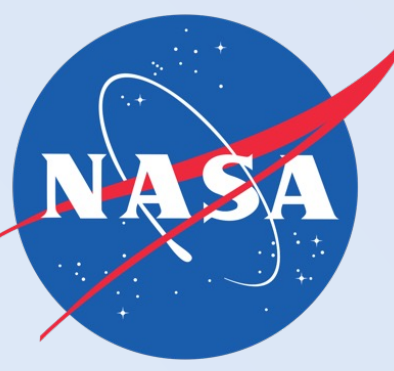


Long term performance stability of TES detectors

3EPo1C-01



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1 Abstract

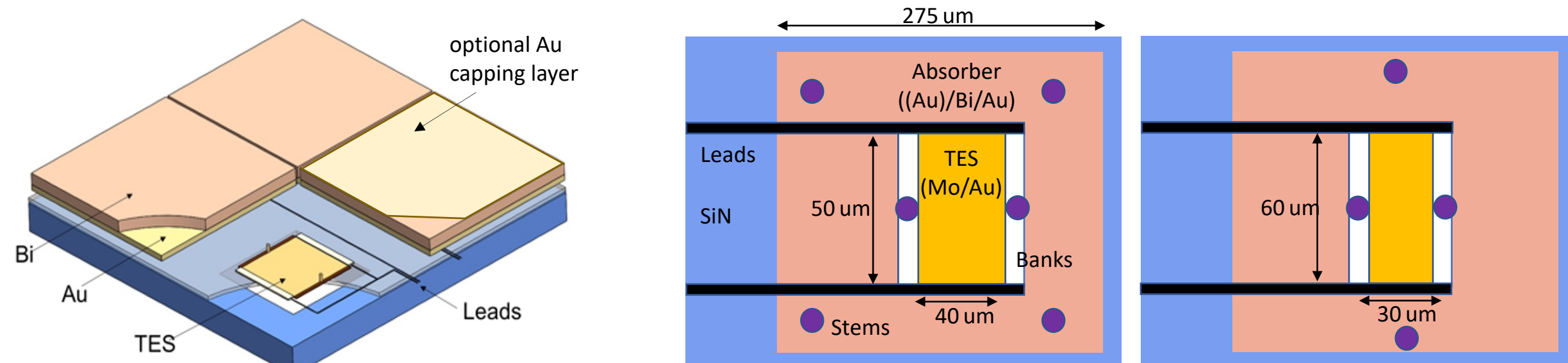
We are developing superconducting transition-edge sensor (TES) microcalorimeter arrays for a variety of applications such as ground-based laboratory astrophysics experiments and next generation space-based X-ray missions. These detectors can provide X-ray spectral information with an unprecedented resolution of ~ 2 eV at 6 keV and have been selected for the X-ray Integral Field Unit (X-IFU) instrument of ESA's large flagship mission Athena.

To maintain detector performance over the lifetime of the mission, it is important to understand whether environmental conditions that the detector may be exposed to will affect its properties over time. This “aging” begins right after the array leaves the fabrication environment, with potential exposure to humidity, oxygen, or elevated temperatures which may affect the detector performance. In a few prior arrays we have observed increased fall times in the pulse shape and/or the introduction of anomalous low energy tails on the X-ray spectrum. This is thought to be an indication of “aging” on chips exposed to such conditions, causing e.g. changes in the absorber properties.

In this contribution, we report on a systematic characterization of TES properties, before and after exposing the chip to various controlled temperature and humidity levels and assess the changes in the measured transition and pulse shapes, energy resolution, and spectral redistribution.

2 Measurements

- This experiment was performed using TES of various aspect ratios ($50 \times 40 \mu\text{m}^2$, $60 \times 30 \mu\text{m}^2$ or $75 \times 25 \mu\text{m}^2$) with dotted stems (4 or 6) and banks.
- The TES bilayer is made of Molybdenum (~ 40 nm) + Gold (~ 300 nm).
- The absorbers are square with $250 \mu\text{m}$ side length, made of Bismuth ($\sim 5.5 \mu\text{m}$) + Gold ($\sim 1.5 \mu\text{m}$). They are attached to the TES sensor via 2 dotted stems.
- On some detectors, when specified, a Au capping layer was added on top of the absorbers (~ 200 nm) [1].



Simplified representation of our TES detectors in 3D (left) and in 2D from the top, for different TES aspect ratios and number of dotted stems (right).

- We measured a critical temperature T_c ranging from 65 to 90 mK, a thermal conductance of 50 to 95 pW/K at 100 mK, and a heat capacity around 0.7 pJ/K at 100 mK.
- We performed our tests on small TES chips of 8×8 detectors.
- We used 2 different sources of X-rays : Fe^{55} , source producing X-rays at 5.9 keV (MnK α line) and a mono-chromatic source [2] producing X-rays at 5.4 keV.
- In this experiment, we characterized the detectors before exposing them to various conditions (increased level of temperature and/or humidity) aiming at accelerating any performance deterioration.
- Such exposures lasted about 2 weeks, after which the TES chip was characterized again.
- Humidity exposure implemented using a drybox with petri dishes field with water. Humidity, temperature and oxygen were monitored using various meters in the box.
- Temperature exposure was implemented using an oven under vacuum.



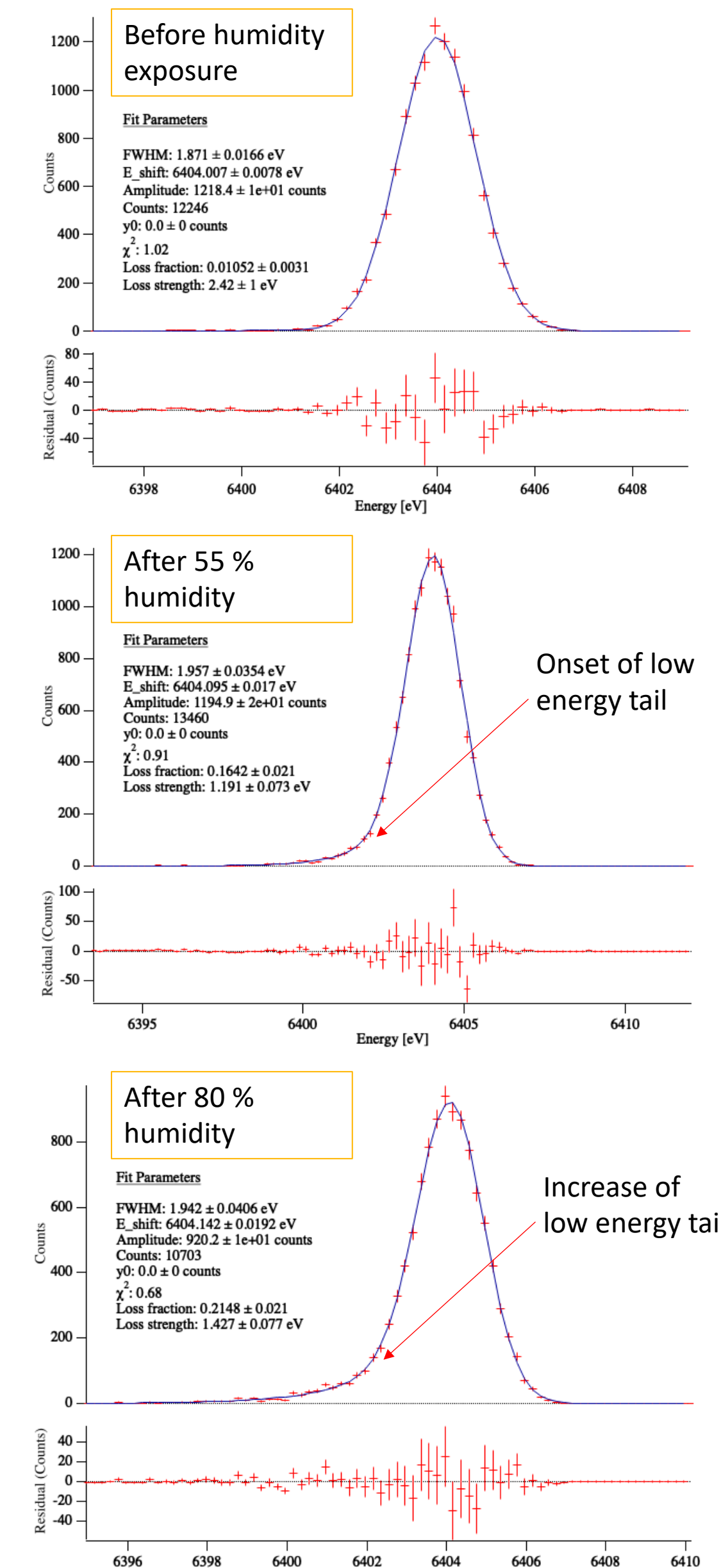
Setups for accelerated environments (left : humidity, right : temperature)

3 Impact of humidity

❖ Energy resolution and spectral redistribution

- Measurements on 2 chips : one without gold capping layer (chip #1), one with (chip #2).

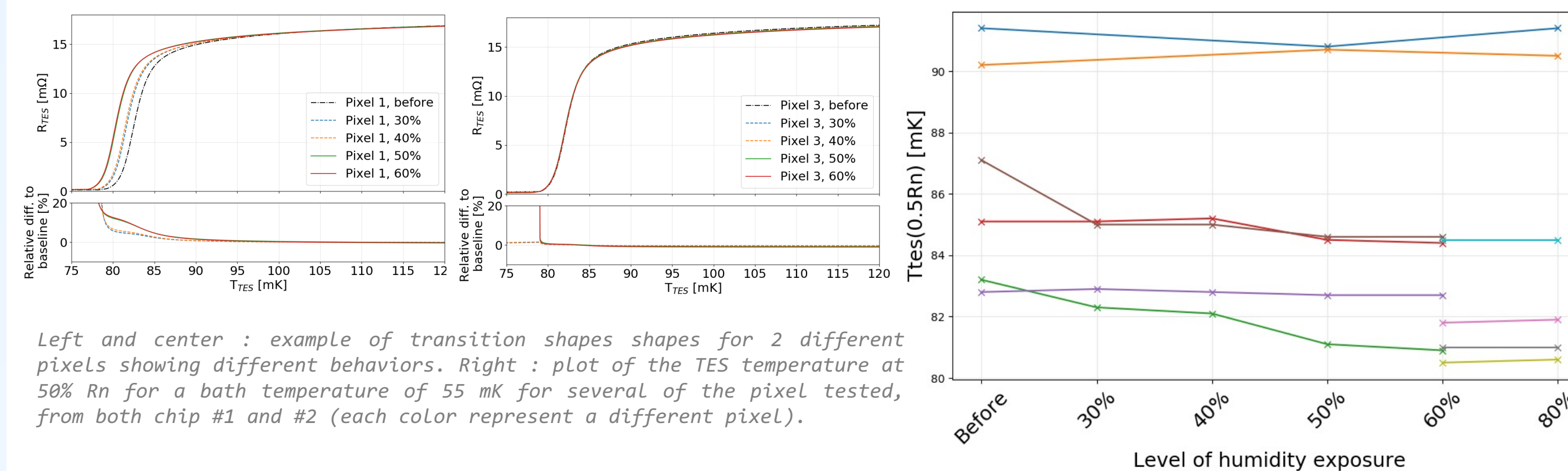
- Chip #1 was exposed successively to ~ 55 % and ~ 80 % humidity, each for 2 weeks.
- Monochromator data showed the appearance of a low energy tail in the spectrum, increasing after each exposure (see left).
- The energy resolution itself remained fairly constant, $\sim 1.9 \pm 0.05$ eV.
- Low energy tail modeled as an exponential with two parameters (tail fraction and length scale) convolved with the line model (here a gaussian).
- This is thought to be due to oxidation of the bismuth from the absorber.
- This was supported by the results from chip #2 with gold capping layer.



- Chip #2 was exposed successively at ~ 30 , 40, 50, 60 and 80 % humidity, 2 weeks at a time.
- No degradation was seen on the energy resolution and no appearance of a low energy tail.
- The gold capping layer, although very thin, appeared to have protected the bismuth from oxidizing.

❖ Transition shapes

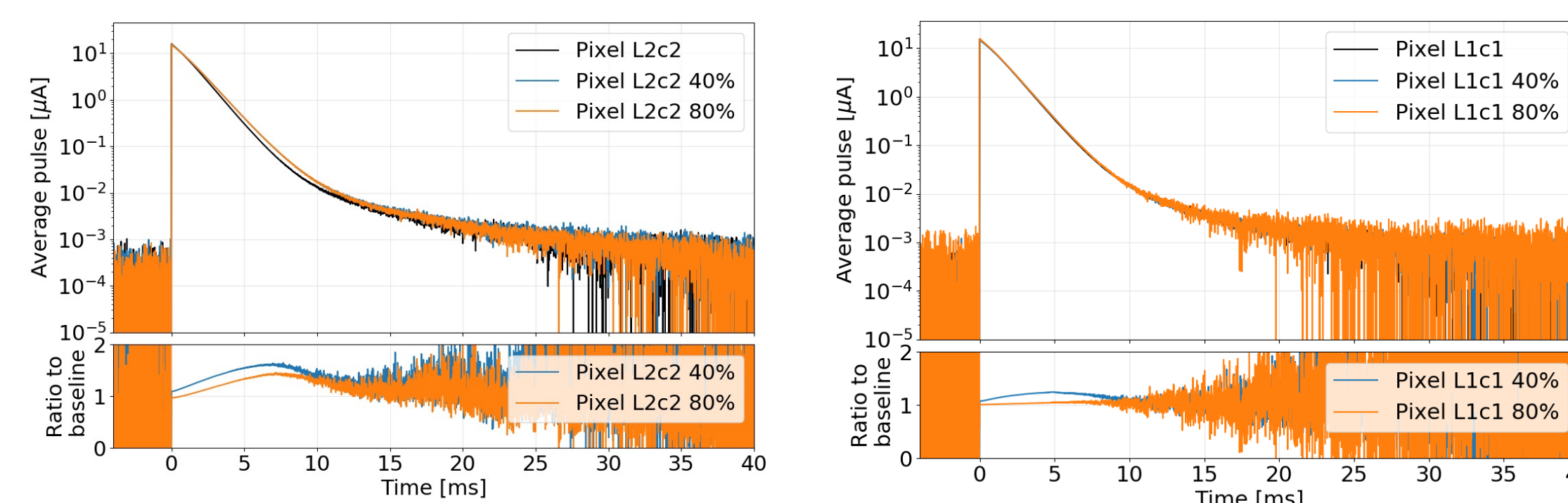
- Throughout the humidity exposures, the transition shapes (R vs T curves) showed little or no variation via small shifts (up to ~ 2 mK) in the transition temperature T_c .
- Examples of little (left) and no (center) variations are shown below.
- Variations appeared only for a couple pixels within the chip and did not vary steadily with the increase in humidity as shown below (right).
- They are hence thought to come from other aspects which can lead to run-to-run variations when characterizing TES detectors such as : local magnetic field not fully compensated for, change in stress locally on the membrane, change in stray power, etc.



Left and center : example of transition shapes for 2 different pixels showing different behaviors. Right : plot of the TES temperature at 50% Rn for a bath temperature of 55 mK for several of the pixel tested, from both chip #1 and #2 (each color represent a different pixel).

❖ Pulse shapes

- The pulse shapes also showed little to no variation from the different exposures to humidity (see below typical examples for 2 different pixels).
- Those differences can be attributed to the run-to-run variations also impacting the R vs T_s .

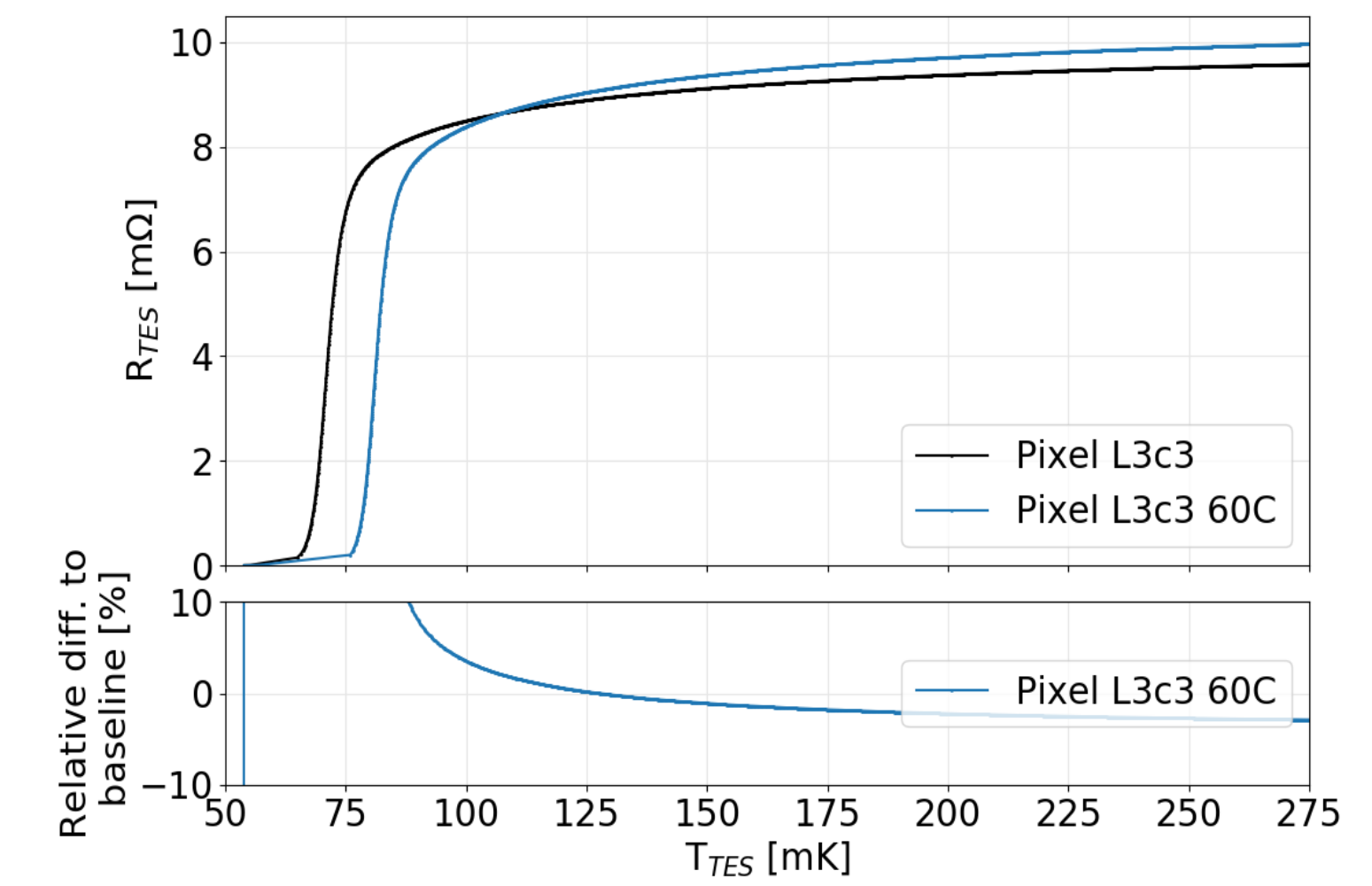


4 Impact of temperature

- Measurement on 1 chip, with gold capping layer.
- Characterization before and after a single exposure to elevated temperature : 10 days at 60°C .

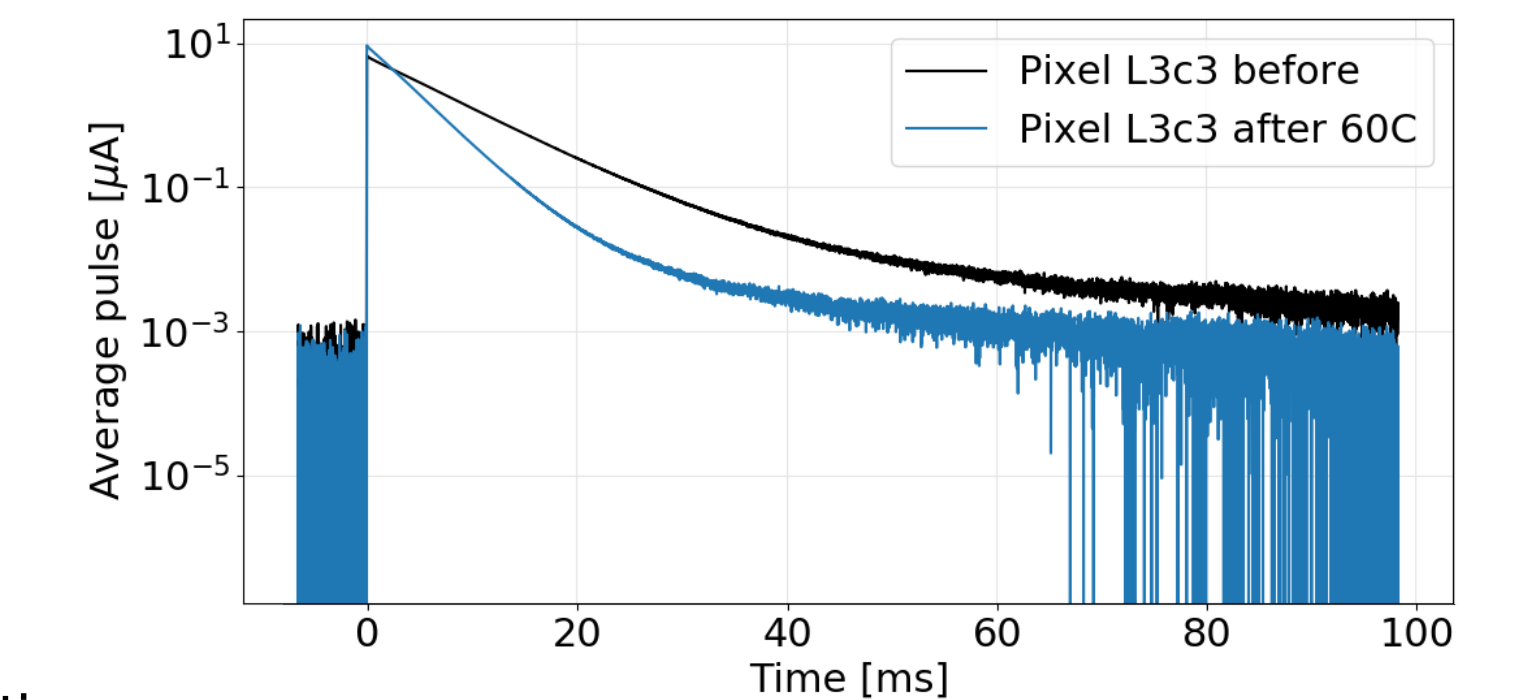
❖ Transition shapes and normal resistance

- Clear change measured on the transition shape and normal resistance for all of the tested pixels.
- Example shown on the right for 1 pixel.
- On average, we consistently observed :
 - + 4 % in normal resistance value
 - + 13-19 % in T_c
- Change unlikely coming from interdiffusion in the TES bilayer (between the molybdenum and gold), since only expected at higher annealing temperature (e.g. $< 150^\circ\text{C}$).
- Increase in both T_c and R_n seems to indicate a film-stress induced change.



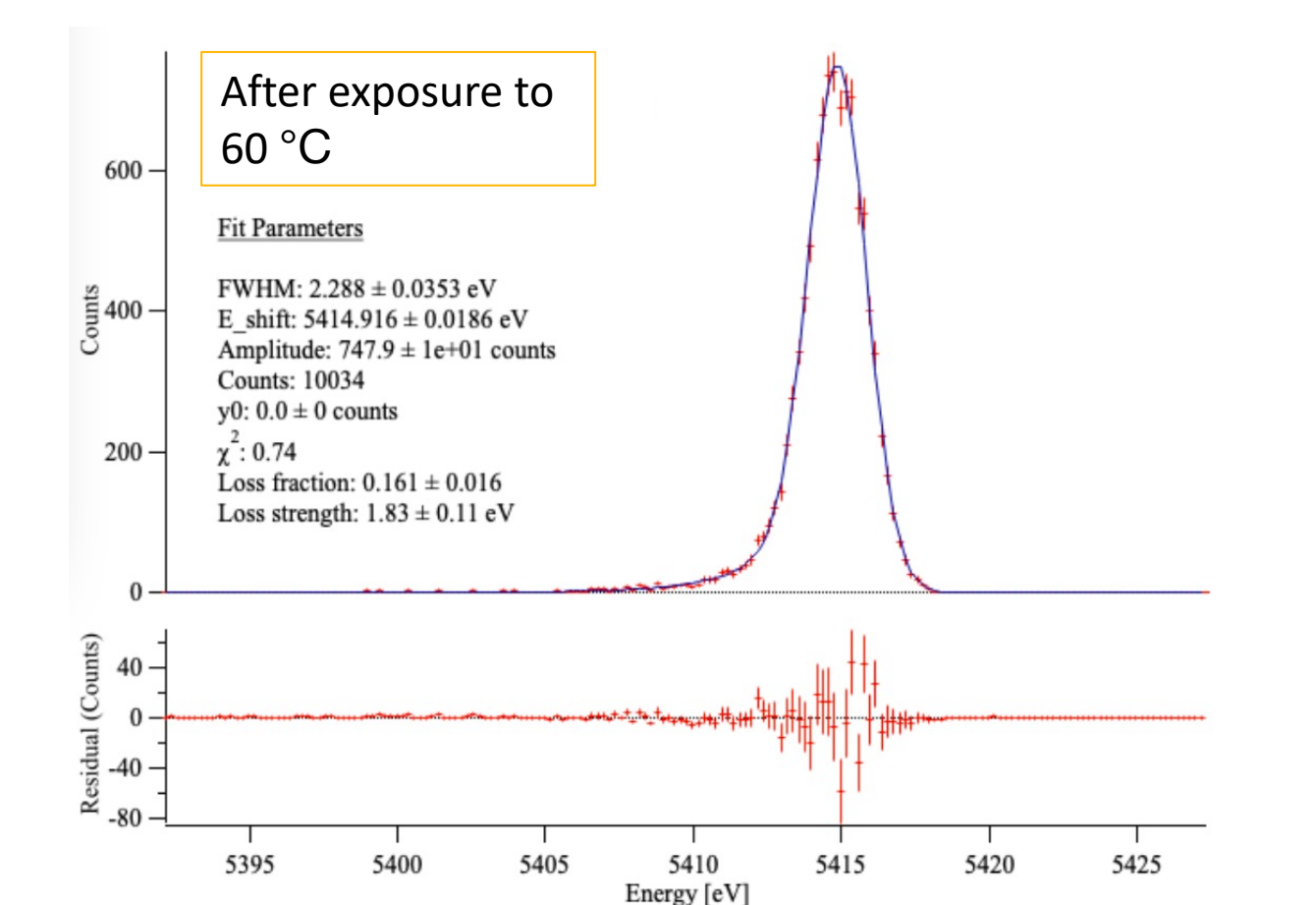
❖ Pulse shapes

- Following the changes observed in the TES characteristics, the pulse shapes also appeared globally changed, with a higher pulse height and faster decay time.



❖ Energy resolution and spectral redistribution

- As expected from the overall changes in the TES characteristics, the spectra showed some difference as well.
- The low energy tail loss fraction increased by 0.02 eV, although with error bars ~ 0.01 eV.
- Interdiffusion in the absorbers (between the gold and bismuth) was potentially expected, but was hard to detect within the overall changes in the TES characteristics.
- Follow up inspection under microscope to be done, to look visually for changes on the absorber surface.



5 Conclusions & Way forward

- Performance of the detectors very sensitive to humid environments.
- Appears this can be mitigated by covering the bismuth from the absorbers with a thin layer of gold.
- Mitigation to be confirmed on a TES chips composed at 50 % of pixels with the gold capping layer and at 50 % without and exposed to humidity as previously done.
- Impact from annealing at 60°C higher than expected.
- Perform new test with exposures at lower temperatures and/or shorter time periods to identify starting point of observed changes.

References and Acknowledgements :

- [1] Eckart et al, IEEE Trans. On Applied Superc., 29, 5 (2019)
 - [2] Leutenegger et al, Rev. Sci. Instrum. 91, 083110 (2020)
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