REFRACTIVE X-RAY LENSES

NEW DEVELOPMENTS

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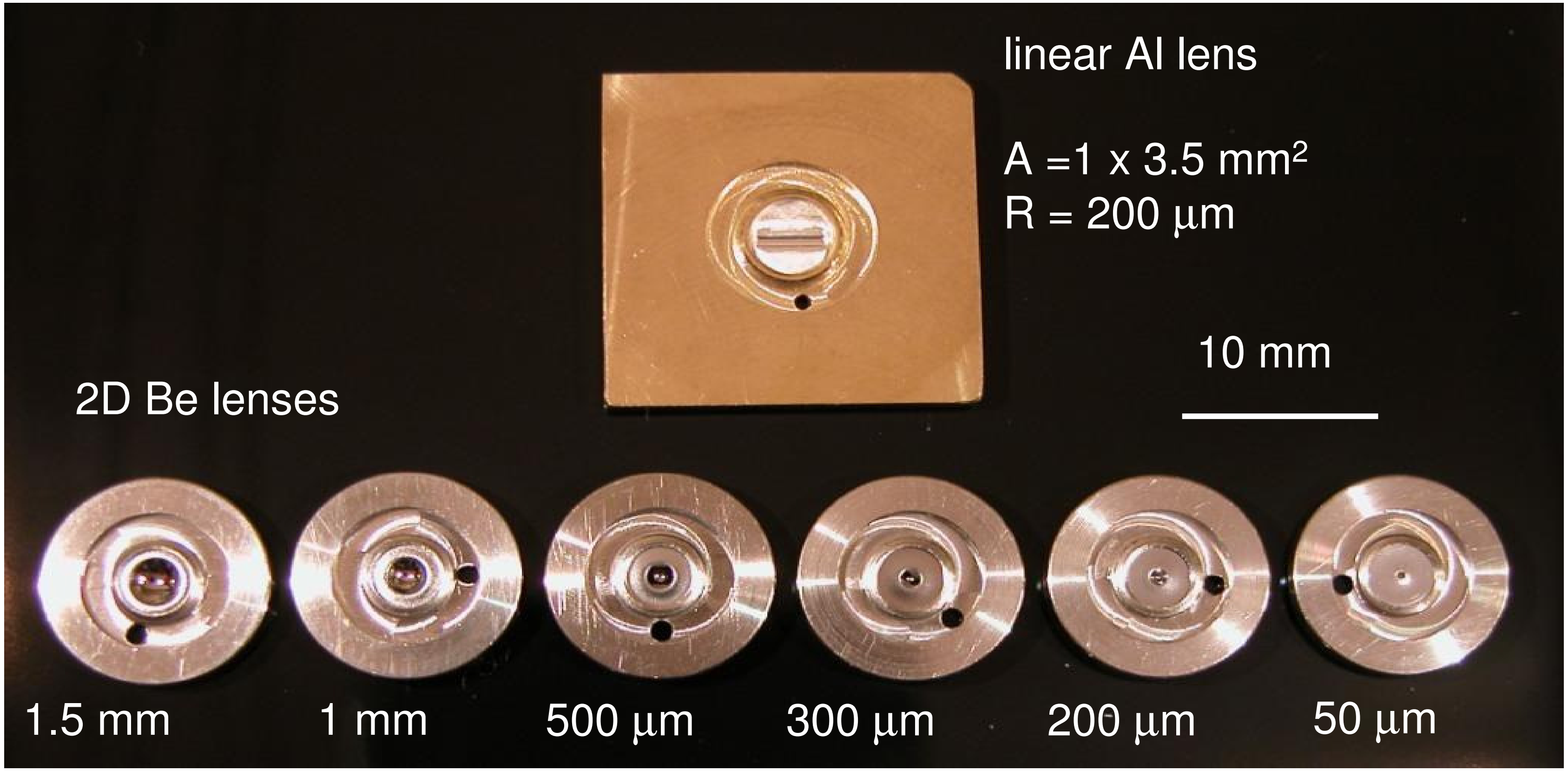
(2012)

Rotational parabolic and linear parabolic x-ray lenses

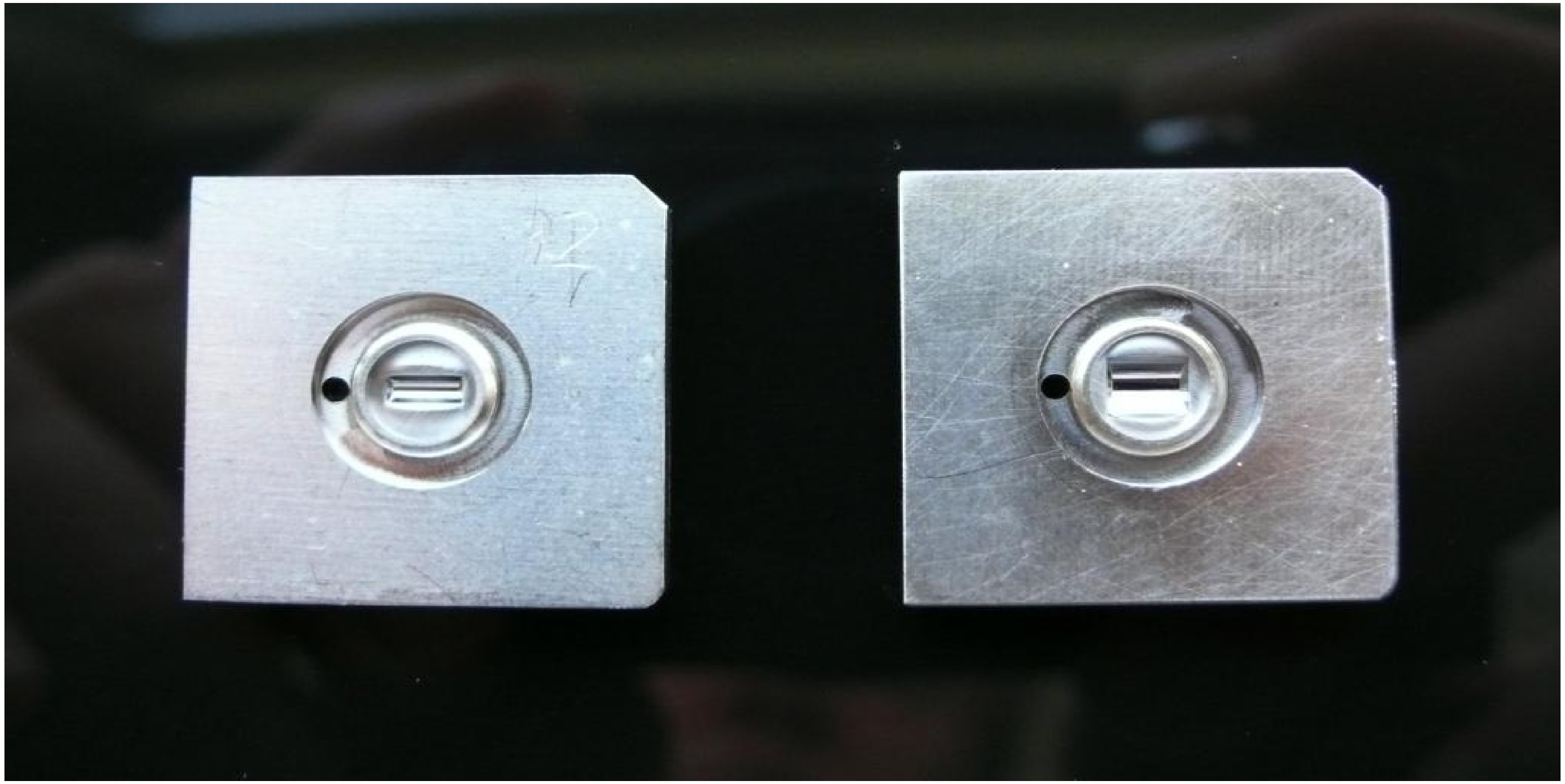
from RXOPTICS



Linear Be lenses (cylinder paraboloids)

length 2.5mm

R=500µm　　　　　　　　R=1500µm



A. HISTORY OF DEVELOPMENT OF REFRACTIVE X-RAY LENSES

1. W.C.Roentgen (1896)

found no refraction of x-rays by matter,
concluded that there are **no refractive lenses for x-rays**,
this statement is still found in most textbooks of optics.

2. P.Kirkpatrick, A.V.Baez (1948)

on search for x-ray optics:
realized the importance of low refraction and of strong absorption that hamper the fabrication of refractive x-ray lenses
mentioned the possibility to stack lenses in order to reduce the focal length,
gave up the idea of refractive lenses in favor of crossed mirrors which carry their names **(K-B mirrors).**

3. R.Gähler, J.Kalus, W.Mampe (1980)

Test of a **refractive neutron lens** developed for the search of a neutron charge:

2 biconcave cylinder lenses stacked behind one another with circular profile (radius 2.4mm), made of quartz, resulting in a focal length of 2.5m for cold neutrons of 20 A wavelength.

The possibility to transfer the concept to x-rays is not mentioned.

N.B.: materials for neutron lenses should have a large coherent cross-section and small incoherent and absorption cross-sections.

4. S.Suehiro, H.Miyaji, H.Hayashi (1991)

considered **one spherical biconcave lens of high Z material** (Au, Pt, W)
no follow-up of idea

5. B.X.Yang (1993)

considered **one parabolic lens of low Z material**
saw problems in manufacturing this lens
proposed Fresnel lenses instead of refractive lenses

6. T.Tomie (1994-1997)

proposed row of **drilled holes in a straight line**
=> stacking of individual lenses reduces focal length
alignment problem is solved

patent: Japan 1994
USA, Germany 1995
USA 1997

presented at XRM conference Wuerzburg (August 1996)

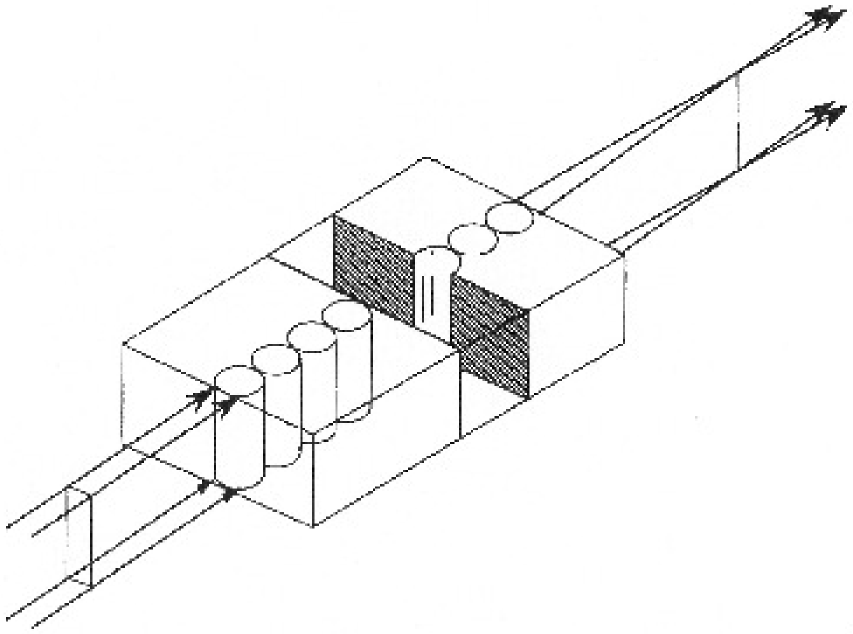
X-RAY LENS

U.S. Pat. No. 5,684,852. Date of Patent Nov. 4, 1997

Inventor: Toshihisa TOMIE
Electrotechnical Laboratory,
Agency of Industrial Science and Technology,
Ministry of International Trade and Industry

Related U.S.Application Data:
Division of Ser.No.389,503, Feb. 16, 1995, Pat. No. 5,594,773

Foreign Application Priority Data
Feb. 18, 1994 Japan



BUT:

* idea was not tested by author

* linear lens with strong spherical aberration

* rough cylinder surfaces

* it is difficult to control the form fidelity:
drilling of a hole deforms the adjacent hole

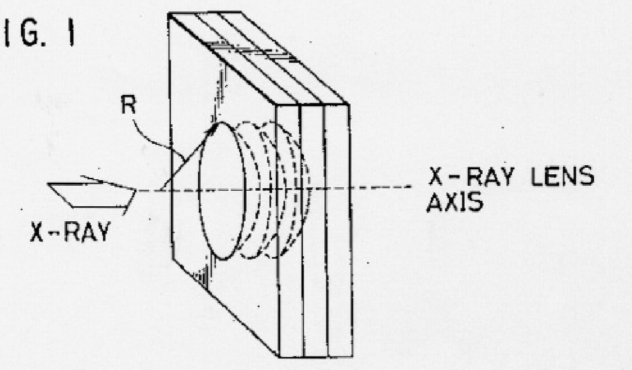
The stacking of individual lenses is explicitely excluded in the patent as not feasible!

Patent: X-ray lens

T. Tomie

U.S. Patent 1997
5,684,852

FIG. 1



…

(3) The total focal distance f_T can be reduced to f/N by cascading N X-ray lenses of long focal distance f, as shown in Fig. 1. In this configuration, however, many unit X-ray lenses have to be arranged after fabricating the individual unit X-ray lenses. The thickness of each unit X-ray lens has to be very thin to avoid strong absorption of X-rays, making each unit X-ray lens very fragile and difficult to handle. Moreover, aligning the optical axes of all unit X-ray lenses along the X-ray lens axis with high precision would be extremely difficult. **Hence, arranging many X-ray lenses in the configuration shown in Fig. 1 is practically impossible.**

…

7. A. Snigirev, I. Snigireva, V. Kohn, B. Lengeler (1996)

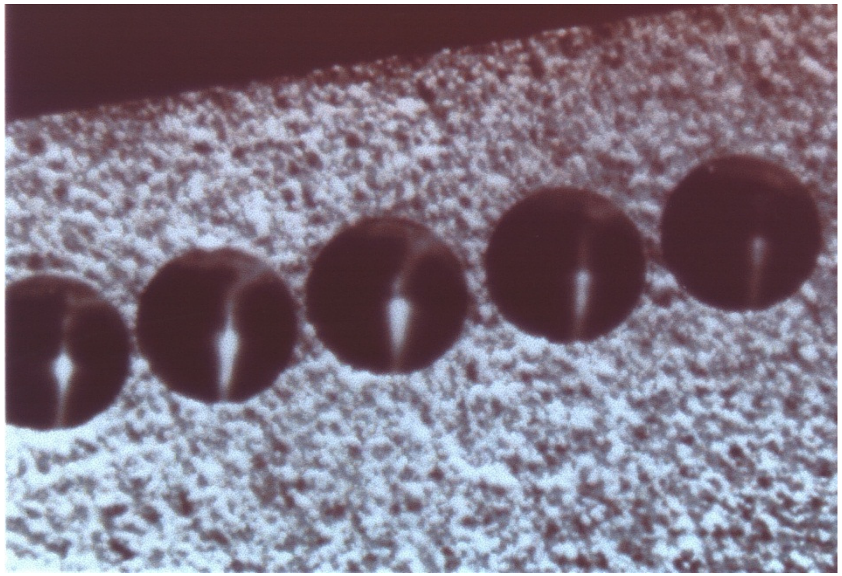
Nature 384, 49 (1996)

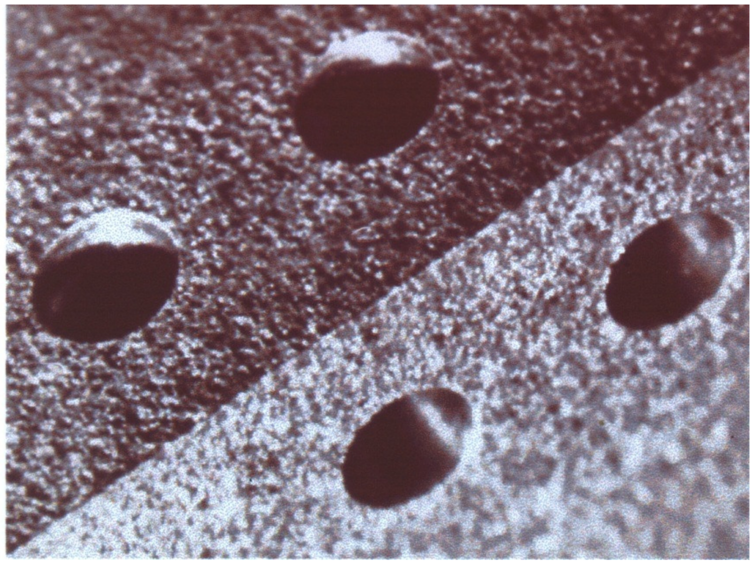
received 19 June 1996, accepted 19 September 1996.

first realisation and test of refracting x-ray lens (linear row of drilled holes in Al and later in Be)

=> showed feasibility of these lenses

=> not suitable as an optical device





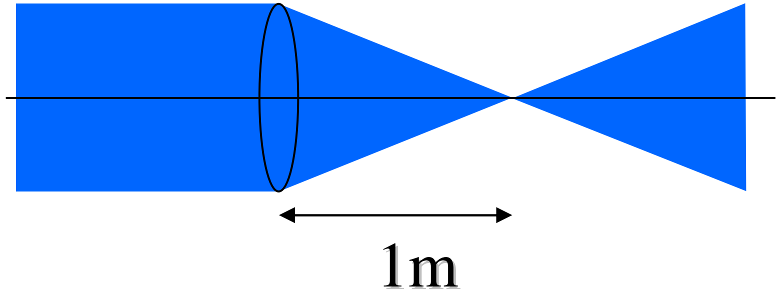
beryllium lenses with holes 0.5 mm in diameter

B. Strategy for refractive x-ray lenses

> **have been considered as not feasible for a long time**

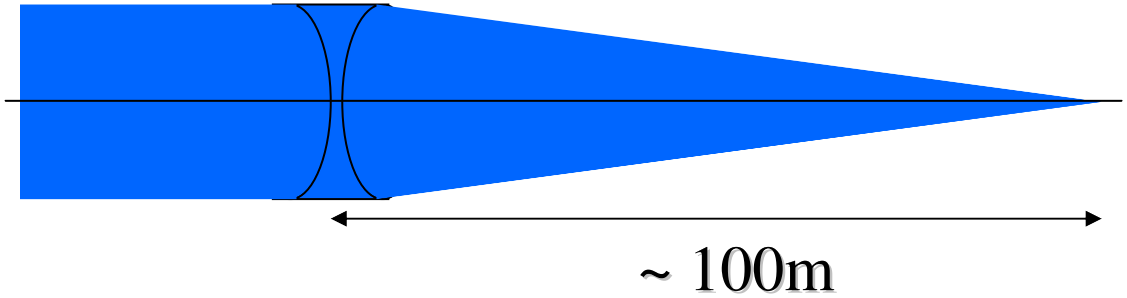
> **visible light**: index of refraction $n = 1 + \delta$ with $\delta \sim 0.5$ for glass

* refraction strong
* absorption weak
* focal length short
* focusing lens convex



> **x-rays**: $n = 1 - \delta + i\beta$ with $\delta, \beta \sim 10^{-6}$ and positive

* refraction weak
* absorption strong
* focal length long
* focusing lens concave



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

BUT: **refraction is not zero and absorption is not infinite!**

Substantial improvement in design and manufacturing made at Aachen University and at RXOPTICS

* **parabolic** form is a must!
* **biconcave** form is a must!
* **stacking of many individual lenses in a row with µm precision was achieved**
* **low Z material**
* in the mean time more than 4000 lenses (rotationally parabolic and cylinder parabolic) made in Be, Al and Ni have been delivered to 11 synchrotron radiation sources in 9 countries.
* 1996-2010: more than 600 publications on and with refractive x-ray lenses
* at ESRF: about 50% of beamlines equipped with refractive x-ray lenses.
* others took over the concept: SPring8, ANKA, Kurchatov.

Design of refractive x-ray lenses

lensmaker formula: $\frac{1}{f} = (1-n)\frac{2}{R}$ or $f = \frac{R}{2\delta}$

$$\delta = 2.70(\lambda^2 \rho Z / A)10^{-6}$$

λ in Angstrom
ρ in g/cm³
Z atomic number
A atomic mass in g

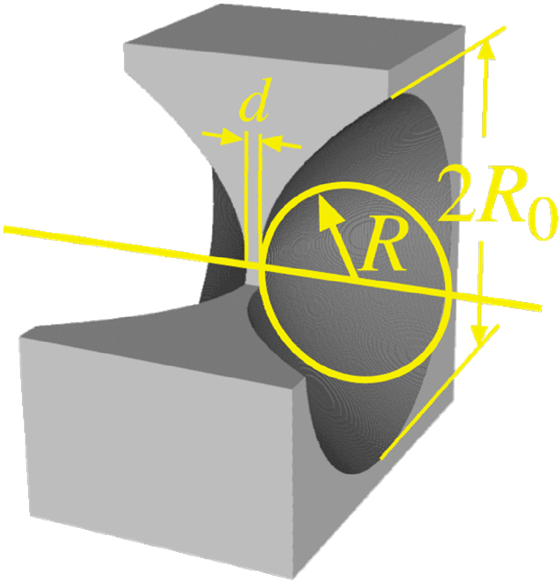
To obtain a **small focal length**:

small radius of curvature R: down to 50µm
high density of lens material

Requirements on refractive x-ray lenses

i). Lens surfaces must be parabolic

single 2D-lens



parameters for Be lenses:

$R = 50$ to $1500\mu m$

$2R_0 = 0.45$ to $2.5mm$

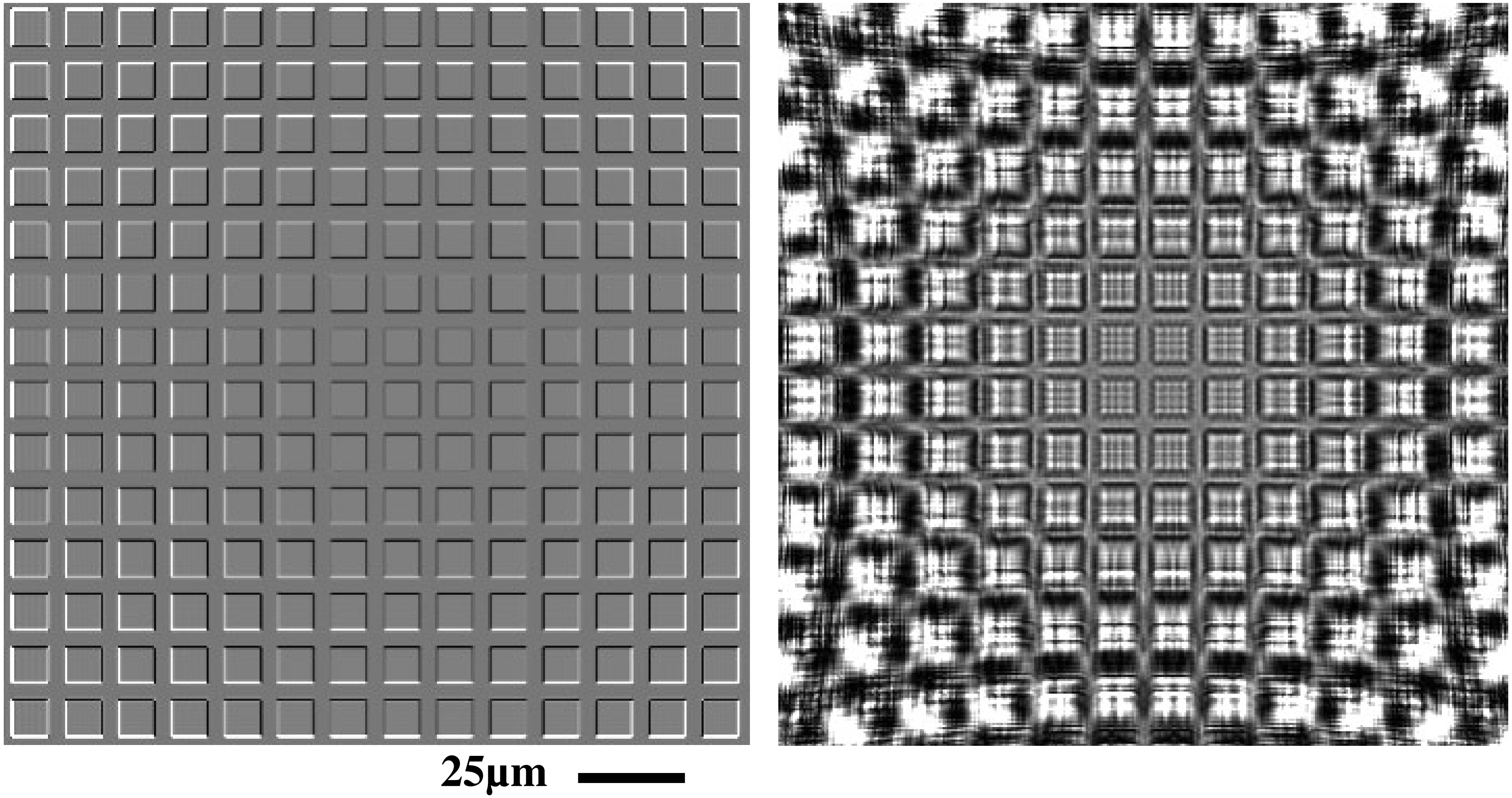
d below $30\mu m$

parabolic profile: no spherical aberration
focusing in full plane

=> excellent imaging optics

Comparison parabolic versus spherical lens

parabolic spherical



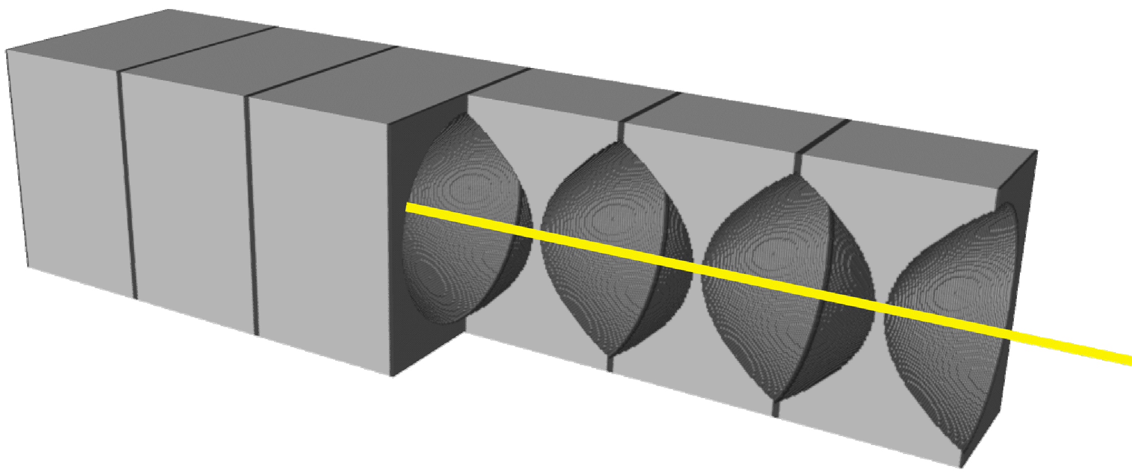
25μm

spherical lenses are inappropriate for imaging!

ii). stacking many lenses in a row

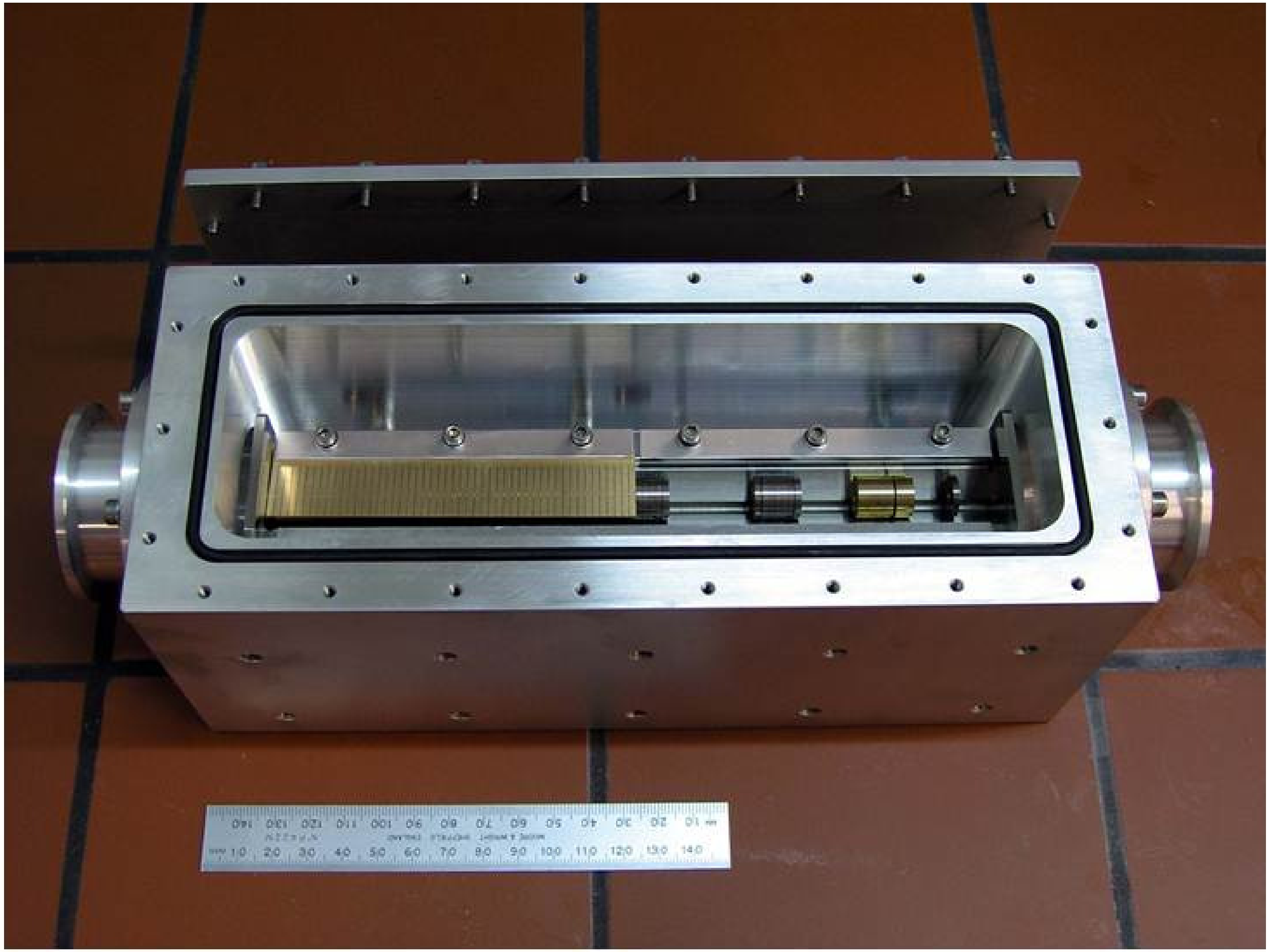
$$f = R / 2\delta N \qquad (\text{thin} - \text{lens})$$

variable number of lenses : N = 1 to about 300
Precision of stacking: better than 1µm



typical: f = 0.2m - 10m

LENS **CASING by RXOPTICS** (can be integrated in vacuum of beam line)



iii). Thick lenses

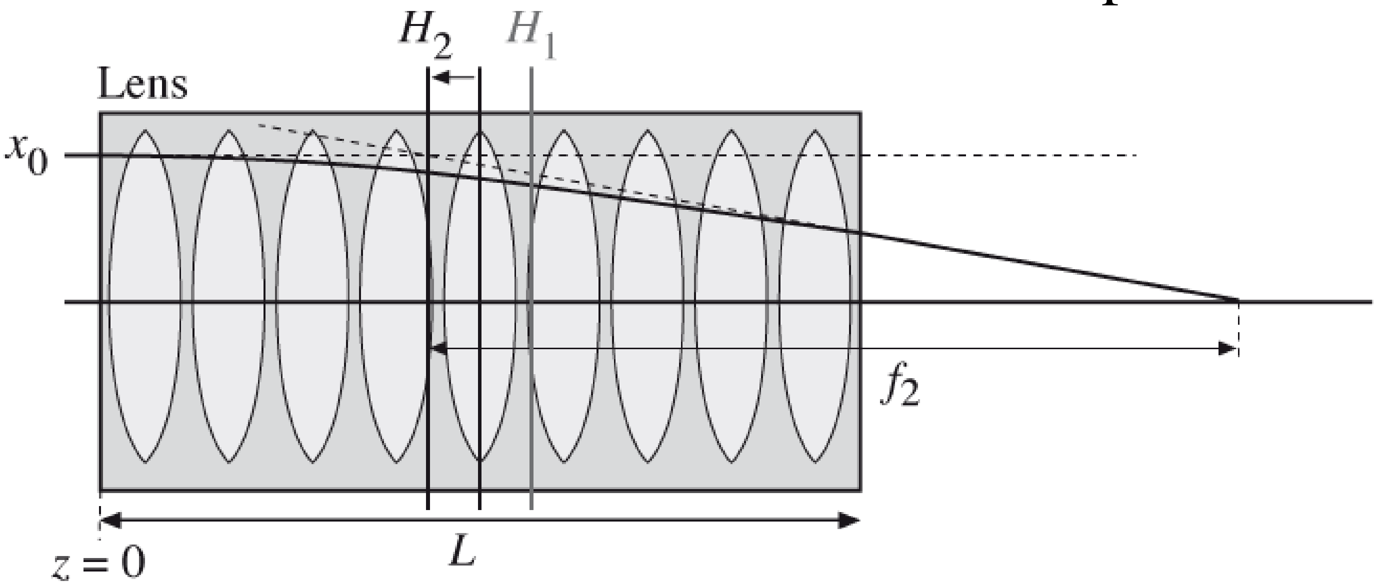
* if $L \ll f$ (thin lens): $f_0 = R / 2\delta N$

* if L comparable to f : rays are bent towards optical axis inside lens

$$r(z) = R_0 \cos \kappa z \qquad \kappa = \sqrt{\frac{2\delta}{RF}}$$

refracting power/length

F: thickness of lens platelet



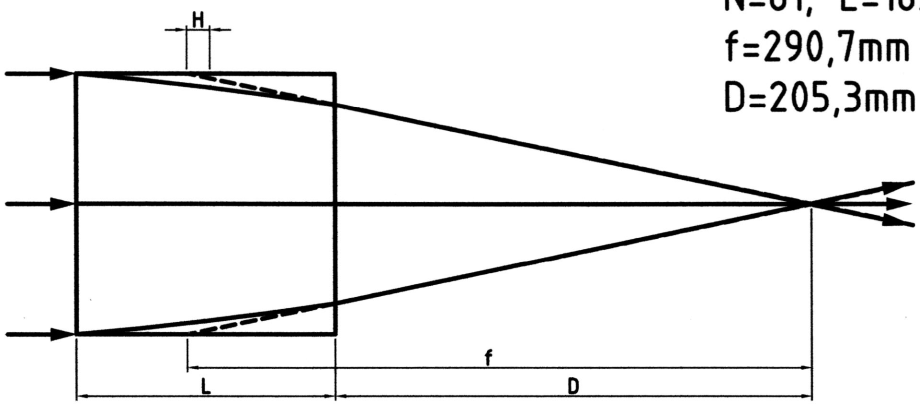
Focal length of thick lens

$$f = f_0 \frac{\sqrt{L/f_0}}{\sin\sqrt{L/f_0}}$$

L length of lens stack ($N*2z_0$)

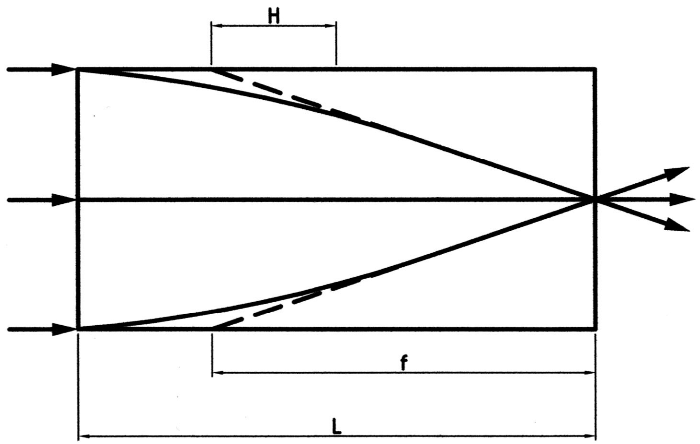
$f_0 = R / 2\delta N$ thin lens approximation

Minimal focal length achievable with Be, R = 50µm at 17 keV



N=81, L=162mm
f=290,7mm f_0=261,7mm
D=205,3mm

Be R=50µm
$2R_0$=447µm
17 keV, 0,7295A
2δ=2,359 10^{-6}
µ=0,4903/cm



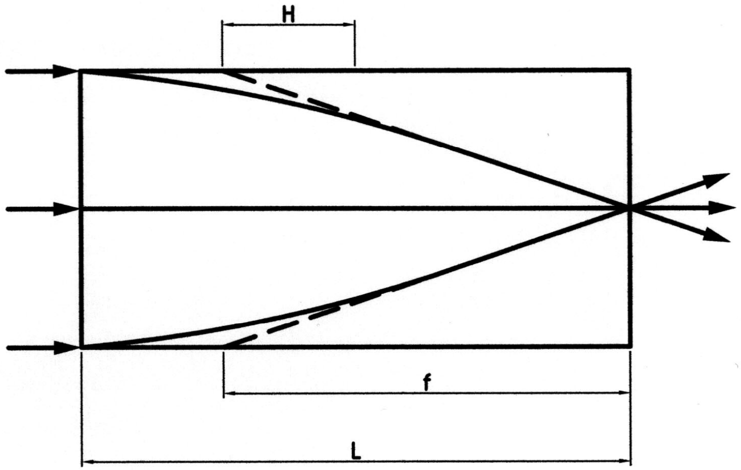
N=162, L=324mm
f=205,9mm, f_0=130,8mm
D_{eff}=295,0 µm
d_{tr}=42,0nm (diffraction limit)

=> effective aperture : 295µm

=> best lateral resolution: 42nm (diffraction limit)

For lenses with constant refracting power:

number of lenses in the stack can be reduced slightly without loss of performance (the last lenses do not refract any more)



N=162, L=324mm
f=205,9mm, f =130,8mm
D=0

D_{eff}=295,0 μm
d_{tr}=42,0nm

Be R=50μm
$2R_0$=447μm
17 keV, 0,7295A
2δ=2,359 10^{-6}
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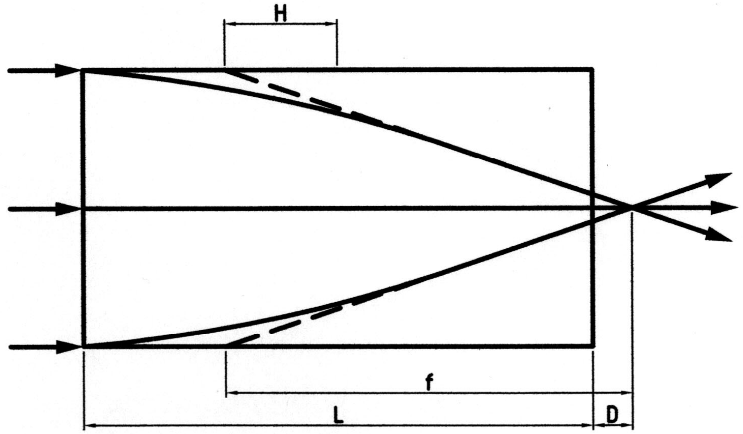


N=150, L=300mm
f=207,2mm f =141,3mm
D=23,5mm
D_{eff}=287,7 μm
d_{tr}=43,3nm

iv). **Lens material** must be mechanically, thermally and chemically stable:

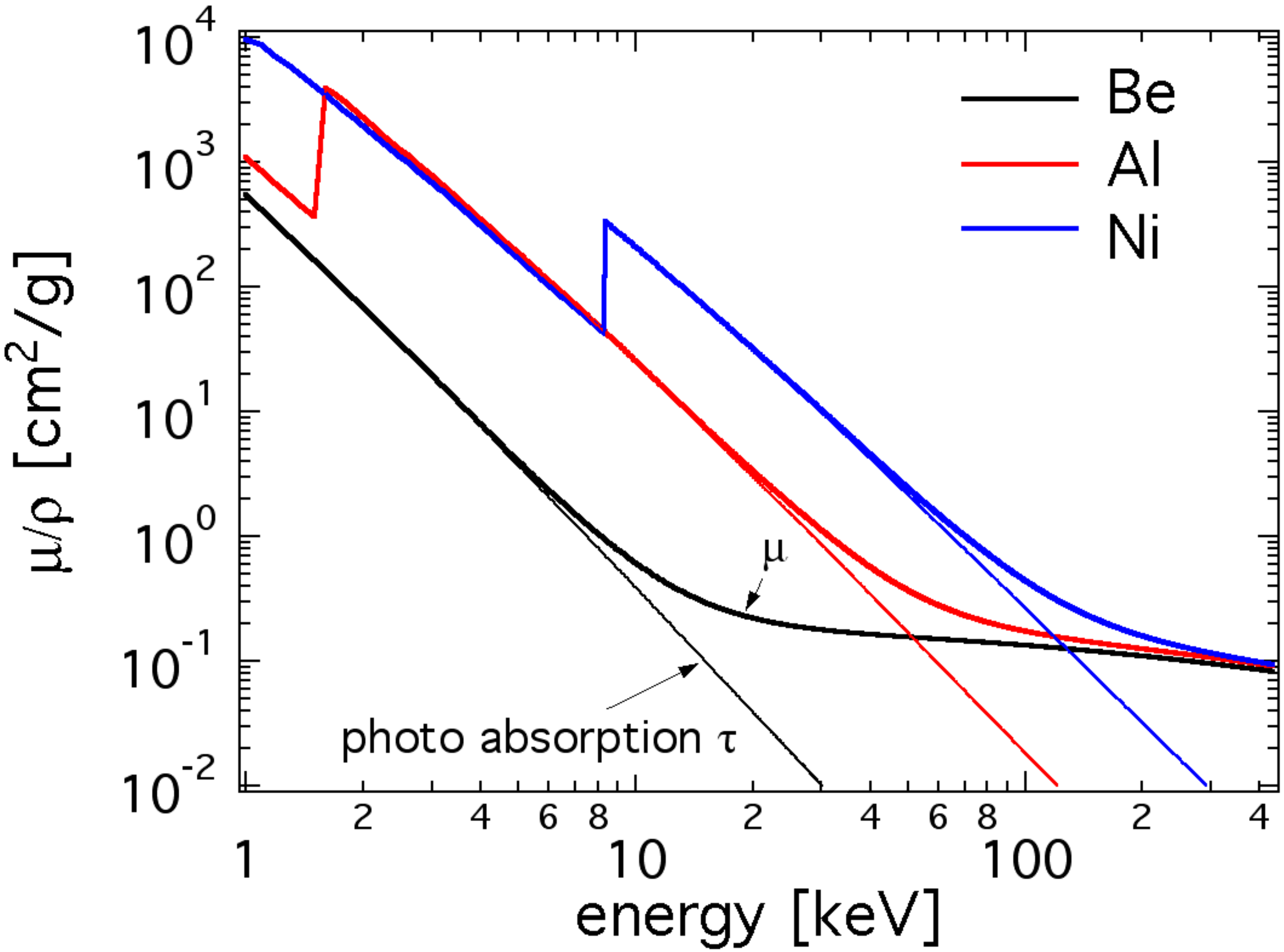
metals are the best choice! (no radiation damage)
plastic is destroyed more or less fast in the x-ray beam!

v). **low Z lens material**:

mass absorption cofficient $\mu / \rho \sim Z^3 / E^3$

candidates: **Be**, B, C, **Al**, **Si, Ni**

Attenuation of x-rays in typical lens materials



Ultimately, **Compton scattering** limits transmission at high x-ray energies!

Refractive x-ray lenses available at RXOPTICS

- material: Be 2 to 40 keV
  Al 40 to 80 keV
  Ni 80 to 150 keV

- profile: rotationally parabolic (2D)
  cylinder parabolic (1D)

- radii R at apex and geometric aperture $2R_0$

  R = 50, 100, 200, 300, 500, 1000, 1500µm …..
  $2R_0$ = 450, 632, 894, 1095, 1414, 2000, 2450µm …..

  length of 1D-lenses: 2.5mm
  lenses with R = 2000, 2500, 3000, 4000, 5000 and 5800µm
  (mainly for XFEL) are also available now.

- small radii for imaging and focusing
  large radii for prefocusing and for parallelisation.

A few examples: **for 1m focal length by lenses with R=50μm**

E (keV)	material	2δ (10^{-6})	N	f (m)
12.4	Be	4.4341	11	1.025
17	Be	2.3591	21	1.009
40	Be	0.4261	117	1.003
40	Al	0.6746	74	1.002
80	Al	0.1687	296	1.002
80	Ni	0.5515	91	0.996

How close can you adjust the focal length f (e.g. at 10 keV) ?

N \ R	200µm	300µm	500µm	1000µm
4	7.334 m	11.001 m	18.334 m	36.668 m
3	9.778 m	14.667 m	24.446 m	48.891 m
2	14.667 m	22.001 m	36.668 m	73.336 m

stacking of different lenses $$\frac{1}{f} = \sum_j \frac{1}{f_j}$$

for f=8m : 3*R=200µm and 1*R=300µm : f=8.000

for f=9m : 3*R=200µm and 1*R=1000µm : f=9.167m

if possible and needed: choose E=9.908keV

then 3*R=200µm and 1*R=1000µm gives f=9.000m

More flexibility by lenses with larger R!

C. Properties of refractive x-ray lenses

In the following we consider mainly Be, Al and Ni

1. Energy range

Be : about 2 to 40keV

d guaranteed below 50µm, typically 30µm

Al : about 30 to 80 keV

d guaranteed below 30µm, typically 22µm

Ni : about 80 to 150 keV

d guaranteed below 20µm, typically 10-16µm

2. Material properties

Beryllium

manufactured by powder metallurgy
contains up to 1wt% of BeO
contains many grain boundaries
=> small angle x-ray scattering
results in background radiation

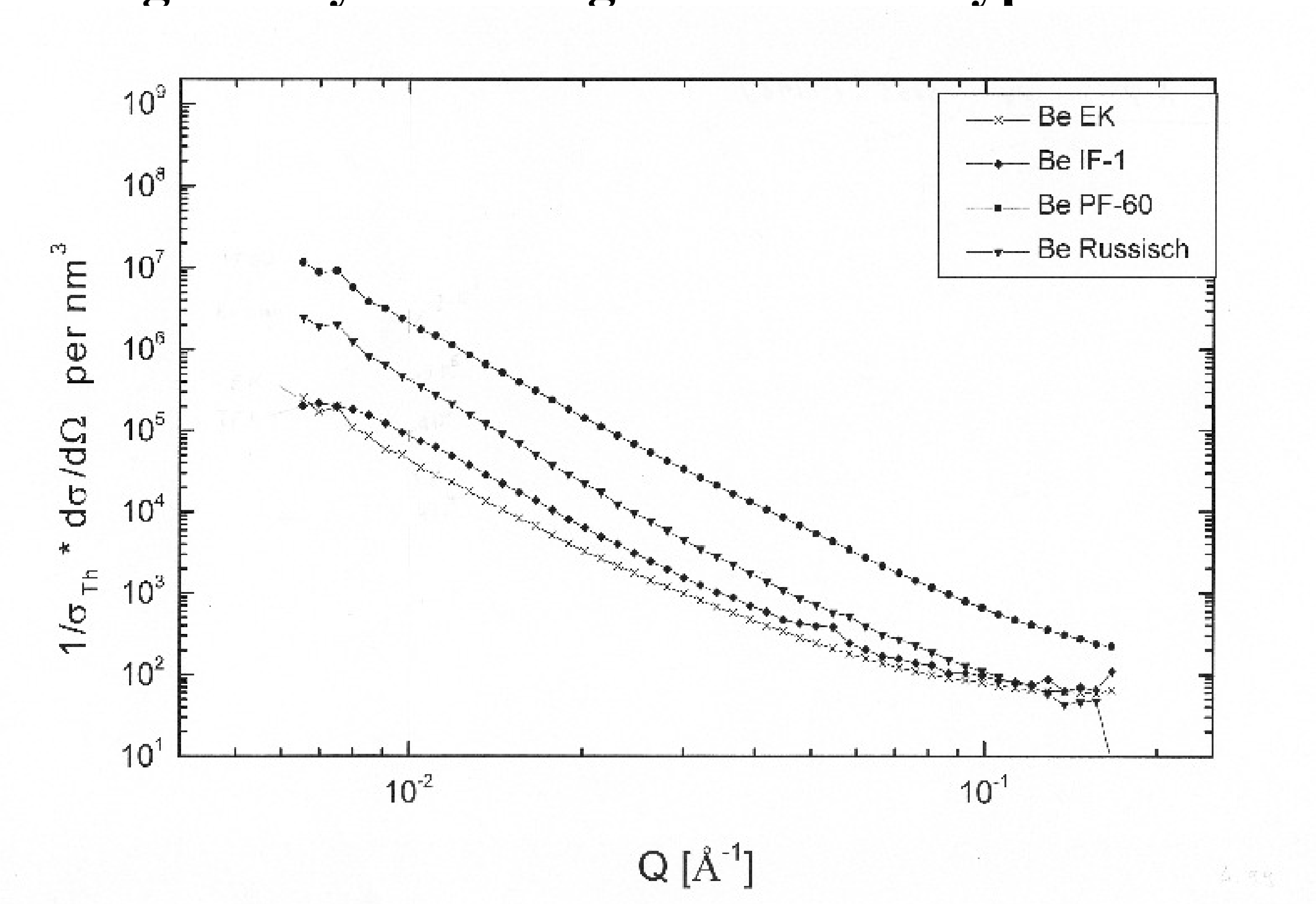
density : 1.85 g/cm³

melting point : 1287 °C

recrystallisation: about 600°C (depending on quality)

main supplier: MATERION- BRUSH-WELLMAN

Small-angle x-ray scattering in different types of Be



PF-60 is standard Be from BW

IF-1 has 20 times less SAXS than PF-60

only 2 times more SAXS than single crystal (EK)

BERYLLIUM from Materion-Brush-Wellman

wt-ppm	BeO	Fe
PF60, I70H	<7000	600 -700
O30H	4000	900
IF1	100 - 600	250

IF1 only available as 0.5mm plates!

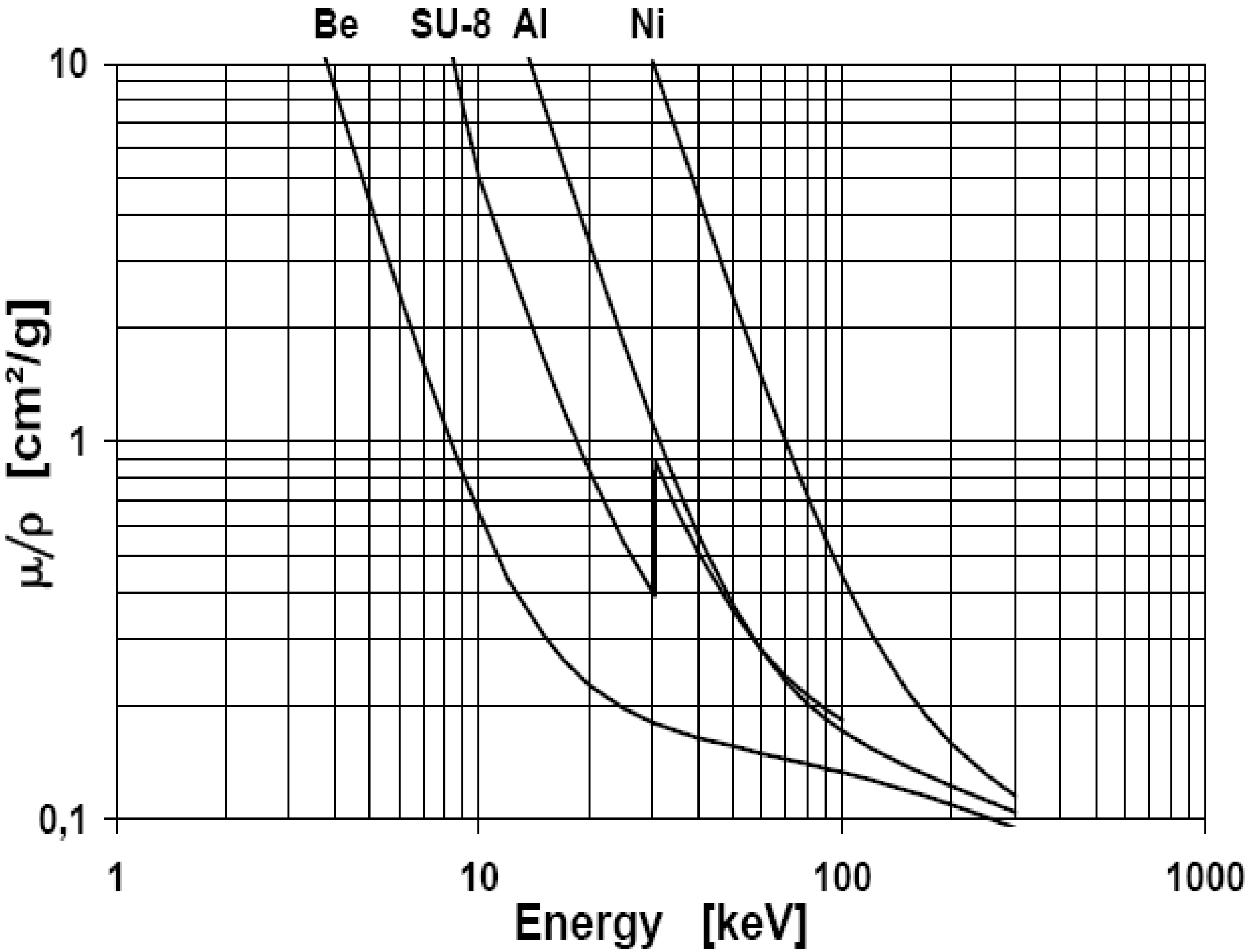
Small angle scattering of different lens materials

Be single crystal	5	* 10^4 σ_{Th}/nm^3 at 0.0565°
Be IF-1	10	or $Q=10^{-2}$ /A
Be PF-60	238	
Be Russian	47	
Al 5N	90	
B HCStarck	20	
diamond	14	
PMMA	2	
Teflon CF_2	770	
Pyro-graphite	200	
glassy carbon	1000-10000	
sapphire Al_2O_3	2	

Lens material: metals versus resists

	metals			resists
	Be	Al	Ni	PMMA, Kapton, SU-8,…
radiation damage	none			yes
heat conductivity (W/m.K)	200	237	91	ca 0.2
melting point (℃)	1277	660	1453	ca 200
SAXS	low to medium			low to high
density	1.85	2.7	8.9	ca 1.1
form	1D and 2D			only 1D
R_{min}	50µm			10µm
kinoform	no			yes

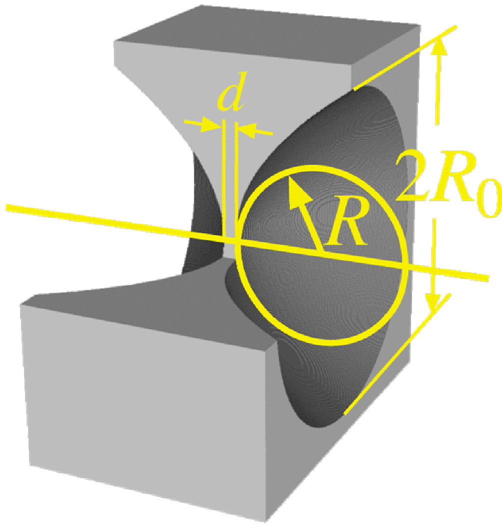
X-ray absorption in SU-8



SU-8 contains 1 atom of Sb per formula unit!

SU-8: no advantage compared to Be and Al !

3. Aperture of paraboloid of rotation:



* no spherical aberration

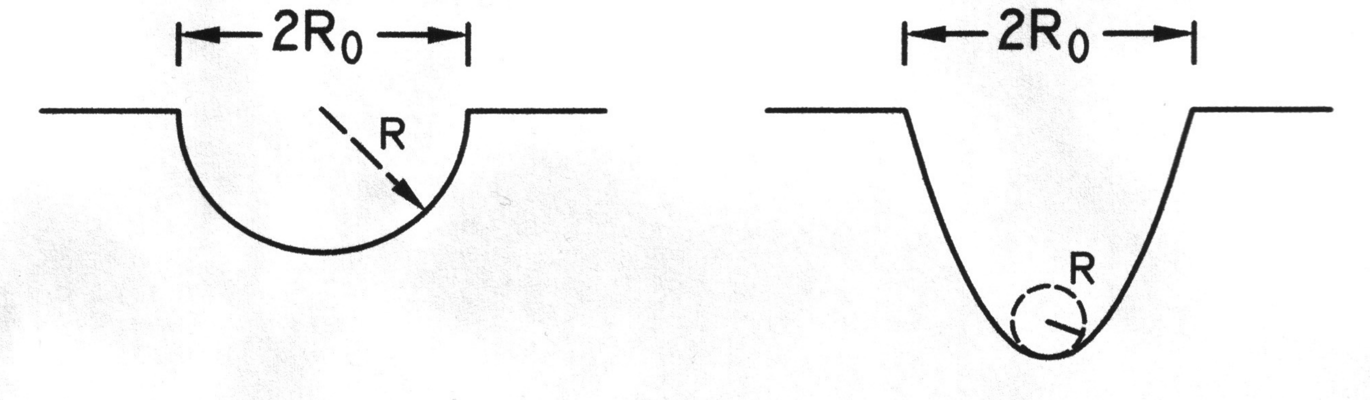
* focusing in full plane

=> excellent imaging optics

* radius R and aperture $2R_0$ are decoupled

spherical lens:

parabolic lens:

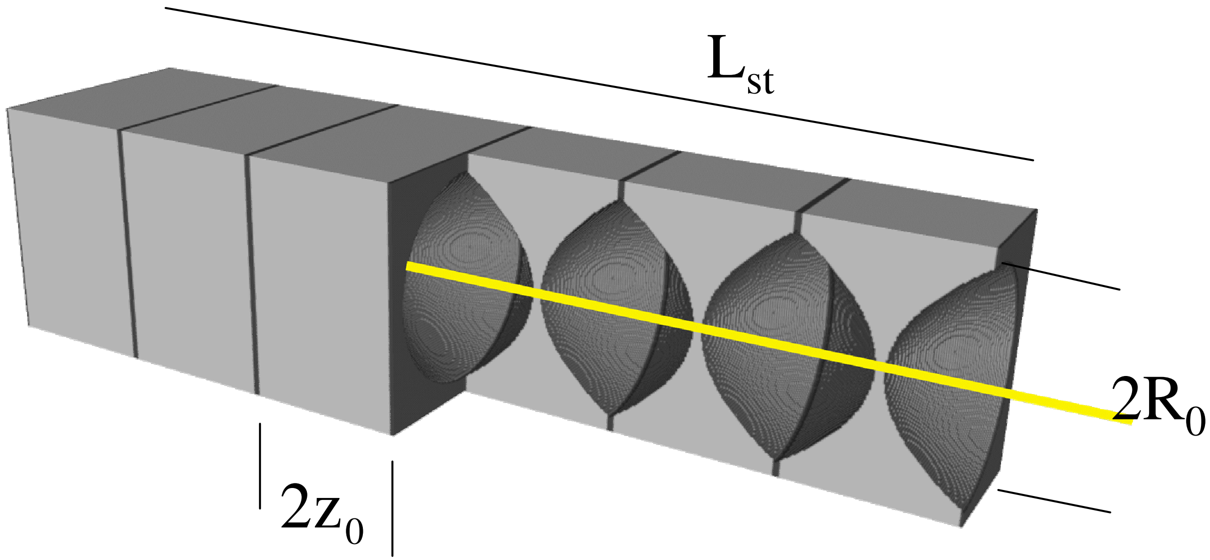


$R_0 \leq R$

R_0 and R independent

Effective lens aperture D_{eff}

Absorption reduces the effective aperture below the value of the geometric aperture $2R_0$



$$D_{eff} = 2R_0\sqrt{\left[1-\exp\left(-a_p\right)\right]/a_p}$$

$$a_p = \mu N z_0 = \frac{1}{2}\mu L_{st}$$

Transmission T versus effective aperture D_{eff} (A_{eff})

transmission T: fraction of transmitted intensity compared to intensity falling on geometric aperture πR_0^2

$$T = \frac{1}{\pi R_0^2}\int_0^{R_0} \exp(-\mu N 2z) = \frac{1}{2a_p}[1-\exp(-2a_p)]$$

$$a_p = \mu N R_0^2 / 2R = \mu N z_0$$

effective aperture D_{eff} reduced by absorption compared to geometric aperture $2R_0$

$$D_{eff} = 2R_0\sqrt{[1-\exp(-a_p)/a_p}$$

Example: Be stack with N = 50, R = 50µm at 17 keV

$2\delta = 2.359\ 10^{-6}$ and $\mu = 0.4903/cm$

f = 423.9mm

z_0 (µm)	$2R_0$ (µm)	$\mathbf{D_{eff}}$ (µm)	T
500	447.2	339.5	37.3%
1000	632.5	386.2	20.2%
	100	98.5	94.1%

The **effective aperture** is the relevant parameter for characterizing the transmission of refractive lenses!

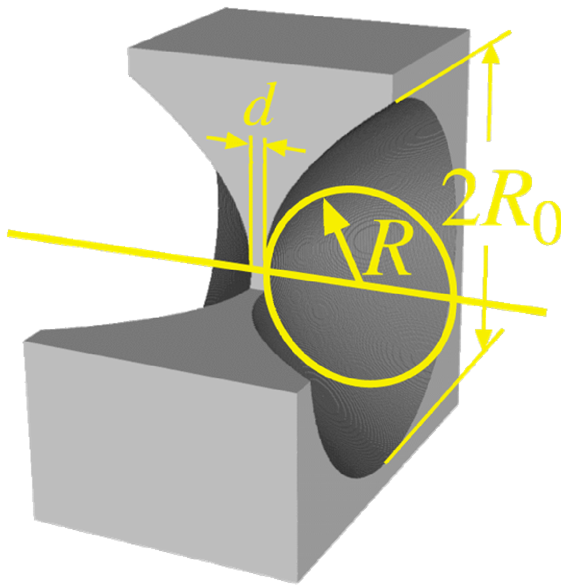
Influence of material between apices on transmission of lensstack (thickness d)

Transmission = exp(-μNd)

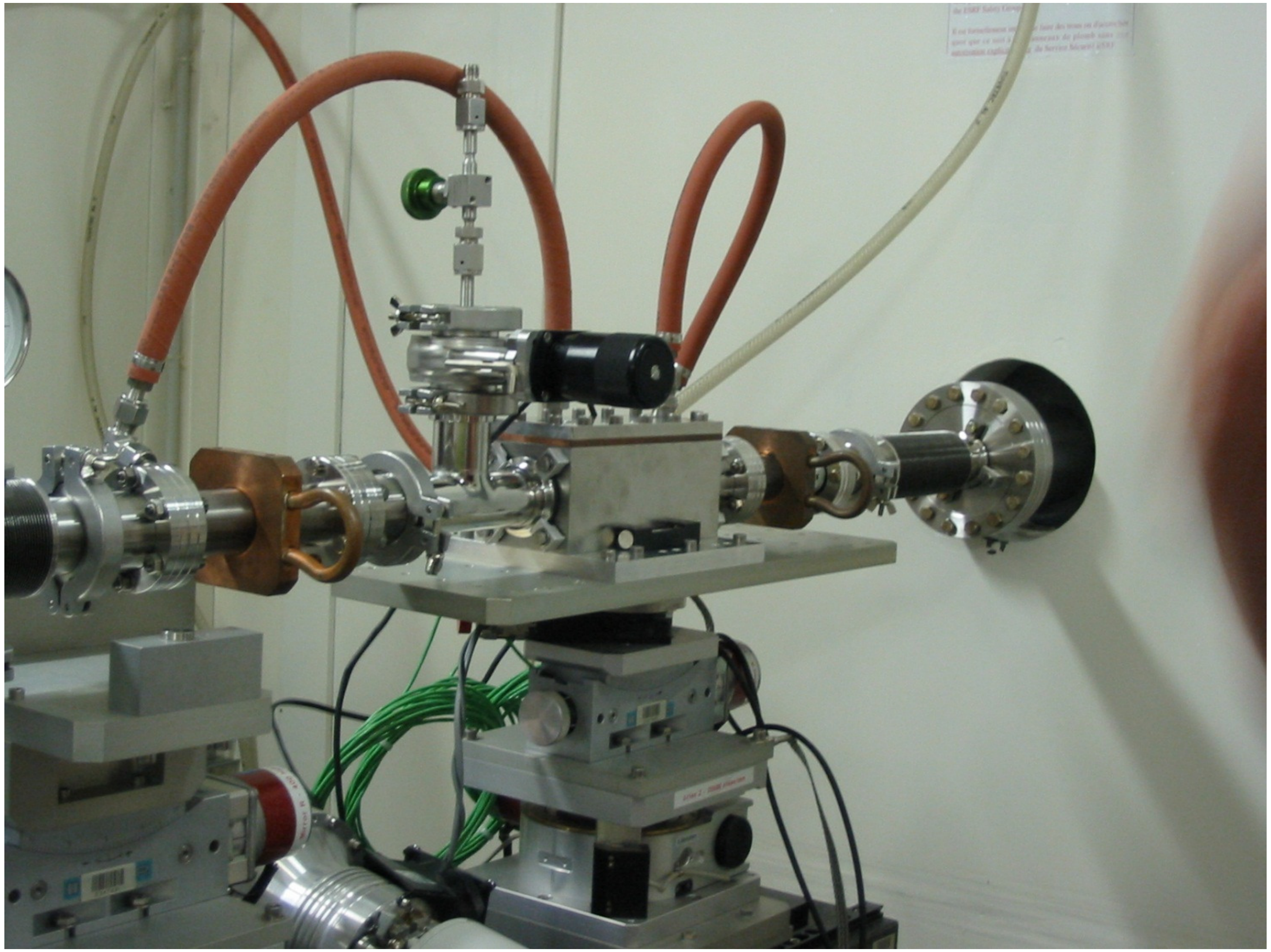
Example : Be lenses R=50μm, d=30μm

1. 12keV, μ=0.8196/cm,
   N=22, f=0.480m
   transmission: 94.7%

2. 17keV, μ=0.4903/cm
   N=42, f=0.505m
   transmission: 94.0%



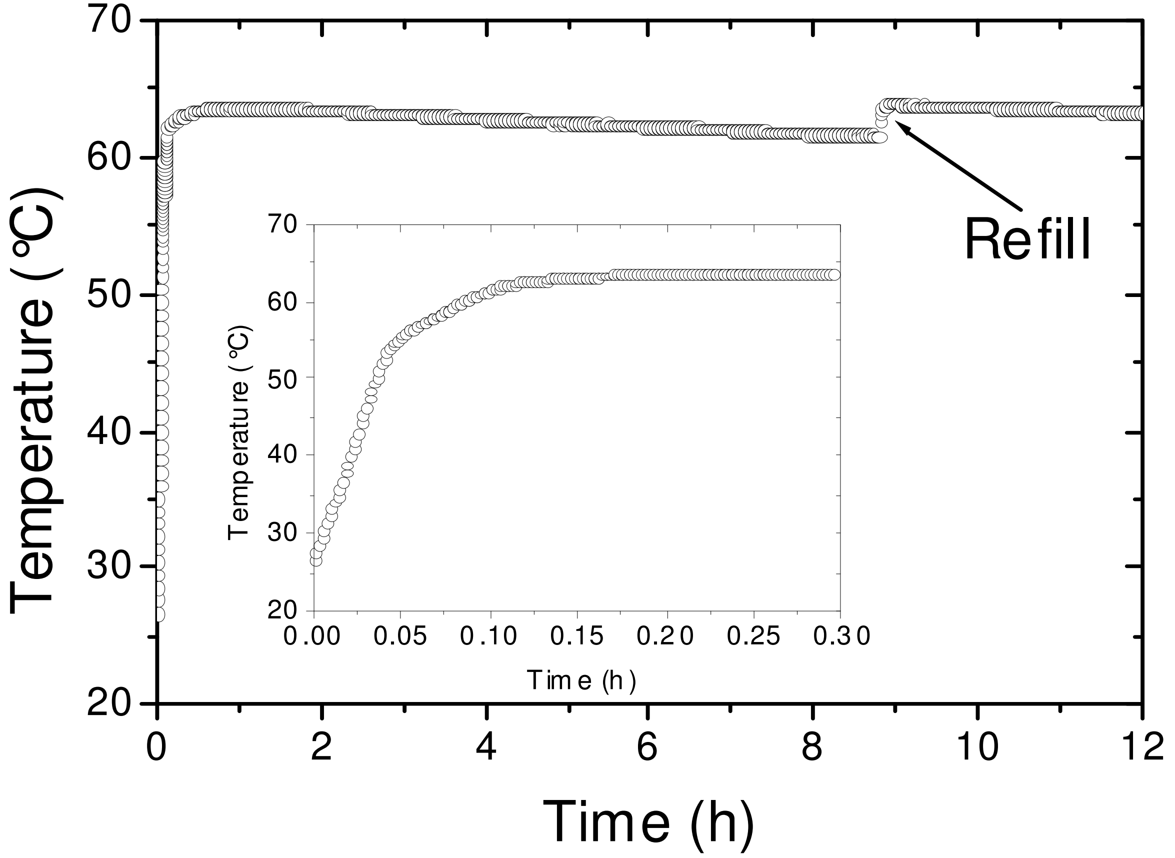
4. Thermal stability in the beam



Water cooled beryllium lens at ESRF (ID10)

Temperature - time profile in white beam at ID10 ESRF

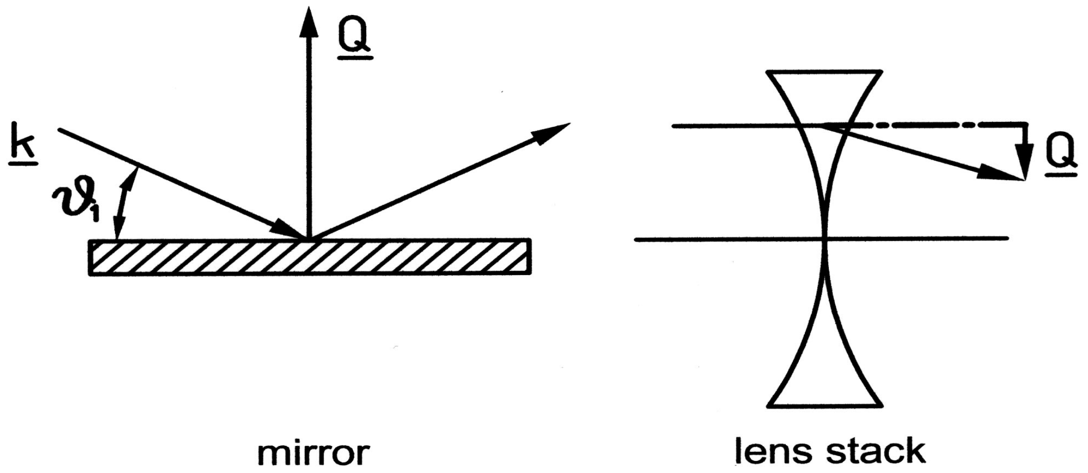
ca. 100 W/mm² & total 40 W **(Be lens)**



In Be lenses the temperature should not exceed about 300°C!

5. Insensitivity of lenses to surface roughness and contamination

(compared to mirrors)



Damping of intensity due to surface roughness σ: ~ $\exp[-Q^2 \sigma^2]$

with **momentum transfer Q** $= 2k \sin\theta_1 \cong 2k\,\theta_1$

mirror $Q = 1.4\ 10^{-1}\ A^{-1}$ at $\theta_1 = 0.6°$ and $\lambda = 1A$

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

A lens is about 1000 times less sensitive to σ than a mirror!

www.rxoptics.de

Typical value of surface roughness of our lenses: 0.1µm

For l = 1A

N = 100

Q = 1.4 10-4 /A

$\exp(-Q^2 s^2) = 0.981$

This is tolerable!

6. Chromatic aberration

refractive x-ray lenses show strong chromatic aberration

$$f = R/2\delta N$$

$$\delta = 2.70 * 10^{-6} * \lambda^2 \rho Z/A$$

Changing the energy at fixed focal length
implies changing the number of lenses in the stack!

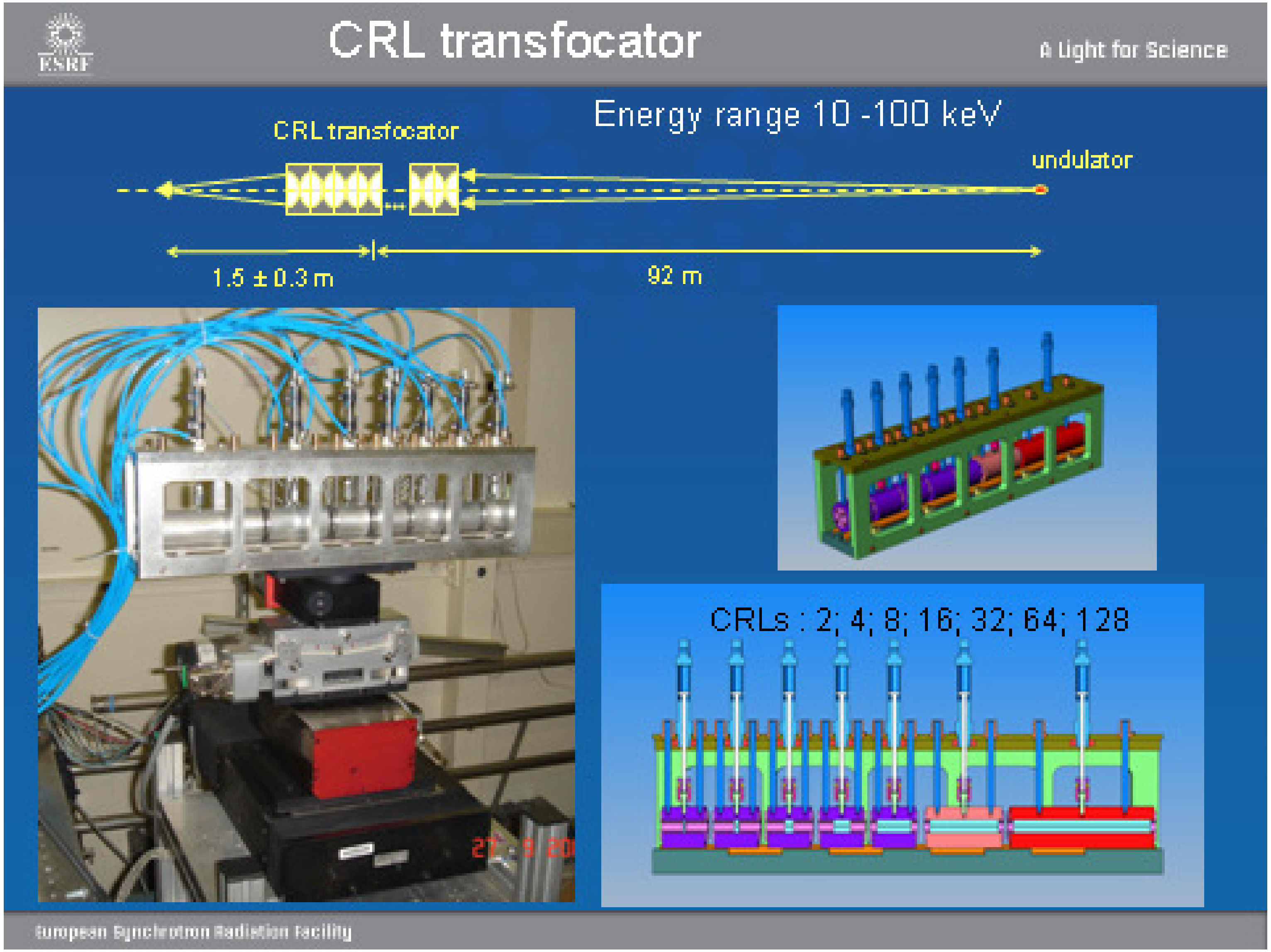
solution: **TRANSFOCATOR** developed at ESRF

flexible change of f

in air and in vacuum

new type of monochromator

TRANSFOCATOR (ESRF development)



7. Handling and adjustment

a. refractive lenses are **robust and compact:**

easily installed and removed
in its own lens casing or in the vacuum of the beam line

b. **focus stays on axis**:

fast adjustment (typically in 15 minutes)
relatively insensitive to misorientation
to vibrations
no need for readjusment of the beam-line components
downstream

c. **comfortable working distance between optics and sample**

REFRACTIVE LENSES: EXCELLENT WORKING HORSES !

D. Applications of refractive x-ray lenses

refractive x-ray lenses can be used like glass lenses are used for visible light

but

the numerical aperture N.A. is very small

typically 10^{-4} to 10^{-3}

New and improved x-ray techniques

1. **Imaging**: x-ray microscopy: 2D image
   x-ray tomography: 3D reconstruction
   in absorption and phase contrast
   monitor of source in storage ring
   test of optical components upstream from lens

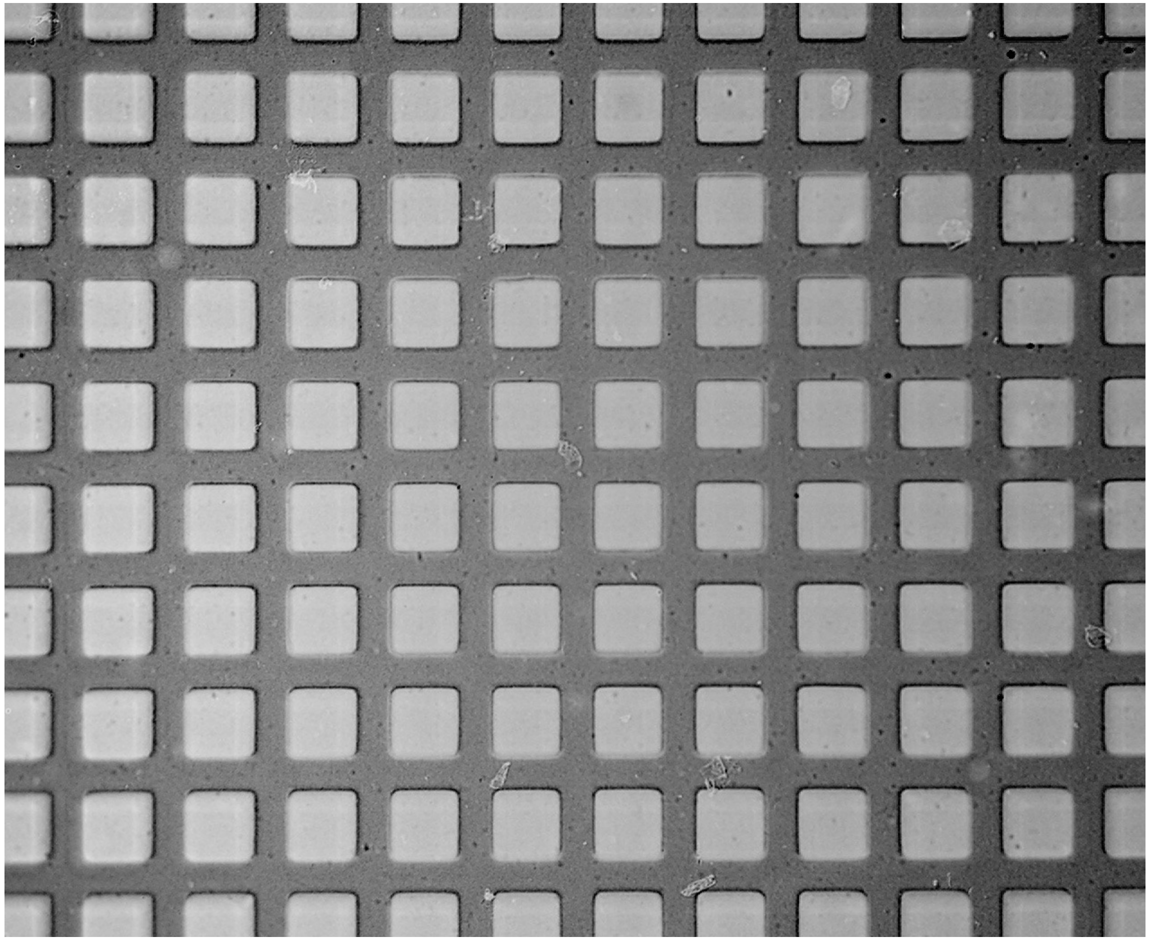
2. **Focusing**: diffraction,
   spectroscopy…..
   with high lateral resolution
   in the sub 100 nm range (50 nm were reached)

3. **Coherent photon flux**:
   X-ray diffraction
   speckle spectroscopy

1. High resolution x-ray microscopy

Example: Ni mesh 12.7µm period

parabolic refractive Be lens N = 91, R = 200µm
f = 495 mm at 12 keV



magnification: 10

detector: high resolution film

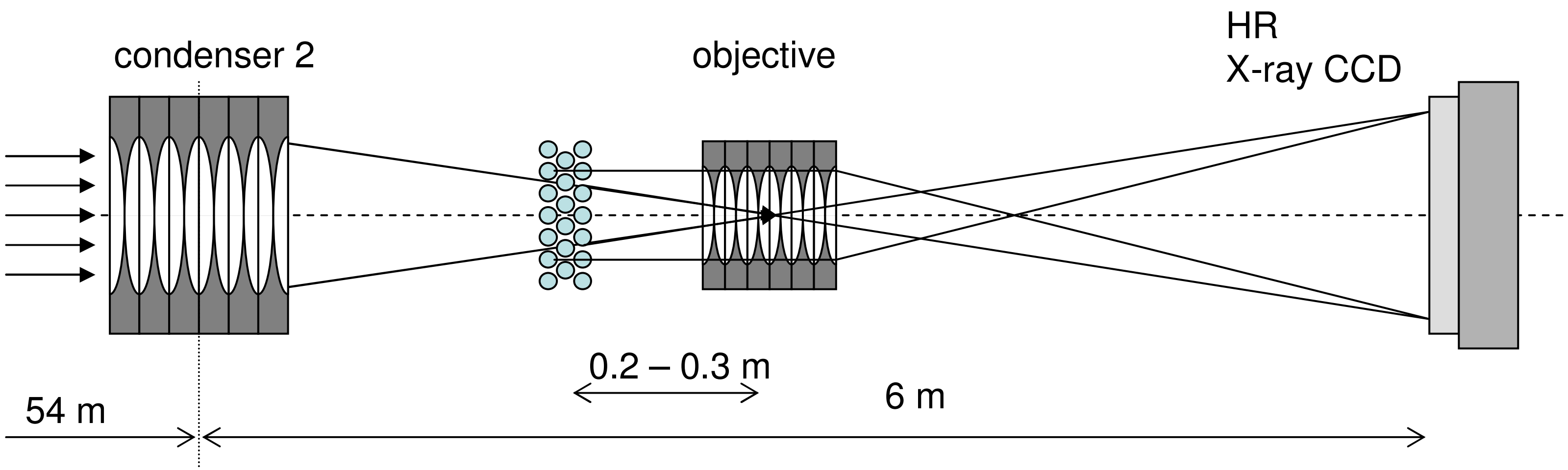
NO DISTORTION!

High-resolution x-ray microscopy

illumination of object from behind via **prefocusing lens** (condenser 2) in order to adjust beam size on sample

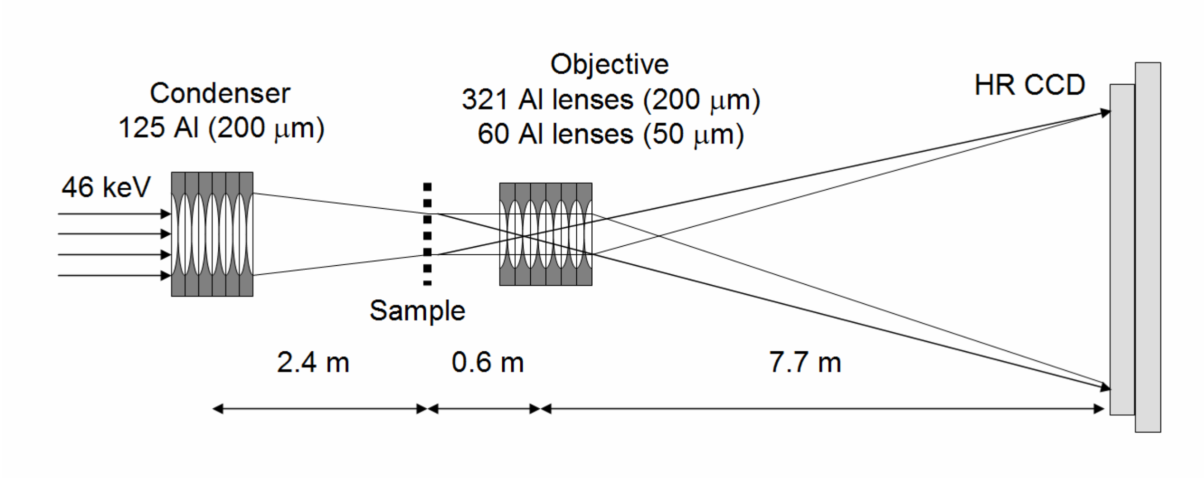
objective with small focal length and low distortion (rotationally parabolic) d_{tr} down to about 50nm

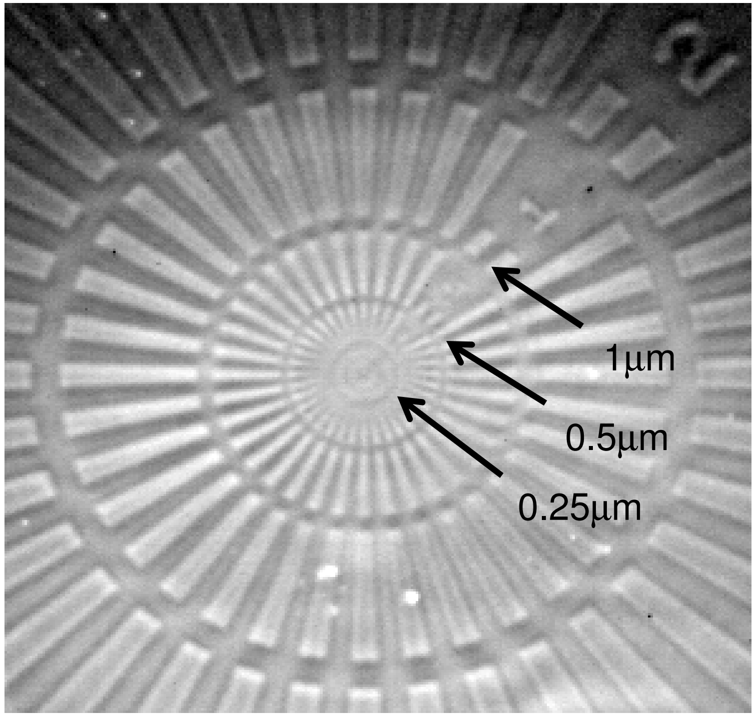
large magnification in order to relieve requirements on CCD camera (object slightly outside focus)



A. Snigirev et al

High Energy X-ray Microscopy at ID15   Al lenses



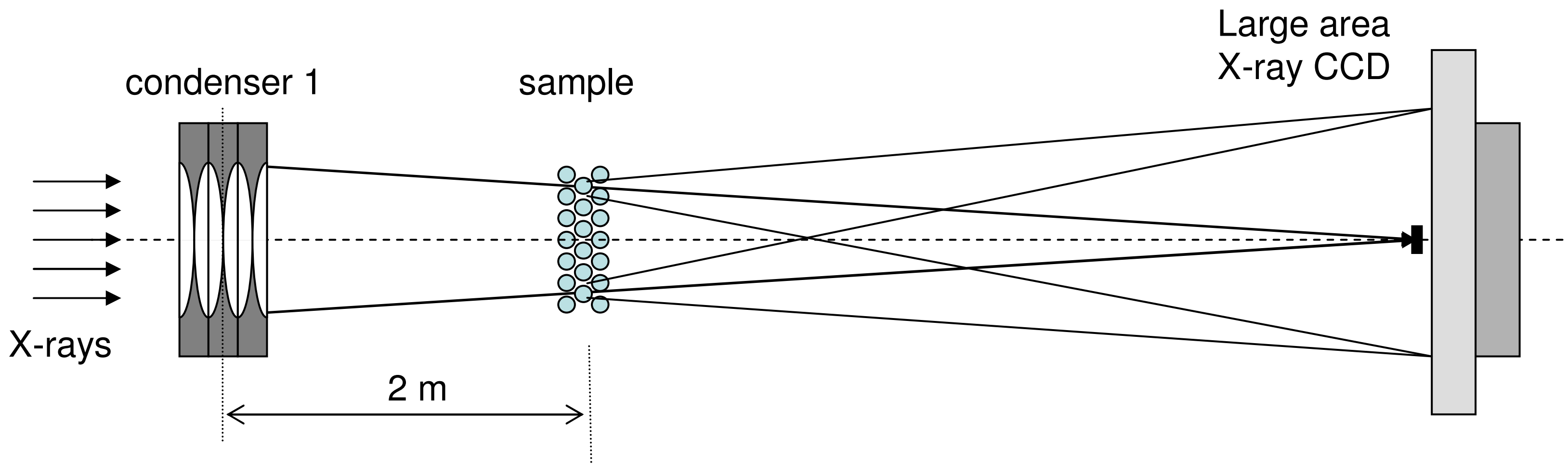


Siemens star
Ta 0.5 μm

E = 46 keV

M. Di Michiel
M. Scheel
A. Snigirev
I. Snigireva

Microscopy in diffraction mode

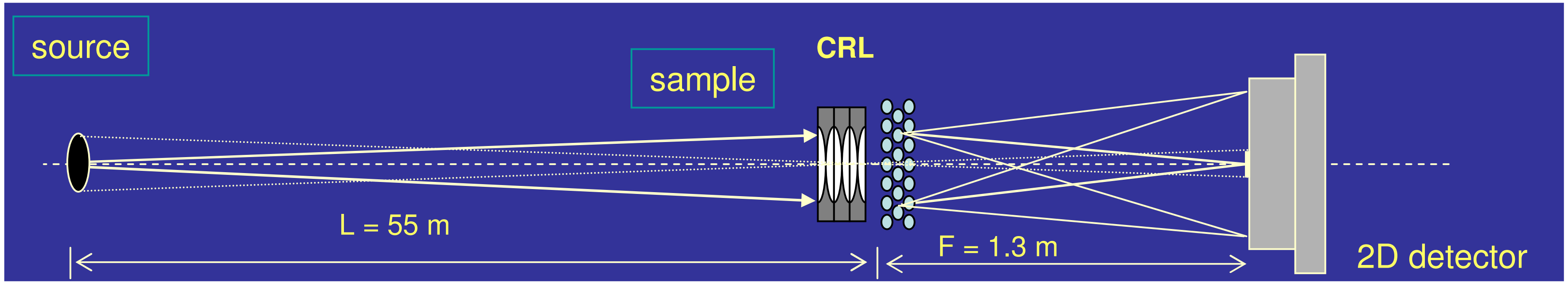


Be N = 19 , R = 300µm

The same place on the sample can be investigated in
imaging mode
diffraction mode

(like in electron-microscopy)

X-ray High Resolution Diffraction Using Refractive Lenses



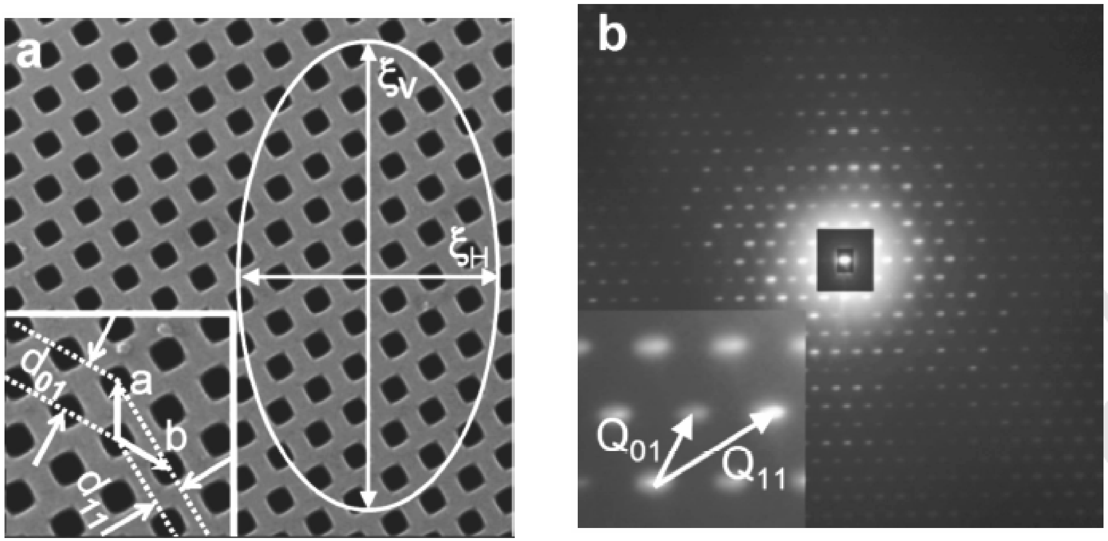
E = 28 keV
Al CRL, N = 112, F = 1.3 m

CCD resolution 2 μm
pixel / Θ = d

Resolution is limited
by angular source size:
s/L ~ 1 μrad

Momentum transfer
Resolution: 10^{-4} nm^{-1}

Si photonic crystal
a=b=4.2 μm d_{01}=3.6 μm d_{11}=2.1 μm



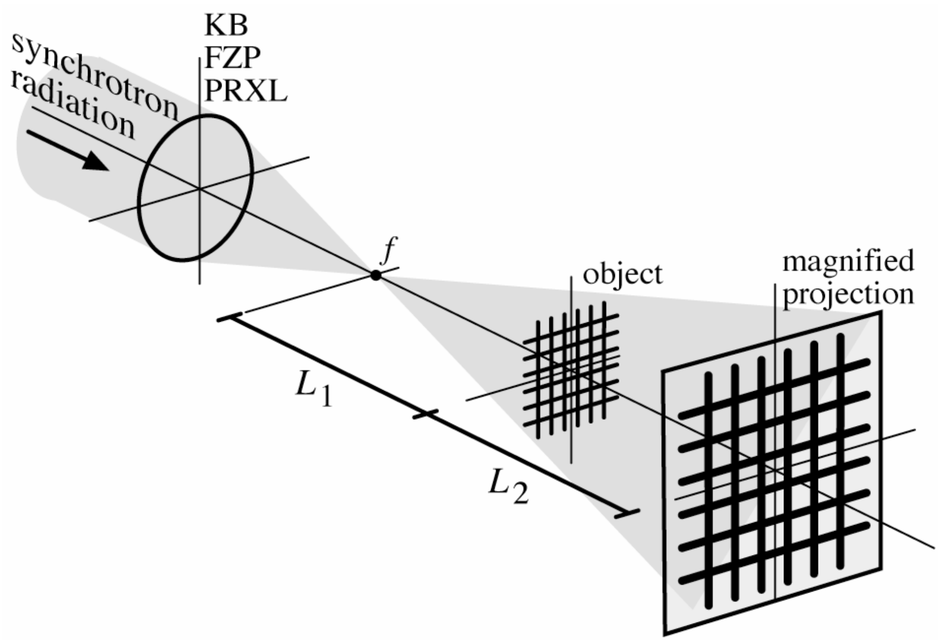
Lattice vectors g_{01} =1.75·10^{-3} nm^{-1} g_{11} =3·10^{-3} nm^{-1}

M. Drakopoulos, A. Snigirev, I. Snigireva, J. Schilling, Applied Physics Letters, 86, 014102, 2005.

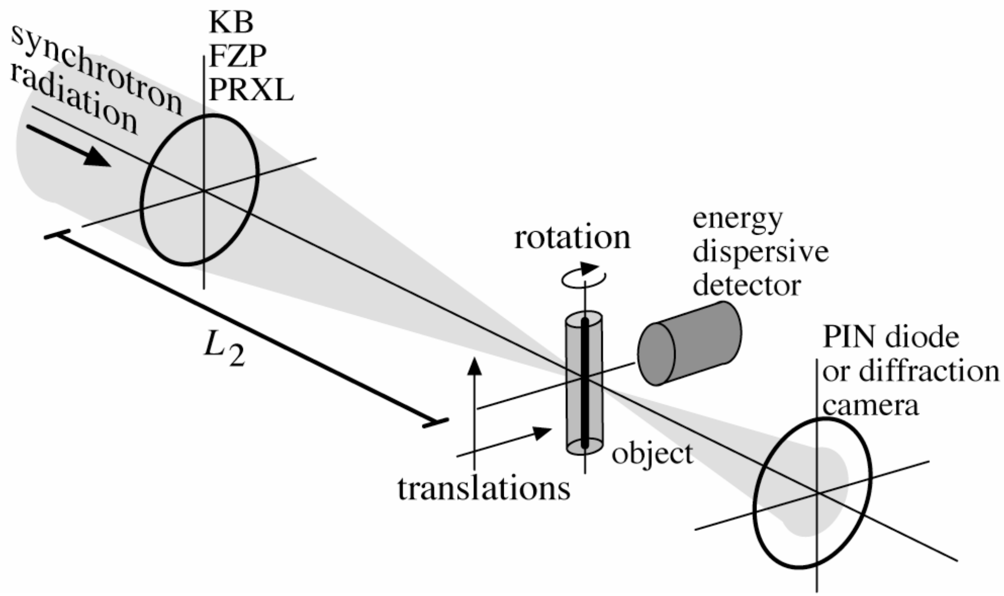
2. Focusing

Microscopy
Object placed close to secondary source:
=> strong magnification

The smaller the focus, the sharper the image!



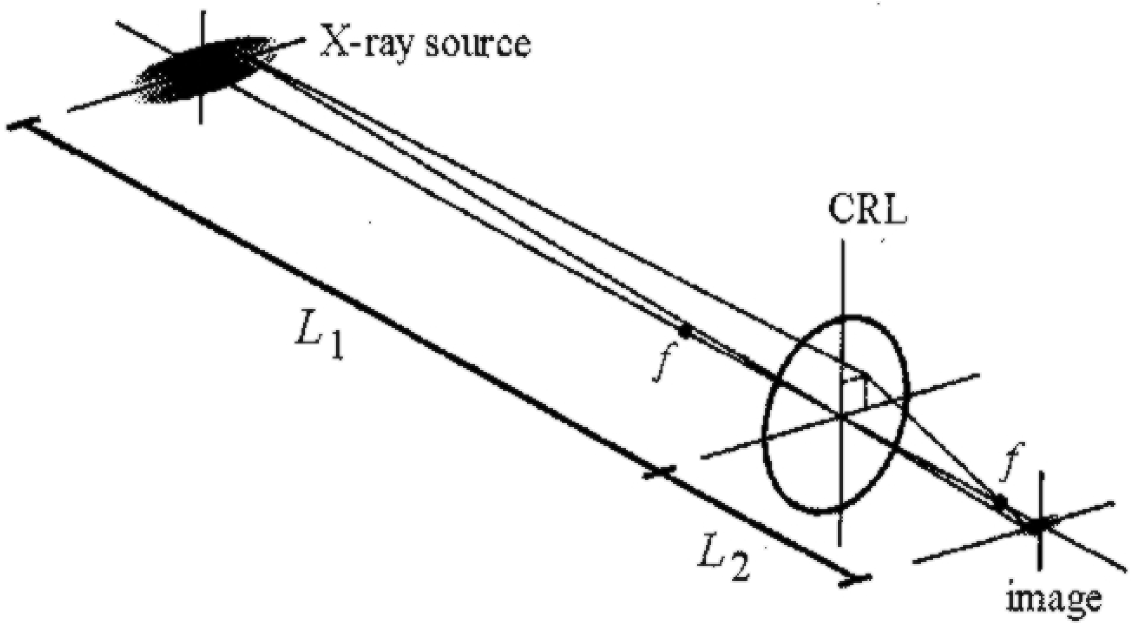
d)



Spectroscopy, tomography
large depth of field
scanning beam over sample
(diffraction, SAXS, XAS, fluorescence…)

Small focus requires

1. small source
2. long distance L_1 source-lens
3. small focal length and large effective aperture of lens



a. FOCUSING with

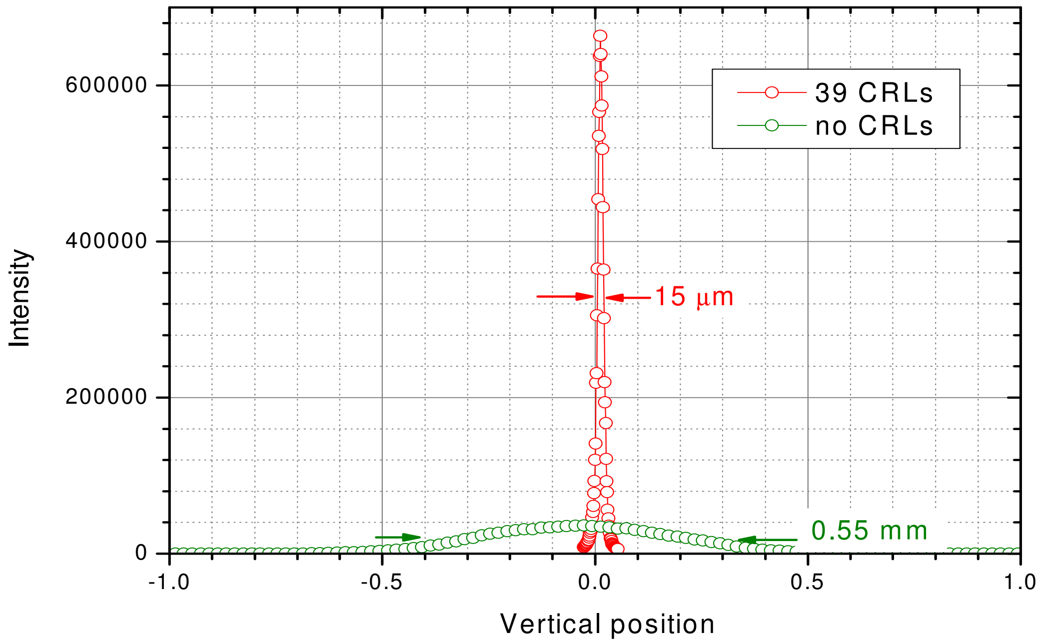
rotationally parabolic Be lenses
(R = 1500µm)

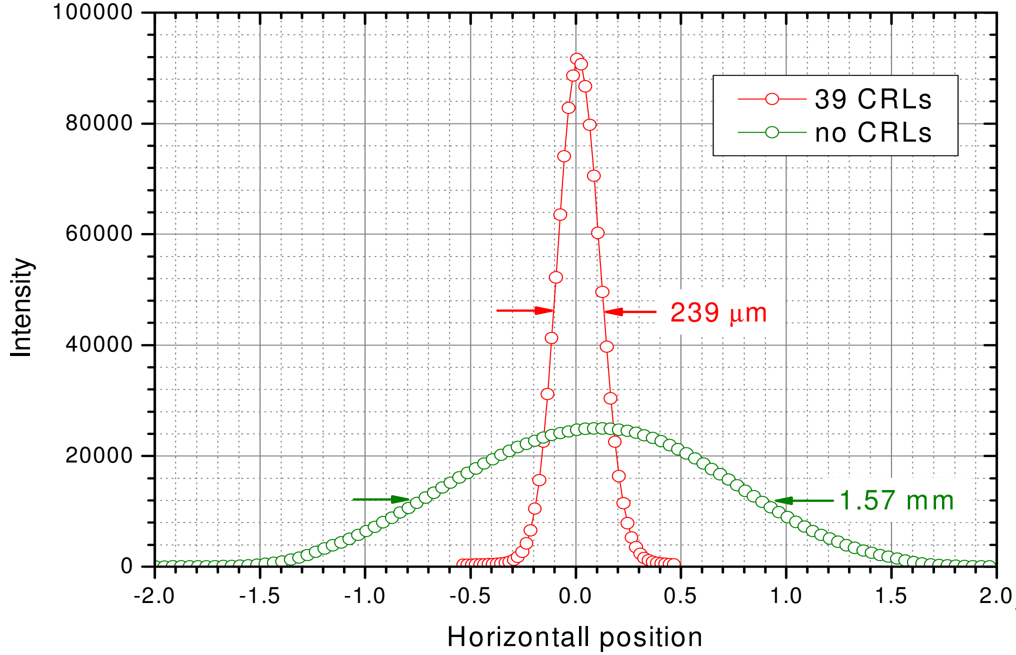
Image of the ID18 source at ESRF

14.4125eV
39 Be lenses
R = 1500µm

f = 11.718m
geometric aperture: 2.5mm

(A. Chumakov ESRF)

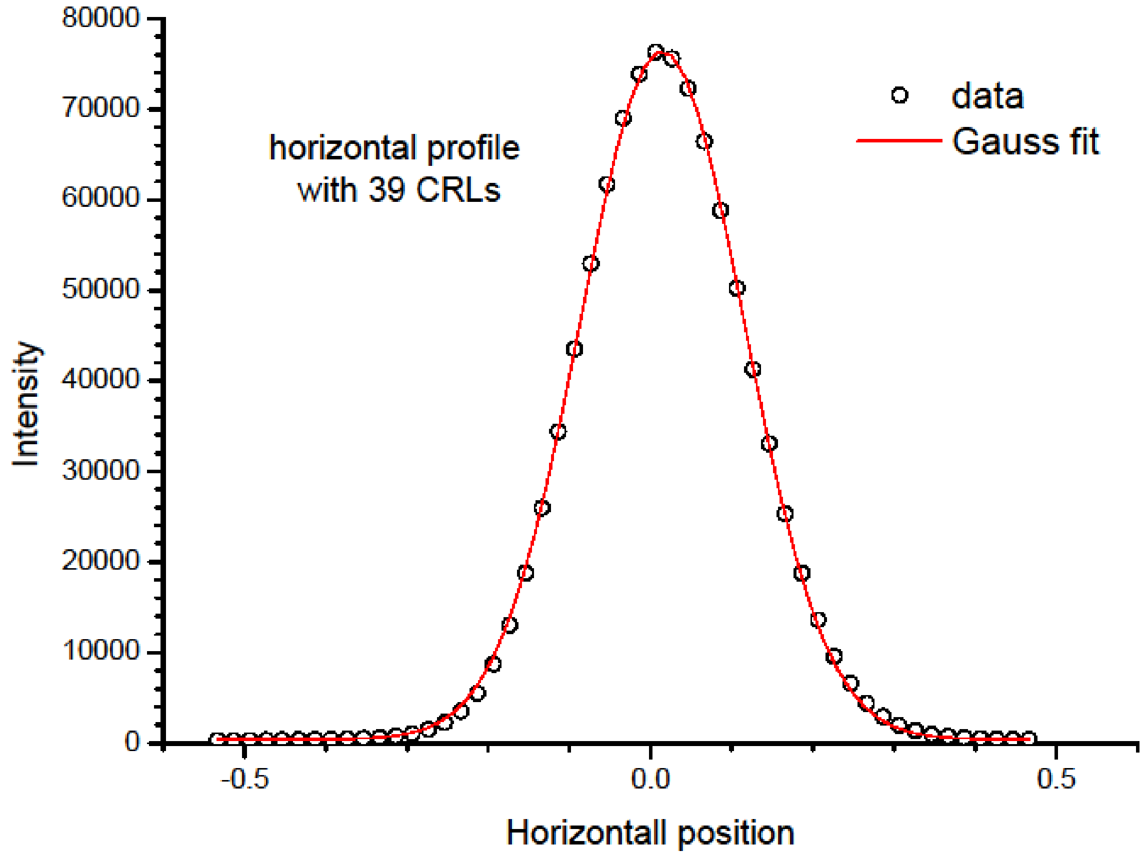




Intensity profile in the horizontal: ID18

well fitted by a Gaussian with 239 µm FWHM

(very low background in the wings)



b. Focusing with Be lens at energies as low as 2keV

ID12 at ESRF (A. Rogalev)

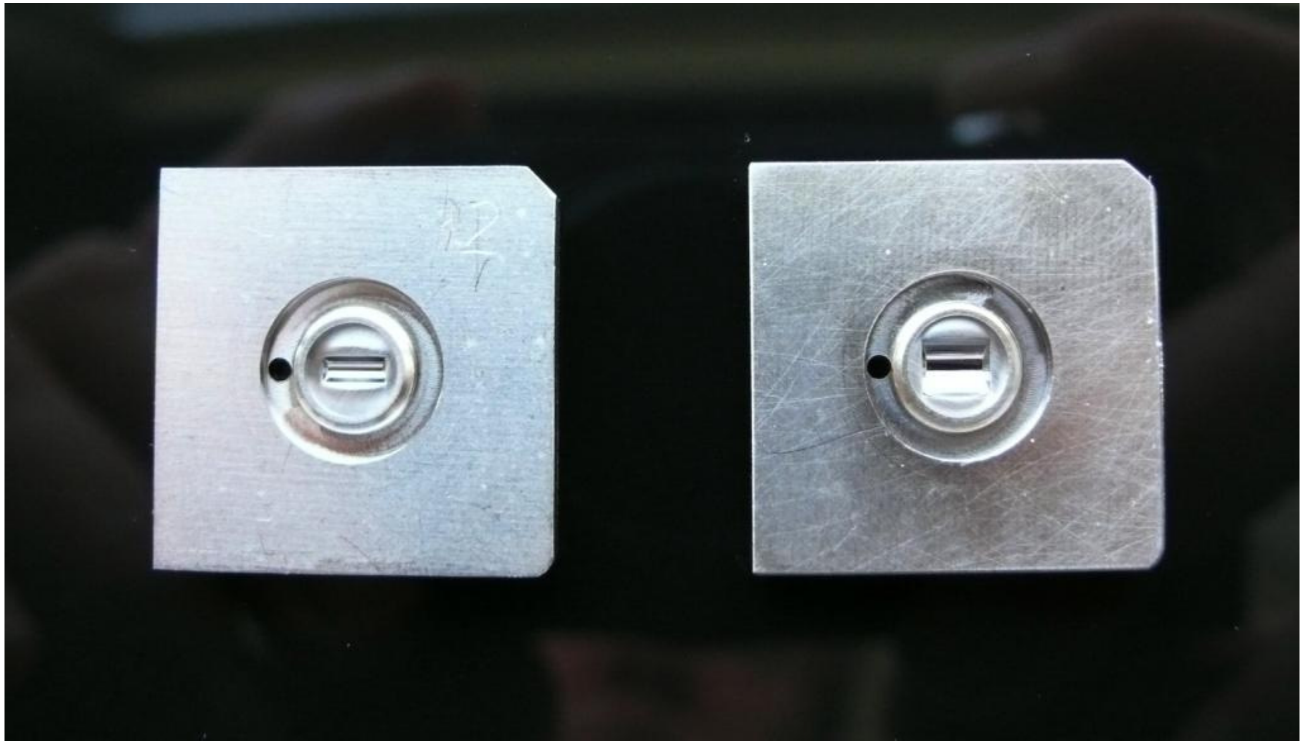
gain in intensity on sample at 2 keV:

factor 500 compared to situation without lens!

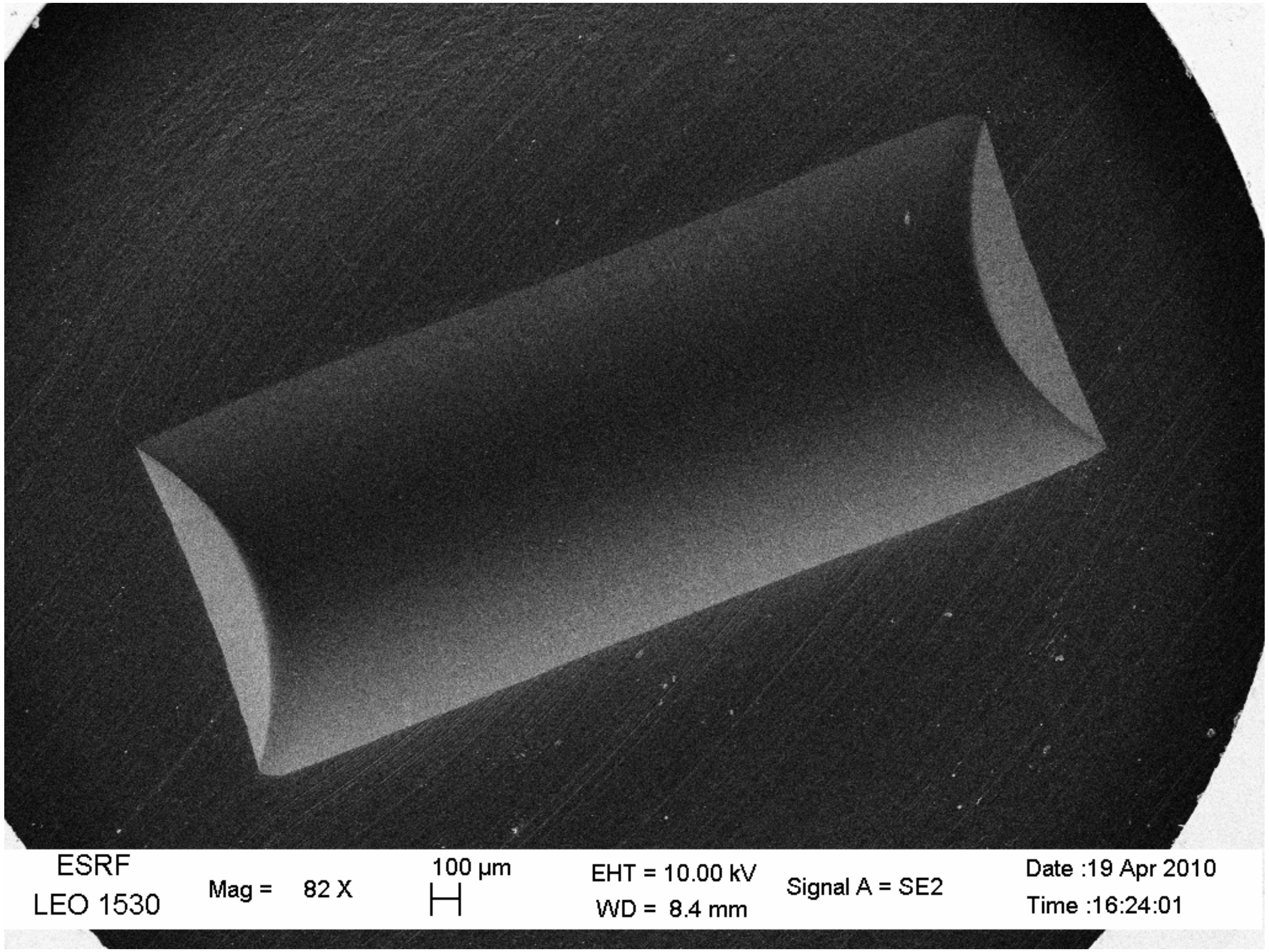
c. Prefocusing with linear lenses Be, Al and Ni

R = 200 to 1000µm, length 2.5 mm

* collecting more intensity
* for making spot on sample more circular (on storage rings)



SEM image of linear Be lens (R=500μm)



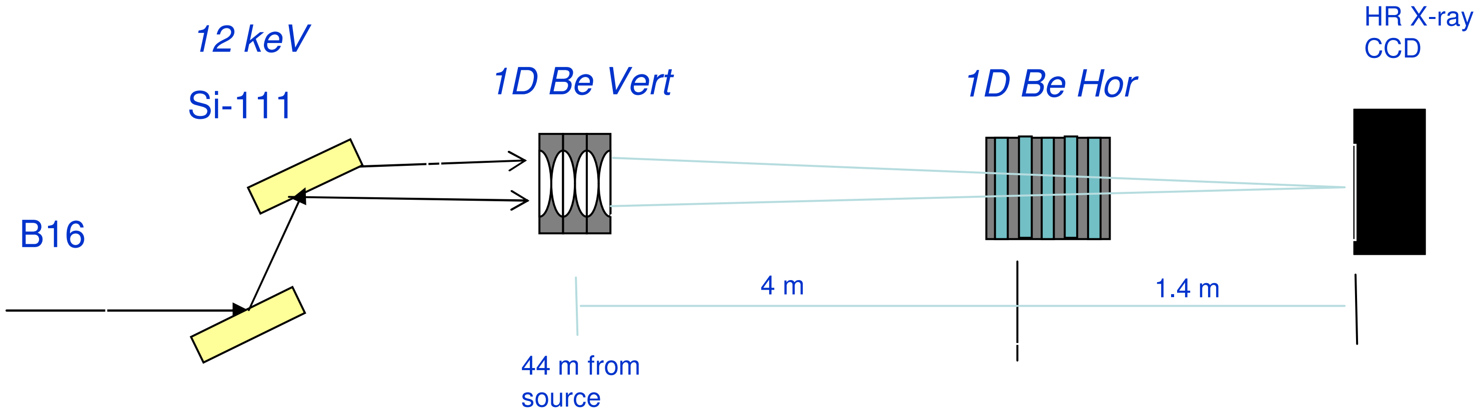
Focusing with 2 independent linear lenses in cross-geometry

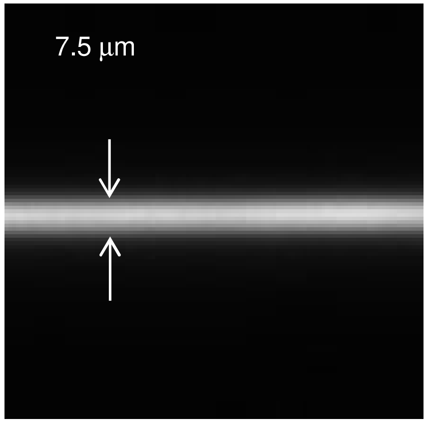
- Ratio of horizontal to vertical source size in storage rings:
  20 and more
  =>elongated spot on sample

- Generation of more circular spot size by astigmatic imaging of source via 2 independent linear lenses in cross geometry

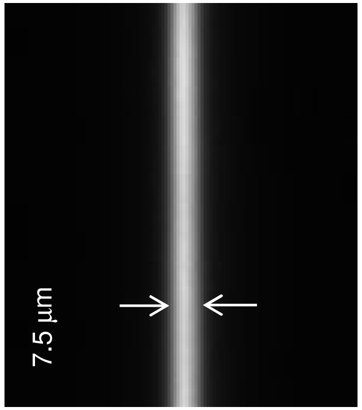
- Example: experiment at DIAMOND Light Source
  by A. Snigirev et al
  with 1D Be from RXOPTICS

Astigmatic focusing with 2 crossed, linear Be lenses

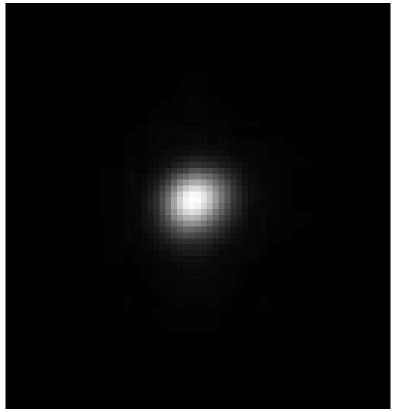




Vertical
N=17 R=300µm
L2 ~ 4m



Horizontal
N=17 R=200µm
N=15 R=300µm
L2 ~ 1.4m

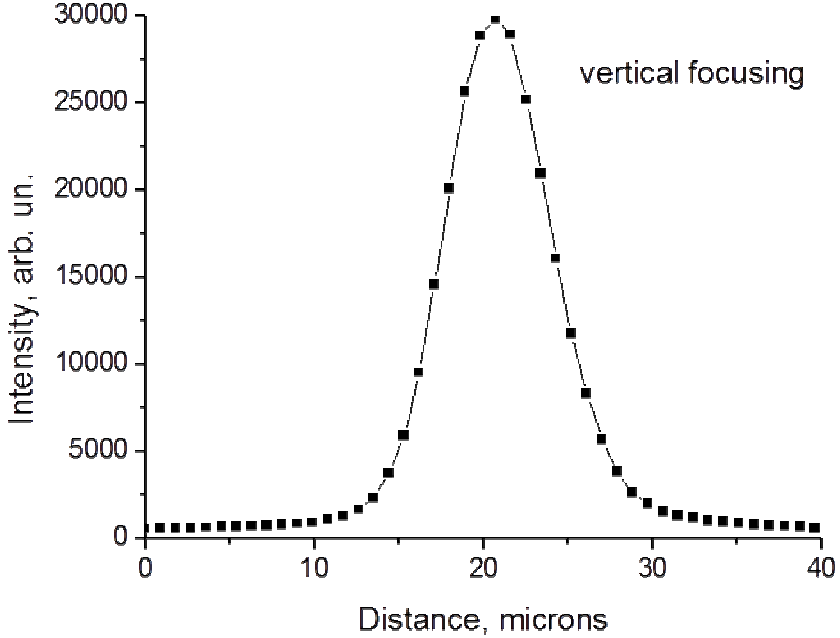


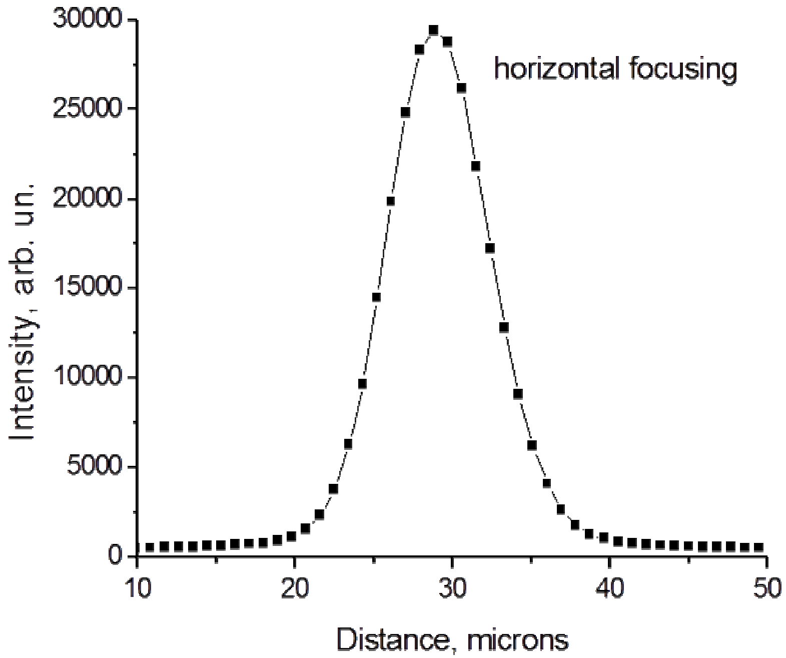
Crossed
gain: 1200

Astigmatic focusing with 2 crossed, linear Be lenses

I & A Snigirev, I. Dolbnya, K. Sawhney
Collaboration with Optics Group at DIAMOND

Profile: vertical 7.5 µm FWHM — horizontal 7.5 µm FWHM





3. Coherent flux

* diffraction of individual large molecules, nanoparticles

* speckle spectroscopy

Illuminated area on sample must be smaller than the lateral coherence area at the sample position. Then all monochromatic photons are undistinguishable, i.e. they are in the same mode!

* coherent photon flux is a property of the brillance B of the source and of the degree of monochromaticity

$$F_c = B\lambda^2 \frac{\Delta\lambda}{\lambda}$$

* the coherent flux can at best be conserved, it cannot be increased by a focusing optic.

Example: **ID13 at ESRF**

Be lens: R = 50µm, N = 162, f = 205.9mm,
D_{eff} = 295µm, d_{tr} = 42nm

L_1 = 100m, L_2 = 206.3mm

geometric image of source $S' = S\frac{L_2}{L_1}$

FWHM	S (µm)	S‘ geom (nm)	S‘ incl diffr (nm)
horizontal	120	248	251
vertical	20	41	59

diffraction limited in the vertical !

Example: **low-betha undulator at ESRF**

1. Be lenses, 17 keV, N = 162, f = 205.9mm, **d_{tr} = 42nm**

L_1 = 100 m, L_2 = 0.2063 m

2.

	Source size FWHM	Geometric image FWHM
horizontal	120μm	248 nm
vertical	20μm	**41nm**

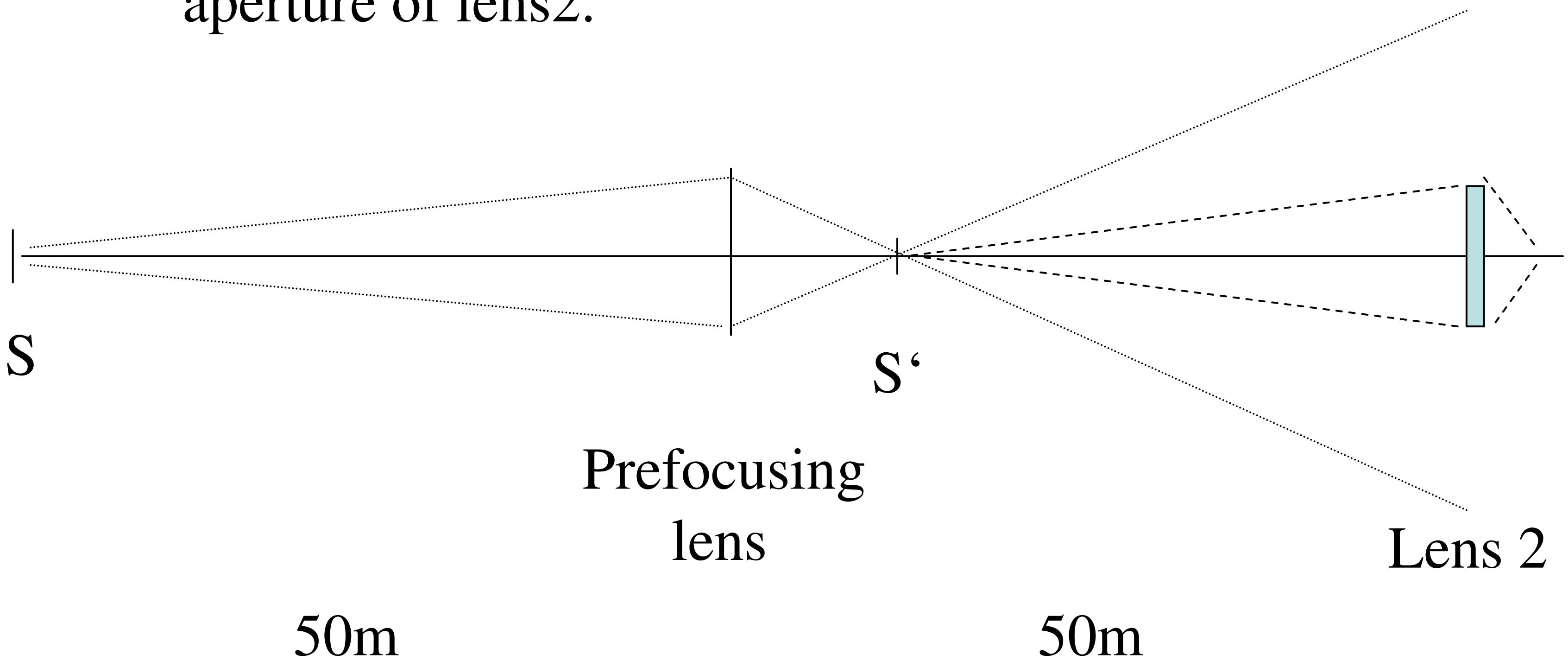
Image is diffraction limited in the vertical:
=> coherent illumination in the vertical

Not so in the horizontal!

3. **remedy for horizontal direction**

* insert a linear lens (prefocussing lens) which focuses only in the horizontal

* the secondary source S‘ must have a lateral coherence length at the postion of lens 2 which is equal to the effective aperture of lens2.



Prefocusing lens

Be linear: R = 500µm, N = 55,
f = 3.854m, D_{eff} = 1048µm

Image S' at b_1 = 4.168m behind horizontal lens

lateral (horizontal) coherence length at position of lens 2: 295µm

this is equal to D_{eff} of lens 2: only the coherent flux passes through lens 2, the rest is peeled off.

gain in flux (compared to no prefocusing): about factor 10.

Coherent Imaging (Ptychography)

(see talk by F. Seiboth, C. Schroer)

* illuminate sample coherently in a small spot by means of Be-lenses

* Scan this microfocus over sample with overlaping neighboring scans

* take a diffraction image on each position

* overlap of images allows for reconstruction of the object when each spot is illuminated coherently

➔ **Our Be lenses preserve coherence well enough to give a resolution which is 10 times better than the spot size!**

MANY THANKS

To

my former students,

Anatoly and Irina Snigirev from ESRF

Christian Schroer and collaborators from TU Dresden

for many years of efficient and pleasant collaboration