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Marcos Bavdaz[1], Eric Wille[1], Mark Ayre[1], Ivo Ferreira[1], Brian Shortt[1], Sebastiaan Fransen[1], Maximilien J. Collon[2], Giuseppe Vacanti[2], Nicolas M. Barrière[2], Boris Landgraf[2], David Girou[2,] Mark Olde Riekerink[3], Jeroen Haneveld[3], Ronald Start[3], Bart Schurink[3], Coen van Baren[4], Desiree Della Monica Ferreira[5], Sonny Massahi[5], Sara Svendsen[5], Finn Christensen[5], Michael Krumrey[6], Dieter Skroblin[6], Vadim Burwitz[7], Giovanni Pareschi[8], Bianca Salmaso[8], Alberto Moretti[8], Daniele Spiga[8], Stefano Basso[8], Giuseppe Valsecchi[9], Dervis Vernani[9], Paul Lupton[10], William Mundon[10], Ethan Dunnell [10], Mirko Riede[11], Tapio Korhonen[12], Mikko Pasanen[12], Alejandro Sanchez[13], Dominique Heinis[13], Carles Colldelram[13], Massimiliano Tordi[14], Norman Niewrzella[15], Richard Willingale[16]

[1] European Space Agency, ESTEC, Keplerlaan 1, PO Box 299, NL-2200 AG Noordwijk, The Netherlands
[2] cosine, Warmonderweg 14, 2171 AH Sassenheim, The Netherlands
[3] Micronit B.V., Colosseum 15, NL-7521 PV Enschede, The Netherlands
[4] SRON, Niels Bohrweg 4, 2333 CA Leiden, The Netherlands
[5] DTU Space, Elektrovej 328, 2800 Kgs Lyngby, Denmark
[6] Physikalisch-Technische Bundesanstalt (PTB), Abbestr. 2-12, D-10587 Berlin, Germany
[7] MPI für extraterrestrische Physik, Giessenbachstrasse, D-85748 Garching, Germany
[8] INAF Osservatorio Astronomico di Brera, Via E. Bianchi 46 I- 23807, Merate (LC), Italy
[9] Media Lario S.r.l., Località Pascolo, I-23842 Bosisio Parini (LC), Italy
[10] Teledyne imaging Ltd.,, 106 Waterhouse Lane, Chelmsford, Essex CM1 2QU, England
[11] Fraunhofer Institute for Material and Beam Technology, Winterbergstrasse 28, D-01277 Dresden, Germany
[12] Opteon Oy, Väisäläntie 20, FI-21500 Piikkiö, Finland
[13] ALBA Synchrotron, Carrer de la Llum 2-26, 08290, Cerdanyola del Vallès, Barcelona, Spain
[14] EIE Space Technologies Srl, Via Torino 151/A - 30172 Mestre-Venezia, Italy
[15] ZEISS Semiconductor Manufacturing Optics GmbH, Carl-Zeiss-Str. 22, D-73447 Oberkochen, Germany
[16] University of Leicester, University Road, Leicester, LE1 7RH, United Kingdom

ABSTRACT

The re-formulation phase of the next generation X-ray observatory ATHENA (Advanced Telescope for High ENergy Astrophysics) – now NewATHENA - is being utilised for further improvements of the optics technology. The Silicon Pore Optics (SPO) remains the technology of choice, since it uniquely combines a low mass, large effective area, and good angular resolution, addressing the challenge of the NewATHENA X-ray optics.

The performance and preparation for the cost-effective implementation of the flight optics is being further evolved in a joint effort by industry, research institutions and ESA. The SPO technology greatly benefits from investments in the semiconductor industry and maximises technology spin-in. Dedicated facilities have been and are being created to produce the required mirror plates, assemble them into stacks and mirror modules, integrate them into the complete telescope and measure the performance and compatibility with the NewATHENA technical and programmatic requirements.

An overview of the activities preparing the implementation of the NewATHENA optics is provided.

Keywords: X-ray optics, X-ray astronomy, ATHENA, NewATHENA, Silicon Pore Optics, X-ray telescopes, X-ray testing, Technology spin-in

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1. NewATHENA MISSION FORMULATION

NewATHENA is the result of a re-formulation of the ATHENA (Advanced Telescope for High ENergy Astrophysics) mission [1, 2], which was initiated in 2022, to reduce the total mission cost while preserving the scientific excellence. In less than one year substantial progress was made in a joint effort by the scientific community, the ESA Executive, and the national funding agencies, together with the international partners. Following a strict design-to-cost approach and optimising synergies a credible new mission baseline was established.

The main simplification and cost reduction of the mission was achieved with the introduction of passive V-grooves radiators to pre-cool the X-ray Integral Field Unit (XIFU) [3] cryostat. By reducing the outside temperature of the cryostat from room temperature to 50 K, the number of the required mechanical coolers and compressors could be drastically reduced. The cryostat becomes much smaller and simpler, and less expensive. Modifications to the Wide Field Imager (WFI) [4] also are required to respond to the reduced radiator area available due to the reconfiguration of its accommodation.

All aspects and elements of the mission have been subjected to this re-formulation, including, e.g., on-board metrology systems, time to point to a target of opportunity (ToO), Assembly, Integration & Verification (AIV) approach, reducing the field of regard, etc.

The optics have also been affected, essentially reducing the number of mirror module rows of the telescope, from 15 to 13, and the associated number of mirror modules from 600 to 492. All the remainder geometrical parameters of the optics remain unchanged. The technologies used remain the same, as do the design and geometry of the mirror modules, the approach to building the mirror assembly and aligning the optical elements, the focal length, the methods of baffling etc.

The technologies required for NewATHENA must reach Technology Readiness Level [5] (TRL) 5/6 before the mission adoption to secure a 9-year implementation. Also, the responsibility scheme must be solidly defined, and is currently being consolidated.

The performance requirements of NewATHENA have been re-defined, mainly by decreasing the energy resolution and number of pixels of the XIFU instrument, and requiring adjustments to the WFI instrument, and by accepting an angular resolution of 9 arcseconds Half-Energy Width (HEW). Figure 1 shows more details on the comparison of ATHENA and NewATHENA. The lower energy resolution leads to mission simplifications due to the reduced susceptibility to electromagnetic noise and micro-vibrations. The new angular resolution requirement relaxes the alignment budgets and reduces the programmatic risks.

NewATHENA remains a large spacecraft, about 14.6 m long with a mass of about 7 tons. Both the optics and the detector instruments are state-of-the art, out-performing previous missions significantly.

Another very important factor of the re-formulation of the mission is the requirement for NewATHENA to maintain the flagship character and provide the associated scientific measurement capability. A dedicated Science Re-definition Team (SRDT) was established, which is currently analysing the performance of NewATHENA and defining the new science objectives of the mission.

It is expected that the re-formulation and evaluation of the scientific performance will be soon progress sufficiently to allow a confirmation of NewATHENA as an element of the ESA Science Programme by the ESA Science Advisory Structure before the end of 2023, concluding the re-formulation phase.

In the following, the NewATHENA spacecraft detailed definition studies will be embarked on (parallel contracts), which will also elaborate detailed development and implementation plans, enabling the Mission Adoption Review (MAR) in late 2026. The instrument consortia will continue their developments and demonstrate the technological readiness, scientific performance, and maturity for the mission adoption, which is targeted early 2027.

The optics performance improvement process (angular resolution, coatings, etc), is being extended to late 2024, and will be followed by a pre-implementation phase until the adoption of the mission. This will prepare the flight model production and complete the facilities required for the production and verification of the NewATHENA optics.

Parameter	NewAthena	Athena
X-IFU telescope effective area	> 1.1 m^2 @ 1 keV	1.5 m^2 @ 1 keV
X-IFU Energy resolution requirement	< 4 eV	2.5 eV
X-IFU Field of view	> 4 arcmin	5 arcmin
X-IFU pixel size	5 arcsec (> 2300 pixels)	5” (3600 pixels)
WFI telescope effective area	> 1.1 m^2 @ 1 keV	1.5 m^2 @ 1 keV
WFI Field of View	TBD, comparable to old Athena	40’x 40’
Optics angular resolution (on axis HEW @ 1 keV)	< 9 arcsec	5 arcsec
Target of Opportunity (ToO) capability	Yes	Yes

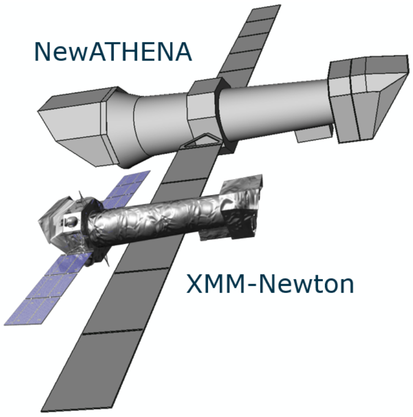

Figure 1: In 2022 ATHENA was found to be technically feasible, but its cost was forecast to be outside the planned budgetary envelope for ESA. A re-formulation phase was initiated, aiming at simplifying the mission, now named NewATHENA, which would comply to the programmatic constraints and at the same time remain a flagship science mission. In a joint effort by the scientific community, the ESA Member States, ESA and the international partner agencies (NASA and JAXA), a solution was found which satisfies these criteria. The main performance parameters are compared for NewATHENA and ATHENA. On the right, an illustration of the size of NewATHENA is shown, providing XMM-Newton as a reference.

2. SILICON PORE OPTICS

NewATHENA is made possible by the Silicon Pore Optics (SPO) technology [6-27], which remains the key technology being developed by ESA for this mission. SPO combines in an unprecedented way the ability to simultaneously deliver a large effective area and a good angular resolution while maintaining a low mass.

Figure 2 compares the performance of X-ray optics flown to date (red dots) [28-38], plotting the area density of the optics, expressed as effective area delivered for a given mass of the optics, as function of the angular resolving power, expressed as angular resolution elements per arcminute that the optics can resolve. The performance of the optics flown to date are clearly correlated, following a power law. Light optics (e.g., foil based X-ray optics, like HITOMI or NuSTAR) deliver large effective area at a low mass, but lack good angular resolution. Monolithic X-ray optics (like CHANDRA or ROSAT) feature an excellent angular resolution, but they are heavy and have a small effective area. Replicated optics (like XMM-Newton or eROSITA) are somewhere in the middle, trading angular resolution for more effective area.

None of the X-ray optics technologies flown to date can deliver what NewATHENA needs. In figure 2 the green dot indicated the NewATHENA requirement, which is decisively off the correlation line mentioned above. Essentially an order of magnitude better angular resolution is required compared to what could be delivered by the heritage technologies considering the available mass and the required effective area. Or alternatively, a prohibitive mass would be needed by the conventional technologies to deliver the required angular resolution and effective area demanded by NewATHENA.

The blue dot in figure 2 indicates the currently demonstrated performance of the SPO technology. The compliance with the effective area and mass requirements has already been achieved, and the angular resolution is very close to the target. The current technology developments are focusing on the further improvement of the angular resolution and the optimisation of the coatings.

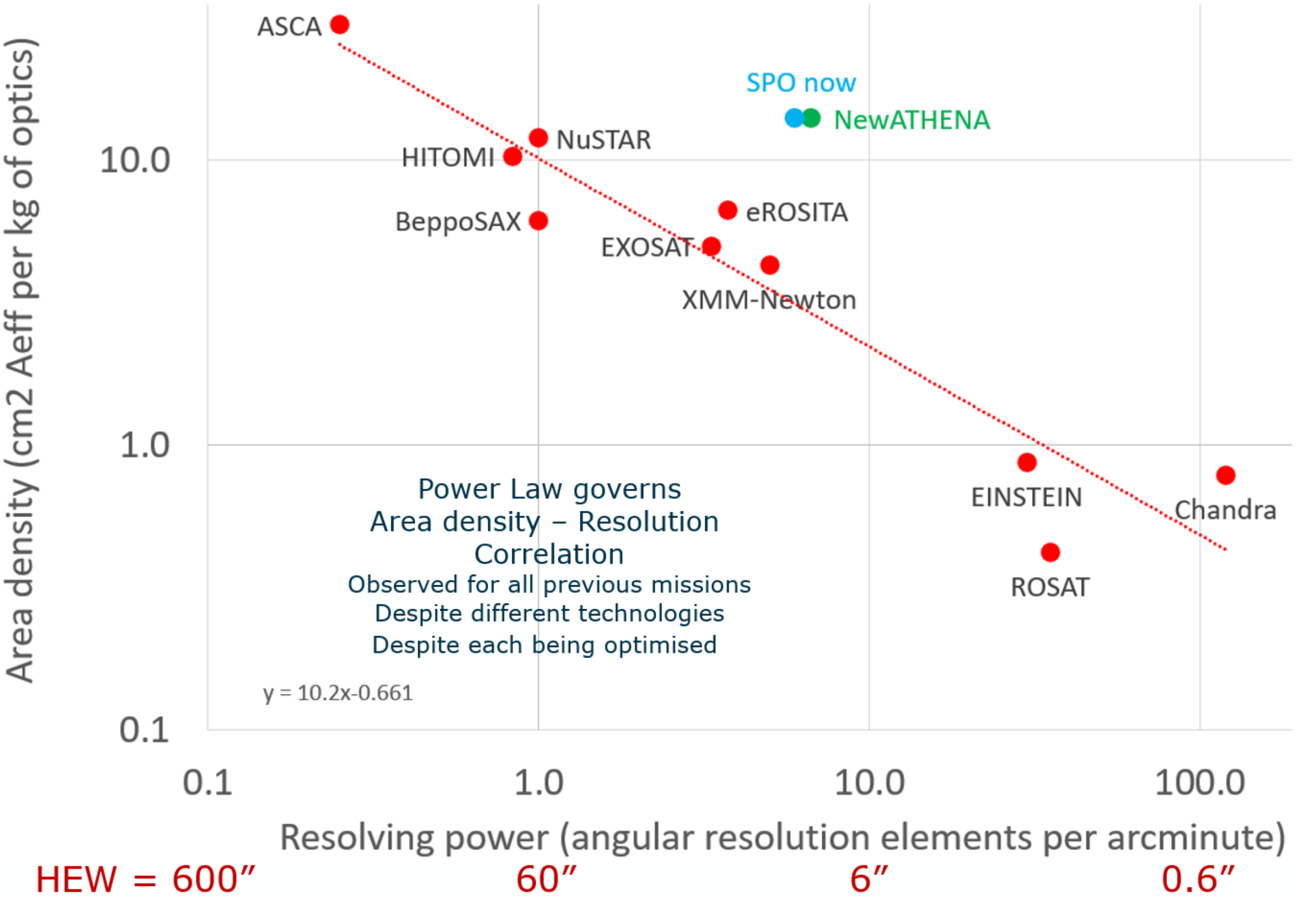

Figure 2: The Silicon Pore Optics (SPO) technology outperforms existing X-ray optics technologies by delivering a good angular resolution, low mass and large effective area in an unprecedented way. In this graph the area density as function of the angular resolving power is plotted. The demonstrated SPO area density is already fully compliant with the NewATHENA requirements, and the angular resolution is very close. Interestingly the performance of the technologies flown to date (red dots) nicely correlate, despite belonging to three different technology groups (foil, electroformed and monolithic optics). The SPO provides an order of magnitude better angular resolution for a given effective area and optics mass (blue dot: currently demonstrated, green dot: NewATHENA requirement). NewATHENA could not be built with any of the existing X-ray optics technologies.

The evolution of the angular resolution achieved over the past years with the SPO technology is shown in figure 3. The performance of X-ray Optical Units (XOUs) was measured at the XPBF beamlines in the laboratory of the Physikalisch-Technische Bundesanstalt at the BESSY II synchrotron radiation facility [39, 40], complemented by additional measurements at the long beam facility PANTER [41, 42]. Each XOU consists of two complete mirror stacks, as they will be used in the NewATHENA mirror, arranged in a Wolter-Schwarzschild configuration. In the current optimised configuration, each mirror stack for NewATHENA consists of 37(+1 base plate) mirror plates. The previous configuration assumed stacks consisting of 34 (+1 base plate) mirror plates.

The complete radial height of the optics was measured, and the complete azimuthal width (CAF100 dots). Also plotted are CAF70 dots, which represent the HEW measured over 70% of the contiguous optics azimuthal width. Note that the spread between the CAF100 and CAF70 HEW values is continuously reducing: this is due to the improvement of the optics uniformity with time, with the degraded left and right rims of the optics becoming steadily smaller.

Many different optimisations and tests were done in the course of time depicted in figure 3, which sometimes led to degradation of the performance. The last few XOUs are built to the NewATHENA specifications: higher stacks, wider rib spacing (2.4 mm) and thinner mirrors (0.11 mm – this is thinner than the envisaged thickness for the flight mirrors, which is 0.15 mm), and with coatings applied to the mirror plates.

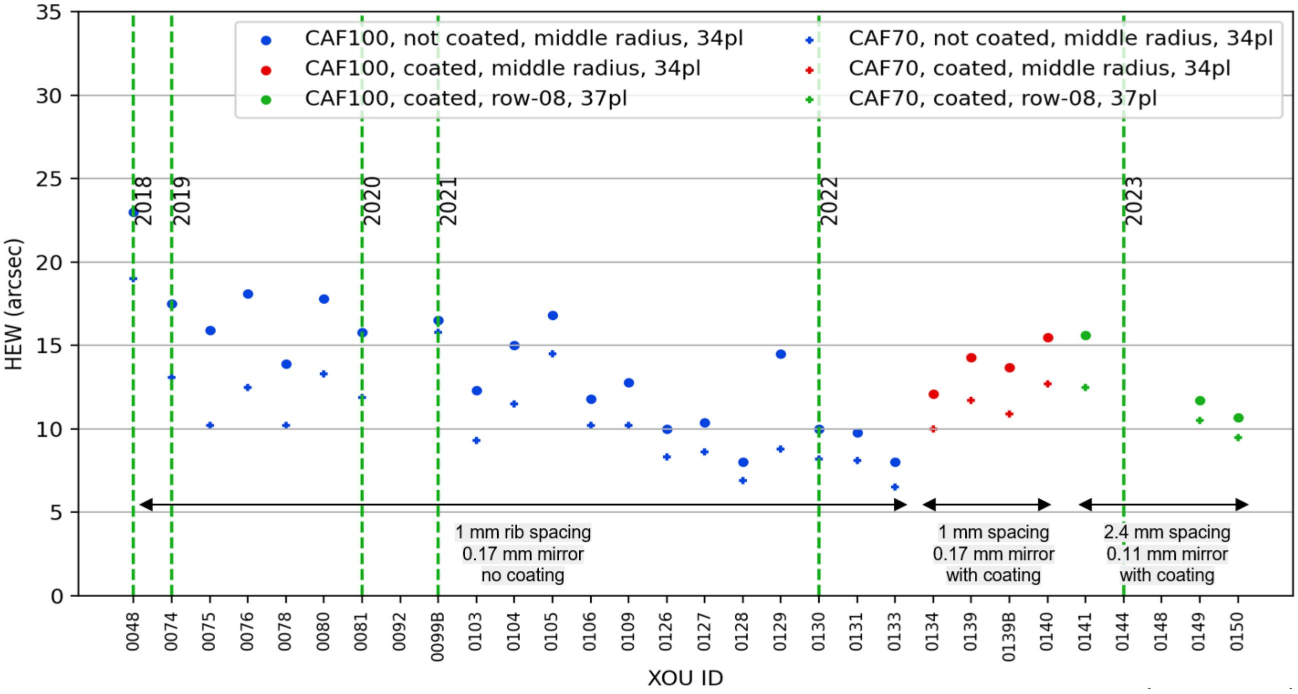

Figure 3: Demonstrated SPO angular resolution as a function of time. The performance of X-ray optical units (XOUs) as measured at synchrotron and long beam X-ray facilities is shown, covering the complete height of the mirror stacks, and 100% of the width (CAF100), and 70% of the width (CAF70). The optimisation of the SPO is an evolutionary process, with the optics configuration steadily approaching the mission configuration. The latest measured XOUs include the final mirror geometry and required coatings. The optimisation process is continuing, taking benefit of the expected delay of the mission adoption, and further improvements of the angular resolution may be expected.

The measured performance of XOUs gives confidence that the angular resolution will meet the requirements of NewATHENA by the time of adoption, i.e., the blue dot in figure 2 will move to the right, to the green dot position or even further. The SPO development will remain focused on the improvement of the angular resolution and the optimisation of the coatings, including multi-layers.

The effective area of the NewATHENA optics is plotted in figure 4, as function of X-ray energy, over the bandpass of covered by the instruments. The geometry and coating of the baseline NewATHENA optics design was used to generate the plot. The coating is a Chromium/Iridium/Carbon tri-layer on top of the Silicon/Silicon-dioxide of the mirror substrate. The effective area is compliant with the NewATHENA requirements.

Not only the compliance of the NewATHENA optics to the scientific requirements (effective area and angular resolution) and the mass allocation must be demonstrated before the mission adoption, but also the programmatic requirements: the NewATHENA optics must be built within budget and on schedule during the implementation phase.

Due to the holistic approach of the SPO development also the programmatic aspects have been considered carefully already in the design phase of this technology. It was always a priority, that the optics can be built on an industrial scale. The largest X-ray optics ever to be flown, the NewATHENA telescope demands a modular approach, with the large number of optical elements being produced by automatic machines, in a cost effective and predictable manner.

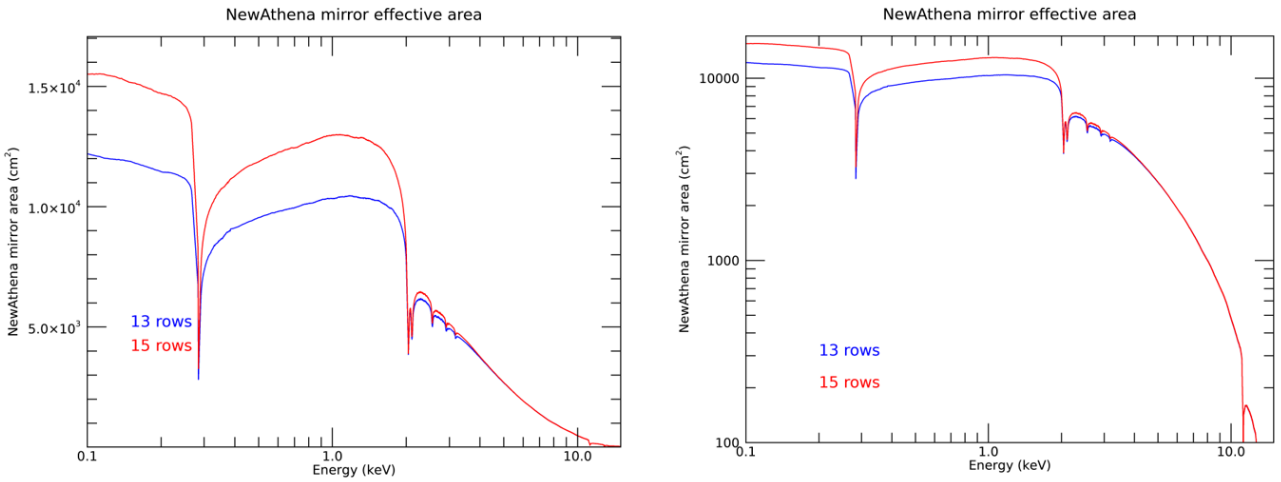

Figure 4: The effective area of the envisaged NewATHENA optics as a function of X-ray energy, shown for two configurations (expected 13 mirror module rows, and 15 rows), in lin/log (left), and log/log (right). The baseline mirror geometry and coating are used. Both configurations are compliant with the NewATHENA requirements.

The huge investments made by the semiconductor industry in materials, processes and equipment made it possible to create the SPO technology in such a short time, and within the available budget. The starting material for the SPO are latest generation silicon wafers, which are produced in large numbers at low cost, despite featuring exceptional qualities. The monocrystalline material is strong and has excellent thermal properties and can be processed with equipment made for fab houses producing the chips for telephones and computers.

The NewATHENA optics technology is therefore well prepared for the building of the flight telescope.

3. PREPARING TRANSITION INTO PRE-IMPLEMENTATION PHASE

The production of the SPO mirror modules is largely automated already, with a significant part of the equipment available today being ready to produce the flight model in the allocated time. Strict product and quality assurance (PA/QA) procedures are already in place, and the details of each production step are specified in software code, and process settings and measured parameters are digitally recorded. Although this may be unusual for the development phase, it has proven very advantageous in the complex optimisation process with many free parameters and has contributed to a high level of repeatability in the production of SPO mirror modules. To give one example of measures taken: each single mirror plate is laser engraved with a unique code, which is traced up to telescope level. This PA/QA approach will become essential in the flight implementation phase.

The SPO mirror module shown in figure 5 is made to the NewATHENA design, produced with equipment which will be later used to make the flight model optics. The mirror plates are manufactured with a high level of automation, resulting in a low cost – an important factor considering that 152 mirror plates are required for each of the 492 mirror modules forming the flight optics module of NewATHENA. Two mirror plate suppliers (Micronit BV in the Netherlands and Teledyne e2v in the United Kingdom) are available, and both are expected to contribute to the flight telescope. The mirror plates are assembled into stacks, a very critical operation, which defines the final figure of the mirror plates. This operation is performed by remotely controlled stacking robots located in cleanrooms at cosine B.V in the Netherlands. The mounting of each plate only requires 6 minutes, which is compliant with the flight model implementation schedule. The four stacks required for each mirror module have different geometries, therefore four stacking robots are required to ensure an efficient production; these four machines are already operational.

Figure 5: The NewATHENA optics consists of 492 SPO mirror modules, concentrically arranged in 13 rows; the figure shows a mirror module for the eighth row. The production processes used in the current development phase are largely the same as will be used for the flight implementation phase, ensuring a smooth transition between the phases. The actual mirror plates are only paper thin, 150 µm, and are fabricated with automated equipment spun-in from the semiconductor industry, starting with 300 mm diameter, 0.775 mm thick latest generation Silicon wafers. Each mirror module consists of four stacks of mirror plates, carefully aligned using synchrotron radiation to produce a single focus. The four stacking robots required to produce the mirror stacks for the flight implementation phase (about 2500 including spares etc) already exist.

The equipment and facilities for the SPO production required substantial space, and cosine B.V is completing the re-location to a new building, in preparation of the flight production phases, see figure 6. Major equipment, like the Van Ardenne coating machine (capable of coating the roughly hundred thousand mirror plates in two years), the Laser MicroJet (LMJ) machine used to trim the mirror stacks, and the Ion Beam Figuring (IBF) machine, are already operational in the new building. The clean room area available today is 900 m^2, which will be expanded to 2000 m^2 before mission adoption. All the environmental testing equipment is also located at the new cosine premises and is fully operational.

The mirror modules are assembled at synchrotron facilities, using a highly collimated X-ray beam. Currently a dedicated beamline at the BESSY II facility in Berlin, Germany, is used for this process, and two more will be installed for the flight production. As a risk mitigation measure to cope with unexpected and unplanned facility shutdowns, a new beamline was built up and is currently being commissioned at the ALBA synchrotron facility [43] near Barcelona, Spain, see figure 7. Operationally compatible with the BESSY II SPO beamline, it includes several upgrades, which will be tested until adoption of the mission, and likely be also implemented in the two future beamlines at BESSY II.

Figure 6: The main facility used to coat the mirror plates, assemble the parts of the SPO mirror modules and to environmentally test the optics are co-located at the premises of cosine B.V., located in Sassenheim, The Netherlands. Large cleanrooms required for the flight implementation phase have been installed, and major equipment like coating, laser cutting, and testing machines are already operational in the new building.

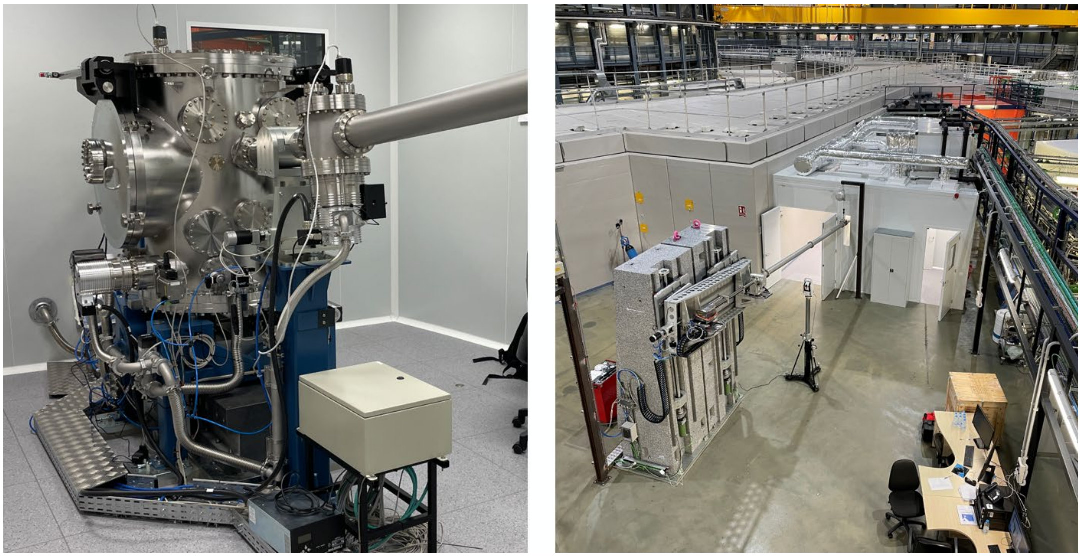

Figure 7: A new dedicated beamline had been built at the ALBA synchrotron radiation facility in Barcelona, Spain. Complementing the beamlines available at the BESSY II facility in Berlin, Germany, the risks associated with any unforeseen major event or shut down during the flight implementation phase are mitigated. The beamline is fully automatised and includes precision laser trackers for accurate positioning of the beam, optics, and focal plane detector.

Four beamlines will be required, since the precise alignment of the four stacks forming a mirror module requires an elaborated and time-consuming process. Each mirror stack is measured at hundreds of positions, and aligned using X-rays to arcsecond level, then mounted to the brackets serving also as interfaces to the optical bench of the telescope. Laser trackers are employed to ensure the correct geometry over the focal distance of the optics (12 m) and provide links between references in the vacuum environment of the beamline to external elements. Further automation and optimisation of the assembly process is foreseen until adoption.

The preparation of the flight model production is extending to the fabrication of the required stacking mandrels, which define the general figure of the mirror stacks. These mandrels are produced by Zeiss SMT in Oberkochen, Germany, and must follow an iterative process to achieve the necessary figure accuracy. Considering the high demand for the equipment required to make the mandrels and taking into account the large competition for laboratory space, it was decided to procure already now two dedicated polishing robots equipped with the proprietary Zeiss figuring heads, and a specific metrology machine. This equipment is now installed and is being commissioned (see figure 8) and will guarantee the timely production of the required mandrels, even in cases of contingency, e.g., a late need to modify the telescope detailed design requiring new mandrels.

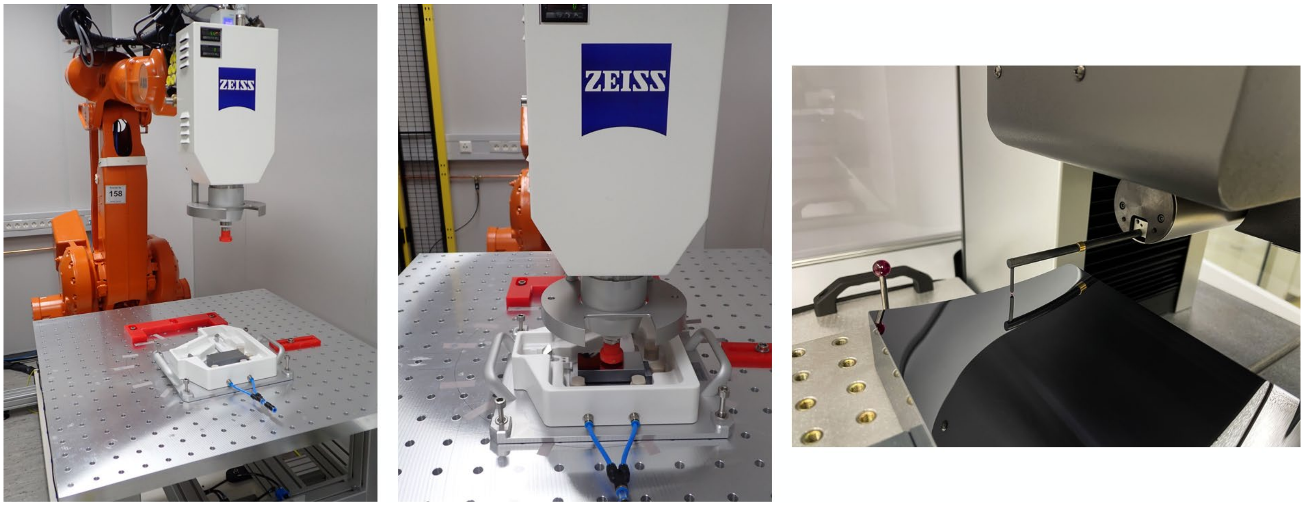

Figure 8: The timely production of the stacking mandrels during the flight implementation phase required early investment in the associated production and measurement equipment. Two polishing robots (one shown on the left) with proprietary polishing heads (middle picture) have been commissioned at the Zeiss SMT premisses in Oberkochen, Germany. A dedicated tactile surface measurement machine was also added.

Further developments are ongoing regarding the AIT facility [44, 45] at Medialario S.r.l., near Milan, Italy, which will be used to co-align all the mirror modules on the telescope optical bench (the Mirror Assembly Module, or MAM). The AIT process has already been demonstrated and currently the facility procurement is ongoing and the associated building to house the facility is being built.

The final verification of the NewATHENA optics cannot be done efficiently in any existing long beam facility. Due to the large diameter of the optics (more than 2 m) and the high angular resolution of the optics an excessively long beamline is required to be able to illuminate the complete optics without reverting to sub-aperturing. A new way was found to verify the performance of the assembled MAM, namely by producing a vertical collimated X-ray beam of limited size (few cm^2) and position this source on a positioning device able to scan the complete aperture of the NewATHENA optics. This facility is called VERT-X [46, 47] and its feasibility has been confirmed by studies. Currently the critical elements of this facility, the collimated X-ray source, and the scanning system, are being implemented.

Due to its complexity and the deep involvement of ESA in the development of the SPO technology, it is anticipated, that the production of the mirror modules will occur under direct contract with ESA. A suitable facility is required for the handover of the mirror modules to the spacecraft prime, who will also be responsible for the complete optics assembly, called MAM. An X-ray facility is required, which can measure the imaging performance of each mirror module in the allocated time. The Osservatorio Astronomico di Brera (OAB), located in Merate, Italy, has invented a new type of beamline, which uses asymmetrically cut crystals and reflective optics to produce a collimated X-ray beam large enough to illuminate a complete mirror module at a time. A first such a facility, called BEaTriX [48-51], was built up at OAB and first measurements with SPO mirror modules have been conducted successfully. It is being considered whether another such beamline will be required in the implementation phase.

4. TECHNOLOGICAL READINESS

As part of the preparations of the anticipated ATHENA MAR, a detailed Technology Readiness Assessment (TRA) of the SPO technology was performed in 2022. The TRA was completed at the time of the decision to re-formulater the mission, and remains valid also for NewATHENA. In areas found deficient for a MAR actions have been identified, which are now being implemented. A delta TRA will be conducted before the NewATHENA MAR.

The SPO TRA went into significant depth, and involved independent experts and required several co-location meeting with the contractors. The TRA covered the complete production and characterisation chain of the mirror modules, from components to the complete mirror module. Performance, PA/QA, compliance with programmatic factors etc have all been covered, and references have been established to the existing documentation to provide extensive information on the status of the technological readiness and its assessment.

Figure 9 illustrates the depth and width of the TRA exercise undertaken for the SPO technology. The TRA concentrated on the mirror module, and the the higher level elements will be covered by the MAR proper, in view of the deep involvement of the spacecraft system design and implementation.

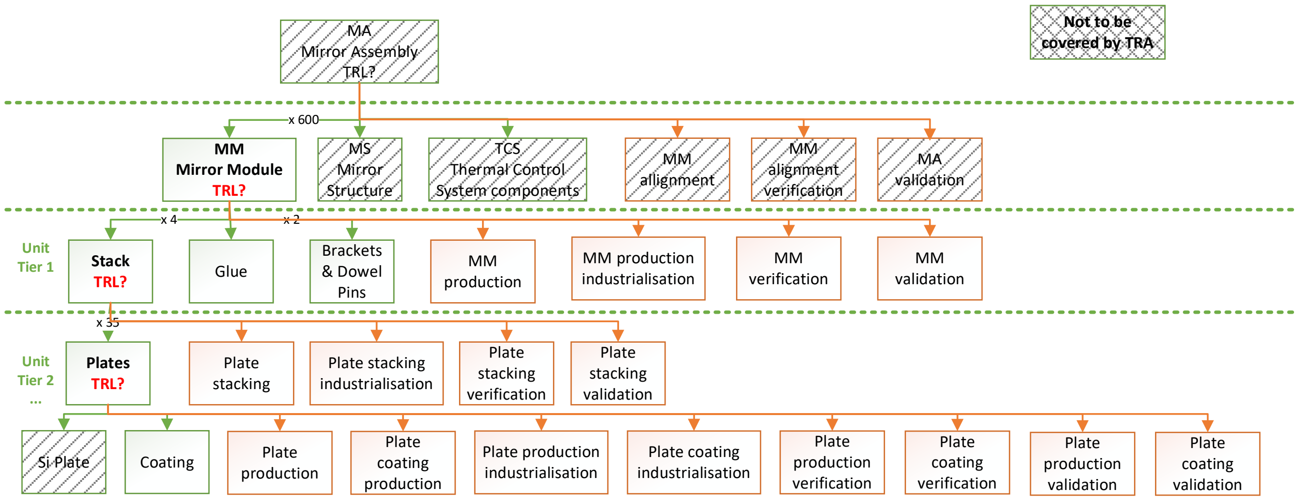

Figure 9: In preparation of the originally planned ATHENA Mission Adoption Review (MAR), a Technology Readiness Assessment (TRA) has been performed for the SPO technology, confirming the readiness of optics for the MAR. A very thorough process was followed, with an independent team investigating all aspects of the SPO mirror module technology. Any critical areas or risks identified are now being followed up with further technology development activities. It is expected that a delta-TRA will be conducted prior to the adoption of NewATHENA.

5. CALIBRATION APPROACH

The size and unprecedented sensitivity of NewATHENA calls for a new approach to the calibration of the optics. An end-to-end calibration is no longer practically feasible, in view of the complexity of the detector instruments and the size and resolution of the optics.

At the same time many more measurements are being taken throughout the fabrication of the optics, and all this data is carefully documented and logged. The process will be even further extended in the implementation phase and will provide a wealth of information on the detailed performance of the telescope. In addition characterisation facilities are being developed and built, specifically VERT-X and BEaTriX, which will provide data on the properties of mirror modules and the MAM.

A computer model of the NewATHENA optics has been built and is being further elaborated, which simulates the physical interactions taking place between the incoming X-ray photons and the mirrors and other parts of the telescope. The GEANT code developped at CERN is an important element of this simulator, and has been extended to the lower energies of interest for NewATHENA, and complemented with tools to ingest the metrology data gathered in the process of the making of the SPO optics to define the detailed characteristics of the real optics as built.

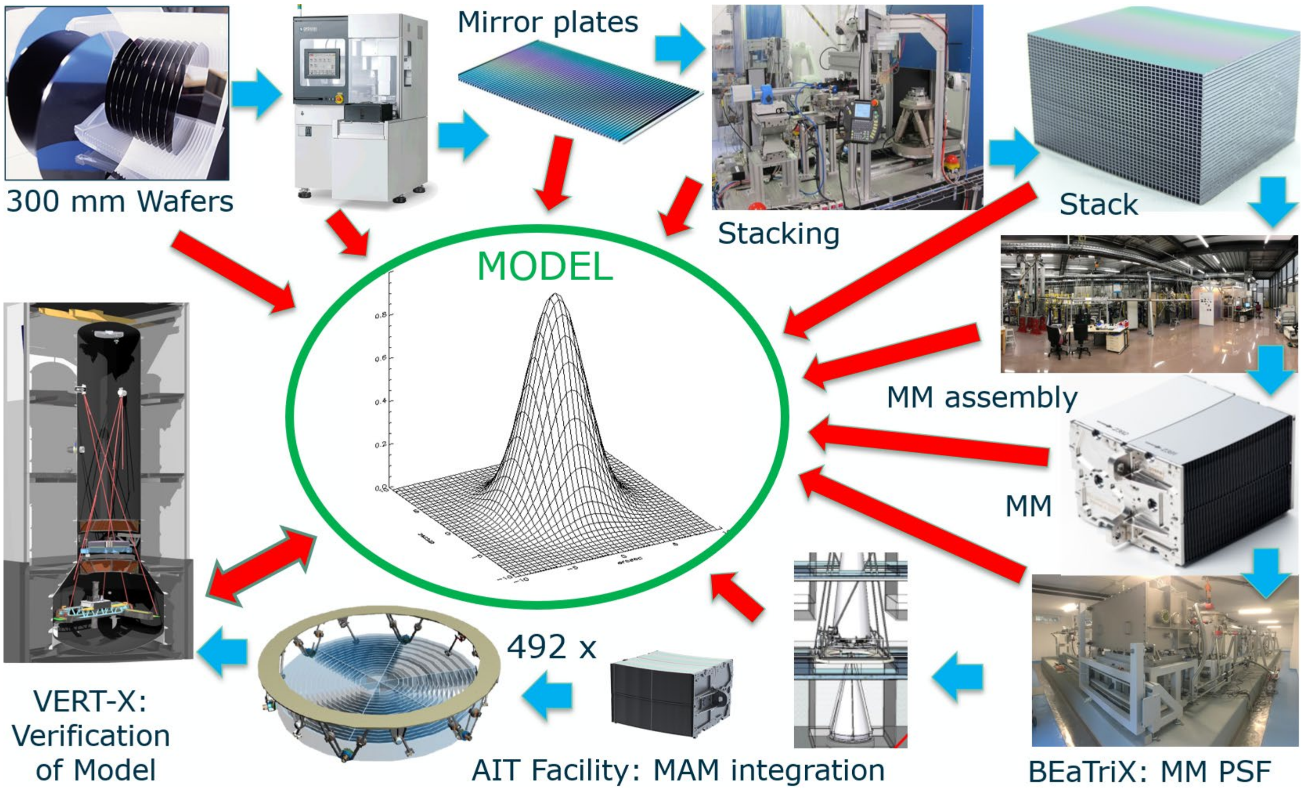

Figure 10: The calibration of the NewATHENA optics is relying on a novel approach, building a computer model of the telescope, which involves modelling of the physics and measured geometry of each mirror plate, and ingesting X-ray, metrology, etc data obtained in all the steps of the production of the optics. The predicted point spread function (PSF), symbolised in the middle of the figure, is calculated by tracing photons through the complete optics and considering the measurements taken at all the different facilities involved in the production of the optics (symbolised by the images on the periphery of the figure). The production of the optics follows the blue arrows, and information flow is illustrated with red arrows. The final validation of the model will be made using VERT-X.

This model based calibration tool (see figure 10 for a graphical representation) combines the available metrology and characterisation data obtained at many different facilities and generates predicted point spread functions and stray-light images etc for any desired configuration and input sources. These model predictions will be verified using the VERT-X, BEaTriX and PANTER facilities.

6. CONCLUSION

Silicon Pore Optics outperforms any of the X-ray optics technologies flown to date. It delivers the effective area while remaining within the mass allocation, and the measured angular resolution of coated X-ray optics elements demonstrates the capability to achieve NewATHENA needs to become the next generation space based high energy astrophysics observatory.

The development phase in which the performance of the SPO can be further optimised was extended by one year, taking benefit from the re-definition of ATHENA into NewATHENA, and the associated postponement of the mission adoption. In the following two years until the expected mission adoption the optics will enter a pre-implementation phase, covering early production of mirror modules and completion of the required facilities.

Due to the early decision in the SPO development to embark on an industrial approach to producing the optics, the transition into the implementation phase will be smooth and evolutionary. The equipment and facilities required for the complete production chain are largely already in place or are being implemented.

The SPO mirror modules are robust, and their production complies with the programmatic constraints of the mission (schedule and cost).

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