AHEAD Workpackage 8
JRA X-ray optics

Deliverable D8.10 – D44

Report on X-ray test and Performance verification → Status of BEaTriX Facility

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1. COMMENT ON CHANGE OF REPORT CONTENT

INAF/OAB started to design the BEaTriX (Beam Expander Testing X-ray) facility in 2012, with the goal to generate a broad, parallel, uniform, monochromatic, and polarized X-ray beam with a compact opto-mechanical system. The basic idea was to use an X-ray microfocus source, a paraboloidal mirror, a monochromation system based on symmetrically cut crystals, and a beam expansion system based on asymmetrically-cut crystals in Bragg diffraction configuration. The facility will be a crucial tool in the development, test, and alignment of Silicon Pore Optics (SPO) modules for the ATHENA X-ray telescope, currently under development by ESA.

The project has been financed with the AHEAD funds, from September 2015 to 2018. The design was mainly focused on the 4.5 keV beam line, making used of Silicon Crystals. It was anyway studied to produced two potential beam lines, by using a single X-ray source capable to emit both 4.5 and 1.5 keV lines, a single parabolic mirror and two sets of crystals, based on Silicon at 4.5 keV and on the organic ADP at 1.5 keV, mounted on dedicated motorizations capable to interchange the crystals, each time a different energy was needed. Few components were purchased and the laboratory prepared to host the BEaTriX facility.

Due to the leverage provided by the AHEAD financing, at the end of 2017 ESA became interested in fitting the facility to the specifications for ATHENA that evolved in the meantime. In order to fulfill ESA requirements for the MM testing facility (PSF and Aeff at 2 energies and at the production rate of 3 MM/day), a more robust design, upgraded with respect to the AHEAD baseline design, was proposed to ESA, which accepted it and decided to fund the new study and its realization. This resulted de facto in a shift of the assembly and commissioning dates for the BEaTriX facility. In April 2018, with the K/O meeting of the ESA contract, the upgraded design started to be studied, and was agreed at the CDR meeting in December 2018. The opto-mechanical design is now robust enough to fulfill the ESA requirements. The improved configuration needs anyway an increased budget for its realization, covered by AHEAD, ESA, and internal INAF funds.

We are now in the realization phase, with the goal of having the BEaTriX facility assembled by the end of 2019, and commissioned by the first half of 2020. This final AHEAD-1 report describes the upgraded design, as agreed with ESA, and the status of the facility realization.

2. UPGRADE TO THE AHEAD BASELINE DESIGN

In order to fulfill ESA requirements, OAB upgraded the AHEAD design to improve the reliability of the system:

1) *the laboratory*: a study of the system foundation was commissioned to BCV-progetti (Milano, Italy) with the goal of constructing a stable foundation that will isolate the beam line from vibrations due to the environment, anthropic-noise sources and vacuum pumps. Rigid elastomers were placed in between the foundations and the under-foundations slab. The laboratory is now completed.

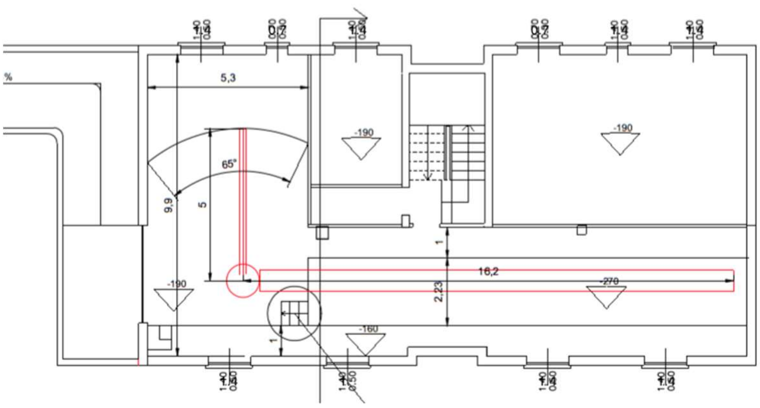


Figure 1A. The AHEAD design of the laboratory.

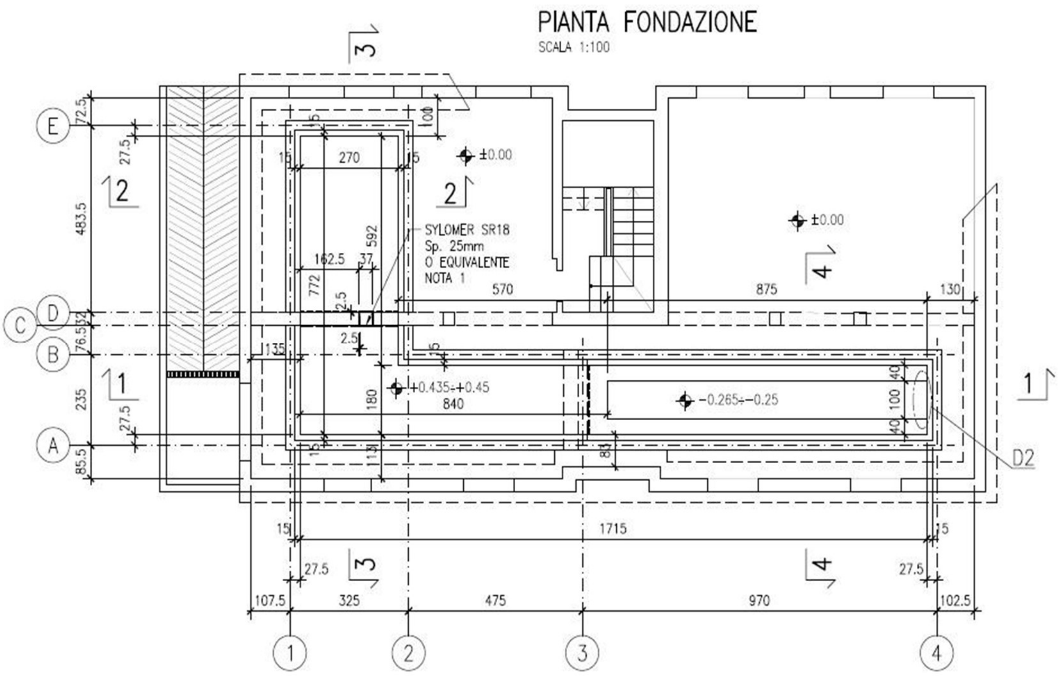


Figure 1B. The upgraded and final design of the BEaTriX laboratory, with damped foundations

2) *the optical design*: a team of experts in crystals was formed, including INAF-OAB, SLAC (California), IMEM-CNR (Parma, Italy), ESRF (Grenoble, France), and PANTER-MPE (Garching, Germany). The energy-dispersive properties of the asymmetrically-cut crystals, was found extremely critical in determining the horizontal beam collimation, dependent on the spectral bandwidth of the beam, as out of the monochromator. Therefore, the monochromator design was modified from 2 to 4 reflections: a tilt of the 1st and 2nd crystals of about 10 arcsec, allows us to reduce the horizontal divergence to 1.5 arcsec (Fig. 3 left). This value has to be compared with 9 arcsec for 2 reflections and no tilt.

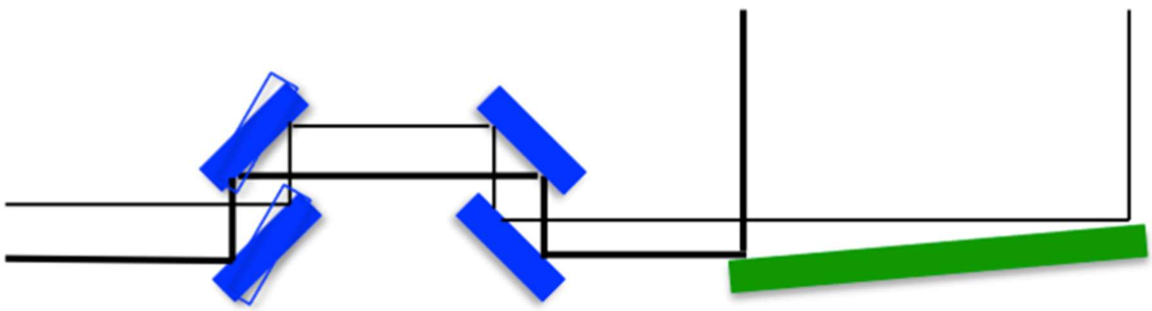


Figure 2: Optical layout of the monochromator (blue) and the beam expander (green). The crystal for monochromation are symmetrically cut, the one for the beam expander is asymmetrically cut. Monochromation with four diffractions, with a possible rigid rotation of the first pair of crystals to detune the rocking curves and so shrink the passing band.

The monochromator will be realized with two Channel Cut Crystals, on two different rotation stages. This configuration gives the possibility to optimize either the horizontal divergence or the flux, depending on the needs and the quality of the sample to be tested.

A photon loss, of about a factor 10, is payed to reach a divergence of 1.5 arcsec also in the horizontal direction (Fig. 3 right). Nevertheless, the expected intensity of the beam at the sample, based on the X-ray source intensity of ($5*10^{11}$ ph/sec/sterad), is estimated to be of 10 ph/s/cm^2, a flux that enables a SPO MM characterization in a ~30 min integration.

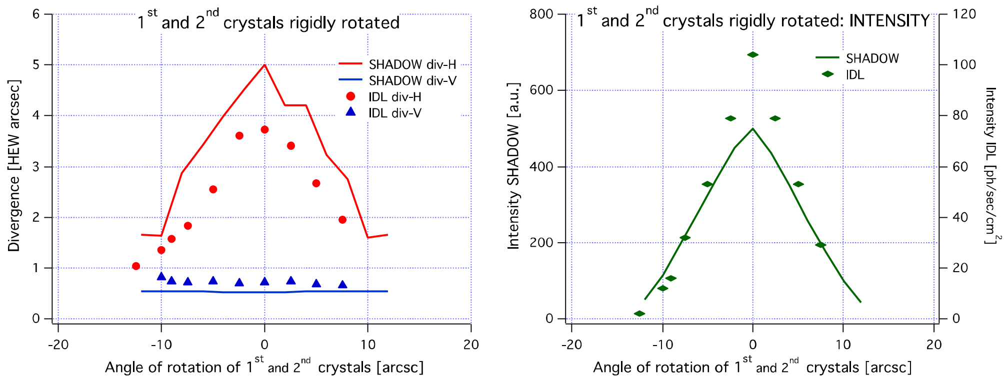


Figure 3: Effect of the tilt of the 1st and 2nd parallel symmetric-cut crystals. Left: Vertical (blue) and horizontal (red) divergence. Right: Intensity loss. Note that the SHADOW result is given in arbitrary units while the result from the IDL code is given in ph/s/cm².

3) *the mechanical design*: in order to guarantee the ESA specifications of calibration of 3 MM/day, and assure a perfect alignment when switching from one energy to the other one, two fixed beam lines were considered the best approach, with two X-ray sources, two parabolic mirrors and two motors lines for the optical components. The study to realize the new system was commissioned to Tecnomotive (Padova, Italy).

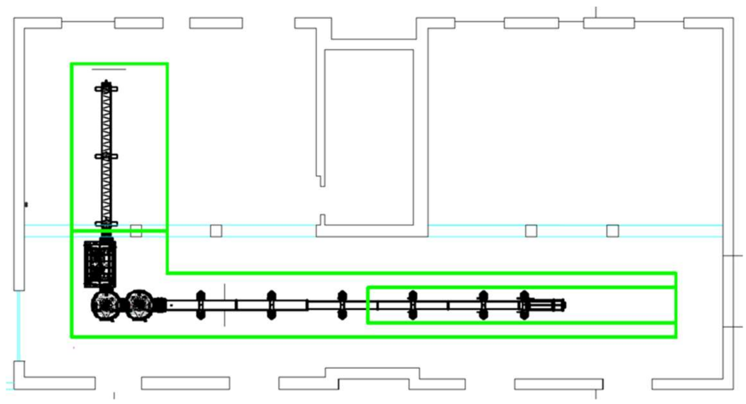


Figure 4A. The AHEAD mechanical design

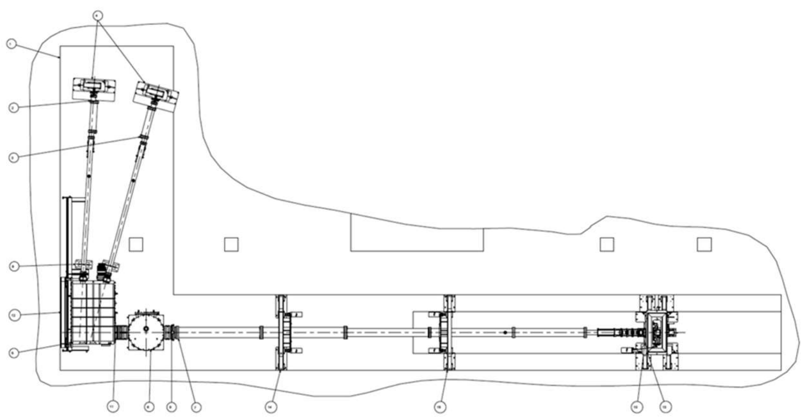


Figure 4B. The upgraded and final mechanical design, with two fixed beam lines

4) *the vacuum level*: in order to guarantee the ESA requirement of 99.7% level of confidence in the Effective Area measurements, the base pressure was modified from 10^{-2} mbar to 10^{-3} mbar aiming to having a stable flux also for the 1.49 keV photons (Fig. 5). The study to realize the new system was commissioned to Tecnomotive (Padova, Italy). The vacuum pumping system now foresees the introduction of turbo pumps, in addition to the primary pumps.

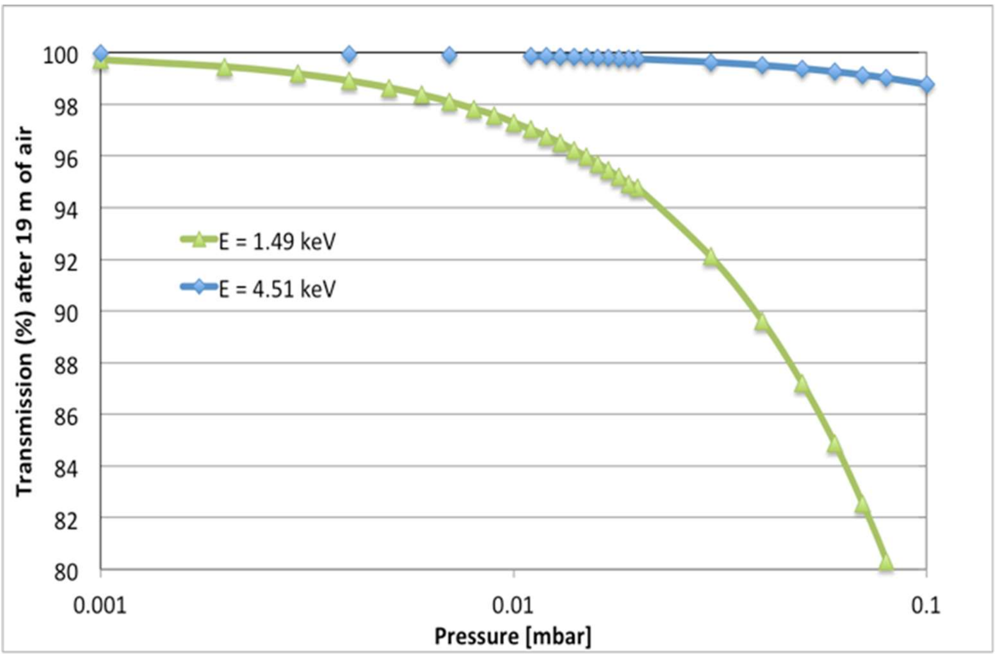
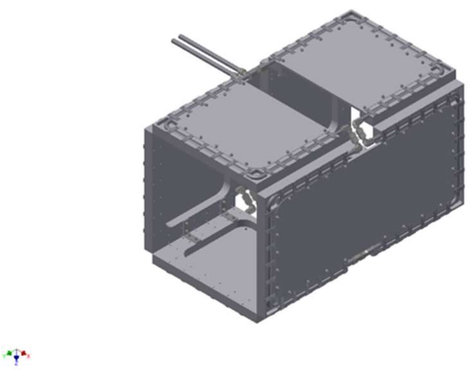


Figure 5 : Transmission of X-ray photons of 4.51 keV and 1.49 keV, along the 19 m vacuum tube of BEaTriX, as a function of residual vacuum pressure

5) *the thermal box for the MM*: ESA have requested for BEaTriX the capability to test the MM in different thermal conditions, with a temperature range T=293±30K. To this end, a thermal box is foreseen: it is positioned inside the MM chamber and surrounds the MM itself, heating and cooling it only radiatively. A liquid line, connected to an external thermostat, modifies the temperature of the thermal box. A special design enables also the application of some thermal gradients to the MM, to test its optical performances variation.



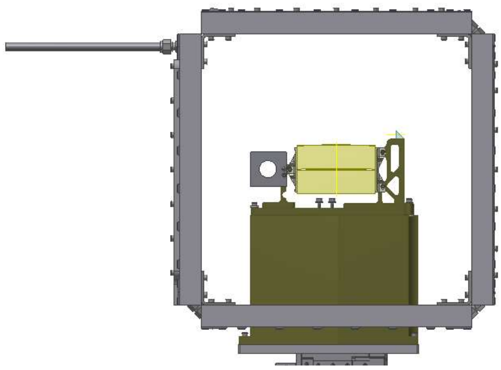


Figure 6: Left: Thermal box drawing; the liquid is flowing only through two faces. The other two are conductively heated/cooled in order to enable gradients on the MM
Right: The MM on its supporting structure, inside the thermal box

6) *the detector XYZ movement*: the new design is more robust and better guarantee the XY movements of the detector for the full beam (170 mm x 66 mm) characterization, and to increase the Z movements enlarging the focal range to 500 mm. A chardanic off-loading mechanism is present in between the MM Chamber and the long arm to enhable the X movement, and a long bellow is present to enable the Z movements.

3. THE UPGRADED AND FINAL OPTO-MECHANICAL DESIGN

The final optical design is shown in Figure 7. An X-ray microfocus source (30 µm focal spot FWHM) is placed in the focus of a paraboloidal mirror; a monochromation system with 4 symmetrically cut crystals produces a highly monochromatic beam, which is diffracted and expanded by an asymmetrically-cut crystal. The expanded beam is fully illuminating the aperture of MM, imaging the focused beam at 12 m distance, where a directly illuminated CCD camera is placed. The high flux ($10^{11} \div 10^{12}$ ph/s/sr) generated by the micro-focused source, and the highly monochromatic beam produced by the optical elements enable the Effective Area and PSF characterization with high accuracy.

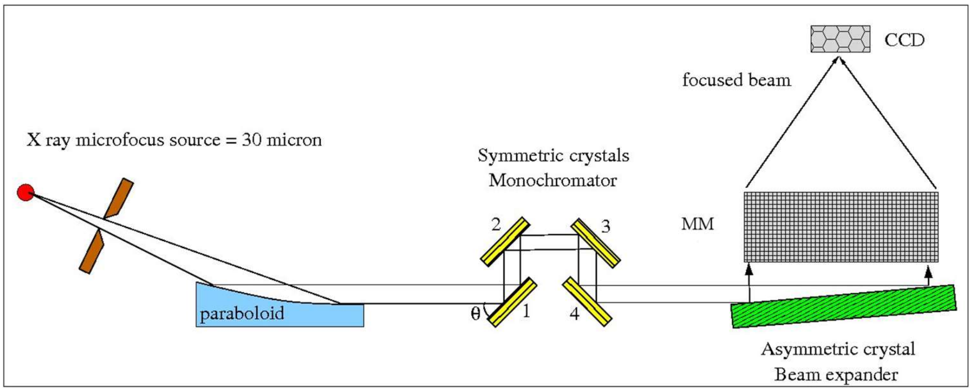


Figure 7: The final optical design

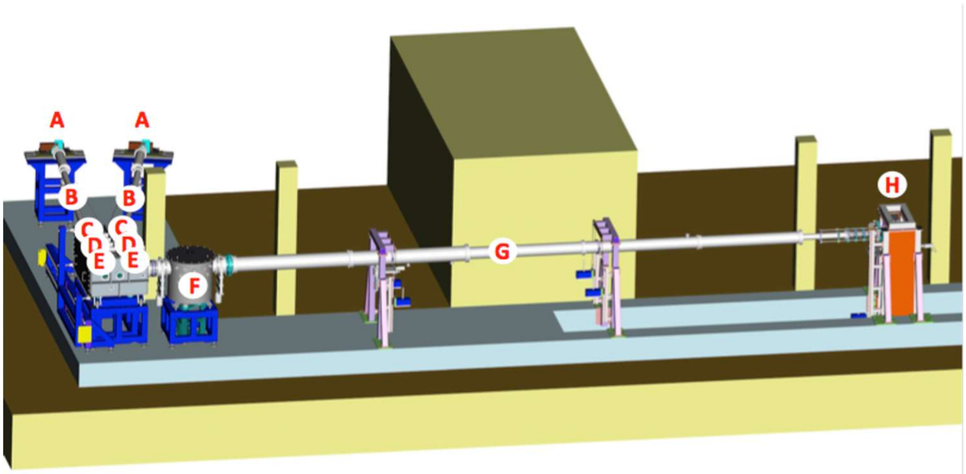


Figure 8: The final mechanical design

Figure 8 presents the final mechanical design. The system is very compact (9 x 18 m^2) and it is designed with modular compartments where the vacuum can be broken independently to replace the optics under test. It works at a vacuum level of 10^{-3} mbar, easily evacuated in a short time.

Two sources (A) are positioned at the beginning of the lines and can be aligned with mechanical adjustments in air.

The beams are propagated through the short arms (B) onto the *Optical Chamber* (rectangular tank in Figure 8), where they are reflected by two sets of optical components, each of which is dedicated to one of the two energies. The parabolic mirror (C) is used for beam collimation; a reflection on 4 symmetrically cut crystals (D) have the function to monochromate the beam, while the asymmetrically cut crystal (E) expand the beam and reflect it at about 90 deg. The optical components (C), (D) and (E) are motorized in vacuum, in order to reach a proper alignment and produce a collimated enlarged beam.

In the *MM chamber* (cylindrical tank in Figure 8), the beam encounters the MM (F), and it is thereby focused. The MM is also motorized in vacuum, in order to be aligned to the beam. A thermal box surrounds the MM, and radiatively heats it, to test its optical properties at temperature ranging from -10 to +50 °C. A clean tent ISO5 will surround the MM tank in order to minimize the deposition of particulate on the MM itself.

The focused beam is propagated through the long arm (G) into the detector (H), placed at 12 m distance. The detector is a directly illuminated CCD with sensor size of 27.6 mm × 27.6 mm and pixel 13.5 µm. It is connected to the long arm, and motorized in air for movements in the vertical (range = 1500 mm) and horizontal (range = 150 mm) directions. A focal range of 500 mm is obtained also with in air motorization and a properly designed bellow in front of the CCD. The long arm is made of 6 tubes with decreasing diameter, to leave the possibility to modify the facility for focal distances other than 12 m.

4. THE VACUUM PUMPING DESIGN

The design of the vacuum pumping system is carried out with the following goals:

- minimize vibrations
- compatibility with a vacuum level of 10^{-6} mbar; operations at 10^{-3} mbar
- evacuation time of the MM Chamber within 30 min
- evacuation time of the Optical Chamber, long arm, and short arms within 60 min (each sector separately)

To reduce vibrations, the following approach is considered:

- use magnetic turbo pumps (reduced vibrations with respect to mechanical turbo pumps)
- turbo pumps without fan (not necessary at the pressure considered; a water cooling system is already foreseen for these pumps)
- switch off the primary pump of the line during measurements

To implement these specifications, two vacuum lines are considered:

- pre-vacuum from 1000 mbar to 0.15 mbar with a single primary pump
- high vacuum from 0.15 mbar to 10^{-4} mbar with magnetic turbo pumps (10^{-4} mbar is considered a safe margin since all the simulations are performed without components in the chamber)

Therefore, two primary pumps (one for the fore-vacuum line - Scroll 18 m^3/h -, the other one downstream the turbo pumps - Scroll 40 m^3/h -) and four turbo pumps are used (two for the two short arms - Turbo mag int 300 l/s - , one for the Optical Chamber - Turbo mag int 600 l/s -, one for the long arm - Turbo mag int 300 l/s -).

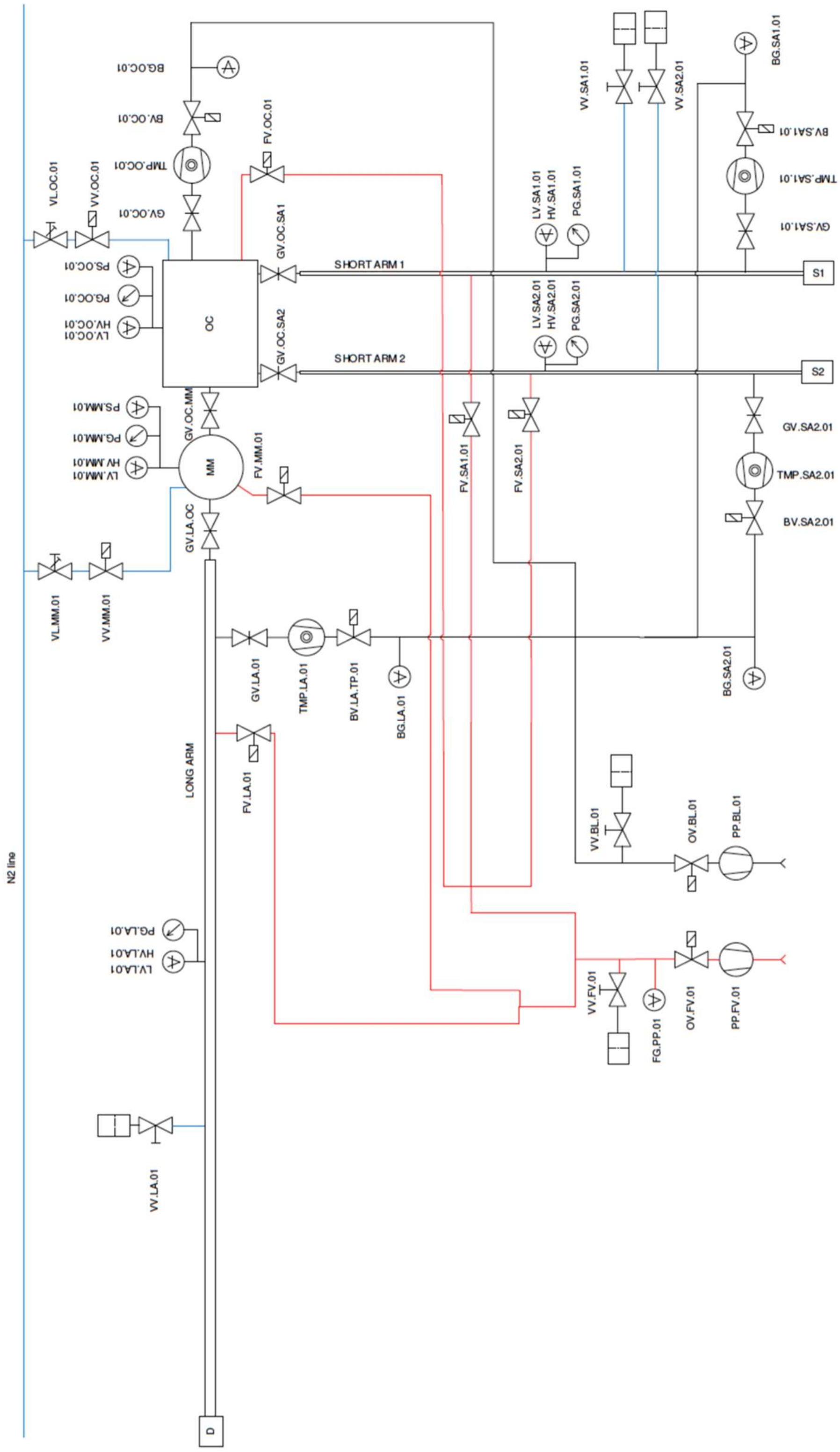


Figure 9: The vacuum pumping layout

5. MOTORIZATIONS IN VACUUM

Thorough simulations have been performed in order to define the alignment tolerances of the optical components. These in turn, have defined the vacuum motors needed for the beam alignment, and their resolutions (Table 1). 14 motorizations in vacuum are required for the 4.51 keV line, and other 11 for the 1.49 keV line, for a total of 25 vacuum motors.

Table 1: 14 motorizations in vacuum are required for the 4.51 keV line. The table shows the number of motors required and their resolutions.

	Number of motor with resolution = 10 μm	Number of motor with resolution = 100 μm
Translation	1	3

	Number of motor with res. = 50 arcsec	Number of motor with res. = 20 arcsec	Number of motor with res. = 5 arcsec	Number of motor with res. = 3 arcsec	Number of motor with res. = 1 arcsec	Number of motor with res. = 0.5 arcsec
Rotation	2	1	1	1	1	4

6. ADVANCEMENT IN THE REALIZATION

At the end of December 2018, the advancement of the BEaTriX facility is as follows:

a) the laboratory is completed, following the BCV project;

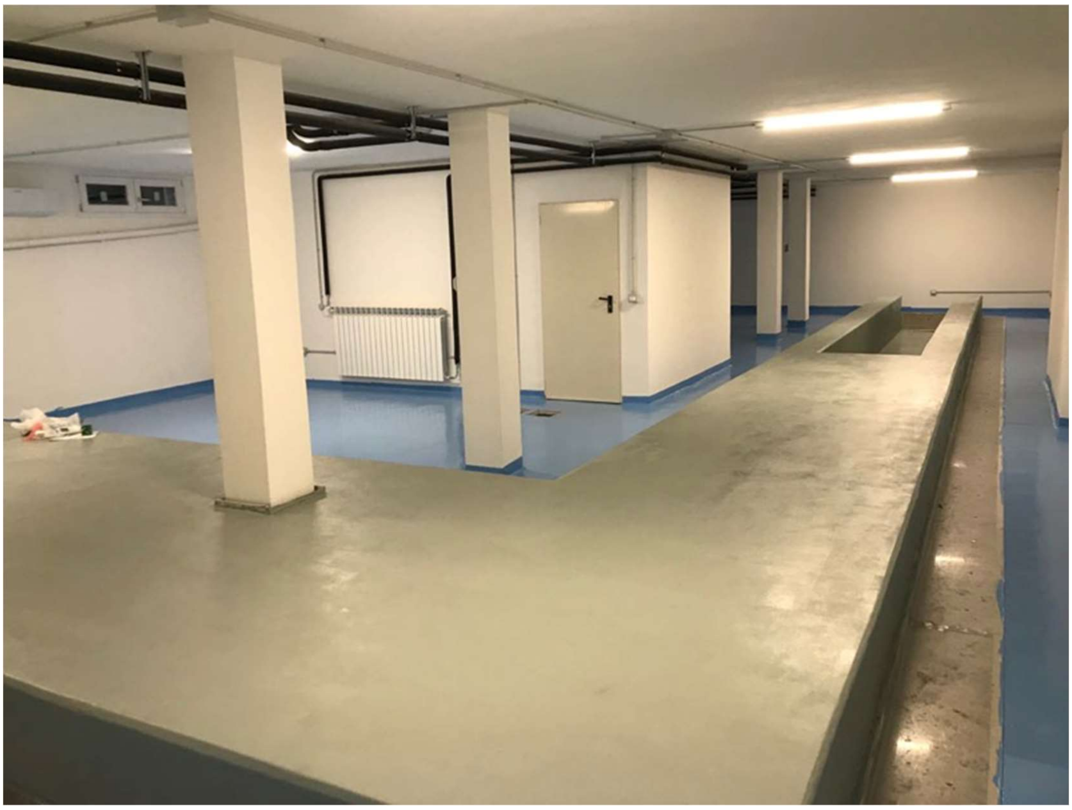


Figure 10: The laboratory and the BEaTriX foundation built on BCV project

b) The vacuum system project is completed and approved by ESA during the CDR. The tender phase for its realization has now started.

c) The X-ray source procurement is at the tender phase;

d) The parabolic mirror is being polished with the Zeeko machine present at INAF-OAB and measured with the optical profilometer MPR at Media Lario. The final shape accuracy have to reach 12 nm rms, with 3 Å roughness. After the Zeeko, the superpolishing and the final figure correction with the IBF will guarantee the surface quality.

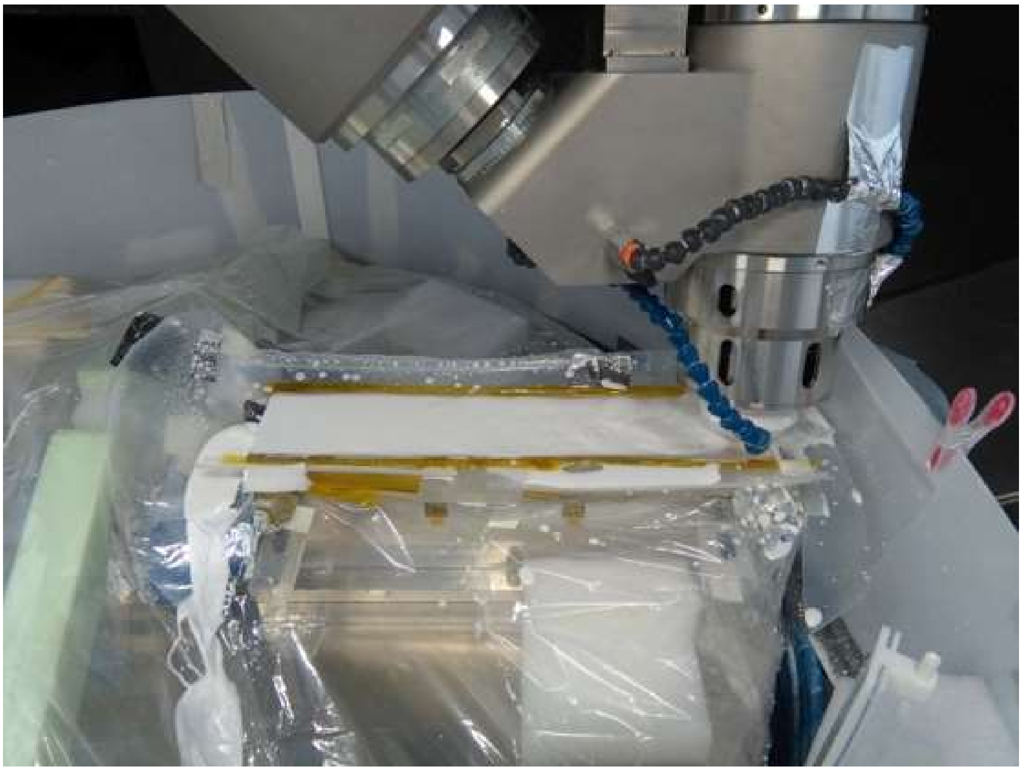


Figure 11: The parabolic mirror. Left: polishing with Zeeko @ INAF-OAB. Right: measuring with MPR @MLT

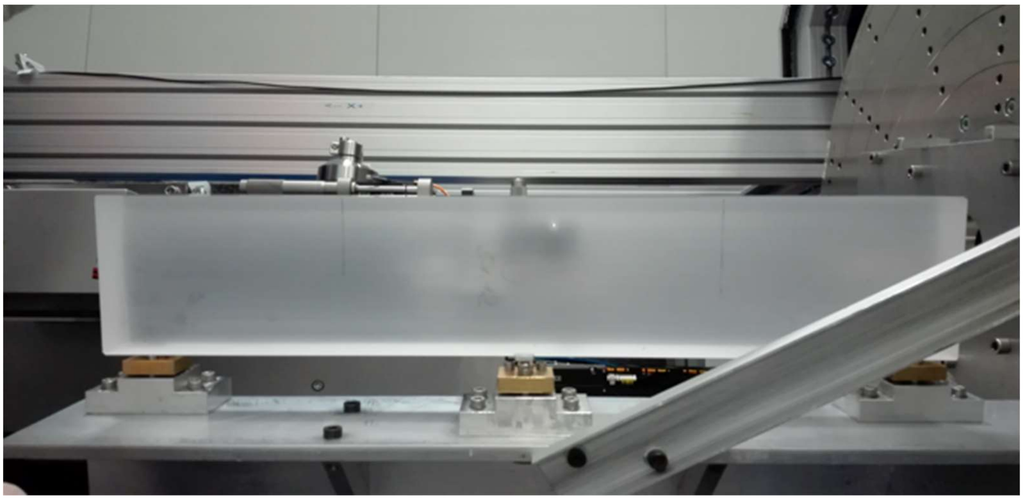


Figure 12: The parabolic mirror: measuring with MPR @MLT

e) The monochromator design is finalized: two Channel Cut Crystals in Silicon (220) have to be procured;

f) The beam expander is ready, produced by IMEM-CNR in Parma;

Figure 13: The beam expander, produced @ IMEM-CNR

g) The CCD detector, the beam monitor, and the phosphor window are finalized and need to be procured;

h) The AIV plan is defined, and the AIV tools need to be procured.

7. CONCLUSIONS

The BEaTriX facility realization is ongoing at INAF-OAB. The design of BEaTriX, started in 2012, has been continuously evolving thanks to an AHEAD grant, and to other dedicated INAF funds. Since 2018, its development is also funded by ESA with a dedicated contract. ESA requirements resulted in modifications to the AHEAD baseline design, with a significant upgrade of the facility, shifting the commissioning of the facility. The opto-mechanical design is now consolidated and approved by ESA during the CDR, held on December 2018. Now the purchasing phase has started. The facility is expected to be assembled by the end of 2019 and commissioned by the first half of 2020.