SIMBOL-X optics: design and implementation

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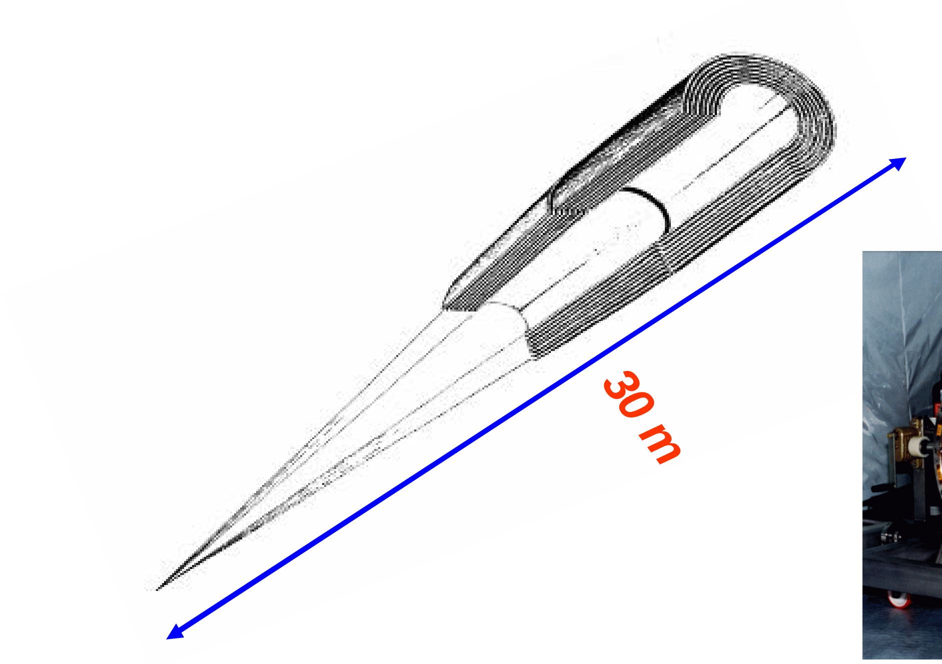


Outline

- the SIMBOL-X optical design

- the replication approach for the realization of the SIMBOL-X mirrors

- possible design improvements based on multilayer coatings

- conclusions

X-ray optical constants

- complex index of refraction to describe the interaction X-rays / matter:

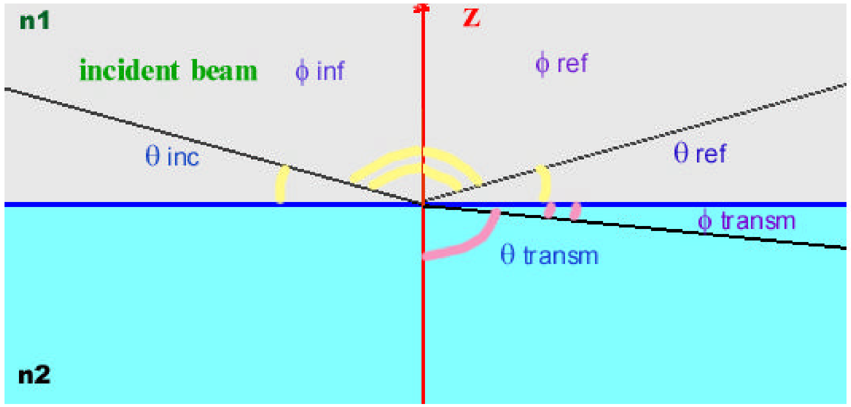
δ → changes of phase

β → absorption

ñ = n + iβ = 1 - δ + iβ

($\mu = 4 \pi \beta/\lambda \; cm^{-1}$) — *Linear abs. coeff.*

- at a boundary between two materials of different refraction index n1, n2 reverse of the momentum P in the z direction:



$$\vec{p}_1 = \frac{h}{2\pi}\vec{k}_1$$

$$\left|\vec{k}_1\right| = \frac{2\pi}{\lambda} n_1$$

$$2p_z \propto \frac{4\pi}{\lambda} n_1 \sin\theta_{inc}$$

momentum transfer

- the amplitute of reflection is described by the Fresnel's equations:

$$r_{12}^{s} = \frac{n_1 \sin\theta_1 - n_2 \sin\theta_2}{n_1 \sin\theta_1 + n_2 \sin\theta_2}$$

$$r_{12}^{p} = \frac{n_1 \sin\theta_2 - n_2 \sin\theta_1}{n_1 \sin\theta_2 + n_2 \sin\theta_1}$$

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Total X-ray reflection at grazing incidence

- if we assume vacuum as a 1st material ($n_1 = 1$) ➔ the phase velocity in the 2nd medium increases ➔the beam tends to be deflected in the direction opposite to the normal.

- If we apply the Snell's law ($n1 \cos\theta_1 = n2 \cos\theta_2$) it easy to find a critical angle for total reflection:

$$\theta_{crit} \approx \sqrt{2\delta} = \sqrt{\frac{r_0 \lambda^2 \rho N_{Av} f_1}{A\pi}}$$

λ = wavelenght ρ = density
A = atomic weight f_1 = scattering coeff.
r_0 = classical electron radius

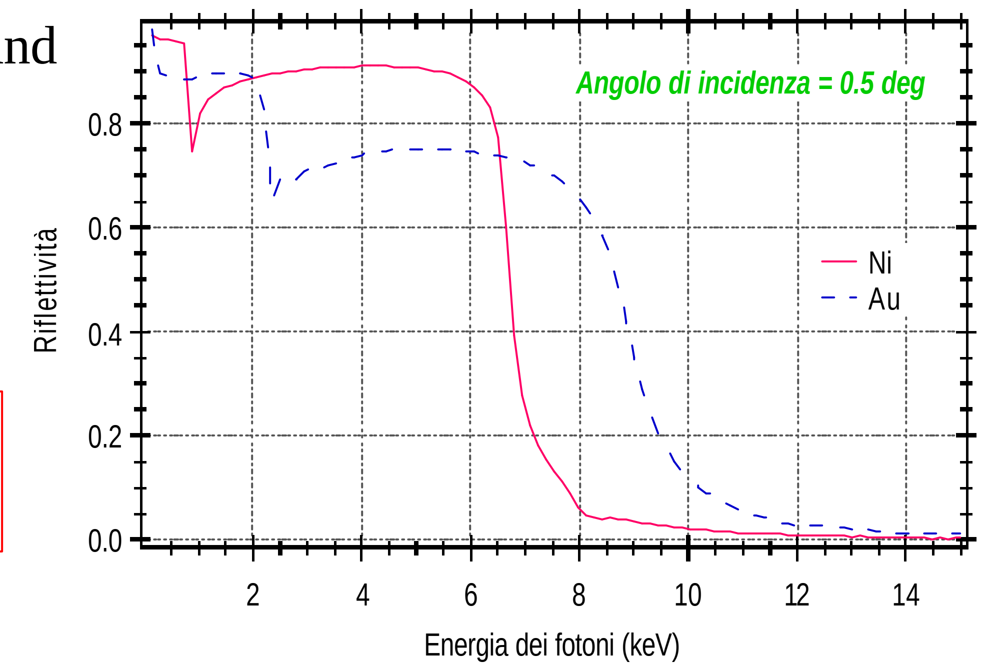
- far from the fluorecence edges $f_1 \approx Z$ and for heavy elements $Z/A \approx 0.5$:

$$\theta_{crit}(\mathrm{arcmin}) \approx 5.6\, \lambda(Å) \sqrt{\rho}$$

- reflectivity loss due to scattering:

$$I_R = I_0 \exp\left[-\left(\frac{4\pi \cdot n \cdot \sigma \cdot \sin\theta}{\lambda}\right)^2\right]$$

σ = rms microroughn. level



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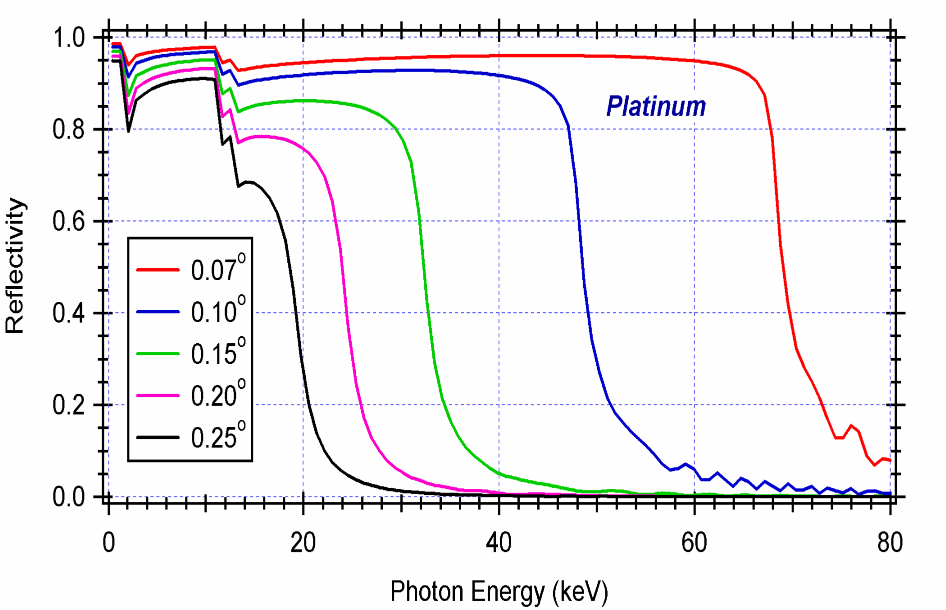
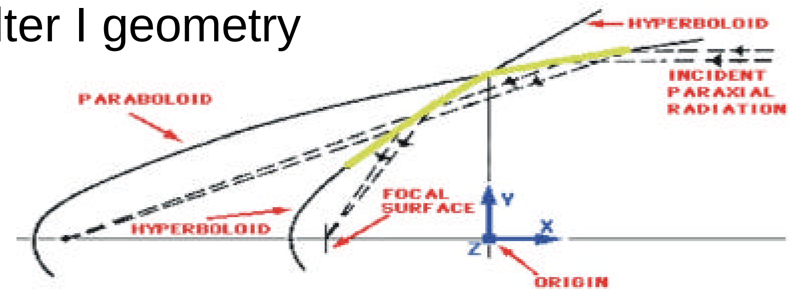
The focusing problem in the hard X-ray region (> 10 keV)



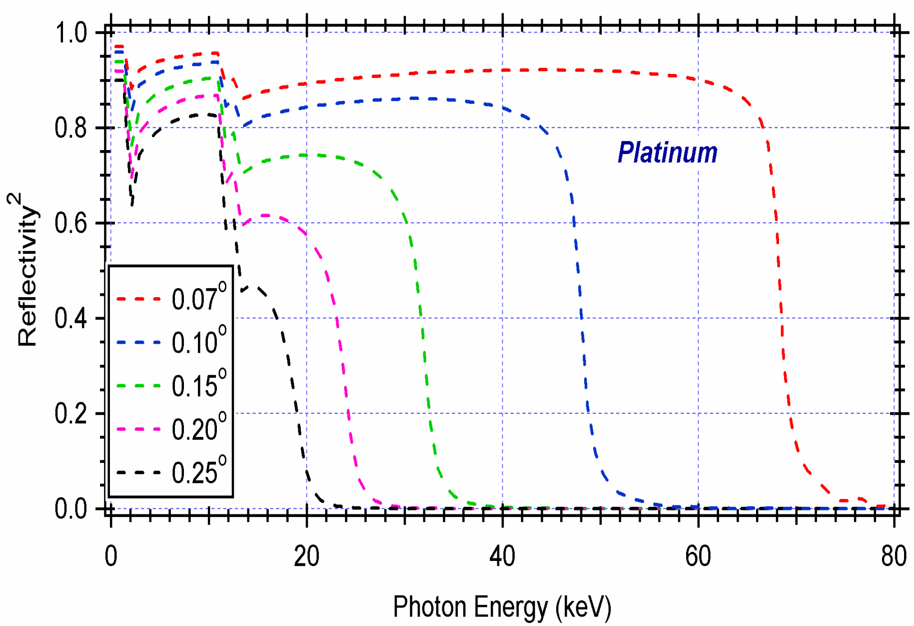
Wolter I geometry



F = focal length   *R = reflectivity*

L = mirror height   *q = incidence angle*

$$A_{eff} \approx 8pLF\, J^{2}_{inc}$$



$$J_{crit} \propto \frac{\sqrt{r}}{E}$$

At photon energies > 10 keV the cut-off angles for total reflection are very small also for heavy metals ➔ ***the attained geometrical areas are in general very small***

SIMBOL-X mirror module: driving design criteria

- use of high density materials coatings (➔ *increase of the reflection angles*)

- possibility to use the Ni replication technology for ***monolithic*** optics (➔ already available and consolidated technology)

- maximum diameter compatible with the standard superpolishing techniques already used for XMM

- *low reflecting angles* but, at the same time, large collecting areas ➔ *long focal length*

the Formation Flight gives the opportunity to implement this concept!

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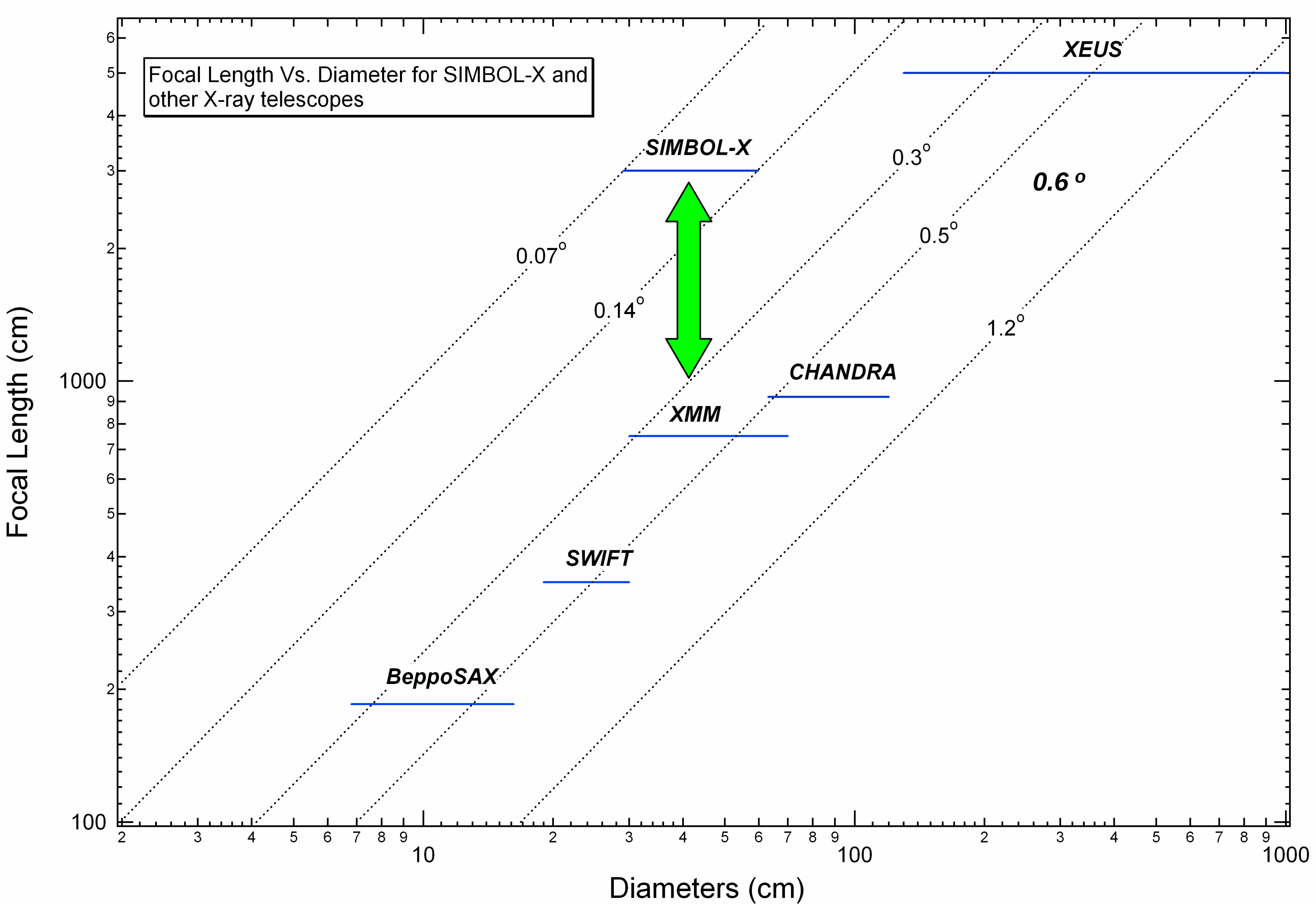
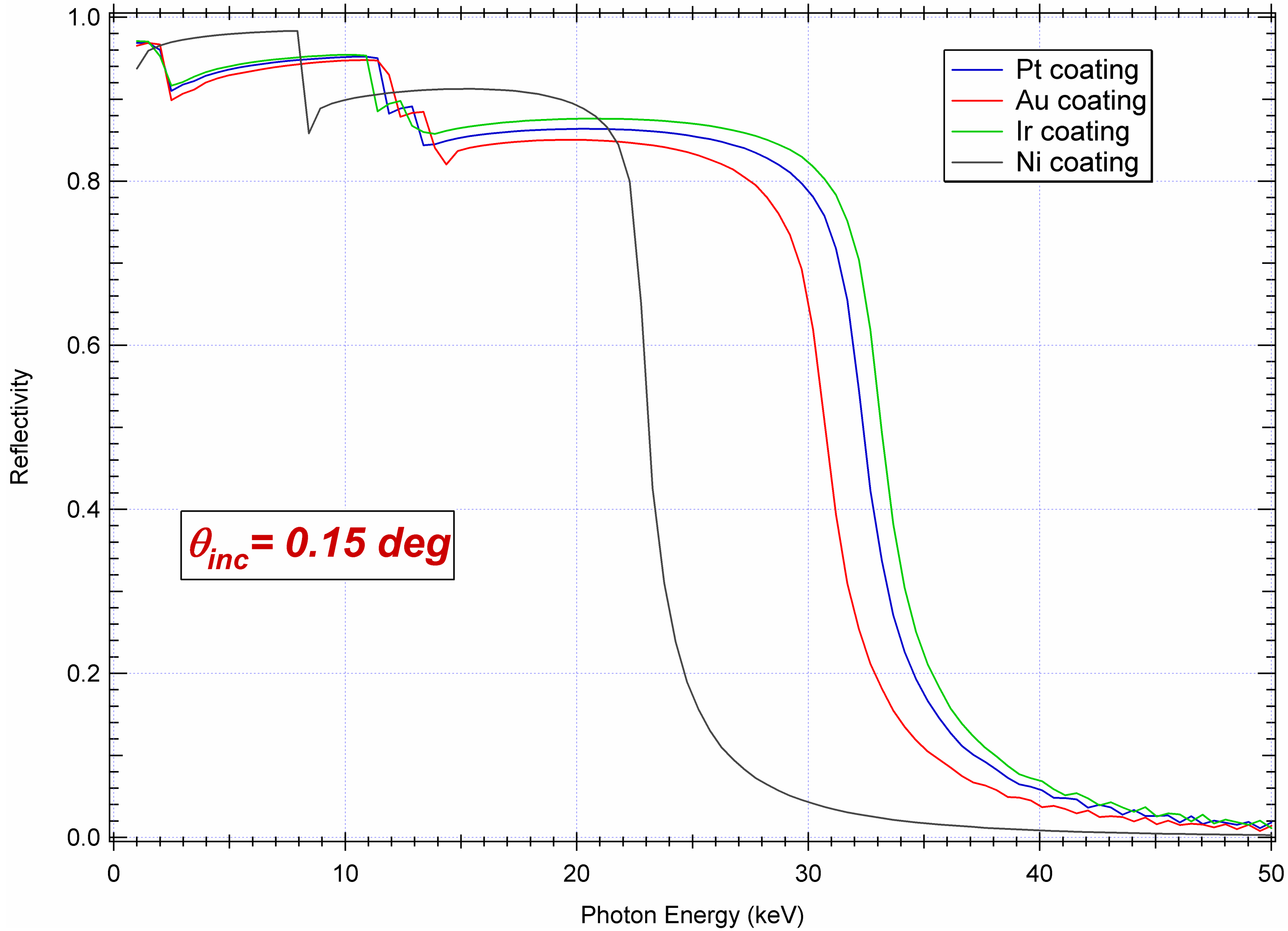
Table 1. Main parameters of the SIMBOL-X mirror module.

Max/Min Diameter	600/290 mm
Focal Length	30000 mm
Mirror Heigth	600 mm
Configuartion	Wolter I
Number of mirror modules	1
Number of Mirror shells	100
Reflecting coating	Pt
Min/Max inc. angles	$0.07^{o}/0.142^{o}$
Material of mirror walls	Ni
Min/Max wall thickness	0.12/0.30 mm
Mass of the mirror module	213 Kg
Field-of-View (FWHM)	6 arcmin
Expected resolution (HEW)	30 arcsec
Effective area @30 keV	550 cm^2

Focal Length Vs. Diameters for SIMBOL-X and other X-ray telescopes

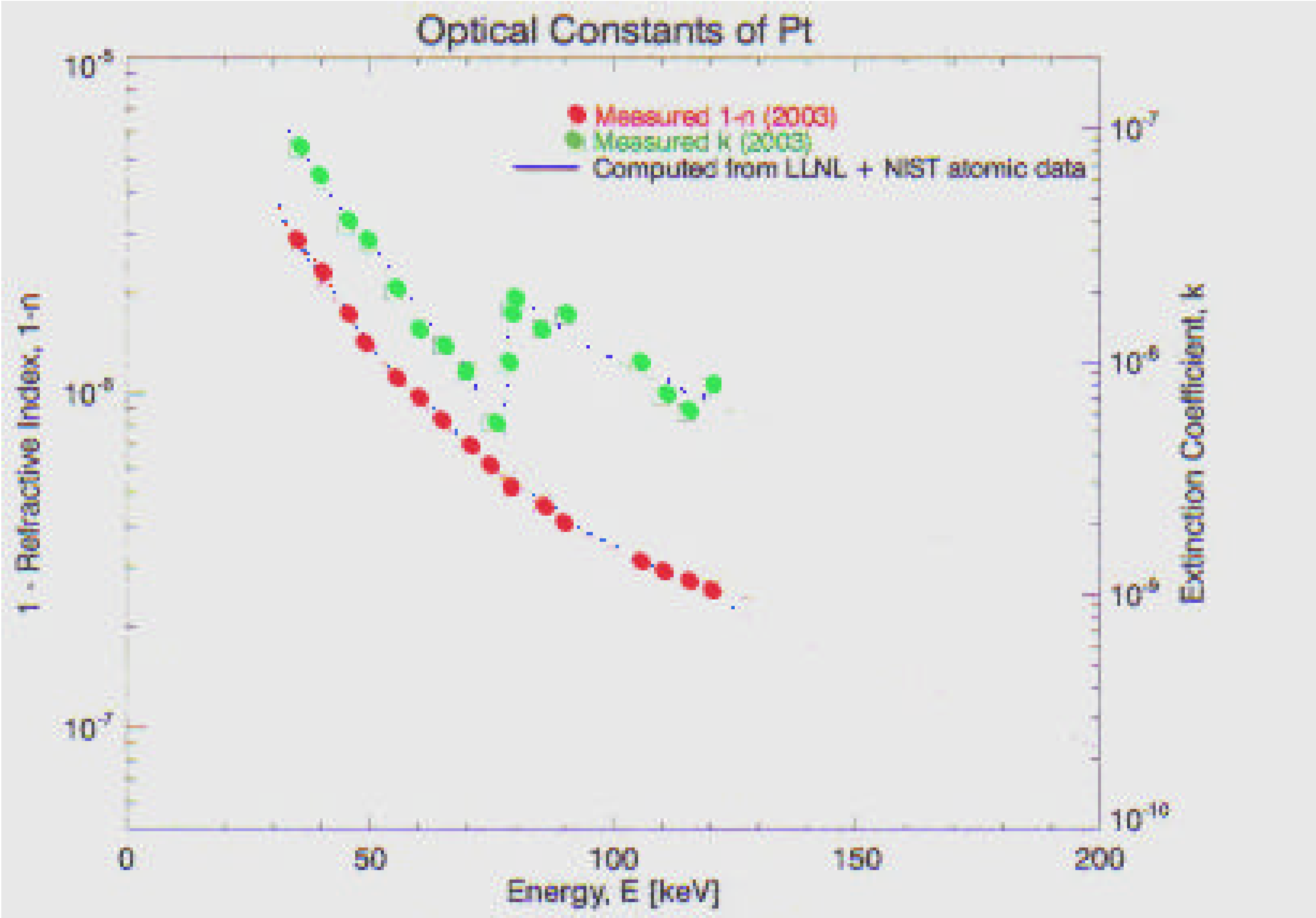


The Platinum choice as a reflecting coating



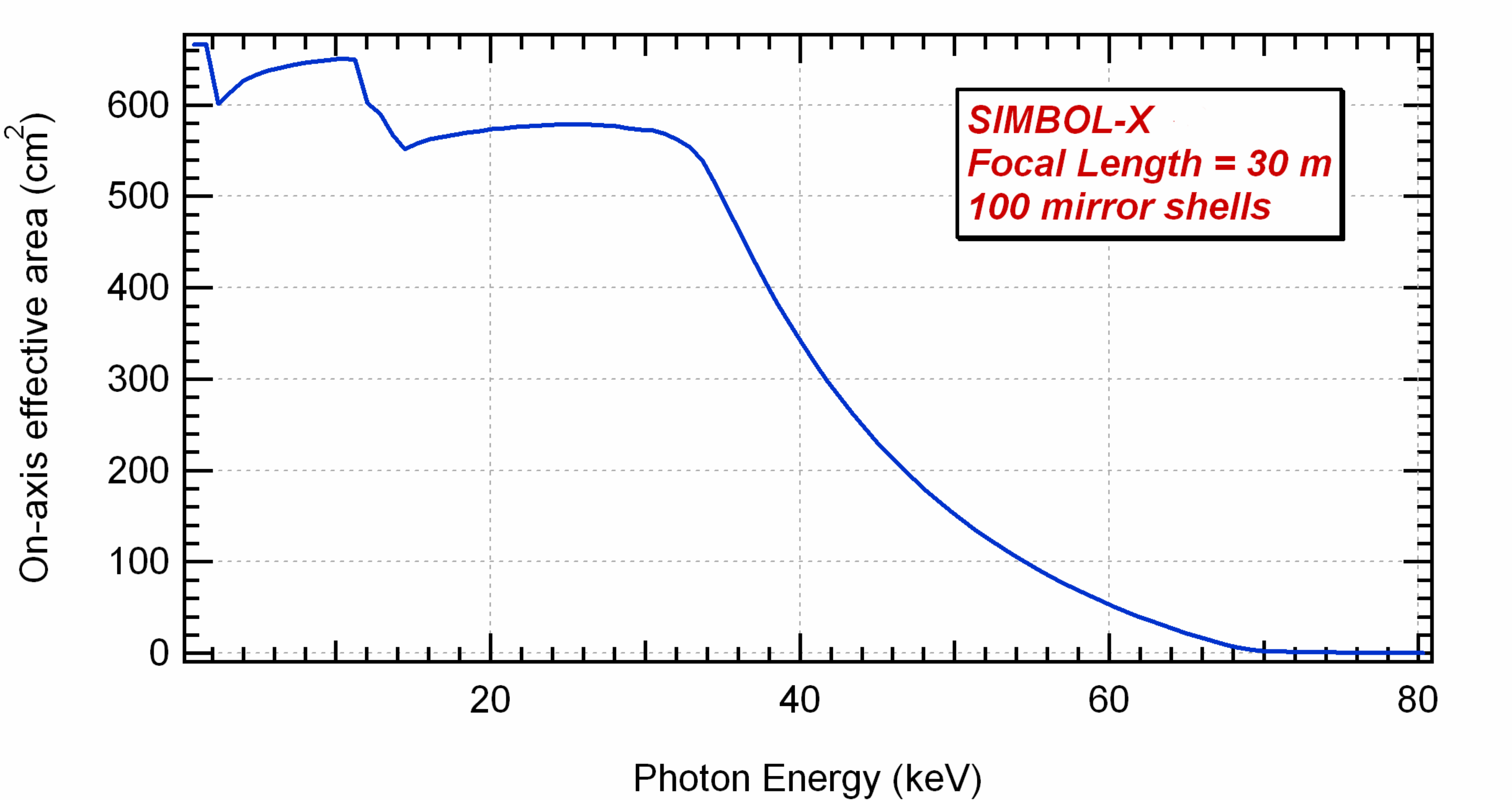
Platinum can act, like Gold, as a release agent in the replication process

Refraction Index measurement of Platinum in the hard X-ray region



Windt et al., SPIE Proc. 5168, 2004 *(data from an sinchrotron radiation experiment at ESRF, ID15 beamline)*

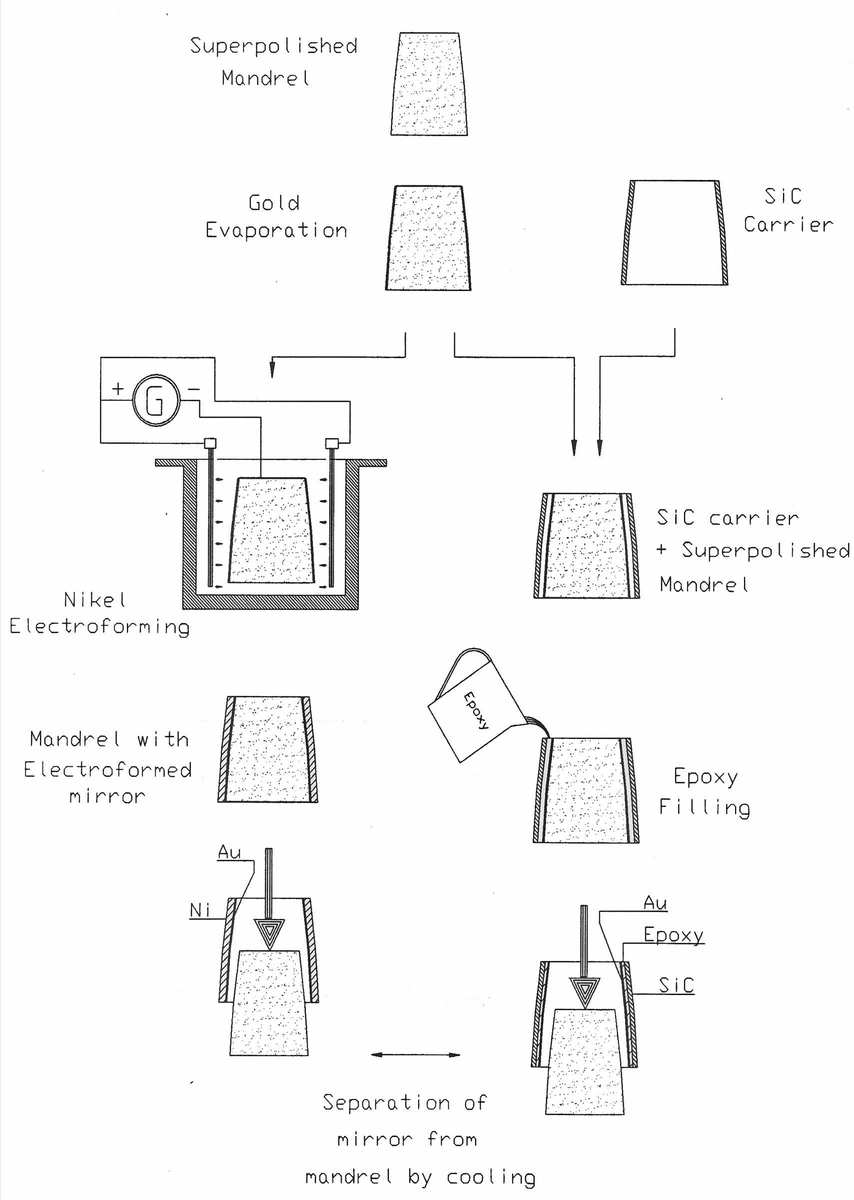
SIMBOL-X: on-axis effective area



Replication methods applied to grazing-incidence optics

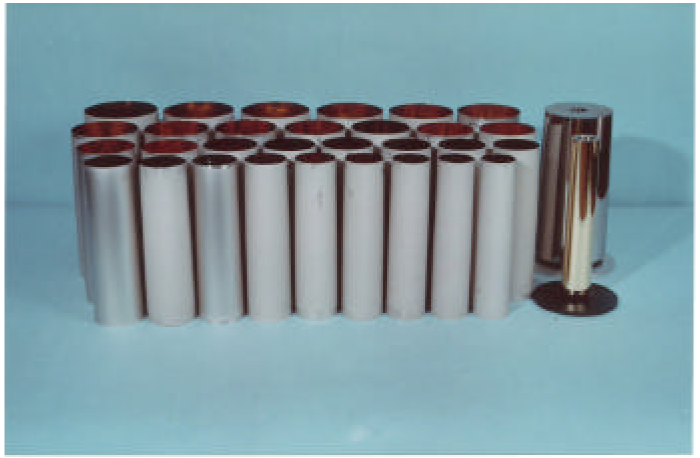
- **Ni electroforming replication** (SAX, JET-X/Swift, XMM, ABRIXAS)

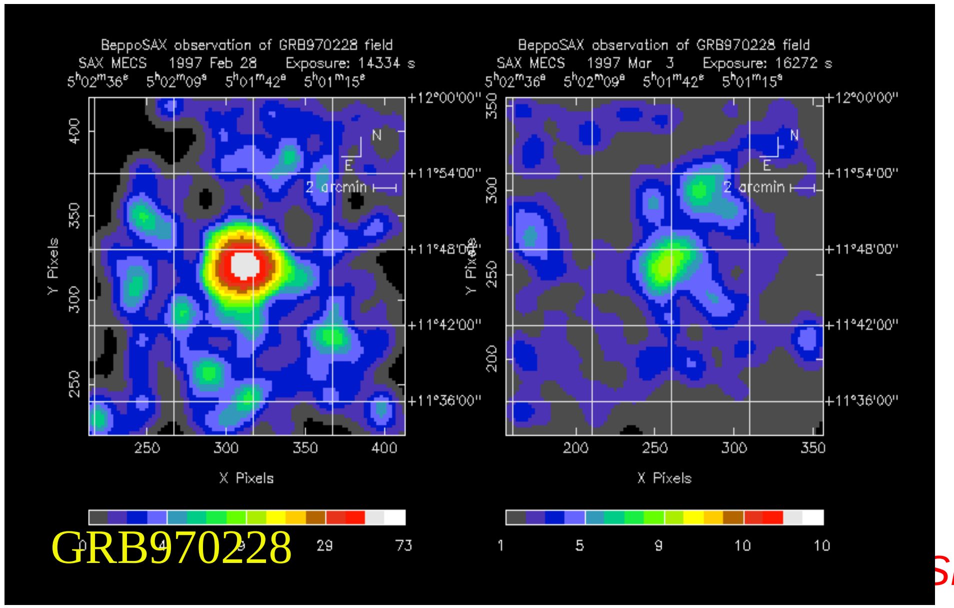
- ***epoxy replication*:** EXOSAT (Be), WFXT (Alumina & SiC prototypes)



Beppo-SAX soft X-ray (0.1 – 10 keV) concentrators

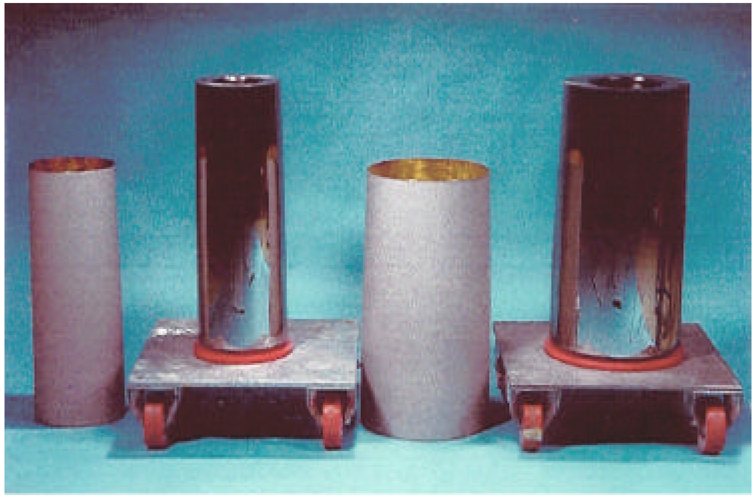
- *Wolter I double-cone approx. – Au coating*
- *4 modules – 30 shells/mod.*
- *F.L. = 180 cm Max diam = 16.1 cm*
- A_{eff} *@ 1 keV = 85* cm^2 */module*
- *HEW= 60 arcsec (mainly corresponding to the double-cone geom. aberration!)*

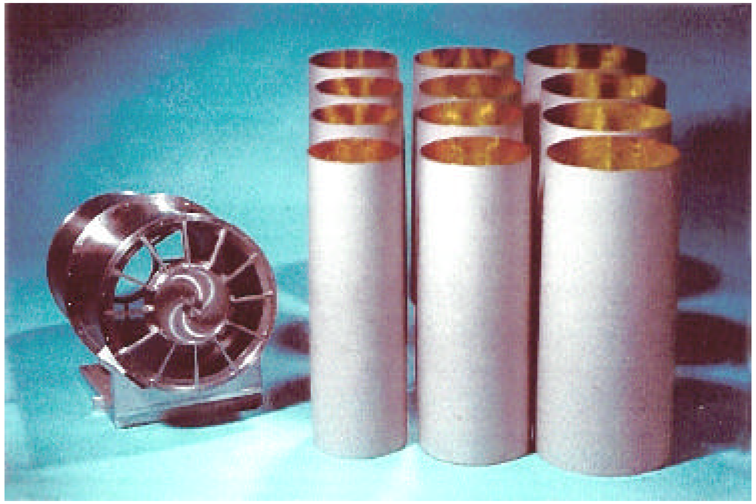




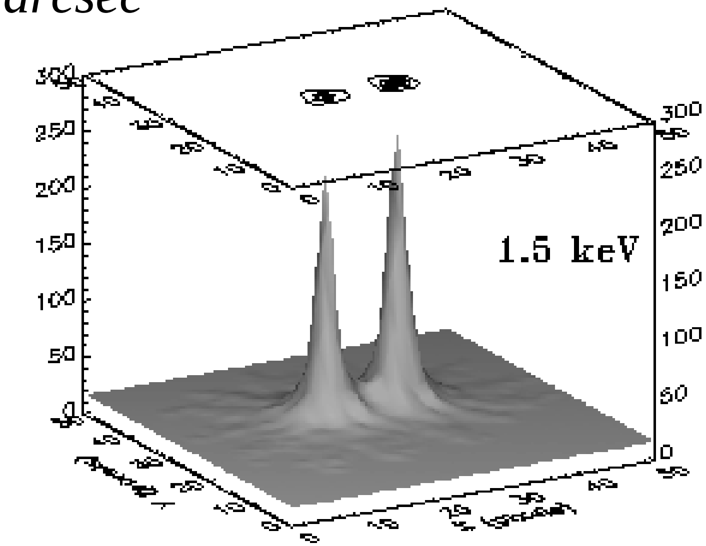
Ref.: Citterio, et al., *Appl. Opt.*, 27, 1470, (1988)

JET-X (optics ready since1996) / Swift-XRT (2004) optics





- Wolter I profile – Au coating (pathfinder of XMM)
- 2 mod. (JET-X) / 1 mod (Swift) – 12 shells/mod.
- F.L. = 350 cm - Max diam = 30 cm
- A_{eff} @ 1 keV= 150 cm^2 /module
- HEW= 15 arcsec

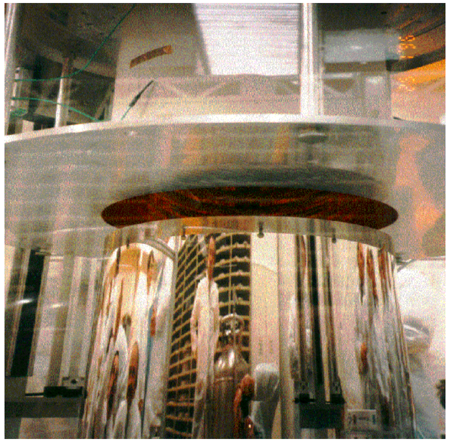


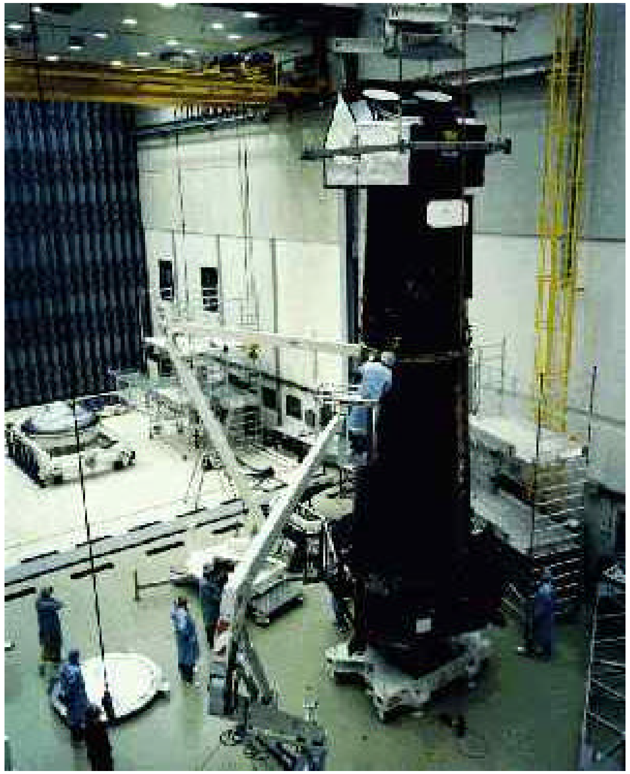
Source separation: 20”

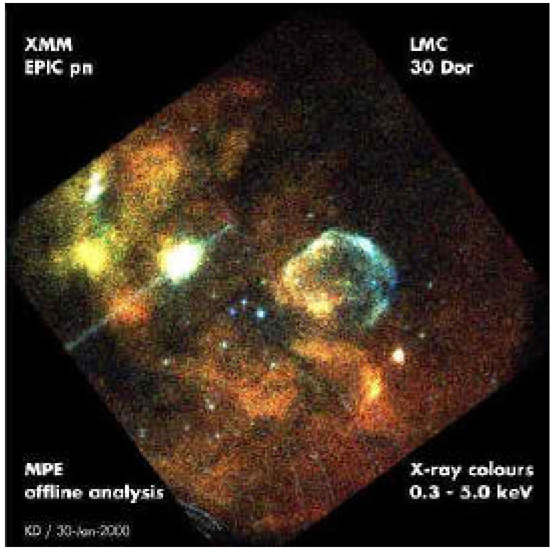
XMM-Newton (operative since Dec. 1999)

- *Wolter I profile – Au coating*
- *3 mod. - 58 shells/mod.*
- *F.L. = 750 cm - Max diam = 70 cm*

- *A_{eff} @ 1 keV= 1500 cm^2 /module*
- *HEW= 15 arcsec*

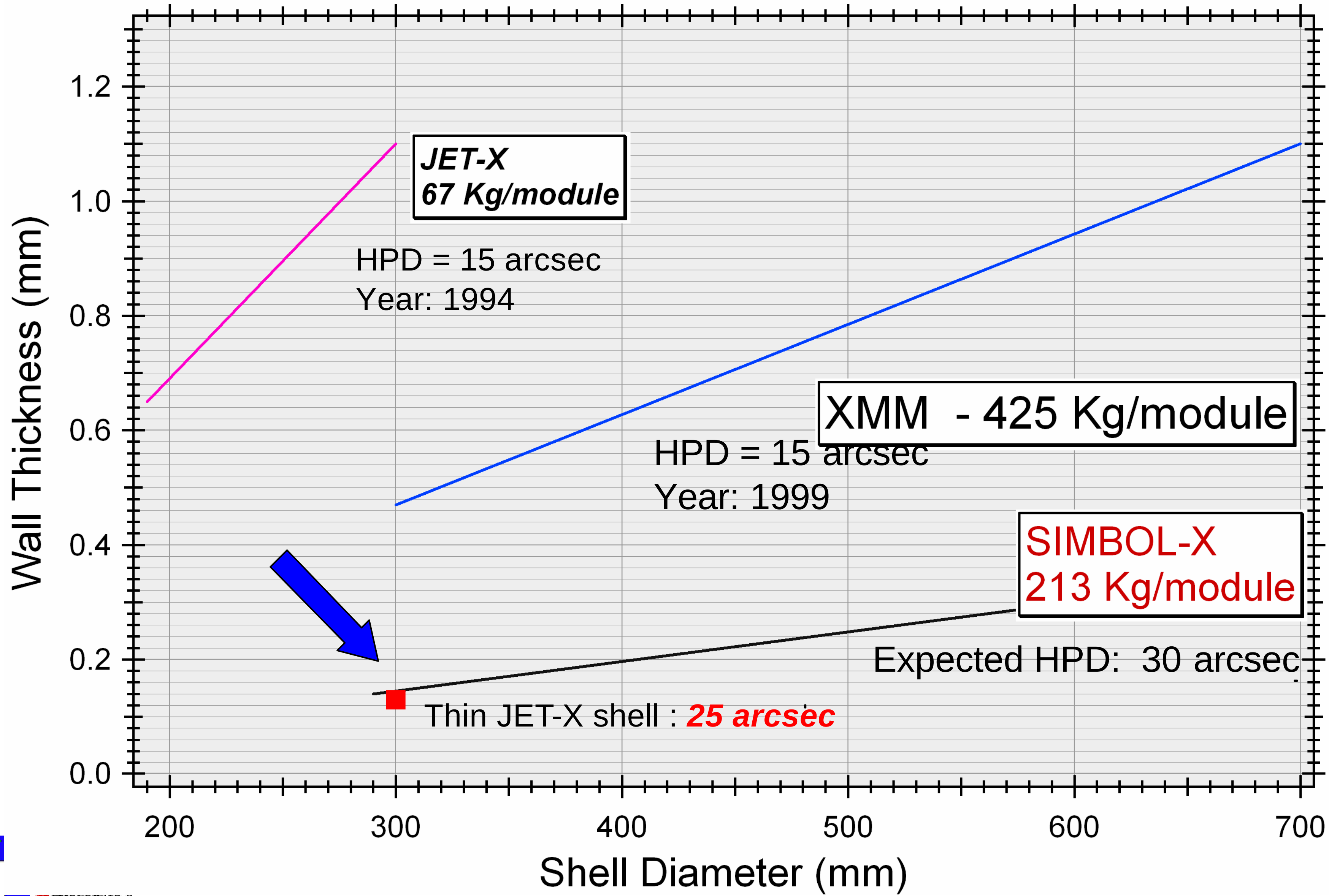






Credits: ESA

Thickness Vs. Diameter trend for Ni-replicated optics

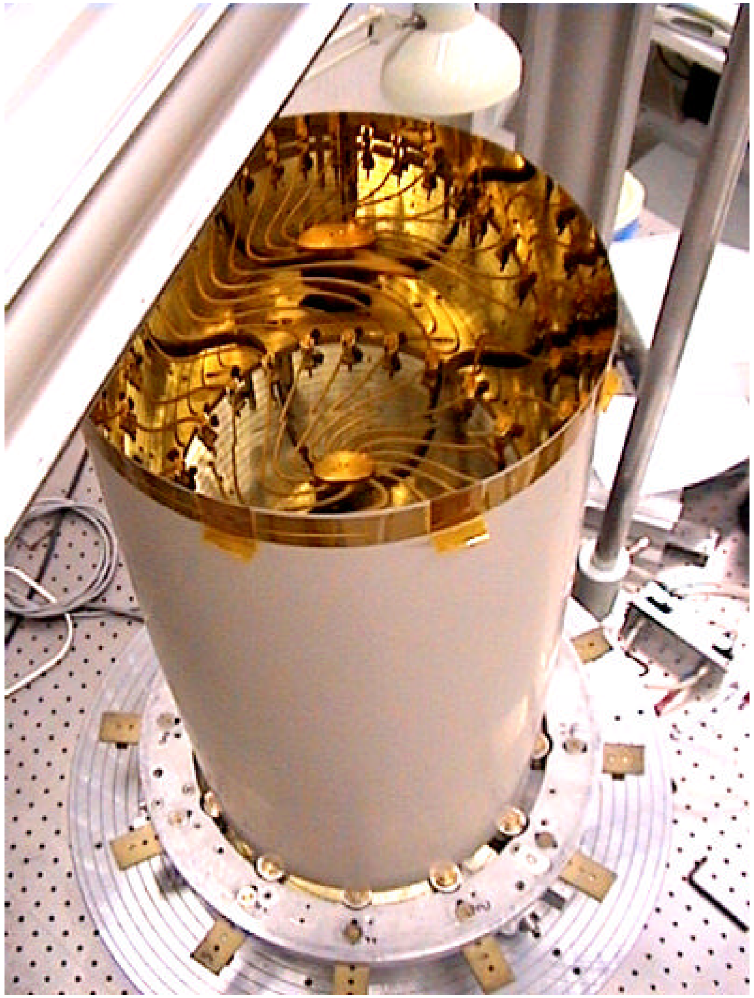


Fabrication of a thin (130 mm) MS from the largest JET-X mandrel

To verify the imaging capabilities of thin Ni electroformed mirrors, we realized a ***0.13 mm*** *Au coated shell exploiting* *<u>the largest JET-X mandrel</u>*

➔ *the thickness has been diminished of a factor* ***8.5*** *with respect JET-X/SWIFT*

Æ = 30 cm	Height = 60 cm
Focal Length = 3.5 m	
Thickness = **0.13 mm**	Mirror mass = **660 g**



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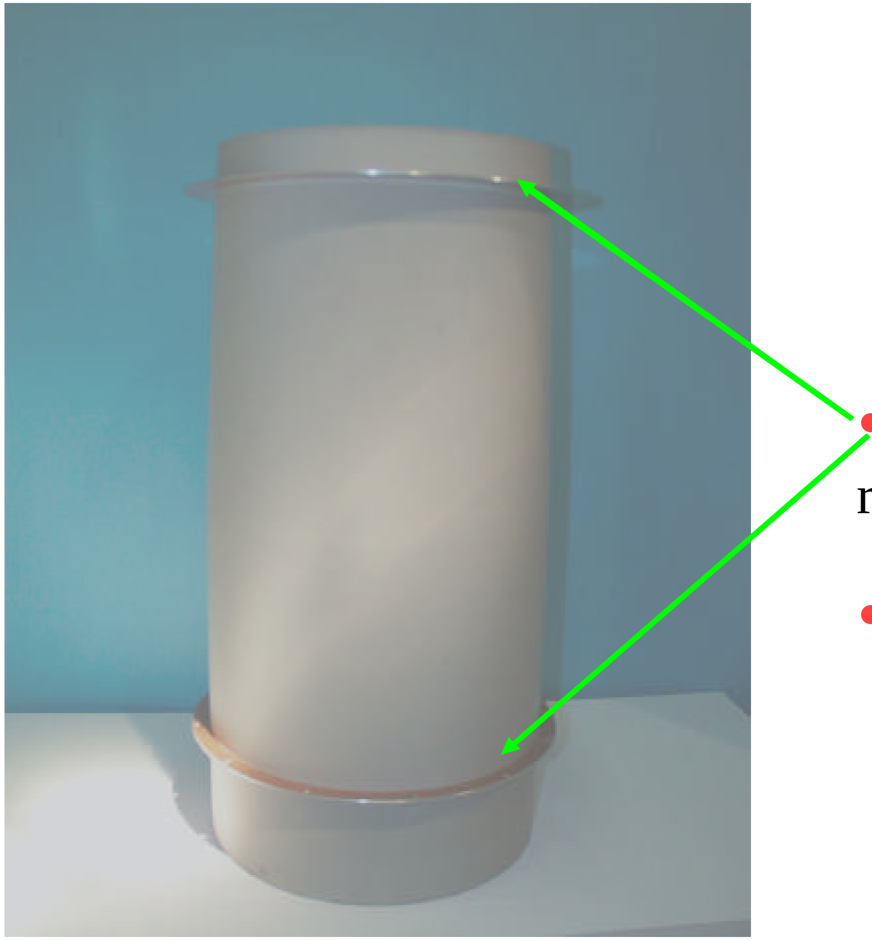
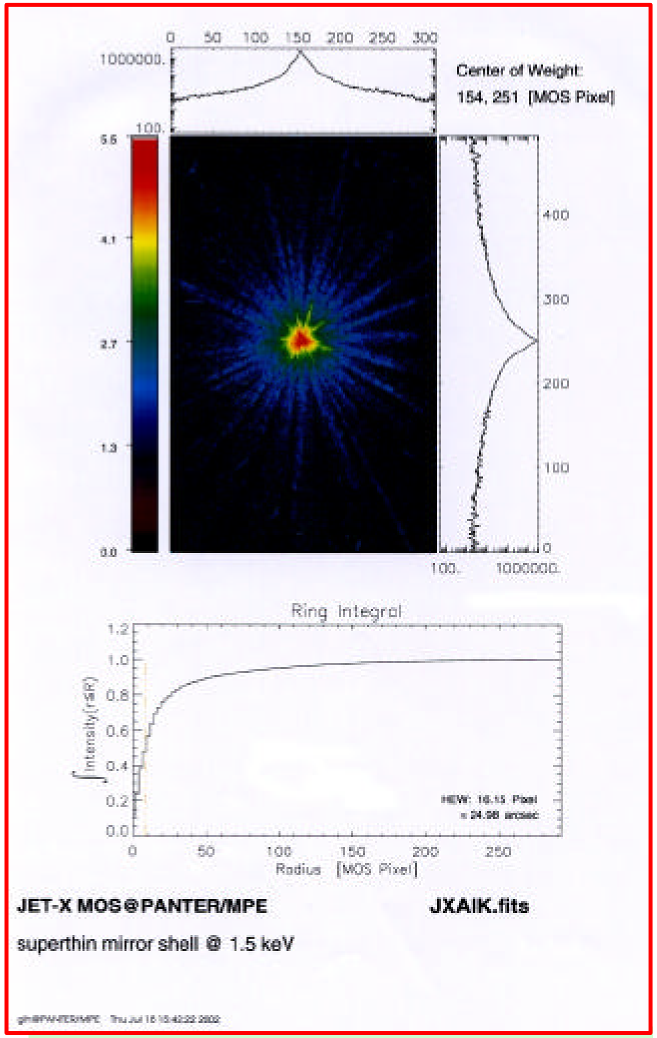
The thin mirror shell with stiffenning rings before integration



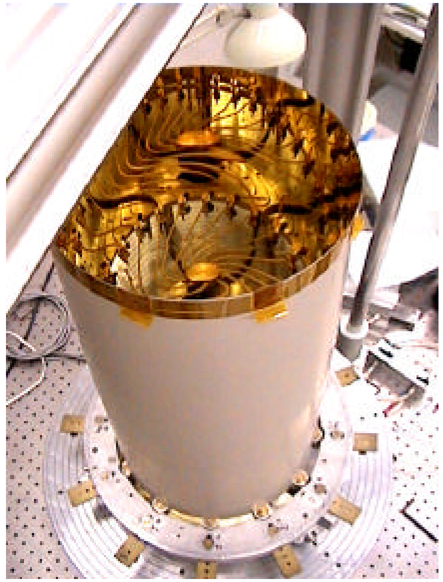
- Two stiffenning rings are inserted to restore and to maintain the MS roundness;
- The rings are removed after integration.

X-ray imaging test of a thin JET-X mirror shell (July '02)



X-Ray test @ Panter-MPE (July '02) - **E = 1.5 keV**

- diam. = 30 cm
- thickness = 130 μm
- wall thickness ***8.5 times*** less than JET-X



HEW_{meas} = 25 arcsec

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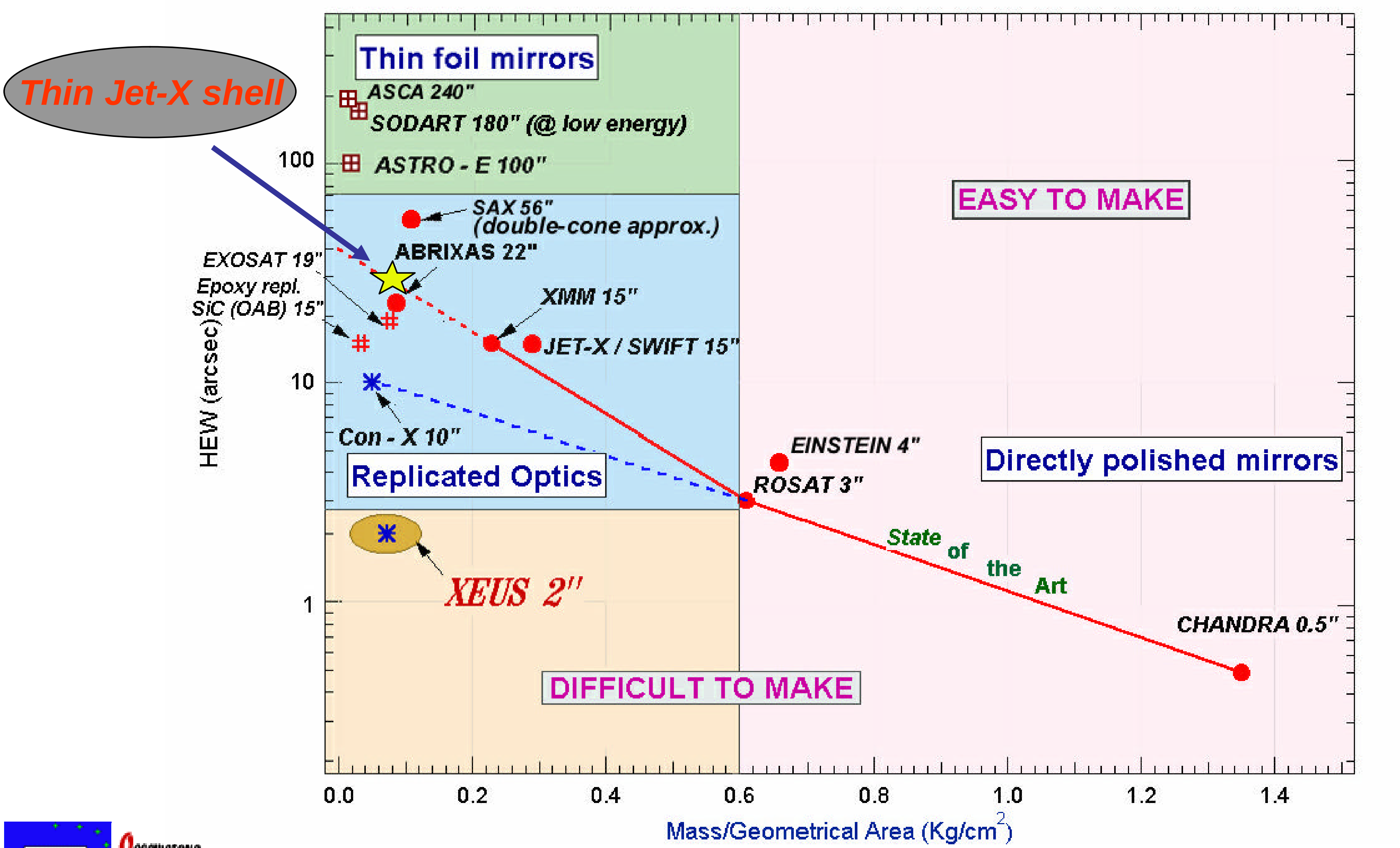
HEW vs. the Mass/Collecting-Area Ratio for past and future X-ray telescopes



Note: HEW for XEUS and Con-X are considered at goal level

Mandrel superpolishing at OAB

Mandrel superpolishing

- A crucial point is given by the surface quality of the mandrel *(that has to be **much better** compared to the soft X-ray mirror with Au coating case).*

- A superpolishing method has been developed at INAF OAB for this specific task. The Zeiss machines developed for the XMM project (now installed at OAB) are used for this application.

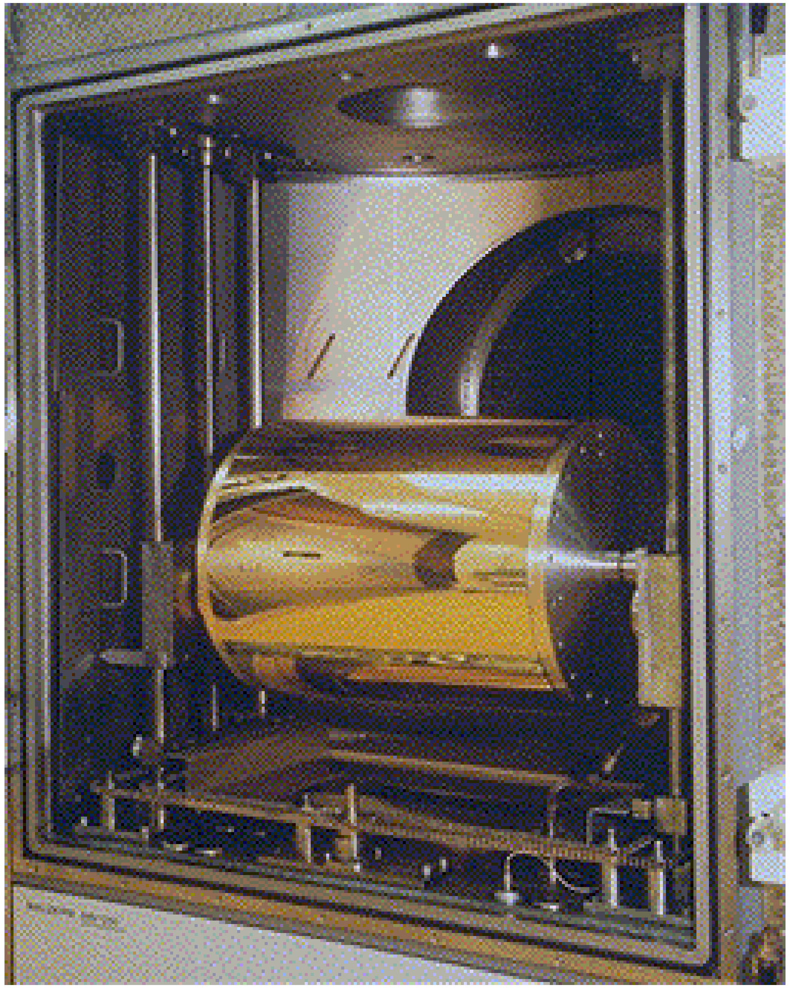
In the table the rms roughness values achieved by the new lapping method on a prototype mandrel surface are compared to those of the SAX mandrel #12

Instrument	Scan Length *(mm)*	Roughness rms (Å) SAX #12 mandr.	Roughness rms (Å) Superpolish. mandr.
WYKO -2.5 X	*6000.0*	*N. A.*	*10.1*
WYKO -20 X	*660.0*	*7.6*	*3.0*
AFM	*10.0*	*6.2*	*2.4*
AFM	*1.0*	*3.4*	*1.8*

Existing Coating Facilities at Media Lario

Media Lario has, at his premises,
two Coating facilities already installed in a Clean Room class 1000.

The coating facilities are not standard: they have been produced appositely by BALZERS for Media Lario for the XMM mirror Production



Capacity

Diameter	1210 mm
Width	1148 mm
Height	1250 mm
Volume	2150 litres

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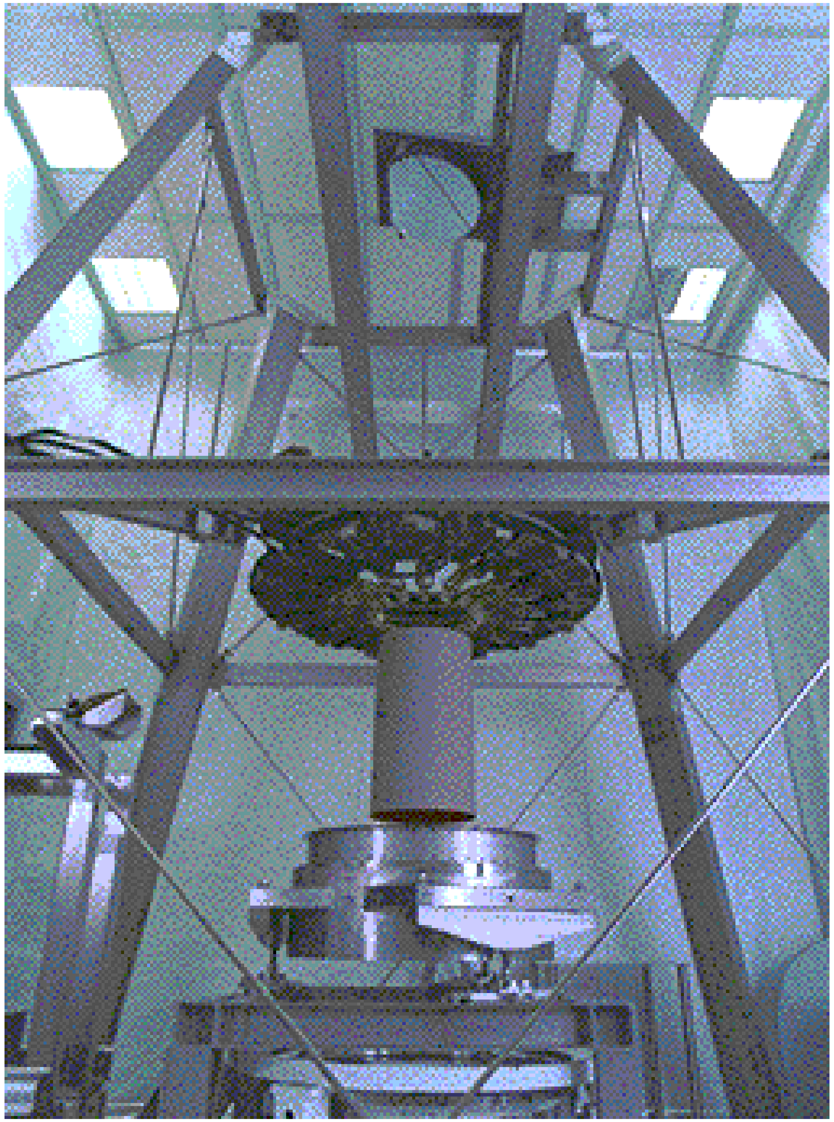
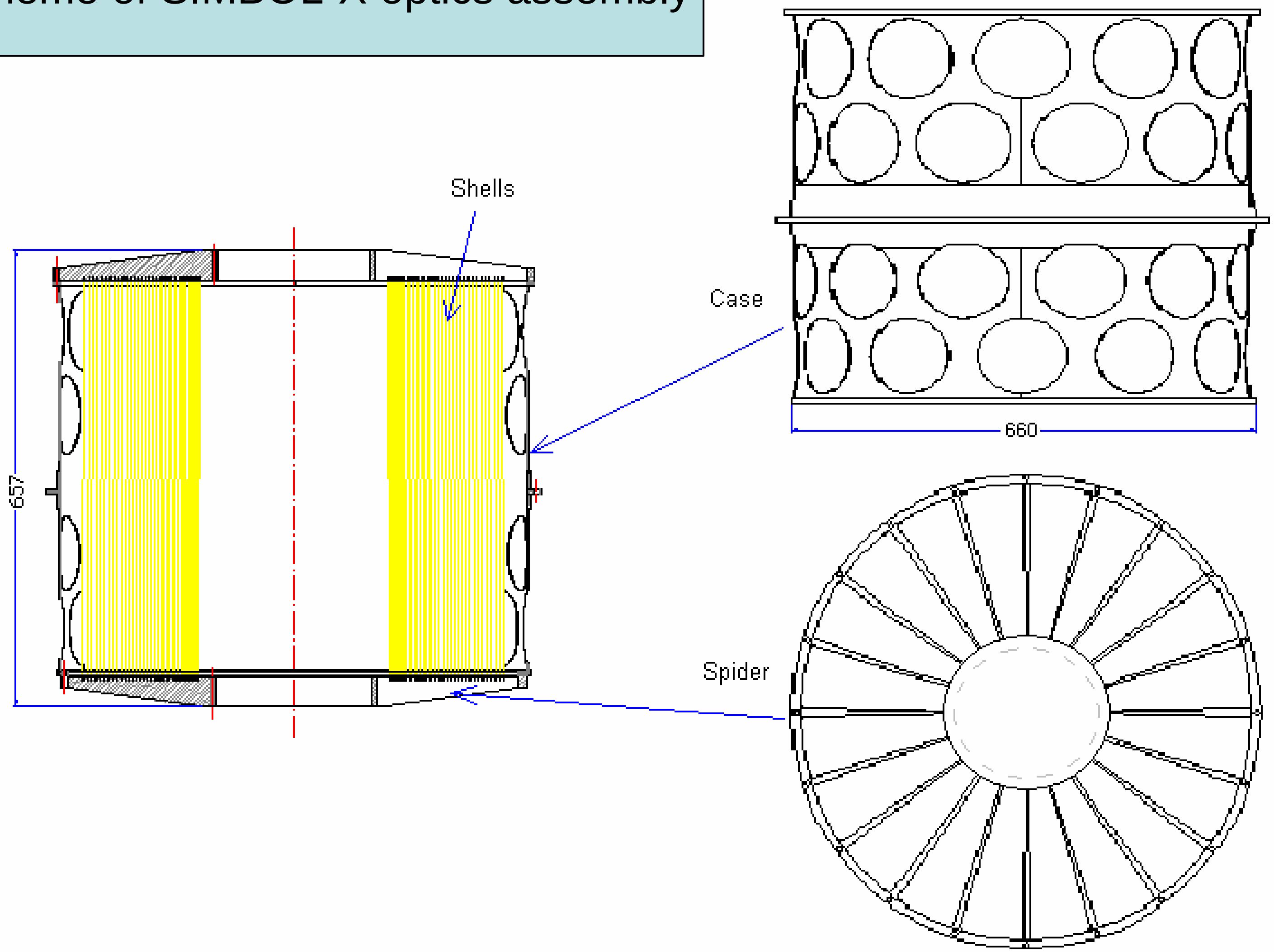
Ni electroforming baths at Media Lario (Italy)

(Credits: Media Lario)

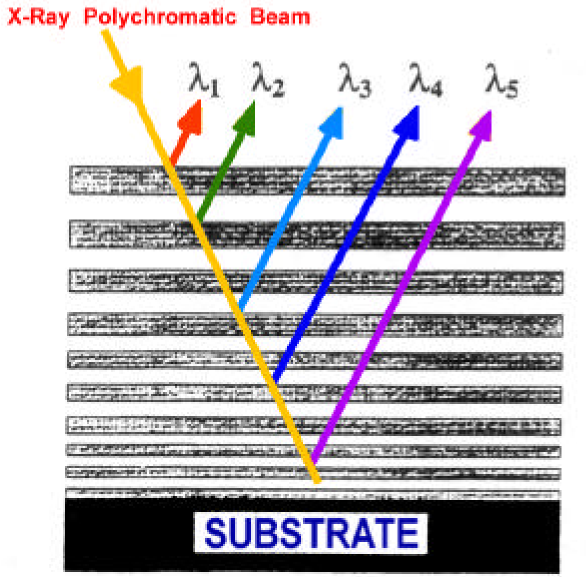
Optical bench to align mirror shells during integration at Media Lario

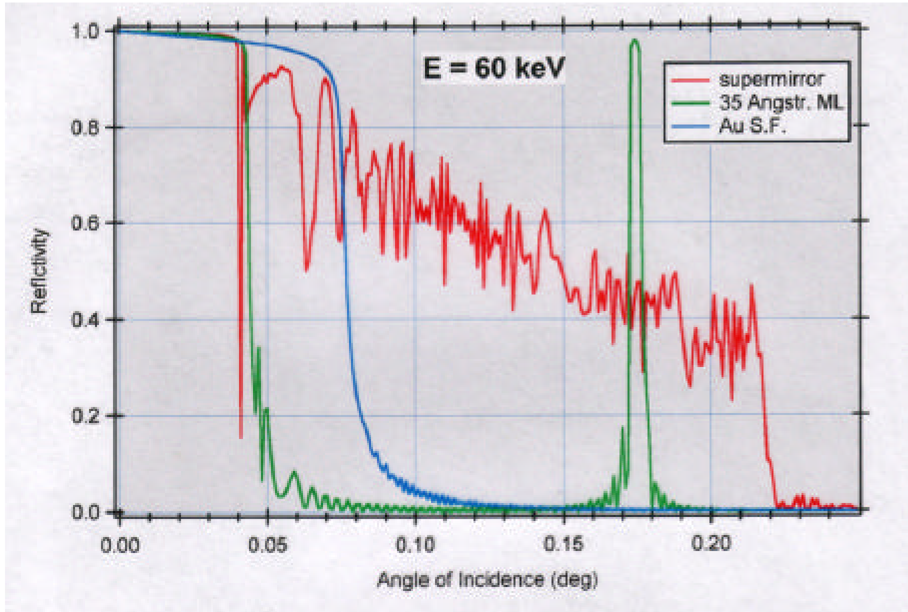


Scheme of SIMBOL-X optics assembly



Wide Band multilayers for hard X-ray (> 10 keV) optics





- if the d-spacing is changed in continuous way along the sequence, and the photoelectric absorption is not too large, (E > 10 keV) it is possible to get reflection windows 3-4 times larger than in total reflection regime.

- The distribution of *d-spacings* follows in general a power law: in

$$d(i) = a / (b+i)^c$$

i = bilayer index $a \approx \lambda/(2 \sin \theta_c)$ $c \approx 0.25$ $b > -1$

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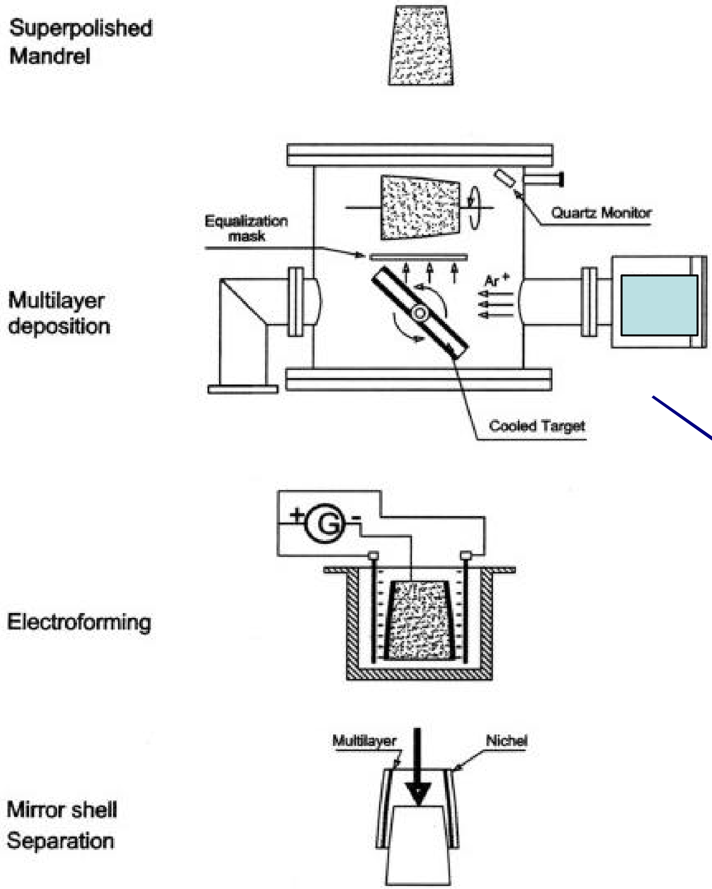
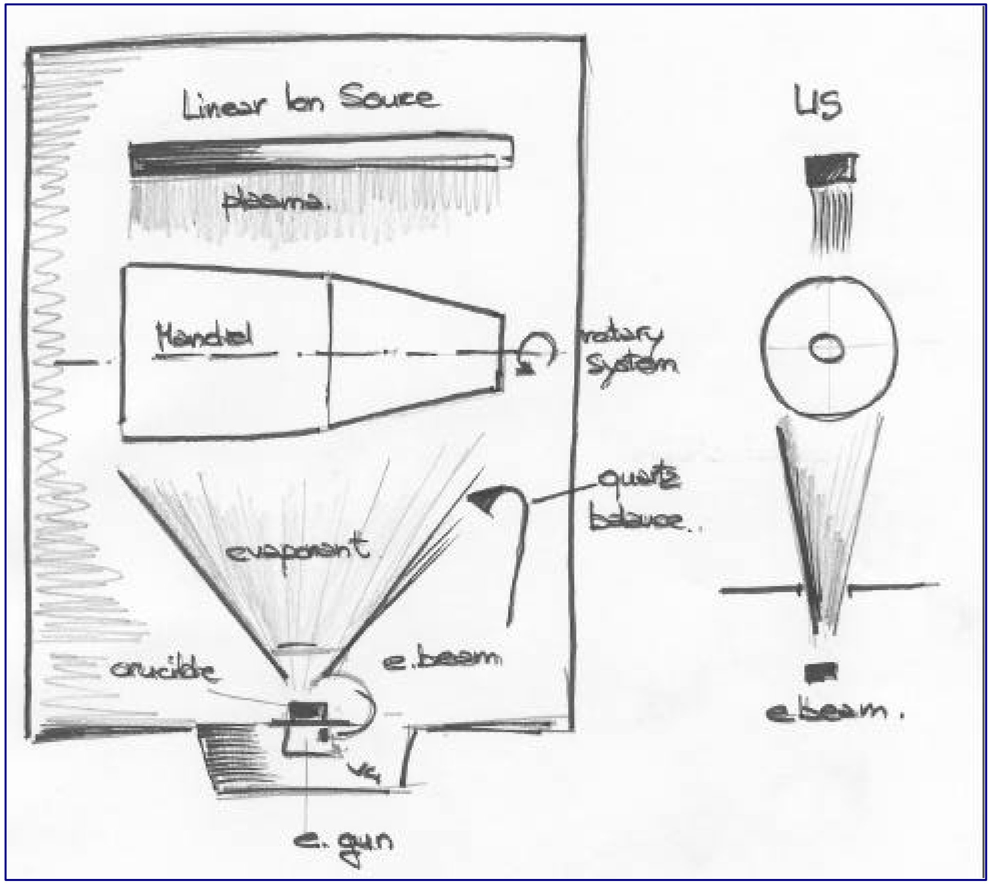
Ni replication of Multilayer coated optics

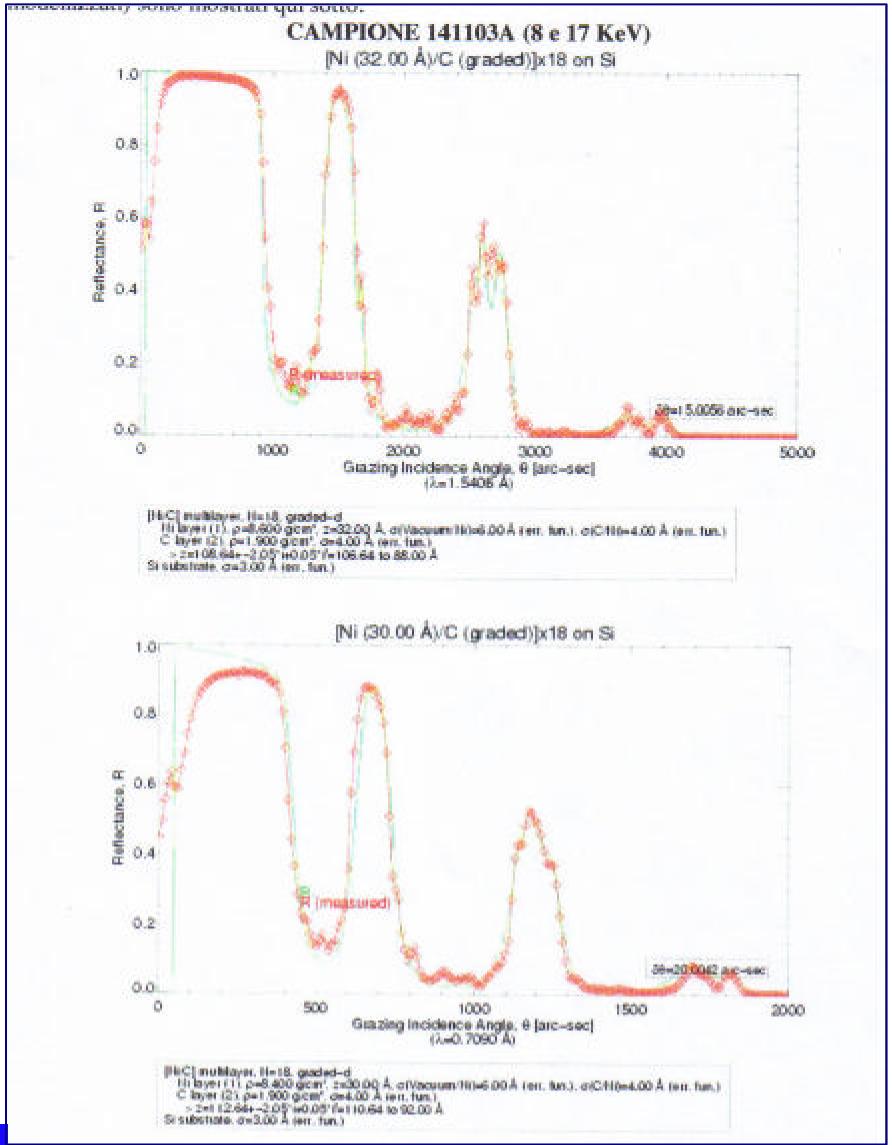


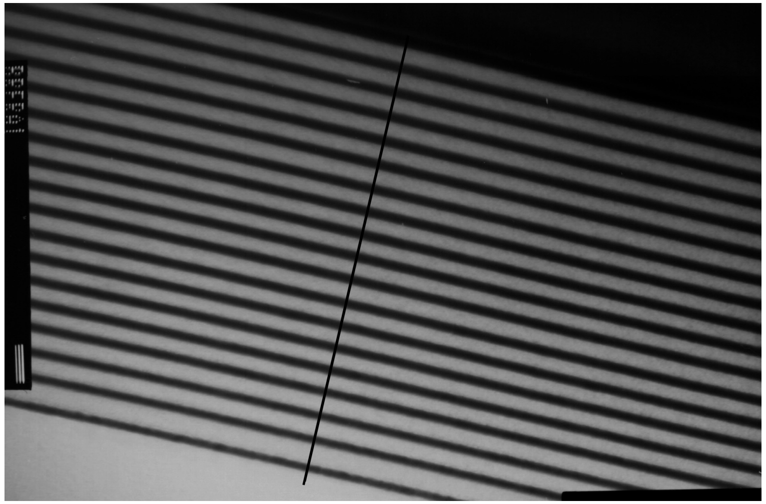


"direct" replication of the multilayer film

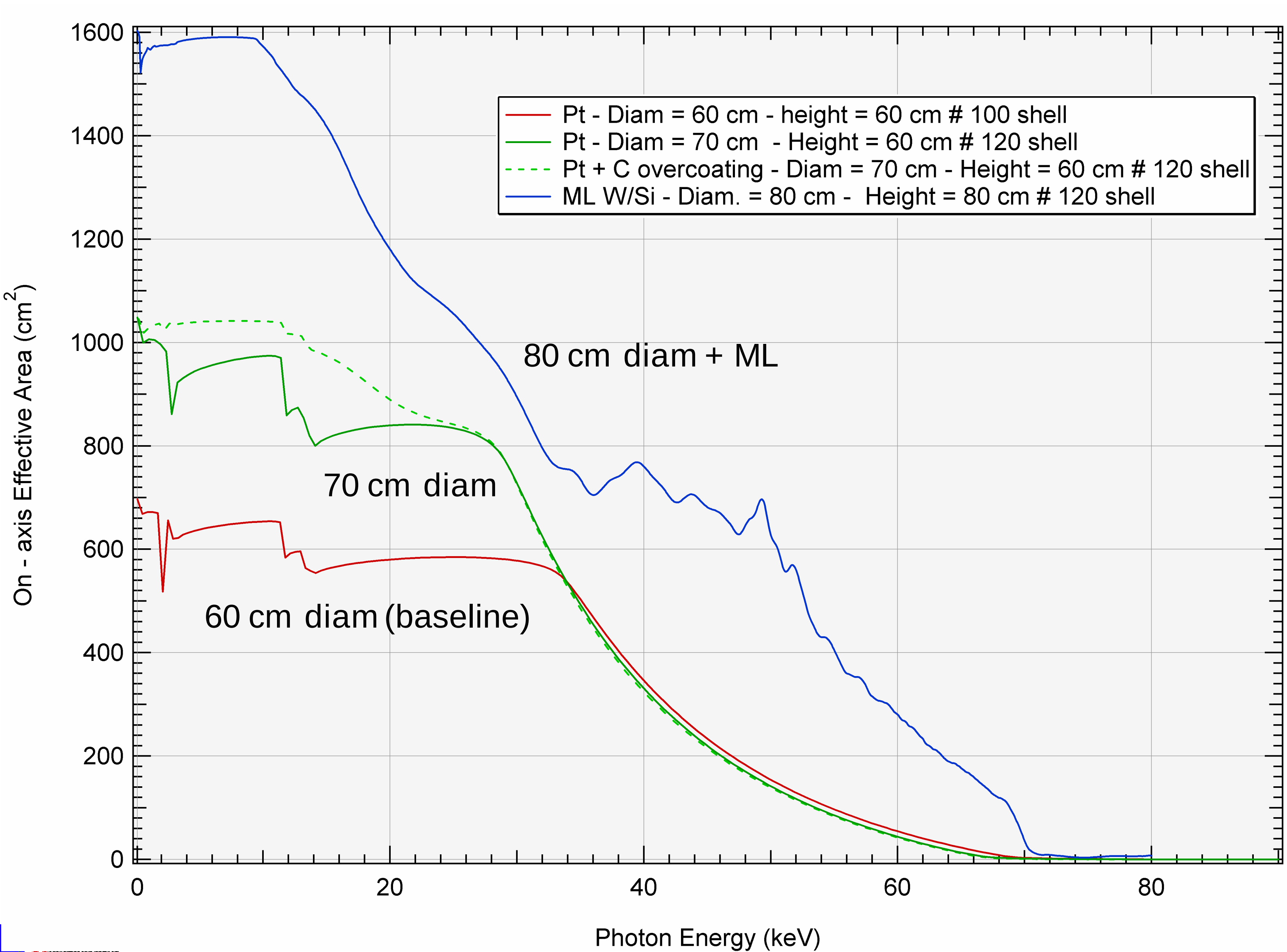
Ion Assisted e-beam evaporation

Ni/C multilayer onto a Si wafer substrate





Ni/C multilayer 20 bilayers
Dec 2003
E-beam depositionby OAB/Media Lario



Pt - Diam = 60 cm - height = 60 cm # 100 shell
Pt - Diam = 70 cm - Height = 60 cm # 120 shell
Pt + C overcoating - Diam = 70 cm - Height = 60 cm # 120 shell
ML W/Si - Diam. = 80 cm - Height = 80 cm # 120 shell
80 cm diam + ML
70 cm diam
60 cm diam (baseline)
On - axis Effective Area (cm²)
Photon Energy (keV)
0
20
40
60
80
200
400
600
800
1000
1200
1400
1600

Conclusions

• the "*Formation Flight*" architecture opens the opportunity to realize hard X-ray (E > 10 keV) telescopes based on *low grazing angles* and *large focal lengths* Wolter I optics

• the design of the SIMBOL-X baseline relies on Pt single-layer mirrors with a 30 m focal length, with shell diameters similar to those assumed for XMM *(but with much smaller reflection angles)*

• the Ni electroforming replication is the *consolidated approach* assumed for the realization mirror shells

• possible improvements of the design can be achieved by increasing the external diameter and using multilayer reflecting coatings for more external shells

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The End