BEaTriX (Beam Expander Testing X-ray facility) for testing ATHENA's SPO modules: advancement status

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ABSTRACT

ATHENA Silicon Pore Optics (SPO) Mirror Modules (MM) have to be tested and accepted prior to integration in the full ATHENA Mirror Assembly (MA). X-ray tests of the MMs are currently performed at the PTB laboratory of the BESSY synchrotron facility in pencil beam configuration, but they require a PSF reconstruction. Full illumination X-ray tests could be performed using a broad, low-divergent X-ray beam like the one in use at PANTER (MPE, Neuried, Germany), but the large volume to be evacuated makes it impossible to perform the functional tests at the MMs production rate (3 MM/day).

To overcome these limitations, we started in 2012 to design a facility aimed at generating a broad (170 x 60 mm^2), uniform and low-divergent (1.5 arcsec HEW) X-ray beam within a small lab (~ 9 x 18 m^2), to characterize the ATHENA MM. BEaTriX (the Beam Expander Testing X-ray facility) makes use of an X-ray microfocus source, a paraboloidal mirror, a crystal monochromation system, and an asymmetrically-cut diffracting crystal for the beam expansion. These optical components, in addition to a modular low-vacuum level (10^{-3} mbar), enable to match the ATHENA SPO acceptance requirements.

The realization of this facility at INAF-OAB in Merate (Italy) is now on going. Once completed, BEaTriX can be used to test the Silicon Pore Optics modules of the ATHENA X-ray observatory, as well as other optics, like the ones of the Arcus mission. In this paper we report the advancement status of the facility.

Keywords: BEaTriX, X-ray test facility, micro-focus source, beam expander, asymmetric diffraction

1. INTRODUCTION

ATHENA (Advanced Telescope for High ENergy Astrophysics) is the selected second large class mission (L2) in the ESA Science Programme [1]. Selected in 2014 after several iterations (XEUS, IXO), it will be adopted in 2021, and will be launched in early 2030's. It is a high energy astrophysics observatory to study the hot and energetic universe, that combines novel ligthweigth optics with advanced detection systems to achieve unprecedented performance (effective area of 1.4 m^2 at 1 keV, and half-energy width (HEW) of 5 arcsec at 1 keV). Since 2004, ESA adopted the technology of Silicon Pore Optics (SPO) [2] as a manufacturing baseline for the ATHENA optics. SPO technology is based on Silicon wafers and benefits from the well consolidated production processes of the semiconductor industry. Its development is carried out at Cosine [3] with ESA [4], academic and other industrial partners.

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ATHENA requires the largest X-ray optics ever made, with a diameter of ~ 2.5 m. To create the aperture of such a large X-ray telescope, a modular approach is foreseen. 35 processed silicon plates are stacked, with dedicated robotic machines, to form an X-ray Optical Units (XOU). 4 XOUs (two of them operating the first reflection in parallel, followed by the two XOUs in charge of the second reflection) are aligned and integrated in the SPO Mirror Module (MM). Several hundreds of MMs need to be finally aligned and integrated in the Mirror Assembly (MA). Each step of this process has to be followed by dedicated tests and calibration procedures, which require new facilities. The integration of the XOUs into MM is performed using synchrotron radiation at the XPBF 2.0 beamline at the BESSY II facility in Berlin, Germany [5]. The MM are, at present, characterized at XPBF 2.0 [6] and at the PANTER long beam facility of the Max-Planck-Institut für Extra-terrestrische Physik located near Munich [7]. Media Lario [8] and Thales CH [9] are studying different co-alignment techniques of the MMs. The completed MA has to be eventually calibrated and different solutions are considered, including an extended PANTER [7], the XRCF facility at MSFC (USA), or a vertical facility that is now under study at INAF-OAB and Media Lario [10].
In between the XOUs integration and the MMs integration, all the MMs will have to be tested for acceptance: at this step, the BEaTriX facility (Beam Expander Testing X-ray facility) will play a key role, to characterize the MMs in full illumination, with a low divergent X-ray beam, and at the requested MM production rate. At the moment, this complete set of characteristics is not fulfilled by any of the existing facilities. X-ray tests of the MMs are currently performed at the PTB laboratory of the BESSY synchrotron facility in pencil beam configuration [6]. Since the beam size can be set from 50 μm × 50 μm to 5 mm × 5 mm, a PSF reconstruction from the exposure of each pore, or groups of pores, is required. Full illumination X-ray tests could be performed using a broad and low-divergent X-ray beam, e.g. at PANTER, possibly compensating the intrinsic beam divergence by the application of a diffractive X-ray lens [11]. However, the large volume to be evacuated makes it impossible to perform the functional tests at the MMs production rate of 3 MM/day [12].
To overcome these limitations, we started in 2012 to design a facility aimed at generating a broad (170 x 60 mm^2), uniform and low-divergent (1.5 arcsec HEW) X-ray beam within a small lab (~ 9×18 m^2) [13,14,15,16]. This will be possible thanks to an X-ray microfocus source (30 μm focal spot FWHM) in the focus of a paraboloidal mirror, a monochromation system with symmetrically cut crystals and an asymmetrically-cut crystal for beam expansion. A beam expander of this type was already implemented successfully at the Daresbury synchrotron [17]. However, the beam expansion was limited to a single direction, and the obtained divergence was much larger. BEaTriX will operate at the monochromatic X-ray energies of 4.51 keV and 1.49 keV, and it will fully illuminate the aperture of SPO mirror modules, imaging the beam focused by an SPO MM at 12 m distance, where the camera will be appropriately placed. The high flux generated by the micro-focused source, and the highly monochromatic beam produced by the optical elements will enable the Effective Area and PSF characterization with high accuracy. All the system will be under a vacuum level of 10^{-3} mbar [18], and the modular vacuum approach will enable a fast interchange of the MMs.
The realization of the laboratory and facility is now on going, funded by an ESA contract, an AHEAD (Activities for the High-Energy Astrophysics Domain) grant awarded from H2020 [19], and to other dedicated INAF funds. Once completed, BEaTriX can be used to test the SPO MMs of the ATHENA X-ray observatory, as well as other optics, like the Arcus mission [20].

2. THE LABORATORY: FOUNDATIONS

BEaTriX is being built over the ground basement of a building already present at the Brera Observatory in Merate. The project have been commissioned to BCV-progetti (Milano, Italy) with the goal of constructing a foundation that would reduce the impact on the BEaTriX equipment due to vibrations possibly arising from soil, anthropic-noise and vacuum pumps. Rigid elastomers (Sylodamp SP300, with $\zeta = 0.235$, and mechanical loss factor = 0.47) were placed in between the foundations and the under-foundations slab [18].
Figure 1 shows the project and the advancement status of the laboratory. According to the BEaTriX mechanical layout (Section 4), the foundations have an L-shape, with length of the two arms of 8.52 m and 17.95 m. At the end of the long arm, a basin is present to allow the vertical movement of the long arm of the facility.

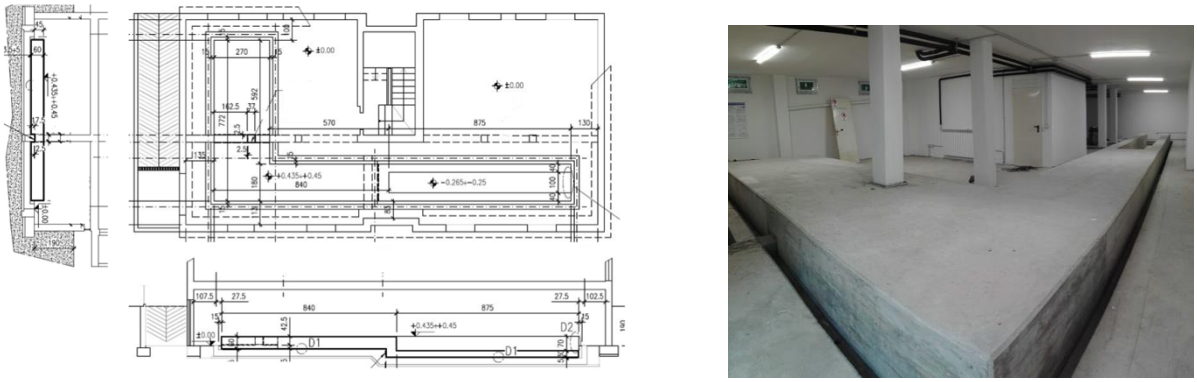

Figure 1: BEaTriX foundations. Left: Sketch of the foundations inside the renovated laboratory. Right: An intermediate phase in the laboratory realization: realization of the foundations

3. OPTICAL DESIGN

The optical design foresees the collimation and the expansion of an X-ray beam produced by a source located at a short distance from the module under test. This is achieved with:

- an X-ray micro-focus source
- a paraboloidal mirror in the focus of the X-ray source
- a monochromation system with symmetrically cut crystals
- an asymmetrically-cut crystal for beam expansion
- a detection system

A beam expander of this type was already implemented successfully at the Daresbury synchrotron [17], for the test of the SODART X-ray telescope aboard the SPECTRUM-RÖNTGEN-GAMMA (SRG) satellite. However, the beam expansion was limited to a single direction (no parabolic mirror was used), and the obtained transversal divergence was much larger.

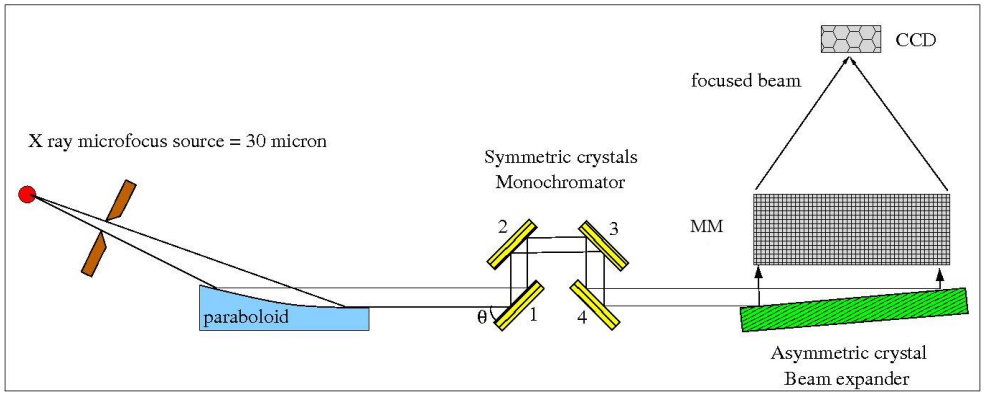

Figure 2: Optical layout of BEaTriX

1.1 X-ray source

An X-ray micro-focus source is necessary to minimize the vertical divergence, with a copious flux required to keep the integration time to acceptable level. A focal spot of 30 μm (FWHM) produces a vertical divergence of 0.74 arcsec (HEW), if the parabolic mirror is located at 4750 mm distance; the horizontal divergence of 1.5 arcsec HEW is guaranteed by the monochromator design. Micro-focus sources with an X-ray flux on the order of 10^{11} ph/sec/sterad are

available on the market: the Incoatec company (https://www.incoatec.de) is a possible provider. Micro-focus X-ray sources generate the fluorescence lines of the elements composing the tube anode, plus a bremsstrahlung continuum: in our case, a titanium anode will be used for the 4.51 keV line, and an hybrid anode with an alloy of aluminum and titanium (50% Al and 50% Ti) for the 1.49 keV line. The hybrid anode solution increases the melting point of the sole aluminum (1400 °C compared to 660 °C), and therefore enables the increase of the source intensity.

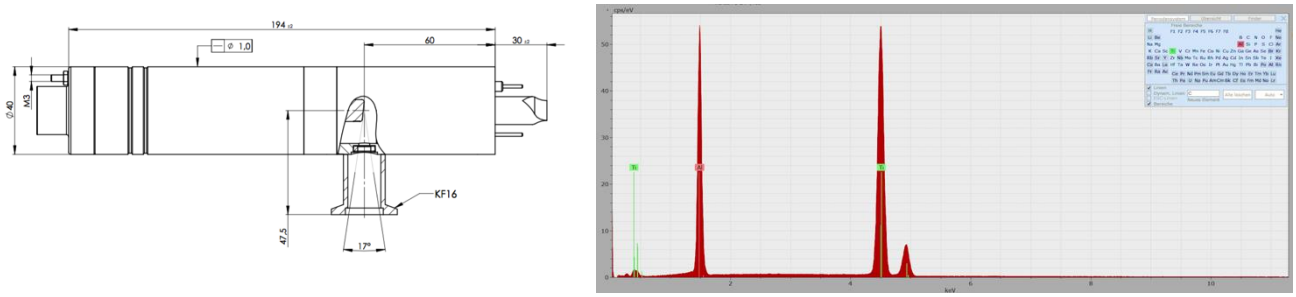

Figure 3: Left: scheme of the Incoatec X-ray microfocus source. Right: measured spectrum of the hybrid X-ray microfocus source with the anode in Ti-Al alloy (50% Al and 50% Ti), showing the X-ray fluorescence lines of both elements (courtesy by Incoatec).

3.1 Collimating mirror

The parabolic mirror makes the beam parallel, defines the vertical dimension of the final beam, and determines the horizontal size of the beam that will be expanded by the asymmetric crystal. For a paraboloidal mirror with geometrical parameters shown in Figure 4, the beam at the exit pupil, to be considered as the rectangle inscribed in the beam, is as large as 60 mm × 4 mm. The 60 mm height will fully cover the 54 mm entrance pupil of the MM, and the 4 mm width will be expanded by the asymmetric cut crystal.

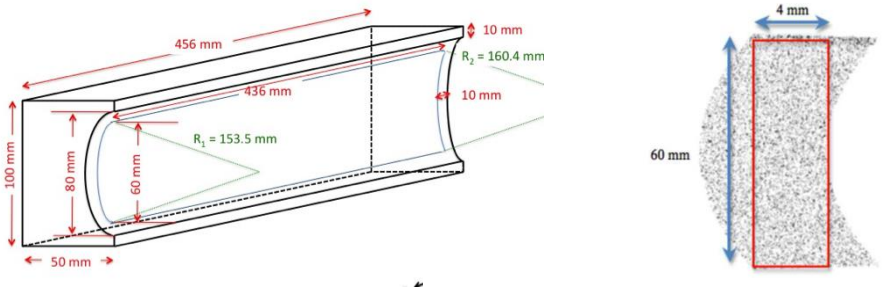

Figure 4: Left: the paraboloidal mirror. Right: the beam at the exit pupil of the mirror

We have already procured two mirrors [16] from Zeiss in fused quartz HOQ 310, one in a preliminary lapped status (shape: PV < 5 µm, roughness: rms < 0.5 µm), the second one just grinded (shape: PV < 15 µm, roughness: rms < 2 µm). The polishing and final figuring will be done in house, aiming at achieving a maximum tolerable HEW of 0.5 arcsec. Subsequently the mirror will be coated with a platinum layer (30 nm) and an amorphous carbon over-coating (3 nm) to enhance at most the reflectivity also at low-energy X-rays [21].



Figure 5: One of the two paraboloidal mirror in fused quartz HOQ 310, procured from Zeiss

3.2 Crystals for monochromation and beam expansion

Symmetrically-cut crystals (i.e., with diffracting planes parallel to the outer surface) are used in BEaTriX to monochromate the beam, followed by asymmetrically-cut crystals to expand the beam in the horizontal direction [18]. Two types of crystals are envisaged for BEaTriX: Si(220) crystals for the 4.51 keV line, and Ammonium Dihydrogen Phosphate - ADP(101) crystals for the 1.49 keV line.

For both energies, a careful design of the monochromator is necessary to reduce the bandwidth of the X-ray beam, due to the enhanced energy dispersion of the asymmetrically cut crystal [22]. A tight monochromation can be obtained by increasing the number of reflections on symmetric crystals, positioning the crystals in energy dispersive configuration, and tilting some of the crystals [18].

The complete analysis of the crystals system has been performed for the 4.51 keV energy, the first beam line to be realized. To define the best configuration of the monochromator, simulations have been performed using the widespread code SHADOW (commonly used for simulations of X-ray optics for synchrotron radiation experiments [23]) in the OASYS package [24] and, in order to return an absolute evaluation of the flux intensity per cm^2 at the sample, via an ad-hoc developed IDL-based ray-tracing code. The results are in good agreement (Figure 7), with some difference due to the different approximations used by the programs and to statistical effects. The design consists of a set of 4 symmetrically cut crystals, where the 1st and 2nd crystals are rigidly rotated with respect to the 3rd and 4th (Figure 6). This configuration can be obtained with 2 Channel Cut Crystals (CCC). From the realization point of view, CCC are standard optical elements, therefore easy to be realized. Two surfaces are obtained in just one crystal, and this assures a perfect alignment of the crystals planes of the two surfaces.

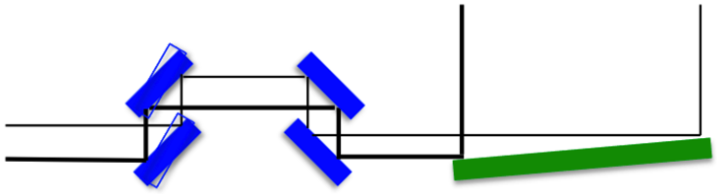

Figure 6: Optical layout of the monochromator (blue) and the beam expander (green). The crystal for monochromation are symmetrically cut, the one for the beam expander is asymmetrically cut. Monochromation with four diffractions, with a possible rigid rotation of the first pair of crystals to detune the rocking curves and so shrink the passing band.

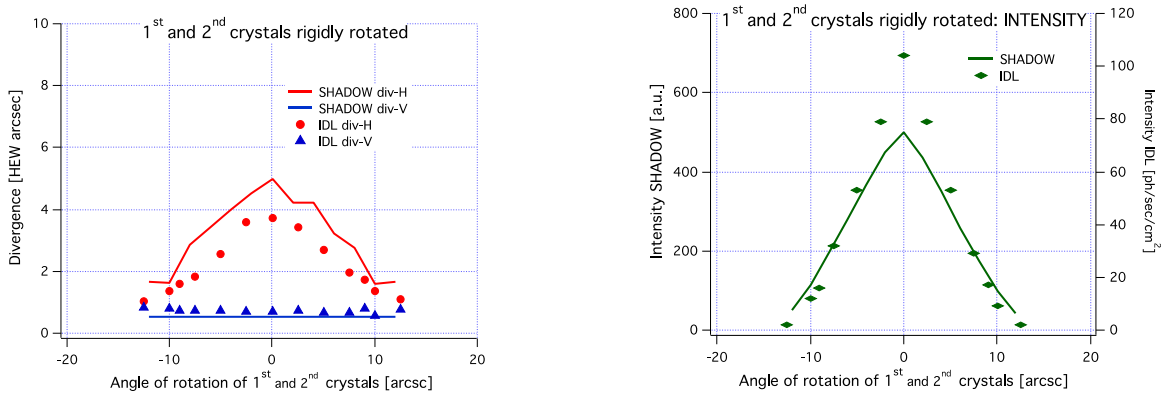

Figure 7: Effect of the tilt of the 1st and 2nd parallel symmetric-cut crystals. Left: Vertical (blue) and horizontal (red) divergence. Right: Intensity loss. Note that the SHADOW result is given in arbitrary units while the result from the IDL code is given in ph/s/cm².

Figure 7 shows the divergence and the flux obtained with the crystals in the configurations of Figure 6, as function of the rotation of the first CCC. It can be seen that this configuration gives the possibility to optimize either the horizontal divergence or the flux, depending the needs and the quality of the sample to be tested.

About 1.5 arcsec can be reached by a 10 arcsec tilt of the first crystal pair; the bandwidth of the beam can be computed as 0.03 eV [18] making the beam extremely monochromatic and avoiding the need of a CCD with photon counting capabilities; a photon loss of about a factor 10 is obtained with respect to the 0 arcsec rotation. With the 10 arcsec rotation, the expected intensity of the beam, in front of the MM, can be assessed as ~10 ph/s/cm^2, a flux that enables a SPO MM characterization in a ~30 min integration.

From the realization point of view, the Silicon beam expander has been already procured, with a size of 170 mm × 60 mm × 20 mm. It has been cut at CNR-IMEM (Parma) from a cylinder of monocrystalline high-purity silicon, purchased from MEMC. X-ray tests have been performed at CNR-IMEM to qualify the beam expander.



Figure 8: The beam expander in silicon for the 4.51 keV beam line. The surface has been polished to remove the lattice damage introduced by the cut (process done at CNR-IMEM). The crystal dimensions are 170 mm × 60 mm × 20 mm

The Silicon CCCs preliminary design is shown in Figure 9. A channel width of 16 mm is sufficient for the beam of Fig. 4-right to pass without obstruction, avoiding the direct beam to pass through. A length of 30 mm enables the two reflections with some margins. The height of 70 mm can propagate, with large margin, the beam emerging from the parabolic mirror.

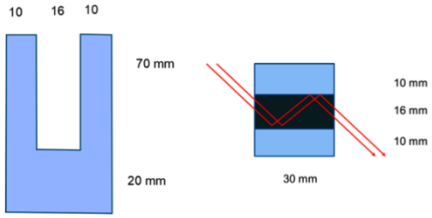

Figure 9: Preliminary design for the CCC of the 4.51 keV line

For what concerns the ADP crystals for the 1.49 keV line, we have procured from Saint Gobain a sample (20 mm × 20 mm × 2 mm) to perform preliminary analysis on the quality of the ADP crystal commercially available. In fact, this crystal is less used than the Silicon, and more challenging. Very promising results indicates that the crystal is almost dislocations free (Figure 10), and with good parallelism of the crystals planes (not shown), which confirm that it is a good candidate for the BEaTriX 1.49 keV beam line. Further tests are on going.

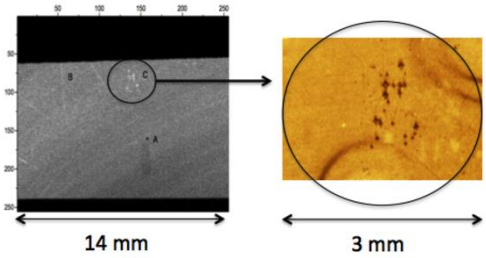

Figure 10: Double crystal X-ray topography, performed at IMEM-CNR, of the ADP sample procured from Saint Gobain (sample size 20 mm × 20 mm × 2 mm). The spots in the area C are dislocations, only present is a very small area of the sample

4. MECHANICAL LAYOUT

BEatriX is designed as an L-shape, where the short arm is used for beam moderation, and the long arm propagates the beam to the ATHENA's nominal focal plane, at 12 m distance from the MM. The long arm has to be moved in the vertical plane, for the detector to follow the focused beam, directed downwards by the double reflection on the MM, with an angle determined by the radius of the MM. For this reason a basin is present in the BEaTriX foundations (Figure 1). In Figure 11, the conceptual design of the BEaTriX vacuum system is presented, while a careful optimization of the various mechanical parts in now on going. We hereafter review the mechanical layout from the conceptual point of view.

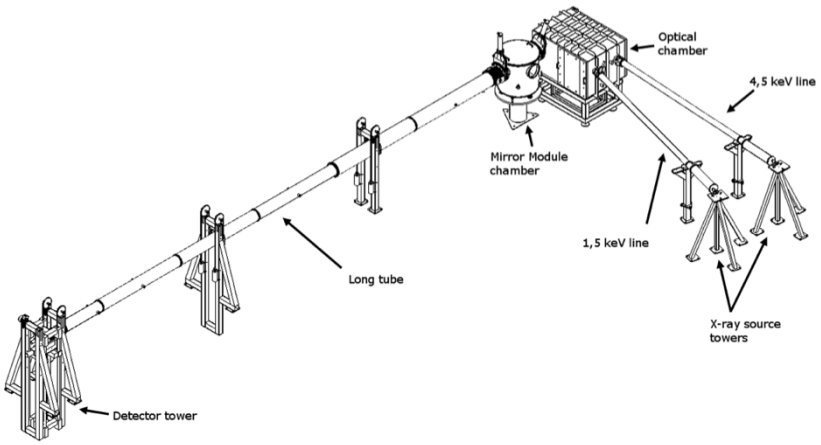

Figure 11: Conceptual design of the BEaTriX vacuum system.

The X-ray micro-focus sources are positioned at the beginning of the short arms. They are mounted on a support structure (the so-called "source tower") that provides the needed stability to the X-ray sources, decoupling them from the short arms by means of bellows, which enable the arms orientation and the sources alignment. The tubes of the short arms allow the propagation of the beam from the source to the optical chamber. This chamber hosts the three optical components responsible for the beam moderation (the parabolic mirror, the monochromator and the beam expander), their motorizations, and a small X-ray detector mounted in the path of the beam emerging from the beam expander, to monitor the stability of the flux. A phosphor screen can be flanged, at different positions of this chamber, to image the beam during the alignment procedure. Finally, the chamber is equipped with vacuum valves on both ends and a vacuum pump system, in order to make it a vacuum independent sector.

The next chamber encloses the MM under test. It will host the motors that enable the MM alignment and a thermal box to perform thermal cycles of the MM in the 20 ± 30 °C range. The thermal box is designed in order to radiatively heat/cool the MM. A lateral porthole is present for sample removal/mounting. This section is equipped with vacuum valves on both ends and an independent vacuum pump in order to vent/evacuate only this section when the sample is changed (30 min are allocated for the evacuation of this tank, to go at the test rate of 3 MM/day).

A 12-m long tube allows the X-rays to propagate to the focal plane, after reflection on the module under test. The tube is supported by proper systems with counterbalance weights. The long arm evacuation is ensured by its own vacuum pump system.

Finally, the so-called "detector-tower" is fixed to the foundation in order to support the end of the long tube, the X-ray camera, and its motorization (XYZ) stage. The translation along the beam is needed for the focus search, while those perpendicular to the beam are used to cover the area of the collimated beam, and to calibrate it in divergence and uniformity, when the tube is in the horizontal position.

A ISO5 clean tent, not shown in Figure 11, will be positioned around the MM chamber to allow the handling of the SPO MM in a clean environment.

5. CONCLUSIONS

The BEaTriX X-ray facility is in the realization phase at the Brera Observatory in Merate/INAF. BEaTriX will generate a broad, monochromatic, parallel, collimated, and polarized X-ray beam in a small space, working at two energies (4.51 and 1.49 keV). Once completed, BEaTriX will provide us with the capability to perform the X-ray acceptance tests of the ATHENA MMs, at the rate of 3 MM/day. Also other applications requiring a broad and parallel beam of soft X-rays can be envisaged.

The laboratory that will host BEaTriX is almost completed. The foundation of the instrument has been designed in order reduce the impact on the BEaTriX equipment due to vibrations possibly arising from soil, anthropic-noise and vacuum pumps. A vacuum level of 10^{-3} mbar will guarantee a stable vacuum level also for the 1.49 keV X-ray energy beam. A monochromator stage, with 4 reflections on symmetrically cut crystals, will reduce the bandwidth to the level necessary to compensate for the energy dispersive properties of the asymmetrically cut crystal (the beam expander), and therefore keep the final divergence within the specification of 1.5 arcsec. This can be achieved by using a couple of channel-cut crystals, where the first one can be rotated with respect to the second one: this configuration can give us the great advantage to optimize either the horizontal divergence or the flux, depending the needs and the quality of the sample to be tested. The optical components of the facility are now in the procurement phase, and some have already been procured. The mechanical layout is sketched, and a careful optimization of some parts is now on going.

ACKNOWLEDGMENTS

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REFERENCES

[1] Nandra, K., Barret, D., Barcons, X., et al., “The Hot and Energetic Universe: A White Paper presenting the science theme motivating the *Athena* mission”, http://arxiv.org/abs/1306.2307 (2013)
[2] Willingale, R., Pareschi, G., Christensen, et al., “Science requirements and optimization of the silicon pore optics design for the Athena mirror,” Proc. SPIE 9144, 91442E (2014)
[3] Collon, M.J., Vacanti, G., Barrière, N.M., Landgraf, B., Günther, R., et al., “Silicon pore optics mirror module production and testing,” Proc. SPIE 10699, 106990Y (2018)
[4] Bavdaz, M., Wille, E., Ayre, M., Ferreira, I., Shortt, B., et al., “Development of the ATHENA mirror”, Proc. SPIE 10699, 106990X (2018)
[5] Krumrey, M., Muller, P. et al., "New X-ray parallel beam facility XPBF 2.0 for the characterization of the silicon pore optics," Proc. SPIE 9905, 99055N (2016)
[6] Vacanti, G., Barrière, N.M., Bavdaz, M., Chatbi, A., Collon, M.J., et al., “Measuring Silicon Pore Optics”, Proc. SPIE 10399, 103990N (2017)
[7] Burwitz, V., Willingale, R., Pelliciari, C., et al., “Developing, testing, and calibrating the ATHENA optics at PANTER”, Proc. SPIE 10399, 103990O (2017)
[8] Valsecchi, G., Bianucci, G., et al., “Results of SPO mirror modules optical integration in the ATHENA telescope”, Proc. SPIE 10699, 106990Z (2018)
[9] Vernani, D., Bavdaz, M., Wille, E., et al., “Integration of the ATHENA mirror modules: development status of the indirect and direct x-ray methods”, Proc. SPIE 10699, 1069910 (2018)
[10] Pareschi, G., Moretti, A., Sironi, G., Tagliaferri, G., Tordi, M., Busatta, A., Bressan, R., Marchiori, G., Marioni, F., Valsecchi, G., Zocchi, F., “A vertical facility based on raster scan configuration for the X-ray scientific calibrations of the ATHENA optics”, Proc. ICSO 2018
[11] Menz, B., Brauninger, H., Burwitz, V., Hartner, G., Predehl, P., "Studying ATHENA optics with divergent and collimated x-ray beams," Proc. SPIE 9144, 91445J (2014)
[12] Wille, E., Bavdaz, M., Ferreira, I., Ayre, M., Collon, M., “Silicon pore optics manufacturing plan and schedule for ATHENA”, Proc. SPIE 10699, 106993L (2018)

[13] Spiga, D., Pareschi, G., Pelliciari, C., et al., “Functional tests of modular elements of segmented optics for x-ray telescopes via an expanded beam facility,” Proc. SPIE 8443, 84435F (2012)
[14] Spiga, D., Pelliciari, C., Bonnini, E., et al., "An expanded x-ray beam facility (BEaTriX) to test the modular elements of the ATHENA optics," Proc. SPIE 9144, 91445I (2014)
[15] Pelliciari, C., Spiga, D., Bonnini, E., et al., “BEaTriX, expanded soft x-ray beam facility for test of focusing optics, an update,” Proc. SPIE 9603, 96031P (2015)
[16] Spiga, D., Pelliciari, C., Salmaso, B., et al. “Design and advancement status of the Beam Expander Testing X-ray facility (BEaTriX),” Proc. SPIE 9963, 996304 (2016)
[17] Christensen, F., Hornstrup, A., Frederiksen, P., et al., "Expanded beam x-ray optics calibration facility at the Daresbury Synchrotron," Proc. SPIE 2011, 540 (1994)
[18] Salmaso, B., Spiga, D., Basso. S., Ghigo, M., Giro, E., Pareschi, G., Tagliaferri, G., Vecchi, G., Pelliciare, C., Burwitz, V., Sanchez del Rio, M., Ferrari, C., Zappettini, A., Uslenghi, M., Fiorini, M., Parodi, G., Ferreira, I., Bavdaz, M., “Progress in the realization of the beam expander testing x-ray facility (BEaTriX) for testing ATHENA’s SPO modules”, Proc. SPIE 10699, 1069931 (2018)
[19] Burwitz, V., Willingale, R., Pareschi, G., et al., “AHEAD joint research activity on X-ray optics”, Proc. SPIE 10699, 106993T (2018)
[20] Ptak, A.F. et al., “Arcus: the x-ray grating spectrometer explorer”, Proc. SPIE 10699, 1069926 (2018)
[21] Cotroneo, V.; Spiga, D.; Barbera, M.; Bruni, R.; Chen, K.; Marcelli, C.; Pareschi, G.; Romaine, S.; Zhao, Y. D.; Zheng, L.; Wu, Z. Y, Carbon overcoatings for soft x-ray reflectivity enhancement, Proceedings of the SPIE, Volume 5536, pp. 49-60 (2004).
[22] Sanchez del Rio, M., Cerrina, F., “Asymmetrically cut crystals for synchrotron radiation monochromators”, Review of Scientific Instruments 63, 936 (1992)
[23] M. Sanchez del Rio, N. Canestrari, F. Jiang, F. Cerrina, *SHADOW3*: A New Version Of The Synchrotron X-Ray Optics Modelling Package, Journal of Synchrotron Radiation, 18, 708-716 (2011)
[24] Rebuffi, L., Sanchez del Rio, M., “OASYS (OrAnge SYnchrotron Suite): an open-source graphical environment for x-ray virtual experiments”, Proc. SPIE 10388, 103880S (2017)