Thermal filters (TF) for the ATHENA X-IFU detector: ongoing activities towards the conceptual design

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and the ATHENA Italian Consortium
The X-ray Integral Field Unit (X-IFU) is one of the two X-ray detectors that will alternatively operate at the focal plane of the large telescope of ATHENA, the high energy L2 mission selected by ESA for launch in 2028.

X-ray Integral Field Unit:
- $\Delta E$: 2.5 eV
- Field of View: 5 arcmin
- Operating temp: 50 mk

Barret et al., 2013 arXiv:1308.6784

Wide Field Imager:
- $\Delta E$: 125 eV
- Field of View: 40 arcmin
- High countrate capability

Rau et al. 2013 arXiv1307.1709
Thermal Filters in the X-IFU Functional Block
Why the X-IFU needs Thermal Filters

1) Radiation Heat Load
The TF have to reduce the IR radiation heat load from the cryostat thermal and structural shields onto the detector array.

Radiation Heat Load < 1 % of Conduction Heat Load and Bias Power (TBC)

2) Photon Shot Noise
The micro-calorimeters are also sensitive to photons at lower energies than X-rays. Although the detector does not trigger on individual low energy photons, the statistical fluctuation of the absorbed energy during the detection time interval, can introduce a degradation of the energy resolution of the detector (photon shot noise).

Photon Shot Noise < 0.2 eV FWHM (TBC)

3) EMI (up to ~ 10 GHz)
Cryostat shields should operate as Faraday cages to protect the detector from EMI coming from the read-out electronics and spacecraft environment (e.g. telemetry).

RF Attenuation level (TBD)
Activity Flow Chart for TF Conceptual Design

- Eritage (Astro-E, Astro-H, rockets, …).
- Detector, Telescope, and Cryostat Specs.
- Science Requirements

Filter design

- UV/VIS/IR transmission modeling
- Thermal modeling
- Radiative heat load and photon shot noise calculation
- RF attenuation modeling
- Structural analysis

Optical load from astrophysical sources (Filter wheel OBF design)

Samples procurement

Preliminary optical and environmental tests

- Cryostat specs.
- Detector specs.
- Satellite, telemetry, and detector specs.
- Launch vibrations, vacuum procedures

Science Requirements
Thermal Filters (TF) Design

• Based on the successful experience from previous missions (e.g. ASTRO-E, SUZAKU, XQC sounding rockets program, ASTRO-H) we choose as baseline material Polyimide* film coated with aluminum

• Since both TES and SQUID electronics are sensitive to EMI, the TF have to provide a certain level (TBD) of attenuation in Radio Frequencies (X-band telemetry ~ 8.2 ÷ 12.4 GHz). Furthermore, the outer filter may need to be warmed up for de-contamination.

• The science requirements pushing to maximize the X-IFU low energy response

Five filters for a total of 2250 Å of polyimide and 1500 Å of aluminum

* Luxel Corp. LUXFilm® Polyimide
Case study 2 design vs. Baseline design (ATHENA proposal)

Five filters for a total of: 2250 Å of polyimide + 1500 Å of aluminum

Aluminum mesh 20 μm thick (96% open area) on the two larger diameter filters.

Baseline design (ATHENA proposal)

Five filters for a total of:
- 2800 Å of polyimide
- 2100 Å of aluminum

Polyimide mesh 10 μm thick (93% open area) on the two larger diameter filters.
UV/VIS/IR transmission

An oxidation layer of 50 Å on each side of the aluminum coated on the polyimide film of each filter is conservatively assumed to become nearly transparent in UV/VIS.

**Five filters** each: 450 Å polyimide + 300 Å aluminum
Thermal Modeling

In order to derive the equilibrium temperature of the TF in the cryostat environment we adopt the following schematic configuration. The thermal modeling was performed with Comsol Multiphysics® 5.0

Detector Array 21 mm diam.

- 1 - FP filter (T = 0.05 K)
- 2 - FP filter 1 (T = 2 K)
- 3 - Inner Shield (T = 10 K)
- 4 - Outer Shield (T = 100 K)
- 5 - Dewar Main Shell (T = 300 K)

Z = 10 mm,  D = 24 mm
Z = 60 mm,  D = 36 mm
Z = 90 mm,  D = 44 mm
Z = 170 mm, D = 64 mm
Z = 200 mm, D = 72 mm
$T_{\text{min}} \sim 255 \text{ K}$

$T_{\text{max}} \sim 180 \text{ K}$
T ~ 10 K

T = 10.4 K

T = 10.0 K

T = 2.1 K

T = 2.0 K

T = 0.8 K

T = 0.1 K
Radiative heat load and photon shot noise calculation

Model assumptions:

1. Each filter behaves as a black body radiation source at the temperature derived from the thermal modeling;
2. Filters are tilted by 1°, in alternate directions, with respect to the horizontal plane;
3. The micro-calorimeter detection time is $\tau_{\text{det}} = 1 \text{ ms}$;
4. The detector array is made of 3844 pixels each one $250 \times 250 \mu\text{m}^2$.

$$NEP^2(T) = \frac{1}{n_{\text{pixels}}} \int_{\lambda_{\text{min}}}^{\lambda_{\text{max}}} 2 \cdot P(\lambda, T) \cdot \frac{hc}{\lambda} \cdot d\lambda \quad [W^2/\text{Hz}]$$

$$\Delta E_{\text{FWHM}} = 2.35 \cdot 6.2415 \cdot 10^{+18} \cdot \sqrt{NEP^2(T) \cdot \tau_{\text{det}}} \quad [\text{eV}]$$

where $P(\lambda, T)$ is the total radiative power spectral density (W/Å) onto the detector array from the filter at temperature $T$. 
Calculated contribution from each filter to the radiative power onto the detector array, and to the photon shot noise ($\Delta E_{FWHM}$). The table also reports temperature ($T$), distance from the detector array ($Z$), and radius ($R$) of each filter.

<table>
<thead>
<tr>
<th>T</th>
<th>Z</th>
<th>R</th>
<th>Power</th>
<th>$\Delta E_{FWHM}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[K]</td>
<td>[mm]</td>
<td>[mm]</td>
<td>[pW]</td>
<td>[eV]</td>
</tr>
<tr>
<td>TF1</td>
<td>0.8</td>
<td>10</td>
<td>12</td>
<td>8033</td>
</tr>
<tr>
<td>TF2</td>
<td>2</td>
<td>60</td>
<td>18</td>
<td>4.446</td>
</tr>
<tr>
<td>TF3</td>
<td>10</td>
<td>90</td>
<td>22</td>
<td>0.286</td>
</tr>
<tr>
<td>TF4</td>
<td>180</td>
<td>170</td>
<td>32</td>
<td>7.225</td>
</tr>
<tr>
<td>TF5</td>
<td>260</td>
<td>200</td>
<td>36</td>
<td>0.092</td>
</tr>
</tbody>
</table>

Radiative power spectral density onto the detector array from the cryostat warm shields, based on the use of the case study 2 thermal filter design.

With no tilt angle of the filters the photon shot noise increases to $> 10$ eV.
RF EMI attenuation

• The telemetry uplink/downlink signals entering the instrument field of view by direct illumination or by diffractions of satellite and instrument structures can cause RF interference on TES detectors and SQUID read-out electronics.

• To evaluate the radiation entering the detectors FOV, we plan to perform RF simulations using the GRASP antenna software (www.ticra.com) as soon as the satellite structure and antenna configuration will be defined.

• For now, a preliminary Finite Element (FEM) Electro Magnetic Modeling was implemented with a 60 mm length standard WR-90 X band waveguide, using the HFSS software (Ansys Corporation), to evaluate the contribution to Loss from conductive meshes in the telemetry X-Band frequency range [8.2 ÷ 12.4 GHz].
The mesh geometry (e.g. honeycomb, square, radial) is irrelevant to first order with respect to other parameters such as mesh pitch, bar width, and thickness.
Electric field attenuation vs. frequency

Two orders of magnitude attenuation in transmitted RF power at 10 GHz.
Structural analysis

• Since the vibrational mask at the level of the FPA and cryostat aperture cylinder is not yet known, preliminary structural analysis have been performed only under static pressure. All results reported hereafter are meaningful just in terms of comparison between the different cases analysed.

• The applied load is the gravity (1g) + a static pressure of 10 mbar. Such reference value (TBC) was derived from the qualification load required for the XMM-Newton EPIC filters.

• Two filters have been analysed so far namely:
  - the filter mounted on the Dewar main shell (D = 72 mm, T = 300 K, supported by mesh)
  - the filter mounted on the Inner shield (D = 44 mm, T = 10 K, free standing)
Honeycomb Mesh (D = 72 mm)

Mesh Pitch = 2.5 mm, Wire cross sect. = 50X50 μm²
Mesh open area = 96 %, Mesh material = Ti alloy (Ti6Al4V)

Deflection under 10mbar static pressure

Max deflection = 1.94 mm.

Stress under 10mbar static pressure

Max Tensile stress = 915 MPa
Max Compressive stress = -591 MP

Stress peaks are localized at the outer edge and are not homogeneous. The stress level in the mesh is slightly larger with respect to failure (880 MPa).
Radial Mesh (R = 72 mm)

Mesh Pitch = 2.25mm, Wire cross sect. = 50X50 μm²
Mesh open area = 95 %, Mesh material = Ti alloy (Ti6Al4V)

Deflection under 10mbar static pressure

Max deflection = 1.59 mm.

Stress under 10mbar static pressure

Max Tensile stress = 784 MPa
Max Compressive stress = -543 MPa

Stress peaks are localized at the outer edge and they are homogeneous along the azimuthal angle. The stress level in the mesh is slightly smaller with respect to failure (880 MPa).
Radial Mesh with Polyimide film (D = 72 mm)

- Mesh Pitch = 2.25mm, Wire cross sect. = 50X50 μm²
- Mesh open area = 95 %, Mesh material = Ti alloy (Ti6Al4V)
- Polyimide film thickness = 45 nm

Max deflection = 1.66 mm.

Max radial tensile stress in the film = 93 Mpa

The Stress level in the film is smaller with respect to failure value at room temperature (310 MPa).
The Stress level in the self standing polyimide film is nearly a factor two higher than failure value at room temperature (310 MPa). Given the low weight of the membrane (0.0001 g), a 10 mbar static pressure corresponds to > $10^6$ g which is orders of magnitude higher than expected vibration levels. Thus the concern is mainly on vacuum/venting procedures setting up a differential pressure.
Stresses in polyimide films due to $\Delta T + \Delta \text{CTE}$

The minimum temperature envisaged for mesh reinforced filters is currently 100 K ($\Delta T = -193$ K with respect to assembly conditions), while it is 50 mK for the self standing films ($\Delta T = -293$ K with respect to assembly conditions). In both cases the films are rigidly connected to structures realised by different materials with CTE mismatch (outer frame and reinforcing mesh).

So for the coupling polyimide-Ti6Al4V we have:

Max. biaxial stress on polyimide with supporting mesh on frame = 45 MPa for $\Delta T = -193$ K
Max. biaxial stress on polyimide self standing on frame = 75 MPa for $\Delta T = -293$ K

While for the coupling polyimide-Al we have:
Max. biaxial stress on polyimide with supporting mesh on frame = 23 MPa for $\Delta T = -193$ K
Max. biaxial stress on polyimide self standing on frame = 32 MPa for $\Delta T = -293$ K

The stress on polyimide induced by $\Delta \text{CTE}$ is in any analysed case significantly lower than failure.

Currently used values of CTE are

<table>
<thead>
<tr>
<th>Material</th>
<th>CTE$_{300\ K}$</th>
<th>CTE$_{100-293\ K}$</th>
<th>CTE$_{4-100\ K}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polyimide:</td>
<td>$30 \times 10^{-6} \text{ K}^{-1}$</td>
<td>$7.85 \times 10^{-6} \text{ K}^{-1}$</td>
<td>$5.95 \times 10^{-6} \text{ K}^{-1}$</td>
</tr>
<tr>
<td>Ti alloy (Ti6Al4V):</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Al alloy:</td>
<td>$18.9 \times 10^{-6} \text{ K}^{-1}$</td>
<td>$14.3 \times 10^{-6} \text{ K}^{-1}$</td>
<td></td>
</tr>
</tbody>
</table>
Stress in polyimide films due to $\Delta T + \Delta \text{CTE}$

- Filter operate at lower temperatures than assembly condition:
  - for the mesh reinforced filter $\Delta T = -193$ K
  - for the self standing filter $\Delta T = -293$ K

- The stress induced on the polyimide films by $\Delta \text{CTE}$ between the different materials is, in all investigated cases, significantly lower than failure.
  - Max. biaxial stress on polyimide < 75 MPa for coupling polyimide/Ti6Al4V
  - Max. biaxial stress on polyimide < 32 MPa for coupling polyimide/Al
Optical load from astrophysical sources

The optical load from bright UV/VIS sources (e.g. massive stars, AGN in outburst, Mars, …) can deteriorate the X-IFU energy resolution by additional photon shot noise. The use of Optical blocking filters (OBF) mounted on the filter wheel (FW) may be needed.

The thin FW filter allows to observe hot stars fainter than $V \sim 7.5$ with no degradation of energy resolution. The thick FW filter allows to observe hot stars as bright as $V=7.5$ with no degradation of energy resolution.
Summary and Conclusions

• Heritage from previous missions suggests to use Polyimide films coated with aluminum.

• Metal reinforcing meshes (open area > 95%) for the larger diameter filters to provide some level (TBD) of EMI RF attenuation and for de-contamination warming up.

• The currently investigate filter design (5 filters for a total of 2250 Å polyimide and 1500 Å Aluminum), provides adequate attenuation of radiative power and photon shot noise;

• We have set-up simulation tools to support filter design verification:
  1. Thermal modeling; 2. Radiative power and photon shot noise calculation;
  3. EMI RF attenuation modeling of metal meshes; 4. Structural analysis;
  5. Optical load from astrophysical sources.

• First procurement of filter samples in Q4 2015, environmental tests in Q1-Q2 2016;

• IR transmission measurements in the range 10-300 K to check transmission modeling and derive aluminum oxidation layer are scheduled in september 2015;

• Synchrotron X-ray transmission measurements and X-ray photoelectron spectroscopy to model transmission near the absorption edges in the range 77-300 K and to derive the amount of surface aluminum oxide are scheduled at the Bach beam-line of the ELETTRA synchrotron in october 2015.
Silicon Nitride membranes can be found on the market with thickness as low as ~ 100 Å, however, self-standing membranes have typical sizes up to few mm² (TEM sample holder windows). Further investigation is needed to verify feasibility of larger self-standing or mesh supported thin membranes;