Thermal impact of cosmic ray interaction with an X-ray microcalorimeter array

Poster n°128

Antoine R. Miniussi [a], [b], Joseph S. Adams [a], [b], Simon R. Bandler [a], Sophie Beaumont [a], [b], Meng P. Chang [a], [c], James A. Chervenak [a], Fred M. Finkbeiner [a], [d], Jong Y. Ha [a], [e], Ruslan Hummatov [a], [b], Richard L. Kelley [a], Caroline A. Kilbourne [a], Frederick S. Porter [a], John E. Sadleir [a], Kazuhiro Sakai [a], [b], Stephen J. Smith [a], [b], Nicholas A. Wakeham [a], [b], Edward J. Wassell [a], [c]

Contact : antoine.r.miniussi@nasa.gov

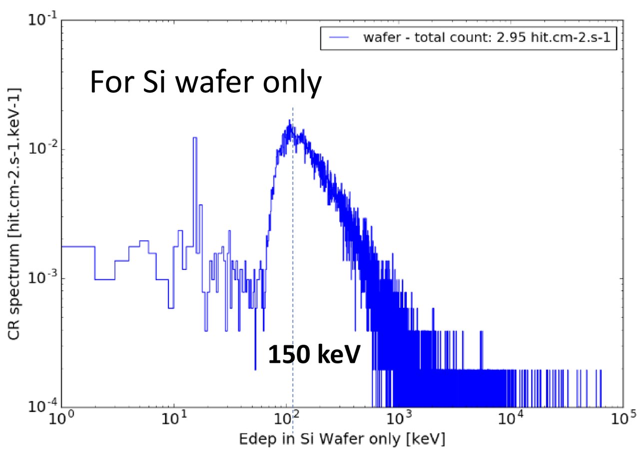
Abstract

The X-ray Integral Field Unit (X-IFU) instrument on the Athena mission will be positioned at the Lagrangian point L2 and be subject to cosmic rays generated by astrophysics sources, primarily relativistic protons. Previous simulations have shown that particles of energy higher than 150 MeV will make it through the outer layers of the satellite. They will reach the detector wafer with a rate of 3 cts·cm^{-2}·s^{-1} and a most probable energy deposited in the Si frame supporting the array at 150 keV. These events can affect the energy resolution of the detectors through the thermal fluctuations that they produce. This study assesses this potential problem and discusses two suggested design approaches to decrease the impact of cosmic ray in order to limit their effect to their allocation of 0.2 eV within the Athena/X-IFU energy-resolution budget. The first is the addition of a coating layer of high heat capacity material (e.g. Pd) and the second is the splitting of this coating into two thermal regions near the TES array to keep the heat away from the array. Implementing these two features is predicted to cause a decrease in the number of events above 1 µK by more than a factor 10 to ~1.5 cps when compared to an equivalent design without these features.

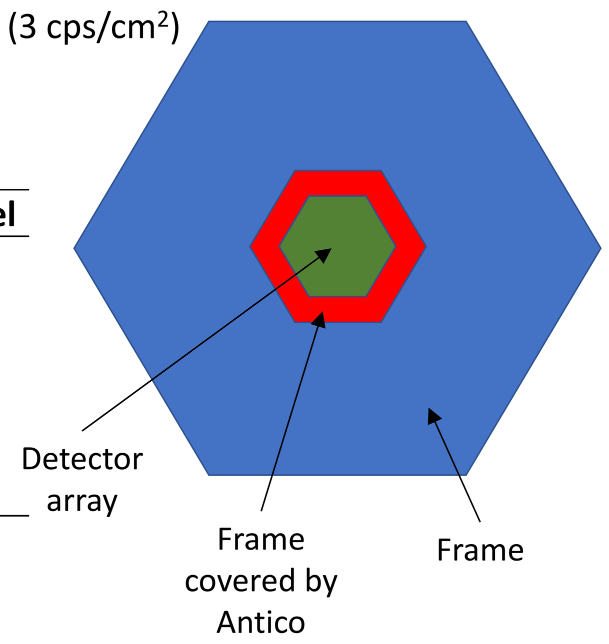
Cosmic ray interaction with the X-IFU instrument

The Athena mission will orbit around Lagrange point L2 and will be subject to Cosmic Ray (CR) background mainly consisting of protons. GEANT4 simulations (INAF) provide the following:

- Protons can penetrate the cryostat and reach the sensor array for E_{prot} > 150 MeV
- At L2, under Solar minimum condition (CR flux maximum), **rate is 190 cps in the whole wafer** (3 cps/cm²)
- Peak of deposited energy in 300 µm Si layer is **150 keV**



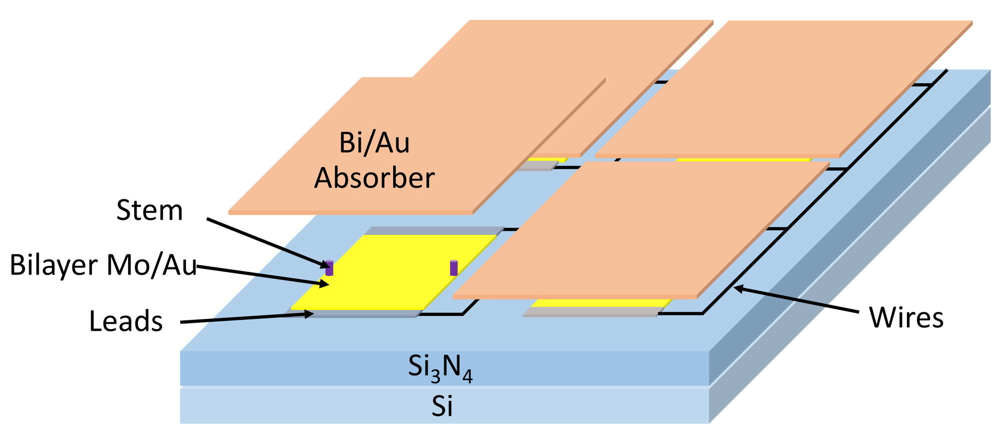
	Surface	Geant 4 model
		3 hit/s/cm²
SiN (whole wafer)	63.90 cm²	**192 hit/s**
Muntin ONLY	1.94 cm²	6 hit/s
TES array area (hexagon)	2.86 cm²	9 hit/s
Frame covered by Antico	7.53 cm²	23 hit/s
Frame ONLY	61.04 cm²	183 hit/s

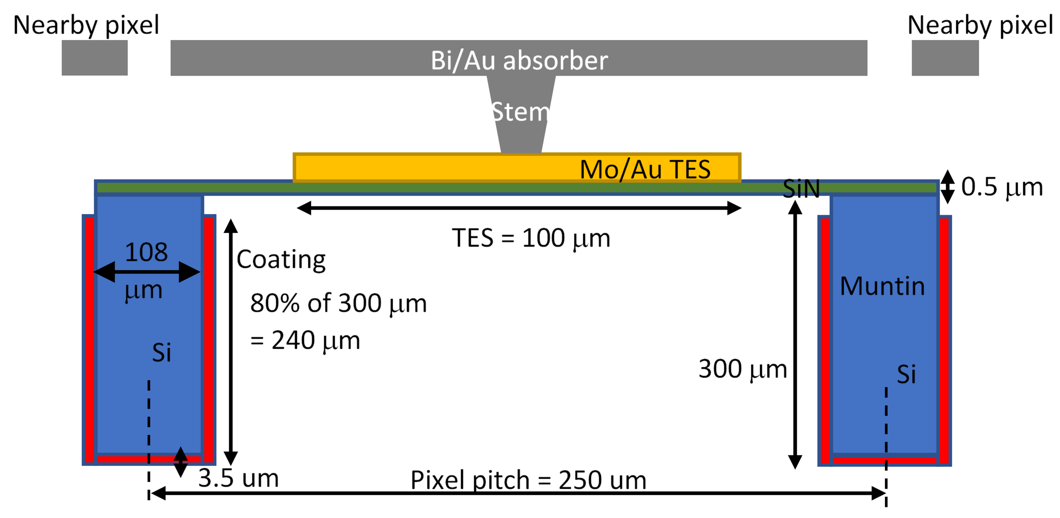


The CR going through the array of sensors are detected by the Cryogenic Anticoincidence detector (CryoAC) lying underneath the array at a distance under 1 mm. But outside of the detector array, **in the frame, all the hits will not be flagged but may still impact the thermal bath of the detectors**. This study is here to assess this effect and demonstrate the ways to mitigate the thermal impact.

Transition Edge Sensor (TES) microcalorimeter

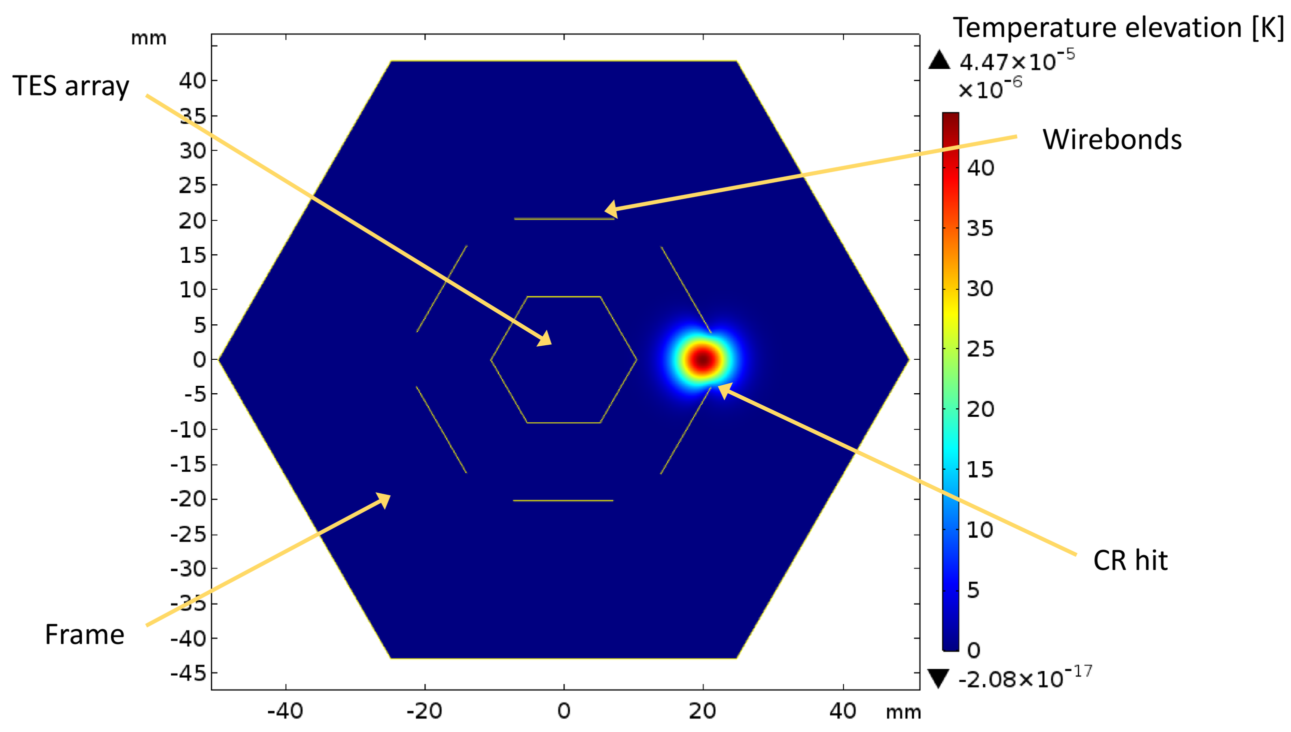
The Athena/X-IFU detector array is composed of more than 3000 Mo/Au bilayer Superconducting Transition Edge Sensor (TES) microcalorimeters centered on a hexagonal frame about 10 cm wide. Each TES is overhung by an X-ray Bi/Au absorber and lays on a SiN membrane. The structure of the array and the frame is made of Si, etched under the TES up to the SiN membrane to shape muntins. The muntins are coated with a thin layer of gold to increase the thermal conductivity and heat capacity of the heat sink.

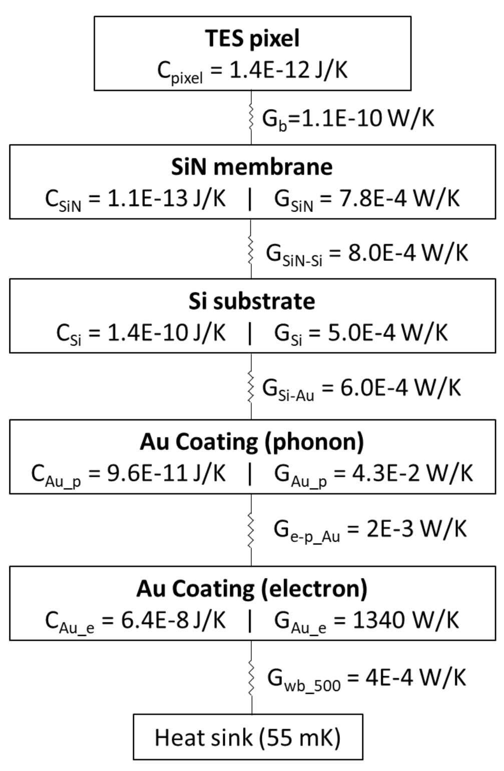




FEM Thermal Model of the detector wafer

This 2D model considers the TES and the absorber as the same component since the absorber dominates the heat capacity by a factor 100. The thermal link Gb is between the whole pixel and the SiN layer (thermal bath). The thickness of the SiN membrane is 0.5 µm thick, the Si substrate 0.5 µm. The square grid muntins are 108 µm wide and are coated with 3 µm of Au. They are approximated in the 2D model by having regions of varying conductance and heat capacity. The electron and phonon components of the Au coating are considered as two different thermal blocks. The number of wirebonds is set at 500 on the thermal block diagram.





Validation of the model

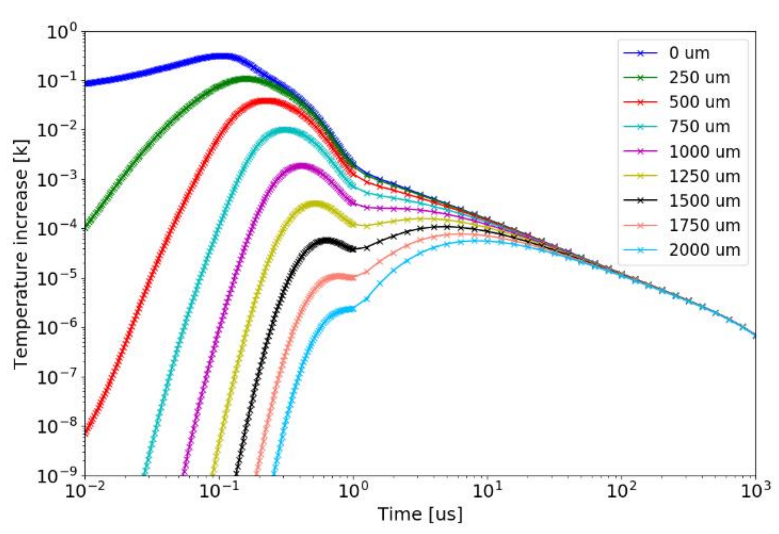
The model has been validated with experimental data from the Hitomi wafer, tested on the ground. The detector chip was loaded with a heater and a calibration pixel to study its thermal behavior through heat pulses. A numerical model was developed to represent the Hitomi wafer and the thermal links between the different blocks. It reproduced within a factor 2.5 the amplitude of the heat pulse measured on the calibration pixel and within 10% of its time constant. The model appears to err on the conservative side, meaning that the modeled effects were larger than the effects actually seen from known energy depositions.

Cosmic Ray hits on the muntins

The muntins were added to the 2D model by the addition of holes to the slab. Energy of 150 keV was deposited at the intersection of 4 muntins at the center of the array. The plot gives the temperature profiles of the bath temperature for various distances between 0 µm to 2000 µm away of the center of the impact

➔ **The temperature rises to almost 1 K at the location of the CR hit**.

➔ **Time constant of the event is very short**. After ~30 µs all temperature profiles coincide and after 1 ms the temperature excursions everywhere in the array are below 1 µK.



Wirebond location and Au coating thickness

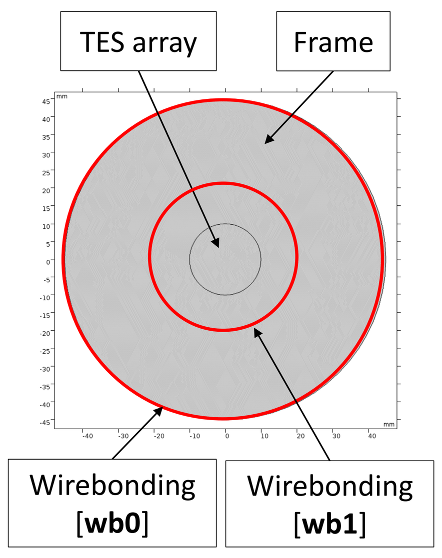
First study: Au coating of 3.5 µm and 500 wirebonds at the position *wb0*, on the outer ring of the frame. The temperature increase at the center of the array for a 150 keV particle hitting 30 mm away is approximately **ΔT = 0.26 µK**.

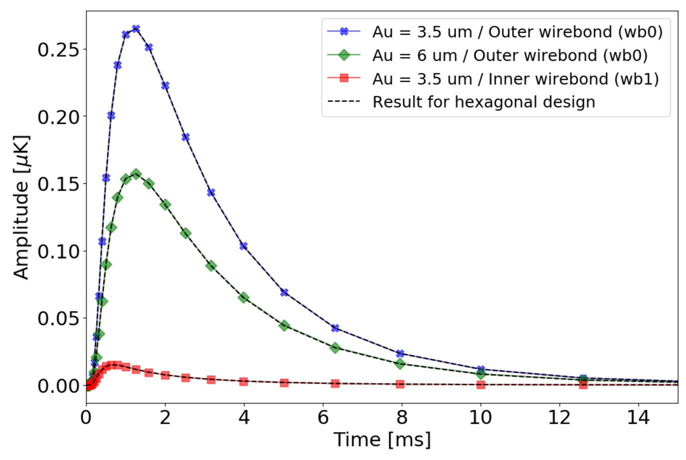
➔ **Thermal bath sensitivity of 0.15 eV/µK and high number of events of higher energies than 150 keV may exceed the energy-resolution budget allocation of 0.2 eV for CR.**

To decrease the impact of the CRs:

- Increasing the thickness of the Au coating to 6 µm ➔ ΔT = 0.17 µK
- Location of wirebonds near TES array (wb1) ➔ ΔT = 0.02 µK

➔ **The wirebonds at the *wb1* location, near the TES array, dominate the drain of the energy deposited by the CR.**





Hexagonal and circle designs of the array show the same results ➔ We can use the circle model to simplify the model

Distribution of temperature

The spectrum of temperature excursion at the center of the array is computed as follow:

1) Temperature excursions are calculated with the FEM model for several hit location of distance *d* and angle *θ* on the frame. The temperature excursion is linear with energy, so only the case for 500 keV deposited is simulated.
2) With each GEANT4 events (deposited energy) is associated a location (*d*, *θ*) in the frame
3) Temperature excursion at the center of the array for each of these events is interpolated using the interpolation tables

Results:

Inner wirebond configuration: **rate of ~17.6 cps for bath temperature excursion above 1 µK**.

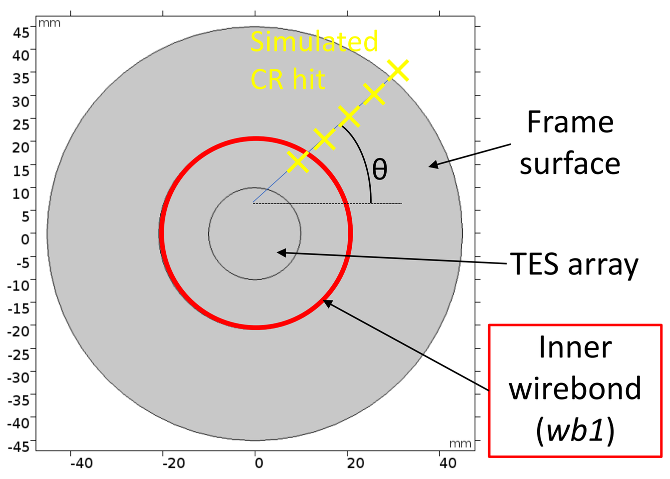
➔ **This rate could impact the energy resolution of the detector, assuming a thermal sensitivity of 0.15 eV/µK.**

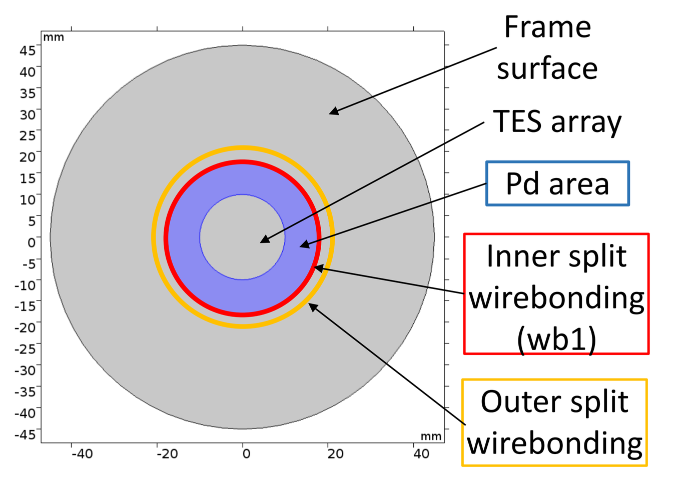
To further reduce the impact of the CRs two further design iterations may be required :

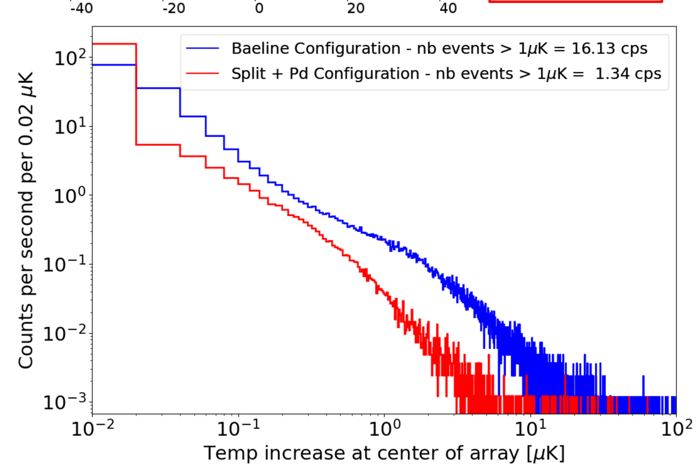
(1) Increasing the heat capacity of the coating with an additional layer of Pd (17 times larger)
(2) Splitting the Au coating outside of the region of the TES array to reduce the heat flowing from the frame to the TES array.

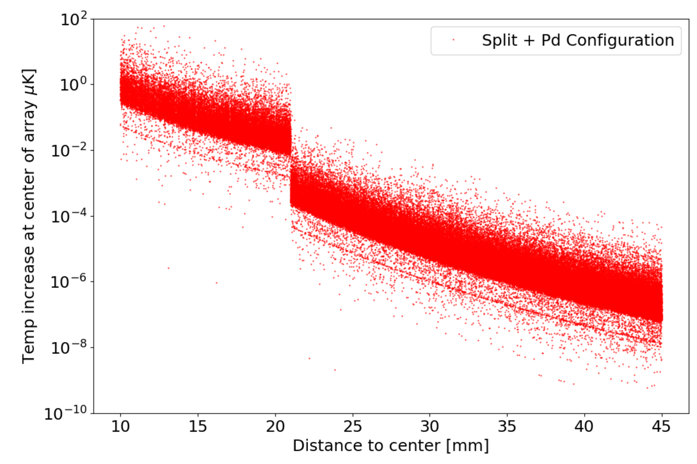
➔ **Our modeling suggests that implementing these two features could allow us to decrease the number of events above 1 µK by more than a factor 10 to ~1.5 cps.**

➔ **The impact of the bath temperature fluctuation on the energy resolution for these two designs is below 0.2 eV. More details available on poster 249 (P. Peille).**









Conclusions

Numerical thermal model

➔ We developed a numerical thermal model to reproduce the impact of deposited energy by cosmic ray inside the frame on the thermal bath temperature

➔ The model can also be used to model thermal bath fluctuation of the muntins

Model validation

➔ Model has been validated with Hitomi measurement within a factor 2

Wirebonding location

➔ Locating the wirebonds as close as possible to the TES array drains a large part of the heat flow from the deposited energy to the heatsink before it gets to the array

Temperature distribution for two configuration

➔ With the wirebonds near the TES array, rate of ~17.6 cps for events above 1 µK

➔ With the additional split and Pd, the rate for events above 1 µK decreases by factor 10 to 1.5 cps

Impact on the energy resolution

➔ The interpolation tables from this study is used in the e2e simulator to simulate the impact of the bath temperature fluctuation on the energy resolution (P. Peille)

Affiliations

[a] : NASA Goddard Space Flight Center
[b] : CRESST II – University of Maryland Baltimore County
[c] : SSAI Science Systems and Applications, Inc.
[d] : Sigma Space Corp.
[e] : SB Microsystems

18th international Workshop on Low Temperature Detectors – July 2019