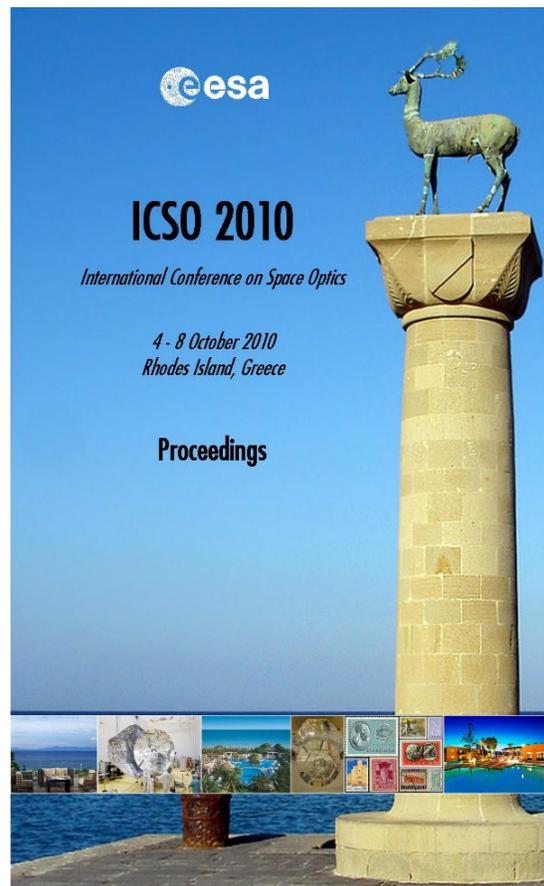


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## Design and Development of the Multilayer Optics for the New Hard X-ray Mission

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### ABSTRACT

The New Hard X-ray Mission (NHXM) project will be operated by 2017 and is currently undergoing a Phase B study, under the coordination of the Italian Space Agency (ASI). The project is being proposed by an international team in the context of the ESA Call CV M3 as a Small Mission program, with a large Italian participation. It is based on 4 hard X-ray optics modules, each formed by 60 evenly spaced multilayer coated Wolter I mirror shells. An extensible bench is used to reach the 10 m focal length. The Wolter I monolithic substrates with multilayer coating are produced in NiCo by electroforming replication. Three of the mirror modules will host in the focal plane a hybrid a detector system (a soft X-ray Si DEPFET array plus a high energy CdTe detector). The detector of the fourth telescope will be a photoelectric polarimeter with imaging capabilities, operating from 2 up to 35 keV. The total on axis effective area of the three telescopes at 1 keV and 30 keV is of 1500 cm<sup>2</sup> and 350 cm<sup>2</sup> respectively, with an angular resolution of 20 arcsec HEW at 30 keV. In this paper we report on the design and development of the multilayer coated X-ray mirrors based on NiCo shells.

### I. INTRODUCTION

The New Hard X-ray Mission (NHXM) **Errore. L'origine riferimento non è stata trovata.**, [2] (Fig. 1) is being developed in Italy as an evolution of the original HEXIT-SAT project [3], and it is improved by the addition of an imaging polarimeter in the focus of one of the four identical telescopes. NHXM is being submitted to ESA an international small mission with a large Italian participation in the context of the ESA call CV M3. NHXM is meant to provide a real breakthrough on a number of hot astrophysical issues, by exploiting the most advanced technology in broad-band (0.2 – 80 keV) high angular resolution (<20 arcsec HEW @30 keV) grazing incidence mirrors and spectroscopic detectors, together with the use of a high efficiency imaging polarimeter. Such issues do broadly fall under two main headings (greatly corresponding to the core scientific objectives of the previous Simbol-X mission[4]: i) making the census of the population of black holes in the Universe and probing the physics of accretion in the most diverse conditions; ii) investigating the particle acceleration mechanisms at work in different contexts, and the effects of radiative transfer in highly magnetized plasmas and strong gravitational fields. In this article the late evolutions of the mirror modules (MMs) concept is presented with the late results achieved with the Technological Demonstrator Module 1 (TDM1) tested at PANTER facility in 2010. The polarimeter [5] is in the focus of one of the four identical telescopes while in the other three telescopes an identical spectro-imaging cameras [6] will be installed. These telescopes have a baseline focal length of 10 m, to be achieved after the launch by means of a deployable structure.

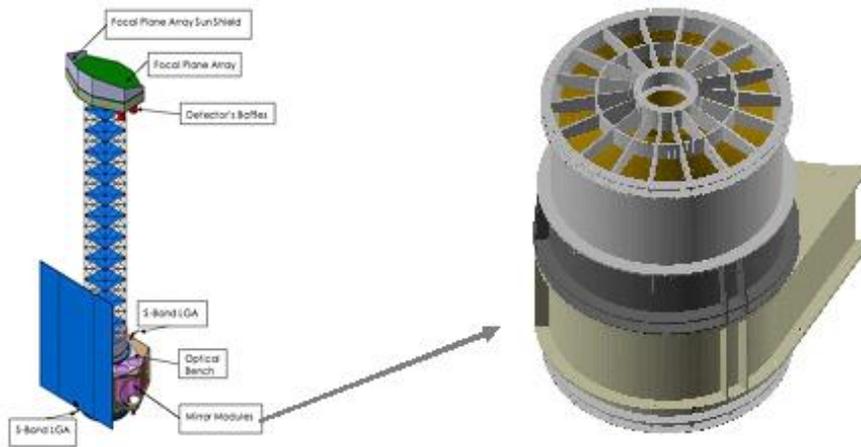
The satellite will be allocated in the fairing of the Vega launcher and the foreseen orbit is a low Earth equatorial orbit (600 km). For the first time, with this instrument complement, it will be possible to obtain simultaneously images, spectral energy distributions and polarization properties (degree and angle) of sources in the X-ray sky.

### II. THE OPTICAL DESIGN

The optical design has been done keeping fixed the length of the Mirror Shells (MSs): 600 mm composed by 300 mm for the parabolic surface and 300 mm for the hyperbolic one. The optimization of the reflecting coating has been performed changing the thickness of the multilayer (ML) d-spacing along the stack. Different ML recipes have been considered [15], but in Fig. 2 (left) two solutions are presented that fulfill the requirements for the single MM.

**Tab. 1.** Requirement (left) and parameters (right) of the mirror modules.

Requirements			Parameters	
# of Telescopes	3+1		Number of MSs	70
Energy band (keV)	0.2 ÷ 80		Mirror length (par. + hyp.)	60 cm
Effective area (for 3 MM) (cm <sup>2</sup> )	at 30 keV	350	Max/Min shell diameter	39/15 cm
	at 5 keV	1000	Wall thickness (Max/Min)	0.33/0.13 mm
Field of View diameter (50% E.A. @30keV)	12		Focal Length (meters)	10



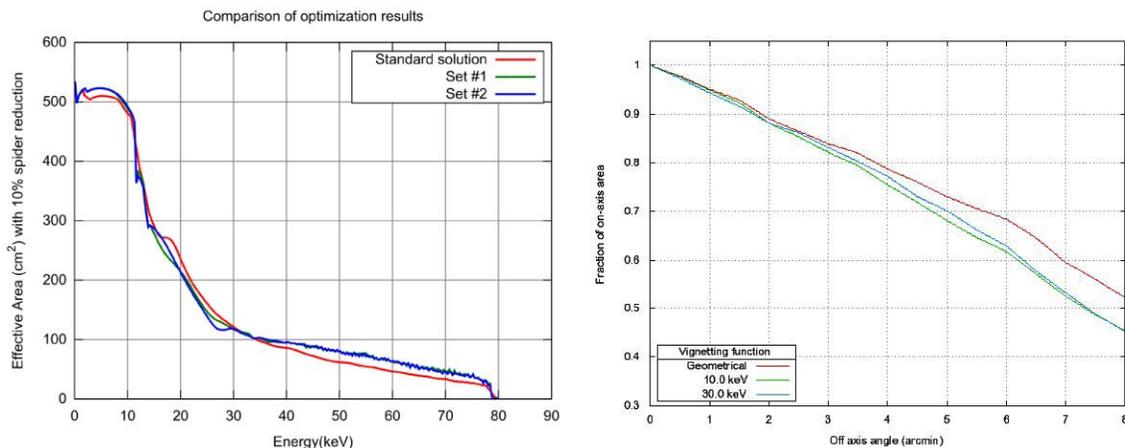
**Fig. 1.** Schematic of the NHXM satellite and of one of the four identical mirror modules

The couples of materials initially considered for the multilayer coating were W-Si and Pt-C; the choice of Pt-C was driven by the necessity to enhance the effective area till  $\sim 80$  keV (the W-Si permits to reach just 69 keV, due to the k-edge energy cutoff of W). The baseline configuration for this phase is a 169 Pt-C bi-layers coating with the bi-layer thickness ranging from  $24.68 \text{ \AA}$  to  $146.69 \text{ \AA}$ . The ML coating will be deposited onto the gold layer (used for allowing the shell separation from the mandrel) at the internal surface of the electroformed MS using a dedicated sputtering facility. The vignetting function for this configuration is presented in Fig. 2 (right). The angular separation between the MSs considered for the design is 6 arcmin. The maximum and minimum diameters considered are 394 and 151 mm respectively. Also the vignetting is low and by the way much better than requested by the requirements, but safety margins have to be taken into account for allowing some tolerance in the integration and alignment phases of the mirror shells.

Concerning the thickness of the MSs, two main constrains push in opposite direction: a large thickness in general helps to get a better performance, since in this way the stiffness is increased and profile deformations due to the handling and integration are lower; however larger wall thicknesses mean an increase of mass and vignetting. The balance of these factors, considering also past experiences, lead us to a wall thickness ranging from 0.13 mm of the innermost MS to 0.34 mm of the outermost MS, i.e. slightly lower than for XMM .

### III. THE MECHANICAL DESIGN AND FEM ANALYSIS

The mission foresees four mirror modules located in a bus interfaced with it with a central supporting cylinder with a diameter of about 937 mm. A preliminary design of the MM is shown in Fig. 1 where also a bracket is modeled. The bracket is the interface part with the rest of the satellite and it could change in design according specific system analyses. Besides the MSs , the main components are listed hereafter. The mass of the parts is summarized in Tab. 2.



**Fig. 2.** Left: effective area of the single MM. Right: vignetting function. The FOV (50%) of the optics is greater than 14 arcmin in diameter also at 30 keV .

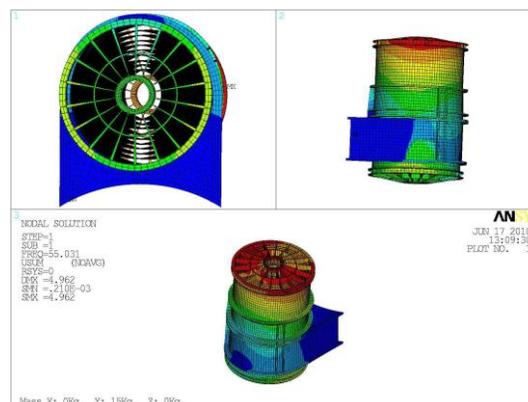
**Tab. 2.** Mass budget of the parts of the whole MM with auxiliary items (without contingency).

Item	Mass [kg]
Spiders	13.89
Case	12.09
MSS	73.17
Pre-collimator	10
Magnetic diverter	10
Front Baffle/Thermal cover	5
Spacer	4.29
Supporting bracket	10.91
TOT (Case+Spid+MSS)	99.16
TOTAL	139.36

1. **Case:** cylindrical tube with a variable thickness (minimum value of 1.5mm) containing the mirror shells that connects the two spiders with two flanges. A third flange connects the MM to the outer structures. The material is the stainless steel SAF2507, whose CTE matches very well the Ni
2. **Spiders:** two spoke wheels on which the mirror shells are glued in their two sides. The connection is obtained by filling the grooves previously machine in the spokes with a space-qualified epoxy glue. The number of the spokes is 18 and on an intermediate diameter a ring element provides the necessary stiffness in the azimuthal direction. The material is again SAF2507
3. **Spacer:** it connects the MM to the outer structure. The interface with the MM is done using a high number of bolts, in order to obtain an uniform distribution of the loads, while the interface with the bracket is based on three points. The three points support permits the alignment of the telescope. The spacer is made in aluminum alloy in order to preserve mass.

*FEM results*

The performed analyses has regarded 1) the frequencies analysis (Fig. 3 and Tab. 3); 2) the thermo-elastic analyses; 3) the random vibration. The frequencies analysis shows that in this preliminary configuration there is a critical point in the bracket connection to the central structural tube. In the present model this connection is considered infinitely stiff. Anyway the MM itself shows a good behavior. These considerations have been the input for designing a new and more robust solution for the connection of the MMs with the satellite structure. **Fig. 4** reports the new design of MMs mechanical interface. This design is based on a well consolidated structural solution. Further FEM analysis are on-going to confirm the increase of the natural frequencies. Concerning the thermo-elastic analysis, a number of possible significant cases have been studied separately because, at the time being, the thermal distribution is not yet known.



**Fig. 3.** Mode shape #1. It is due to the bracket behavior.

**Tab. 3.** The main natural frequencies with their associated masses along the three directions

Mode	Freq	Mass X	Mass Y	Mass Z
n.	[Hz]	[%]	[%]	[%]
1	55	0.0	11.1	0.0
2	64.2	15.9	0.0	4.1
3	71.2	0.0	74.5	0.0
4	95.8	52.6	0.0	21.8
5	115.9	26.1	0.0	65.4
26	152.4	0.0	8.1	0.0

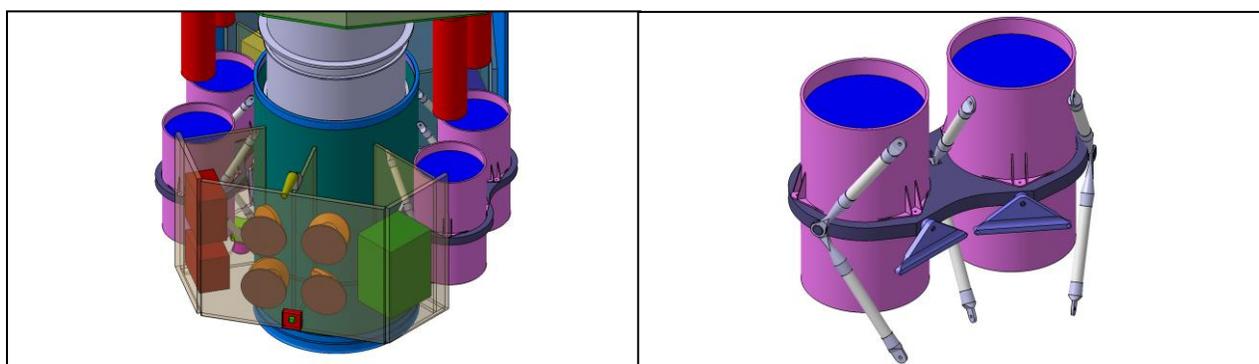
The main errors are originated by the bi-linear gradient case, but this kind of gradient is the less probable for this kind of object in a space mission because the thermal conductivity of the different used materials is similar and there are no heat source inside the MM. Also a random vibration analysis has been performed using spectra provide in the ECSS with an acceleration equal to 11.14g rms. The results of this analysis impose the use of a central ring in the spiders to reduce the stress level on the MSs in the point of connection with the spiders.

### III. THE DEMONSTRATOR MODULE

A telescope demonstrator (TDM1) with three MSs has been developed and tested at PANTER facility (Fig. 5). The MSs have been produced at Media-Lario and the MSs have been integrated into a mechanical structure with a stiffness similar to that developed for the Simbol-X mission during phase A. The MSs have been glued on both sides with two spiders with 20 spokes that obscure 10% of the area. The three MSs have a diameter of 286, 291 and 297mm a total length of 600 mm and a focal length of 10 m. Their thickness is about 0,25mm. Concerning the multilayer the three mirror shells were coated with two different multilayers: 95 bilayer of W-Si for the innermost, 200 bi-layers W-Si for the other two.

#### Integration

The integration has been performed at OAB using a vertical UV bench with a UV source at 370 nm according the procedure developed for very thin shell. The only difference is that the central shaft and the temporary structure is not been used because some tests have shown that, after that the MS is glued on lower spider, the two stiffening rings that have been used to maintain the correct shape could be removed without introducing profile errors. We remind that the MSs are integrated with the optical axis in vertical and it proceeds from the inner one to the outer one. The results of the integration is reported in Fig. 6. The results obtained show a very little degradation of the angular resolution except for the MS S286/4: in fact when the upper spider was fixed to the telescope and the MS was glued the HEW passed from 18 to 25 arcsec. The most likely reason for this degradation is that a contact between the MS and the spider occurred during the polymerization of the glue. For this defect we decided to mask the MS S286/4 during the PANTER campaign considering also that we were able with the available jig to test separately only two MSs.



**Fig. 4.** Connection of the MM with the satellite in the last proposed design

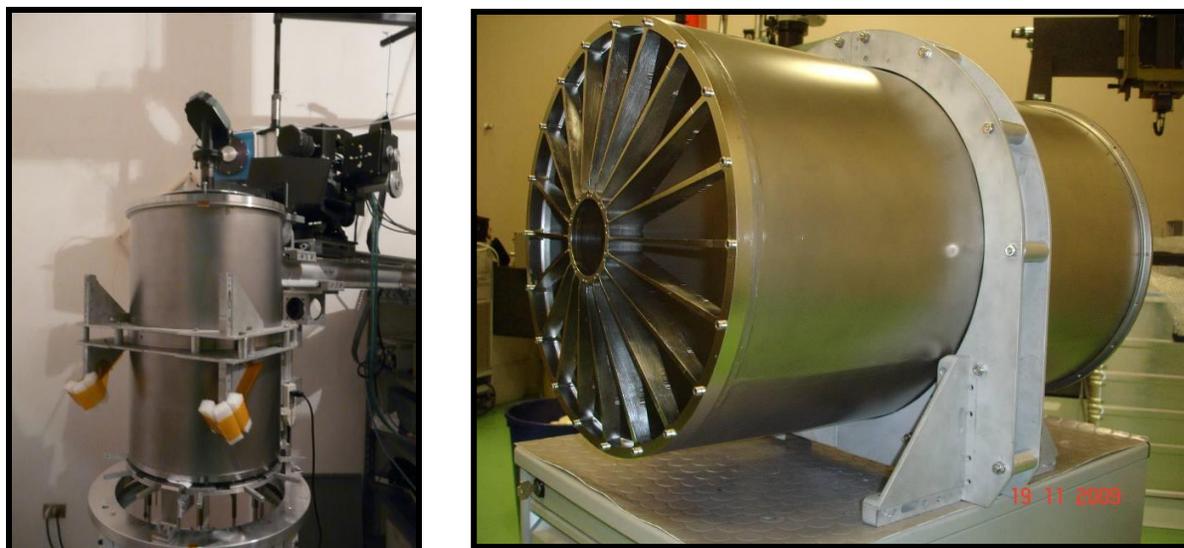


Fig. 5. TDM1 during the integration and the mechanical structure before integration

*X-ray results*

At PANTER we measured with an X-ray full illumination beam the angular resolution and the effective area. The effective area results are presented in Fig. 7 and the good agreement between the measured and expected effective area demonstrates the capability of the multilayer process. It has to be noted also the very slow increase of the HEW in function of the energy, indication of the good roughness level. The best results concerning the angular resolution are achieved in the demonstrator module named as EM2 tested at PANTER in the 2008 (Fig. 8). The HEW at low energy was 15 arcsec.

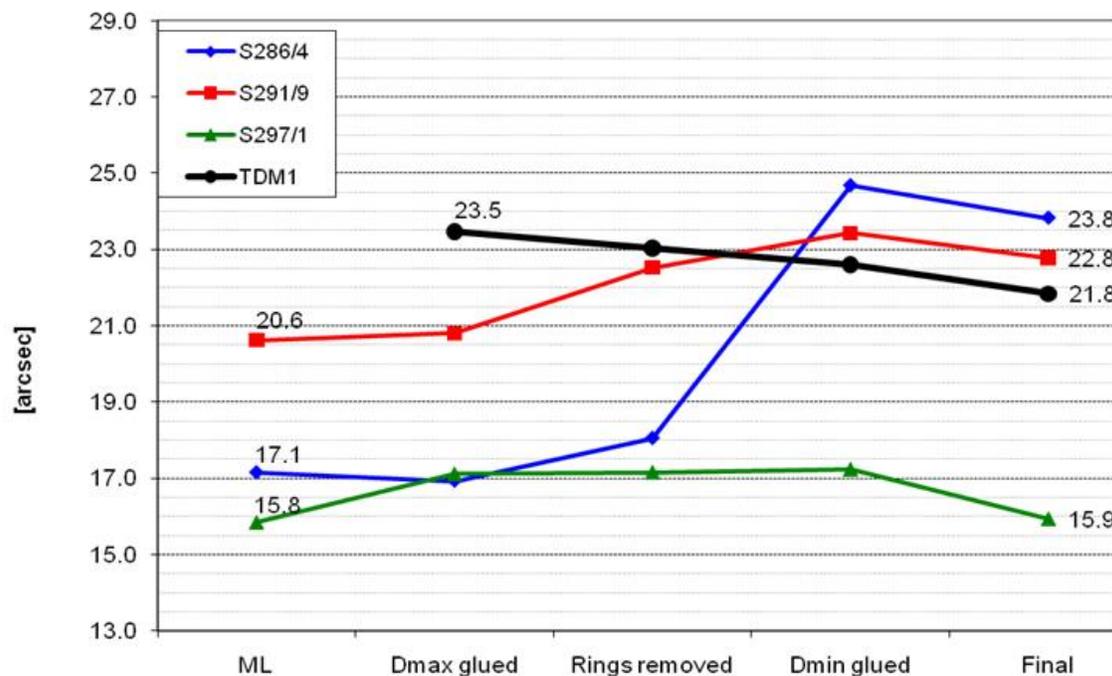
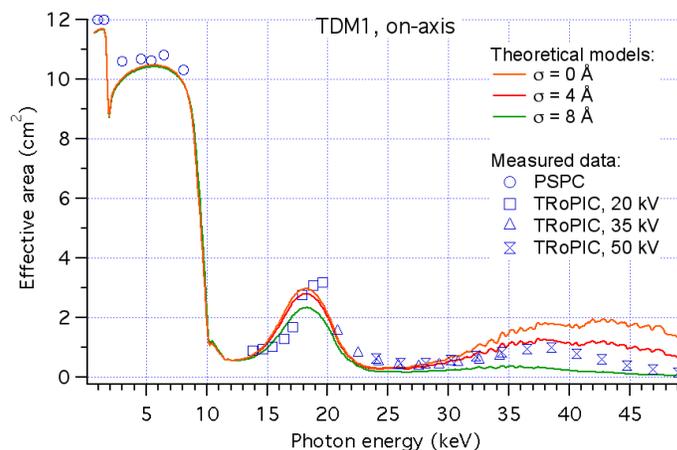


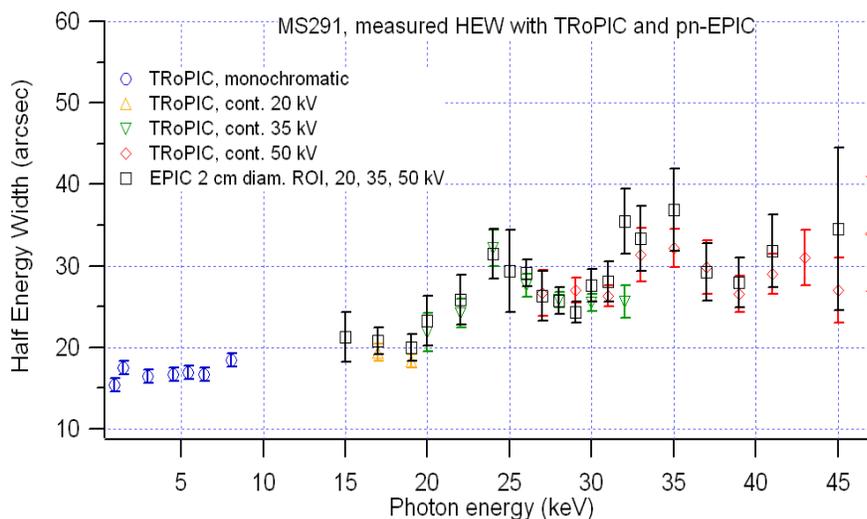
Fig. 6. Evolution of the HEW during the integration process of the TDM1 as measured at the UV optical bench. The presented HEW values is the computed after having removing the diffraction UV HEW of the vertical optical bench. The rings in the third step are the stiffening rings that must be used to maintain the stiffness and that must be adopted for this very thin MSs.



**Fig. 7.** Effective areas for the TDM1 measured with the calibration at Panter up to 50 keV. The data are compatible with a 4 Å Debye-Waller microroughness.

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**Fig. 8.** X-ray angular resolution of the MS291 integrated in the prototype EM2. The oscillations above 20 keV are anti-correlated with the effective area and are due to the modulation of the multilayer scattering.