Preliminary Mechanical Characterization of Thermal Filters for the X-IFU Instrument on Athena

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Abstract The X-ray Integral Field Unit (X-IFU) is one of the two instruments of the Athena astrophysics space mission approved by ESA in the Cosmic Vision Science Program. The X-IFU consists of a large array of TES microcalorimeters that will operate at ~ 50 mK inside a sophisticated cryostat. A set of thin filters, highly transparent to X-rays, will be mounted on the cryostat thermal shields in order to attenuate the IR radiative load, to attenuate RF electromagnetic interferences, and to protect the detector from contamination. In this paper, we present the current thermal filters design, describe the filter samples developed/procured so far, and present preliminary results from the ongoing characterization tests.

Keywords Athena · X-IFU · X-ray microcalorimeters · Thermal filters

1 Introduction

The X-ray Integral Field Unit (X-IFU) [1] is one of the two instruments of the Advanced Telescope for High-ENergy Astrophysics (Athena) space mission [2]. Athena has been selected by ESA in 2014 to address the "Hot and Energetic Universe" science theme

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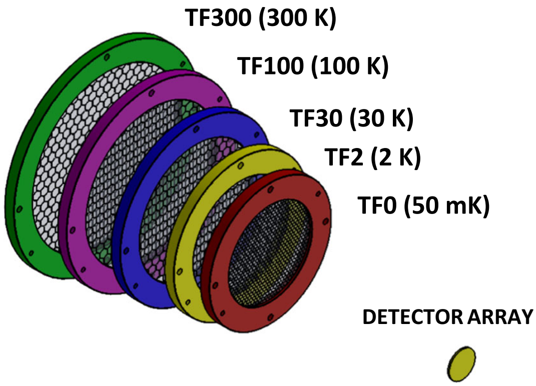

Fig. 1 Schematic drawing of the filters configuration (Color figure online)

[3]. The X-IFU will provide spatially resolved high-resolution X-ray spectroscopy from 0.2 to 12 keV, with 5″ pixels over a field of view of 5′ equivalent diameter and a spectral resolution of 2.5 eV up to 7 keV.

The X-IFU consists of a large array of Transition Edge Sensor (TES) microcalorimeters with 3840 individual pixels operating at ~ 50 mK inside a sophisticated cryostat. A set of thin filters will be mounted on the windows opened on the cryostat and focal plane assembly thermal/EMI/mechanical shields, in order to attenuate the IR radiative load onto the detector and thus, avoid energy resolution degradation due to photon shot noise. The thermal filters (TF) will also have to attenuate Radio Frequency EMI onto the detector and the read-out electronics and to protect the detector from contamination.

We presently consider using five filters operating at different temperatures, each one consisting of 45 nm thick polyimide foil coated with 30 nm of aluminum [4, 5]. In order to provide mechanical support to the thin membranes, to provide attenuation in the RF up to 12 GHz, and to allow filter de-contamination bake-out, we are currently investigating the use of a metal mesh on each filter. At this stage, stainless steel (SS) 304 meshes have been procured and tested for a preliminary concept evaluation.

Four modulated X-ray sources (MXS), located outside of the cryostat between the door and the filter wheel, will be used in flight for detector gain calibration. In order to allow for a uniform illumination of the TES array by the MXS, the filter diameters (I.D.) range from 56 to 100 mm at the current distances from the focal plane (Z) which range from 130 to 240 mm. Figure 1 shows a schematic drawing of the filters configuration, and Table 1 provides the main filter parameters.

Table 2 describes the main characteristics of the currently investigated meshes. Both types of meshes have a hexagonal pattern and are made of SS 304. Since the iron-line spectroscopy in X-ray astronomy is of great importance and relevant in many science cases of the Athena core program, the meshes are plated with 5 µm of gold to absorb iron fluorescence lines that may be generated by background particles interacting with the SS.

In this paper, we describe the filter samples developed/procured so far, present preliminary results from the ongoing characterization tests, and discuss areas of trade-offs to fully meet the scientific requirements.

Table 1 Main characteristics of the presently investigated set of thermal tilters

Name	T (K)	Z (mm)	I.D. (mm)	Mesh type[a]	Polyimide (nm)	Al (nm)
TF0	0.05	130	56	1	45	30
TF2	2	150	64	2	45	30
TF30	30	180	76	2	45	30
TF100	100	210	88	2	45	30
TF300	300	240	100	2	45	30

[a]The mesh type is described in Table 2

Table 2 Characteristics of the investigated supporting meshes

Mesh type	Wires width (μm)	Wires thickness (μm)	Pitch (mm)	Blocking factor (%)
1	30	60	2	4
2	65	130	5	3

2 Filter Test Samples

For the first vibration test campaign, we concentrated on testing the performances of supporting metal meshes with very low blocking factors. For this purpose, two filters have been manufactured consisting of a stretched polypropylene membrane (BASF Novolen 1302L) ~ 600 nm thick, coated with 40 nm of titanium, supported by mesh, and mounted on aluminum custom frames, made of two separate pieces, representative in size and design to TF300 and TF0 (samples #1 and #2).

The response to dynamic loads is mainly affected by membrane stiffness (Young modulus * thickness) and areal density (mass per unit area) of the assembly mesh + film. In our case, the membrane performance is dominated by the SS mesh (Young modulus = 210 GPa) which has an effective thickness (accounting for the blocking factor) of 1.8 and 3.38 μm, for mesh type 1 and 2, respectively (see Table 2). By using a polypropylene (Young modulus = 1.6 GPa) film 600 nm thick instead of a polyimide (Young modulus = 6.9 GPa) film 45 nm thick attached to the SS mesh, the membrane (filter + mesh) stiffness changes by few per thousands, and the areal density changes by few percents. For this reason, tests are fully representative of the stress level on the metallic mesh. The same is not true for the plastic film, since the polypropylene film is stiffer by a factor ~ 3 with respect to Polyimide. The metal coatings applied to the plastic foils do not give structural contribution and thus should not affect the results.

A second vibration test campaign was performed in November 2017 on smaller size filter samples with 45 nm thick polyimide foil coated with 30 nm of aluminum supported by the same type of meshes (samples #3 and #4). Such tests are representative of the stress level on the thin polyimide/Al film. Results from this second campaign will be reported elsewhere. Figure 2 shows pictures of the four filter samples listed in Table 3.

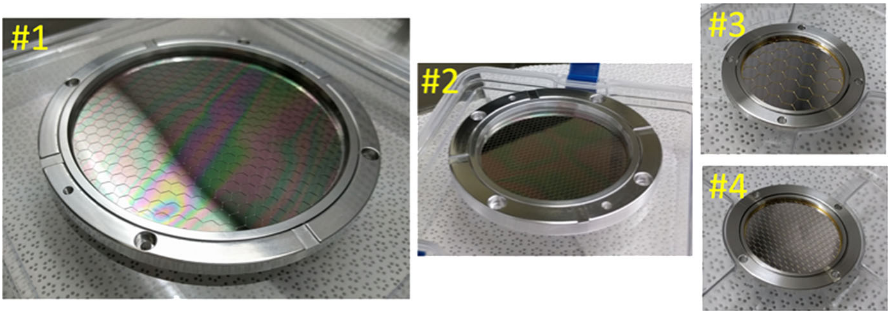

Fig. 2 Pictures of the Ti coated polypropylene filter samples #1 and #2, and the Al-coated thin polyimide filter samples #3 and #4 (Color figure online)

Table 3 List of procured test filter samples

Sample #1: Polypropylene/Ti	I.D. = 100 mm (TF300), mesh type 2
Sample #2: Polypropylene/Ti	I.D. = 56 mm (TF0), mesh type 1
Sample #3: Polyimide/Al	I.D. = 30 mm (TF2÷TF300), mesh type 2
Sample #4: Polyimide/Al	I.D. = 30 mm (TF0), mesh type 1

3 Vibration Tests

Performed/scheduled vibration tests in 2017 are not qualification tests but development tests to support the filter design. Tested prototypes partially represent the current design, which could still undergo significant changes (materials and geometries) before adoption.

Sine and random vibration tests were carried out using the shaker model 4522 LX at the Centre Spatial de Liege (Belgium) thanks to the TNA program of the H2020 AHEAD project. The shaker is inside a class 100 environment. Both out of plane and in-plane tests were carried out.

The X-IFU TF samples were kept in vacuum during the vibration tests in order to reproduce the launch conditions and to reduce potential damages from flying particles (Fig. 3).

High-resolution images of the filter samples were taken in transmission and reflection mode between nearly every two tests using a photographic scanner (Epson Perfection V850 PRO).

The Reference Vibration Test Levels derived from Req. #14 in APPENDIX A of the ESA ITT AO/1-8786 entitled "Athena: Large area high-performance optical filter for X-ray instrumentation" [6] are reported in Tables 4 and 5. Increasing load levels were applied to each filter approaching the reference level. Lower levels had shorter duration, in order to reduce the risk of fatigue failure. The most dangerous load direction is out of the filter plane; for this reason, a more extensive out of plane test program was carried out. Both the two X-IFU filter samples #1 and #2 have survived lateral vibration reference levels and axial vibration reference levels increased by + 10 g 0-peak sine load and + 3 db random. The film defects present before vibration

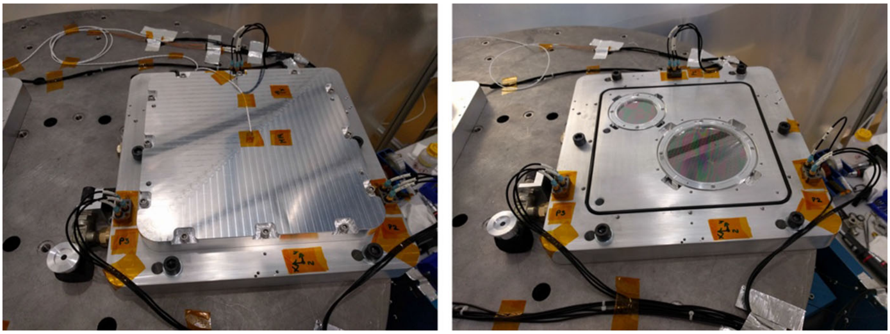

Fig. 3 Vacuum chamber (left) hosting the TF samples under test (right) (Color figure online)

Table 4 Sine vibration reference levels (25.0 g 0-peak, sweep rate = 2 Oct/min)

Frequency range (Hz)	Level
5–25.0	9.9 mm (0-peak)
24.1–26.2	1.5 m/s (0-peak)
26.02–100	25.0 g (0-peak)

Table 5 Random vibration reference levels (16.9 g RMS, duration = 150 s)

Frequency range (Hz)	PSD
20–100	3.0 dB/oct
100–300	0.5 g^2/Hz
400–2000	− 3.0 dB/oct

tests (e.g., ripples on the filter) did not change significantly also after the highest loads levels.

On each filter, ~ 20 native pinholes (typical size 50 μm) are found before the vibration tests. Such defects do not seem to have changed after vibration tests. Two scratches slightly larger than typical pinholes are found on filter sample #1 after the last and most severe vibration test. A few tens of dust particles are present on the filter since the beginning (size ranging between 10 and 300 μm). Most of the particles move around the filter during the vibration tests.

4 Thermo-Vacuum Tests

A first campaign of thermo-vacuum (TV) tests was performed using the cryostat of the LIFE facility at INAF-OAPA (Palermo) [7]. The sample holder was designed to accommodate both samples #3 and #4 simultaneously. The tests were performed in a VHV environment (~ 1.2×10^{-9} mbar). Ten temperature cycles 300 K −> 12 K −> 300 K were performed with a 3 K/min ramp rate and 20 min hold time at 12 K and at 300 K according to Req. #13 in APPENDIX 1 to the ESA ITT AO/1-8786.

The images were acquired with the high-resolution photographic scanner before and after the first cycle and at the end of 10 cycles. No evident visible damage or alteration of both filters has been observed.

5 Summary and Perspectives

Vibration and thermo-vacuum tests were performed on large size filter samples partially representative of the current investigated X-IFU thermal filter design. The SS meshes designed on the base of a detailed structural analysis and procured by LUXEL corp. worked as reliable products under vibration loads significantly higher than required. New vibration tests will allow us to verify the performance of the thin polyimide/Al foils supported by such meshes.

Thermo-vacuum tests performed on small size partially representative filter samples have also confirmed the reliability of the current investigated TF design under thermal stresses.

The current investigated X-IFU TF design differs from the baseline design:

1. thinner total layer of polyimide (225 vs. 280 nm);
2. thinner total layer of aluminum (150 vs. 210 nm);
3. use of metal meshes in place of polyimide meshes.

While the first two points allow the investigated design to be more performing with respect to the baseline at low energies; the use of metal meshes, driven by the need to provide mechanical robustness, RF attenuation, and good thermal conductance, implies a transmission at high energy currently below the requirements.

The positive results from mechanical tests, showing that the current designed meshes can survive the Ariane 5 launch vibration load, suggest to perform new structural modeling to try to optimize the design of the meshes in order to increase the overall transmission. In addition, EM modeling and measurements will be taken to verify the RF attenuation level of thin Al layers and thus try to release a bit the attenuation requirements on the meshes. Different materials (both meshes and foils) as well as geometries will be further investigated before consolidating the TF design and procuring representative filter samples to demonstrate the TRL 5 before the adoption of Athena by ESA.

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