Immanuel Kant
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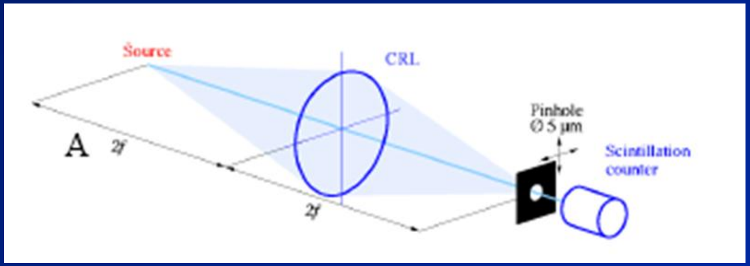
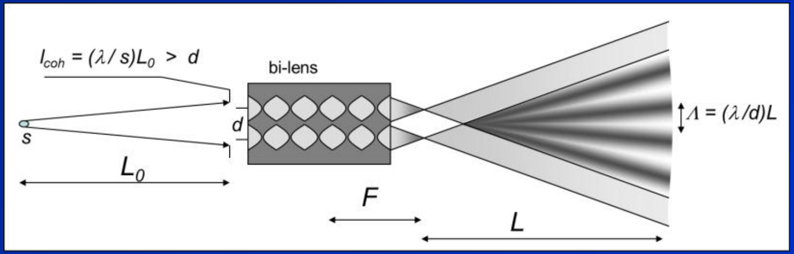
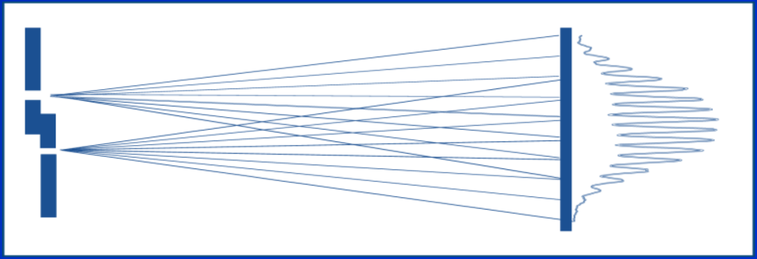
Beam size diagnostics using x-ray imaging and interferometry

Anatoly SNIGIREV

Immanuel Kant Baltic Federal University
Kaliningrad, Russia







Temporal coherence $\lambda^2/\Delta\lambda$ – monochromaticity $\Delta\lambda/\lambda$

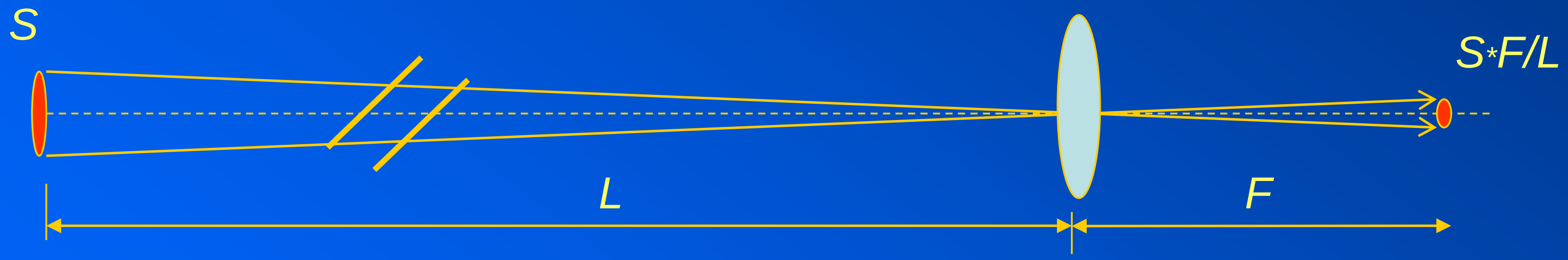
Si 111: 10^{-4}-10^{-5}

ML: 10^{-2}

- **Spatial coherence**

source size $S \sim 10\ \mu$m spatial coherence $L\lambda/s$

source distance $L \sim$ 50-100 m ~ **500 μm**



*For 100m BL: F=10 cm focus = S*F/L =* ***20 nm!***

angular source size: ~ 0.1 - 0.2 μrad

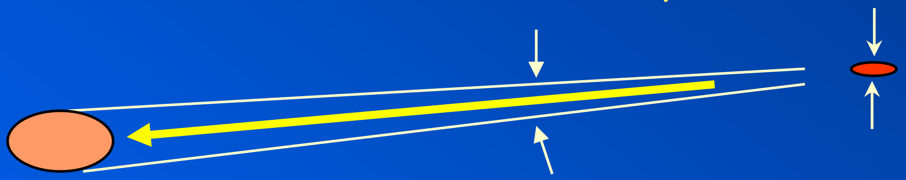
Crystals: $\Delta d/d$ $< 10^{-6}$

Mirrors: slope error $< 10^{-6}$

Si-111 $\Delta\theta \sim 20\ \mu$rad ($\lambda$ =1Å, E = 12.4 keV)

Si-555 $\Delta\theta \sim 0.5\ \mu$rad ($\lambda$ =1Å, E = 30 keV)

Diffraction limited SR sources



~ 10 μrad V

source size (FWHM)

$s_v = 10\ \mu m$
$s_h = 10\ \mu m$

200 μm x 500 μm
at 20 m

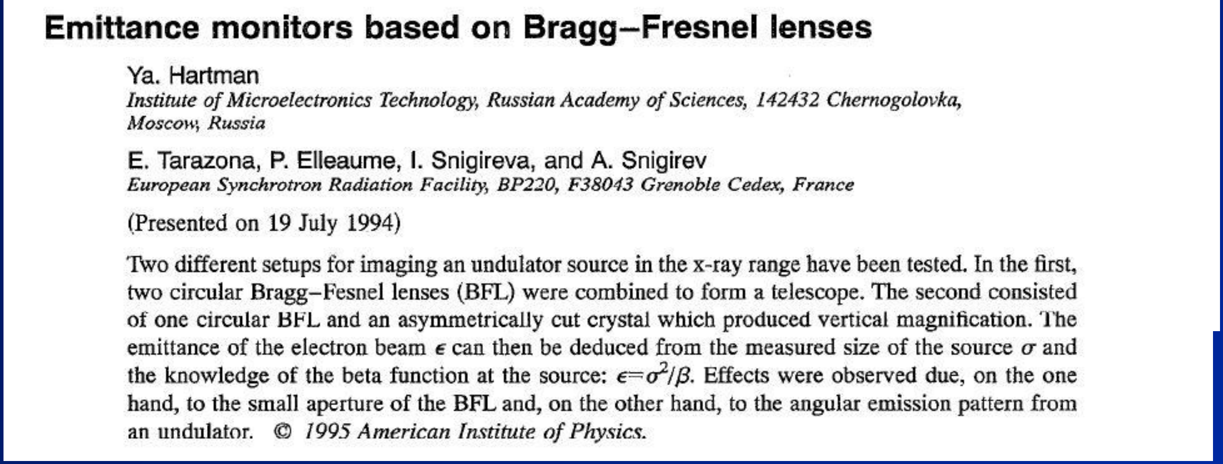
wavelength / source size ~ beam divergence

For 12.4 keV

$\lambda = 10^{-10}$ m
$s = 10\ \mu m$

$\lambda/s = 10\ \mu rad$!

Beam/source diagnostics at ID6@ESRF 1993



Emittance monitors based on Bragg–Fresnel lenses

Ya. Hartman
Institute of Microelectronics Technology, Russian Academy of Sciences, 142432 Chernogolovka, Moscow, Russia

E. Tarazona, P. Elleaume, I. Snigireva, and A. Snigirev
European Synchrotron Radiation Facility, BP220, F38043 Grenoble Cedex, France

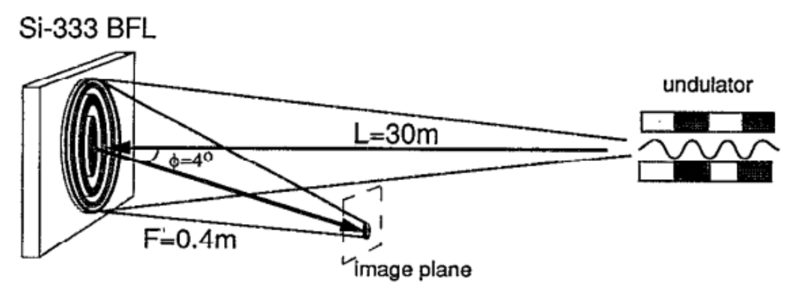
(Presented on 19 July 1994)

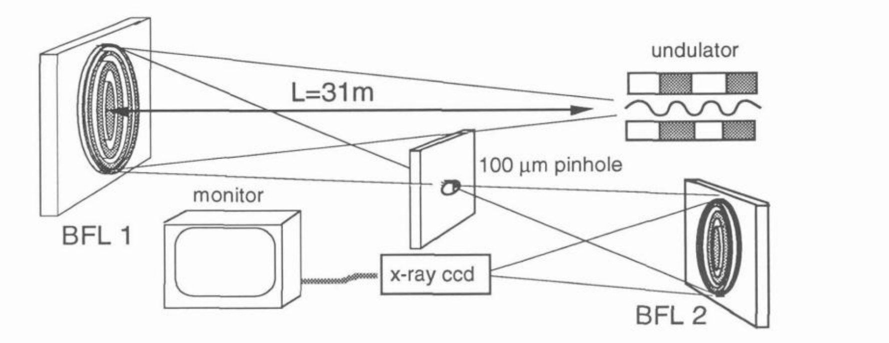
Two different setups for imaging an undulator source in the x-ray range have been tested. In the first, two circular Bragg–Fesnel lenses (BFL) were combined to form a telescope. The second consisted of one circular BFL and an asymmetrically cut crystal which produced vertical magnification. The emittance of the electron beam ϵ can then be deduced from the measured size of the source σ and the knowledge of the beta function at the source: $\epsilon = \sigma^2/\beta$. Effects were observed due, on the one hand, to the small aperture of the BFL and, on the other hand, to the angular emission pattern from an undulator. © *1995 American Institute of Physics.*

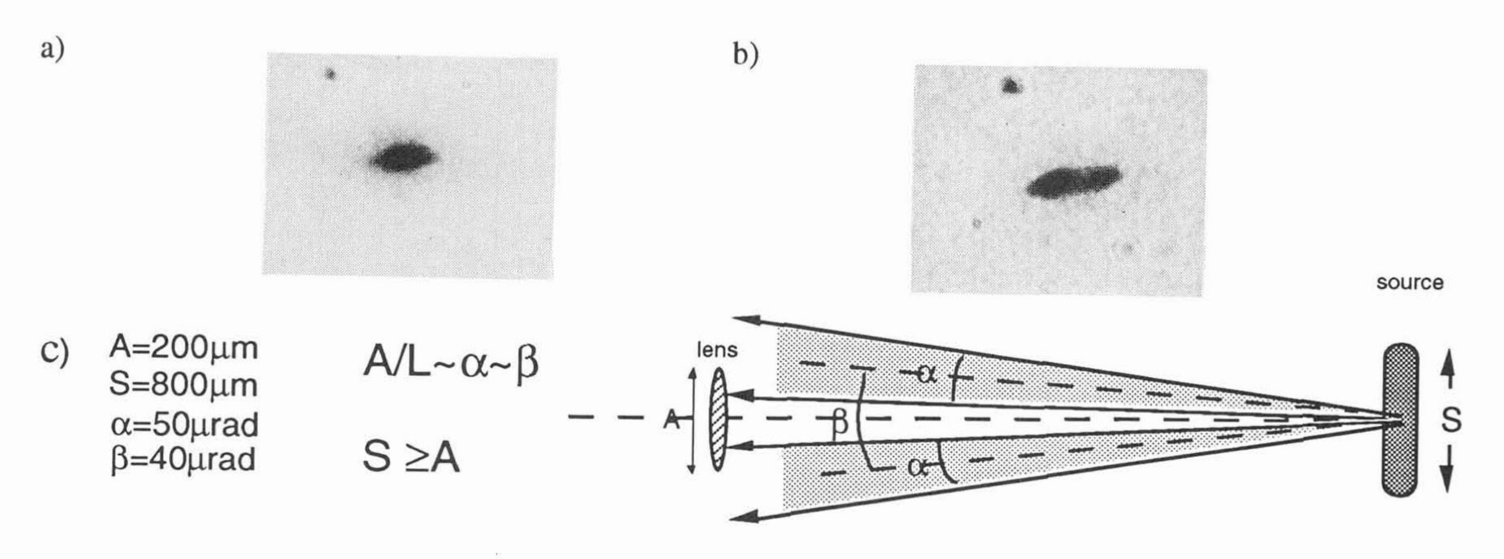
ESRF 1993 -1995

$\sigma_h = 400\ \mu$

$\sigma_v = 100\ \mu$







A=200µm
S=800µm
α=50µrad
β=40µrad

A/L~α~β

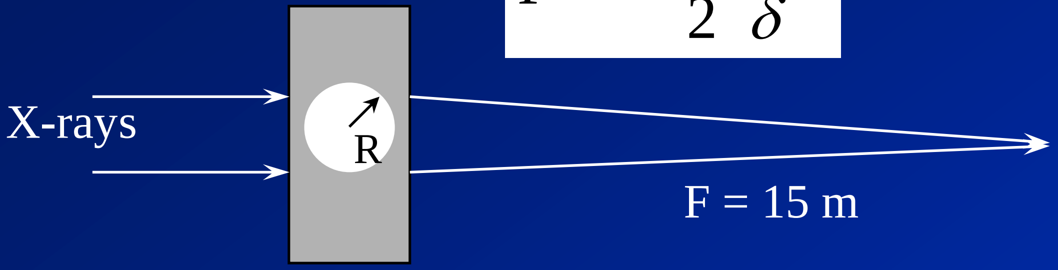
S ≥A

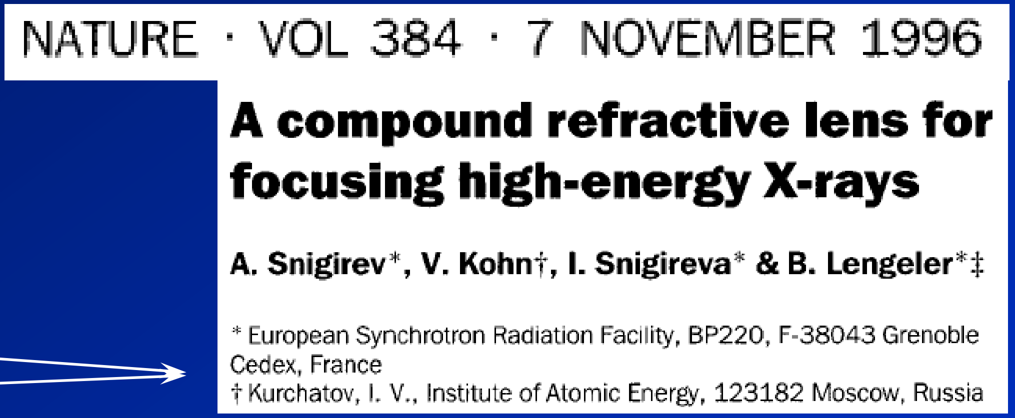
X-ray Compound Refractive Lenses

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

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

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





NATURE · VOL 384 · 7 NOVEMBER 1996

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

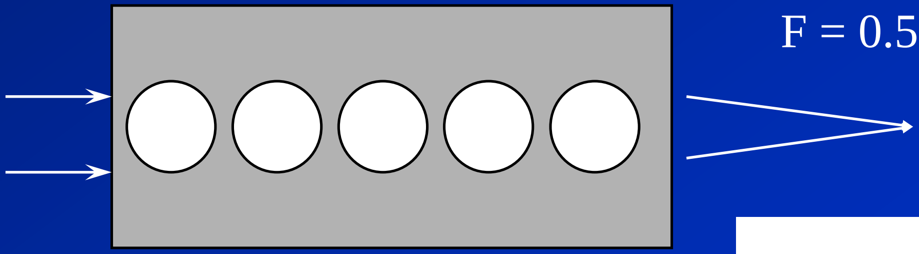
Be

E = 10 keV

$\delta = 3.4 * 10^{-6}$

R = 100 µm

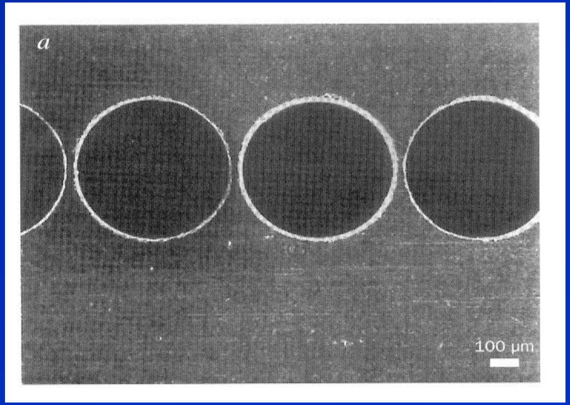
x N



F = 0.5 m

N = 30

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



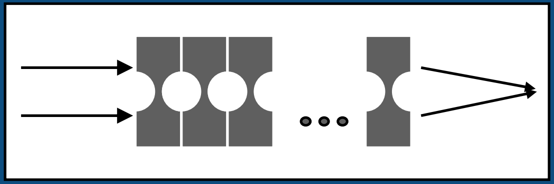
Al, $R = 300\mu m$

Parabolic Compound Refractive Lenses

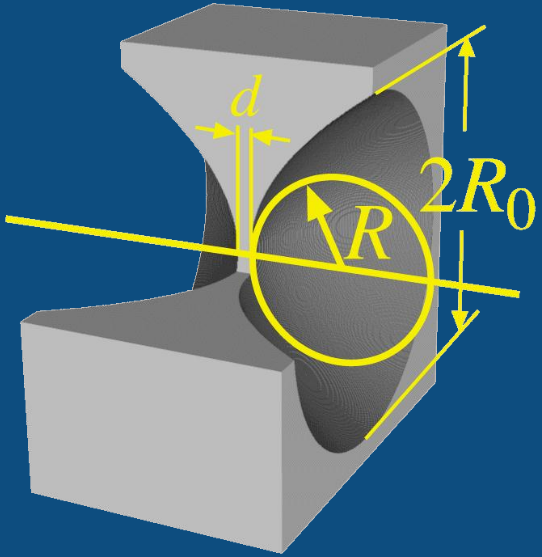
single lens

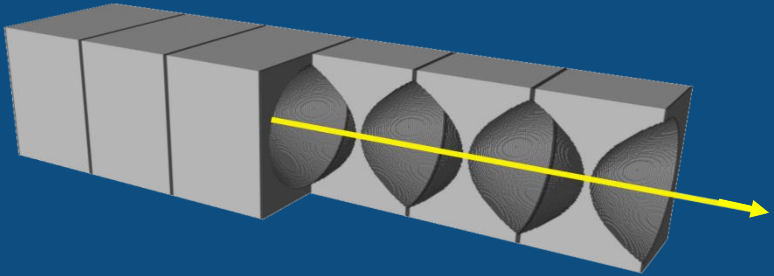
stack of lenses:
compound refractive lens (CRL)

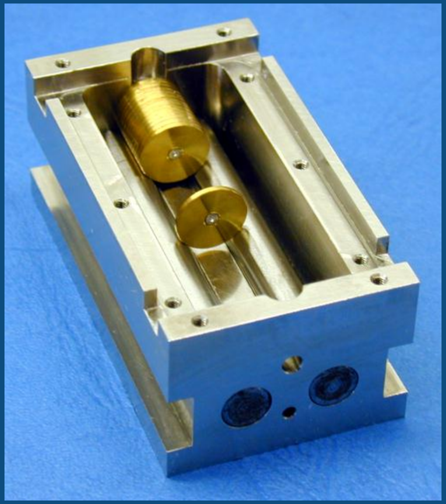
Collab. B.Lengeler,
RXOPTICS, Aachen,
Germany



Al, Be, Ni







R = 50 μm – 1.5 mm
$2R_0$ = 1 - 3 mm
d = 5 - 20 μm

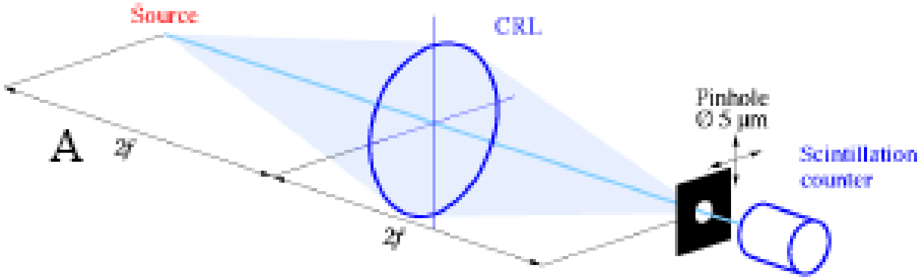
$$F = \frac{R}{2N\delta}$$

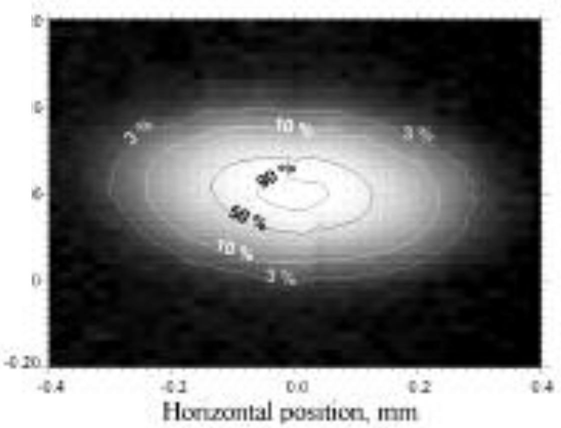
variable number of lenses: $N = 10 \ldots 300$

resolution ~ 100 nm

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

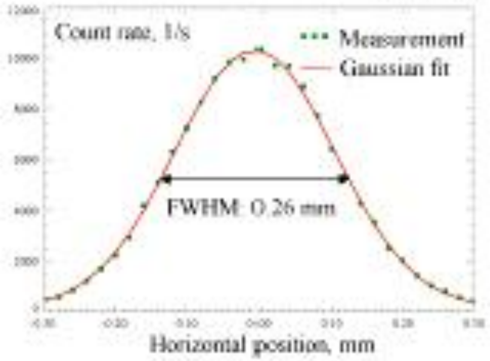
T. Weitkamp, O. Chubar, M. Drakopoulos, I. Snigireva, A. Snigirev, ESRF, Grenoble, France
C. Schroer, F. Guenzler, B. Lengeler, RWTH, Aachen, Germany

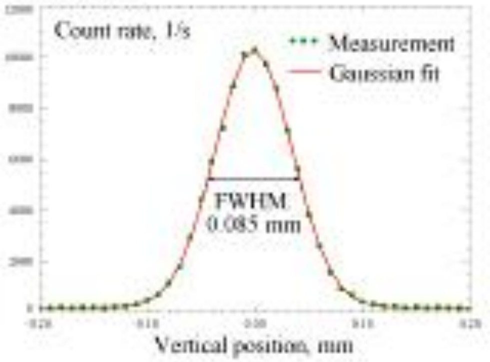




1999

BM5 85 x 260 μm^2



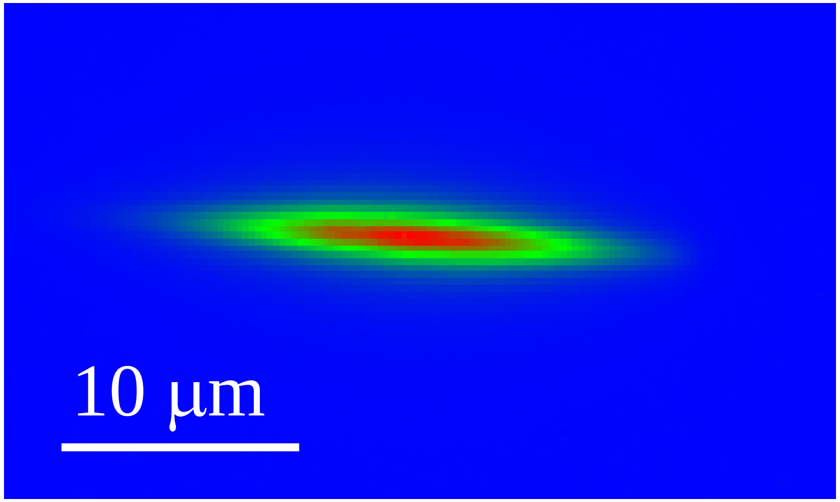


Focusing with Al parabolic CRL

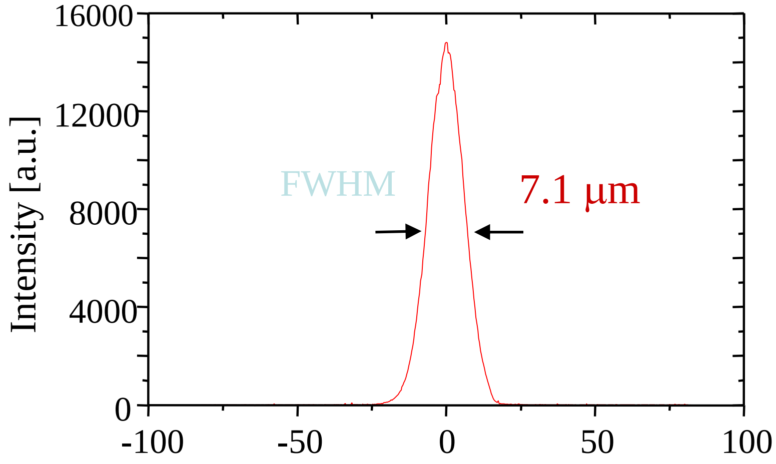
E = 15 keV

N = 83 lenses
F = 0.514 m

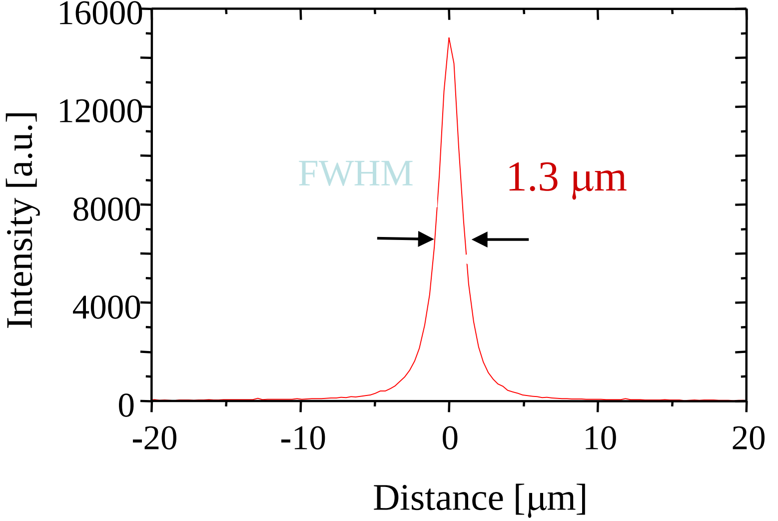
Gain = 50



Horozontal focusing



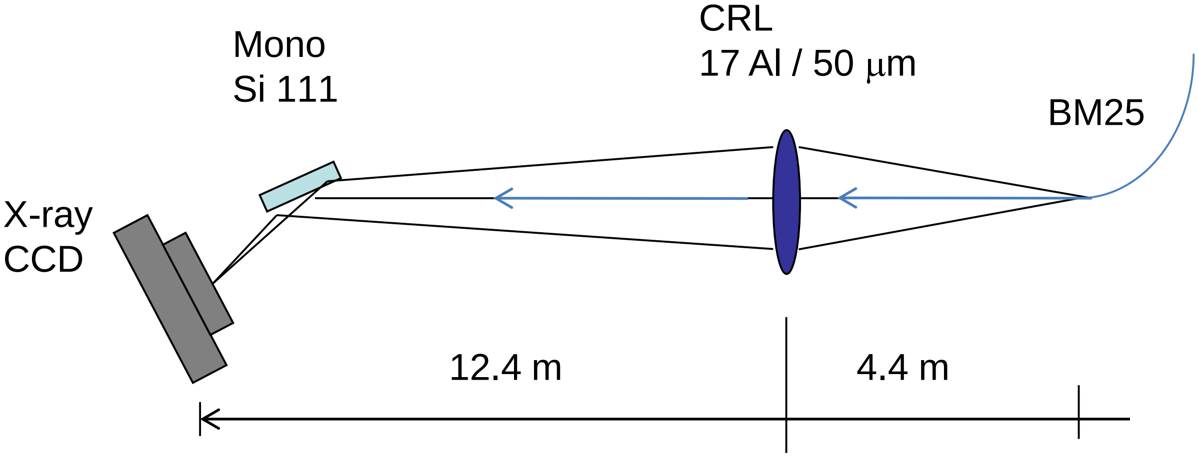
Vertical focusing

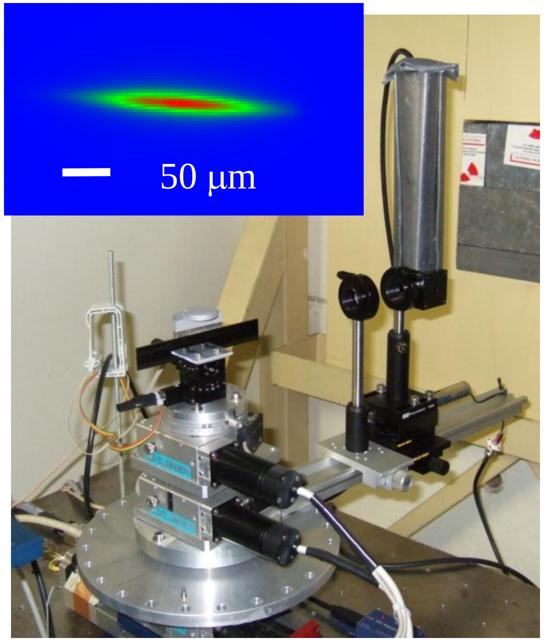


CRL based emittance diagnostics

DIPAC 2011, Hamburg, Germany

25 pm – 20 µm (FWHM)
5 pm - 10 µm
1-2 pm – 5 µm -diffraction limited source!





first test 25 Jan, 2011

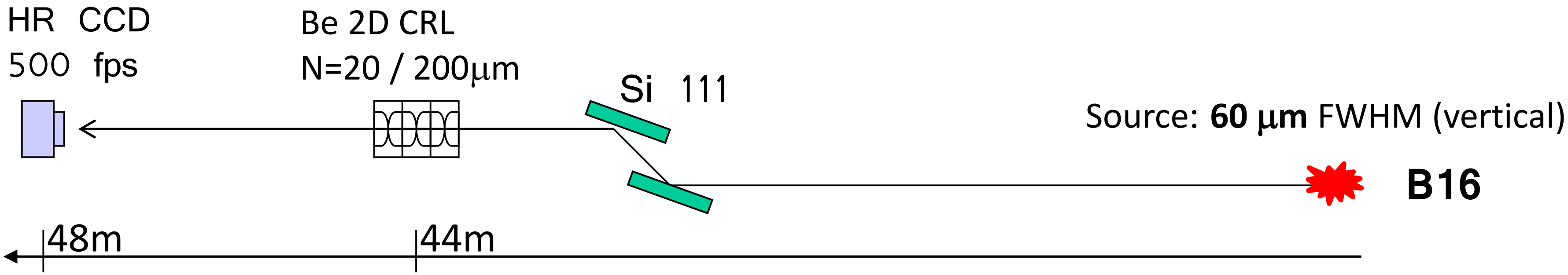
3.5 pm – 15 µm (FWHM)

(25 pm - 75 µm)

F. Ewald, J. Chavanne, K. Scheidt, L. Farvacque, P. Elleaume

Top-up - beam/source stability test at Diamond

8 March 2012



HR CCD
500 fps

Be 2D CRL
N=20 / 200µm

Si 111

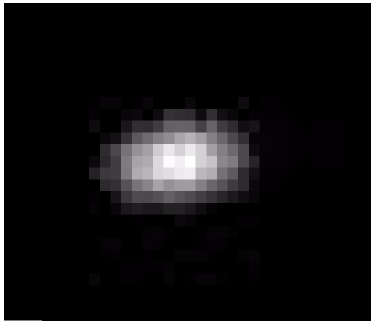
Source: **60 µm** FWHM (vertical)

B16

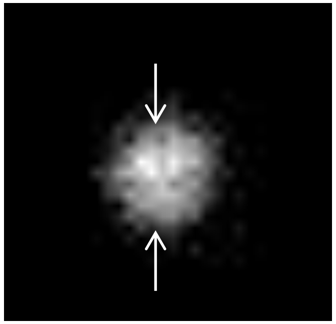
48m

44m

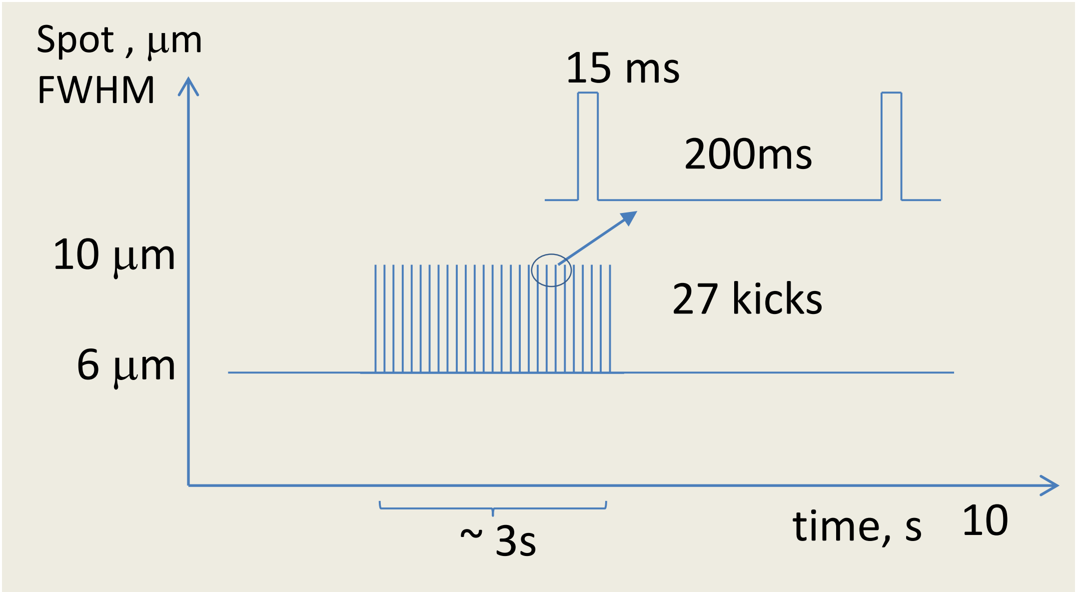
exposure 0.5 ms



FWHM = 5.8 µm



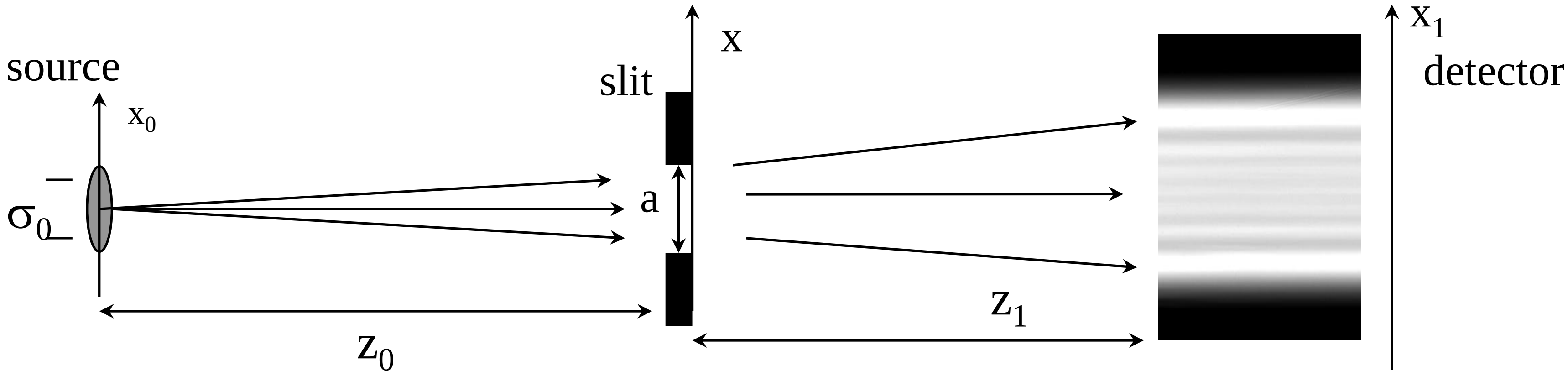
FWHM = 9.9 µm



Phantom CCD *Vision Research*
800 * 600 pixels / 500 fps (6600)
22 µm pixel size CCD
objective x20
1.1 µm optical pixel size

A Snigirev
Collab. Optics Group @ Diamond
I. Dolbnya and K. Sawhney

Coherence Characterisation by Fresnel Diffraction / Slits



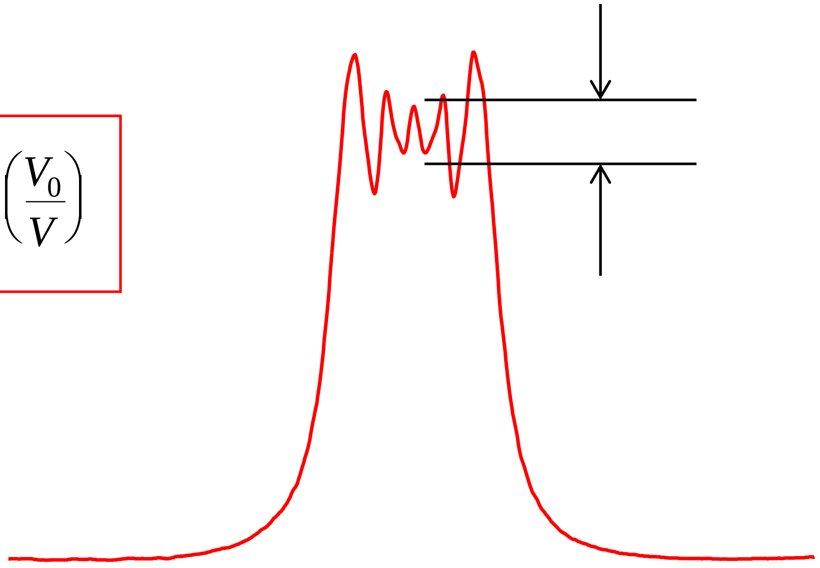
$$I(x_1) = 1 + \frac{4}{\pi}\left(\frac{4\lambda z_0 z_1}{z a^2}\right)^{1/2} \cos\left(\frac{\pi z a^2}{4\pi z_0 z_1} - \frac{3\pi}{4}\right) \exp\left(-\frac{a^2}{4\sigma_{mc}^2}\right) \cos\left(\frac{\pi a}{\lambda z_1} x_1\right)$$

$$V(x_1) = \frac{I(x_1)_{\max} - I(x_1)_{\min}}{I(x_1)_{\max} + I(x_1)_{\min}}$$

$$V = V_0 \exp\left(-\frac{a^2}{4\sigma_{mc}^2}\right), \quad \sigma_{mc} = \frac{2\lambda z_0}{\pi\sigma_0} \quad \Rightarrow \quad \boxed{\sigma_0 = \frac{4\lambda z_0}{\pi a} \ln^{1/2}\left(\frac{V_0}{V}\right)}$$

$$V_0 = \frac{4}{\pi}\left(\frac{4\lambda z_0 z_1}{z a^2}\right)^{1/2} \left|\cos\left(\frac{\pi z a^2}{4\pi z_0 z_1} - \frac{3\pi}{4}\right)\right|$$

$$a \geq 3\left(\frac{2\lambda z_0 z_1}{z}\right)^{1/2}, \quad x_1 = \frac{a z}{10 z_0}$$



V. Kohn, I. Snigireva, A. Snigirev. Phys. Rev. Let.85, 13, 2745-2748 (2000)

Fresnel Diffraction at a Slit for a Point Source:

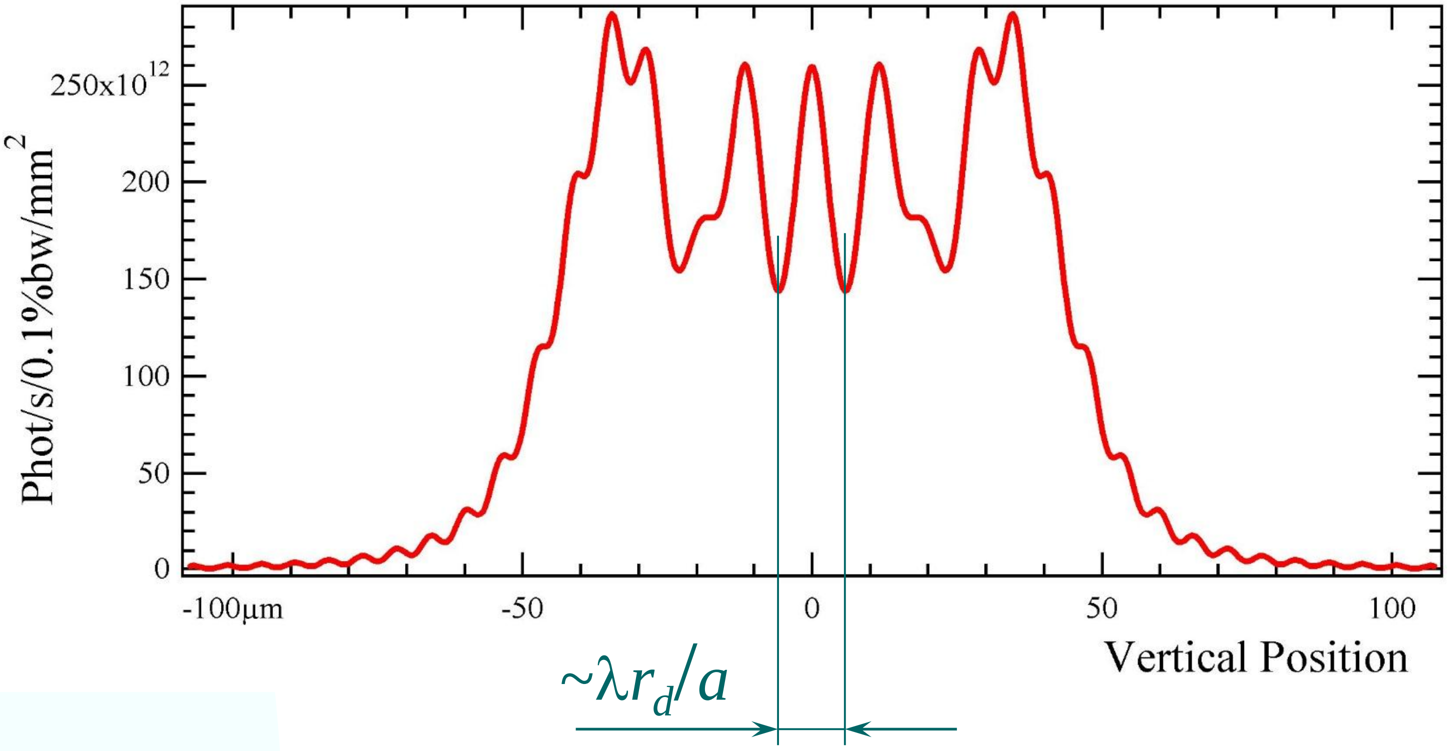
"Large" and "Small" Fringes

Photon Energy: **11 keV**

Distance from Source to Slit: r_s **= 37 m**

Distance from Slit to Detector: r_d **= 5.5 m**

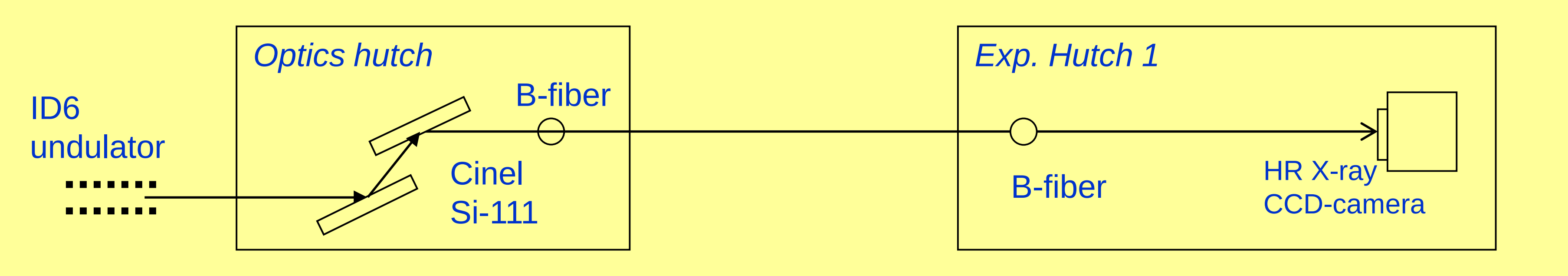
Slit Size: a **= 100 μm**



$\sim\lambda r_d/a$

"Propagated" e-beam size: $\sim\Delta y r_d/r_s$

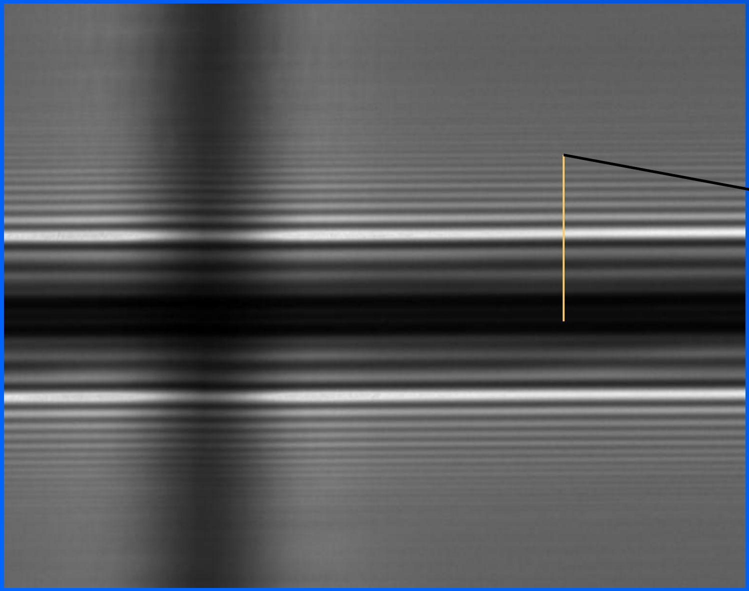
Spatial Coherence/Source Characterisation

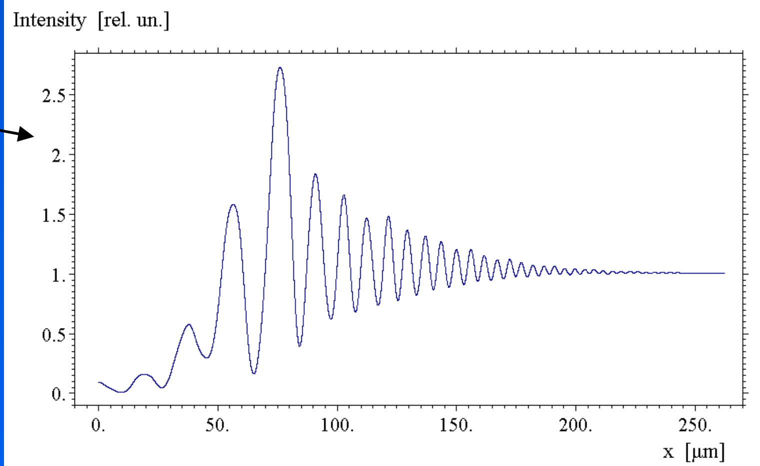


More than 15 fringes are visible !

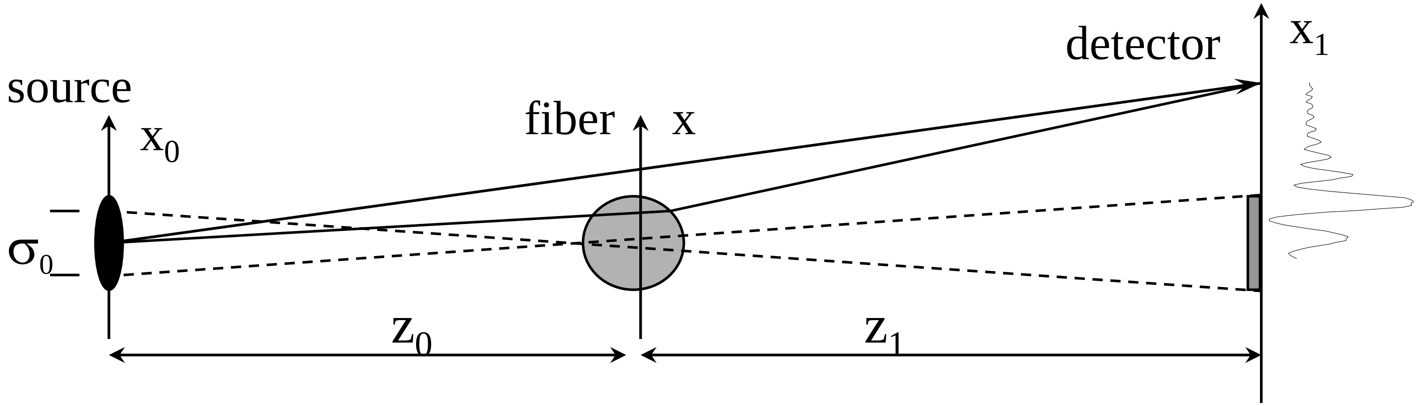
Source size (vert.) = 35 μm (FWHM)

t exp < 20 mc 24-28 μm !
vert. emittance 26 - 44 pm
MDT test : emittance vs source size





Coherence Characterisation by Holography / Boron fiber



$$I(x_1) = 1 + A(x_1) + 2A(x_1)F(x_1)$$

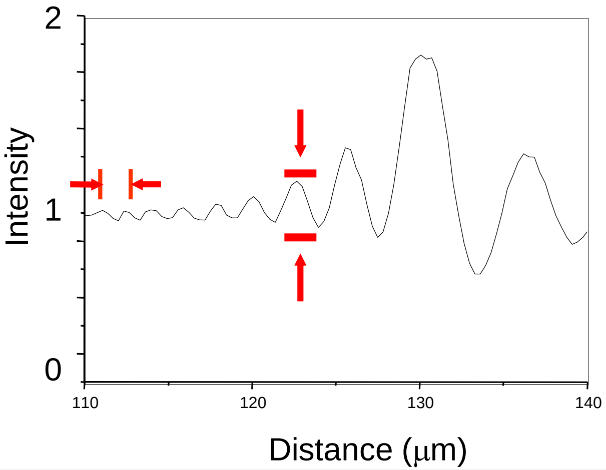
$$A(x_1) = \frac{f_1/2(x_1)}{(1+f(x_1))^{1/2}}, \quad f(x_1) = \frac{\alpha^2 R}{(x_1-R)^3}, \quad \alpha = 2\delta z_1$$

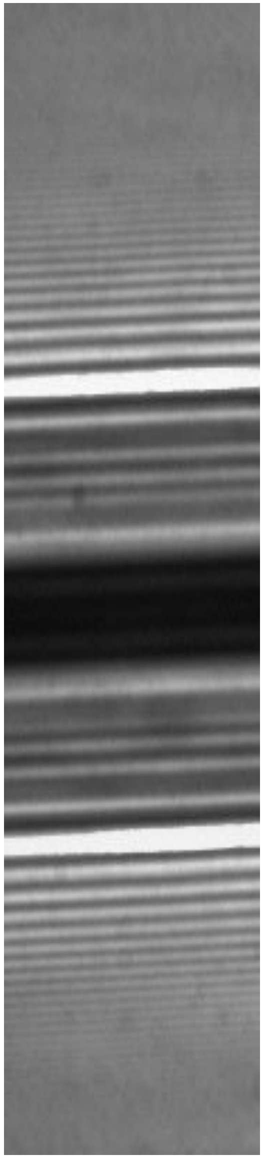
$$F(x_1) = \cos\left(\pi\frac{(1-\beta^2)}{\lambda z1}(x_1-R)^2\right)\exp\left(-\frac{(x_1-R)^2}{\sigma_{mc}^2}\right),$$

$$\sigma_{mc} = \frac{2\lambda z_0}{\pi\sigma_0}$$

$$V(x_1) = \frac{I(x_1)_{max} - I(x_1)_{min}}{I(x_1)_{max} + I(x_1)_{min}}$$

$$\sigma_0 = \frac{z_0}{z_1}\frac{\lambda z_1}{(x_1-R)}C(x_1), \quad C(x_1) = \frac{2}{\pi}\ln^{1/2}\left(\frac{V_0(x_1)}{V(x_1)}\right)$$



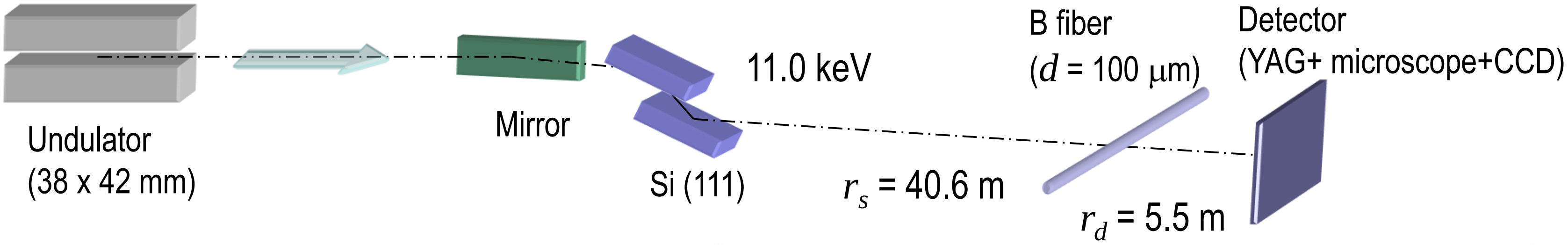


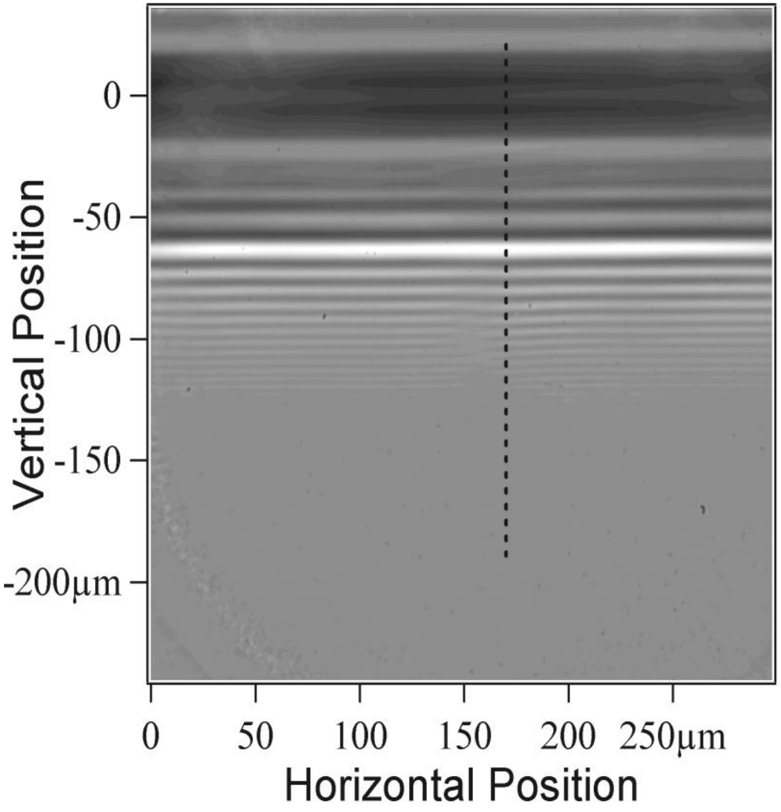
50µm

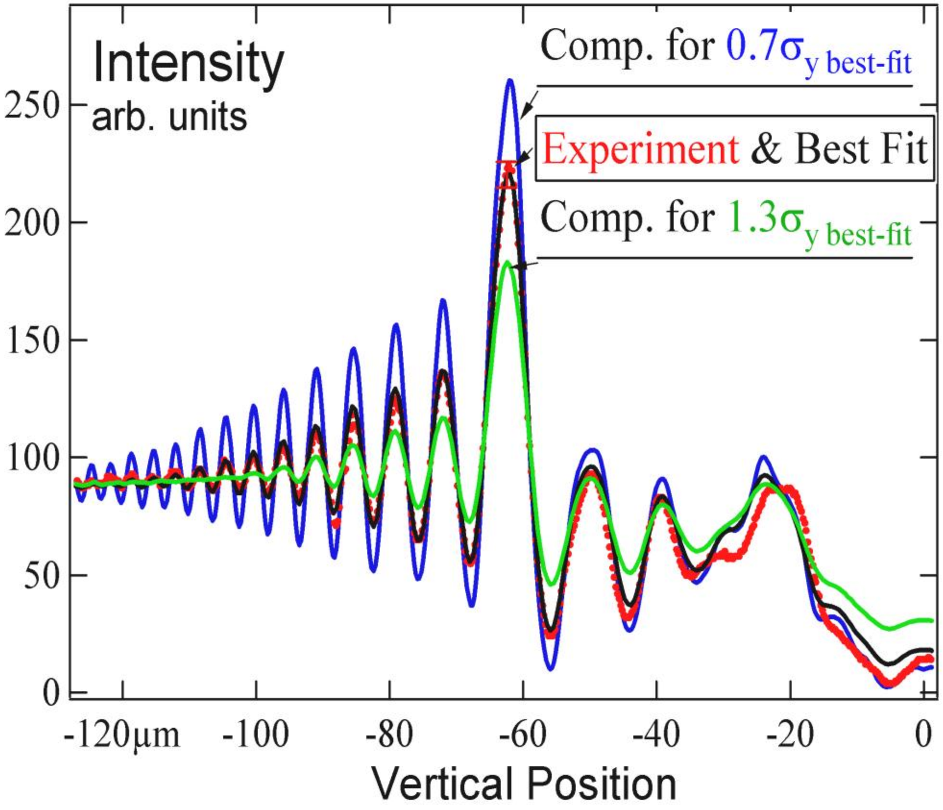
V. Kohn, I. Snigireva, A. Snigirev. Phys. Rev. Let. ***85****, 13, 2745 (2000)*

Measurements & Data Processing:
Interference from a Fiber

O. Chubar, A. Snigirev, T. Weitkamp, V. Kohn. DIPAC-2001



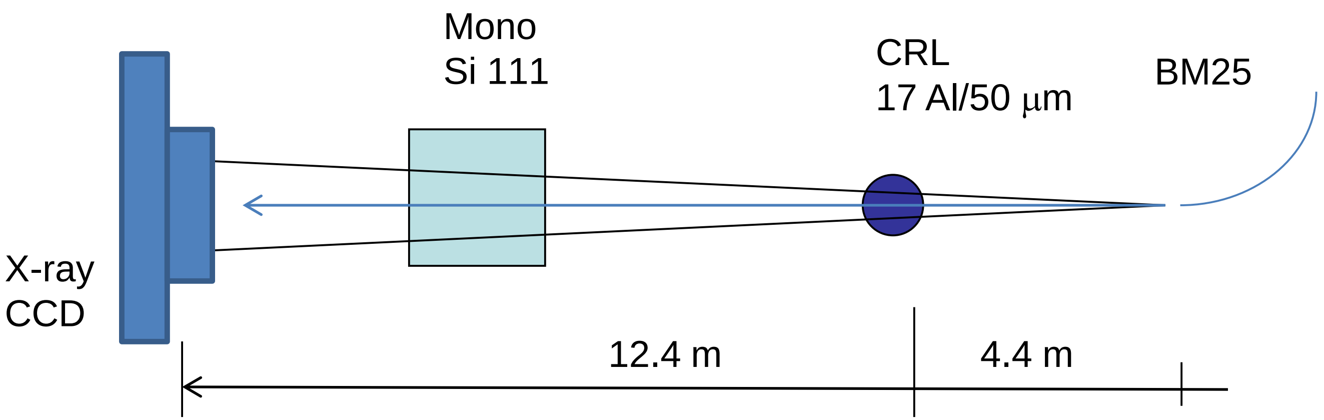


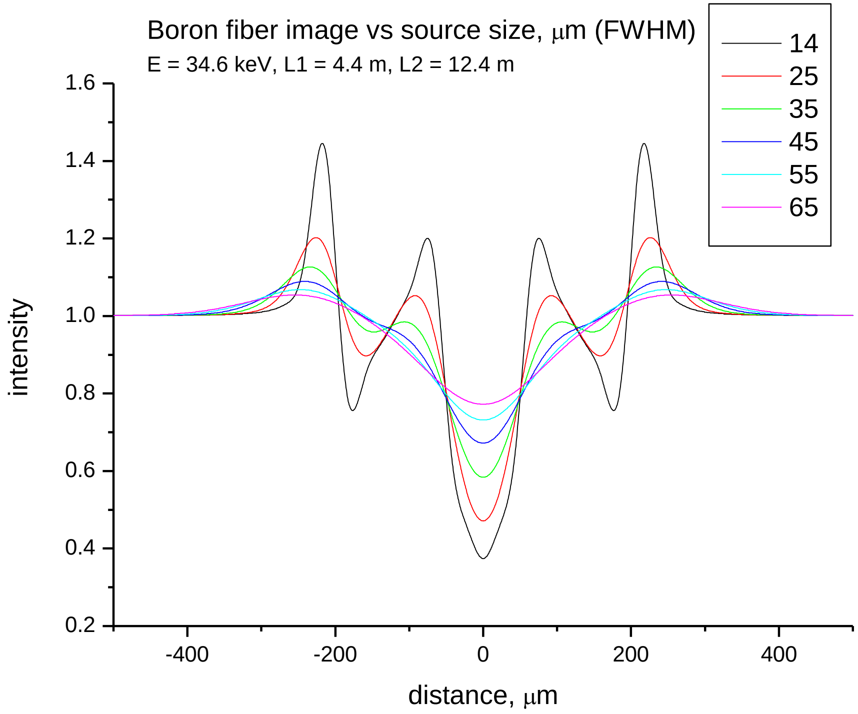


$$\sigma_{y\ best\text{-}fit} = 24 \pm 5\ \mu m \quad (\varepsilon_{y\ best\text{-}fit} = 0.23 \pm 0.1\ nm)$$

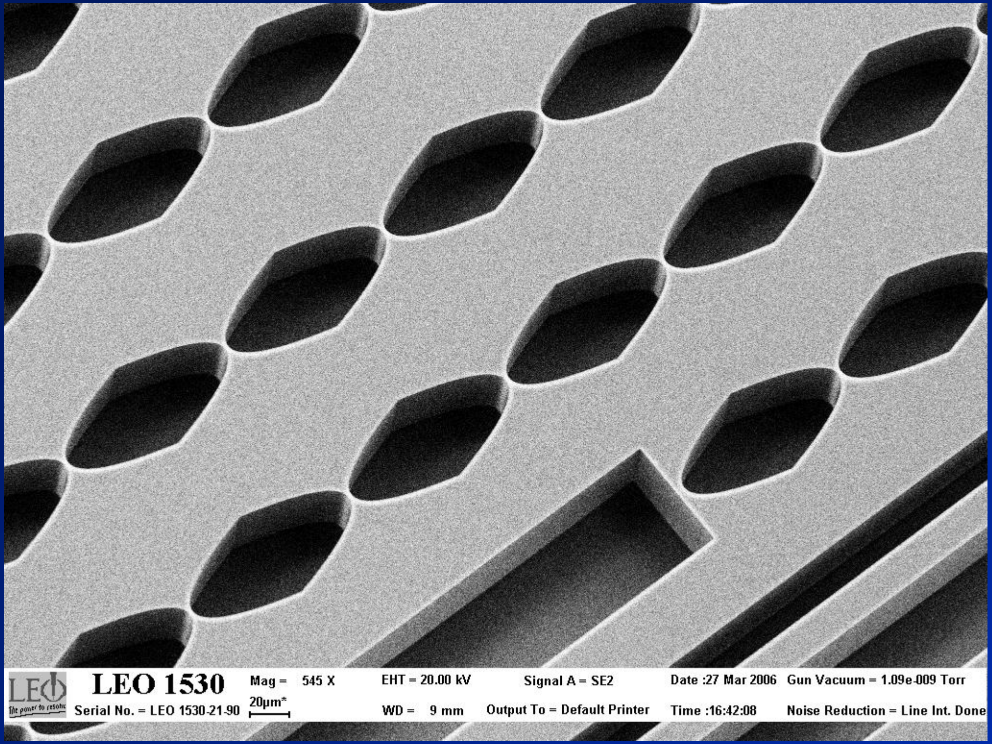
ESRF ID22, Apr. 2001

B-fiber based emittance diagnostics

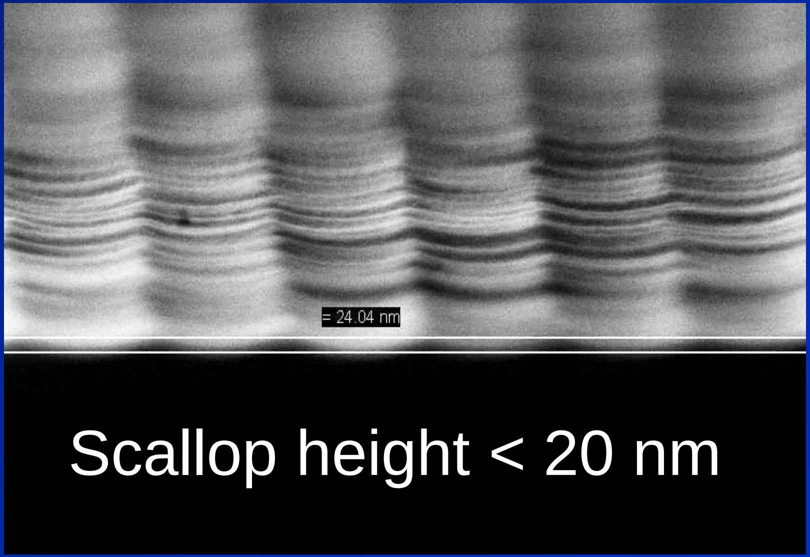


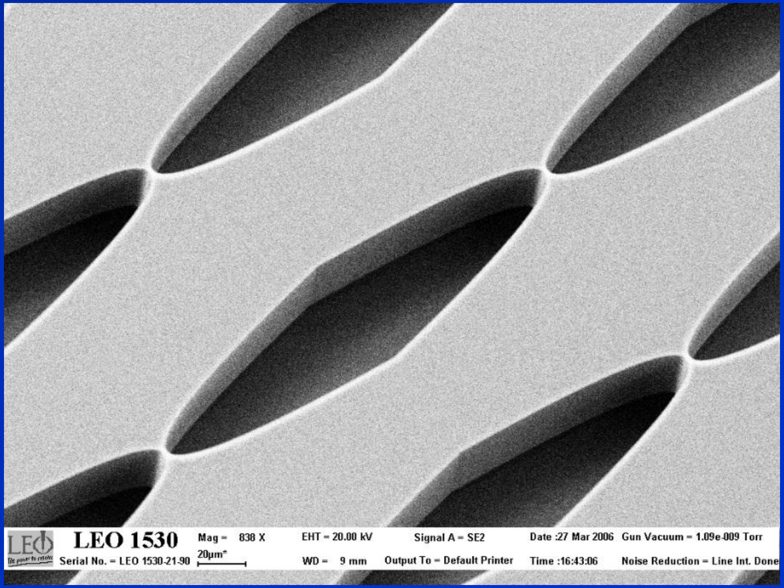


Si nanolenses




2 µm web size


Scallop height < 20 nm



X-ray bilens

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

X-Ray Nanointerferometer Based on Si Refractive Bilenses

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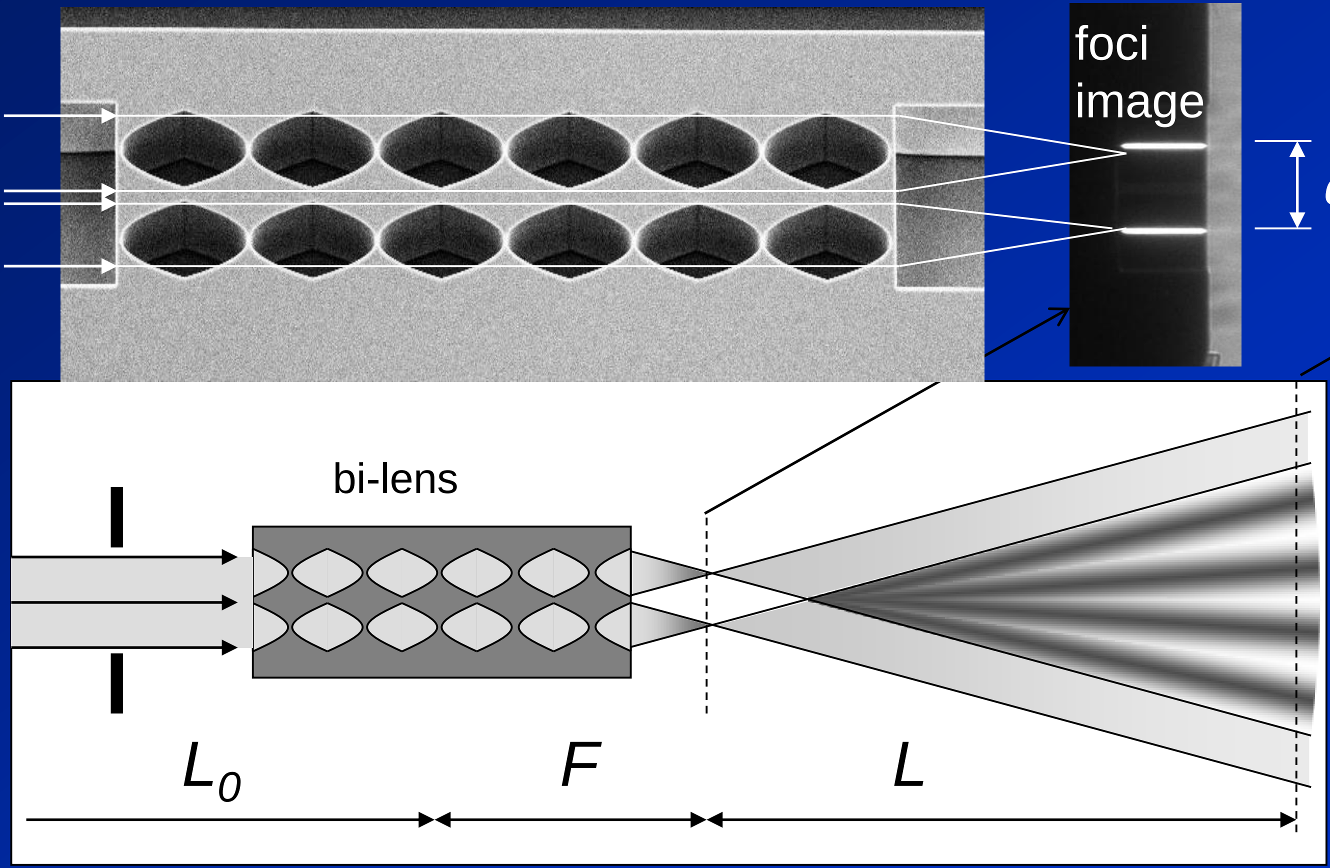
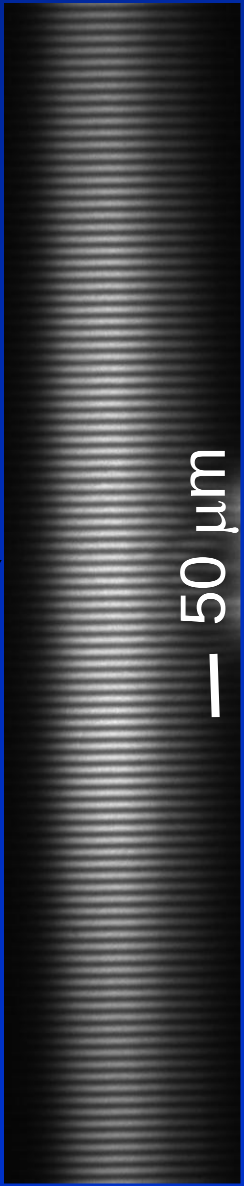
(Received 28 April 2009; published 3 August 2009)



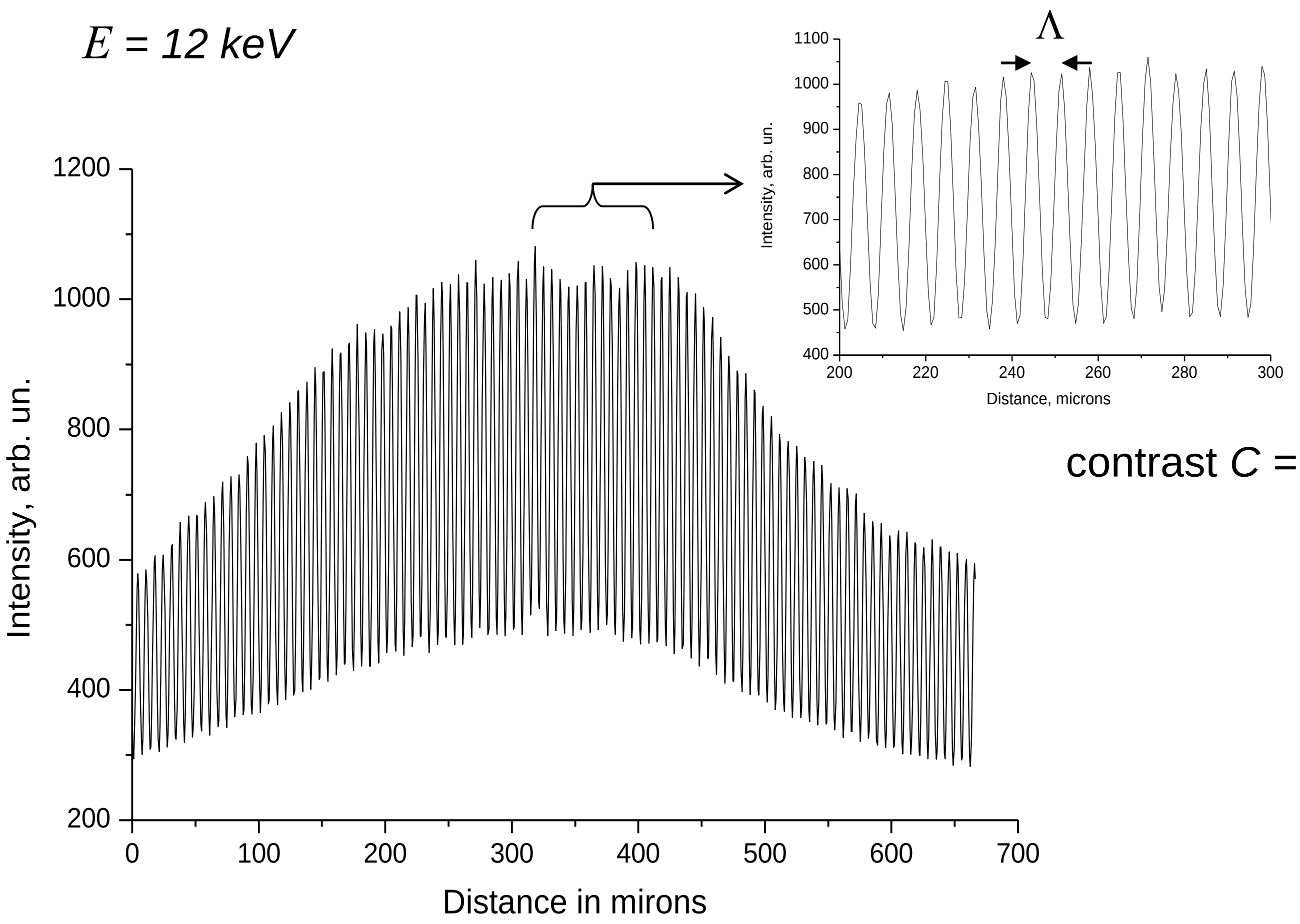
$\Lambda = \lambda L / d$



far-field
interference

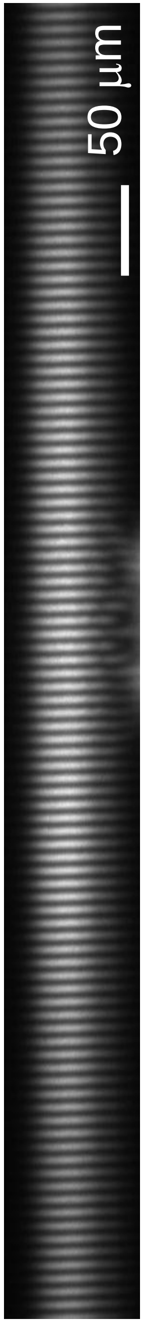
X-ray bi-lens interferometer

E = 12 keV



contrast *C = 40%*

far-field
interference



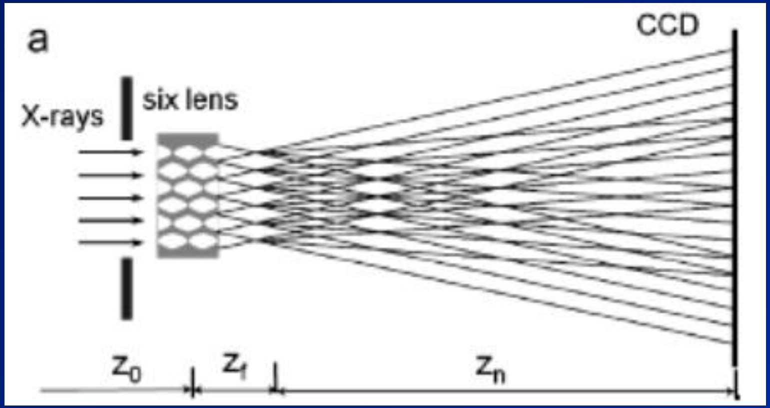
source size: $$S = \frac{\Lambda L_0}{L_1}\left(-\frac{\log C}{3.56}\right)^{1/2}$$

S = 28 *μm (FWHM)*

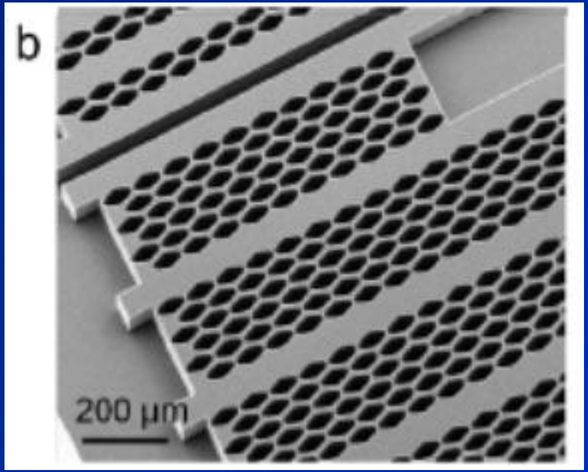
X-ray multilens interferometer based on Si refractive lenses

A. Snigirev,[1*] I. Snigireva,[1] M. Lyubomirskiy,[1] V. Kohn,[2] V. Yunkin,[3] and S. Kuznetsov[3]

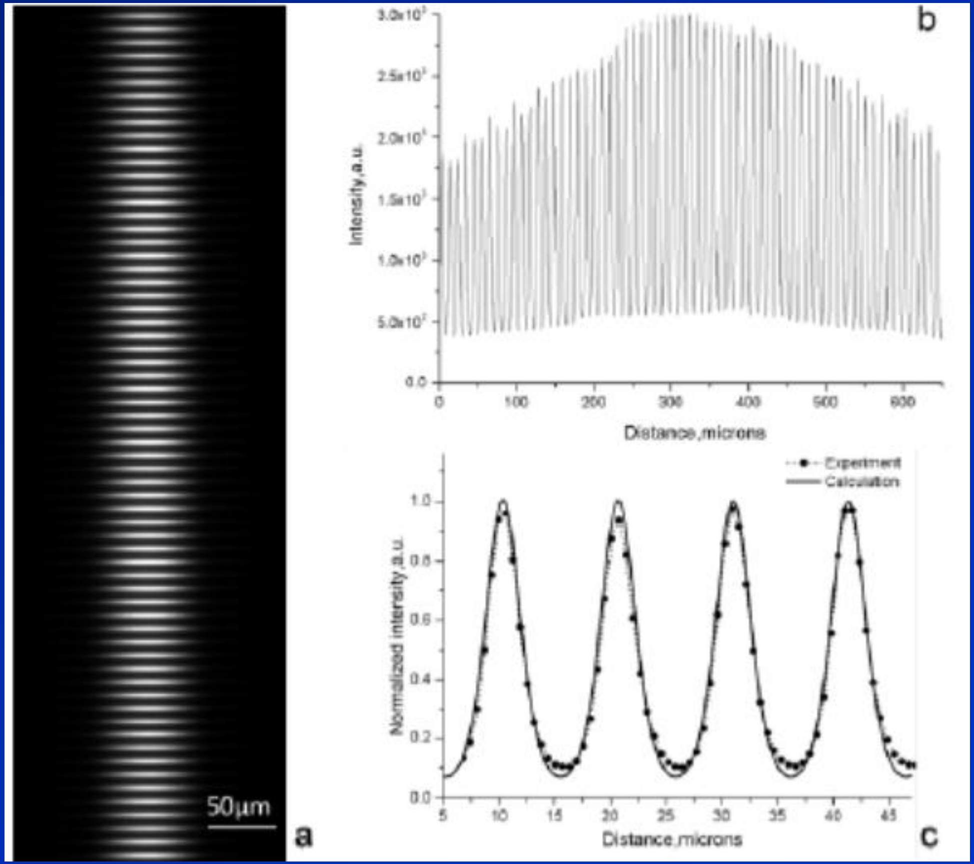
#216861 - $15.00 USD Received 11 Jul 2014; revised 9 Sep 2014; accepted 10 Sep 2014; published 14 Oct 2014
(C) 2014 OSA 20 October 2014 | Vol. 22, No. 21 | DOI:10.1364/OE.22.025842 | OPTICS EXPRESS 25842



(a) Schematic view of six lens interferometer.

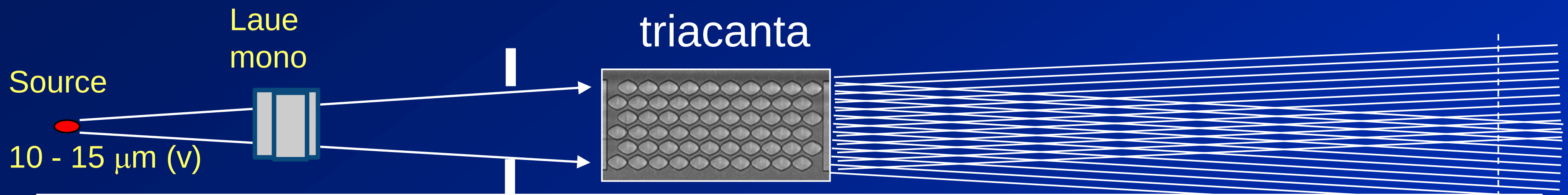


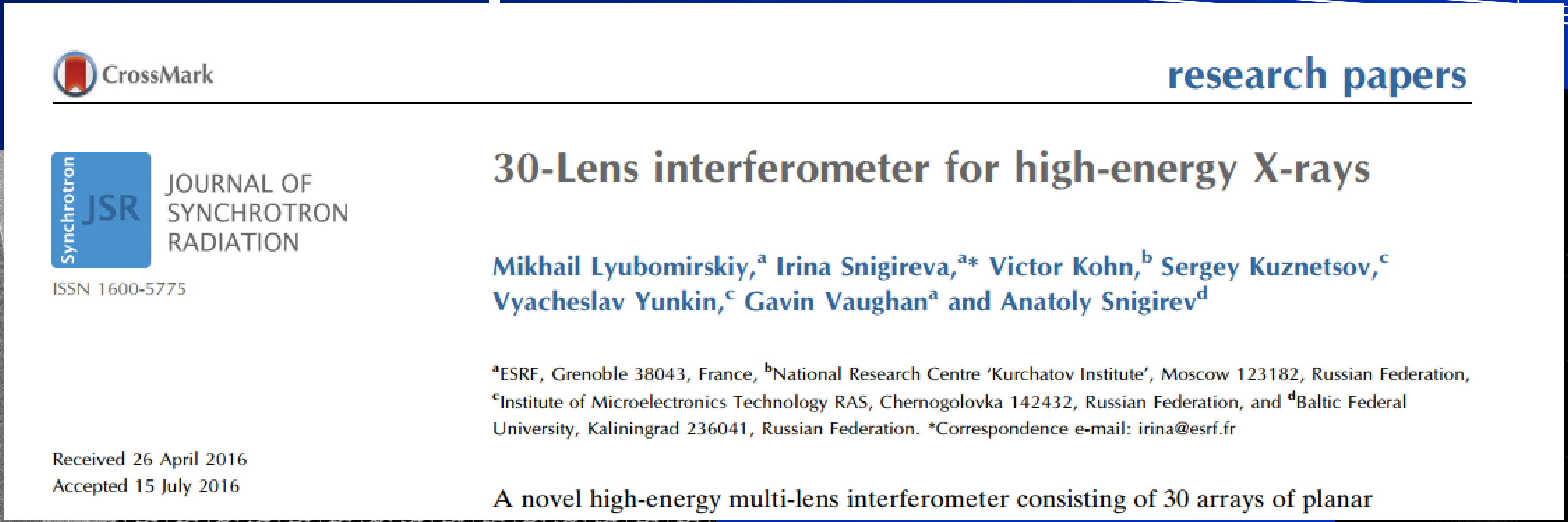
(b) SEM image of six lens interferometer.



(a) Interference pattern recorded at 12 keV
(b) Intensity variations with 72% contrast
(c) Comparison measured and calculated intensity variations.

Coherence diagnoctics *@ 30 - 65 keV!*

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research papers

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30-Lens interferometer for high-energy X-rays

Mikhail Lyubomirskiy,[a] Irina Snigireva,[a]* Victor Kohn,[b] Sergey Kuznetsov,[c] Vyacheslav Yunkin,[c] Gavin Vaughan[a] and Anatoly Snigirev[d]

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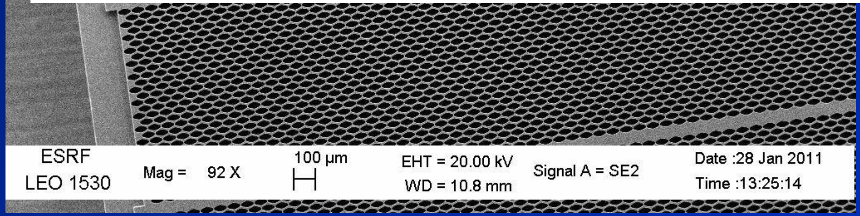
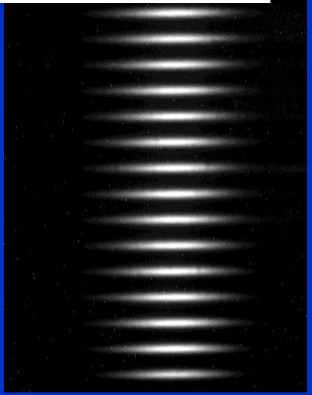
A novel high-energy multi-lens interferometer consisting of 30 arrays of planar

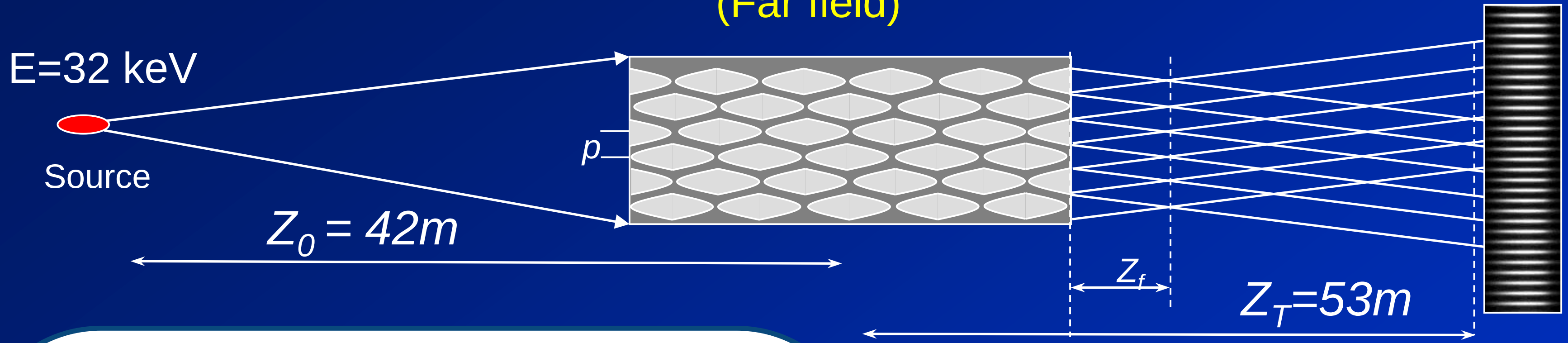


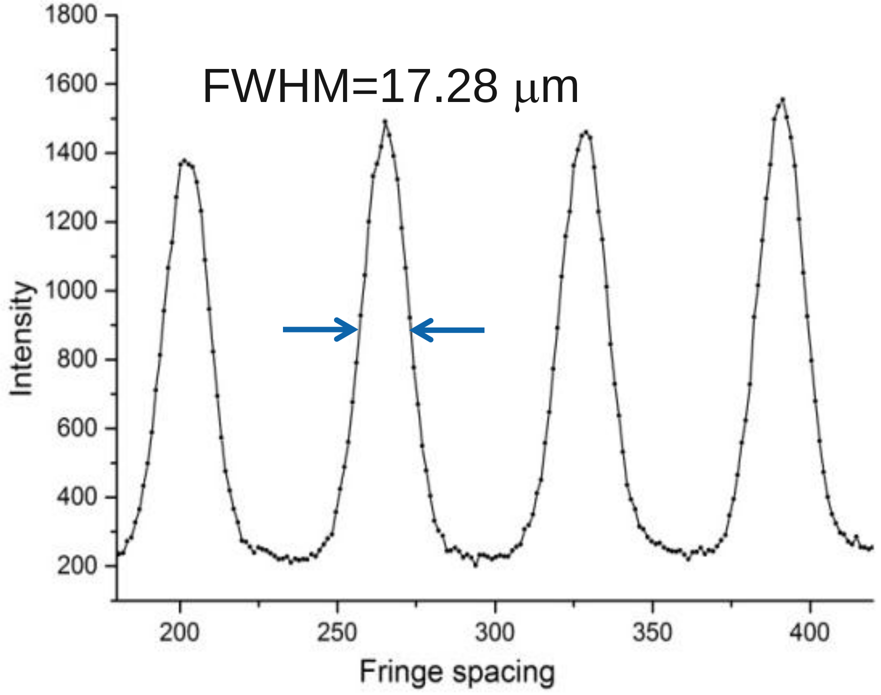
source size
14 μm (v) FWHM



Multilens Interferometer

Fundamental Talbot imaging
(Far field)





FWHM of single fringe = 17.28 µm

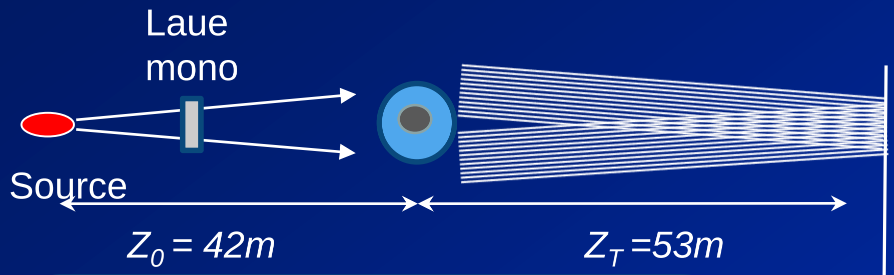
source to interferometer Z_0=42m
Imaging distance Z_T = 53m

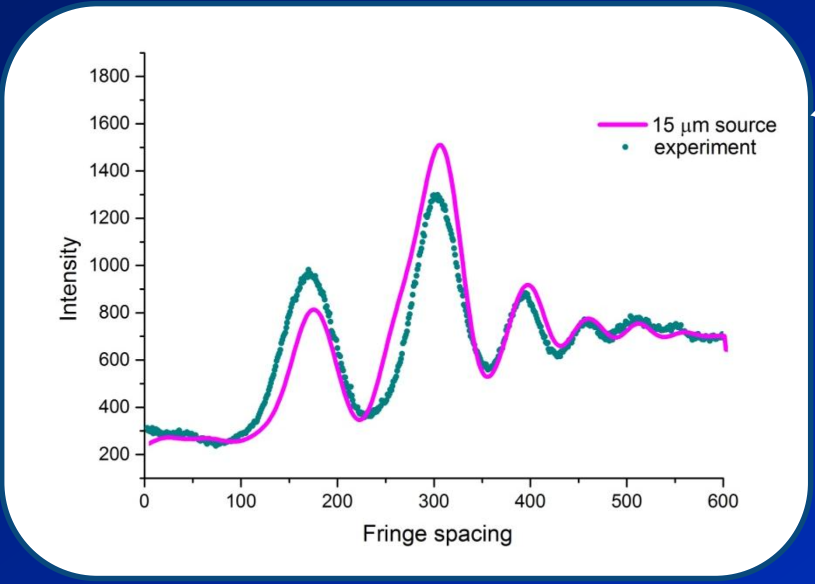
Source size =

*17.28 * 42/53 = 13.69* µm

ID11 source size test

B-Fiber interference (34keV)

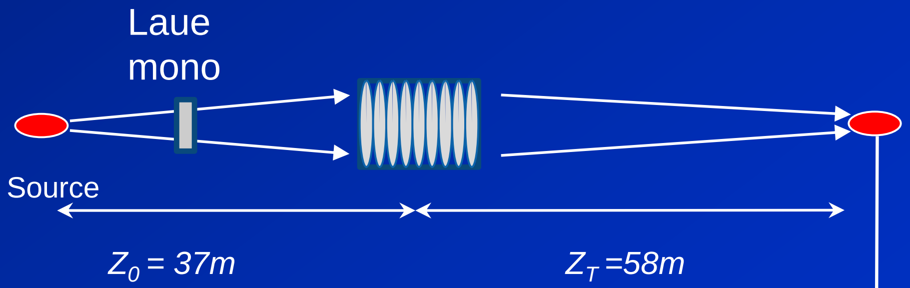


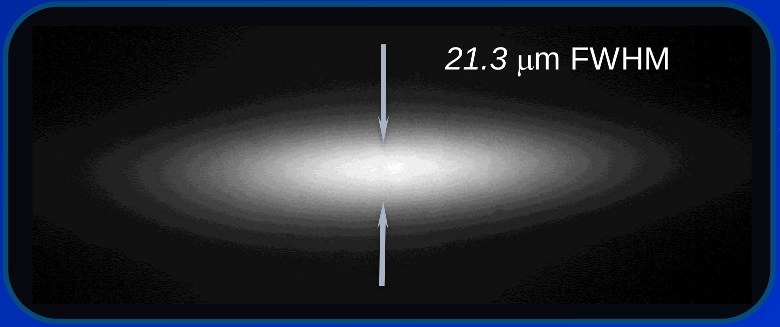


By resolving of an inverse problem of X-Ray beam diffraction was calculated source size=15 µm

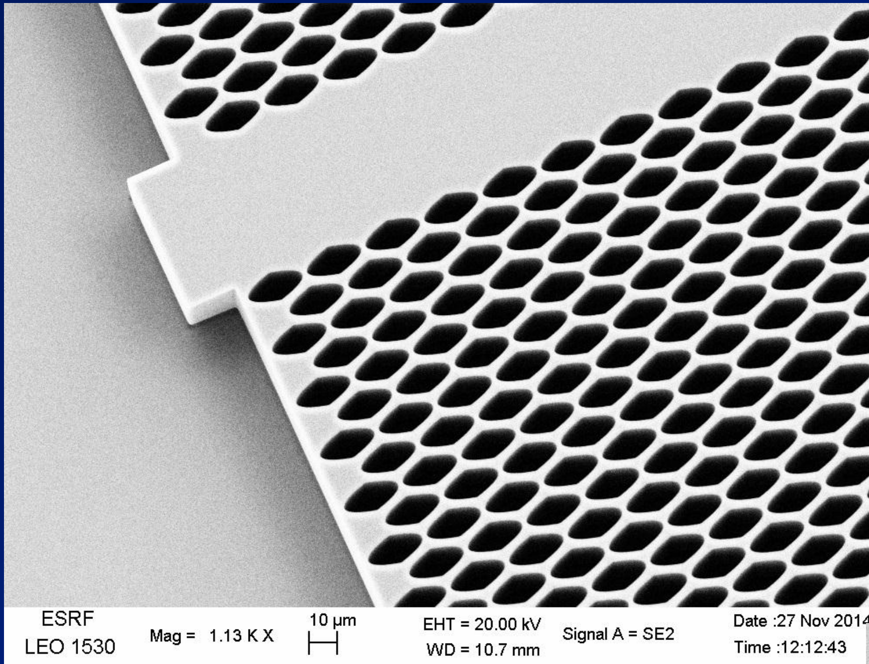
CRL imaging (34 keV)

By using common beamline transfocator TF-6 (16 Be lenses, 200 µm)



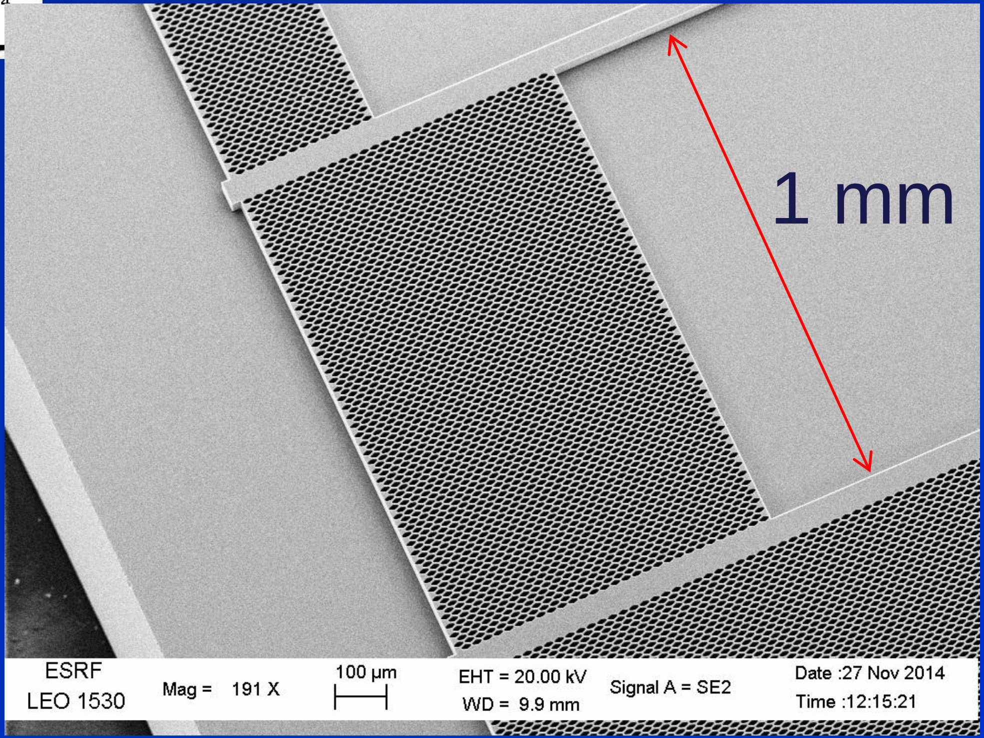


Measured focal spot FWHM=21.3 µm
Distance from source to CRL=37m
Imaging distance=58m
*Source size=21.3*37/58=13.57 µm*



100 lens array
“centum” or “hekaton”

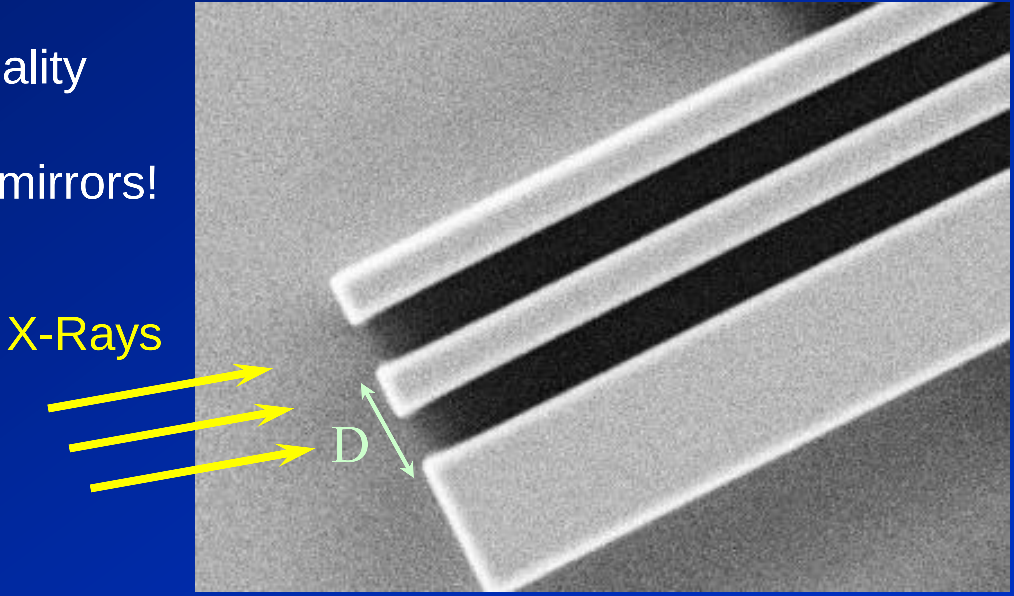
aperture – 1 mm
single lens aperture10 μm



Bimirror interferometer

Si MEMS technology - high surface quality

sidewalls of trenches can be used as mirrors!



Advantages

- Direct beam filtration (high harmonics)
- High contrast with low coherence conditions (close location of mirrors)
- Angular control of projection of mirrors = narrow slits in Young interferometer

May 15, 2015 / Vol. 40, No. 10 / OPTICS LETTERS 2205

Hard x-ray single crystal bi-mirror

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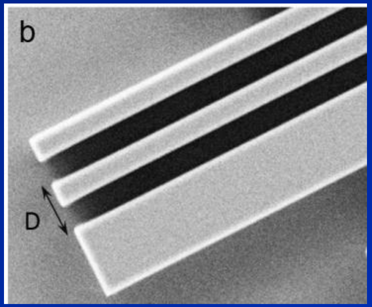
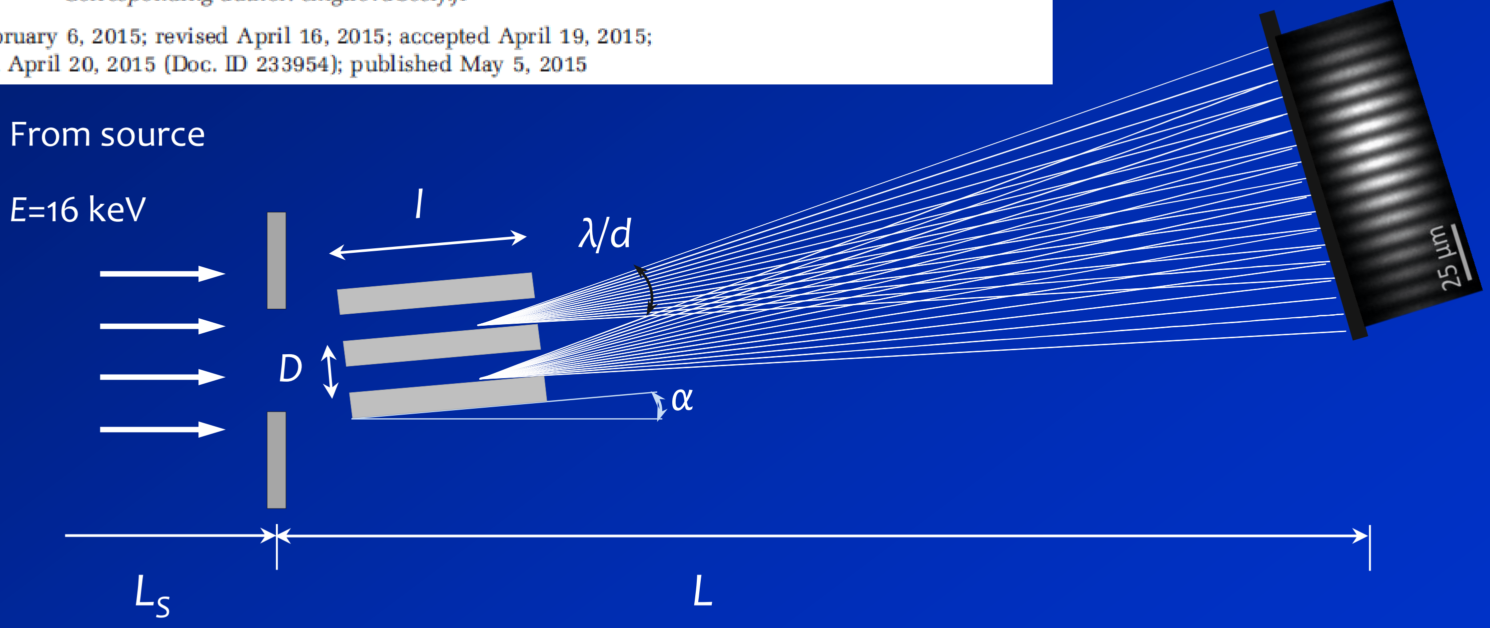


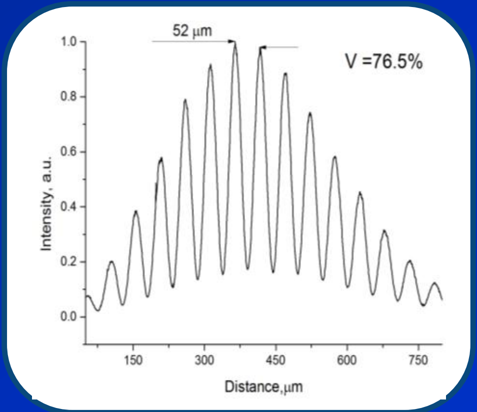
$d = l^{x}\sin\alpha$
$l = 20$ mm
$L = 15$ m
$L_S = 56$ m
$S = 40$ µm

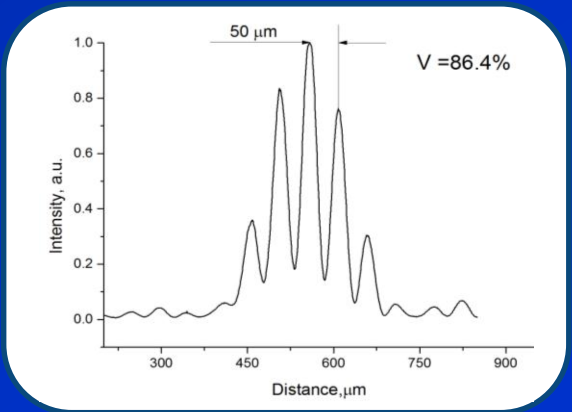


From source

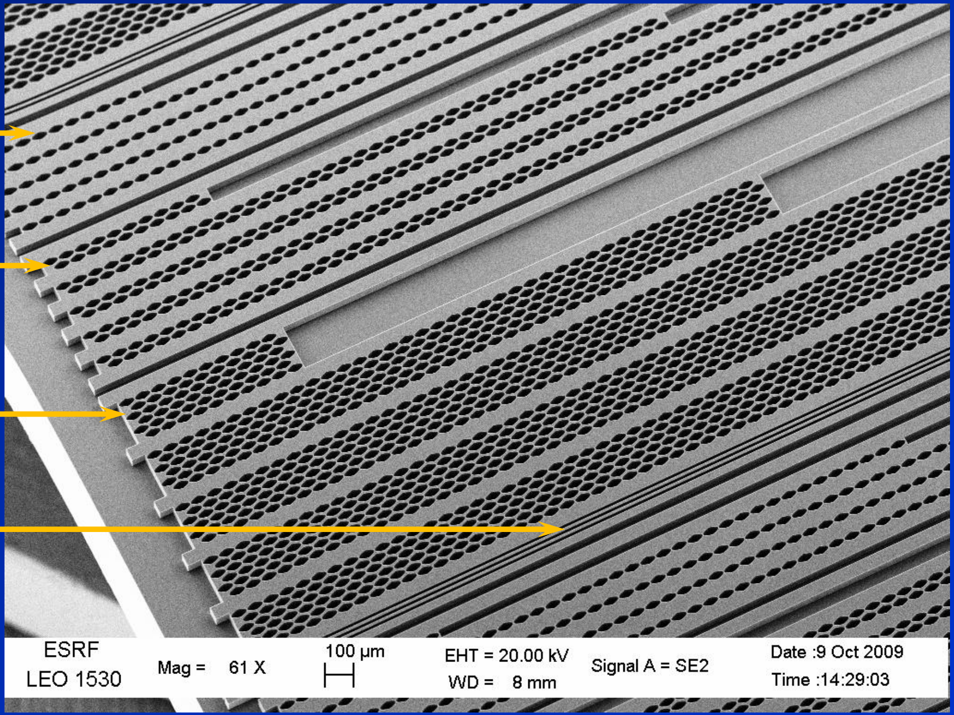
E=16 keV

bi-mirror equivalent to
ultra small,
highly absorbing
Young double-slits





Integrated X-ray Optics chip



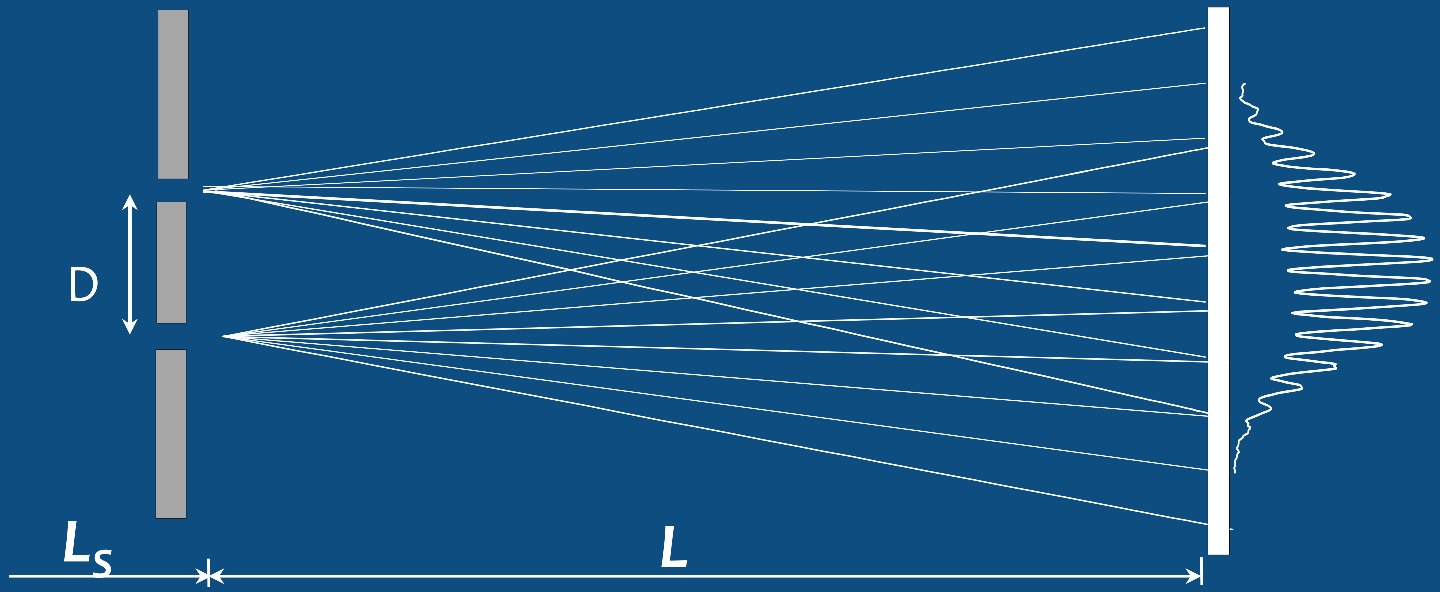
Planar lenses

Bilens interferometer

Multilens interferometer

Micro - mirror interferometer

Young's double slit experiments



Soft X-rays:

C. Chang, P. Naulleau, E. Anderson, and D. Attwood, Opt. Commun. 182, 25 (2000).
A. Singer, I. A. Vartanyants, M. Kuhlmann, et al, Phys. Rev. Lett. 101, 254801 (2008).

Hard X-rays:

D. Paterson, B. E. Allman, P. J. McMahon, et al, Opt. Commun. 195 , 79 (2001).
W. Leitenberger, H. Wendrock, L. Bischoff, et al, J. Synchrotron Radiat. 11, 190 (2004).
W. Leitenberger and U. Pietsch, J. Synchrotron Radiat. 14, 196 (2007).

XFEELs

I. Inoue, K. Tono, Y. Joti, T. Kameshima, et al, IUCrJ 2, 620 (2015).

Sensitivity of double slit interferometer

$$I(x) = I_0 \left[\frac{\sin(k_d x)}{k_d x} \right]^2 \left[1 + V \cos(k_D x) \right] + I_b$$

$$k_D = \frac{2\pi D}{\lambda L}, \qquad k_d = \frac{2\pi d}{\lambda L},$$

$$V = \frac{\sin(\pi s D / \lambda L_s)}{\pi s D / \lambda L_s}$$

D is the distance between slits
s is the source size
d is the slit size
L is the i pattern observation distance
L_S is the source-interferometer distance
I_b is a background intensity
x is the vertical coordinate at the detector

$$V = \frac{\left(I_{\max} - I_{\min}\right)}{\left(I_{\max} + I_{\min}\right)} * 100\%$$

I_{max} *and* I_{min} are irradiances corresponding to the maximum and adjacent minimum on the interference pattern

E = 12 keV

L_s = 50 m

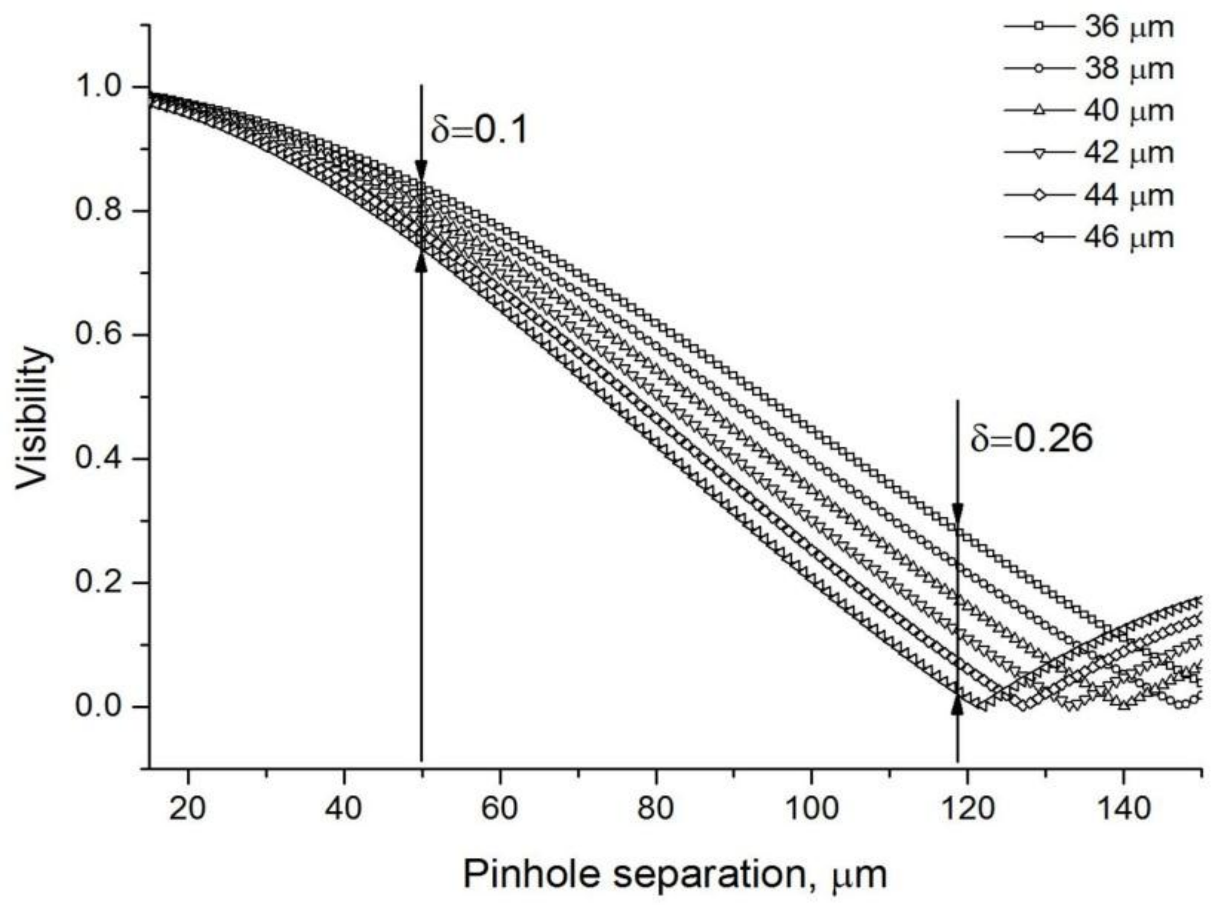
Slit separation, μm	100	400
Visibility for 10 μm source, %	93	24
Visibility for 12 μm source, %	90	4

3 % **20 %**

Spatial coherence length $l_{coh} = \lambda L_s / s$ ~ 500 microns

Far field observation distance $z >> D^2/\lambda$ ~ 2.5 km

Sensitivity of double slit interferometer



Fringe visibility vs separation at 50 m from the source at 12 keV

Spatial coherence length $l_{coh} = \lambda L_s / s$ ~ 125 microns

Far field observation distance $z \gg D^2/\lambda \sim 100$ m

Requirements for hard X-rays at SR sources

Separation distance between slits 10 – 500 μm

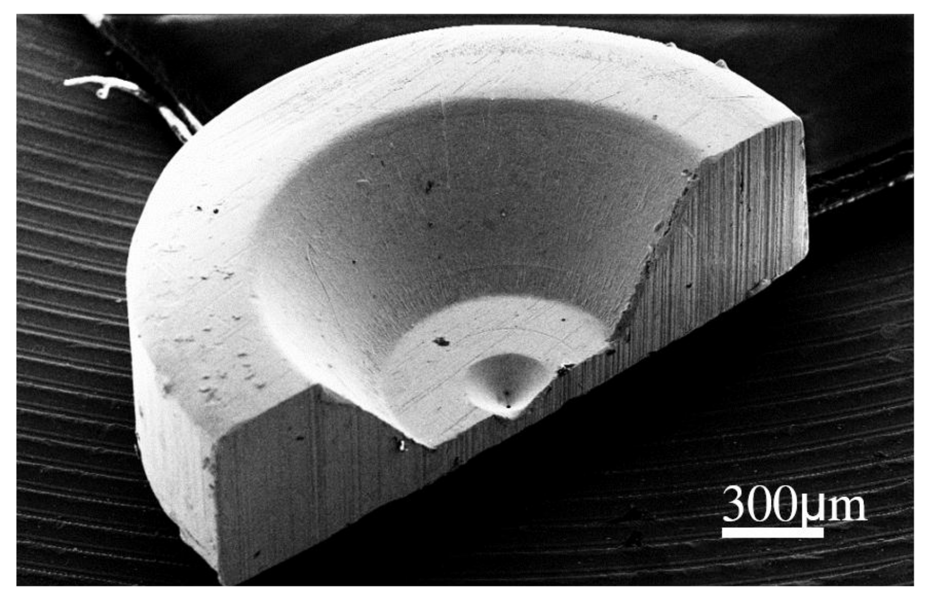
Tunable pinholes

Far field observation distance $z \gg D^2/\lambda$

D = 400 μm $z \sim$ 1600m
D = 100 μm z ~ 100m

Use of refractive lenses as Fourier transformers

Tunable double apertures manufacturing



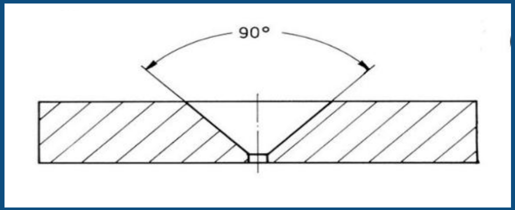
The discs were produced from a platinum

Apertures were made with *d* = 11 µm hole

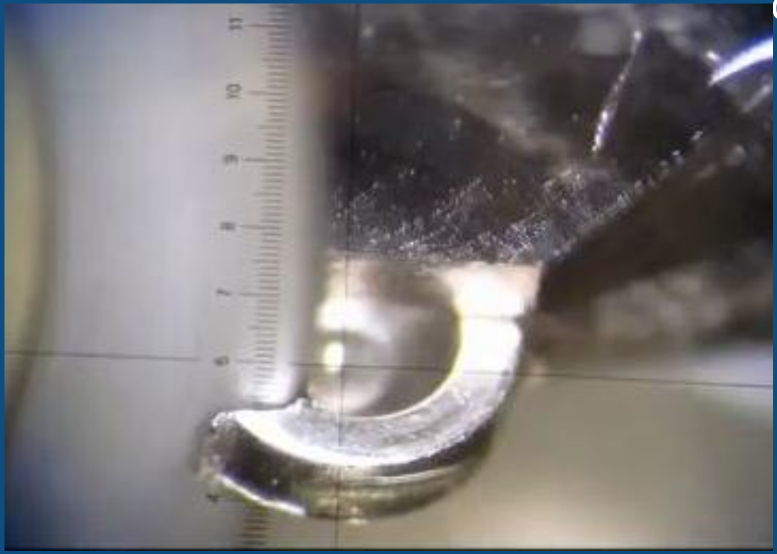
The diameter of the round substrate was 2 mm

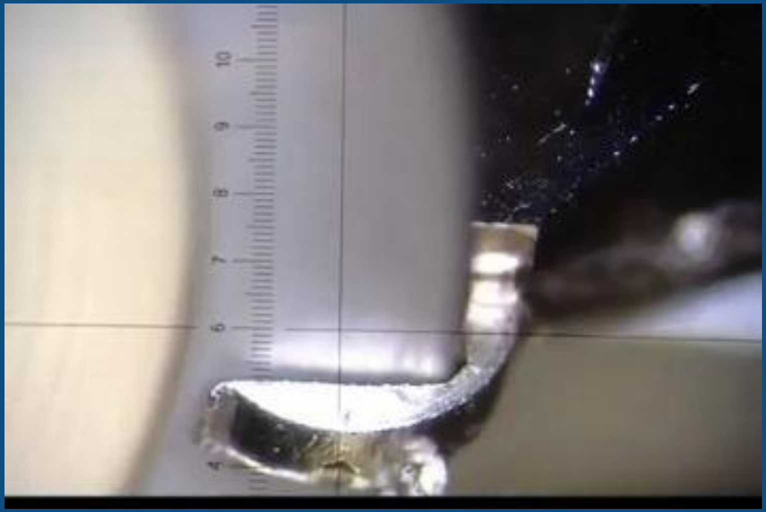
The min thickness of the aperture is above 25 µm

The attenuation of X-rays below 25 keV is >> 99%,

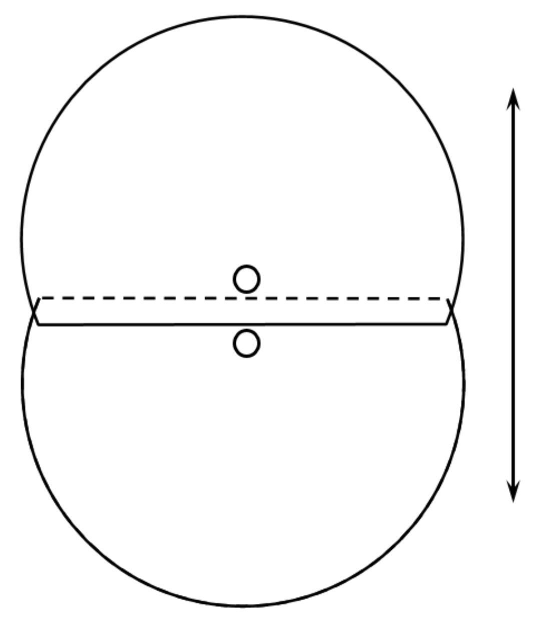


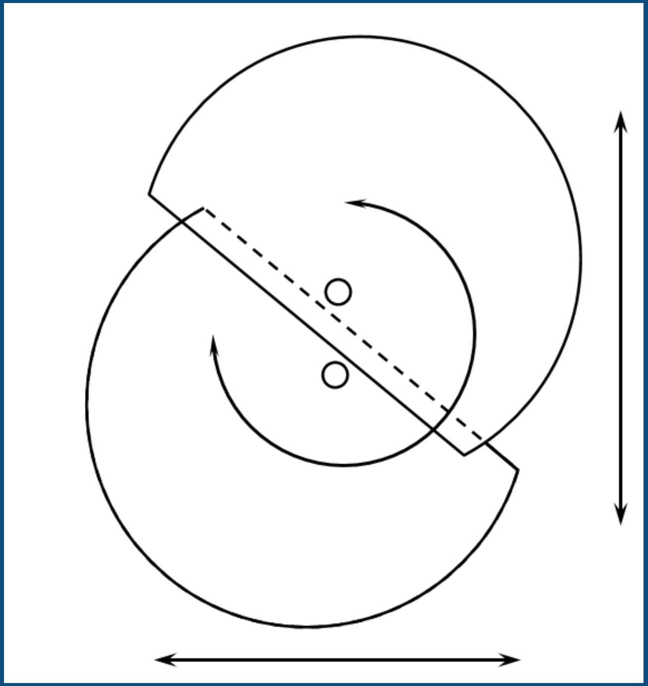
optical images during the cutting





Schematic view of apertures arrangement.

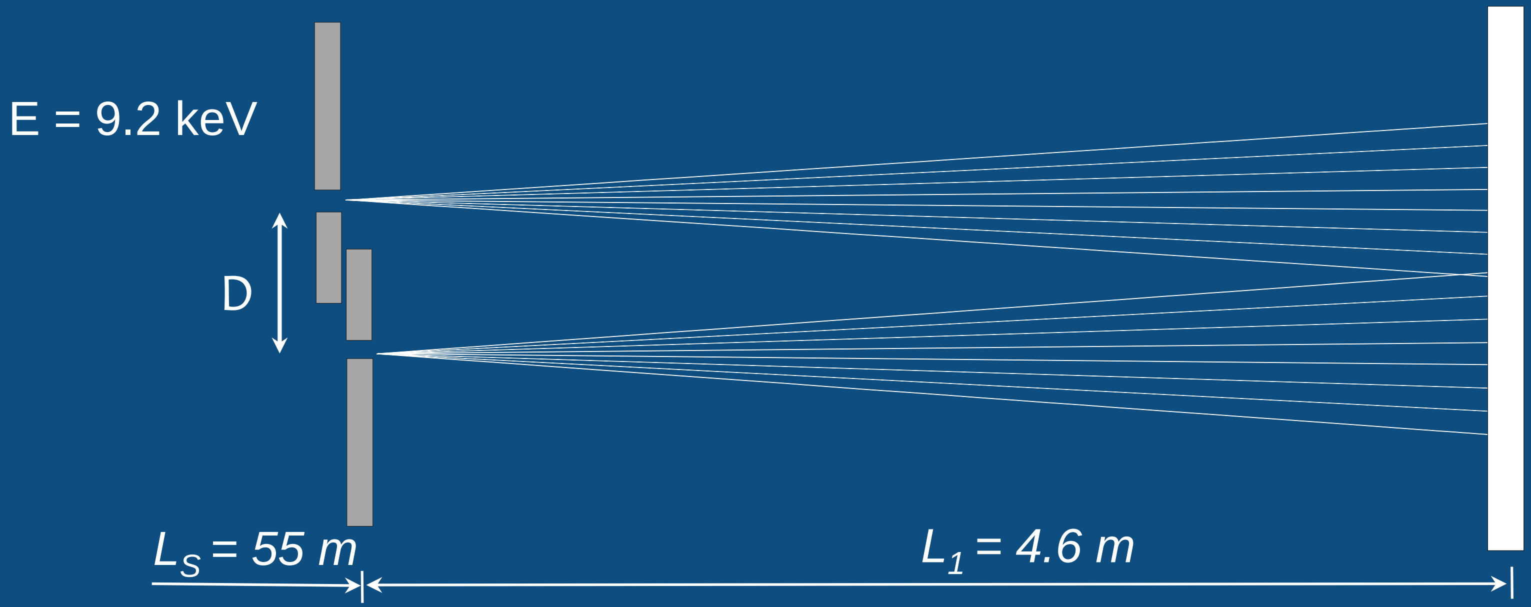




Translation stages
Min overlapping 10 μm
Max overlapping 80 – 90 μm
Split distance 90 – 160 μm

Translation & rotation stages
Min overlapping 10 μm
Max overlapping 80 – 90 μm
Split distance 90 – 400 μm

Tunable double apertures



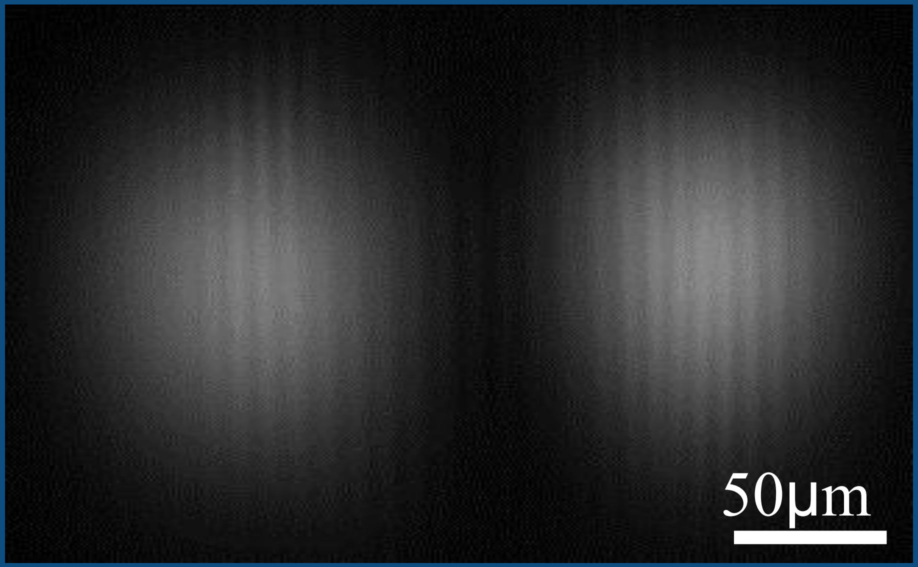
E = 9.2 keV

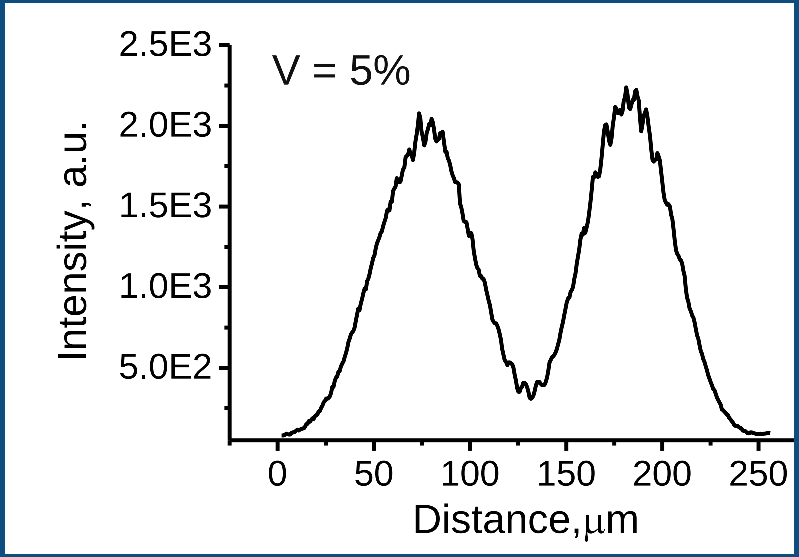
D

$L_S = 55\ m$

$L_1 = 4.6\ m$

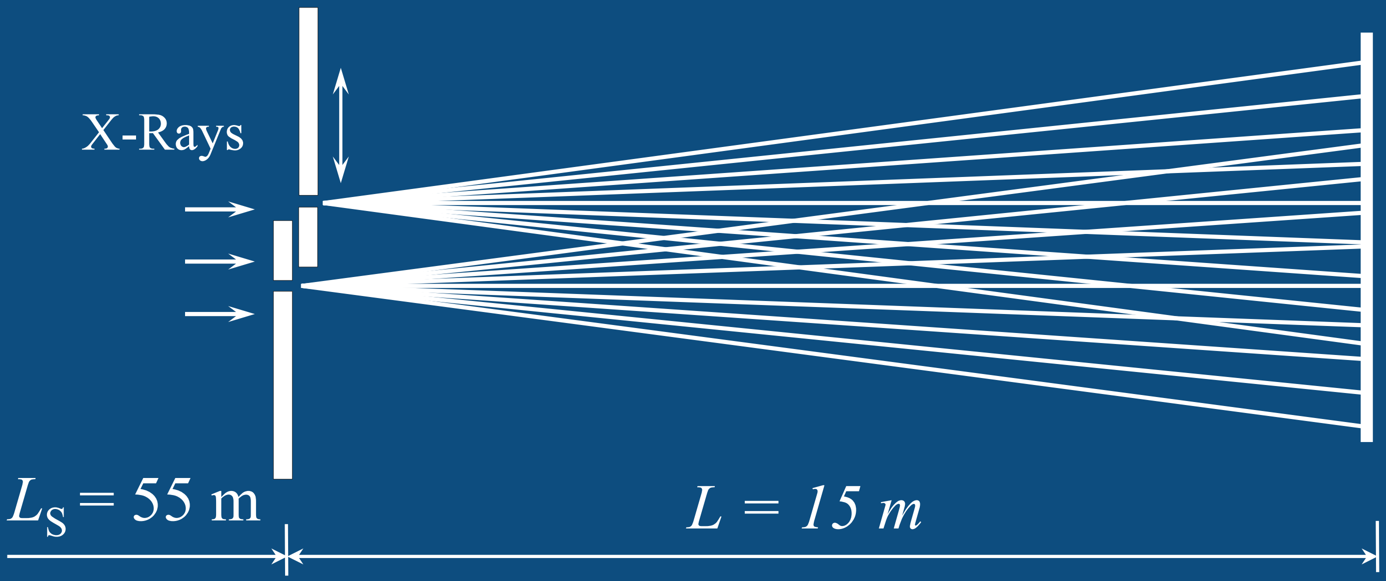
D = 90 µm





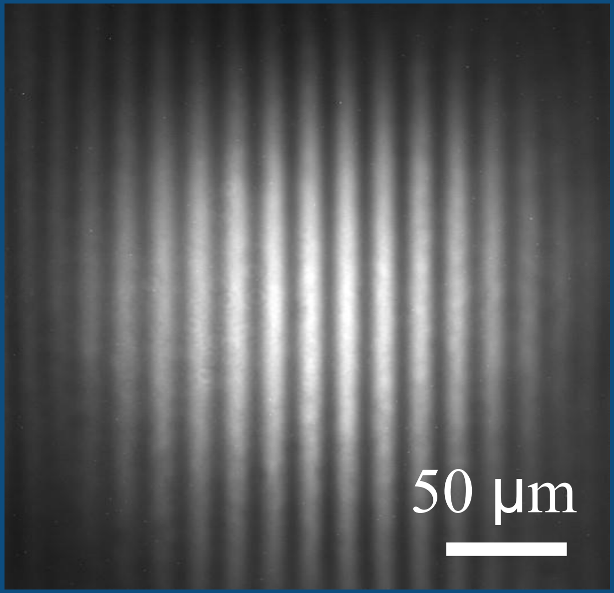
Tunable double apertures

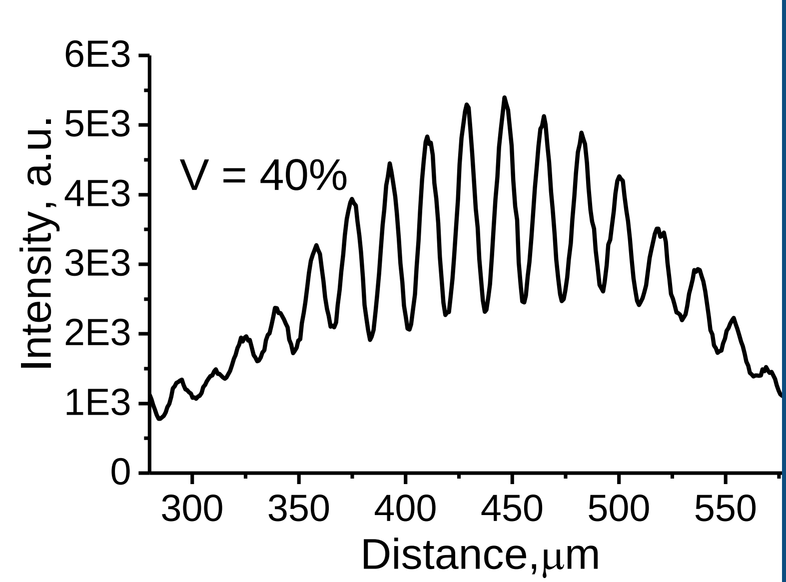
E = 11 keV



D = 90 μm
Δ =18 μm

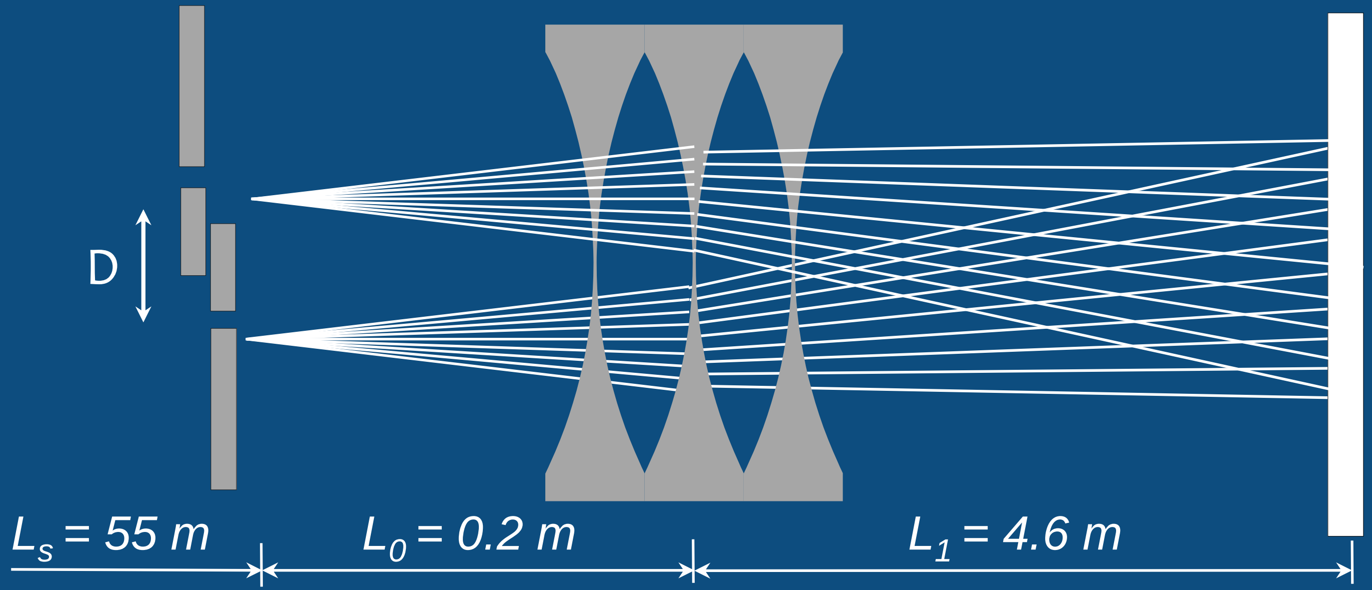
V_{theory} = 55%
V_{exp} = 40%

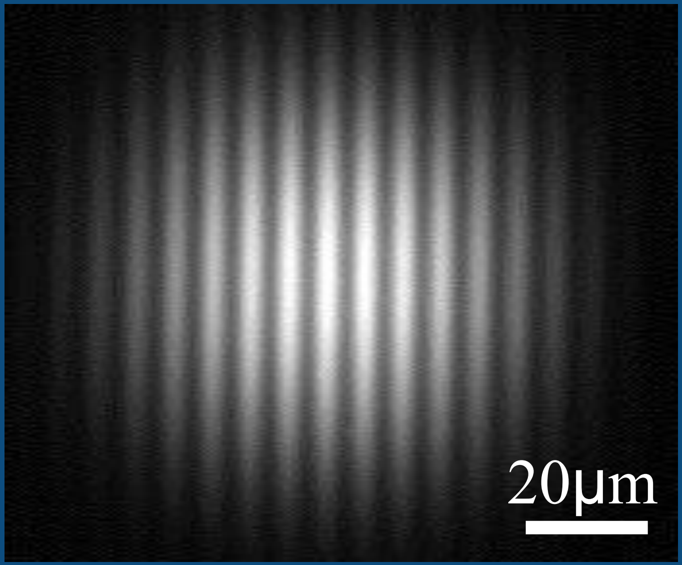




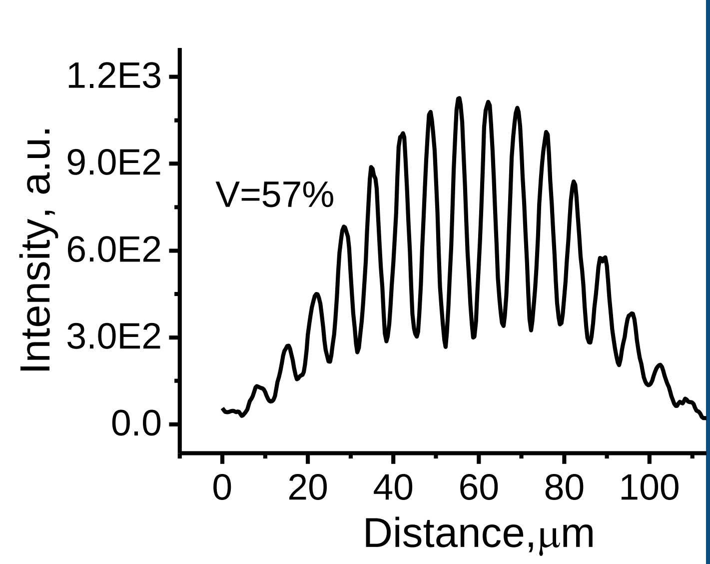
Tunable double apertures coupled with CRL

E = 9.2 keV
CRL Be
N = 6
R = 200 μm
F = 4.15 m





D = 90 μm
Δ =6.5 μm
V = 57%
s = 40 μm



Diamond Refractive Optics

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Large-acceptance diamond planar refractive lenses manufactured by laser cutting

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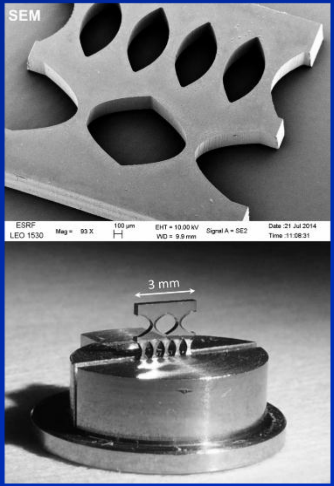

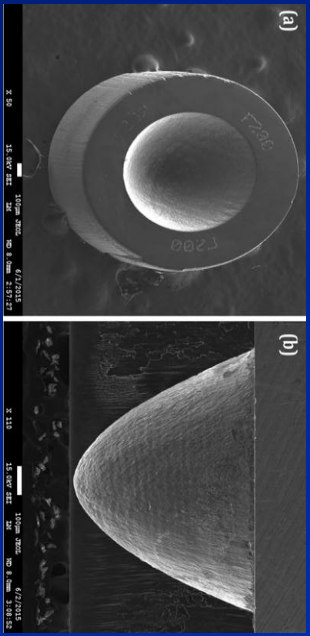

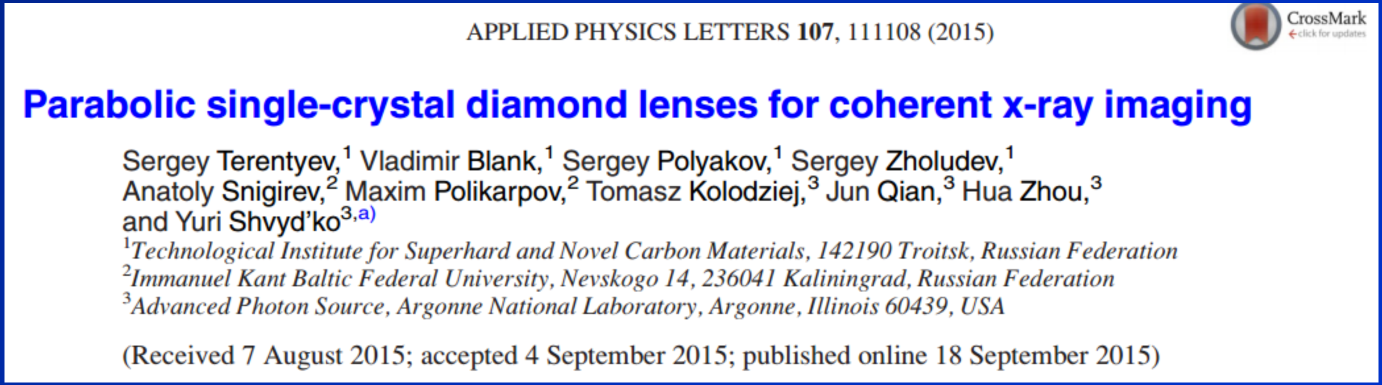

APPLIED PHYSICS LETTERS **107**, 111108 (2015)

Parabolic single-crystal diamond lenses for coherent x-ray imaging

Sergey Terentyev,[1] Vladimir Blank,[1] Sergey Polyakov,[1] Sergey Zholudev,[1]
Anatoly Snigirev,[2] Maxim Polikarpov,[2] Tomasz Kolodziej,[3] Jun Qian,[3] Hua Zhou,[3]
and Yuri Shvyd'ko[3,a)]

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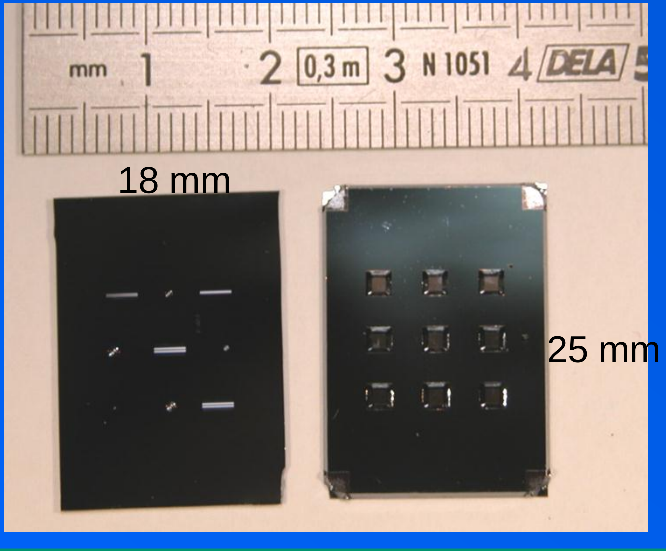
Si FZP chip



Chip	T_m / *h*, μm	E_{range}, keV	η_{max}, %	E_{max}, keV
DOE-4	12 / 9	6 - 12	30	7.5
DOE-5	80 / 16	11 - 21	26	14
DOE-7	90 / 30	17 - 40	32	23