

Преломляющая Рентгеновская Оптика Сокращая Разрыв между Электронной Микроскопией и Оптической Интерферометрией

Анатолий Снигирев
ESRF, Grenoble, France



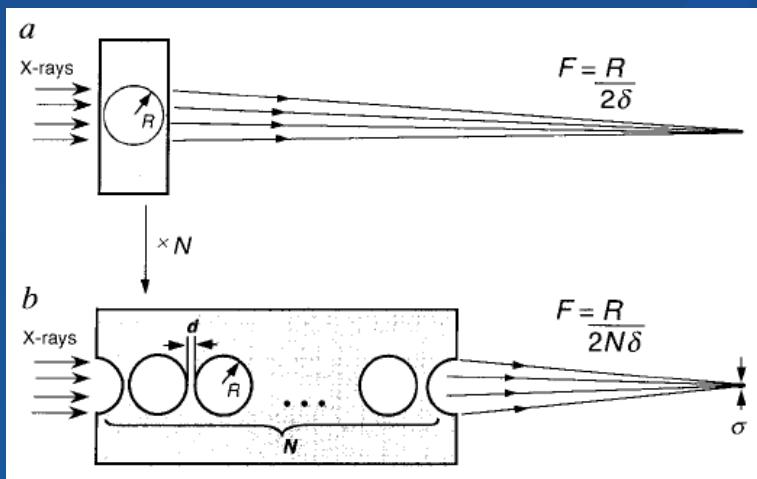
Фонд некоммерческих программ «Династия»

<http://www.dynastyfdn.com/>



*Проф. Владимир Бушуев
кафедра физики твердого тела
физического факультета
Московского государственного университета
им. М. В. Ломоносова*

*Foundation Dynasty
Prof. Vladimir Bushuev
Moscow State University, Moscow, Russia*



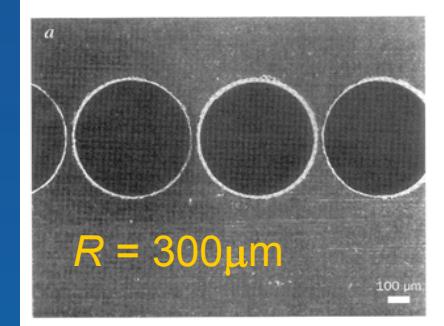
A compound refractive lens for focusing high-energy X-rays

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* European Synchrotron Radiation Facility, BP220, F-38043 Grenoble Cedex, France

† Kurchatov, I. V., Institute of Atomic Energy, 123182 Moscow, Russia

The first AL CRL



Refractive optics after 10 years development

standard tool at SR beamlines worldwide.

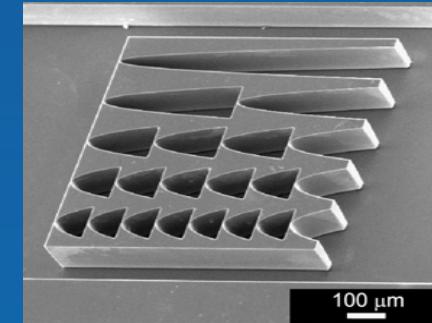
~ 50% of ESRF beamlines use refractive lenses

the most versatile and adaptable X-ray optics

- energy range -from a few keV to hundreds of keV
- focal length -from a few millimeters to tens of meters
- focal spot -from tens of nanometers to tens of microns
- microradian collimation
- high stability and low cost

applications: microdiffraction, microfluorescence and imaging,
standing wave microscopy etc.

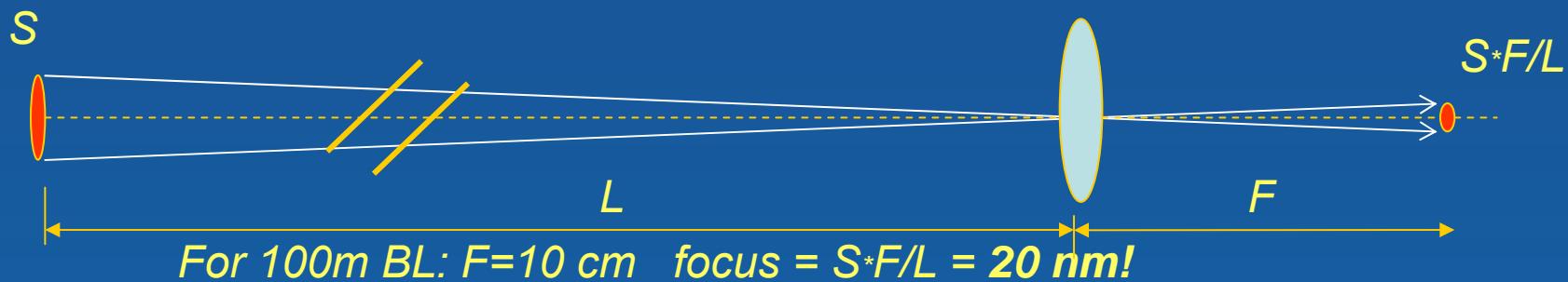
Si parabolic lens



Temporal coherence $\lambda^2/\Delta\lambda$ – monochromicity $\Delta\lambda/\lambda$
 Si 111: 10^{-4} - 10^{-5}
 ML: 10^{-2}

• Spatial coherence

source size	$S \sim 20 \mu\text{m}$	spatial coherence $L\lambda / s$
source distance	$L \sim 50\text{-}100 \text{ m}$	$\sim 100\text{-}500 \mu\text{m}$



angular source size: $< 0.4 \mu\text{rad}$

PETRA-III, NSLS-II, MAX-IV : $\sim 0.1 \mu\text{rad}$

Crystals: $\Delta d/d \sim 10^{-7}$

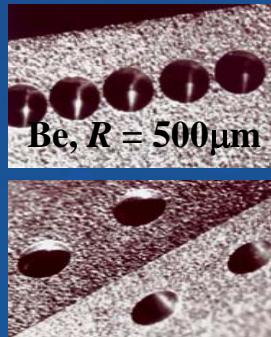
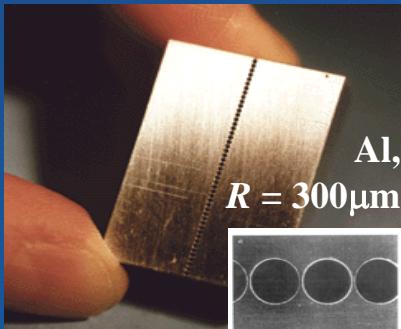
Mirrors: slope error $\sim 10^{-7}$

Si-111 $\Delta\theta \sim 20 \mu\text{rad}$ ($\lambda = 1\text{\AA}$, $E = 12.4 \text{ keV}$)
 Si-555 $\Delta\theta \sim 0.5 \mu\text{rad}$ ($\lambda = 1\text{\AA}$, $E = 30 \text{ keV}$)

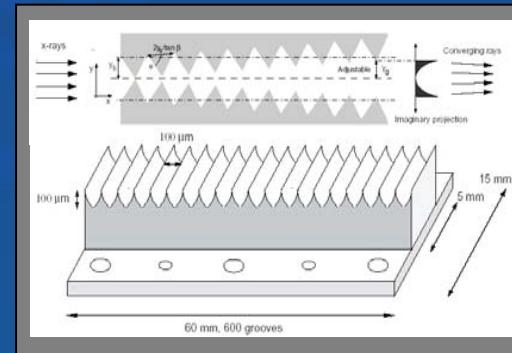
Refractive lenses

A Light for Science

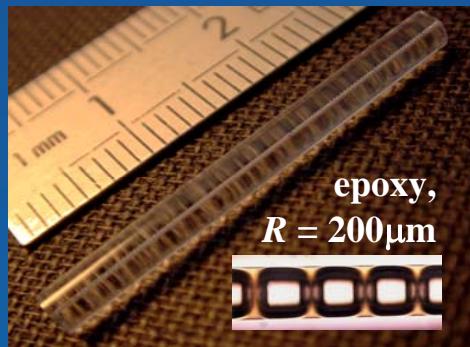
drilling



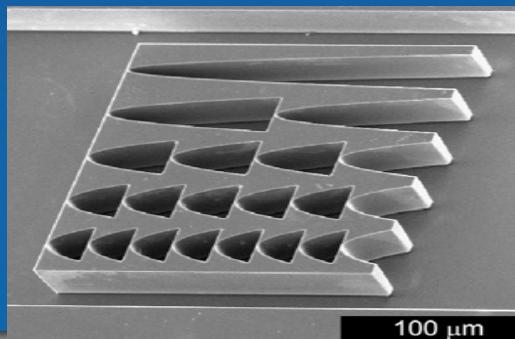
anisotropic chemical etching



printing/molding



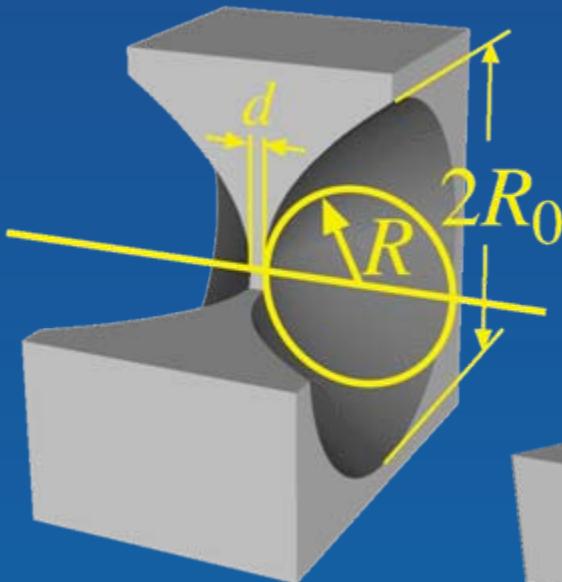
microfabrication (lithography, RIE)



extrusion



single lens



$$R = 0.2\text{mm}$$

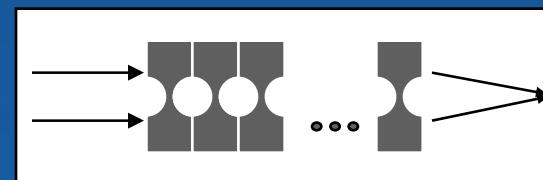
$$2R_0 = 0.9\text{mm}$$

$$d \approx 5\mu\text{m}$$

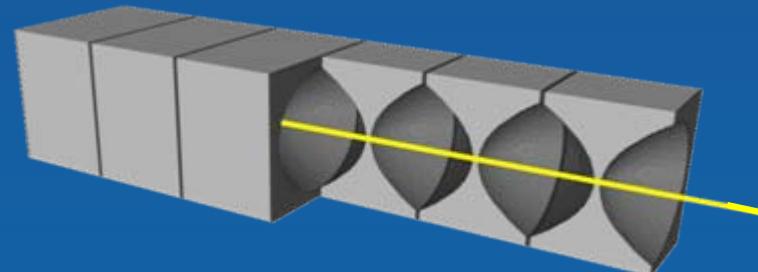
$$F = -\frac{R}{2N\delta}$$

Collab. B.Lengeler,
RWTH, Aachen, Germany

stack of lenses:
compound refractive lens (CRL)

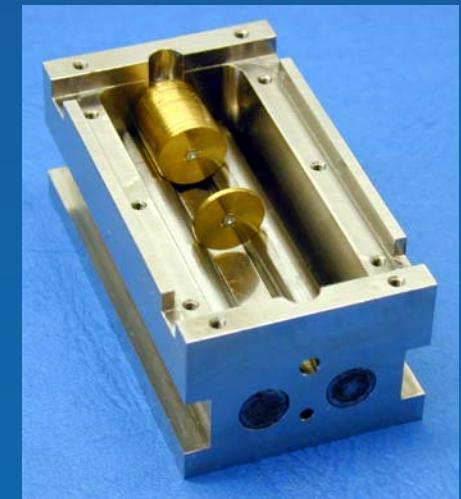


Al, Be, Ni



$$\begin{aligned} R &= 0.5 - 1.5\text{mm} \\ 2R_0 &= 2-3\text{ mm} \end{aligned}$$

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



Effective aperture A_{eff}

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

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

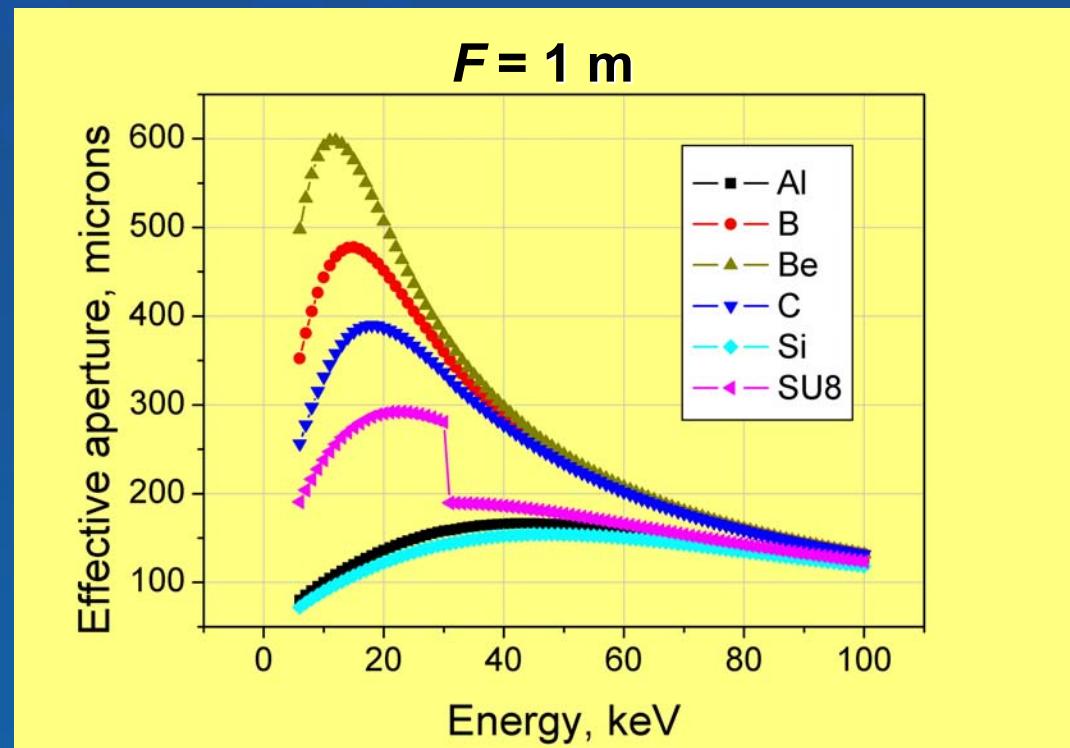
λ - wavelength

f - focal length

δ - real part of decrement of refraction index

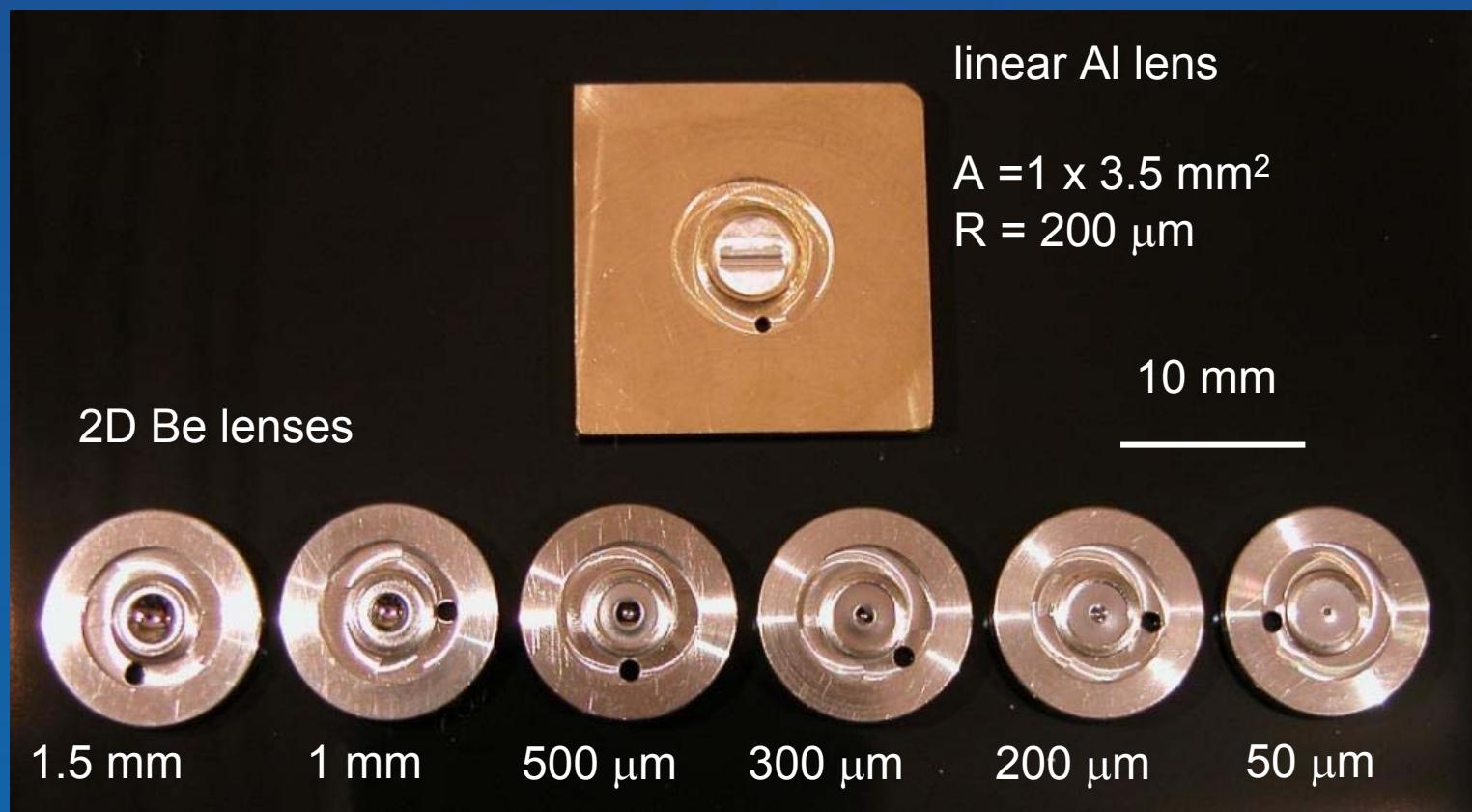
β - imaginary part of decrement of refraction index

μ - linear attenuation coefficient



Effective aperture for the focal length $F = 1 \text{ m}$

Be / AL parabolic lenses (Aachen)



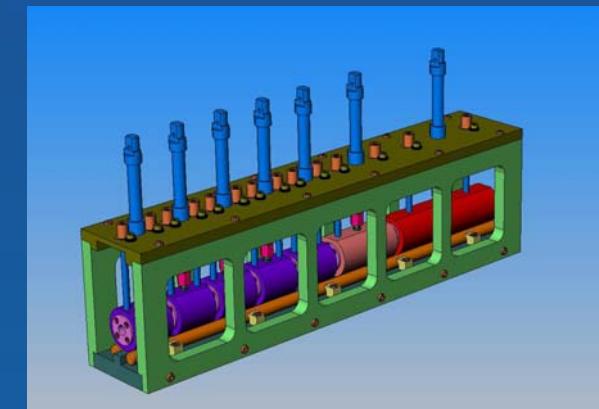
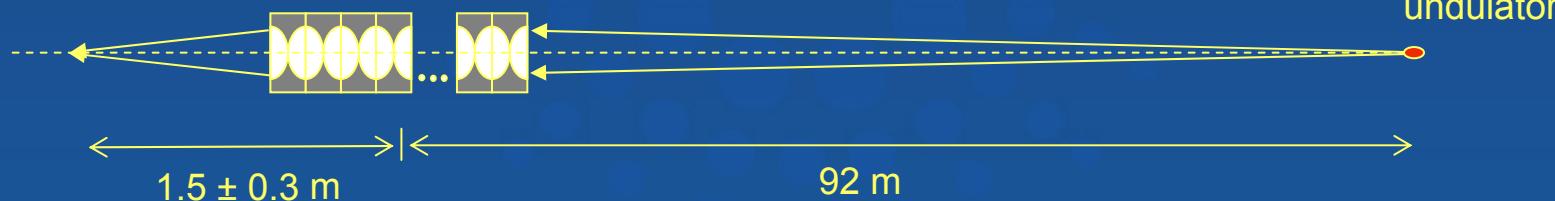
CRL transfocator

A Light for Science

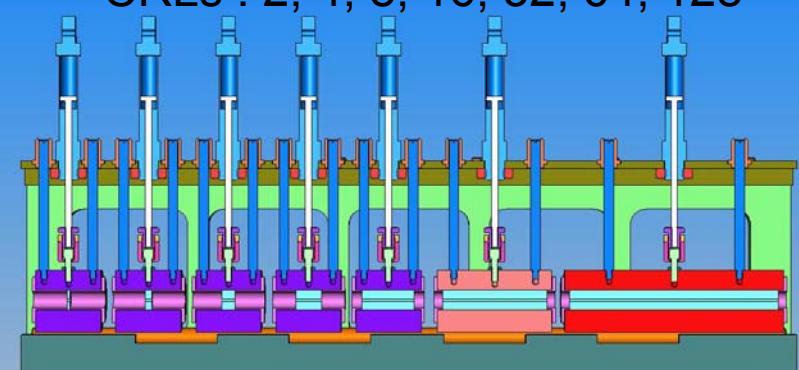
CRL transfocator

Energy range 10 -100 keV

undulator



CRLs : 2; 4; 8; 16; 32; 64; 128



In-Vacuum Transfocator ID11 (white beam)

A Light for Science



cartridge and lenses



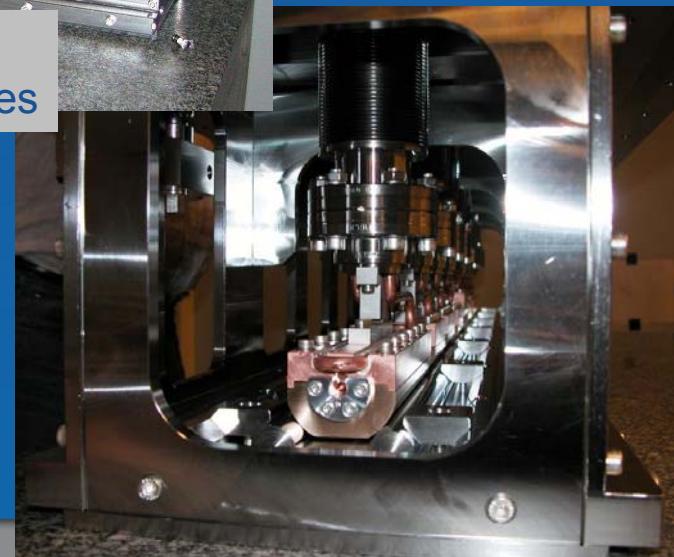
actuators



aboard view



vacuum chamber





10/12/2008

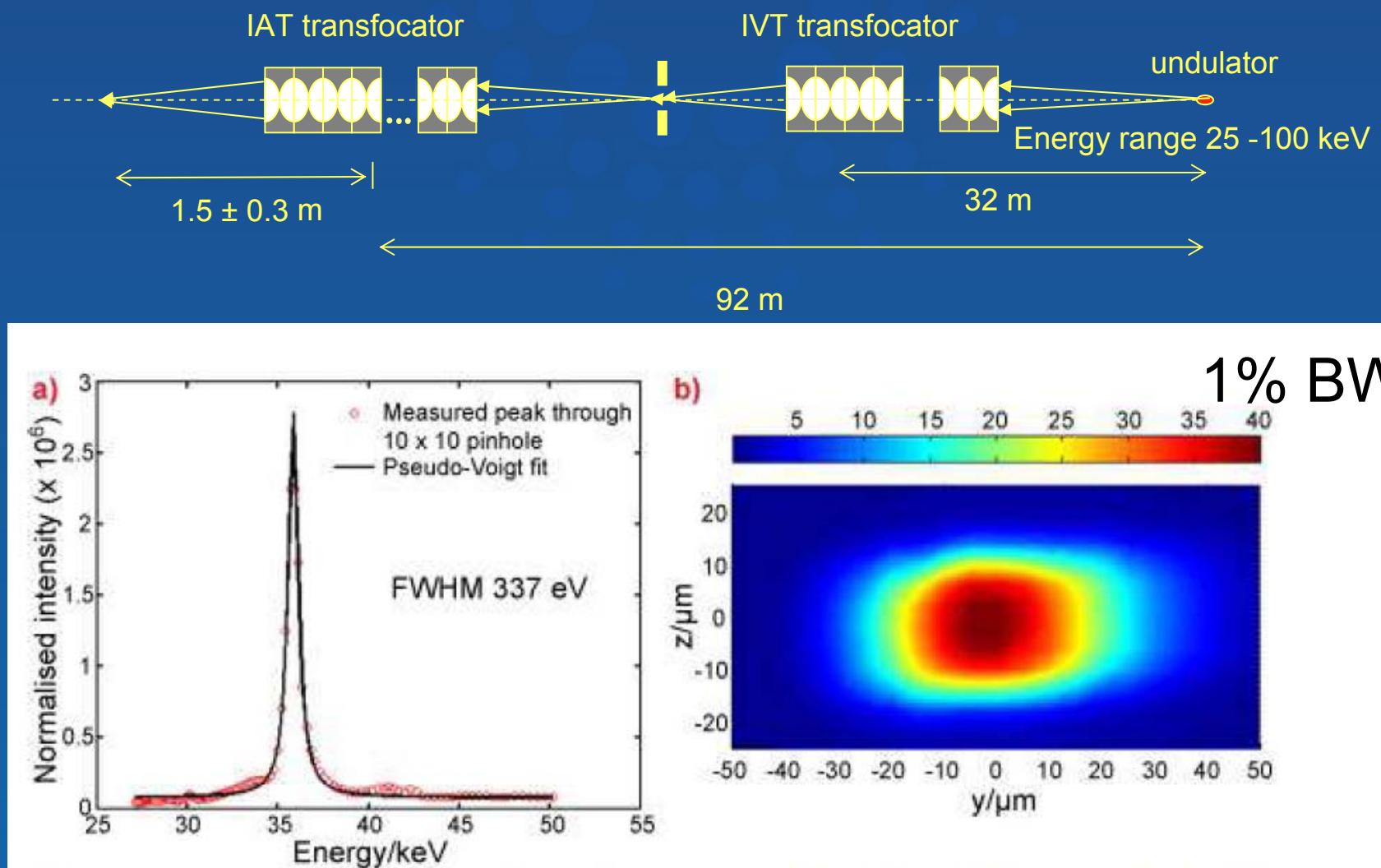
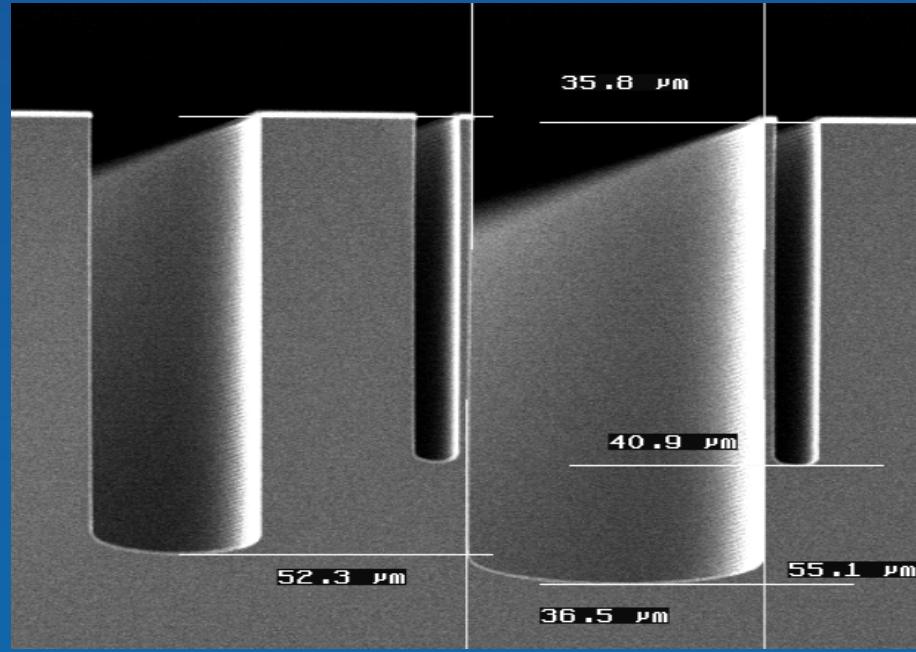
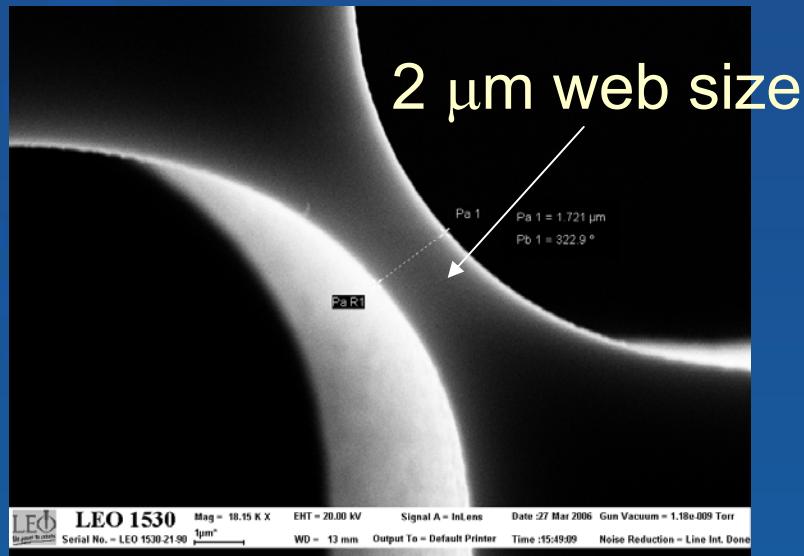
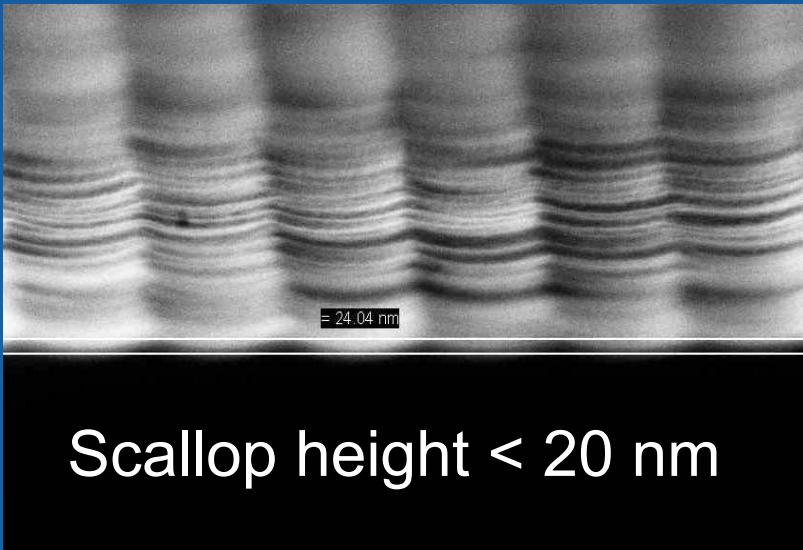
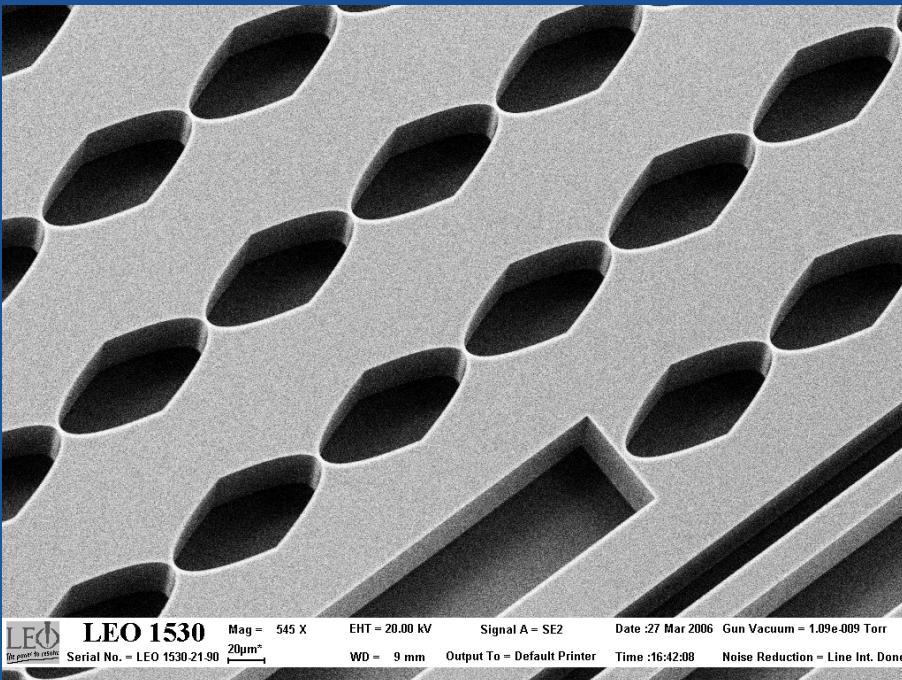


Figure 4. a) Measured spectrum through a $10 \times 10 \mu\text{m}^2$ pinhole of the beam optimized for 35.5 keV. b) spatial distribution of the flux at 35.500 ± 0.005 keV perpendicular to the beam at the focus.

Si nanolenses

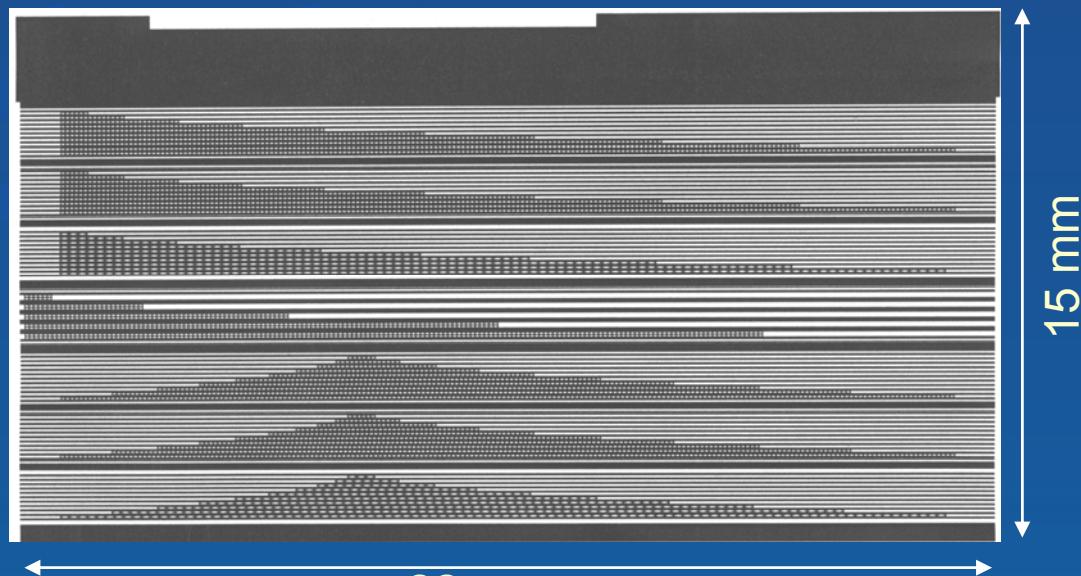
A Light for Science



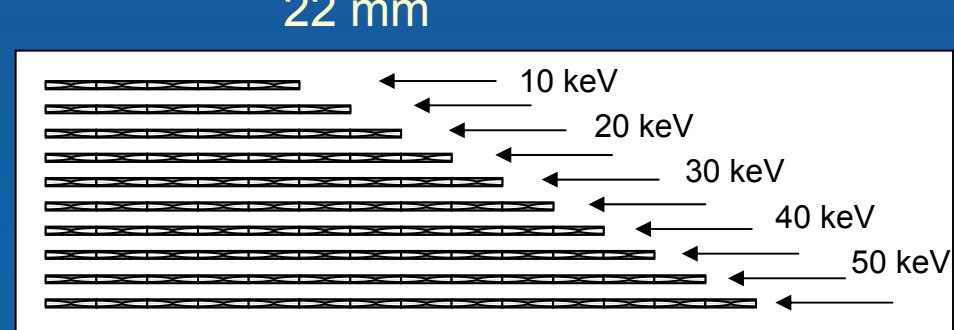
6" Si wafer with NFLs structures



$F = 10\text{cm} @ E = 10 - 50 \text{ keV}$



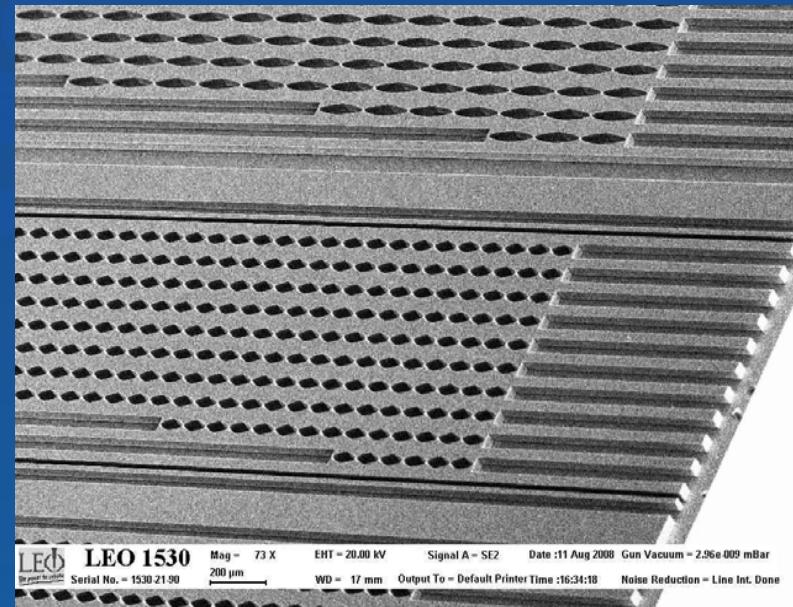
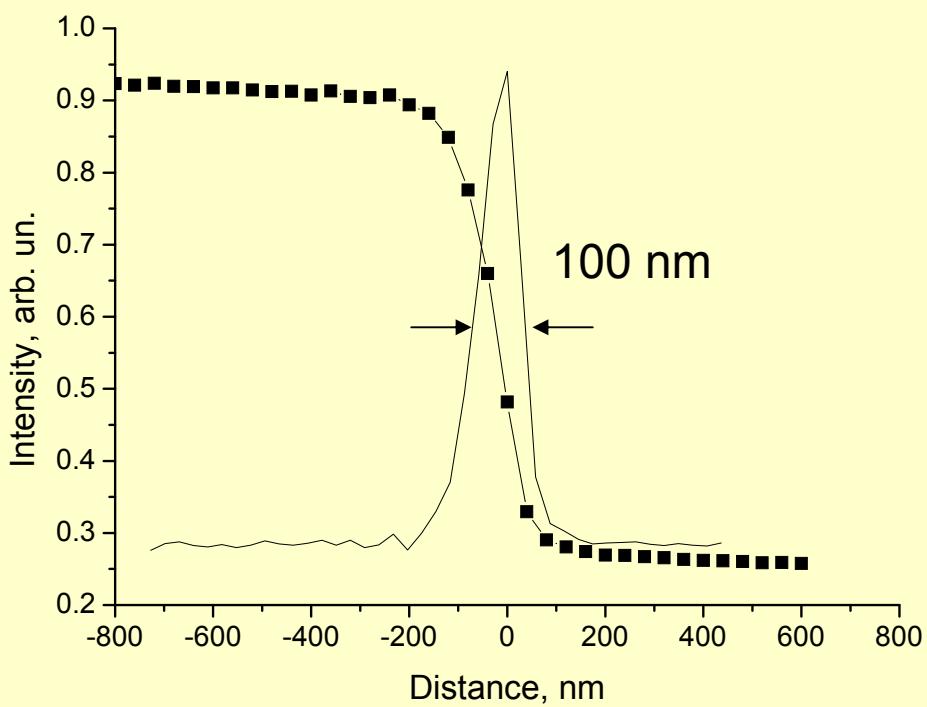
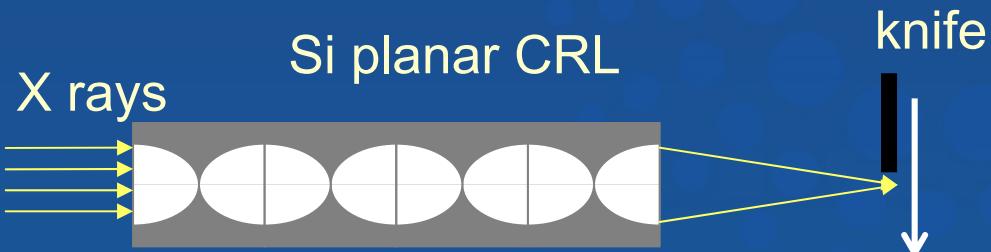
NN	Energy (keV)	Single lens length (μm)	Number of lenses	Radius of parabola apex (μm)	Total lens length (μm)
1	10	50	12	6.25	620
		100	6	3.13	614
2	15	50	28	6.25	1436
		100	14	3.13	1422
3	20	50	52	6.25	2660
		100	26	3.13	2634
4	25	50	80	6.25	4088
		100	40	3.13	4048
5	30	50	116	6.25	5924
		100	58	3.13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



10 lenses per set

7 sets

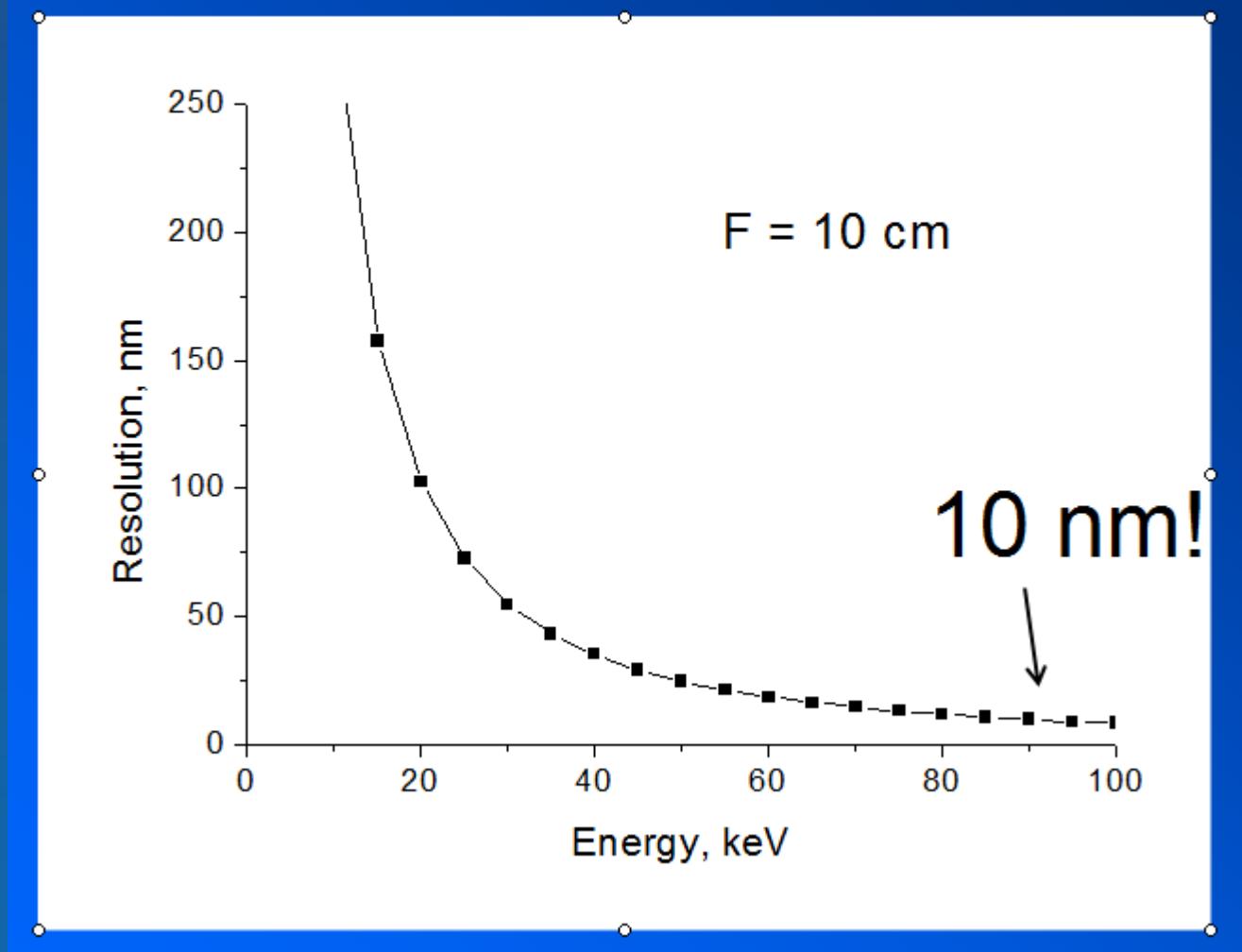
~ 70 CRLs !



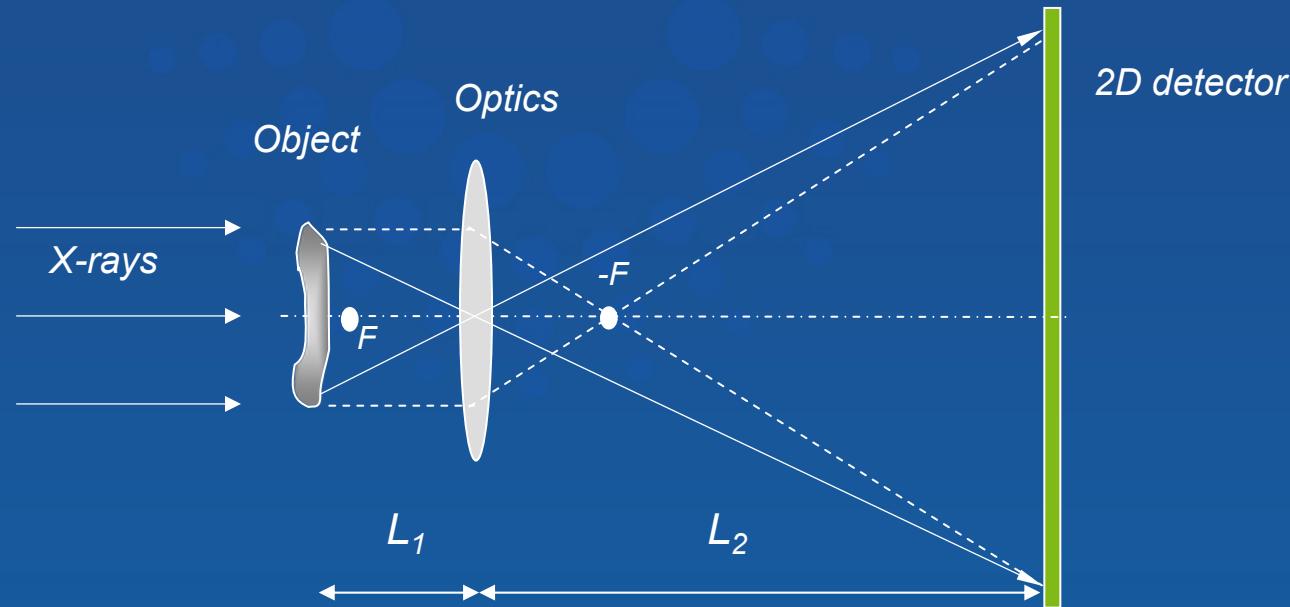
ID6, Sept. 2008
 $F = 40 \text{ mm}$
 $E = 31 \text{ keV}$

	<i>reflective</i>			<i>diffractive</i>	<i>refractive</i>	
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 $\Delta E/E$	w. b.	10^{-2}	w.b.	10^{-3}	$10^{-3} - 10^{-4}$	10^{-3}
resolution	25 nm @15keV Mimura 2006 8 nm ??	41x45nm² @24keV Hignette 2006	50 nm Bilderback 1994	40x25 nm² Salditt 2004	30 nm @20 keV Kang, 2006 <u>17 nm</u> , 2007 ??	50 nm @20keV Schroer, 2004 150nm @50keV Snigirev,2006

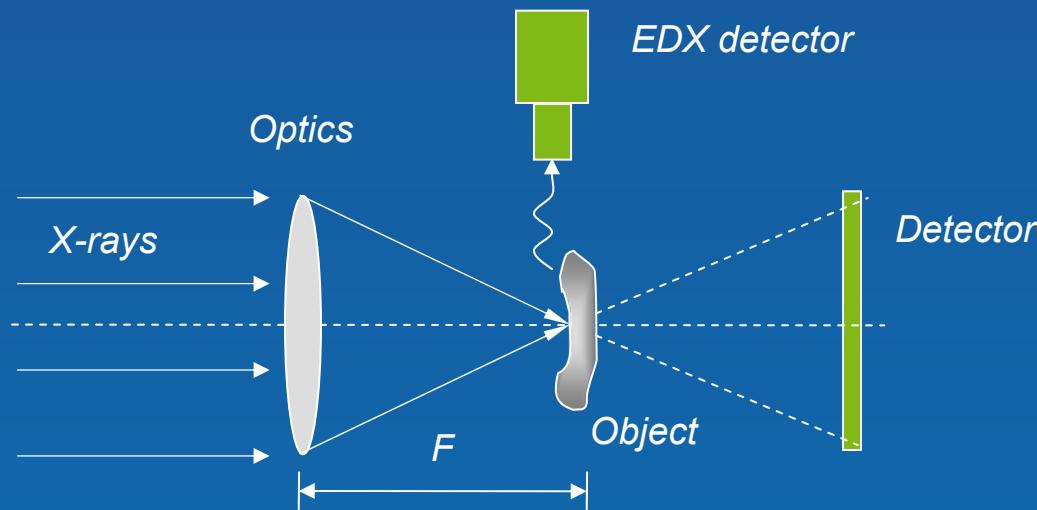
$$\sigma_f = 0.47 \sqrt{2\lambda F \gamma} = 0.47 \sqrt{\frac{2\lambda F \beta}{\delta}}$$



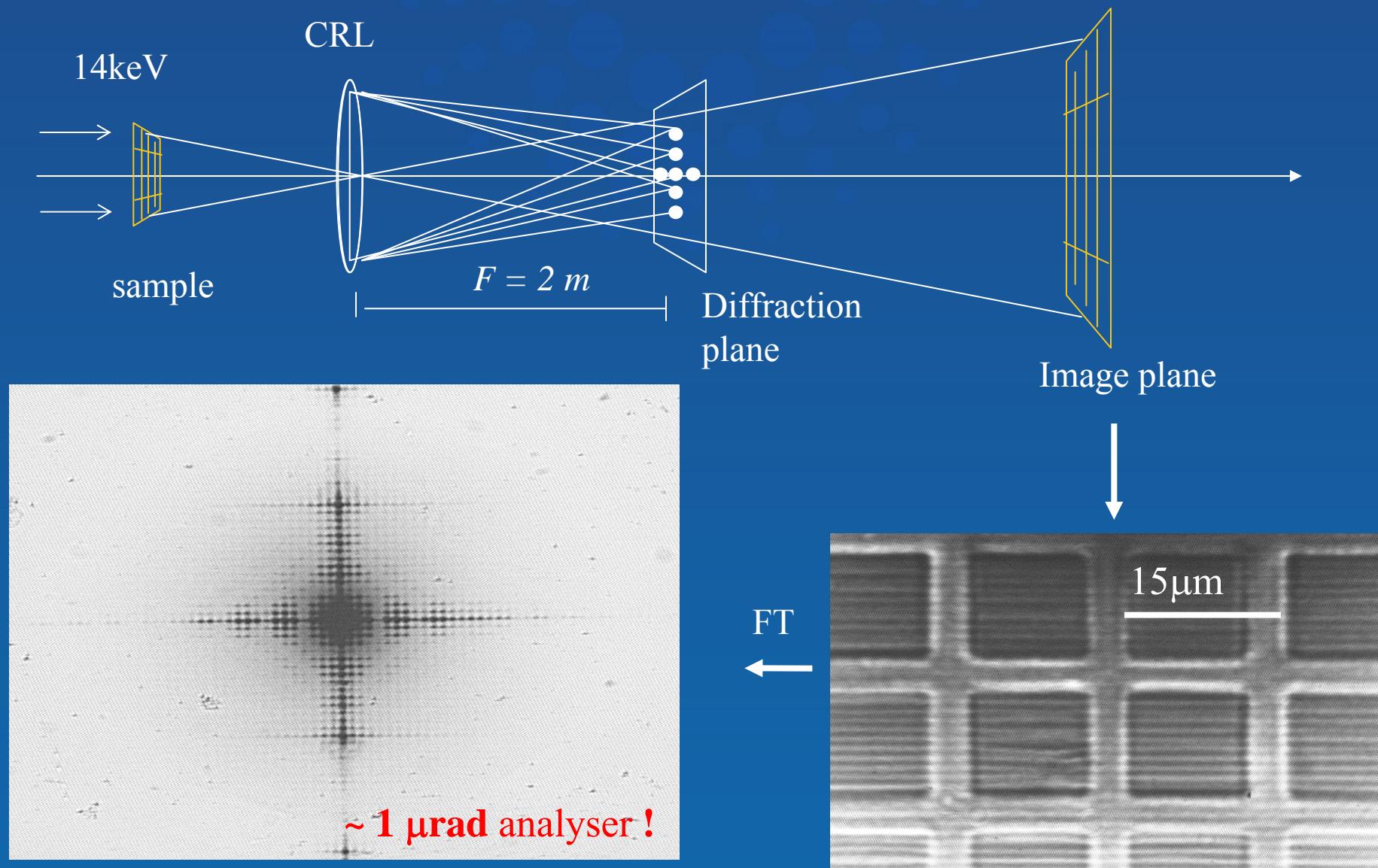
Full-field



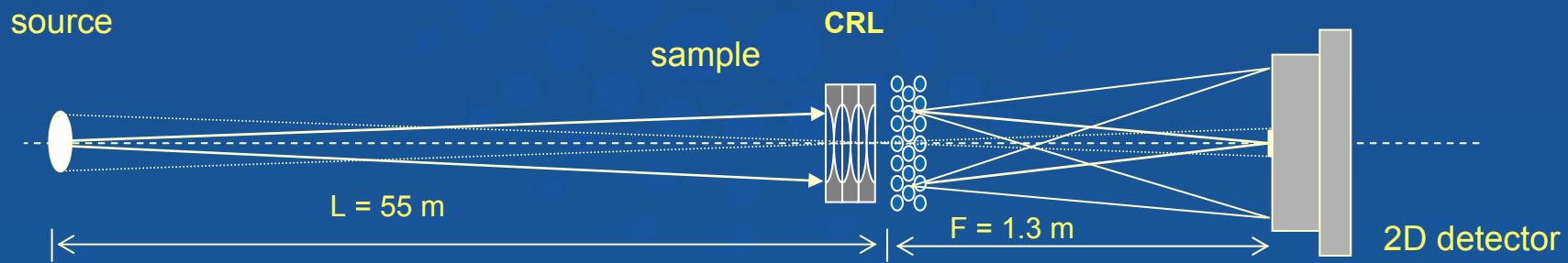
Scanning



Fourier Transform Diffraction/Imaging



X-ray High Resolution Diffraction Using Refractive Lenses



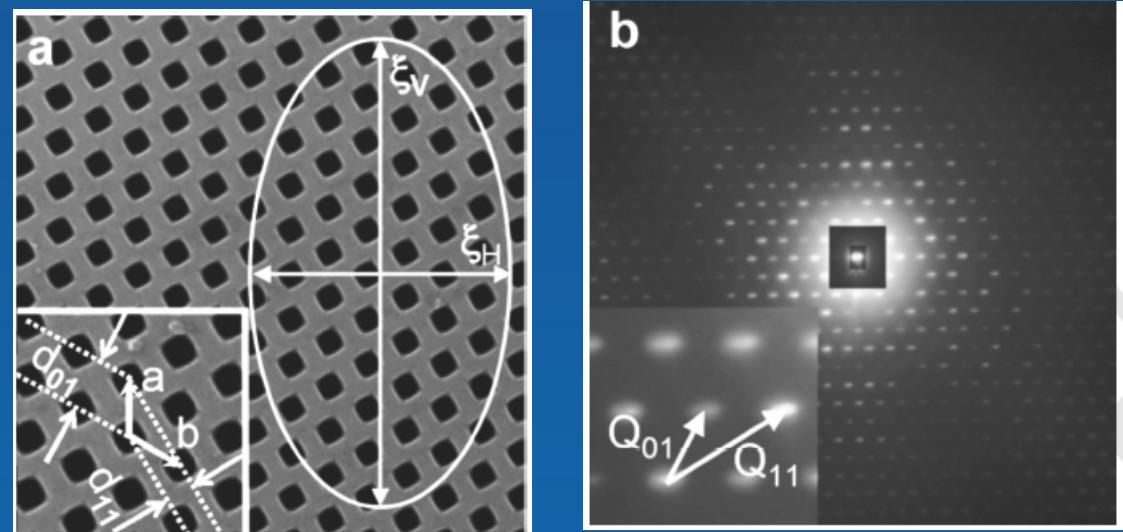
$E = 28 \text{ keV}$
Al CRL, $N = 112$, $F = 1.3 \text{ m}$

Si photonic crystal
 $a=b=4.2 \mu\text{m}$ $d_{01}=3.6 \mu\text{m}$ $d_{11}=2.1 \mu\text{m}$

CCD resolution $2 \mu\text{m}$
pixel / $\Theta = d$

Resolution is limited
by angular source size:
 $s/L \sim 1 \mu\text{rad}$

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



Lattice vectors $g_{01} = 1.75 \cdot 10^{-3} \text{ nm}^{-1}$ $g_{11} = 3 \cdot 10^{-3} \text{ nm}^{-1}$

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

Why X-rays?

Electrons

-electron microscopy:

limited sample volumes
in-situ investigation hardly possible

Light

-confocal optical microscopy:

limited sample volumes.
index matching is not option for infiltrated PCs
thin crystals consisting of a few layers.

- micro-optical spectroscopy :

Light diffraction suffers from too strong scattering!

Neutrons

- small-angle neutron diffraction:

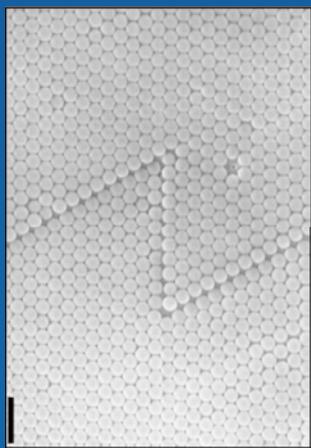
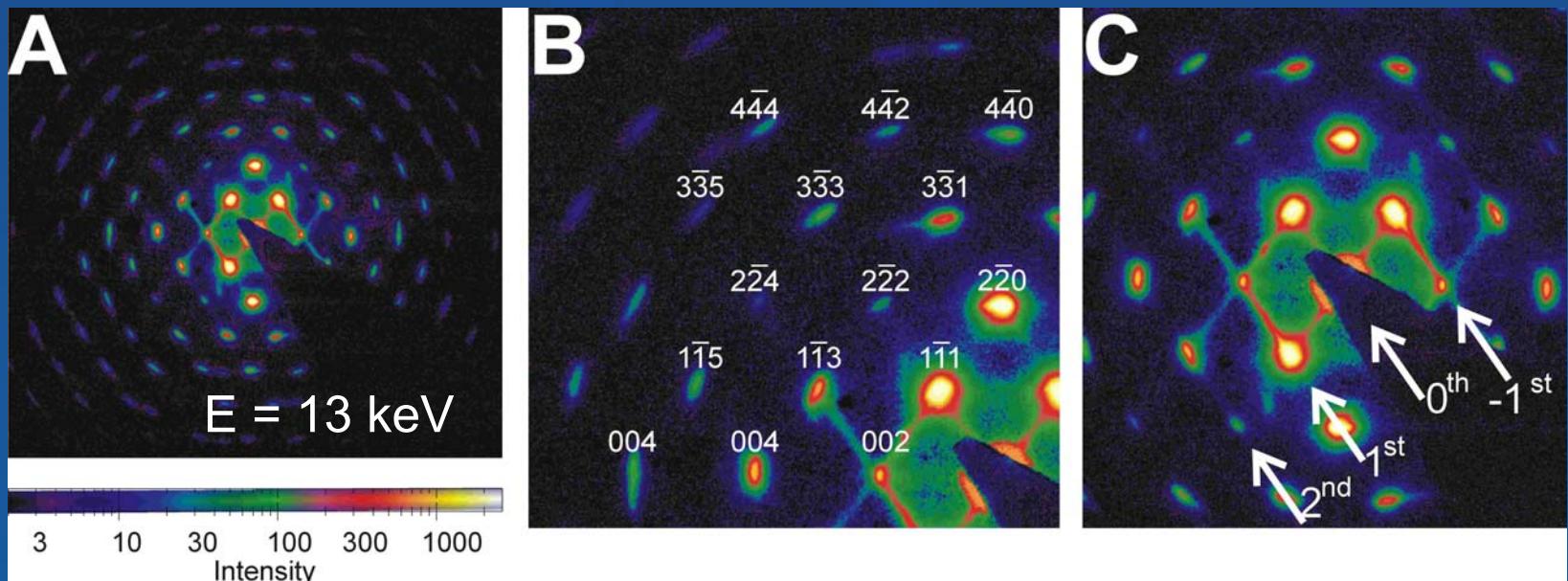
insufficient resolution
unable to reveal important details in the
diffraction patterns

X-rays

- allow in-situ investigation

- give structural information on the scales ranging from tens of nanometers to
tens of micrometers

- can be used to study materials that strongly scatter visible light.

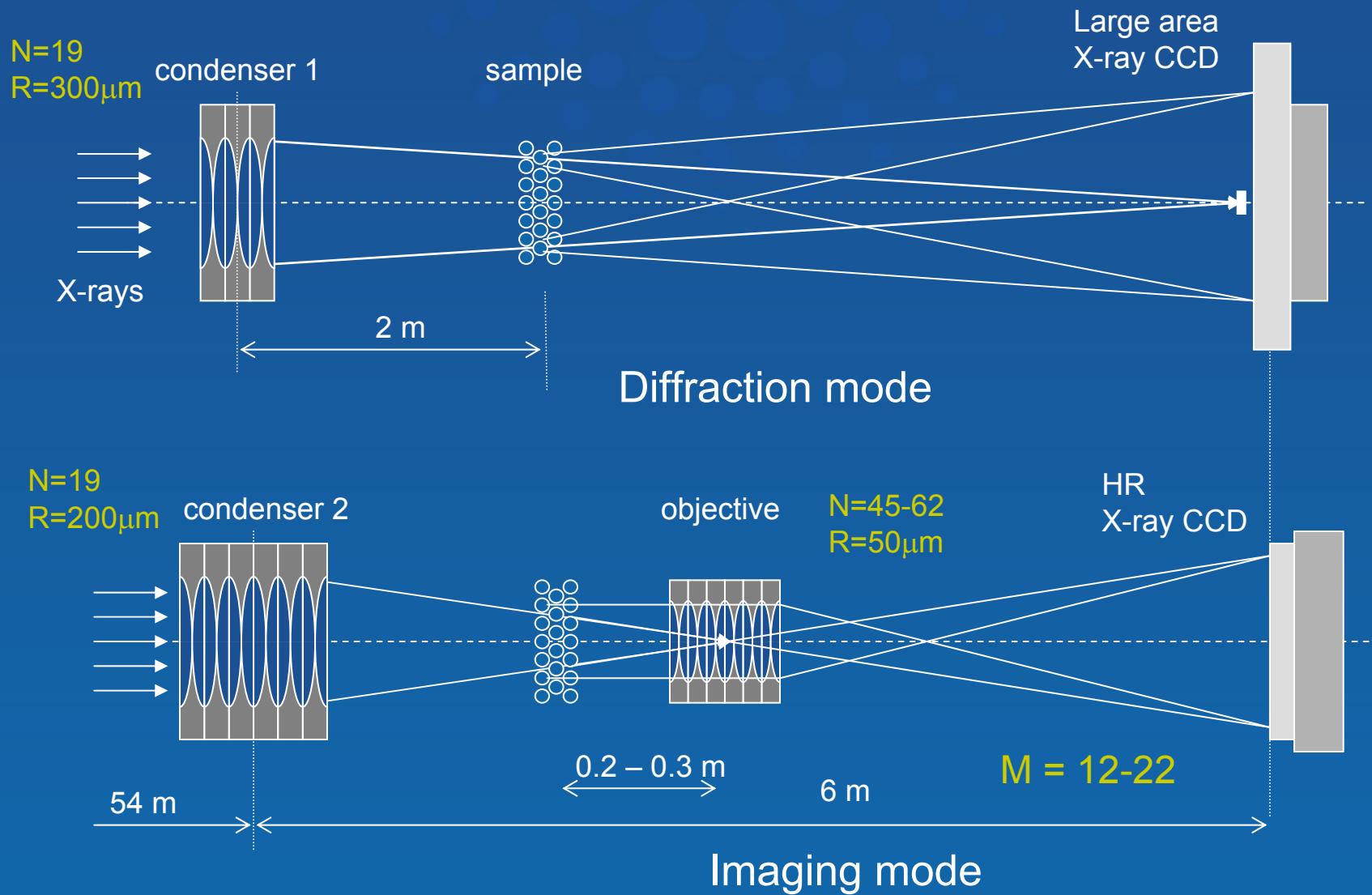


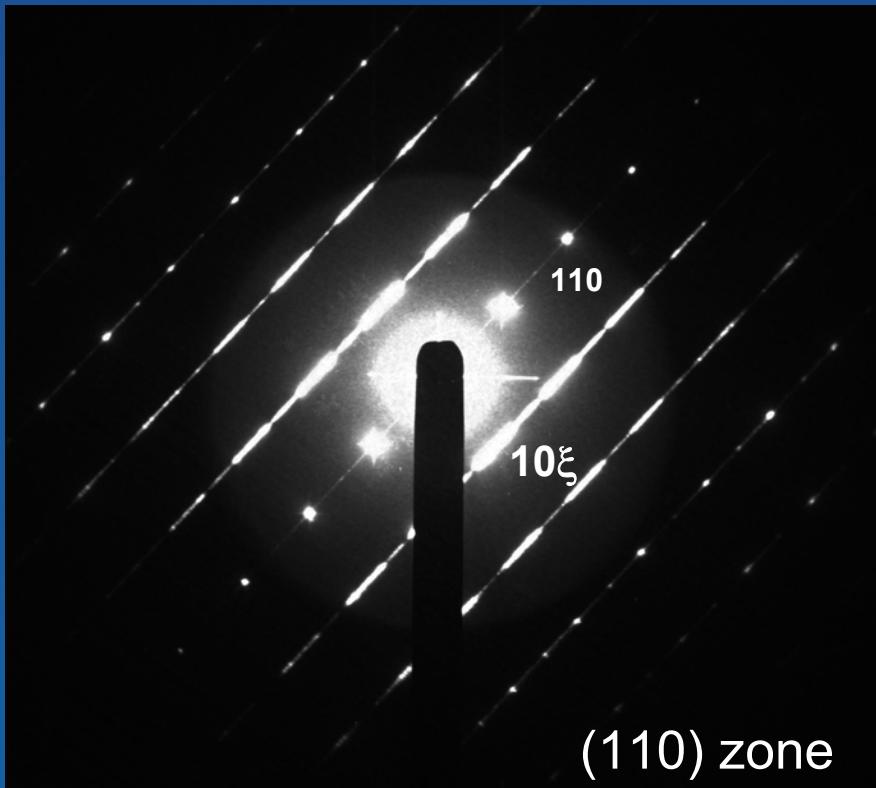
Clear face-centred cubic structure

- Presence of sliding defects
- These defects are crucial in generating ...ABCABC... stacking order

Panel A displays a full diffraction pattern while a zoom into one quarter is given in B along with the crystallographic assignment of the peaks. Again, the relative weakness of the 002 , 222 and 224 reflections can be understood on the basis of Fig. 1C. A closer look on the central part of the pattern reveals presence of the Bragg rods, which are caused by the presence of the stacking disorder.

Conceptual layout of HRXRM





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

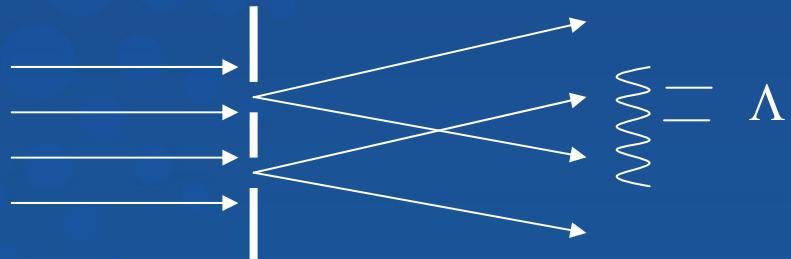
Forbidden reflections (HKL+1/2)



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

Double slit

W. Leitenberger, S. Kuznetsov, A. Snigirev,
Interferometric measurements with
hard X-rays using a double slit
Optics Communications **191**, 91-96 (2001)



$$\Lambda \sim 1 - 10 \text{ } \mu\text{m}$$

Double mirror

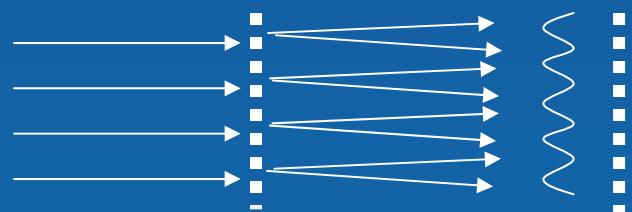
K. Fezzaa, F. Comin, S. Marchesini, R. Coisson, M. Belakhovsky,
X-ray interferometry at ESRF using two coherent beams from Fresnel mirrors
Journal of X-Ray Science and Technology **7**, 12-23 (1997)



Grating interferometers

P. Cloetens, J. P. Guigay, C. De Martino, J. Baruchel, and M. Schlenker,
Fractional Talbot imaging of phase gratings with hard x rays ,
Opt. Lett. **22**, 1059-1061 (1997)

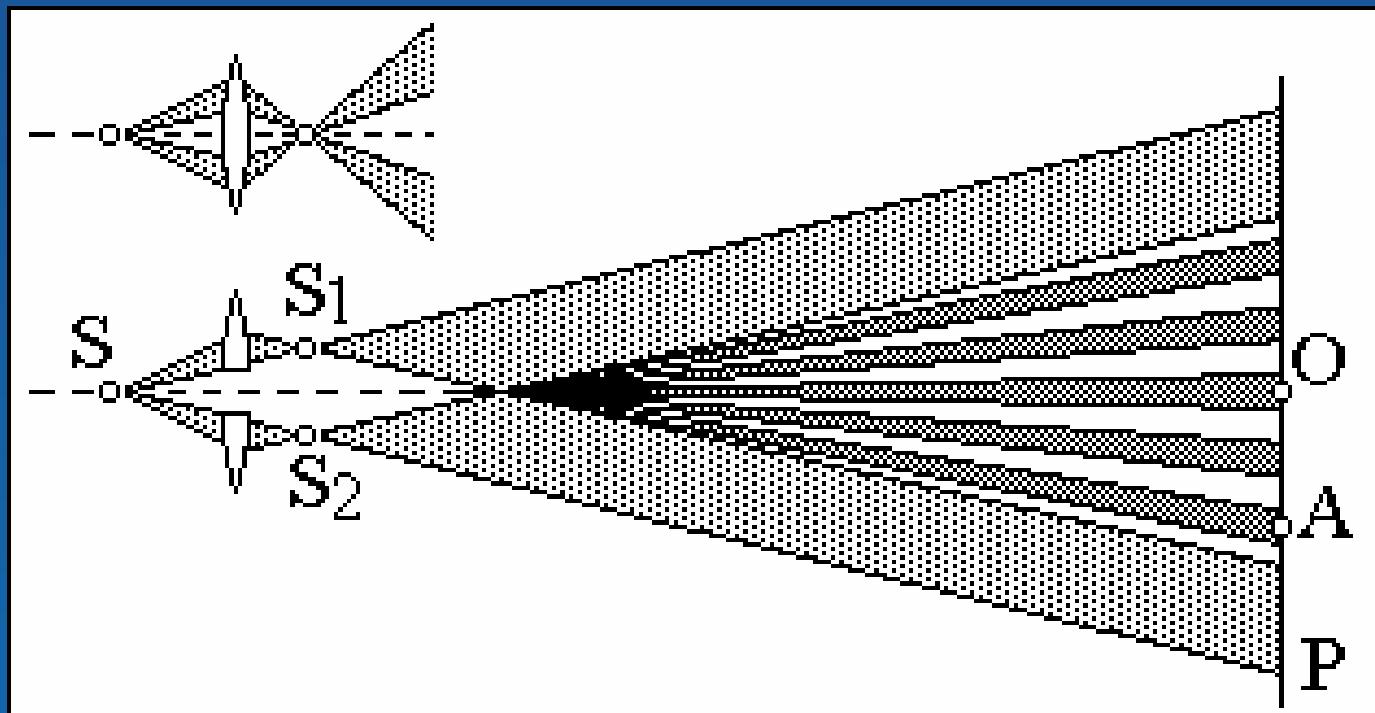
T. Weitkamp, B. Nohammer, A. Diaz, C. David, E. Ziegler,
X-ray wavefront analysis and optics characterization with a grating interferometer
Appl. Phys. Lett., 86, 054101 (2005)



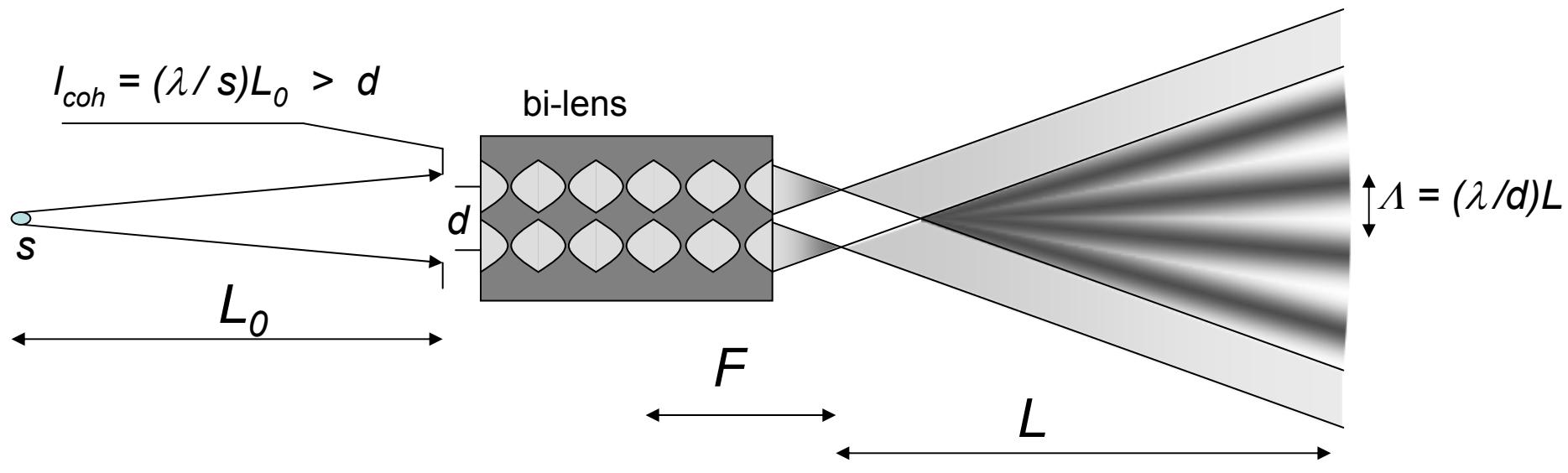
Billet split lens

to pay a tribute to

Professeur Felix Billet (1808 -1882)
la Faculté des sciences de Dijon depuis 1843



Billet split lens

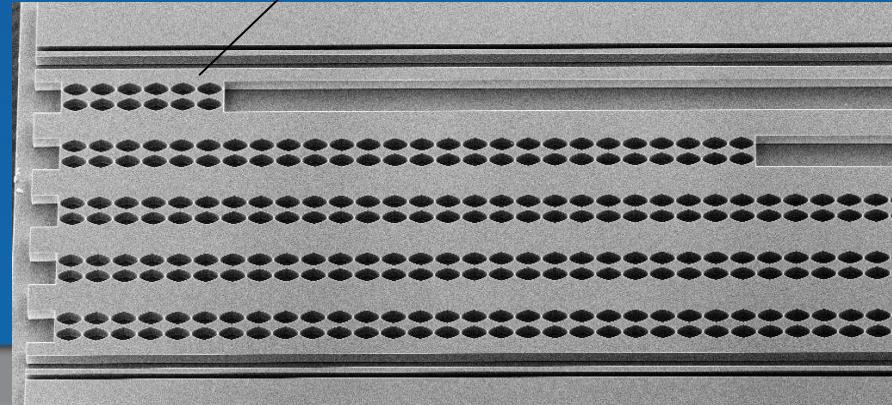
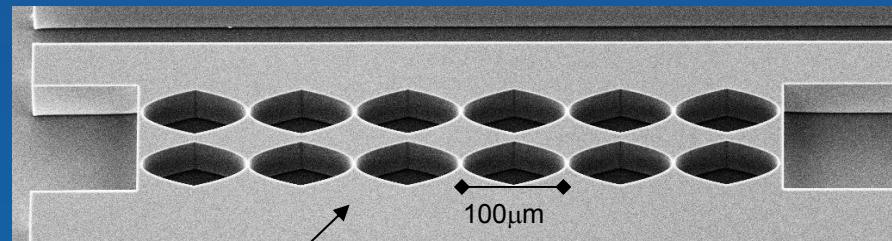


$$I_{coh} = 100 - 200 \mu m$$

$$E = 12 \text{ keV}$$

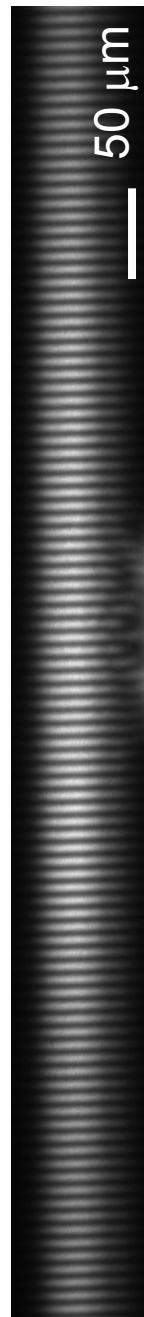
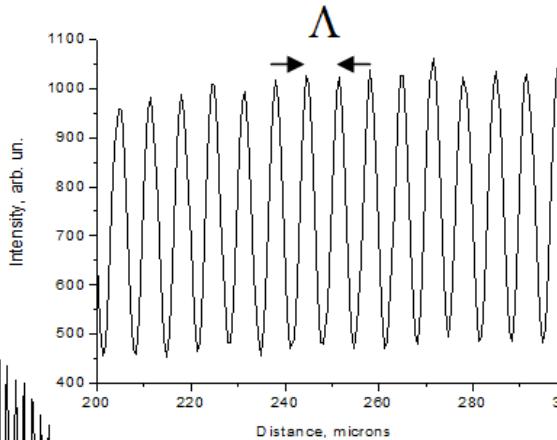
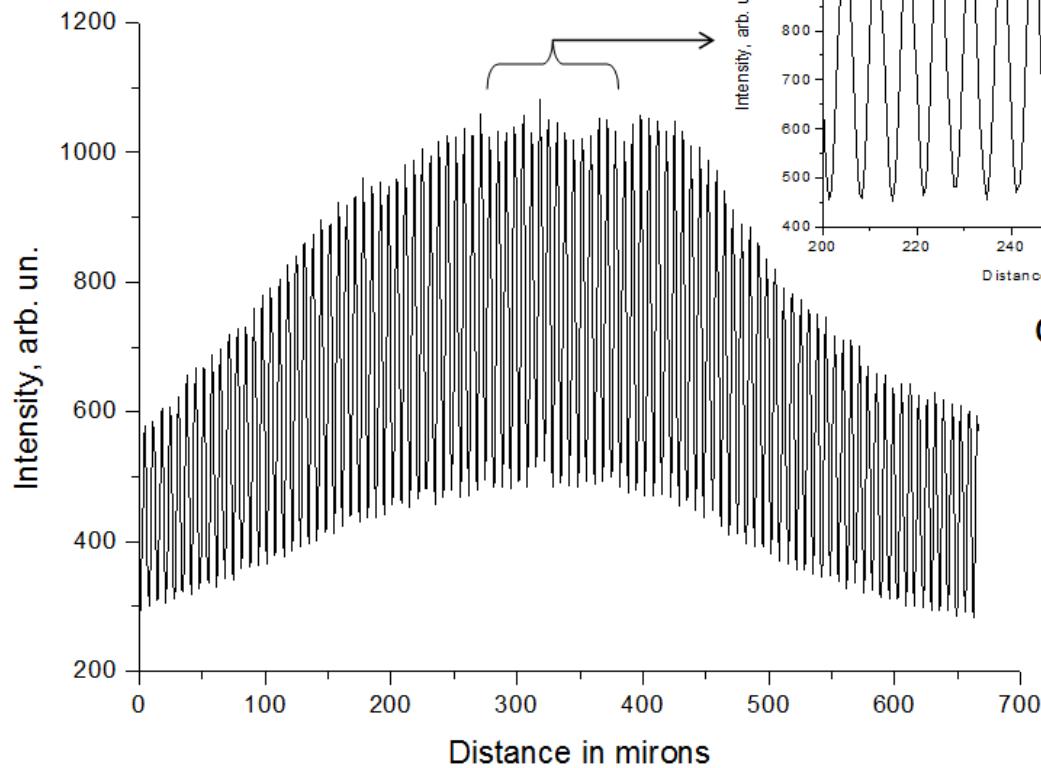
$$s = 25 - 50 \mu m$$

$$L = 50m$$



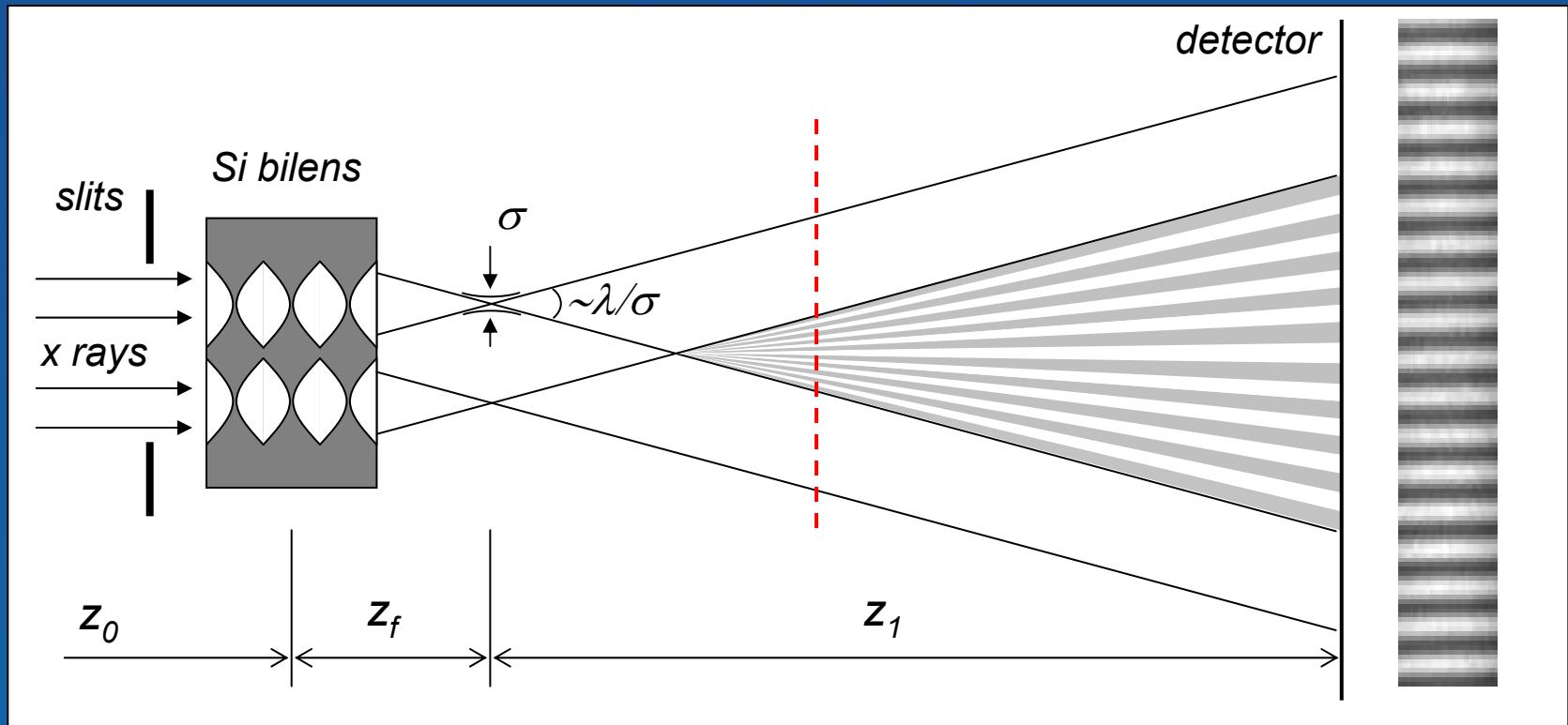
X-ray bi-lens interferometer: far-field interference

$E = 12 \text{ keV}$



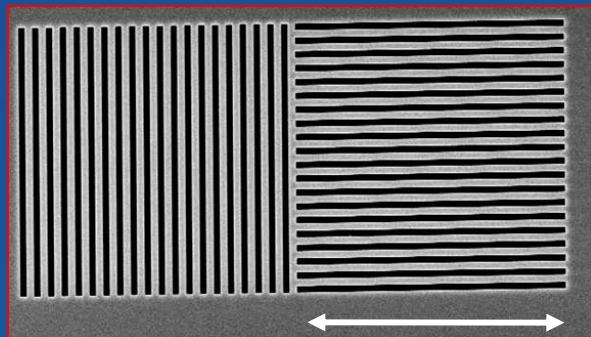
source size:
$$S = \frac{\Lambda L_0}{L_1} \left(-\frac{\log C}{3.56} \right)^{1/2}$$
 $S = 28 \mu m \text{ (FWHM)}$

Near-field interference

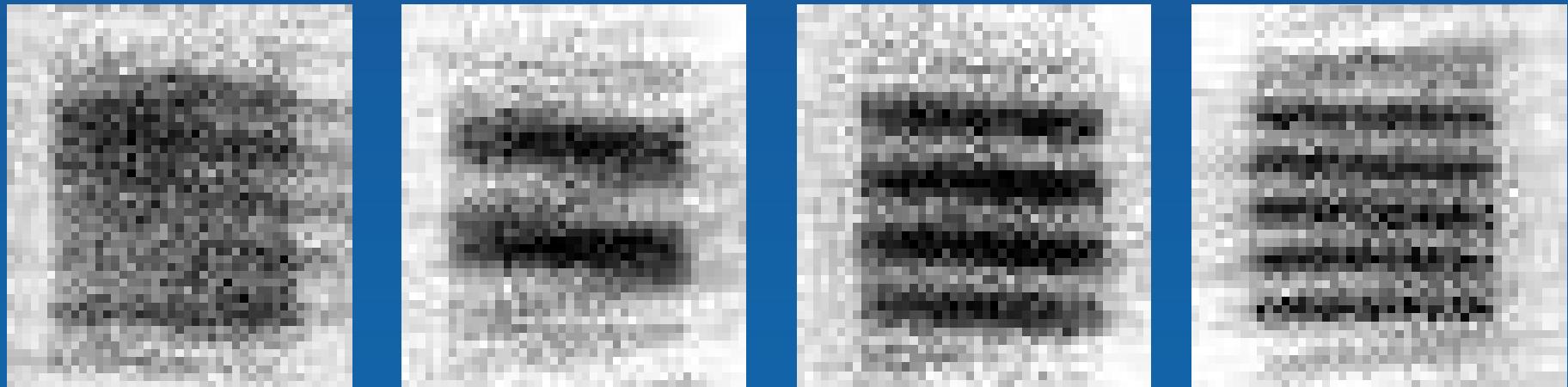
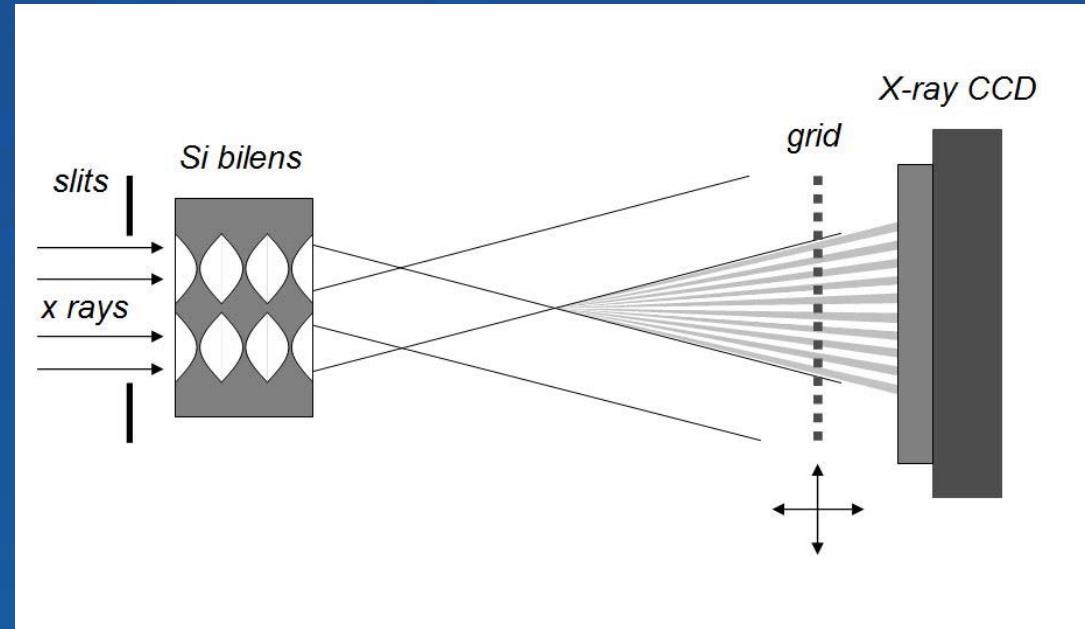


Near-field imaging mode

200 nm bar / 200 nm slit



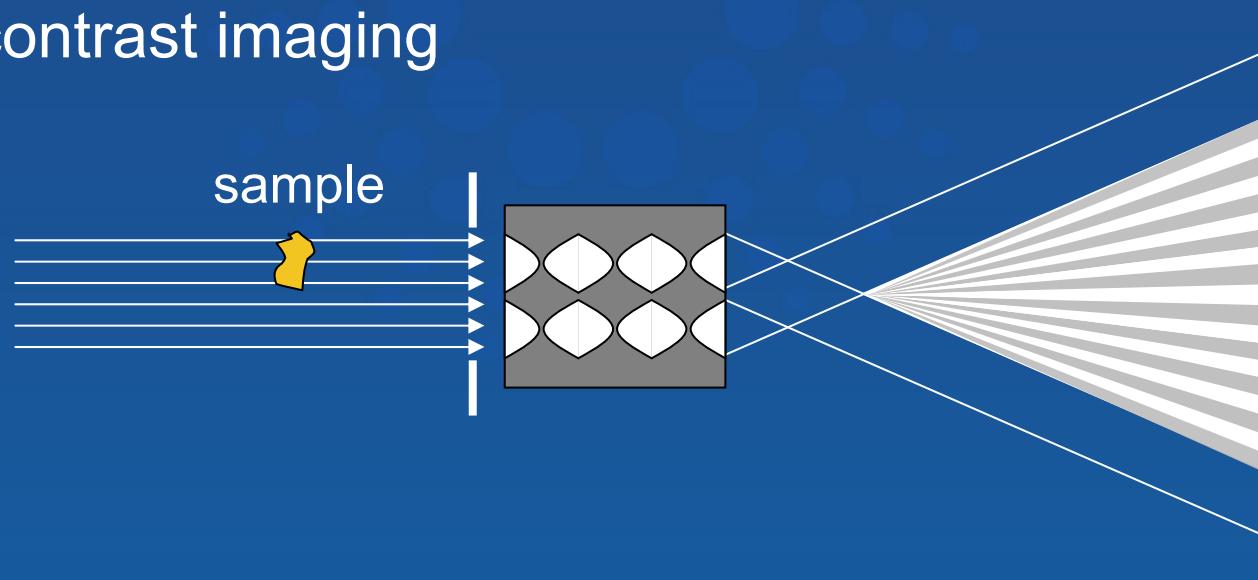
20 μm



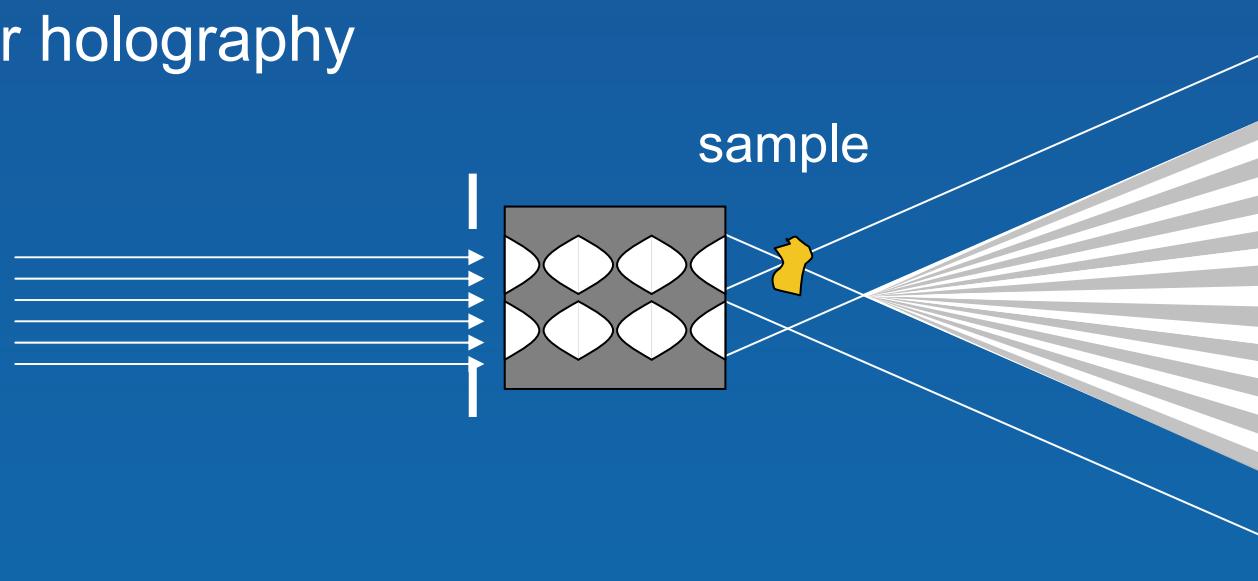
10 μm

$$\Lambda_5 - \Lambda_4 = 5 \text{ nm} !$$

Phase contrast imaging



Fourier holography



- Coherence / Optics characterization
- Interferometry – phase contrast
- Moiré radiography
- Fourier holography
- Standing wave technique

Crystal interferometer

0.1 – 10 nm

Bilens interferometer

10 – 1000 nm

Grating interferometer

>1000 nm

- E 1keV – 100 keV !!!



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. Detlefs¹

¹ESRF, B.P. 220, 38043 Grenoble, France

²Russian Research Center "Kurchatov Institute," 123182, Moscow, Russia

³IMT 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.

Gravitation and Astrophysics

Cosmic Ray Electrons and Positrons from Supernova Explosions of Massive Stars	061101
P. L. Biermann, J. K. Becker, A. Meli, W. Rhode, F. S. Seo, and T. Stanev	
Scaling Laws of Turbulence and Heating of Fast Solar Wind: The Role of Density Fluctuations	061102
V. Carbone, R. Marino, L. Sorriso-Valvo, A. Noullez, and R. Bruno	
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