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Developing, testing, and calibrating the ATHENA optics at PANTER

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ABSTRACT

A lot of effort is being put in, now and during the next years at the PANTER X-ray test facility of the Max-Planck-Institut für extraterrestrische Physik, to develop, test, and calibrate the f = 12 m Silicon Pore Optics that are being developed in preparation of ESA's ATHENA (Advanced Telescope for High ENergy Astrophysics) mission [1,2,3]. In addition, work towards the Arcus mission which uses the same optics as ATHENA is helping with the development of the ATHENA optics. We present and discuss the type of measurements that are and will be done at PANTER based on experience of testing and calibrating the telescopes for ROSAT, XMM-Newton as well as eROSITA. This encompasses the testing of single SPO's and mini petals as part of ATHENA mirror AIT efforts. Finally the testing of the complete ATHENA mirror during different stages of integration as well as for the final calibration will have to be performed in a new upgraded X-ray test facility. Furthermore, detailed trade-off studies on possibilities to accommodate and calibrate the ATHENA mirror at the current PANTER facility or in a new facility are ongoing.

Keywords: X-ray astronomy, X-ray telescopes, X-ray optics, Silicon Pore Optics, X-ray testing, ATHENA, Arcus, PANTER X-ray test facility.

1. INTRODUCTION

The PANTER X-ray test facility of the Max-Planck-Institut für extraterrestrische Physik, which is located at Neuried on the south west border of Munich, was setup at the end of the 1970s for developing high quality X-ray mirrors for balloon, rocket, and satellite missions. In 1982 its 120 m beam line for testing the ROSAT optics went online and together with a new large vacuum chamber (3.5 m diameter and 6 m long) was ideally suited for testing the f = 2.4 m and up to 0.84 m diameter telescope mirrors for the ROSAT mission that was active from 1990 to 1998.

The current incarnation of the PANTER X-ray test facility, especially the large test chamber, see Figure 1, was designed and built in the 1990s to optimally measure and calibrate the f = 7.5 m and 0.7 m diameter optics developed and produced for the XMM-Newton mission that is currently still in operation since 1999. With the PANTER X-ray source located at a distance of 123.8 m from the optic the image is then formed, following the thin lens equation, at a distance 8.0 m from the optic.

Currently for X-ray telescope optics with focal lengths of up to 9 m both the optics and the detectors can fit into the large chamber at PANTER without any major modifications. Optics for many projects such as JET-X, Swift, eROSITA, XIPE, HXMT, amongst others have been developed, tested, and calibrated at PANTER in its current setup.

Tests of long focal length optics XEUS (f = 50 m) [4], IXO (f = 20 m) were performed intra-focally at 8 m from the optic until the extension to PANTER in 2012 [5] was setup to allow the in-focus measurement of 20 m optics. Part of that setup was designed to be able to reuse part of the hardware to measure in focus the f = 12 m optics that will be used for ATHENA.

The ongoing upgrades to PANTER are described in Section 2, the PANTER optical layouts in Section 3, general issues concerning the testing and calibration of the ATHENA mirrors in Section 4 and the test facilities for testing ATHENA are described in Section 5.

2. ONGOING UPGRADES TO PANTER

In order to accommodate f = 12 m ATHENA type optics in PANTER many activities are ongoing of which several have been completed:

- A new 3 m long optical bench has been mounted at the end of the 1 m diameter beamline tube to allow the SPO mirror modules to be mounted at 13.3m image distance in front of the detector in the large chamber (see Figures 1 and 2 right).
- To ensure stable measurements this has required the implementation of a new thermal control system to stabilise the temperature of the first section of the 1 m diameter beamline that contains the new optical bench.

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- The two new hexapods each with 6 degrees of freedom to control the positioning of the optics and gratings have been mounted onto our optical bench (see Figure 2 centre). Thermal issues arising from running the hexapods have been studied and measures are being taken to mitigate the effects.
- In addition to the long travel 0.54 m focus translation and 1.2 m horizontal translation stages a new 1.2 m travel vertical translation stage has been implemented to give our CCD camera the chance to measure large radius SPO mirror modules as well as the combination of SPO mirror modules with CAT [6] and OPG [7] gratings such as those used in the Arcus [8] project (see Figures 1 and 2 left).
- Further preparations are being done at PANTER to be able to support ESA's ongoing AIT studies by Media Lario [9] and Thales CH [10] in which different co-alignment techniques of two mirror modules will be studied. These tests require that we reconfigure our extension chamber for the X-ray detector from the f = 20 m optic configuration [5] to the f = 12 m optic configuration (see Figure 3 bottom).
- Work is currently ongoing to implement the thermal test system which allows a precise setup and definition of the temperature environment (including gradients) around SPO mirror modules to be able to study the changes to optics PSF under X-ray illumination in real time.

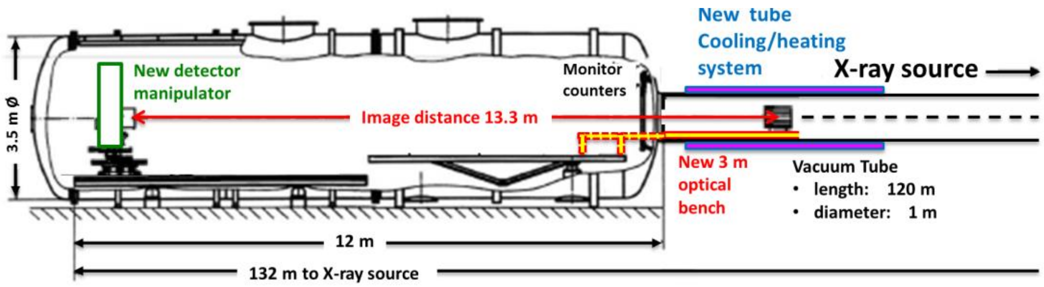

Figure 1. Overview of the large chamber of the PANTER X-ray test facility and the ongoing upgrades for the ATHENA and the Arcus missions that are currently under study. In (green) the vertical/horizontal CCD camera position translation stage is indicated. (yellow/dashed red) shows the preparatory optical bench for mounting the optics in the chamber, in (yellow/red) the new 3 m long optical bench in the 1 m diameter vacuum tube is shown that allows the accommodation of f=12 m optics to be studied alone or in conjunction with gratings. In (blue/magenta) the new 1 m tube environment temperature stabilization system is shown.

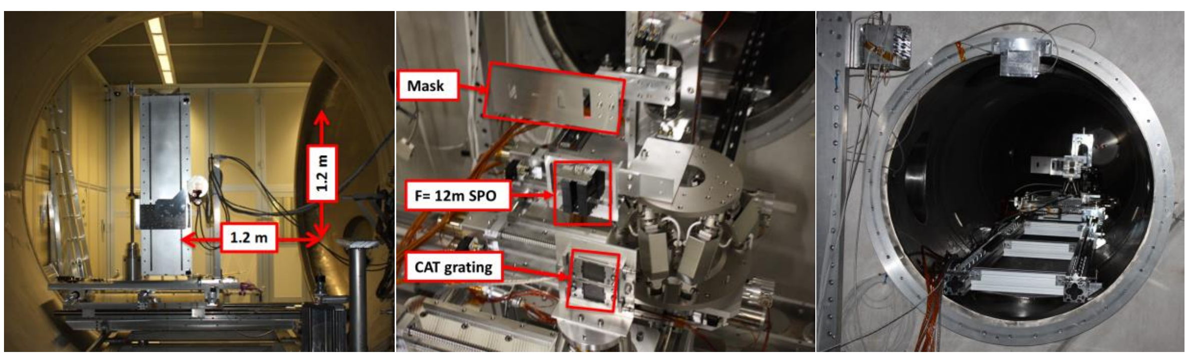

Figure 2. (Left) the upgraded camera translation stages have movement in the vertical and horizontal ranges of 1.2 m each and a 0.54 m travel range along the optical axis for focusing. (Centre) the first 12 m focal length Silicon Pore optic (ATHENA type) and a critical angle transmission (CAT) grating as will be used for Arcus are being prepared to be accommodated on the new optical bench in the 1 m tube. (Right) shows the mask, optic and grating all at their final position in the tube prior to testing.

3. OPTICAL LAYOUTS IN PANTER

To measure f = 12 m focal length optics at PANTER two possible solutions are viable:

- The first solution that has already been implemented and tested (see Figure 3 top) is optimised for measuring single SPO mirror modules (with or without gratings) using the new optical bench in the 1 m diameter tube (see Figure 2 right). Small petals such as envisioned for Arcus (smaller than 600 mm x 450 mm) populated with up to 38 SPO mirror modules would also fit onto the 1 m beamline optical bench. For the petal setup a new gimbal manipulator for tilting the petal is being designed.

- For more complex tests such with controlled modification of the thermal environments of optics while under X-ray illumination or alignment of SPO mirror modules to a common focus a setup is need where the optic sits in the main chamber and the camera is mounted on a 2.2 m long focusing translation stage that is located in the 3 m long extension chamber that is now directly connected to the large chamber (see Figure 3 bottom). This setup is designed and will be implemented for the tests. Also larger petals that do not fit into the tube solution can be tested here.

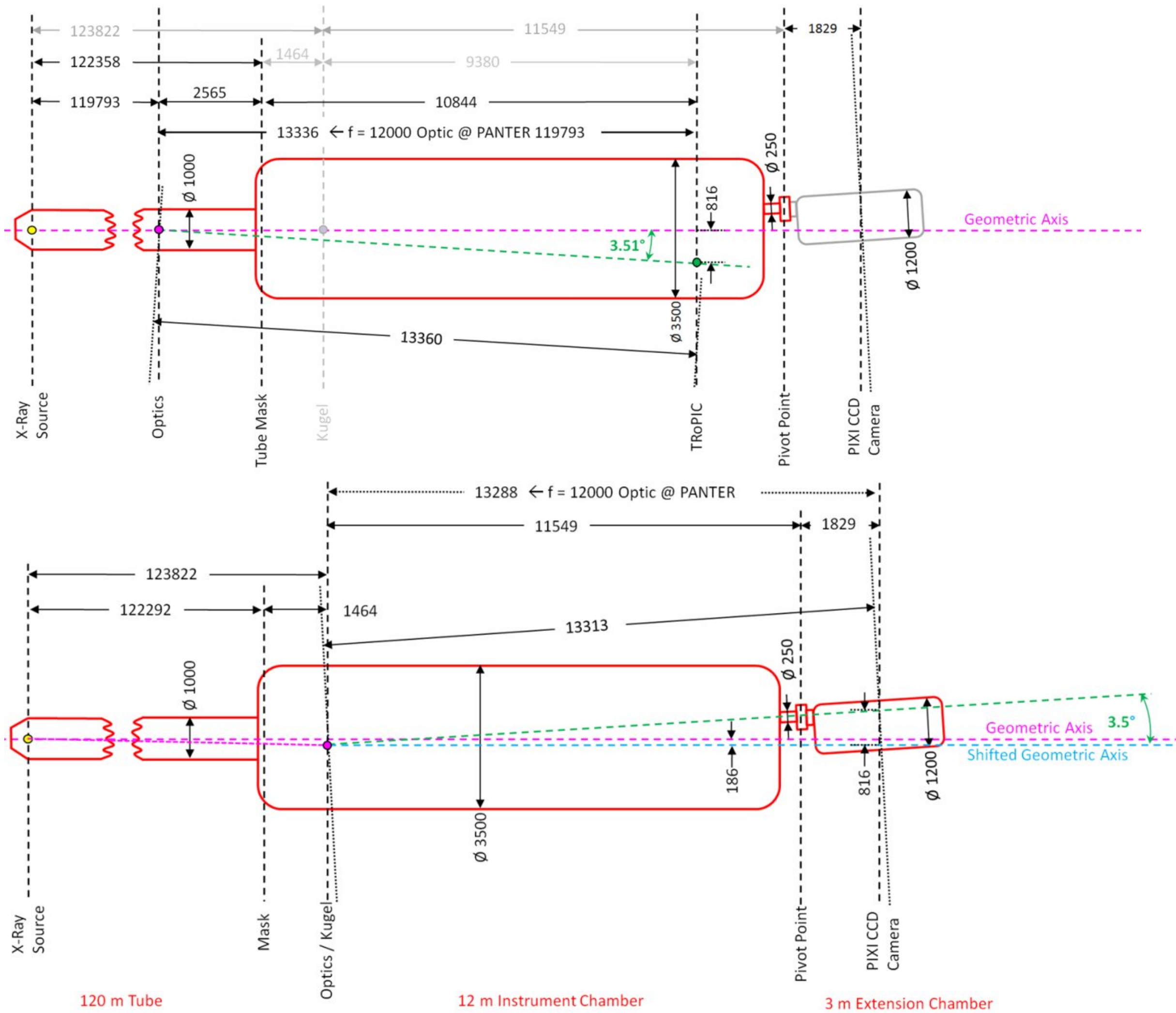

Figure 3. Sketches show the possible layouts for measuring f = 12 m optics in PANTER. All lengths are given in mm. (Top) layout for measuring single or small groups of optics placed on the new optical bench in the 1 m diameter tube. (Bottom) layout that uses our 3 m long extension chamber. In this layout even large petals can be measured at the standard optics position “über Kugel” in the large chamber from where the X-rays are focused onto a detector in the small chamber.

4. TESTING AND CALIBRATION

4.1 General considerations

Testing and calibrating the X-ray optics with an X-ray source at a finite source distance as opposed to infinity introduces:

- a shift of the focal plane that can be computed using the thin lens equation
- collecting area losses mainly due to shadowing by the inner shells (plates) of the optic
- point spread function aberrations which lead a degradation of the measured HEW

The magnitude of the finite source distance induced errors is strongly dependant on the beam divergence and therefore on the length and diameter of the beamline.

4.2 Mirror Performance verification / Calibration

For this the use of an X-ray source located at “quasi” infinity is required to check the following properties of the ATHENA mirror:

- the alignment accuracy of integrated modules in mirror structure in order to achieve 5 arcsec angular resolution for the telescope
- determine the focal length to better than 1 mm
- determine the collecting area to better than 10 % with at least 90% of the mirror surface illuminated
- measure the PSF keeping the aberrations smaller than 1 arcsec

To meet all the above criteria with a full illumination aperture calibration requires an X-ray beam line with a distance between X-ray source and optic larger than 800 m and the vacuum tube expanded from about 1 m diameter at the X-ray source to at least 3.2 m at the entrance to the test chamber that holds the optics.

4.3 Full illumination versus sector-wise illumination

Classically mirrors for X-ray missions have been tested in full illumination. The largest diameter X-ray mirrors tested to date were the 1.2 m diameter mirrors of the Chandra X-ray telescope that were tested at the X-Ray Calibration Facility (XRCF) at Marshall Spaceflight Center (MSFC) in Huntsville, Alabama. PANTER with a 1 m diameter beamline was designed for testing the ROSAT 0.84 m diameter X-ray optics and later it was also used to test the 0.7 m diameter XMM-Newton optics. Therefore, ideally, the fully integrated ATHENA X-ray optic should be placed under full illumination in an X-ray beam with a very small divergence to obtain calibration results comparable to the Chandra and XMM-Newton mirrors. Due to the large ATHENA mirror diameter, there is no current test facility that would allow such a full illumination of the mirror and this type of measurement would only be possible in a custom designed facility (see Section 5.2) because modifications to existing facilities are not possible or too expensive. In Figure 4 different illumination scenarios are shown.

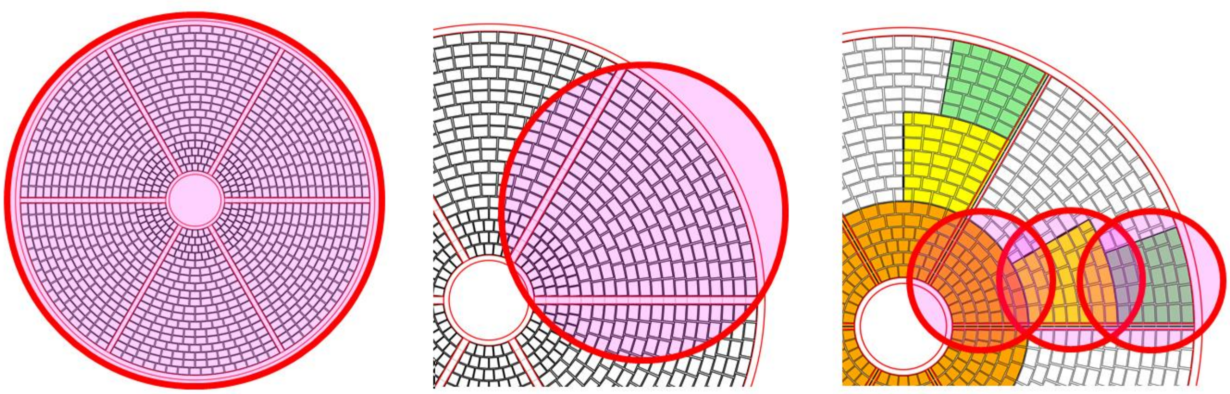

Figure 4. From left to right: full illumination of the 3.0 m diameter ATHENA mirror with a 3.2 m diameter beam, illumination of a 60° mirror sector with a 1.6 m diameter beam, a total of 6 sectors have to be illuminated, and illumination of a total of 36 sectors is necessary with a 0.65 m diameter beam. The red circle indicates the beam size.

However, in case no new large facility becomes available for calibration, a sector wise illumination of the ATHENA mirror is being studied [11]. The impact of stitching the measurements together on the resulting point spread function and effective area measurements is significant but can be mitigated if an accurate positional metrology of the mirror with respect to the X-ray beam and X-ray camera is available. The source distance has a direct impact on the maximum size of the aperture that can be illuminated due to shadowing in the pores of the optic. At the existing PANTER X-ray test facility, with a source distance of 123 m, a maximum of 10 modules could be illuminated simultaneously to meet the accuracy requirements for mirror verification. In this case about 100 sub apertures of the full ATHENA mirror would have to be measured and then stitched together. To be able to make use of much larger portions of the PANTER beamline aperture the source would have to be shifted to a distance of approximately 300 m (see section 5.1) and then fewer sub apertures are needed. As the source distance increases the fewer sub apertures are needed due to the smaller beam divergence. The sub aperture measuring process is dominated by the errors introduced by the precise knowledge of the relative positions of the mirror with respect to the test camera (use of laser trackers and/or similar systems e.g. fiducial lights is required).
The following issues crop up when considering the sector wise measuring strategy. The more sectors that have to be measured the longer the measuring time and the more positional errors have to be corrected for. In addition the on-axis measurements are simple as it is possible to combine the sector measurements directly but for off-axis measurements this becomes much more measurement intensive as it becomes necessary to measure the EA and PSF at all pitch and yaw angles at each of the off-axis angles in order to reconstruct the full aperture illumination.

4.4 Calibration exposure time calculator tool

In order to optimise the use of the calibration exposure time, a calculator tool has been developed into which all necessary measurements required for the calibration can be inserted. Furthermore constraints given by the available facility, whether a sector wise (number of sectors) or full illumination calibration will be possible, the calibration detector characteristics (size, efficiency, and pile-up limit) and the calculated effective areas of the ATHENA mirror to be tested are folded in.
First exercises with this tool show that having a large detector with characteristics close to those of the ATHENA wide field imager brings the calibration time into the realm of the doable. Pile-up count rate limitations (~1 count/sec/pixel) as in the existing test setup would lead to calibration campaign times that are not compatible with the ~6 months currently planned in for the ATHENA mission. Moving from full illumination to sector wise illumination requires additional measurement at different off-axis positions that have to be performed for each sector.

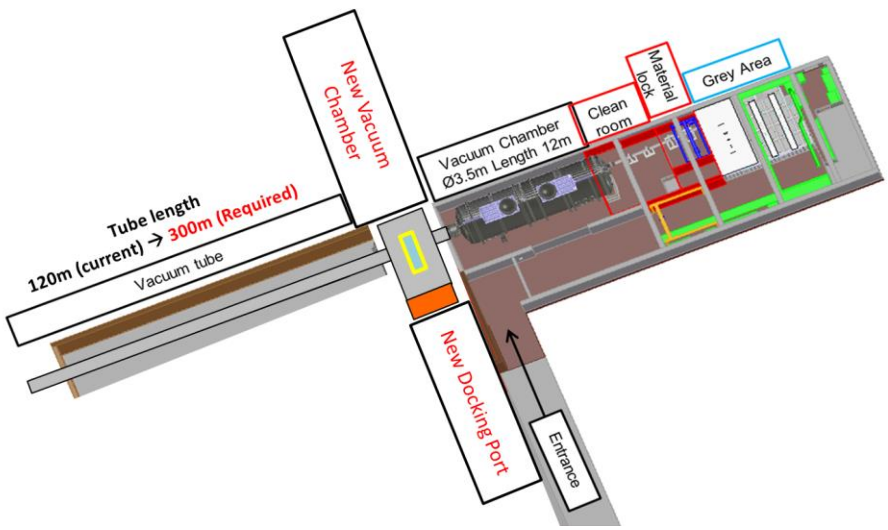

Figure 5. Modifications that would have to be done to the current PANTER X-ray test facility to accommodate a complete 3 m diameter ATHENA X-ray mirror to calibrate the mirror using a sector wise measuring approach. This requires an extension of the beamline by 180 m to a total of 300 m, a new chamber (grey rectangle with the yellow outline 3 m diameter optic in it) to handle the mirror and its high precision handling jig (for shifting, tipping and tilting) under vacuum, and a docking port (orange rectangle) to transfer the mirror form its transport container to the new vacuum chamber.

5. CALIBRATION FACILITIES

Studies are ongoing to determine what final approach will be used for testing the ATHENA EM, QM and FM mirrors. It is a rather complex issue that is constrained by many factors, especially the possibilities of upgrade to the existing facilities or even build a completely new one. Studies and trade-offs are ongoing so that science requirements can be translated to calibration requirements and these finally to facility requirements.

5.1 Upgrading the existing PANTER facility

To upgrade PANTER for a full 3 m diameter mirror aperture illumination is not possible as there is no space available to extend the existing beamline up to the required minimum length of 800 m needed for such full illumination tests.
Therefore a new large chamber (3 m x 6 m x 5 m) together with a docking port that can connect to the transport container has to be added to the facility. This chamber has to be able to hold the 3 m diameter optic and its high precision handling jig. Also an extension of the beamline by 180 m to a total length of 300 m would have to be implemented. This is theoretically possible but depends on getting the affected property owners to agree to having a tube pass through their properties. The extension of the beamline would not change the 1.0 m diameter of the tube and thus only a sector wise (30-36 sectors) measurement of the properties of the X-ray mirror will be possible. In Figure 5 the modifications needed to upgrade the facility are shown.

5.2 New 800m beamline test facility

Making large modifications to an existing facility such as PANTER that is also involved in the development program for the ATHENA mirrors can have a negative impact on the development as an expected downtime of 6-12 months would have to be factored in. In addition making a large investment into an existing facility without being able to upgrade to a full beam illumination is questionable. Therefore investing a somewhat larger amount of money in a new facility that meets all calibration requirements for the ATHENA mirror would make more sense as this does not impact the mirror development schedule and allows for a full illumination of the ATHENA mirror. A CAD design of the required vacuum chamber and cleanroom areas to handle the ATHENA mirror hardware is shown in Figure 6. A further idea would be to locate the mirror integration facility adjacent to the X-ray test facility cleanroom. It would allow regular X-ray tests of the partially integrated mirror as needed as well as reduce shipping of the mirror to a minimum.

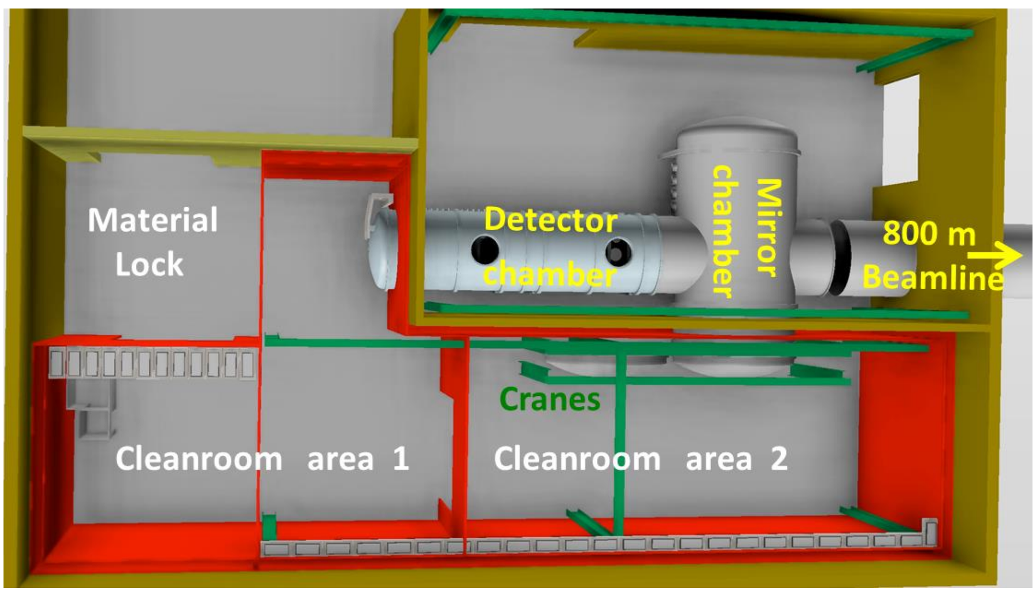

Figure 6. This picture shows a possible building layout of a new X-ray Test Facility that would allow a full illumination of the ATHENA mirror. The large 5.5 m diameter chamber perpendicular to the beamline is designed to accommodate the 3 m diameter mirror and its manipulator for shifting, tipping and tilting in vacuum. To the left is the detector chamber ~15 m long and 3.5 m in diameter, on the right leaving the building is the beamline that starts at 3.5 m diameter tapering stepwise down to 1.0 m diameter over its 800 m length.

5.3 XRCF

The X-Ray Calibration Facility, now X-Ray Cryogenic Facility (XRCF) at Marshall Spaceflight Center (MSFC) in Huntsville, Alabama was upgraded in 1989 to be able to test and calibrate the up-to 1.2m diameter mirrors of the Chandra X-ray telescope. Lately it was used to test the James Webb Space Telescope (JWST) optic under cryogenic conditions. For testing X-ray mirrors the long beam facility has a 500 m long beamline with a 1.45 m entrance diameter of the X-ray beam to the very large (6 m diameter and 18 m long) test chamber where the optics and detectors are located attached to a large cleanroom in which the optics and detectors can be prepared for the tests.
A study is currently ongoing to determine the suitability and necessary upgrades to the XRCF facility that would be needed to test and calibrate the ATHENA mirror. Using the existing beamline only a sector wise (at least 6 sectors) calibration of the ATHENA mirror can be performed. Furthermore the ATHENA mirror would have to travel back and forth several times from the integration facility in Europe to the XRFC in Alabama, USA.

6. SUMMARY

Many upgrades to the current PANTER X-ray test facility have been completed to accommodate the f = 12 m optics and AIT petals for the ATHENA optics development and test program. Parallel to this work final trade-off studies of full versus sector wise illumination of the complete ATHENA mirror are being done. These will have an impact on the test facility (i.e. modified PANTER, XRCF, or a new test facility) that will be used to test the complete mirror during its different stages of development and the calibration of the fully populated mirror. Different facility solutions are possible and the facility solution will depend on the details of the final calibration requirements and funding channels.

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