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ABSTRACT

Silicon Pore Optics (SPO), developed at cosine with the European Space Agency (ESA) and several academic and industrial partners, provides lightweight, yet stiff, high-resolution x-ray optics. This technology enables ATHENA to reach an unprecedentedly large effective area in the 0.2 - 12 keV band with an angular resolution better than 5". After developing the technology for 50 m and 20 m focal length, this year has witnessed the first 12 m focal length mirror modules being produced. The technology development is also gaining momentum with three different radii under study: mirror modules for the inner radii ($R_{min} = 250$ mm), outer radii ($R_{max} = 1500$ mm) and middle radii ($R_{mid} = 737$ mm) are being developed in parallel.

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

1. INTRODUCTION

The development of SPO [1-25] has gained significant momentum with the adoption of ATHENA [26] as second L (large) mission of the ESA Cosmic Vision 2015-2025 program. ATHENA, currently under study in phase A [27], will be the largest X-ray observatory flown to date, with a ~3 m diameter X-ray lens [28] and two detectors, one to perform spatially-resolved high resolution spectroscopy (X-IFU) at cryogenic temperatures and a Wide Field Imager (WFI) to perform imaging spectroscopy.

The launch date of ATHENA is set to 2028, which requires a formal mission adoption in 2020. The adoption requires amongst other items the optics to reach a technology readiness level (TRL) of 6, which shall be demonstrated by building and testing a segment of the optic, populated with three types of SPO mirror modules. The test shall demonstrate that ATHENA can reach the required angular resolution of 5", and survive the harsh conditions of launch and operation. For this reason ESA had started several activities [30] that cover amongst others the development of SPO modules for three types of radii, as depicted in Figure 1.

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SPO development was focused in the last years on producing optic for a focal length of 20 m, a requirement stemming from earlier mission proposals. The year 2016 marked then the transition to the ATHENA focal length of 12 m, including the development of all the necessary parts and equipment to develop and produce mirror modules at three representative radii, as further described in this paper.

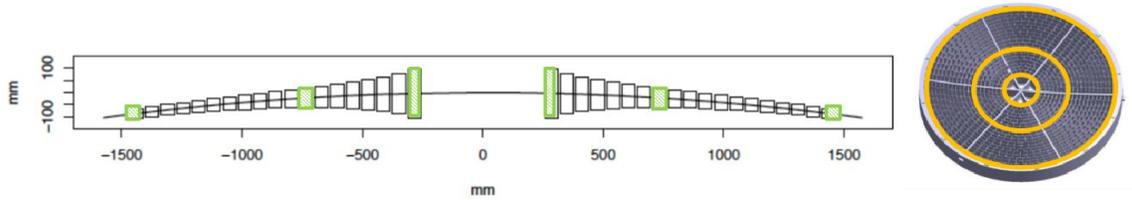


Figure 1. Cross section through the ATHENA optic (left). ATHENA optical bench as seen from the top (right). The radii for which SPO is being development are marked in green (left) and yellow (right). The innermost radius is 250 mm, the outermost 1500 mm and as middle radius we chose 737 mm.

2. PLATE DEVELOPMENT

The production capacity for making SPO plates has been increased by an order of magnitude to several thousand plates per year, to accommodate the demands of the different development activities. This required a review of all of the involved production processes, from wafer sourcing, over plate dicing, ribbing, coating to plate transport and inspection. The overall plate production process has already been described in [7].

As a result we have developed three types of wedged plates (see Figure 2), one per development radius, each of which demonstrates different plate production techniques:

1. Inner radius plates with a length of 110 mm and an azimuthal width of 49 mm. Those feature a rib spacing of 2.3 mm to demonstrate the possibility to increase the field of view. To reduce springback effects the plates have a membrane thickness of only 140 μm .
2. Middle radius plates with a length of 40 mm and a width of 66 mm. These plates are created by dicing already ribbed 66 x 66 mm² plates into a shorter length, to remove wedging artefacts.
3. Outer radius plates with a length of 21 mm and a width of 102 mm, which are created by dicing larger wedged plates into shorter segments. This is done to test increasing the production efficiency.

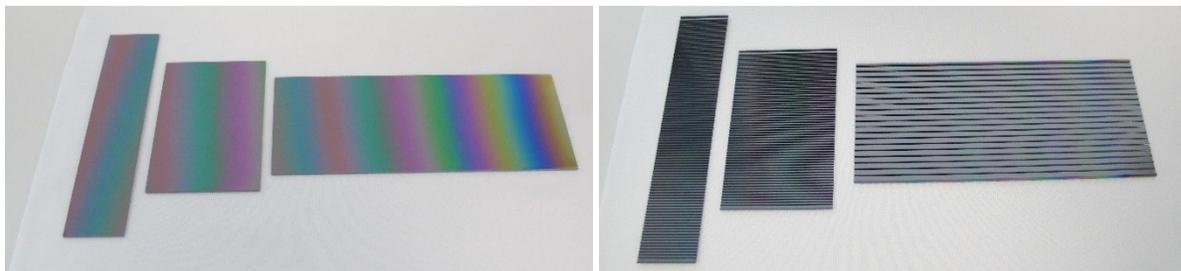


Figure 2. Three types of plates developed for the $f=12$ m SPO development. The left picture shows the reflective side, the right picture the ribbed side. In each picture the outer radius plate is left, middle radius plate is in the centre and the inner radius plate is on the right.

We have also upgraded the wet benches, dicing machines and lithography equipment to be able to handle large volume of plates. A second plate supplier is in the process of commissioning its plate production equipment and will start to deliver first wedged plates as of November 2017.

The larger number of plates to be processed also required an update of incoming inspection equipment, to automatically process the plate production measurement data (e.g. wedging profiles), measure the cleanliness of the plates, check their

dimensions and compare the results to newly defined acceptance/rejection criteria. Those criteria have been synchronized with the plate suppliers and ongoing work concerns the development of a total thickness variation measurement equipment for wedged plates, as so far we have been limited to measuring the thickness variation of the wedge itself.

To prepare plates for coating, a lithographic mask has to be applied. We have improved the deposition process in order to minimize any residual contamination left after lifting off the mask after coating. The coating process itself is based on magnetron sputtering of materials such as Ir and B₄C, where the development and optimization of the coating recipe is being performed by the Danish Technical University (DTU), as discussed elsewhere in this conference [29]. Together we have focused on selecting a coating machine large enough and suitable to coat up to 100.000 plates per year, in line with the requirements of the ATHENA mission. After a detailed trade-off a drum sputter coating system from a German supplier has been selected and ordered (Figure 3), which will be installed at cosine early 2018. It can coat up to 150 plates in one run, enough to make 4 stacks for a mirror module.



Figure 3. Schematics of the drum sputter coating system with the loading door removed, showing the carousel that moves carriers with SPO plates past three magnetrons. The chamber is about 2 m high, with a diameter of about 1.8 m and it can coat up to 100.000 plates per year.

3. STACKING PROCESS DEVELOPMENT

The stacking process has been described in detail elsewhere [21] and can be roughly summarized as follows: A set of plates is cleaned in a wet bench to remove particulate contamination and to activate them for bonding.

Then the cleaned plates are loaded into a dedicated stacking robot, which carries out the following sequential tasks:

1. Inspection of the cleanliness of each plate
2. Plate deposition
 - a. Only first plate: deposition of the first plate on a concave super-polished mandrel to provide the correct figure
 - b. All other plates: Pre-bending of the plate into a convex shape using a so-called die, then bonding onto previous plate
3. Figure measurement of each bonded plate using a fringe reflection technique

Steps 1-3 are repeated 35 times, until the stack is completed and it can be removed from the mandrel. In the following sub-chapters we describe the various development that were carried out recently.

3.1 Inner radius developments

The major difficulty to overcome was developing a pre-forming die that can adjust for the 118 μm difference in sag due to the curvature change when stacking 35 plates starting from a radius of 277 mm down to a radius of 250 mm. For this we have developed a novel die concept using so-called changeable heads, that can better pre-shape the plates into a convex conical form to facilitate the bonding step.

We also designed and procured a set of inner radii silicon mandrels from Carl-Zeiss, having the required conical shape to form a primary and secondary stack in approximation of a Wolter-I optics [30]. The secondary mandrel also has a meridional curvature in order to meet the angular resolution requirement at a focal length of 12 m.

All other parts required for an inner radius stacking robot were procured and installed and we commissioned the first inner radius stacking robot in September 2016. The stacking robot was then used to perform trial stacking in November 2016 and we achieved to produce a first ever conical stack of 35 plates (see Figure 4) with an innermost radius of curvature of 250 mm. While this stack demonstrated that we could successfully bond plates together at this small radius of curvature, it also highlighted a number of smaller issues that still need to be tackled, such as the cleanliness of the new mandrels, the speed at which we can exchange the die heads and the stacking of coated plates at this radius.

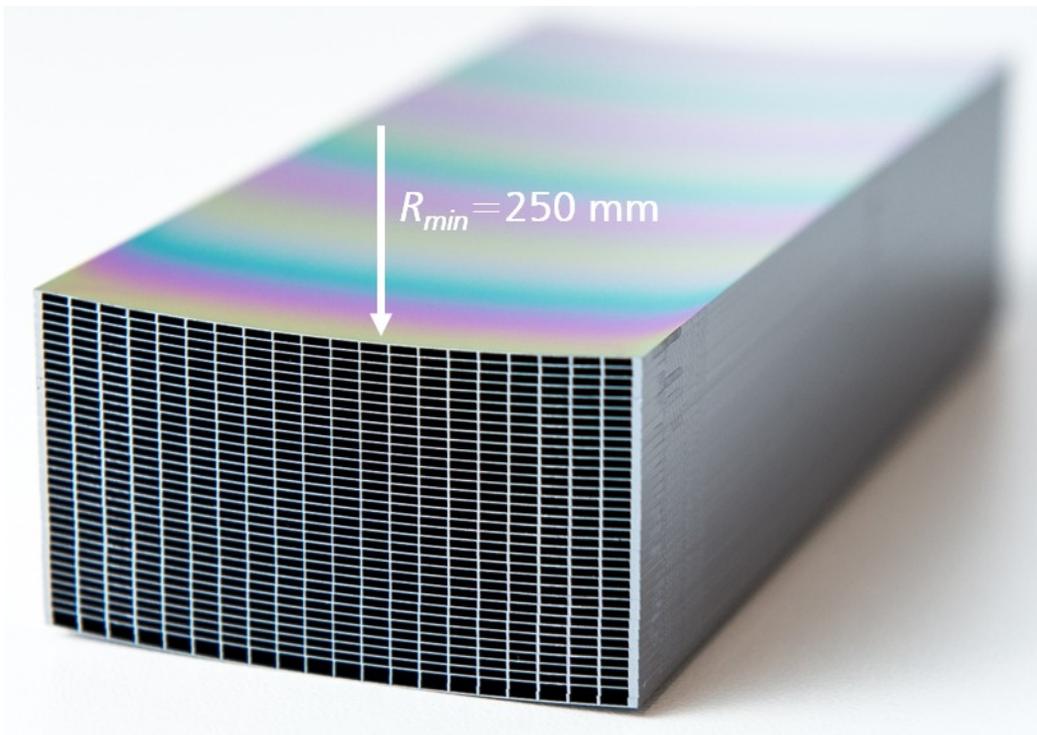


Figure 4. First ever inner radius stack of 35 plates, with an innermost radius of $R_{min} = 250$ mm.

We are now proceeding to manufacture several stacks that will be combined into a mirror module to be measured in x-rays in double reflection. For this step we have already developed the required set of mounting brackets and manufactured an assembly jig (see Figure 5), which allows gluing two pairs of primary-secondary stacks into two invar brackets, then forming a SPO mirror module. The process of gluing stacks into brackets has already been demonstrated several times at other focal lengths for middle radius stacks and is further discussed elsewhere in these proceedings [37].

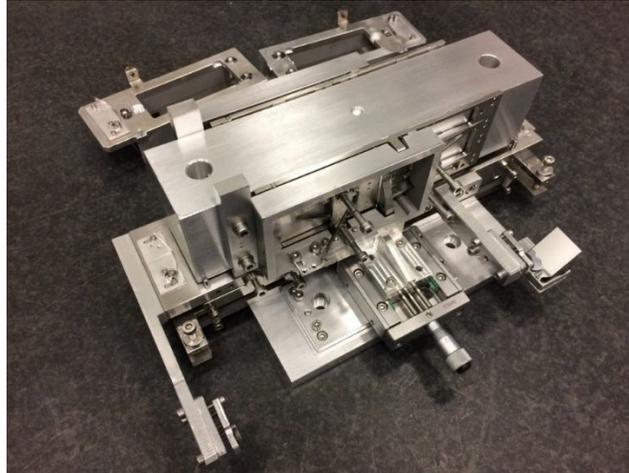


Figure 5. Inner radius mirror module assembly jig. Note that the large aluminum block in the centre between the two Invar brackets is only an alignment device for the calibration of the jig.

3.2 Middle radius developments

The $f = 20$ m middle radius stacking equipment has been the only stacking process development work-horse for several years. In July 2016 a pair of 20 plate stacks was measured in double reflection at the PANTER [35] test facility of the Max Plank Institut für extraterrestrische Physik (MPE). The point spread function (PSF) had a half-energy width (HEW) of $13.9''$ at 1.49 keV, with the central 60% of the width of the stacks having a HEW of $8''$ [21]. With these very promising results it was decided to transition to a focal length of 12 m, which started in September 2016 with the development of shorter wedged plates with a length of 40 mm. We decided to keep the width at 66 mm, in order to minimize changes to existing equipment. Nevertheless, the shorter length required the procurement of new mandrels from Carl-Zeiss and also of new dies. The $f = 20$ m stacking robot still used dies with vacuum suction to pre-form the plate. For the 12 m focal length we developed novel dies with electrostatic plate attachment. Those have a continuous surface, which improves the figure of a stacked plate closed to its edges. We also invested in the further industrialisation of the production equipment in order to increase the stacking speed from 45 minutes to less than 20 minutes per plate, which allows producing a stack within a single day.

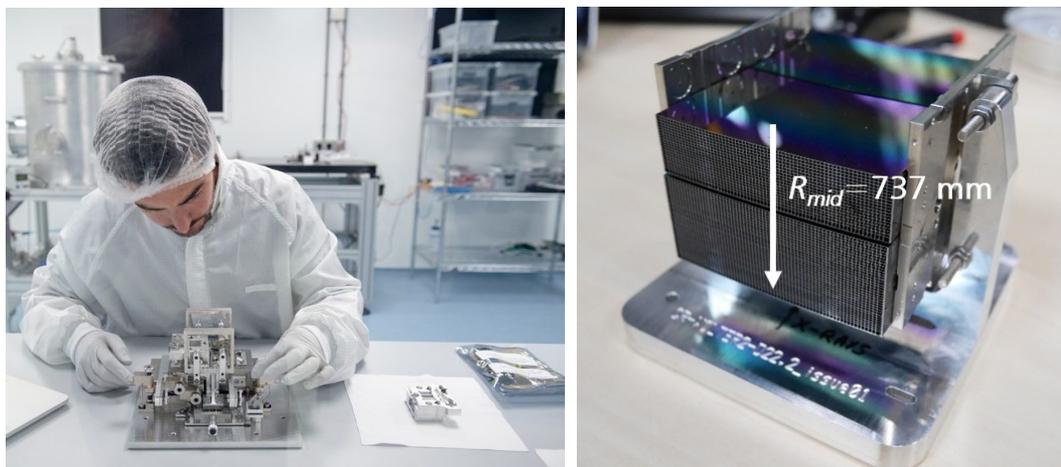


Figure 6. Left: Testing of the middle radius mirror module integration jig. Right: First ever $f = 12$ m middle radius mirror module.

In October 2016 two first pairs of 20 and 35 plate test stacks were fabricated to ensure the functionality of all new components. The stacking metrology indicated that these stacks would not yet yield a small PSF, as is to be expected when commissioning new equipment and having to adjust the process parameters first. The transversal width of the PSF however, important for mission proposals such as ARCUS [34], was measured at the NASA Marshall Straylight Test Facility (SLTF) in Huntsville to be 1.42" Full Width Half Maximum (FWHM) [34]. In combination with a Critical Angle Transmission (CAT) grating [32] a resolution of >2500 was achieved. To also test the new mirror module brackets and integration tools, it was decided to integrate the stacks at the XPBF 1.0 facility [23] of the Physikalisch-Technische Bundesanstalt (PTB) at the BESSY synchrotron radiation facility into a mirror module (see Figure 6).

With these very encouraging results we are now proceeding to tune the process parameters of the new stacking robot and to adjust the design of the electrostatic die in order to manufacture mirror modules that shall approach the goal of a 4.3" HEW. To this end, a larger number of tests stacks will be produced in the coming months and will be assembled into mirror modules, serving as test objects for other ESA activities [38, 39].

3.3 Outer radius developments

In June 2017 we have finished the assembly of the first stacking robot to make stacks for a focal length of 12 m with an outer radius of curvature of 1500 mm, bringing the total of active stacking robots to three. Similar to the inner and middle radius activities we had to develop new mandrels, dies, brackets and assembly jigs. Several smaller test stacks have been made (Figure 7) and the process of tuning the stacking parameters has started. We expect to make the first 35 plate stacks in the second half of 2017 and to produce the first mirror module in Q2/2018.

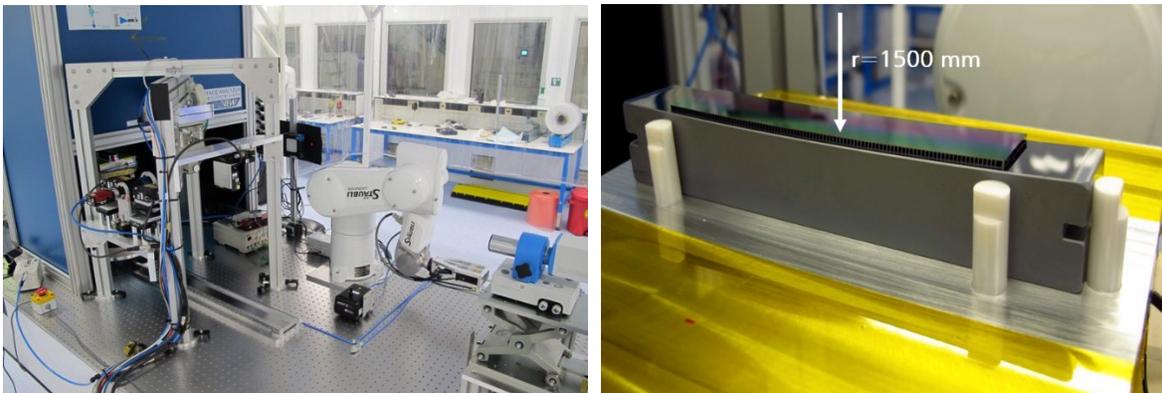


Figure 7. The outer radius ($R_{out} = 1500$ mm, $f = 12$ m) stacking robot is operational (left). The right picture shows the very first test stack of 2 plates, still on the mandrel.

4. CONCLUSIONS

The Silicon Pore Optics development is progressing and addressing all critical areas (resolution, production rates, environmental qualification) in parallel, according to the technology development plan of ESA. The transition from 20 m to 12 m focal length has been completed. Stacking robots for three different representative radii of ATHENA have been installed and have produced first stacks for inner, middle and outer radii, in a newly commissioned stacking facility. The stacking process development is ongoing for all three representative radii, together with a number of other activities that address the mirror modules integration in the mirror structure [38, 39], ruggedisation [33], simulation [25] and the coating [36] of the optics.

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