UNITED NATIONS EDUCATIONAL, SCIENTIFIC AND CULTURAL ORGANIZATION
INTERNATIONAL ATOMIC ENERGY AGENCY
INTERNATIONAL CENTRE FOR THEORETICAL PHYSICS
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H4.SMR/1013-25

SCHOOL ON THE USE OF SYNCHROTRON RADIATION
IN SCIENCE AND TECHNOLOGY:
"John Fuggle Memorial"

3 November - 5 December 1997

Miramare - Trieste, Italy

BRAGG-FRESNEL OPTICS
Principles and Applications

Werner Jark
Area di Ricerca
Sincrotrone Trieste, Italy

BRAGG-FRESNEL OPTICS

Principles and Applications

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PLAN

- **Bragg-Fresnel Optics Principles**
  from Zone Plate to Bragg Fresnel Lens

- **Experimental Results for 1D focussing optics**

- **Experimental Results for 2D focussing optics**

- **Applications**
  Imaging
  Hard X-RAY Microprobe (LURE- ESRF)

- **Conclusion**

[redacted]

BRAGG-FRESNEL LENSES

Association of 2 kinds of MICROSTRUCTURE

Multilayer
Crystal

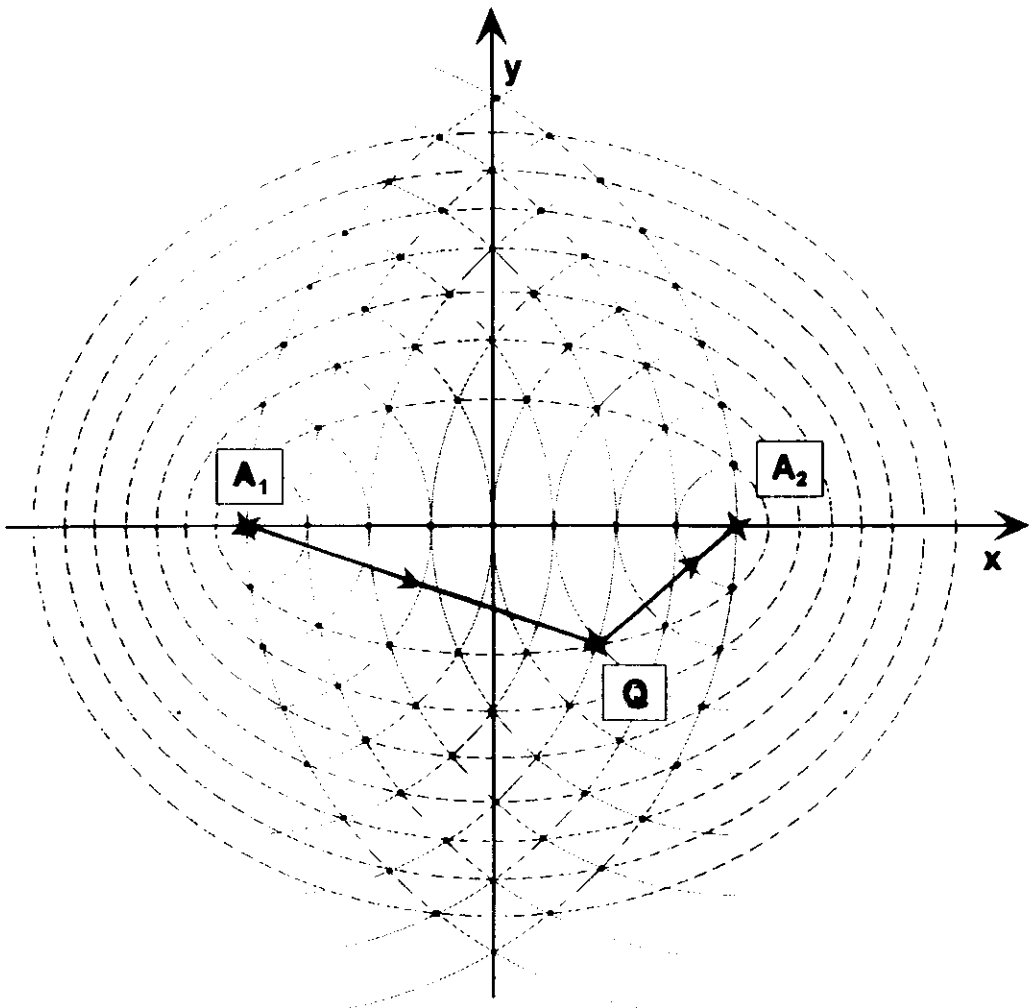
↓

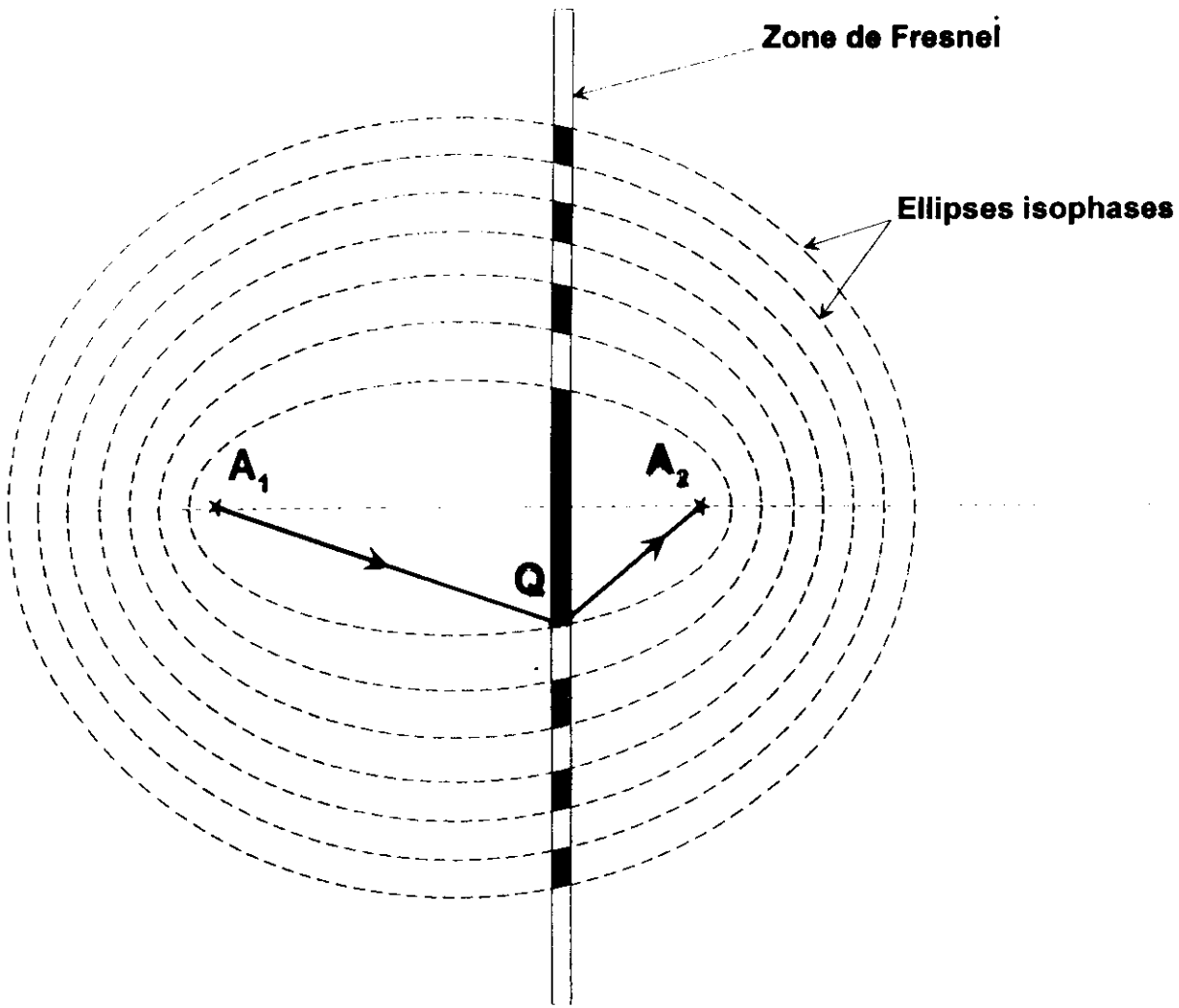
BRAGG
DIFFRACTION

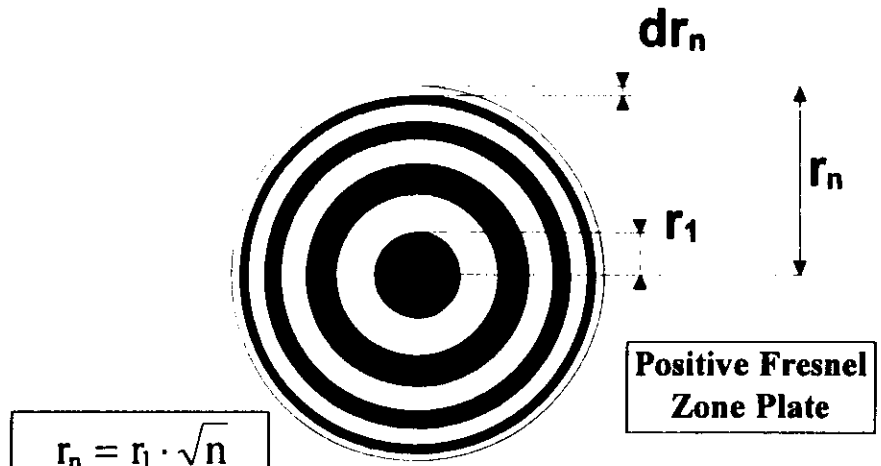
GRATINGS
ZONE PLATE

↓

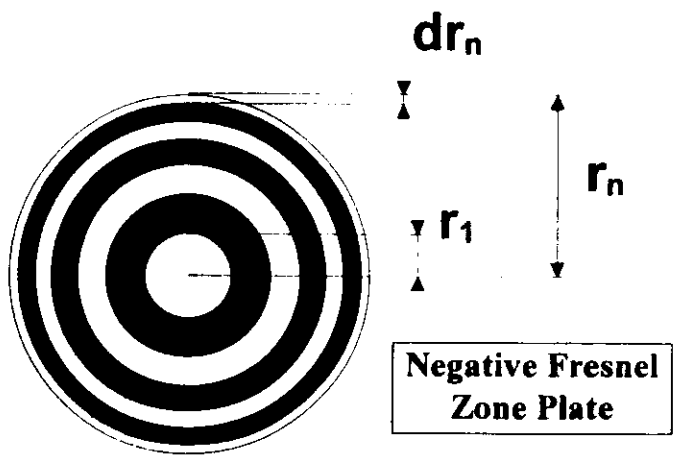
FRESNEL
DIFFRACTION


y
x
A1
A2
Q


Zone de Fresnel
Ellipses isophases
A1
A2
Q

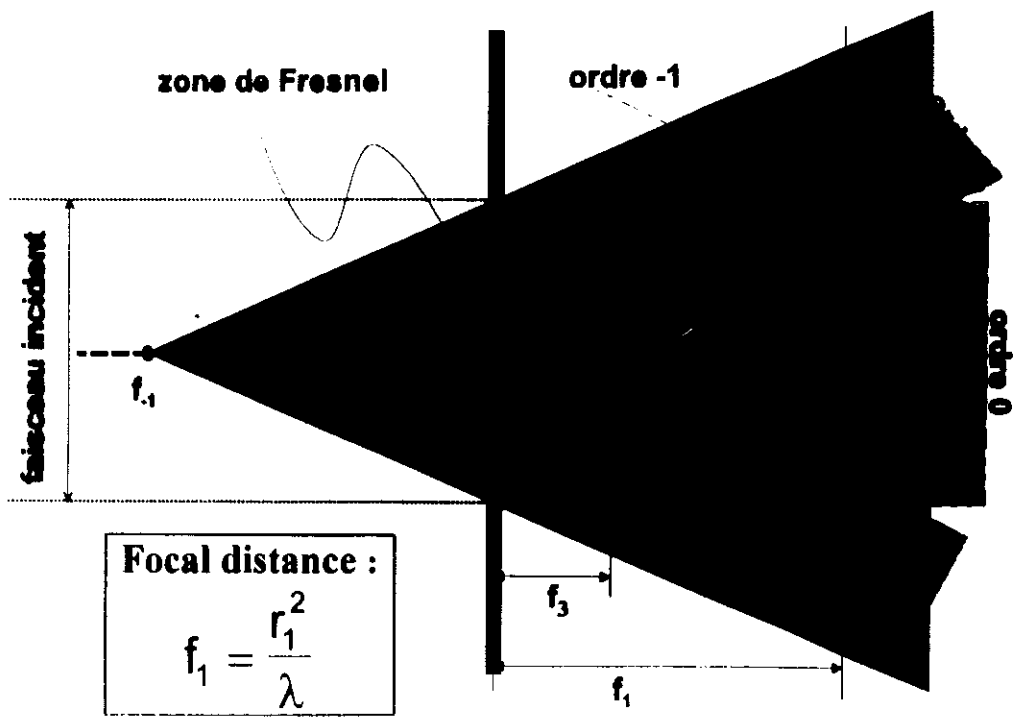


Positive Fresnel Zone Plate



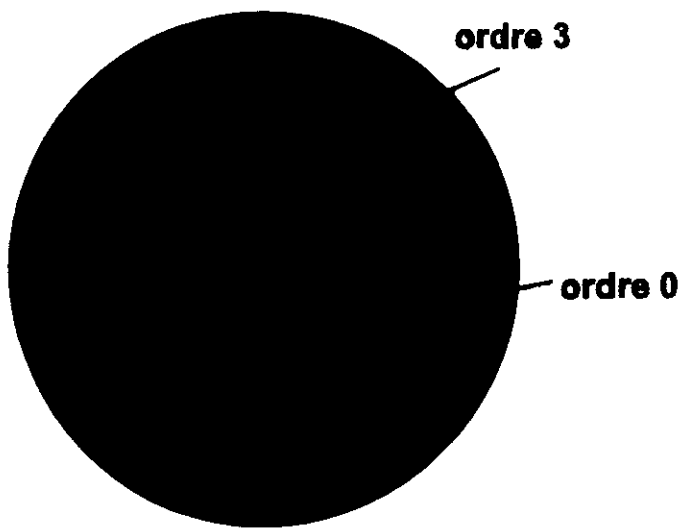
Negative Fresnel Zone Plate

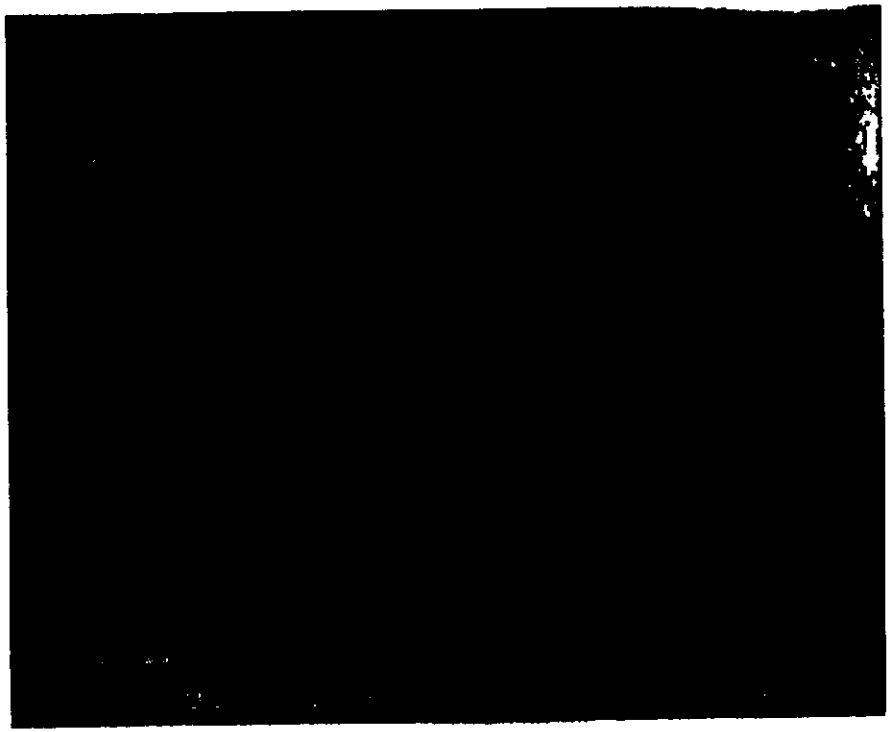
$$r_n = r_1 \cdot \sqrt{n}$$



Focal distance :

$$f_1 = \frac{r_1^2}{\lambda}$$





N=68 zones
r_1=6,63 µm
D=110 µm
r_n=0,4 µm
e=0,5 µm

[redacted]

A) MULTILAYER FABRICATION

Sputtering of the two materials.

B) MICROLITHOGRAPHY TECHNICS

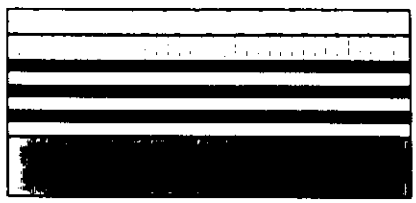
TWO STEPS :

1) Electronic lithography
Writing of " THE HOLOGRAM" at the multilayer surface.

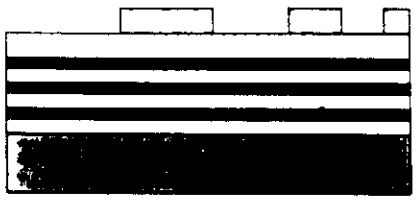
2) Reactive ion etching
Transfer of " THE HOLOGRAM" in the multilayer.

1) Substrat de Silicium poli

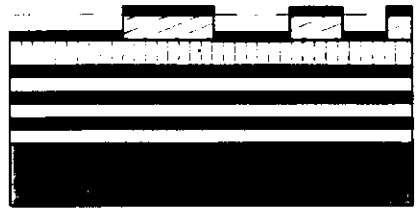
2) Dépôt d'une multicouche



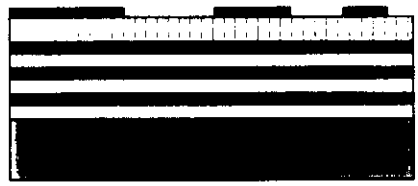
3) Dépôt d'une couche de Germanium et de la résine PMMA



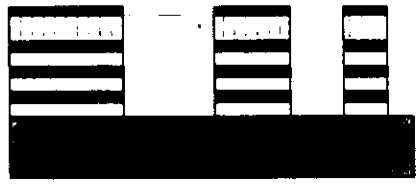
4) Ecriture par faisceau d'électrons et développement de la résine PMMA



5) Dépôt de Nickel

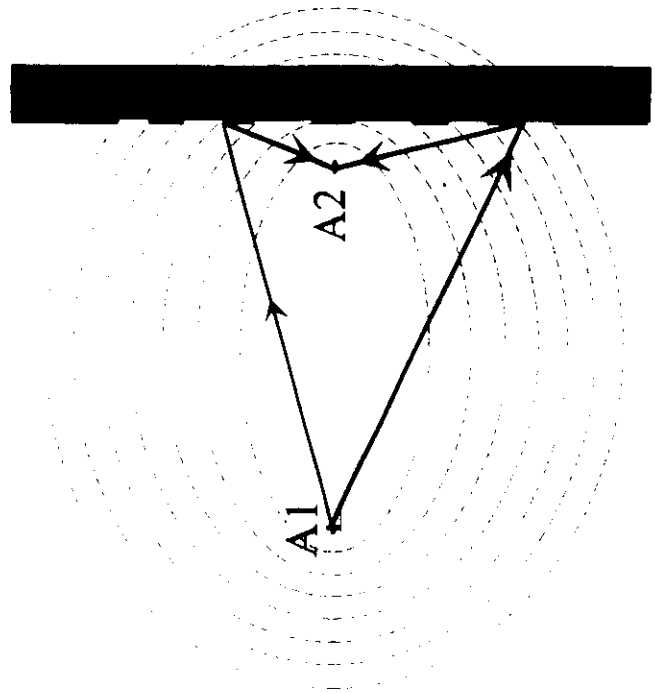


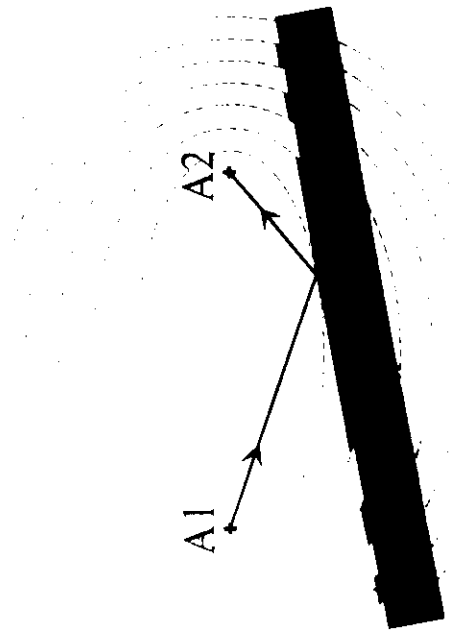
6) "Lift-off" du Nickel par élimination de la résine et du métal supporté



7) Gravure ionique réactive dans un plasma fluoré

8) Elimination du masque de Nickel et du Germanium


A2
A1

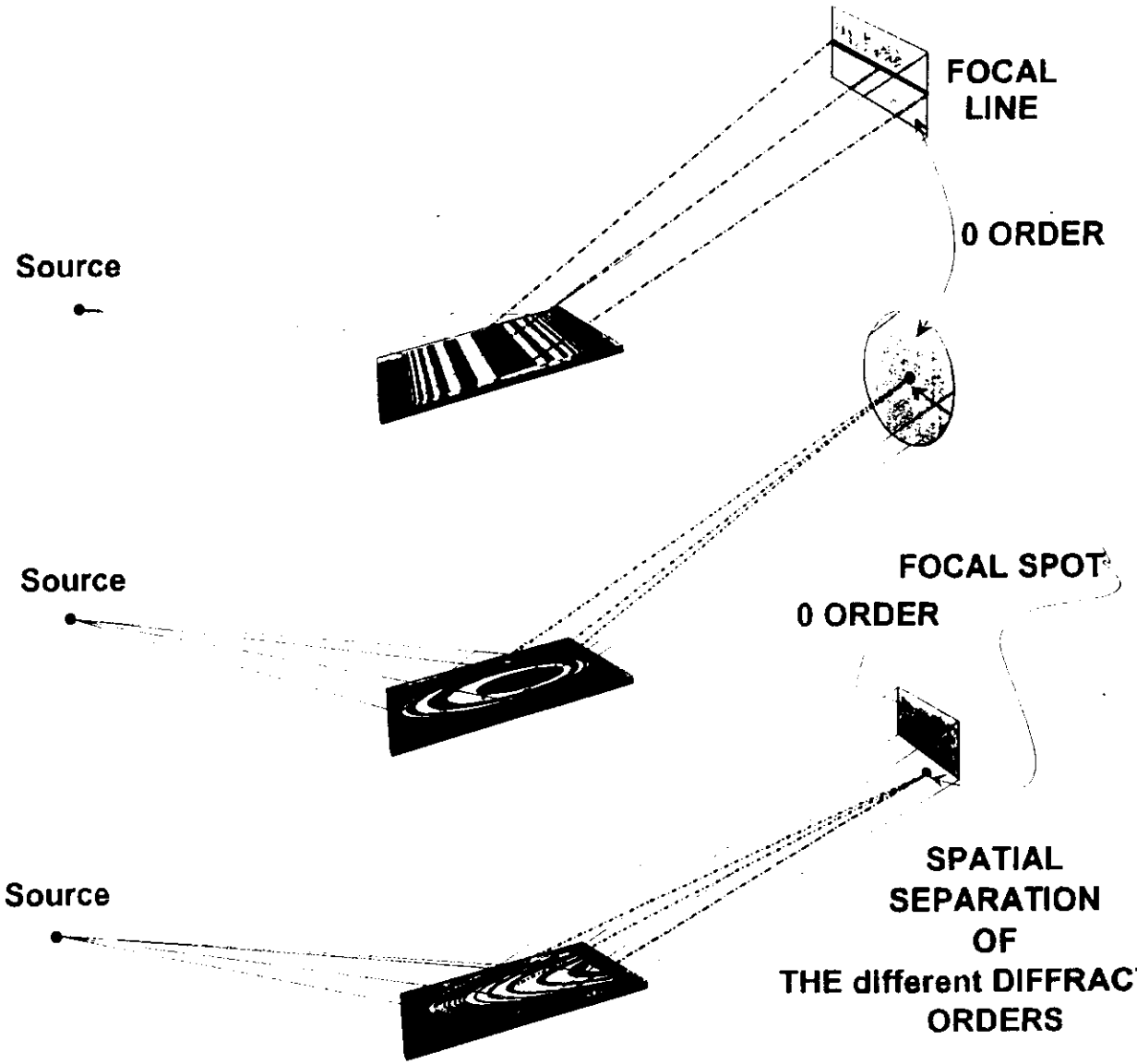

A2
A1

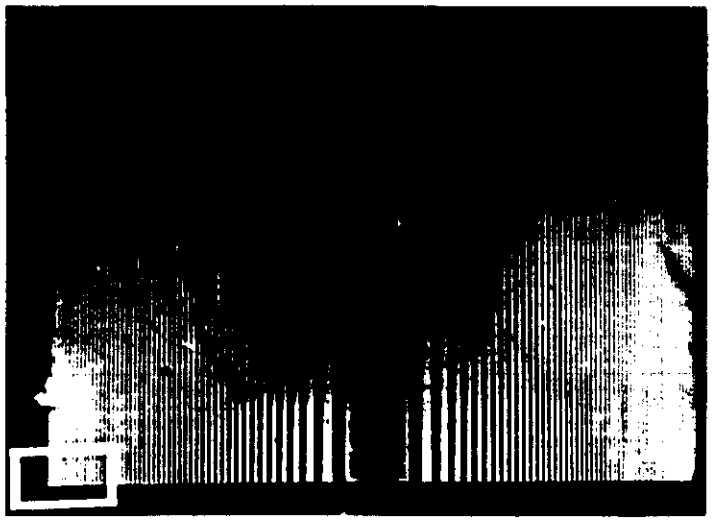
NEW KIND of FOCUSING and IMAGING OPTICS
for the X and XUV ENERGY RANGES

LINEAR LENS

ELLIPTICAL LENS

ELLIPTICAL OFF-AXIS LENS

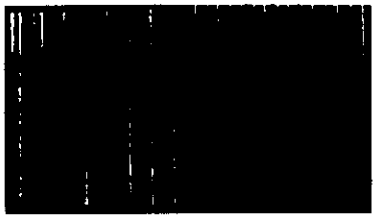




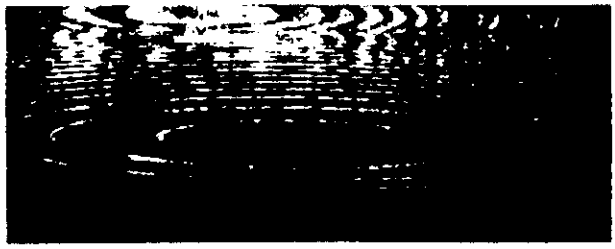
Zoom

Lentille de Bragg-Fresnel

linéaire positive



2 µm

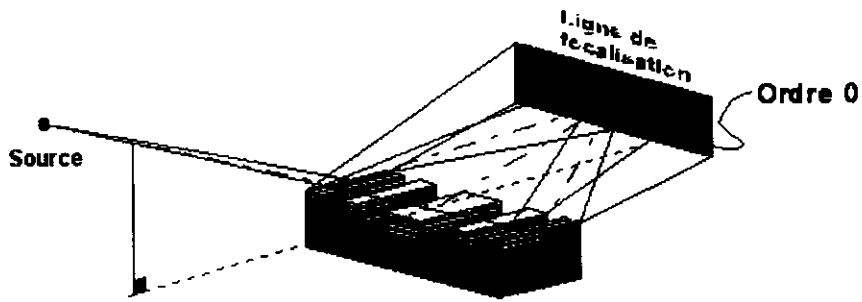


Zones centrales

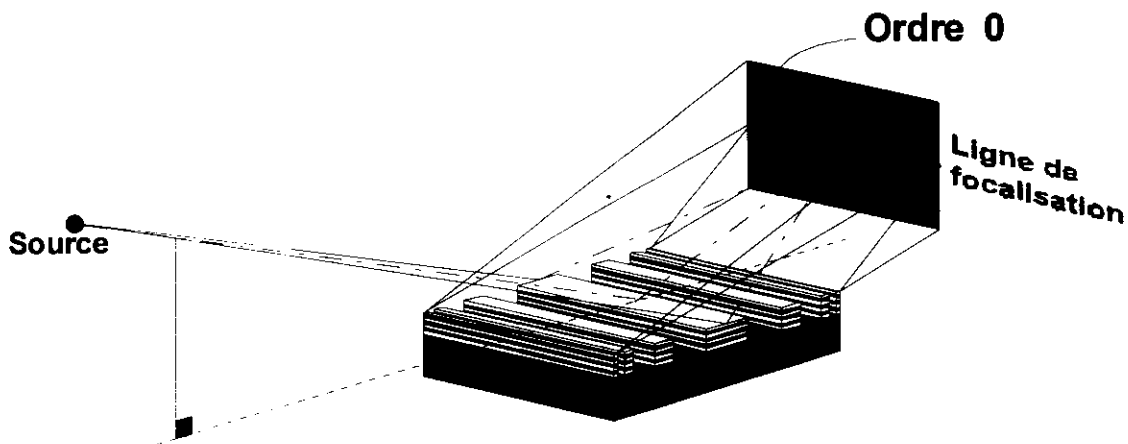
Lentille de Bragg-Fresnel elliptique positive

[redacted]

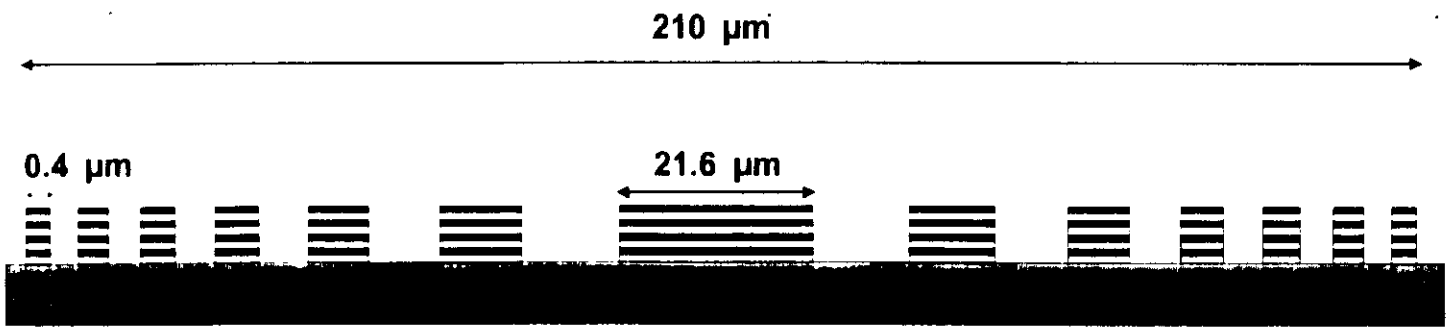
CONICAL DIFFRACTION



CLASSICAL DIFFRACTION



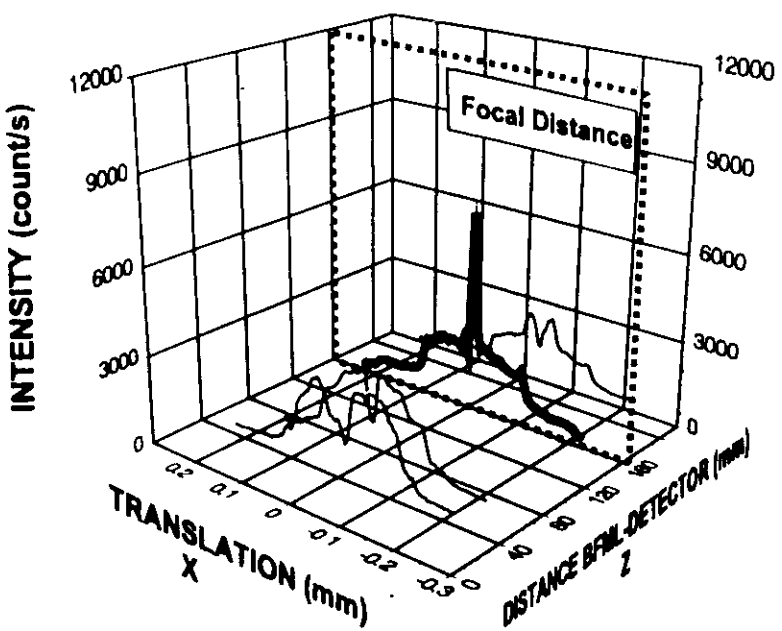
Multilayer W/Si 25 paires d= 53 Å E=1750 eV



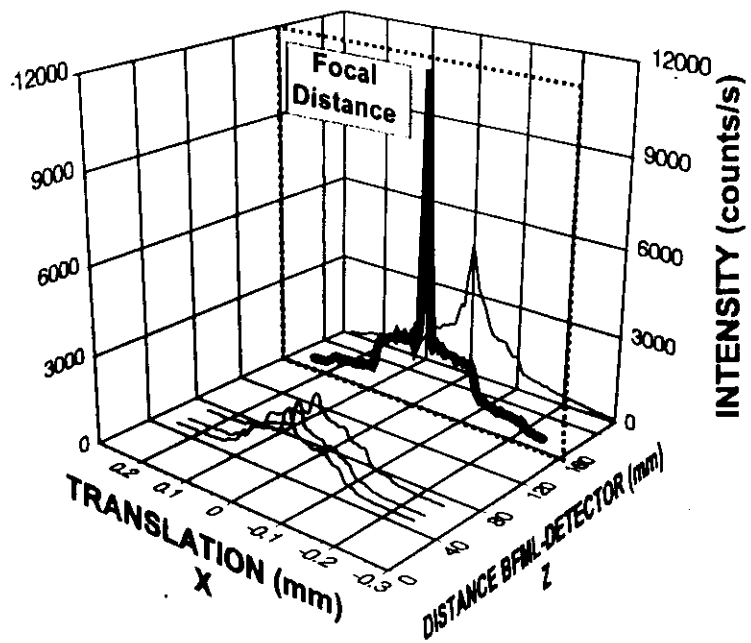
100 TRAITS **POSITIVE**

NEGATIVE

[redacted]

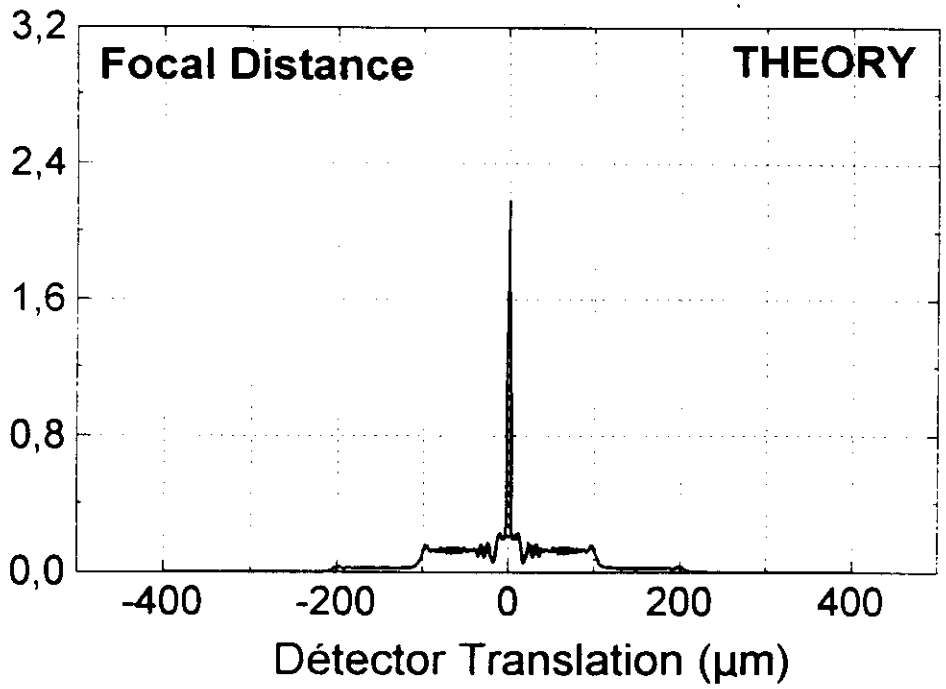


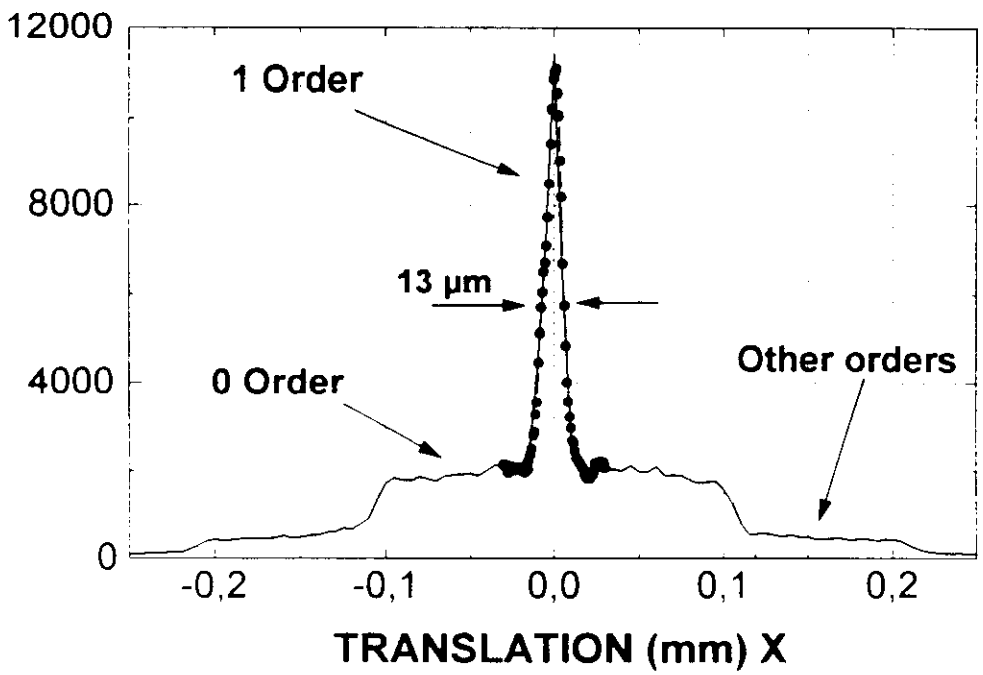
NEGATIVE LENS

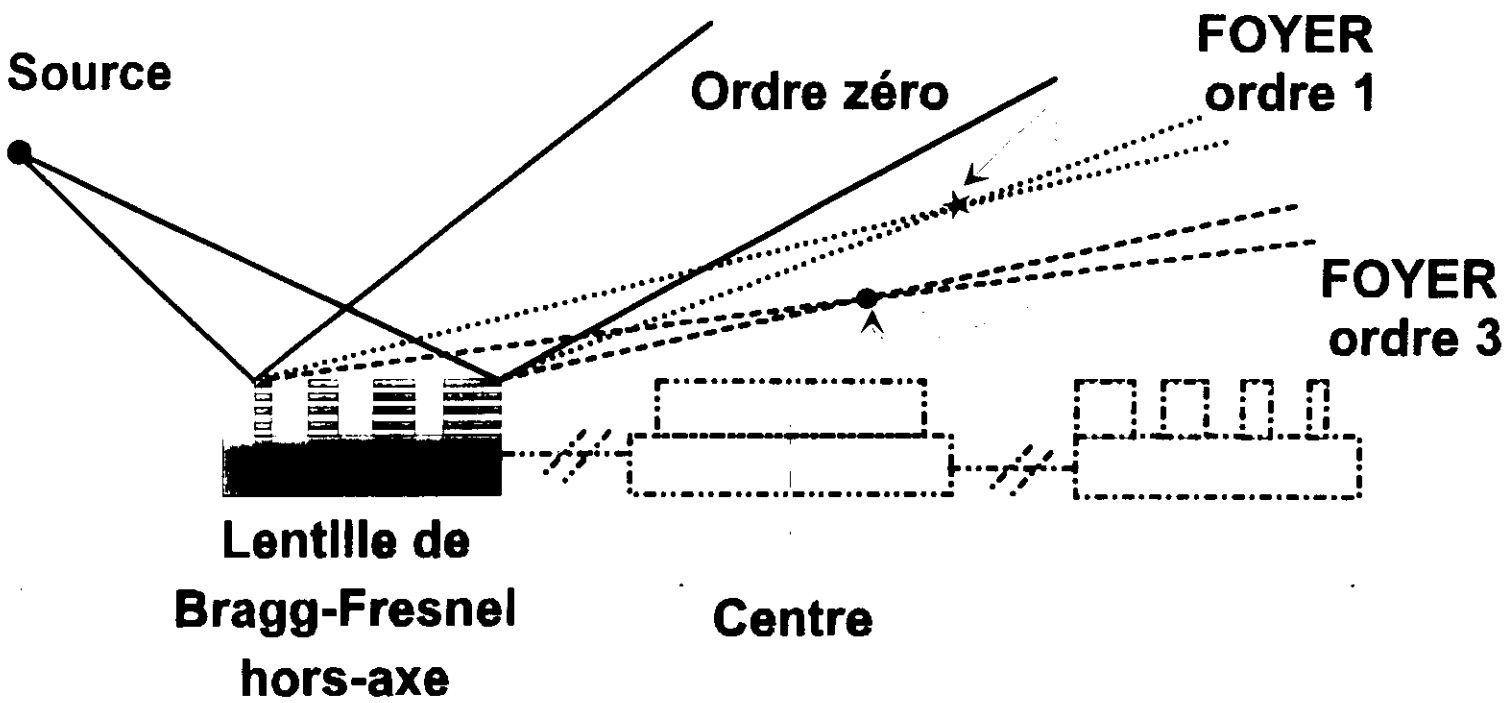


POSITIVE LENS

BRAGG-FRESNEL LENSES used in the [redacted] **mode**


Focal Distance
THEORY
3,2
2,4
1,6
0,8
0,0
-400
-200
0
200
400
Détector Translation (µm)


12000
8000
4000
0
1 Order
13 µm
0 Order
Other orders
-0,2
-0,1
0,0
0,1
0,2
TRANSLATION (mm) X


Source
Ordre zéro
FOYER
ordre 1
FOYER
ordre 3
Lentille de
Bragg-Fresnel
hors-axe
Centre

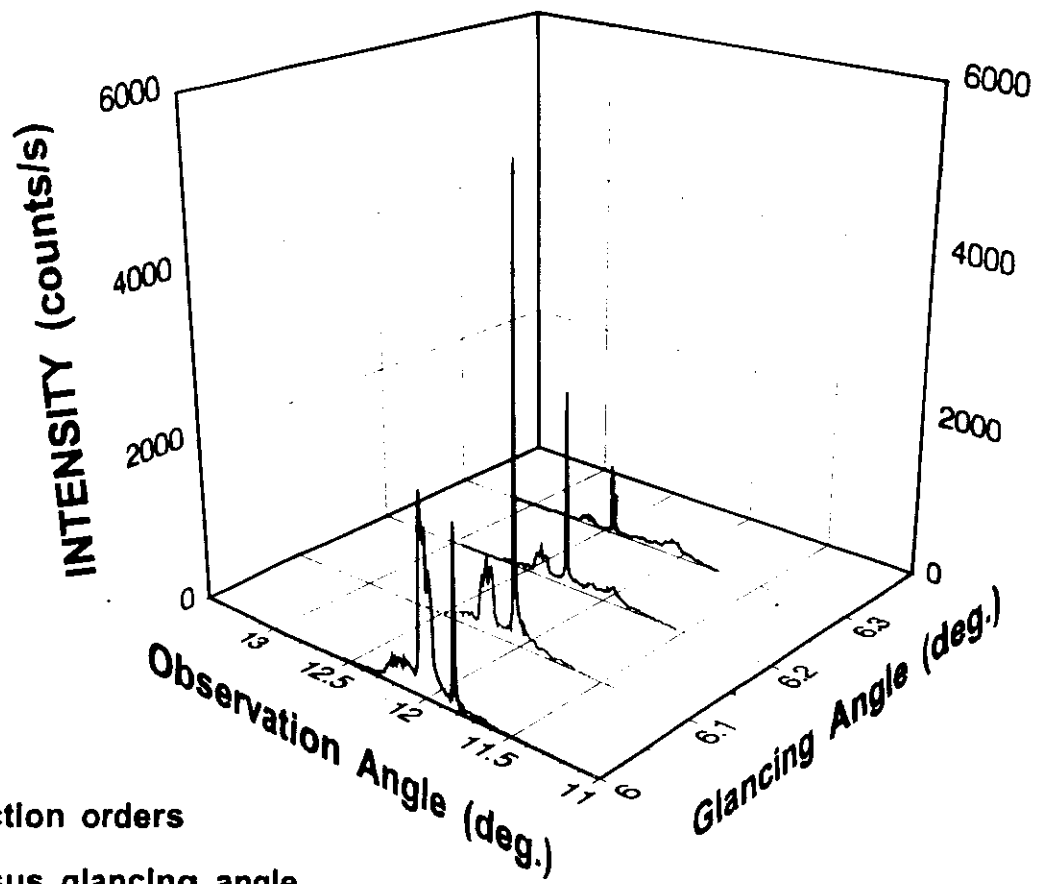
W/Si

d=34 A 65 bilayers

E=1750 eV

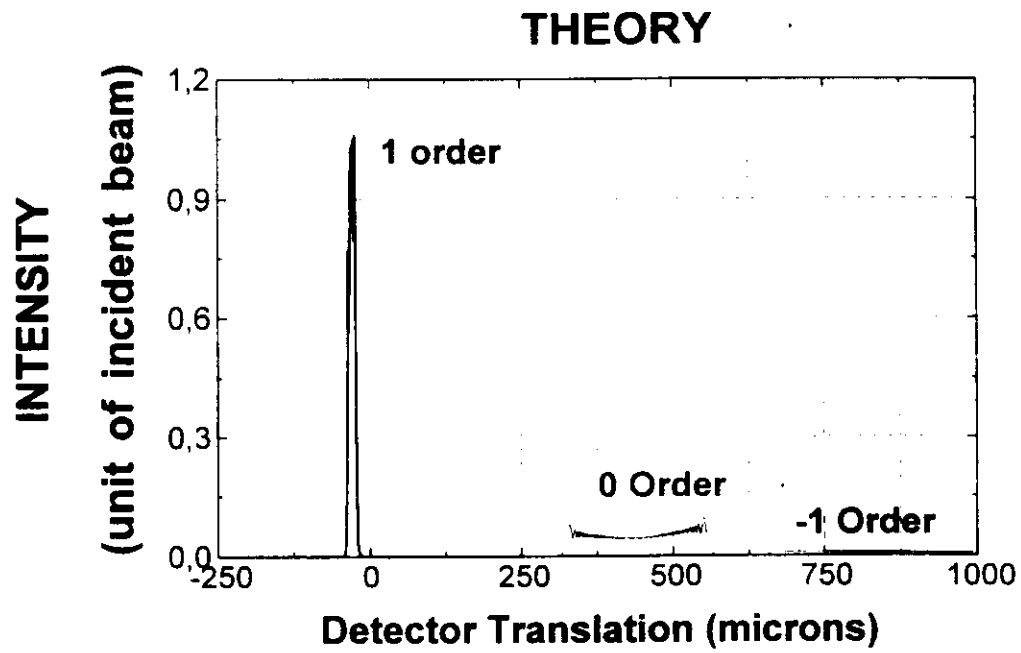
minimum zone width 0.9 µm

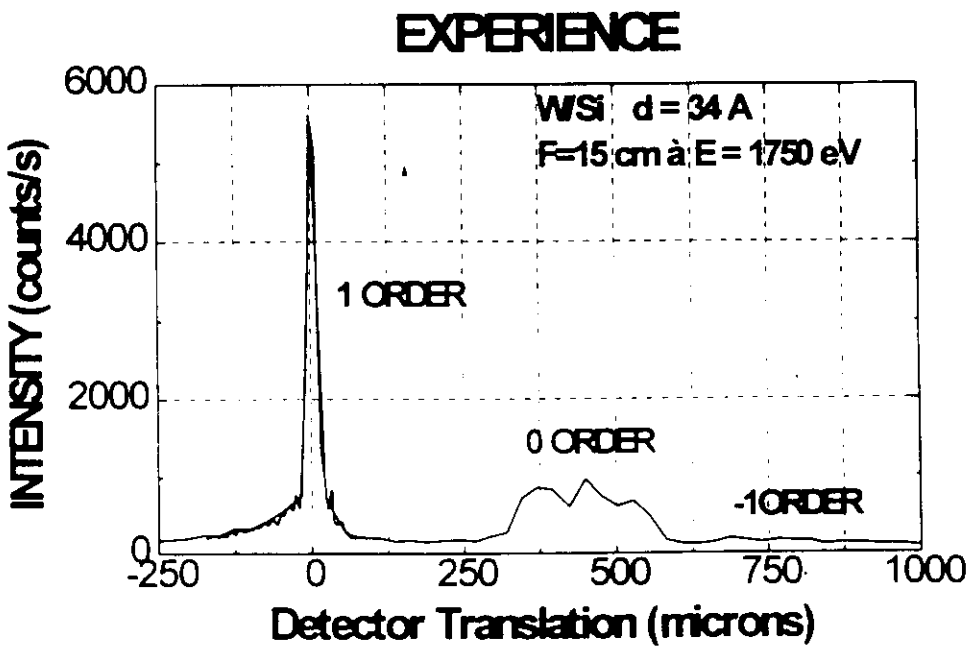
maximum zone width 1.5 µm



Separation of the different diffraction orders

Optimisation of the intensity versus glancing angle





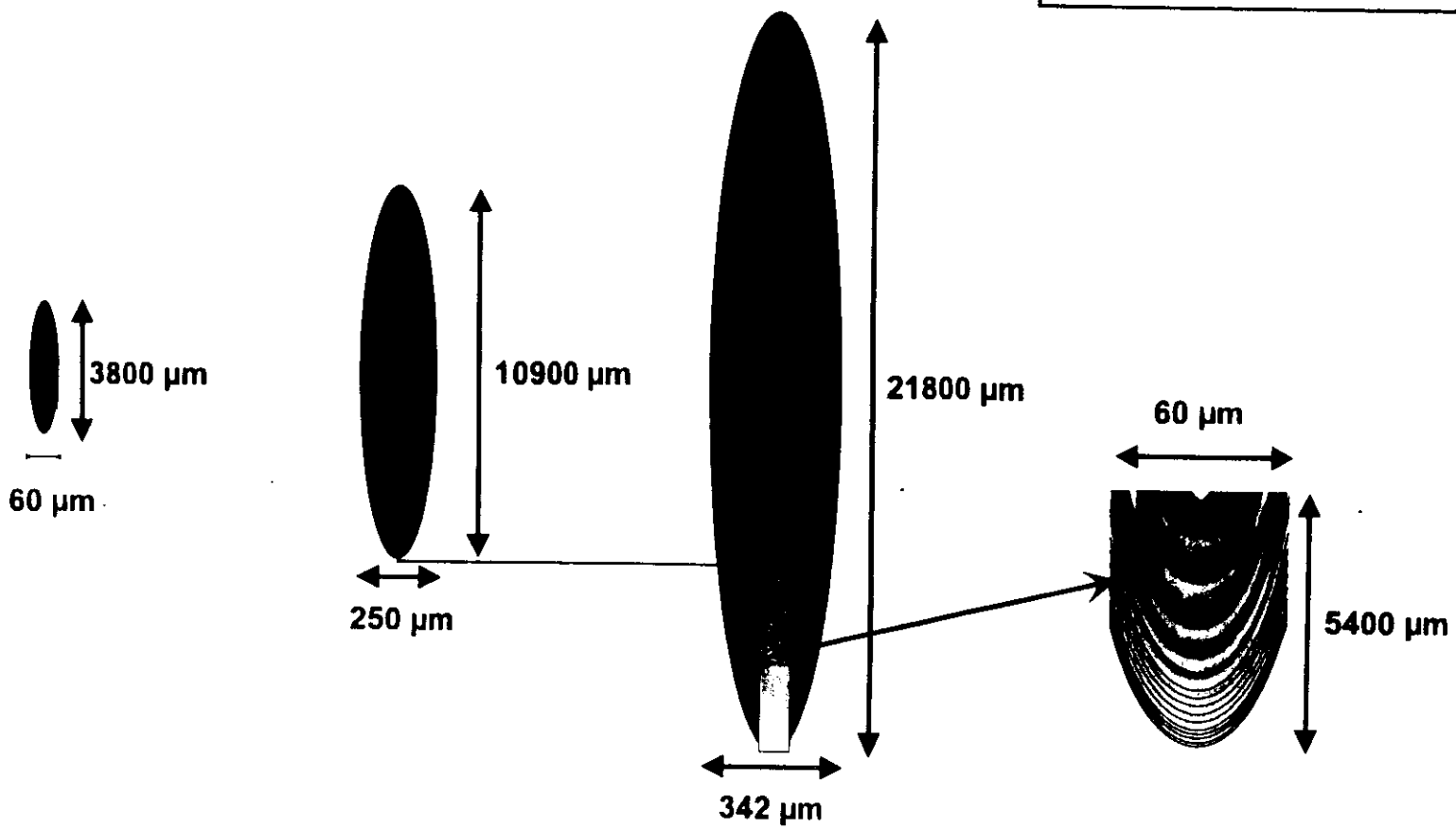
INCIDENCE ANGLE : 6.1 DEG.

30 traits
$\delta x = 0.26$ µm
$\delta y = 15.6$ µm

250 traits
$\delta x = 0.1$ µm
$\delta y = 5.9$ µm

1000 traits
$\delta x = 0.04$ µm
$\delta y = 2.7$ µm

Paramètres des lentilles
$\lambda = 1$ Å F = 15 cm
$\theta = 0.8$ deg.

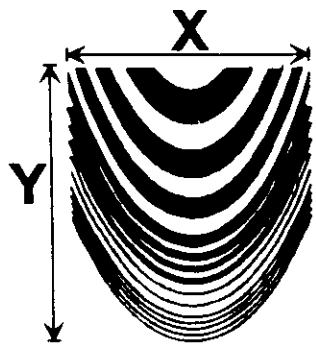


Material	Period : d_{∞} (Å)	γ	E / λ (eV / Å)	Number of bilayers
W / C	32	0.31	2535 / 4,89	65

Multilayer parameters

Number of grooves	size (µm) x direction / y direction	size of the first zone y direction (µm)	size of the last zone y direction (µm)	size of the zone in the center y direction (µm)
500 (du 12810 ième au 18810 ième)	200,1 / 2850,1	0,42	0,33	0,37

Parameters of the off-axis elliptical lens



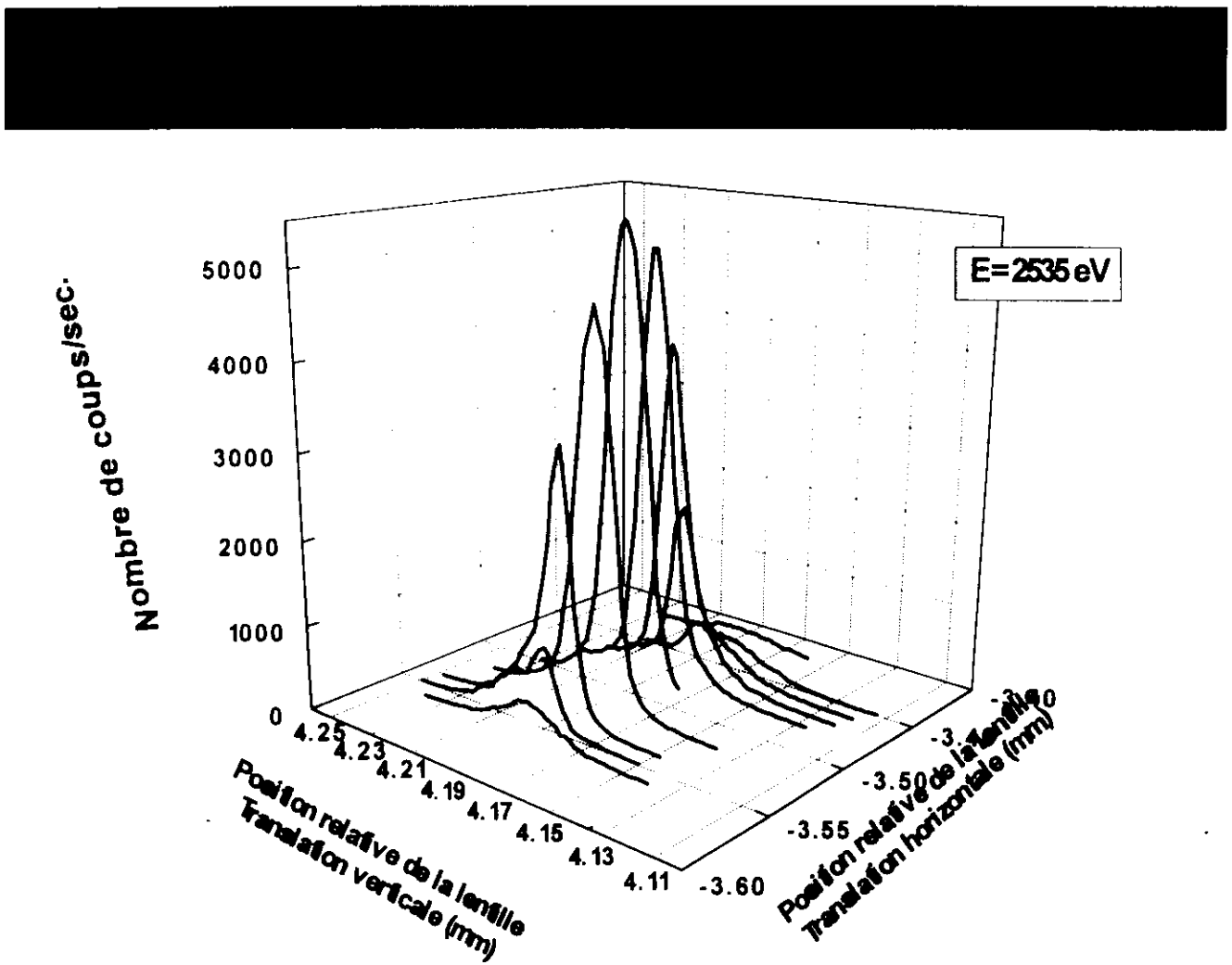
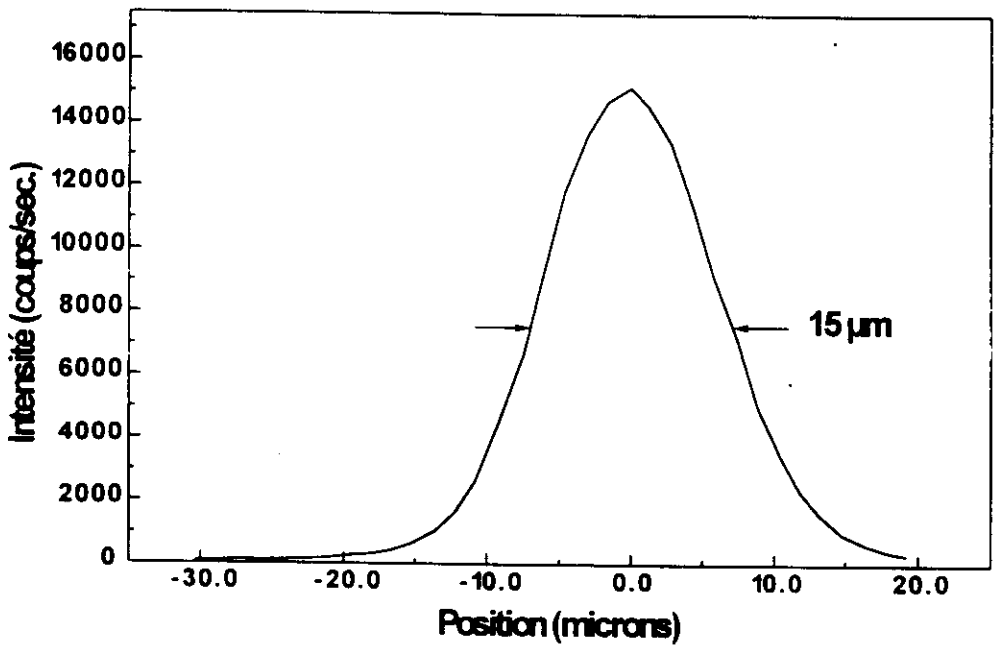
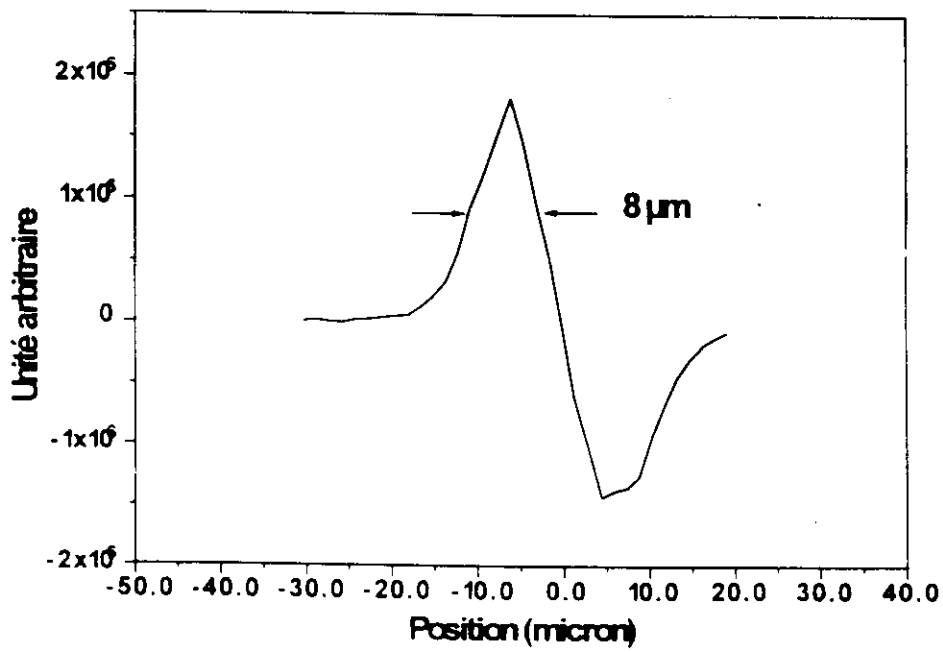
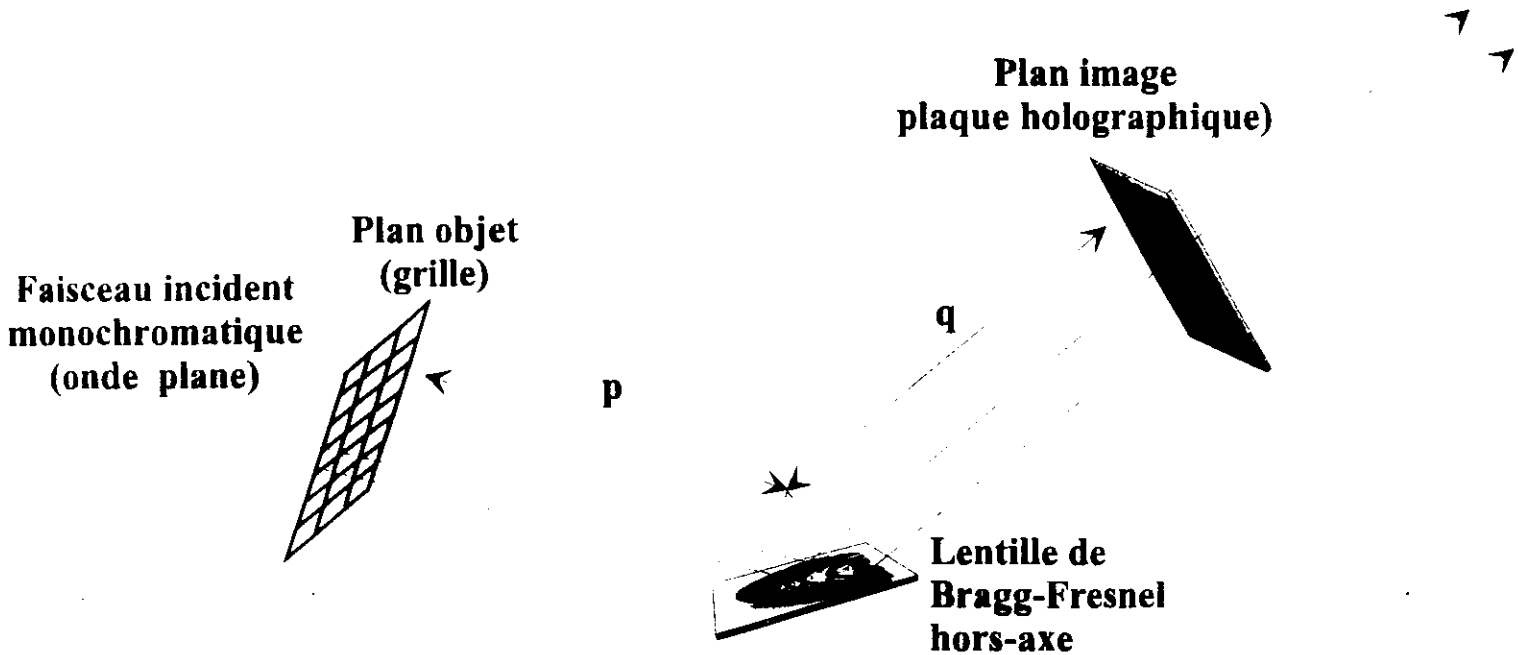


Image of the source of Super ACO ring (LURE) with the off-axis Bragg-Fresnel zone (proportional counter d=15 μm)

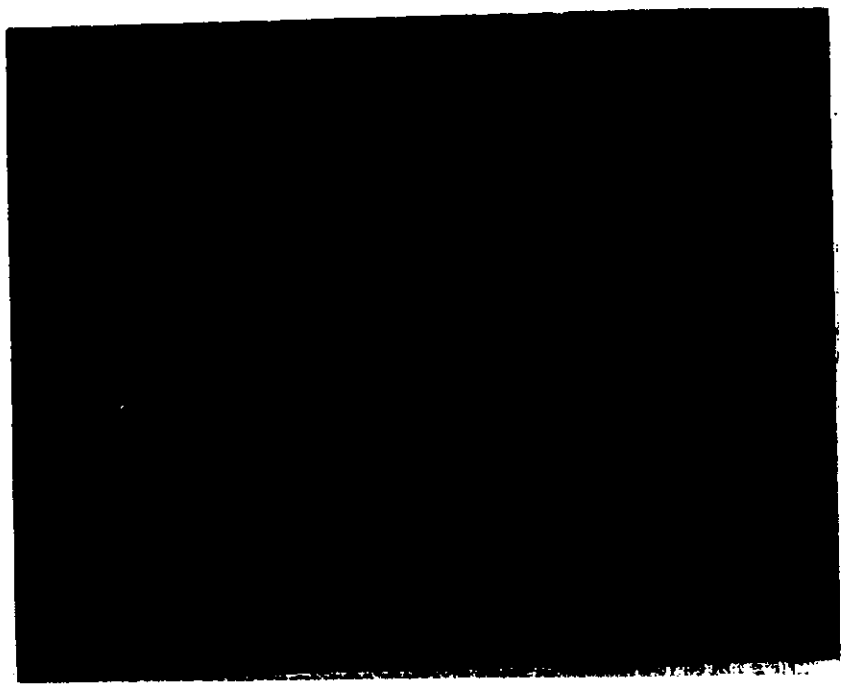

16000
14000
12000
10000
8000
6000
4000
2000
0
Intensité (coups/sec.)
-30.0
-20.0
-10.0
0.0
10.0
20.0
Position (microns)
15 µm


2x10⁶
1x10⁶
0
-1x10⁶
-2x10⁶
Unité arbitraire
-50.0
-40.0
-30.0
-20.0
-10.0
0.0
10.0
20.0
30.0
40.0
Position (micron)
8 µm

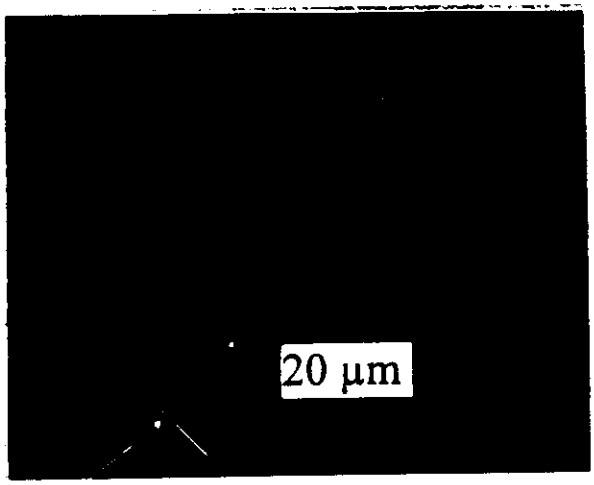


With : p=32 cm et q=30 cm

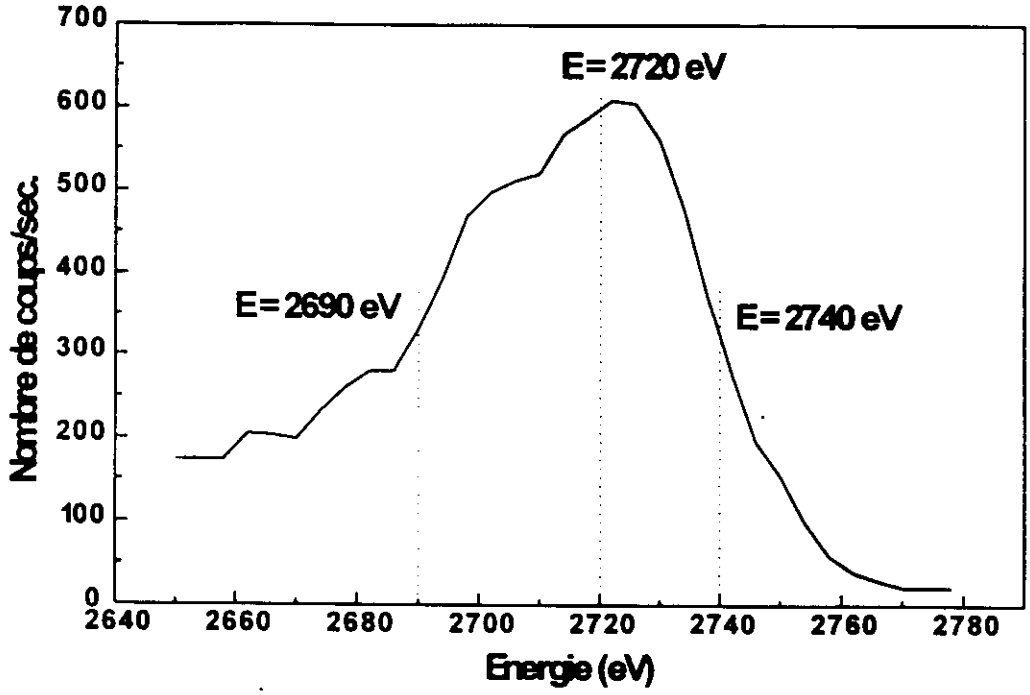
G=30/32=0,94

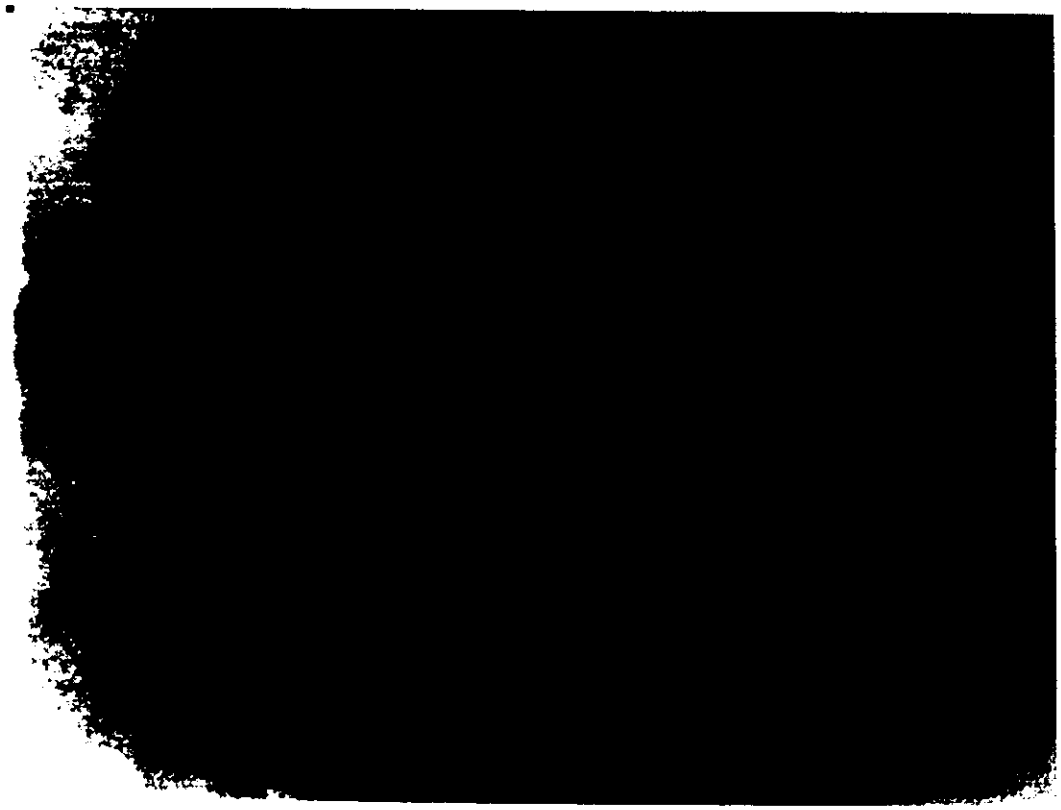


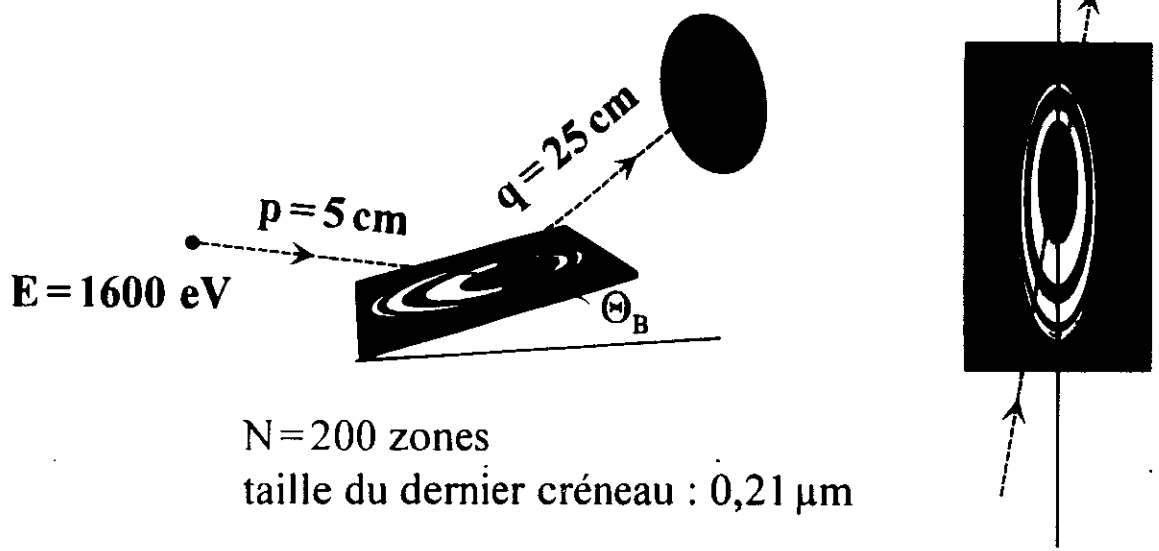
Test object: grids with bars of 15 µm length and periods of 50, 75, 100, 150 µm



Test object : 3 grids
superimposed with bars of
5,5 µm length and step of 20 µm


E=2720 eV
E=2690 eV
E=2740 eV
Nombre de coups/sec.
Energie (eV)
0
100
200
300
400
500
600
700
2640
2660
2680
2700
2720
2740
2760
2780



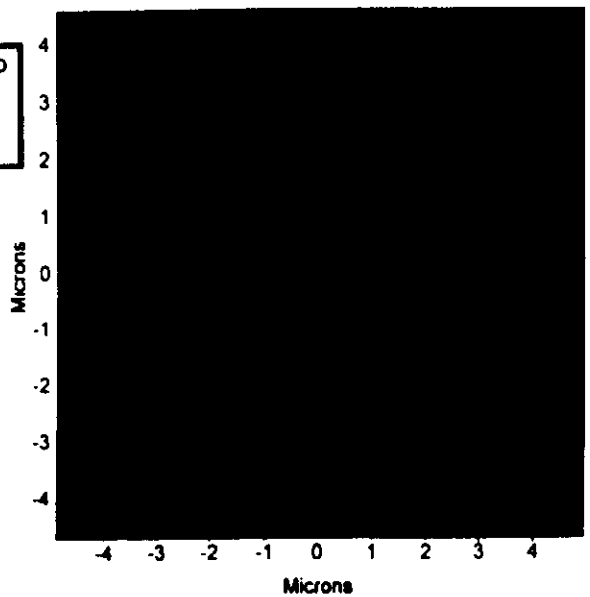


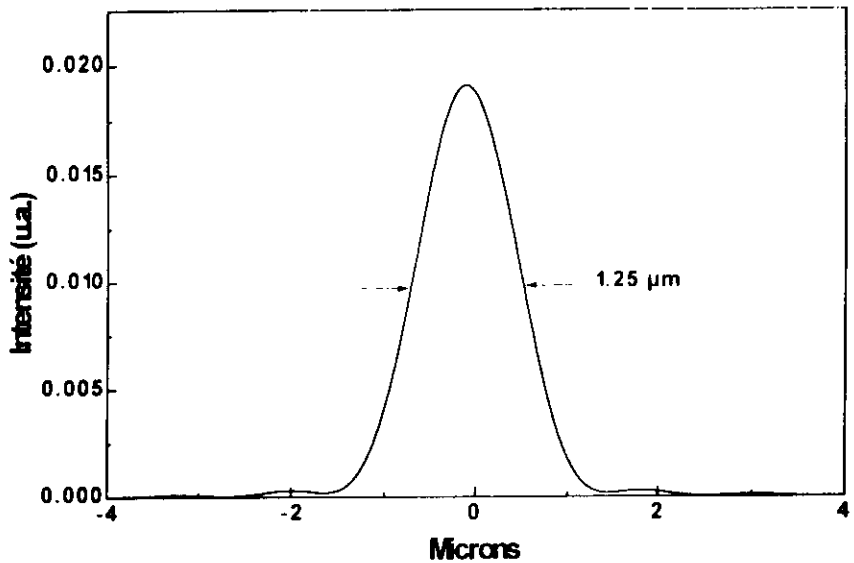
N = 200 zones
taille du dernier créneau : 0,21 µm

Multilayer : W/Si, 65 bilayers of 2,55 nm, $\gamma = 0{,}5$

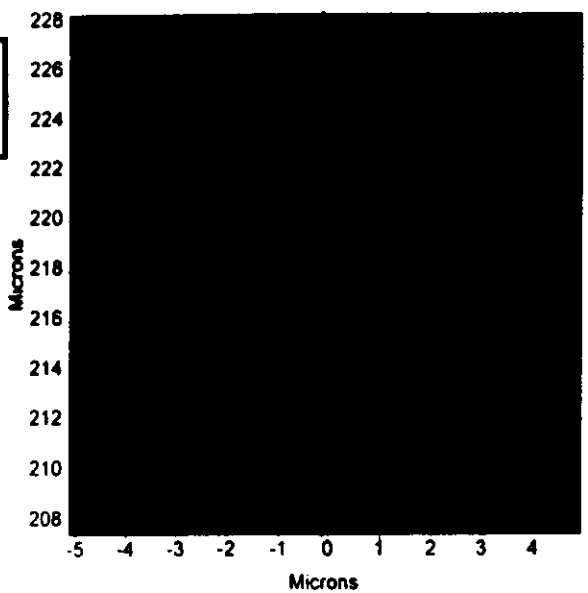
[redacted]

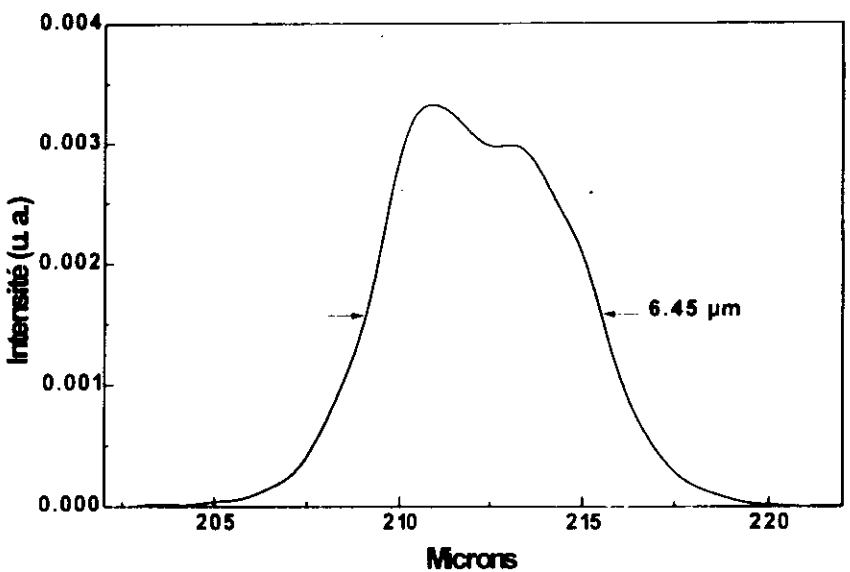
$\Theta = \Theta_B = 8{,}86°$
$\Phi = 0°$





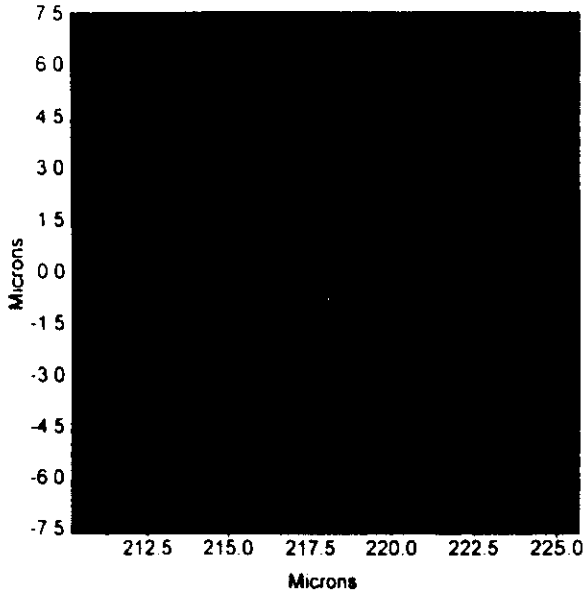
$\Theta = \Theta_B + 0{,}05°$
$\Phi = 0°$

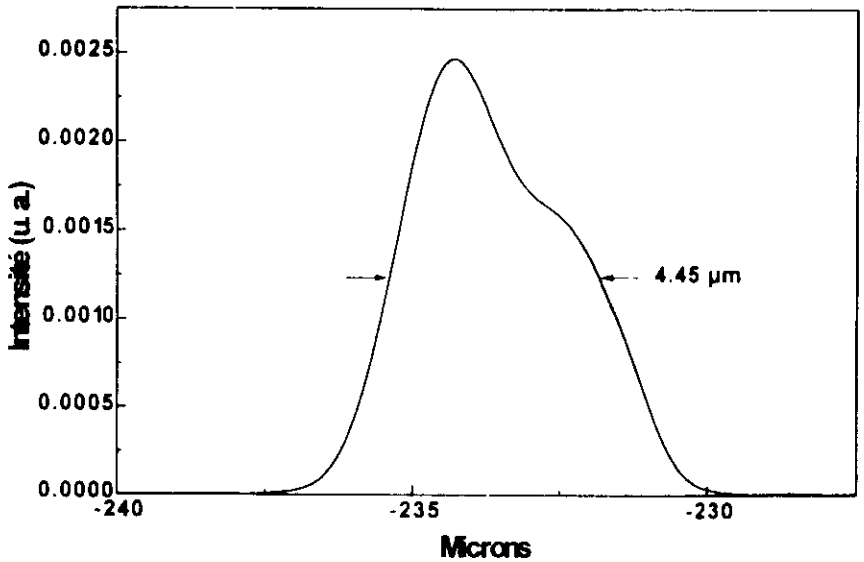




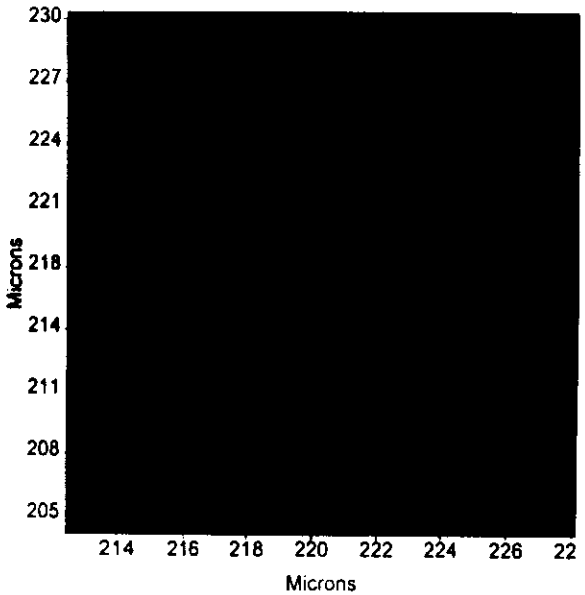
[redacted]

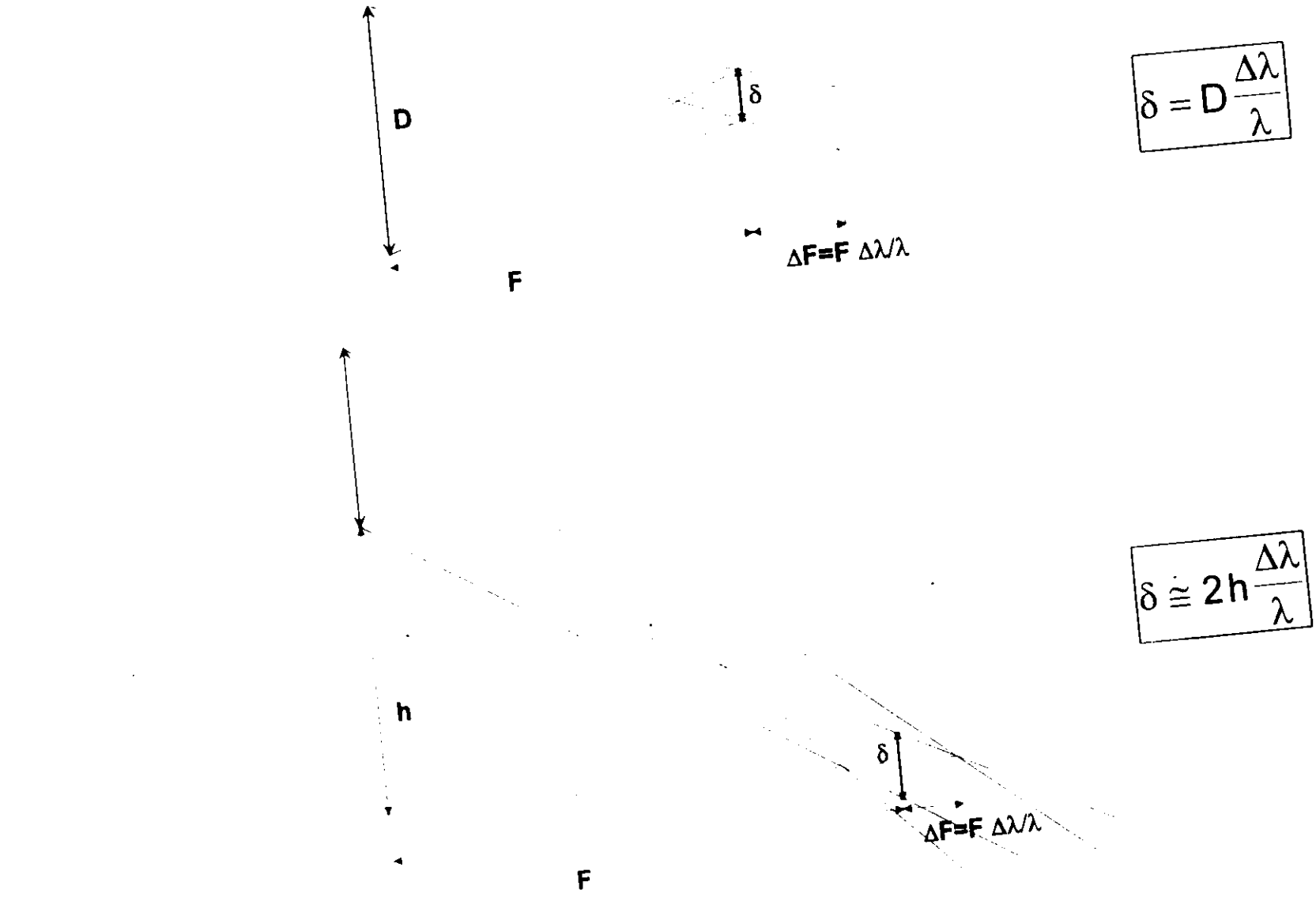
$\Theta = \Theta_B$
$\Phi = +0{,}05°$





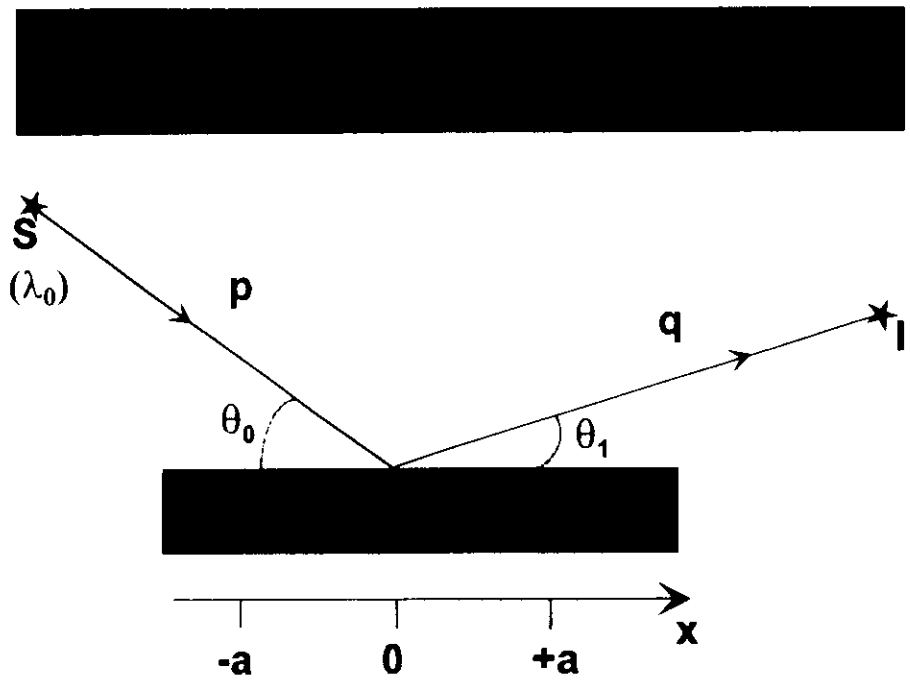
$\Theta = \Theta_B + 0{,}05°$
$\Phi = +0{,}05°$





$$\delta = D\frac{\Delta\lambda}{\lambda}$$

$$\delta \cong 2h\frac{\Delta\lambda}{\lambda}$$



The grating function C(x) of a lens is defined by : $C(x) = s(p, x, \theta_0) + s(q, -x, \theta_1)$

where $s(a, x, \theta) = \sqrt{a^2 + x^2 + 2\,a\,x\cos(\theta)}$

The profil of a Bragg-Fresnel multilayer lens is choosenby placing the zone borders at positions r_n such that : $C(r_n) - C(r_{n-1}) = \frac{\lambda_0}{2}$

For the wavelenght $\lambda_0 + \Delta\lambda$, the optical path function is :

$$(x) = s(p, x, \theta_0) + s(q', -x, \theta') - \frac{\lambda_0 + \Delta\lambda}{\lambda_0} C(x) = s(q', -x, \theta') - s(q, x, \theta_1) - \frac{\Delta\lambda}{\lambda_0} C(x)$$

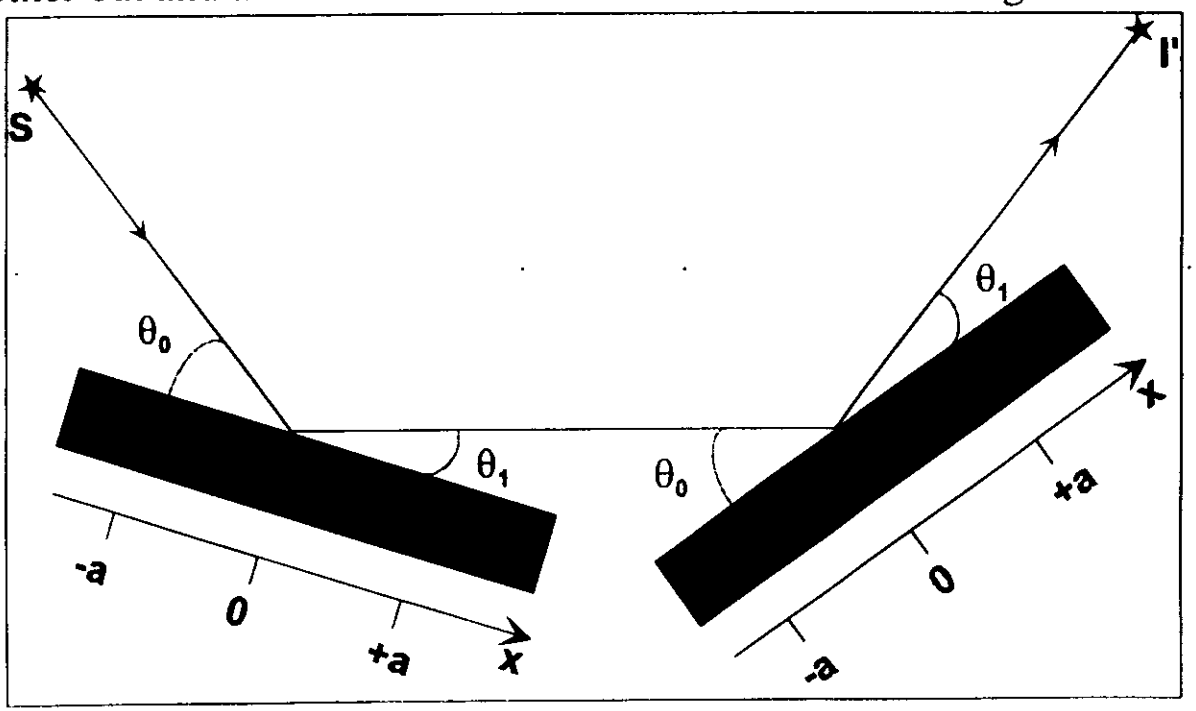
With a Taylor development like : $s(a,x,\theta) \cong a + x\cos(\theta) + \frac{x^2}{a}$

$$(x)\Big|_{\substack{\theta'=\theta_1 \\ q'=q}} = \frac{\Delta\lambda}{\lambda_0}\left[q + p + x(\cos(\theta_1) - \cos(\theta_0)) + \frac{x^2}{2}\left(\frac{\sin^2(\theta_0)}{p} + \frac{\sin^2(\theta_1)}{q}\right)\right]$$

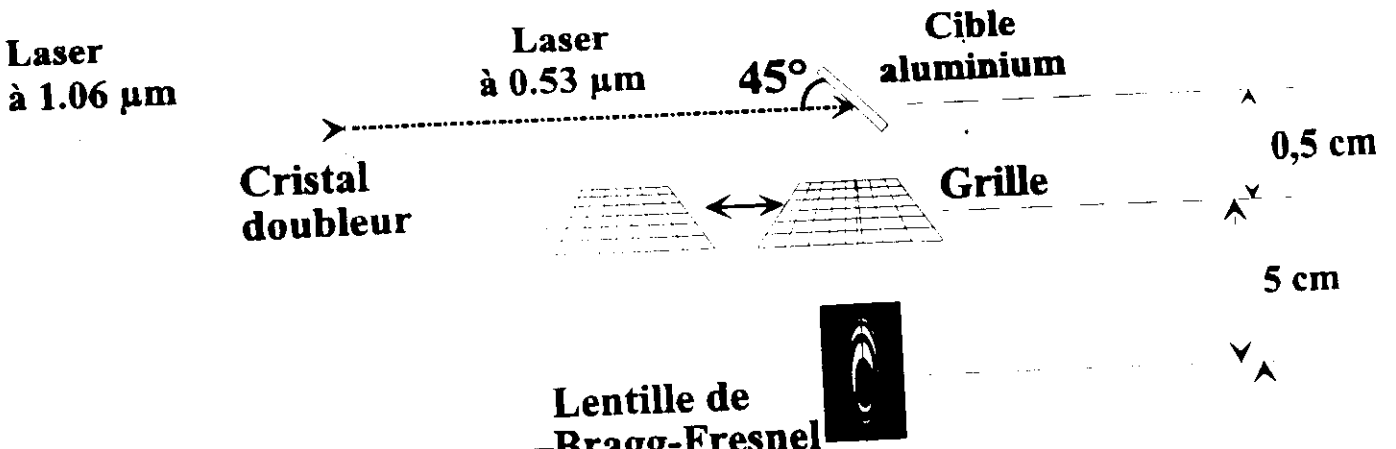
The linear term in x is absent in centered lenses and, for off-axis lenses, can cause strong chromatic aberrations.

A double reflection with two equivalent off-axis lenses can reduce the chromatic aberrations (linear term of P(x).

If the distance between lenses is small compared to the focal one, one can say that, from a geometrical point of view, a ray hitting the first lens at x, hits the second at -x. This way, the linear termcancel each other out and aberrations are reduced to the ones occuring in centred lenses.



[redacted]



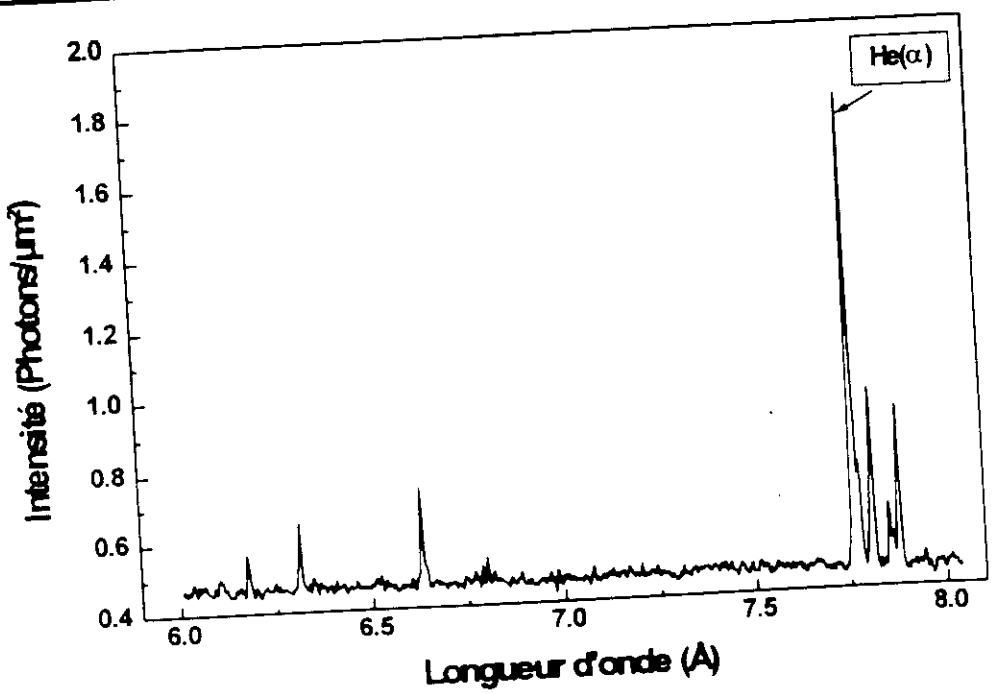
$$\delta_s = \frac{1.22\lambda p}{2r_n}$$

$$= \frac{1.22 \times (7.725 \cdot 10^{-10}) \times 0.05}{2 \times 170 \cdot 10^{-6}}$$

$$\delta_s = 0.15\ \mu m$$

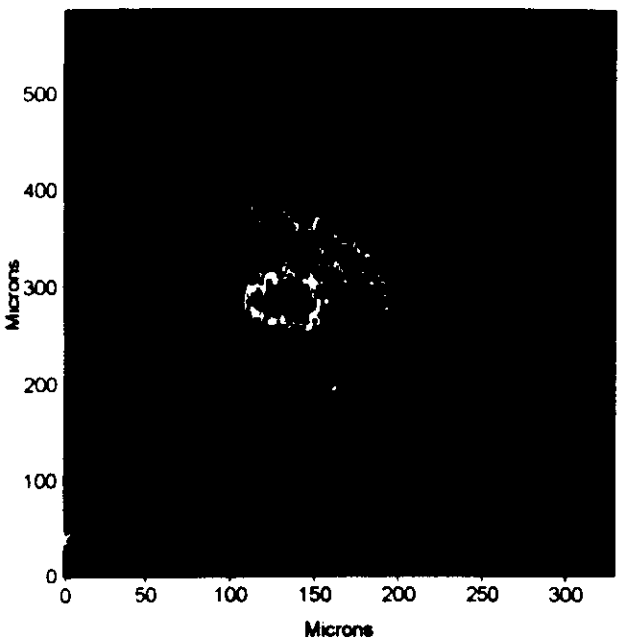
$$\delta_i = G \cdot \delta_s \quad \text{avec } G = 5$$

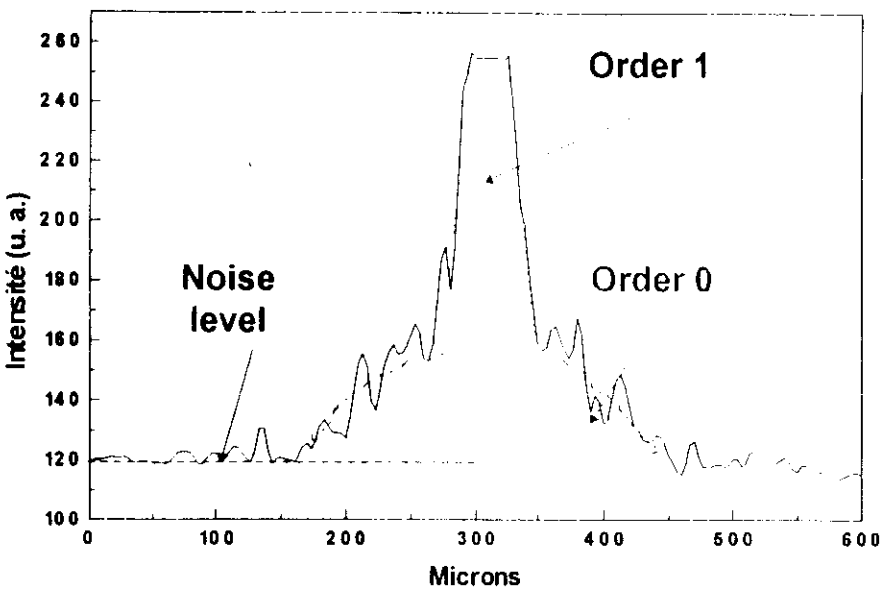
$$\delta_i = 0.75\ \mu m$$

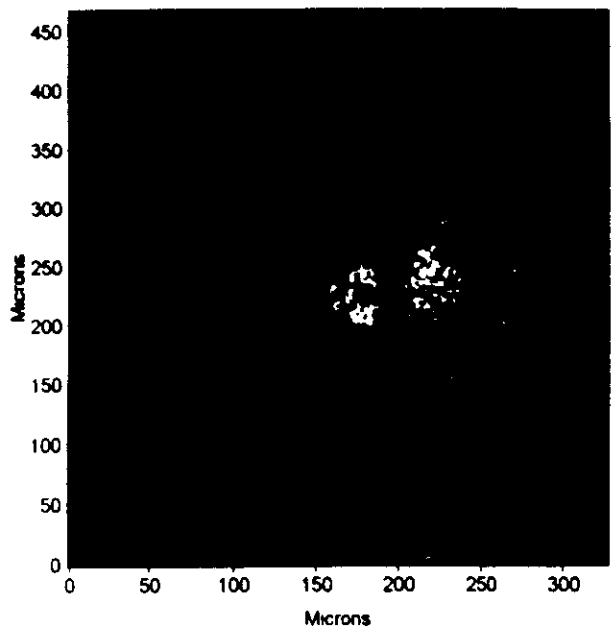


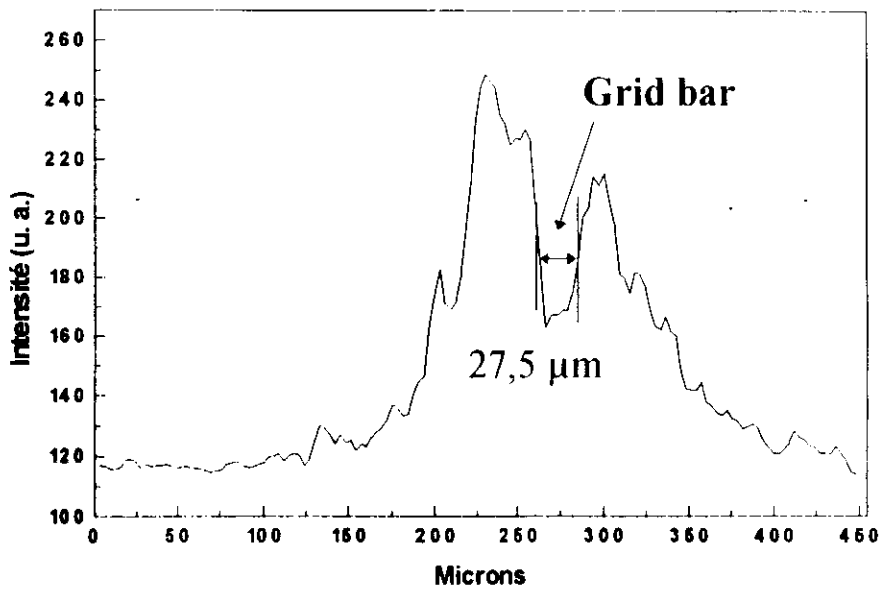
Material	Period : d_∞ (Å)	γ	Number of bilayers
W / C	32	0,31	65

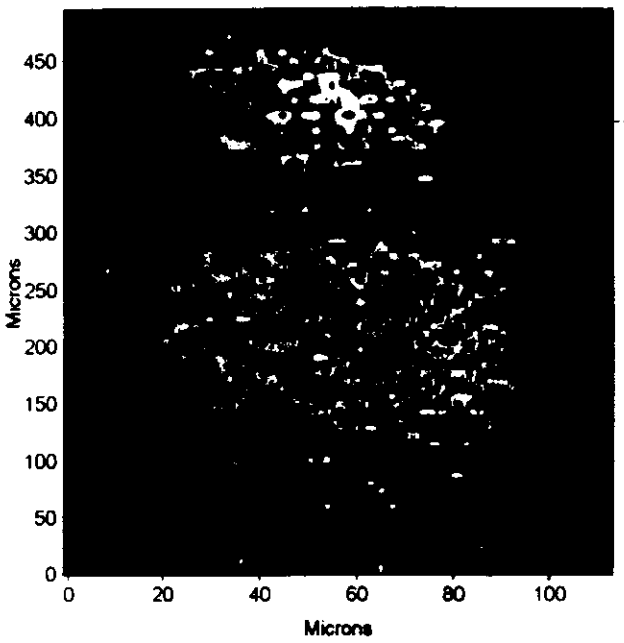
	Off-axis lens	Elliptical lens
Wavelenght / Energy	7,725 Å / 1605 eV	7,725 Å / 1605 eV
Size	174,2 x 1166,1 µm	167,5 x 1094 µm
Number of grooves	de 175 à 350	100
Focal distance	4,2 cm	4,5 cm

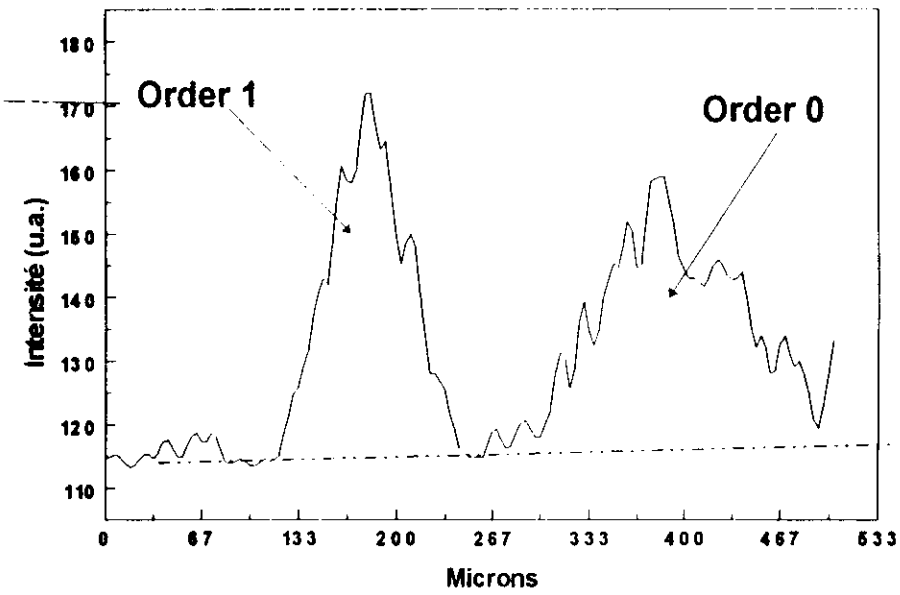

Microns
Microns

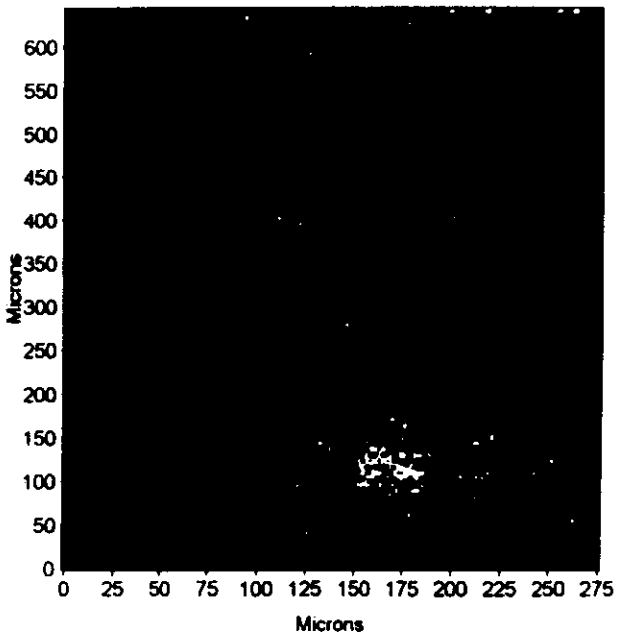

Order 1
Noise level
Order 0
Intensité (u. a.)
Microns

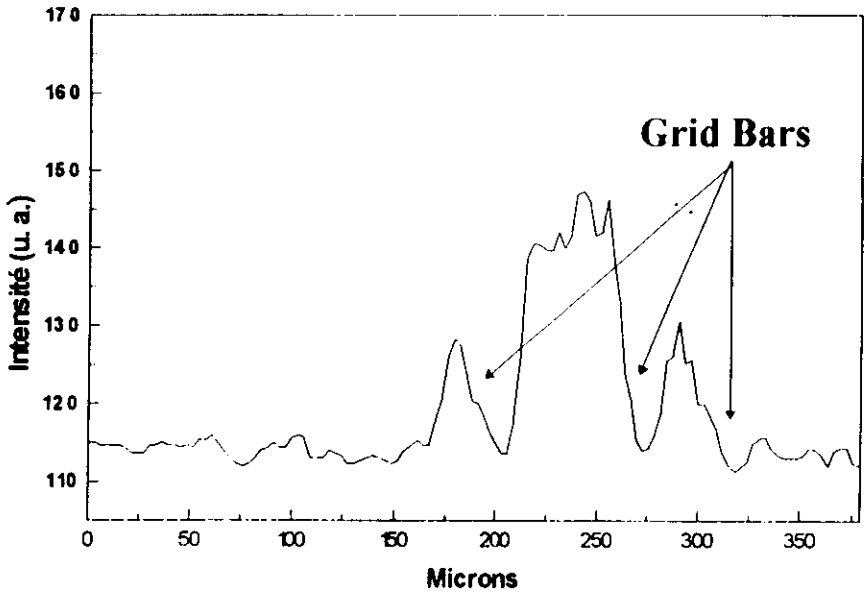

Microns
Microns

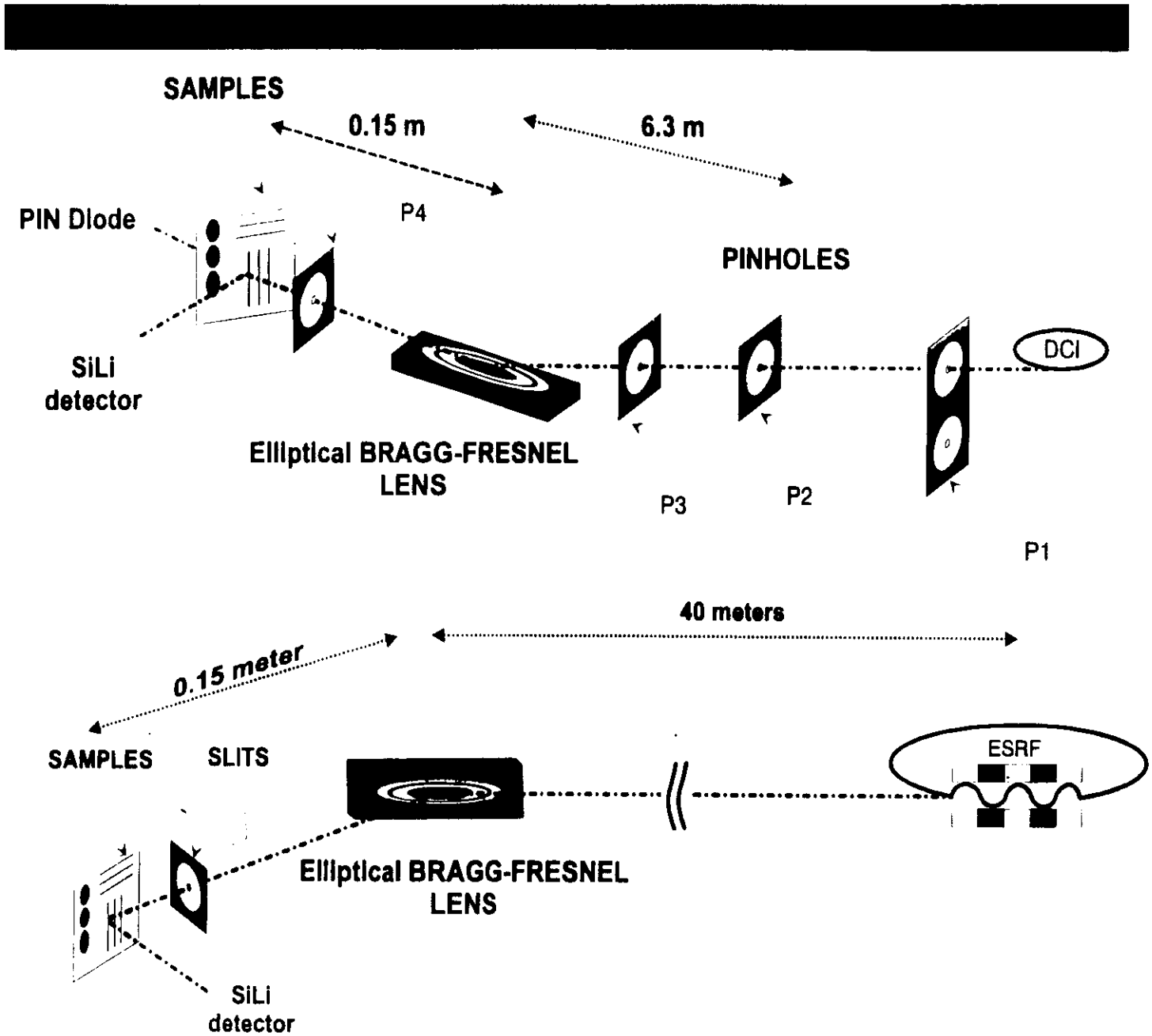

Grid bar
27,5 µm
Intensité (u. a.)
Microns


Microns
Microns


Order 1
Order 0
Intensité (u.a.)
Microns

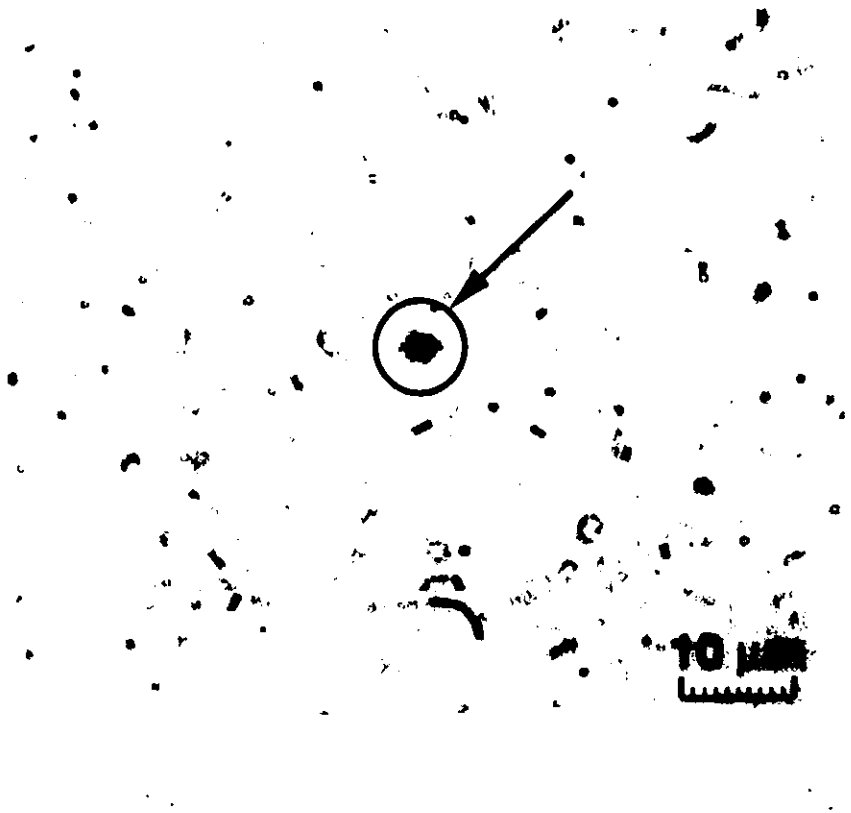

Microns
Microns

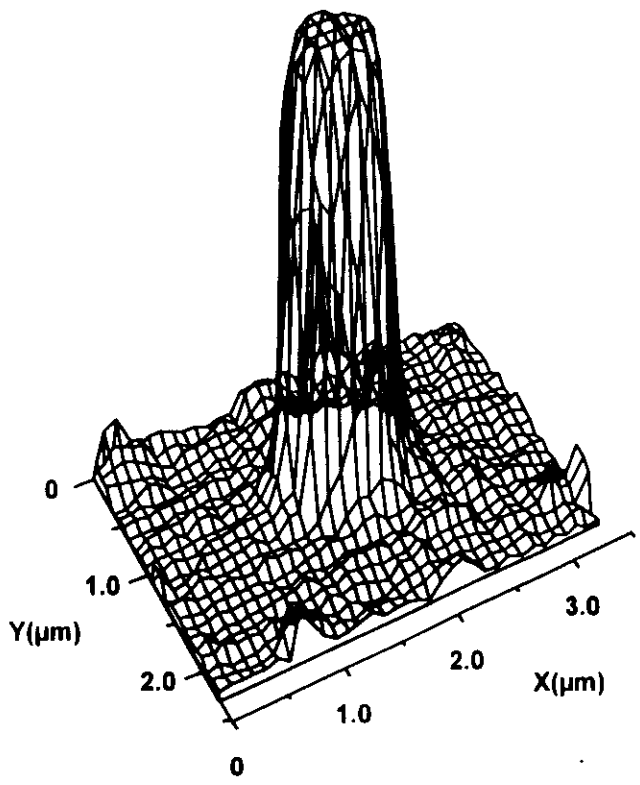

Grid Bars
Intensité (u. a.)
Microns


SAMPLES
0.15 m
6.3 m
P4
PIN Diode
PINHOLES
SiLi
detector
DCI
Elliptical BRAGG-FRESNEL
LENS
P3
P2
P1
40 meters
0.15 meter
SAMPLES
SLITS
ESRF
Elliptical BRAGG-FRESNEL
LENS
SiLi
detector

Multilayer characteristics : W/C d= 32.5 Å 65 bilayers

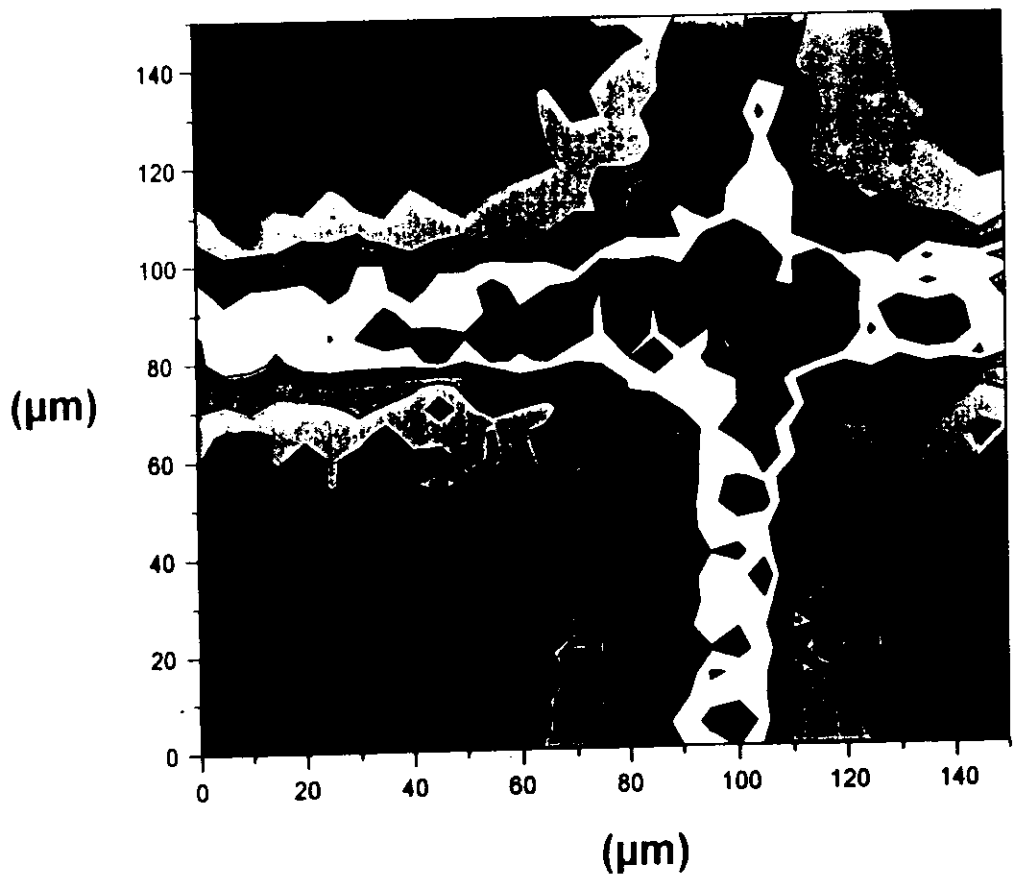
Lens characteristics : Size 60μm x 2.48 mm
Last zone width 0.25 x 10.7 μm
F= 15 cm





Storage ring DCI Beamline D15A
Energy : 12,4 keV
Intensity in the focal spot :~710^5 phot/sec
Spatial resolution :1 x 1 µm
Emtrance pinhole : 50 µm

Storage ring ESRF Beamline Troika ondulator
Energy : 11.8 keV
Intensity in the focal spot :~710^9 phot/sec
Spatial resolution :2.3 x 5 µm (v x h)



140 -- 160
120 -- 140
100 -- 120
80.0 -- 100
60.0 -- 80.0
40.0 -- 60.0
20.0 -- 40.0
0 -- 20.0

Multilayer

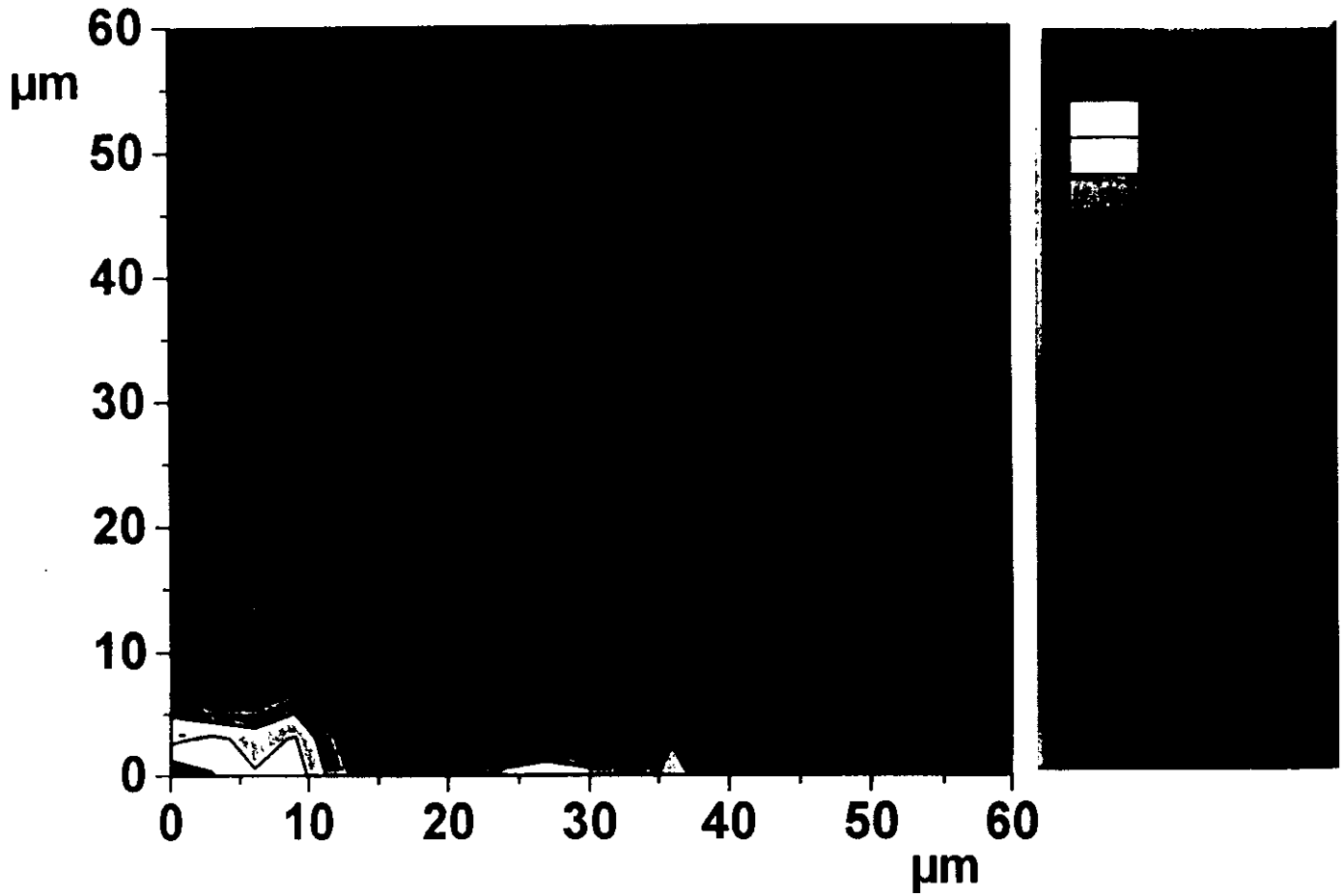
E= 12.5 keV
W/C
d=32.5 A
65 bilayers

Lens Characteristics

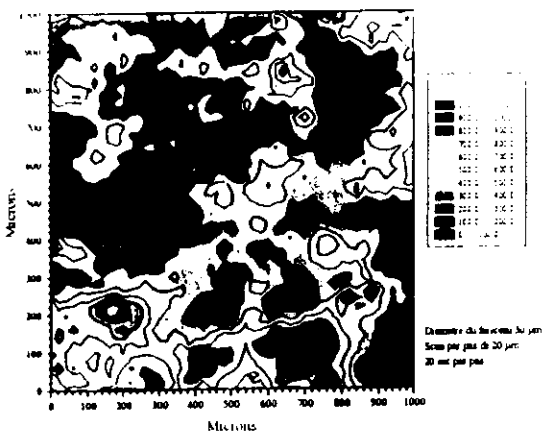
60 µm X 2.48 mm (SIZE)
0.25 µm x 10.7 µm (Zone width)
F=15 cm

Micrométéorites from Antarctica

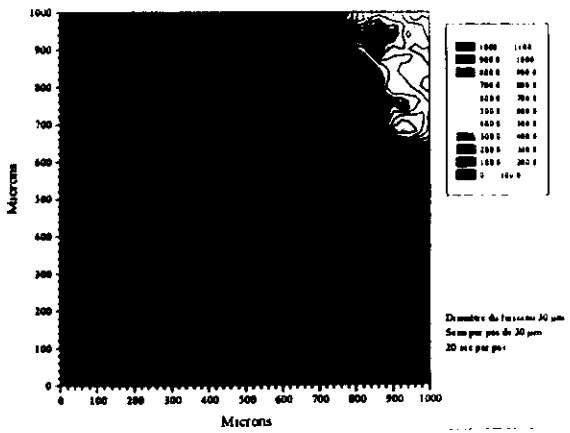
- C. Engrand & M. Morette — CSNSM-Orsay
- Microsonde on DCI — Iron K lines



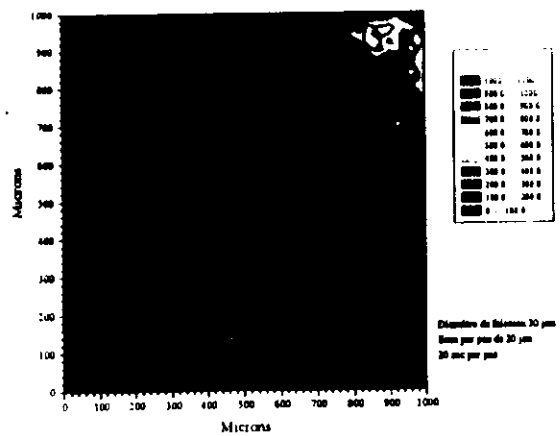
Cartographie du fer
P28-16



Cartographie du plomb
P28-16



Cartographie du zinc
P28-16



Cartographie de Mn
P28-16