The development of the mirror for the Athena x-ray mission

Collon, Maximilien J.; Abalo, Luis; Barrière, Nicolas M.; Bayerle, Alex; Castiglione, Luigi; Eenkhoorn, Noë; Girou, David; Günther, Ramses; Hauser, Enrico; Van Der Hoeven, Roy

Total number of authors:
45

Published in:
Proceedings of SPIE

Link to article, DOI:
10.1117/12.2689003

Publication date:
2023

Document Version
Publisher's PDF, also known as Version of record

Citation (APA):
Collon, M. J., Abalo, L., Barrière, N. M., Bayerle, A., Castiglione, L., Eenkhoorn, N., Girou, D., Günther, R., Hauser, E., Van Der Hoeven, R., Den Hollander, J., Jenkins, Y., Keek, L., Landgraf, B., Lassise, A., Okma, B., Da Silva Ribeiro, P., Rizzos, C., Thete, A., ... Phillips, G. (2023). The development of the mirror for the Athena x-ray mission. In K. Minoglou, N. Karafolas, & B. Cugny (Eds.), *Proceedings of SPIE: International Conference on Space Optics - ICSO 2022* (Vol. 12777). Article 127770R SPIE - International Society for Optical Engineering. https://doi.org/10.1117/12.2689003

The development of the mirror for the Athena X-ray mission

Maximilien Collon, Luis Abalo, Nicolas Barrière, Alex Bayerle, Luigi Castiglione, et al.

Maximilien Collon, Luis Abalo, Nicolas Barrière, Alex Bayerle, Luigi Castiglione, Noë Eenkhoorn, David Girou, Ramses Günther, Enrico Hauser, Roy van der Hoeven, Jasper den Hollander, Yvette Jenkins, Laurens Keek, Boris Landgraf, Adam Lassise, Ben Okma, Paulo da Silva Ribeiro, Chris Rizos, Aniket Thete, Giuseppe Vacanti, Sjoerd Verhoeckx, Mark Vervest, Roel Visser, Luc Voruz, Marcos Bavdaz, Eric Wille, Ivo Ferreira, Mark Olde Riekerink, Jeroen Haneveld, Arenda Koelewijn, Maurice Wijnperle, Jan-Joost Lankwarden, Bart Schurink, Ronald Start, Coen van Baren, Jan-Willem den Herder, Michael Krumrey, Dieter Skroblin, Vadim Burwitz, Sonny Massahi, Desirée della Monica Ferreira, Sara Svendsen, Finn Christensen, William Mundon, Gavin Phillips, "The development of the mirror for the Athena X-ray mission," Proc. SPIE 12777, International Conference on Space Optics — ICSO 2022, 127770R (12 July 2023); doi: 10.1117/12.2689003

Event: International Conference on Space Optics — ICSO 2022, 2022, Dubrovnik, Croatia

International Conference on Space Optics—ICSO 2022

Dubrovnik, Croatia

3–7 October 2022

Edited by Kyriaki Minoglou, Nikos Karafolas, and Bruno Cugny,

ICSO 2022
International Conference on Space Optics
3 – 7 October 2022 | Dubrovnik | Croatia
esa

The development of the mirror for the Athena X-ray mission

esa icso proceedings cnes

International Conference on Space Optics — ICSO 2022, edited by Kyriaki Minoglou, Nikos Karafolas,
Bruno Cugny, Proc. of SPIE Vol. 12777, 127770R · © 2023 ESA and CNES · 0277-786X · doi: 10.1117/12.2689003

The development of the mirror for the Athena X-ray mission

Maximilien J. Collon*[1], Luis Abalo[1], Nicolas M. Barrière[1], Alex Bayerle[1], Luigi Castiglione[1], Noë Eenkhoorn[1], David Girou[1], Ramses Günther[1], Enrico Hauser[1], Roy van der Hoeven[1], Jasper den Hollander[1], Yvette Jenkins[1], Laurens Keek[1], Boris Landgraf[1], Adam Lassise[1], Ben Okma[1], Paulo da Silva Ribeiro[1], Chris Rizos[1], Aniket Thete[1], Giuseppe Vacanti[1], Sjoerd Verhoeckx[1], Mark Vervest[1], Roel Visser[1], Luc Voruz[1],
Marcos Bavdaz[2], Eric Wille[2], Ivo Ferreira[2],
Mark Olde Riekerink[3], Jeroen Haneveld[3], Arenda Koelewijn[3], Maurice Wijnperle[3],
Jan-Joost Lankwarden[3], Bart Schurink[3], Ronald Start[3],
Coen van Baren[4], Jan-Willem den Herder[4,9],
Michael Krumrey[5], Dieter Skroblin[5],
Vadim Burwitz[6],
Sonny Massahi[7,10], Desirée della Monica Ferreira[7,10], Sara Svendsen[7], Finn E. Christensen[7,10],
William Mundon[8], Gavin Phillips[8]

[1] cosine, Warmonderweg 14, 2171 AH Sassenheim, The Netherlands
[2] European Space Agency, ESTEC, Keplerlaan 1, 2200 AG Noordwijk, The Netherlands
[3] Micronit B.V., Colosseum 15, 7521 PV Enschede, The Netherlands
[4] SRON, Niels Bohrweg 4, 2333 CA Leiden, The Netherlands
[5] Physikalisch-Technische Bundesanstalt (PTB), Abbestr. 2-12, 10587 Berlin, Germany
[6] MPI f. extraterrestrische Physik, Giessenbachstrasse 1, 85748 Garching, Germany
[7] DTU Space, Technical University of Denmark, Building 327, DK - 2800 Kgs. Lyngby, Denmark
[8] Teledyne imaging Ltd., 106 Waterhouse Lane, Chelmsford, Essex CM1 2QU, England
[9] Anton Pannekoek Institute, University of Amsterdam, 1090 GE Amsterdam, The Netherlands
[10] CHEXS, Diplomvej 373B, 2800 Kgs. Lyngby, Denmark

ABSTRACT

Athena is the European Space Agency's next flagship telescope, scheduled for launch in the 2030s. Its 2.5 m diameter mirror will be segmented and comprise more than 600 individual Silicon Pore Optics (SPO) mirror modules. Arranged in concentric annuli and following a Wolter-Schwartzschild design, the mirror modules are made of several tens of grazing incidence primary-secondary mirror pairs, each mirror made of silicon, coated to increase the effective area of the system, and shaped to bring the incoming photons to a common focus 12 m away. The mission aims to deliver a half-energy width of 5" and an effective area of about 1.4 m^2 at 1 keV.

We present the status of the optics technology, and illustrate recent X-ray results and the progress made on the environmental testing, manufacturing and assembly aspects of the optics.

Keywords: X-ray optics, X-ray astronomy, silicon, wafer, stack, pore optics, X-ray telescopes, ATHENA, ARCUS, SPO

1. INTRODUCTION

For the past 15 years, Silicon Pore Optics have been developed in order to support upcoming X-ray telescopes like Athena [1], a so-called L-class mission part of the European Space Agency Cosmic Vision 2020 program [2–6].

Athena needs a light-weight reflecting optic that can attain an angular resolution of 5", weigh less than 1000 kg and can deliver an effective area of about 1.4 m^2 at 1 keV [7]. Since no existing X-ray mirror technology can meet these

---

[1]* m.collon@cosine.nl

requirements [1], Silicon Pore Optics were created by the European Space Agency and partners, and have been under development for a number of years [8-18].

The assembly of the Athena mirror is a challenge not just from the point of view of the performance, but also for the sheer manufacturing effort: In fact the 2.5 m diameter mirror assembly will be segmented into 600 separate imaging elements (mirror modules) of 15 different geometries (one for each annulus), and require the manufacturing, handling and assembly of almost 10^5 silicon plates for a total of 300 m^2 of reflecting surfaces. All to be done in two to three years, at a pace compatible with the mission timeline.

The Mission Adoption Review (MAR), which was scheduled for late 2022, had prompted ESA, cosine, and its partners to step up their efforts to get the technology ready: in this paper we report the most recent results stemming from these activities. From the beginning the development of the optics has covered both the scientific and industrial aspects of the optics, with an iterative development that made it possible to identify and address criticalities at a very early stage and has led to a manageable list of residual risks that can be efficiently targeted.

2. MASS-PRODUCTION OF SILICON PORE OPTICS

The production steps of Silicon Pore Optics have been described in detail in [9] and are pictorially summarized in figure 1. The process has been consolidated and automatized at such a level that one is mostly left with process optimization steps to obtain the highest possible optical performance from the technology.

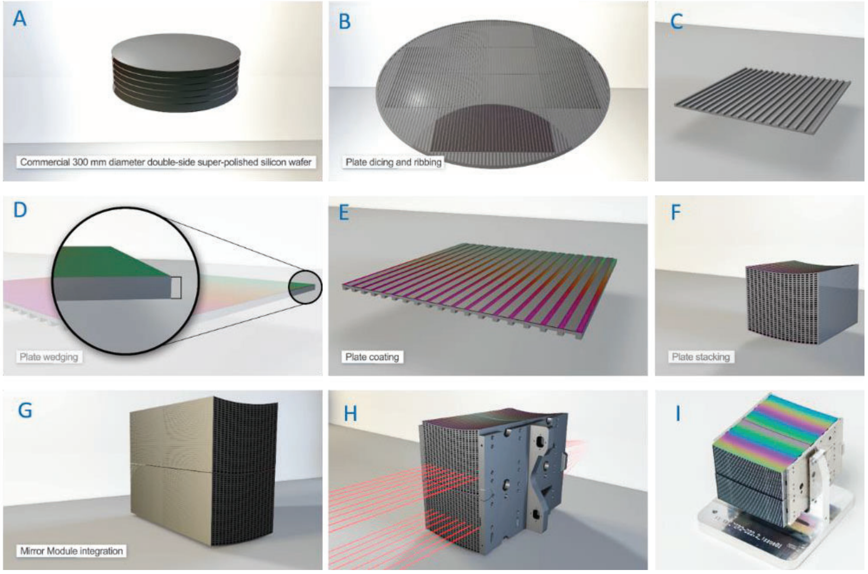

Figure 1: Production process of Silicon Pore Optics, starting with 300 mm silicon wafers (A). Those are ribbed and diced into plates (B, C), which are then wedged (D). The wedged plates are lithographically masked and coated (E) and subsequently stacked using automated stacking robots (F). Pairs of primary and secondary stacks (called X-ray Optic Unit, XOU) are co-aligned using X-rays and glued into two invar brackets (G, H), resulting in a completed mirror module (I).

Recent developments have led to the production of optics coated with iridium and carbon that have been shown to be able to withstand the chemical and optics assembly steps required for the mass production effort [19] (figure 2).

Once diced and ribbed, the SPO plates are assembled into a stack with an assembly robot. The stacks are then sent to laboratory of PTB at the synchrotron radiation facility BESSY II, where they are co-aligned and assembled at the XPBF 2.0 facility [20, 21] under active X-ray illumination into mirror module and bonded to brackets using glue [22]. The completed mirror module is then packed into dedicated containers and subjected to environmental testing before eventual integration in the optical bench.

All process steps up to stack level are now executed with the speed required to make it possible to assemble two mirror modules per day, as required by the Athena timeline. Pilot production runs are regularly performed to identify process variability and to exercise the production flow. Figure 3 shows an example of such a production run analysis, where the time required to complete 8 middle-radius SPO stacks was recorded. The robots required about 4.7 h to complete one stack, and with manual preparation and finalization steps an average time of 6.6 h per stack was achieved.

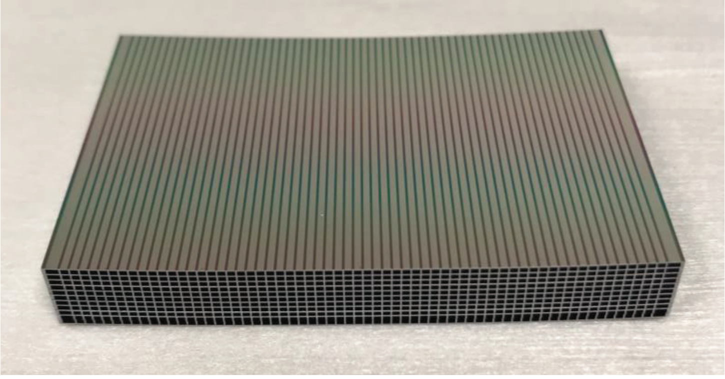

Figure 2: Patterned iridium coated and thermally annealed stack, as used for process control to measure the quality and stability of the coating, lift-off, cleaning, stacking and annealing process.

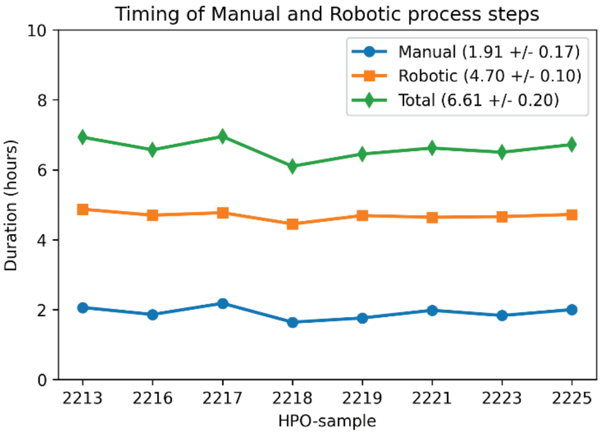

Figure 3: Pilot-production run of middle radius stacks using one stacking robot, showing manual, automated and total times for each of the 8 stacks (identified by their HPO number).

Some of the manual steps can be carried out simultaneously with the automated robot operations, which leads to us being able to produce two stacks per robot in a 12-hour shift, and with our complement of four robots achieve the target production rate of 8 SPO stacks per day: this was one of the aspects that needed to be demonstrated for the Athena MAR.

Besides working on the manufacturing aspects, progress has also been made on the optical quality of the optics. One of the goals to be achieved by the MAR was to show our ability to produce stacks of similar quality in a consistent manner. In figure 4 we show the evolution of the half-energy width (HEW) as a function of time, as measured in double reflection using 1 keV X-rays at the XPBF 2 facility, operated by PTB at the BESSY II synchrotron radiation facility in Berlin [21]. XOUs produced and measured in 2022 are all measured to be better than 10" over 100% of their mirror area. If one were to block the last 10 mm on each side of the optics (for a total of 30% of the 66 mm wide stacks the data refer to), one would achieve a HEW of about 7", as shown in figure 5 (independent measurements taken at the PANTER facility). For more details on these measurements see [23].

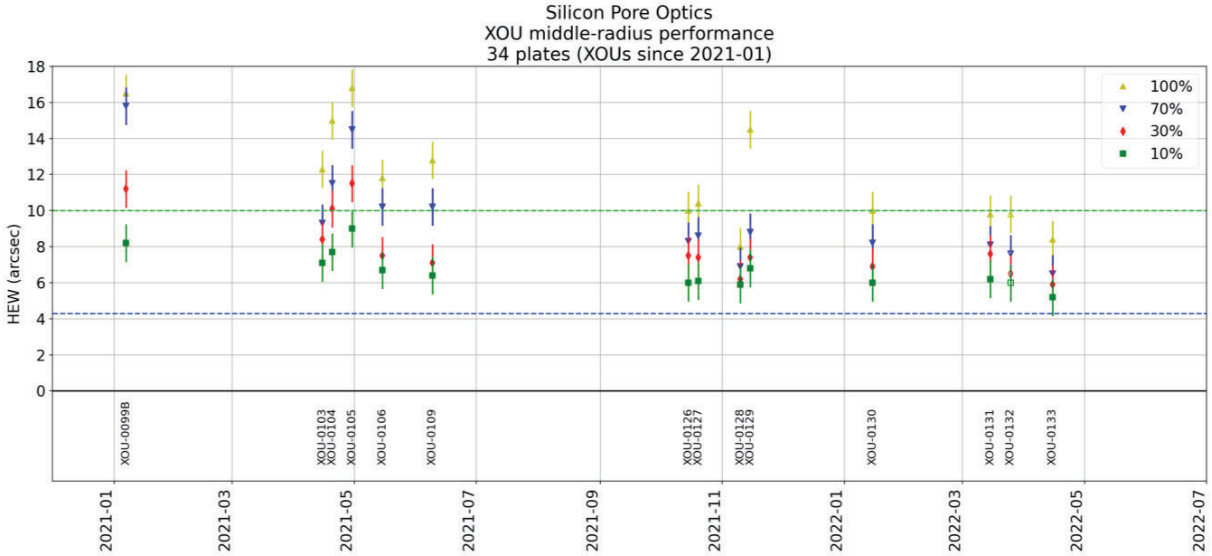

Figure 4: The time evolution of the quality (expressed as half-energy width) of uncoated middle radius (r ~ 740 mm, rib pitch 1 mm, membrane thickness 0.17 mm) stacks with a height of 34 plates, as measured in double reflection at an energy of 1 keV at the XPBF 2 facility, operated by PTB at the BESSY II synchrotron radiation facility in Berlin. An XOU is made of a primary and a secondary stack. The XOUs measured in 2022 have a HEW better than 10" over 100% of their mirror surface, with the central 70% area fraction being as good as 6.5". For information we also show the central 30% and 10% area fraction.

3. PERFORMANCE IMPROVEMENTS FOR THE ATHENA DESIGN

As reported earlier [9] we are in the process of transitioning the mirror plate and stack geometries from the development ones in use for a number of years to the those defined by ESA in the Athena nominal optical design. These changes, besides achieving a better packing of the available aperture, also improve the vignetting properties of the system through thinner mirror membrane (0.11 mm instead of 0.17 mm) and increased the rib spacing (2.37 mm instead of 1 mm). At a radius of about 750 mm (at the so-called row 8 of the 15 rows – or rings – in the nominal design) we have equipped two stacking robots and in 2021 we started developing what we call *stacking recipes* for this geometry.

One conclusion of the work done at the development geometries has been that the optical quality is affected by the thickness of the SiO_2 layer (about 600 nm) on the plates: this variable-thickness layer is required to make the reflecting surfaces in a stack gradually change their angle as required by the optical design.

One way to reduce the thickness of the oxide layer is to machine this slope directly into the silicon, dispensing with the need to create a thermal oxide layer that is then shaped by chemical etching: this can be achieved using Ion Beam Figuring (IBF). We have recently acquired a fully automated IBF machine that is able to do this on 300 mm wafers (figure 6). The machine is equipped with a wafer handler that can extract 300 mm wafers from their cassettes in a clean manner and move them into the processing chamber. The wafers are held by a chuck and then moved according to a predefined pattern in front of a tunable ion beam to achieve the desired thickness profile (see figure 7). The machine can automatically process 25 wafers per run (a standard cassette size in the semiconductor industry): depending on the amount of material to be removed processing one wafer can take between a few and several hours. Once a cassette is processed it is sent to the plate manufacturer, where the wafers enter the plate production chain described in figure 1 (obviously, this means that the chemical etching step in the process can now be removed).

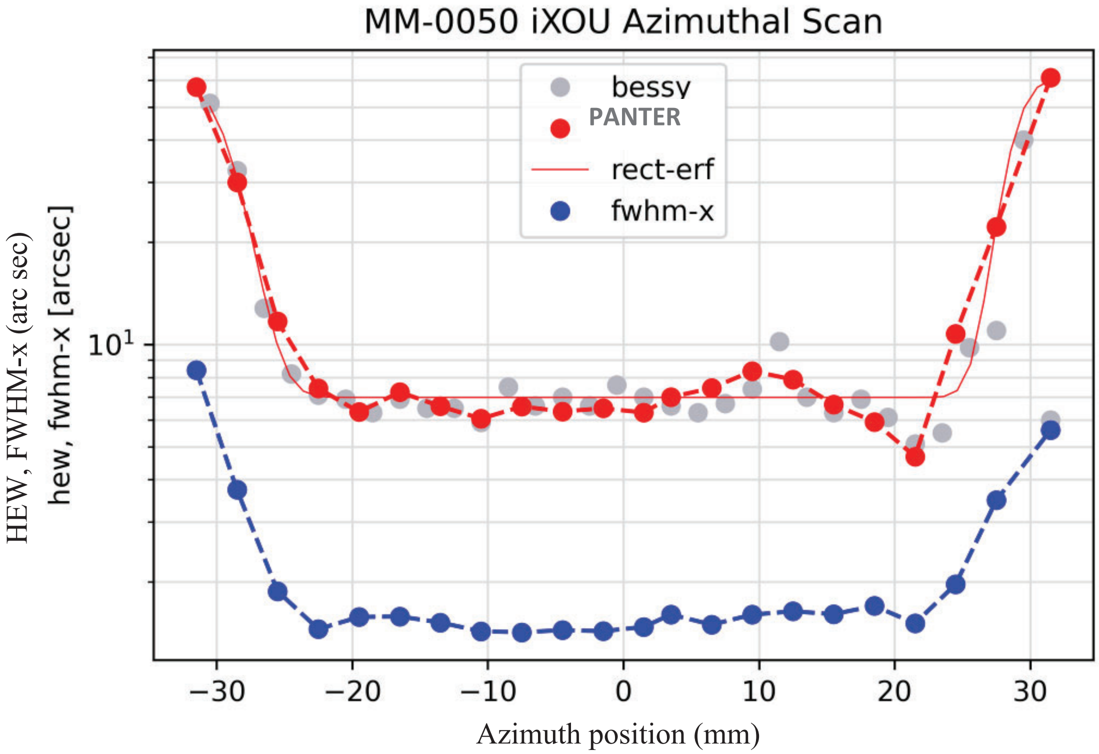

Figure 5: The HEW (including a fit) and Full-Width-at-Half-Maximum (FWHM) of XOU-0128 as measured at PANTER at an energy of 1.5 keV as a function of azimuthal position using a 3 mm wide slit mask. A HEW scan, using a 0.1 mm wide beam at the XPBF 2 facility of PTB at BESSYII is overlaid to show the good agreement between the measurements done at the two facilities. Reproduced from [23]. Note also the excellent angular resolution in the lateral direction, which is very beneficial for grating spectrometers, as were proposed for the ARCUS mission.

Figure 6: Ion Beam Figuring machine (left) including a fully automated wafer cassette loader (right), as recently installed at cosine.

Besides leading to a reduced oxide thickness, better stacks and a more uniform angular profile of the plates–all factors contributing to better optical performance–, the IBF process makes it possible to manufacture plates with more complex plate angle combinations that simulations show would lead to an increased effective area, especially at higher energies (> 6 keV).

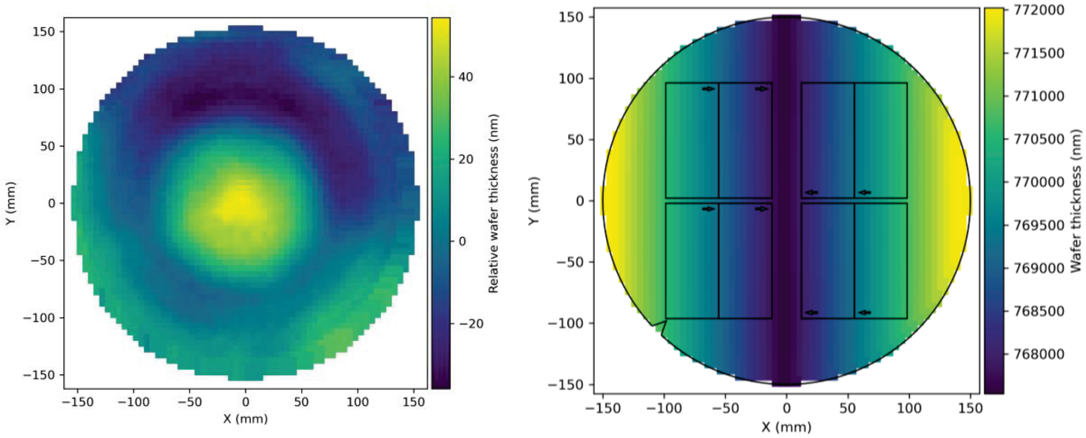

Figure 7: Relative height deviation map of a 300 mm wafer compared to its average thickness (left). Pattern for ion beam figuring the silicon wafer into wedged plates (right). Out of such a wafer 8 SPO plates with an identical wedge, but slightly different absolute thickness, can be cut.

4. COMPLETING THE SPO PRODUCTION CHAIN

Almost every SPO process step has been demonstrated with equipment installed on premises and used as intended for flight production. One of the steps, cutting the over-sized stacks to the final geometry using a laser has so far been only done on a demonstration machine at an external supplier. ESA has decided to procure a dedicated machine (see figure 8), which will be installed at cosine in December 2022.

Figure 8: Laser computer numerical controlled (CNC) machine to cut oversized stacks to size (left). BEATRIX beamline, as installed at BRERA (right).

Assembly of segmented X-ray optics requires the availability of a pencil beam X-ray beamline like the XPBF 2, at the BESSY II synchrotron radiation facility. The BESSY II synchrotron operates in a suitable configuration only for about half of the time, the remaining time being devoted to special operations, machine shifts and maintenance shut downs. In order to add redundancy to the assembly process, reduce risk and increase the available beam time, ESA has invested into the development of a new X-ray beamline, called MINERVA [24], at the ALBA synchrotron near Barcelona (Spain). The beamline is currently being constructed and we expect first light early 2023.

Finally, work is being done also on the acceptance testing process of the mirror modules. They will be assembled at either BESSY II or ALBA, and then transported back to cosine for environmental testing. The acceptance criterion will be that the on-axis point spread function, before and after environmental testing, remains the same, which can be efficiently tested with a full area illumination beamline such as BEATRIX, as developed by INAF. BEATRIX has seen first light in March 2022, using an SPO inner radius module as test object [25]. We will together with OAB start developing a copy of this beamline, termed BEATRX-2, to be installed at cosine after the Athena MAR, such that the complete production and testing rate of two mirror modules per day can be achieved.

5. CONCLUSION

Significant effort has gone in advancing all aspects of the Silicon Pore Optics technology for Athena, to bring it to the level required for the next mission milestone, the Mission Adoption Review. Progress has been made on the optical quality, the effective area, the industrialization of the processes, and the related testing and acceptance facilities. The SPO technology readiness has reached a TRL of about 6 and is ready for adoption. The mass production chain is in place with all process steps having been demonstrated on actual hardware.

The SPO performance is steadily improving, with the most recent optics modules (in the development geometry with 1 mm rib pitch and no coating) measured on 100% of their area better than 10" and on a large part of the optic better than 7" HEW. Iridium and Ir+C patterned coatings can be mass produced with high quality and we have started to test developing multi-layer coatings, to enhance the effective area at 7 keV.

The process optimization will continue, using the established process chain, including the transition to the nominal Athena geometries, a step that will increase both the effective area and the field of view that can be realized for the mission.

ACKNOWLEDGMENTS

We would like to acknowledge the excellent work of the many people and institutions that contribute to the development of Silicon Pore Optics and especially the contribution of the laboratory technicians of cosine. Without everybody’s efforts, dedication and talent we would not be able to build the lens required for the largest X-ray observatory to be flown so far. We also like to acknowledge the ESA, NWO (ATHENA, 184.034.002) and MPE funding that makes the development of SPO possible.

REFERENCES

[1] Bavdaz, M., et al., “ATHENA optics technology development”, these proceedings.
[2] K. Nandra, “ATHENA: Exploring the Hot and Energetic Universe”, Proc. American Astronomical Society HEAD meeting (#14), (2014).
[3] Ayre, M.. et al., “ATHENA: phase A study status and optics/instrument accommodation”, Proc. SPIE 11119, Optics for EUV, X-Ray, and Gamma-Ray Astronomy IX, 111190R (9 September 2019).
[4] Meidinger, N., et al, “The Wide Field Imager instrument for ATHENA”, Proc. SPIE 9905, Space Telescopes and Instrumentation 2016: Ultraviolet to Gamma Ray, 99052A (18 July 2016)
[5] Barret, D., et al, “The ATHENA X-ray Integral Field Unit (X-IFU), Proc. SPIE 10699, Space Telescopes and Instrumentation 2018: Ultraviolet to Gamma Ray, 106991G (31 July 2018)
[6] Ferreira, I., et al., “ATHENA reference telescope design and recent mission level consolidation”, these proceedings

[7] Willingale, R. et al, "Science requirements and optimization of the silicon pore optics design for the ATHENA mirror", Proc. of SPIE Vol. 9144, 91442E (2014)
[8] Vacanti, G., et al., “On the optical design of a large X-ray mirror based on silicon pore optics”, these proceedings
[9] Collon, M. et al, “X-ray mirror development and production for the Athena telescope”, Proc. SPIE 11852, International Conference on Space Optics — ICSO 2020, 118521Z (11 June 2021)
[10] Wille, E., et al, “Silicon pore optics manufacturing plan and schedule for ATHENA”, Proc. of SPIE Vol. 10699, 106993L (2018)
[11] Valsecchi, G., et al., “Facility for alignment, assembly, and integration of the SPO mirror modules onto the ATHENA telescope”, these proceedings
[12] Landgraf, B., et al, “Development and manufacturing of SPO X-ray mirrors”, Proc. SPIE 11119, Optics for EUV, X-Ray, and Gamma-Ray Astronomy IX, 111190E (30 October 2019).
[13] Massahi, S., et al, “Installation and commissioning of the silicon pore optics coatings facility for the ATHENA mission”, Proc. SPIE 11119, Optics for EUV, X-Ray, and Gamma-Ray Astronomy IX, 111190F (9 September 2019).
[14] Girou, D., et al, “Plasma etching for the compatibility of thin film metallic coatings and direct bonding of silicon pore optics”, Journal of Applied Physics. 128, 9, 7 p., 095302
[15] Massahi, S., et al., “The effect of deposition process parameters on thin film coatings for the ATHENA X-ray optics”, these proceedings
[16] Svendsen, S., et al., “Compatibility of iridium thin films with the silicon pore optics technology for ATHENA”, these proceedings
[17] Keek, L., et al, “Stacking of mirrors for silicon pore optics”, Proc. SPIE 11119, Optics for EUV, X-Ray, and Gamma-Ray Astronomy IX, 111190H (9 September 2019).
[18] Vacanti, G, et al., “X-ray testing of silicon pore optics”, Proc. SPIE 11119, Optics for EUV, X-Ray, and Gamma-Ray Astronomy IX, 111190I (9 September 2019).
[19] Svendsen, S., et al., “Characterisation of iridium and low-density bilayer coatings for the Athena optics”, these proceedings.
[20] Krumrey, M., et al, “New X-ray parallel beam facility XPBF 2.0 for the characterization of silicon pore optics”, Proc. SPIE 9905 (2016).
[21] Handick, Evelyn, et al, “Upgrade of the X-ray parallel beam facility XPBF 2.0 for characterization of silicon pore optics”, Proc. of SPIE Vol. 11444, 114444G (2020)
[22] Barrière, N. M., et al., “Assembly of confocal silicon pore optics mirror modules”, Proc. SPIE Vol. 11822, 1182208 (2021)
[23] Burwitz, V. et al., "X-ray testing ATHENA optics at PANTER", these proceedings.
[24] Heinis, D., et al, “X-ray facility for the characterization of the ATHENA mirror modules at the ALBA synchrotron”, Proc. of SPIE Vol. 11852, 1185222 (2021)
[25] Salmaso, B., et al., “X-ray tests of the ATHENA mirror modules in BEaTriX: from design to reality”, these proceedings.