ESA Optics Technology Preparation for IXO

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ABSTRACT

The International X-ray Observatory (IXO) is a candidate mission in the ESA Space Science Programme Cosmic Visions 1525. IXO is being studied as a joint mission with NASA and JAXA.

The mission is building on novel optics technologies to achieve the required performance for this demanding astrophysics observatory. The European X-ray optics technology baseline is the Silicon Pore optics (SPO), which is being developed by an industrial consortium. In a phased approach the performance, environmental compatibility and industrial production aspects are being addressed. As a back-up technology ESA is also investigating slumped glass optics, which forms the baseline for the NASA approach.

The paper presents a summary of the ESA led optics technology preparation activities and the associated roadmap.

Keywords: IXO, High-energy Astrophysics, X-ray optics, Silicon Pore Optics

1. INTRODUCTION

The International X-ray Observatory (IXO) is a collaborative venture between NASA, ESA and JAXA. At ESA it is a candidate mission for a Large Mission (L-class) in the ESA Cosmic Visions 2015-2025 (CV1525) science programme. IXO resulted from the merger of the XEUS mission candidate and the studies done in the USA on the equivalent mission, the Constellation-X X-ray observatory concept [1 - 4].

A major science driver for the design of IXO is the large required effective area with a goal of 3 m^2 at 1.25keV, combined with the required angular resolution of 5 arc seconds half energy width (HEW) below 7 keV, together with the limited available mass allocation.

The ESA baseline for the IXO optics technology is the Silicon Pore Optics (SPO) [5 -14], which is characterised by a compact and rigid packaging of the X-ray mirrors into Mirror Modules (MM). The NASA baseline is to use Slumped Glass Optics (SGO) technology, which is also regarded as the backup for ESA [15-19].

2. SILICON PORE OPTICS (SPO)

The SPO solves the mass-area-resolution challenge, which IXO poses on the telescope optics, by introducing a new approach to mounting the X-ray mirrors into a matrix-like structure. The resulting MM are intrinsically very stiff and robust, keeping the figure of the mounted X-ray mirrors stable to the arc second level. Contrary to the established X-ray optics technologies, which use a limited number of interface points to attach the mirror optics elements to the support structure, the SPO technology relies on a much stronger inter-linkage of the X-ray mirror elements, as is illustrated in figure 1.

The second moment of inertia is strongly dependent on the effective thickness of the mirror membrane thickness. In the SPO MM the mirror element effective thickness is equivalent to the mirror plate pitch, since the separating ribs are an integral part of the mirror elements. This increased stiffness of the individual mirror plates significantly simplify the handling of the mirror plates before and during the assembly into Mirror Modules (MMs).

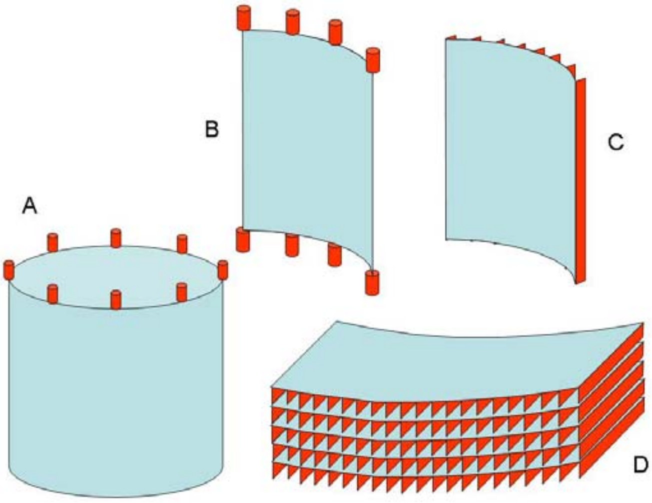

Figure 1: (A) and (B): Traditionally X-ray optics rely on holding the individual X-ray mirror elements at a limited number of points. Accordingly, the free span of the optics elements between suspension locations is rather large, typically of the order of centimetres up to several decimetres. (C): The optical elements of the SPO are very stiff in the critical direction parallel to the optical axis (longitudinally), whilst being very thin and lightweight. The stiffness is provided by ribs at the back of the mirror membranes. (D): These ribs interlink the optical mirror elements in a dense pattern, resulting in a matrix-like structure of the SPO.

The individual mirror plates are assembled into a matrix-like structure, whereby the ribs of a mirror plate bond to the surface of the preceding mirror plate (see figure 1 (D)). The individual mirror plates are fused with each other, forming a monolithic structure, formed completely of mono-crystalline silicon (see figure 2, left). These mirror plate stacks are therefore very rigid. Each mirror plate in the stack is slightly inclined to the previous one, as required for the Wolter geometry of the telescope design.

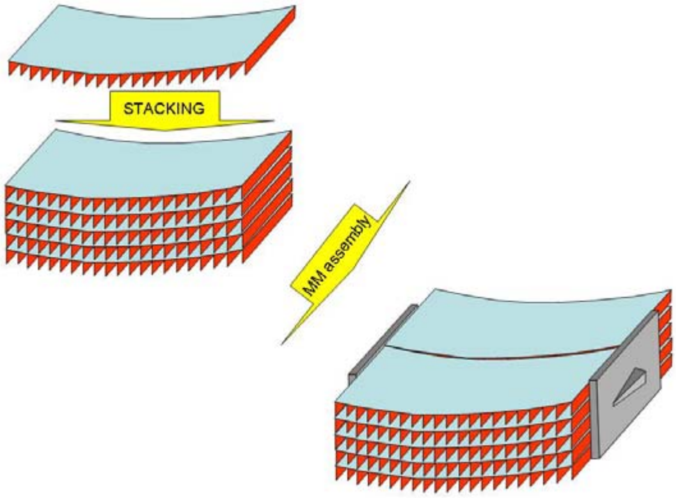

Figure 2: Mirror plates are stacked and bonded together to form monolithic blocks of mounted mirror plates. Two such stacks are then assembled into the Mirror Module(MM), employing two brackets. The MM provide attachment points for the isostatic mounting to the telescope structure.

Two such mirror plate stacks are then assembled to a Mirror Module, using two brackets. These brackets solidly connect the two stacks and also provide the interfaces for the isostatic mounting to the telescope structure.

The production processes, equipment and materials used to build SPO Mirror Modules are largely inherited from the electronics industry. Latest generation doubly polished 300 mm wafers already feature the super-polished finish required for X-ray optics reflectors. By mechanical and chemical processes derived from industrial standards, the mirror plates are cut and structured. The number of Mirror Modules required for IXO was always kept in mind when developing the SPO technology and the associated equipment. An important factor is the compact size of the SPO Mirror Modules, requiring only table-top production and metrology equipment and limited clean-room space.

3. THE SILICON PORE OPTICS STATUS

Focused developments have been undertaken to address the challenging requirements for the optics concerning angular resolution, effective area density, feasibility of the required mass production, compatibility with the environmental specifications, and an accurate mounting system. At present the SPO technology already fulfils many of the IXO requirements and is constantly approaching the remaining ones.

The full production process for SPO has been demonstrated. Mirror plates are being produced, including dicing the pores, angular wedging, masking and coating, cleaning and packaging. All required equipment is in place and builds on investments from the semiconductor industry, which ensures that future fully automated mass production is possible. This also includes the modifications that where developed in order to solve SPO specific requirements.

Stacking of the mirror plates is currently done with the 2nd generation stacking robot. A stack with the required height of 45 plates, as baselined for the IXO telescope, is shown in Fig. 3. While the past technology developments demonstrated stacks with a radius of 2 m (as was required for XEUS), the 3rd generation stacking robot (currently under construction) will produce stacks with a radius of ~0.7 m. The feasibility of producing stacks with radii of down to 0.25 m is well understood by FEM models and was recently proven by manually bending and bonding mirror plates with the inner radius of IXO as shown in Fig. 4. This proves that SPO Mirror Modules can be produced for radii covering and extending the complete range required for IXO.

Figure 3: SPO mirror plate stack, consisting of 45 bonded mirror plates, as required for the IXO telescope baseline design.

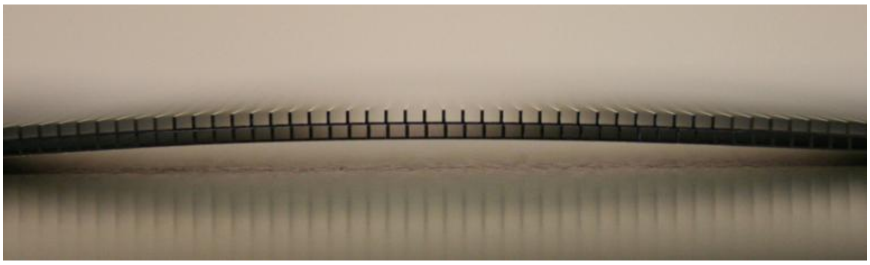

Figure 4: Bonded mirror plates curved for the inner-most IXO radii. The mirror plates were manually bonded to each other and maintain their curvature on their own. Photograph courtesy of Micronit.

The integration of two mirror stacks into a mirror module in flight configuration requires the alignment of the two stacks with an angular accuracy below one arc second. This is achieved using a dedicated integration setup and X-ray beam metrology. The integration of mirror modules into a full size petal was already demonstrated within the former XEUS activities. Figure 5 shows a complete SPO Mirror Module, with two aligned and locked mirror stacks.

The very critical IXO requirement of providing the effective area of >2.5 m² (at 1.25 keV) with a goal of 3 m² within the mass budget for the total set of IXO SPO Mirror Modules is fulfilled. All critical parts to achieve the required effective area mass density have been build and demonstrated by now. The present design for the mirror modules consists of two stacks of 45 mirror plates each, connected with a pair of CeSiC brackets and three flexible dowel pins acting as interface to the petal structure. Depending on the radial position in the mirror assembly, one mirror module weights between 1100 g and 240 g (including brackets, pins and margins). This design enables a layout of for example 1864 SPO Mirror Modules with an effective area of 2.9 m2 (including 10% loss due to residuals imperfections and contamination effects) at a total mass below 700 kg. This yields an effective area density below 240 kg/m², being about 10 times lighter than the optics of XMM Newton and approximately 100 times lighter than the optics for Chandra.

Figure 5: Complete SPO Mirror Module, consisting of two mirror bonded plate stacks. The mounting brackets provide the interfaces for the isostatic mounting to the telescope structure. This design enables a layout of for example 1864 SPO Mirror Modules with an effective area of 2.9 m2 (including 10% loss due to residuals imperfections and contamination effects and the isostatic mounting pins (not shown)) at a total mass below 700 kg.

Full illumination X-ray measurements have been performed at the Panter facility of MPE near Munich. The results show that the effective area of one mirror module in flight configuration is 95% of the theoretically expected value, being in line with the IXO design requirements.

The most demanding requirement is the angular resolution of 5 arc seconds HEW for the IXO telescope. Measurements of the mounted SPO mirror modules are performed at two independent X-ray facilities, at Panter and at the synchrotron beam facility Bessy 2 in Berlin.

Significant progress with the measured angular resolution was achieved over the past three years. The measurements were obtained with the mirror module mounted in flight configuration. Full beam illumination (at Panter) and pencil beam measurements (at the PTB Bessy 2 laboratory) in 2009 have shown a 9 arc seconds HEW, integrating over the complete area of 4 mirror plates. This is to be compared to 17 arc seconds measured also on 4 plates in 2007 and demonstrates the significant improvement of the SPO technology within two years (see also Figure 6).

Dedicated metrology equipment monitoring the stacking process delivers clear insights into the parts of the stack that do not yet reach 5 arc seconds. Having a proper understanding of the current limitations, we expect to reach the IXO requirement of 5 arc seconds within the next technology development activities by using more industrialised equipment and therefore increase the yield of the optics having the required angular resolution.

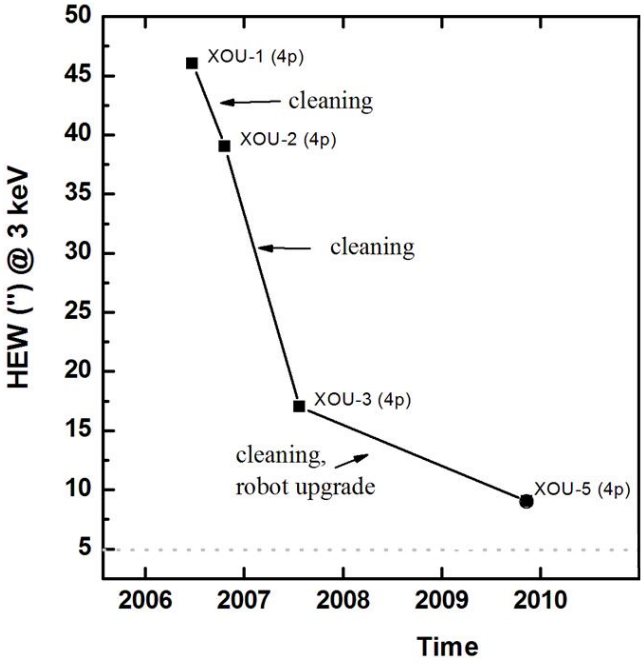

Figure 6: Measured X-ray angular resolution performance of the SPO mirror Modules between mid 2006 to the end of 2009, when 9 arc seconds HEW has been achieved. The performance was measured over the complete area of four mounted plates, in double reflection.

Dedicated activities concentrate on developing a ruggedised mounting system that fulfils the mechanical and thermal requirements for the IXO spacecraft. A first design was developed and verified by model calculations. First environmental tests to verify the simulated properties of the optimized design are foreseen within the next year.

4. THE IXO OPTICS TECHNOLOGY DEVELOPMENT PLAN

The IXO Mirror Technology Development Plan (TDP) describes developments that are required to reduce technical and programmatic risk associated with implementation of the mirror subsystem of the IXO mission. The plan identifies key technology development areas, mission and system drivers, leading to a number of Technology Development Activities (TDA's) to be pursued during the early stages of the programme. This TDP is scoped and scheduled to demonstrate technology readiness to commence to flight programme with the key elements and systems at TRL 5. The TDP is currently being implemented by ESA with its industrial and institutional partners.

The IXO Optics Technology is the main enabling technology required to be developed for IXO. The development risk is being mitigated by the parallel development of two independent optics technologies, the SPO (ESA baseline), and the SGO (NASA baseline).

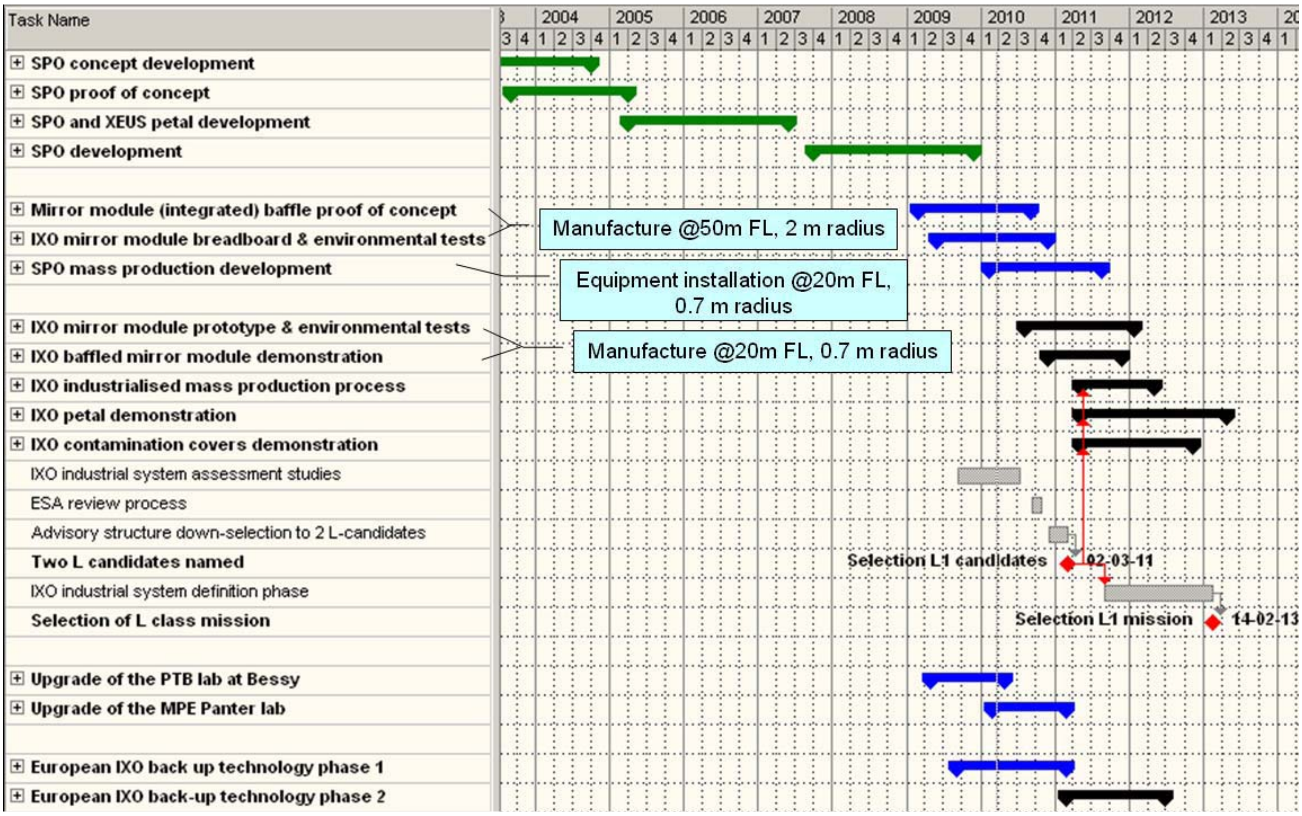

Figure 7: Summary of the ESA Technology Development Plan (TDP) for the IXO optics. Green: completed Technology Development Activity (TDA), blue: running TDA, black: projected TDA, grey: system level activities. Note that the SPO development started for the XEUS focal length of 50 m.

5. X-RAY TEST FACILITIES

The SPO technology has achieved a performance level requiring the upgrading of the X-ray test facilities, in order to progress further towards the IXO requirements. The TDP considers these activities, in parallel with the other TDAs, coherent with schedules for X-ray characterisation:

1. Upgrade PTB laboratory at Bessy 2 synchrotron to accommodate the IXO focal length and alternative energies via new crystal monochromator and an optimised manipulator with on-line metrology.
2. Upgrade MPE Panter laboratory to accommodate the IXO focal length and thermal shrouds, including new focal plane detectors and manipulators.

The facility upgrades are progressing to plan, and figures 8 and 9 provide a view on the Bessy 2 ESA beamline and an overview of the modification required at Panter, respectively.

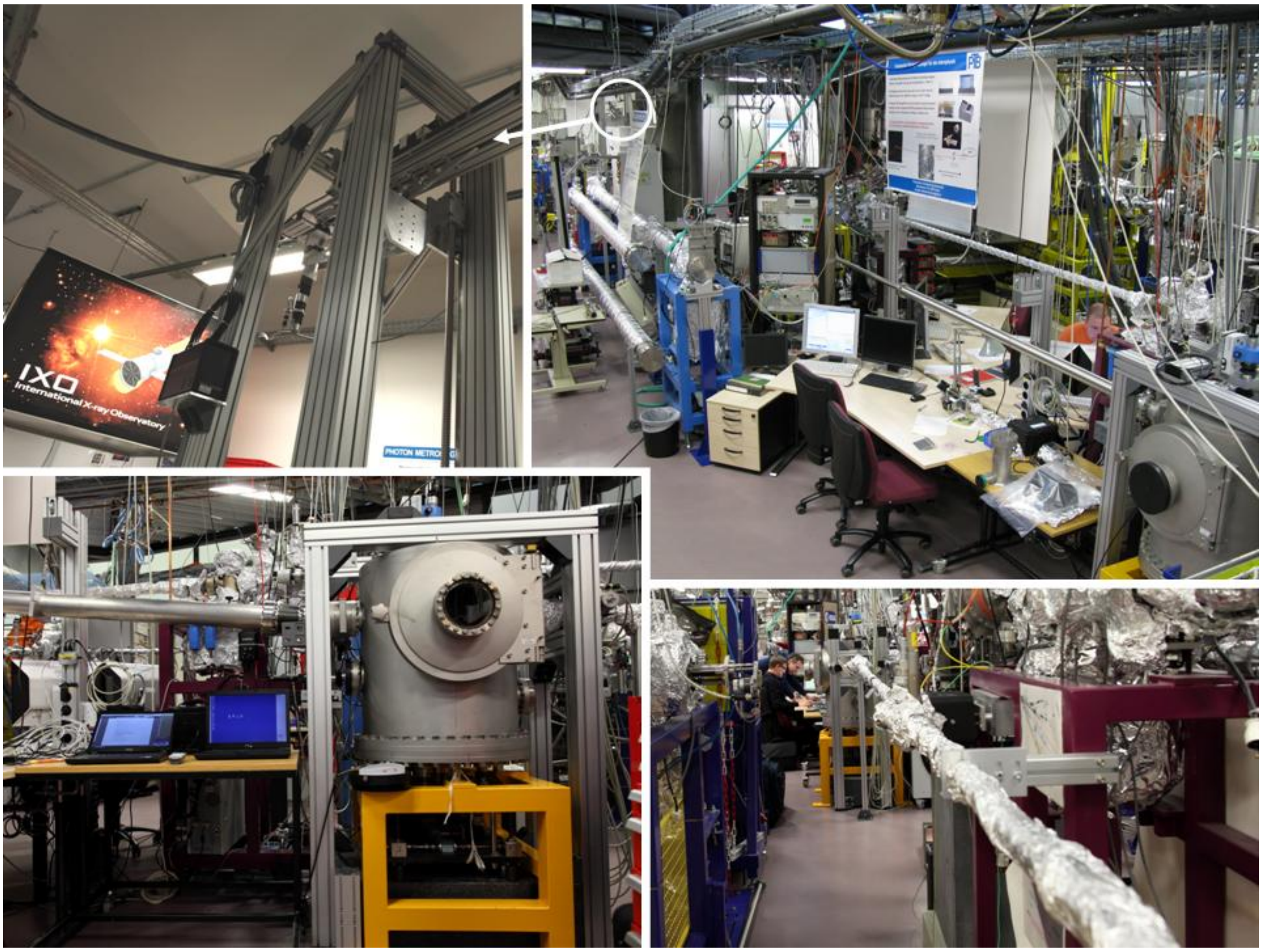

Figure 8: X-ray beamline at Bessy 2, operated by PTB. Utilising synchrotron radiation, intense very collimated and monochromatic radiation is available to measure the performance of X-ray optics and their components. Local properties of the test specimens can be measured with high accuracy (arcsecond and micron level) in a short time. The measurements scans are performed automatically and can also run autonomously through the nights. The facility was extended to the 20 m focal distance required for IXO. Upper left: focal plane assembly with CCD detector on motorised positioning tower. Upper right: 20 m long beamline between focal plane assembly and the optics sample chamber. Lower left: Optics sample chamber containing sample manipulator and several autocollimators. Lower right: beamline to the monochromator and further to the synchrotron radiation source.

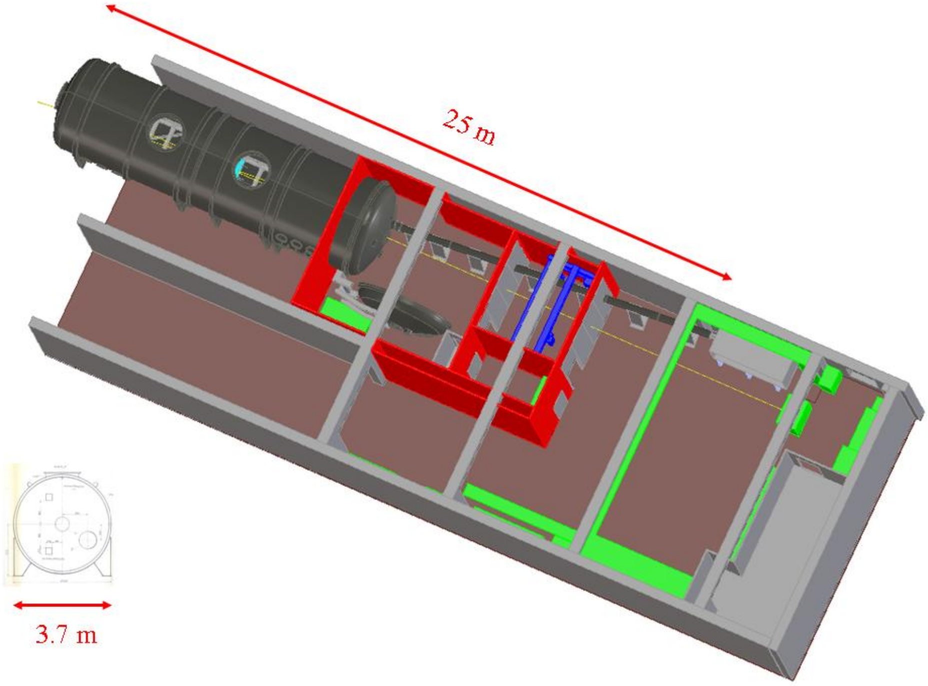

Figure 9: The Panter facility is being upgraded to accommodate the 20 m focal length configuration of the IXO telescope. The facility provides a wide beam and offers full-beam illumination, complementing the metrology done at the Bessy 2 facility.

6. CONCLUSION

The IXO mission is an L-class candidate in the Cosmic Visions 1525 Science Programme, and the study by ESA is building on a novel X-ray optics technology, the Silicon Pore Optics (SPO). With this technology very thin and therefore lightweight X-ray mirrors can be fabricated and mounted into optics modules suitable for flight.

The SPO technology developments address three main areas:

- The demonstration of the required X-ray performance: mirror modules in flight representative configuration have been build and measured at X-ray facilities, demonstrating:
    - Achievement of the required mass density: the total mass of all required mirror modules for IXO is under 700kg, including the isostatic interfaces to the IXO telescope structure and margins
    - Very good progress with the angular resolution, on technology development schedule: 9 arcseconds for the complete area of 4 mounted plates (representatively mounted plates, double reflection, measured in X-rays)
- Ruggedisation of the mirror modules to the environmental specifications of IXO: this required the construction of a new mirror stacking robot and associated equipment to produce mirror modules to the IXO specification with a 20m focal length.
- Cost effective mass production of mirror modules: optimisation of processes and equipment required to produce the almost two thousand mirror modules required for IXO. Further automation and streamlining of all production steps is being undertaken.

In view of the progress achieved by the SPO technology, upgraded X-ray test facilities to the full IXO standards including 20 m focal length became a necessity. Two major facilities will become operational this year for testing in the 20 m focal plane:

- The dedicated beamline at the BESSY-2 synchrotron radiation laboratory, which provides a high precision (to arcsecond angles and micron positions) scanning facility with a metrology station, was extended to the 20 m focal position and commissioning is being completed.
- The proven Panter X-ray test facility, which was already used for test and calibration metrology of past X-ray space missions, is being modified so as to accommodate the 20 m focal length of the IXO telescope.

In view of the importance of the IXO optics technology, a mission enabling factor, a second independent optics technology based on thermally slumped glass is also being investigated. The European heritage in this field was bundled and is being brought to fruition. A new mirror mounting technology was designed, and the required production equipments developed.

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