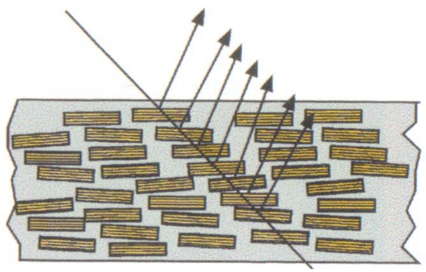
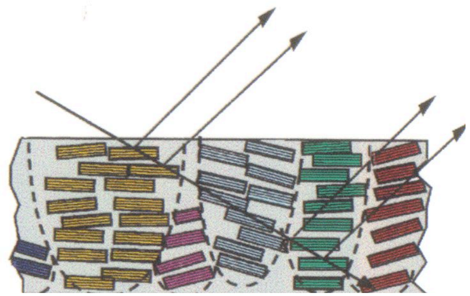
Hard X-ray optics based on Bragg reflection with mosaic crystals: a review

Giovanni Pareschi[1] and Filippo Frontera[2,3]

(1) INAF – Osservatorio Astronomico di Brera – Milano/Merate – Italy
(2) University of Ferrara – Italy
(3) INAF-IASF - Bologna





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Gialuca Loffredo
Damiano Pellicciotta
Vito Carrasiti
Paola De Chiara
Alessandro Pisa
Alessandra Tuffanelli
Alessandra Fantini
Carlo Pelliciari

ESRF Grenoble

Manuel Sanchez del Rio
Michael Ohler

ILL Grenoble

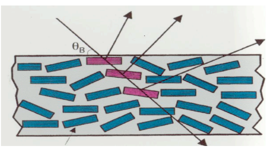
Lucia Alianelli

INAF/IASF Bologna

Daniele Dal Fiume
Gianni Landini

Special Thanks to:

Advanced Ceramics
Optigraf
ESRF



Outline

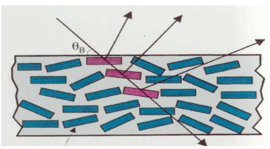
- ***Historical notes***

- ***Bragg diffraction with mosaic crystals: basic principles and comparison with other techniques used in astronomy fore focusing at high energy***

- ***Mosaic crystals materials***

- ***Example of Hard X-ray Bragg telescopes configurations***

- ***Final remarks and critical discussion***



Mosaic crystal telescopes in Bragg configuration: some historical milestones

- 1967-69 F.W. Lyt... propose and investigate the use of Bragg crystal... Wolter I optics. A la...

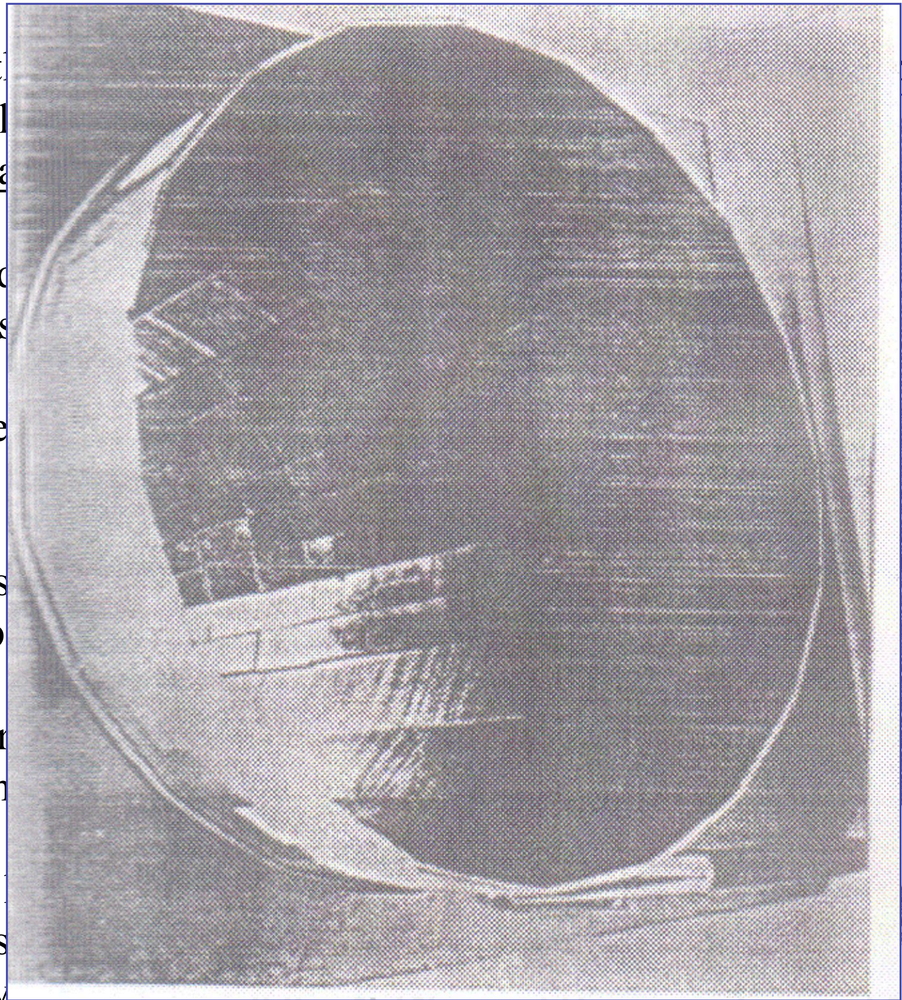
-1975 J.B. Trice and... made of HOPG crys...

- 1981 H. Schnoppe... X-ray astronomy.

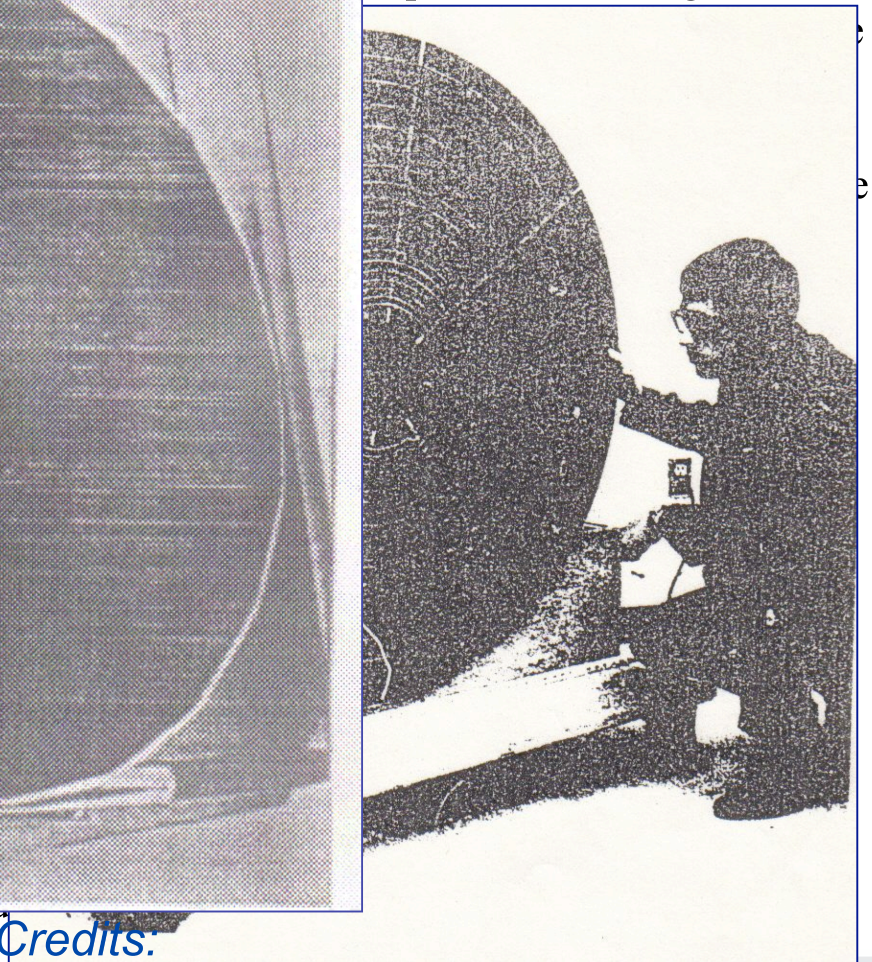
- 1983 NASA funds... Diffraction Telecop...

- 1992 at the Univer... optimization and im...

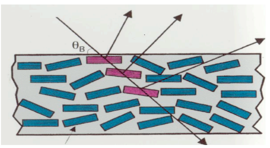
- 1994 "Imaging in... possible approaches... diffraction, multilayer mirrors, microcapillaries and...



Tryce & Locker – 1975 (Credits: Naval research Labs)

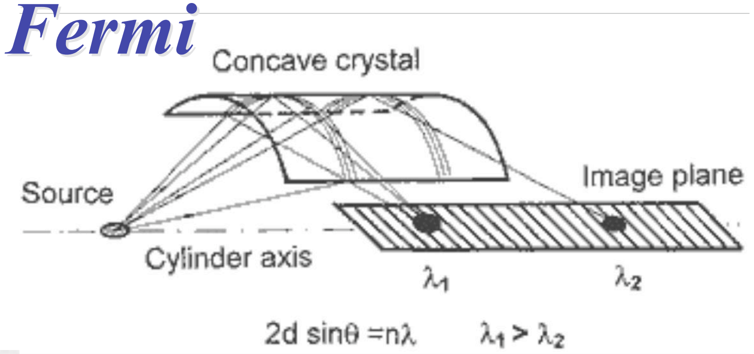


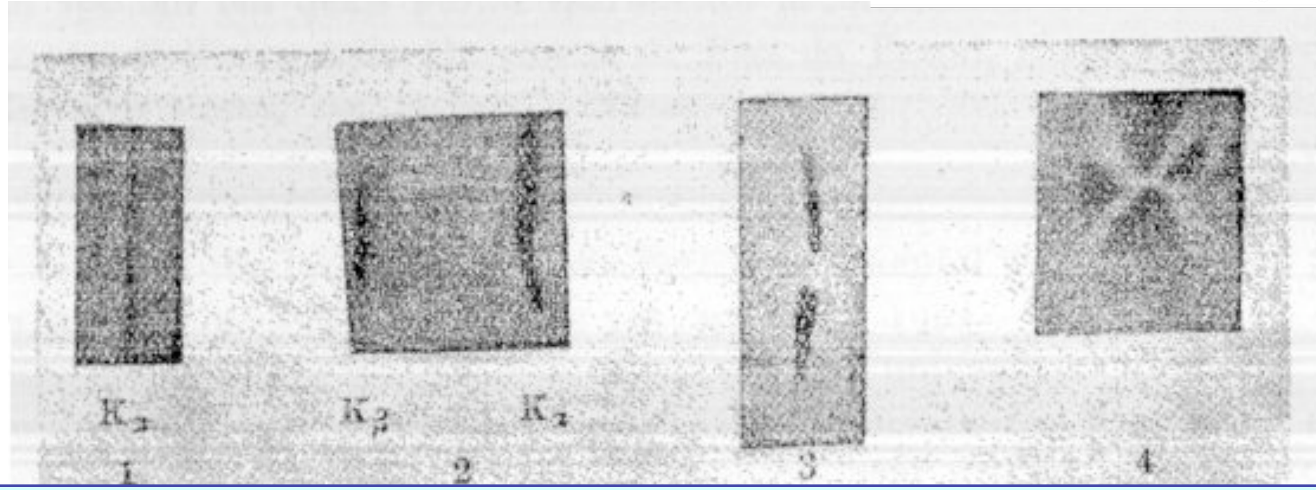
Lytle & Bingham - 1969 (Credits: Boeing)



Imaging experiments by using mica crystal foils performed by E. Fermi

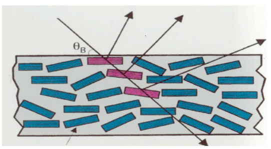
"Cold slumping" of mica sheets using a brass mandrel and application of sealing-wax to maintain the curvature





1922: E. Fermi – Thesis of Laurea, "Formazione di immagini con i raggi Roentgen", Univ. of Pisa -1922 (*Il Nuovo Cimento*, **25**, 63, 1923) – First Experimental focusing by crystals proofs using the concept suggested by Gouy (1915). Dardord (*J. Physique et Radium*, **3**, 218, 1922) independently obtains a similar result.

Thanks to Giorgio Palumbo!

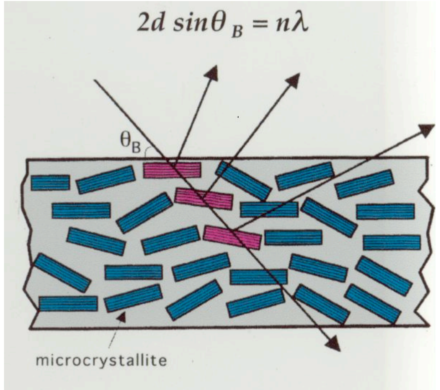


Bragg diffraction with mosaic crystals

• Bragg diffraction from a crystal lattice ➔ reflectivity peaks at: **$2\,d\,\sin\theta = n\,\lambda$**

• mosaic crystals: at microscopic level a structure of microcrystals almost-parallel to the external crystal surface. The distribution of the crystallites normals is in general described by a Gaussian law:

$$W(\Delta) = \frac{1}{\sqrt{2\eta}} \exp\left(- \Delta^2 \big/ 2\eta^2 \right)$$

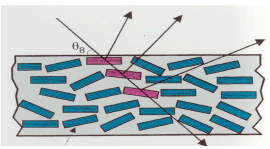


•each crystallite reflects in an independent way (without any interferometric coupling with the beams reflected by the other crystallites) ➔ the integrated reflectivity results to be much larger (>100) than for a perfect crystal, even if the peak is lower

• approximately, the integrated reflectivity is given by: **$R_{int} \approx R_{peak} * \beta$**

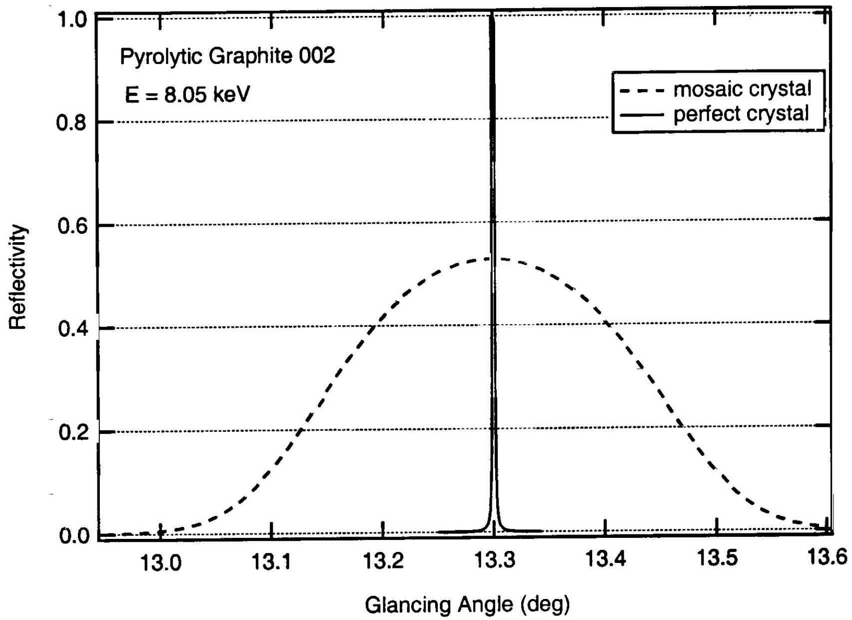
With β = FWHM of the Gaussian distribution (***"mosaicity"***), while the energy reflection band under the Bragg peak is:

$$\Delta E \approx \beta \cdot \frac{12.4}{2d} \cdot \cot\theta$$



Mosaics vs. perfect crystals

In a perfect crystal, when a monochromatic & collimated beam hits at the Bragg angle, the reflection is due to the cooperative effect of several atomic layers close to the surface, and the penetration depth until the beam its extinction is just a few tens of microns. Very high peak reflectivity, but typical "Darwin width" of a few arcsec



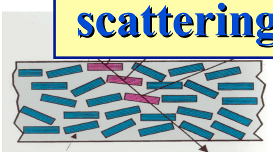
For "ideally imperfect" mosaic crystals crystallites are so small that the primary extinction is negligible. However secdondary extinction must be considered, i.e. the effect due to the mosaic blocks close to the surface reflects away part of the incident beam, and thus screen the lower lying mosaic blocks

→ **an additional attenuation to be added to photo-absorption and Compton scattering!**

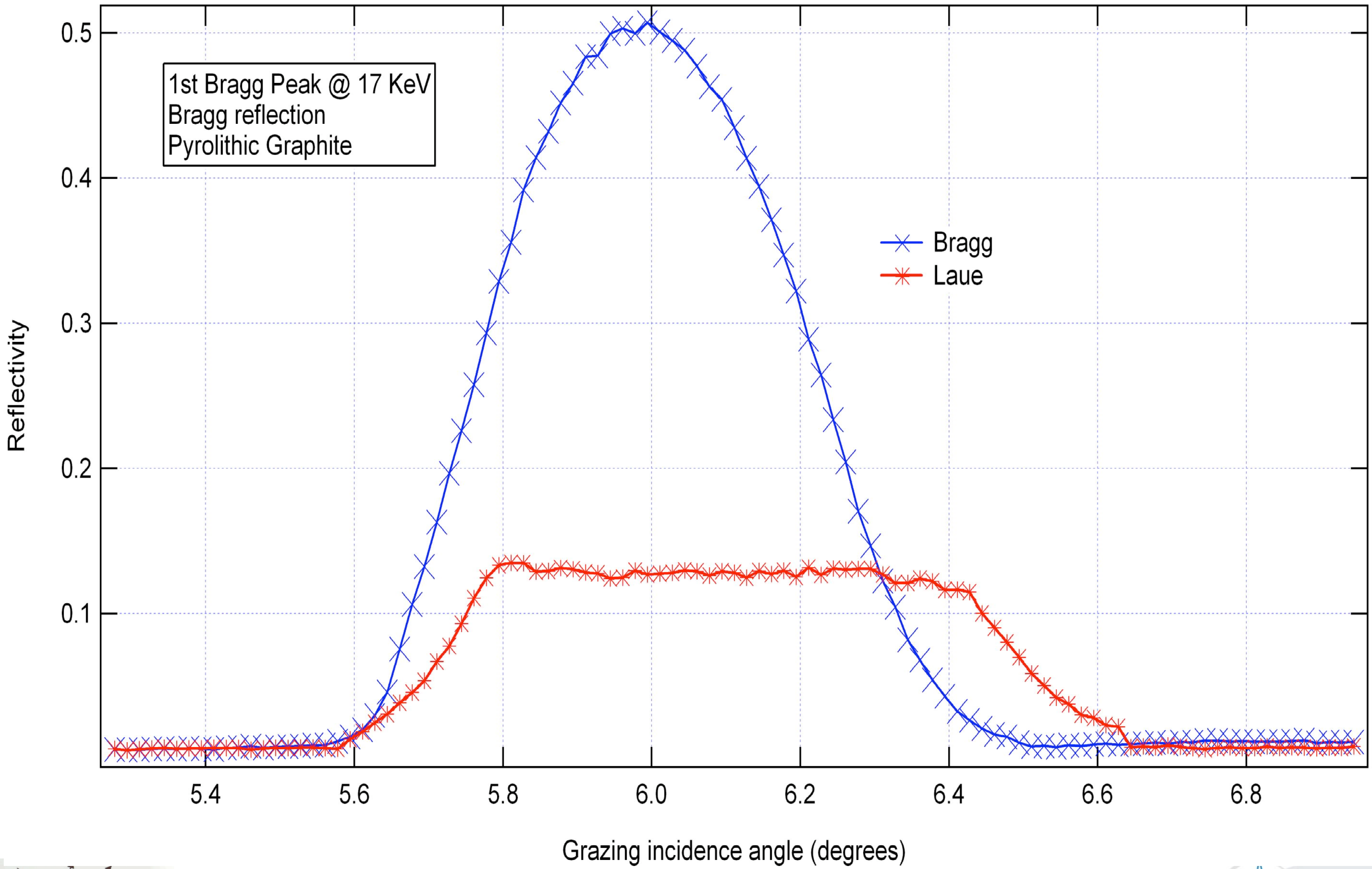
$$\mu_{true} = \mu_{abs} + \mu_{sec\text{-}ext}$$

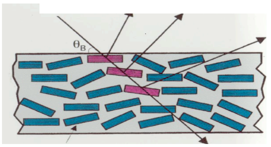
with $\mu_{sec\text{-}ext}$ *proportional to:*

- *the FWHM of the Gaussiann distribution of crystallites*
- the $(F/V)^2 \lambda^3$ *term, with F =Structure Factor, V = volume of the crystallographic cell,* λ *= incident wavelength*



Bragg vs. Laue configurations

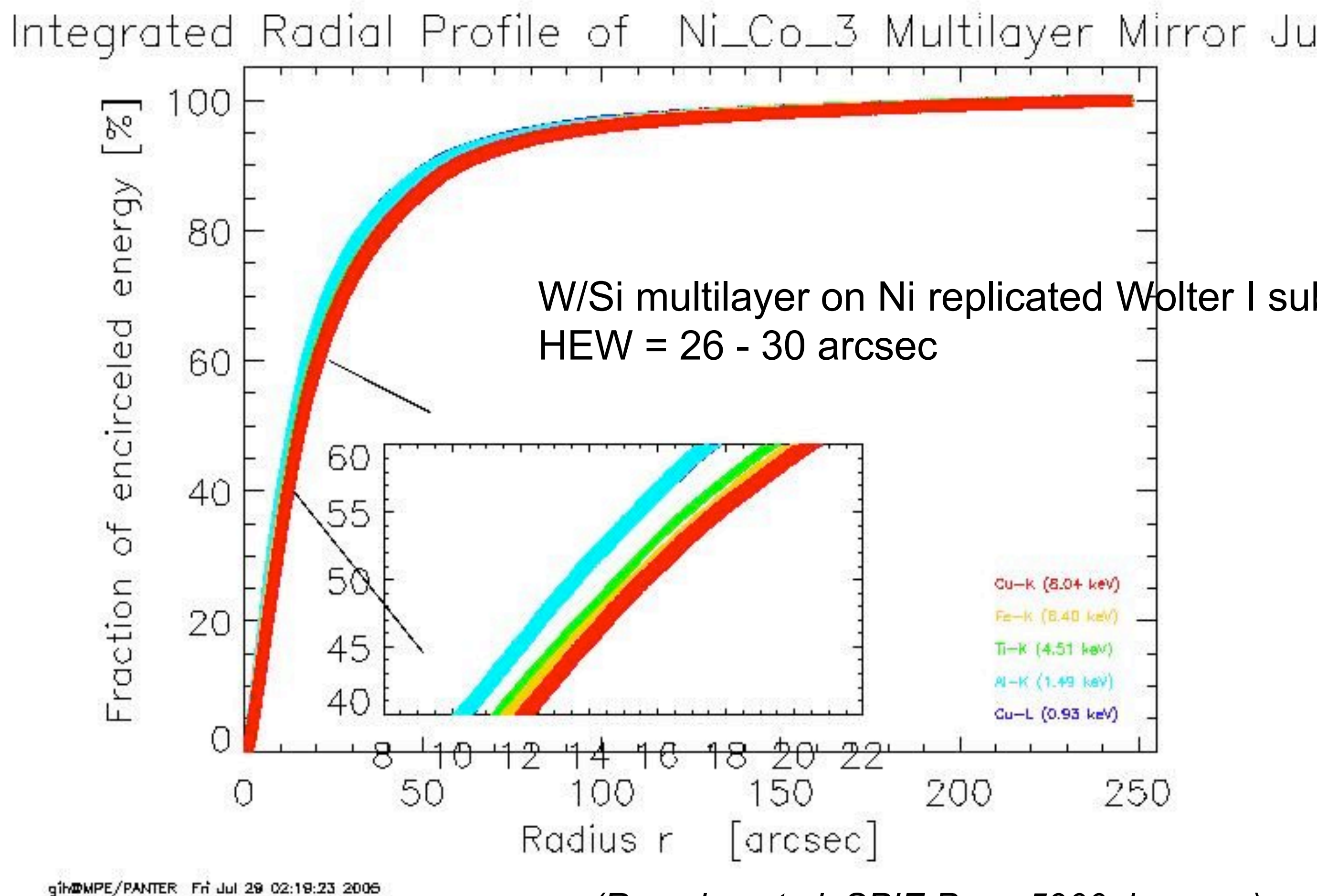




Bragg telescopes based on mosaic crystals

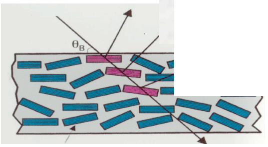
Bragg diffraction with Mosaics vs. grazing incidence mirrors single and multilayer coatings)

on)



W/Si multilayer on Ni replicated Wolter I substrate
HEW = 26 - 30 arcsec

(Romaine et al, SPIE Proc, 5900, in press)



The material choice guidelines & aspects

- In order to optimized the Integrated Reflectivity, the ***$(F/V)^2$ $1/\mu$*** term should be maximized

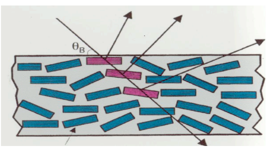
F *= Structure Factor,* ***V*** *= volume of the crystallographyc cell,* ***μ*** *= linear absorption coefficient (low density materials preferable!)*

- d-spacing sufficiently small (< 5 Å) to allow large reflection angles

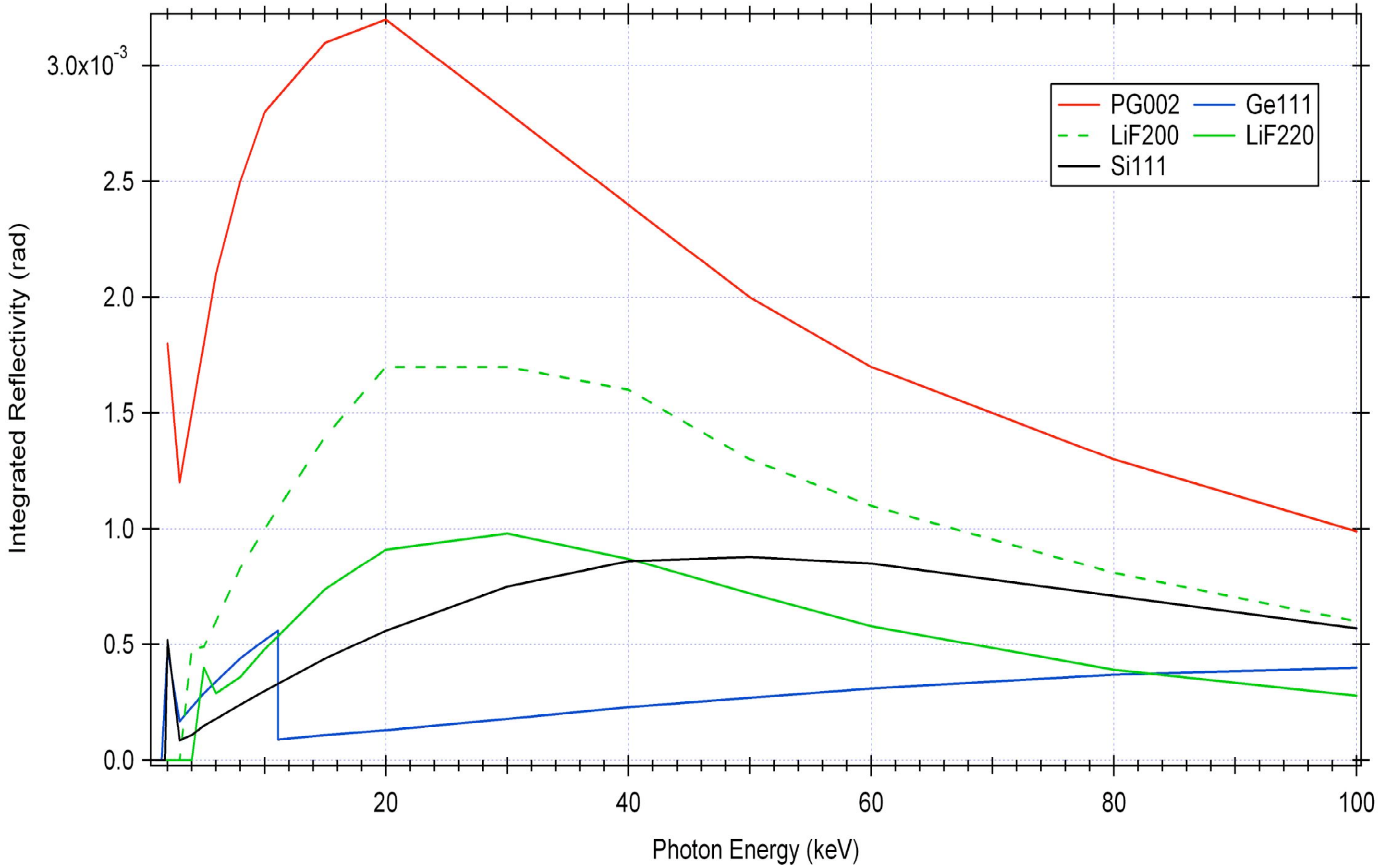
- Materials which would be of interest cannot be obtained with a well defined and uniform mosaic spread. In some cases (e.g. HOPG) the mosaic structure is intrinsic and the mosaicity has to be controlled and possibly diminished; in other materials (e.g. Si and Ge) the mosaic structure has to be introduced by special treatments

- The selected materials should offer the possibility to fit double-curvatures mirror profiles without figure degradation ➔ ***very critical point!***

- costs & availability

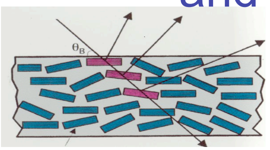


Theoretical Integrated reflectivity for several "ideally imperfect" mosaic crystals

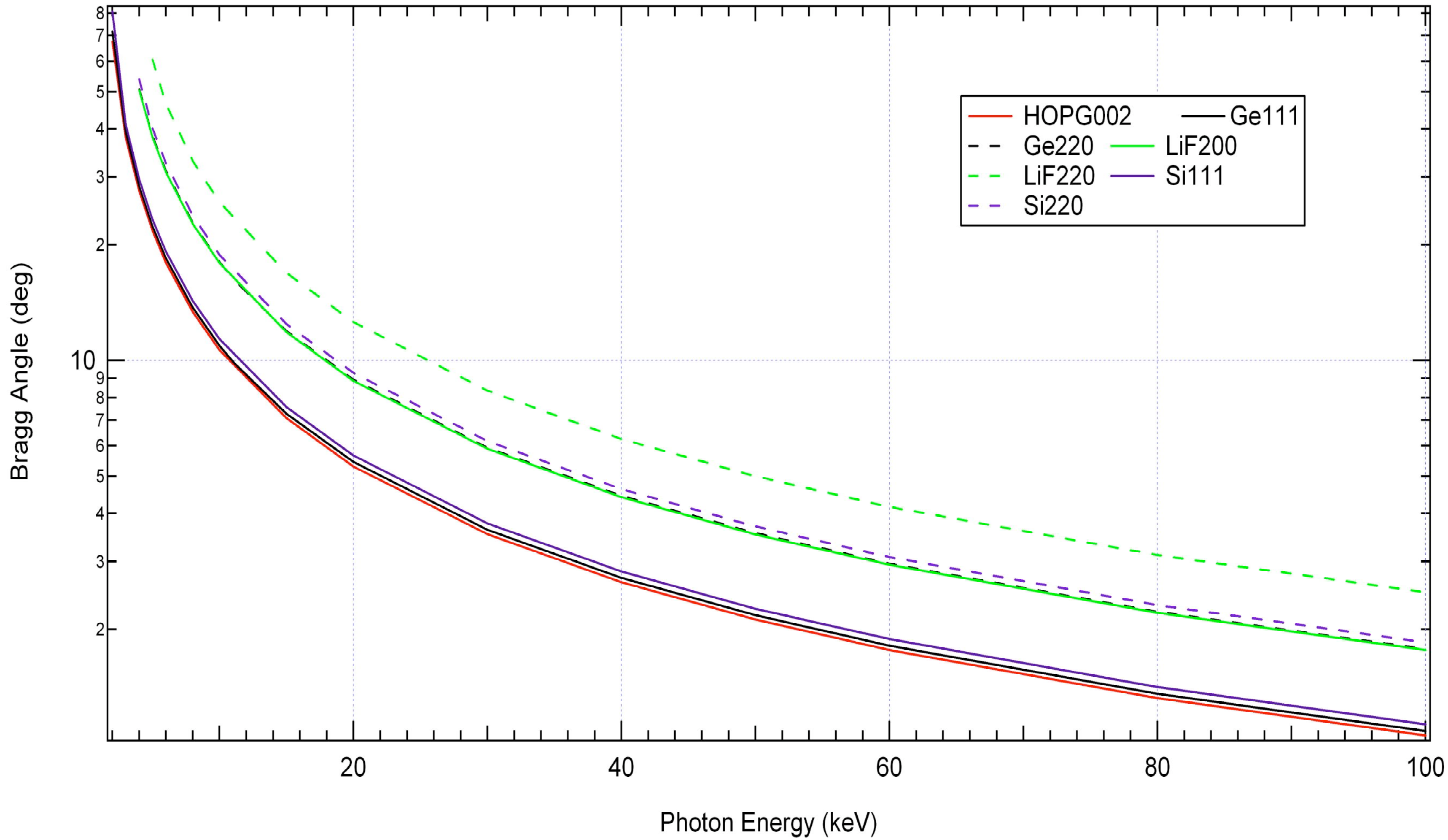


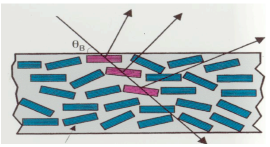
Higly Oriented Pyrolytic Graphite (HOPG) offers the best parameters:

d_{002} = 3.35 Å, F = 17.3, V = 35.9 Å^3, ρ = 2.21 g/cm^3 and μ @15 keV = 0.71 cm^{-1} and @80 keV 0.17 cm^{-1}

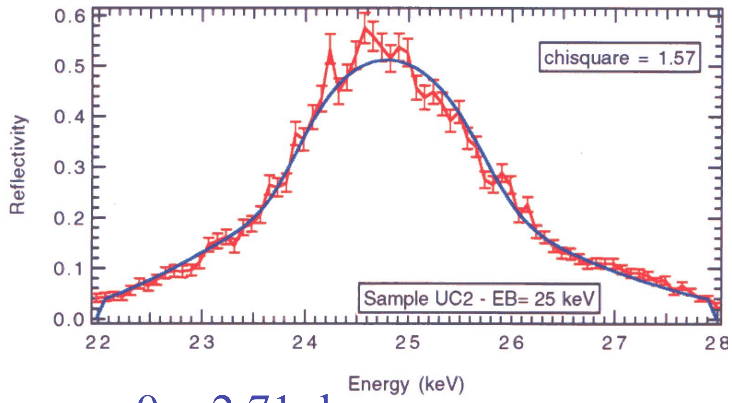


Bragg Angle vs. Photon energy for several mosaic crystals

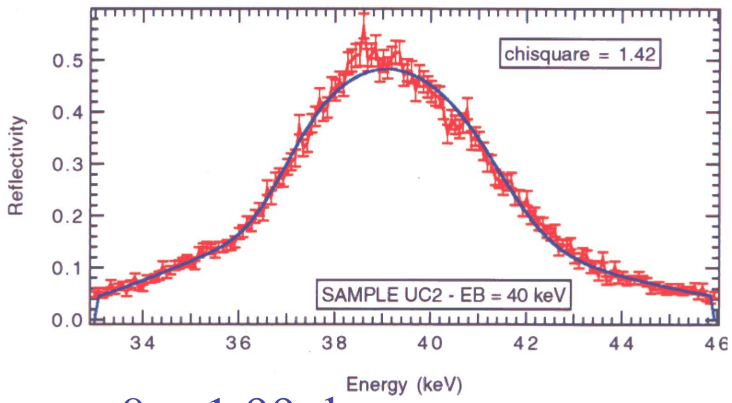




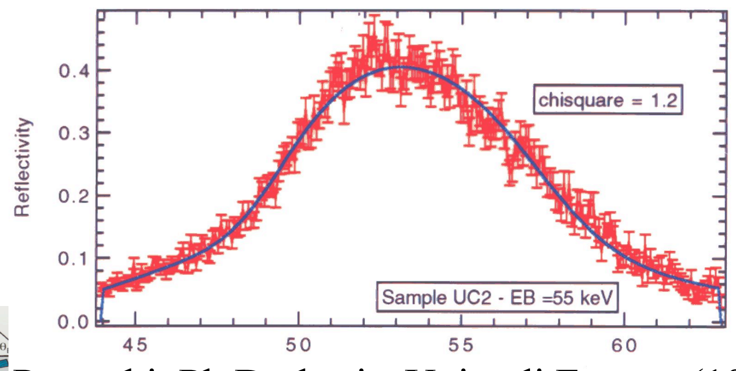
θ = 4.25 deg

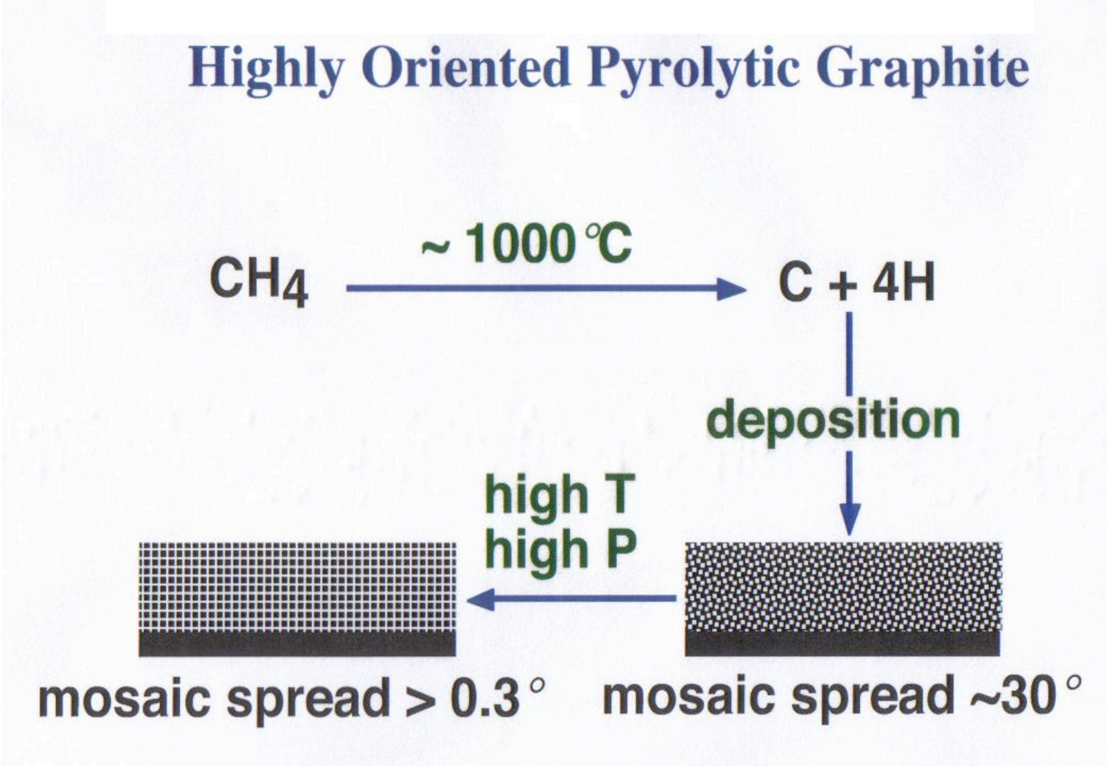


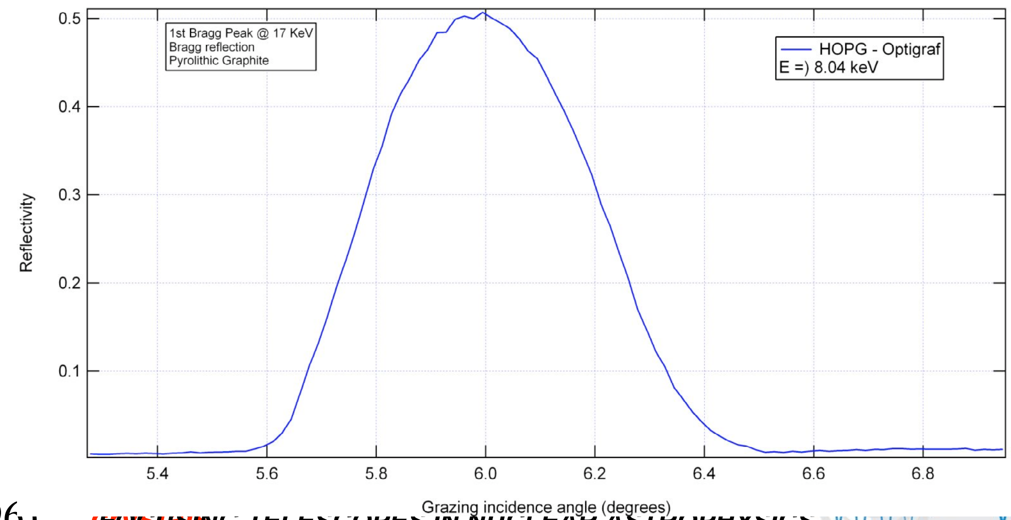
θ = 2.71 deg



θ = 1.99 deg

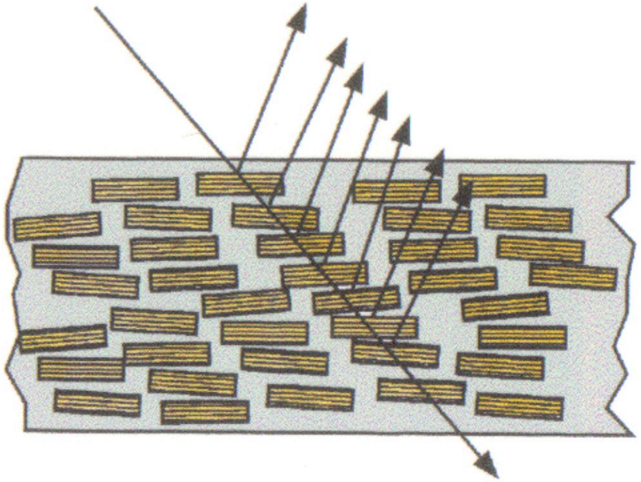




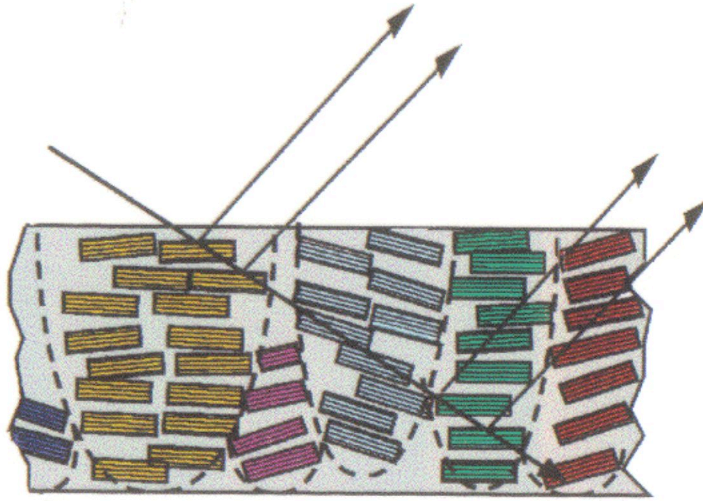


G. Pareschi, Ph.D. thesis, Univ. di Ferrara (1996)

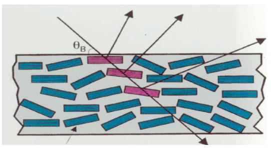
HOPG mosaic observed configurations



Bragg diffraction of a laminar monochromatic beam with an *ideally imperfect crystal* (perfect mosaic)

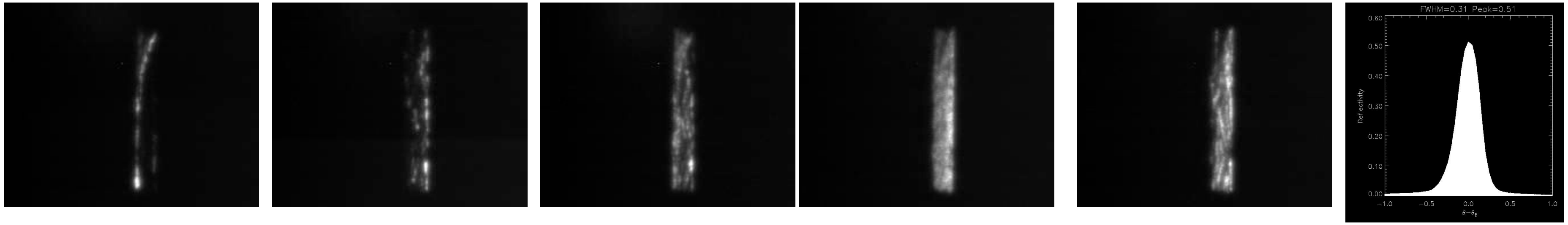


Bragg diffraction of a laminar monochromatic beam with an mosaic crystal containing macrostructures

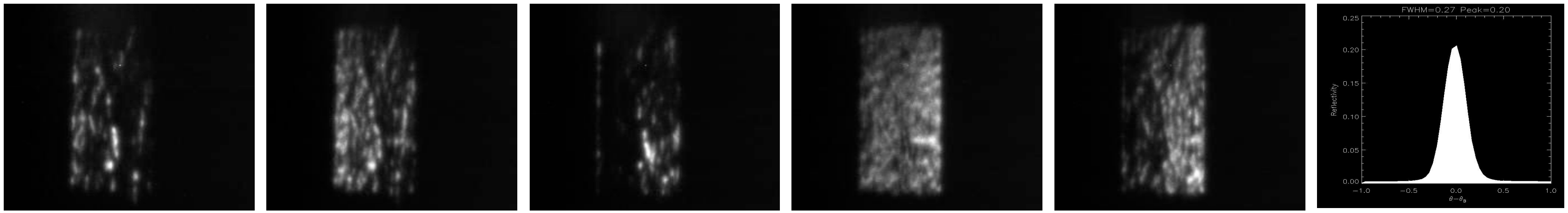


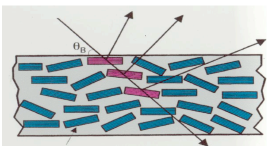
Advanced Ceramics sample

Mosaic sample: AC1, Face: A, Reflection (002)



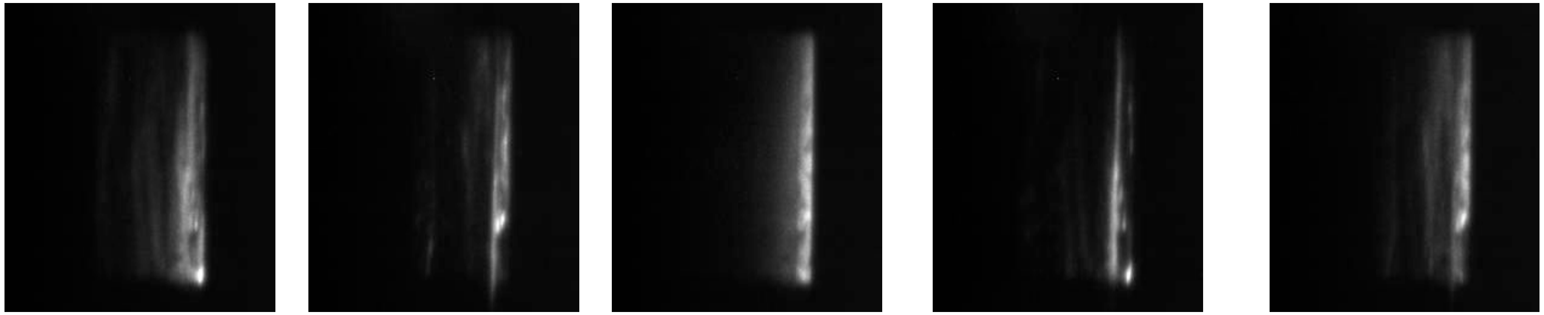
Mosaic sample: AC1, Face: A, Reflection (004)

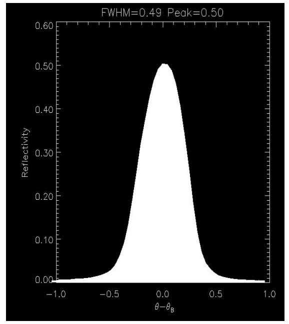




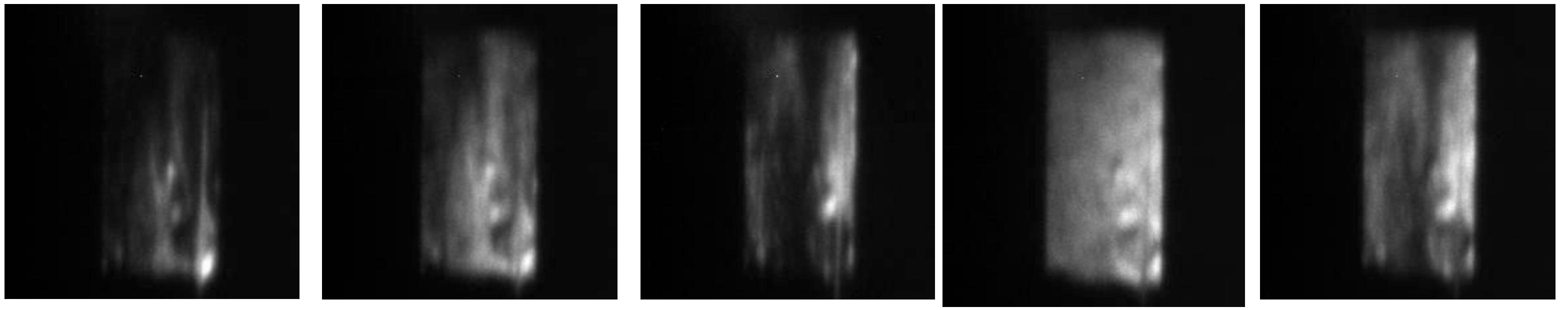
Optigraf sample

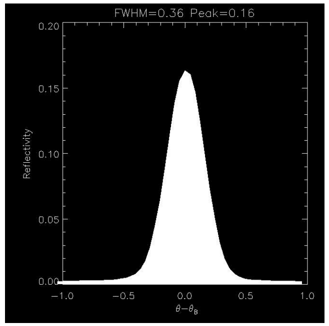
Mosaic sample: o12N, Face: A, Reflection (002)

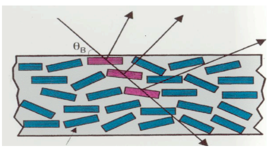


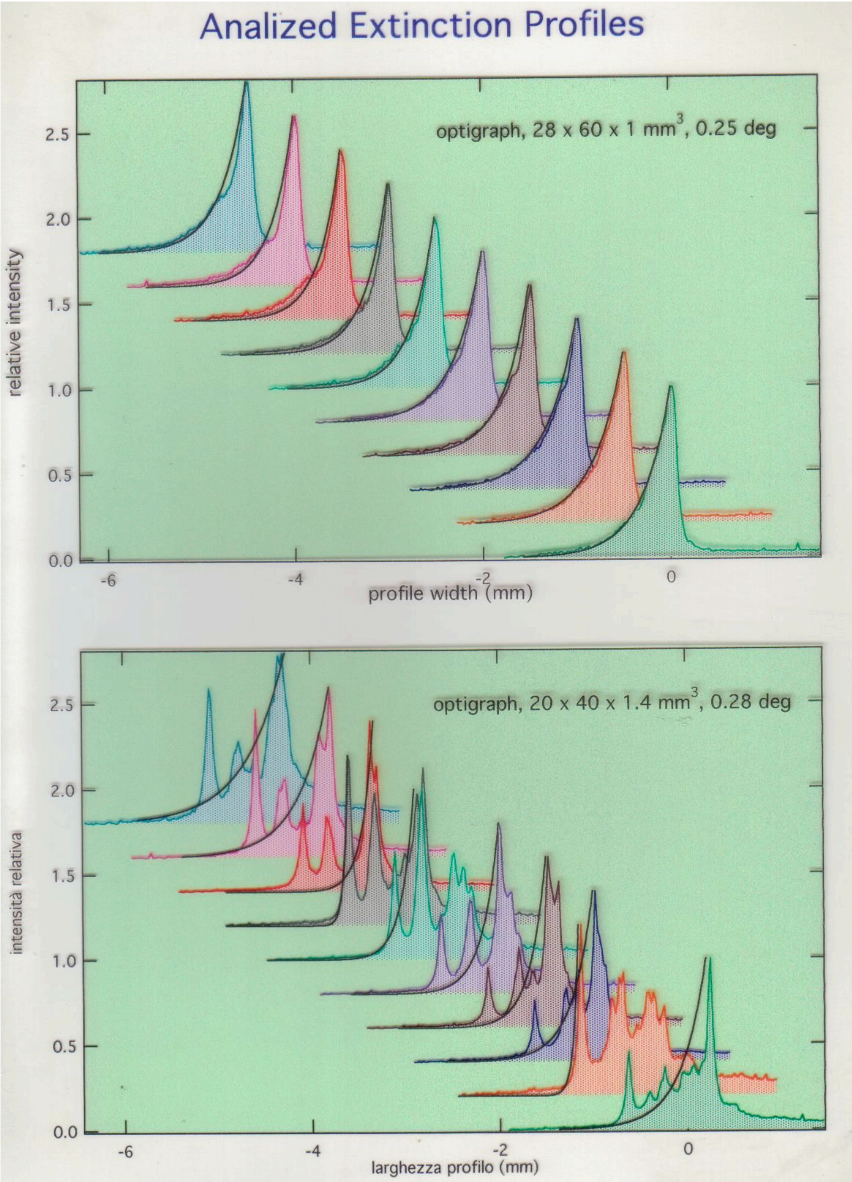


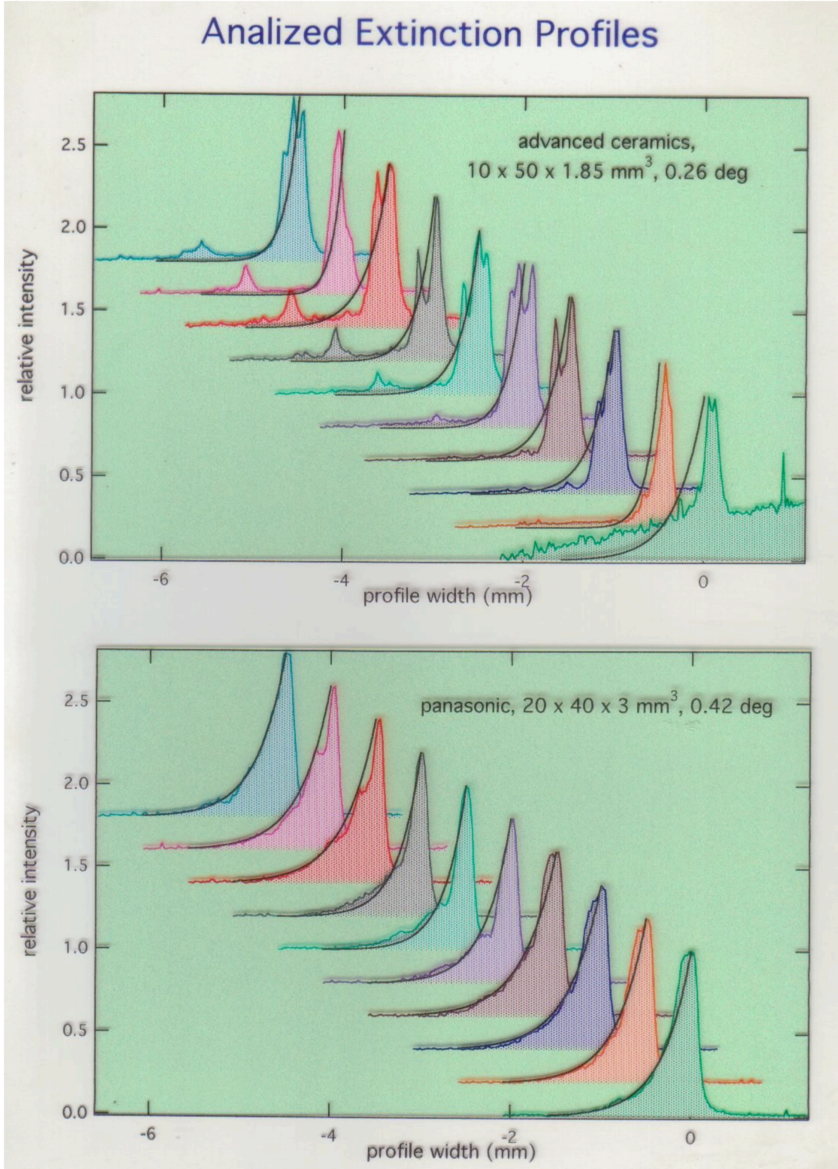
Mosaic sample: o12N, Face: A, Reflection (004)

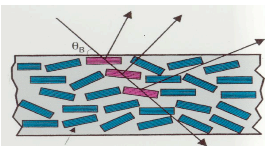




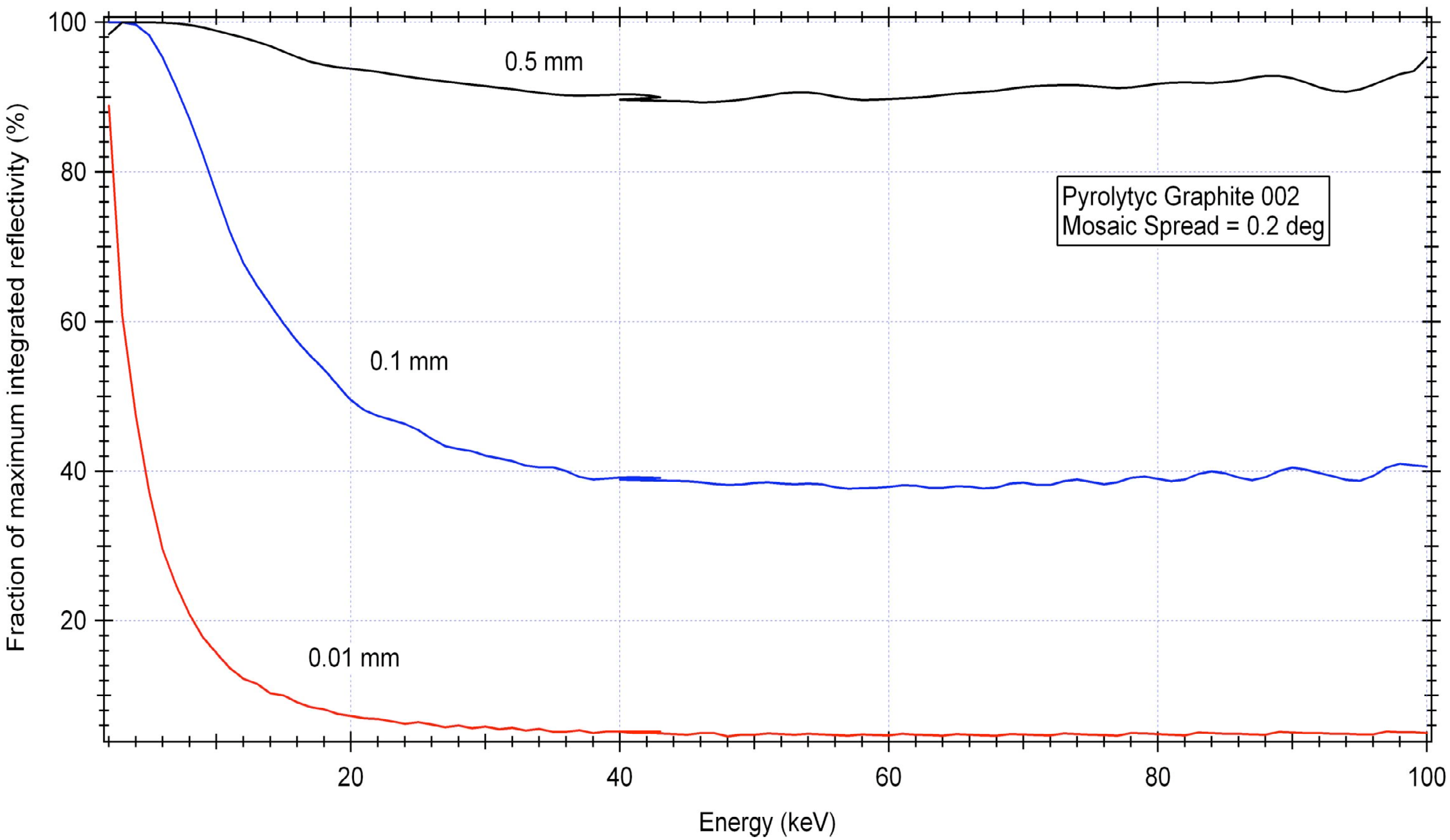



Analized Extinction Profiles
optigraph, 28 x 60 x 1 mm^3, 0.25 deg
relative intensity
profile width (mm)
optigraph, 20 x 40 x 1.4 mm^3, 0.28 deg
intensità relativa
larghezza profilo (mm)

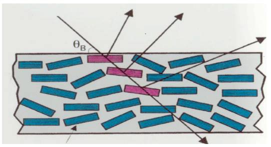

Analized Extinction Profiles
advanced ceramics,
10 x 50 x 1.85 mm^3, 0.26 deg
relative intensity
profile width (mm)
panasonic, 20 x 40 x 3 mm^3, 0.42 deg
relative intensity
profile width (mm)



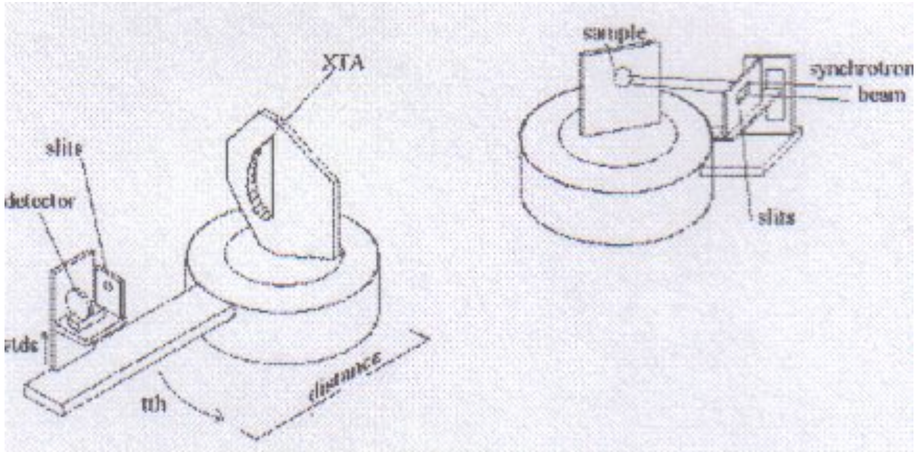
Integrated reflectivity Vs. crystal thickness

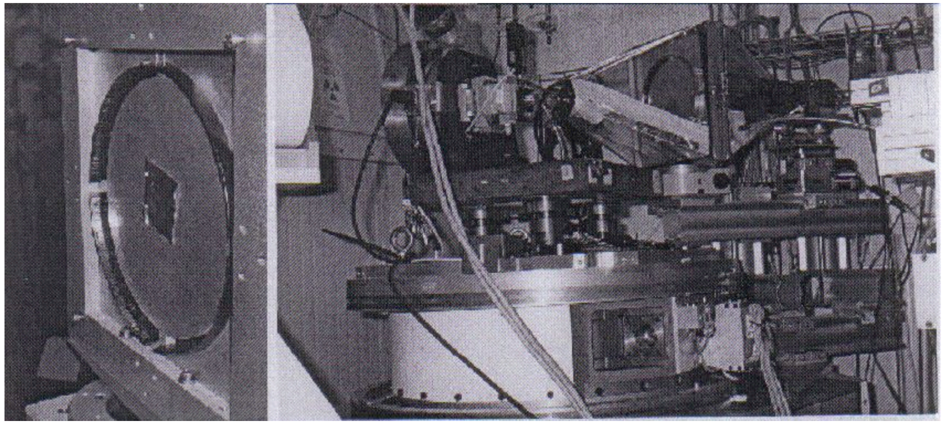


Trade off on the reflection/thickness behavior has to be considered. Thinner crystals allow us to reduce the cost and to better fit the shape of figured double-curvature mirrors!



Bragg concentrator for flurecence analysis at ESRF





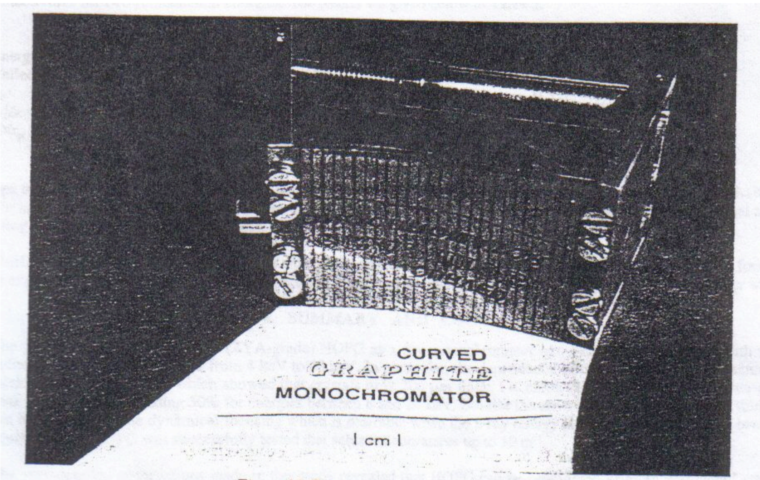
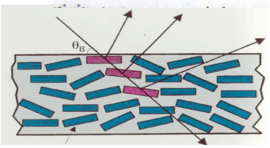


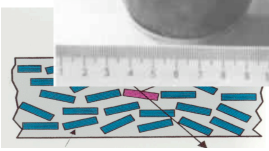
Figure 10: Photograph of the curved HOPG.

Cylindrical concentrator based on thin (300 μm thick) HOPG curved crystals

Freund et al., 1997
Marchesini et al., 1998



New approach to coat figured optics (developed at Optigraf, Russia)



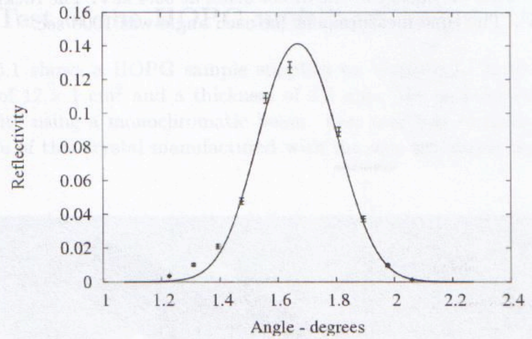


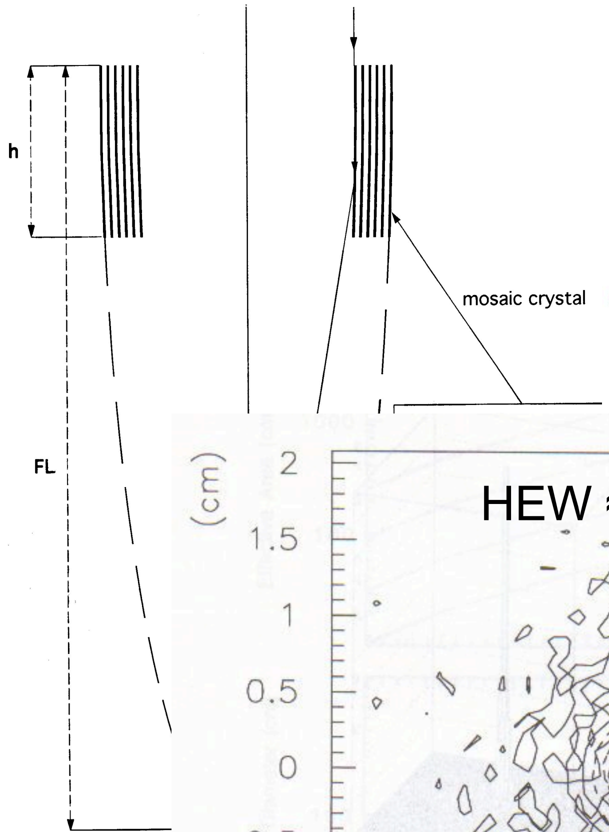
Figure 5.3: Reflectivity curve at 63.4 keV.

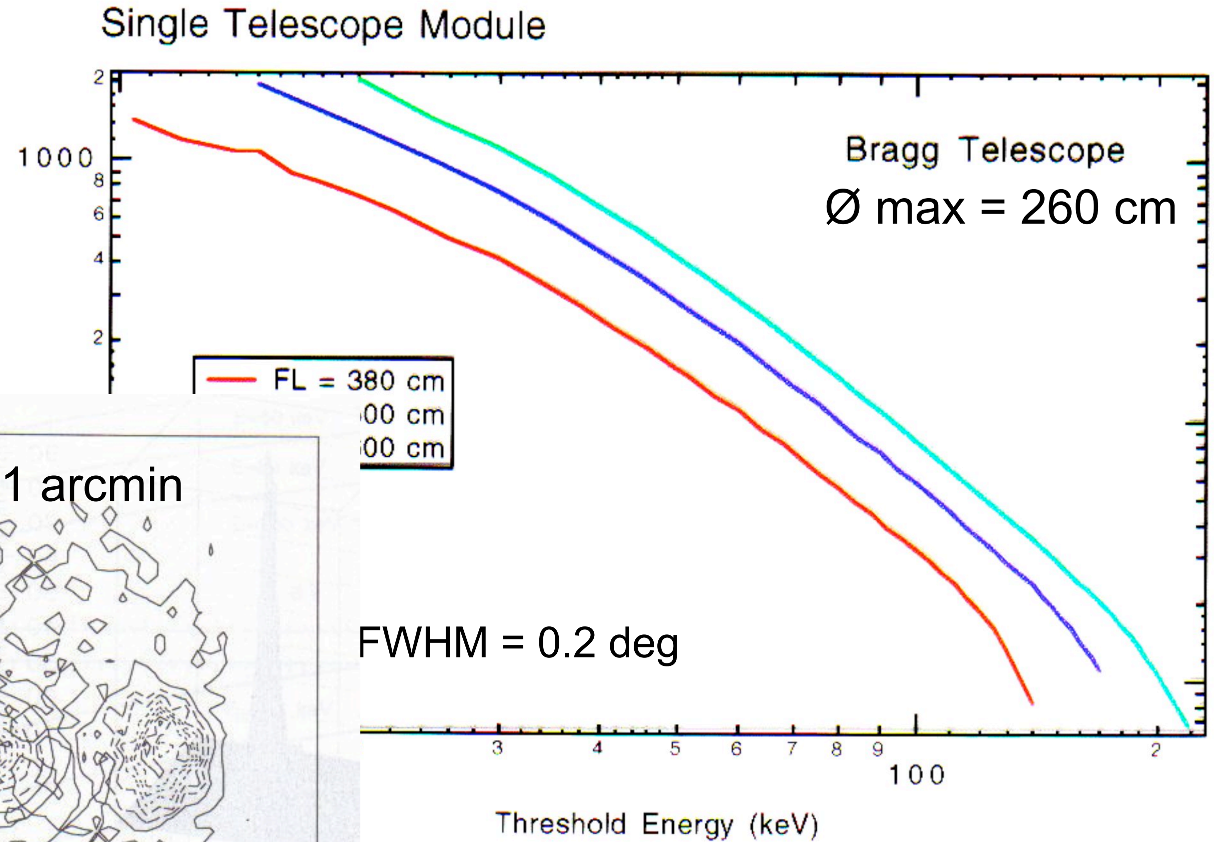
Figure 5.4: The sample of HOPG crystal by *Advanced Ceramics*, $6 \times 2 \times 0.2$ cm^3.

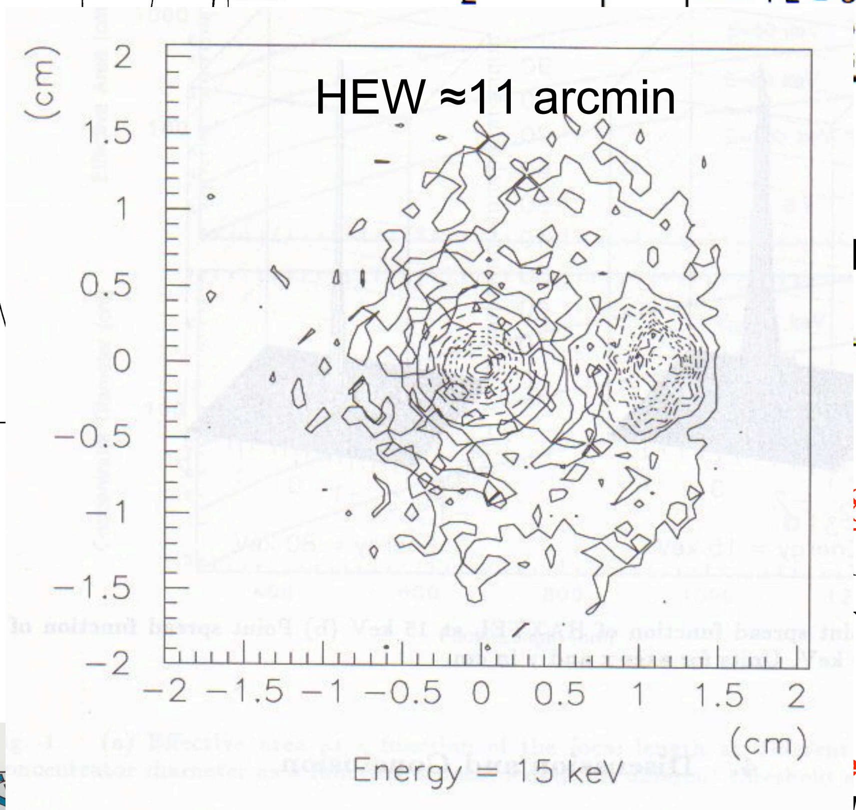
Layers of HOPG are peeled of from bulky crystals and then applied to figured substrates

G. Loffredo, Ph. Thesis, Univ. of Ferrara, 2004

The HAXTEL telescope concept



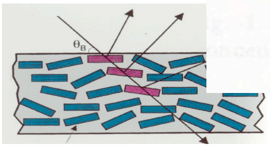




30 cm:

vity of ~ 20 μCrab @ 20 keV in 10^5 s

vity of ~ 200 μCrab @ 60 keV in 10^5 s



Conclusions & discussion

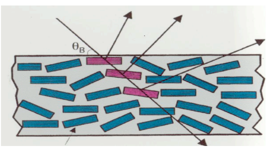
• Bragg diffraction with mosaic crystals is a very effective focusing techniques for the hard X-ray domain whose investigation for astronomy applications started in parallel with the development of Grazing incidence Wolter I optics;

• the use of the diffraction Bragg approach in the 10 – 150 energy band is very attractive compared to grazing incidence optics with single and multilayer coatings because of the much larger angles involved

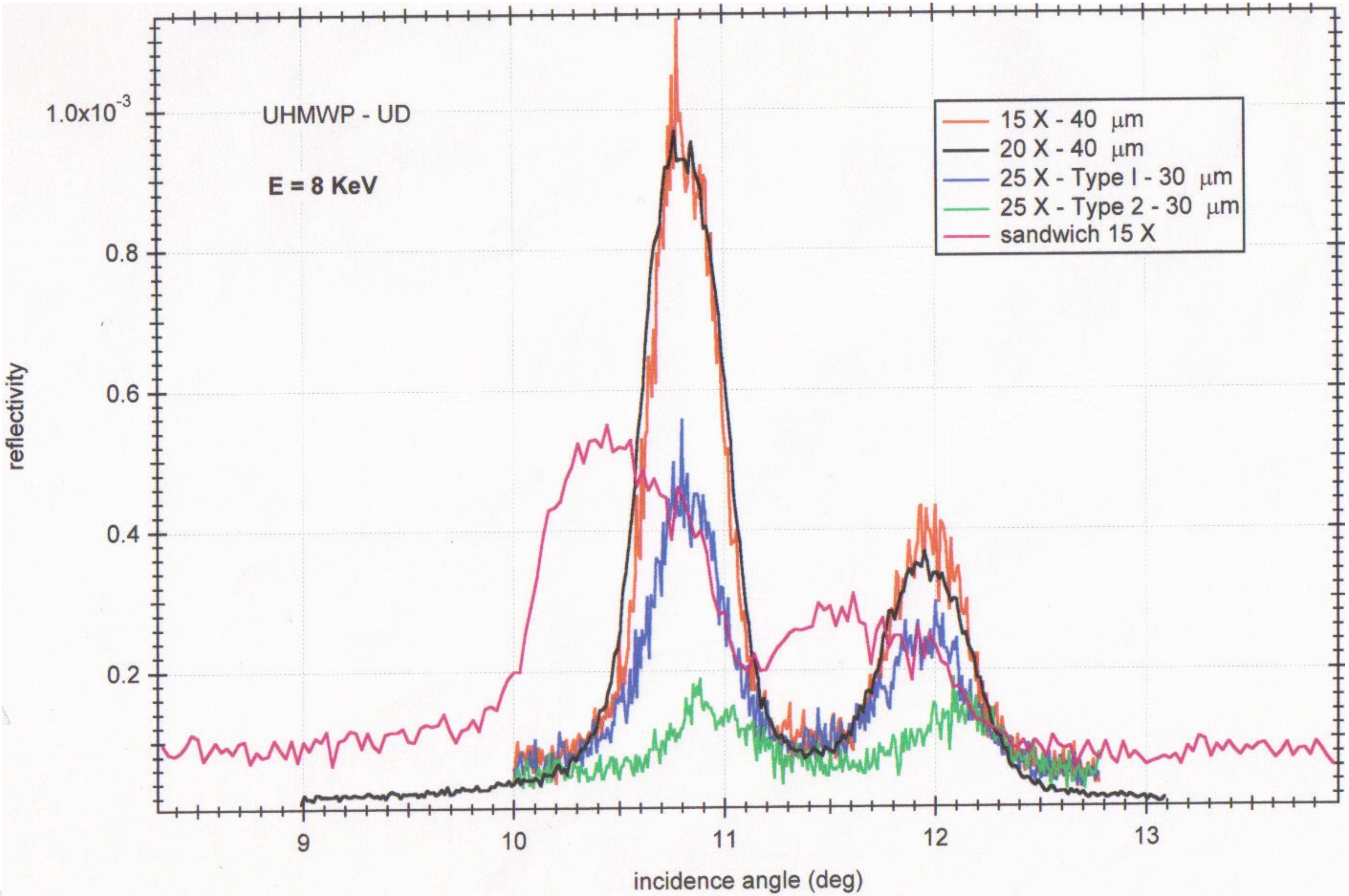
• a major drawback is related to the focal spot blurring due to the mosaic misalignment of microcrystals, together with the difficulty of following a curved profile with bulky flat crystal pieces. *Independently of the focusing feature, hard X-ray telescopes should present **a better angular resolution than INTEGRAL/IBIS!*** (unless to remain limited to spectroscopic applications in the 60 – 150 keV band)

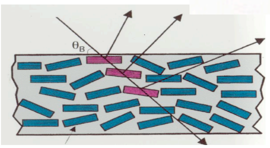
• HOPG is at the moment the best performing material for making hard X-ray Bragg concentartors. The possibility of using thin structures reduces the cost and enables to better follow the desired mirror profiles.

• more reduced mosaic spreads with a trade-off in terms of integrated reflectivity is required in order to improve the angular resolution!

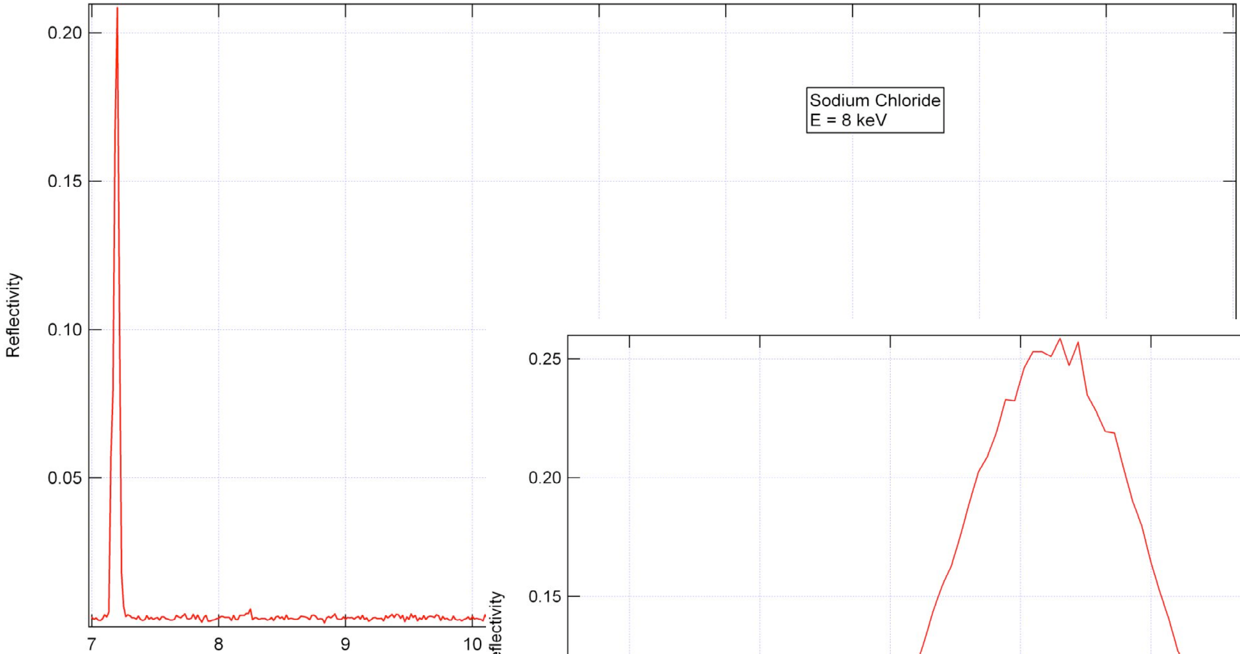


UltraHMWP-UD

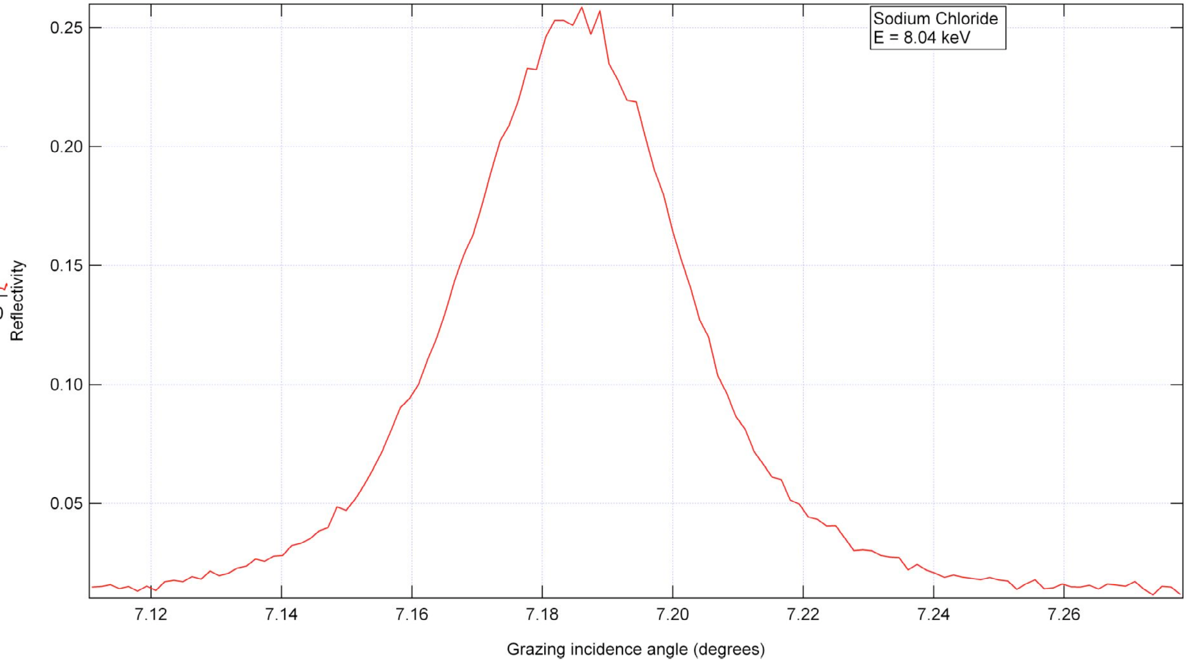




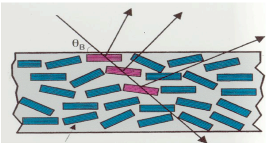
Rock Salt

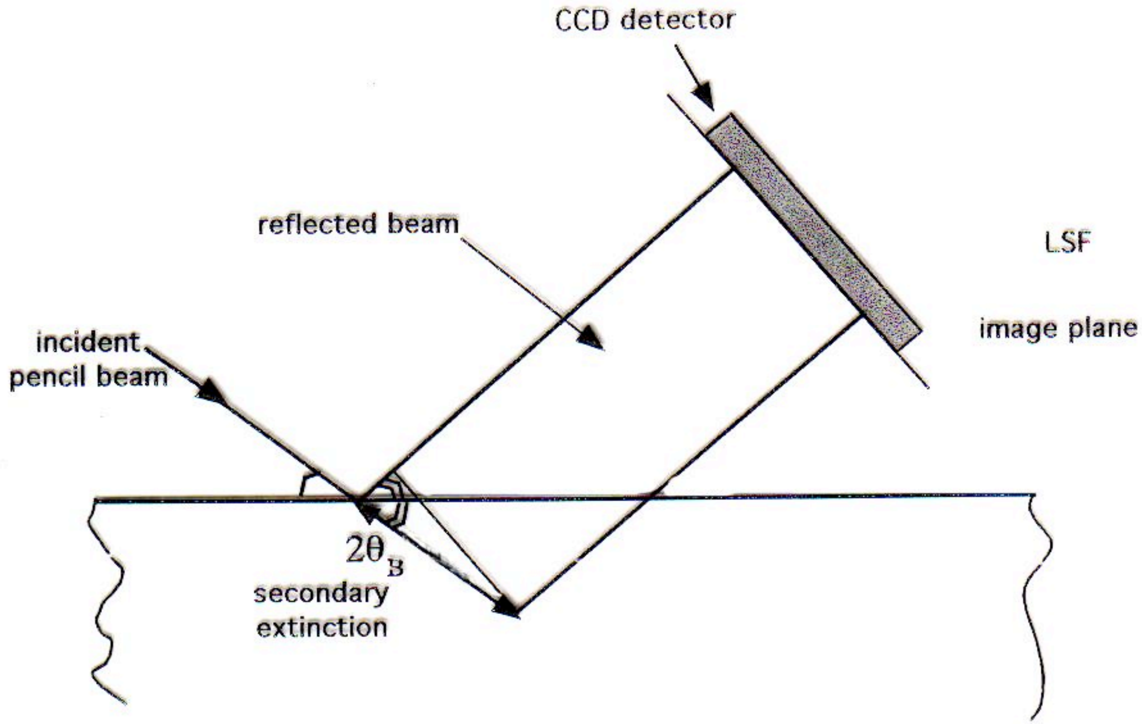


Sodium Chloride
E = 8 keV
Reflectivity
0.20
0.15
0.10
0.05
7
8
9
10



Sodium Chloride
E = 8.04 keV
Reflectivity
0.25
0.20
0.15
0.10
0.05
7.12
7.14
7.16
7.18
7.20
7.22
7.24
7.26
Grazing incidence angle (degrees)





$$Ext_s = \lambda / \sin(2\theta_B)$$