Publication Year	2015
Acceptance in OA	2020-03-25T15:29:38Z
Title	Silicon pore optics mirror modules for inner and outer radii
Authors	Wille, Eric, Bavdaz, Marcos, Oosterbroek, Tim, Collon, Maximilien, Ackermann, Marcelo, Günther, Ramses, Vacanti, Giuseppe, Vervest, Mark, Yanson, Alexei, van Baren, Coen, Haneveld, Jeroen, Koelewijn, Arenda, Leenstra, Anne, Wijnperle, Maurice, PARESCHI, Giovanni, CIVITANI, Marta Maria, Conconi, Paolo, SPIGA, Daniele, Valsecchi, Giuseppe, Marioni, Fabio, Zuknik, Karl-Heinz, Schweitzer, Mario
Publisher's version (DOI)	10.1117/12.2187486
Handle	http://hdl.handle.net/20.500.12386/23545
Serie	PROCEEDINGS OF SPIE
Volume	9603

Silicon Pore Optics Mirror Modules for Inner and Outer Radii

Eric Wille[a], Marcos Bavdaz[a], Tim Oosterbroek[a]
Maximilien Collon[b], Marcelo Ackermann[b]
Ramses Günther[c], Giuseppe Vacanti[c], Mark Vervest[c], Alexei Yanson[c]
Coen van Baren[d]
Jeroen Haneveld[e], Arenda Koelewijn[e], Anne Leenstra[e], Maurice Wijnperle[e]
Giovanni Pareschi[f], Marta Civitani[f], Paolo Conconi[f], Daniele Spiga[f]
Giuseppe Valsecchi[g], Fabio Marioni[g]
Karl-Heinz Zuknik[h], Mario Schweitzer[h]

[a] European Space Agency, Keplerlaan 1, PO Box 299, 2200 AG Noordwijk, The Netherlands
[b] cosine Research B.V., J.H. Oortweg 19, 2333 CH Leiden, The Netherlands
[c] cosine Science & Computing B.V., J.H. Oortweg 19, 2333 CH Leiden, The Netherlands
[d] SRON, Sorbonnelaan 2, 3584 CA Utrecht, The Netherlands
[e] Micronit Microfluidics B.V., Colosseum 15, 7521 PV Enschede, The Netherlands
[f] National Institute of Astrophysics – Astronomical Observatory of Brera, Via E. Bianchi 46, 23807 Merate (LC), Italy
[g] Media Lario Technologies S.r.l., Localita Pascolo, 23842 Bosisio Parini (LC), Italy
[h] OHB System AG, Wolfratshauserstrasse 48, 81379 Munich, Germany

ABSTRACT

Athena (Advanced Telescope for High Energy Astrophysics) is an x-ray observatory using a Silicon Pore Optics telescope and was selected as ESA's second L-class science mission for a launch in 2028. The x-ray telescope consists of several hundreds of mirror modules distributed over about 15-20 radial rings. The radius of curvature and the module sizes vary among the different radial positions of the rings resulting in different technical challenges for mirror modules for inner and outer radii.

We present first results of demonstrating Silicon Pore Optics for the extreme radial positions of the Athena telescope. For the inner most radii (0.25 m) a new mirror plate design is shown which overcomes the challenges of larger curvatures, higher stress values and bigger plates. Preliminary designs for the mounting system and its mechanical properties are discussed for mirror modules covering all other radial positions up to the most outer radius of the Athena telescope.

Keywords: X-ray optics, X-ray astronomy, pore optics, X-ray telescopes

1. INTRODUCTION

Silicon Pore Optics (SPO) are the baseline technology for ESA's Athena x-ray observatory. Athena has been selected as the second large class (L2) mission in the ESA science programme. The observatory consists of a single, large telescope, assembled from several hundreds of mirror modules. The key requirements for the optics are an angular resolution of below 5 arcsec half energy width (HEW) and a large effective area. An ESA internal concurrent design facility (CDF) study has established a first mission design [1,2] and two parallel system studies by the European space industry are starting in 2015. The size of the telescope is an important driver to maximise the effective area (towards the 2 m² effective area at 1 keV as requested by the mission proposal), but other constrains like available launch adapter sizes, mechanical stability and the mission cost cap of about 1 billion Euro to ESA have to be further evaluated before establishing the mirror radius.

Optics for EUV, X-Ray, and Gamma-Ray Astronomy VII, edited by Stephen L. O'Dell, Giovanni Pareschi,
Proc. of SPIE Vol. 9603, 96030L · © 2015 SPIE · CCC code: 0277-786X/15/$18 · doi: 10.1117/12.2187486

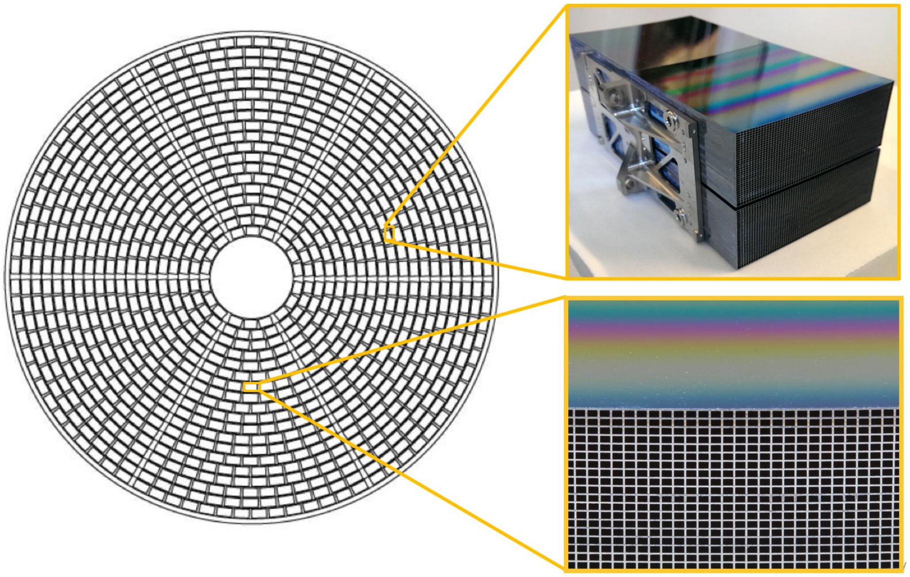


Figure 1: An example of the telescope layout is shown on the left with a mirror design using 19 rings and a total of 972 MMs. A photo of the MM is shown on the top right together with a detailed view (bottom right) of the reflective Silicon surface (without coating) and the pore structure.

The Silicon Pore Optics technology is based on using a modular approach, where the telescope is segmented into many small (about 10x5x20 cm^3) mirror modules (MM) [3,4]. Each MM is an off-axis Wolter I optics. Figure 1 illustrates the concept with a layout example using 972 MMs distributed over 19 rings. One MM consists of 70 plate pairs distributed over 4 mirror stacks. Each plate has many pores, separated by ribs which are used to bond the plates together and to form a stack with a rigid structure.

The SPO technology has been developed during the past decade by ESA and a large consortium of industrial and institutional partners. During these past years, several mission proposals were discussed (XEUS, IXO, Athena [5-7]) with different mirror diameters and focal lengths. But the SPO technology can be applied over a large range of these optical design parameters (focal length: f, inner and outer mirror radius: r_{in} and r_{out}) by only adjusting a few design parameters of the mirror plates. The affected parameters on the mirror plate level are the plate length l, the bending radius r and the plate wedge angle δ. During the initial phase of the technology development all SPO manufacturing processes were developed and demonstrated for a typical set of values l, r and δ, corresponding to a MM in the middle position of the telescope (as shown in Figure 1). With the selection of Athena, a more precise (although not yet final) telescope design envelope became available which allows to extend the development activities to demonstrate the most inner and outer MMs currently considered for the Athena mission. In 2014 and 2015 ESA started activities to design and manufacture MMs for the innermost radius (r_{in} = 25 cm, l = 11 cm) and outermost radius (r_{out} = 1.5 m, l = 2 cm). The following sections will first present the current status for the innermost mirror module development and then present mechanical designs for MMs covering all radii.

2. INNER RADIUS MIRROR PLATE DESIGN

The innermost MMs have the smallest bending radius, the largest plate length and the largest wedge angle. All of these three extremes pose specific challenges to the design and manufacturing process and equipment. The current design of the innermost mirror plates is shown in Figure 2 together with a photo of a plate from the first manufacturing batch.

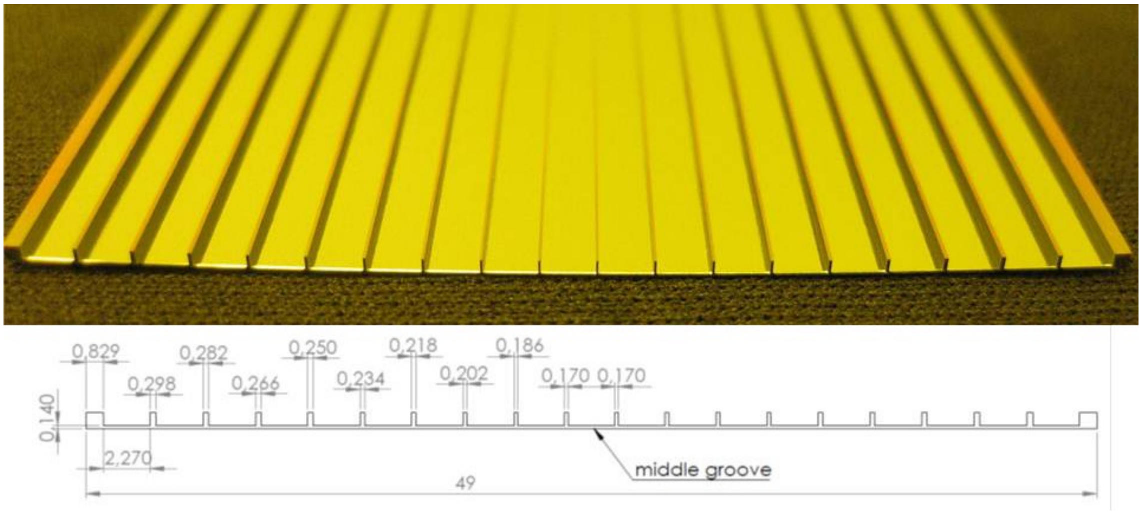


Figure 2: Inner mirror plate (radius 250 mm) with a width of 49 mm, large rib spacing (2.27 mm) and thinner membranes (140 µm thick mirrors). This mirror plate has been manufactured in preparation for the production of the first inner mirror module for Athena. The mirror plate production equipment was upgraded to maintain the good production yield despite the tighter requirements.

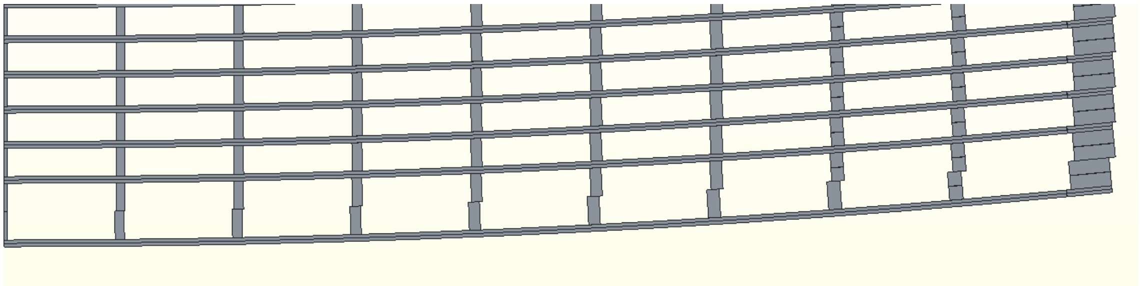


Figure 3: Drawing of the bottom, right part (base plate and first 5 mirror plates, right half only) of an inner radius stack. The centre ribs (left side of the illustration) are co-aligned while the ribs towards the outside (right side of the illustration) accumulate a significant offset.

The plate size is ultimately limited by the size of available double-side polished Silicon wafers with sufficient surface quality. Currently, 300 mm wafers offer the best quality and are sufficiently large to dice them into mirror plates with the required length of 11 mm. The width of the mirror plates is a free design parameter independent on the optical telescope design. But MMs with wider plates become more complex to manufacture, while MMs with less wider plates offer less effective area as a larger part of the telescope aperture is blocked by the mounting interfaces of the MMs. In general, plate widths of up to 10 cm are foreseen for the Athena telescope design. For the innermost radius, a width of 49 mm was selected as a baseline for the technology development. This allows for a cost-effective use of manufacturing 8 mirror plates from a single 300 mm wafer and to use existing metrology equipment for surface measurements. The effective area at 6 keV of a telescope layout with about 50 mm wide MMs for the innermost radii has been calculated to be 2540 cm² (including 10% loss allocated to manufacturing inaccuracies and contamination) which is compliant with the Athena requirement of 2500 cm². The effective area at 1 keV is dominated by the middle and outer radii and not affected significantly by the design of the inner radii. It is also noted, that the plate design now uses a pore size of 2.27 mm (instead of 0.83 mm of previous SPO MMs) which further helps increasing the effective area, especially off-axis.

The smaller bending radius for the innermost MMs leads to two design challenges. First, the bending moment induced by the elastic deformation of the plates scales with the power of $1/r$. Second, the ribs of the mirror plates are having a larger offset when being stacked on top of each other as is illustrated in Figure 3. This is specifically important for the (inverted) baseplate and the first mirror plate, where a sufficiently large contact area between the ribs is required to maintain a stable bonding.

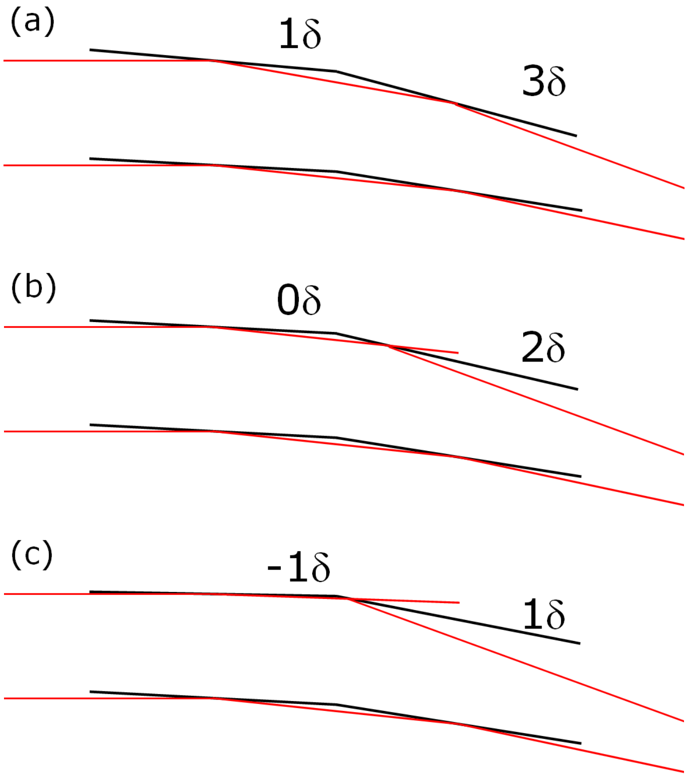


Figure 4: The effect of different wedge angles is illustrated for three configurations (a): 1/3, (b): 0/2, (c): -1/1. Two collimated beams (red) are each subject to two reflections on mirror surface pairs (black). The top pair of mirror surface is tilted by a different angle (an integer multiple of δ) with respect to the bottom mirror. The total relative deviation angle on the two beams is 4δ in all three cases. The figure is not to scale and highly exaggerates the angle δ which is a 3.3 arcsec for the Athena design. See text for a more detailed explanation.

The bending moment can be reduced by using a smaller mirror membrane thickness t. Manufacturing of first trial plates has demonstrated that the membrane thickness can be reduced from 170 µm (from previous projects) to 140 µm (current baseline for the inner MMs) without a strong impact on the process yield. As the bending moment scales with t^3, the impact of the design changes for the inner most modules leads to a (140^3 µm³ x 74 cm)/(170^3 µm³ x 25 cm) = 1.65 times higher bending moment compared to the previously built and tested MMs [8]. A further optimisation of the structural robustness is reached by increasing the width of the outermost end-ribs to about 0.8 mm (see also Figure 2 and 3).

The problem of increasing rib offsets can also be mitigated by adapting the rib width. A design with a variable rib size (small ribs in the plate centre and increasing ones towards the edges, see Figure 2 and 3) leads to a constant rib-to-rib bonding area. In the specific case of the 25 cm radius MM design, the rib width is increasing from 170 µm to 298 µm (excluding the outermost ribs).

The final design aspect of the innermost mirror plates discussed in this paper is the wedge angle. Each mirror plate within one stack needs to be inclined by a small angle δ with respect to the neighbouring ones in order to focus a collimated beam towards a common focal point. In a Wolter I mirror configuration, the two reflections are usually designed to have nearly equal grazing angles with respect to the mirror surfaces. For two plates (and using the conical approximation for simplicity), this leads to wedge angles of 1δ (3δ) for the first (second) mirror plate as illustrated in the top part (a) of Figure 4. We refer to this geometry as 1δ/3δ, or in short 1/3. The total correction of the reflection angle is 4δ. The wedging angle scales as $\delta \sim h/4f$, where h = 775 µm is the plate height (equal to the wafer thickness). With the wedge angle being constant over all MMs, the varying plate length results in a larger wedge height $h_w = l \tan\delta$ for the innermost MMs.

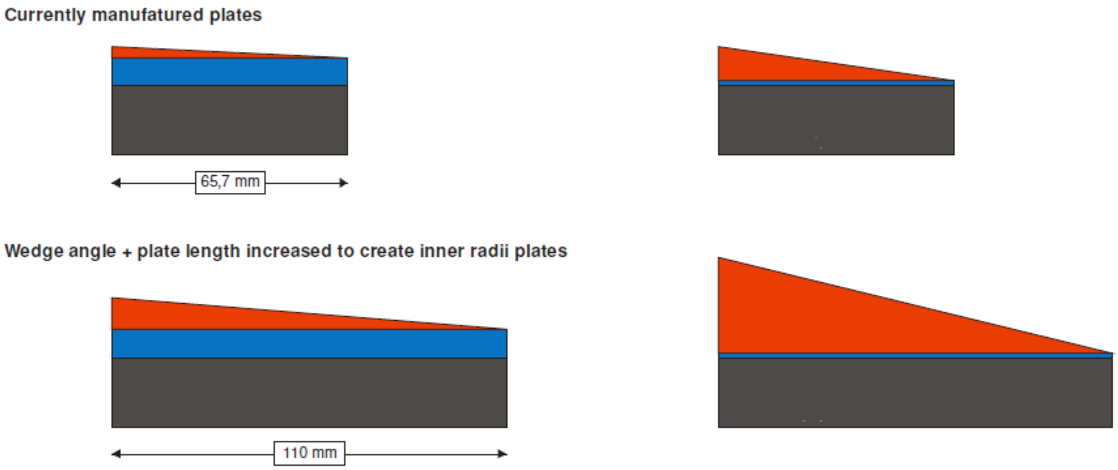


Figure 5: Different wedging configurations (not to scale) for middle radius MM plates and inner radius MM plates. The top, red triangles indicate the wedge (in the SiO2 layer), the middle, blue layer indicates the remaining SiO2 layer remaining on top of the Si wafer (grey, bottom part). 3δ plates for the inner radii (bottom right) would require a significant larger SiO2 layer as used so far. The -1/1 configuration would only need the 1δ plates as shown on the lower left side.

The wedge angle is manufactured into a SiO2 layer covering the Silicon wafers (see Figure 5). The commercial availability of wafers with SiO2 layers above 2 µm is very limited and therefore defines an upper end for the wedge height. For the Athena design configuration with $f = 12$ m the 3δ wedge of the secondary mirror plate would approach the limits of the available SiO2 thickness and an alternative solution is presented in the following.

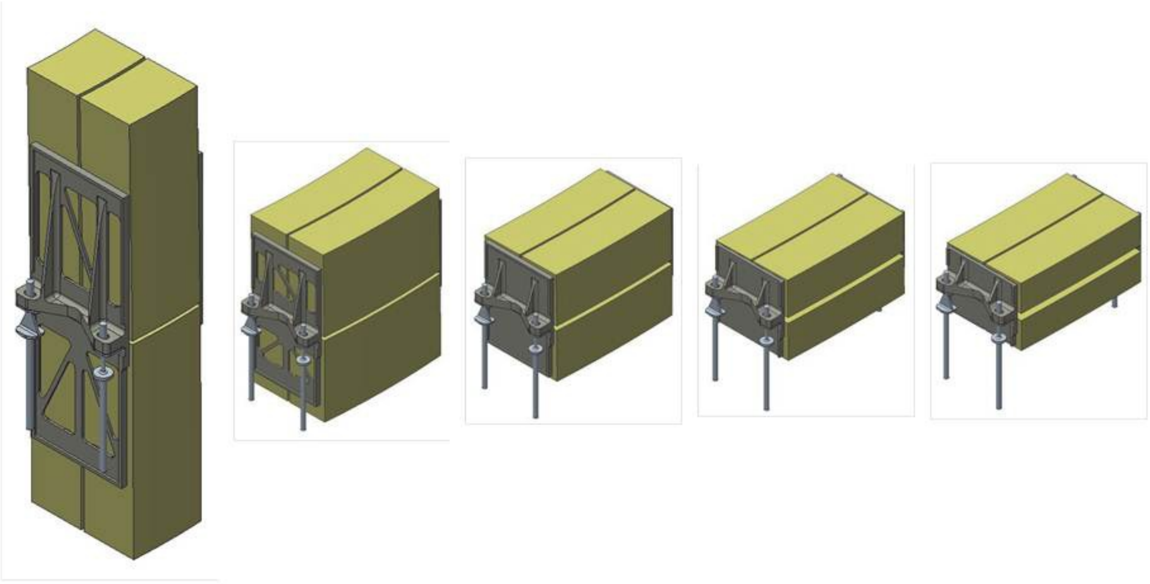
The 4δ correction can not only be achieved in the 1/3 configuration, but also with different wedge angles as long as the difference between the first and the second plate is always 2δ. Two more examples are illustrated in Figure 4. The middle part (b) shows a 0/2 configuration and the bottom part (c) a -1/1 configuration.

Only the 1/3 configuration is the optimal one from the point of view of minimizing aberrations. But other combinations are equivalent to rotating each plate slightly with respect to the ideal position: each plate is progressively more off-axis, but still focus properly. Monte Carlo simulations were performed to compare the standard configuration 1/3 with other configurations and no significant differences could be observed in the imaging quality. This is not a surprise as the HEW of the optics changes very slowly with off-axis angle for the first few arcmin. With a 0/2 wedging strategy each plate accumulates one wedge unit of off-axis angle, in this case about 3 arcsec. After 35 plates this amounts to 1.8 arcmin, not enough to have any significant impact on the angular resolution of the entire system. The -1/1 configuration is also possible, it simply means that the plates are rotated by two wedge units at each step, leading to a total of 3.4 arcmin for a stack of 35 plates.

Using the 0/2 or the -1/1 configuration significantly reduces the technical challenge of manufacturing larger wedge heights for the innermost MMs and even has several additional advantages. In case of the 0/2 configuration, the primary mirror plate does not require wedging at all, removing this process step for 50% of all mirror plates. In case of the -1/1 configuration, the plate design for the primary and secondary plates is identical, they are only used in different orientations when being stacked on top of the primary or secondary mandrels. Here, the number of different plate designs is reduced by 50%. The SPO development activities have selected the -1/1 configuration as the best baseline for the innermost radii but the same configuration is also evaluated for being used at other radii.

3. MIRROR MODULE MECHANICAL DESIGN

Previous activities have developed a mature design for the brackets and dowel pins for MMs with 20 m focal length at 0.74 m radius and environmental tests have qualified the mounting system design for the expected Athena vibration and thermal load cases [8]. The design has been adapted for the larger, heavier, innermost MMs, including detailed mechanical and thermal FEM analysis to demonstrate the compliance with the launch and operational environment. The inner MM design is shown in Figure 6 together with preliminary design extrapolations for other radial positions.



Row 01 Row 05 Row 10 Row 15 Row 20

Figure 6: Five examples of MM designs for radii ranging from 0.25 m (row 01) to 1.5 m (row 20).

Having a first set of more detailed MM designs is important to enable larger scale FEM analysis of all ~1000 MMs mounted into the mirror structure as part of the system studies. For this purpose, simplified models for all 20 different MMs were created, which include the basic geometry, mass, moments of inertia, eigenfrequencies, interface locations and thermal properties.

4. CONCLUSIONS

We have presented a new design for SPO mirror modules for inner radii. Smaller membrane thicknesses and larger, variable rib widths are used to optimise the structural stability of the stacks. A new wedge angle configuration reduces the height requirements for the SiO2 layer by a factor of 3 while also reducing the plate manufacturing cost. First batches of mirror plates have been manufactured to demonstrate the feasibility of all process step changes without reducing the yield. A first MM mounting system design for all different radii required for the 12 m Athena configuration was presented.

REFERENCES

[1] Ayre, M., “ATHENA – System design and implementation for a next generation X-ray telescope”, same proceedings (2015)
[2] ESA, [ATHENA: Assessment of an X-Ray Telescope for ESA Cosmic Vision Program], CDF-150(A), (2014)
[3] Bavdaz, M. et al, “Preparing the optics technology to observe the hot universe”, Proc. of SPIE Vol. 9144, 91442F (2014)
[4] Collon, M. et al, “Making the ATHENA optics using Silicon Pore Optics”, Proc. of SPIE Vol. 9144, 91442G (2014)
[5] Bavdaz, M. et al, “X-ray evolving universe spectroscopy mission (XEUS): x-ray mirror design and technology”, Proc. of SPIE Vol. 3766, 94 (1999)
[6] Bookbinder, J., “An overview of the IXO Observatory”, Proc. of SPIE Vol. 7732, 77321B (2010)
[7] Rando, N. et al., “Status of the ESA L1 mission candidate ATHENA”, Proc. of SPIE Vol. 8443, 844328 (2012)
[8] Wille, E. et al, “Qualification of Silicon Pore Optics”, Proc. of SPIE Vol. 9144, 91442H (2014)