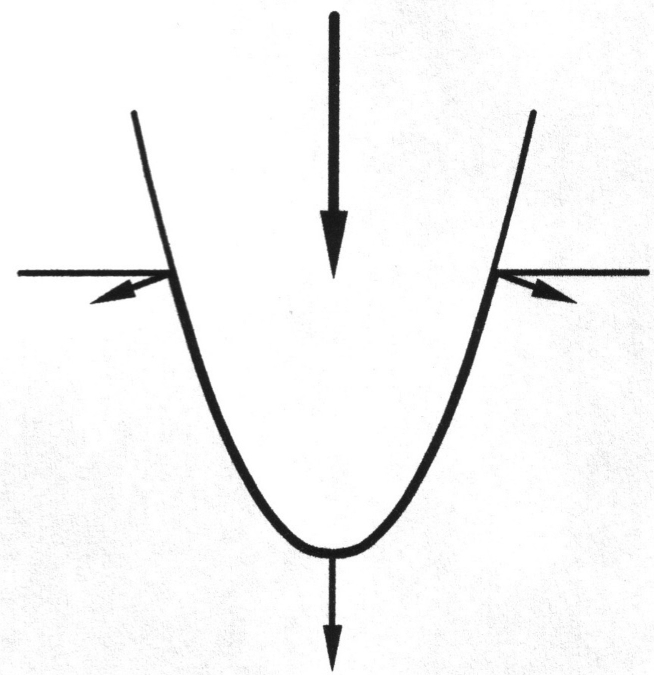
Advantage: fabrication easier than for spherical profile

spherical lens:



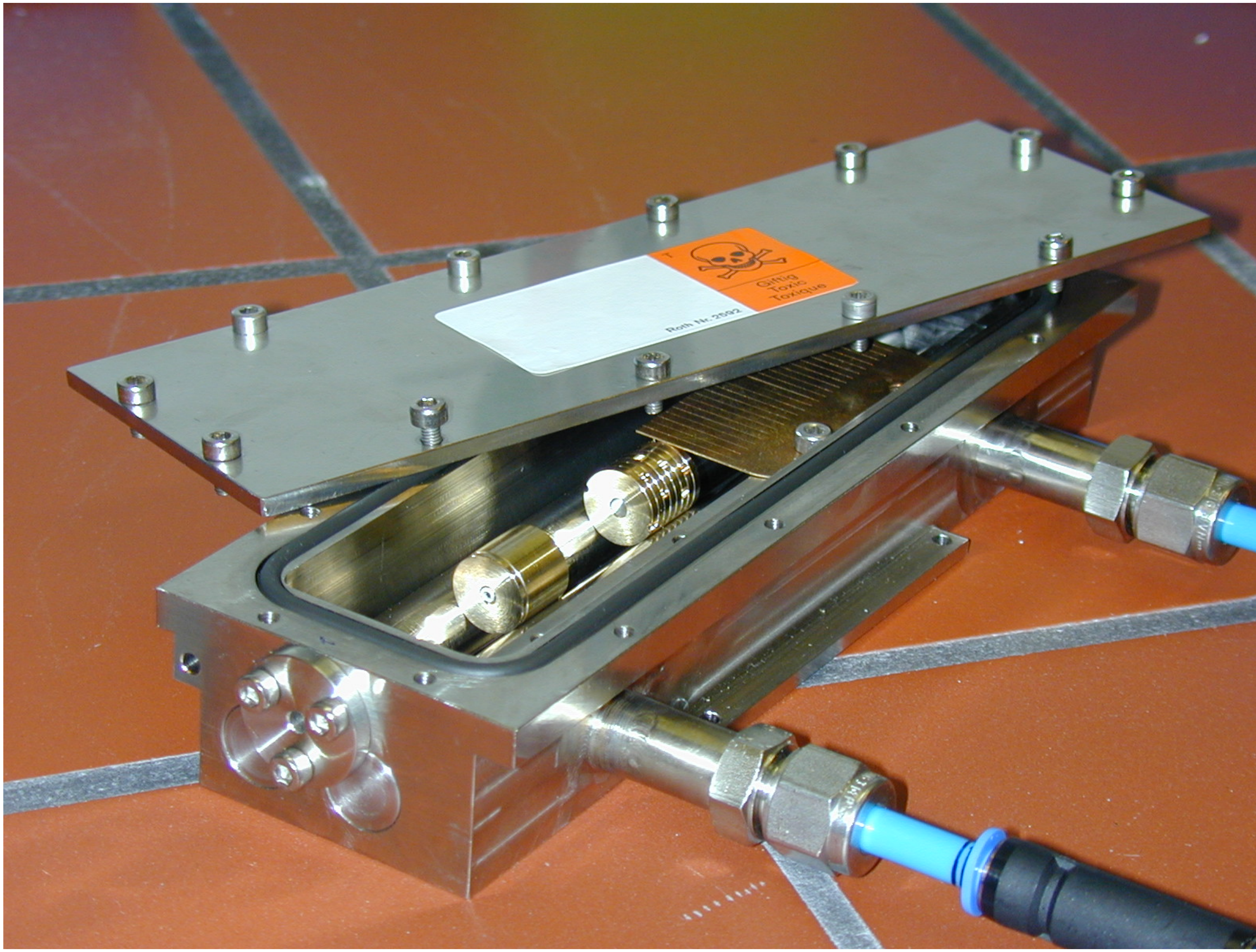
no normal force at equator

parabolic lens:



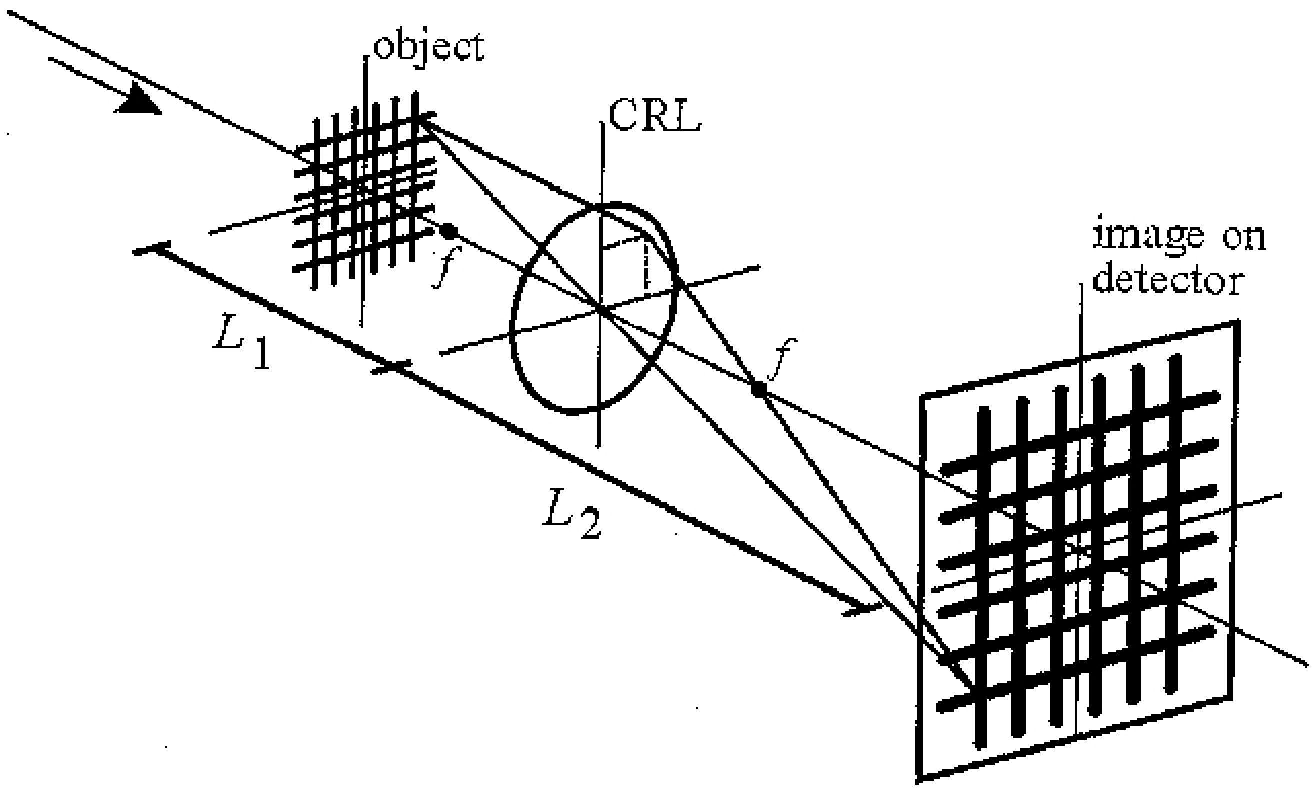
normal forces yield smooth surface

Beryllium Lenses



B. HARD X-RAY MICROSCOPY

Illumination of object by synchrotron radiation

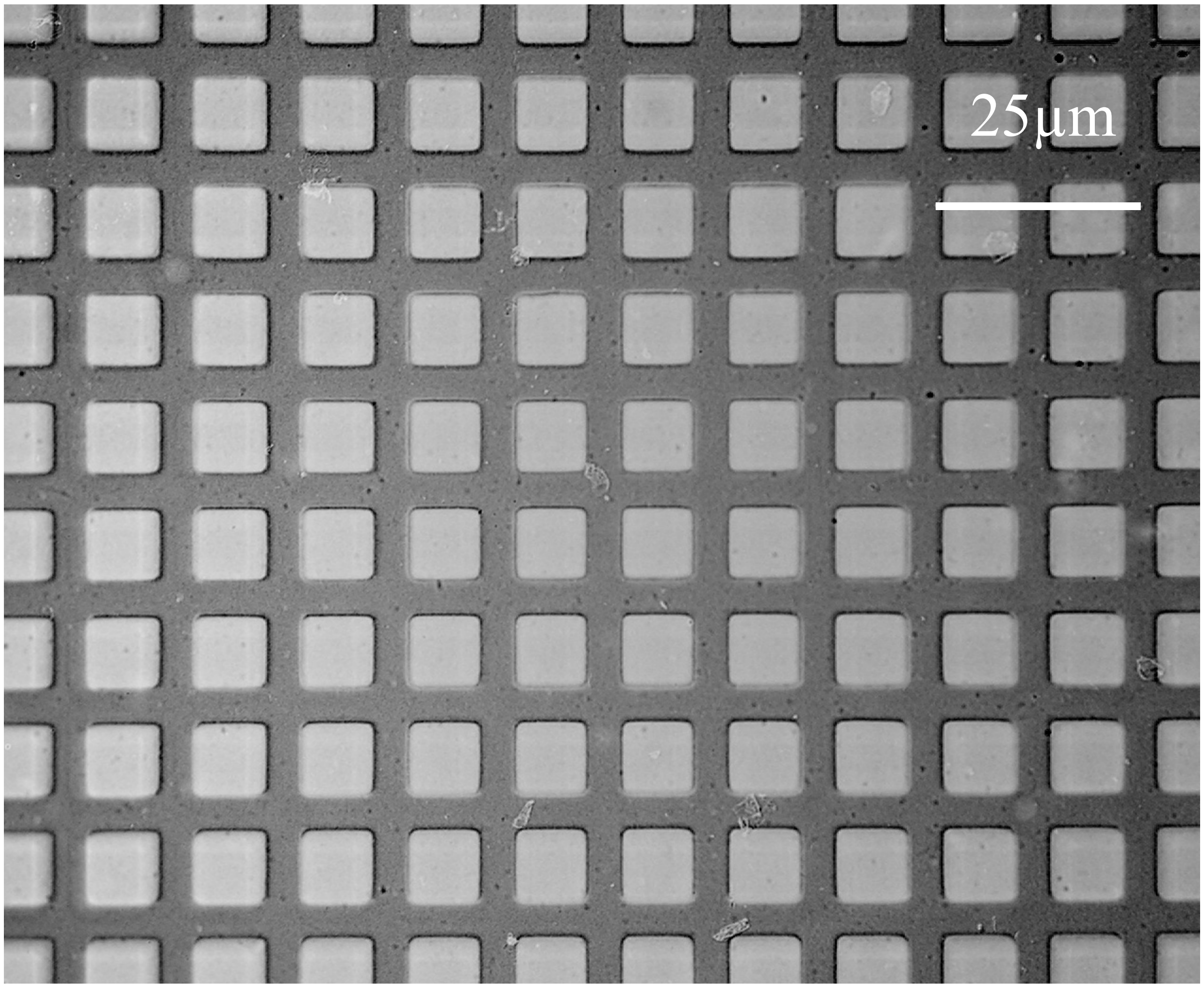


Magnified image for $L_2 >> L_1$

magnification $M = L_2 / L_1$ $\qquad$ $L_2 = L_1 f / (L_1 - f)$

Hard X-Ray Microscopy

Ni-mesh (2000mesh) imaged by Be lens



parameters:

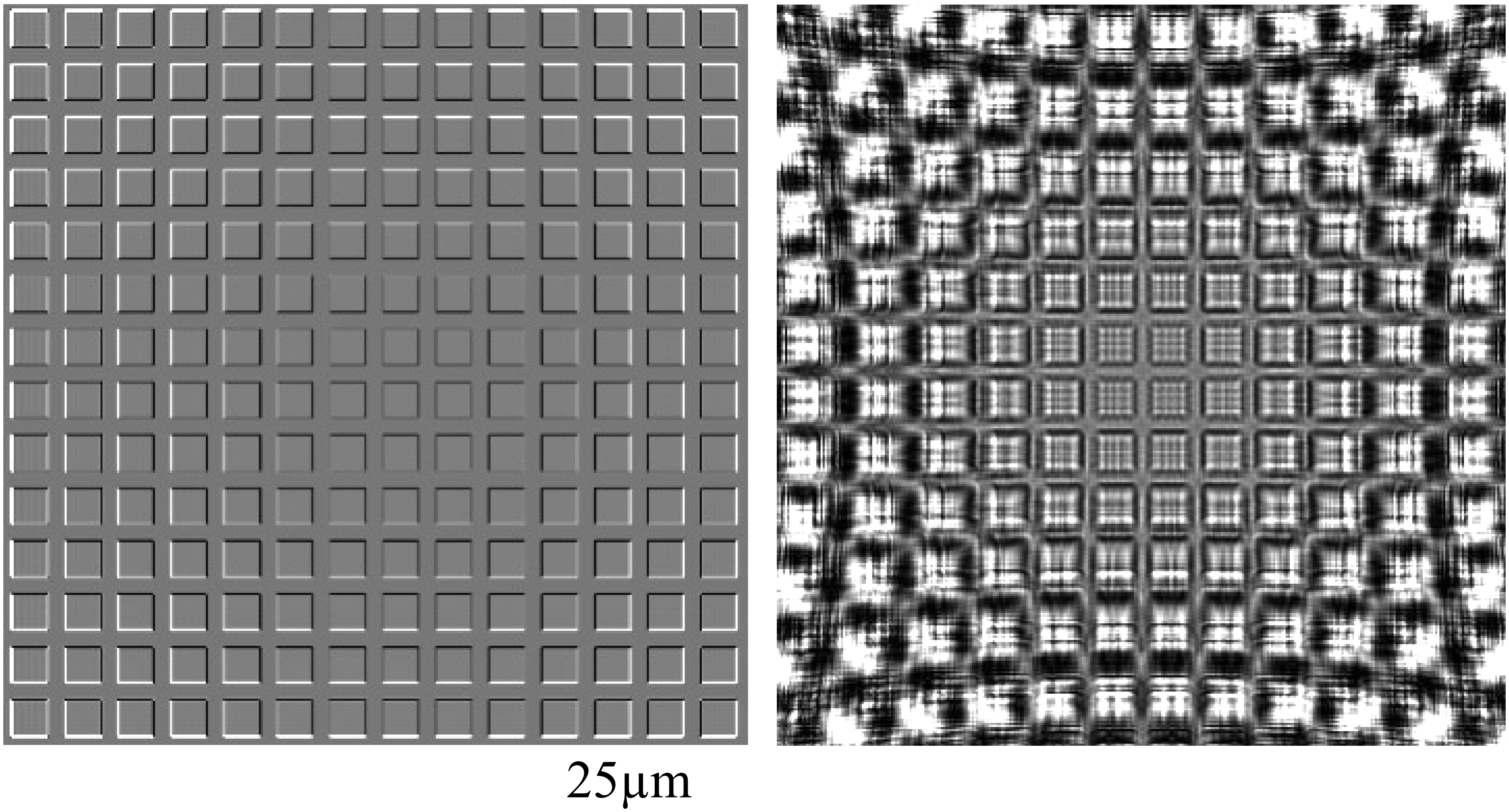
- E = 12keV
- N = 91 (Be)
- f = 495mm,
- m = 10x

Detector:

high resolution
x-ray film
(inverted contrast)

Hard X-Ray Microscopy

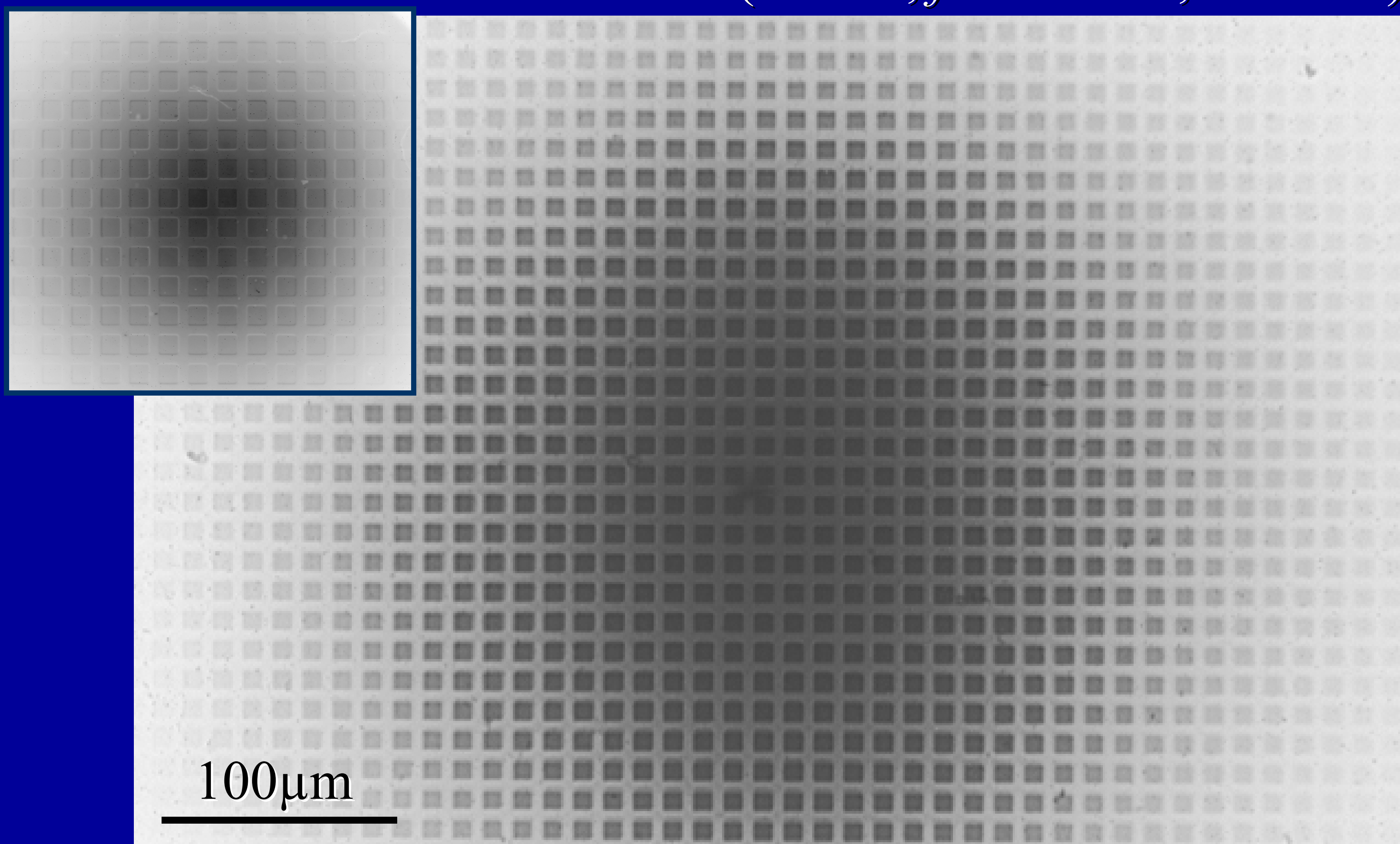
parabolic lenses　　　　spherical lenses



Field of View

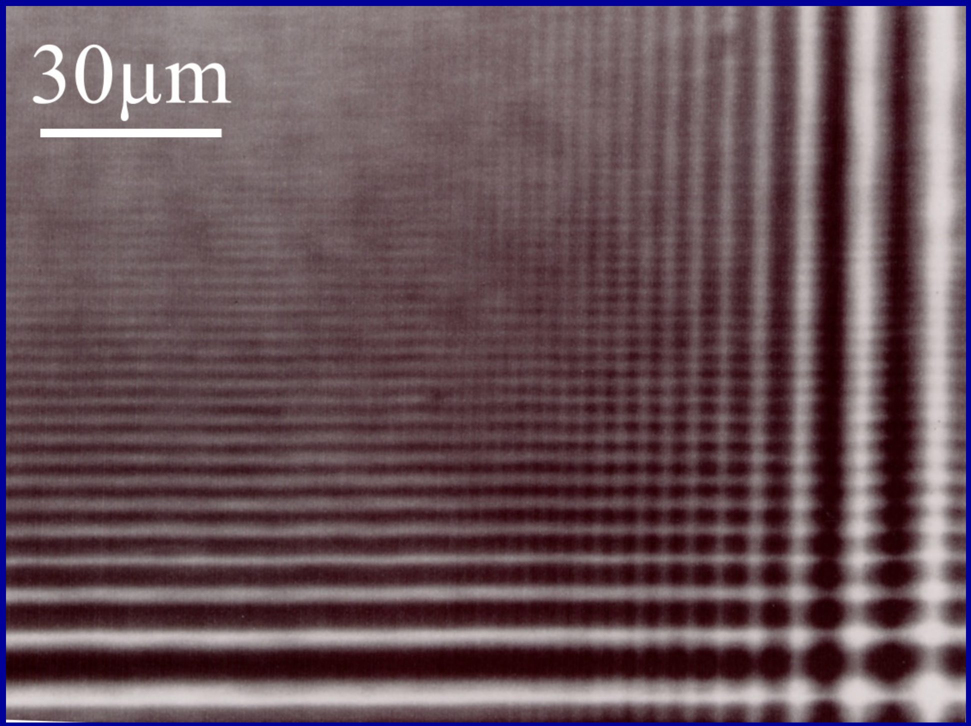
Al: 25.5keV
(f = 1.05m)

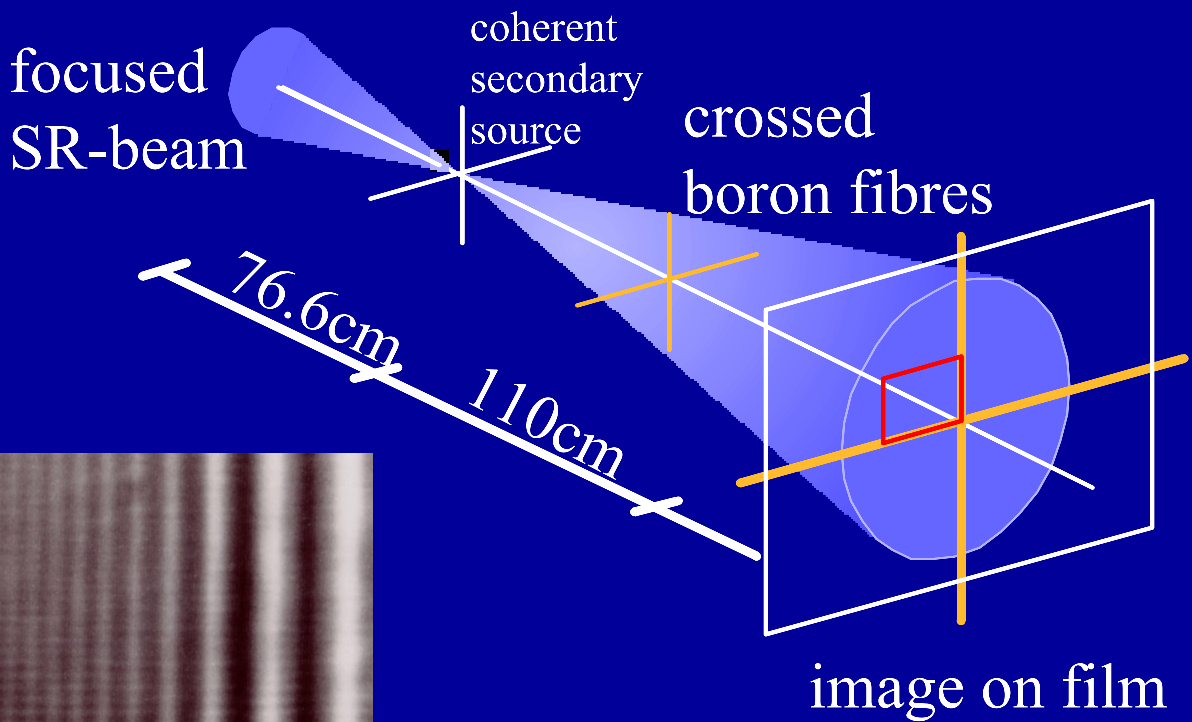
Be: 12keV (N = 91, f = 495mm, m = 10x)



Coherent Microsource

Energy: 14.4keV
CRL: $N = 50$
$f = 764$mm,
$d_{lat} = 451$nm,
spot size: 0.5µm





Lateral resolution of microscope

$d_{tr} = 0.75\ \lambda / 2\ N.A. = 0.75\ \lambda\ L_1 / D_{eff}$

D_{eff} decreases by photoabsorption

is ultimately limited by Compton scattering

D_{eff} typically 100 to 300 µm for Al

300 to 900 µm for Be (matched to U beam size)

resolution

achieved in Al: 350 nm

in Be: 100 nm (80 nm expected for this geometry)

expected in Be : about 50 nm (present technology)

ultimately 10 to 20 nm

see poster 6.49 on nanolenses today

Hard X-Ray Microscopy

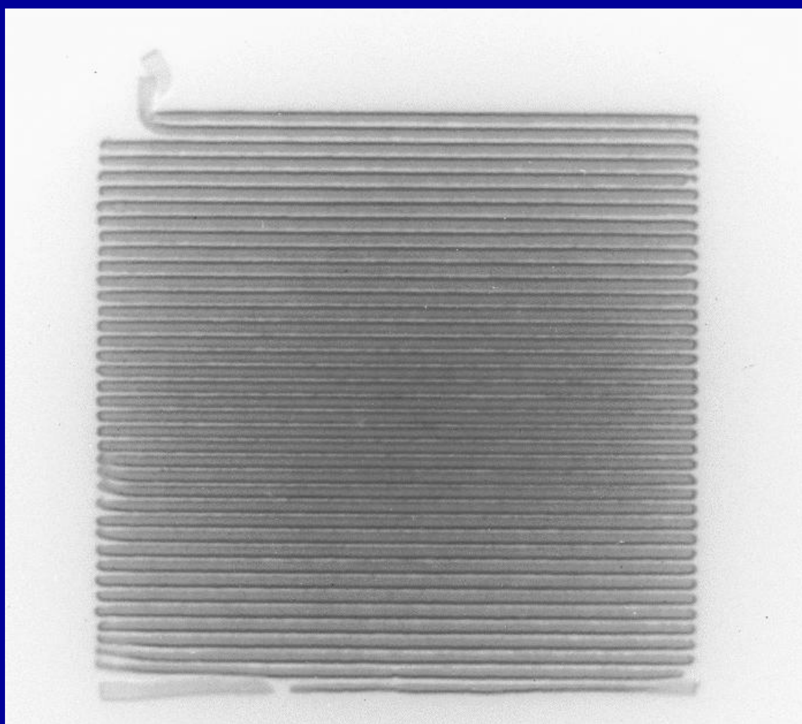
gold test structure:

- pitch: 2µm
- line width: 1µm
- thickness: 2µm

parameters of microscope:

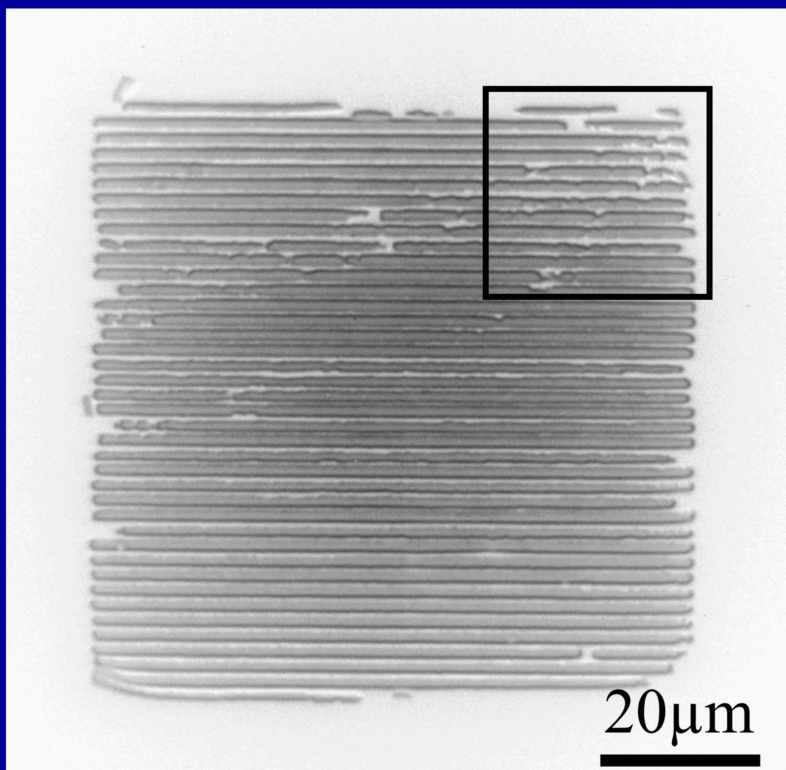
E = 25.5keV, N = 120 (Al)

f = 1.05m, magn.: 21x



Sample by C. Zimprich, RWTH

test structure with defects



Lateral Resolution

Demonstration of resolution:
conventional projection image:

10µm

high resolution x-ray camera
(FReLoN2000, E = 20keV)

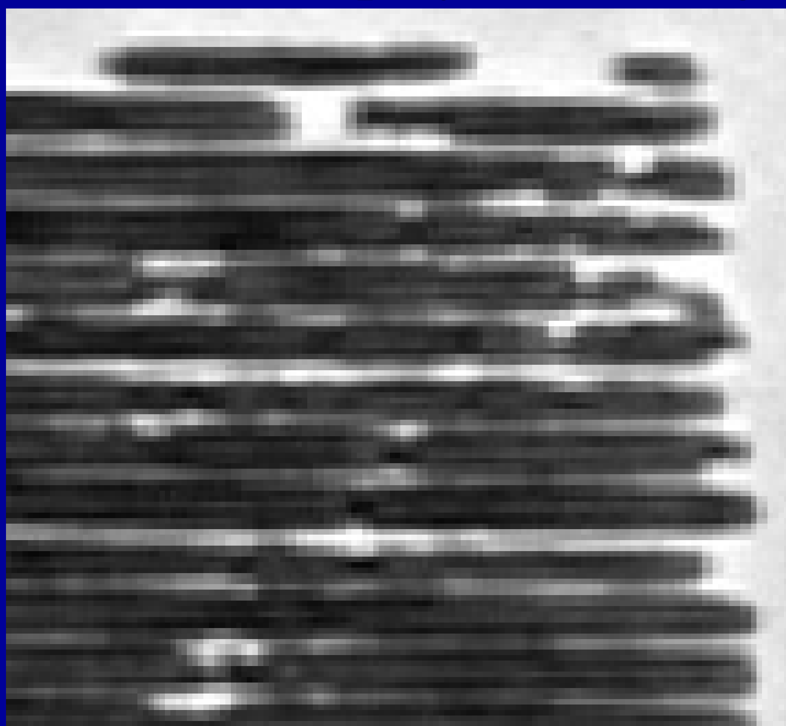
resolution about 0.8µm

limited by
- scattering in scintillator
- resolution of visible light optics.

Lateral Resolution

Demonstration of resolution:

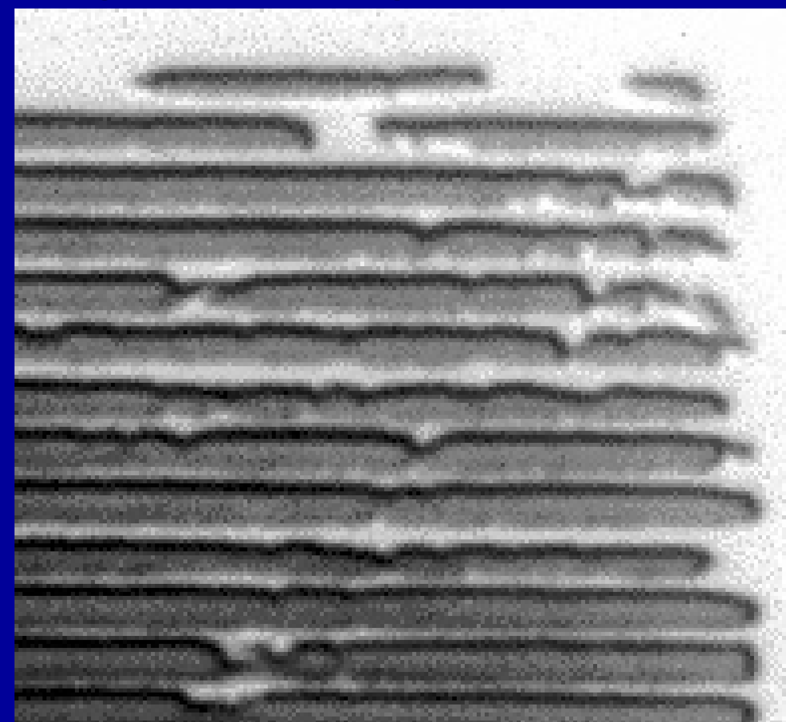
conventional projection image:



10µm

high resolution x-ray camera
(FReLoN2000 , E = 20keV)

magnified image:



Al objective lens (N = 120)
(E = 25.5keV, f = 1.05m,
m = 21x)

Lateral Resolution

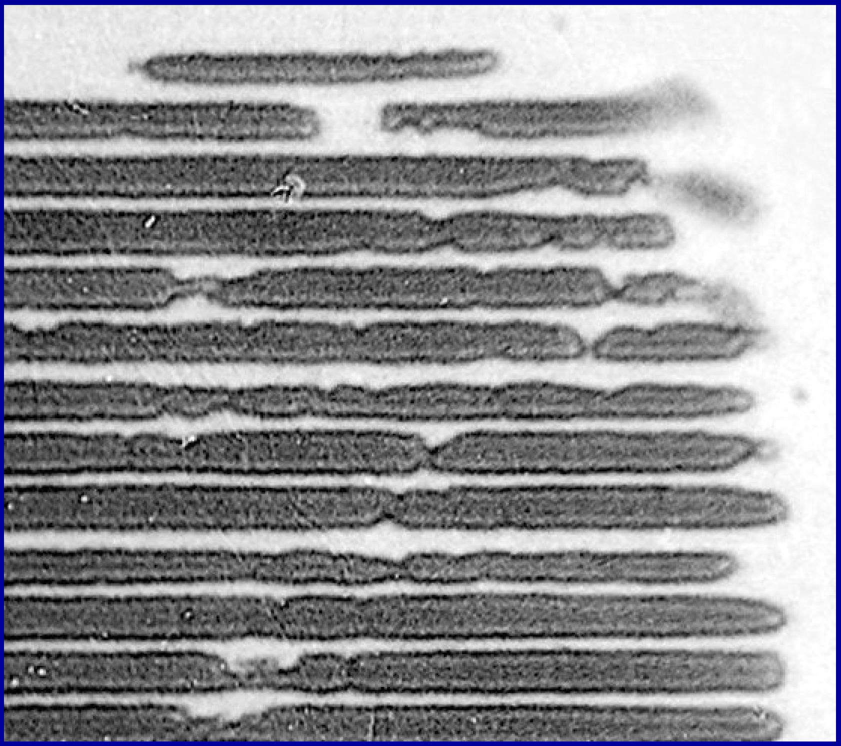
Demonstration of resolution:

conventional projection image:

10µm

high resolution x-ray camera
(FReLoN2000 , E = 20keV)

magnified image:

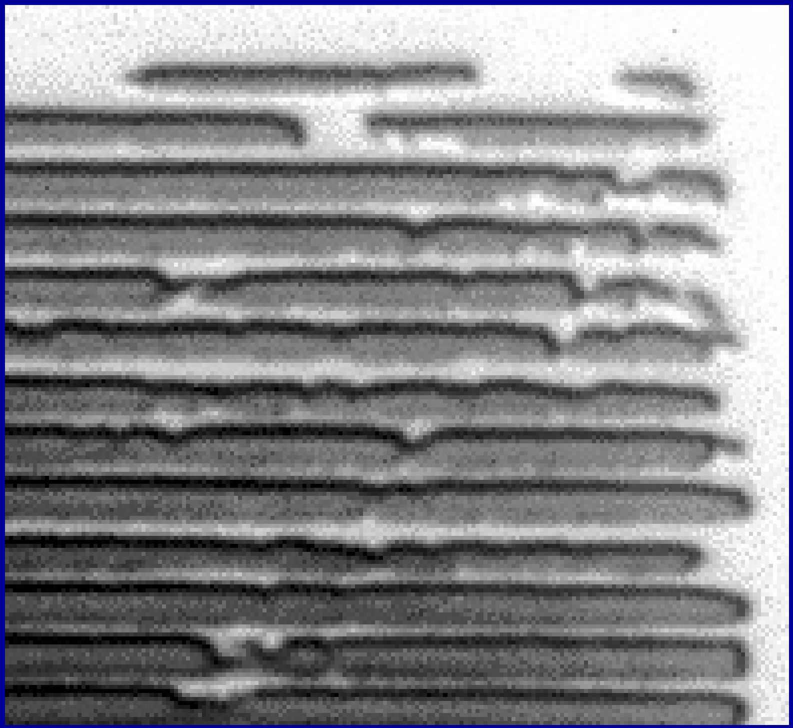


Be objective lens (N = 91)
(E = 12keV, f = 495mm,
m = 10x)

Lateral Resolution

Demonstration of resolution:

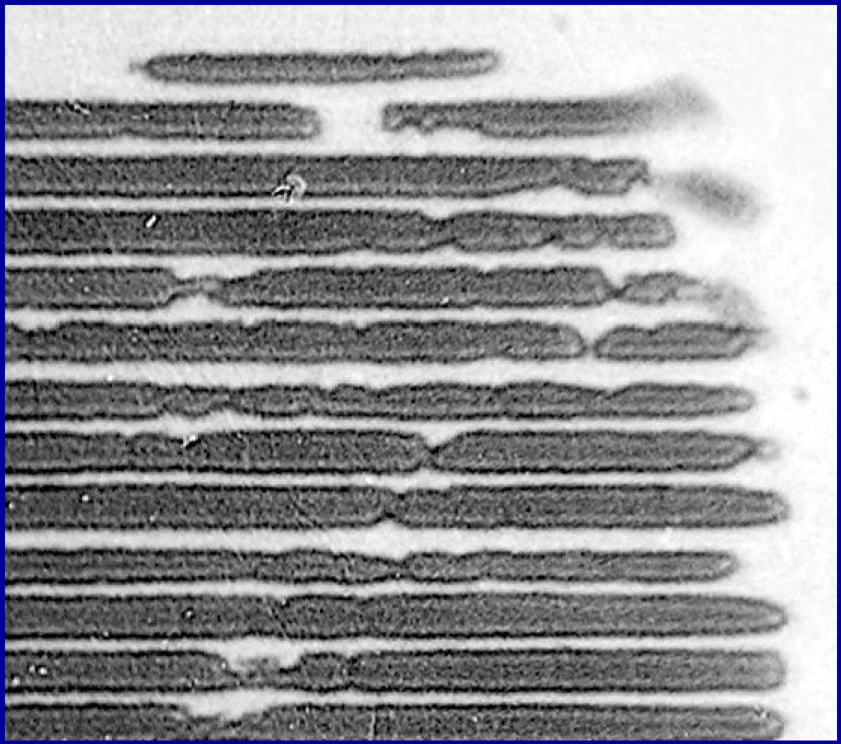
magnified image:



Al objective lens (*N* = 120)

(E = 25.5keV, f = 1.05m,
m = 21x)

magnified image:

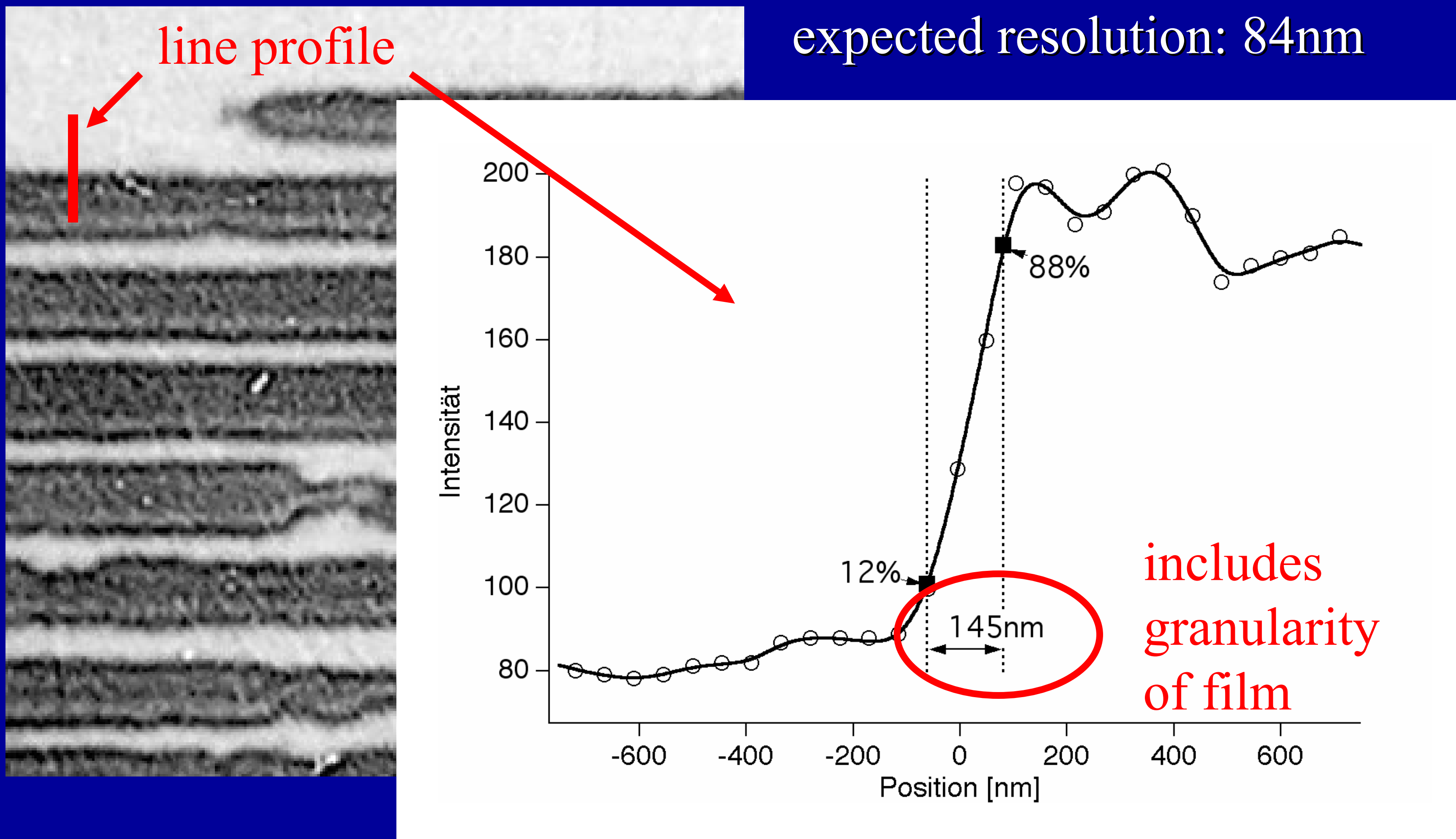


Be objective lens (*N* = 91)

(E = 12keV, f = 495mm,
m = 10x)

Lateral Resolution

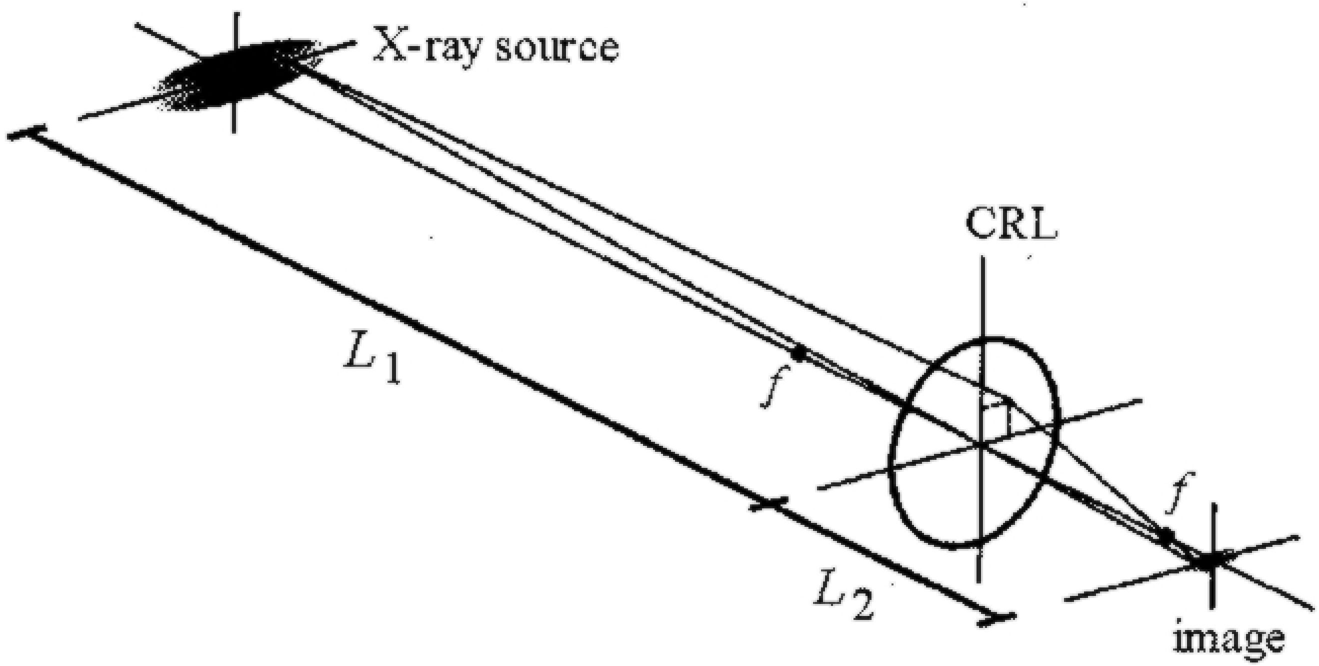
expected resolution: 84nm



→ deconvolution: optical resolution: 105nm ± 30nm

C. MICROBEAM GENERATED BY PARABOLIC Be LENSES

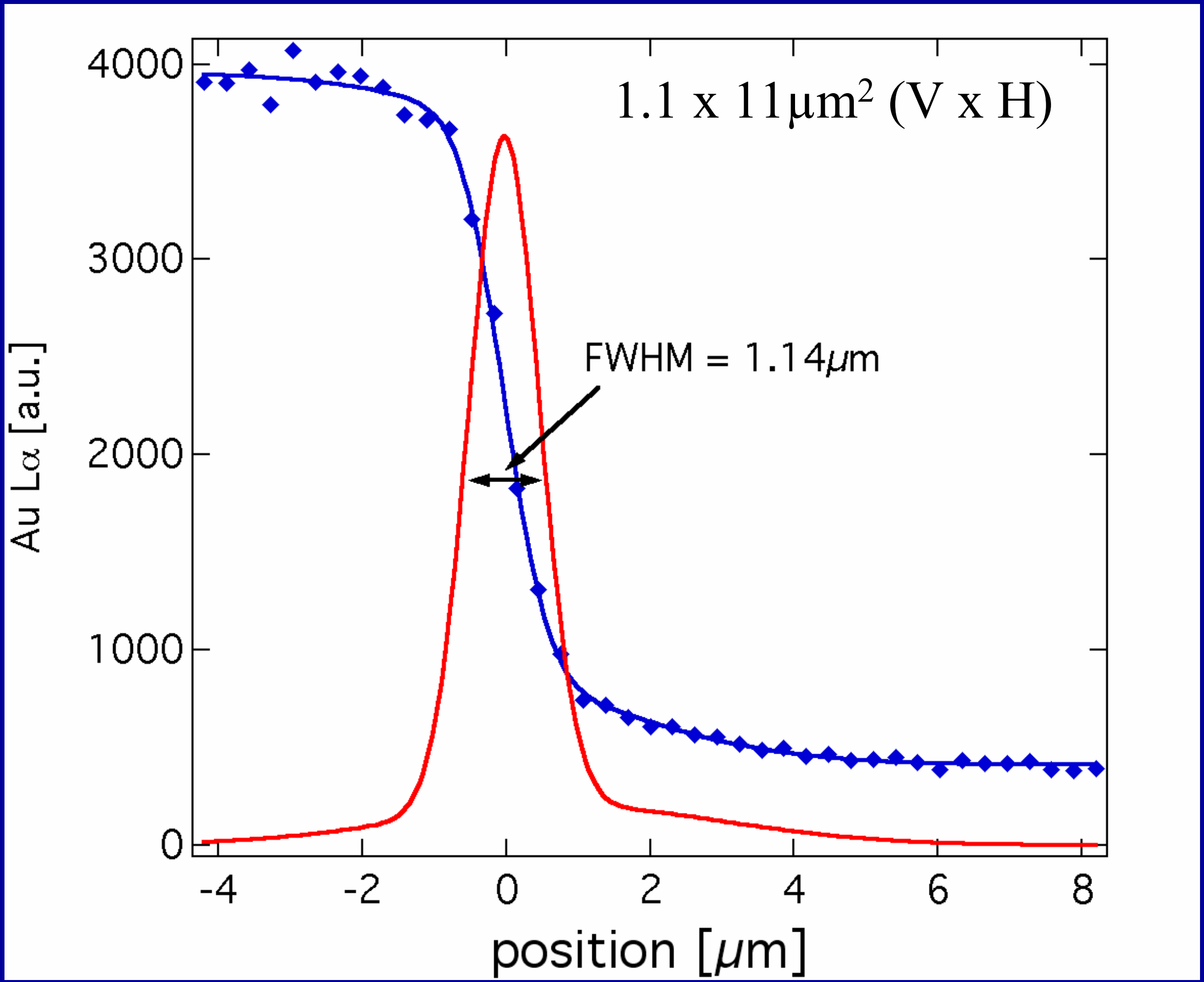
- parabolic lens images synchrotron radiation source onto sample



- x-ray microanalysis
  - diffraction choose $L_2 \ll L_1$ for small image !
  - fluorescence
  - absorption, small angle scattering ....

Microbeam ESRF ID22

Be lens ($N = 91$), $E = 12$keV, $L_1 = 41$m, $L_2 = 500$mm



flux in 1 x 1mm²:

$I_0 = 3.05 \cdot 10^{12}$ ph/s

flux behind lens:

$I_{tr} = 1.05 \cdot 10^{11}$ ph/s

lens cross-section:

0.024 mm²

⟶ $d = 170$µm

equivalent to ideal phase ZP with 275µm aperture.

- in the meantime d = 50µm is standard
- focal spot still limited by laws of geometrical optics

  i.e. by source size, by source to lens distance and by focal length
- ESRF undulator: source size 20µm FWHM in vertical

  => 100 to 200nm focal size to be expected,

  in reality often (much) larger due to jitter in mirrors, monochromator.

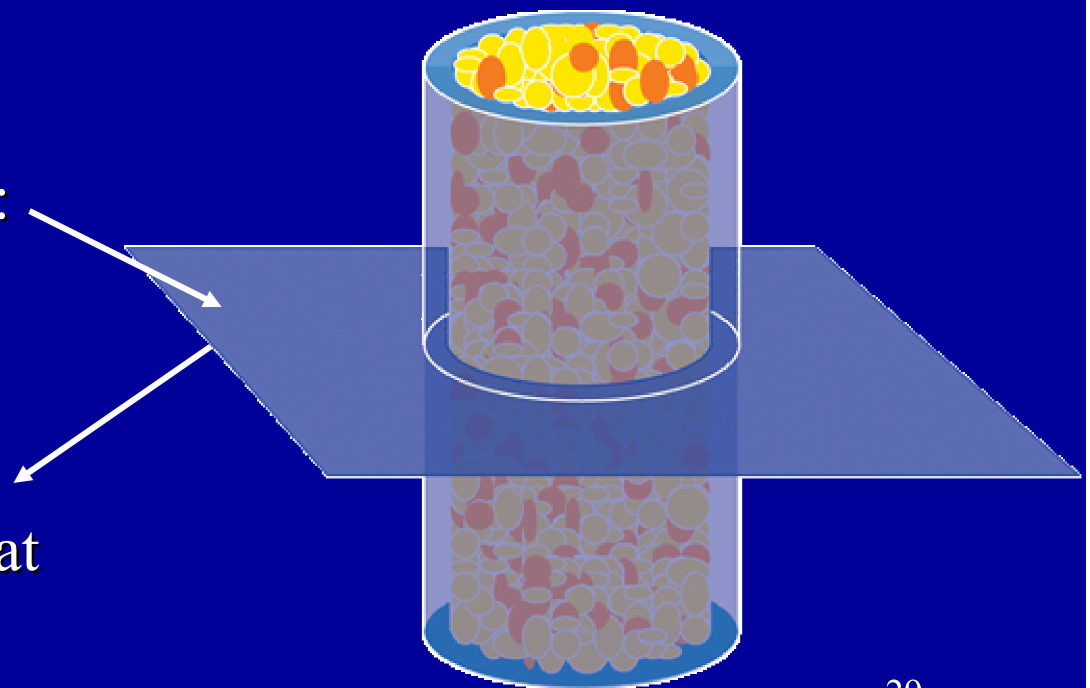
XANES Microtomography

Probe chemical state of a given element on a virtual section through the sample

nondestructive probe to the interior of sample

Sample:
CuO/ZnO catalyst + BN powder in glass capillary

virtual slice through sample:



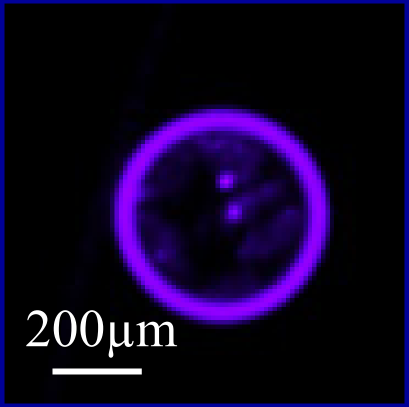
obtain absorption spectrum at each point of reconstruction

coop.: J.-D. Grunwaldt, A. Baiker, ETH Zürich

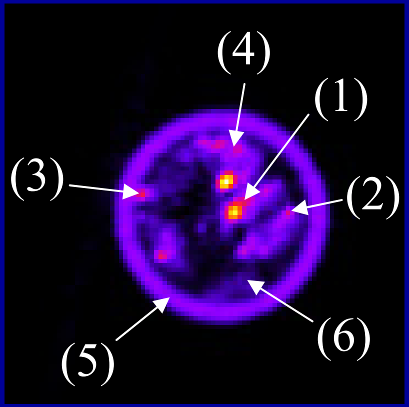
Reconstruction

At each energy: Standard filtered backprojection

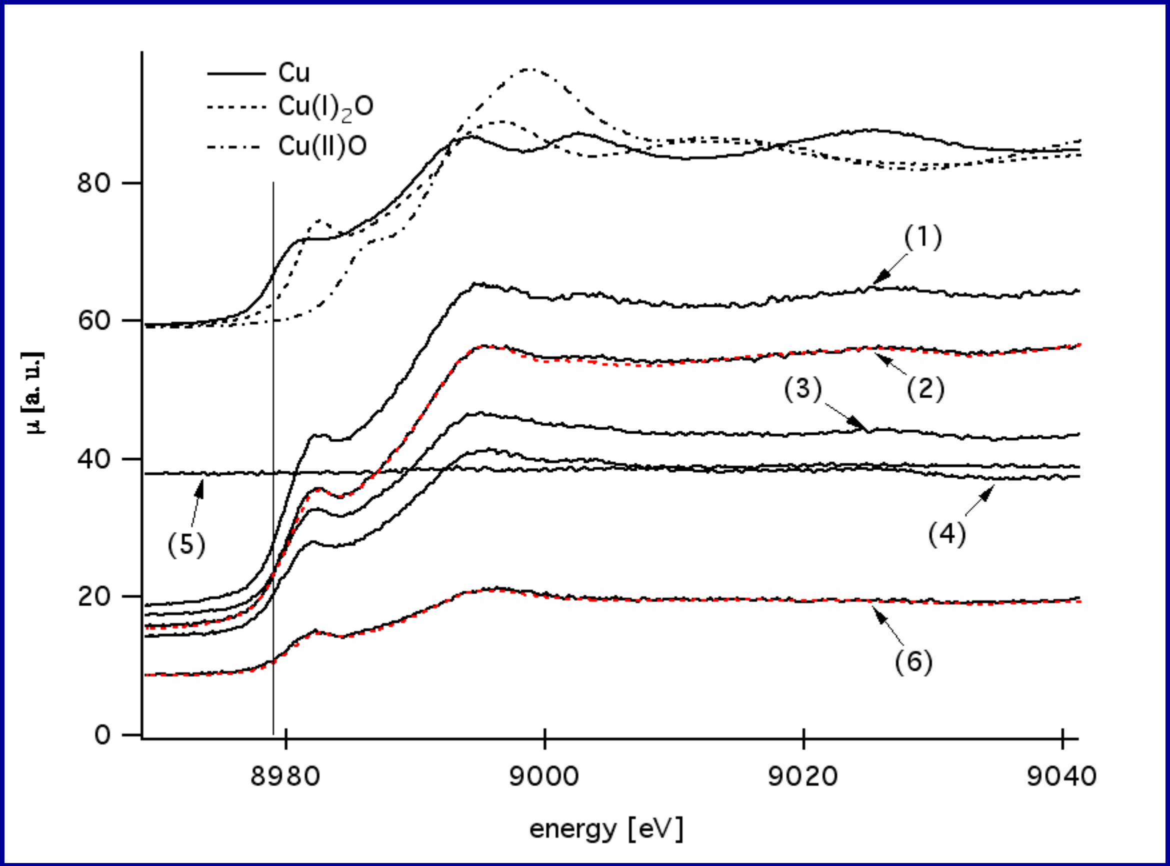
below Cu K-edge



above Cu K-edge

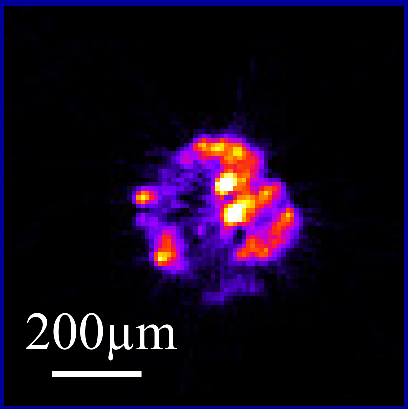


Reconstructed and reference spectra

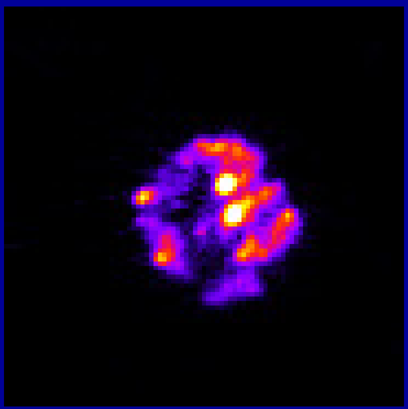


Distribution of Chemical Compounds

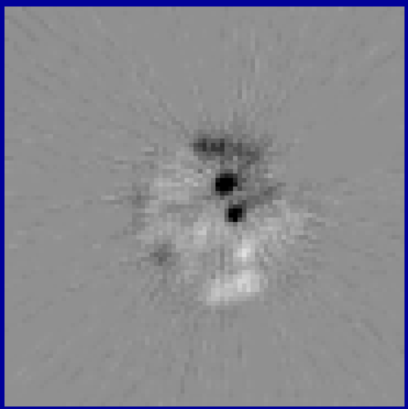
Cu (metallic)



Cu(I)$_2$O

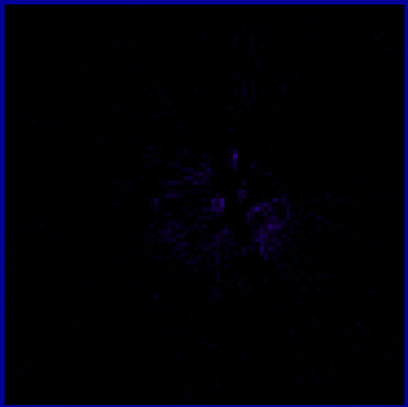


difference

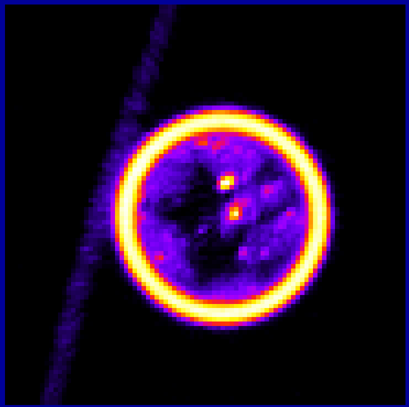


- Cu (metallic) + $Cu(I)_2O$ = difference

Cu(II)O



other elements



µ [a.u.]

see poster 10.22 tomorrow

Summary

- refractive lenses are excellent optical components for 5 to 120 keV,

  robust, stable in beam, easy to align and to operate, tunable

- well suited for imaging

  no spherical aberration

  large field of view

  lateral resolution: reached 100 nm, expected 50 nm

  limited by Compton scattering: 10 to 20 nm

- well suited for microfocus applications

  focus limited by geometrical optics

  large depth of field => tomography

- improvement: better quality Be with less small angle scattering!