17TH ADVANCED BEAM DYNAMICS WORKSHOP ON

FUTURE LIGHT SOURCES

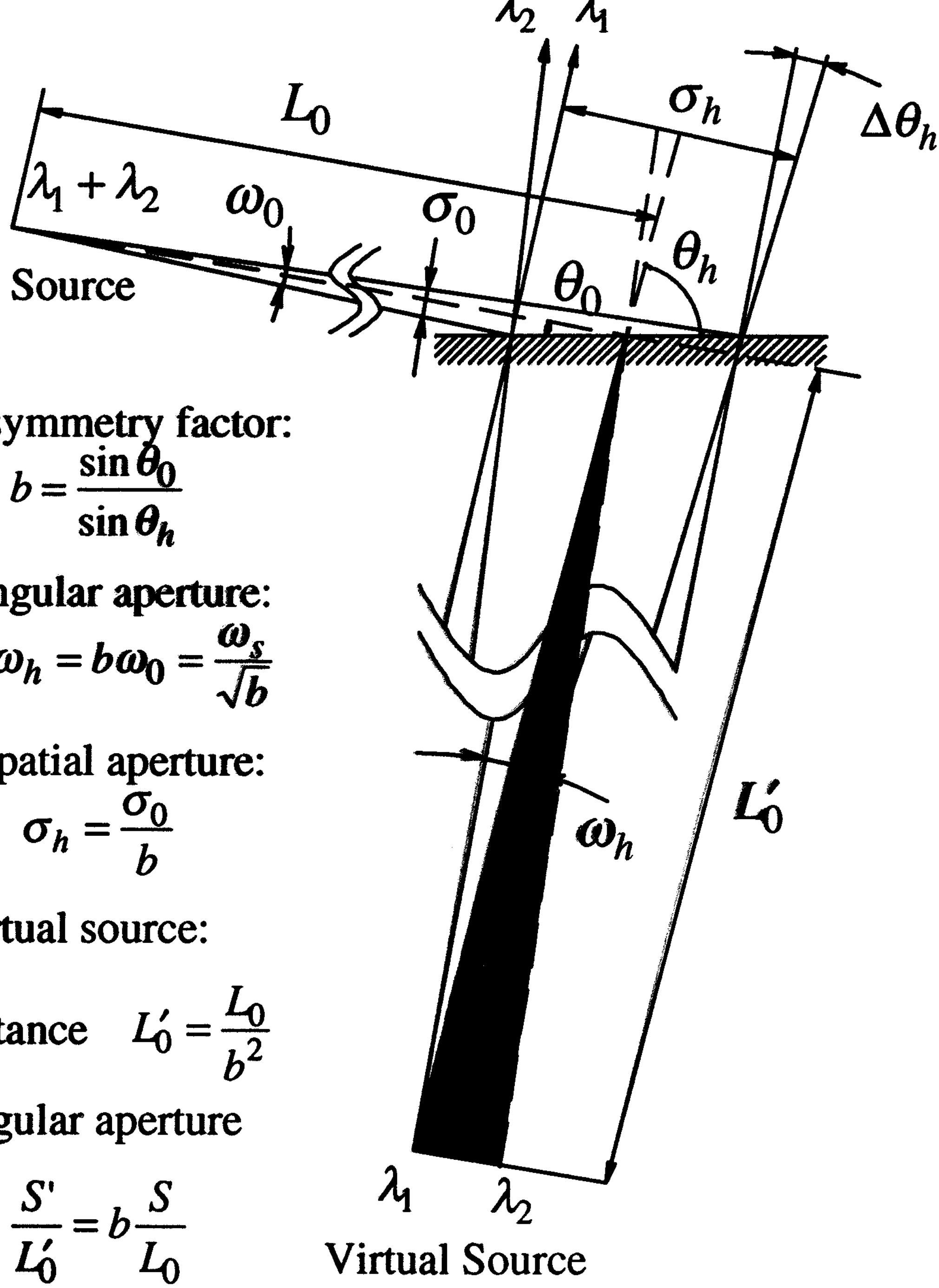
X-ray Optics

A. Freund, ESRF

APRIL 6-9, 1999
ARGONNE NATIONAL LABORATORY, ARGONNE, IL U.S.A.

Optical Properties of a Single Asymmetrically Cut Crystal

Case of |b|<1



Asymmetry factor:

$$b = \frac{\sin\theta_0}{\sin\theta_h}$$

Angular aperture:

$$\omega_h = b\omega_0 = \frac{\omega_s}{\sqrt{b}}$$

Spatial aperture:

$$\sigma_h = \frac{\sigma_0}{b}$$

Virtual source:

distance $L_0' = \dfrac{L_0}{b^2}$

angular aperture

$$\frac{S'}{L_0'} = b\frac{S}{L_0}$$

Courtesy: A. SOUVOROV (ESRF)

EXAMPLES: Si AND DIAMOND AT 1.5 Å *

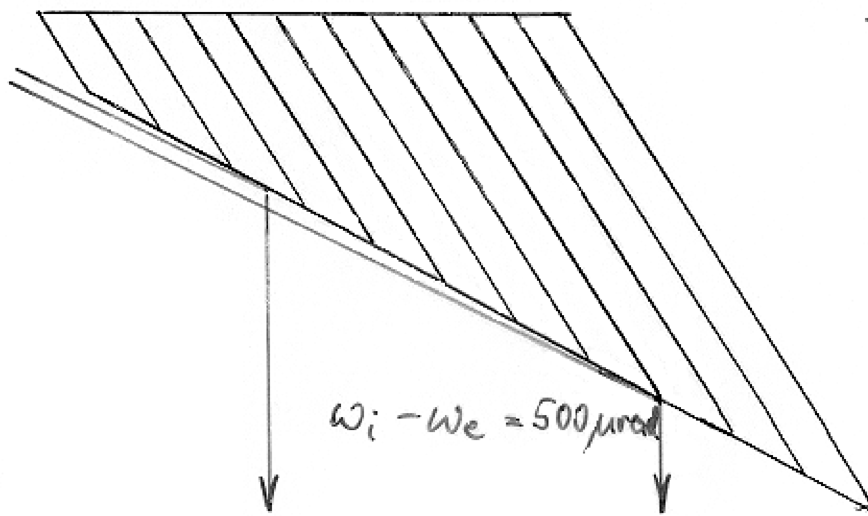
Crystal	d(Å)	θ_B	θ_i	θ_e	b	foot-print (mm)	$\Delta E/E$	t_{ext} (μm)	t_{abs} (μm)
Si (220)	1.9200	22.99°	0.1°	45.88°	411	85.9	1.2×10^{-3}	0.10	~~$3\cdot10^{-4}$~~ 0.124
C* (111)	2.0593	21.36°	0.1°	42.62°	388	85.9	1.2×10^{-3}	0.11	~~0.65~~ 2.33

Power spreading factor : ≈ 600 !

full range reflected

Surface should be very smooth and precisely oriented : feasible !

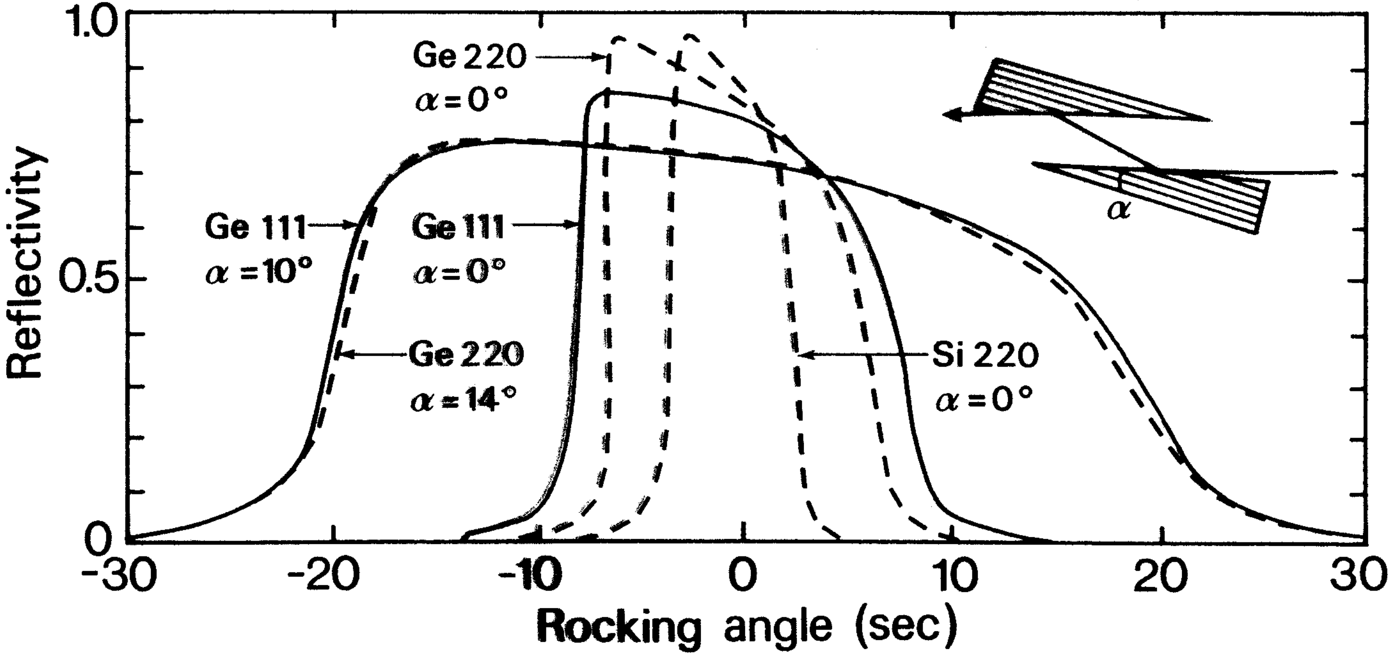
* No refraction corrections of the Bragg angle included.



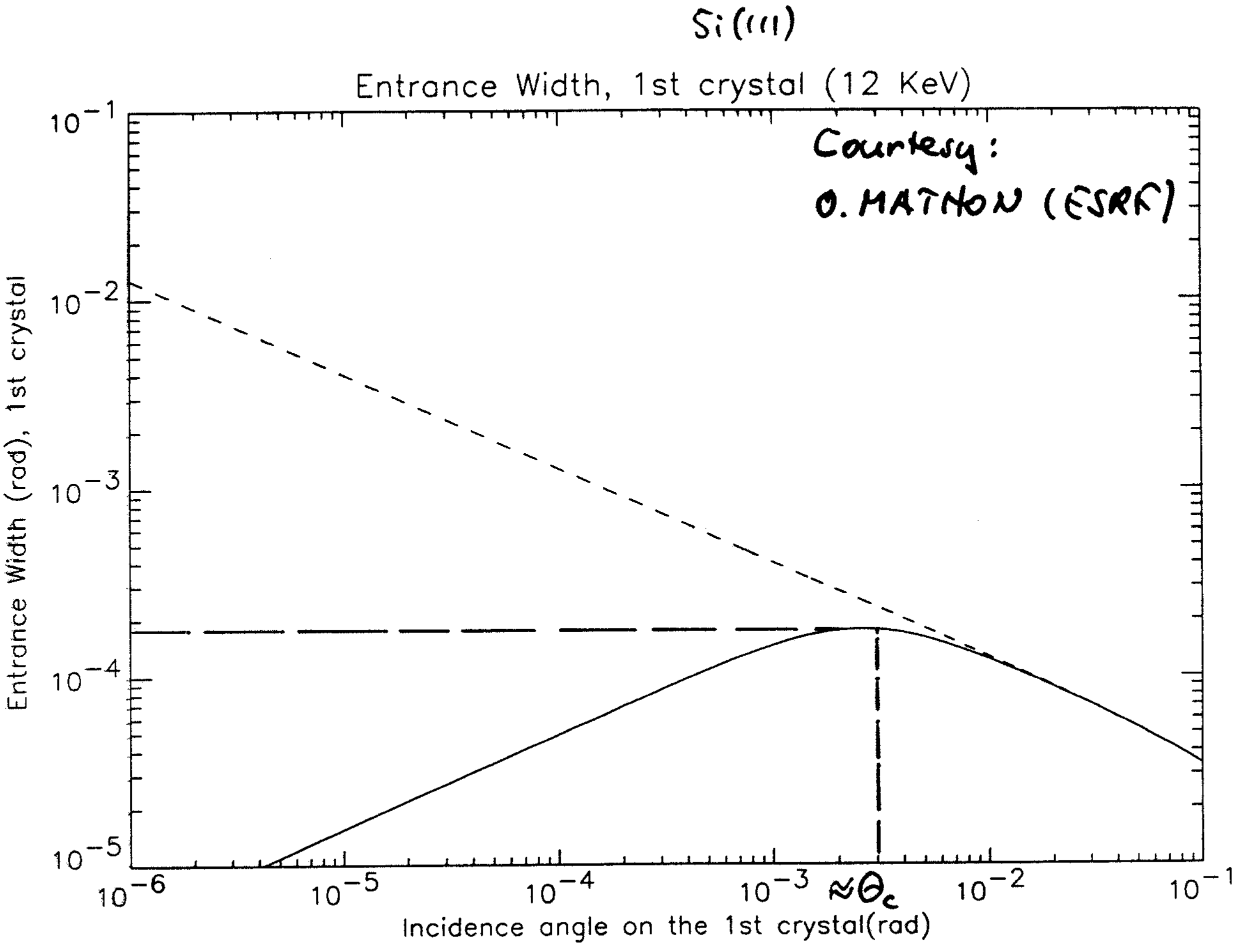
Further possibilities:

- inclined geometry
- Borrmann effect (anomalous transmission)
- long beamlines

From:
A. Freund
SLAC Workshop (1997)



From: MATSUSHITA & HASHIZUME (1983)



Symmetric $\quad \omega_D = \frac{\Delta E}{E} \, tg\,\theta = 2.3 \times 10^{-5}$ rad $\qquad \frac{\Delta E}{E} = 1.4 \times 10^{-4}$

Asymmetric $\quad \omega_{A,i} = \omega_D / \sqrt{b}$; max : 2×10^{-4} rad $\quad \left(\frac{\Delta E}{E}\right)_{max} = 1.4 \times 10^{-3}$

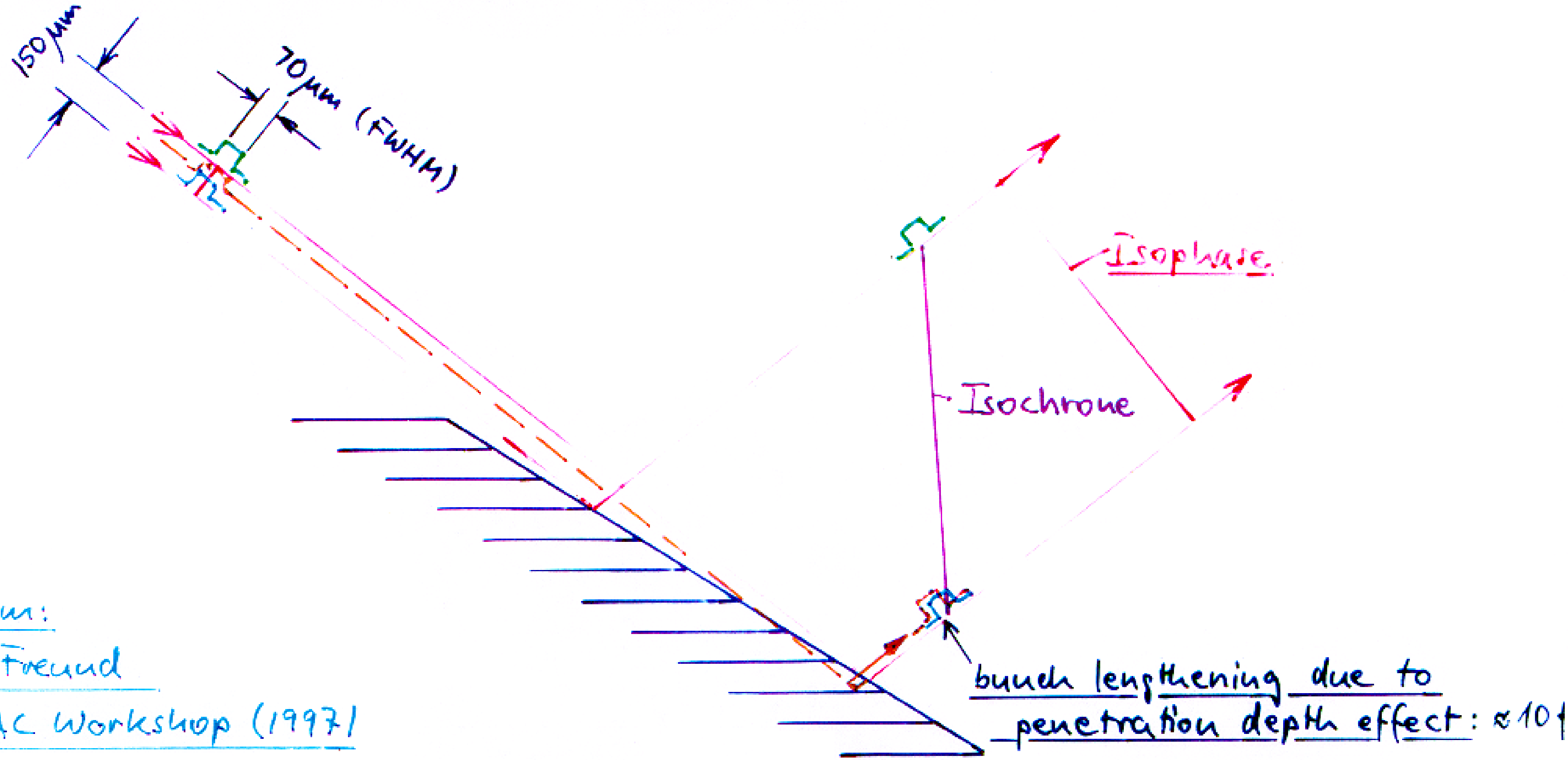
$$b = \frac{\sin\theta - \alpha}{\sin\theta + \alpha} \Rightarrow b_{min} \approx \frac{1}{100}$$

$\omega_{A,e} = \omega_D \sqrt{b}$; min $= 2 \times 10^{-6}$ rad ;

ISOPHASES AND ISOCHRONES

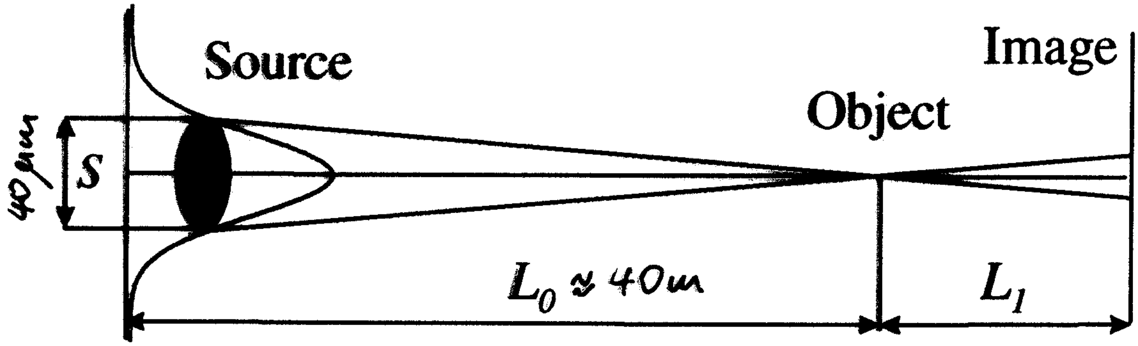
Possibilities:
- Time dispersion
- Time focusing
- Bunch lengthening
- Bunch compression

In connection with:
- Time-Energy dependence of source
- Gradient crystals



From:
A. Freund
SLAC Workshop (1997)

Introduction



While distance L_0 is large,

COHERENCE ➞ SPATIAL + TEMPORAL

SPATIAL COHERENCE is inverse to the source size

$$\propto \frac{\lambda}{S} L_0 \approx 100 \mu m$$

TEMPORAL COHERENCE is inverse to the spectral width

$$\propto \frac{\lambda^2}{\Delta\lambda}$$

Can we control coherence?

TEMPORAL COHERENCE ➞ crystal monochromators provide $\Delta\lambda/\lambda \sim 10^{-4}-10^{-6}$

SPATIAL COHERENCE ➞ distance, filters, mirrors

The suitability of asymmetrically cut crystals to control spatial coherence: true or false ?

Courtesy: A. SOUVOROV (ESRF)

Requirements on quality of monochromators

II. Tolerance on miscut in (+,-) asymmetrical reflection

$$|\Delta\varphi| = \frac{\eta\omega_s \sin^2(\theta_B - \varphi)}{\sqrt{b_1}\,\omega_c \sin 2\theta_B}$$

Example:

The same parameters as before, plus

$\varphi = 8.48^o$ which gives $b_1 = 4\cdot 10^{-2}$, $b_2 = 25$

Then

$|\Delta\varphi| < 10^{-5}$ rad (which is ~2'')

III. Tolerance on temperature difference in (+,-) asymmetrical reflection

$$|\Delta T| \leq \frac{\eta\omega_s \sin^2(\theta_B - \varphi)}{\alpha_T \sqrt{b_1}\,\omega_c \sin 2\varphi \tan\theta_B}$$

Example:

The same parameters as before, plus

$\alpha_T = 2.5\cdot 10^{-6}\ K^{-1}$

Then

$|\Delta T| < 30^o$

Courtesy: A. SOUVOROV (ESRF)

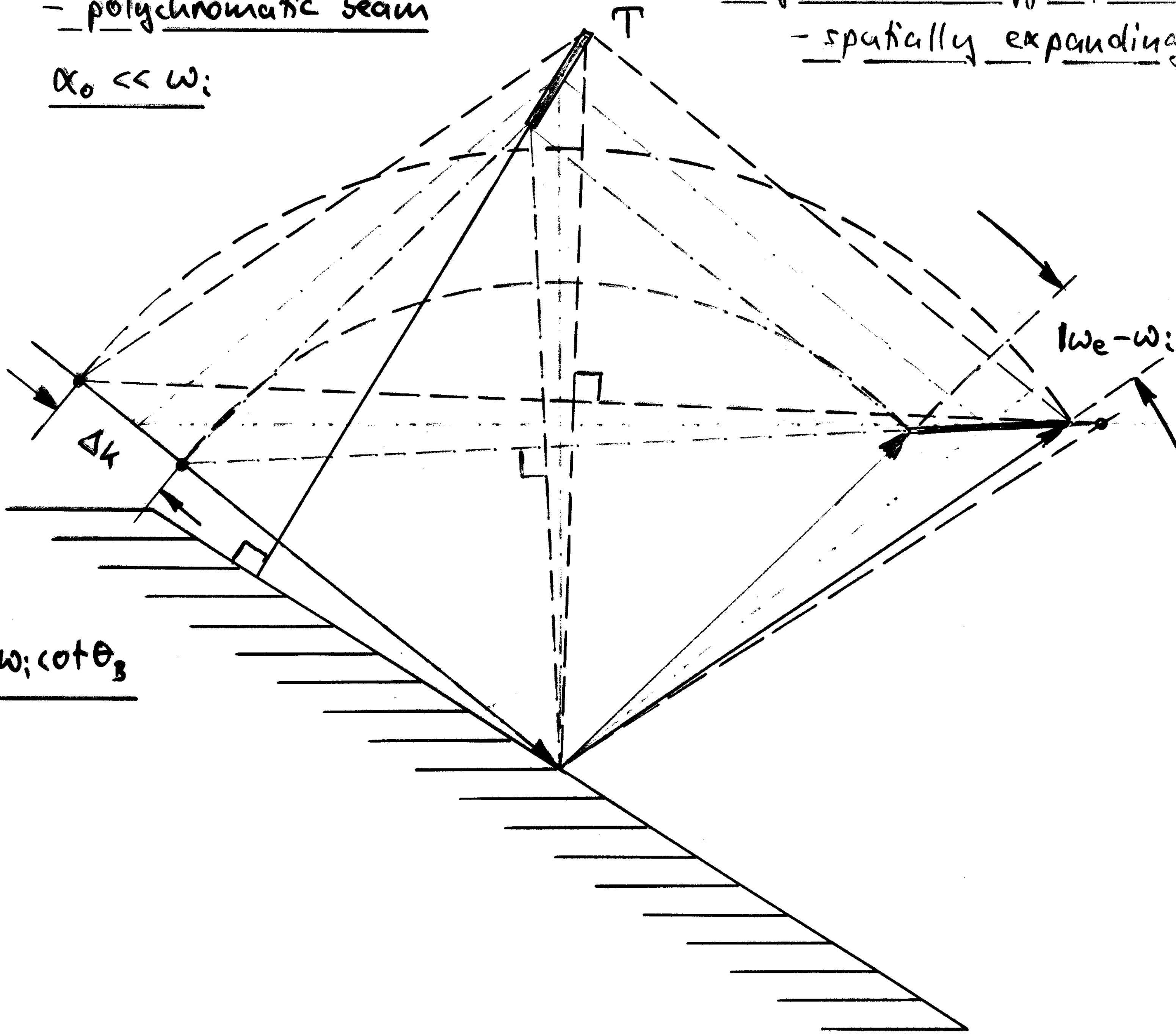
RECIPROCAL SPACE DIAGRAM

– polychromatic beam

$\alpha_0 \ll \omega_i$

Asymmetric Bragg reflection

– spatially expanding case



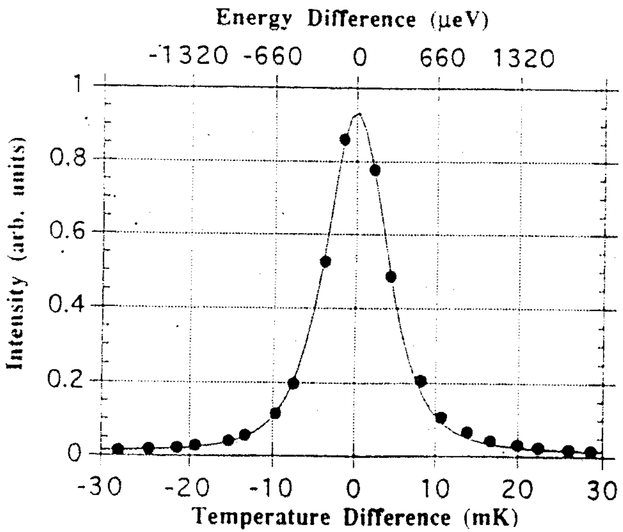
$$\frac{\Delta k}{k} \approx \omega_i \cot\theta_B$$

SOME CRYSTAL PARAMETERS AT 8 KEV

Material (h k l)	$d_H = \frac{1}{2}\lambda_{max}$ (Å)	$r_0 F_{Hr} e^{-M}/v_0$ (10^{-14} cm^{-2})	Darwin width ω_H (μrad)	energy resolution ε_H (10^{-6})	extinction thickness t_e (μm)	absorption t_a (μm)	
Be (002)	1.7916	5.59	10.7	22.8	5.0	1200	
Be (110)	1.1428	4.27	6.49	7.1	10.3	1874	
C* (111) (diamond)	2.0593	11.1	24.1	59.7	2.20	250	
C* (220)	1.2611	9.55	14.9	19.3	4.16	408	
Si (111)	3.1354	10.82	34.3	135	1.48	8.7	most commonly used
Si (220)	1.9200	12.29	25.3	57.7	2.12	14.2	
Ge (111)	3.2663	23.06	76.0	313	0.66	2.94	for high energies
Ge (220)	2.0002	27.51	58.5	140	0.91	4.79	

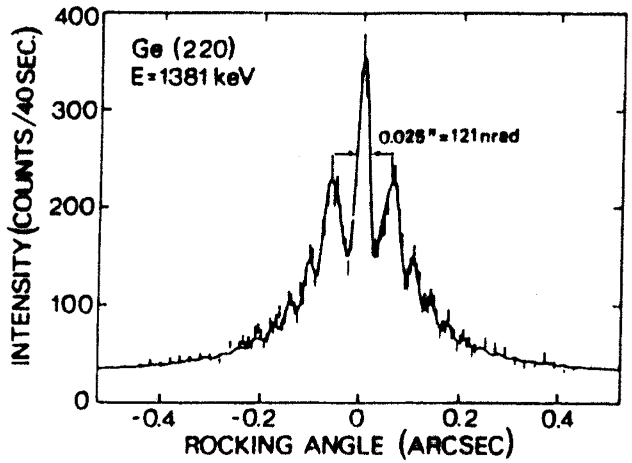
SINGLE CRYSTAL PERFECTION

SILICON



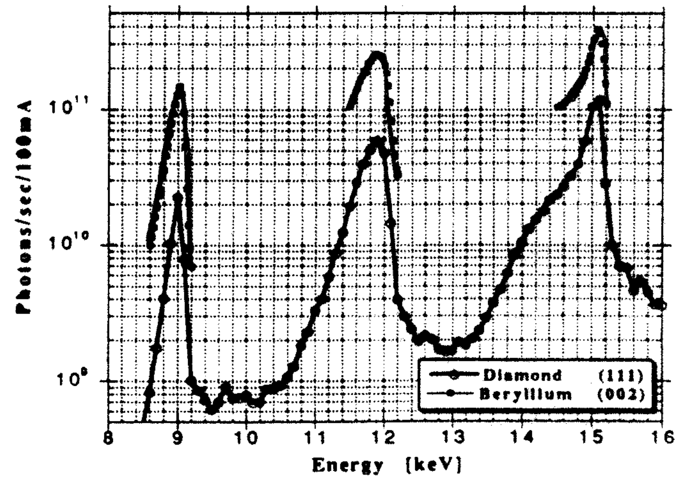
Backscattering Si (13,13,13)
rocking curve, T-scan at 26 keV
0.5 meV! $\Delta E/E = 2\cdot10^{-8}$ (FWHM) $\approx \Delta d/d$
(best value ever achieved)
Sette et al., ESRF Report (1995)
improved to $\Delta E/E = 9\cdot10^{-9}$!

GERMANIUM

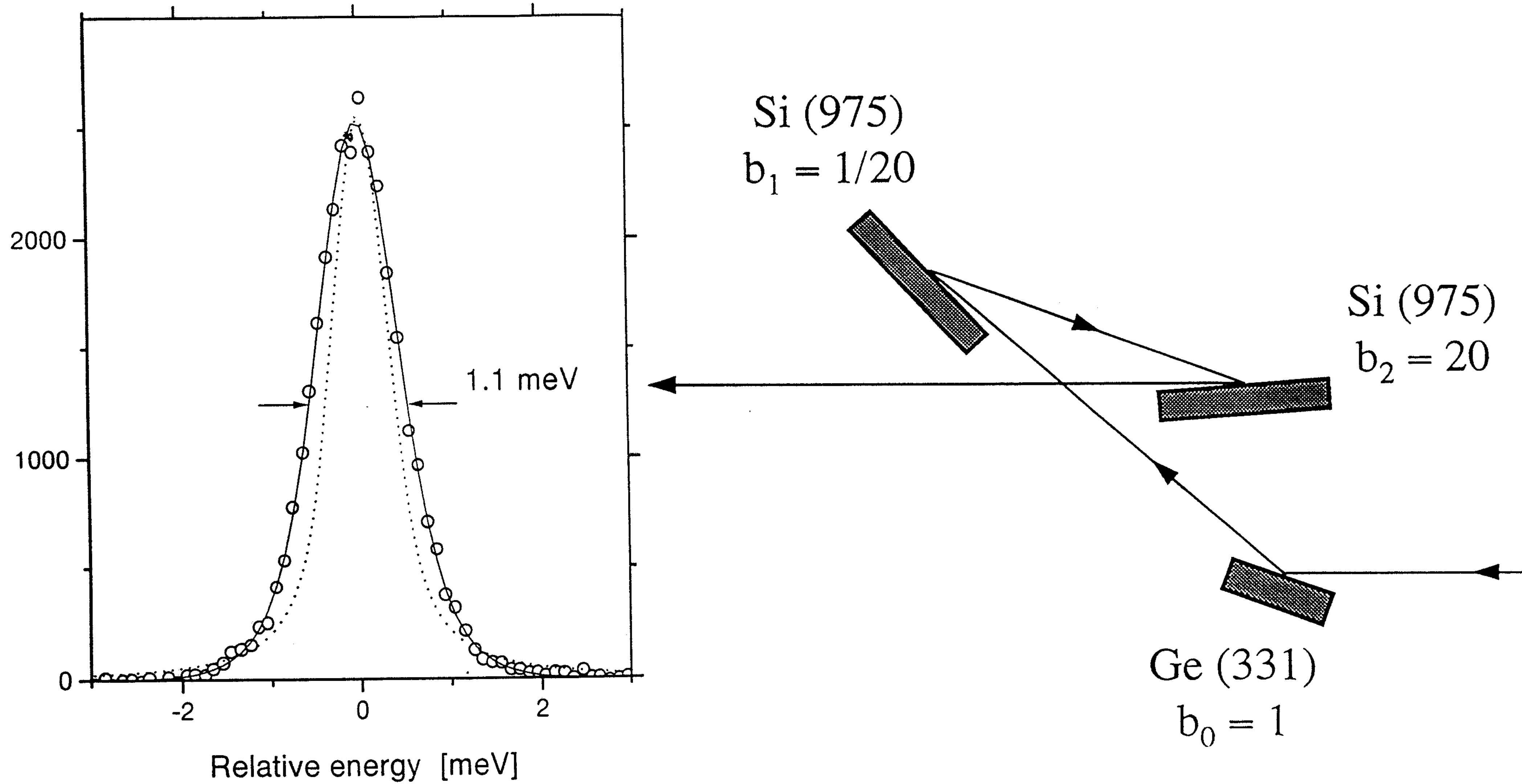


Ge double crystal Laue
diffraction pattern at 1.4 MeV.
Excess width: $3\cdot10^{-8}$ rad.
(best value ever achieved)
Freund, RSI **63**, 414 ('92)
Dewey et al., PR **B50**, 2800 ('94)

BERYLLIUM, DIAMOND

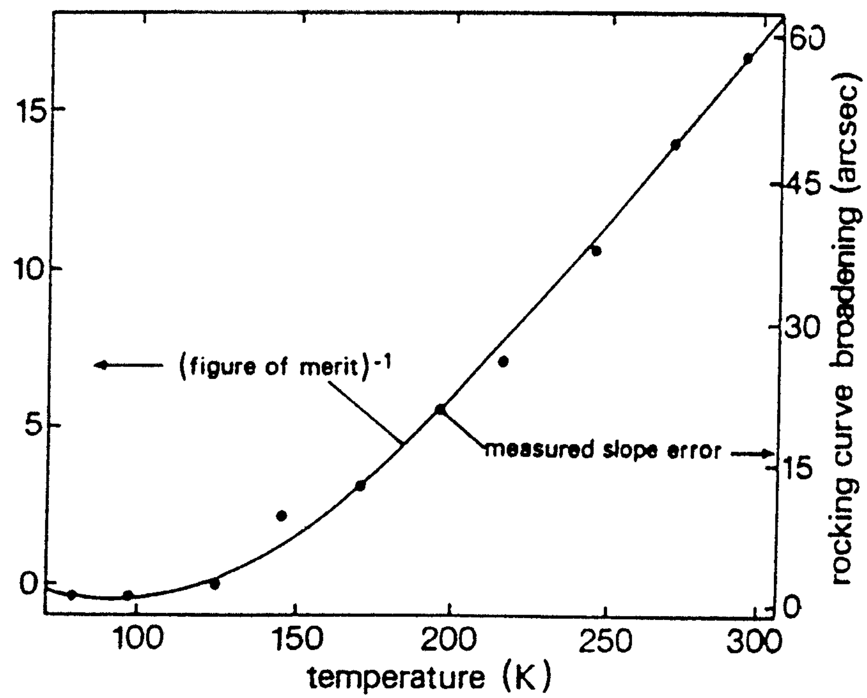


ID10 undulator spectra
recorded with diamond
and Be single crystals.
0.5 x 0.5 mm² at 44 m.
Grübel et al. J.Phys. C9, 27 ('94)



Courtesy: A. CHUMAKOV (ESRF)

Cryogenic cooling for crystal (and multilayer substrates)



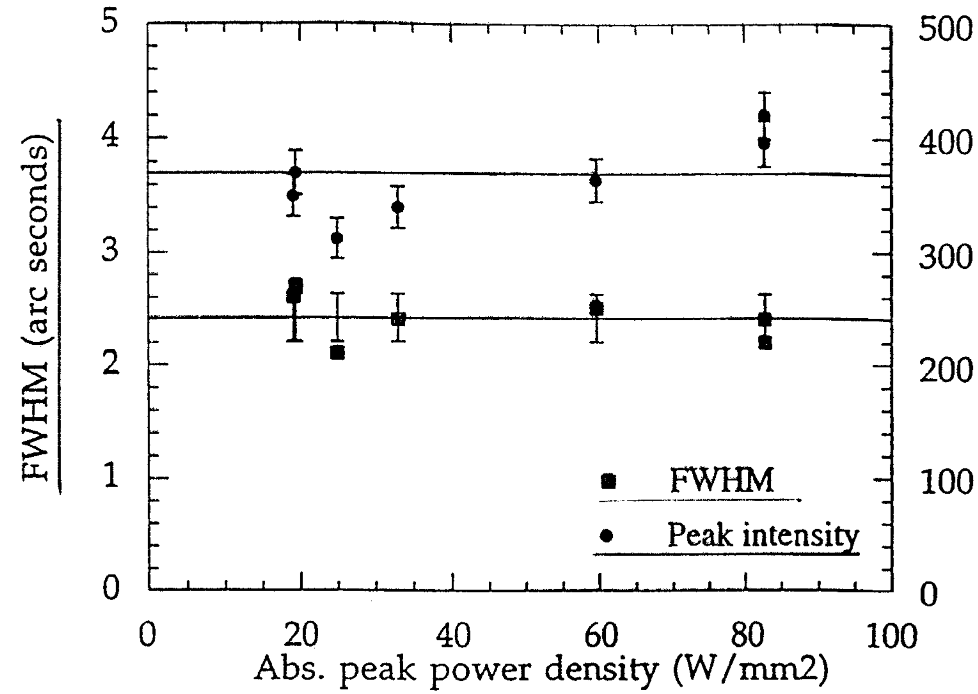
Thick crystal, side cooled

$P_s = 150W/mm^2$, $P_t = 80W$

NSLS X25

A. Freund, Rev Sci. Inst., 63, (1992)

G. Marot et al. Rev Sci. Inst., 63, (1992)



Thin crystal, direct cooled

$P_s = 415W/mm^2$, $P_t = 167W$

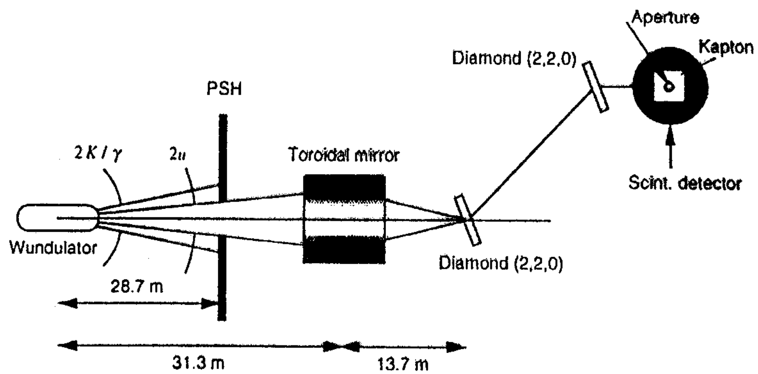
ESRF BL3

peak power density ≈ 20 kW/mm²

A. Rogers et al., Rev Sci. Inst. , 66, (1995)

Diamond single crystal - the ultimate

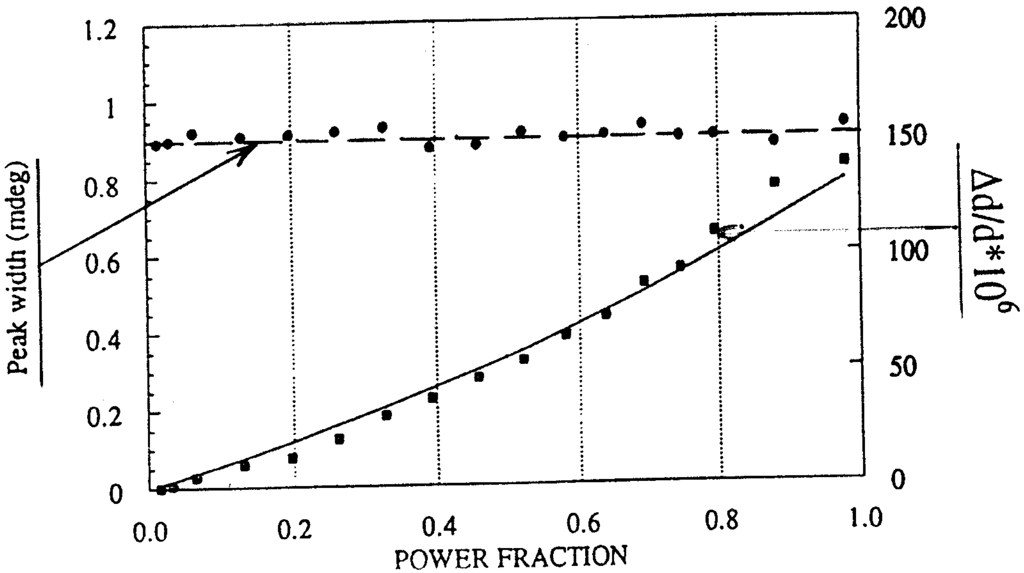
heat load tests @ ESRF on wundulator source BL3/ID9

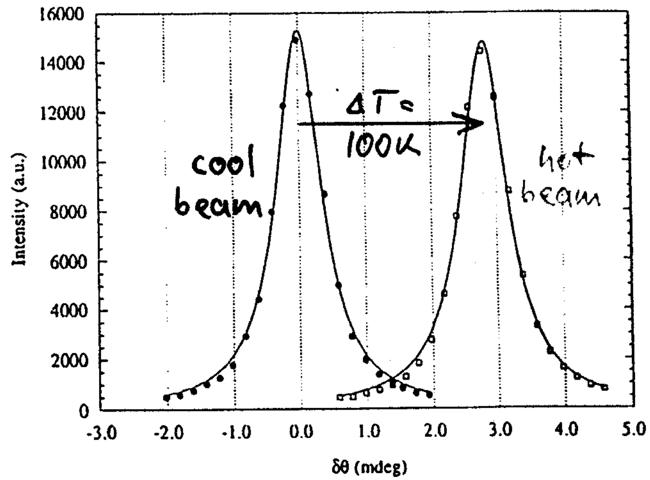


the beam is focused by the toroidal mirror onto a 4 x 8 x 0.1 mm^3 synthetic diamond crystal (Laue case)
(supplied by F. Sellschop, University of Johannesburg)

- ➡ incident [spot 0.2(h) x 0.4(v) mm^2]: P_t = 280W => **P_s = 3500W/mm^2**
- ➡ absorbed : P_t = 8.7W (3.1%) and **P_s = 109W/mm^2**

Heat Flux 50 x that on the sun's surface!!!

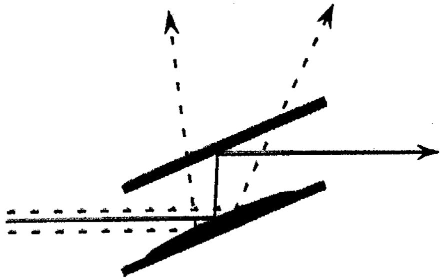




from J. Als-Nielsen et al., NIM B, 94 (19

Heat Problem : Crystal case

- usually P_s very high => $\Delta_{bump} > \Delta_{bending}$: for undulator radiation.

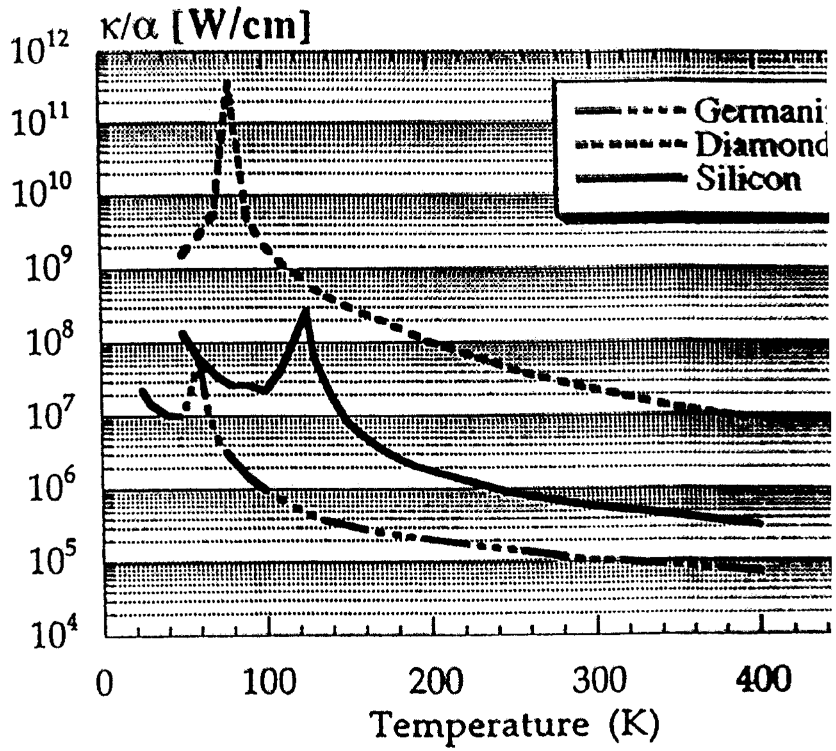


$$\Delta_{bump} \propto \frac{\alpha}{\kappa} G P e^{-\mu x} \begin{cases} \mu x < 1 \Rightarrow x = t \\ \mu x > 1 \Rightarrow x = t_{abs} \end{cases}$$

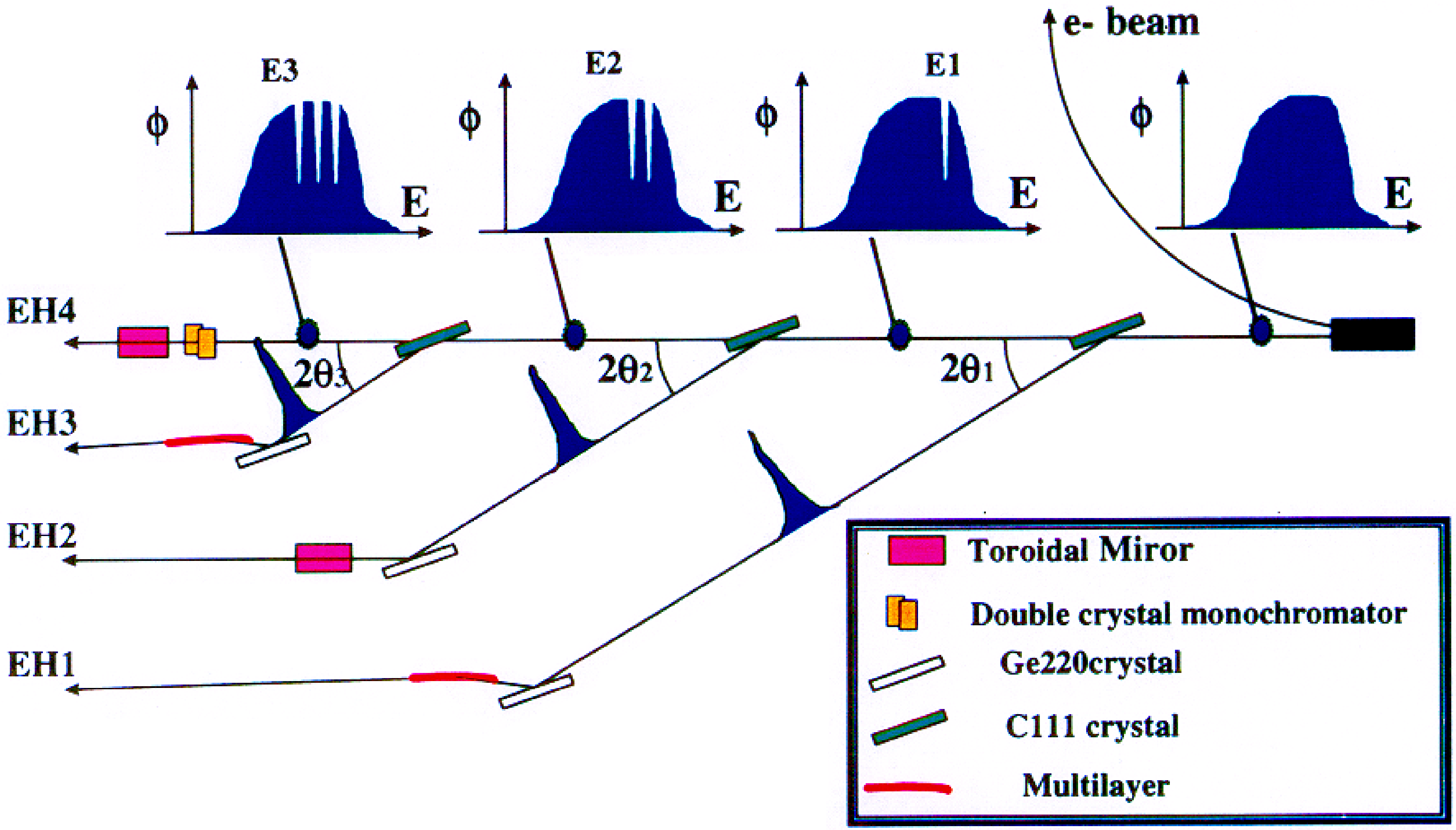
↳one reflection : increase of beam divergence and bandpass

↳double reflection : loss of transmission

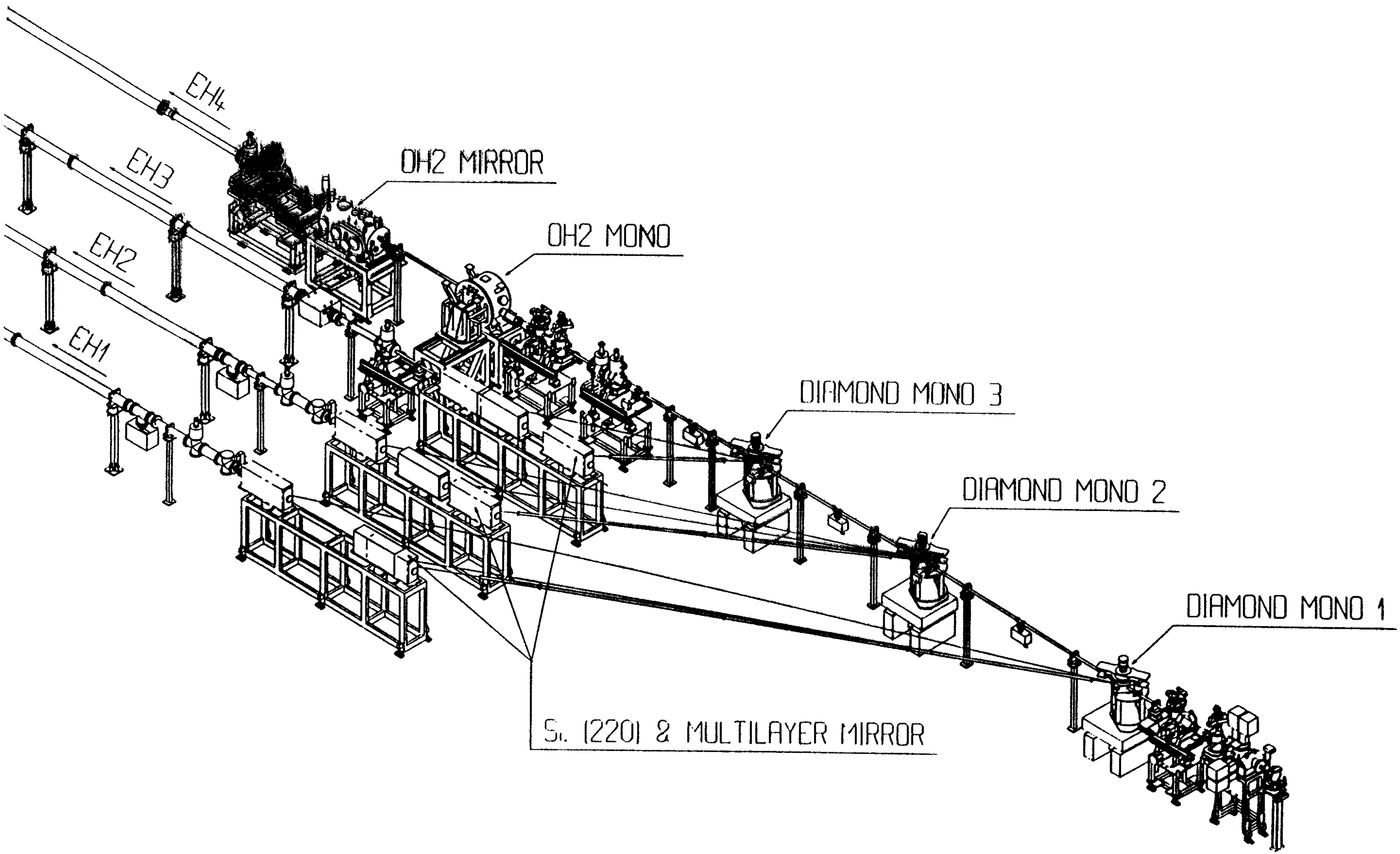
Material	Be	C*	Si	Ge
Crystal	hcp	diamond	diamond	diamond
μ @8keV [cm^{-1}] 200 μm	3.5% 1.8	14% 7.5	94% 141	99.97% 402
κ @297K [$Wcm^{-1}K^{-1}$]	1.94	23	1.5	0.64
α @297K [10^{-6} K^{-1}]	7.7	1.1	2.4	5.6
κ/μα @ 297K [MK]	0.14	2.80	$5\ 10^{-3}$	$3\ 10^{-4}$
@ 77K [MK]	11	120	$2\ 10^{-1}$	$7\ 10^{-3}$



ID14-Quadriga principle



Courtesy: S. WAKATSUKI (ESRF)



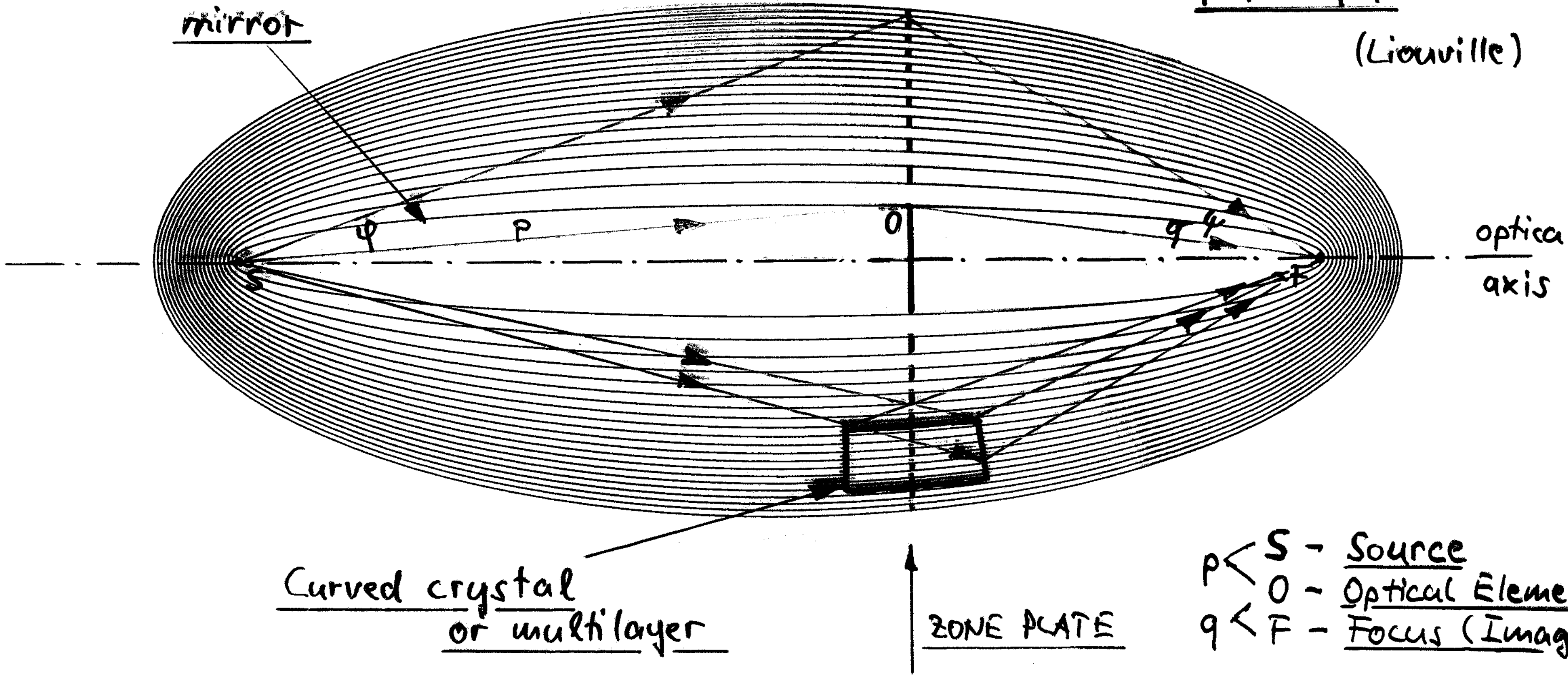
Courtesy: S. WAKATSUKI (ESRF)

FOCUSING

⇨ All imaging elements can be seen as sections of holograms of a point with a spherical reference wave.

$$p \cdot \varphi = q \cdot \psi$$

(Liouville)



p < S – Source, O – Optical Element

q < F – Focus (Image)

$$M = q/p = \varphi/\psi$$

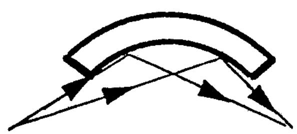
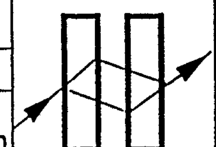
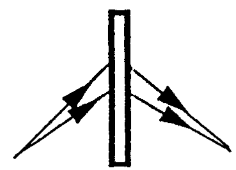
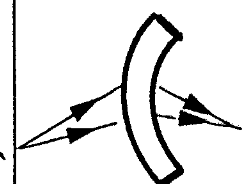
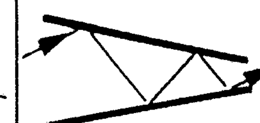
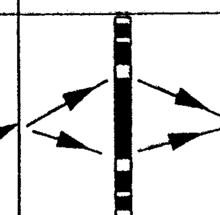
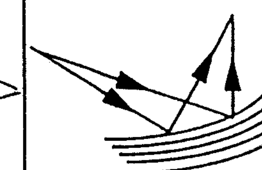
(Magnification)

⇨ The isophase figures are confocal ellipses

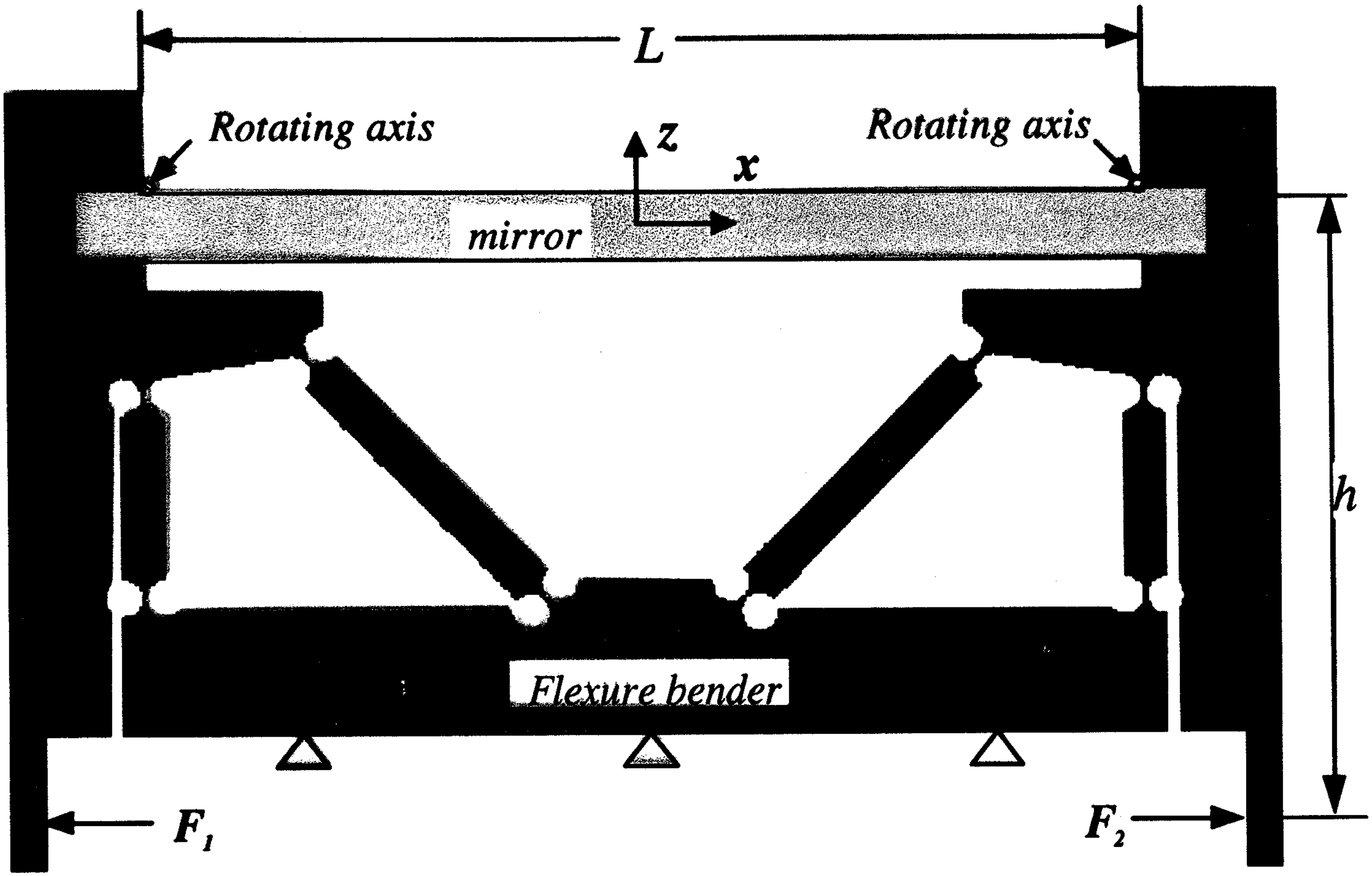
(see also: Spiller: "Soft X-ray Optics", SPIE, 1994)

FOCUSING OPTICS FOR HARD X-RAYS
3 keV < E < 100 keV

(after Snigirev, 1995)

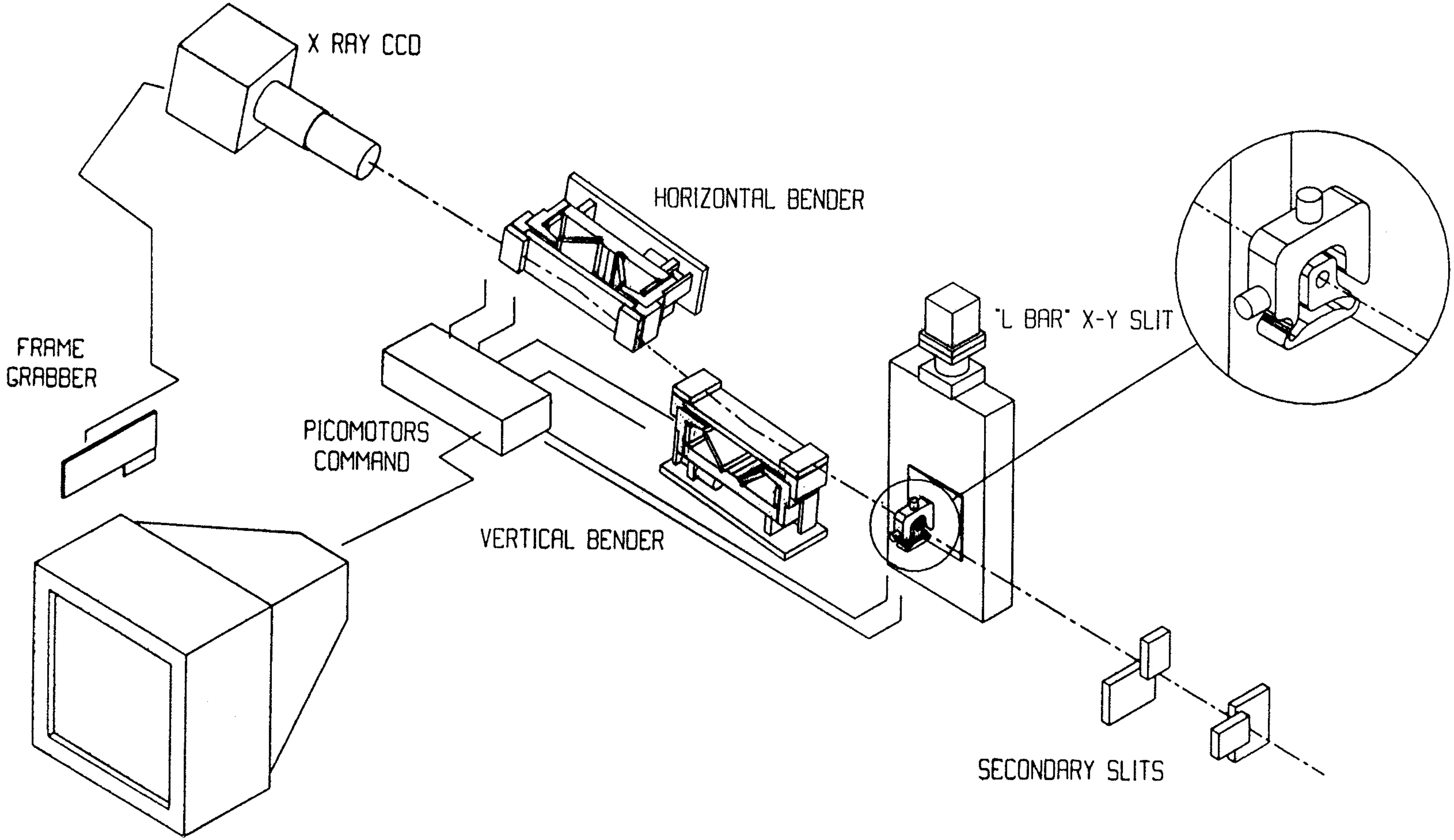
	KINEMATICAL FOCUSING BENT MIRROR OR CRYSTAL			DYNAMICAL FOCUSING			CAPILLARY OPTICS	FRESNEL OPTICS	BRAGG-FRESNEL OPTICS
				Indenbom 1974	Afanas'ev, Kohn 1977	Petrashen', Chukhovsky 1976	Kreger 1948	Baez 1952	Aristov et al 1986
	mirror	multilayer	crystal						
	Kirkpatrick, Baez 1948	Underwood, Barbee, Frieber 1986	Johann, Johansson 1931-1933						
angular apperture	10^{-3}	10^{-3}	10^{-4}	10^{-4} - 10^{-5}			10^{-3}		
resolution	5μm Suzuki et al 1992	5μm Underwood et al 1988	10μm Van Lagevelde 1992	<10μm			0.05 Bilderback et al 1994	0.6μm Yun et al 1992	0.5-0.7 Snigirev et al 1994-95

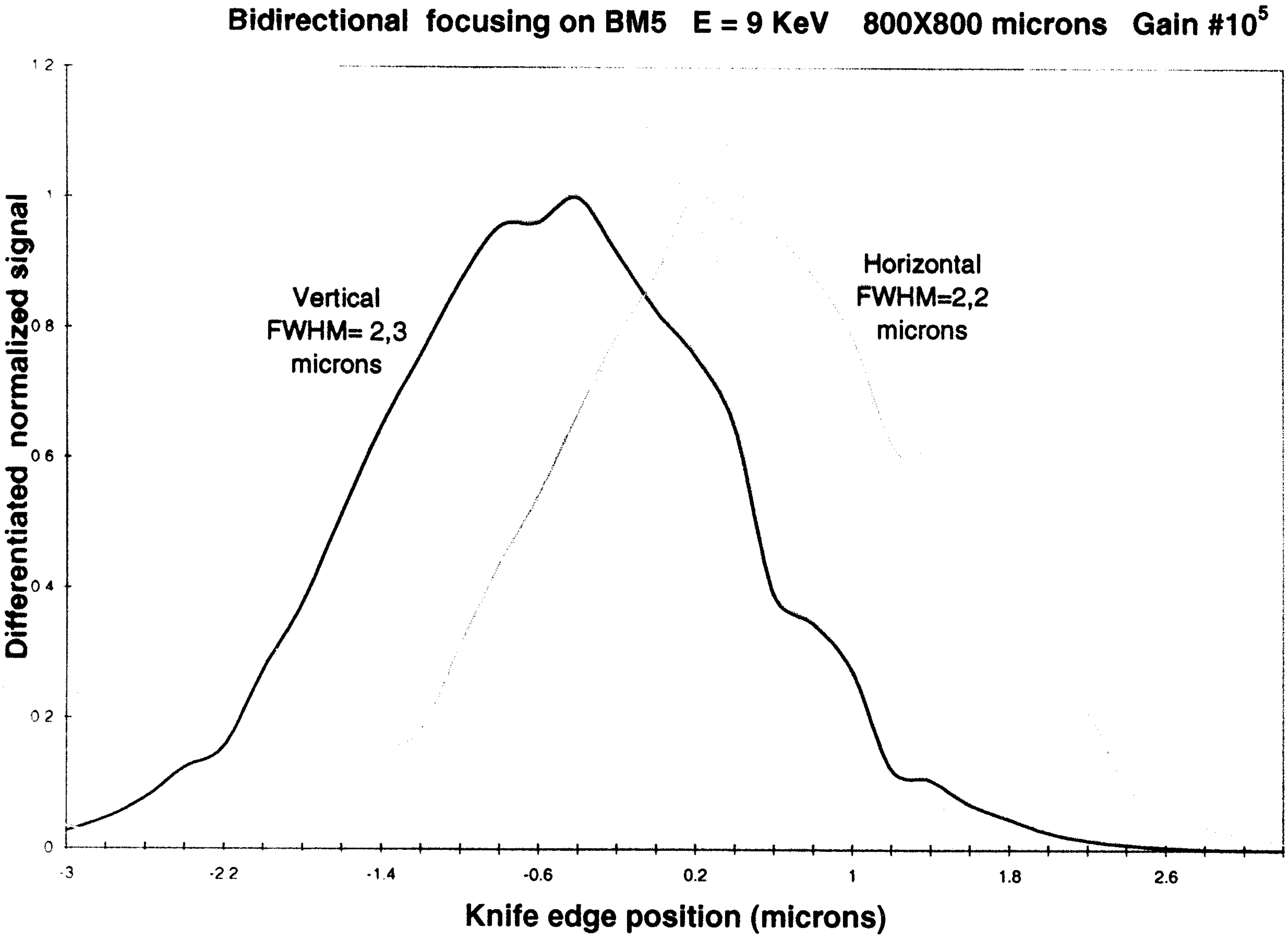
Finite element model of the flexural hinge-based bender



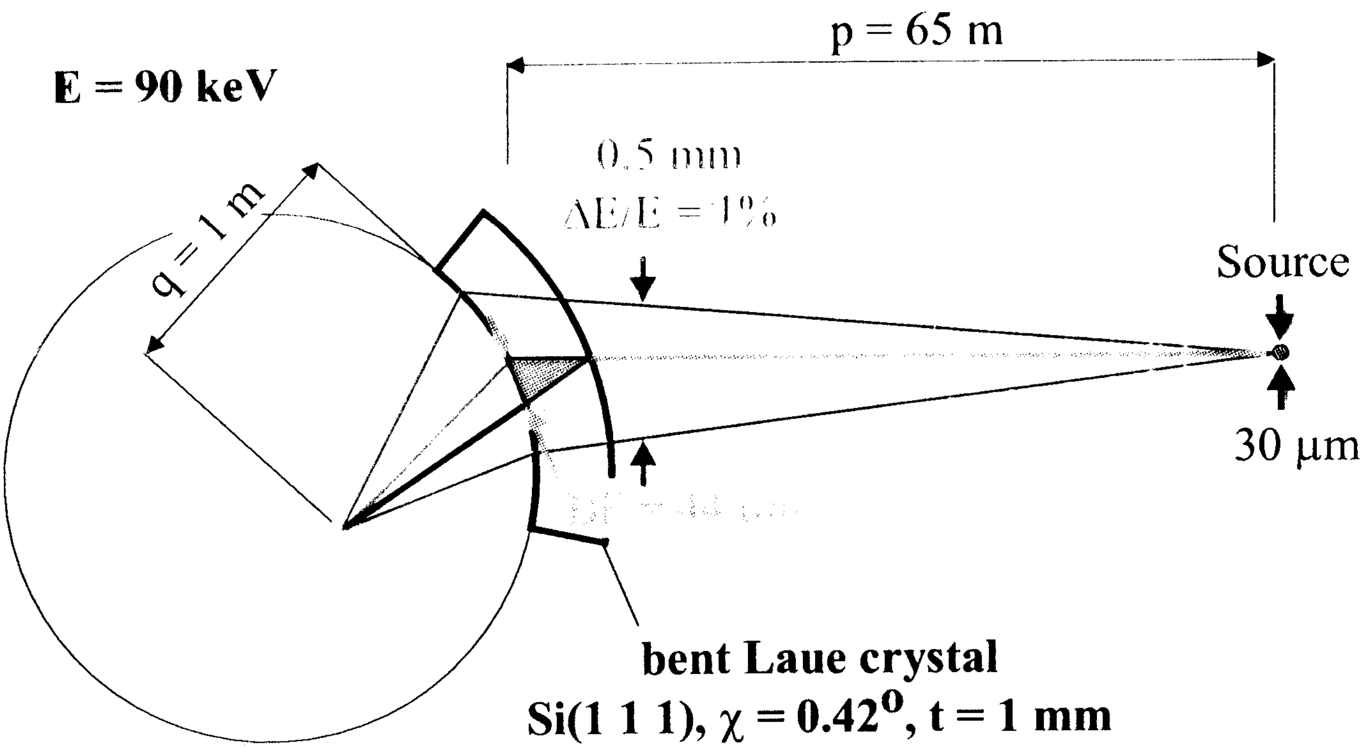
the piezo actuators are illustrated by 2 arrows
the triangles Δ represent fixations

KIRPATRICK BAEZ AUTOMATED SHAPING

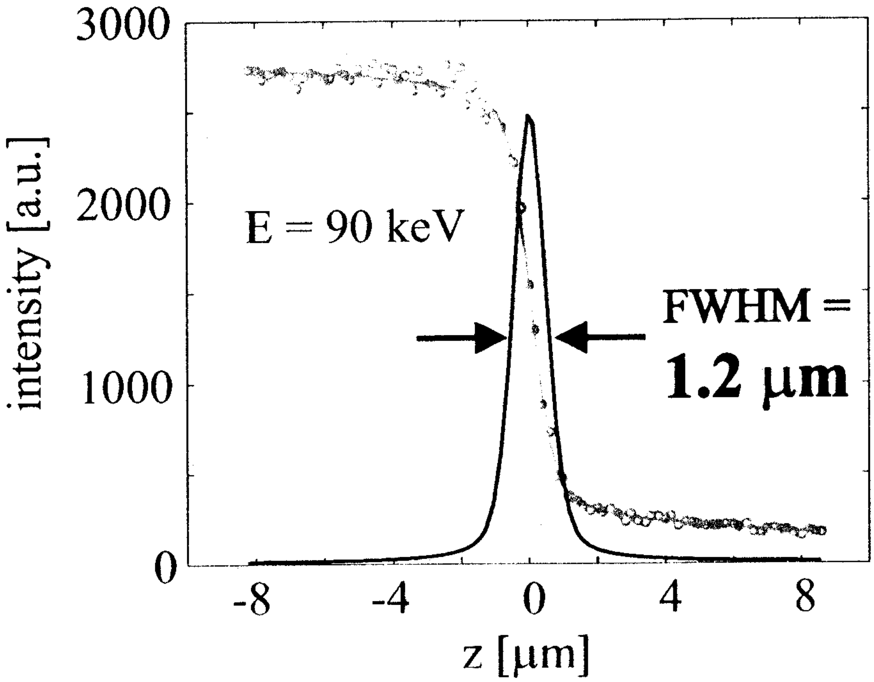



Bidirectional focusing on BM5 E = 9 KeV 800X800 microns Gain #10^5
Vertical
FWHM= 2,3
microns
Horizontal
FWHM=2,2
microns
Differentiated normalized signal
Knife edge position (microns)
0
0.2
0.4
0.6
0.8
1
1.2
-3
-2.2
-1.4
-0.6
0.2
1
1.8
2.6

Laue focusing



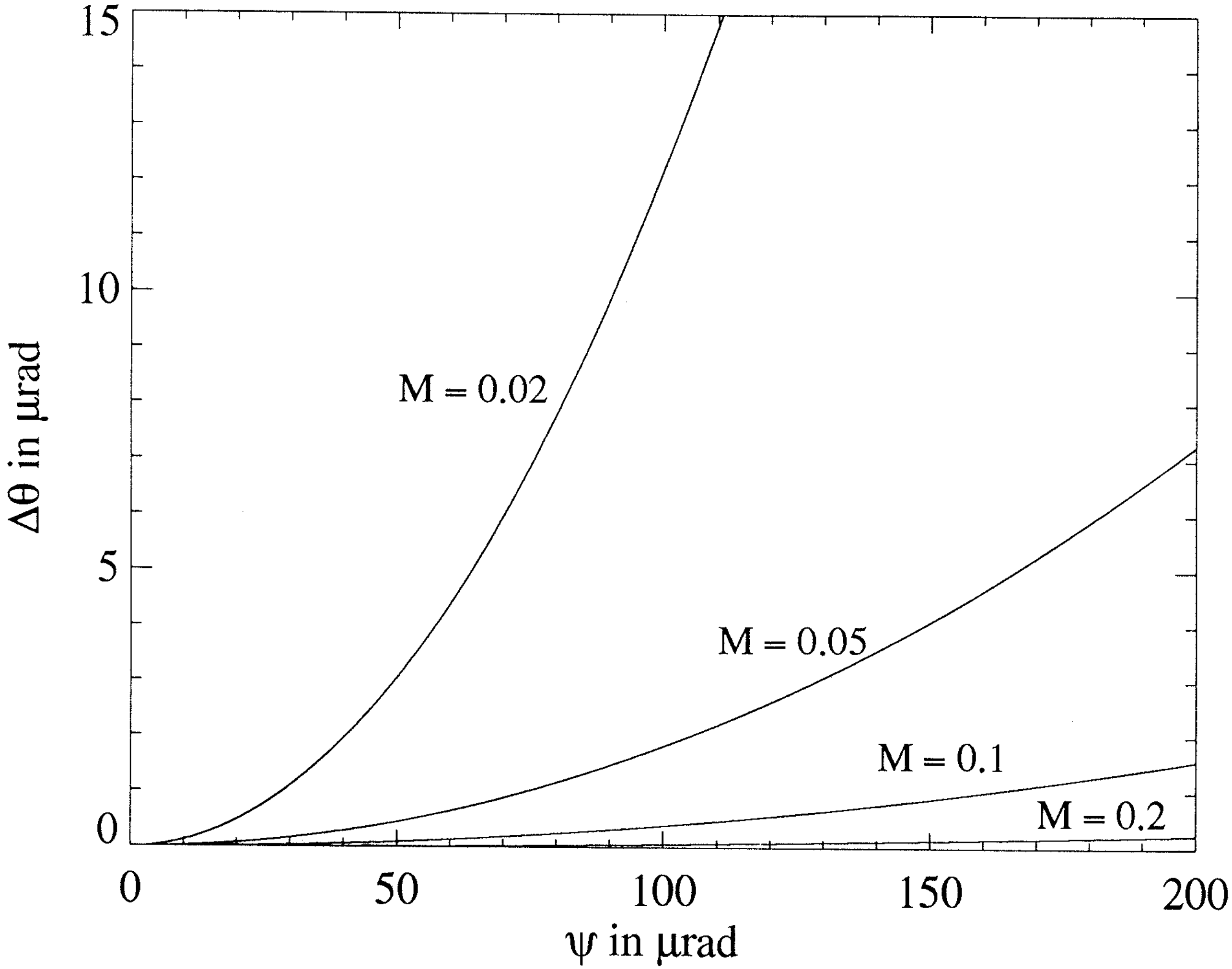
Fluorescence knife-edge scan



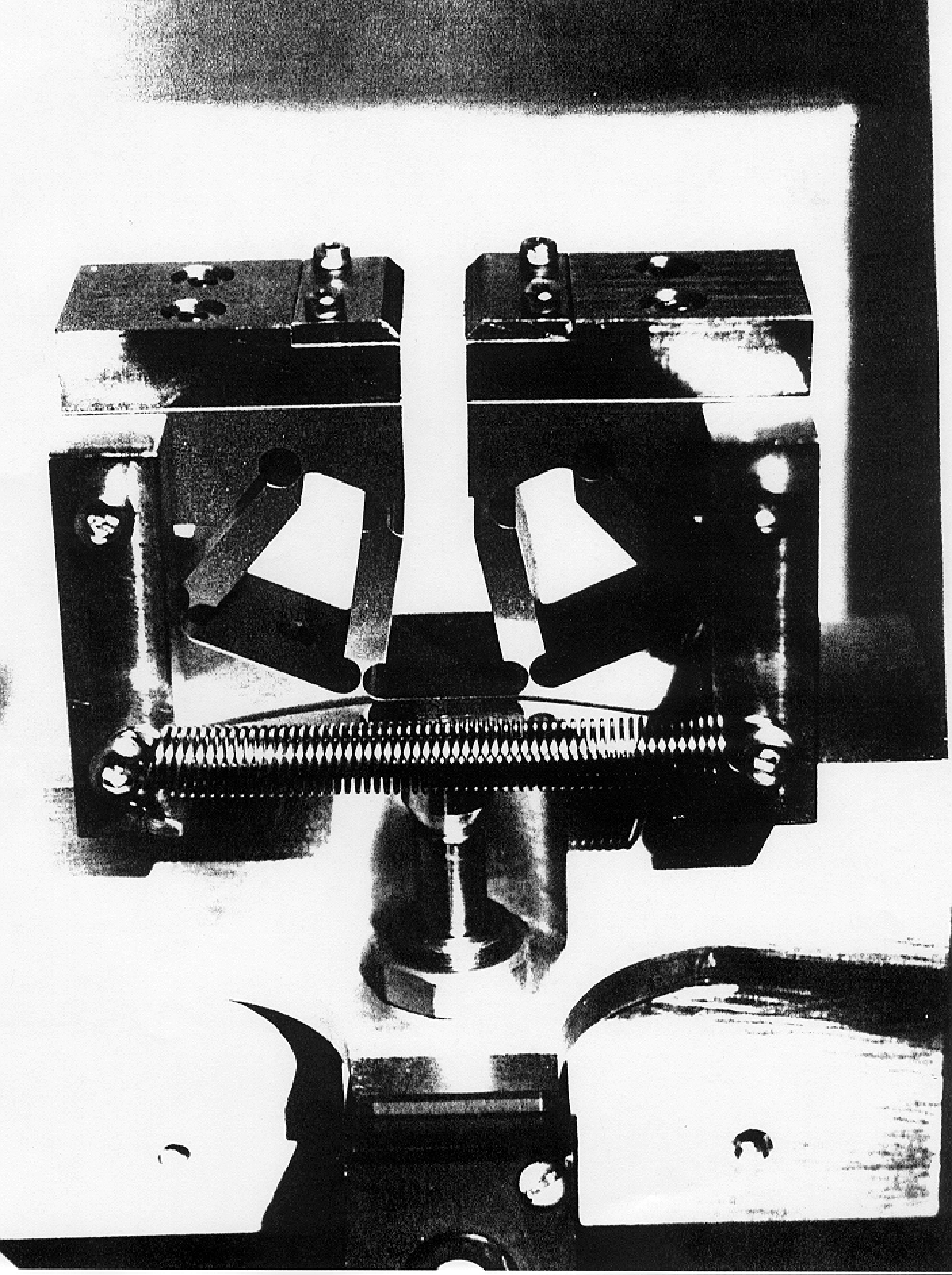
- flux in 1.2 x 500 µm: $4.3\ 10^9$ ph/s/0.1 A
- efficiency: 90 %
- gain factor: 300

(U. Lienert, C. Schulze et al., Proc. SRI97)

$$\Delta\Theta = \frac{\psi^2 (1+M)(3M-1)}{8 M^2 \sin\Theta_B}$$

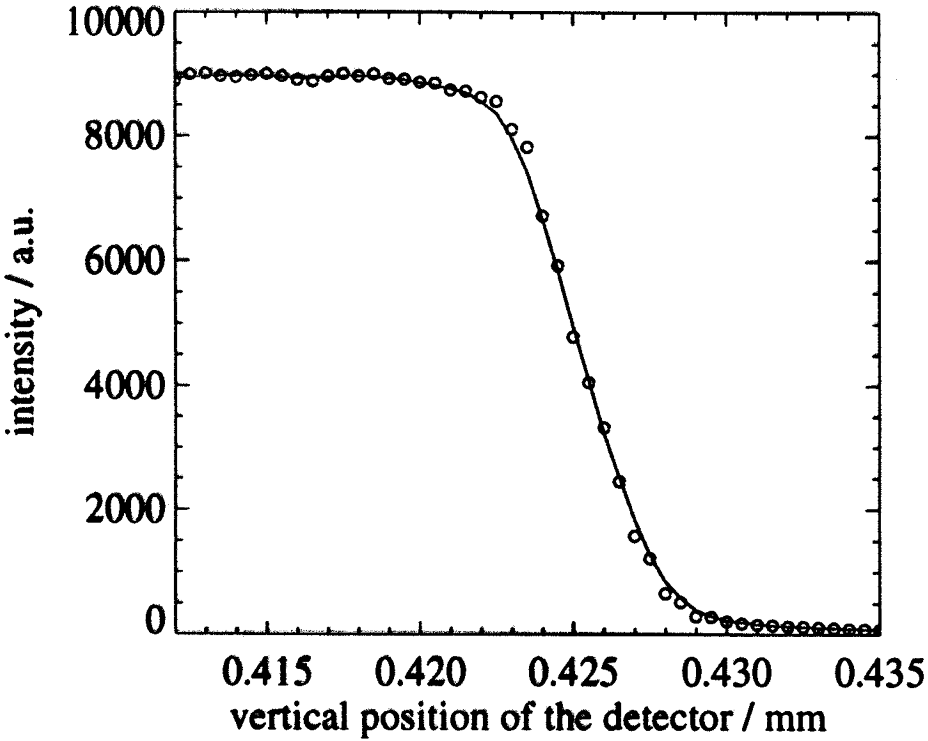


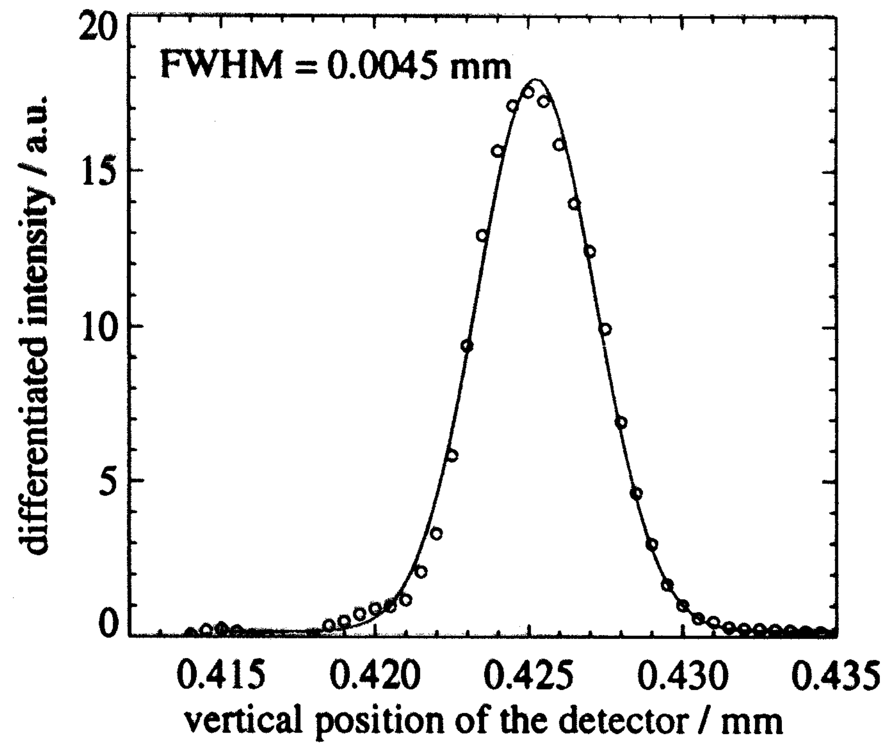
Angular errors in dependence of the divergence ψ, for different magnifications. Calculated for Si(111) and an energy of 8047.8 eV.



Focal spot, produced by a bent silicon[111] crystal

Knife edge scan; Energy = 8.047 keV

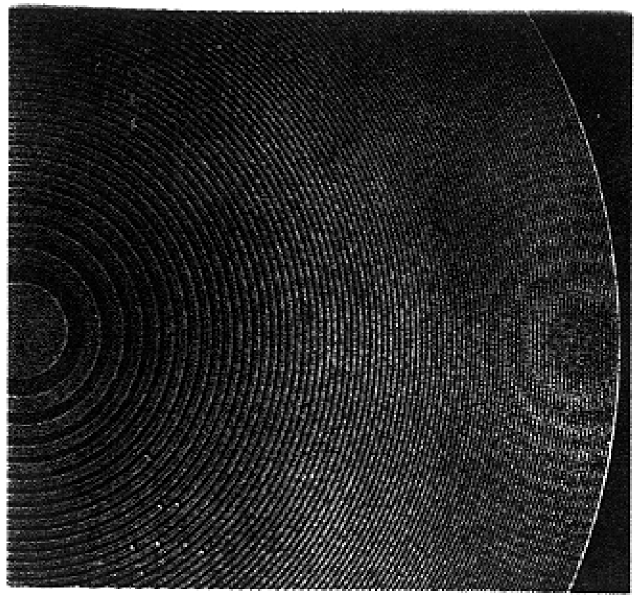


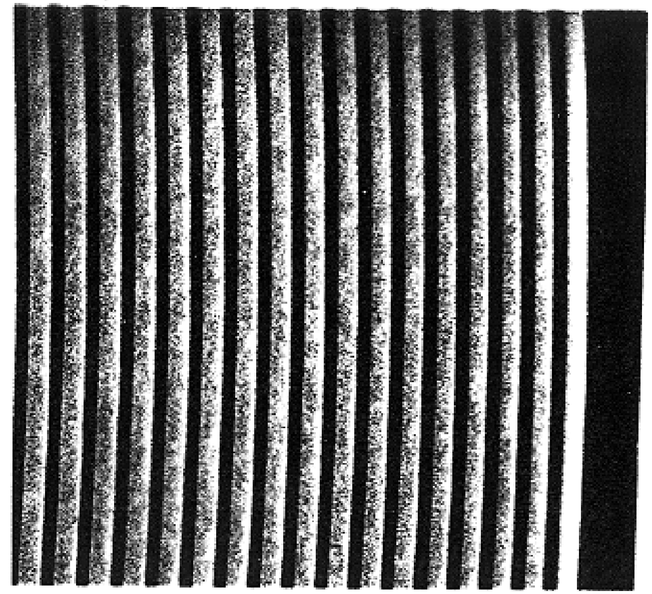


A. Freund et al., SPIE Proc. 1998

FZP

E.Di Fabrizio,
M. Gentili,
IESS, CNR, Rome, Italy

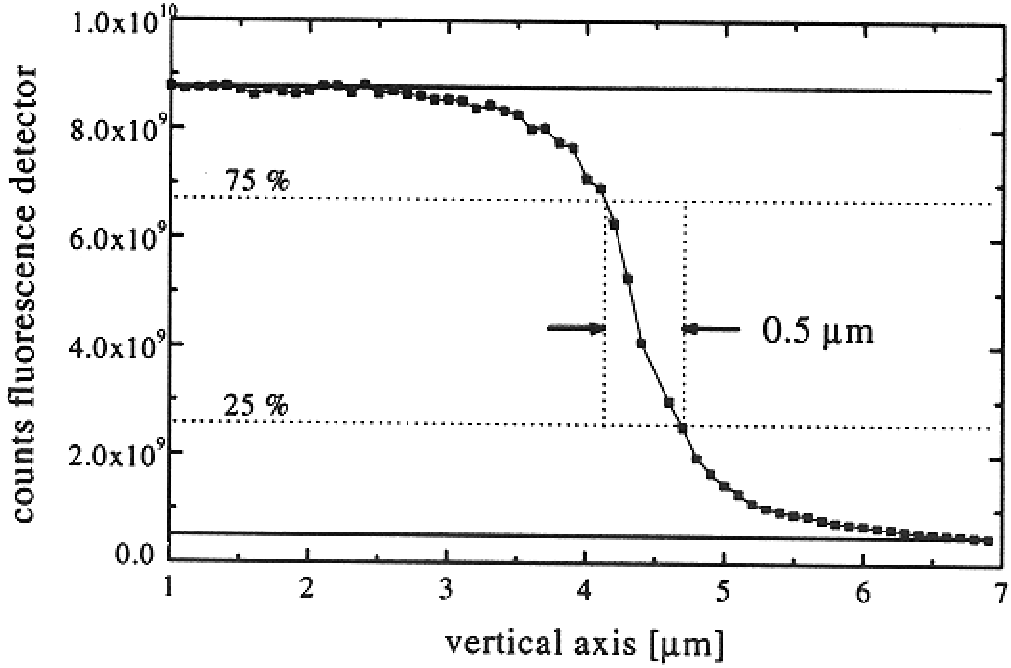




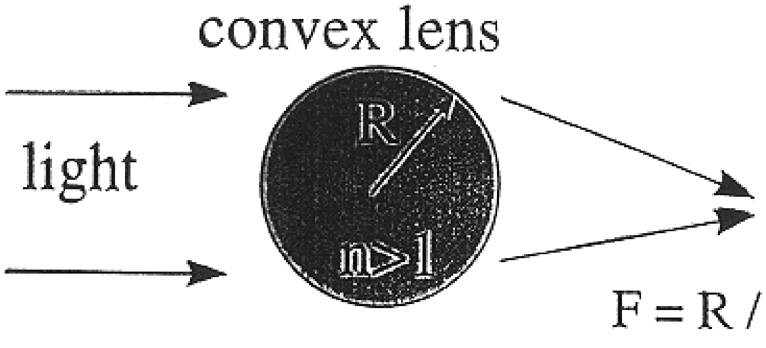
Cr-mask scan to resolve the spot size: 0.5 μm (V), 6 μm (H), flux 10^{10} ph/s

Fresnel zone plate parameters

169 zones, radius first zone: 7.8 μm
radius last zone: 0.3 μm
zone material: gold, thickness: 1.15 μm
substrate: SiN, thickness: 2 μm
aperture: 200 μm
focal length 8 keV: 400 mm
12 keV: 600 mm

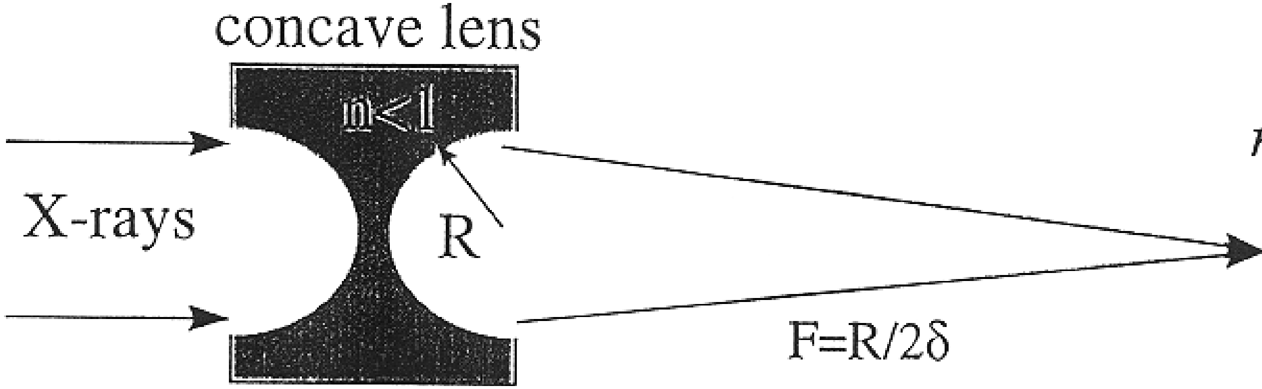


X-rays versus Light



$n > 1$

$n-1 \sim 0.1$



$n = 1 - \delta + i\beta < 1$

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

Be

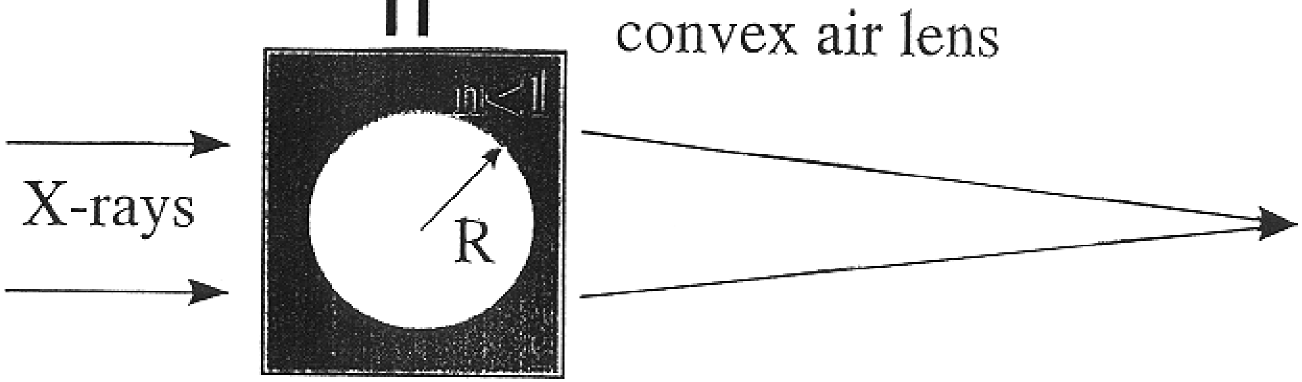
E = 10 keV

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

R = 100 μm

F = 15 m

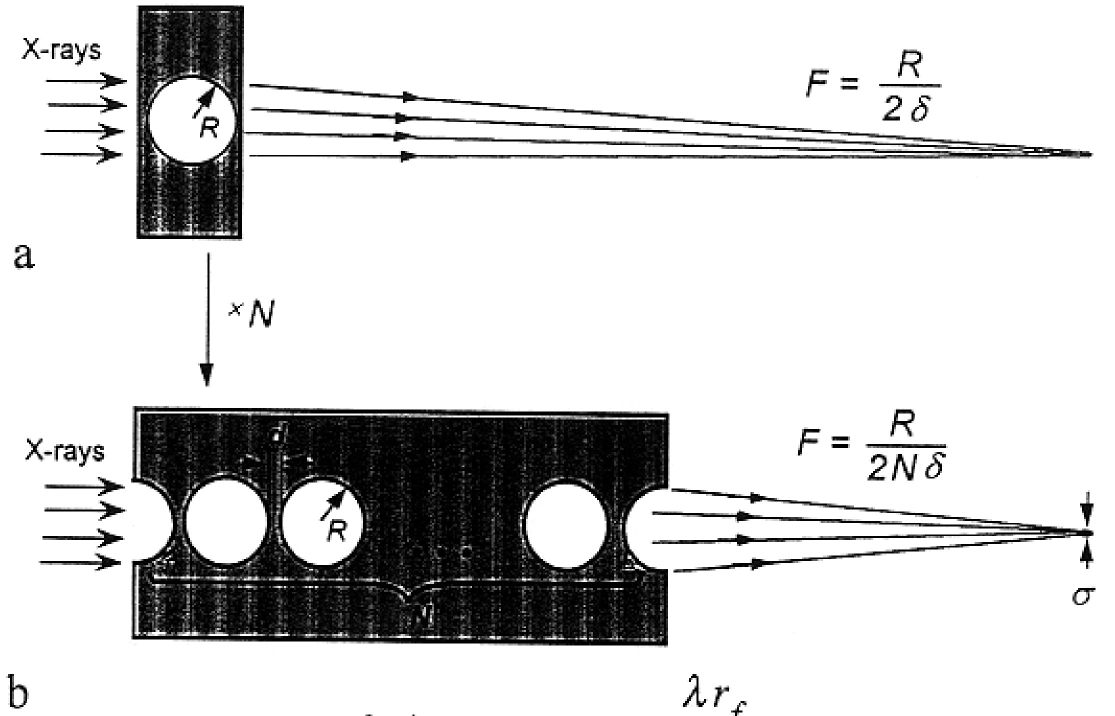
=



A. Snigirev

Compound Refractive Lens

Snigirev A., Kohn V., Snigireva I., Lengeler B., ***Nature***, *November 7, 1996*



index of refraction

$n = 1 - \delta + i\beta < 1$ $\quad (\delta > 0)$,

X-ray collecting lens has a **concave shape**

for Al at E = 10 keV $\quad \delta = 0.55\ 10^{-5}$

1 hole of 100 μm radius - $\quad$ F = 9 m

15 holes of 100 μm radius - $\quad$ F = 60 cm

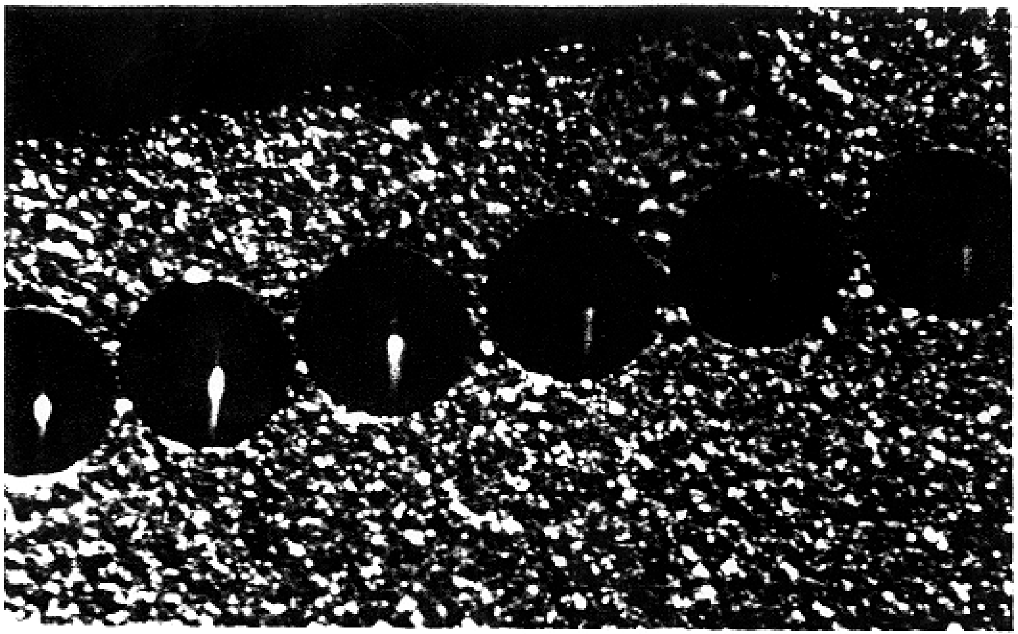
Gaussian lens formula: $r_f = F\left(1 - \frac{F}{r_0}\right)^{-1}$

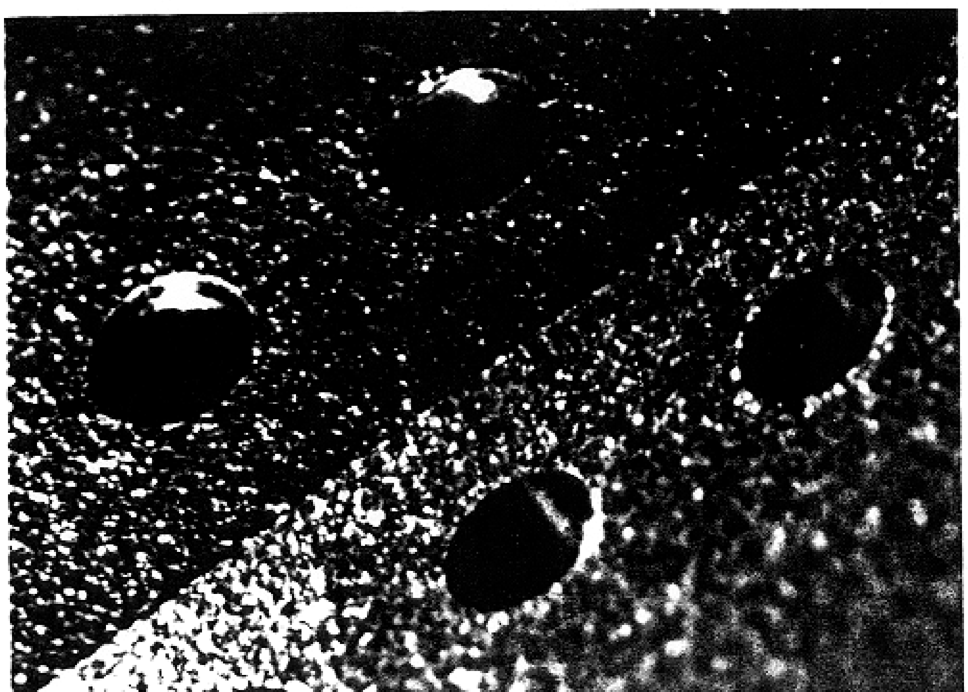
resolution $\quad \sigma_f = \frac{\lambda r_f}{A}$, $\quad$ effective aperture is limited by spherical aberrations or by absorption

$$A_t = 2R\left(4\frac{\lambda r_f}{R^2}\right)^{\frac{1}{4}}, \qquad A_a = 2R\left(\frac{2}{\mu R N}\right)^{\frac{1}{2}},$$

real gain $\quad g = aG\frac{\sigma_f}{\sigma_1} = a\frac{A}{\sigma_0}\left(\frac{r_0}{r_f} + 1\right)$, where $a = \exp(-\mu N d)$, $\sigma_1 = \sigma_0 r_f / r_0$

chromatic aberrations $\quad \frac{\Delta\lambda}{\lambda} \approx \frac{\beta}{\delta}$





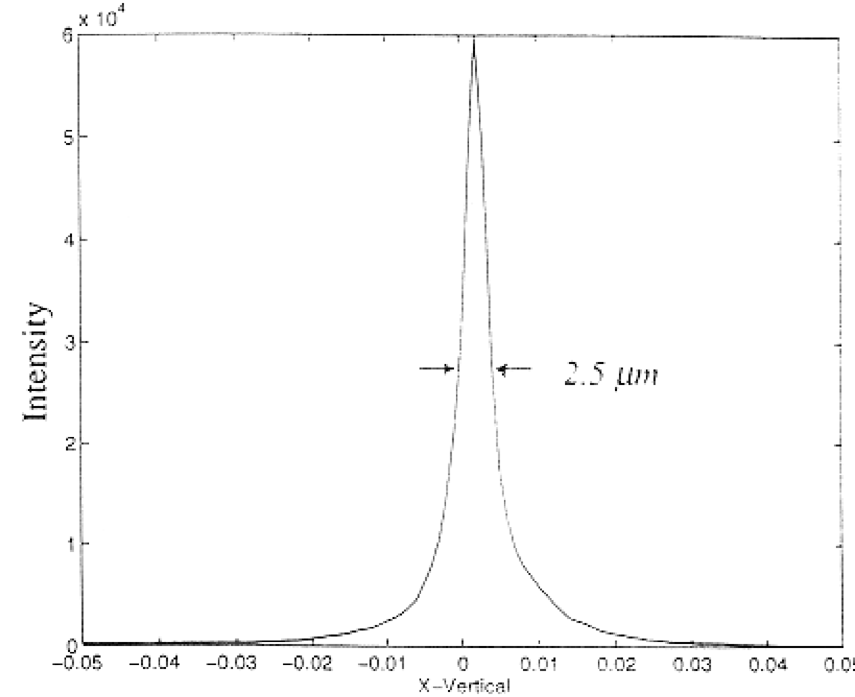


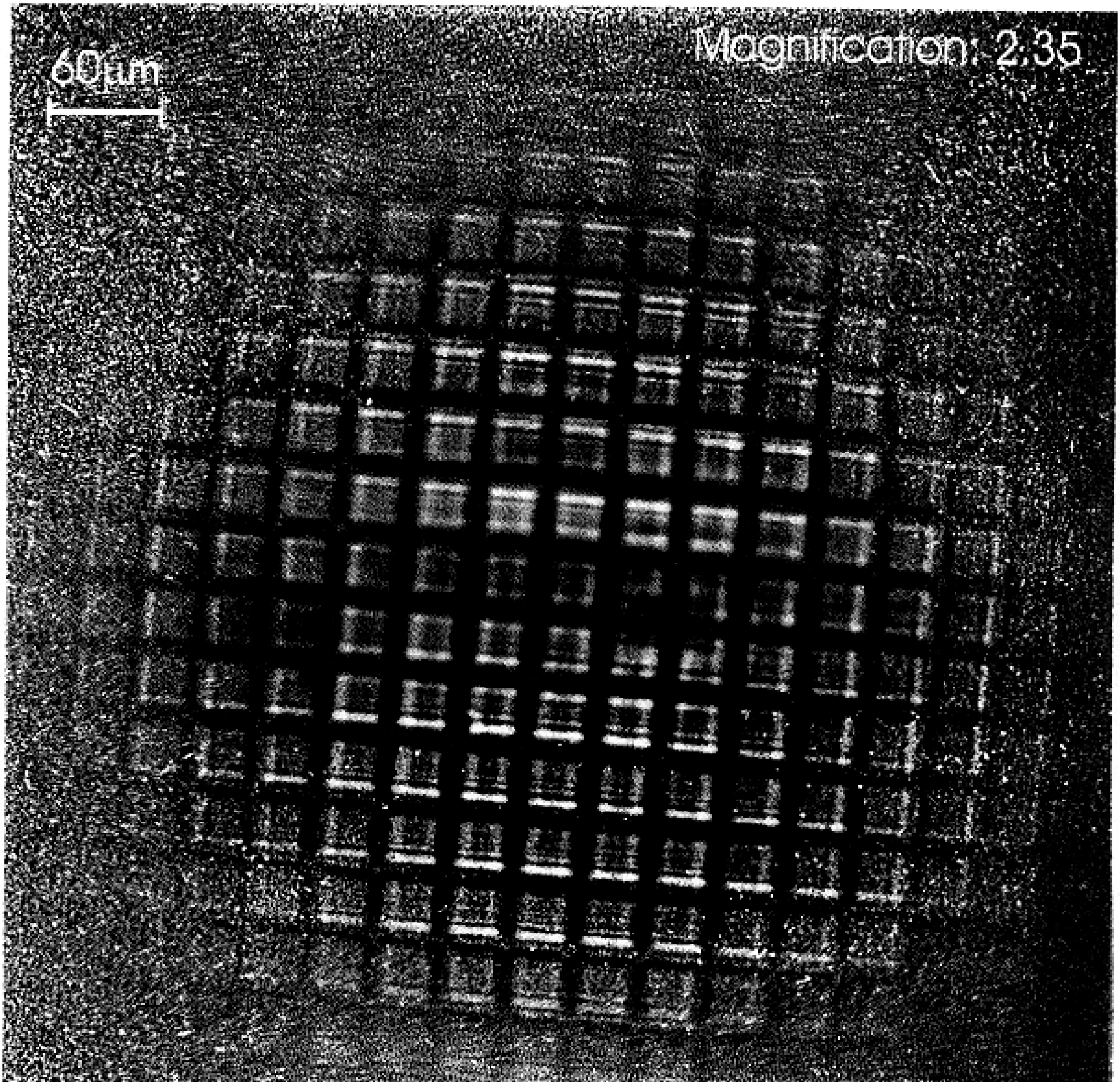
Image in optical microscope of linear and two-dimensional Be CRLs with 69 holes of 500 μm diameter. Spacing in the thinner part between holes is about 100 μm.
Intensity distribution of the focal spot at 0.9 m focal distance for Be CRL at 9 keV X-ray energy. Width of the focusing line was measured of about 2.5 μm and was limited by the source size.

B. Lengeler, J. Tummler, I. Snigireva, C. Raven, A. Snigirev
Journal of Applied Physics, 1998

Optical properties of cylindrical CRLs. Experimental results.

Material	Hole radius, R (mm)	Distance between the holes, d (μm)	Energy, E keV	Focal length, F (m)	Number of holes, N	Spot size (FWHM), (vert./hor.) Δ (μm)	Gain, g
Be	0.50	100	12.6	1.7	69	3.4	5.7
Be	0.50	100	9.0	0.87	60	2.6	2.0
Be	0.25	20	12.5	1.09	53	3.3	9.0
Be crossed	0.50	50	9.2	1.82	36.5/37	7.6/19	13.6
Boron Nitride	0.25	50	12.5	1.64	39	-	-
Pyrocarbon	0.35	39	16.4	1.70	59	4.2	12.6
Teflon	0.35	38	23.7	1.78	134	11.0	1.0
Teflon crossed	0.35	38	16.7	1.83	67/67	5.2/18	0.8
PMMA	0.25	30	12.5	1.27	59	10.0	4.5
Polycarbonate	0.25	50	12.5	1.88	40	4.9	6.5
Polyoxymethyline	0.25	30	12.5	1.61	40	3.5	4.4
Vespel	0.25	30	12.5	1.28	50	5.0	1.9
Al (0.5%Mg))	0.50	38	18.8	1.70	96	3.5	1.3
Al(2x)	0.50	38/40	27.1	1.70	192	4.5	1.3

Imaging of a gold grid (15 μm period) by X-ray refractive lens at 15 keV



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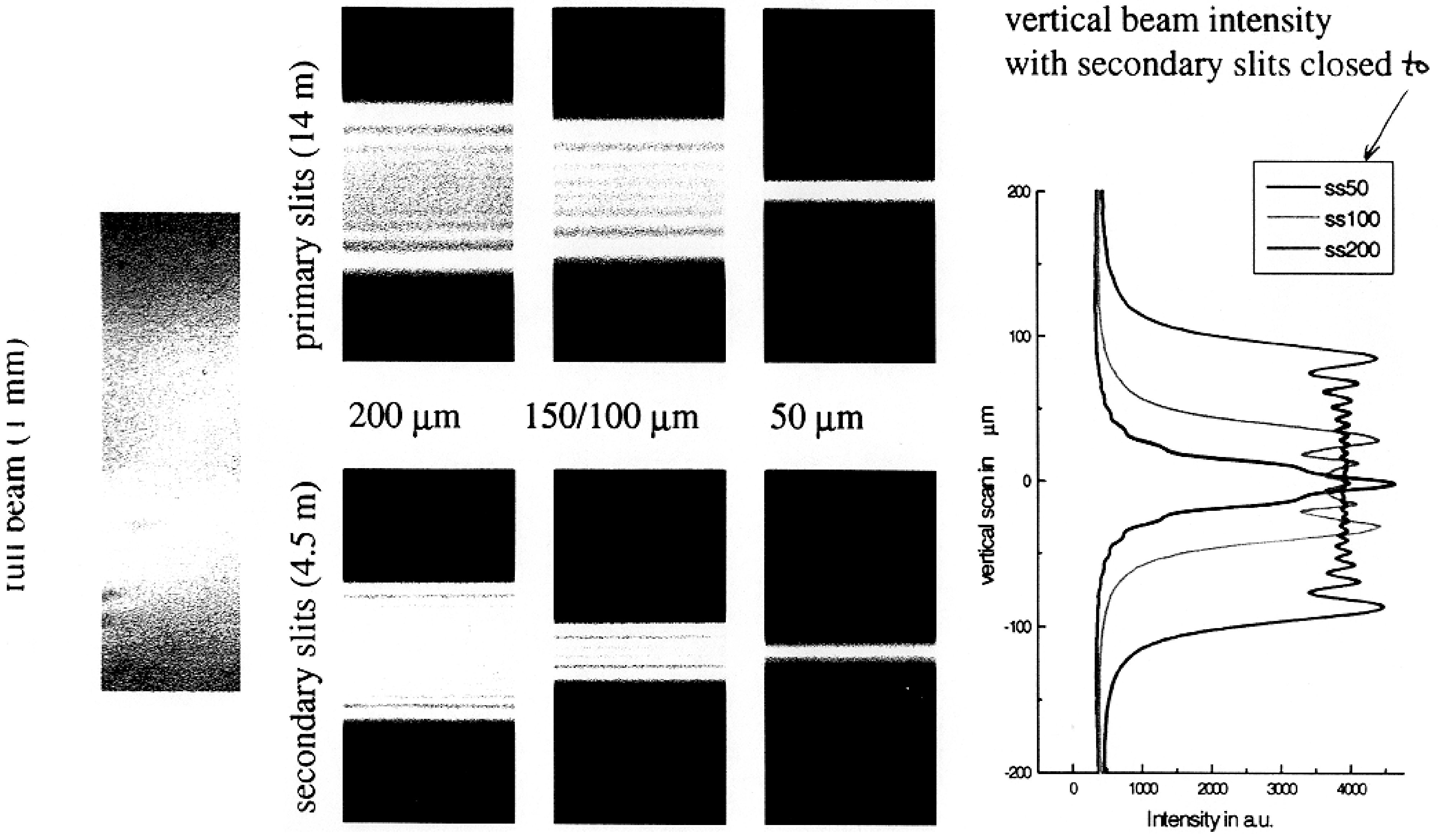
Fresnel diffraction on the slits / ID22

A. Snigirev, I. Snigireva, V. Kohn, C. Raven (ESRF)

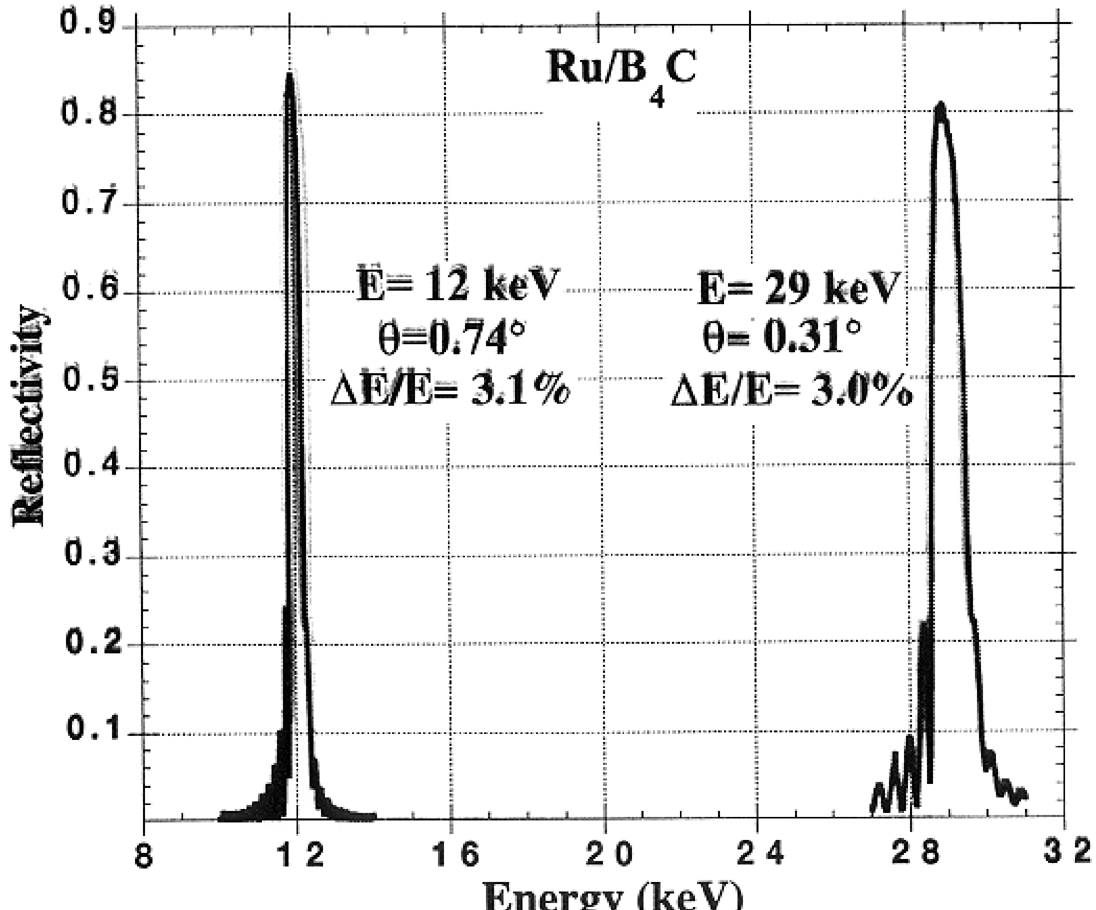


MULTILAYER CHARACTERISTICS

Courtesy: E. ZIEGLER, Ch. MORAWE (ESRF)

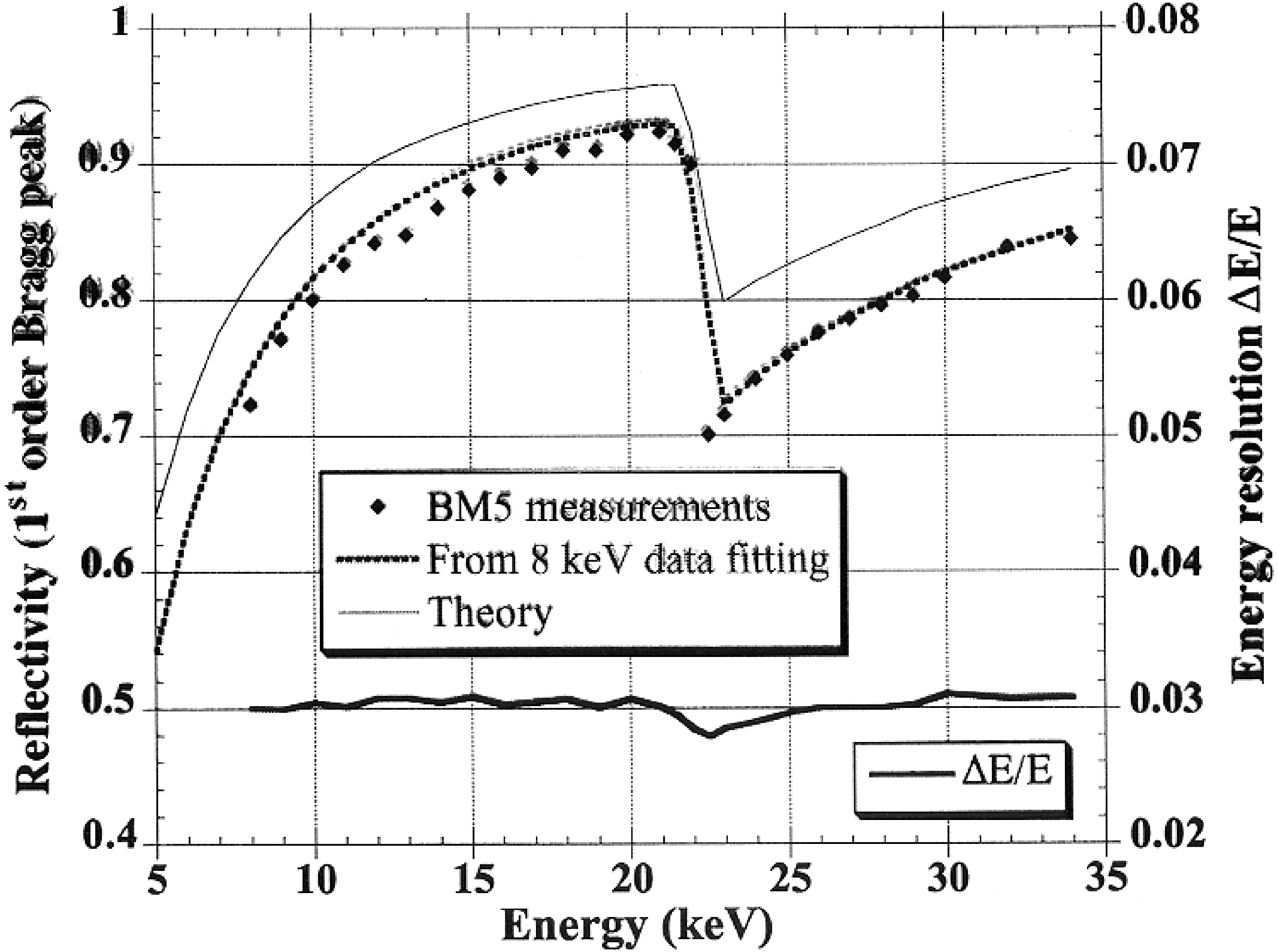
[Ru/B$_4$C]65 d-spacing: 4.19 nm manufactured at ESRF02

interface roughness: σ_{rms}=0.25 nm

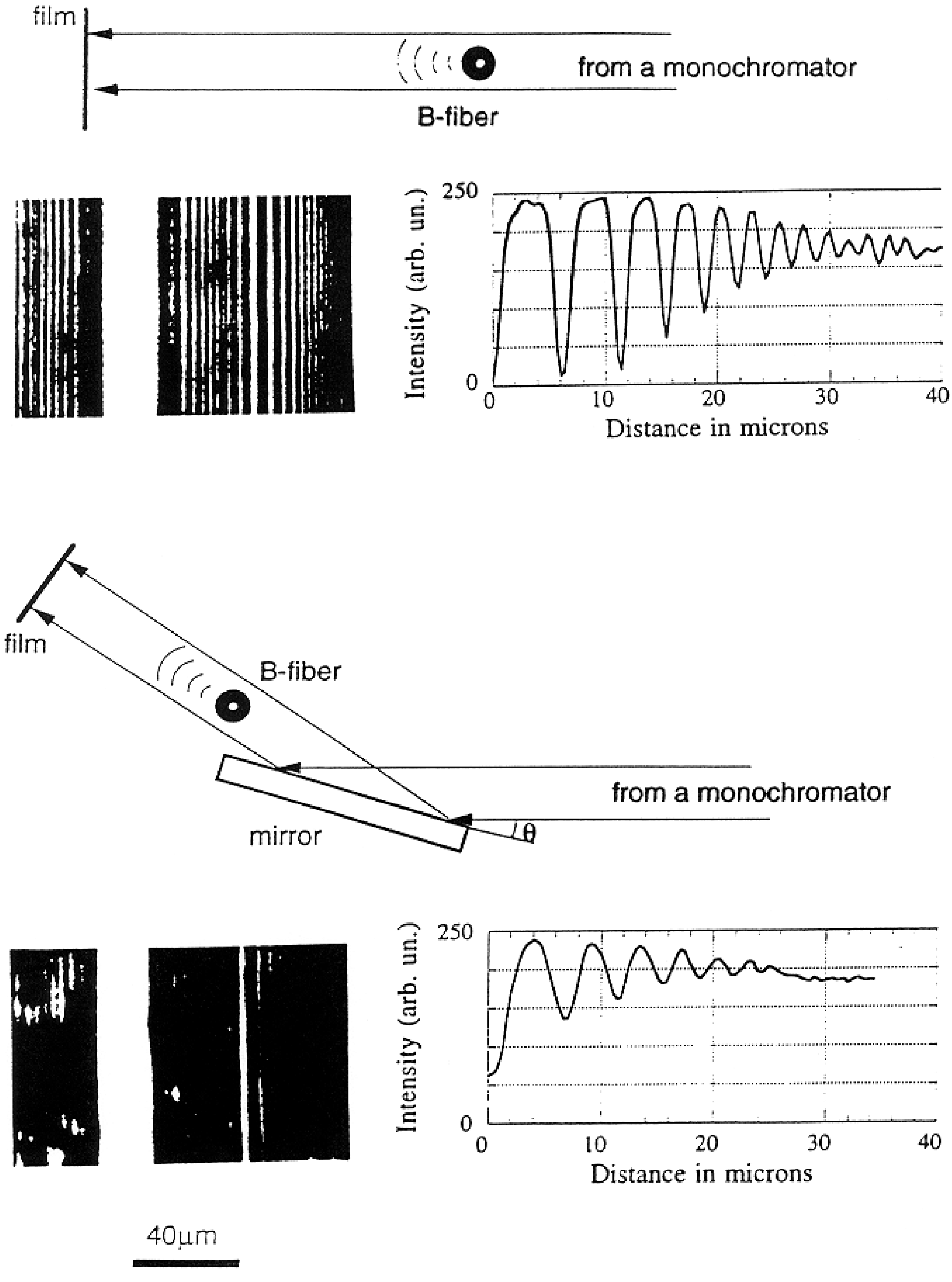


MULTILAYER PERFORMANCE vs ENERGY

Courtesy: E. ZIEGLER, Ch. MORAWE (ESRF)

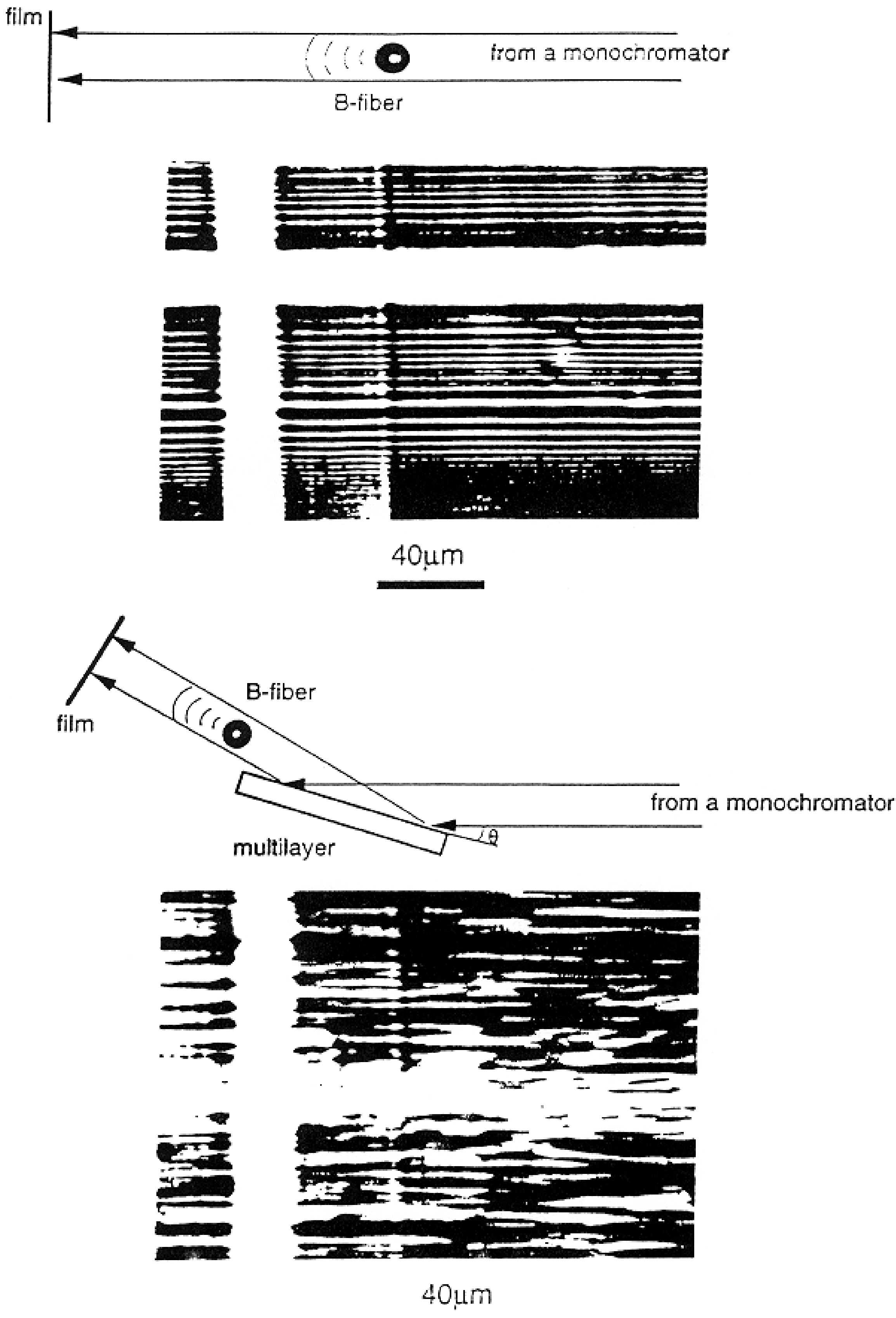


E=10keV
B-fiber ø100µm (W-core ø15µm)
fiber-to-film distance 50cm



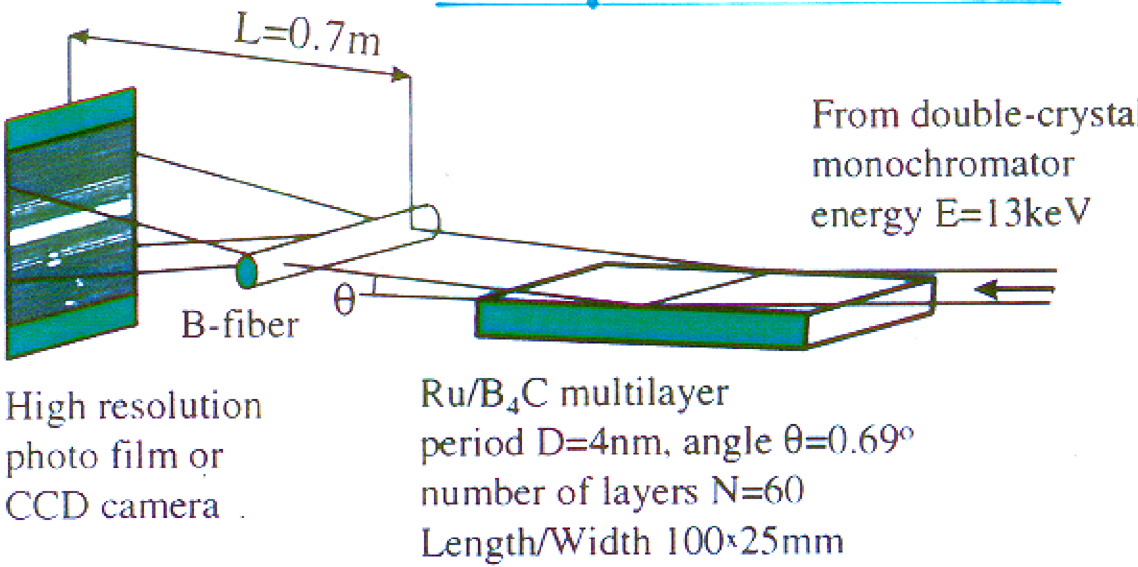
Snigirev et al., 1995.

B-fiber ø100μm (W-core ø15μm)
fiber-to-film distance 50cm
W-Si multilayer d=35Å



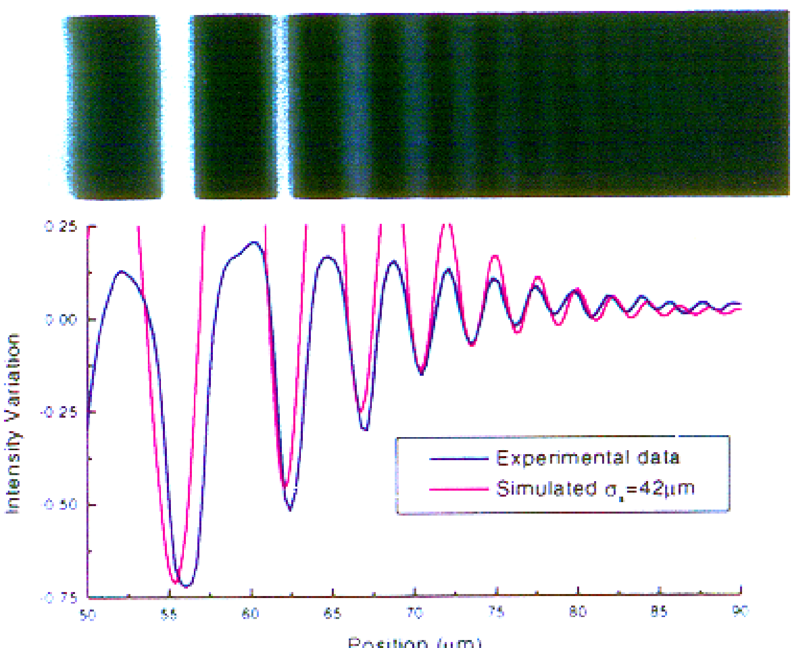
Snigirev et al., 1995.

Courtesy: A. Souvorov (ESRF)

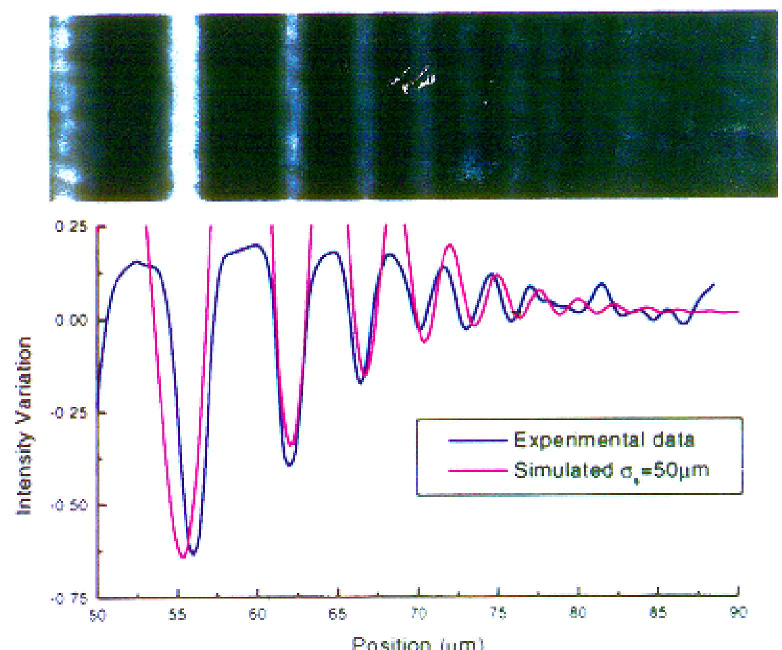


Intensity RMS~10.4%

Incident beam

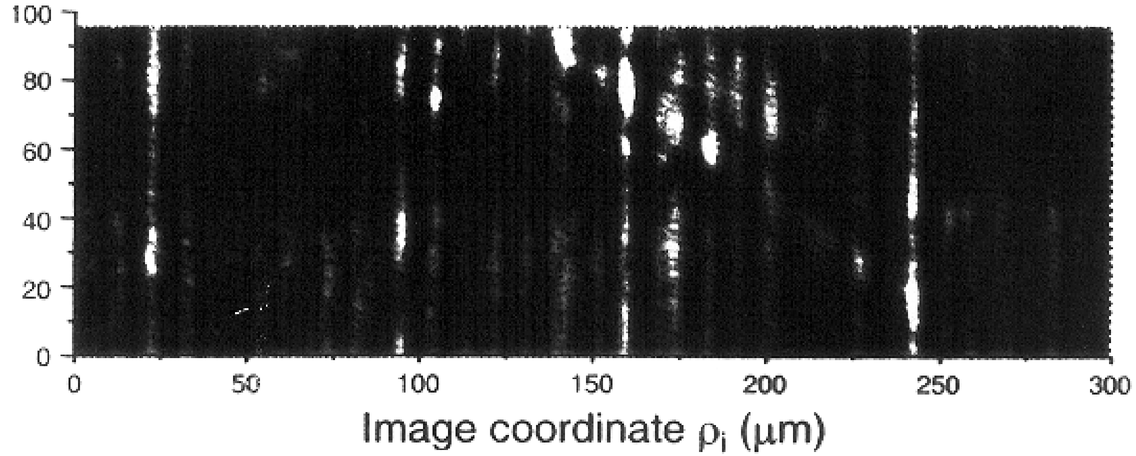


Reflected beam



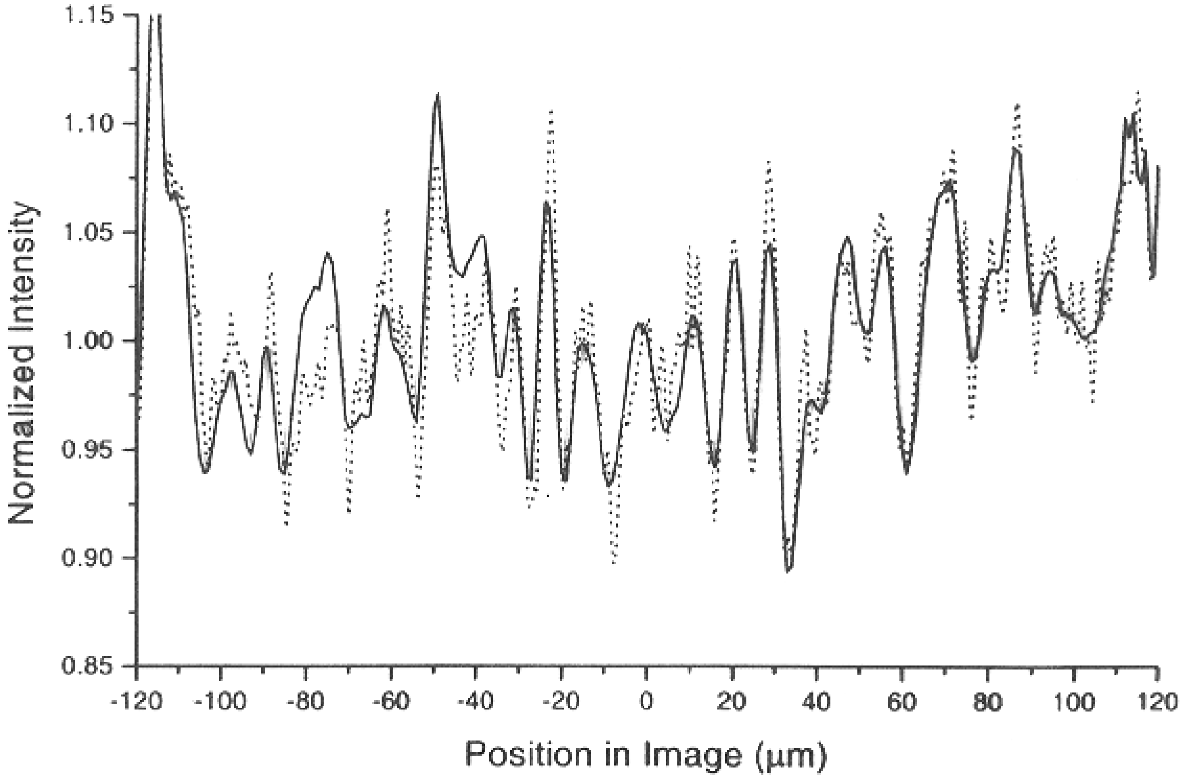
Source size increment by 20%

Souvorov A.



100
80
60
40
20
0
0
50
100
150
200
250
300
Image coordinate ρ_i (μm)

a)



Normalized Intensity
1.15
1.10
1.05
1.00
0.95
0.90
0.85
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
120
Position in Image (μm)

b)

Figure 3