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MINERVA installation status, an X-ray facility for the characterization of the ATHENA mirror modules at the ALBA synchrotron

Dominique Heinis*[a], Antonio Carballedo[a], Carles Colldelram[a], Guifré Cuní[a], Núria Valls Vidal[a], Alejandro Sánchez[a], Joan Casas[a], Josep Nicolàs[a], Maximilien J. Collon[b], Giuseppe Vacanti[b], Michael Krumrey[c], Ivo Ferreira[d], Marcos Bavdaz[d]

[a]ALBA Synchrotron, Carrer de la Llum 2-26, 08290 Cerdanyola del Vallès, Spain
[b]cosine measurement systems, Oosteinde 36, 2361 HE Warmond, The Netherlands
[c]Physikalisch-Technische Bundesanstalt (PTB), Abbestr. 2-12, 10587 Berlin, Germany
[d]European Space Agency, ESTEC, Keplerlaan 1, PO Box 299, 2200 AG Noordwijk, The Netherlands

ABSTRACT

MINERVA is an X-ray beamline designed to contribute to the development of the ATHENA[1,14] mission (Advanced Telescope for High Energy Astrophysics) at the ALBA synchrotron[2] (Barcelona, Spain). Originally based on the monochromatic pencil beam XPBF 2.0 at the Physikalisch-Technische Bundesanstalt (PTB at BESSY II), MINERVA will be furnished with the necessary equipment to produce and characterize the mirror modules (MM) of ATHENA by adjusting and assembling 4 SPO stacks together (manufactured by cosine measurement systems) [4,5]. The construction of MINERVA is also an opportunity to bring some innovations in order to improve the characterization time of each MM produced[6]. Full interoperability with XPBF 2.0 is secured to allow operators to work on both beamlines the same way. The MINERVA project started in March 2020 and the last past months were dedicated to the definition, design, procurement, partial assembly and installation of the different beamline components. MINERVA is funded by the European Space Agency (ESA) and the Spanish Ministry of Science and Innovation and will be completed for operation at the turn 2022/2023.

Keywords: X-ray optic, Silicon Pore Optics, Synchrotron, Metrology, ATHENA, X-ray astronomy

*Dominique Heinis.: E-mail: dheinis@cells.es, telephone: +34 93 592 4052

1. INTRODUCTION

The ATHENA telescope is a space observatory that will answer fundamental questions about energetic objects[3] (accretion disk around black holes, large-scale structure, etc...) that emits photons in the X-ray spectrum. Among all the different components of the telescope, the modular architecture of its optics makes ATHENA an innovative instrument to collect light coming from space. In Figure 1 a) is summarized the multiscale approach used to build the optics. Based on a modified Wolter-Schwarzschild geometry, it consists in a structure made of 15 concentric rings, filled by about 600 sub-elements called Mirror Modules (MMs). Individual MM are organized in a set of four stacks constituted each by a pile of 38 highly polished silicon wafer plates of which 36 contribute to the optics (Silicon Pore Optics technology (SPO)). Photons in the energy range from 0.2 keV to 12 keV are reflected on two consecutive plates reaching the focal point located 12 meters further. At the focal plane, the telescope will be equipped with both imaging and spectroscopy instrumentation. Since the optics is based on the assembly of hundreds of individual and independent parts, the alignment operation is a crucial step to comply with the performance requested for the full assembled optics. It is precisely in the mass production of aligned MM where lies the main task of MINERVA. Currently, at the parallel beam facility XPBF 2.0 (BESSY II in Berlin), cosine measurement systems is developing and improving the experimental procedures to manufacture and characterize MM at large scale. MINERVA rely entirely on these previous precursor know-hows acquired during the past years. Indeed, the chosen method is briefly sketched in Figure 2 (more details can be found in [6])

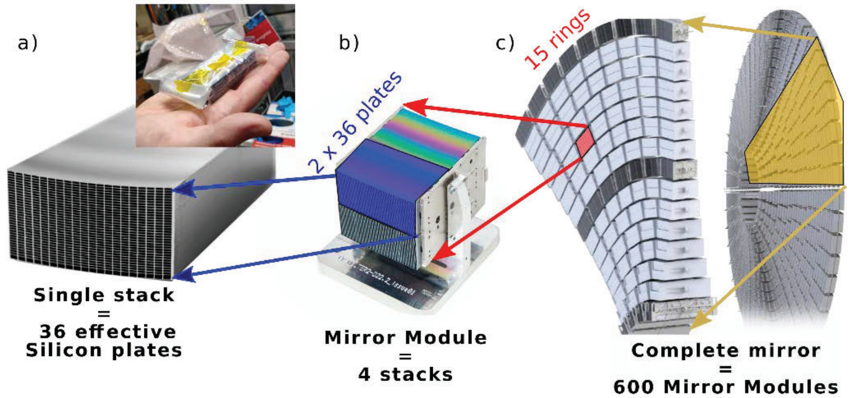

Figure 1 The ATHENA optics made of 15 rings and populated by about 600 mirror modules. a) Single stack produced by cosine with the Silicon Pore Optics technology b) Mirror module made of 4 stacks c) Full optics of ATHENA with about 600 MMs

It is presented a jig populated with 4 stacks labelled OP, OS, IP and IS and composing a complete MM. Three of them (OS, IP and IS) are rigidly attached to a dedicated hexapod while the first one (OP) remains still. The relative position and orientation adjustment of an individual stack independently from the others is then easily realized within the jig itself. An X-ray collimated beam is then sent at normal incidence towards the optics. The jig is itself rigidly fixed on the top platform of a larger hexapod in order to control the 3D position of the MM respect to the incident X-ray beam. Light is then deflected and partially focused by 2 consecutive stacks (first OP and then OS in the figure) toward a 2D array detector about 12 meters further (close to the focal plane of the ATHENA optics). The Point Spread Function (PSF) is then collected and recorded for further analysis. Since the incident synchrotron X-ray beam dimensions are smaller than the entrance aperture of a single stack, a complete characterization requires to repeat this operation over the entire entrance of the optics by mechanically moving the MM along a plane perpendicular to the input beam. At XPBF 2.0, this scan is performed thanks to the main hexapod. The data of the different PSF patterns generated during the MM scan leads to the computation of the relative geometrical misalignment between the 4 stacks. A correction is then applied by readjusting the 3 smaller hexapods and optimization of the position of the 4 stacks within a MM is accomplished.

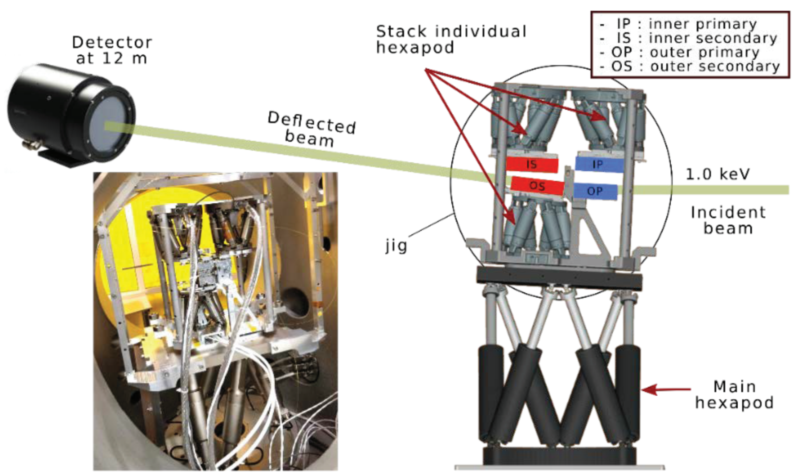

Figure 2 Experimental method to align and characterize a whole mirror module. The main hexapod scans the MM optical entrance in front of the incident X-ray beam produced by a synchrotron light source. The photo shows the jig populated with 4 stacks on top of the main hexapod at the XPBF 2.0 beamline (PTB, BESSY II).

2. GENERAL BEAMLINE DESCRIPTION

As mentioned already earlier, MINERVA is mainly a replica of XPBF 2.0 and keeps globally the same layout. In Figure 3 are shown the three main components of the beamline: the multilayer monochromator enclosed in a radiation shielding hutch, the MMs assembly environment placed inside a temperature-controlled enclosure, and the detector which 3D location is mechanically adjusted depending which MM geometry is under characterization. In the following we describe more in detail the different components of the beamline (a short video with a virtual overview of the beamline is also available at [16]).

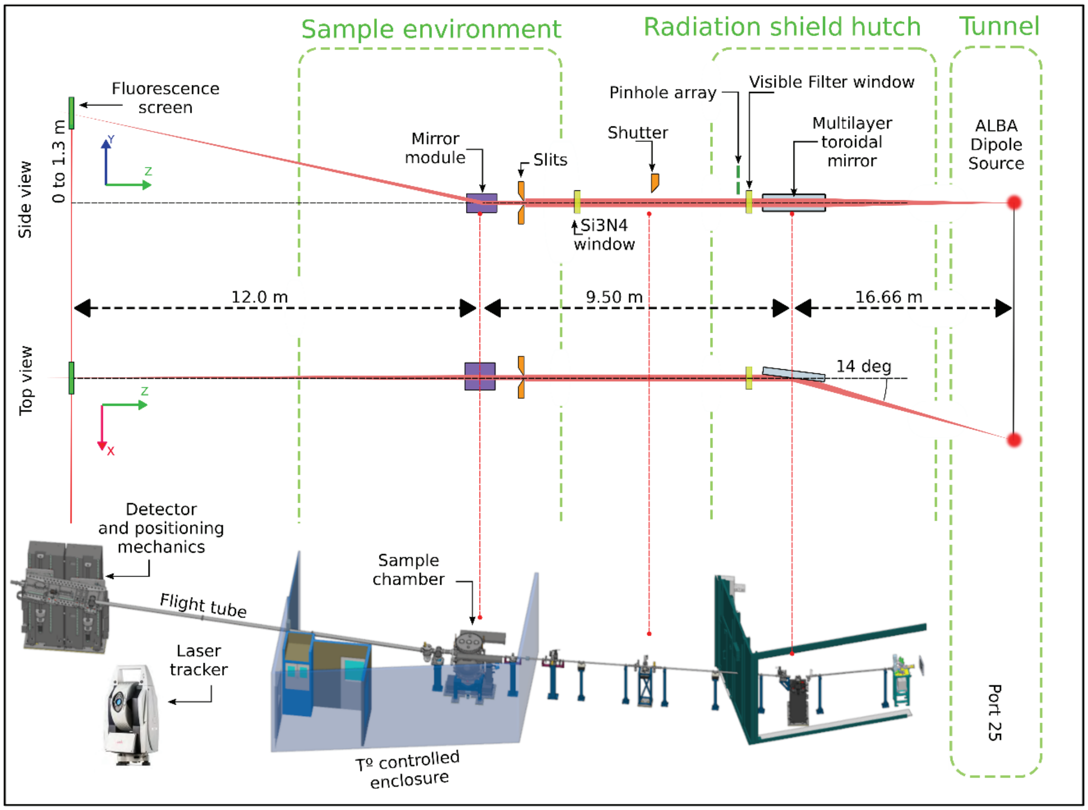

Figure 3 MINERVA layout presenting the main components of the beamline.

2.1 Collimated 1.0 keV X-ray generation

At MINERVA, the synchrotron radiation is produced by a bending magnet of 1.4 Tesla. All the main characteristics of the source are given in [15]. The beam produced has about 1 mrad divergence and has a very broad energy spectrum. It is why the first optical element of the beamline is a toroidal shaped multilayer coated mirror. The multilayer selects a narrow bandwidth of the incoming radiation about the nominal energy of 1.0 keV. Figure 4 presents the calculated reflectivity for the multilayer manufactured by AXO-Dresden and made of 30 bilayers of Silicon/Tungsten. The parameters (bilayer thickness □ 5.4 nm and Γ □ 0.5) have been chosen to optimize the output at 1.0 keV while canceling out the second harmonic reflection. The toroidal shape of the mirror collimates vertically and horizontally the beam emitted by the bending magnet with an expected residual divergence below 1.0 arcsec for a maximum beam dimensions of 8.0 x 8.0 mm^2. The silicon substrate produced by Thales-SESO has a sagittal radius of about 4.0 meters and a meridional radius of about 273.4 meters. The mirror deflects the beam horizontally inboard by 14 degrees (incidence angle 7.0 degrees respect to surface) and will be held in position by a precision positioning system which will provide remote control of the pitch mirror (incidence angle adjustment) and displacement along the normal of the mirror surface. The motion will be based on an in-air stepper motor driven mechanics, and will include encoders to provide position feedback on control. The mirror is enclosed in a UHV chamber and will be side cooled by means of a copper water circuit.

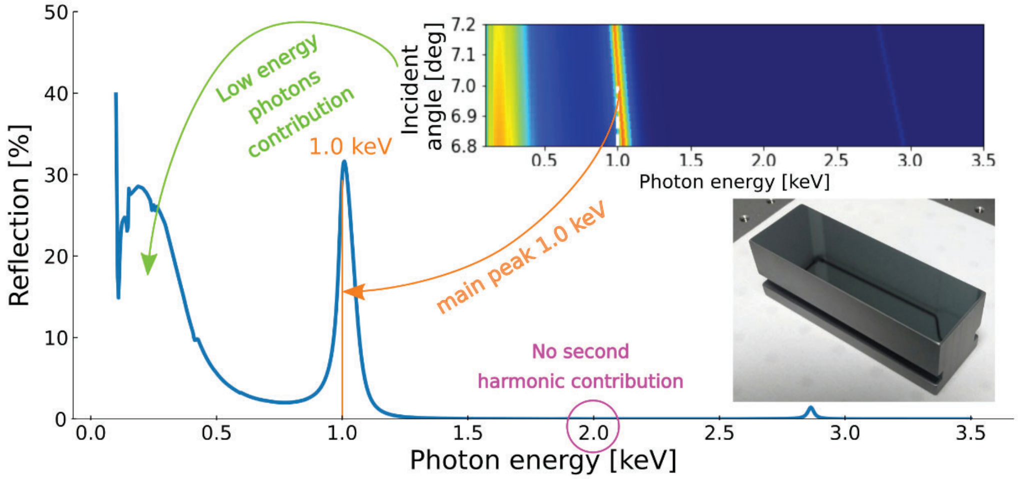

Figure 4 Computation of the multilayer reflectivity manufactured for MINERVA. The parameters are optimized to favor reflectivity at 1.0 keV and suppress also the second harmonic contribution (Γ = 0.5 and d =5.4 nm). For illustration, the inset plot shows how the main peak shifts only few tens of eV when the mirror is tilted by 200 mdeg, which is comparable to the width of the peak itself. Calculations done with XOP. The photo shows the toroidal mirror substrate (SESO Thales) with its coating (AXO-Dresden).

2.2 Apertures, filters, diagnostic

In addition to the main opto-mechanical components described above, the beamline will include also several apertures, filters and diagnostics. They are briefly described in the following:

- downstream the monochromator is placed a motorized array of molybdenum pinholes with different diameters: Ø10 µm, Ø20 µm, Ø50 µm, Ø100 µm, Ø200 µm, Ø500 µm. The array can also be fully retracted to allow the entire beam passing through.
- together with the pinholes, a 600 nm thick Si_3N_4 membrane coated with 240 nm of Aluminum is placed to suppress photons with low energy. Indeed, as seen in Figure 4, the multilayer coating still reflects a huge amount of low energy photons that has to be cut off. The combination of Si_3N_4 and Aluminum allows to get rid of this part of the spectrum.
- right upstream the chamber, is placed a photon shutter actuated pneumatically. It consists on a plate coated with phosphor that absorbs X-ray and reemits visible light. When closed, it provides an image of the beam shape and position and is visible from the viewport that is used for diagnostics.
- a window which separates the upstream UHV section from the downstream HV. It consists of Si_3N_4 membrane installed on a CF40 flange. This membrane also contributes to the suppression of low energy photons as mentioned earlier.
- a slits system with four motorized and encoded blades allows to adjust the beam dimension form 10x10 μm^2 to 8.0 x8.0 mm^2.
- an actuated attenuator which holds several Kapton or Aluminum foils of different thicknesses used to attenuate the incident beam intensity.

2.3 Mirror Modules assembly environment

The MM are assembled inside a vacuum chamber that is almost a full reproduction of the one built at XPBF2 to guaranty complete interoperability between the two beamlines. The sample station is placed about 9.50 meters downstream the monochromator. The chamber is large enough to allocate the MM positioning stage and their alignment mechanics. The vacuum chamber is mechanically decoupled from the MM positioning stages, and it is supported by means of an independent steel frame, fixed directly to the floor. The MM vacuum chamber (Figure 5) accommodates several ports, purposed for electrical or optical fibers feedthroughs, and two adapted viewports used by autocollimators for positioning control (explained later in this article). It includes also two large ports with hinged doors at both sides, to allow accessing the sample platform from both sides.

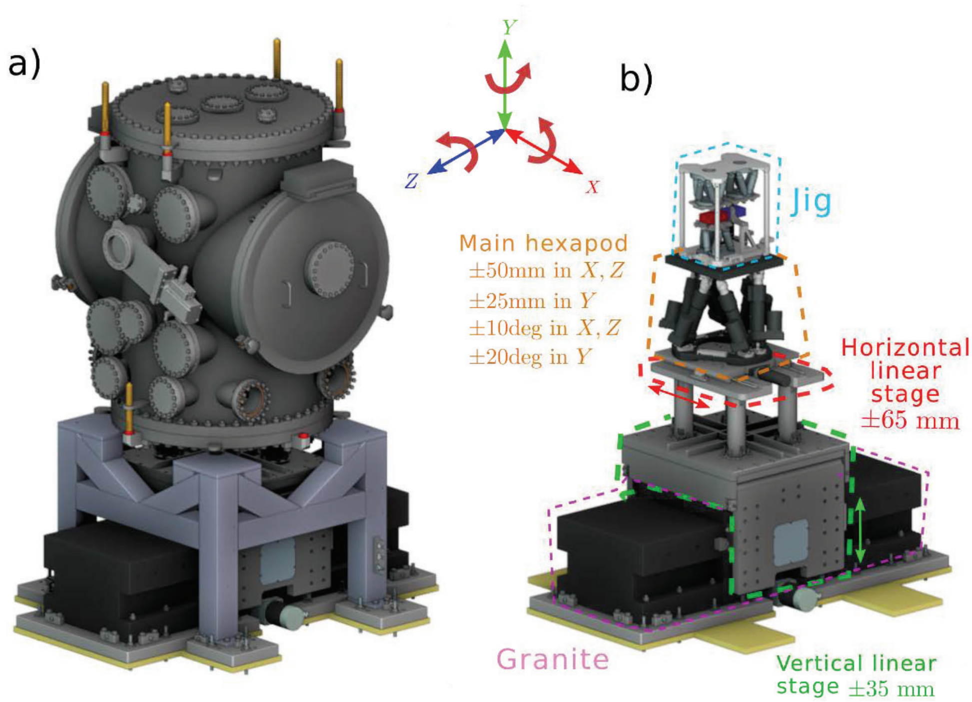

Figure 5 Sample environment. In a) is shown the vacuum chamber. In b) mechanical solution to limit the number of hexapod orientation corrections

As mentioned earlier in the context of the MM optical characterization presented at Figure 2, the main hexapod is responsible to scan the MM in front of the incident X-ray beam at XPBF 2.0. In MINERVA this task is now assigned by two dedicated linear stages added specifically to the original design (see Figure 5 b) to speed up the MM characterization (more detailed explanation will be given later in section 3 of this article). The main hexapod is mounted on top of two high precision linear stages, providing vertical (Y axis) and horizontal motion (X axis). The whole system is mounted on the top of the granite block. The vertical motion takes place in air and is connected to the rest of the chamber via edge welded bellows. This motion is particularly designed to keep constant the orientation of the MM during a vertical scan thanks to rigid linear guideways fixed on both sides of the granite. On the other hand, both the hexapod and the horizontal linear stage work under vacuum. Both direction scanning range are compatible with all the different MM geometries.

The MM station is located in a clean environment enclosure, which provides also temperature stability. The enclosure will be equipped with an air conditioning system that will stabilize the temperature to a level better than ± 1°C. The set point temperature will be set about 20°C, below the nominal temperature of the ALBA experimental hall. Since cleanliness is required for the MM manipulation, the air conditioning system of the enclosure will include high-efficiency particulate air filters (HEPA).

2.4 Flight tube and Detector tower

A flight tube links the MM station to the detector and preserves the vacuum along the 12 m long beam path between the MM and the detector (see Figure 3). It can adapt its position to the range of the different deflection angles (its orientation can range from horizontal to about 7 degrees upwards). In addition, its adjustable length through a series of bellows can compensate motion of the detector longitudinal position. Following XPBF 2.0, the imaging detection is also based on an indirect detection. The main difference lies in the use of a scintillator (Gadox) coupled to the optical sensor by an optical fiber bundle. The scintillator is directly deposited on the fibers with 100% efficiency at 1.0 keV. Since the fibers are directly glued on top of the CMOS sensor, no preliminary alignment is needed. The 2-dimensional array detector will be mounted on a vertical structure (called tower) with enough controlled degrees of freedom to maintain its position in the line of sight of the beam deflected by each MM. In MINERVA, the architecture of the tower deviates also from the one of XPBF 2.0. In Figure 7, is shown the conceptual implementation consisting of two large flat and stable granite blocks that provide an outstanding reference plane, mechanical and thermal stability. The height position and orientation of the detector is now realized by the different elevation of two vertical moving platforms along the two granite columns. As shown on the picture, the detector can also move along the deflected beam to find the focus point (longitudinal direction). Motion in the transverse direction are also available. All translations are based on the combination of ball spindle, preloaded ball guides and stepper motor. All positioning motions will be remotely controllable by stepper motors and absolute encoders. We should highlight also that the present design leaves a complete side free from any mechanical support allowing the full visibility of the detector at any positions. This feature is relevant when a laser tracker needs to measure the position of the detector in the 3D space. This point is going to be described now in the following section.

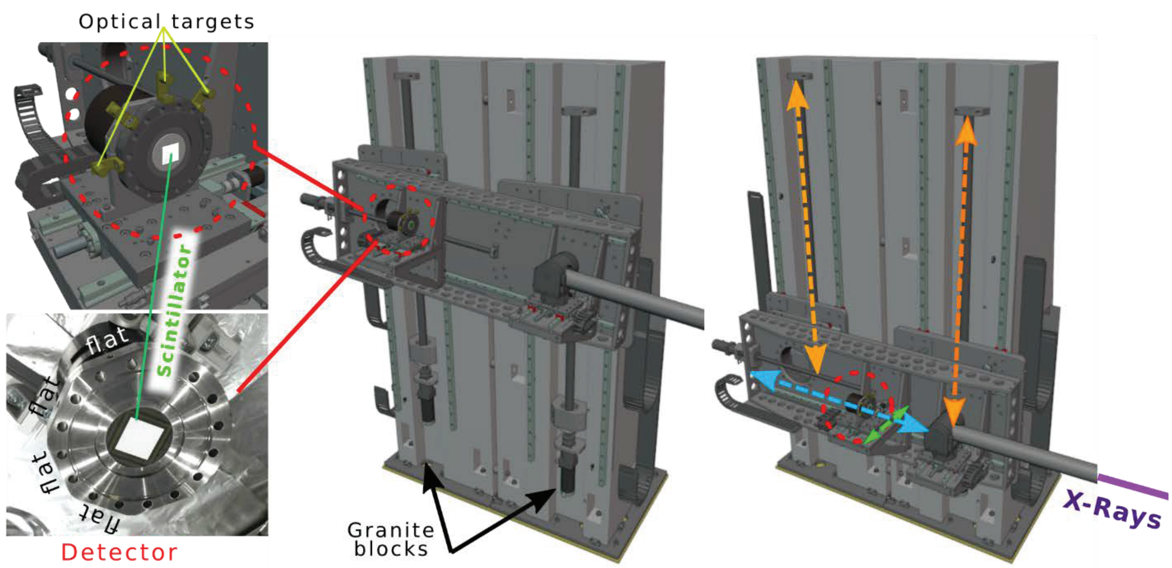

Figure 6 The detector positioning mechanism allows all the suitable degrees of freedom to intercept the deflected beam by any kind of MM needed for the ATHENA optics. The detector can move up-down and be tilted according to the height difference of the two vertical platforms (orange arrows). The detector can also move along the beam direction (blue arrow) and transversally (green arrow). The photo shows the CMOS sensor by Photonic Science covered with a scintillator layer of about 30 x 30 mm² and with flats on the flange periphery to hold optical targets. Some mechanical parts have been removed from the drawings to help the identification of the different elements.

3. CONTROL AND MONITORING OF THE BEAMLINE GEOMETRY

The 4-stacks alignment method presented at Figure 2 is effective only if two conditions are satisfied. First that the MM orientation is kept within 1.0 arcsec during a scan. Secondly that the distance between the MM center and the detector scintillator screen is known within hundreds of microns. At MINERVA the chosen strategies to comply with these constrains are identical to the ones used at XPBF 2.0.

We start first to describe how to maintain the orientation of the MM within 1.0 arcsec. The method retained is based on a regulation feedback loop where two optical autocollimators read continuously the orientation of the jig. The autocollimators are placed around the vacuum chamber in air and emit light (about 640 nm) toward two large flat reflective surfaces orientated at 90 degrees from each other and rigidly attached at the main hexapod platform. Light returns back into the autocollimator optics after being reflected and is analyzed to retrieve the direction of the reflection. The combination of both autocollimators read-out gives the 3 orientation angles of the main hexapod inside the vacuum chamber. If a deviation of more than 1.0 arcsec is detected, an algorithm computes the proper adjustments to be applied to the main hexapod to correct the MM orientation. The implementation of this scheme differs also slightly from the one of XPBF2.0 and is presented in Figure 7. MINERVA uses a single rectangular cuboid substrate with two adjacent reflective faces polished at λ/10 (Pecchioli Research). This solution is more compact and looks more stable than having two independent large reflective mirror one for each autocollimator as in XPBF2.0. One autocollimator is placed in front of the vacuum chamber whereas the second one will have its optical axis coming from the bottom and pointing up. Light emitted by the second autocollimator travels first horizontally underneath the vacuum chamber, gets reflected 90 degrees and enters vertically inside the vacuum chamber from the bottom through an anti-reflective coating viewport. The 90 degrees direction change is performed thanks to a pentaprism directly attached to the tube of the autocollimator and placed underneath the vacuum chamber.

This feedback loop is the most time-consuming step during a complete scan. Consequently, the full duration of a MM characterization depends substantively on the number of orientation corrections that has been needed to keep its orientation within the 1.0 arcsec required. It is mainly why in MINERVA the scan is delegated to dedicated linear stages. Since the straightness of the linear stage is better than the one of the hexapod in the full motion range, we expect less calls to the previously described feedback loop reducing then the overall time to characterize a single MM.

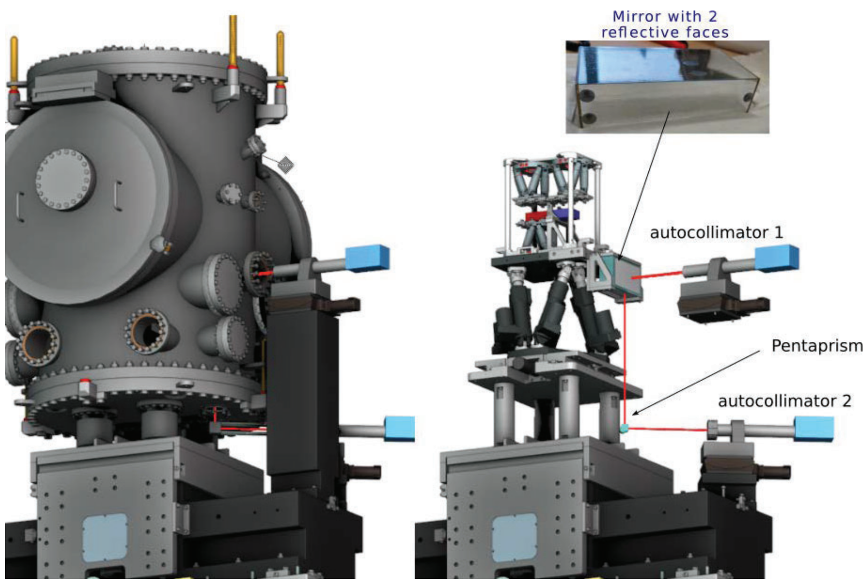

Figure 7 Proposed solution to measure orientation of the jig. Two autocollimators (Elcolmat 300/40) measure the 3D orientation of a double polished mirror attached to the main hexapod. Any deviation above 1.0 arcsec detected during a scan will reposition the main hexapod for compensation.

The other critical constraint specified at the beginning of the section requests to know with high accuracy the distance between the center of the MM and the detector scintillator surface. Here again, MINERVA follows the current operating mode set up at XPBF2.0. The method relies entirely on laser tracker technology (Absolute Distance Measurement) that reaches absolute measurement lengths under 100 µm accuracy over 10 m distances. Mainly due to the infrastructure constraints (the MM lies inside a vacuum chamber that in turn is placed inside a clean room), the methodology consists in a two steps operations. First a laser tracker is installed permanently close to the detector tower and determine the positions of optical targets moving with the detector. As shown in Figure 6, the detector vacuum flange is customized with 4 flats at its periphery to host several (at least 3) open air corner cube reflector. With an adequate calibration, this design enables the possibility to measure with laser tracker technology accuracy the position of the scintillator layer. In the second step, the clean room is designed and prepared to host a second laser tracker used sporadically to calibrate the main hexapod position. This calibration consists on recording the location of corner cube reflectors fixed on the hexapod (or jig) at different configurations. This operation is performed in air with the vacuum chamber door open. Finally, in order to combine data taken by both laser tracker, the beamline needs to place multiple common reference points of measurement visible by the two instruments. This operation should be repeated few times a year (2 times a year are sufficient according to the experience gained by XPBF2.0). To conclude, the distance between the MM center and the scintillator is deduced by reading on the one hand the absolute encoders of MM positioning mechanics (fully calibrated) and on the other hand the direct measurement of the scintillator position with the permanent laser tracker.

4. ADVANCEMENTS AND STATUS

MINERVA as a project has been initiated as soon as the agreement with ESA for its construction has been definitive. During 2020 the design of the optical layout was completely defined and the specifications of most of the beamline components characterized.

During the year 2021, many achievements were reached. More precisely the radiation shielding system (protection hutch and the associated personal safety system) has been installed. The radiation protection enclosure houses mainly the toroidal mirror. It is designed to take into account the specification coming from the radiation safety group of ALBA and fixed to a maximum dose rate of 0.5 µSv/h. During the winter 2021/2022 the Front End of the beamline has been installed with success and all its components are today under vacuum. The Front End provides the connection between the Storage Ring and the beamline, fulfilling at the same time several objectives related to vacuum integration, safety and X-ray beam monitoring.

In 2022 all the main opto-mechanical components of the beamline (monochromator, detector, laser tracker, hexapod, autocollimator, precision mechanics, etc) were or are still in production phase and some of them are already ready for assembly. We expect having most of the opto-mechanical elements installed by end of the year 2022. The MM environment (clean room) is now installed and ready to host the main vacuum chamber.

The proposed control system to drive MINERVA follows the standard of the ALBA beamlines and will be deployed gradually until March 2023. This system called Sardana[8,9] includes the vacuum control, motion control, detector integration, archiving and alarm systems, alignment procedures, command line and graphical user interfaces. The control system will include macro execution and flexible scripting in order to allow for scan automation. Data acquisition will record the detector images together with the necessary configuration parameters of the beamline.

Figure 8 MINERVA under construction in the ALBA experimental hall.

5. CONCLUSION

MINERVA is a new X-ray beamline under construction at the ALBA synchrotron. The optical layout is a replica of XPBF 2.0 already in operation in the PTB laboratory at BESSY II and used continuously by cosine measurement systems. However, MINERVA will bring some innovation by trying to reduce the MM characterization time with a different measurement scheme based on dedicated linear actuators to perform scans. Also more stability and repeatability are expected with the adoption of an innovative tower concept bringing enhanced mechanical and thermal stability. MINERVA is today in an assembly and installation phase and full completion is expected by spring 2023. All that makes of MINERVA an enhanced instrument for metrology characterization of the ATHENA MMs and further x-rays optical elements.

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