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Integration of the Athena mirror modules: development of indirect and X-ray direct AIT methods

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ABSTRACT

Within the ATHENA optics technology plan, activities are on-going for demonstrating the feasibility of the mirror module Assembly Integration and Testing (AIT). Each mirror module has to be accurately attached to the mirror structure by means of three isostatic mounts ensuring minimal distortion under environmental loads. This work reports on the status of one of the two parallel activities initiated by ESA to address this demanding task. In this study awarded to the industrial consortium, the integration relies on opto-mechanical metrology and direct X-ray alignment. For the first or "indirect" method the X-ray alignment results are accurately referenced, by means of a laser tracking system, to optical fiducial targets mounted on the mirror modules and finally linked to the mirror structure coordinate system. With the second or "direct" method the alignment is monitored in the X-ray domain, providing figures of merit directly comparable to the final performance. The integration being designed and here presented, foresees combining the indirect method to the X-ray direct method. The characterization of the single mirror modules is planned at PTB's X-ray Parallel Beam Facility (XPBF 2.0) at BESSY II, and the integration and testing campaign at Panter. It is foreseen to integrate and test a demonstrator with two real mirror modules manufactured by cosine.

Keywords: ATHENA, X-ray optics, X-ray mirror integration, Silicon Pore Optics

1. THE CONTEXT OF THE STUDY

ATHENA is a technologically innovative mission [1], demanding a novel high performance telescope optics technology. The required large effective area, several times larger than that of its predecessor XMM-Newton, combined with an improved angular resolution, less than half that of XMM-Newton, while effectively maintaining the mass, would not be achievable with the established X-ray optics technologies. Replicated nickel shells or polished Zerodur have typically been used for X-ray focusing in space missions. Although these are able to achieve very good angular resolution, they are too heavy for many applications. ATHENA requires the provision of high energy optics that can still provide low mass, high resolution and high energy response across a broad spectrum. A new optics technology, the Silicon Pore Optics (SPO) is being developed in the last decades [2-4] under the lead of ESA, and this technology is the baseline for the adoption of ATHENA.

Due to the small effective area of each single X-ray reflecting surface, a large aperture telescope is required, and ATHENA envisages a diameter of 3 meter. To create the aperture of such a large X-ray telescope, a modular approach is envisaged to form the mirror. The aperture area is filled with smaller modules, which are easier to handle during production, alignment and characterization. The optic modules for ATHENA are required to have an in-orbit half-energy-width (HEW) resolution better than 5 arcsec over an energy range of 0.1 to 6 keV. This demanding requirement places tough constraints on the performance of individual modules and their integration. Each mirror module (MM) is formed from Silicon Pore Optics (SPOs), approximating the parabolic input (SPO-P) and hyperbolic output (SPO-H)

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surfaces of a Wolter I configuration, aligned and fixed into a pair of brackets [5]. The brackets include three points from which the MM can be mounted into the larger X-ray aperture. A modular approach using about 1000 mirror modules is foreseen for the ATHENA X-ray observatory. These mirror modules need to be integrated and co-aligned in a mirror support structure. The support structure, the mirror module and the interface have to be compliant with environmental conditions during launch and in orbit operation. Furthermore, a process is needed to integrate about two mirror modules per day in a flight production environment. An accurate co-alignment of the mirror modules is required which needs to be verified during populating the mirror support structure.

This paper reports on the status of one of the two parallel activities initiated by ESA to address the mirror modules integration aspects. In the study here presented, the integration relies on opto-mechanical metrology and direct X-ray alignment. The trade-off of different concepts has been performed as first phase of the study, followed by the design of the demonstrator, by the design of the mirror module characterizations set-up at XRBF 2.0 [8] and of the integration set-up at Panter.

2. CONSIDERATIONS ON THE MIRROR STRUCTURE

2.1 Mirror Structure Material

Different materials have been considered, in terms of their suitability for the 3 m diameter ATHENA Mirror Structure, that acts as a precision support for the individual Mirror Modules. It has to be considered that the properties of some materials depend also on the envisaged manufacturing process. Casted titanium, for instance, differs in its properties from titanium used for machining.

Table 1. Physical properties of candidate materials for the mirror structure.

Material	Young's modulus **E**	Yield Strength σ_y	Ultimate Strength σ_u	Density ρ	Coefficient Thermal expansion α	Thermal Conductivity κ
	(GPa)	(MPa)	(MPa)	(kg/m^3)	(10^{-6}/K)	(W/mK)
Aluminum (AA 6063 T651)	68.9	209	215	2710	23	150
Aluminum (AA 6061 T651)	68.3	265	260	2710	23	200
Aluminum (AA 6061 T4 / T6 sheets)	68.3	110	205	2710	23	150
Aluminum (AA 7075 T7351 sheets)	71	325	415	2800	23	160
Aluminum (casting)	69	110	240	2700	23	150
Aluminum (ALM)	65	240	325	2700	23	150
AlBeMet (AM162)	179	193	262	2071	13.9	210
Invar	142	186	490	8100	2	11
Invar (ALM)	133	352	456	8100	1.5	11
Magnesium Alloys	44	150	200	1740	24	45
Titanium (Ti6Al4V 3.7164.1 sheets)	117	825	905	4400	9	7.3
Titanium (Ti6Al4V 3.7164.7 bars)	117	1000	1070	4400	9	7.3
Titanium (casting)	117	825	905	4400	9	7.3
Titanium (ALM)	120	920	990	4400	8.6	7.3
SiC	420	270	400	3150	2.2	180
Carbon Fiber (YSH70 quasi-isotropic)	153	170	170	1900	-0.6	150

For the evaluation of the suitability it is not sufficient to look at the materials only. At the same time the manufacturing method needs to be included in the trade-off. The following manufacturing methods were considered:

- Assembly for Carbon Fiber.

- Assembly of machined parts for AlBeMet, Aluminium, Titanium, Invar, SiC.
- Additive Layer Manufacturing (ALM) of the complete Mirror Structure in one piece for Aluminium, Titanium, Invar.
- Monolithic casting of the complete Mirror Structure in one piece for Aluminium (in Titanium only 45° sectors for a 3 m Mirror Structure can be casted according to our market search).
- Monolithic casting of the complete Mirror Structure in one piece for Aluminium with higher wall thicknesses (casting process easier to handle). This oversize is removed in a second step with machining.
- Monolithic machining of the complete Mirror Structure in one piece for Aluminium, Titanium (not for Invar since market availability of the required 3 m bulk material appears unlikely).

The criteria used to assess the different options are Performance (including optical aspects such as the effective area), Technical Feasibility, Maturity & Risk and Cost, Schedule and Procurement. As baseline Titanium is selected (with Addictive Layer Manufacturing as suitable method, considered as critical technology for which ESA has initiated a development activity), Aluminium as second best material and Invar as third.

2.2 Mirror Structure Design

The 3 meter Mirror Structure (MS) design has been established and analysis checks have been performed, so to assess the performance compliance of the monolithic solution in Titanium (assuming ALM material data). The Mirror Modules (MMs) are mounted on the "detector" side of the MS cells, on a spherical surface with 12 m radius which equals the focal length of the telescope. Six radial spokes divide the circular area into 6 sectors. These spokes together with the outer and inner ring represent the main load carrying parts of the MS. The design of the MS is plotted in Figure 1.

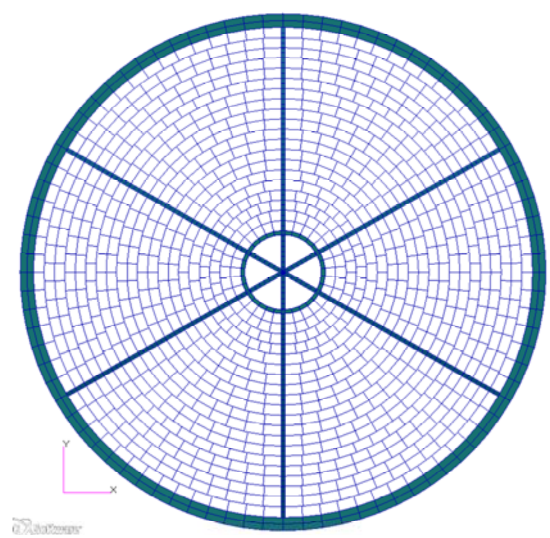

Figure 1. Design of the Mirror Structure (1:44 scale).

The disciplines, which have been checked to justify the selected design of the mirror structure, cover:

- Strength analysis of Mirror Structure and Mirror Modules under:
    - sine vibration loads plus;
    - thermo-elastic induced stresses due to temperature variations during launch.
- Performance analysis (check of half energy width HEW diameter) under:
    - 1 g gravity release (difference between in orbit conditions and conditions during AIT on ground);
    - thermo-elastic induced displacements due to temperature variations in orbit.

3. METROLOGY ASPECTS

3.1 Mirror Modules sensitivity to misalignments

A working tool to simulated the HEW degradation caused by the misalignment of the Mirror Modules (MM) has been developed using Zemax® and Matlab®. Using such a combination of data handling and optical software, has been preferred w.r.t. raytracing the full telescope geometry made of 1062 Mirror Modules. For the needs of this study it would have led to unnecessary heavy simulations, and a full optical model for ATHENA is under preparation by scientific institutes in a dedicated ESA study [10].

The HEW performance model is therefore constituted by two main elements:

- the Zemax® part generates a pseudo-PSF of one MM for a chosen radius from the optical design, and allows observing the centroid shift of the spot in function of the three translations Tx,Ty,Tz and rotations Rx,Ry,Rz. This sensitivity is simulated with different amplitudes of misalignment for the min, mid and max MM radii and then extrapolated for all the MM radii. The global centroid shift is then calculated as a quadratic sum of the rotation and translation contributions. For our purpose, the optics are considered perfect and without diffraction effects.
- These information are transferred to the Matlab® program, where a nominal spot of 4.3 arcsec HEW is added simulating the specified manufacturing performance of the MMs. The program contains the geometrical parameters of all the MMs of the optical design. For each MM radius, based on the Tx,Ty,Tz,Rx,Ry,Rz given as input, the program shifts the spot randomly inside the alignment range adopted in the sensitivity analysis, then rotates it around the optical axis, and finally weights it according to a factor that takes into account the effective area. At the very end, another program gets back the radius encircling 50% of the energy.

3.2 AIT budget

For the Assembly Integration and Testing (AIT) budget, both HEW and Effective Area have been considered. Looking at the HEW criterion, the most sensitive MMs are the outermost, and the innermost MMs are the most sensitive to loss of effective area. For the assignment of the alignment budget given in Table 2, we have considered the outermost MM with regards to HEW criterion and the tightest tolerance of the innermost MM corresponding to a loss of effective area of 1%. Note that:

- in reality the weighting of the different MM radii on the overall telescope performance is a function of the photon energy.
- In reality the contribution of the in plane MM misalignment (Rx,Ry and Tx,Ty) is not symmetric. Being symmetry more convenient for the AIT, the most stringent of the two is adopted.

Table 2. AIT budget considered for the study.

Contributor	Alignment Tolerance	HEW	Alignment Tolerance	Area loss
Tx	25 μm	0.42”	-	-
Ty	25 μm	0.24”	-	-
Tz	300 μm	0.40”	-	-
Rx	160 μrad	0.03”	27 μrad	1.0 %
Ry	160 μrad	0.14”	30 μrad	0.3 %
Rz	30 μrad	1.35”	-	-
RSS contribution		1.5”		1.0 %

3.3 Metrological methods for the alignment

In the first phase of the study three metrology methods have been compared:

1. Direct X-ray metrology. The direct X-ray approach provides real time figure of merit that can be directly related to the operational performance. For this study it has been assumed the future availability of an X-ray facility with a direct beam big enough to illuminate the diameter of the telescope.
2. Indirect metrology. This is a two steps approach, that requires at first a dedicated characterization of each individual MM, followed by the alignment into the mirror structure. In the characterization step, the X-ray focus position is referenced to optical elements (fiducials) mounted on the MMs themselves. Once this step is done, the coordinate system is transferred to the mirror structure and the alignment is performed according to the previous characterization of each individual MM. The challenge of the indirect method is to put in place a sufficiently accurate metrology over the 12 m focal length, a solution with laser tracker devices has been studied as the most promising among other possible indirect methods.
3. Optical metrology. The optical method has been assessed in the visible light, for aligning the MMs in the telescope using the centroid of their diffraction pattern. The optical method does not need a priori characterization of the MMs, and each MM can be aligned in the telescope for all the degree of freedom following the optical response.

For each method a detailed breakdown of the errors has been perfomed, and the software presented in §3.1 has been used to calculate the corresponding HEW contribution:

- 0.4 arcsec HEW for the X-ray
- 0.7 arcsec HEW for the indirect
- 0.9 arcsec HEW for the optical

Pro and cons have been weighted for criteria beyond the Performance, such as Technical Feasibility, Maturity & Risk and Cost & Schedule. As conclusion of the trade-off, the direct X-ray has been assumed as baseline method, and at the same time it has been considered worth further studying the indirect method. The expected alignment tolerances, for the different degrees of freedom, of the direct X-ray and the indirect methods are presented in Table 3.

Table 3. Expected alignment tolerance achievable by the direct x-ray and the indirect methods.

Method	**Position (μm)**			**Rotation (μrad)**			**HEW (arcsec)**
	Tx	Ty	Tz	Rx	Ry	Rz	
Indirect	18	18	15	53	64	64	0.7
Direct X-ray	8	8	8	38	38	38	0.4

4. DEMONSTRATOR DESIGN

A demonstrator is currently under manufacturing, having the goal of experimentally verify the achievable alignment tolerance of the indirect and direct X-ray methods. The optical part of this demonstrator will consist of 2 real mirror modules representative of the flight design, in terms of materials, processes and as close as possible to the required performance of 4.3” HEW.

The 2 mirror modules (MMs) will be identical and with the following characteristics:

- MM mid radius = 709.184 mm
- Width of the MM stacks = 65.678 mm
- Plate thickness = 3 mm

The Mirror Structure Element of the demonstrator, is designed to accommodate the two identical mirror modules as described above. It features titanium plates which are bolted together, such that the geometry of the two cells is representative of the full mirror structure design (see Figure 2 left). The spacing between the MMs has been chosen in order to maximize the effective area of a given row, but keeping sufficient clearances for integration and alignment of the MMs. This spacing is defined by the angle between two consecutive MMs of the same row.

The mirror structure element has been designed also taking into account the following considerations:

- the design is representative of the material and local geometry of the mirror structure;
- the design implements the interfaces for two neighboring MMs;
- the design provides interfaces and references for the MMs integration, co-alignment and metrology;
- the design provides interfaces suitable for environmental testing;
- mass and stiffness representativeness is not possible since the manufacturing technique differs from the one assumed in the design of the flight mirror structure.

The MM mounting concept is based on stainless steel dowel pins bolted at the base of mirror structure element. The 3 interface points are defined so to lie on a radial line w.r.t. the mirror structure. This is a purely bolted interface, so that the exchange of a MM can be easily perfomed if needed. A shim with a defined nominal thickness is foreseen for adjustment along Z (direction of the optical axis). For the demonstrator, no adjustment for the MMs focal length will be performed. However, a shim is integrated in order to keep representative interfaces. In-plane adjustments are not performed at this interface but at the upper interface, where the MMs are integrated via a bonding line making use of the MM bracket features.

The X-ray Optical Units (XOUs) of the MMs are held in position by the use of two Invar brackets, one on each side of the MM. The two brackets are not identical in the number of interface points towards the mirror structure element: one bracket has one lug and the other bracket has two lugs.

In the frame of this study, the brackets design, inherited from previous ESA/SRON studies, has been slightly adapted in order to:

- have sufficient area on the lugs for the bonding;
- create interfaces for the optical elements needed by the indirect method;
- adapt the interfaces for the handling of the MMs during alignment and integration.

The updated design of the brackets can be seen in the Figure 2 right.

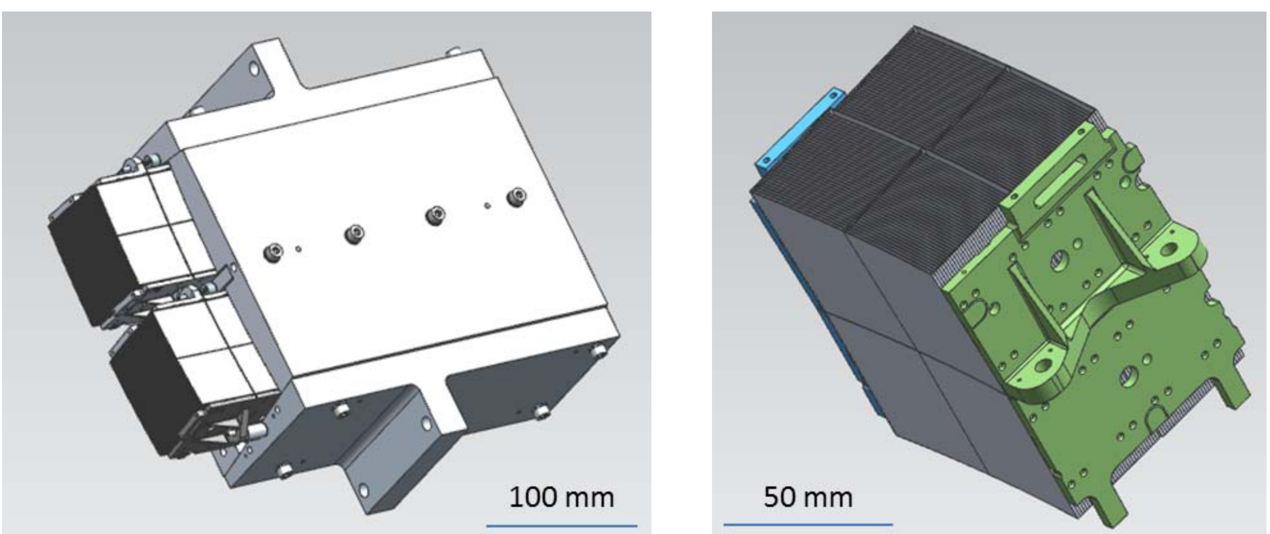

Figure 2. Design of the Demonstrator (left) and of one Mirror Module with the modified brackets (right).

5. CHARACTERIZATION OF THE MIRROR MODULES

As described in §3.3, the first step needed by the indirect method is the characterization of the individual MMs. This characterization is foreseen with laser trackers at the X-ray Parallel Beam Facility (XPBF 2.0) in the laboratory of the Physikalisch-Technische Bundesanstalt (PTB) at the electron storage ring BESSY II [8]. BESSY II is a 3rd generation synchrotron radiation facility using bending magnets and insertion devices to produce intense radiation from the infrared to the hard X-ray region.

5.1 PTB beamline XPBF 2.0

The two Mirror Modules (MMs) for the demonstrator are currently under manufacturing, and they will be integrated using XPBF 2.0 (see Figure 3).

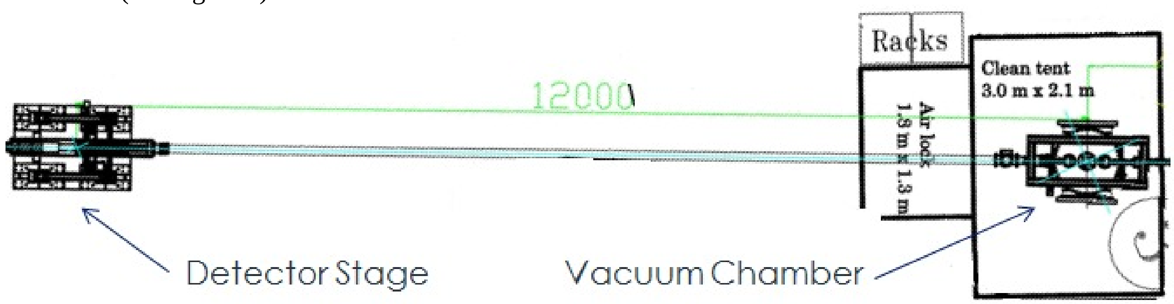

Figure 3. PTB beamline XPBF 2.0.

Once each integrated MM will be available, dedicated optical fiducials, to be monitored by the laser trackers, are installed on the MM's brackets. On the detector stage (Figure 3 – left side), some laser tracker optical targets are as well mounted, whose positions w.r.t. the detector focal plane are a priori characterized. The MM is installed on the hexapod inside the vacuum chamber (Figure 3 – right side), and aligned for a maximum intensity and best focus position under X-ray. The optical tracking is performed through the chamber optical windows, without the need of venting:

- two Laser Trackers (LTs) with autocollimation capabilities are adopted, so to determine the two rotations (Rx, Ry) of the MM in the laser trackers reference frame.
- The following step consists in the measurement of the targets on the MM with each of the laser trackers. This gives the absolute position (Tx, Ty, Tz) of the MM in the laser trackers reference frame.
- The last step is the measurement of the focal point position, via the targets placed on the detector assembly.
- All together results in the absolute position of the focal point w.r.t. the MM optical references and MM orientation for maximum effective aperture.

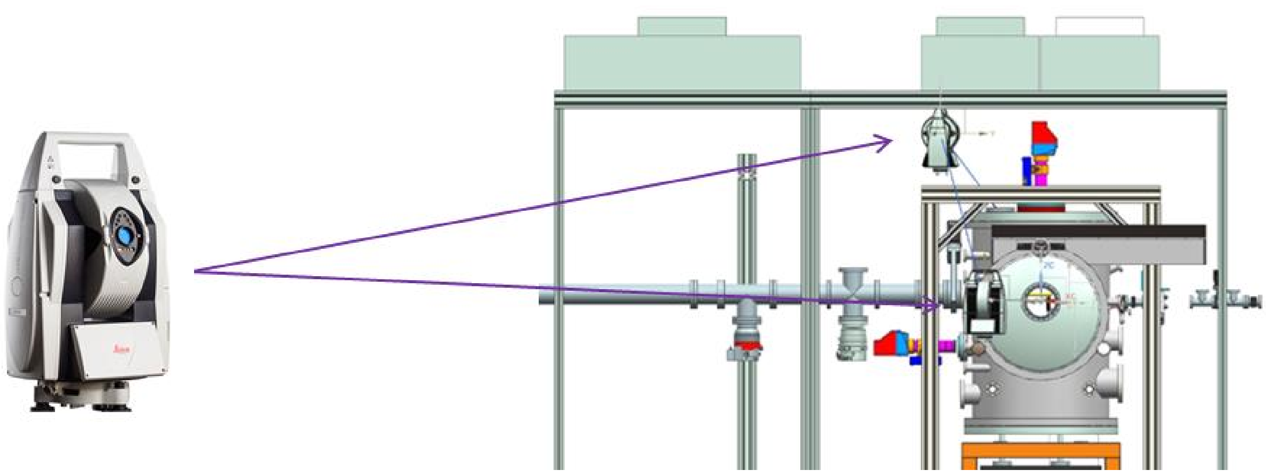

Figure 4. Laser Tracker System to be used for the characterization of the MMs.

5.2 Characterization budget

The accuracy of the indirect method depends on the accuracy of this characterization step. The overall budget (presented in Table 3) is the results of the root sum squared of the characterization and of the alignment steps. The different sources of error for the definition of the MM position and rotation have been deeply investigated, as for example:

- position and pointing accuracy of the laser tracker and of the targets;
- the definition of the centroid position on the detector;
- stability and knowledge of the X-ray beam direction;
- reference frame transfer error within the laser trackers.

The resulting global errors for the characterization phase of each MM are presented in Table 4.

Table 4. Expected MMs characterization accuracy.

Position (μm)			**Rotation (μrad)**		
Tx	Ty	Tz	Rx	Ry	Rz
16	16	13	23	23	23

6. DEMONSTRATOR INTEGRATION AND TESTING

6.1 Integration set-up

The MPE Panter facility in Munich will host and support the integration of the demonstrator, and also the final test campaign. A combined metrology between indirect and X-ray illumination will be used. As alignment under X-ray requires vacuum environment, the equipment (e.g. the Hexapod) has to be vacuum compatible, except the laser trackers which will be operated at ambient pressure conditions.

The global view of the setup is given below in Figure 5.

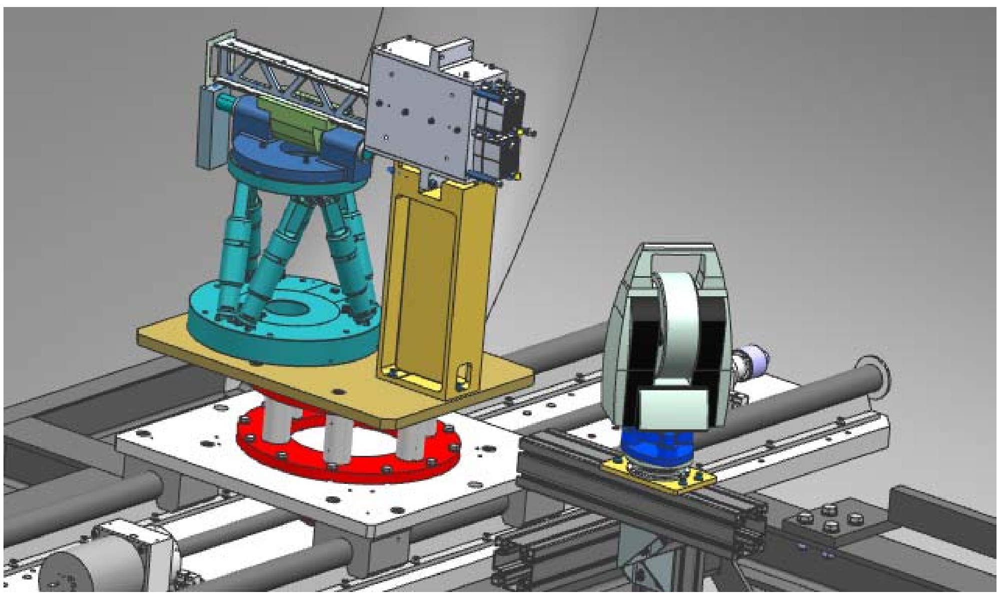

Figure 5. Demonstrator integration set-up in the Panter chamber.

6.2 Alignment under indirect metrology

This alignment phase relies on the data from X-ray Parallel Beam Facility (XPBF 2.0) characterization, and makes use of two Laser Trackers to be installed at Panter. The MM to be integrated is mounted on a hexapod allowing precise manipulation in 6 Degree of Freedom. Each MM is aligned according to the information from the previous characterization described in section 5. At first, the effective aperture is maximized by aligning the in-plane rotations (Rx, Ry) via autocollimation measurements. Then the position of the focus is adjusted by moving Rz, Tx, Ty and Tz without modifying the previous parameters. This step is considered successful when the both out of plane and in-plane alignments are completed, and the metrology measurements are within the defined tolerance .

6.3 Alignment under direct X-ray

This alignment method is used to align directly the X-ray spot of the MMs w.r.t. a common focal point. The focus position of the first MM is measured under X-ray and recorded in the detector. This spot is then used as reference for aligning the following MM. The MM is aligned in vacuum by means of the remotely controlled hexapod, and monitored in real-time with the X-ray beam. The hexapod is moved such that the throughput is maximized by using the in-plane rotations (Rx, Ry). Then the focus point is brought into the best common focal point, by adjusting the remaining parameters (Rz, Tx, Ty, Tz). Once these two phases are sequentially performed the alignment is considered as successful.

6.4 Alignment sequence of the demonstrator

The foreseen sequence of the demonstrator integration is shown in the flow chart in Figure 6. This sequence allow to verify the performance of both the indirect and the direct X-ray method: i) the first MM is aligned and then bonded using the indirect metrology; ii) the second MM is aligned using the indirect metrology but not bonded; iii) the 2^{nd} MM is kept in position by the hexapod, while the chamber is evacuated and the X-ray performance measured; iv) the chamber is vented and the position of the MMs re-measured, so to check for potential influence of the air-vacuum transition on the stability; v) the chamber is once more evacuated and the 2^{nd} MM aligned under direct X-ray; vi) the chamber is vented to allow bonding; vii) after curing of the adhesive bonding, the vacuum is re-establish for the final performance measurement in X-ray.

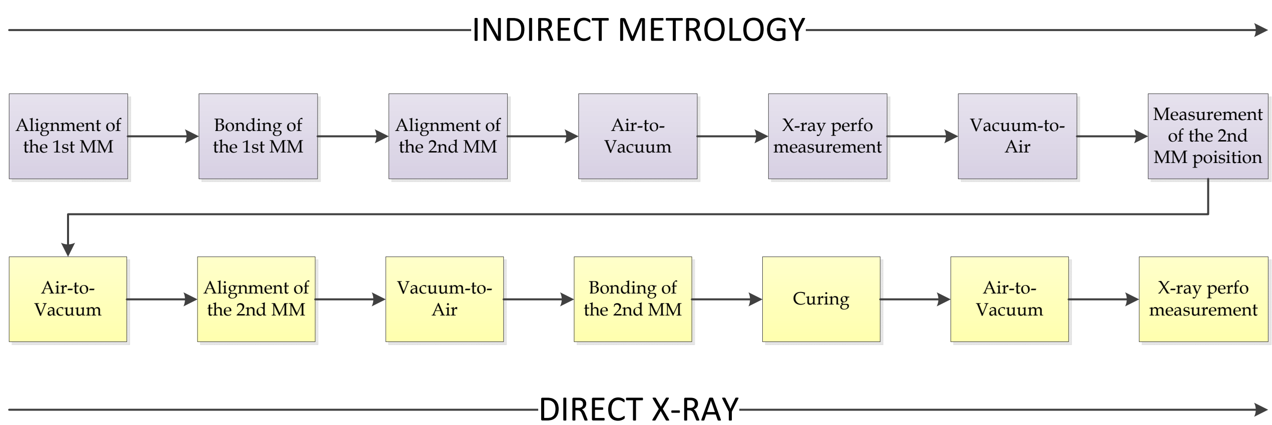

Figure 6. Demonstrator integration sequence

7. CONCLUSION

The status of the integration process, involving both indirect metrology and alignment under direct X-ray illumination, has been presented with the associated HEW budgets.

The indirect metrology relies on metrology on optical fiducials attached to the MM and reference measurements performed during the assembly of the MMs at the synchrotron facility. The alignment under direct X-ray illumination, is done using the wavelength for which the MMs are built for. Both method will be verified at Panter, by means of a dedicated demonstrator, with two real SPO MMs in a representative Mirror Structure element.

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