Aperture cylinder on Athena X-IFU: development status

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ABSTRACT

The Athena mission in general and the X-ray Integral Field Unit (X-IFU) instrument in particular are designed to address a wealth of scientific questions related to the science theme of the Hot and Energetic Universe.

X-IFU provides medium spatial resolution and high resolving power by means of a calorimetric detector.

As the X-IFU detector needs to be operated at 50mK, the instrument is contained in a dewar. The aperture cylinder consists of a set of structural and thermal elements that carry and position at correct distances from the detector the first three dewar thermal filters, provide adequate thermal interfaces and protect the filters from contamination.

In this paper, we present the Phase A-B1 contribution of Centre Spatial de Liège (CSL) to the X-IFU consortium. This summarizes to the elaboration of a baseline design for the aperture cylinder, and several demonstration models as a de-risking activity with the intent to increase the aperture cylinder maturity.

Keywords: X-ray spectrometer, micro calorimeter, aperture cylinder, X-IFU, Athena X-ray observatory, system design, prototype

1 INTRODUCTION

Athena [1] is the second L-class mission of ESA's Cosmic Vision program with a launch foreseen in the mid-2030s. Athena will be dedicated to the understanding of high-energy astrophysics phenomena. To this aim, it will observe the universe in the X-rays as successor of XMM Newton. The spacecraft architecture is composed of a 12m focal length X-ray telescope and two instruments:

- A high spectral resolution imager named X-IFU (X-ray Integral Field Unit)
- A wide field imager with moderate spectral resolution named WFI (Wide Field Imager)

Figure 1-1 presents the spacecraft architecture with the service module surrounding the Silicon Pore Optics telescope on the left side and the focal plane module supporting the two instruments on the right side [2].

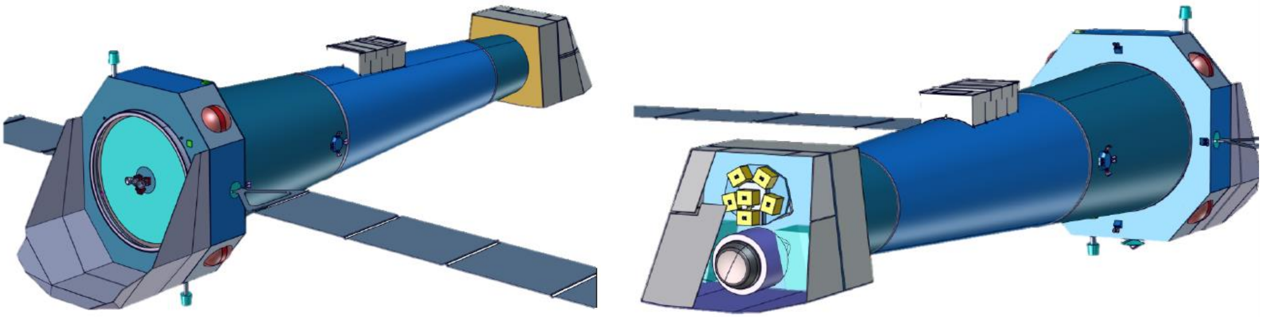

Figure 1-1 : Athena spacecraft with Service Module including the mirror assembly (left) and Focal Plane Module integrating the WFI and X-IFU (right).

1.1 The X-IFU micro-calorimeter

The X-IFU [3] is a cryogenic imaging spectrometer, based on a large micro-calorimeter array of Transition Edge Sensors (TES), providing 2.5eV spectral resolution, with 5″ pixels over a field of view of 5′ in diameter.

As the X-IFU detector needs to be operated at 50mK, the instrument is contained in a dewar with a successive set of cryo coolers and thermal shields specifically designed to achieve the required thermal performance. Figure 1-2 shows the baseline design of the dewar. It consists of:

- an outer vessel (OV) in 200K-300K range, passively cooled,
- an outer cryo shield (OCS) cooled down around 100K,
- an inner cryo shield (ICS) operating around 30K,
- a 4K shield surrounding the 2K structure of the focal plane assembly (FPA).

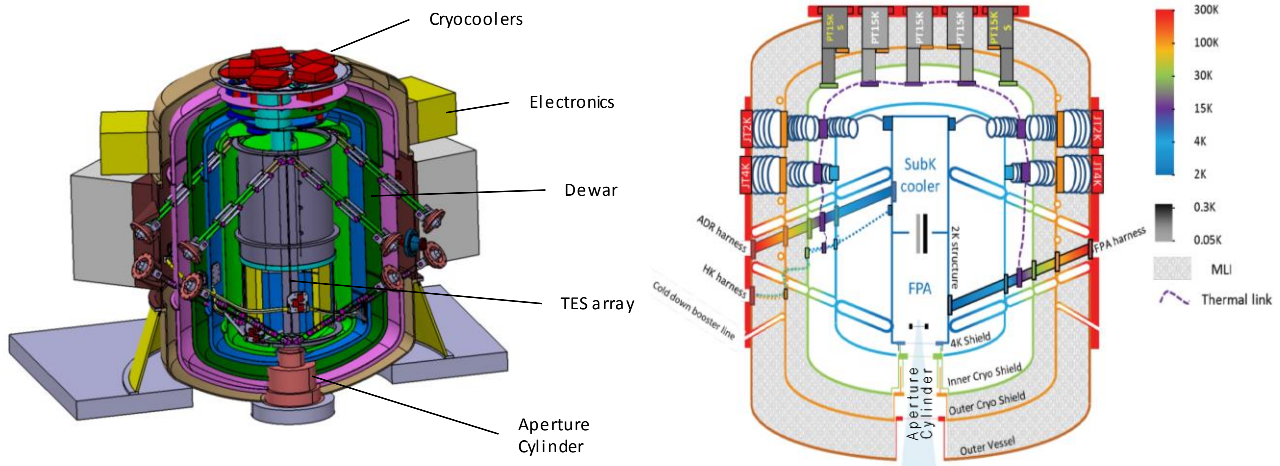

Figure 1-2 : X-IFU cryostat: an open view (left) and the different mechanical coolers and thermal shields (right).

1.2 The aperture cylinder

To provide the necessary optical aperture through the different thermal shields of the dewar, an *Aperture Cylinder (ApC)* is mounted on the cryostat assembly.

The aperture cylinder supports three ultra-thin aluminum filters providing the required spectral filtering, rejecting unwanted IR, visible and UV light. The 30nm of aluminum are supported by 45nm of polyimide and the filters are mechanically reinforced by a hexagonal stainless steel mesh [4]. The ApC thermal filters are thermally anchored on separate cryostat thermal shields. One filter is linked to the outer vessel (300K), one to the outer cryo shield (100K), and one to the inner cryo shield (30K). The filter stack is completed with two extra filters mounted inside the FPA structure. The design is inspired from the Japanese ASTRO-H mission [5].

The X-IFU is presently in phase B1, progressing to the System Requirements Review. In a multinational consortium led by CNES[1], the Centre Spatial de Liège (CSL) is responsible for the development of the aperture cylinder.

In this paper, we draw a general overview of the design and experimental demonstration activities performed to support the design consolidation of the X-IFU ApC, in view of the mission adoption.

[1] Centre national d'études spatiales, FR

2 APERTURE CYLINDER DESCRIPTION

Figure 2-1 presents the overall configuration of the aperture cylinder. It is composed of three separate mechanical sub-assemblies:

- The outer vessel (OV) sub-assembly supported by the cryostat outer vessel and supporting:
  - The 300K carrier and THF300 thermal filter,
  - The outer cryo shield (OCS) sub-assembly, including the 100K carrier and THF100 filter,
- The inner cryo shield (ICS) sub-assembly supported by the cryostat inner cryo shield and supporting the 30K carrier and THF30 filter,
- The lower cryo shield (LCS) baffle.

The aperture cylinder assembly provides clear aperture to the telescope and in-flight calibration sources field of views. The optical filters are interfaced through intermediate supports called carriers designed to facilitate the integration operations.

The 100K OCS sub-assembly is mechanically coupled to the OV sub-assembly to minimize the mass supported by the outer cryo shield. The OCS sub-assembly is thermally coupled to the cryostat OCS through flexible thermal straps.

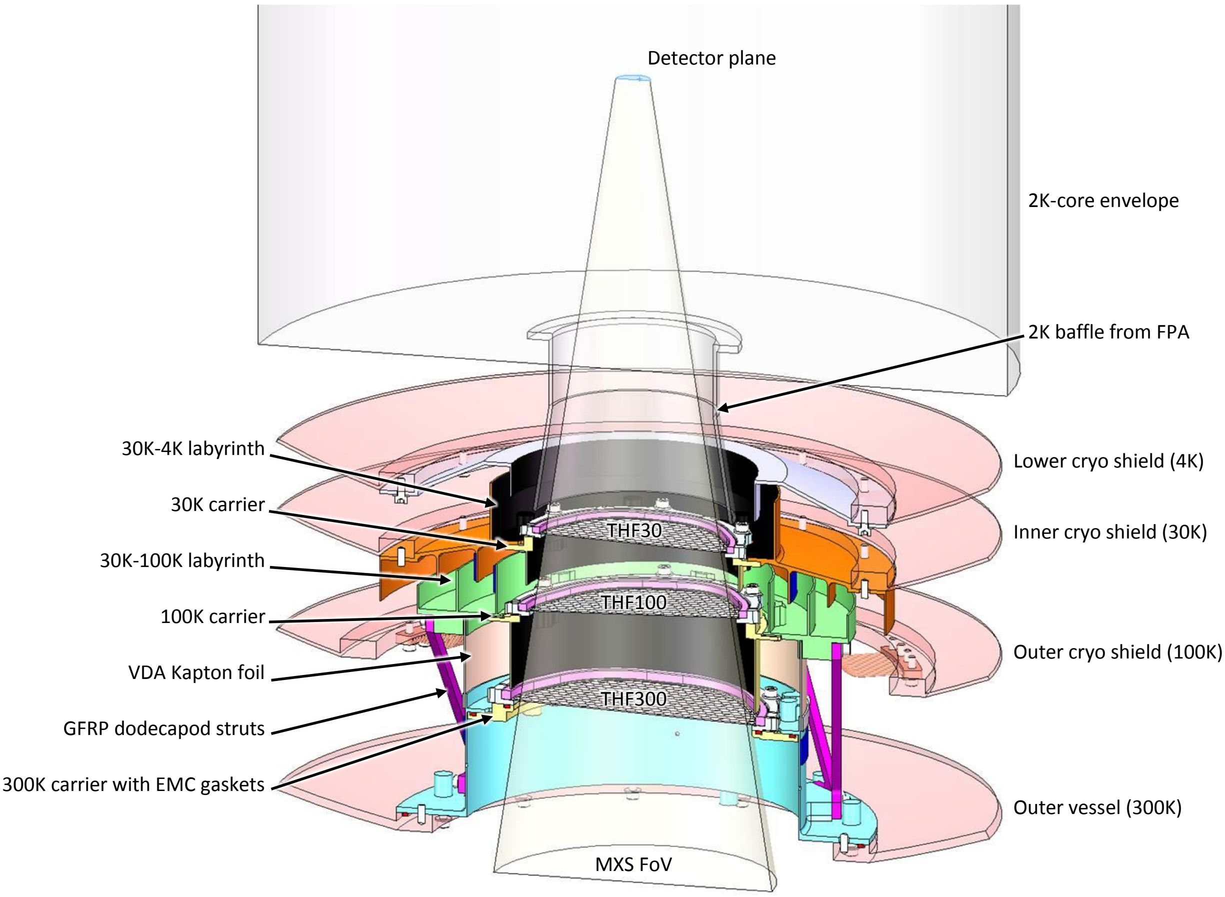

Figure 2-1 : Aperture cylinder overall description.

2.1 Functions

Generic

The aperture cylinder supports mechanically the THF300, THF100 and THF30 thermal filters and provides them with the proper thermal environment, based on the cryostat interfaces. The filters clear apertures are respectively 128mm, 111mm and 99mm.

The ApC limits the radiative heat load from the external environment and hotter stages through the optical aperture towards the colder stages. It provides baffling capabilities, accommodates housekeeping sensors and protects the filters from contamination.

During transient warm up or cool-down phases, the need for preventive heating to mitigate contamination is under discussion and has been conservatively implemented. Continuous heating of the THF300 filter may be required in case the outer vessel interface is colder than the required filter temperature.

Outer vessel stage

The outer vessel (OV) flange (in blue in Figure 2-1) supports the THF300 carrier (in yellow) and ensures the correct positioning of the THF300 filter with respect to the cryostat OV interface. The OV flange forms a cavity between the cryostat door and the first filter THF300. Dedicated openings will ensure the venting of that cavity towards the cryostat OV-OCS interspace.

The OV flange supports the Outer Cryo Shield (OCS) flange through GFRP struts.

The cavity between the THF300 and THF100 filters is closed on the side with an aluminized polyimide foil, providing water vapor and IR straylight barrier.

A main function of the OV stage is to ensure the continuity of the dewar Faraday cage from the cryostat interface until the THF300 filter interface. This is enabled by the continuous metallic flange, coupled with EMC gaskets at each interface.

Finally, the OV flange includes dedicated interfaces with the tooling required for integration of all three filters at the end of the cryostat integration sequence.

Outer cryo shield stage

The outer cryo shield (OCS) flange (in green in Figure 2-1) supports its corresponding carrier with the THF100 filter and correctly positions it with respect to the cryostat OV interface. Through the GFRP struts, it is mechanically coupled to the structurally stiff OV flange but thermally coupled to the colder OCS interface via flexible thermal straps.

The OCS includes cylindrical rings protruding towards the inner cryo shield (ICS) flange to form together a barrier to molecular contamination from the cryostat.

The THF100 carrier supports a black coated cylindrical baffle extending towards the THF300 filter, designed to reduce the IR photon shot noise on the instrument detector.

Inner cryo shield stage

The inner cryo shield (ICS) flange (in orange in Figure 2-1) ensures the support of the THF30 carrier and its correct position with respect to the cryostat ICS interface.

The ICS flange includes cylindrical rings protruding towards the OCS flange to complete the contamination barrier, forming a molecular labyrinth.

In a way similar to the THF100 carrier, the THF30 carrier includes a cylindrical baffle extending towards the THF100 to reduce IR shot noise.

Lower cryo shield stage

The lower cryo shield (LCS) flange (in light grey in Figure 2-1) provides the functions of thermal shielding and shot noise reduction between the inner 2K baffle protruding from the focal plane assembly and the ICS. Together with the ICS flange and 2K baffle, it also reduces the contamination path from the cryostat towards the 2K filter, nested at the base of the 2K baffle.

2.2 Mechanical design

Semi-monolithic structure

During conceptual design phase, a trade-off was conducted between

- a monolithic structure mechanically linking the OV, OCS and ICS aperture cylinder stages and
- a semi-monolithic structure only linking the OV and OCS stages while leaving the ICS stage mechanically decoupled and supported by the cryostat ICS flange.

Due to the combination of stringent heat load budget at ICS level and structural requirements, the semi-monolithic structure was selected as baseline for System Requirements Review.

In the selected design, the OCS sub-assembly is therefore supported by the OV sub-assembly through a truss structure made of 12 GFRP struts. This material provides both stiffness and thermal decoupling. The challenge is to limit strongly (<0.5W) the conductive heat load between the two stages separated by 200K. The stiffness of the GFRP truss structure limits deformation of the THF100 filter interface during vibrations, and mitigates the amplification of the vibration levels seen at the filter interface.

It is expected that the various cryostat interfaces will present relative displacements of several millimeters, due to thermoelastic deformation during cool down and vibrations at launch. The thermal coupling of the OCS aperture cylinder sub-assembly to the cryostat OCS interface is thus performed through flexible thermal straps. Their stiffness shall be negligible with respect to the struts structure to allow the expected relative displacements between their extremities.

The ICS aperture cylinder sub-assembly is directly mounted onto the cryostat ICS interface. Together with OCS flange, they form a contamination labyrinth. The size of the gap in the labyrinth is driven by the relative displacements between the cryostat shields.

The current mass of the aperture cylinder including the thermal filters and 30% design margin is 4.3kg. The largest dimensions of the assembly are 285mm in diameter and 180mm in height.

Materials

The dominant material in the ApC is aluminum. In particular, aluminum is selected on the filters carriers to match the material of the filters frames [4].

The OV flange is made of titanium to both ensure sufficient stiffness while reducing the thermally conductive coupling to the OV interface. In case the THF300 filter interface requires to be heated continuously, this allows reducing the heater power consumption.

The GFRP struts forming an open structure, the cavity between the THF300 and THF100 filters is closed on the side with a polyimide foil. This foil is clamped on the OV flange side and free in a groove on the OCS flange side to allow thermo-elastic deformation. Water vapor and IR straylight barrier is ensured by a double-sided aluminum coating.

2.3 Thermal design and control

One of the main purpose of the aperture cylinder is to provide thermal anchoring of the three warmest filters of the X-IFU. Each of the three filters needs to be thermalized in a specified range: 20-40K for the coldest one THF30 and 80-120K for the intermediate one THF100. These requirements are driven by the need to reduce the heat load and photon shot noise towards the inner stages and the 2K-core. In addition, the cleanliness of the entrance filter THF300 requires keeping it above 320K to avoid trapping external contamination. The THF300 is expected to exhibit a significant temperature gradient between the center that is cooled down by the inner stages and the border that is thermalized. To meet the 320K requirement, the frame of the filter might therefore need to be kept at 340K during operations.

Except for the THF300 that might be constantly kept above 320K through heaters, the thermal design in the operating mode is passive. The temperature of the aperture cylinder inner stages is driven by the temperatures of the cryostat interfaces thanks to a good thermal coupling. The THF100 stage is coupled through custom flexible copper thermal straps to allow mechanical decoupling. The THF30 stage is conductively coupled through its aluminum flange.

Heaters are foreseen on each filter stages for the transient phases (cool-down and warm-up) to protect them from contamination by keeping them hotter than their environment. As the conductive coupling between the filter and the cryostat interface is good, most of the gradient during the transient phases is taking place in the respective cryostat shells since the coolers are connected on the opposite side to the aperture cylinder.

In operating mode, the allowed interface heat loads from the aperture cylinder to the cryostat OCS and ICS interfaces are 1000mW and 30mW, respectively. These values include both conductive and radiative contributions. Out of the 1000mW to the OCS stage, a radiative heat exchange of 500mW is expected, leaving 500mW for the mechanical coupling between the OV and OCS stages. The 30mW allocated heat load at ICS level prevented any sufficiently stiff mechanical coupling with the hotter stages and therefore a full monolithic concept of the aperture cylinder was discarded.

In order to minimize the radiative heat exchanges between the different stages of the aperture cylinder and meeting the allocated heat load, most of the surfaces are gold plated to provide a very low thermal emissivity. Heat loads through sensor and heater harnesses are also minimized by benefiting from electrical interfaces provided by the cryostat at each level.

2.4 Shot noise mitigation

The filters are tilted by 2arcdeg with respect to each other to reduce transmission of multi-reflected photons, directing them to a black absorbing coating on a cylindrical baffle on the edges of the filters cavity. The baffle is supported - thus cooled - by the colder filter carrier, to limit the thermal shot noise emitted by the baffle itself, and by the cavity in general. This shot noise baffle is implemented in both 300K-100K and 100K-30K aperture cylinder cavities.

In addition, the polyimide foil closing the THF300 – THF100 cavity is coated with vacuum deposited aluminum on both sides (typical thickness of aluminum is 2 x 100nm), forming a barrier to the IR shot noise coming from the cryostat OV-OCS interspace.

2.5 Venting and contamination mitigation

The filters being extremely sensitive to acoustic load, it is mandatory to launch the cryostat under vacuum. Nevertheless, the instrument test sequence might require several pumping and repressurization phases during which the air flow and pressure gradient inside the cryostat should not endanger the filters integrity. On the other hand, cleanliness of the filters is very critical and contamination should be prevented, both from molecular sources to ensure no degradation of the instrumental response, and from particles to mitigate the risk of filter foil puncture. The filters cavities should therefore be as contamination tight as possible while ensuring sufficient venting.

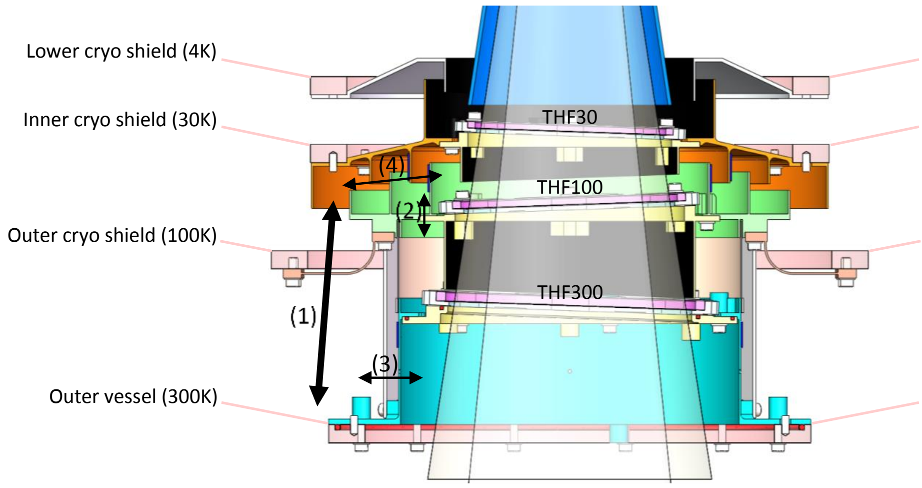

Figure 2-2 : Highlights of the venting and contamination paths in the aperture cylinder.

Figure 2-2 shows the venting strategy. First, outside the aperture cylinder, there is a significant path between the 30K interface and the outer vessel (1). This path shall be blocked from a thermal point of view while still allowing relative displacements between the cryostat shells, possibly with multi-layer insulation, but it is not expected that this radiative barrier prevents contamination to flow through. Inside the ApC, the 300K-100K filter cavity is vented towards the 30K colder and cleaner stage (2). The 300K filter – door cavity is vented radially towards the “dirtier” 300K-100K cryostat interspace (3), the contaminant being potentially water vapor desorbing from the cryostat shells and insulation. The venting of the 100K-30K filter cavity is done towards the 100K-30K cryostat interspace, these ApC stages being mechanically decoupled. A cold trapping labyrinth covers the venting path (4).

The 100K-30K labyrinth design is preliminary and is to be confirmed once the source, type and amount of contaminant in the cryostat will be better known, together with the cryostat warm-up and cool-down strategy. It is important to highlight that the in-flight labyrinth efficiency is linked to the presence of a sufficiently efficient contamination sink outside the aperture cylinder vicinity, be it venting towards deep space or cold trapping. The path to this contamination sink should be easier than the path through the labyrinth towards the filters. Otherwise, contamination will eventually, with time, distribute uniformly in the considered cavity. In addition, the labyrinth only offers poor protection against particular contamination during repressurization of the cryostat since particles will move together with the air flow.

2.6 Housekeeping

A pair of thermal sensors (nominal + redundant) provides temperature information on each of the three filters interfaces. The sensors connect to electrical interfaces provided by the cryostat at each level, and form an extension of the cryostat housekeeping harness.

2.7 Integration aspects

Because of the fragility and criticality of the optical filters, they shall be integrated into the cryostat as late as possible. This implies that the ApC design allows mounting the inner filters while the rest of the ApC and cryostat is already assembled. This need translates in geometrical constraints, the inner filters and their respective supports having to fit through the upper stages. The late integration requires dedicated mechanical ground support equipment designed to insert the filters through the different shields and fasten them while mitigating the risk of particles generation.

During integration of the aperture cylinder on the cryostat, non-flight caps will replace the filters, protecting the inner layers of the cryostat from contamination. The cap on the 30K sub-assembly will have the additional function to support temporarily the 300K-100K sub-assembly, ensuring co-alignment until it is securely fastened on the outer vessel interface.

The filters are mounted on their respective carriers, before integration in the ApC. The carriers provide interface to filter integration tool and to temporary protection covers.

Once the filters are integrated, it is of paramount importance to mitigate the risk of delta-pressure due to air displacement inside the cryostat. The cryostat should therefore be pumped down as quickly as possible after filter integration.

3 DEMONSTRATION ACTIVITIES

3.1 Equipped filter carrier

Demonstration activities allowed early validation of key design aspects, thanks to partially representative development models (DMs). The first phase A demonstration activity focused on the handling and thermal performance of the THF300 filter and its carrier (Figure 3-1).

One objective was to assess the filter and carrier integration complexity, with potential design features such as indium gaskets and fastener-free spring lock mechanism. The experience gained was valuable, though these features were not retained.

The other objective was to improve the knowledge of the assembly from a thermal point of view. Early thermal modelling of the aperture cylinder showed that the THF300 filter could experience a significant temperature gradient between its center and its frame, the center being radiatively cooled by the lower stages of the ApC. A thermal vacuum test was set up to estimate this gradient, as well as the filter thermo-optical properties, the gasket contact conductance and, implicitly, the survival of the filter to the stress of a thermal vacuum session. These objectives were achieved in 2021. We introduce here the original method to measure the filter center temperature.

Filter temperature gradient measurement

Measuring the temperature at the center of the filter is not straightforward. Due to the fragility of the filter, it is not possible to install a temperature sensor. Measuring the temperature through infrared imaging would also not give satisfactory results as the filter is highly reflective in the IR (>95%).

An alternative way to extract the temperature of the filter was therefore implemented. It is based on the bi-phasic equilibrium of water vapor. The filter separates two cavities under vacuum. Its support ring is first thermalized at the measurement temperature. A given quantity of pure water vapor is then injected in the first cavity. The filter foil is progressively cooled by a baffle in the second cavity, and a cold spot at the center of the filter is created. This cold spot of increasing amplitude is the coldest point of the cavity with vapor. The water vapor eventually condenses when saturation conditions are met, the driving temperature being the center of the filter. By measuring the absolute pressure at the exact moment when it starts dropping due to condensation, the temperature of the cold spot located at the center of the filter could be extracted.

The method was validated and calibrated using a Kapton filter with a thermal diode glued on the center, providing a reference point for temperature comparison (Figure 3-2).

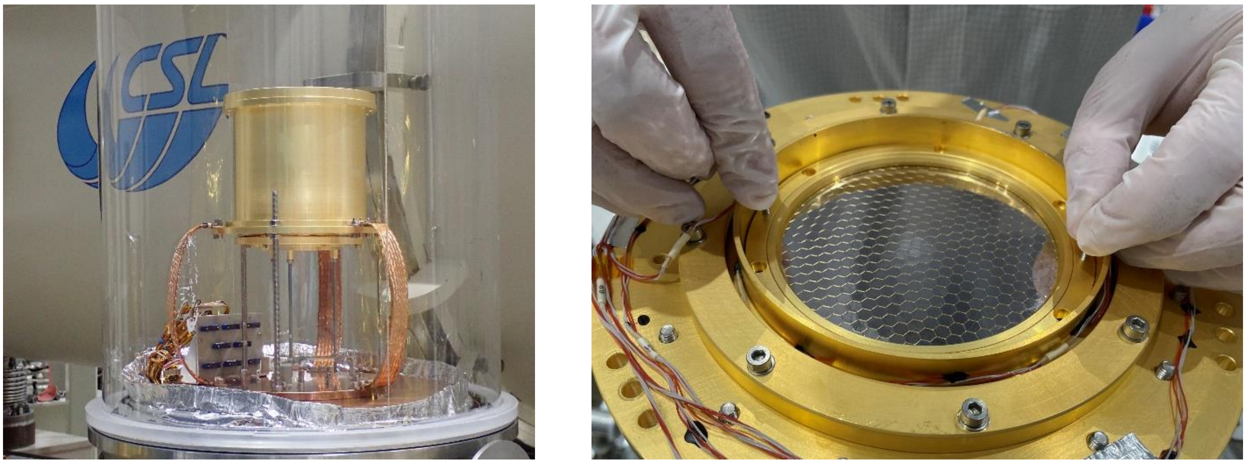

Figure 3-1 : DM1 test setup (left) and DM1 100mm diameter filter (right).

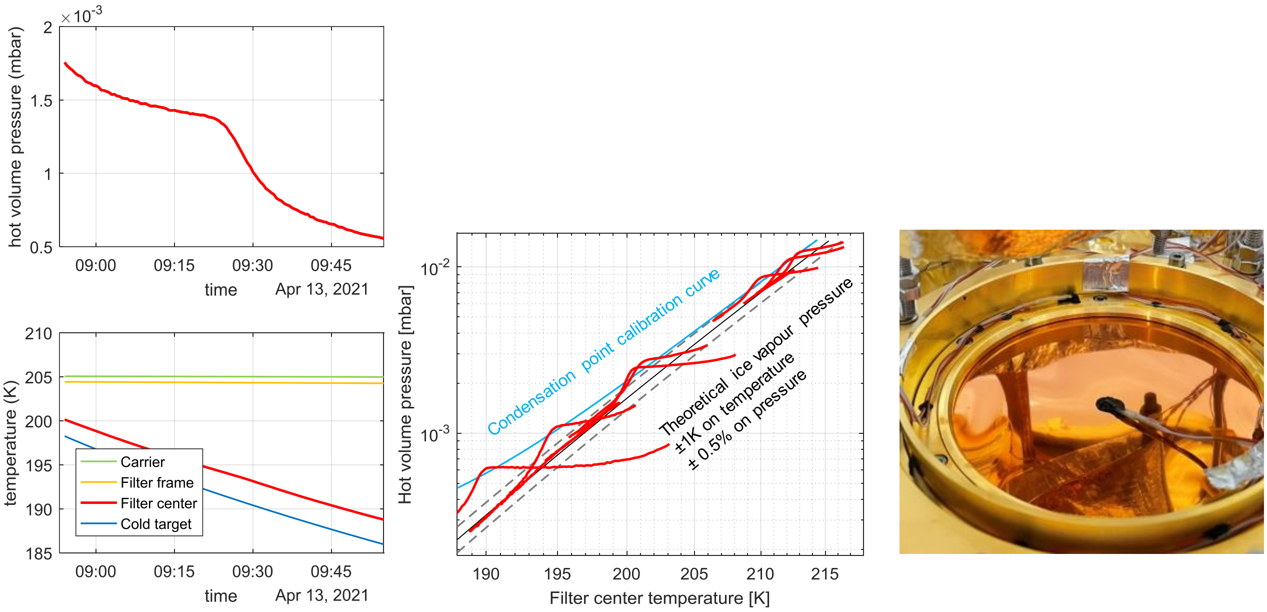

Figure 3-2 : Filter gradient measurement with condensation method : measurement of temporal evolution of vapor pressure and filter temperature (left), resulting calibration curve (center), instrumented Kapton filter used for calibration (right).

3.2 Heating mesh - feasibility assessment

The potentially large thermal gradient in the THF300 filter was initially a worrying design constraint and the consortium investigated several methods to limit its amplitude. One of these methods makes use of a hypothetical heating filter mesh. The application of the heating power directly on the filter surface renders the method very power efficient. This demonstration activity performed in 2019 consisted in a technological feasibility assessment of such a heating mesh, using laser induced forward transfer (LIFT) deposition of gold tracks with sol-gel encapsulation on stainless steel machined mesh profiles. The limitations found were related to the minimum required mesh width. The thermal gradient in the filter is currently managed by an adequate combination of grid material and geometrical design [4].

3.3 Aperture cylinder prototype

The demonstration activities will be completed in Q1 2023 with the development and test of a full-scale ApC prototype based on the design selected at system requirement review (SRR) and presented in this paper. The tests planned are sine and random vibrations, thermal balance with development filters and EMC. The mechanical tests will serve to correlate the numerical model and characterize the amplification factor at filters interfaces. The thermal balance will allow measuring aperture cylinder temperatures in flight representative cases and correlating the thermal model. The EMC test will measure the efficiency of the aperture cylinder as an element of the cryostat outer shell acting as a Faraday cage.

4 CONCLUSIONS

A semi-monolithic aperture cylinder has been selected and studied for SRR. The main functions and design features have been presented in the paper. The design progress towards PDR will require synergies with other X-IFU sub-systems (filters, focal plane assembly) and with the instrument cryostat.

A set of development models have been manufactured and tested to investigate aperture cylinder key design features.

In the coming months, a full-scale prototype of the aperture cylinder will be manufactured, assembled and tested. In particular, the prototype will be used to validate and correlate the numerical models but also to ensure the aperture cylinder behaves as expected, and to refine the interfaces with the X-IFU instrument cryostat.

ACKNOWLEDGEMENTS

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The Belgian team includes the Centre Spatial de Liège (CSL), in charge of the aperture cylinder, and the High-Energy Astrophysics Group (GAPHE), member of the Athena Science Study Team. Both are part of Liège University.

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