Functional tests of modular elements of segmented optics for X-ray telescopes via an expanded beam facility

Daniele Spiga^{1a}, Giovanni Pareschi^a, Carlo Pelliciari^b, Bianca Salmaso^a, Gianpiero Tagliaferri^a

^a INAF / Osservatorio Astronomico di Brera (OAB), (Italy) ^b IRSPS, D'Annunzio University, Viale Pindaro 42, 65127 Pescara (Italy)

ABSTRACT

Future large X-ray observatories will be equipped with very large optics obtained by assembling modular optical elements. The final quality of the modular optic is determined by the accuracy in the assembly alignment, but also by the compliance of the focusing elements to the nominal shape and the roughness tolerance in order to avoid excessive levels of X-ray scattering. Because of the large number of modules, quality tests need to be routinely performed to assess the technology readiness, and, in a later phase, to select the most performing stacked blocks to be integrated into the final optic. Besides the usual metrology based on profile and roughness measurements, a direct, at-wavelength, focusing measurement in X-rays would be the most reliable test. Synchrotron light beams are in general not sufficiently broad to cover the aperture of a block without scanning it, which requires a focal spot reconstruction. To this end, we designed a 12 m long X-ray facility to be realized at INAF/ OAB, devoted to the functional tests of the focusing elements. A grazing incidence parabolic mirror and an asymmetric Silicon crystal will produce a wide, parallel, and uniform beam of X-rays to illuminate the entire aperture of the focusing elements. A X-ray camera at the focal distance from the mirrors directly records the image. The tests will be performed at 4.5 keV, with the components operating in gaseous Helium to minimize the absorption.

Keywords: large X-ray observatories, X-ray tests, beam expander

1. INTRODUCTION

One of the frontiers of the high-energy astrophysics is the observation of the X-ray Universe with high sensitivity and high angular resolution. High sensitivity is chiefly obtained by increasing the optic effective area, i.e., the diameter and the number of the optical modules, consisting of coaxial double reflection mirrors^[1]. Future X-ray observatories like the previously proposed IXO and ATHENA^[2] will be characterized by a large aperture, and long focal lengths (≥ 10 m) to preserve the grazing incident angles needed to reflect X-rays. In the case of ATHENA two mirror modules with 0.9 m maximum radius and a 12 m focal length were foreseen. With such large diameters it is not convenient to manufacture monolithic mirrors, e.g., obtained by Nickel electroforming of mandrels like the ones made for Newton-XMM^[3], Swift-XRT^[4], or eROSITA^[5]. Optical modules of that size are to be composed by several modular blocks of mirror sectors, each of them with high focusing performances, to be aligned at a few arcsec accuracy to fulfill the high angular resolution requirements.

Finally, to fulfill the low mass/geometrical area ratio requested, lightweight material, like Silicon or glass, have to be adopted. In the technological development of the ATHENA optics the two approaches are being pursued:

- The baseline technology, under development at ESA/ESTEC since 2004, is based on the *Silicon Pore* optics^{[6],[7]}.
- The backup technology, also financed by ESA and being studied at INAF/OAB since 2009, is based on the *hot* slumping of thin glass foils with pressure assistance^{[8],[9]}. The hot slumping (without pressure) is the technique adopted to manufacture the NuSTAR optics^[10].

Regardless of the adopted technique, a mass production is required, and, accounting for unavoidable alignment errors, all the blocks with a HEW worse than 5 arcsec HEW have to be rejected. Accurate metrological characterizations (including both profile and roughness) are routinely performed to predict the optical quality degradation of the mirror assembly^[11]. Nevertheless, because of the complexity of the optical modules, only small portions of the surface can be sampled. Hence, *a systematic quality control on the modular focusing elements of segmented optics has to be directly performed in X-rays*.

¹ contact author: <u>daniele.spiga@brera.inaf.it</u>

Indeed, X-ray full-illumination tests require a homogeneous and low-divergent X-ray beam and as wide as the optic itself. This can be achieved if a point-like X-ray source is placed at a large distance *much larger than the focal length* (and at least 4 times as large). To date, the facility in Europe that better fulfills these conditions is PANTER^[12], where the source is at about 120 m distance from the optic location. Even so, owing to the finite distance, a variable fraction of rays that increases with the focal length misses the reflection on the hyperbola^[13]. Adopting a pencil beam setup would partly fix this problem, but a large facility like PANTER (that, e.g., requires each time 1 day of pumping-down time before operation) cannot be used to routinely perform the functional tests – for instance - of the more than 500 focusing stacks foreseen for ATHENA. Using dedicated beamlines at a synchrotron light facility does not provide a direct full illumination measurement, because the beam is in general too narrow. Hence, the optic has to be dithered or rotated, and the full PSF (Point Spread Function) of the mirror stack has to be reconstructed by superposing the partial exposures^{[14].}

To overcome these problems, in this paper we propose the construction at INAF-OAB (where the research based on the hot slumped glass is being carried out) of a dedicated and versatile X-ray facility. The X-ray system shall illuminate the aperture of a modular element (on the order of 20×5 cm size) with a uniform and collimated (within a divergence below a few arcsec) X-ray beam. It shall enable the mounting, the alignment, the Point Spread Function characterization and the replacement of the optical element in only a few hours time. Finally, it has to be small enough to fit in a typical lab size, and be mostly based on commercial X-ray instrumentation.

2. THE BEAM EXPANDED TESTING X-RAY (BET-X) FACILITY PROJECT

We therefore designed the BET-X facility (Fig. 1), to be realized at the INAF-OAB labs, to perform the X-ray full illumination tests of the modular elements for composed focusing X-ray optics, without the need of locating the source at a very large distance. This is achieved by means of two essential components:

- 1) A glass parabolic mirror sector in grazing incidence, with Platinum coating, to parallelize the beam and expand it in vertical direction.
- 2) Two Silicon crystals to filter and expand the beam in horizontal direction via an asymmetric diffraction. A beam expander of this type was already implemented successfully at the Daresbury synchrotron^[15].

The required clean room environment is a $12 \text{ m} \times 6 \text{ m}$ area. The former dimension fits the focal length of the focusing blocks, while the latter accommodates the one of the expanding mirror.



Fig. 1: optical layout of the BET-X facility project (not to scale). The whole system is kept in gaseous Helium (1 atm) to minimize the X-ray absorption, excluding the source and the camera. The Si crystals can be finely (to a 2 arcsec accuracy) tilted to align the diffraction angles and tune the selected X-ray energy.

The optical components of the BET-X facility are sized to perform the tests at the standard X-ray energy of 4.51 keV (the Ti-K α fluorescence line), in the sensitivity range of almost all X-ray telescopes and easy to reflect with both grazing incidence mirrors and Silicon crystals. To avoid operating vacuum pumps and the related vibrations during the measurement, and to prevent absorption from the air, the system but the source and the camera is closed in a tank filled with gaseous Helium at 1 atm pressure (Fig. 2). The transmission at 4.51 keV of a 18 m range in Helium plus a few cm of air is > 70% (Fig. 3, left), therefore a high-count rate will reach the camera, enabling a PSF characterization with good statistics. Using a tank filled with Helium at 1 atm pressure also avoids venting the tank to change the sample with a subsequent evacuation, saving energy and time. As the sample is changed from an aperture in the bottom side of the tank, the Helium remains trapped in the tank while the air does not enter noticeably (Fig. 3, right). After a small refill of Helium, the tank is closed and ready to measure.



Fig. 2: outer layout of the BET-X facility. The tank filled with Helium includes all the system but - possibly – the CCD camera to ease the alignment of the long arm to the focused beam.



Fig. 3: (left) attenuation of a 12+6 m range in Helium at 1 atm pressure plus some cm of air between the window and the CCD. (right) layout of the sample replacement stage. The sample is changed from the bottom side, keeping the Helium inside the tank without venting and re-evacuating the tube.

The X-ray source can be a conventional sealed X-ray ceramic tube with Titanium anode, emitting a narrow and intense K α doublet centered at 4.51 keV, plus the bremsstrahlung continuum emission. Alternatively, a more performing - but expensive - μ focus source might be used: advantages would be a smaller source, higher flux intensity, and no need of water-cooling. The source size is then reduced to 0.1 mm by means of a pinhole, and the beam is preliminarily collimated by a vertical slit to avoid stray X-rays.

The divergent X-ray beam is made *parallel and expanded in the vertical direction by grazing reflection* (0.8 deg) *on a parabolic mirror* (focal length 5.58 m), with the X-ray source in its focus. To reduce the costs, the glass mirror will be purchased with a conical shape, then at INAF-OAB figured to the correct parabolic profile using the Ion Beam Figuring chamber^[16]. The mirror surface will then be polished using a dedicated lapping machine to a few angström level. The shape accuracy to be reached is better than 3 arcsec; the subsequent Platinum coating endows the mirror with high reflectivity up to 6.5 keV. The reflectivity at 4.51 keV is close to 60%.

A scheme of the paraboloid to be manufactured is shown in Fig. 4, while a ray-tracing simulation showing the shape of the beam at the paraboloid exit is displayed in Fig. 5. After the reflection, the X-ray beam is expanded to 5 cm in the vertical direction, with a 5 mm radial thickness, and still polychromatic up to 6.5 keV. However, only the 3 mm × 50 mm rectangle inscribed in the sector will impinge the asymmetrically cut crystal to be expanded in width.



Fig. 4: scheme of the parabolic mirror used to expand the beam in the vertical direction. After the reflection, the reflected beam is stretched in the vertical direction as in Fig. 5.



Fig. 5: ray- tracing of the beam reflection on the parabolic mirror. The red rectangle is the region that strikes onto the Silicon crystal. The subsequent diffraction increases the width to 200 mm.

The parallel beam is diffracted by an asymmetric–cut Silicon crystal, i.e., with the crystalline planes parallel to the surface. X-rays are diffracted only if the incidence angle ϕ_B on the crystalline planes fulfills the Bragg law: if the incidence angle is 26 deg, only the 4.51 line is reflected and the continuum is filtered out. In the symmetric reflection, the reflection angle equals the incidence angle; therefore the beam width remains unchanged. However, the preliminary monochromation improves the final collimation of the beam, as it removes the Bragg diffraction at different incidence angles by the subsequent asymmetric crystal.

Once monochromated, the beam expansion to a 20 cm width in the horizontal direction (keeping the 5 cm height) is obtained by Bragg diffraction onto an asymmetrical-cut Silicon crystal (Fig. 6). If the crystal is cut so that the crystalline planes form an angle $\alpha = 25.5$ deg with the surface and the beam impinges the surface at a grazing angle $\theta = \phi_B \cdot \alpha$, = 0.85 deg, the reflection of 4.51 keV rays occurs with respect to the normal to the crystalline planes (Fig. 6). In this way, the width of the beam collected by the crystal (Fig. 4, right) is expanded from 3 mm to almost 200 mm. The diffraction efficiency of the two combined crystals is 35%. Expanding the beam by a larger factor is difficult, because this requires shallower angles that would cause the beam to be totally reflected at the surface without expansion. For the same reason, expanding an X-ray beam with energy below 4.5 keV would require an increase of the incidence angle, with a compensation of the initial beam width by the same factor. Owing to the higher reflectivity, this might be obtained by increasing the incidence angle on the paraboloid (i.e. reducing the focal length) without the need of extending its length, even though operating in vacuum becomes mandatory below 3 keV. A sizing change in the opposite direction might be suited to tune the facility to somehow higher X-ray energies, without problems of absorption in Helium.



Fig. 6: scheme of the asymmetric reflection on the Silicon crystal used to expand the X-ray beam. The diffracted beam is expanded to a uniform and parallel 50 x 200 mm size.

The resulting parallel beam, *expanded to a 200 \times 50 mm size*, illuminates the mirror(s) under test, mounted onto a precision goniometer and a translational stage to perform an accurate alignment with respect to the beam, controlled from outside via a RS232 interface.

The focused beam propagates through Helium in a 12 m tube toward the CCD camera. With respect to the parallel beam direction, the tube is angled to match the beam deviation caused by the mirror stack. The angle has to be varied to fit the reflection angle.

The focused beam emerges from the He tank through a Mylar window and is recorded by a Silicon CCD camera. The camera, located just outside the tube to ease its movements, is enclosed in a simple X-ray shield to avoid radiation leaks. An alternative could be to rotate the beam expander in vertical and reflect the beam laterally. In this case, the CCD might be enclosed in the tank. Once aligned, the PSF characterization of the modular element can be achieved in a few minutes integration. The expected intensity of the expanded beam at the sample is 40 to 120 counts/sec/cm², depending on the characteristics of the X-ray source that will be adopted.

3. CONCLUSIONS

We have designed an X-ray test facility based on a hybrid beam expander (parabolic mirror + asymmetric Si crystal) that will enable to test and select the best-performing mirror module elements of large X-ray telescope optics. It will exhibit several advantages with respect to other X-ray facilities:

- A direct, full-illumination, non-destructive X-ray characterization of single and stacked integrated mirrors as modular elements of future large area X-ray telescopes is performed without suffering from the finiteness of the source distance.

- The Point Spread Function measurement does not require any reconstruction, by either rotating or dithering the optic.
- The small size tank is evacuated in a few hours. The Helium filling has to be done only once, and shall not be repeated when the sample is changed. Hence, a large number of samples can be tested in a given time and a quicker feedback after the manufacturing can be provided.
- The test in *real time* allows us to directly check the performances of *active X-ray optics*^[17] optimizing their shape under X-ray illumination.

Finally, for mirror modules with a different focal length, the facility can be easily adapted by adding, or removing, or trimming segments of the 12 m long tube between the optic and the camera.

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