от классической оптики к новым рентгеновским экспериментам и методам

Анатолий Снигирев
ESRF

История оптики

Зеркала, линзы -	???
Дифракционные решетки, Френелевские зонные пластинки Relay, Fresnel, Wood	(18)-19 век
Лазеры - Голография 3D дифракция и оптика	20 век
Когельник, Денисюк	

X-ray optics history

1895	W. C. Roentgen	discovery
1898	W. C. Roentgen	no refraction – no X-ray lens
1912	Friedrich&Knipping Braggs	crystals !
1917	Laue - 3D diffraction	

Dynamical diffraction, Pendellosung fringes, Interferometers

Lang, Kato, Bonse, Hart, Indenbom, Afanasiev, Iveronova

X-ray crystal optics

1948 -	Kirkpatrick&Baez :	mirrors
1996 -	A. Snigirev, V. Kohn, I. Snigireva, B. Lengeler *Nature*	refractive optics – X-ray lens

Acta Cryst. (1980). A**36**, 1002–1013

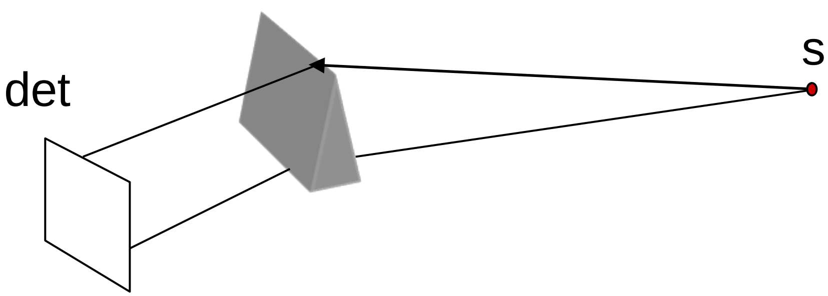
Pendellösung Fringes for X-ray Spherical-Wave Diffraction in a Perfect Crystal

By V. V. Aristov and V. I. Polovinkina

Solid State Physics Institute, USSR Academy of Sciences, Moskovskaya Oblast, Chernogolovka 142432, *USSR*

and A. M. Afanas'ev and V. G. Kohn

I.V. Kurchatov Institute of Atomic Energy, Moscow 123182, *USSR*



Crystal image (Laue)

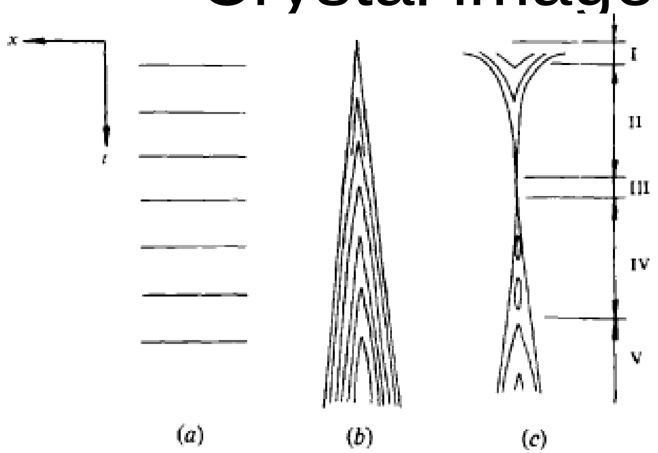
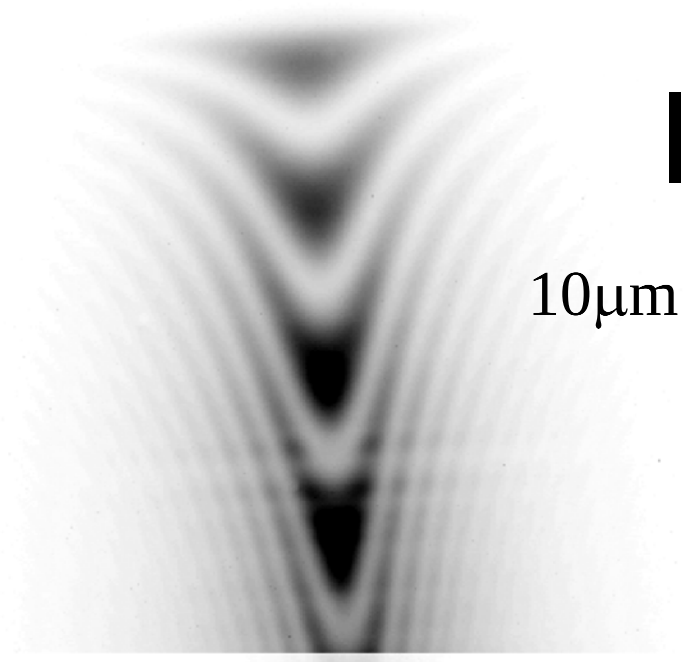
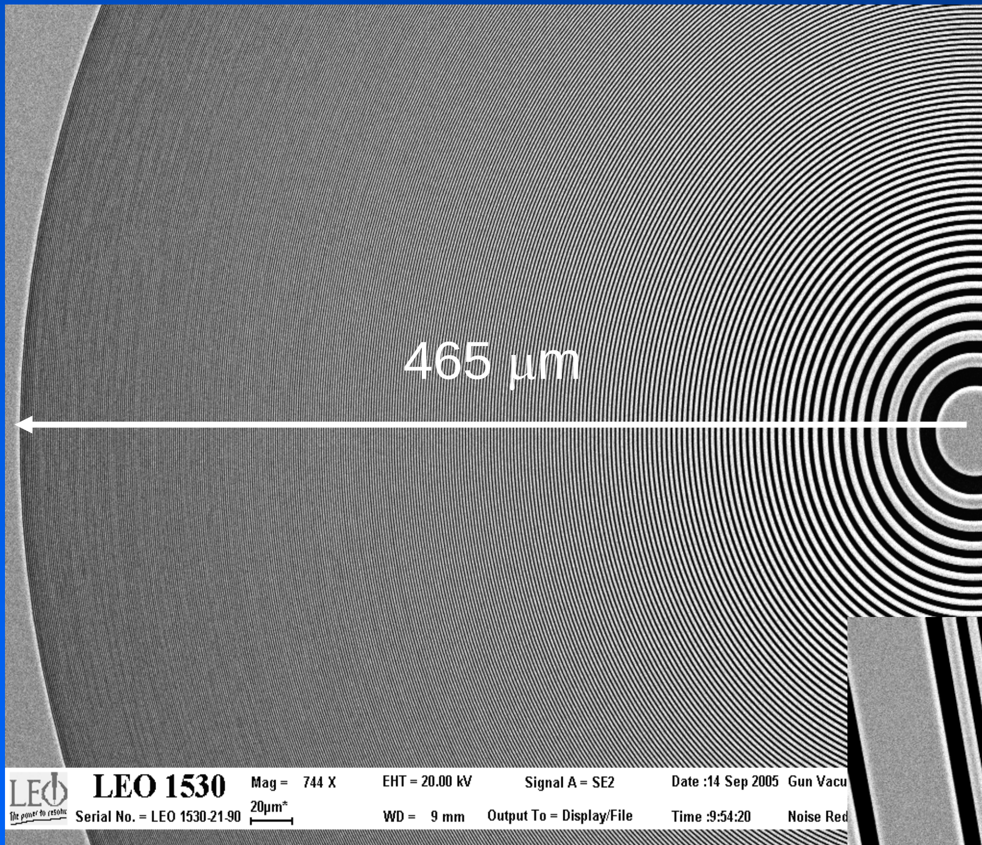


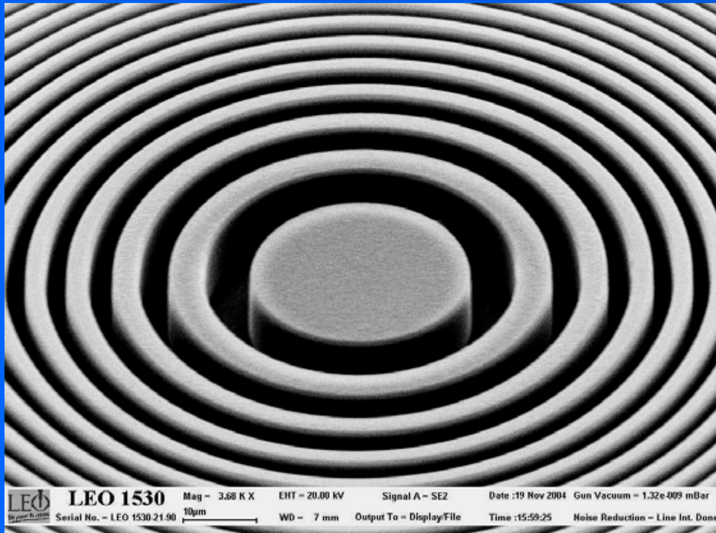
Fig. 1. *Pendellösung* fringes in a perfect crystal. (*a*) Incident plane X-ray wave. (*b*) Incident spherical wave; interference pattern of Kato's type. (*c*) Incident spherical wave; interference pattern obtained in the present paper.

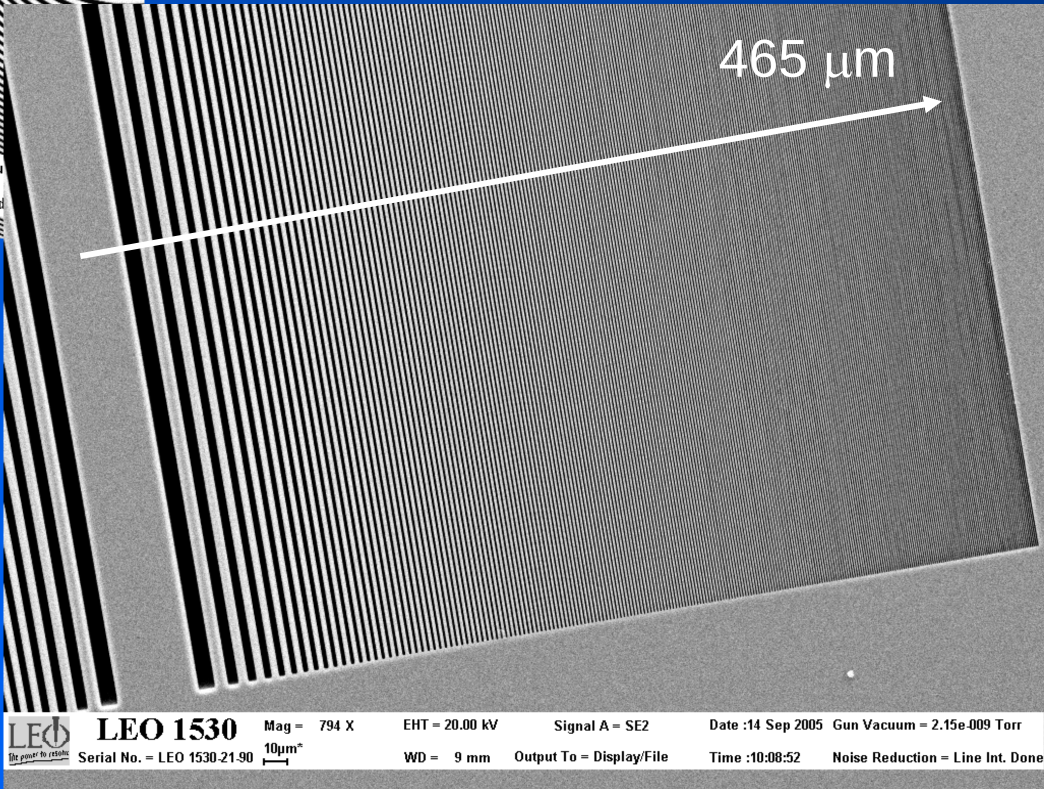


Bragg –Fresnel Optics

SEM images







JOURNAL OF THE OPTICAL SOCIETY OF AMERICA VOLUME 38, NUMBER 9 SEPTEMBER, 1948

Formation of Optical Images by X-Rays

PAUL KIRKPATRICK AND A. V. BAEZ
Stanford University, Stanford, California

(Received March 12, 1948)

JOSA, Sept 1948

X-RAY LENSES

Roentgen's[1] first experiments convinced him that x-rays could not be concentrated by lenses; thirty years later his successors understood why. X-ray refractive indices are less than unity by an amount δ which for common solids and x-rays of general practice has a value of the order of 10^{-5}. It may readily be shown that the focal length f of a single refracting surface of radius R is approximately R/δ. For several surfaces in series, arranged cooperatively, we have $1/f=\delta(1/R_1+1/R_2+\text{etc.})$. To make a successful lens we require a large δ and slight absorption. Unfortunately materials of large δ are also strong absorbers, the absorption coefficient increasing much more rapidly than δ with increasing atomic number. An element of low atomic number, such as beryllium, is indicated.

In choosing a usable x-ray wave-length we note that δ is proportional to λ^2 and the absorption coefficient to λ^3. This makes long waves undesirable. For concreteness of argument let the wave-length be that of the K_α lines of molybdenum (0.71A), which in beryllium gives $\delta=1.13\times10^{-6}$. For one refracting surface we shall have $f\approx10^6R$. If a radius of one centimeter be assumed it is found that about one hundred lens surfaces in series would be required to bring the focal length down to one hundred meters. This would produce a cumbersome and very weak lens system of poor transparency. These discouraging considerations incline us toward other methods.

[1] W. C. Roentgen, *Sitzungsberichte der Würzburger Physikalischen-Medicinischen Gesellschaft* (1895).

X-ray refractive optics history

1898 - W. C. Roentgen: no X-ray lens

1948 - Kirkpatrick&Baez : first idea about compound refractive lens
but: "…x-ray refractive lens is impractical"

1980 - R. Gähler et al Neutron refractive lens of quartz *(ILL)*
J. Phys. E: Sci. Instr. ***13****, 546, 1980.*

1991 - S. Suehiro et al. high-Z refractive lens
Nature

1991 - A. Michette no X-ray lens
Nature

1996 - A. Snigirev, V. Kohn, I. Snigireva, B. Lengeler first experiment with compound refractive lens
Nature

1996 - 2012 more than 1000 articles

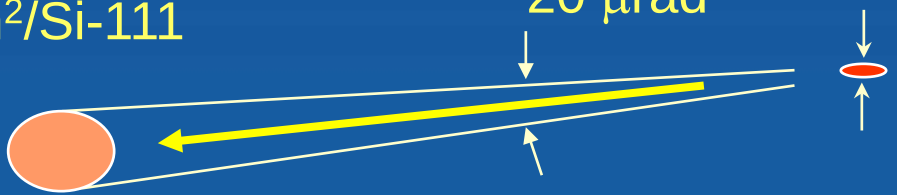
ESRF undulator X-ray beam

200 mA

high-β undulator

$10^{13\text{-}14}$ ph/s/mm²/Si-111

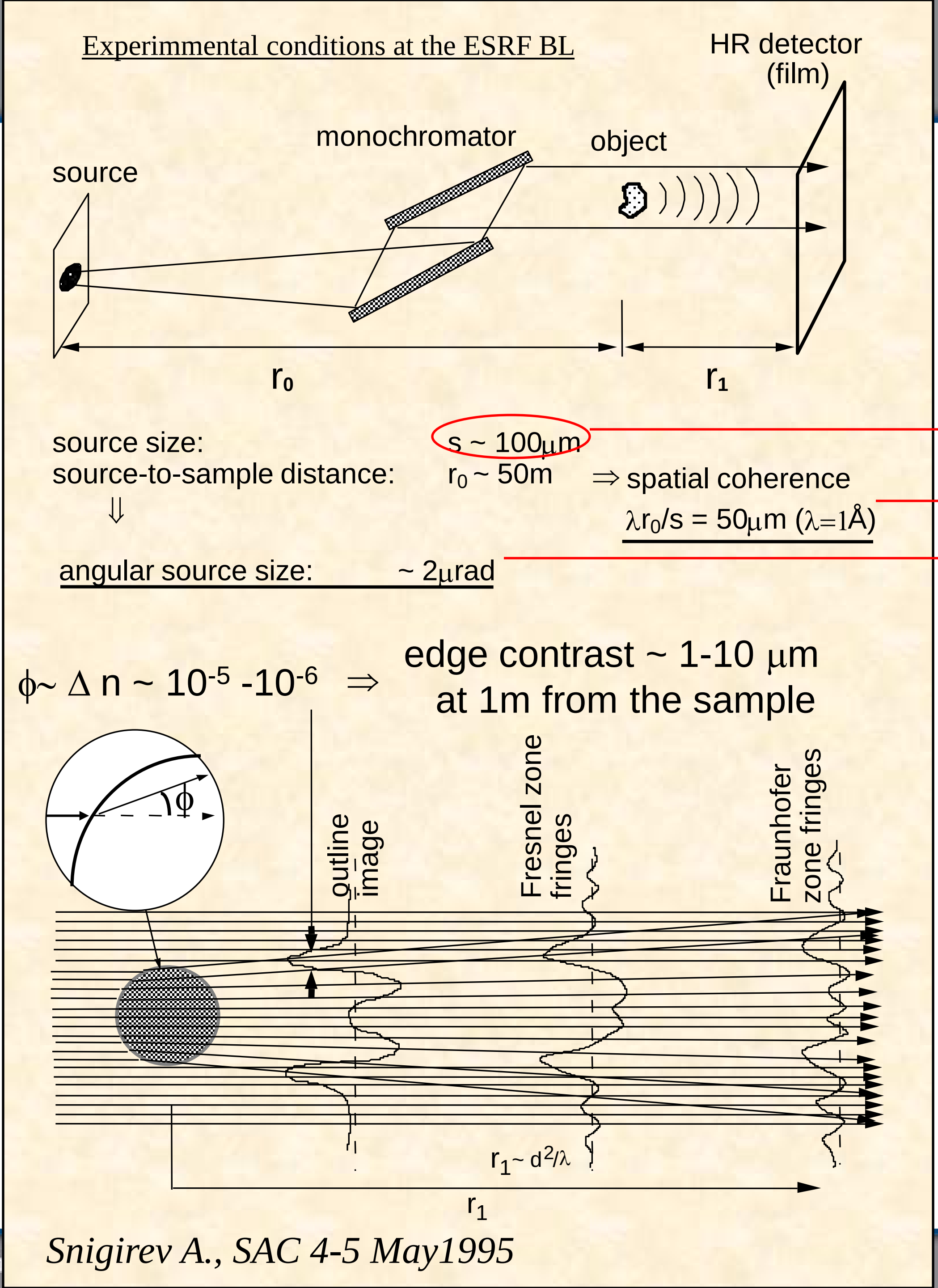
~ 20 μrad



S_v = 20 μm

S_v = 900 μm

∅ ~1mm at 50 m



ESRF source from 1995 to 2005

source	20 μm
coherence	250 μm
ang. source size	0.4 μrad

Si-111 $\Delta\theta \sim 20$ μrad

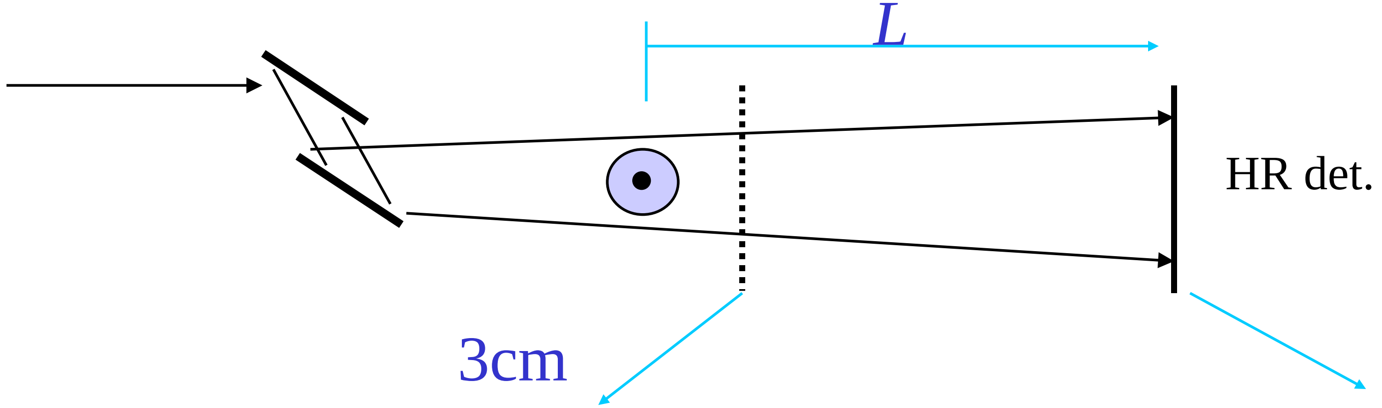
(E = 12.4 keV)

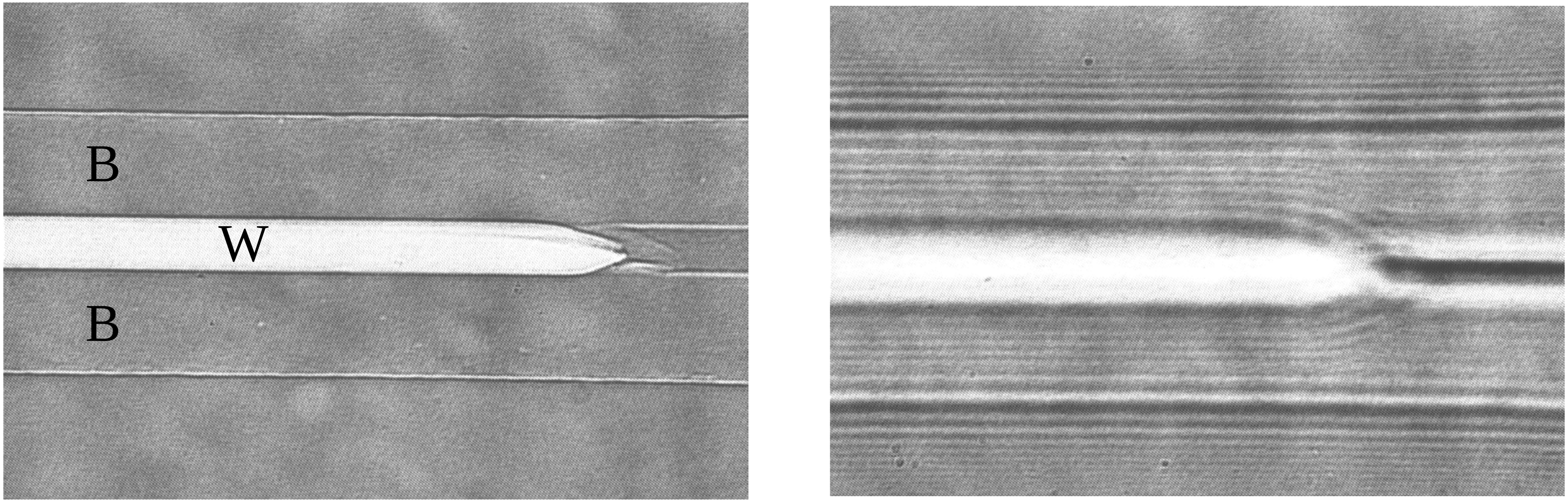
Si-555 $\Delta\theta \sim 0.5$ μrad

(E = 30 keV)

Coherent Imaging of Non-absorbing Samples

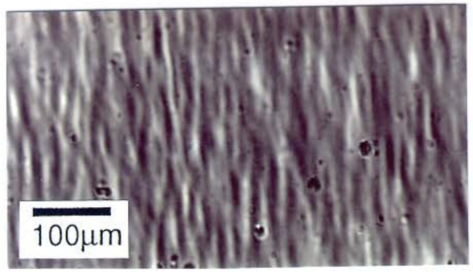
Boron fiber
(100μm diameter)
E = 16 keV



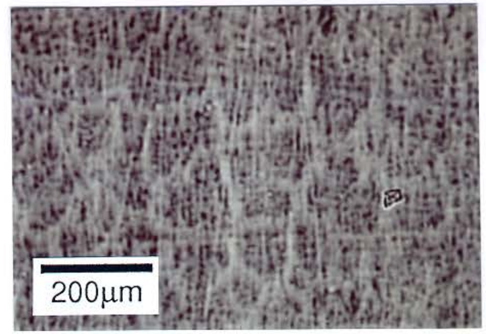


100 μm

Polished Be : 0.1µm
2 000 kFF



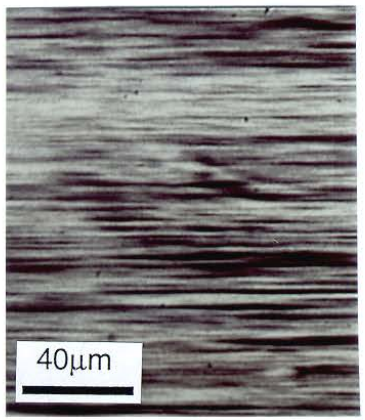
Be windows



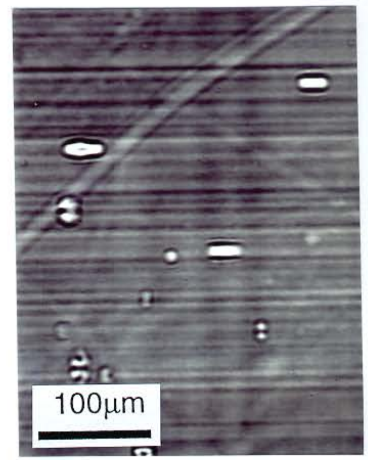
Green paper

Polished filters (Si)
FE- diamond
(no graphite)

Multilayers



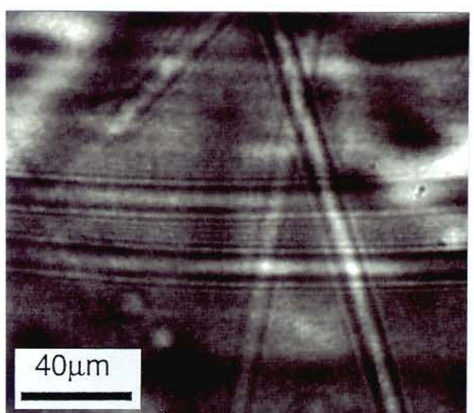
Multilayers



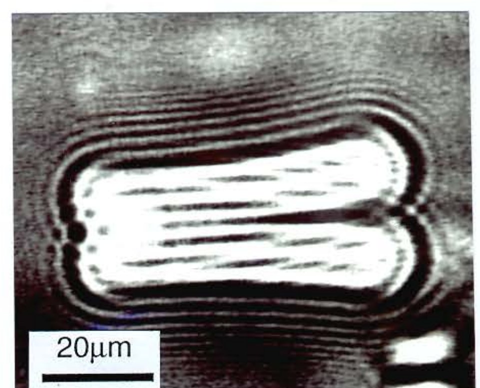
Mirrors

Super Polished mirrors
<1Å, <1µrad
horiz. deflection

Micro-scratches
Chemical etching



Crystals



Dust particles

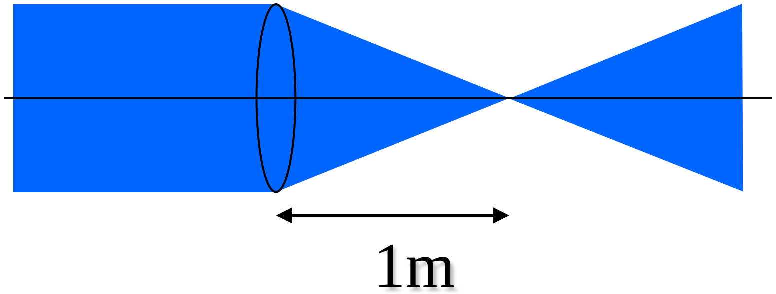
Cleaning !?

A. Strategy for refractive x-ray lenses

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

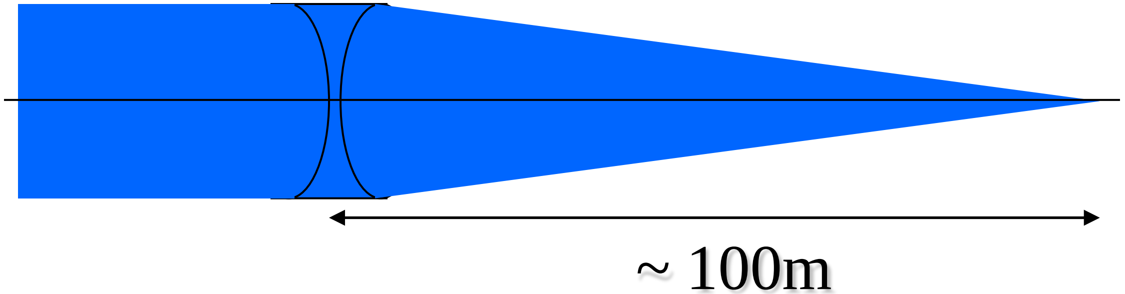
> **visible light**: index of refraction $n = 1 + \delta$ with $\delta \sim 0.5$ for glass

* 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!**

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**:

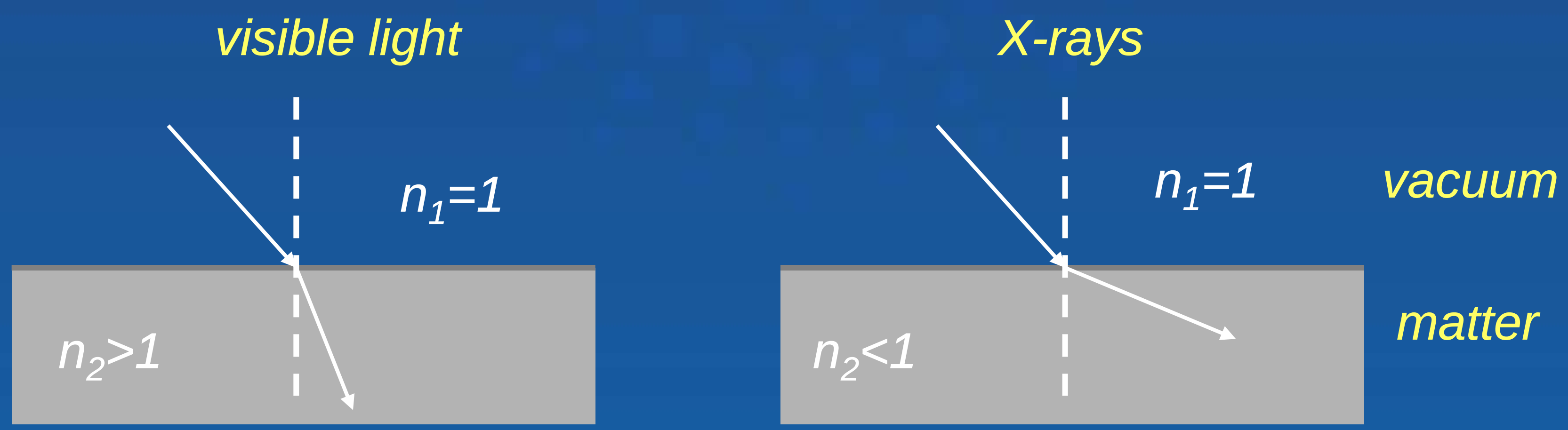
i) small radius of curvature R:
typical: R = 50 to 1500µm

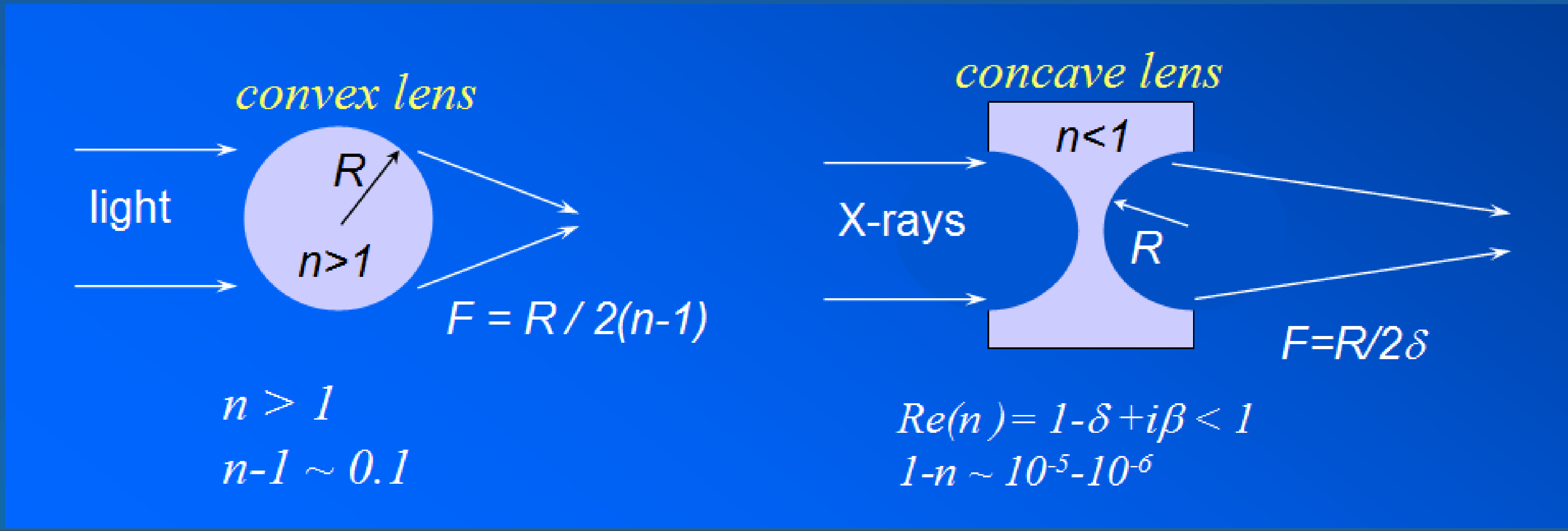
ii) high density of lens material

iii) profile must be parabolic: no spherical aberration

X-rays versus Light

Snell's law: $n_1\cos(\theta_1) = n_2\cos(\theta_2)$





X-ray Compound Refractive Lenses

$$F = \frac{R}{2\,\delta}$$

$Re(n) = 1 - \delta + i\beta < 1$

$1 - n \sim 10^{-5} - 10^{-6}$

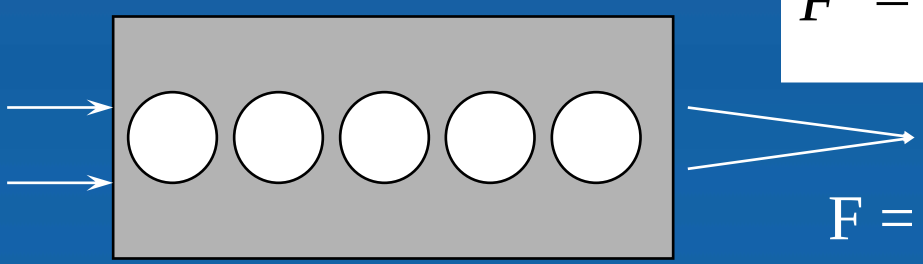
F = 15 m

A. Snigirev, V. Kohn,
I. Snigireva, B. Lengeler
Nature, Vol. 384, 49, 1996

Be
E = 10 keV
$\delta = 3.4 \cdot 10^{-6}$
R = 100 µm

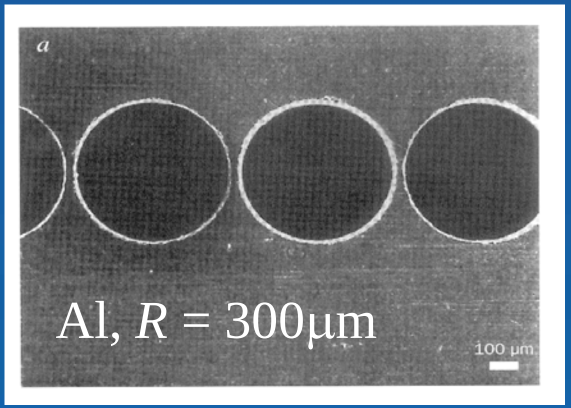
x N

$$F = \frac{R}{2\,N\delta}$$



F = 0.5 m

N = 30



The New York ...
15 February 1997 No2069 Weekly £1·80 US$3·75 ISSN 0262 4079 Science
NEW SCIENTIST NEW SCIENTIST

New Lens Focuses X-Rays

By Malcolm W. Browne
New York Times Service

NEW YORK — A team of physicists in France and Russia has invented a new kind of lens that promises to make X-ray focusing easier, cheaper and accessible to many more users than in the past.

The invention may help in the creation of finer photolithography masks for cramming more circuits on a silicon chip, as well as in exploring the arrangement of atoms in crystals and other materials in much finer detail.

X-rays have much shorter wavelengths than visible light, and can therefore "resolve," or form images, of much smaller objects than those seen in visible light. But forming magnified images of objects using X-rays requires X-ray focusing, a longstanding problem because X-rays pass through most substances without being appreciably deflected.

The new device was built by drilling a row of very thin holes in a block of aluminum. It can focus an X-ray beam to a spot a few millionths of an inch in diameter, and because it is so much simpler to make than comparable devices developed at Lawrence Livermore National Laboratory and elsewhere, it is expected to make X-ray analysis and chip lithography much more accessible to users.

The lens, which was invented by Dr. Anatoly Snigirev, his wife, Dr. Irina Snigireva, and their colleagues at the European Synchrotron Radiation Facility in Grenoble, France, and at the Kurchatov Institute of Atomic Energy in Moscow, was described in the journal Nature.

THE focusing ability of any optical system based on lenses depends on the difference in the refractive indexes, or abilities to bend beams, between the lenses themselves and the matter surrounding the lenses: glass and air, in the case of visible light. The X-ray focusing system devised by the Grenoble group exploits the differences in refractive indexes between the empty holes and the aluminum surrounding them to bend the beam. Aluminum, although opaque to light, is nearly transparent to X-rays.

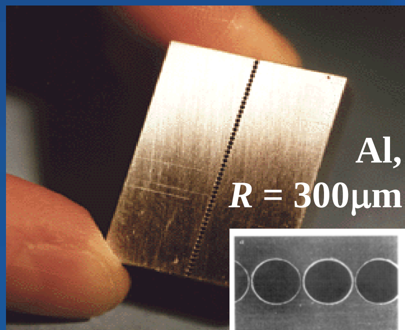
No single hole in the aluminum block has much bending effect on an X-ray beam, but when many holes are arrayed in front of the beam, their cumulative effect is to bring the beam to a sharply focused spot only a few yards from its origin.

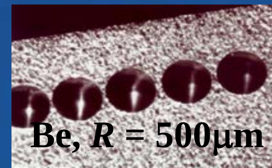
A single row of cylindrical holes produces a flattened beam, but if one or more additional rows of holes are placed in the beam path, either perpendicular to the plane of the first row or set at angles of 120 degrees from it, the beam can be squeezed to a tiny circular spot.

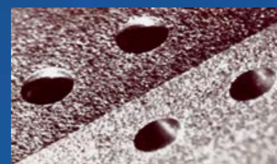
X-ray lenses are not new. Several X-ray telescopes and microscopes embody X-ray counterparts of lenses or focusing mirrors, but they are far more expensive to build than the Grenoble device.

Refractive lenses

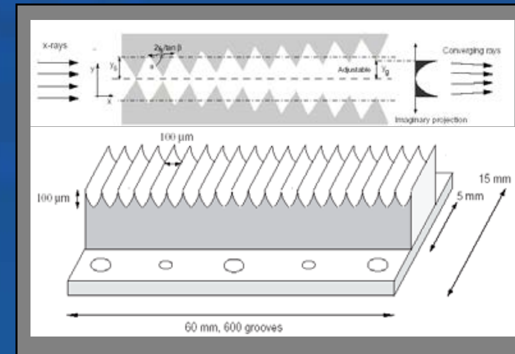
drilling





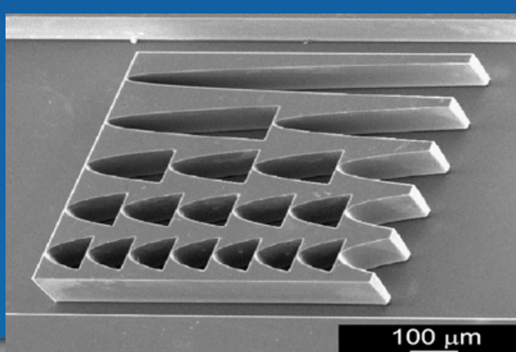


anisotropic chemical etching



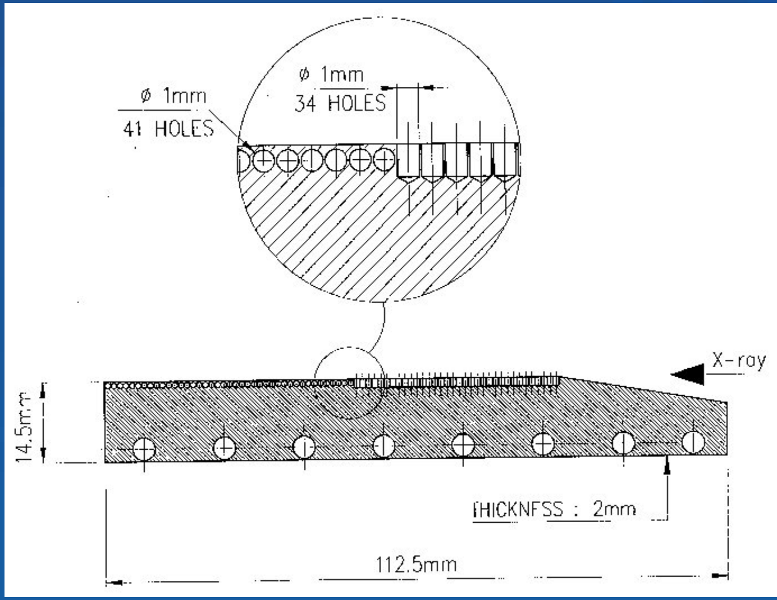
printing/molding

microfabrication (lithography, RIE)



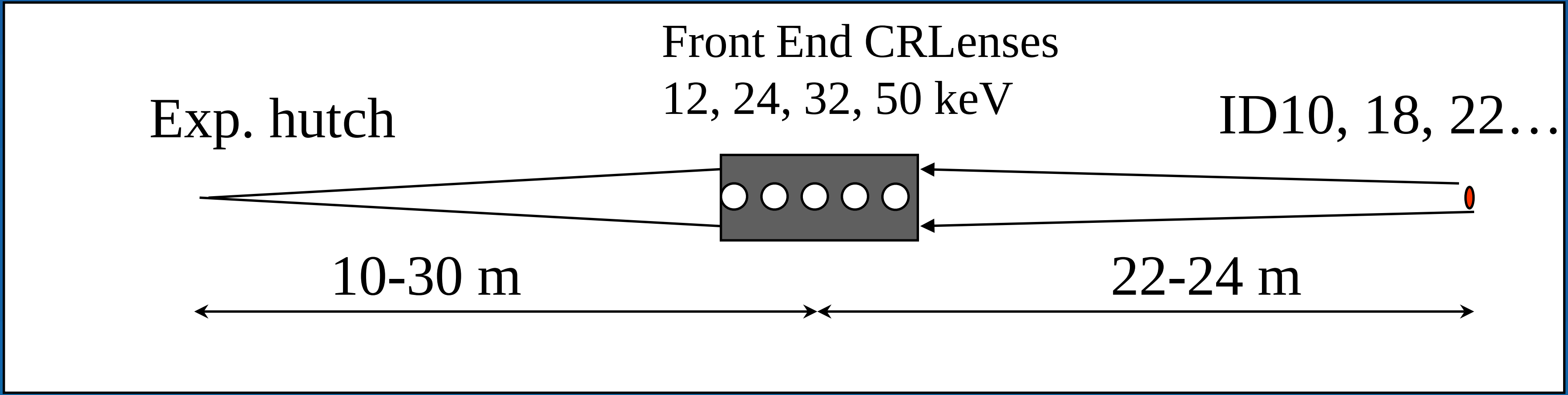
extrusion

Front-end Compound Refractive Lenses

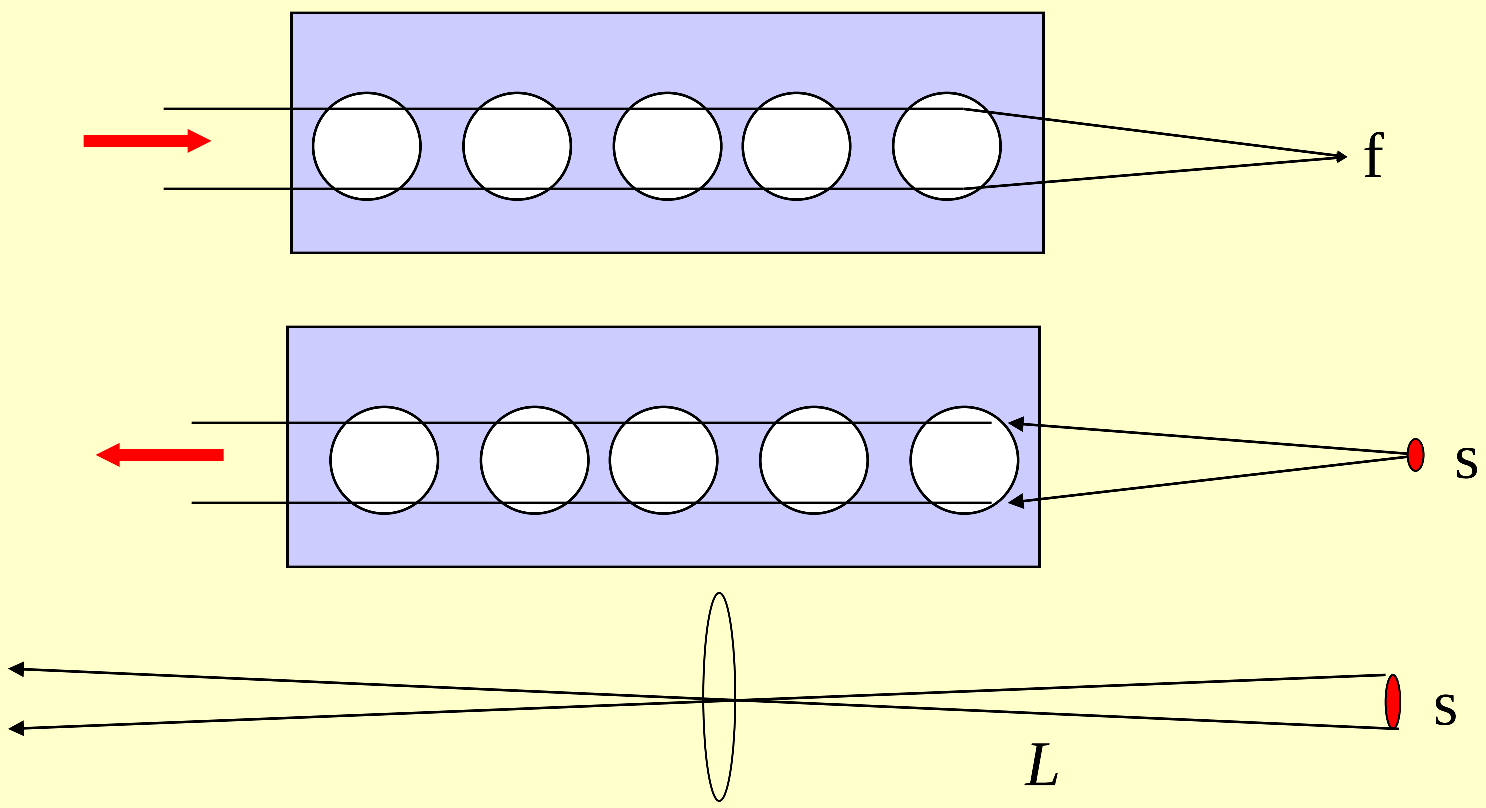


P. Elleaume, *J. Synchrotron Radiation*, 5, 1998.

1997
FE refractive lenses at 5 ESRF beamlines



Refractive as a collimator



$\phi \sim s/L = < 2\ \mu\text{rad}$ s = 50 µm; L = 30-50 m

from 10-20 µrad to 1-2 µrad

ESRF:	Chumakov et al
Spring 8:	Baron et al
APS:	A. Alp et al

PREFOCUSING with

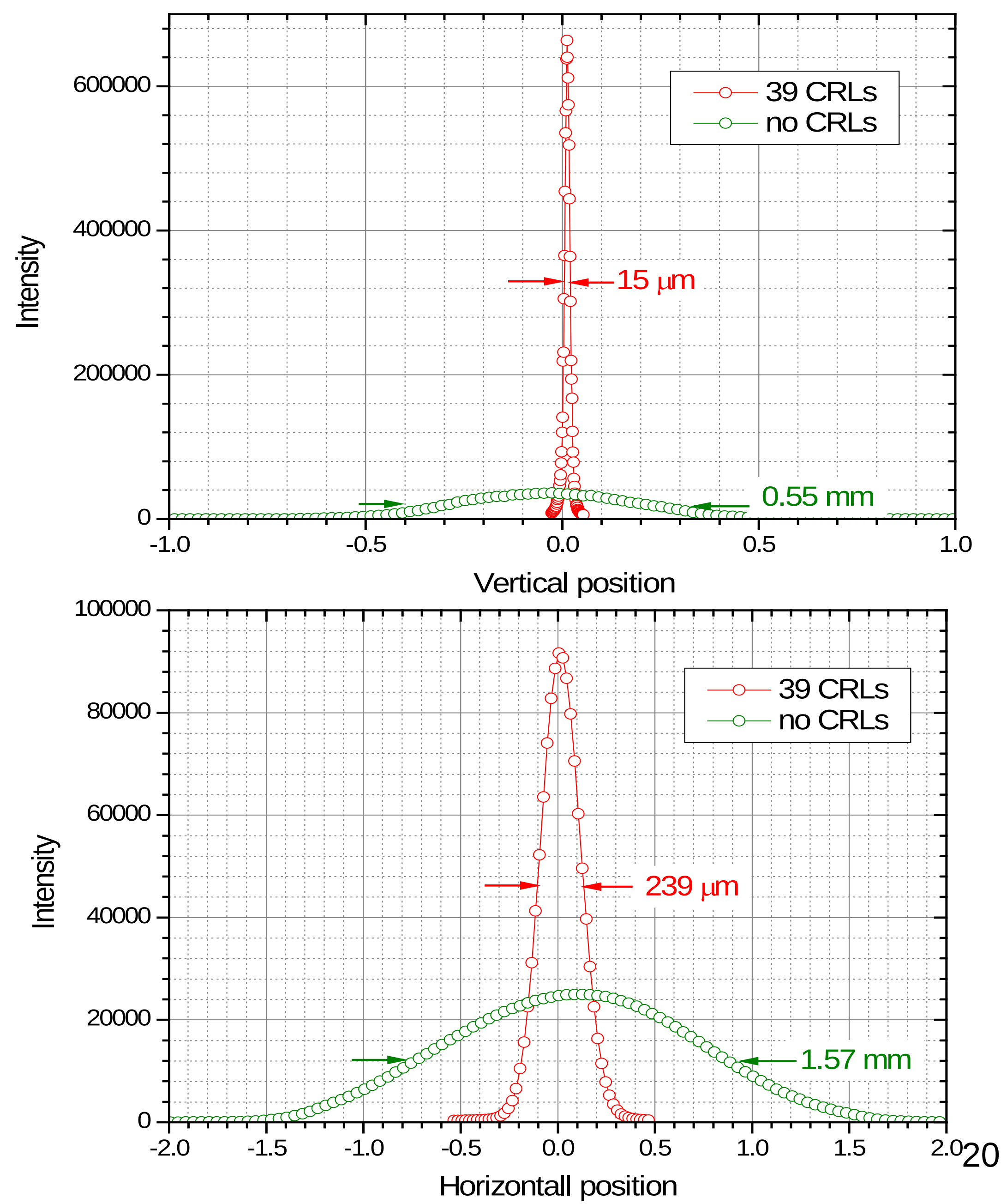
rotationally parabolic Be lenses (R = 1500µm)

Image of the ID18 source at ESRF

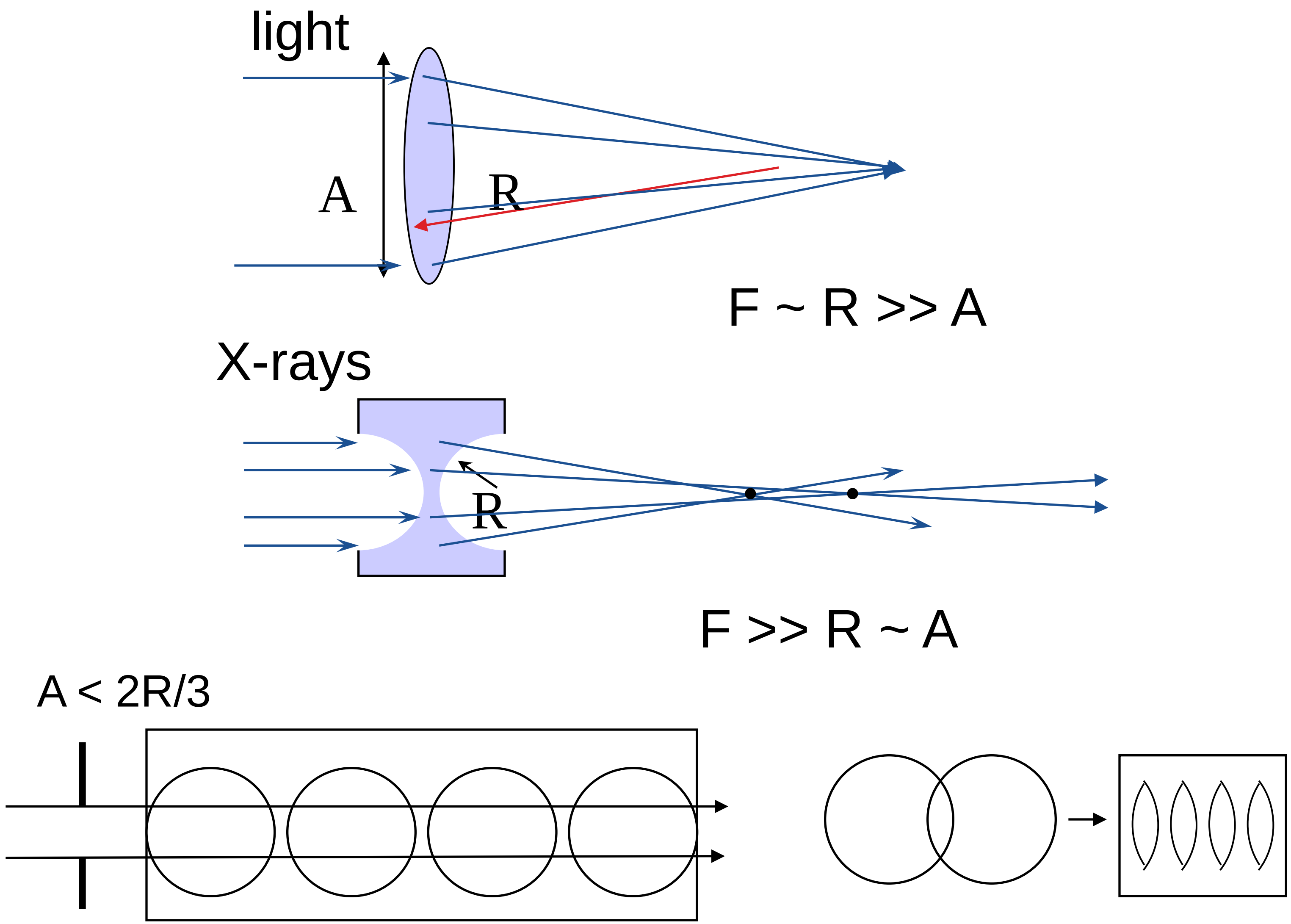
14.4125eV
39 Be lenses
R = 1500µm

f = 11.718m
geometric aperture: 2.5mm

(A. Chumakov ESRF)



Spherical aberrations

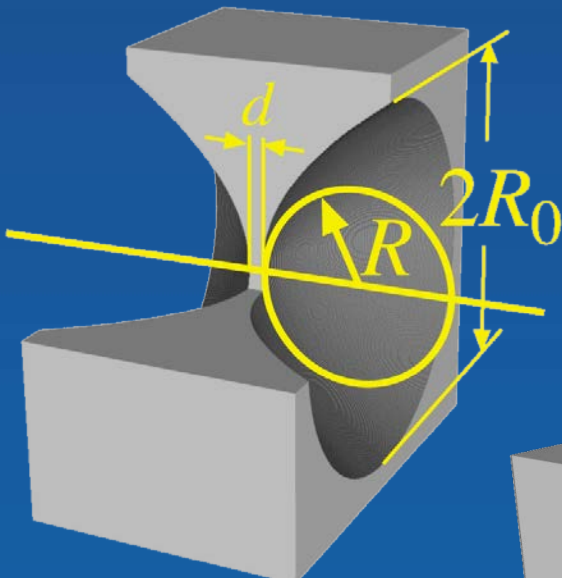


Parabolic Compound Refractive Lenses

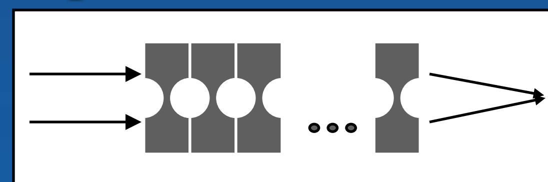
Collab. B.Lengeler,
RWTH, Aachen, Germany

single lens

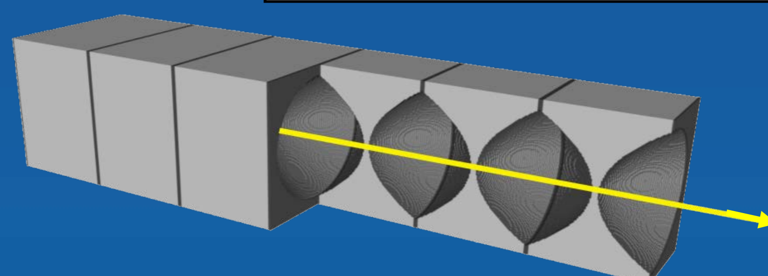
$$F = \frac{R}{2N\delta}$$

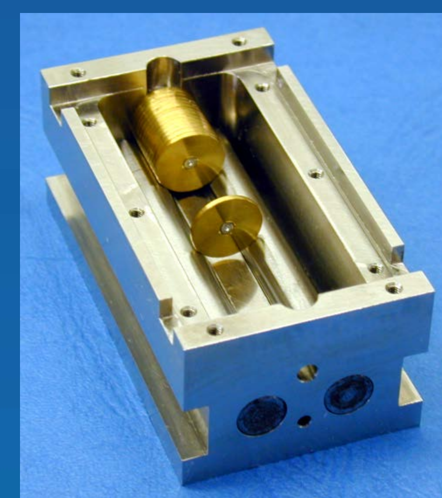


stack of lenses:
compound refractive lens (CRL)



Al, Be, Ni



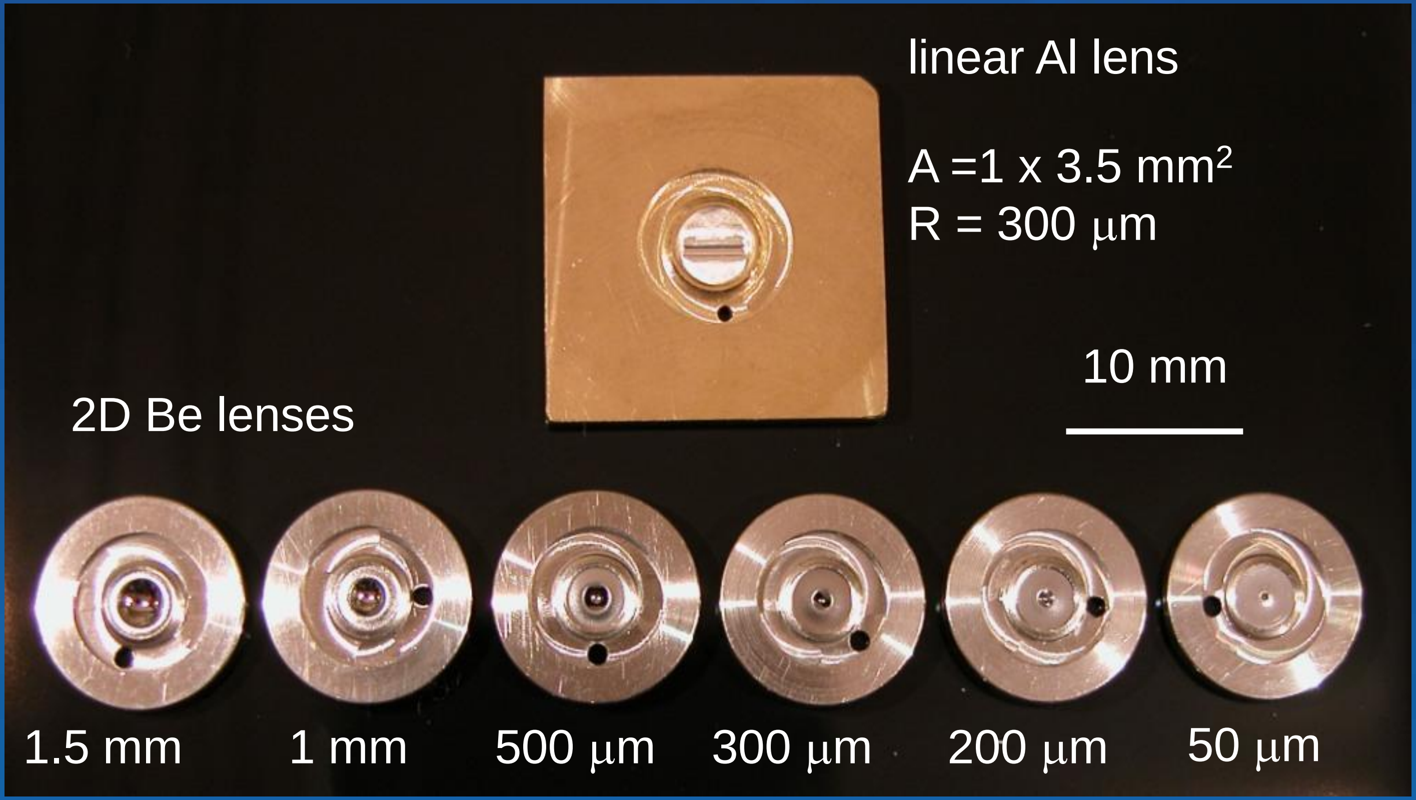


$R = 0.2\text{mm}$
$2R_0 = 0.9\text{mm}$
$d \approx 5\mu\text{m}$

R = 0.5 – 1.5mm
$2R_0$ = 2-3 mm

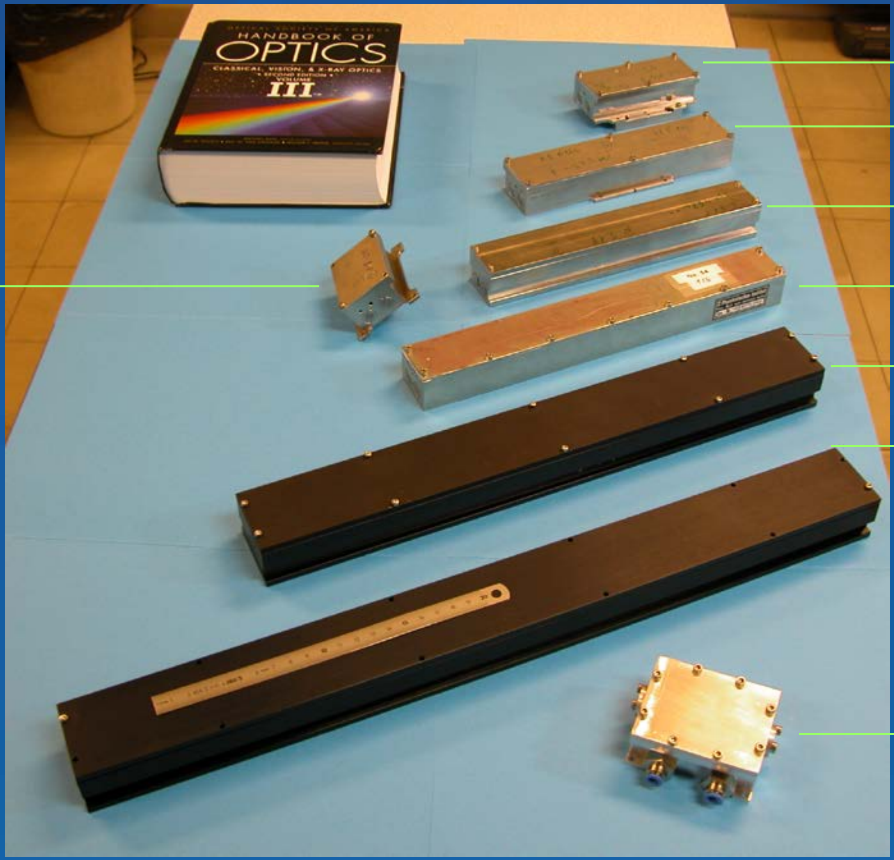
variable number of lenses: $N = 10 \ldots 300$

Be / AL parabolic lenses (Aachen)



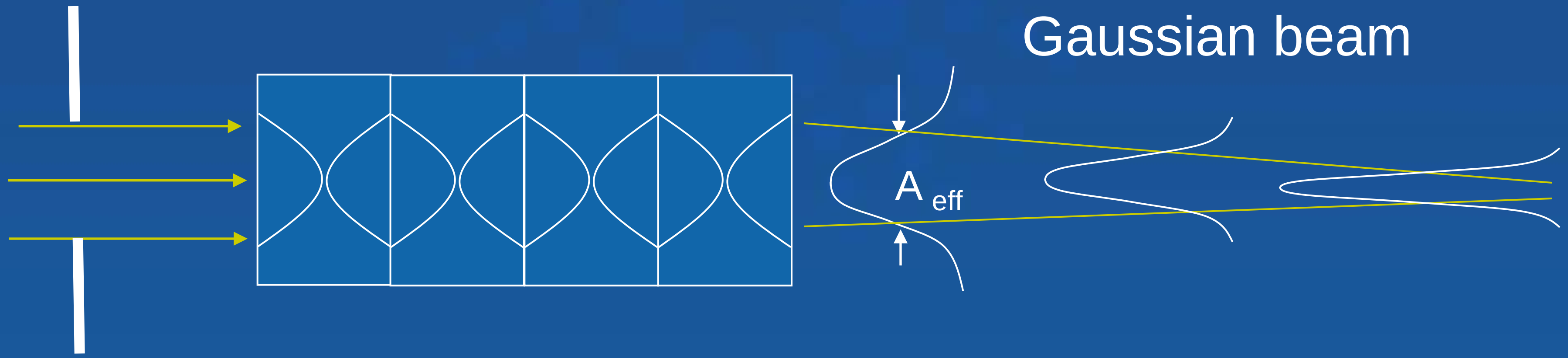
R	t	A
mm		
0.05	1	0.45
0.2	1	0.9
0.3	1	1.1
0.5	1	1.4
1	1	2
1.5	1.5	3

Lens holders for CRLs



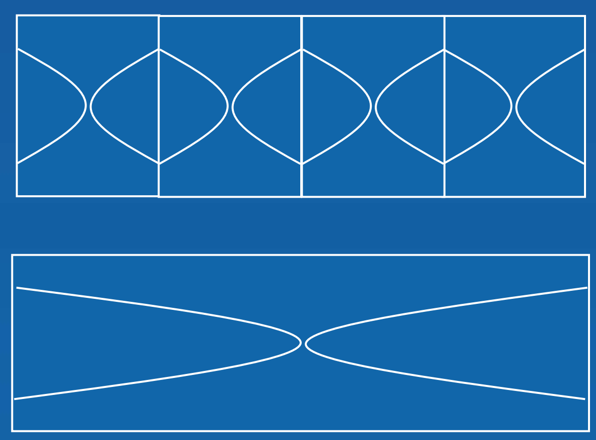
100
200
240
300
400
500
50
30 (Be)

Parabolic lenses



Effective aperture A_{eff}

A



A

$$F = \frac{R}{2N\delta}$$

Choice of material for X-ray parabolic lenses

Effective aperture A_{eff}

V. Kohn, I. Snigireva and A. Snigirev, Opt. Comm. 216 (2003), 247

$$A_{eff} = \left(\lambda f \frac{\delta}{\beta} \right)^{1/2} = \left(4\pi f \frac{\delta}{\mu} \right)^{1/2}$$

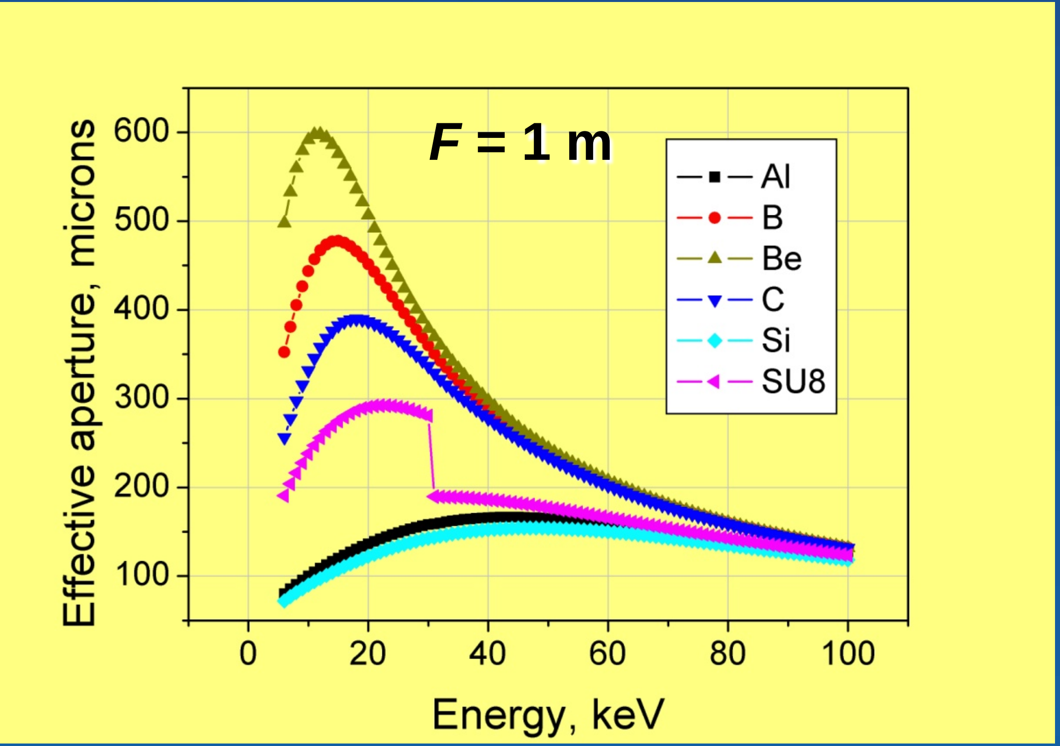
λ - wavelength

f - focal length

δ - real part of decrement of refraction index

β - imaginary part of decrement of refraction index

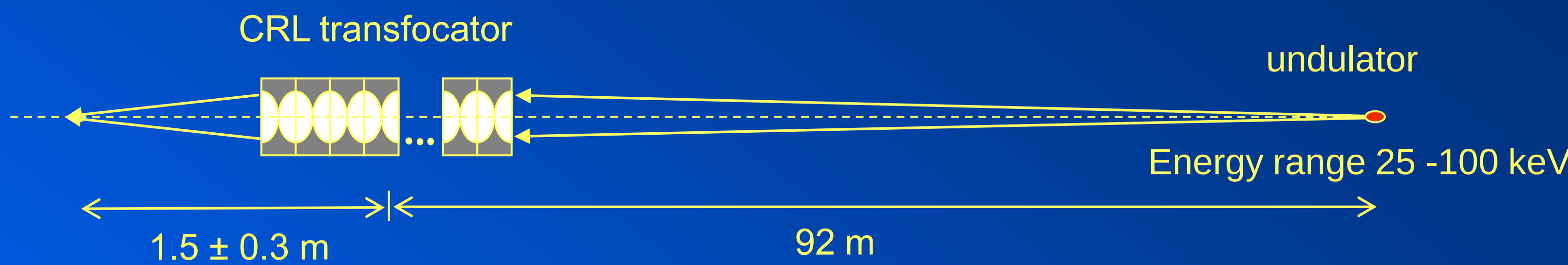
μ - linear attenuation coefficient

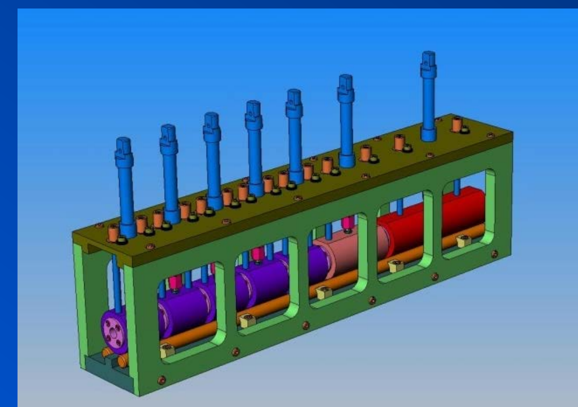


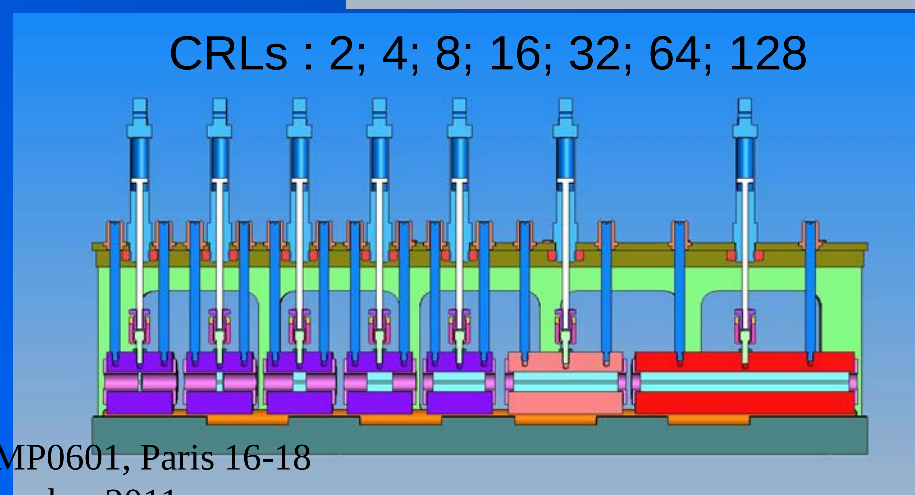
Effective aperture for the focal length F = 1 m

Трансфокатор

CRL transfocator Energy range 10 -100 keV







Cinel X-ray Refractive Lens Transfocator

(in-vacuum/white beam) ID11

lens and cartridges assembly	5.12.08
chamber assembly	8.12.08
installation at ID11	January 2009
test / commissioning	Jan-Feb 2009

cartridge and lenses

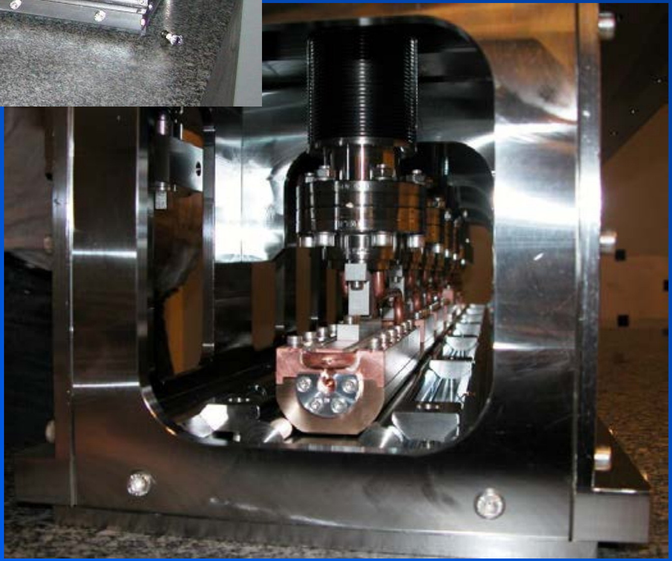
actuators

32 + 64 = 96 Al lenses
1 + 2 + 4 + 8 + 16 + 32 = 63 Be lenses

cartridges
with Be lenses

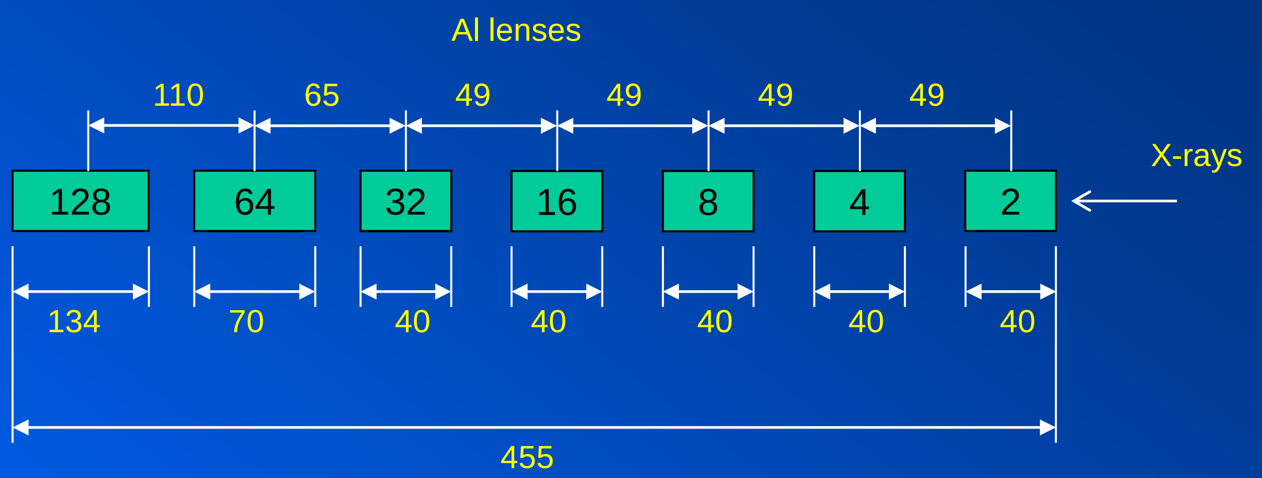
vacuum chamber

aboard view

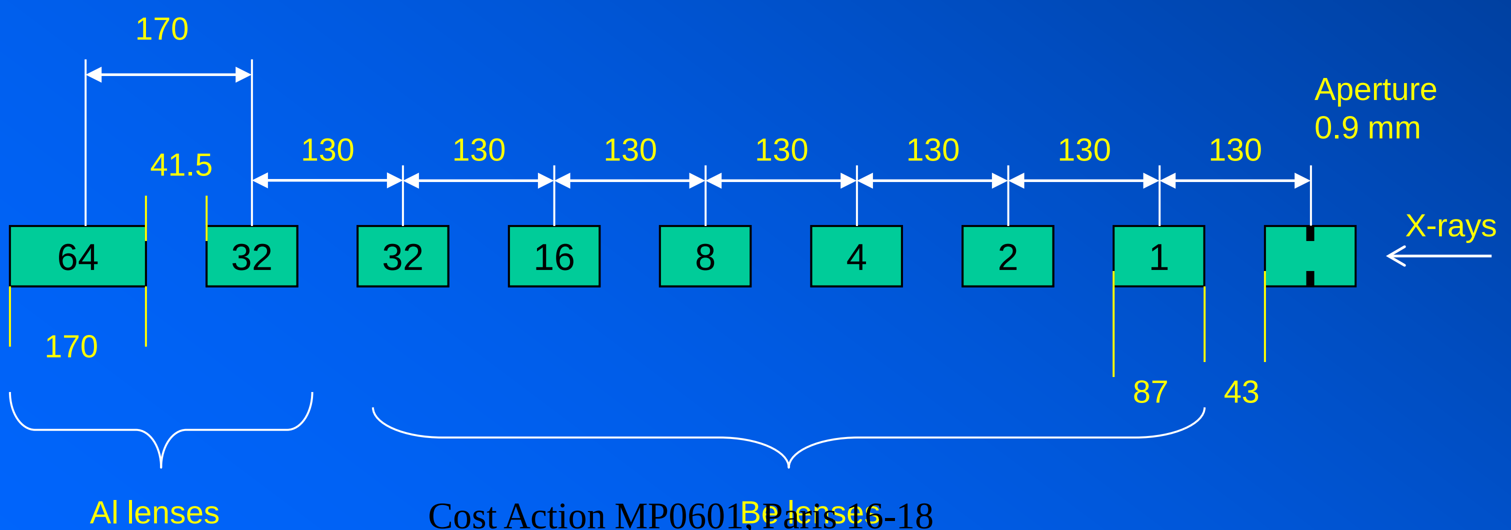


lens assembly layout

IAT transfocator



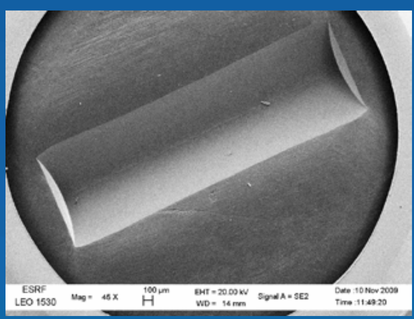
IVT transfocator

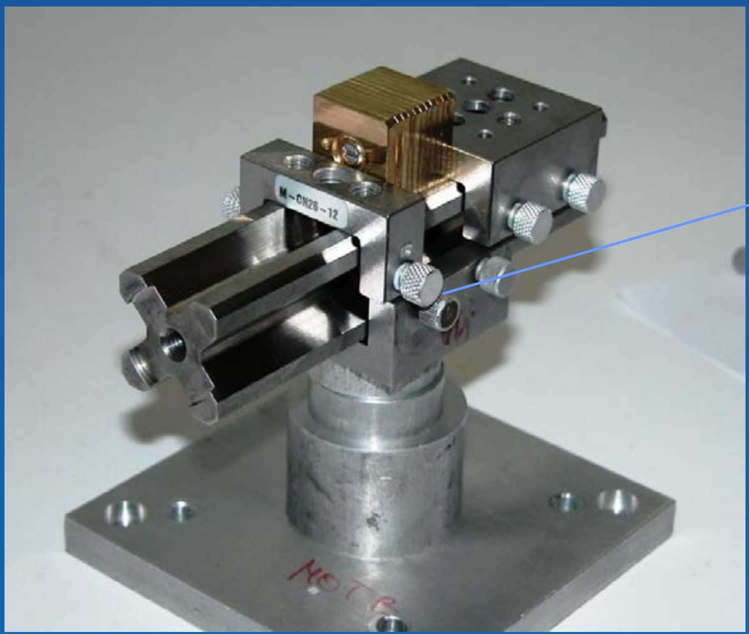



"EMERGENCY"
STOP
ARRET
10/12/2008

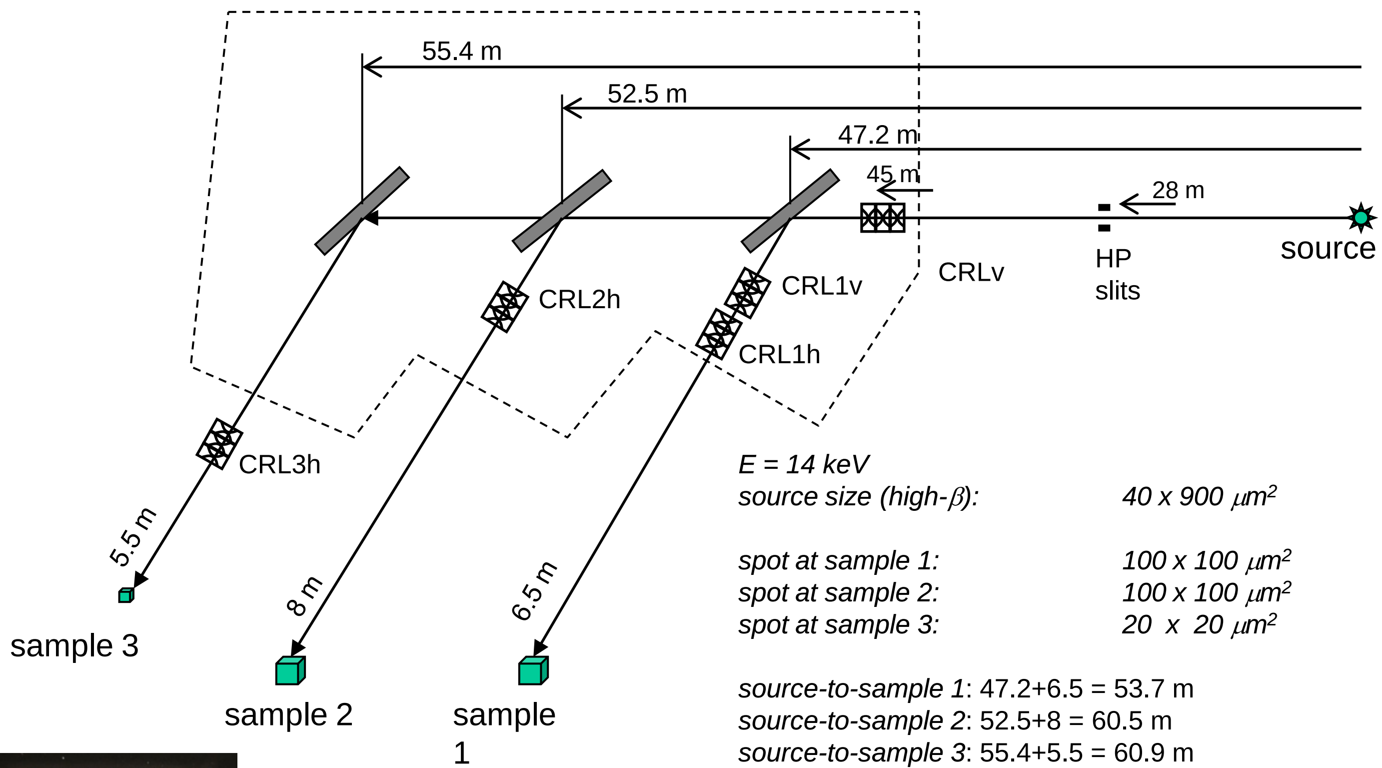
Test of first Al linear parabolic lenses from Aachen (B. Lengeler)

E = 12 keV, N = 10 lenses, R = 300 μm





MASSIF layout based on linear CRLs (astigmatic focusing)

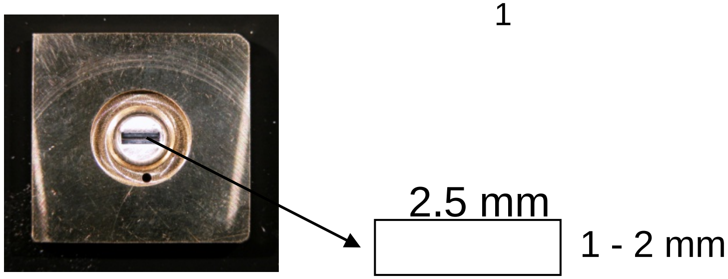


E = 14 keV
source size (high-β): *40 x 900 μm²*

spot at sample 1: *100 x 100 μm²*
spot at sample 2: *100 x 100 μm²*
spot at sample 3: *20 x 20 μm²*

source-to-sample 1: 47.2+6.5 = 53.7 m
source-to-sample 2: 52.5+8 = 60.5 m
source-to-sample 3: 55.4+5.5 = 60.9 m

CRLv:
2v) L1=45m L2=15.5m δ=50μm (def 15.5m-sample vs 15.9m-focus)
3v) L1=45m L2=15.9 N =12 R = 500μm Ag=1.4mm Aef=1.5mm
δ=14μm

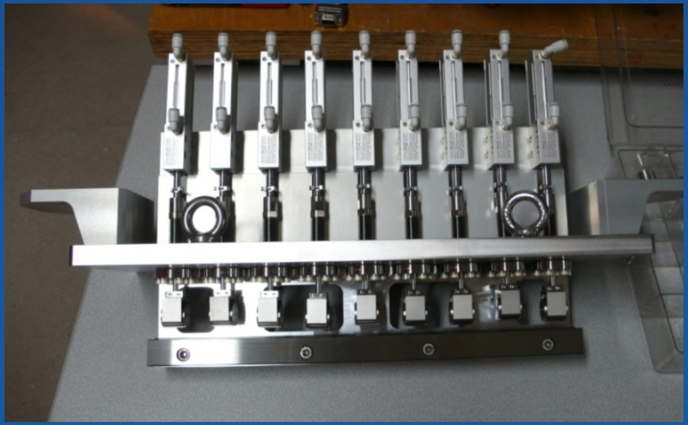


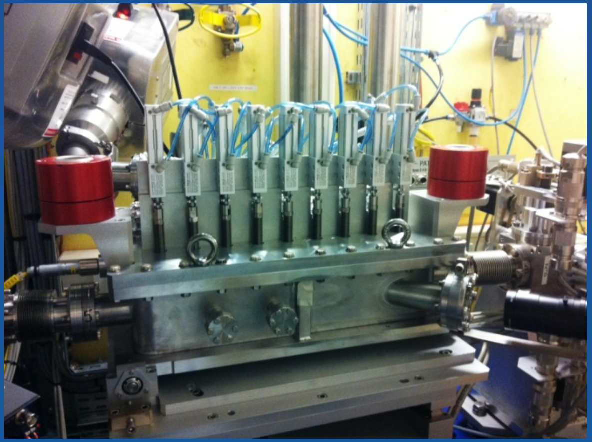
Total number of lenses N = 125 = 102(300) + 23(500)

Linear parabolic lens

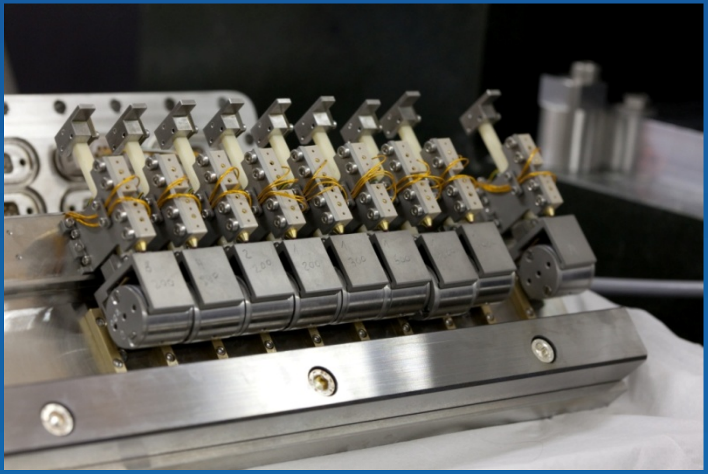
New transfocators

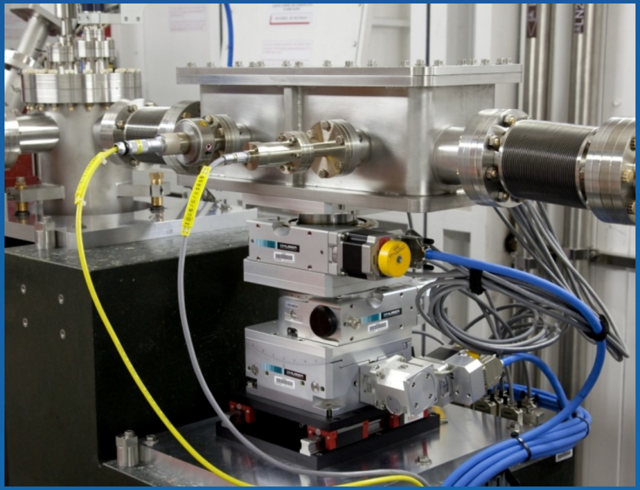
ID32





ID6

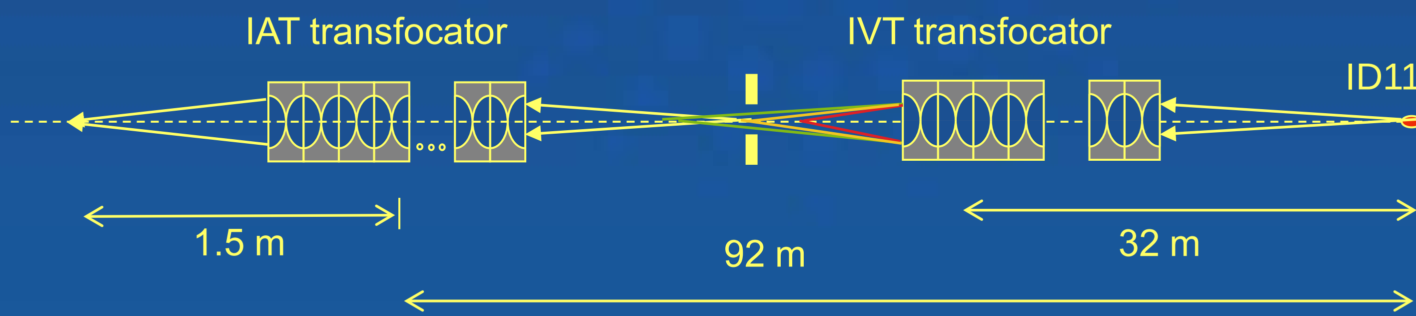




Focusing monochromators

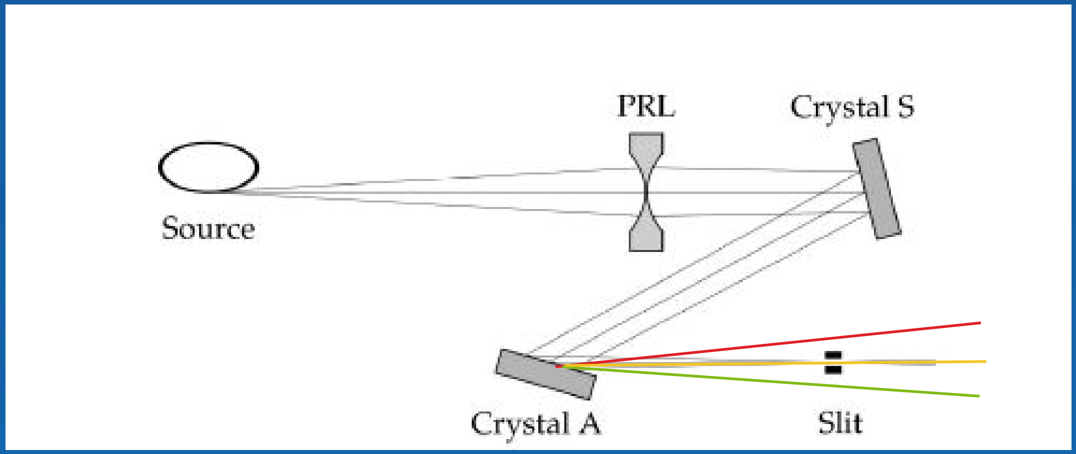
Low energy resolution monochromator (longitudinal)

ΔE ~ 1 %



G. Vaughan et al., J. Synchrotron Rad., to be published.

High energy resolution monochromator (transversal)



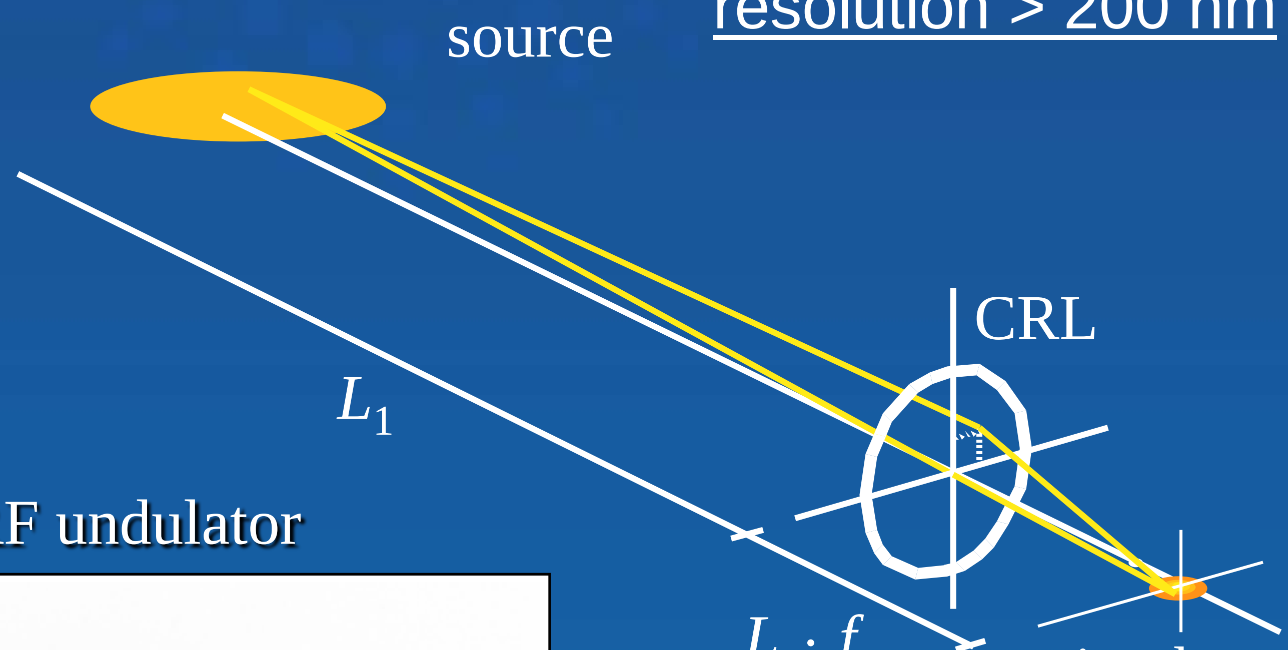
ΔE ~ 0.1 meV !!!

V. Kohn, A. Chumakov, R. Ruffer, J. Synchrotron Rad., 16, 635-641, 2009.

Microbeam

Using CRL: Microbeam is reduced image of source

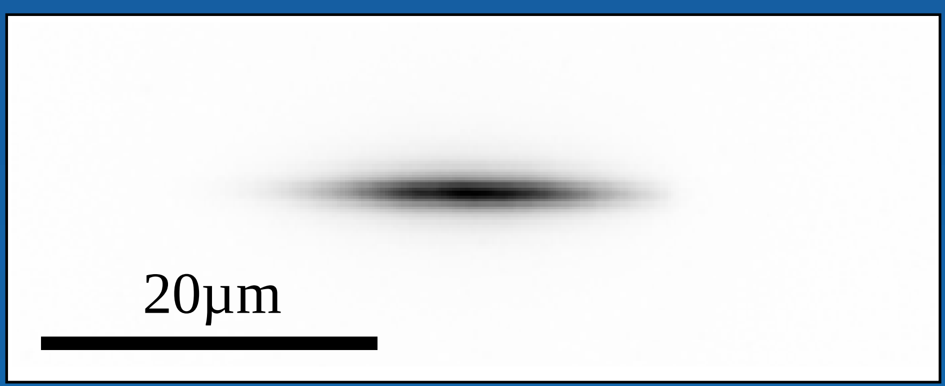
resolution > 200 nm



microbeam
on sample

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

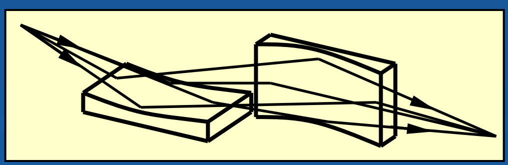
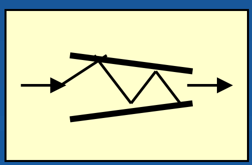
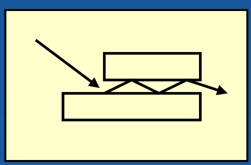
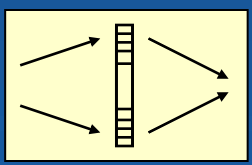
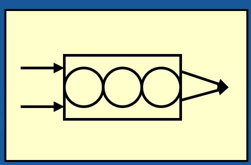
reduced image
of source: ESRF undulator



detector: Sensicam 0.645 µm

magnification: $m = \frac{L_2}{L_1}$

Focusing Optics for Hard X-rays (E > 6 keV)

	reflective				*diffractive*	*refractive*
	Kirkpatrick Baez systems		Capillaries	Waveguides	Fresnel Zone plates	Refractive lenses
	mirrors Kirkpatrick Baez, 1948	multilayers Underwood Barbee, 1986	Kreger 1948	Feng et al 1993	Baez 1952	Snigirev et al, 1996
						
Energy	< 30 keV	< 80keV	< 20keV	< 20keV	< 30 keV (80)	<1 MeV
Bandwidth ΔE/E	w. b.	10^{-2}	w.b.	10^{-3}	10^{-3} - 10^{-4}	10^{-3}
resolution	**25 nm** @15keV Mimura 2006 8 nm !	**41x45nm^2** @24keV Hignette 2006	**50 nm** Bilderback 1994	**40x25 nm^2** Salditt 2004	**30 nm** @20 keV Kang, 2006 17 nm, 2007 ??	**50 nm@20keV** Schroer, 2004 **150nm@50keV** Snigirev,2006

Applications

- Beam diagnostics
- Beam conditioning optics
    - condensers,
    - collimators
    - monochromators
- Micro (nano)-beam
    - diffraction, scattering & spectroscopy
- Microscopy

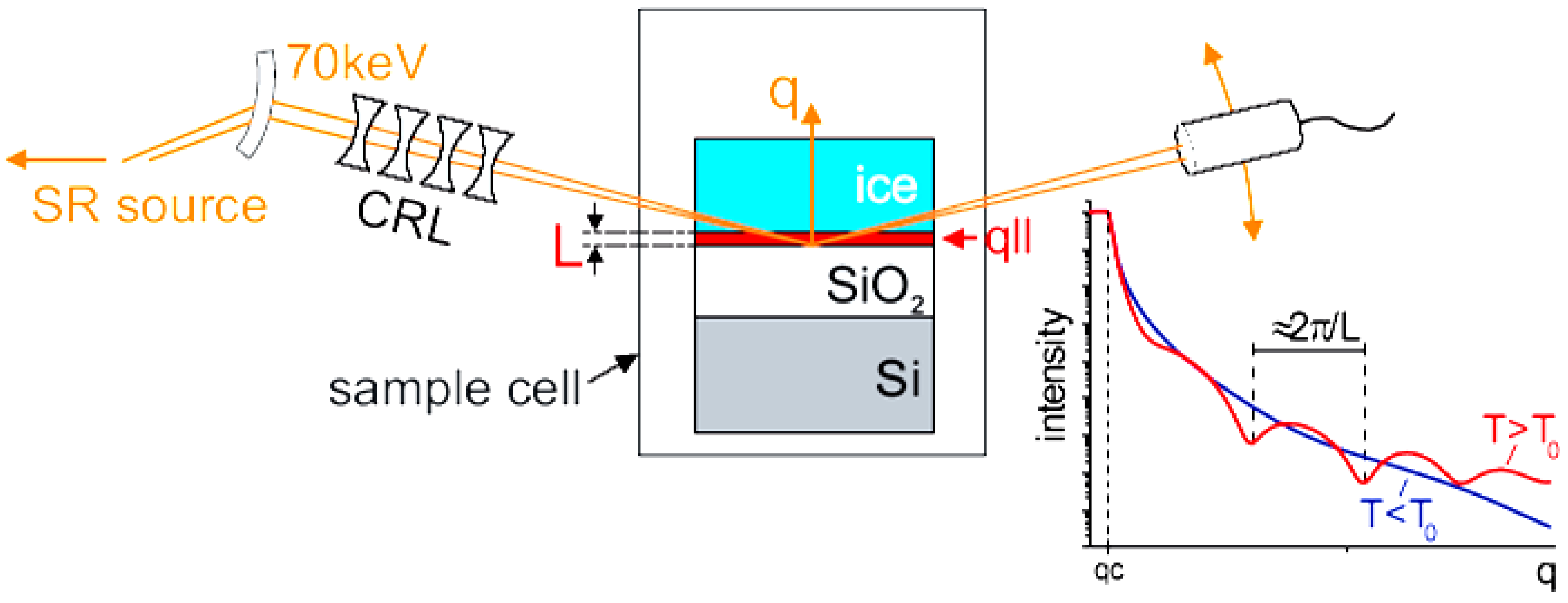
  full-field imaging and diffraction
- Interferometry

VOLUME 92, NUMBER 20 PHYSICAL REVIEW LETTERS week ending 21 MAY 2004

Interfacial Melting of Ice in Contact with SiO_2

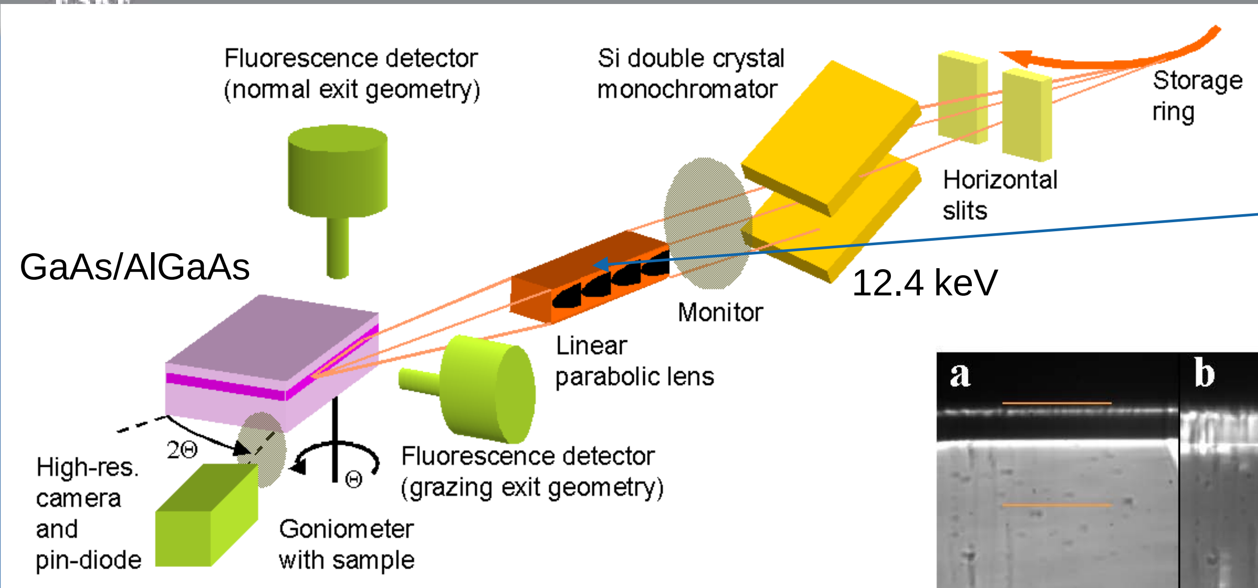
S. Engemann,[1] H. Reichert,[1] H. Dosch,[1,2] J. Bilgram,[3] V. Honkimäki,[4] and A. Snigirev[4]
[1]*Max-Planck-Institut für Metallforschung, Heisenbergstrasse 3, D-70569 Stuttgart, Germany*
[2]*Institut für Theoretische und Angewandte Physik, Universität Stuttgart, D-70569 Stuttgart, Germany*
[3]*Laboratorium für Festkörperphysik, ETH Zürich, CH-8093 Zürich, Switzerland*
[4]*European Synchrotron Radiation Facility, F-38043 Grenoble, France*
(Received 15 January 2004; published 17 May 2004)

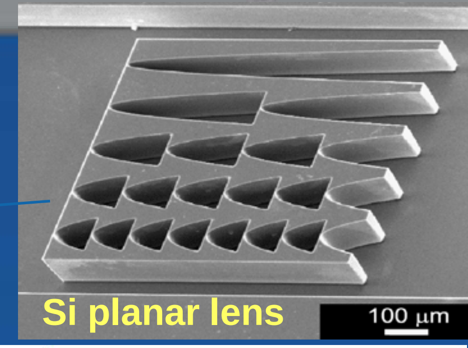
The physical behavior of condensed matter can be drastically altered in the presence of interfaces. Using a high-energy x-ray transmission-reflection scheme, we have studied ice-SiO_2 model interfaces. We observed the formation of a quasiliquid layer below the bulk melting temperature and determined its thickness and density as a function of temperature. The quasiliquid layer has stronger correlations than water and a large density close to $\rho_{HDA} = 1.17\ g/cm^3$ of high-density amorphous ice suggesting a structural relationship with the postulated high-density liquid phase of water.

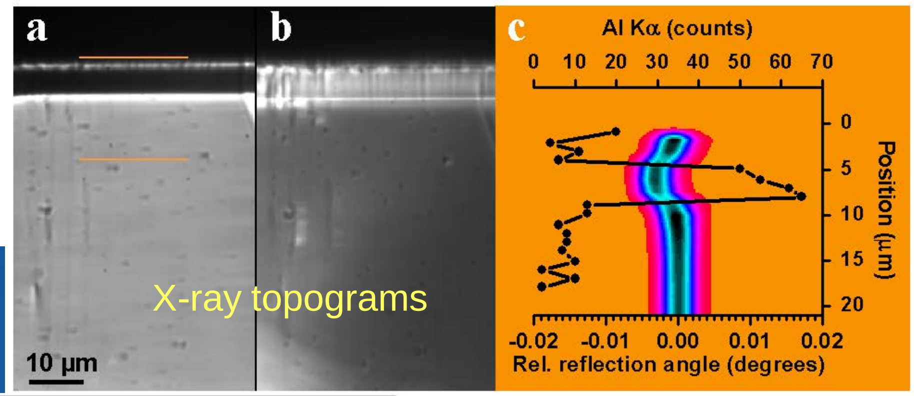


Europ

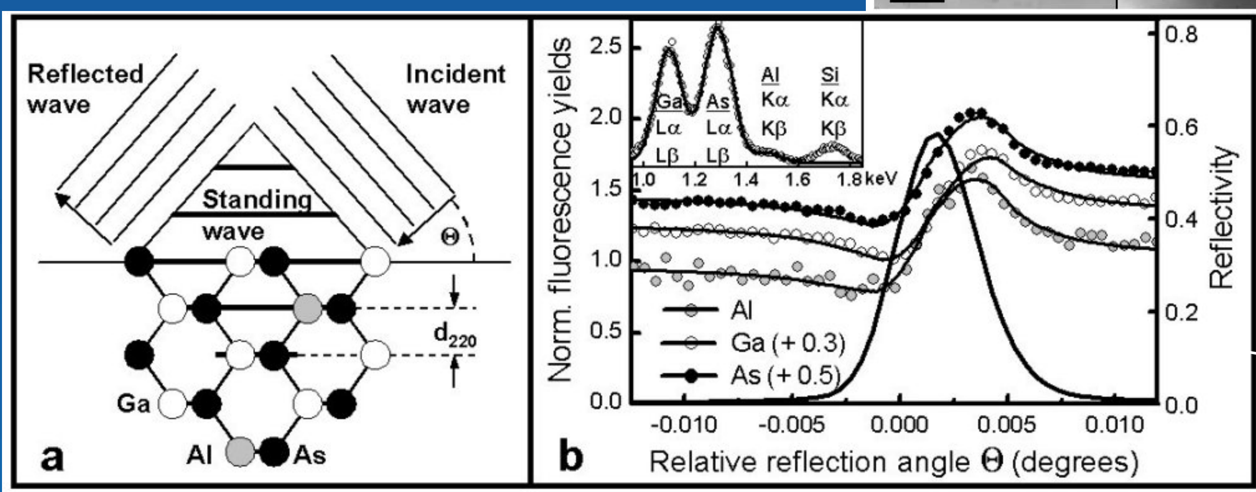
X-ray standing wave microscopy







rocking curves mapping with focused x-ray beam

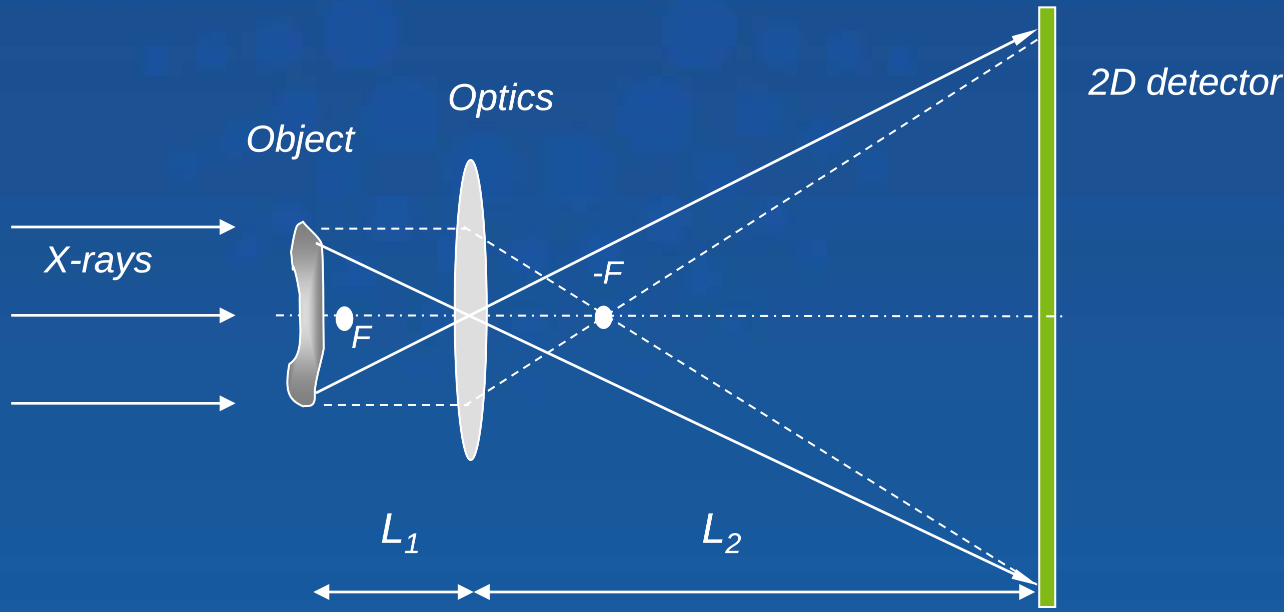


Reflectivity and fluorescence yields from the epitaxial $Al_{0.1}Ga_{0.9}As$-layer as a function of the glancing angle Θ

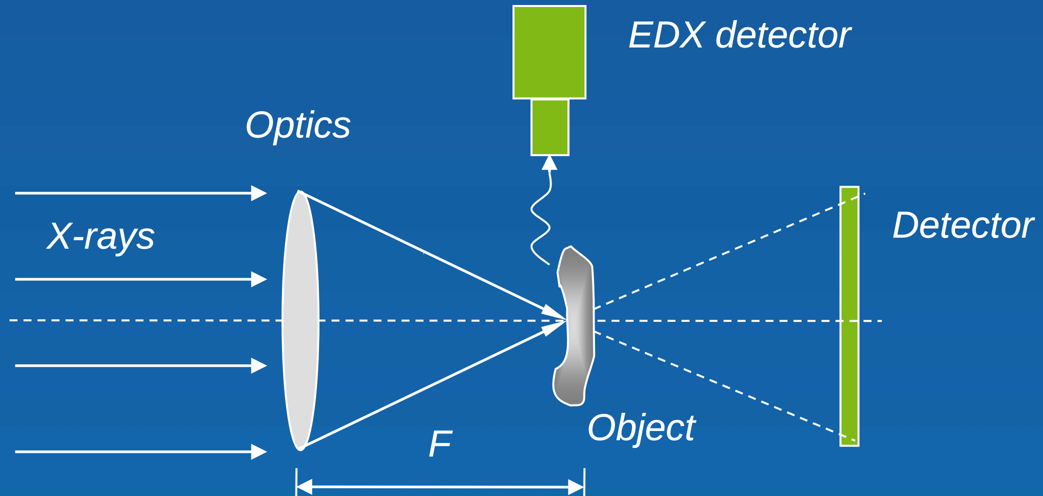
M. Drakopoulos, J. Zegenhagen, A. Snigirev, I. Snigireva, K. Eberl, V. V. Aristov, L. Shabelnikov, V. Yunkin (APL, 81(12), 2279-2281, 2002)

X-ray microscopes

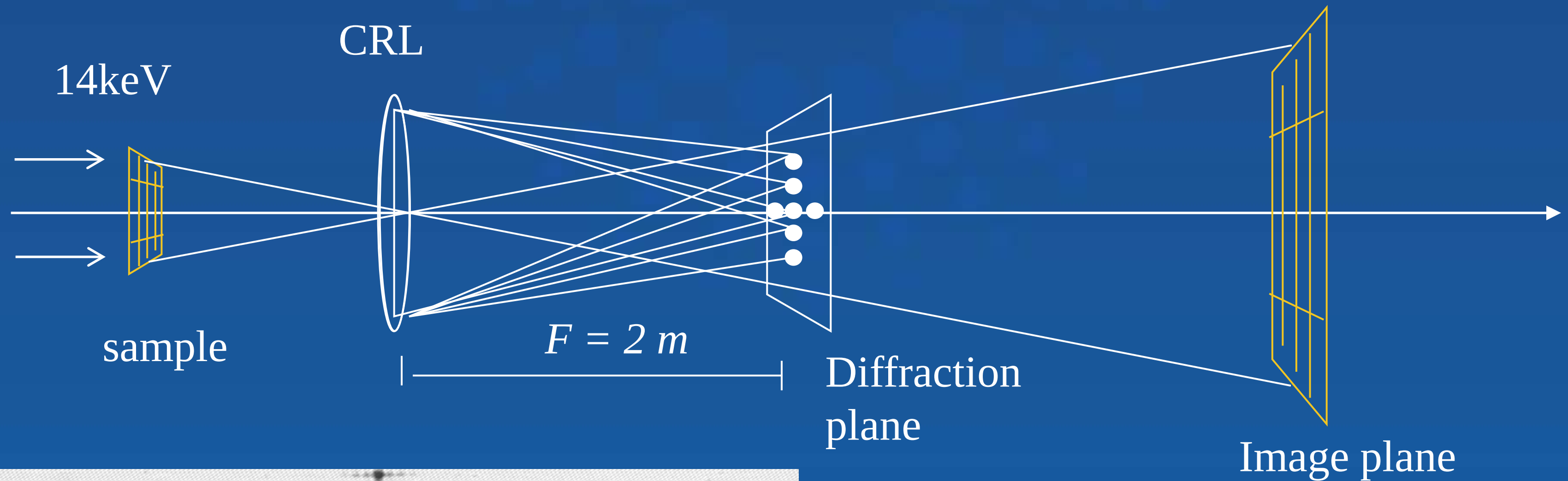
Full-field

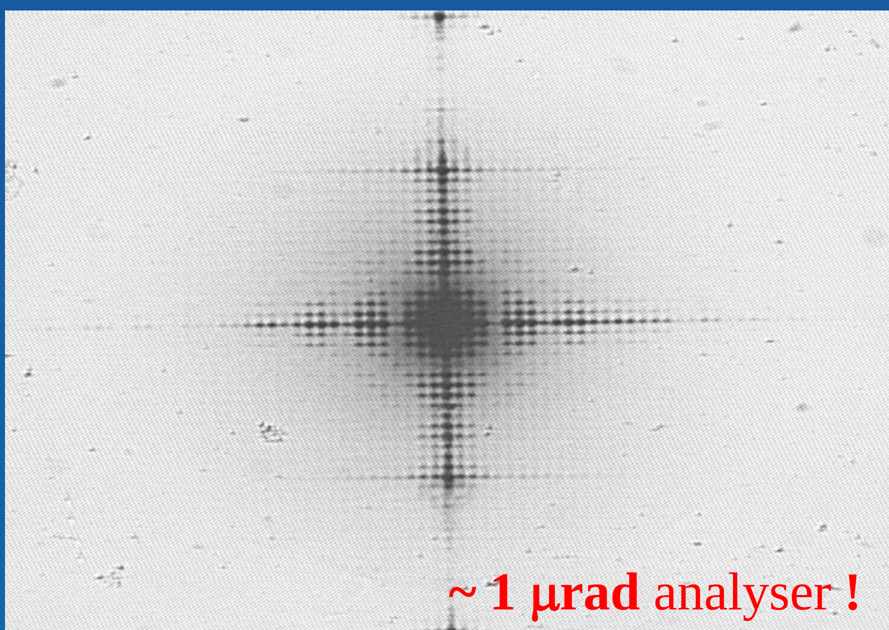


Scanning

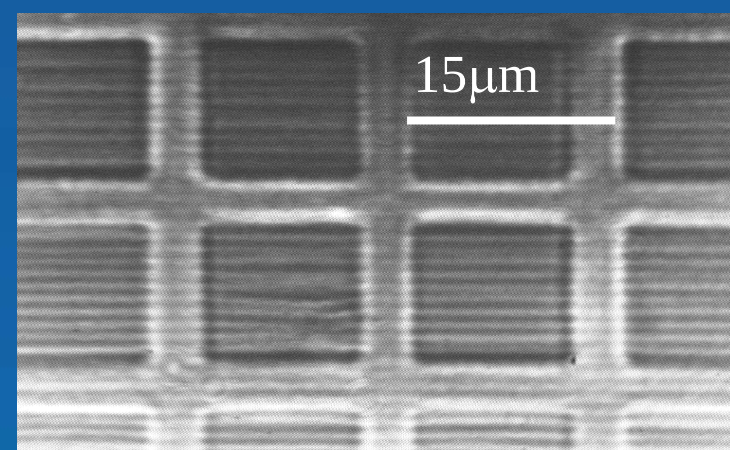


Fourier Transform Diffraction/Imaging

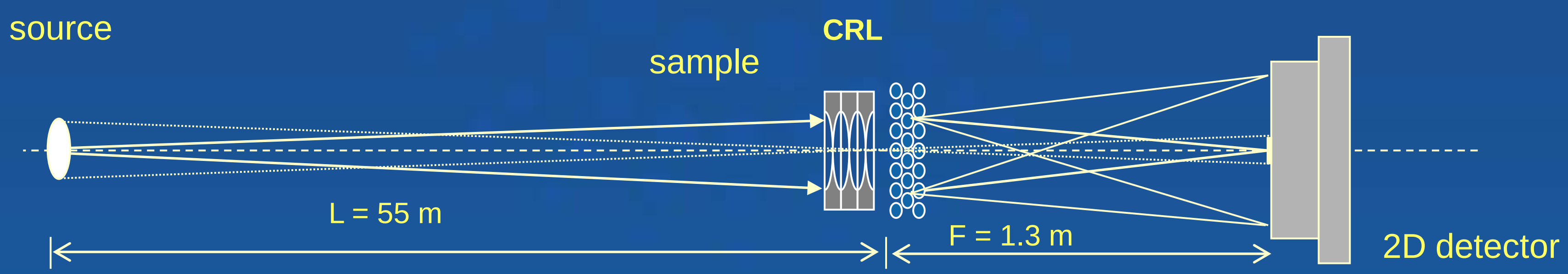




FT



X-ray High Resolution Diffraction Using Refractive Lenses



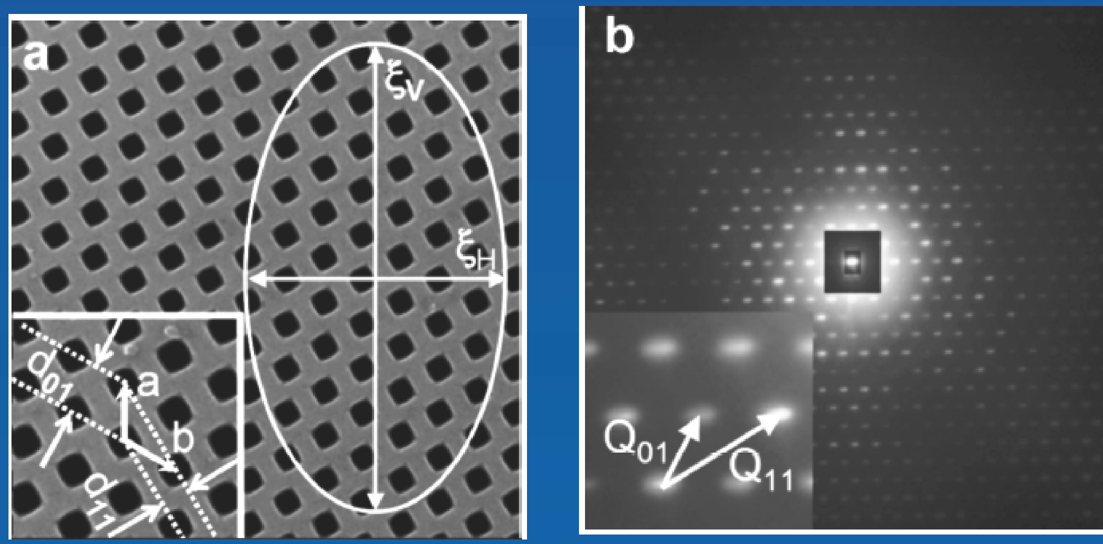
E = 28 keV
Al CRL, N = 112, F = 1.3 m

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.

Where do we need HRXRM?

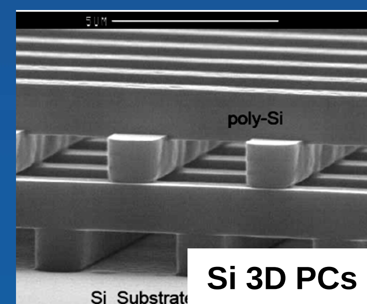
Mesoscopic materials

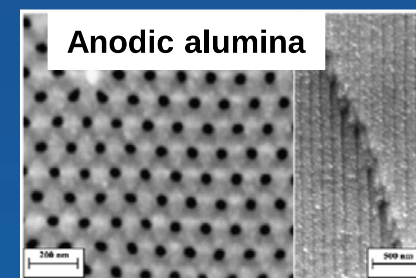
Natural

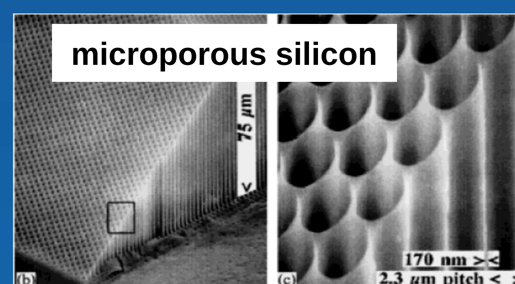
- Mineral (Zeolites, Opals, Quartz, Clays)
- Single Cell (Lipid, Protein, Cellulose, Silica)
- Exoskeleton (Sea shells, crabs, butterflies)
- Connective Tissues (Collagens, Fibers)
- Endoskeleton (Cartilage, Bone, Teeth)
- Epithelial (Skin, Hair, Feathers)

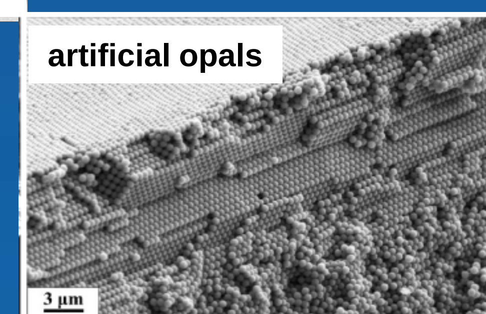
Man-made

- Photonic crystals:
  - microfabrication-lithography and etching
  - self-assembled colloidal crystals
- Self-organized anodic alumina
- Microporous silicon etc.









structure period from 100 nm to 1000 nm.
diffraction angles 10^{-4} …. 10^{-3} radian

require high resolution in reciprocal space !

Why X-rays?

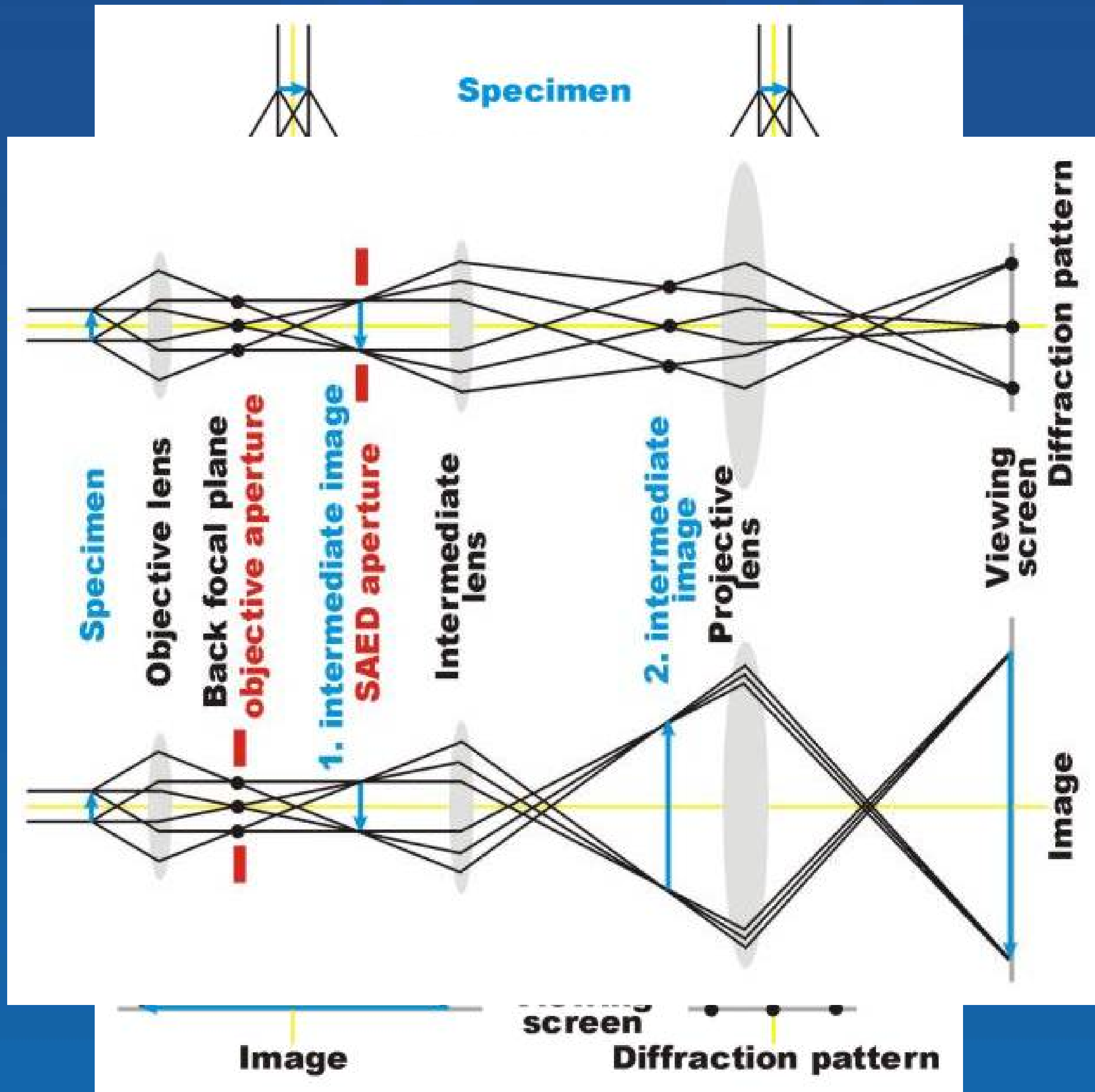
Electron microscopy:
tiny sample
surface structure
in-situ investigation hardly possible

Light microscopy:
- confocal optical microscopy:
limited sample volumes
too strong scattering!
not applicable for inverted photonic crystals

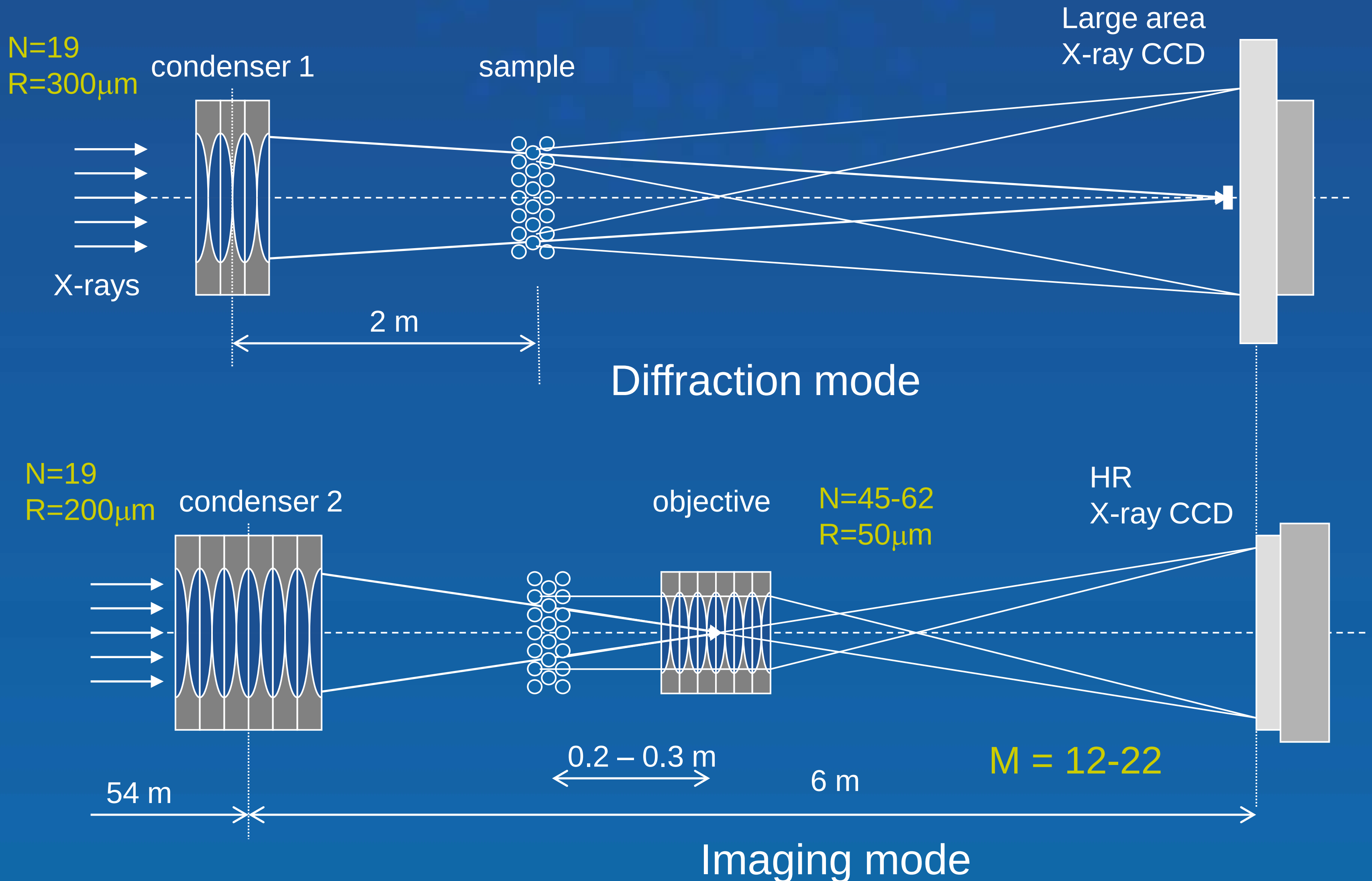
Laser diffraction:
too high refractive index contrast
can be applied for periodic structures with sufficiently large periodicity

Neutrons:
- small-angle neutron diffraction:
poor resolution
unable to reveal important details in the diffraction patterns

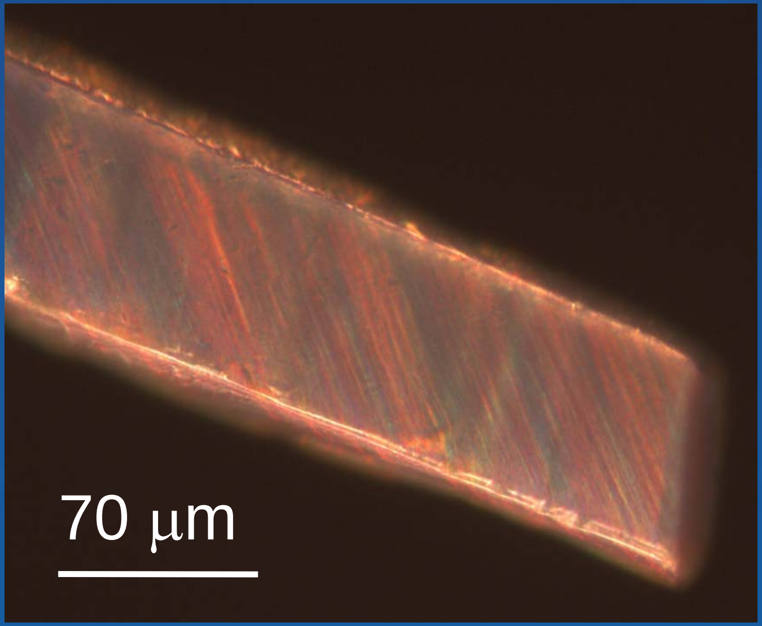
Transmission Electron Microscope



Conceptual layout of HRXRM

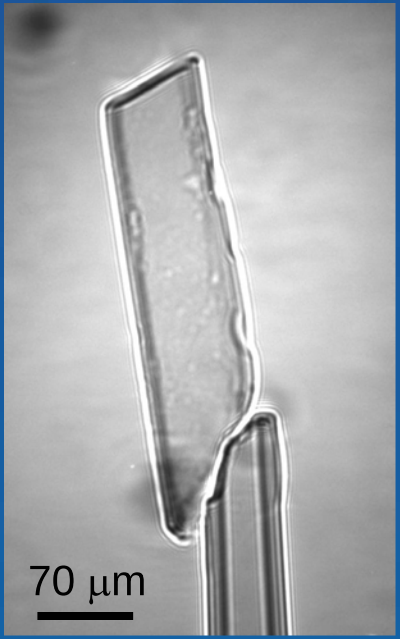


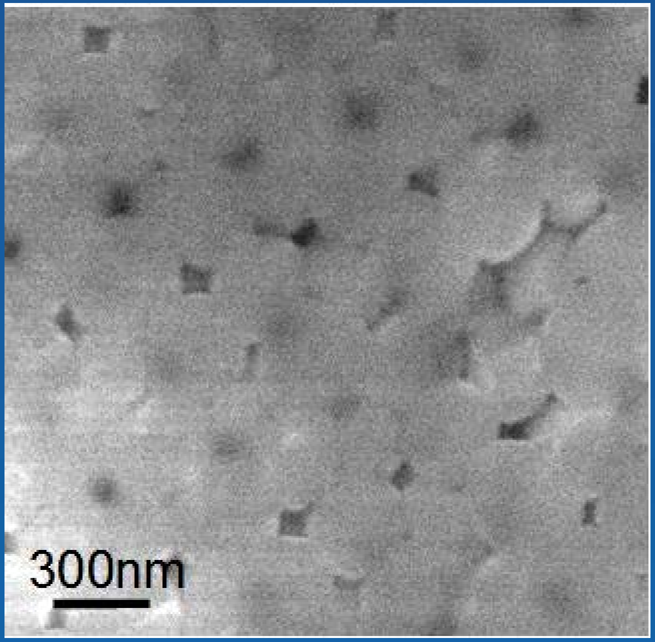
Images of opal sample



Optical microscope

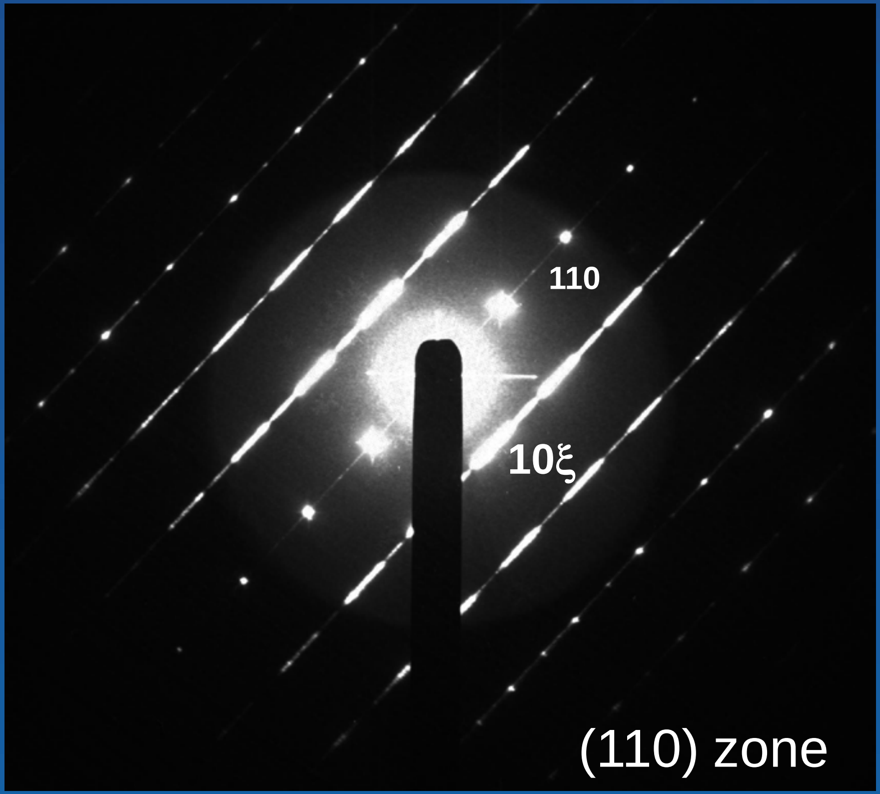
X-ray image





Scanning electron microscope

Diffraction patterns



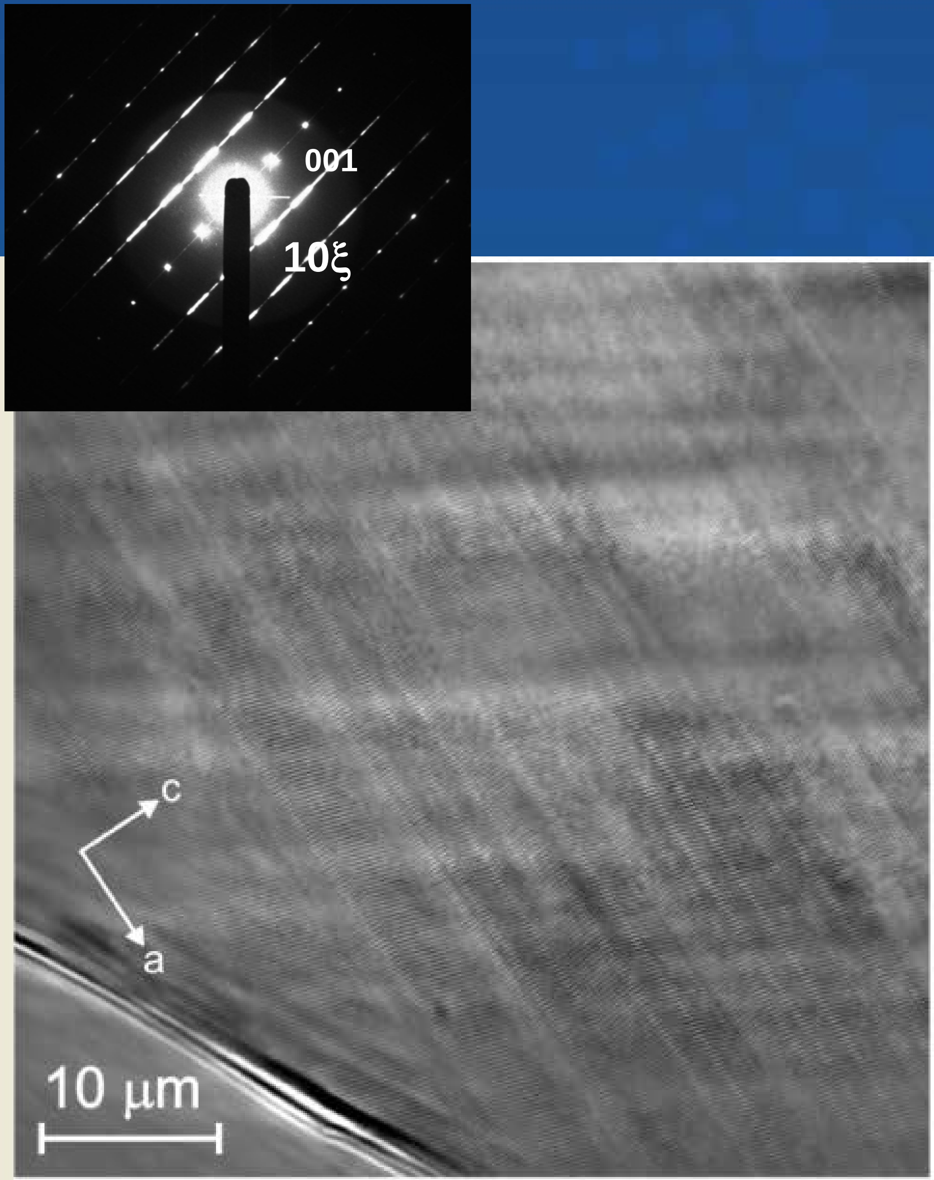
exposure 5 seconds
$\theta = 19.4^{\circ}$

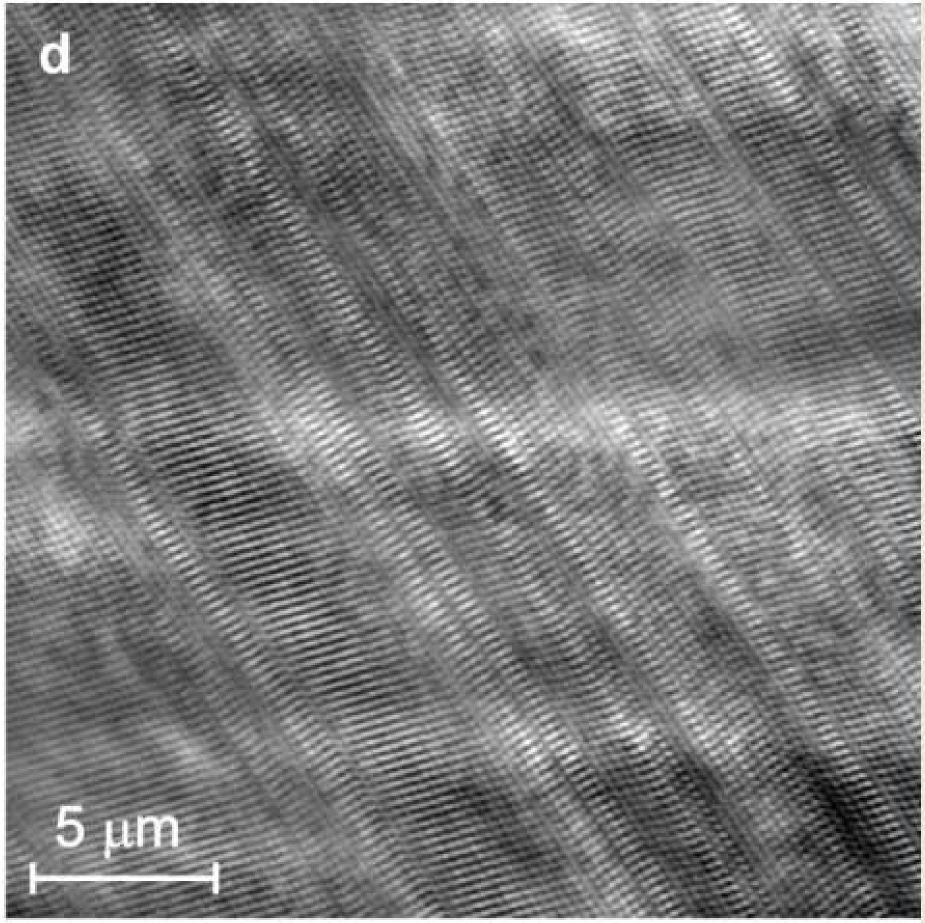
exposure 1 second
$\theta = 37.7^{\circ}$

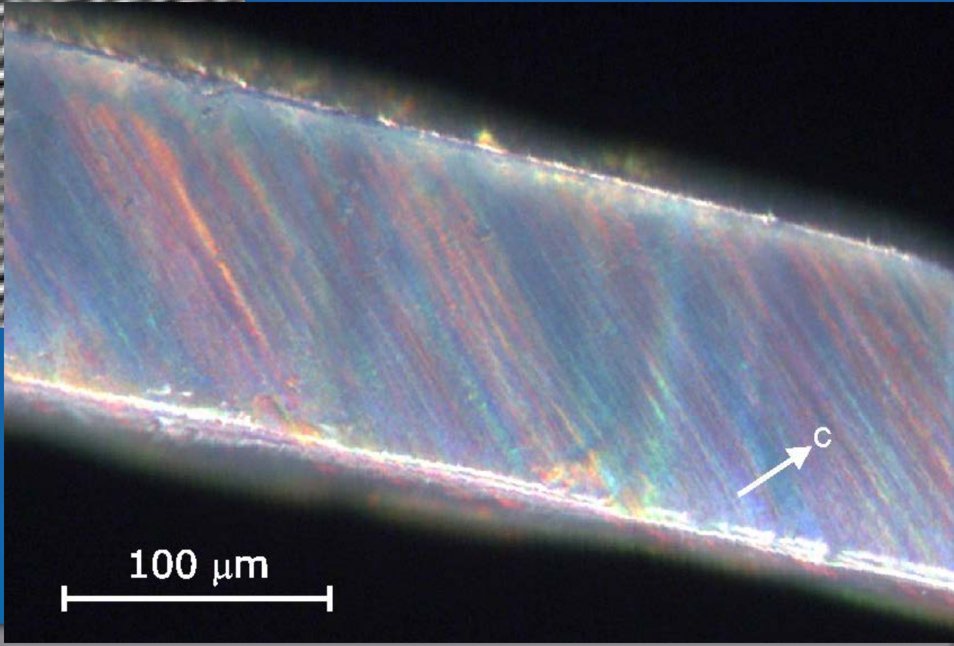
Forbidden reflections (HKL+1/2)

X-ray microscopy on opal sample

E = 12 keV







E = 12 keV
Resolution ~ 160 nm

ADVANCED MATERIALS
www.advmat.de

Materials Views
www.MaterialsViews.com

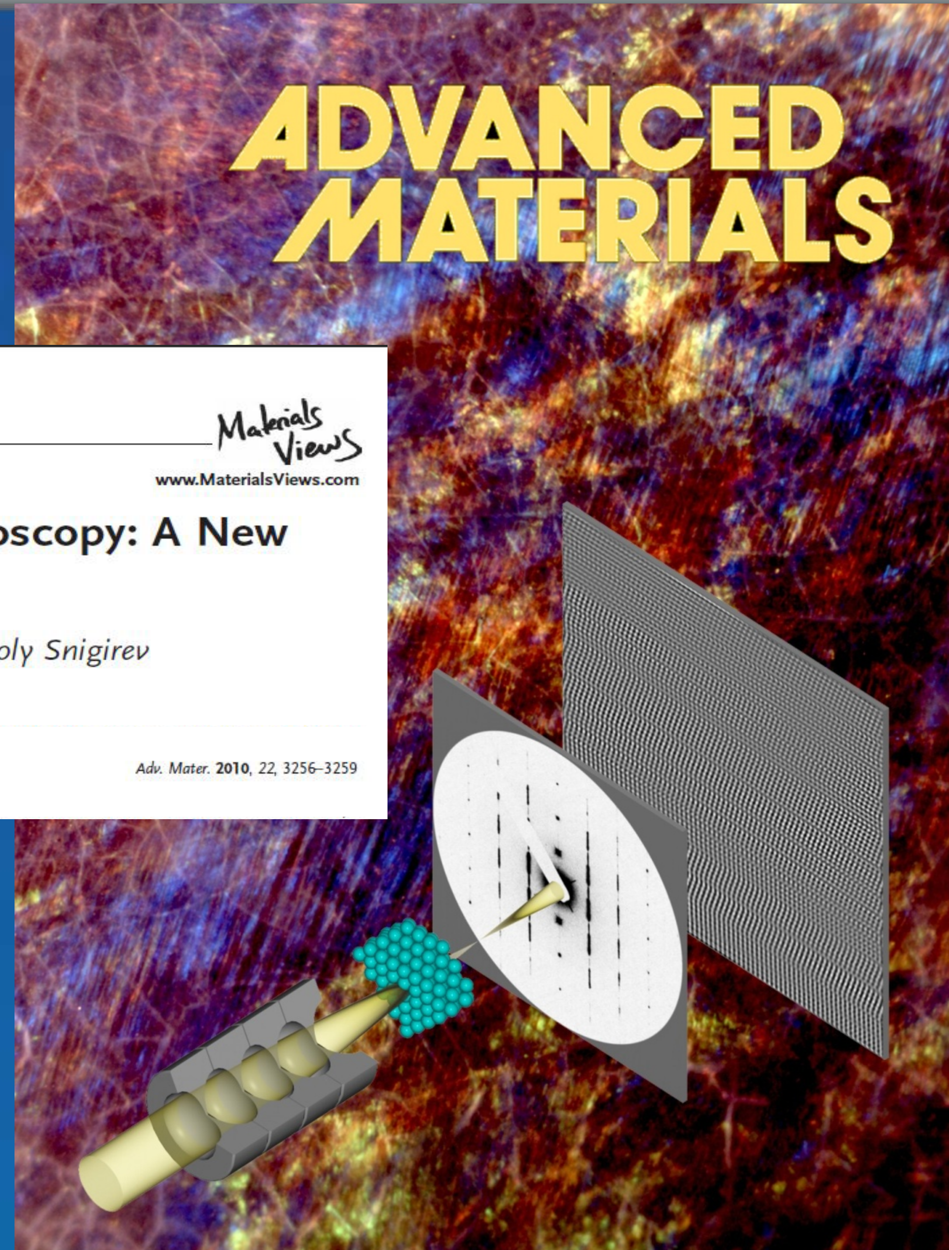
COMMUNICATION

High-Resolution Transmission X-ray Microscopy: A New Tool for Mesoscopic Materials

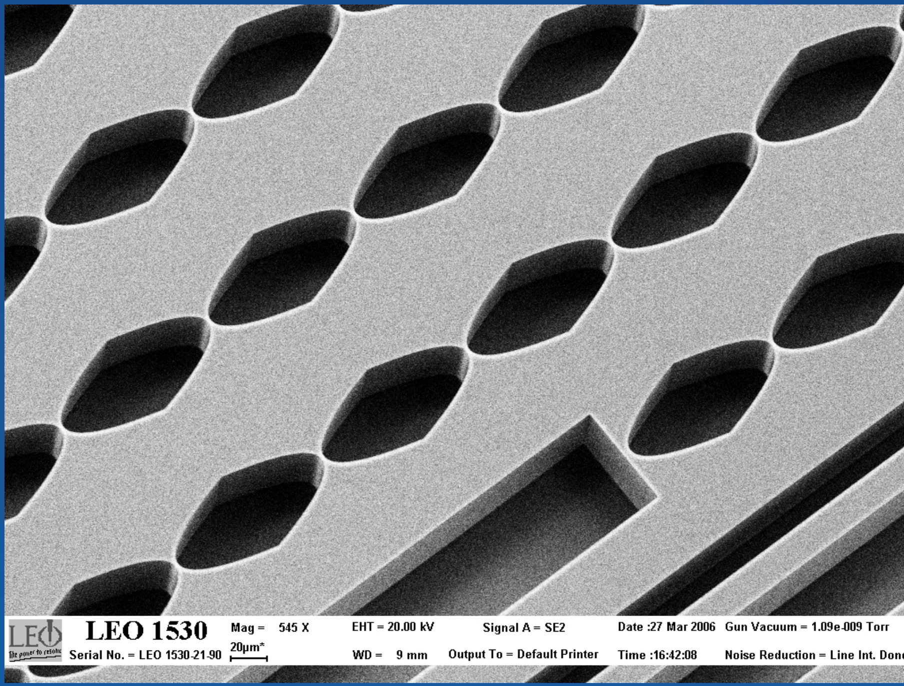
By *Alexey Bosak, Irina Snigireva,* Kirill S. Napolskii,* and *Anatoly Snigirev*

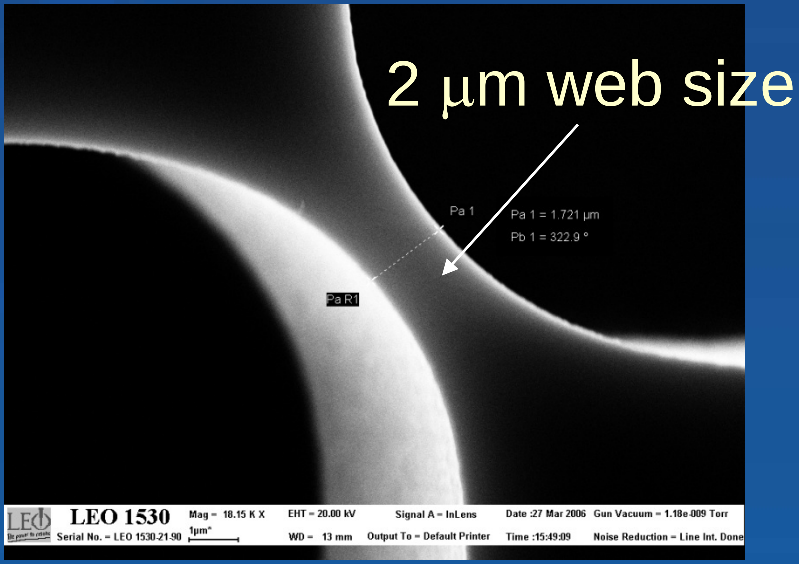
3256 WILEY InterScience DISCOVER SOMETHING GREAT

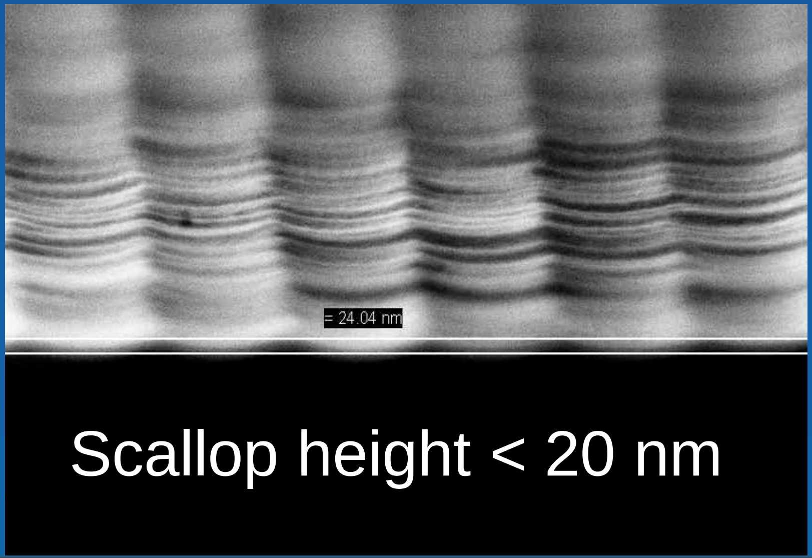
Adv. Mater. **2010**, 22, 3256–3259

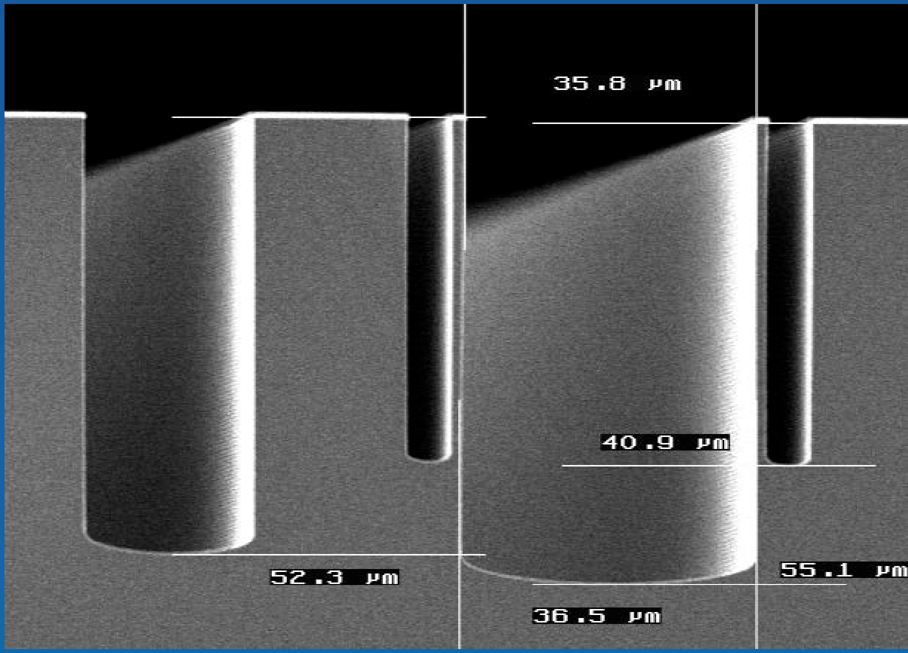


Si nanolenses



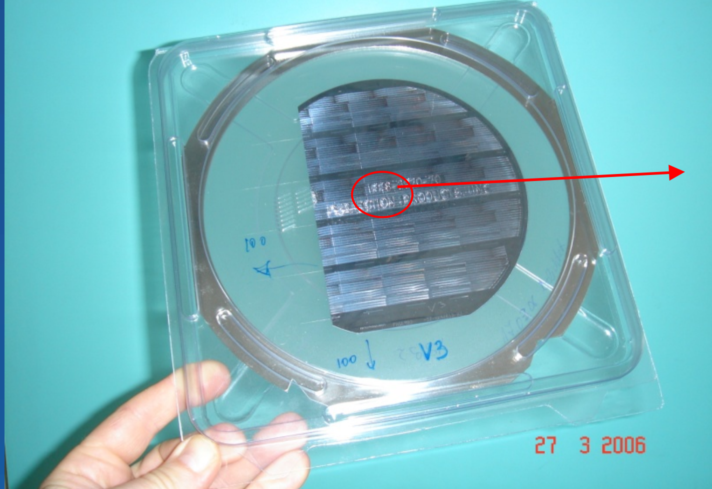




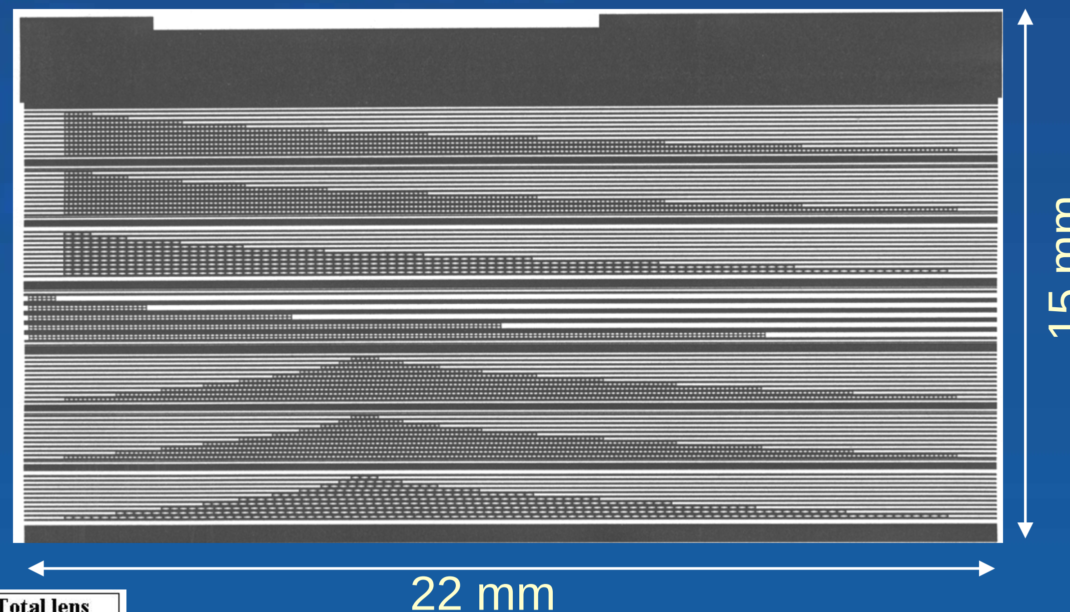


Lens chip design

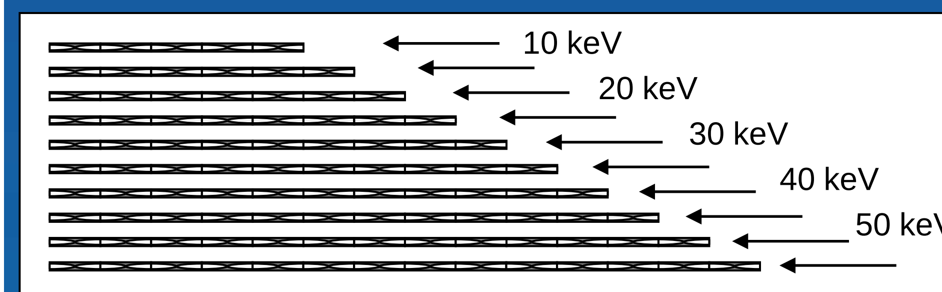
6“ Si wafer with NFLs structures



F = 10cm @ E = 10 - 50 keV



NN	Energy (keV)	Single lens length (µm)	Number of lenses	Radius of parabola apex (µm)	Total lens length (µm)
1	10	50 100	12 6	6.25 3.13	620 614
2	15	50 100	28 14	6.25 3.13	1436 1422
3	20	50 100	52 26	6.25 3.13	2660 2634
4	25	50 100	80 40	6.25 3.13	4088 4048
5	30	50 100	116 58	6.25 3.13	5924 5866
6	35	50 100	160 80	6.25 3.13	8168 8088
7	40	50 100	208 104	6.25 3.13	10616 10512
8	45	50 100	264 132	6.25 3.13	13472 13340
9	50	50 100	324 162	6.25 3.13	16532 16370
10	55	50 100	392 196	6.25 3.13	20000 19804



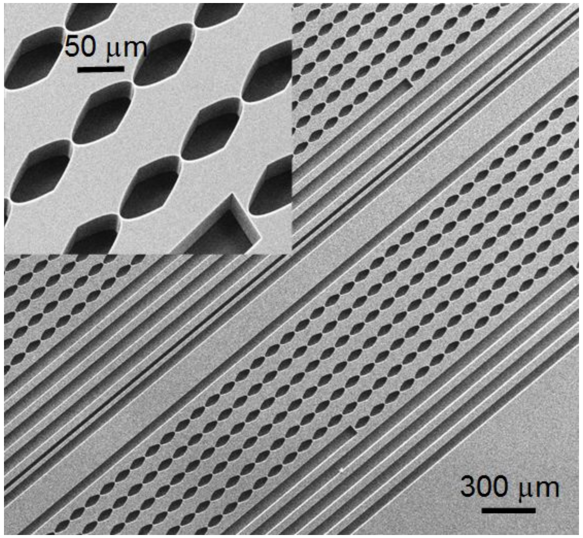
10 lenses per set

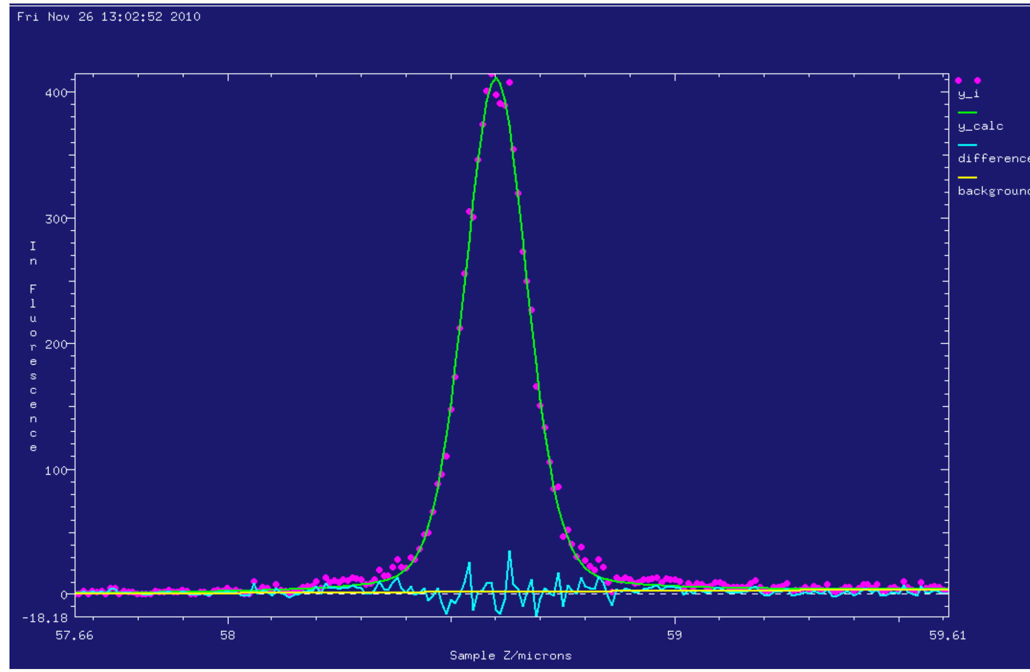
7 sets

~ 70 CRLs !

ID11 Toward the < 100 nm Frontier

ID11:
90 nm beam at 35 keV !!!





Nano-fluorescence using Si nano-lenses gives a vertical spot 90nm at 35 keV

• A scan of a 130 nm thick ***In*** film gives ~160 nm wide peak. Deconvolution indicates an 90 nm bean height.

• In this configuration:

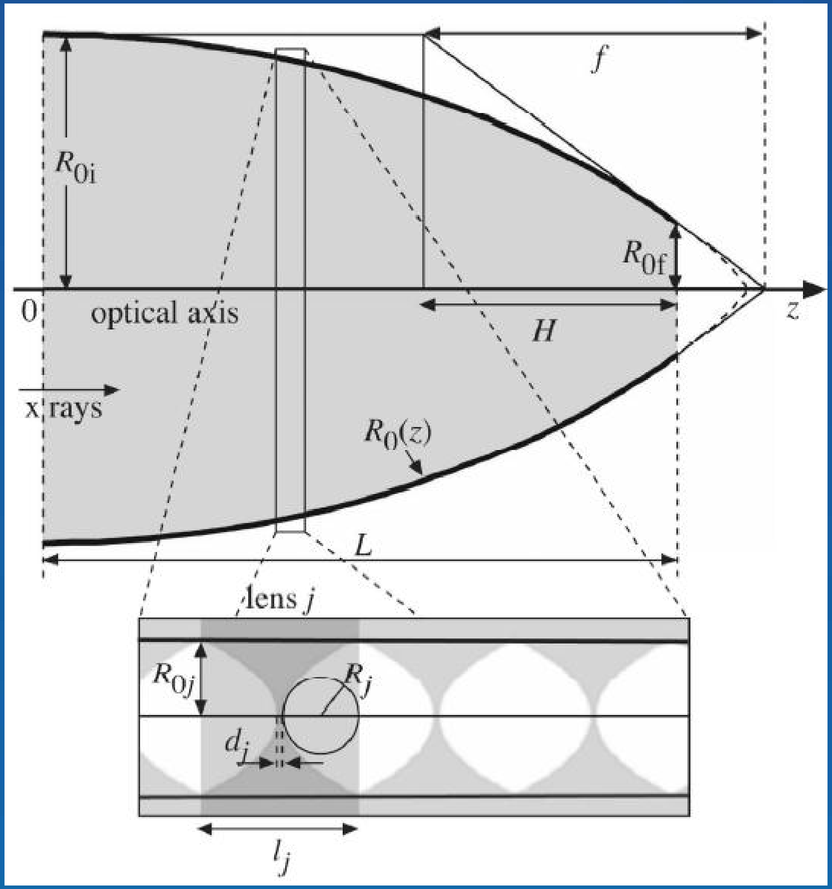
- Diffraction limit ~ 45 nm
- Geometrical limit < 20 nm (considering 20 micron source size as measured)
- Vertical vibrations in prototype assembly ~50 nm (measured)
- Band-pass broadening ~ 80 nm probably dominates at this point.

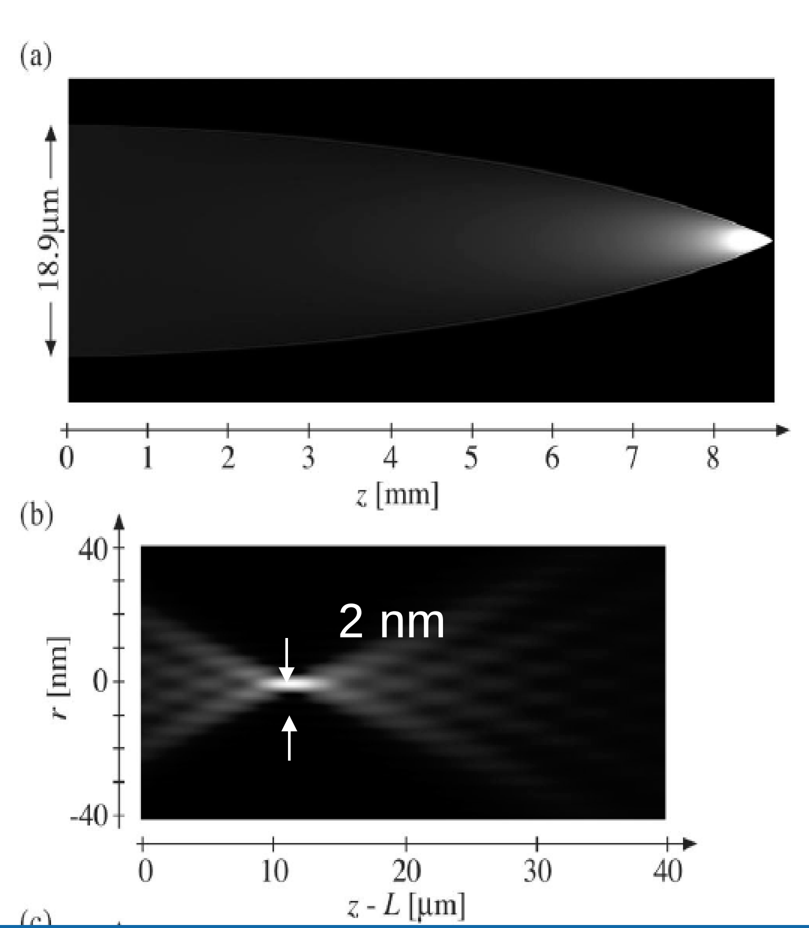
J. White, G. Vaughan, A. Snigirev

PRL 94, 054802 (2005) PHYSICAL REVIEW LETTERS week ending 11 FEBRUARY 2005

Focusing Hard X Rays to Nanometer Dimensions by Adiabatically Focusing Lenses

C. G. Schroer[1] and B. Lengeler[2]
[1]HASYLAB at DESY, Notkestrasse 85, D-22607 Hamburg, Germany
[2]II. Physikalisches Institut, Aachen University, D-52056 Aachen, Germany



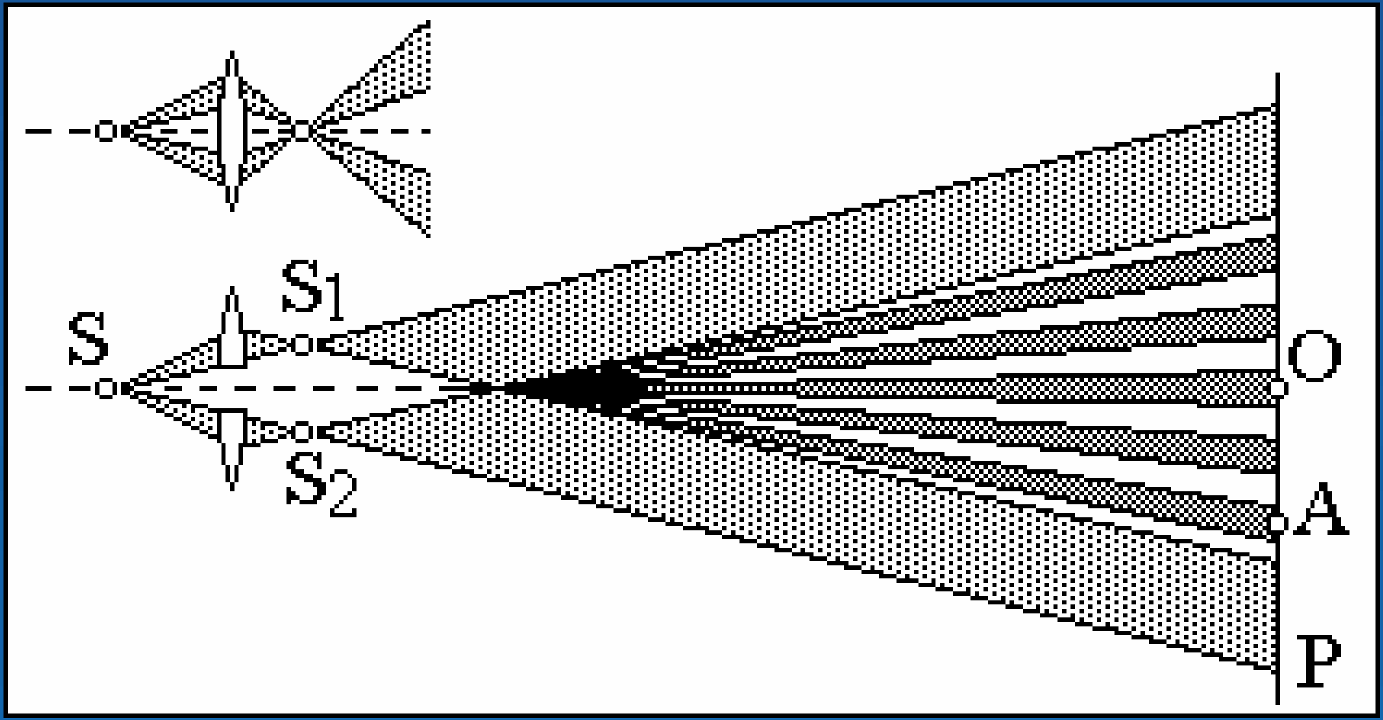


Billet split lens

to pay a tribute to

Professeur Felix Billet (1808 -1882)

la Faculté des sciences de Dijon depuis 1843



PHYSICAL REVIEW LETTERS

VOLUME 46 | 13 APRIL 1981 | NUMBER 15

Neutron Interference by Division of Wavefront

A. G. Klein, P. D. Kearney, G. I. Opat, and A. Cimmino
School of Physics, University of Melbourne, Parkville, Victoria 3052, Australia

and

R. Gähler
Institut Laue-Langevin, F-38042 Grenoble, France
(Received 24 February 1981)

A novel type of neutron interferometer was constructed and tested employing a split cylindrical zone plate with neutrons of 20 Å wavelength. Its performance and relative merits are discussed.

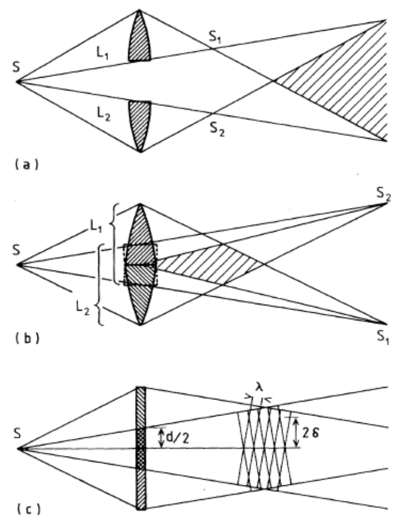


FIG. 1. Split-lens interferometer configurations: (a) positive separation of lens, (b) negative separation with overlapping region removed, (c) special case of (b) which gives constant fringe spacing and employing a zone plate instead of a lens.

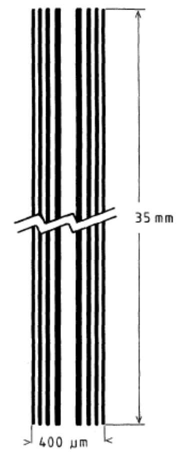
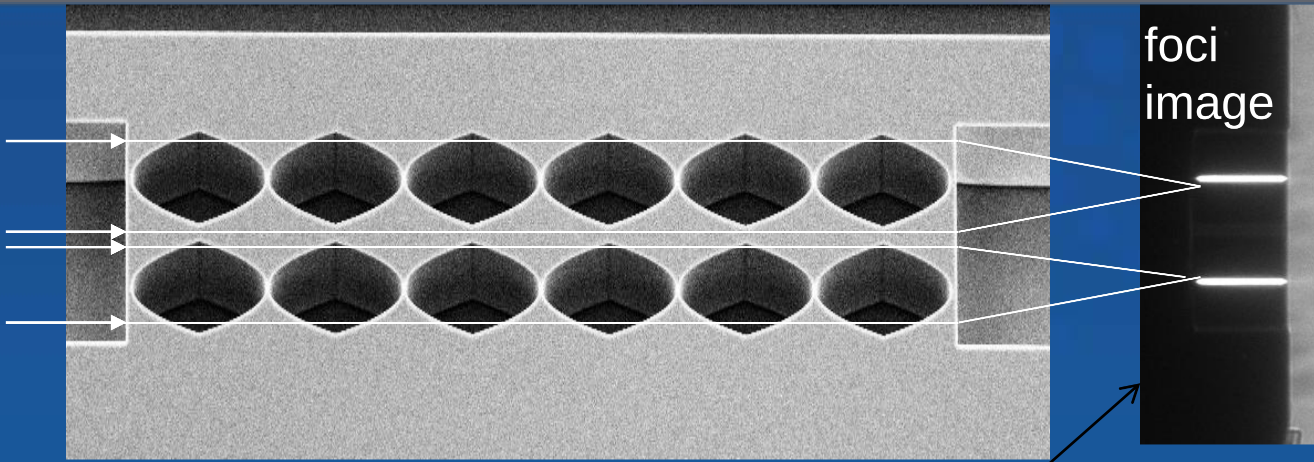


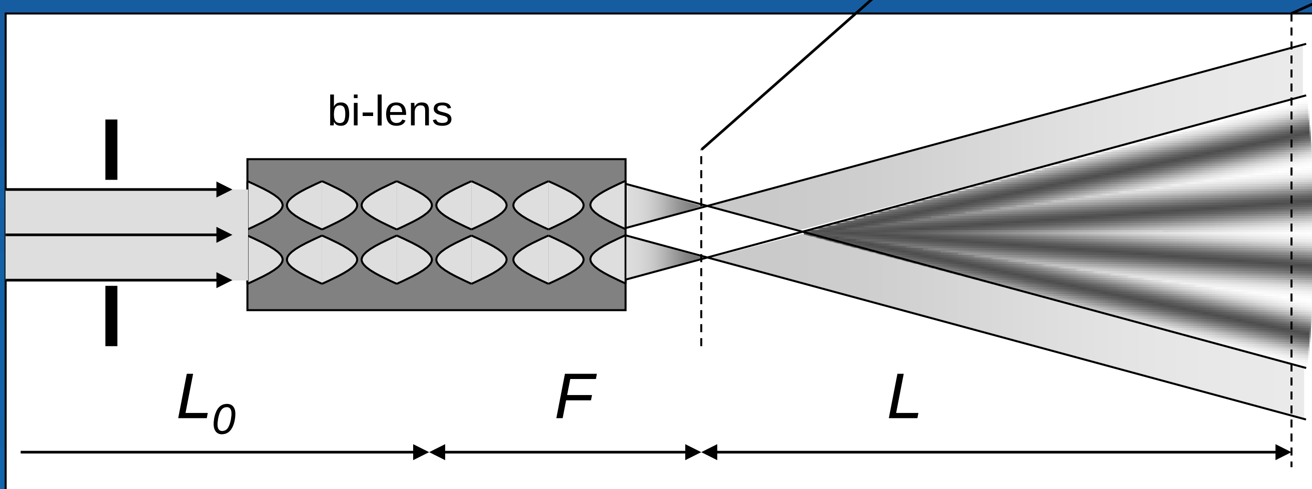
FIG. 2. Split-lens geometric pattern for a cylindrical zone plate.

tern. This gives rise to a much higher intensity in the focused beams. Furthermore, since a primary source in the form of a narrow slit is preferable to a pinhole, cylindrical zone plates were used in order to get a higher intensity.[11] Instead

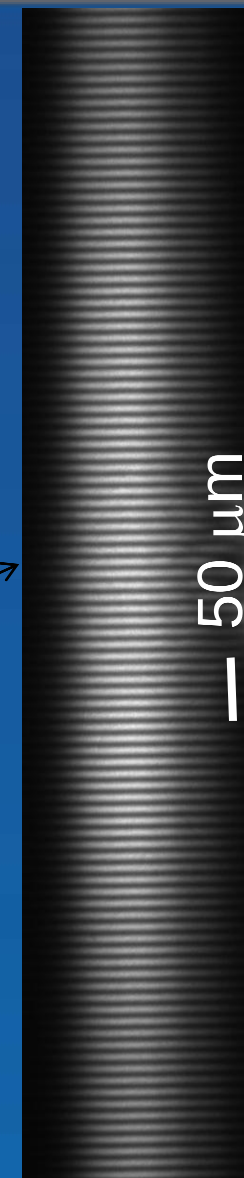
X-ray bilens



Si bi-lens chip



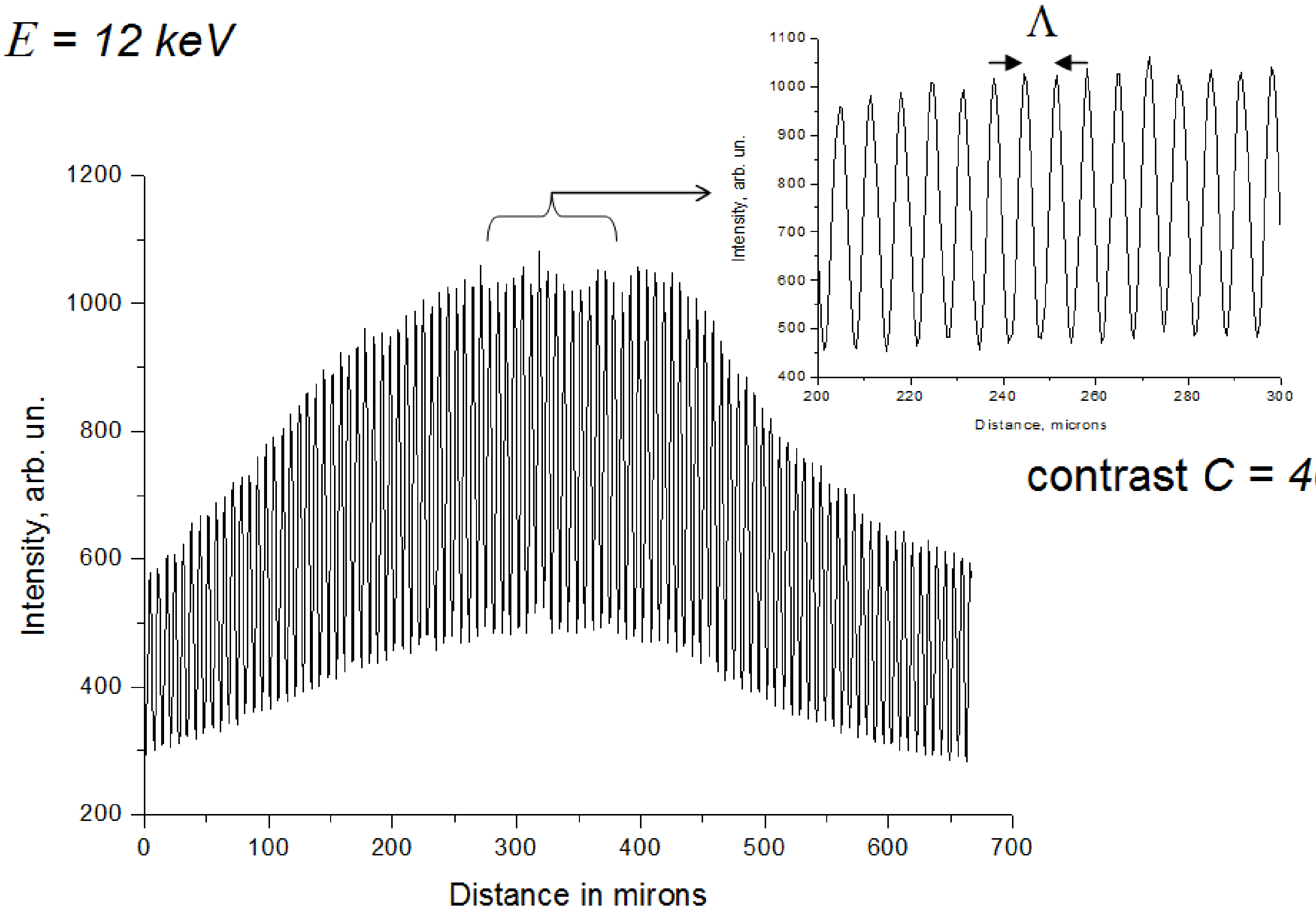
$\Lambda = \lambda L / d$



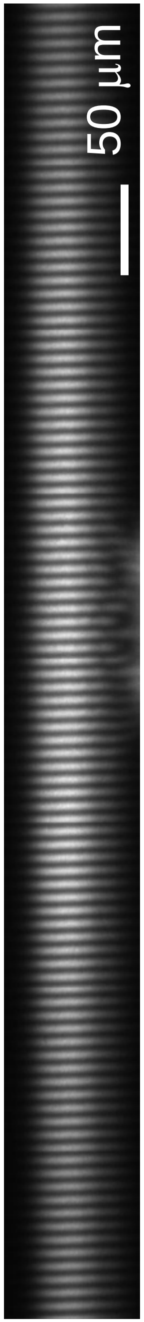
far-field
interference

X-ray bi-lens interferometer: far-field interference

E = *12 keV*



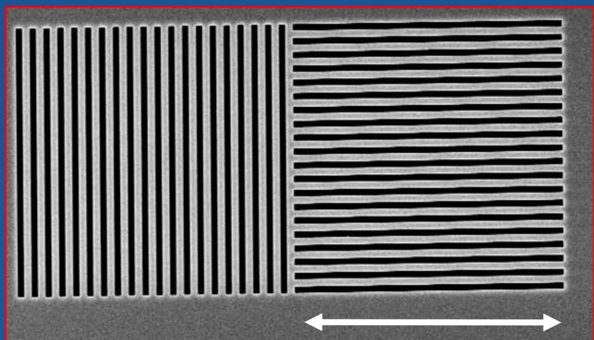
contrast C = *40%*



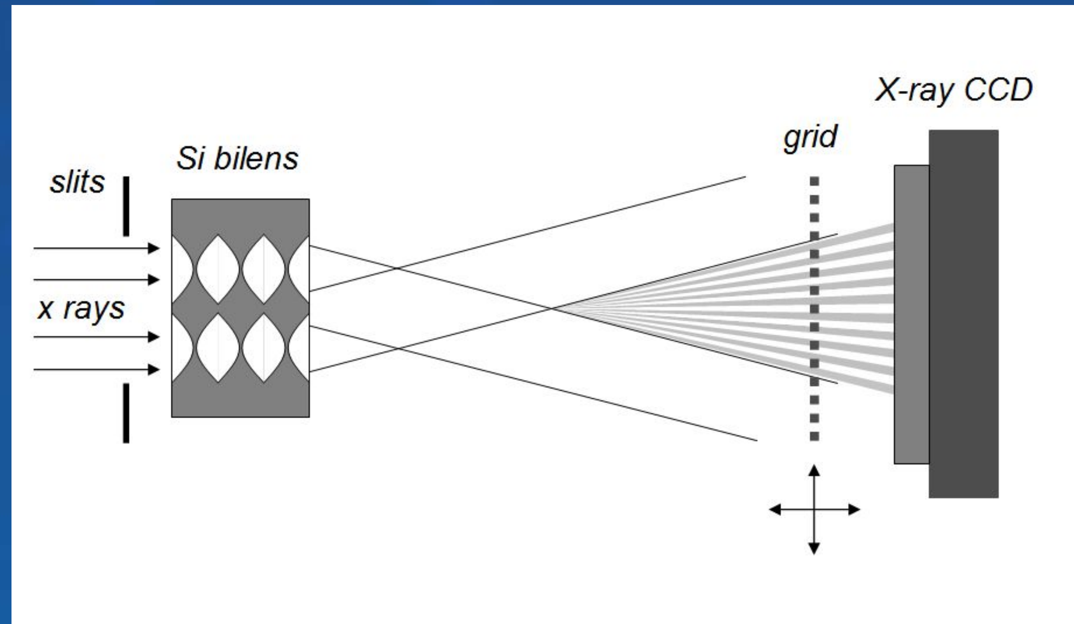
source size: $$S = \frac{\Lambda L_0}{L_1}\left(-\frac{\log C}{3.56}\right)^{1/2}$$ S = *28 μm (FWHM)*

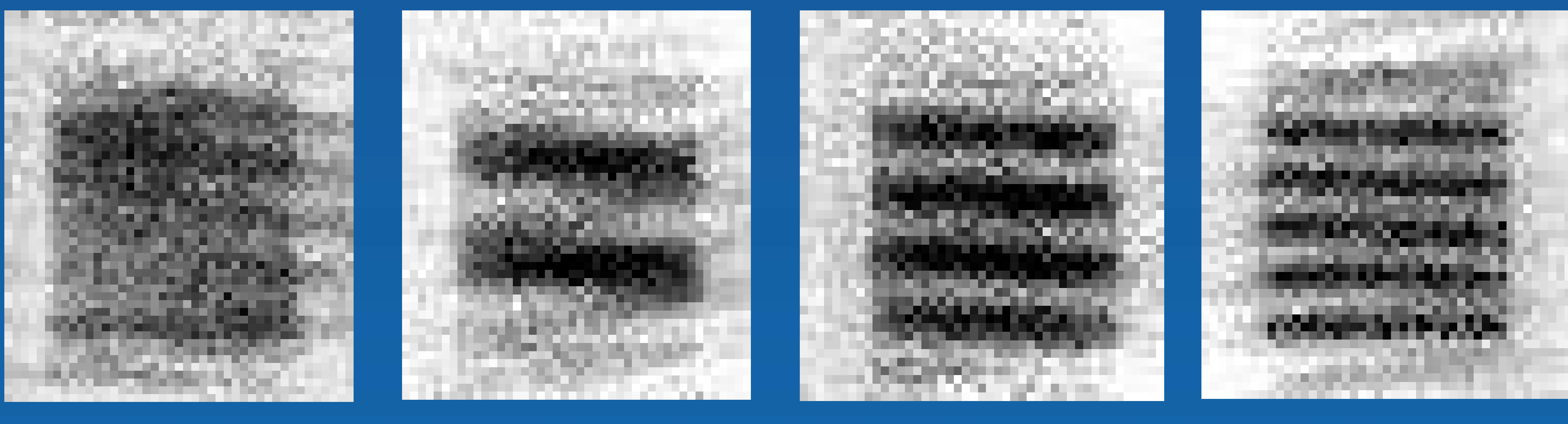
Near-field imaging mode

200 nm bar / 200 nm slit



20 µm





10 µm

$\Lambda_5 - \Lambda_4 = 5$ nm !

PRL 103, 064801 (2009) PHYSICAL REVIEW LETTERS week ending 7 AUGUST 2009

X-Ray Nanointerferometer Based on Si Refractive Bilenses

A. Snigirev,[1] I. Snigireva,[1] V. Kohn,[2] V. Yunkin,[3] S. Kuznetsov,[3] M. B. Grigoriev,[3] T. Roth,[1] G. Vaughan,[1] and C. Detlefs[1]

[1]*ESRF, B.P. 220, 38043 Grenoble, France*
[2]*Russian Research Center "Kurchatov Institute," 123182, Moscow, Russia*
[3]*IMT RAS, 142432 Chernogolovka, Moscow region, Russia*

(Received 28 April 2009; published 3 August 2009)

We report a novel type of x-ray interferometer employing a bilens system consisting of two parallel compound refractive lenses, each of which creates a diffraction limited beam under coherent illumination. By closely overlapping such coherent beams, an interference field with a fringe spacing ranging from tens of nanometers to tens of micrometers is produced. In an experiment performed with 12 keV x rays, submicron fringes were observed by scanning and moiré imaging of the test grid. The far field interference pattern was used to characterize the x-ray coherence. Our technique opens up new opportunities for studying natural and man-made nanoscale materials.

(Continued Inside)

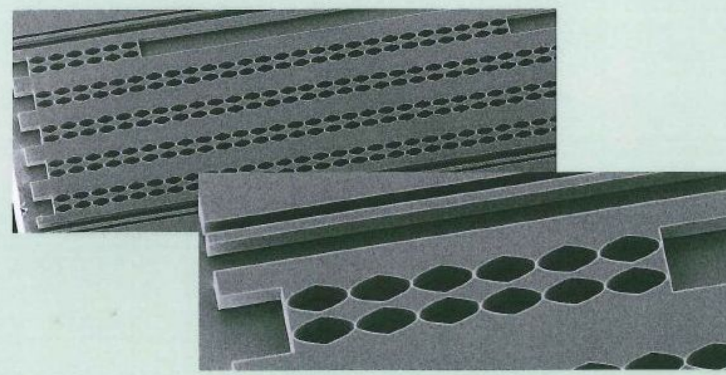
Selected for a Viewpoint in *Physics*. Please visit http://physics.aps.org/.
By suggesting a few manuscripts each week, we hope to promote reading across fields. Please see our Announcement Phys. Rev. Lett. 98, 010001 (2007).

0031-9007(20090807)103:6;1-9

PHYSICAL REVIEW LETTERS

Articles published week ending 7 AUGUST 2009

(6), 060401–069902, 7 August 2009 (320 total pages)



6

Published by the American Physical Society

APS physics

Volume 103, Number 6

PRL 103, 075501 (2009) PHYSICAL REVIEW LETTERS week ending 14 AUGUST 2009

Solution of the Phase Problem in the Theory of Structure Determination of Crystals from X-Ray Diffraction Experiments

Emil Wolf*

Department of Physics and Astronomy and the Institute of Optics, University of Rochester, Rochester, New York 14627, USA

(Received 6 May 2009; published 10 August 2009)

We present a solution to a long-standing basic problem encountered in the theory of structure determination of crystalline media from x-ray diffraction experiments; namely, the problem of dete ing phases of the diffracted beams.

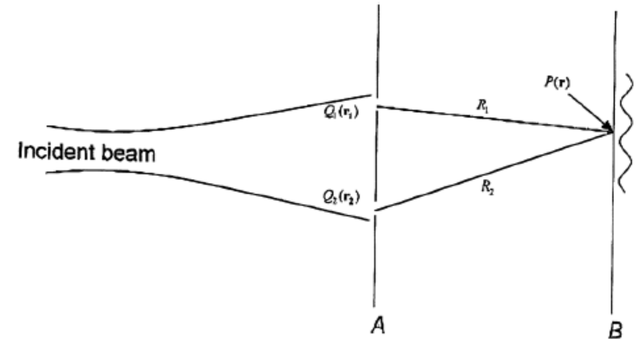
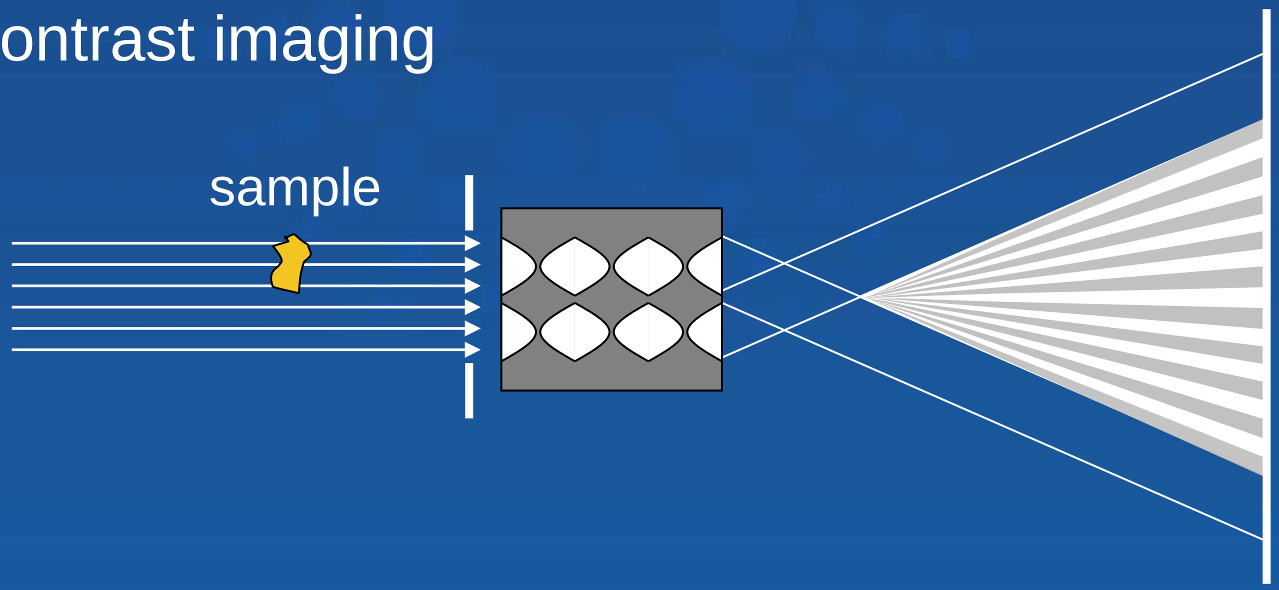


FIG. 1. Illustrating notation relating to Young's interference experiment.

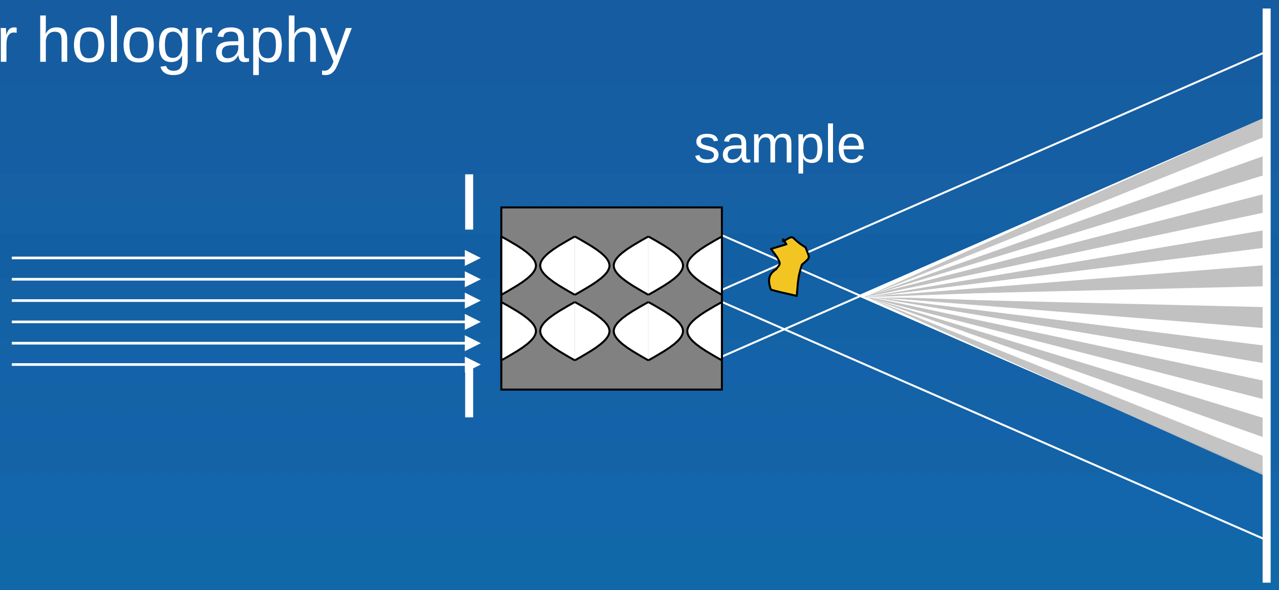
Emil WOLF

San Jose, USA 2009

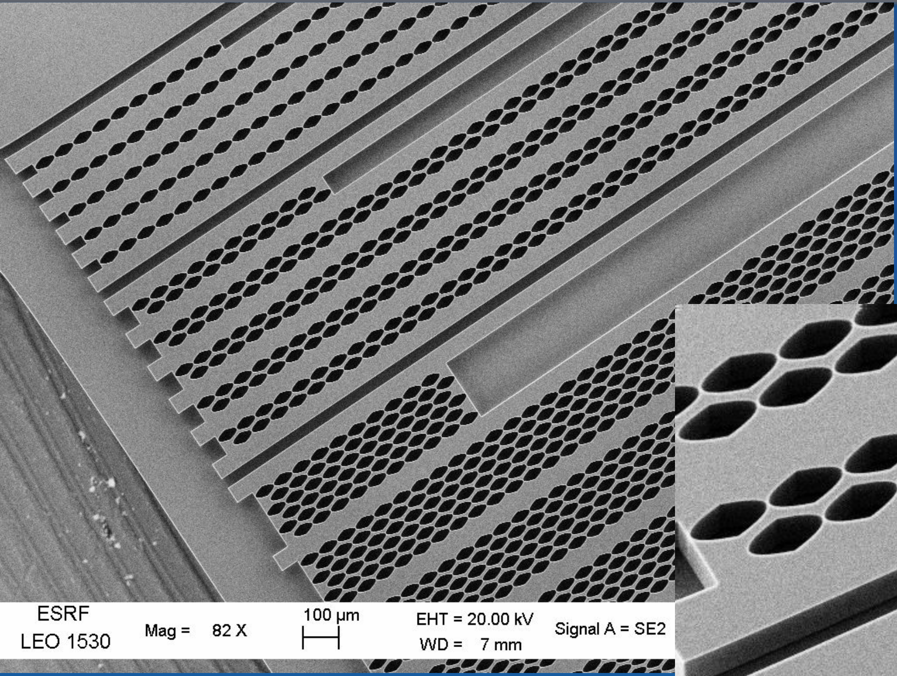
Phase contrast imaging

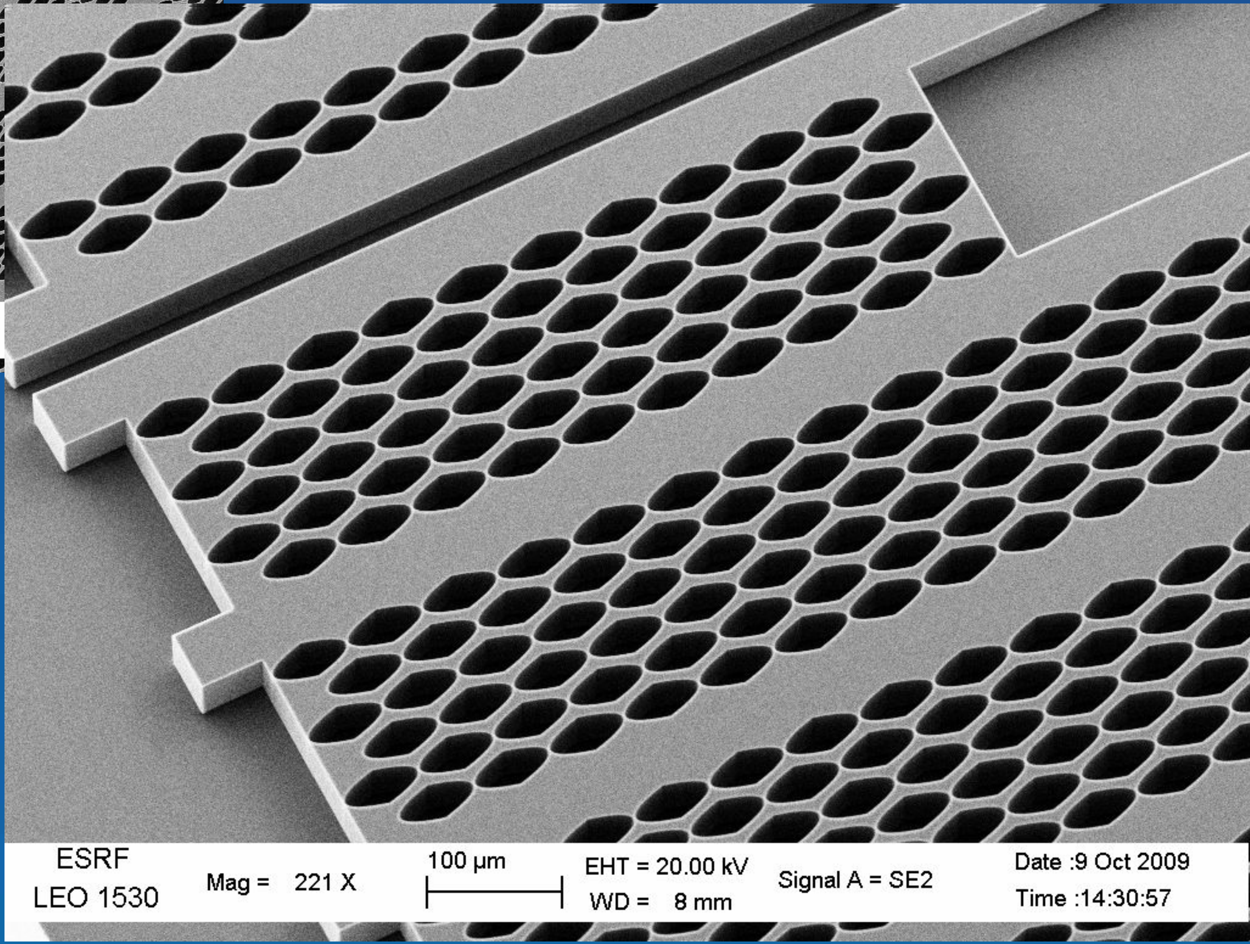


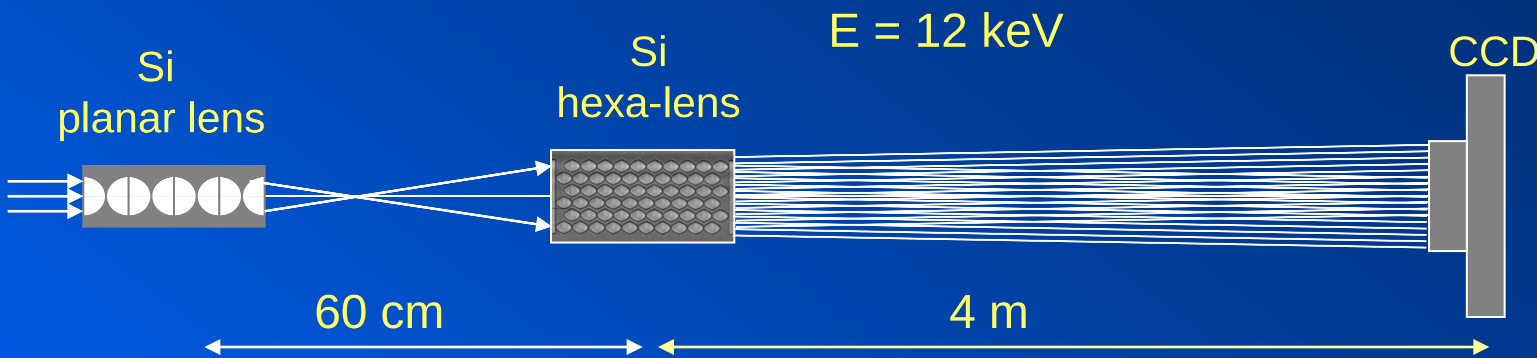
Fourier holography

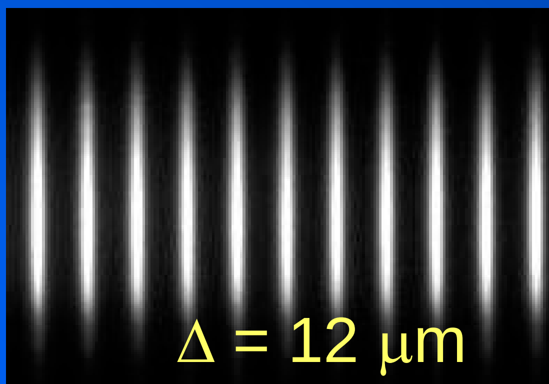


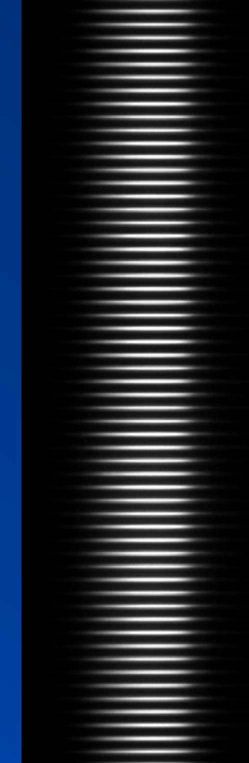
HEXALENS: Six-lens system



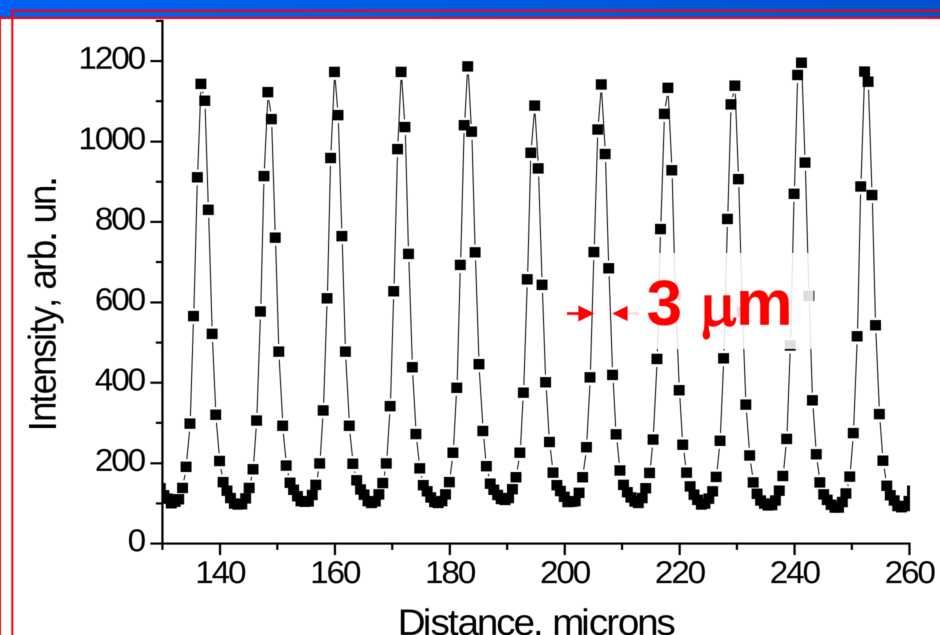


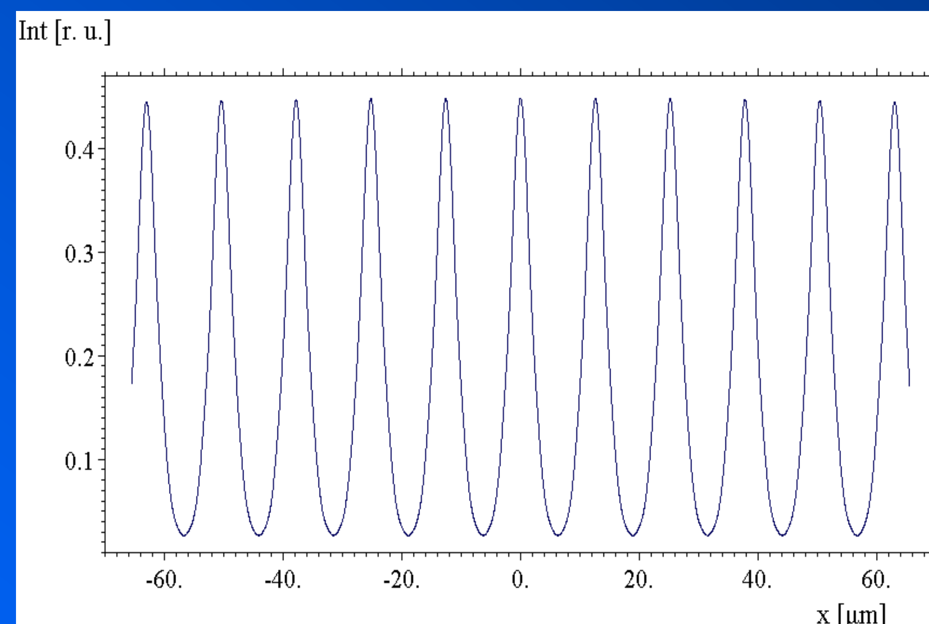




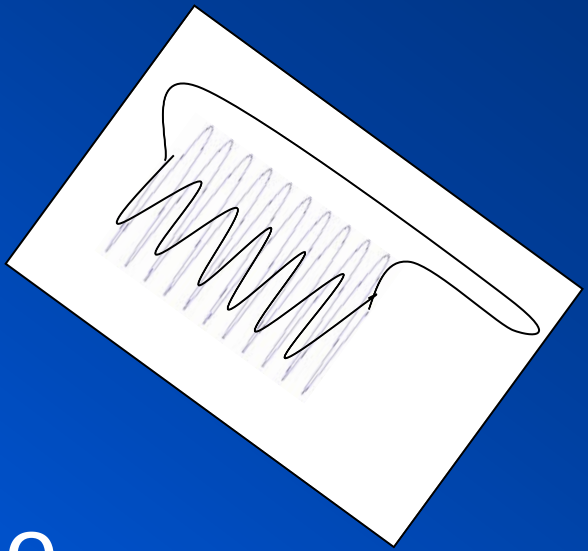


C = 90 %
(theory 93 %)
δ ~ 100 nm





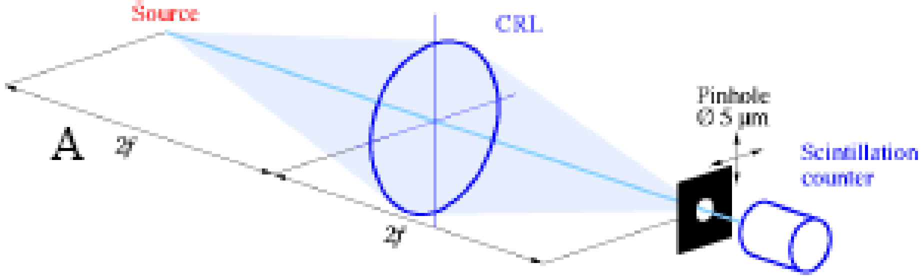
“Nano-comb”

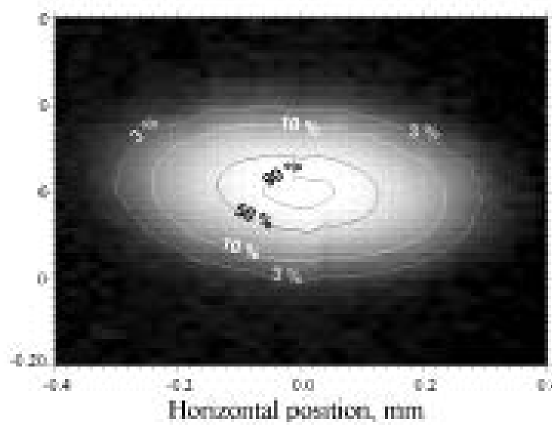


- in-line
- high energy
- remote distance
- tunability: 10 nm – 10 μm
- large depth of field
- large energy bandwidth (~ 1%)

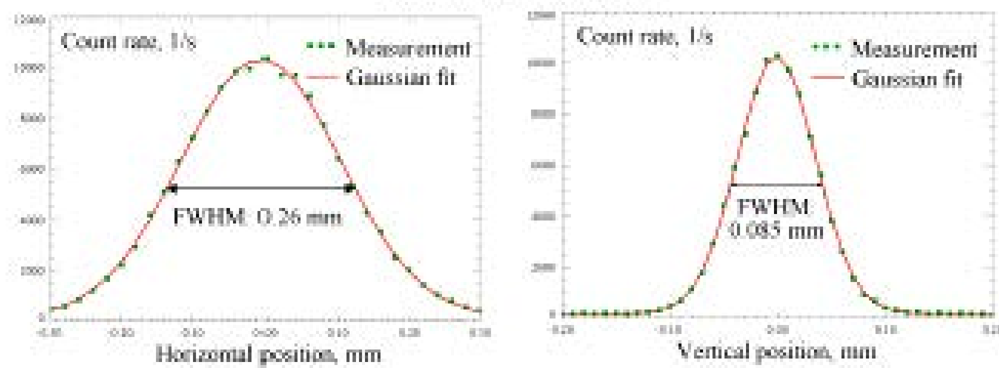
ELECTRON BEAM SIZE AND PROFILE MEASUREMENTS WITH REFRACTIVE X-RAY LENSES

T. Weitkamp, O. Chubar, M. Drakopoulos, I. Snigireva, A. Snigirev, ESRF, Grenoble, France
C. Schroer, F. Guenzler, B. Lengeler, RWTH, Aachen, Germany





1999
BM5 85 x 260 μm^2

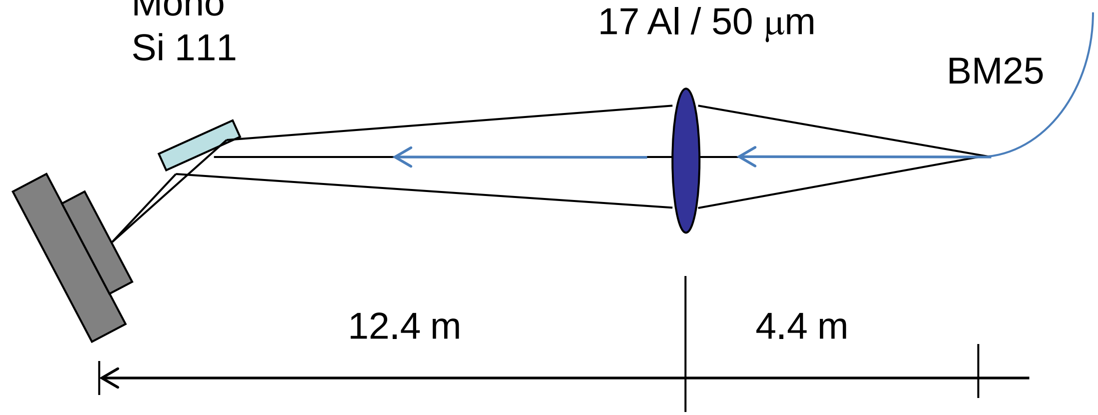


CRL based emittance diagnostics

25 pm – 20 μm (FWHM)

5 pm - 9 μm

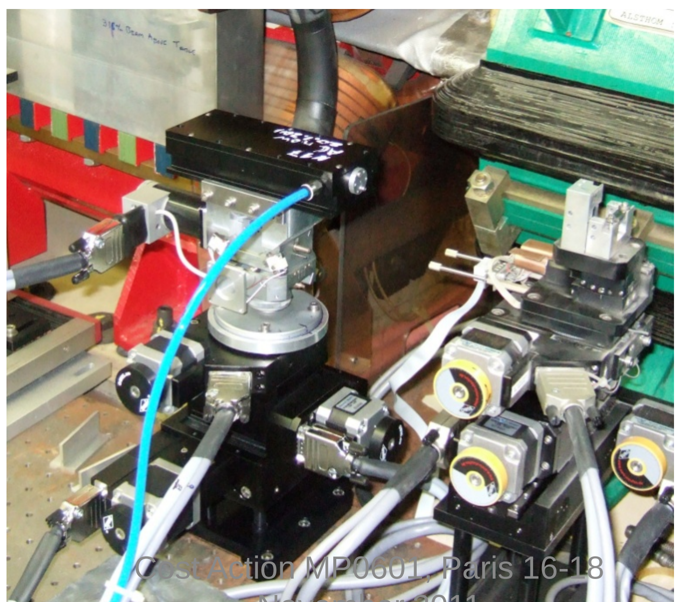
1 pm – 4 μm -diffraction limited source!



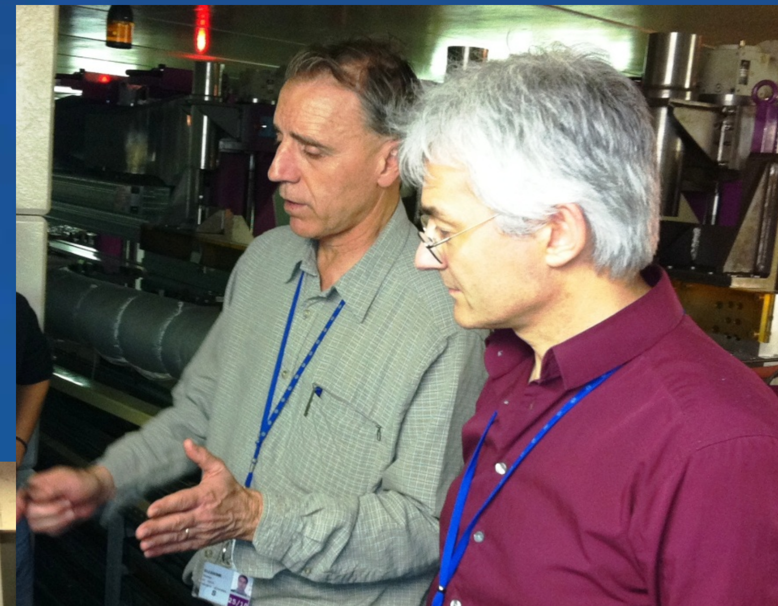
first test 25 Jan, 2011

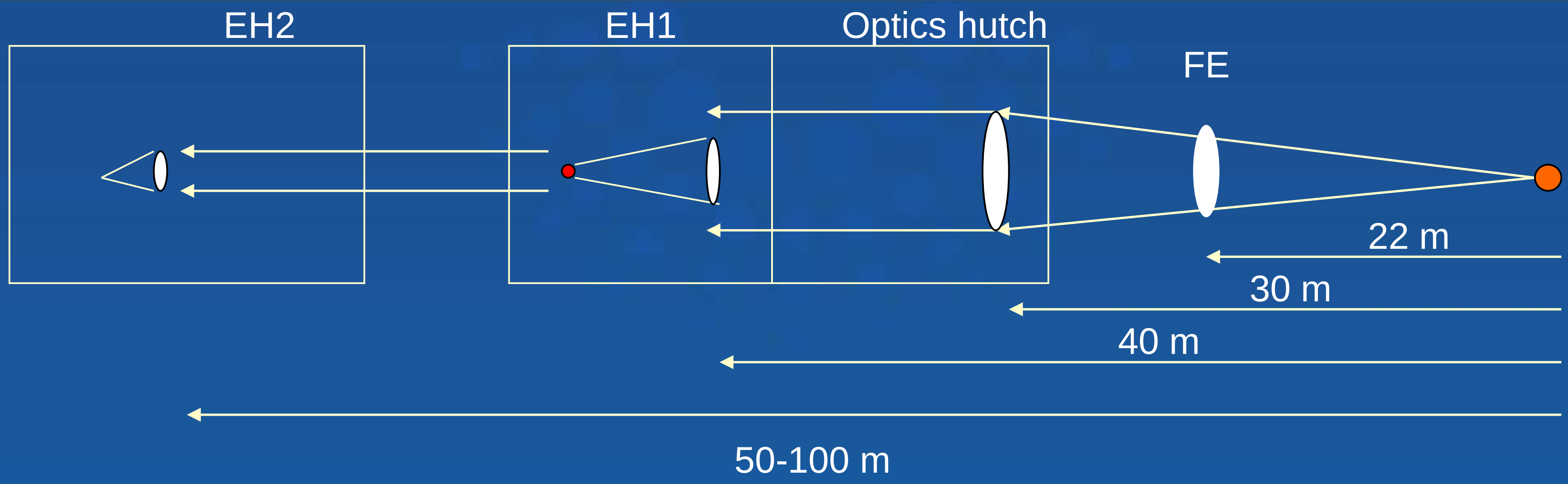
7 pm – 35 μm (FWHM)

(25 pm - 65 μm)



Pascal ELLEAUME





Refractive optics:

Condensers/collimators	**F ~ 10 m**	**10 μm**
Micro-optics	**F ~ 1 m**	**1 μm**
Nano-optics	**F ~ 10-100 mm**	**10 – 100 nm**

Energy range:

CRL 1 – 100 – (1000) keV

Who is using refractive X-ray lenses?

- Few thousand linear and two-dimensional lenses have been delivered to 7 SR sources in 5 countries:
  - ESRF Grenoble France
  - HASYLAB Hamburg Germany
  - Diamond Oxford UK
  - ALBA Barcelona Spain
  - APS Argonne Chicago USA
  - NSLS Brookhaven USA
  - SSRL Stanford USA / XFEL
- Others who took over the development
  - SPRing8
  - ANKA Karlsruhe Germany
  - Kurchatov SR center Moscow Russia
  - …..

Vision of the future

OPTICS

X-ray lenses near reality

Jerome Hastings

X-RAY sources have already evolved from the original sealed vacuum tubes into sophisticated electron-storage rings, and free-electron X-ray lasers may be just beyond the horizon. These advances promise intense, highly parallel and tuneable photon beams. To focus and manipulate this radiation, a variety of X-ray optical devices have been developed, ranging from concentrators, in the form of tapered capillaries[1], to Fresnel zone plates[2]. But a dream of X-ray opticians for some time has been to make a *refractive* lens, the X-ray equivalent of conventional optics for visible light. On page 49 of this issue[3], Anatoly Snigirev and colleagues describe the first significant step towards that goal. This should allow us to reach a submicrometre focus with much greater efficiency than before.

ESRF

The European Synchrotron Radiation Facility in Grenoble, France. Compound refractive lenses may soon make its intense X-ray beams much more effective.

The desire in a multitude of scientific disciplines for intense submicrometre X-ray beams has driven the construction of new electron-storage-ring X-ray sources in Europe (the European Synchrotron Radiation Facility in Grenoble, France), the United States (the Advanced Photon Source in Argonne, Illinois) and Japan (the Spring-8 Project in Harima). The objective is to perform the various 'standard' X-ray analytical techniques of diffraction and spectroscopy on individual particles or grains.

These measurements could provide information about the atomic and electronic structure of systems of chemical, biological and technological interest, ranging from the characterization of an individual grain in a commercial catalyst to measuring the strain in the metallic interconnections of large integrated circuits. But the limited ability of available X-ray optics to focus the X-ray beams prohibits such applications.

The existing optics fall into a few categories: reflecting optics such as grazing-incidence X-ray mirrors; tapered capillaries; and various types of Fresnel zone plates. Refractive lenses, routinely used in visible-light optics, had been thought to be impractical at X-ray wavelengths. In the X-ray regime, the difference in the index of refraction between air and ordinary materials is tiny — typically of the order of 10^{-6} — which appeared to present an insurmountable problem. To maximize the effect, heavy-element materials were proposed, but they have high absorption. Light elements do not, but with their low refractive-index decrement they would have long focal length and thus provide little practical focusing of the X-ray source.

Snigirev and colleagues[3] have now proposed and demonstrated a compound refractive lens for hard (14 keV) X-rays that overcomes the difficulties of earlier schemes. A series of *N* refractive lenses has a focal length shorter than a single lens by a factor of *N*, and, in aluminium, absorption is slight for X-ray wavelengths below one ångström, so a series of tens to hundreds of lenses can be used. The authors made their lens by simply drilling small round holes in an aluminium block (see Figs 1 and 3 on pages 49 and 50, respectively).

This 'crude' technology permitted a demonstration of their ideas and showed the potential for future optics. With more sophisticated fabrication techniques, one can imagine extending these lenses from cylinders to spheres to provide focusing in two dimensions. Such lenses should then be commonplace at synchrotron sources, and the full potential of the X-ray beams already available will be realized. This development bodes well for the future of synchrotron-based microanalytical techniques that are impossible today but should be standard in the future. □

Jerome Hastings is at the Brookhaven National Laboratory, 75 Brookhaven Avenue, Building 725, Upton, New York 11973, USA.

1. Bilderback, D. H. & Thiel, D. J. *Rev. Sci. Instrum.* **66**, 2059–2063 (1995).
2. Lai, B. *et al. Rev. Sci. Instrum.* **66**, 2287–2289 (1995).
3. Snigirev, A., Kohn, V., Snigireva, I. & Lengeler, B. *Nature* **384**, 49–51 (1996).

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Jerry HASTINGS, Nature 1996

Development of Refractive Optics for Synchrotron Radiation Applications

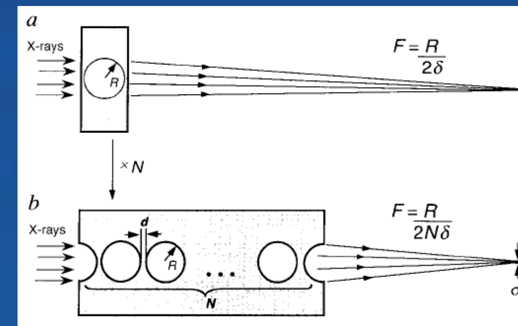
NATURE · VOL 384 · 7 NOVEMBER 1996

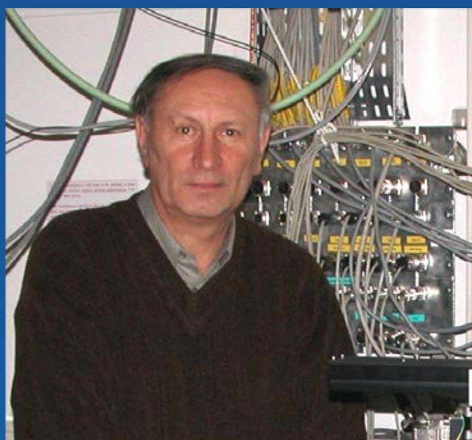
~ 600 citations

A compound refractive lens for focusing high-energy X-rays

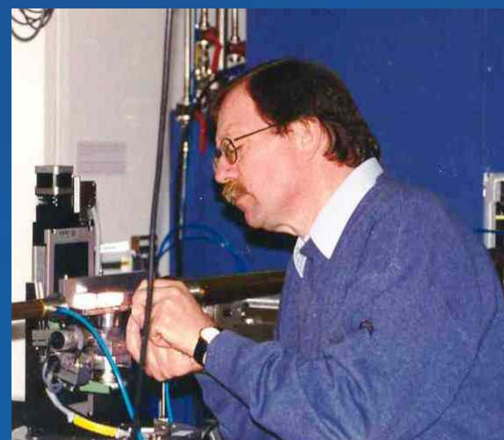
A. Snigirev*, V. Kohn†, I. Snigireva* & B. Lengeler*‡

* European Synchrotron Radiation Facility, BP220, F-38043 Grenoble Cedex, France
† Kurchatov, I. V., Institute of Atomic Energy, 123182 Moscow, Russia

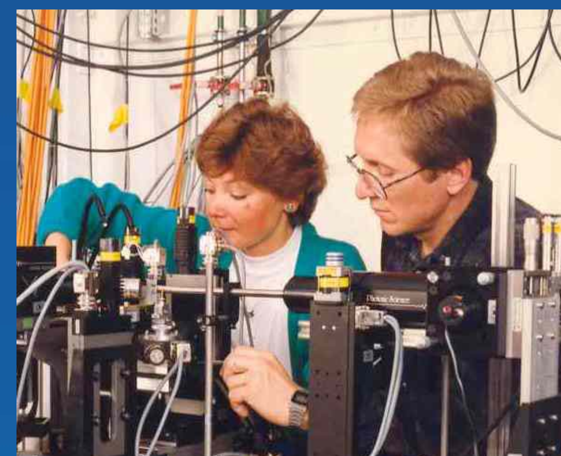




Victor KOHN
Kurchatov Institute, Moscow



Bruno LENGELER
RWTH, Aachen



Irina SNIGIREVA and Anatoly SNIGIREV
ESRF, Grenoble

15 years development: > 100 publications

standard tool at SR beamlines worldwide
50% of ESRF beamlines use refractive lenses
transfocators

the most versatile and adaptable X-ray optics -
variable energy range and tunable focal length and spot

high stability and low cost !

applications:
- high resolution diffraction and imaging
- SR beam diagnostics

new coherent techniques:
microscopy and interferometry