Optimization Design Proposal of the X–ray Collimators of the High Energy Instrument aboard HXMT

Mauro Orlandini[1], Filippo Frontera[1,2], Gianni Landini[1]

[1] INAF/IASF Bologna, via Gobetti 101, Bologna, Italy
[2] Ferrara University, Physics Department, via Saragat 1, Ferrara, Italy

Contents

List of Figures

List of Tables

1 Goal of the report

In this report we present a study we performed to optimize the collimator design of the High Energy (HE) instrument aboard HXMT. We also propose a new design of the collimator, the cells of which are built by interlocking Tantalum or Tungsten slats. This proposal has been investigated within the collaboration agreement preliminary established between ASI and CNSA in December 2006.

2 Introduction

The high energy (HE) instrument aboard the Chinese Hard X–ray Modulation Telescope (HXMT) consists of 18 cylindrical detectors, each formed by a phoswich module and its collimator. Each detector unit is a NaI(Tl)/CsI(Na) phoswich scintillation detector with a diameter of 19 cm. The thickness of the NaI main detector is 3.5 mm, while that of the CsI shielding is 40 mm. A 5-inch PMT is used to collect the fluorescence of both NaI and CsI crystals.

According to the document *The Hard X–ray Modulation Telescope (HXMT) Mission* [1], dated 20/08/2007, the collimator assembly is as follow:

Figure 1: Realization of the first collimator solution above the High Energy instrument aboard HXMT.

"There are two candidate collimators for HXMT. Both of them have a height of 300 mm, and the distance of two neighboring slats in the long axis of the FOV is 30 mm and that along the short axis is 6 mm.

The structure of the first candidate collimator is given in Figure 1. The tube and the schemes of the collimator are cut from one Aluminum cylinder. The thickness of the schemes is currently 2 mm and will be reduced to 1 mm. On the schemes a number of troughs will be cut, and thin (0.15 mm) Tantalum plates will be inserted in these troughs. On the wall of the tube and schemes, thin (0.15 mm) tantalum strips will be pasted. To further shield the background, two thick (2 mm) tantalum tubes will be installed in the center and outside the HE detector assembly.

For collimator candidate 2, only the cylinder tube uses Aluminum, and a series of "square-wave"-like Tantalum plates are used to construct the FOVs of the telescope. For this collimator, there is an inner layer of Tantalum (1.6 mm) in the lower 1/3 of the tube, and so the big tantalum tubes around the HE detector assembly are not necessary for this collimator.

The above two collimators have their advantages and disadvantages. For collimator candidate 1, the manufacturing is easier and so of high precision. Measurements show that the directions of all the FOV pixels are parallel to each other within 0.4′. However, the structure blocks about 9% of the on-axis detecting area. Also, two big Tantalum tubes are needed to shield the particles with large incident angles, which might bring changes to the overall mechanical structure. For collimator 2, the required manufacturing precision (0.5′) is difficult to reach, but it only blocks about 4% of the axis detecting area."

Table 1: Collimator weight for the first option configuration. In the computation of the total weight of the collimator assembly we must include two 2 mm thick Tantalum tubes installed in the center and outside of the HE collimator assembly [1] (see Appendix B), that weight 7595 g (inner ring) and 37989 g (outer ring).

Cylindrical Structure		**Cell Structure**	
Al tube (2.5 mm)	1224 g	Al schemes (1 mm)	826 g
Ta layer (0.15 mm)	447 g	Ta slats (0.15 mm)	3337 g
		Ta strips (0.15 mm)	830 g
Total	1671 g	**Total**	4993 g
Weight/collimator unit			**6664 g**
Total Weight inclusive of Ta tubes			**165.54 Kg**

3 Analysis of the first option collimator configuration

We concentrated on the first option collimator configuration described above (tube and schemes of the collimator being cut from one Aluminum cylinder), that gives the most precise geometry. In Figure 2 we show, on the top panel, the collimator geometry as described in [1] with Al scheme thickness of 2 mm. We took into account also the 0.15 mm thick Tantalum strips pasted on Al schemes and tube. In this configuration we find that the supporting area covers 10% of the total detecting area.

3.1 Proposed optimization of the scheme thickness

The reduction of Al scheme thickness to 1 mm, as also described in [1], is a desirable improvement, that we suggest together with the change of the distance a between contiguous schemes as shown in Figure 2 (bottom panel). Indeed, if this distance is held unchanged, two small new schemes (quite difficult to manufacture and useless from the scientific point of view) are needed. The weight of this configuration is listed in Table 1. The total weight of the collimator assembly for the 18 modules is 165.5 Kg (taking into account also the two Tantalum tubes installed in the center and outside of the HE detector assembly [1]. See Appendix B details).

3.2 Response function of the first option collimator

Using the analytical approach described in Appendix A.1, we have evaluated, at various energies, the response function of the HXMT collimator in the case of the first option, with 0.15 mm thick Tantalum strips pasted on the Al schemes and tube. The results along the scheme direction and the orthogonal direction are shown in Figure 3 and Figure 4, respectively. As can be seen from Figure 3, along the direction perpendicular to the schemes, either taking into account only the photoelectric or the total (photoelectric plus scattering) absorption by the wall materials [2], the collimator response is **unacceptable** at energies above 100 keV. In the next section we present our proposal for the thickness optimization of the collimator cells, assuming Tantalum as wall material.

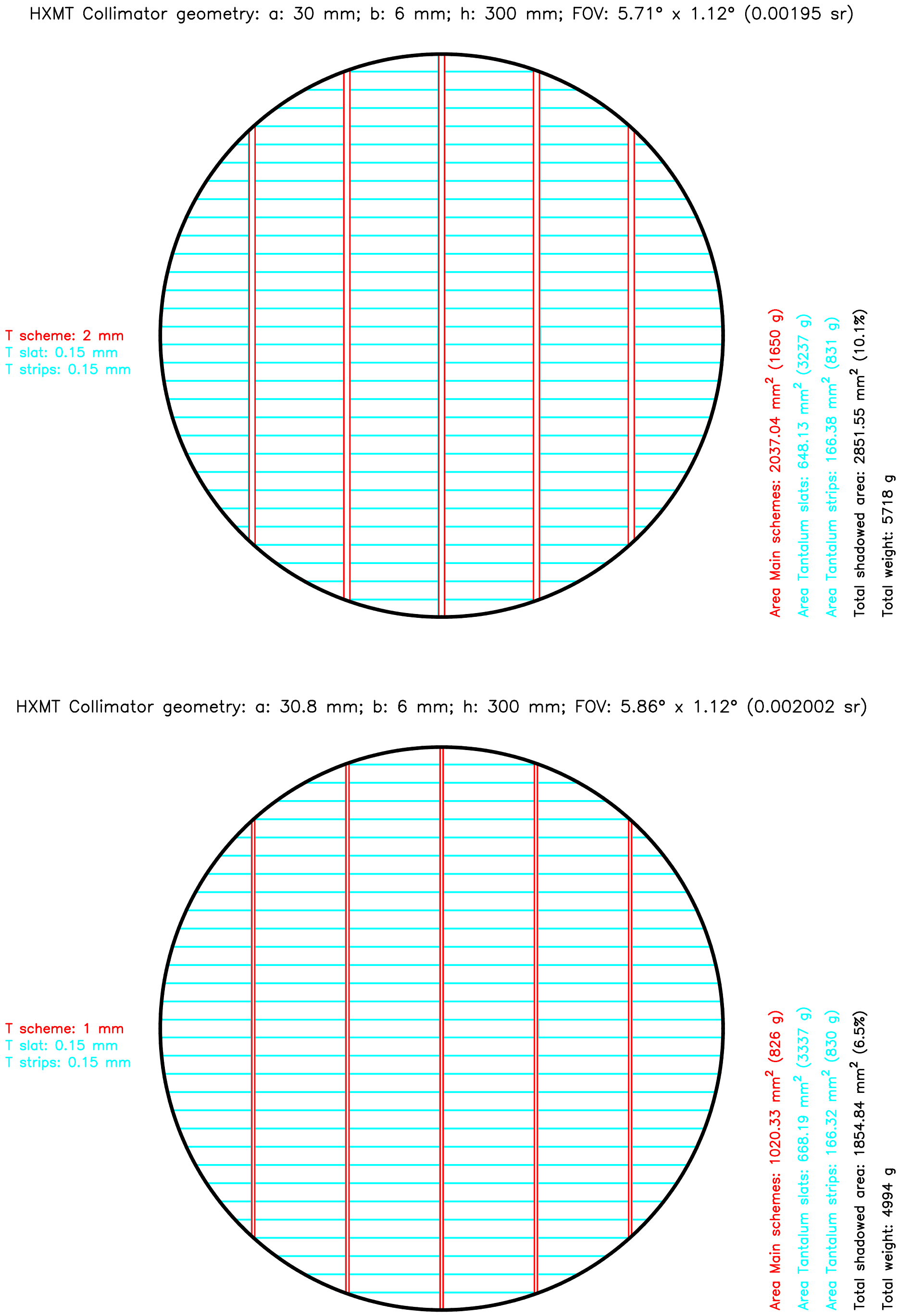
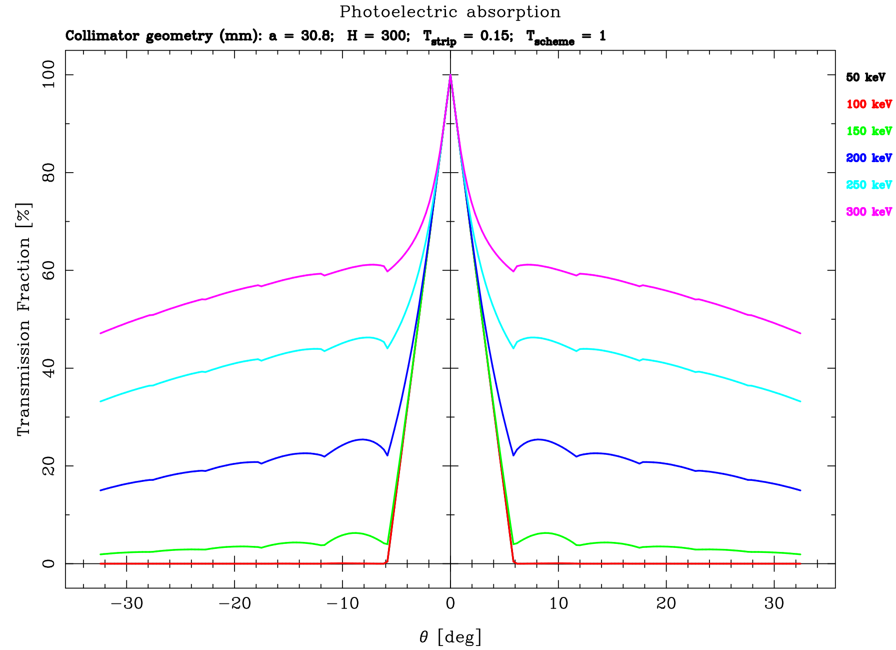


Figure 2: Candidate options of the HXMT collimator units. Thickness T of the various materials and other properties are shown. *Top:* first candidate option collimator geometry as described in [1]. *Bottom:* the same as *Top* but with the main Aluminum scheme thickness decreased to 1 mm, and the a side increased to 30.8 mm.



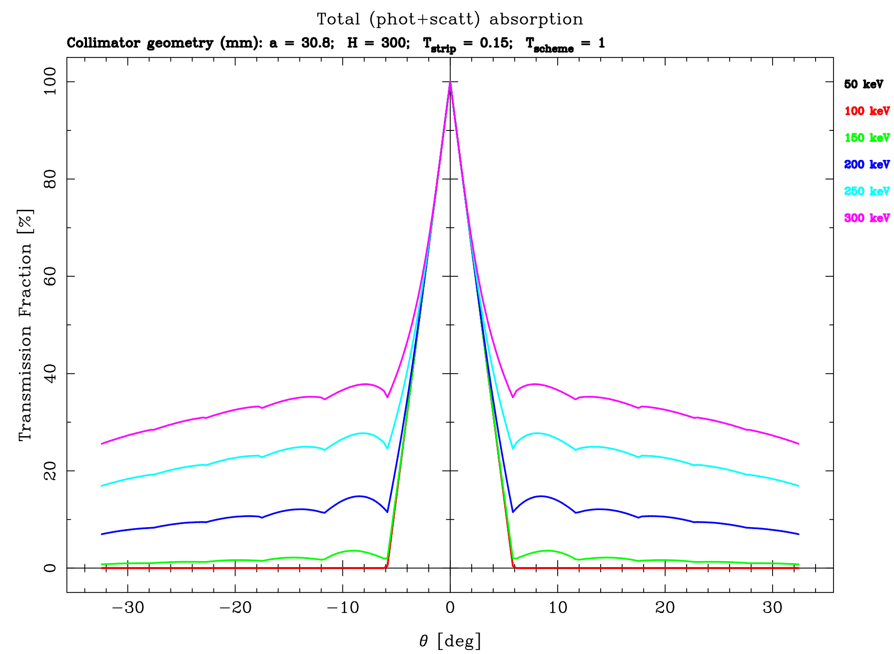
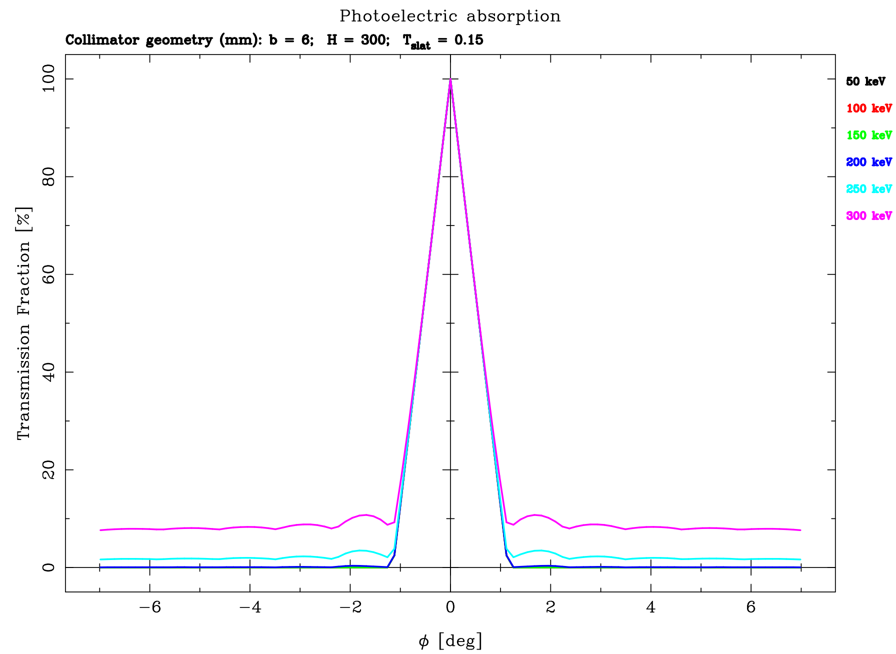


Figure 3: First option collimator angular response along the direction perpendicular to the Al schemes. 0.15 mm thick Tantalum strips are assumed to be pasted on the main schemes (of 1 mm thickness). Different colors correspond to different photon energies, as coded on the right of the plots. *Top:* only photoelectric absorption is assumed. *Bottom:* both photoelectric absorption and scattering are assumed.



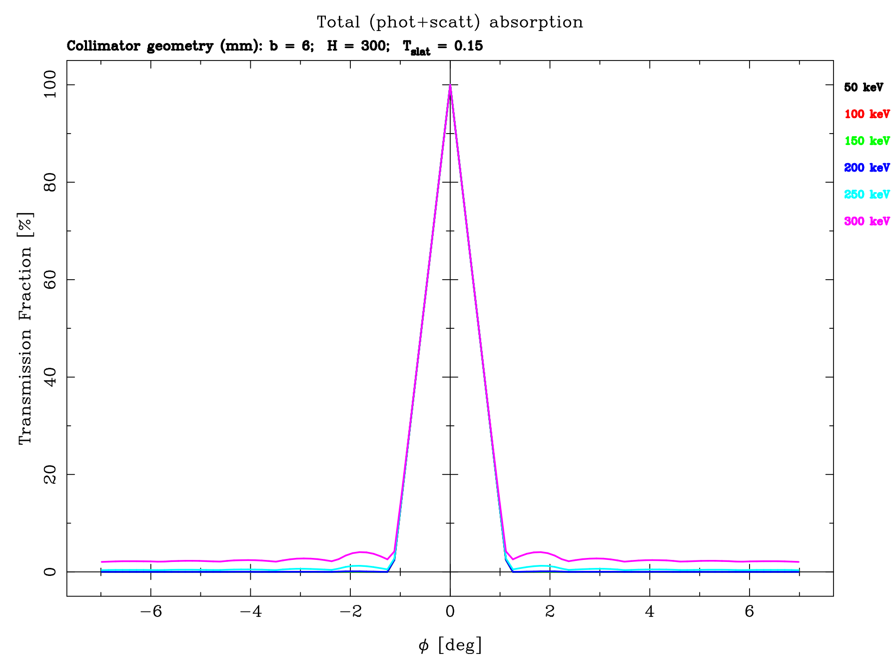


Figure 4: Angular response of the first candidate option collimator along a direction parallel to the Al schemes. 0.15 mm thick Tantalum plates are assumed. *Top:* only photoelectric absorption is assumed. *Bottom:* both photoelectric absorption and scattering are assumed.

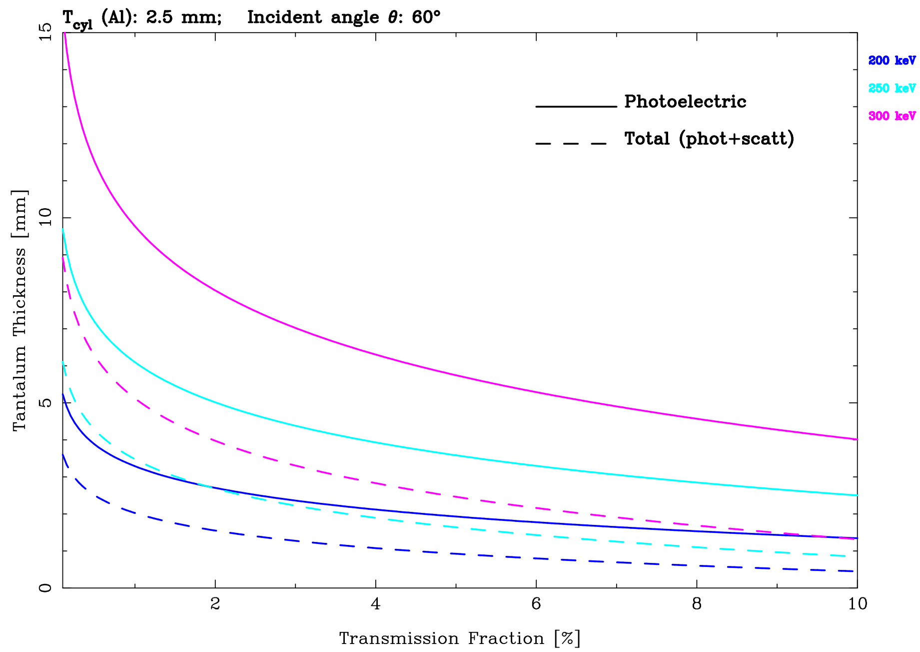


Figure 5: Thickness of a Tantalum layer as a function of the fraction of photons of various energies transmitted through the layer for an incident angle of 60° with respect to the cylinder axis.

4 Proposed optimization of the first option collimator configuration

From the derivation of the collimator angular response it has been possible to optimize the Tantalum thickness of both strips and slats by imposing constraints on the maximum fraction of X–rays that can be transmitted through the collimator walls. In particular we have derived the best tantalum thickness of the cylinder around the collimator and of the collimator cells that gives an acceptable angular response.

4.1 Cylinder configuration around the collimator

In the current candidate configuration, the cylinder around each collimator is made of Aluminum approximately 2.5 mm thick, with its inner surface covered with 150 μm of Tantalum. Clearly this layer is insufficient to adequately shield each collimator at high offset angles. In order to compensate this low collimator shield, two cylindrical tubes of tantalum 2 mm thick are foreseen to be installed in the center and outside of the HE collimator assembly (see [1]). *We find this solution not optimized for weight, collimator response and background shielding.*

Our proposal is to use a fully absorbing cylinder around each collimator unit, in the special configuration described below (details in Appendix A.3).

To this end, we first computed the Tantalum thickness required to have a maximum transparency of 2% (assuming the total absorption coefficient) for 200 keV photons with an incident angle of 60° with respect to the cylinder axis. In Figure 5 we show the result. As can be seen, a Ta layer of 1.5 mm is needed.

With this thickness and the goal of optimizing both the collimator response and its weight, we have assumed a 2.5 mm Aluminum cylinder (as in the case of the first candidate option), covered with three Ta layers

Table 2: Weight of the external Tantalum cylinder for different values of thickness and height. The best compromise between weight and transmission for 200 keV X–rays incident at an angle of 60° is obtained for the solution marked in red.

T_1 (mm)	T_2 (mm)	T_3 (mm)	Trans$_1$ (%)	Trans$_2$ (%)	Weight (g)
H1=300, H2=150, H3=75					
0.2583	0.2895	1.3187	2.0	3.0	2257
0.2583	**0.2687**	**1.2583**	**2.0**	**3.5**	**2178**
0.2583	0.2792	1.1375	2.0	4.0	2100
0.2375	0.2479	1.3791	2.5	3.0	2176
0.2375	0.2375	1.3187	2.5	3.5	2113
0.2375	0.2375	1.1979	2.5	4.0	2019
H1=300, H2=200, H3=100					
0.1750	0.2479	1.4396	2.0	3.0	2528
0.1854	0.2062	1.3792	2.0	3.5	2412
0.1750	0.2375	1.2583	2.0	4.0	2319
0.1646	0.2062	1.5000	2.5	3.0	2473
0.1542	0.2271	1.3792	2.5	3.5	2358
0.1646	0.1854	1.3188	2.5	4.0	2242

of different height and thickness (see Appendix A.3 for details on the proper angular response function). We have studied the behavior of the angular response of this cylinder as a function of the layer thickness and height, and evaluated its corresponding weight by taking into account the assumed maximum wall transmission (2% at 200 keV for an offset angle of 60°). In Table 2 we show the Tantalum weight as a function of the thickness and height of the layers. We can see that the best compromise between weight and maximum transmission occurs for the following configuration (unit is mm): $H1 = 300$, $H2 = 150$, $H3 = 75$. The response function for this configuration is shown in Figure 6.

4.2 Collimator cells configuration

With the collimator cylinder shaped as above, we have evaluated the response function of the collimator units to X–rays using, as before, either the photoelectric absorption alone or the total (photoelectric plus scattering) absorption by the cell wall materials, in which also the presence of the Al schemes is taken into account. For details see Appendix A.1.

As far as the Tantalum slats are concerned, we have imposed a constraint of 2% transmission at 200 keV for **photoelectric absorption**. As can be seen from Figure 7, in order to reach this constraint, a slat thickness of 80 μm is sufficient. On the other hand, to achieve the same transmission fraction through the Tantalum strips, a 350 μm thickness is needed. This configuration is shown in Figure 8. The supporting area covers 6.2% of the total detecting area. Note that the now proposed collimator configuration does not require the large Ta belt around the entire collimator assembly.

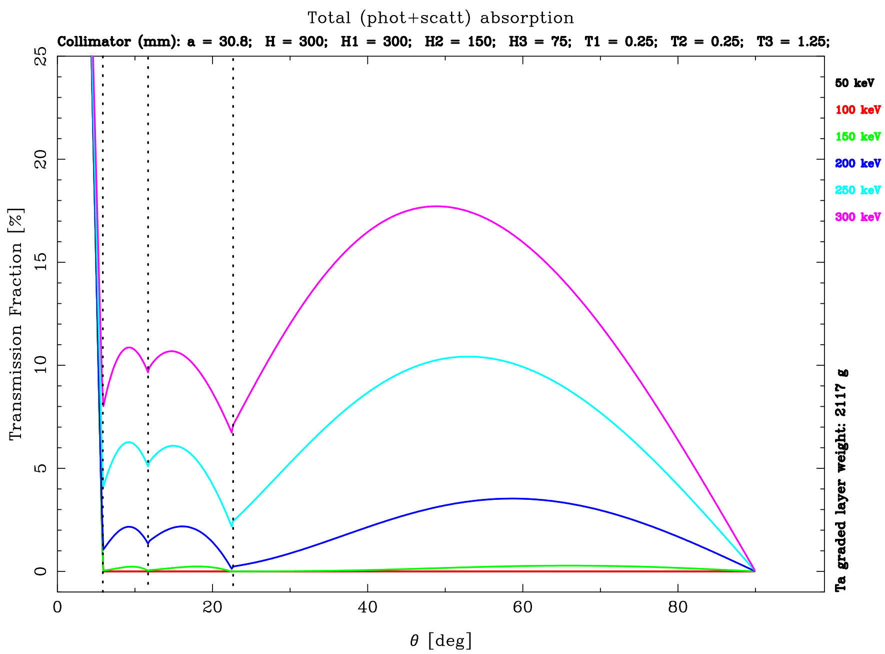


Figure 6: Angular response of the outermost cells along the direction orthogonal to the Al schemes for a collimator cylinder made of Al 2.5 mm thick surrounded by three Ta layers with heights 300, 150, and 75 mm and thicknesses 0.25, 0.25 and 1.25 mm, respectively (see Table 2 and Figure A.2 for the geometry). In the absorption coefficients, both photoelectric absorption and scattering are taken into account.

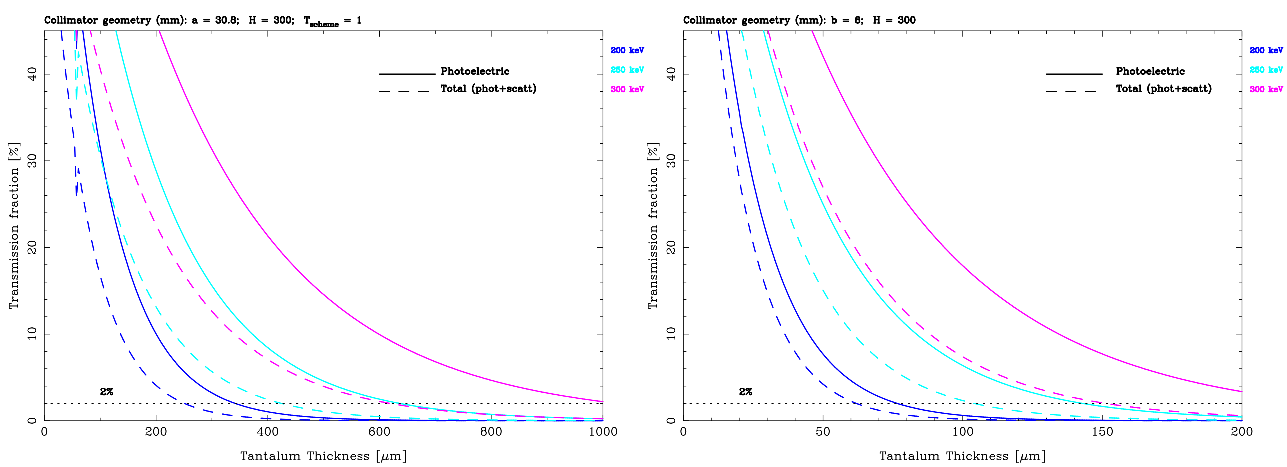


Figure 7: Collimator X–ray transmission vs Tantalum thickness for the strips (*left*) and for the slats (*right*). Continuous curves correspond to photoelectric absorption, while dashed curves correspond to total (photoelectric plus scattering) absorption.

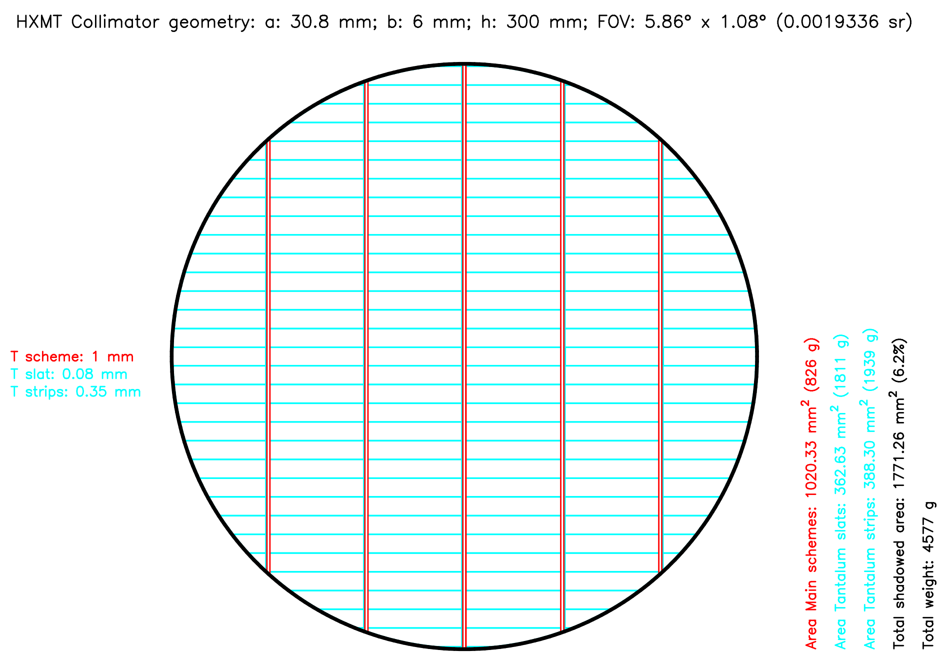


Figure 8: Collimator geometry with Tantalum thicknesses derived by imposing a 2% transmission at 200 keV, *i.e.* 350 μm for the Tantalum strips pasted on the 1 mm Al schemes, 80 μm for the Tantalum slats.

With the thickness values derived above, the angular response of the proposed collimator is shown in Figure 9, to be compared with that of the current configuration (see Figs. 3 and 4).

4.3 Weight of the revised first option configuration

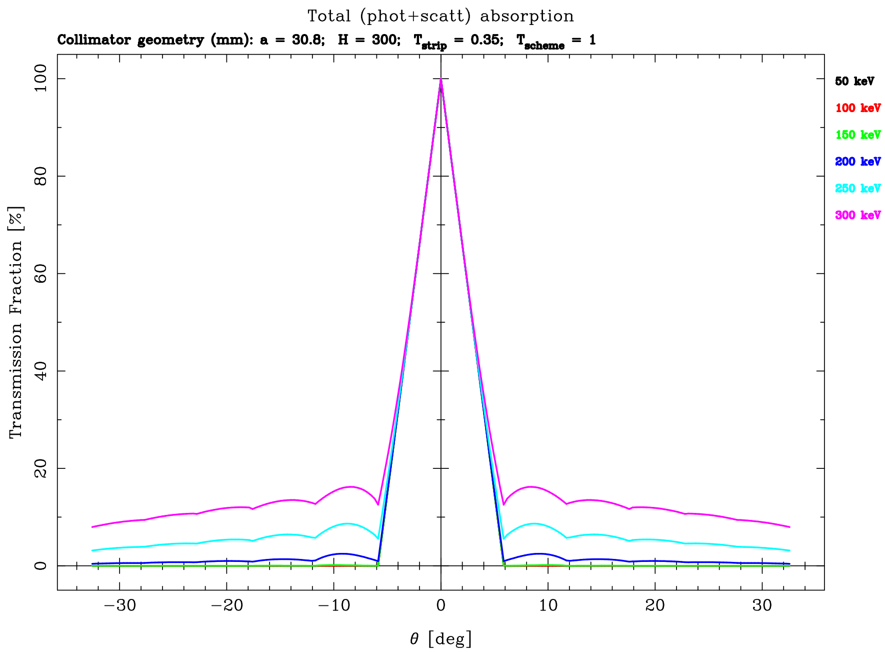
The weight of the new candidate first option configuration (see Figure 8), with the proposed external cylindrical shield as discussed in the previous section, and the new thickness of the collimator cells in order to improve the angular response, is $\sim$8 Kg per unit. Details are given in Table 3. Notice that in the new configuration no inner and outer cylindrical shields are needed.

Comparing the total HE collimator assembly weight (145 Kg) here proposed with the 165 Kg of the default configuration (see Table 1), we can see that we have a reduction of 20 Kg.

4.4 Graded Sn-Cu shield around the Ta walls

The collimator configuration proposed above shows various advantages (optimized angular response function, low weight, easy to build), but one problem: the production of a high K fluorescence line feature at about 60 keV. The experience acquired with the *BeppoSAX* PDS instrument has shown that a graded shield of Sn+Cu around the Ta walls significantly contribute to the background reduction in correspondence of the X–ray K line of the Tantalum and avoids the introduction of artificial features in the background–subtracted source spectra.

We have investigated the impact of a similar graded shield around each Ta wall. First, from the study of the solid angle subtended by the detector area through each collimator cell as a function of the distance from



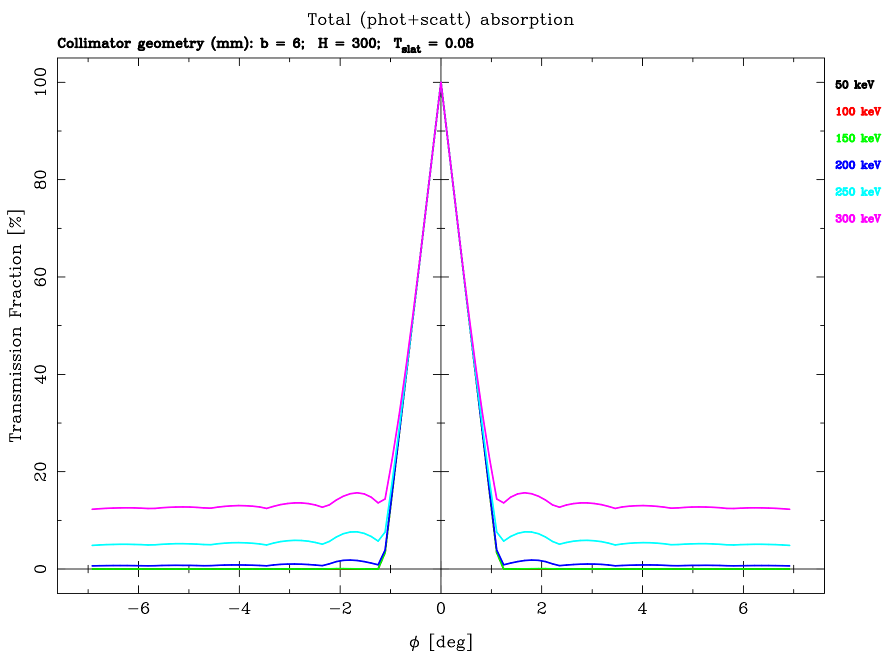


Figure 9: Angular response for the proposed optimization of the first option configuration. Total (photoelectric plus scattering) absorption coefficients are assumed. *Top:* response along a direction orthogonal to the scheme direction. Tantalum strips 0.35 mm thick are assumed to be pasted on the main schemes (of 1 mm thickness). *Bottom:* response along the direction parallel to the schemes. Tantalum plates 0.08 mm thick are assumed.

Table 3: Collimator weight layout for the optimized first option configuration.

Cylindrical Structure		**Cell Structure**	**No graded shield**	**Graded Shield**
Al tube (2.5 mm)	1224 g	Al schemes (1 mm)	826 g	826 g
Ta cylinder (three layers)	2257 g	Ta slats (80 μm)	1811 g	1811 g
		Ta strips (350 μm)	1939 g	1939 g
		Sn + Cu layer (100 + 50 μm)		959 g
Total	3481 g	**Total**	4576 g	5536 g

	No graded shield	Graded Shield
Weight/unit	**8057 g**	**9017 g**
Total weight of the HE collimator assembly (18 units)	**145.02 Kg**	**162.31 Kg**

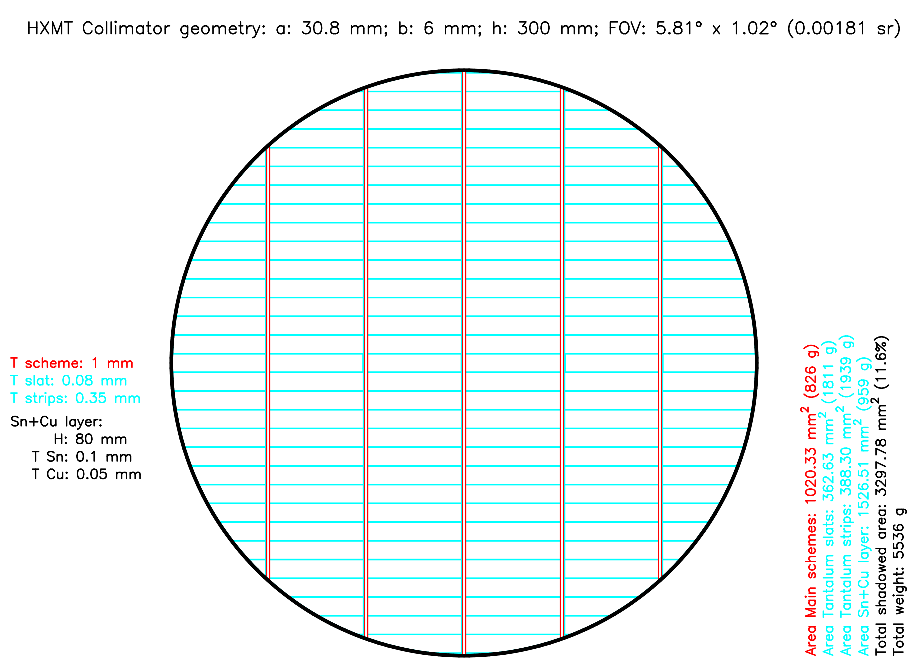


Figure 10: Our proposed collimator geometry (same as Figure 8) with a Sn+Cu graded shield.

the collimator bottom, we have evaluated the height of the graded shield that gives a significant reduction. The result is that a graded shield 80 mm high is sufficient. For the graded shield we have assumed the same thickness of Sn (100 μm) and Cu (50 μm) used for SAX/PDS [3]. With this graded shield, the detection area through the collimator passes from 6.2% to 11.6% and the collimator weight slightly increases. The new values of these quantities are reported in the last column of Table 3. The new configuration of the collimator units, that leaves almost unchanged the FOV of the instrument and thus its solid angle, is shown in Figure 10.

Table 4: Collimator weight layout for our new assembly configuration.

Cylindrical Structure		**Cell Structure**			
Al tube (2.5 mm)	1224 g	Ta slats (80 μm)	1867 g	W slats (65 μm)	1736 g
Ta cylinder (three layers)	2257 g	Ta strips (350 μm)	2021 g	W strips (300 μm)	2008 g
		Sn + Cu layer (100 + 50 μm)	989 g		989 g
Total	3481 g	**Total**	4879 g	**Total**	4764 g
Total single collimator weight			**8360 g**		**8245 g**
Total HE Collimator weight (18 units)			**150.48 Kg**		**148.41 Kg**

5 Proposal of a new assembling design of the collimator units

The new collimator configuration discussed above is based on the same assembly design concept of the first candidate option (use of Aluminum schemes and Al cylinder around each collimator), in which we have determined the best Ta thickness for the cells and for the cylindrical layer around each collimator unit in order to improve its angular response.

In order to optimize the collimator weight and simplify the collimator assembly design, we have investigated a new assembling technique of each collimator unit in alternative to the candidate option 1. The results of this investigation are shown in Figs. 11, 12 and 13. We have discussed this design with a Tantalum leader supplier and manufacturer (PLANSEE, Reutte, Austria), who was also involved in the *BeppoSAX* PDS collimator development, obtaining from them a positive answer about the design feasibility.

In this new assembly design, we make use of two equal sets of Tantalum plates of 2 different thicknesses (80 μm and 350 μm), like before, 300 mm height (height of the collimator), and variable width in order to fit the collimator round geometry. Each of the plates is covered with a Sn+Cu graded shield as described above for 80 mm of its height. The plates are then properly cut along their height in order to interlock with each other in orthogonal directions and obtain a collimator with rectangular cells and a round geometry, as shown in Figure 13. The cuts length are done for half of the plate length and produce slits of two different widths: 80 μm for a set, and 350 μm for the other (see Figure 11 and 12).

Around each collimator unit, the Ta+Al cylinder described above is positioned. A top view of this collimator configuration is shown in the upper panel of Figure 14.

The angular response of each collimator unit is the same of the optimized configuration of the candidate option 1 (see Figure 9), while its estimated weight is 8.36 Kg, to be compared with the 9.02 Kg weight of the optimized configuration of option 1 with graded shield (see Table 3). The weight layout of the new assembly configuration is reported in Table 4. The weight of the new collimator assembly is 150.5 Kg to be compared with that (162.3 Kg) of the candidate option 1.

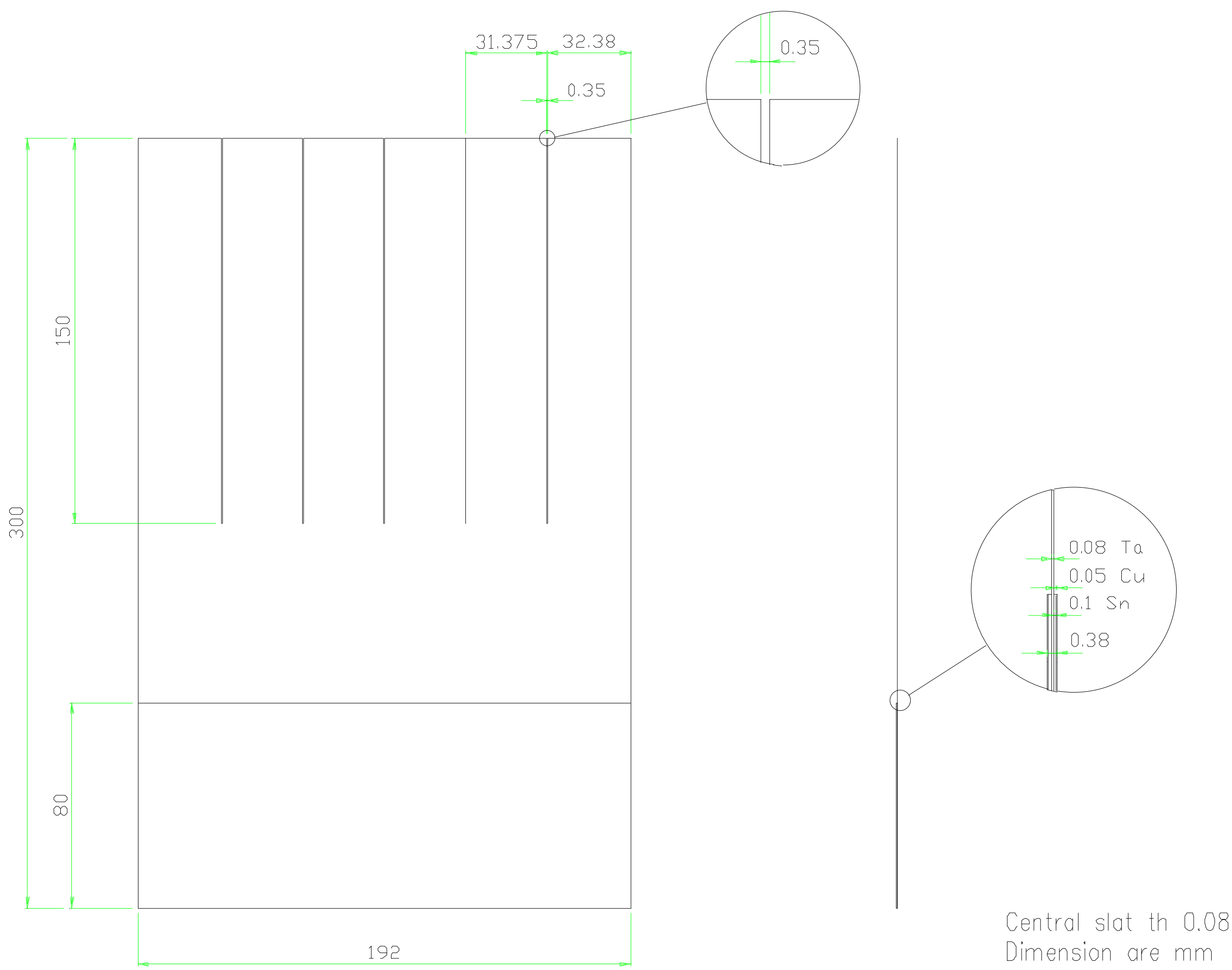


Figure 11: Detail of the 80 μm central slat.

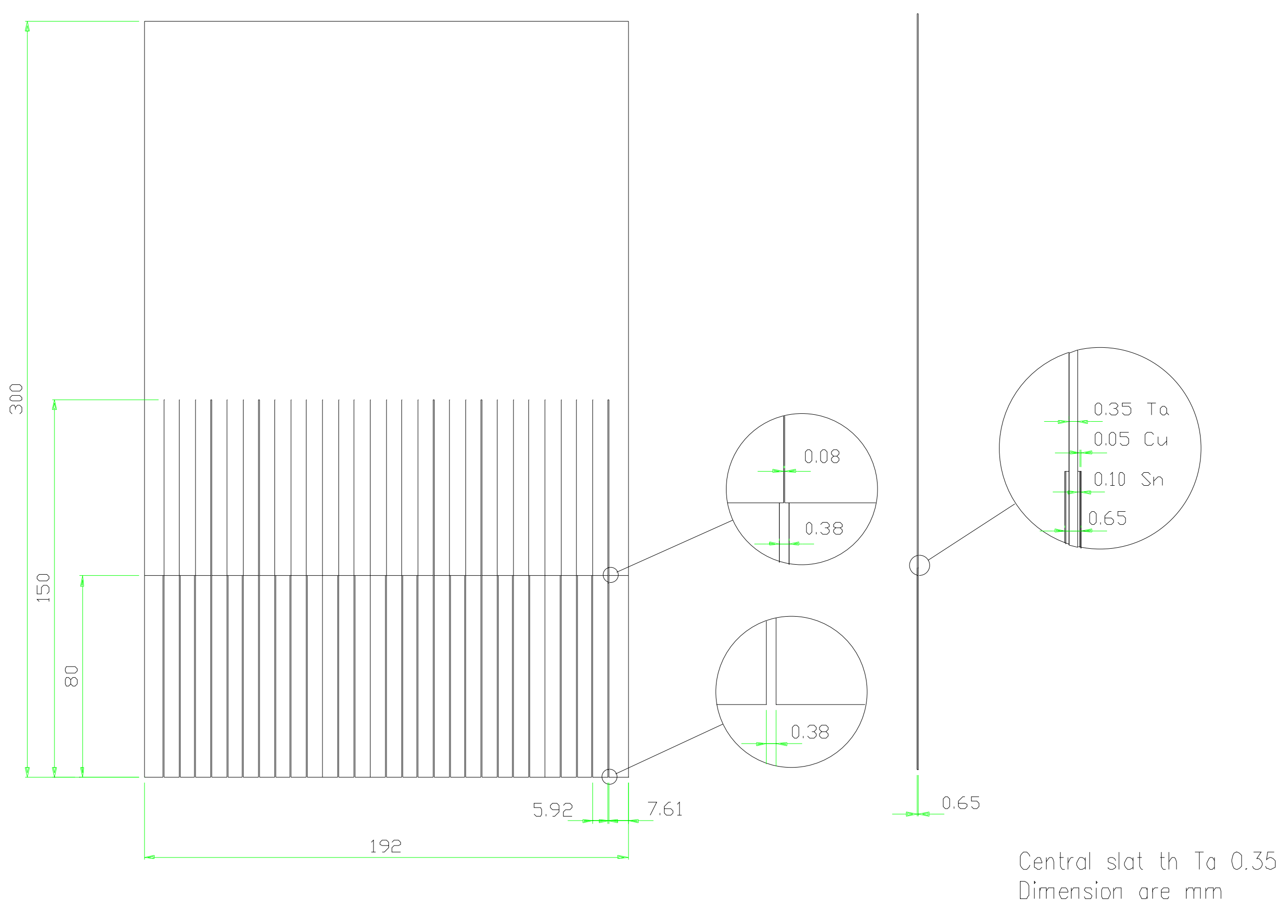


Figure 12: Detail of the 350 μm central slat.

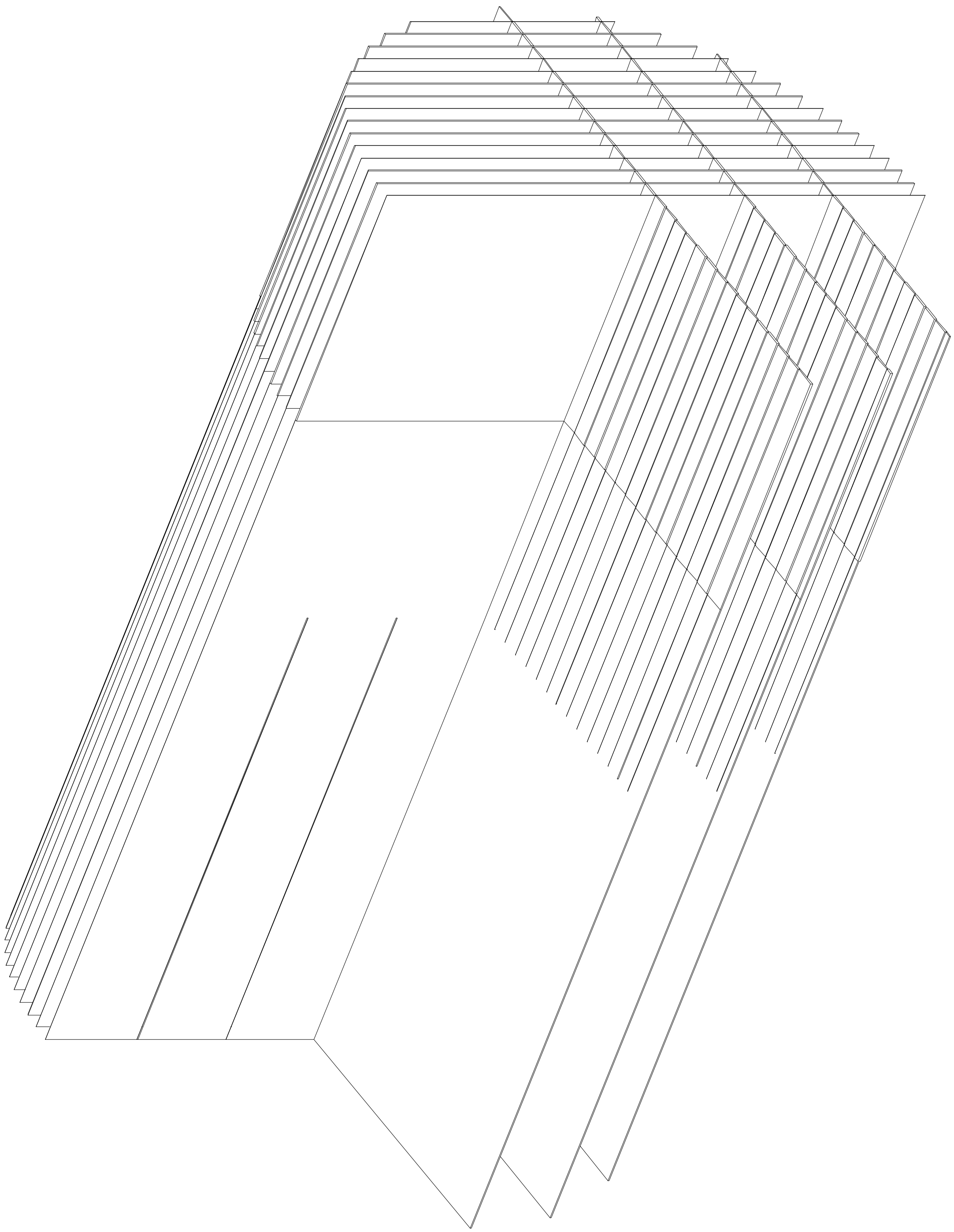
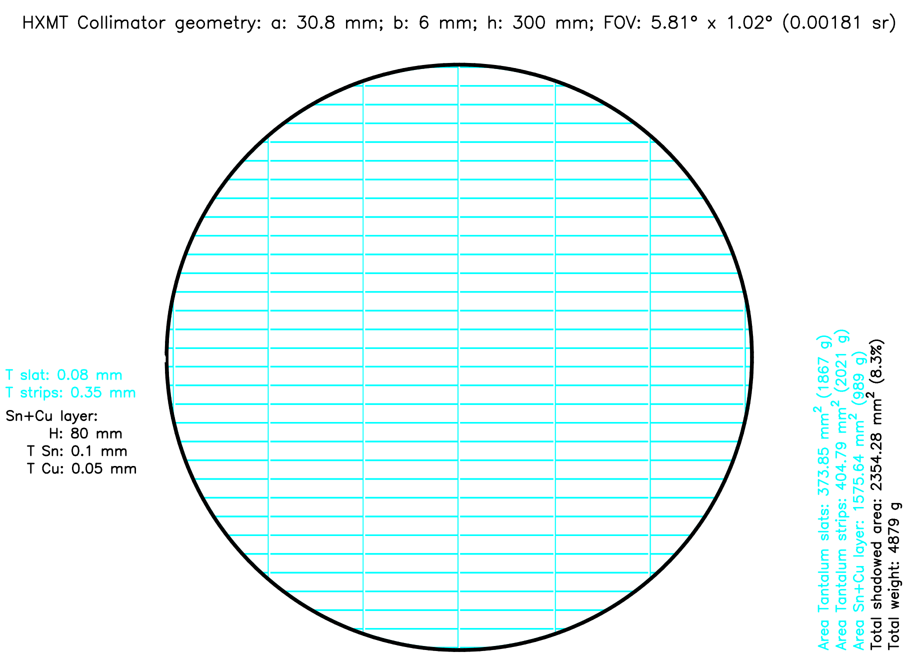


Figure 13: Exploded view of the HXMT slat assembly.



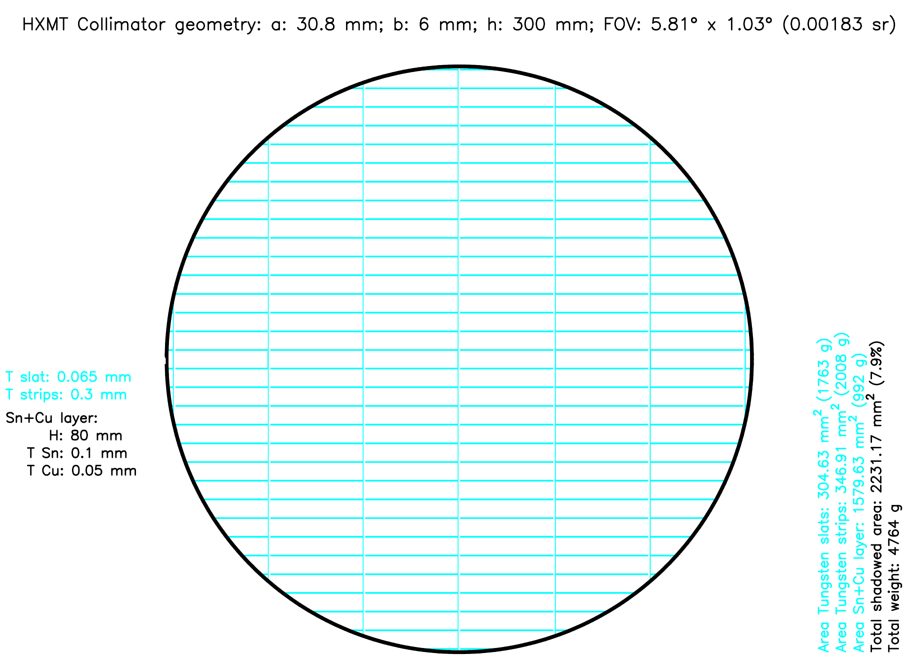


Figure 14: Geometry of the new assembly design collimator. *Top:* with Tantalum strips and slats. *Bottom:* with Tungsten strips and slats.

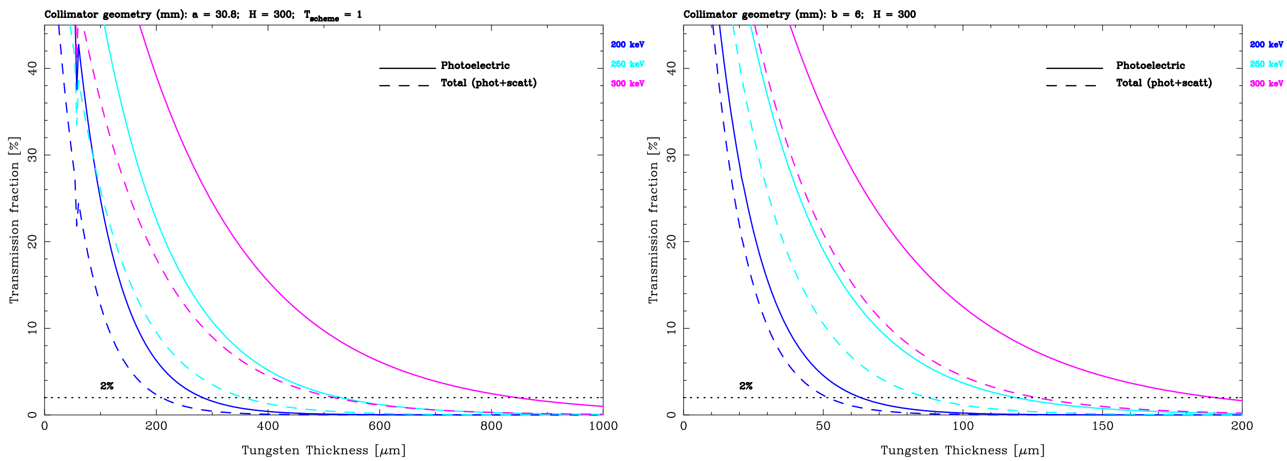


Figure 15: Collimator X–ray transmission vs Tungsten thickness for the strips (*left*) and for the slats (*right*). Continuous curves correspond to photoelectric absorption, while dashed curves correspond to total (photoelectric plus scattering) absorption.

5.1 Use of Tungsten instead of Tantalum

Because of the softness of Tantalum, the dimensions (especially of the central ones) and the small thickness of the slats, the manufacturing of the 80 μm Ta slats could be problematic. Therefore we suggest the use of Tungsten instead of Tantalum. We performed the same analysis as described in Section 4.2 to find out the optimal thicknesses of the two slats. The result is shown in Figure 15 (to be compared with Figure 7).

In order to reach a 2% transmission at 200 keV for photoelectric absorption, a Tungsten thickness of 65 μm and 300 μm in the two directions are sufficient. This configuration is shown in the bottom panel of Figure 14, and its weight is listed in Table 4. The supporting area covers 7.9% of the total detecting area.

Table 5: Summary of proposed solutions.

	First Option Solution [1]	Our Optimized First Option Solution	Our Optimized First Option Solution with Sn+Cu	Our New Assembly Solution in Ta (with Sn+Cu)	Our New Assembly Solution in W (with Sn+Cu)
Collimator Assembly Weight (Kg)	165.54	145.02	162.31	150.48	148.41
Supporting Area (%)	6.5	6.2	11.6	8.3	7.9

6 Summary and conclusions

We have optimized the design of the X–ray mechanical collimators for the High Energy instrument aboard HXMT starting from the first candidate option configuration (option 1) described in [1], while do not discuss the second candidate option there described. Indeed it implies a a variable Tantalum thickness along the two orthogonal directions of the cells and provide a less precise collimator manufacture. Thus we do not suggest to use this option.
Three results have been obtained:

1. We have optimized the angular response of the first candidate option described in [1] by finding the best thickness of the Ta cell walls and of the cylinder around each collimator units. We have obtained the the following configuration (see also Figure 8):

   - ☞ Aluminum cylindrical structure of 2.5 mm thickness;
   - ☞ Supporting Aluminum schemes of 1 mm thickness;
   - ☞ Distance between schemes of 30.8 mm, in order to optimize the collimator geometry. The resulting collimator field of view is $5.86° \times 1.08°$, corresponding to 1.93×10^{-3} sr;
   - ☞ Tantalum strip to be pasted on *one side* of the schemes, of 350 μm thickness;
   - ☞ Tantalum slats to be inserted between schemes, of 80 μm thickness;
   - ☞ Three Tantalum layers of heights 300, 200, and 100 mm and thicknesses 0.2, 0.3 and 1 mm, respectively (see Figure A.2 for the geometry) to be pasted around the Aluminum cylindrical structure of *each* collimator unit.

   With this configuration the supporting area covers 6.2% of the total detecting area (comparable to the value of 6.5% of the default configuration. See Table 5). The weight of the collimator is 8 Kg, and the total weight for the HE collimator assembly will be 145 Kg. In this configuration the two tubes, that were foreseen to be installed in the center and outside of the HE detector assembly, are no more needed. Our solution allows a reduction of 20 Kg with respect to the standard configuration (165.5 Kg).

2. We also propose for the above configuration to use a graded Sn+Cu shield for suppressing the 60 keV K_α fluorescence line due to Tantalum.

   This is quite important for the background reduction and for avoiding artificial features in the background–subtracted source spectra. With this graded shield the supporting area covers 11.6% of the total detecting area and the total weight for the HE collimator assembly will be 162 Kg.

3. We also suggest a new assembly technique of the collimator which appears simpler, lighter (150.5 Kg if using Tantalum, 148.4 Kg if using Tungsten) and it increases the detection area through the collimator (the supporting area covers 8.3% of the detecting area if using Tantalum and 7.9% if using Tungsten). With respect to the default first candidate option described in [1] (see also Table 1), there is a weight reduction of 15–17 Kg even if we add the Sn+Cu graded shield, and a quite similar supporting area.

References

[1] *The Hard X–ray Modulation Telescope (HXMT) Mission* description, 20/08/2007

[2] *XCOM: Photon Cross Sections Database*, available online at `http://physics.nist.gov/PhysRefData/Xcom/Text/XCOM.html`

[3] Frontera F., Costa E., Dal Fiume D., Feroci M., Nicastro L., Orlandini M., Palazzi E., and Zavattini G. 1997. The high energy instrument PDS on-board the BeppoSAX X–ray astronomy satellite. *Astron. Astrophys. Suppl. Ser.*, **122**, 357

[4] Dong Y., Jin Y., Zhang A. and Li G. 2008. On the HE/HXMT collimator design

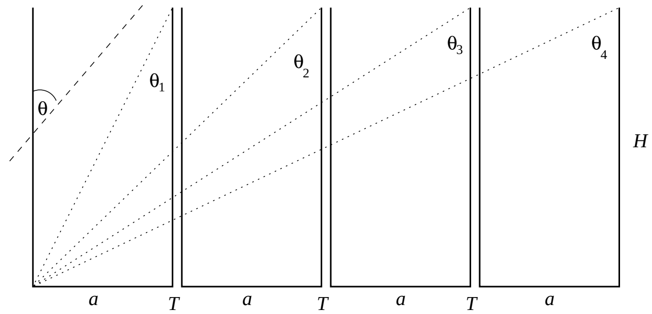


Figure A.1: Geometrical representation of the collimator cells and definition of the characteristic angles θ_n.

A Derivation of the collimator angular response function

A.1 The case of inner cells

To derive the equations describing the collimator angular response function (see, e.g., Figure 3) we start from the geometrical representation of the collimator cells (length a and height H) as in Figure A.1:
Because we do not take into account the azimuthal dependence, our equations will describe the collimator angular response along one of the sides of the collimator.
The characteristic angles θ_n define how many cell walls are crossed by the X–rays before being collected on the detector. From Figure A.1 we have

$$\tan\theta_n = \frac{na + (n-1)T}{H} \tag{1}$$

where T is the wall thickness, assumed the same for all the walls. Each time X–rays cross a wall with an angle θ with respect to the vertical, their intensity is reduce by a factor

$$f \equiv \exp\left(-\frac{\mu\rho T}{\sin\theta}\right) \tag{2}$$

where $\mu = \mu(E)$ is the absorption coefficient (in units of cm^2/g) of the X–rays in the wall material, and ρ is the density of the absorbing material.
According to the X-ray incident angle θ we have the following cases:

- Case $0 < \theta < \theta_1$

  In this case we will have that the detector area will be directly illuminated (therefore no absorption by the walls) on a rectangular area

$$(a - H\tan\theta) \times b \tag{3}$$

  where b is the other collimator dimension. On the other hand the area

$$H\tan\theta \times b \tag{4}$$

will be illuminated by X–rays that passed once through the collimator wall. Therefore the normalized (that is, divided by the cell area $a \times b$) area illuminated will be

$$\mathcal{R}_0(0 < \theta < \theta_1) = 1 - \frac{H}{a}\tan\theta + f\frac{H}{a}\tan\theta = 1 + \Theta[f-1] \tag{5}$$

where we have defined

$$\Theta \equiv \frac{H}{a}\tan\theta \quad . \tag{6}$$

This is our angular response function in the a direction for $0 < \theta < \theta_1$.

- Case $\theta_1 < \theta < \theta_2$

  We will deal with two situations: in the first, X–rays will pass through only one collimator wall, while in the other they will reach the detector by passing through two walls. In the first situation we will have that the illuminated normalized area will be

$$f\,\frac{(2a+T) - H\tan\theta}{a} = f\left[\left(2 + \frac{T}{a}\right) - \Theta\right] \tag{7}$$

  while in the second situation we will have that the illuminated normalized area will be

$$f \cdot f\,\frac{H\tan\theta - (a+T)}{a} = f \cdot f\left[\Theta - \left(1 + \frac{T}{a}\right)\right] \tag{8}$$

  Therefore the angular response function in the a direction for $\theta_1 < \theta < \theta_2$ will be

$$\mathcal{R}_1(\theta_1 < \theta < \theta_2) = f\left[\left(\Theta - \frac{T}{a}\right)(f-1) + (2-f)\right] \quad . \tag{9}$$

- Case $\theta_2 < \theta < \theta_3$

  In perfect analogy with the previous case, we will have that the angular response function is

$$\mathcal{R}_2(\theta_2 < \theta < \theta_3) = f \cdot f\left[\left(\Theta - 2\frac{T}{a}\right)(f-1) + (3-2f)\right] \quad . \tag{10}$$

From the previous discussion we will have that the angular response function along the a direction for $\theta_n < \theta < \theta_{n+1}$ will have the form

$$\mathcal{R}_n(\theta_n < \theta < \theta_{n+1}) = f^n\left\{\left(\Theta - n\frac{T}{a}\right)(f-1) + [(n+1) - nf]\right\} \tag{11}$$

and the *total* response function for angles in the range $0 < \theta < \theta_{k+1}$ will be the sum of the responses in their angle ranges

$$\mathcal{R}(0<\theta<\theta_{k+1})=\sum_{n=0}^{k}\mathcal{R}_n=\sum_{n=0}^{k}f^n\left\{\left(\Theta-n\frac{T}{a}\right)(f-1)+[(n+1)-nf]\right\} \quad . \tag{12}$$

Equation 12 must be multiplied by a $\cos\theta$ factor because X–rays will illuminate only the projection of the detector area, therefore

$$\mathcal{R}_{\rm proj}(0<\theta<\theta_{k+1})=\cos\theta\,\mathcal{R}(0<\theta<\theta_{k+1}) \quad . \tag{13}$$

Equation 13 is plotted in Figure 3 and following, taking into account the different materials composing the collimator walls (only Tantalum in the case of the slats and Aluminum plus Tantalum in the case of the schemes) and the different absorption coefficients (only photoelectric absorption or photoelectric absorption plus scattering).

A.2 The case of border cells

The cells that are on the border of the collimator structure must be treated differently, because X–rays will always cross only one wall before being detected. In this case our general case discussed in the previous section reduces to only two cases:

- Case $0<\theta<\theta_1$

  To be treated exactly as in the case of inner cells, with response function given by Eq. 5

$$\mathcal{R}_0(0<\theta<\theta_1)=1+\Theta[f-1] \quad . \tag{14}$$

- Case $\theta>\theta_1$

  For any other incident angle θ X–rays will always pass through one wall, with response function

$$\mathcal{R}_k(\theta>\theta_1)=f \quad . \tag{15}$$

Therefore the *total* response function for angles in the range $0<\theta<\frac{\pi}{2}$ will be the sum of Eqs. 5 and 15. As before, a $\cos\theta$ factor must be considered to take into account the projection of the detector area.

$$\mathcal{R}_{\rm proj}(0<\theta<\frac{\pi}{2})=\cos\theta\,(1+\Theta[f-1]+f) \quad . \tag{16}$$

A.3 The case of border cells: grading wall

We analyzed the case when the thickness of the cylindrical structure is not constant but varies with height (grading wall). The situation is illustrated in Figure A.2. We will assume that the external, cylindrical structure of the collimator be formed by three rings, each of height h_1, h_2, and h_3, and thickness T_1, T_2, and T_3, respectively. The case of a homogeneous external wall will correspond to $h_1=h_2=h_3=H$ and $T_1=T_2=T_3=T$.

The three characteristic angles are such that

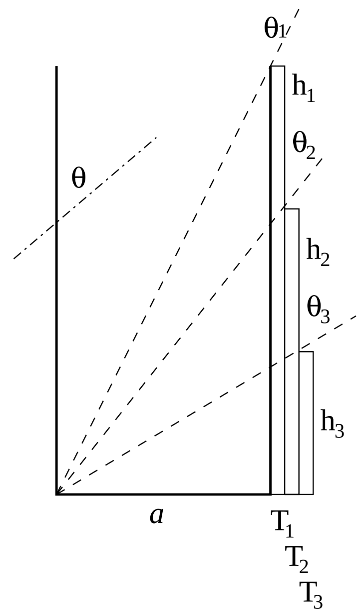


Figure A.2: Geometrical representation of a graded collimator external wall, and definition of the characteristic angles θ_n.

$$\begin{aligned} \tan\theta_1 &= \frac{a}{h_1} \\ \tan\theta_2 &= \frac{a+T_1}{h_2} \\ \tan\theta_3 &= \frac{a+T_1+T_2}{h_3} \quad . \end{aligned} \tag{17}$$

As usual we will divide our problem into different cases according to the X–rays incident angle θ:

- Case $0 < \theta < \theta_1$

  An X–ray beam incident onto the grading wall will form four regions:

  1. X–rays illuminate directly the detector, with response

  $$1 - \frac{h_1}{a}\tan\theta \tag{18}$$

  2. X–rays pass through the upper, thinner (thickness T_1) part of the wall, with response

  $$f_1 \cdot \frac{h_1 - h_2}{a}\tan\theta \tag{19}$$

  where we have defined

$$f_1 \equiv \exp\left(-\frac{\mu T_1}{\sin\theta}\right) \tag{20}$$

3. X–rays pass through the central (thickness $T_1 + T_2$) part of the wall, with response

$$f_2 \cdot \frac{h_2 - h_3}{a} \tan\theta \tag{21}$$

where we have defined

$$f_2 \equiv \exp\left(-\frac{\mu(T_1 + T_2)}{\sin\theta}\right) \tag{22}$$

4. X–rays pass through the bottom (thickness $T_1 + T_2 + T_3$) part of the wall, with response

$$f_3 \cdot \frac{h_3}{a} \tan\theta \tag{23}$$

where we have defined

$$f_3 \equiv \exp\left(-\frac{\mu(T_1 + T_2 + T_3)}{\sin\theta}\right) \tag{24}$$

Therefore the response function for $0 < \theta < \theta_1$ is

$$\mathcal{R}_0(0 < \theta < \theta_1) = 1 + \frac{h_1}{a}\tan\theta(f_1 - 1) + \frac{h_2}{a}\tan\theta(f_2 - f_1) + \frac{h_3}{a}\tan\theta(f_3 - f_2) \quad . \tag{25}$$

- Case $\theta_1 < \theta < \theta_2$

  In this case the different illuminated regions will be three, and the response function will be

$$\mathcal{R}_1(\theta_1 < \theta < \theta_2) = f_1 + \frac{h_2}{a}\tan\theta(f_2 - f_1) + \frac{h_3}{a}\tan\theta(f_3 - f_2) \quad . \tag{26}$$

- Case $\theta_2 < \theta < \theta_3$

  In this case the different illuminated regions will be two, and the response function will be

$$\mathcal{R}_2(\theta_2 < \theta < \theta_3) = f_2 + \frac{h_3}{a}\tan\theta(f_3 - f_2) \quad . \tag{27}$$

- Case $\theta > \theta_3$

  In this last case the response function will be

$$\mathcal{R}_3(\theta > \theta_3) = f_3 \quad . \tag{28}$$

Therefore, summing up the contributions of all the angle intervals, and taking into account the $\cos\theta$ factor, the total response function due to a grading external wall will be

$$\mathcal{R}_{\rm proj}(\theta > 0) = \cos\theta \sum_{k=0}^{3} \mathcal{R}_k \tag{29}$$

As it should be, in the case $h_1 = h_2 = h_3 = H$ we obtain Eq. 16.

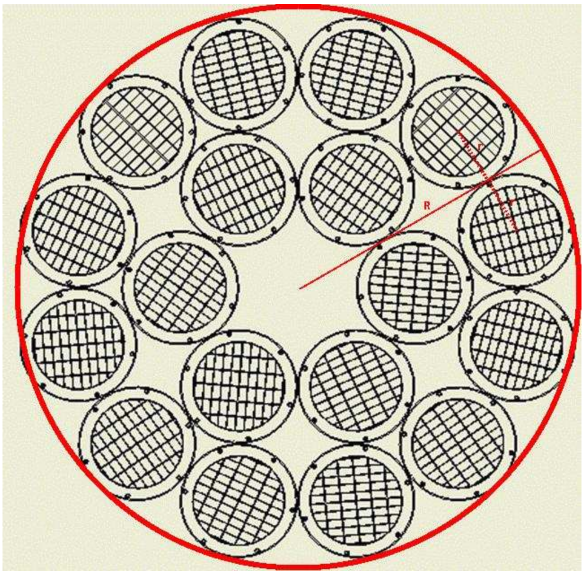


Figure B.1: The High Energy experiment configuration.

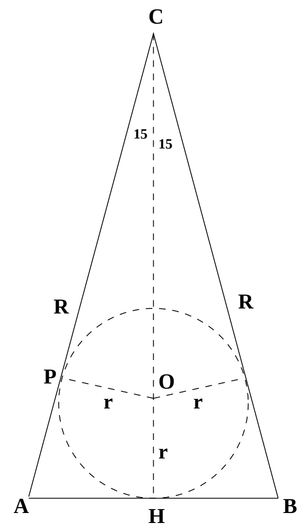


Figure B.2: Detailed geometry for the definition of the characteristic dimensions.

B Determination of the maximum incident angle

The High Energy (HE) experiment aboard HXMT is composed by 18 cylindrical detectors, as shown in Figure B.1. In order to establish the radius R of the HE experiment as a function of the detector radius r let us start from Figure B.2, in which all the angles and dimensions are explicited.
Because of the similarity of the two triangles AHC and CPO we can write

$$\frac{R}{R \sin 15} = \frac{R \cos 15 - r}{r} \tag{30}$$

from which we have

$$R = \frac{r}{\cos 15}\left(1 + \frac{1}{\sin 15}\right) = 4\,r\left(\frac{1}{\sqrt{6}+\sqrt{2}} + 1\right) \simeq 5.03\,r \qquad . \tag{31}$$

Therefore, because $r = 95$ mm, we have $R = 47.8$ cm. The maximum incident angle such that X–rays will be able to illuminate one of the detectors will be given by

$$\theta_{\max} = \arctan\frac{2R}{H} \simeq 72.5^{\circ} \tag{32}$$

where H is the collimator height.

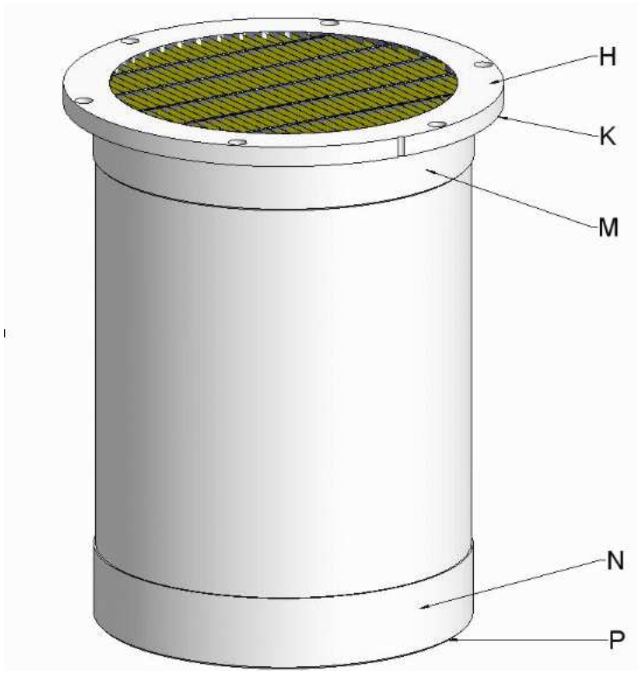


Figure C.1: The HE HXMT collimator assembly.

C Engineering requirements on the collimator assembly

These are the engineering requirements on the collimator assembly as stated in the document *On the HE/HXMT collimator design* [4] (see Figure C.1):

1. The schemes and the plates are parallel to each other within 0.5$'$;
2. The schemes and the plates are perpendicular to the lower surface of the flange (K) within 0.5$'$;
3. The upper surface (H) and the lower surface (K) of the flange are parallel within 0.2$'$;
4. The ellipticities of M and N are $<$0.01 mm;
5. The axes of cylinder M and N are perpendicular to the upper surface (H) of the flange within 0.5$'$;

Items 1. and 2. are the most critical requirements, to ensure that the 18 collimators have all the same orientation. Further (preliminary) engineering requirements on the collimator assembly are:

6. collimator assembly must withstand testing in a temperature range from -55 to $+150$ °C;
7. collimator assembly must withstand static pressure tests of 11 atm;
8. collimator assembly must be stiff enough to have a resonance frequency $>$120 Hz;
9. collimator assembly must withstand lateral design loads of 4 g and axial design loads of 9 g;
10. safety margins for materials must be 1.25 for yield, 1.5 for tensile strength, and 2.0 for buckling.