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AHEAD (Integrated Activities in the High Energy Astrophysics Domain)	**Status Report**	Doc No: AHEAD-WP7.2-TN1-2017 Issue: 1 Date: February 23, 2017 Page: 1 of 12

Title: WP7: X-IFU mass model.

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DOCUMENT CHANGE RECORD

Issue	Date	Changed Section	Description of Change

Abbreviations and acronyms

Item	Meaning

Applicable Documents

[AD#]	Doc. Reference	Issue	Title
[AD1]	AHEAD project (grant agreement n. 654215)		AHEAD (Integrated Activities in the High Energy Astrophysics Domain)

Reference Documents

[RD#]	Doc. Reference	Issue	Title
[RD1]	doi:10.1117/12.2232432		The Athena X-ray Integral Field Unit (X-IFU)
[RD2]	http://geant4.web.cern.ch/geant4/		Geant4 website
[RD3]	doi:10.1117/12.2231298		The Cryogenic AntiCoincidence Detector for ATHENA X-IFU: a program overview.
[RD4]	SRON-XIFU-TN-2014-002		X-IFU FPA MASS MODEL
[RD5]	http://geant4.web.cern.ch/geant4/UserDocumentation/UsersGuides/ForApplicationDeveloper/html/index.html		Geant4 Application Developers Manual
[RD6]	DOI 10.1007/s10909-012-0523-9		Kapton Polymeric Films to Shield X-Ray Detectors in Orbit
[RD7]	DOI: 10.1117/12.2232381		Updates on the background estimates for the X-IFU instrument onboard of the ATHENA mission

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1 EXECUTIVE SUMMARY

In this technical note we will report the status of the activity related to the implementation of the X-IFU (X-ray Integral Filed Unit) [RD1] mass models in the context of the Geant4 simulation in order to get expectation values about primary and secondary particles distribution in the neighborhood of the detector.

The ultimate task to be performed is to have the best expectation of the residual particle background of the instrument in L2 orbit by adopting technological solutions, not in the ATHENA baseline, in order to reduce at best such a background to increase the instrument sensitivity.

2 THE GEANT4 TOOLKIT

Geant4 (GEometry ANd Tracking) [RD2] is a Monte Carlo toolkit that simulates the passage of particles through matter.

The software allows to reproduce the particle environment where the detector is placed, and handles its interaction with the payload and instrument mass models, producing as output information on the processes happening inside the detector that can be reduced to the output of the real detector.

In order to perform the simulations the user has to describe:

- The particle environment where the instrument is placed, in terms of particle kinds, spectra, fluxes and angular distribution
- The entire geometry of the system (i.e., the mass model), specifying materials, shapes and dimensions of the physical objects involved
- The physics involved in the simulations. In fact, each particle has its processes modeled separately from each other, and for each process more than one modelization can be available for the user to choose from according to his needs.

Besides allowing to foresee the instrumental background flux and spectrum, the particle tracking capabilities of this software allow to identify the processes happening in the detector surroundings and the origin of every secondary particle, and therefore to pinpoint the major sources of background.

3 X-IFU MASS MODEL

The X-ray Integral Field Unit (X-IFU) [RD1] on board of the Advanced Telescope for High-ENergy Astrophysics (ATHENA) 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 arc minute equivalent diameter and a spectral resolution of 2.5 eV up to 7 keV. It consists of a kilo-pixel

array of TES (Transition Edge Sensor) microcalorimeters to be cooled at 50 mK, so enclosed in a cryostat. To meet the scientific objectives, the derived performance requirements can be achieved with a large format array of actively cooled X-ray absorbers thermally coupled to Transition Edge Sensors (TES) array (3840 TES) operating at ~ 90 mK, and shielded by an active cryogenic anti-coincidence system (the CryoAC) made of 4 Si absorbers sensed by Ir TES [RD3].
The required level of the non-X-ray residual background is set at $5\cdot10^{-3}$ cts/cm^2/sec/keV.

The first background estimates were obtained using a simplified mass model for the Cryostat and the Focal Plane Assembly (FPA), due to the lack of information suffered in early stages of the work
Figure 1 - left). However, with the mission progressing new information became available and we were able to upgrade the FPA mass model using a more realistic CAD model provided by SRON (Figure 1 – right).

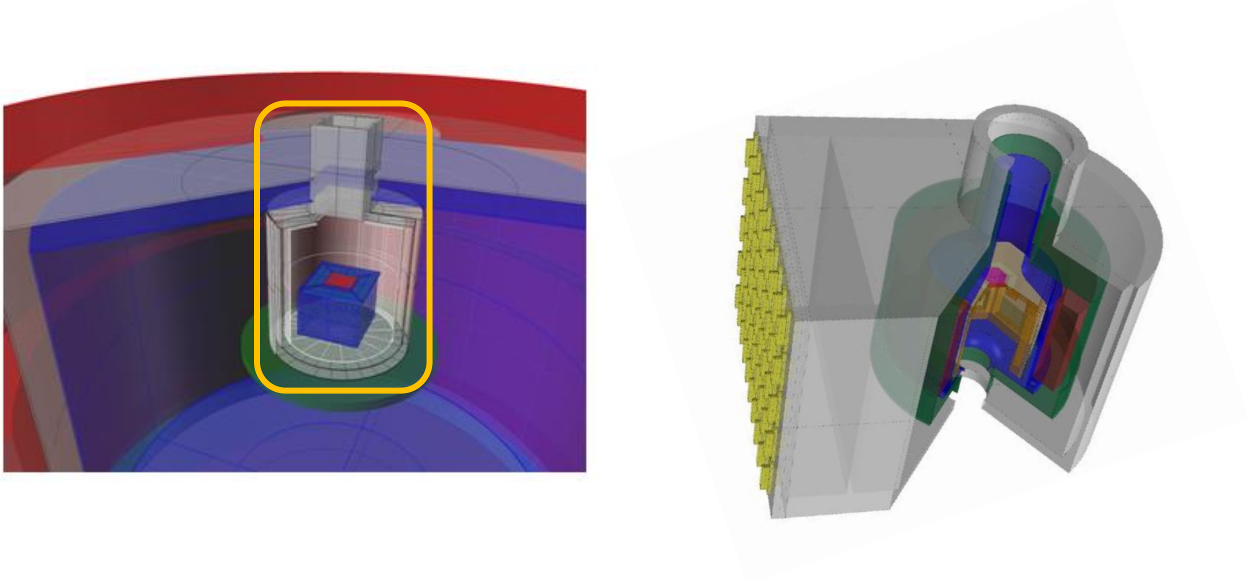

Figure 1: the old FPA mass model (left, inside the orange square), and the new FPA provided by SRON (right).

We have also upgraded the Geant4 [RD2] version used in the simulations from 9.4 to 10.1. Both these updates required a revision of the Geant4 settings in terms of cuts, regions definition and assignment, and physicslists.

Starting from the new configuration we investigated the effectiveness of different solutions, not present in the baseline configuration, aimed to reduce the secondary particles component of the background.

3.1 X-IFU FPA Mass Model

3.1.1 The CAD Drawing and the bill of materials

The CAD model provided by SRON (responsible for the FPA design and development), although not final, is quite detailed and it is not suited for implementation inside Geant4. This is because very complex shapes and high level of details in the mass model sensibly slow down the computational time with no appreciable benefits.

We had to proceed with a simplification work in order to implement the FPA model inside the Monte Carlo simulation (Figure 2).

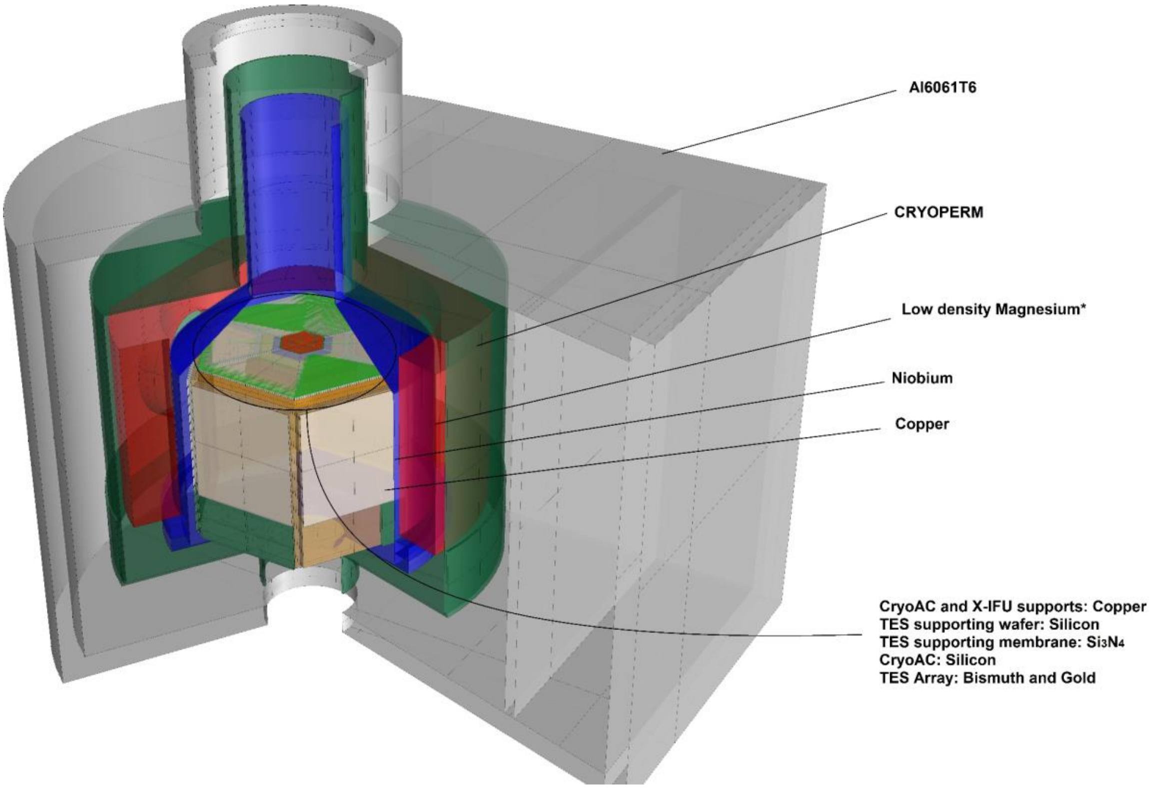

Figure 2: CAD model of the mass model used in the simulations. Materials are listed on the right. The density of the magnesium has been scaled to keep the mass of the solid accurate despite the different shape. The red hexagon in the centre is the TES array, while the cyan hexagon below is the CryoAC.

The description of the FPA model and of the materials present in it can be found in [RD4] and are reported in the figure.

3.1.2 The Geant4 model

Once obtained a CAD model suited for implementation in Geant4 we translated the mass model into a Geant4 geometry file. The simplified CAD model and the corresponding Geant4 mass model are shown in Figure 3.

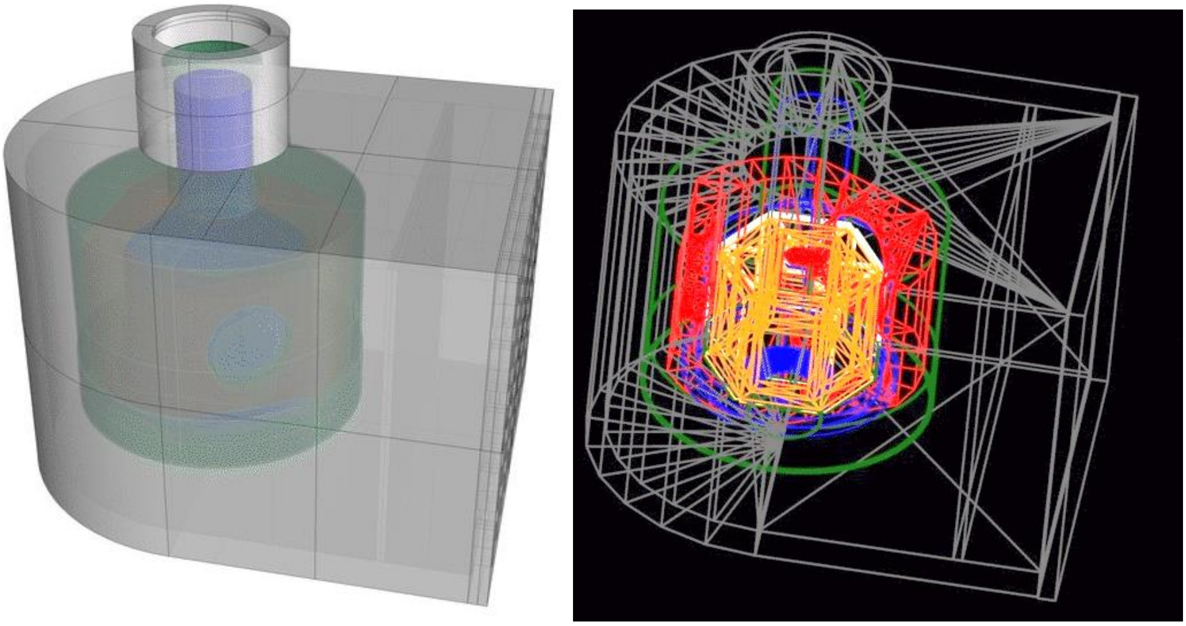

Figure 3: the simplified CAD model (left) and the same model inserted in Geant4 (right)

The different solids in the mass model were assigned to different regions within Geant4, each with different settings of the cut for the generation of secondary particles [RD5]:

- The detector, the supports, and the surfaces directly seen by the detector were assigned to the "inner region" with the lowest possible cut values (few tens of nm, high detail level)
- The remaining solids in the FPA were assigned to an "intermediate region" with higher cut values (few um)
- The cryostat and the masses outside the FPA were assigned to the "external region" were the cut (few cm) allowed the creation only of high energy secondary particles

3.2 Some solution to reduce the X-IFU particle background

The main components of the background are secondary electrons (~75%), and secondary photons (~20%, of which roughly half in the form of escape peaks or fluorescence lines), both mainly produced in the Niobium shield (the surfaces directly seen by the detector).
Most of these secondary particles are completely absorbed in the detector, or backscatter on its surface depositing a small fraction of their energy, so avoiding interaction with the anticoincidence detector and becoming de facto unrejectable.
In order to reduce the flux of these secondary particles we studied two different approaches:

1. Introducing a passive shield (liner) composed of materials with low electron yield between the Niobium and the detector. This will reduce the flux of secondary particles towards the X-IFU.
2. Inserting a thin filter just above the detector. This way a fraction of the secondary electrons will be backscattered there and not in the detector. Such filter needs to be thicker than the backscattering depth but thin enough to be transparent to X-rays.

3.2.1 The secondary electron liner

One way to reduce the fluence of secondary electrons is by interposing a liner with electron absorbance capability and low yield of secondary electrons emission between the detector and the structures producing them. In this respect, Kapton seems to be one of the most reasonable choices, being composed of low density, low atomic number elements, and being widely used in space and cryogenic applications [RD6].
We tested several geometrical configuration of the electron liner to understand how its shape and thickness influenced the residual background. The optimal geometrical configuration we have found is with a 250 µm thick liner, placed as close as possible to the detector (without obstructing its field of view) and it is shown in Figure 4 - left.

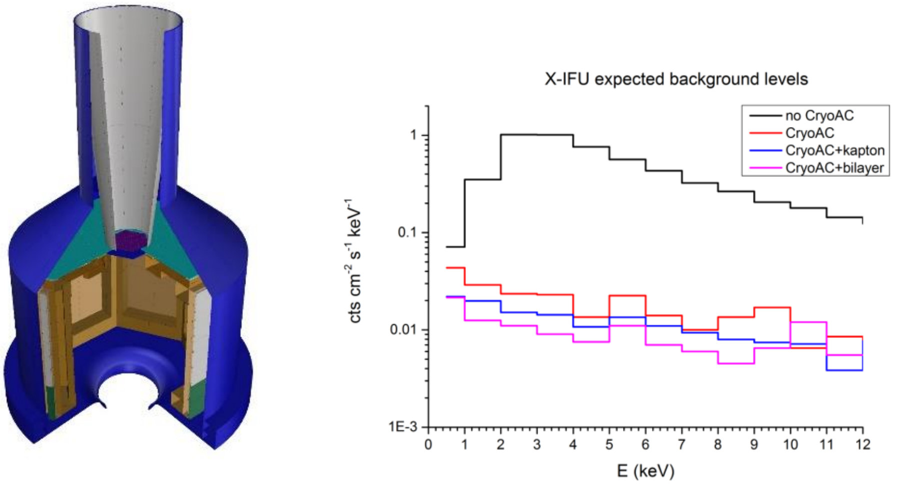

Figure 4: the kapton shield (grey) implementation inside the new FPA (left), and the background levels in different conditions

The insertion of this shield further reduced the expected background level in the 2-10 keV band by ~35%. The main components of this residual background are again secondary electrons and photons.

One half of the secondary photons component comes from fluorescence lines produced inside the Nb shield: when these photons impact the detector they induce the emission of fluorescence photons from the absorber. These photons escape, leaving inside the detector a fixed amount of energy in the form of escape peaks.
The other half is given by low energy photons that are completely absorbed and by high energy photons that Compton scatter in the detector, leaving a small fraction of their energy.

Further optimizations of the liner are currently being tested in order to reduce the photons component: we tested the introduction of thin layers (few tens of µm) of high-Z materials to block the Nb fluorescences before reaching the Kapton. Several configurations of double/tri-layered shields were tested [RD7], and the best result was obtained using a bilayer made of 250 µm of Kapton and 20 µm of Bi (see Figure 4 and Table 1).

Configuration	Unrejected background level	
Without CryoAC	0.57	$p\ cm^{-2}\ s^{-1}\ keV^{-1}$
With CryoAC	1.7×10^{-2}	$p\ cm^{-2}\ s^{-1}\ keV^{-1}$
CryoAC + Kapton	1.1×10^{-2}	$p\ cm^{-2}\ s^{-1}\ keV^{-1}$
CryoAC + Kapton-Bi	7.8×10^{-3}	$p\ cm^{-2}\ s^{-1}\ keV^{-1}$

Table 1. Average background levels in the 2-10 keV energy band. The errors due to the statistic of the simulations are below 10%.

This work identified different materials applicable to background reduction: the feasibility verification and the implementation is however entrusted to the X-IFU instrument team. Thanks to the work carried on in the AHEAD framework the adoption of a passive shielding for secondary particles has entered the baseline for ATHENA X-IFU. This work is concluded for what concerns the AHEAD framework, and will be carried on inside the main contract for the instrument development.

3.2.2 The electron filter.

Secondary electrons constitute the greatest contribution to the unrejected background. They have energies up to ~1 MeV and impact the detector surface with skew trajectories, backscattering and depositing only a fraction of their energy, not reaching the CryoAC detector.

We tested if it is possible to reduce the background induced by secondary electrons that backscatter on the detector surface inserting a thin filter just above the detector, to induce backscattering there. We remark that this solution is not inside the ATHENA X-IFU baseline design.

At present we found that there is no significant reduction of the backscattered electrons component using a 500 nm thick Al filter, while we obtain a ~20% background reduction above 2 keV using 50 nm of Au, or 3 μm BCB, however the X-ray transmission of such filters is too low to be considered for implementation. In conclusion, the insertion of a filter right above the detector, seems to result in too high thicknesses required for such a filter to reduce the background by a significant amount.

It was expected a validation of the backscattering process in Geant4 inside the AREMBES framework (ESA contract). However, it emerged that there is a lack of experimental data regarding the interaction depth of the backscattering process, so the current level of confidence in these results is still low. This work will however be carried on as best effort, following possible updates from AREMBES on literatures data.

3.2.1 The CryoAC as a box: lateral coverage of the TES array detector.

Another solution to be probed that could have an impact on the reduction of the particle background is related to the addiction of lateral walls to the present baselined detector. These walls are made of active detectors, as the baseline one. This way, the TES array detector is enclosed in an active anticoincidence “box” that reject particles hitting the detector from any direction outside the FoV of the instrument, so improving the rejection of the secondary particles and reducing the unrejected background value, ultimately increasing the instrument sensitivity.

From analytical calculations we found that lateral walls square-shaped, 1x1 cm^2, would cover ~70% of the solid angle seen by the detector so expecting roughly a factor 3 of reduction with respect to previous solutions. The 1x1 cm^2 area was chosen since we are already capable of producing such devices and thus represents a solid solution.

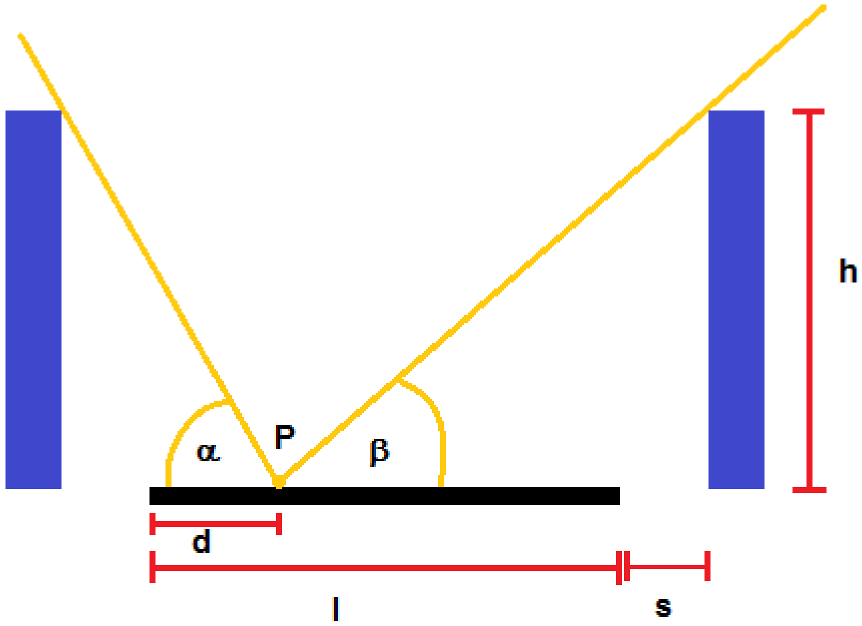

Figure 5. Schematics of the CryoAC lateral walls (in blue) and the detector (in black).

In a first order approximation in fact we can consider a detector of size l, and the CryoAC lateral walls of height h, placed at a distance s from the side of the detector (see Figure 5). Taken a point P at a distance d from the detector side, the angle covered by the lateral walls will be $\theta = \alpha + \beta = arctan\frac{h}{d+s} + arctan\frac{h}{l-d+s}$, and the fraction of solid angle covered by the lateral CryoAC will be $\frac{\Omega}{2\pi} = cos\left(\frac{\pi-\theta}{2}\right)$.

We implemented such a solution inside Geant4, with s=0 and h=1 cm, surrounding the TES array by 6 square shaped CryoAC pixels (see Figure 6), and found a residual background level of 3.1 × 10 $^{-3}$ p cm^{-2} s^{-1} keV^{-1} in the 2-10 keV energy band, shown in Figure 7 alongside the other levels presented here.

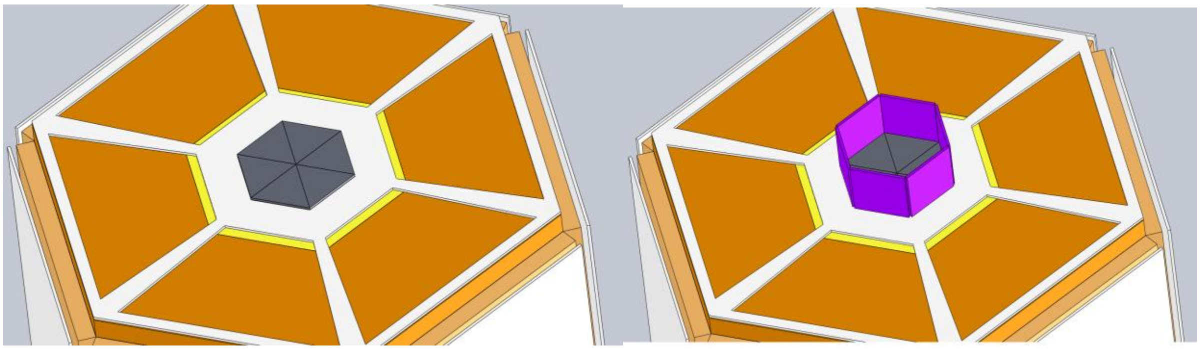

Figure 6. CAD model of the focal plane with (right) and without (left) the lateral CryoAC. The TES array is the grey hexagon in the center.

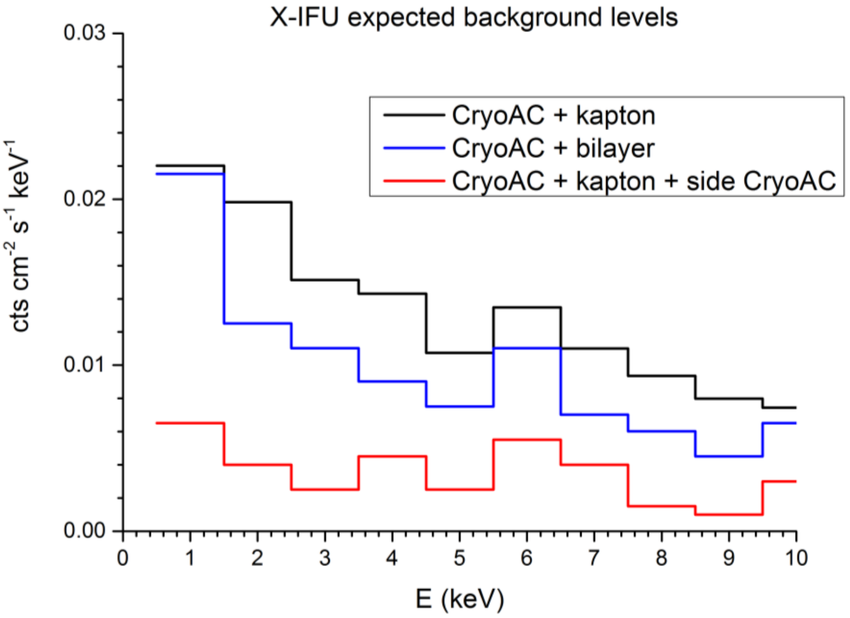

Figure 7: background levels expected in different conditions

Due to the low statistic of the simulation this is however to be considered a preliminary result, though with respect to the value of the "CryoAC + Kapton" reported in Table 1 it is roughly reduced by 70%. Further studies will be carried on to optimize this setup and better characterize the residual background.

4 CONCLUSION

Inside the AHEAD context, the activity of the X-IFU mass model, and related not in baseline solutions are on good track. The next deadline to be taken into account is March 1st 2018, when the ultimate X-IFU background is due.

About the X-IFU, one of the probed solution (the electron liner), has provided interesting results, and it has now inserted in the baseline configuration. This configuration has been optimized, allowing to further reduce the residual background expected on the X-IFU.
In the next phase we plan to perform the following activities:

- The detailed Geant4 mass model developed for simulation of the X-IFU FPA and Cryostat
- The consolidation of all the results obtained so far with the "space dedicated" physics settings created in the AREMBES framework.
- To investigate and optimize the possibility to use the CryoAC as a "box", so having an active anticoincidence detector enclosing the TES array.