

# Silicon Pore Optics Development

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## ABSTRACT

Future X-ray astrophysics missions, such as the International X-ray Observatory, IXO, require the development of novel optics in order to deliver the mission's large aperture, high angular resolution and low mass requirements. A series of activities have been pursued by ESA, leading a consortium of European industries to develop Silicon Pore Optics for use as an x-ray mirror technology.

A novel process takes as the base mirror material commercially available silicon wafers, which have been shown to possess excellent x-ray reflecting qualities. These are ribbed, curved and stacked concentrically in layers that have the desired shape at a given radii of the x-ray aperture. Pairs of stacks are aligned and mounted into doubly reflecting mirror modules that can be aligned into the x-ray aperture without the very high angular and position alignment requirements that need to be achieved for mirror plates within the mirror module. The use of this silicon pore optics design substantially reduces mirror assembly time, equipment and costs in comparison to alternative IXO mirror designs.

This paper will report the current technology development status of the silicon pore optics and the roadmap expected for developments to meet an IXO schedule. Test results from measurements performed at the PTB lab of the Bessy synchrotron facility and from full illumination at the Panter x-ray facility will be presented.

**Keywords:** IXO, silicon pore optics, x-ray optics, XEUS

## 1. INTRODUCTION

In May 2008 ESA and NASA established a coordination group involving ESA, NASA and JAXA, with the intent of exploring a joint mission merging the ongoing XEUS (Europe) and Constellation-X (USA) efforts. The coordination group met twice, first in May 2008 and then in June 2008. As a result of these meetings a joint understanding was reached by the coordination group on a proposal to proceed towards the goal of developing an International X-ray Observatory (IXO).

A joint study of IXO is now being pursued with a single, merged set of top level science goals and derived key science measurement requirements. The starting configuration for the IXO study is a mission featuring a single, large X-ray mirror and an extensible optical bench of 20-25m focal length, with an interchangeable focal plane. Studies in Europe and the USA will explore how to enhance the response to high-energy X-rays, via developments in high performance x-ray imaging optics. The IXO mission terms of reference include the following input elements to the IXO configuration:

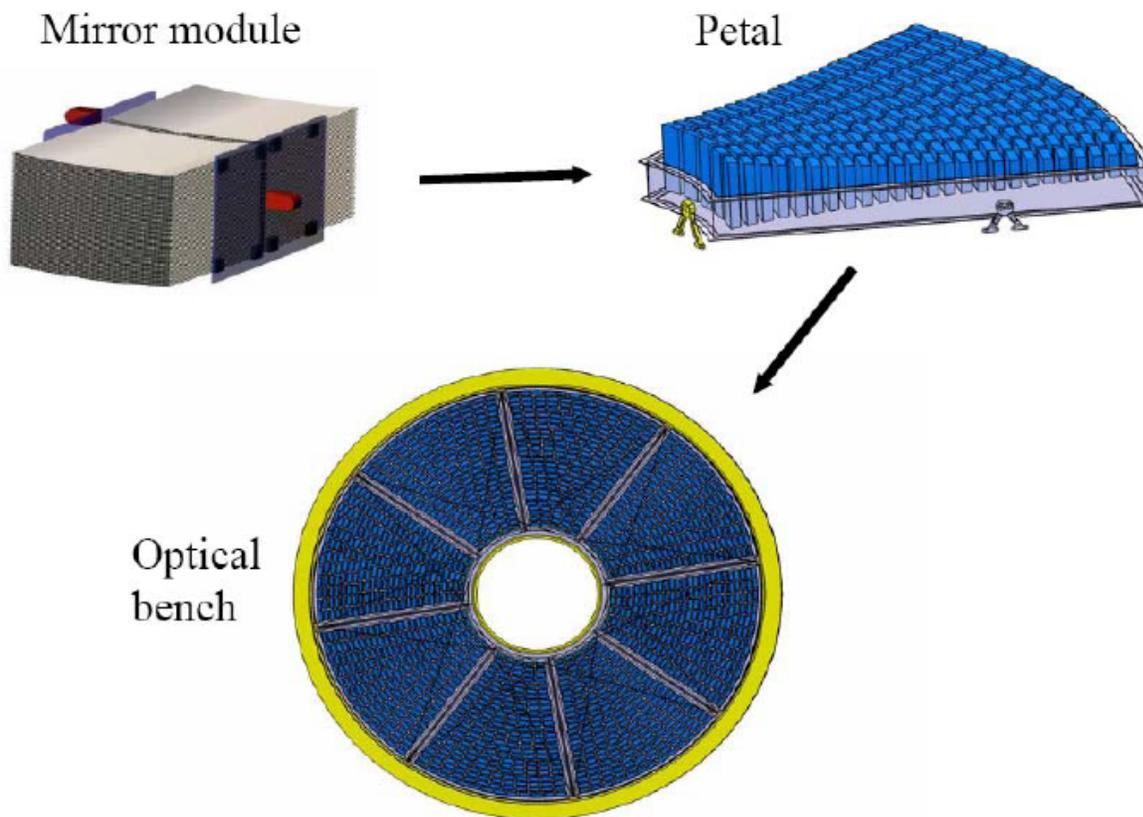
1. A single large X-ray mirror assembly compatible with both silicon pore optics (European) and slumped glass (American) technology developments;
2. An extensible optical bench of 20 to 25m focal length, plus ways to maximise effective area above 6 keV;

3. Instruments to include a wide field imager, a high resolution non-dispersive spectrometer, an X-ray grating spectrometer, plus instruments with modest resources;
4. Concept compatible with both Ariane V and Atlas V 551 launchers.

ESA's development plan for a large x-ray telescope for IXO considers the criticality of technology developments, related to their influence on the ability to carry out the mission and meet performance requirements. The plan stages developments according to the mission selection process, with priority assigned to mission critical elements. To increase cost effectiveness, selected developments are delayed until after ESA's first down selection of large missions to ensure that budget is not expended until a higher level of certainty is obtained regarding mission implementation.

## 2. TECHNOLOGY DEVELOPMENT PROCESS

IXO depends upon successful implementation of x-ray optics to form the x-ray mirror. The European concept to form the IXO x-ray telescope aperture is summarised in Figure 2-1. Following successful demonstration of proof of the concept of silicon pore optics in 2004, further developments focused on the mirror modules and industrialisation of the assembly process, alignment, metrology, and demonstration of a fully representative mirror petal are required. Additionally, baffling must be addressed for stray light and out of field x-rays, the mounting method of petals on to the optical bench must be considered and contamination covers with a failsafe protection cover and mechanism at petal level are required.



**Figure 2-1:** Mirror module and petal in context of IXO aperture; the main technology demonstrations address the mirror modules, whereas the petal and optical bench can be implemented base-lining state of the art technology

A novel technology using commercially available silicon wafers from the semiconductor industry forms the European baseline for the IXO optics. The European concept for the IXO aperture envisages use of individual, silicon pore optic

mirror modules, each of which forms a focusing optic at a particular radius of the IXO aperture. Mirror modules at a particular radius meet identical requirements. Each mirror module is formed from a pair of mirror plate stacks that are silicon pore optics. The two, monolithic, silicon pore optics are manufactured to form an input and output pair (parabola and hyperbola approximations to form a Wolter I optic) that are aligned to very high precision and permanently mounted into the mirror module brackets. The mounted SPO pair in the brackets form a mirror module, which includes an isostatic mount. Mirror modules are delivered to the telescope prime to be aligned and mounted into petals and are individually removable and replaceable.

The mirror plates are formed from silicon wafers that are commercially available with a surface quality suitable for x-ray optics. The bonded stacks of mirror plates form a monolithic, self-supporting structure. Mirror modules are rugged, easy to transport and have much lower alignment requirements than individual mirror shells, allowing a cost effective concept for industrial assembly, integration and test of the telescope aperture. Petals can be individually integrated and characterised, including under x-ray. Petals are mounted onto the telescope optic bench to form the aperture. The opportunity to perform petal level characterisation in x-ray has been foreseen as beneficial, because there is currently no facility available large enough to test the entire IXO aperture in x-ray.

### 2.1. Principal requirements

The IXO telescope will operate with a focal length of 20-25 m with a clear aperture 0.25 to 1.9 m radius. IXO optics must deliver an area-to-mass ratio of about 35 cm<sup>2</sup>/kg, whilst providing 5 arcsec performance at 0.1 to 10 keV, 18 arcmin diameter field of view and an effective collecting area of 30,000 cm<sup>2</sup> at 1.25 keV, 6500 cm<sup>2</sup> at 6 keV and 150 cm<sup>2</sup> at 30 keV. This represents a significant improvement over that provided by current technology and can be compared with:

- Chandra Observatory (NASA) with modest a collecting area of ~400 cm<sup>2</sup> at 1 keV, high angular resolution of 0.5 arcsec and an area-to-mass ratio of ~0.8 cm<sup>2</sup>/kg;
- XMM-Newton Observatory (ESA) comprising 3 identical mirror systems each with a high collecting area of ~1400 cm<sup>2</sup>, a modest angular resolution of ~15 arcsec at 1 keV and an area-to-mass ratio of ~6 cm<sup>2</sup>/kg.

The optics must also accommodate the environmental requirements, which are currently being refined for IXO via system level studies. The European requirements for XEUS of an operational temperature of 90 K have been superseded by the relaxed requirement for IXO of an operational temperature around 293 K. Thermal gradients of up to 2 Km<sup>-1</sup> along the optical axis and 20 Km<sup>-1</sup> perpendicular will be considered for optic development activities. Mechanical loading values for IXO static acceleration are also expected to be relaxed in comparison to those used in previous SPO developments for XEUS, where accelerations of 100 g normal to the optical axis and 80 g in the perpendicular axes were the design values.

The requirements of the SPO technology development plan are:

- Demonstration of required performance of the novel technology;
- Demonstration of technical feasibility of IXO mirror production;
- Industrialisation plan and design of related equipment, with implementation and demonstration of the critical components.

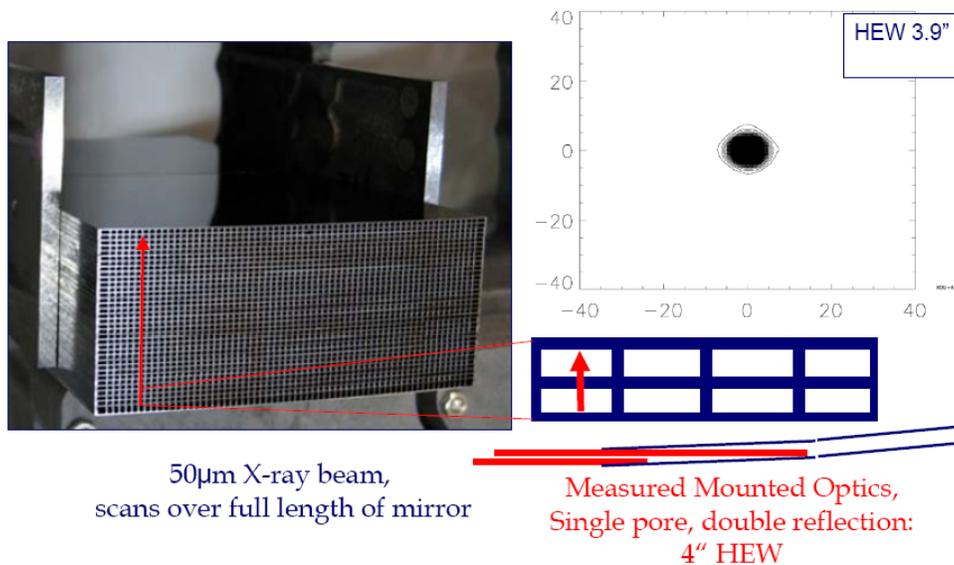
### 2.2. Conceptual development for IXO telescope using SPOs

It is clear that a quantum leap in optics design is required to match the very demanding requirements for IXO. Mirror substrates or shells must be very thin and hence low mass, but also be held in a rigid, stiff structure so that their angular resolution is maintained. To meet these requirements SPO is proposed for development by ESA. Technology development has already been pursued by ESA for some years and proof of the concept has been demonstrated [1, 2]. Recent developments and results are presented in [3] and elsewhere in these proceedings.

Silicon mirror surfaces from commercially available wafers have been shown to be of adequate smoothness (~3 Å rms roughness), flatness (< 0.2 µm over 25x25 mm<sup>2</sup>) and uniform thickness (< 3 µm PTV on 750 µm), without additional

processing. Wafers have been diced to the relevant mirror plate size and structured with rectangular grooves, the ribs of which form the pore walls. Also demonstrated is introduction of a wedge on the mirror plates, with a height and length according to the mirror module radial position in the telescope aperture. Ribbed plates, bent to shape, have been bonded into stacks to form monolithic silicon pore structures. Coatings of suitable heavy metal have been applied and patterned such that the bonding surfaces are left bare. A robotised process has been developed that allows automated assembly of the mirror stacks and Wolter units (using a conical approximation) have been assembled into brackets with isostatic mounts and characterised.

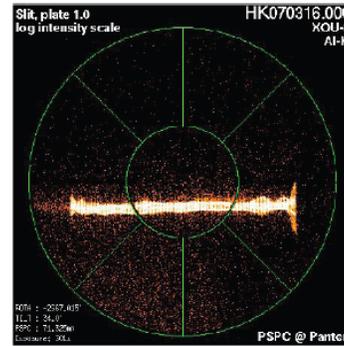
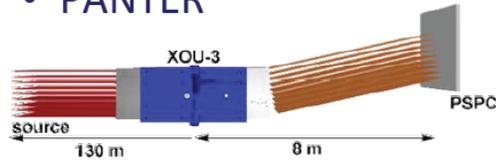
The current performance status of the technology has been demonstrated on mirror plates mounted into a representative mirror module breadboard. No measurement facility is available to perform measurements at the focal length of the manufactured optic. However, pencil beam measurements allow the module to be scanned to predict the output position of beams reflected from the x-ray optic, extrapolated to the focal plane position. Focusing at the measurement position of the full aperture measurements (8m) can be correlated with the ray trace model and pencil beam measurements. Pencil beam measurements made using 2.8 keV x-rays have demonstrated 4" HEW spot size for a single pore in double reflection (see Figure 2-2). X-ray measurements over the full area of the first 4 plates of a mirror module have demonstrated 17" HEW, without subtraction of any of the known errors (such as for the mandrel or known locations of dust particles trapped between bonded surfaces); complementary pencil beam and full area measurements have been correlated (see Figure 2-3). The technology demonstration to date has been limited by particulate contamination during stacking. Trapped particles, which are visible in interferometer measurements of each stacked plate before x-ray testing, create slope errors in the mirror surfaces. This topic is being addressed in running activities.



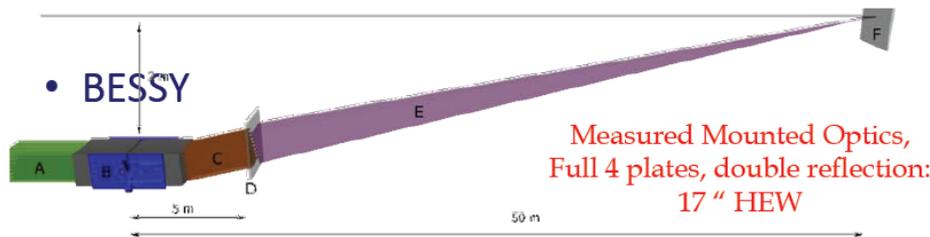
**Figure 2-2:** Silicon pore optic mirror module and results of single pore measurements made at the PTB lab, Bessy II synchrotron.

## Complementary full-beam metrology at Panter

- PANTER



- BESSY



**Figure 2-3:** Results of x-ray measurements demonstrate 17" HEW for 4 mirror plates in double reflection, with pencil beam measurements made at PTB, Bessy II and full aperture measurements made at the MPE Panter facility correlated. No subtraction made for known errors, for example in the mandrel.

### 2.3. SPO development future planning

A technology development plan is proposed that prioritises activities in three stages that are designated assessment, definition and (pre-)implementation stages:

1. ASSESSMENT: Mirror module including fully isostatic mount;
2. DEFINITION: Mainly petal developments;
3. IMPLEMENTATION: Industrialisation and programmatics for a flight model production.

#### 2.3.1. Assessment

The assessment phase is characterised by fast-track developments of the mirror modules that are necessary to demonstrate that the novel technology can provide the necessary performance:

1. Demonstrate angular performance and effective area requirements can be met;
2. Mirror modules isostatic mount;
3. Mirror modules ruggedisation;

In parallel:

4. Coating;
5. Module level baffling;
6. Improved and lower cost mirror plates;

Followed by:

7. Production and testing of complete mirror module (demonstration of mirror modules in relevant environment - coated, without baffles, with isostatic mount).

### 2.3.2. Definition

The definition phase is characterised by system level developments, centring on the petal. Petal developments are scheduled to start only when necessary inputs are received from mirror module developments and from system studies, which will provide requirements such as operational temperature, ensure that straylight is understood and that the method of baffle implementation is available. When such data is available the following activities can run in parallel:

1. Petal structural design and build, demonstrating suitable material characteristics and minimised footprint;
2. Contamination covers with failsafe roll-back mechanism (system input required regarding petal or optical bench implementation);
3. Baffled mirror module test in relevant environment, if required;
4. Mirror module production at different radii, coherent with petal design (necessitates additional mirror module tooling, demonstration of tightest bending radii, strain energy);
5. Development of AIT tools to align and mount a mirror module into a petal and allow replacement of individual mirror modules;
6. Cost reduction of mirror modules (phase 1);

Followed by:

7. Integration and alignment of mirror modules into a petal and demonstration of replacement of individual mirror modules;
8. Performance tests of a petal, populated with real and dummy mirror modules, in relevant environments, including mission-like temperatures and gradients plus vibration testing.

### 2.3.3. (Pre-)Implementation

The final development stage concerns pre-industrialisation and it is here that serious investments will be important. However, large investments in infrastructure cannot reasonably be expected before final mission selection. Therefore a staged approach has been considered:

1. Reductions in mirror module cost;
2. Design of mirror module production line equipment;
3. Build and demonstration of key industrial equipment;

Following final down-selection of missions the final industrialisation stage could be expected:

4. Implementation of full FM production line (carried out by an industrial consortium involving the prime).

### 2.3.4. X-ray facility upgrades

In parallel with the activities listed above and coherent with schedules for X-ray characterisation, the following upgrades are necessary at x-ray facilities to accommodate characterisation of IXO optics:

1. Upgrade of facilities of the PTB laboratory at Bessy synchrotron to accommodate the IXO focal length and alternative energies via a four crystal monochromator;
2. Upgrade of facilities at the MPE Panter laboratory to accommodate the IXO focal length and equipment for introducing thermal gradients. Modifications in this case need to be coherent with the needs and upgrade schedule of testing for other x-ray missions planned at MPE Panter.

## 2.4. Technology development schedule

A flow diagram of ESA's technology development planning is presented in Figure 2-4.

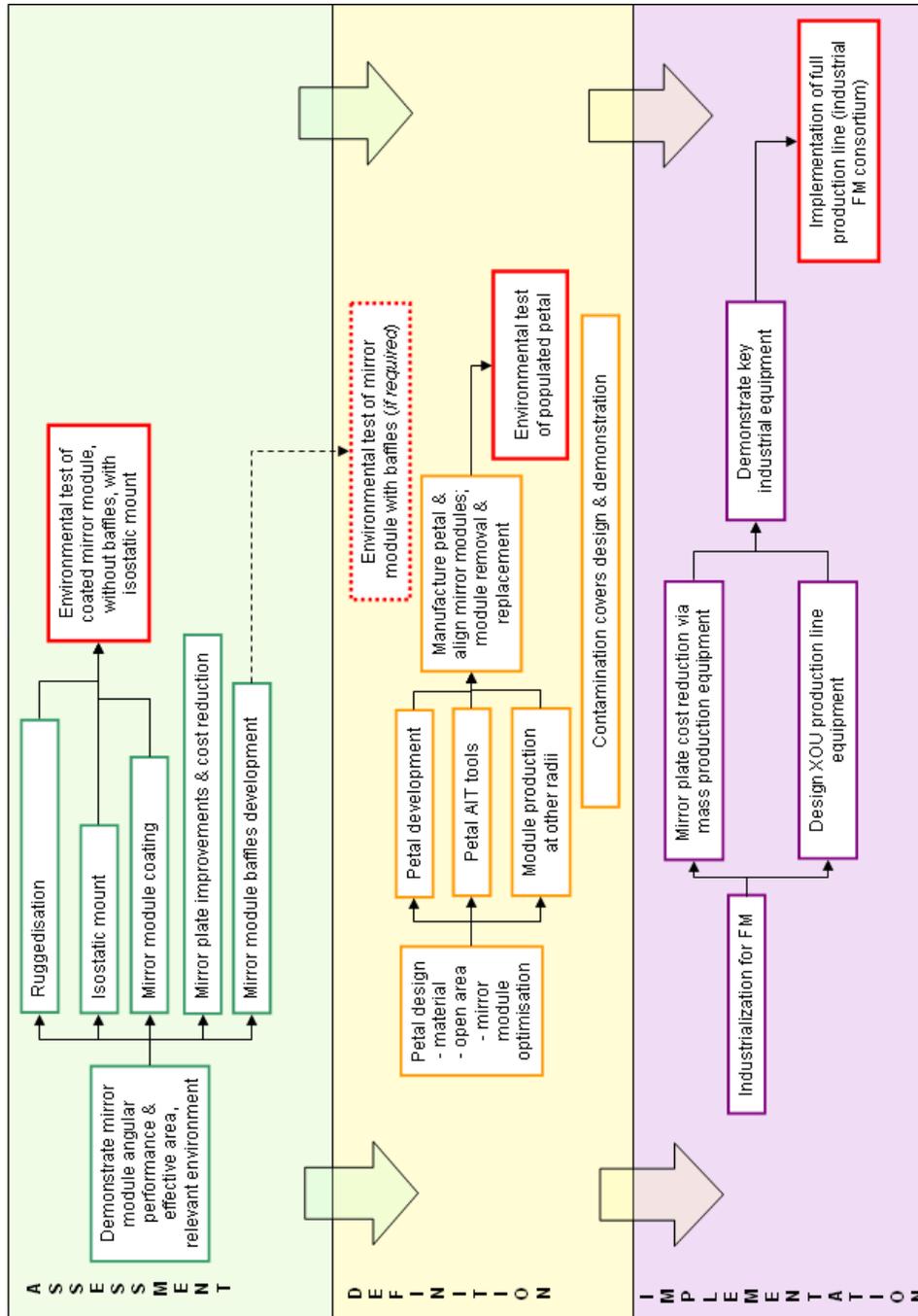


Figure 2-4: Flow diagram of the technology development process, pre-selection and flight

In addressing the points 2.3.1 to 2.3.3 above, an industrial consortium has been gathering, that has provided the capabilities needed to date in order to perform the necessary development. Developments use adaptations of standard industrial processes wherever possible, in consideration of the industrial mass production foreseen for a flight model. ESA's development plan aims to demonstrate successive Technology Readiness Levels (TRLs) with the ultimate goal of reaching the necessary TRL in order to progress to a flight programme. The schedule for development of SPOs and related telescope equipment is described in Figure 2-5. A number of activities have already closed, with demonstration from TRL 0 in 2001 to TRL 4 in 2007. ESA is currently working towards demonstration of TRL 6 – prototype demonstration in the relevant environment – for 2011.

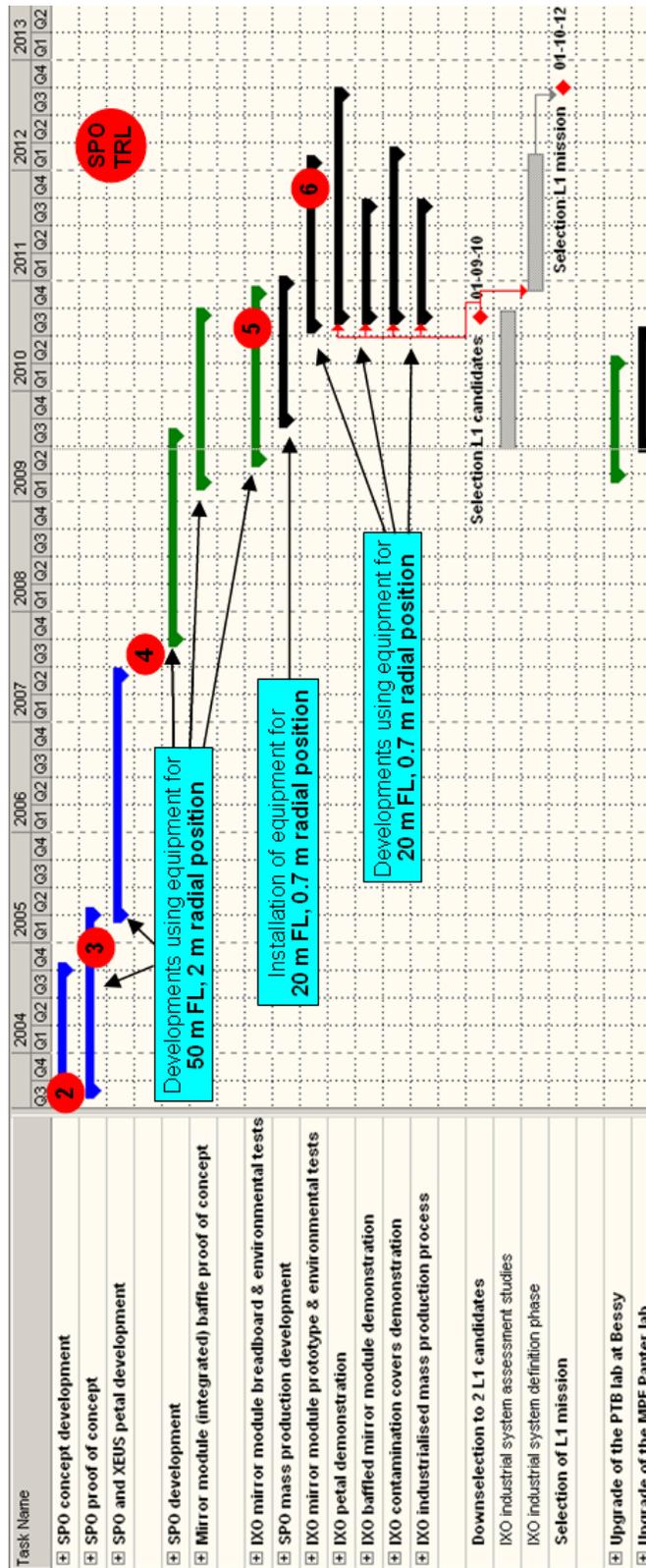


Figure 2-5: ESA's schedule for pore optic Technology Development Activities for the IXO telescope

Early demonstration of the concept was carried out to meet the old XEUS requirements, which included a 50 m focal length (FL). Therefore manufacturing equipment was developed for 50 m FL and a radial position in the aperture of 2 m. The necessary installation of new manufacturing equipment (mandrels, dies, metrology equipment such as interferometers etc.), in order to demonstrate the technology at IXO requirements, is planned to commence in 2009.

The technology development at mirror module level has to date addressed automated cleaning of plates including particle detection and subsequent removal. The 3<sup>rd</sup> generation of a fully automated stacking robot has been completed, which is capable of selecting plates, accurately bending them into cylindrical and conical shapes and subsequently stacking them on a mandrel. This table-top robot is based on a combination of standard cleanroom class robotic arms and stages. It is fully automated and can be remote controlled. The robot includes interferometric metrology to accurately measure the figure of every stacked plate. The stacks are being assembled into mirror modules at a synchrotron facility, which makes it possible to directly align and measure the modules at the wavelength at which they will operate.

### 3. CONCLUSIONS

From conception, the development of SPOs has pragmatically considered the technology's use in an industrialised context, addressing from a programmatic viewpoint the issues associated with mass production in a flight programme. A technology development plan has been presented here that addresses ESA's development needs regarding technology demonstration, support equipment and manufacturing processes for silicon pore x-ray optics; manufacturing; assembly, integration and test; periphery sub-systems; industrialisation and cost reduction. The plan is staged to prioritise development activities (and their associated costs) in coherence with system level studies and mission selection activities that are running in Europe/USA. ESA's development plan has been scoped and scheduled to address the technology development required to demonstrate readiness to commence to a flight programme in 2011. Implementation of the plan is proceeding and TRL 4 - breadboard validation in a laboratory environment - has been demonstrated for a mirror module breadboard formed from silicon pore optics. Demonstration of TRL 6 - prototype demonstration in the relevant environment - is targeted for 2011.

### REFERENCES

1. Bavdaz, M., Lumb, D., Wallace, K., Buis, E.-J., Vacanti, G., Beijersbergen, M., Collon, M., "Large effective area high angular resolution x-ray optics," Proc. SPIE 7011-08, (2008)
2. Collon, M. J., Günther, R., Ackermann, M., Buis, E. J., Vacanti, G., Beijersbergen, M. W., Bavdaz, M., Wallace, K., Freyberg, M., Krumrey, M. "Performance of silicon pore optics", Proc. SPIE 7011, (2008)
3. Olde Riekerink, M. B., Lansdorp, B., de Vreede, L. J., Blom, M. T., van 't Oever, R., Ackermann, M. D., Collon, M. J., Wallace, K., Bavdaz, M., "Production of Silicon Mirror Plates," Proc. SPIE 7437, (2009)