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MINERVA, A NEW X-RAY FACILITY FOR THE CHARACTERIZATION OF THE ATHENA MIRROR MODULES AT THE ALBA SYNCHROTRON

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Abstract

In this paper we present the newly built beamline MINERVA, an X-ray facility recently under commissioning at the ALBA synchrotron. The beamline has been designed to support the development of the X-ray observatory newATHENA (Advanced Telescope for High Energy Astrophysics) mission. MINERVA will host the necessary metrology equipment to integrate the stacks produced by cosine in a mirror module and characterize their optical performances. The beamline optical and mechanical design is originally based on the X-ray Parallel Beam Facility (XPBF) 2.0 from the Physikalisch-Technische Bundesanstalt (PTB), at BESSY II already in use to this effect. The construction of MINERVA is meant to significantly augment the capability to produce mirror modules.

The development of MINERVA has addressed the need for improved technical specifications, overcome existing limitations and achieve enhanced mechanical performances.

We describe the design and implementation of MINERVA that lasted three years. Even though the beamline is still under a commissioning phase, we expose tests and analysis that have been recently performed, remarking the improvements accomplished and the challenges to overcome, in order to reach the operational readiness for the mirror modules mass production.

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INTRODUCTION

The newATHENA telescope [1] is a space observatory that will address fundamental questions about energetic objects (accretion disk around black holes, large-scale structure, etc...). One of the key elements of the telescope is the innovative modular architecture of its optics subdivided by 13 concentric rings and filed by about 600 sub-systems called mirror modules (MMs) as seen in Fig. 1. These allows to maximize the effective collection area for a given geometry reducing its weight, critical aspects to be considered in space missions. The technology used to manufacture the MM is based on the Silicon Pore Optics technology developed at cosine. Based on a modified Wolter-Schwarzschild geometry, 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. At XPBF 2.0 [2], cosine is currently optimizing the method to produce MMs at large scale [3] and today MINERVA is built to strengthen and boost their production and characterization while preserving the interoperability between beamlines.

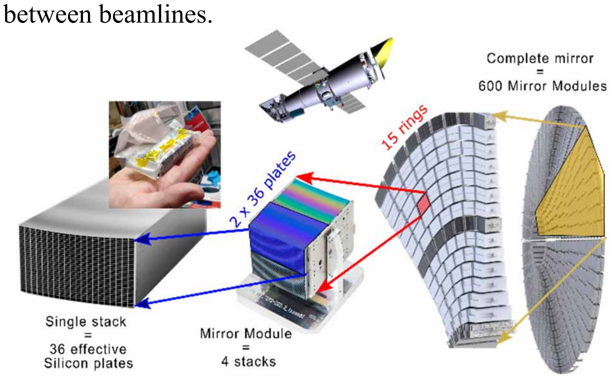

Figure 1: ATHENA Telescope Multiscale Optics Scheme

BEAMLINE OPERABILITY

MINERVA beamline works with samples consisting in a jig populated with 4 stacks composing a complete MM (Fig. 2). The relative position and orientation adjustment of an individual stack independently from the others is realized by using small hexapods. A 1 keV X-ray collimated beam impacts the optics at normal incidence. 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 toward a 2D array detector about 12 meters further (close to the focal plane of the newATHENA optics). A complete characterization requires to repeat this operation over every single pore of the optics by mechanically moving the MM along a plane perpendicular to the input beam.

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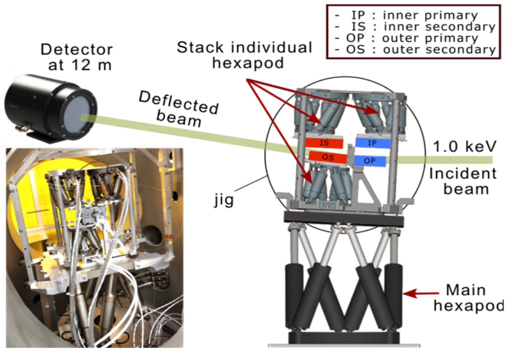

Figure 2: Mirror Module JIG and reflection scheme (from PTB).

The final angular resolution of newATHENA strongly depends on the alignment accuracy between the 4 stacks constituting a singular MM. It is why stability, accuracy and repeatability are crucial parameters for the optomechanical components specifications.

GENERAL BEAMLINE DESCRIPTION

MINERVA is located at the Front End 25 exit port of the ALBA experimental hall. The beamline X-ray source is a bending magnet that provides optimal spatial distribution to allow future upgrades of the components. The beamline will operate under Ultra High Vacuum (UHV) conditions from the source to the exit of the photon shutter, where a 1 µm thickness Silicon Nitride vacuum window will separate them from the rest of the beamline. Downstream the vacuum window, the beamline will operate under High Vacuum conditions (HV, 10^{-5} mbar). The beamline will provide a distance between the end detector and the MM origin with the required level of accuracy for data analysis. This measurement is performed by the combination of laser tracking technology and high positioning repeatability of the mechanics. MINERVA follows the optical layout sketched in Fig. 3 where the following components are presented:

- A bending magnet of the ALBA storage ring as the X-ray source and the front-end elements.
- A monochromator, consisting on a toroidal mirror (M1) with a multilayer coating which deflects the beam inboard, with a total deflection angle of 14 degrees. It collimates the beam in both the horizontal and vertical planes. Its reflective surface selects a narrow bandwidth at the nominal energy of 1.0 keV.
- A filter unit consisting of one Si_3N_4 membrane coated with a thin Al deposition which removes the visible light reflected by the M1 mirror.
- A set of pinholes ranging from 10 µm to 500 µm in diameter.
- A photon beam shutter which includes a fluorescent screen beam diagnostic unit.
- A Si_3N_4 window, which separates the upstream UHV
- A four-blade slit system that allow for apertures from fully closed to more than 10 mm in aperture.
- The sample station, which includes an in-vacuum hexapod and 2 linear stages for vertical and horizontal linear translations. The sample chamber and slits seats inside a temperature-controlled enclosure.
- A flight-tube, which links the sample station to the detector. It preserves the vacuum along the 12 meters long beam path between the MM and the detection system.
- The imaging detection is based on an indirect detection. The scintillator is coupled to the optical sensor by an optical fiber bundel. The camera proposed is based on sCMOS technology allowing fast readout.

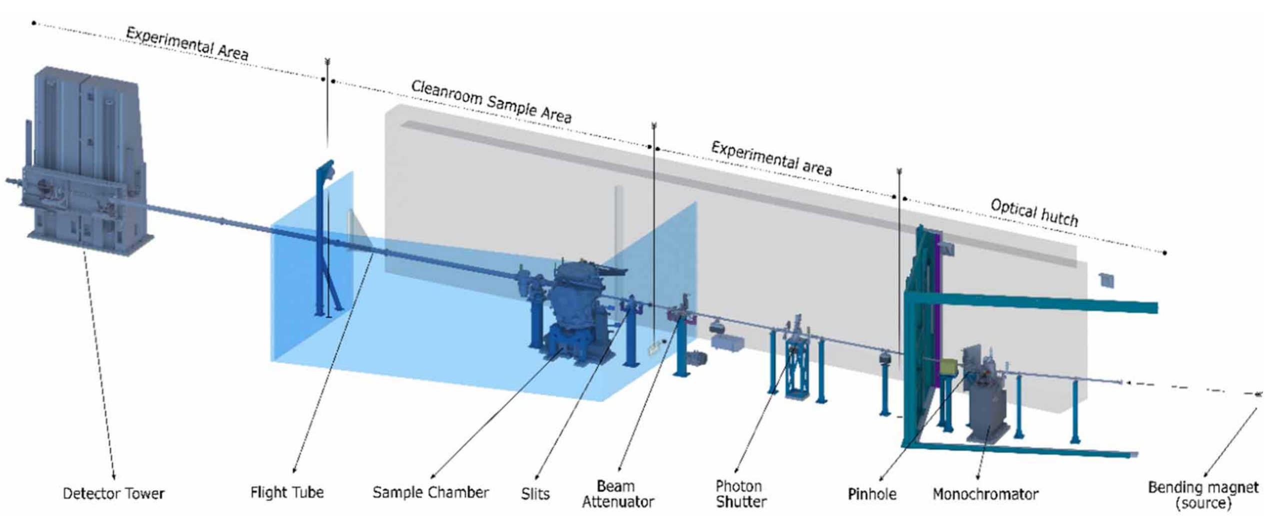

Figure 3: MINERVA layout presenting the main components of the beamline.

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BEAMLINE IMPLEMENTATION

As described above, MINERVA beamline consists of multiple equipment; however, there are three key components that play a central role and will be described in more detail, including their design, construction, installation and commissioning.

Monochromator

The first beamline optic is based toroidal mirror (M1) with a multilayer coating. The mirror substrate holder and surrounding elements are mounted on a single column as has been done before for MIRAS and LOREA beamline [4] with a proven outstanding resolution and stability reaching up to 192 Hz for the first resonance mode. The column is decoupled from the vacuum chamber thanks to a large bellow and acts as a standalone insert that constitutes the base for the mirror holder, the cooling pipes and electrical feedthroughs. The column motion mechanics are based on a high precision goniometer (Fig. 4) that adjusts the angular X-ray beam incidence angle with a sub-micro-radian angular resolution and a horizontal translation stage that move the substrate perpendicular to its surface. Everything is supported at beam height by a solid granite column, mounted on top of a flat plate grouted to the floor. The mirror holder itself is based on a kinematical mount preloaded with springs, which provides fine adjustment and repeatability. The mirror itself lies upon three balls (punctual contact) preloaded with springs and it is kept in position by clamps.

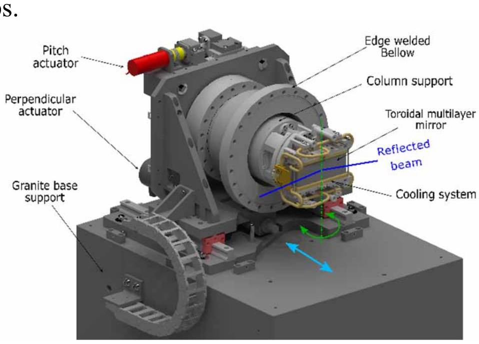

Figure 4: Monochromator.

Table 1: Monochromator Mechanical Specification

Parameter	Performance
Pitch rotation (Incidence angle variation)	
Stroke	≥(± 12 mrad)
Motion Resolution	≤0.5 μrad
Repeatability (open Loop)	≤1 μrad
Backlash (open Loop)	≤20 μrad
X-translation (Perpendicular mirror surface)	
Stroke	≥(± 5 mm)
Motion Resolution	≤0.4 μm
Repeatability (open Loop)	≤0.5 μm
Backlash (open Loop)	≤6.5 μm
Linearity (open Loop)	≤1.2 μm

In Table 1 are shown some values of the performance. The instrument's commissioning has met expectations; however, refinement tasks for alignment are still necessary to enhance the pencil beam in terms of divergence.

Sample Environment

For the characterization of each MM, the optical entrance is scanned both vertically and horizontally in front of the fixed incident beam. The main components used to fulfil those requirements are shown in Fig. 5. The jig is mounted on top of an in vacuum hexapod and two high precision linear stages. The vertical stage takes place in air and is particularly designed to keep constant the orientation of the MM during a vertical scan. It is based on the ALBA skin concept [5], where two precision synchronized vertical actuators are mounted at both sides of the granite for better mechanical and thermal stability. The combination of ball spindles and ball linear guides accurately move a thick horizontal platform with two flexures joints on its sides. The horizontal linear stage works under vacuum and consists in a ball spindle and cross roller linear bearings actuated by a stepper motor. Both vertical and horizontal stages are equipped with optical absolute encoders. The vacuum chamber is fully decoupled from the sample positioning stages by means welded bellows with robust columns holding the in-vacuum base plate.

Keeping the orientation of the MM the closest to 1.0 arcsec during the scan and the assembly is the target. To do that, a metrology system consisting of two autocollimators measuring the three orientation angles MM respect of the incident beam is provided. The signal then is reused to act on the main hexapod for orientation correction.

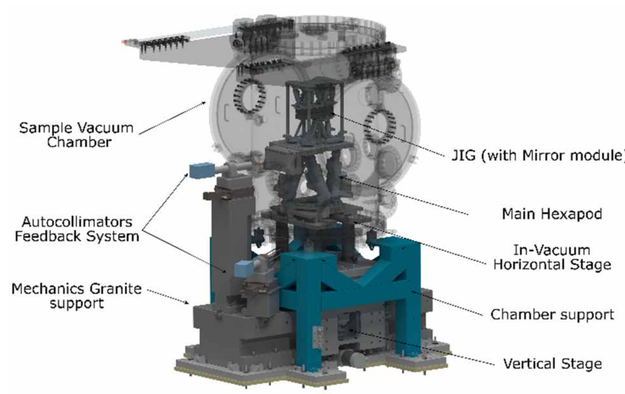

Figure 5: Sample environment.

Different motion tests measuring changes in orientation with autocollimators were done. Repeatability measurements within tolerance were observed; however, the orientation change across the entire range remained at 30 arcsec (Fig. 6). The implementation of the feedback control with autocollimators should allow to reach the required tolerances. Regarding the in-vacuum horizontal movement, some hysteresis issues and poor linearity have emerged and are currently under investigation.

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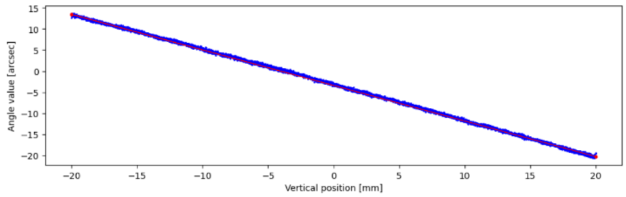

Figure 6: Orientation variation in 40 mm vertical range.

Another crucial aspect for the characterization of MM is stability. Measurements using both available autocollimators and the absolute encoders show almost constant values for a few hours, equivalent to the duration of one of the sample measurements (Fig. 7).

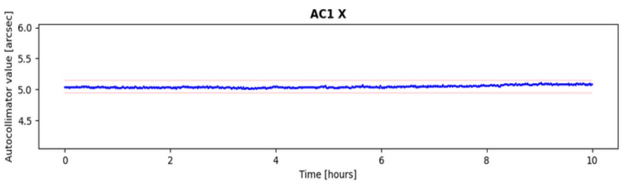

Figure 7: Orientation stability during 10 h scan.

Detector Tower

The beam deflected by the MM is then sent to a 2-dimensional array detector. To fully characterize a MM, the detector has to move on the portion of a cylinder surface with radius between 11.5 and 12.5 m. This trajectory is performed by using a 4-axis positioning combination as shown in Fig. 8. The height and the orientation of the detector are achieved by a pair of vertical linear stages placed side by side. The detector can also follow the line of sight of the deflected beam and be adjusted to find the focus of the optics. The mechanics of all the stages are based on precision ball spindles and ball linear guides, all actuated by stepper motors. Each stage position feedback is given by optical absolute encoders. The position of the detector is accurately measured and related with the MM position by a permanent laser tracker.

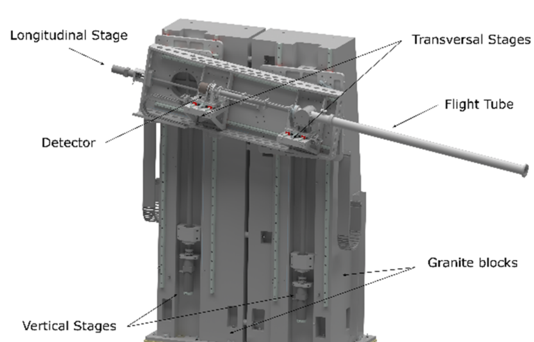

Figure 8: Detector tower.

Several stability measurements using the absolute encoders were performed. Cyclical position changes on the order of few microns were observed, closely associated with minor thermal variations on the experimental area throughout the day (Fig. 9).

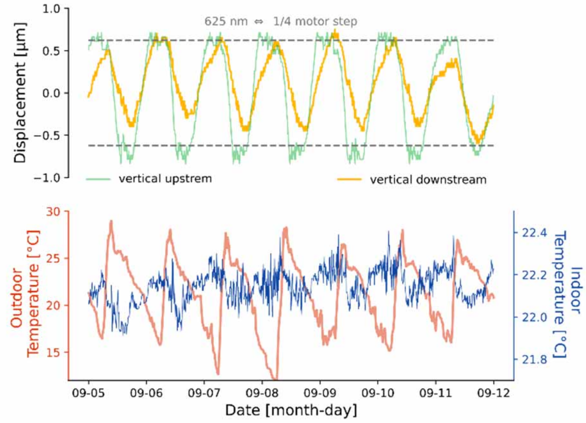

Figure 9: Position variation and temperature with time.

Nevertheless, as seen in Fig. 10 a proper configuration of the encoder closed-loop has allowed reducing those changes to almost negligible levels.

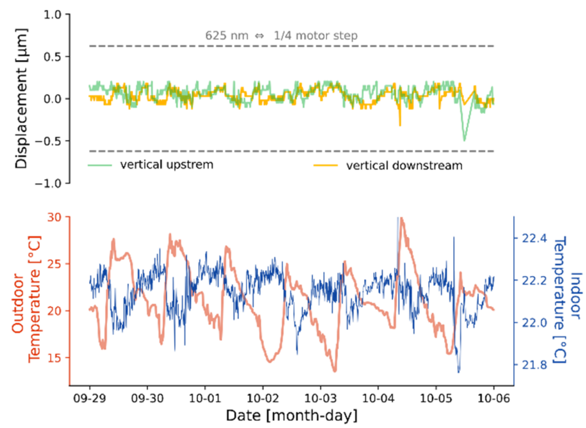

Figure 10: Position variation and temperature with time (fine close loop tunning).

CONCLUSIONS

A new X-ray beamline under commissioning at the ALBA synchrotron has been described. Although the optical layout is a replica of XPBF 2.0, MINERVA aims to reduce the MM characterization time by using, among other aspects, different approaches in the design of its mechanics. Various tests were performed, demonstrating favourable results in terms of repeatability and stability. However, there is a lot of commissioning work remaining from now until operational readiness for the mirror modules mass production by 2027.

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