HRTES-X

High Resistivity TES micro-calorimeter :

a path toward breaking the power dissipation technological lock for future X-ray space telescopes

Benjamin Criton

IRFU/DEDIP : B. Criton, X. de la Broïse

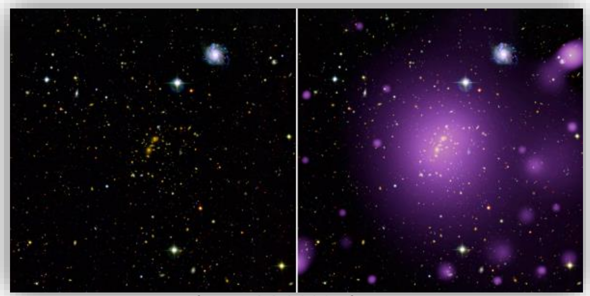
IRFU/DAp : J.-L. Sauvageot

IJCLab : S. Marnieros, C. Oriol, L. Bergé

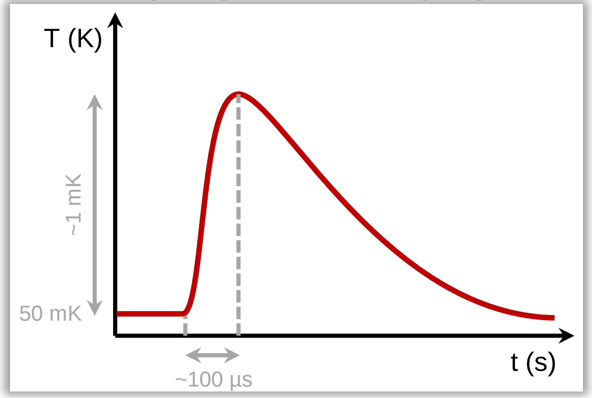
Introduction (1)

Context : Development of space spectro-imagers for X-ray astronomy

- Need from astrophysicist to obtain fine energy resolution of X-ray emitting objects : galaxies, supernovae, black holes, the ICM, etc.
- Technology of choice : **matrices of micro-calorimeters** :
  - A photon **absorber** is maintained at 100 mK by a weak thermal link to a heat sink.
  - When a X-photon arrives, its temperature increases (~mK), and then recovers its initial value.
  - The temperature increase is measured by a very sensitive superconducting **thermometer** (TES) maintained inside its transition ⇒ very high dR/dT.
  - The **resistance** increase is proportional to the **energy** of the incident **photon** (linearity).
- Requirements :
  - High **spectral resolution** ⇒ pixels with high **sensitivity** and low noise chain.
  - High **spatial resolution** and wide **field of view ⇒ large number of pixels.**
- **Our goal :**
  - Make a reduced ***demonstrator*** prefiguring a space spectro-imager with **>10000 pixels**,
  - using a **new technology** for thermometers, the **High-Resistivity TES** (1-5 MΩ),
  - which allows to place the first electronics stage at higher temperatures (4 K) where power budget is much higher.



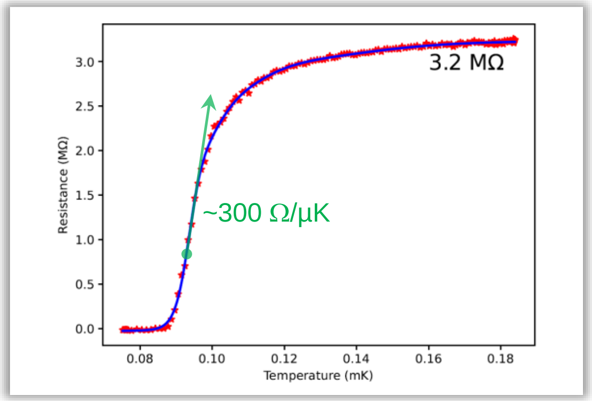
The XLSSC006 cluster : visible light image, X-ray image.



Micro-calorimeter signal shape.

High resistivity TES (HR-TES) technology

- Based on **NbSi** alloy, developed by IJCLab.
- **Advantages** :
  - tunable **high** normal-state **resistance** ~3 MΩ ⇒ facilitates signal transport from 50 mK to 4 K ⇒ low consumption at 50 mK (< 20 pW/pixel) : < 1 µW for > 50 000 pixels,
  - *according simulations*, **high** energy **resolution** : ~2 eV for 500 µm pixels → state of the art.
- **Disadvantage :**
  High electron-phonon **decoupling** that until now reduced resolution.
  But we solve this problem thanks to an innovation : the **active** electro-thermal **feedback**.



R(T) characteristic of NbSi HR-TES thermometer.

Introduction (2)

Active electro-thermal feedback (constant current biasing)

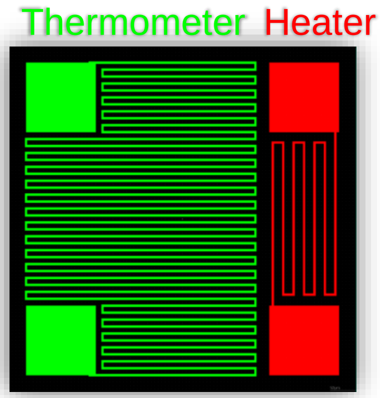
- **Working principle**
  - A **resistive heater** and a **superconducting thermometer (NbSi alloys)** deposited on each pixel.
  - The electronic feedback makes heater continuously dissipate a weak Joule power.
  - When a photon arrives, this power is reduced by feedback
    ⇒ the **temperature** tends to **remain constant**.
  - So the **signal** is no more the temperature increase, but the **power decrease** in the heater.
- **Advantages**
  - The biasing current in the thermometer can be low and constant
    ⇒ reduces drastically the **electron-phonon thermal decoupling**
    ⇒ allows better electronic temperature restitution of the phonon temperature variations.
  - Excellent **stability**.
  - **Photon energy dynamic range** is increased.

Development plan : 4 stages

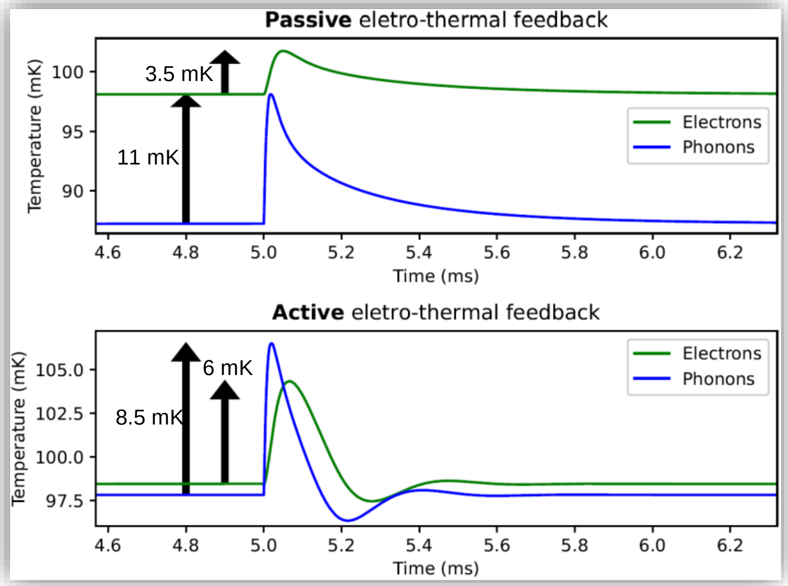
- **WP1** : **Individual pixels** suspended by bonding wires.
  → *For quick tests and optimization.*
- **WP2** : **Mechanical matrices** of suspended membranes.
  → *To check the mechanical solidity.*
- **WP3** : **Sensitive matrices** of suspended membranes **equipped** by HR-TES.
  → *To obtain a reduced demonstrator.*
- **WP4** (in parallel) : Multiplexing **integrated circuit** and electronic boards.
  → *To prove the scalability to large matrices.*

Funding

- **P2IO** :
  - WP1, WP2, WP3 : 40 k€ → **detector manufacturing** by **IJCLab**
  - WP4 : 20 k€ → **electronics**, **cold tests** and setup by **IRFU**



Design of a pixel : a 500 µm Si square with two NbSi meanders : one is a thermometer, the other an heater.



Simulation of the same pixel working with passive (top) and active (bottom) feedback. In blue : phonons temperature (resulting from the incident photon energy deposition). In green : e⁻ temperature (inducing the electrical signal).

Modelling – simulation – optimization

Modelling

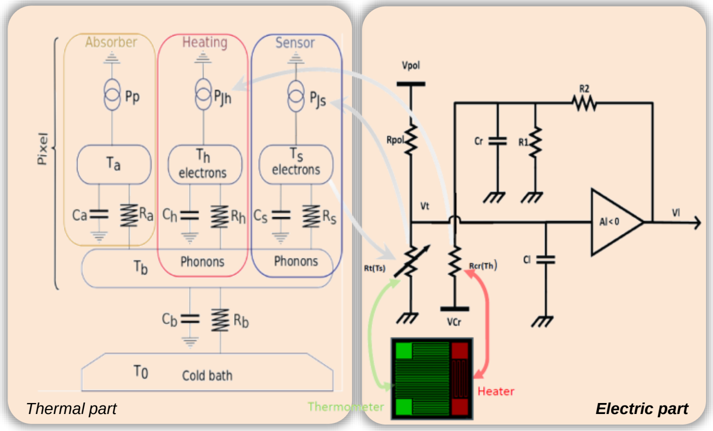
- Take into account the **thermal** part, the **electrical** part, and the **interactions** (by thermometer response and Joule dissipations).
- **Variables** :
  - **Temperatures** of absorber, pixel phonons, heating and thermometer electrons.
  - Electrical **voltages**.
- Simulation **parameters** :
  - **Thermal conductances** between absorber, thermometer, heater, cold bath.
  - **Thermal capacities** of absorber, thermometer, heater, substrate.
  - **Electrical** resistances and capacities.
  - **Noise sources**.

Simulation

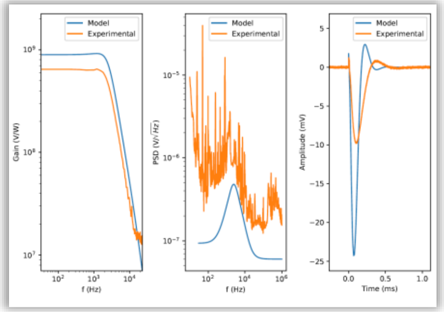
- Physical model implemented in two forms :
  - **Spice** simulator transient model → biasing, **signal shape**, saturation.
  - Linearized **analytical** model → noise spectra, **spectral resolution.**
- Validated by comparison between simulation and measurements : reasonable **agreement** ⇒ good confidence in simulation predictions.

Optimization

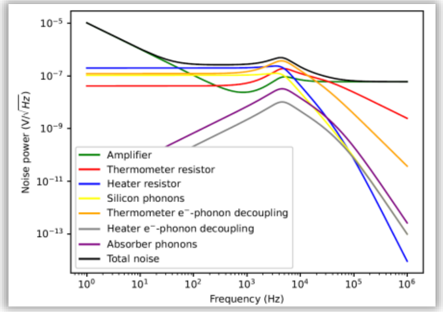
- Used to optimize the **dimensional parameters** to maximize the **spectral resolution.**
- Studied parameters : cold bath temperature, transition temperature, heater resistance and thermometer normal resistance, etc.
- Results :
  - The most influential parameters are the **thermometer resistance,** the **transition temperature** and the **heat conductance with sink**.
  - When optimized the theoretical **spectral resolution** is around **2 eV**.
  - ⇒ **Used** to set the characteristics of the new individual pixel **prototypes** we manufactured.



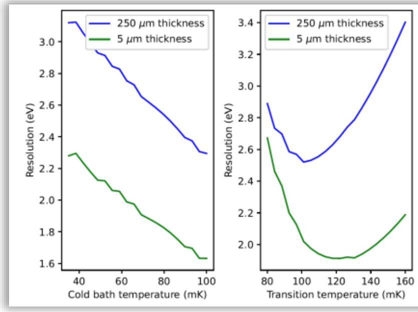
Electro-thermal model.



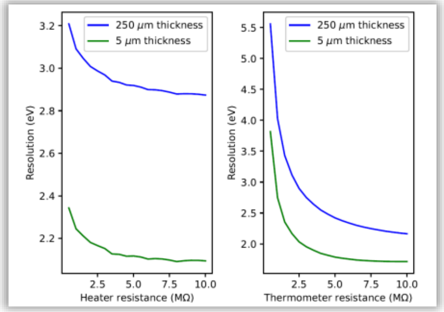
Comparison between model and experimental results.



Simulated noise PSD and its components.



Spectral resolution as a function of cold bath temperature (left) and transition temp. (right).



Spectral resolution as a function of heater (left) and thermometer (right) resistances.

New individual pixels (WP1)

Description

- Manufactured by IJCLab, implemented and tested by IRFU.
- On each 500 µm pixel : a **thermometer** (NbSi, Tc ≈ 130 mK),
  an **heater** (NbSi, without superconducting transition).
- **Suspended** and interconnected by **bonding wires** that adjust the thermal link resistance (2 Al → "no" thermal conduction, 2 Au → low thermal conduction).

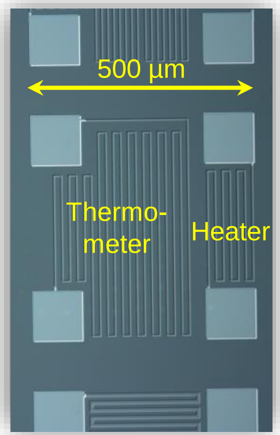
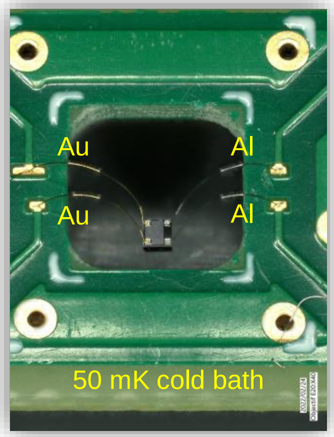


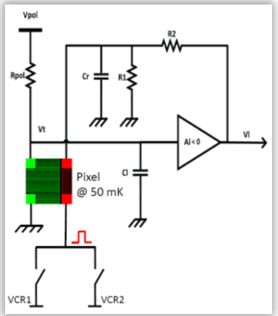
Photo of a pixel on its wafer, before cutting.



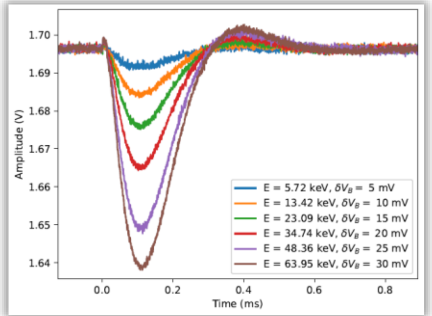
A pixel suspended by its Al and Au bonding wires.

Cold measurements

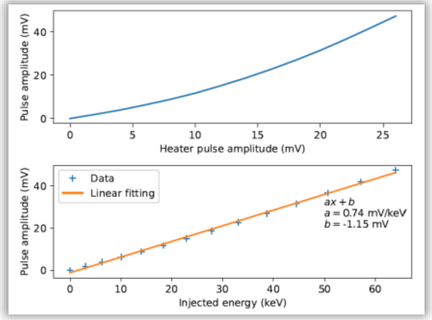
- Two types of stimuli :
  - **Heat pulse (Joule)** generated by on-chip **injection system**.
    ⇒ allows the energy calibration of the whole readout chain, the control of linearity, etc.
  - **X-photons** generated by **^{55}Fe source**.



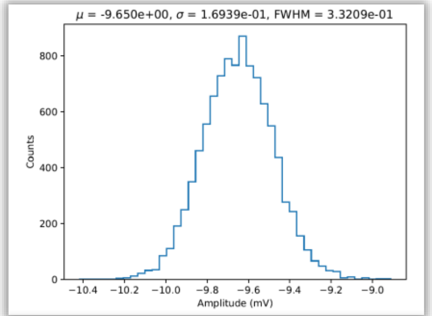
Schematic of heat pulse injection system.



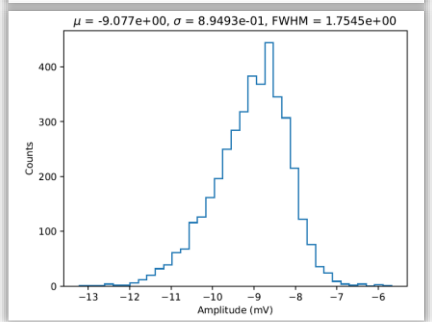
Output signal shape for heat pulses corresponding to various photons energies.



Output signal amplitude according to the heat pulse amplitudes (top) and to the corresponding injected energies.



Energy spectrum with heat injection system.



Energy spectrum with ^{55}Fe source.

Conclusion

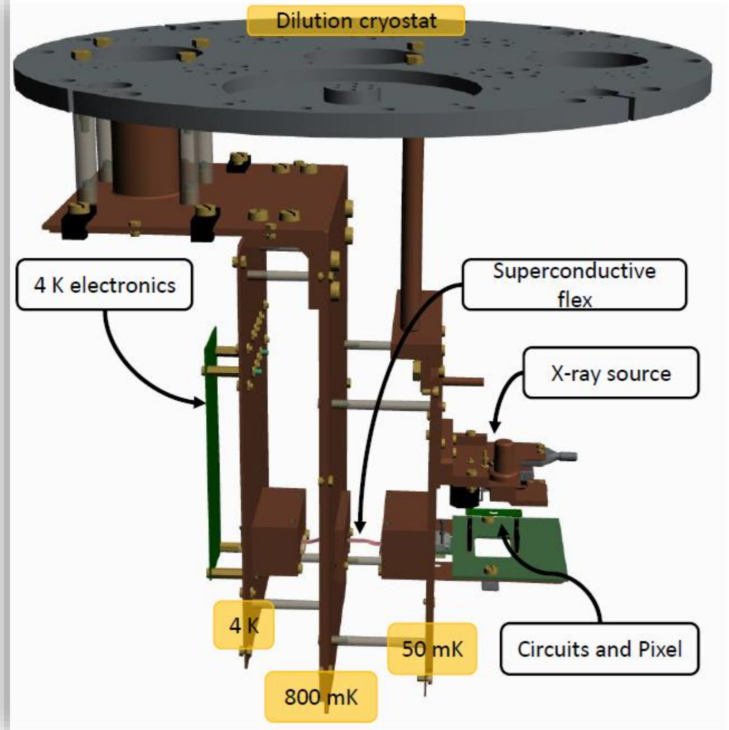
- Good **linearity** (⇒ constant voltage/energy gain : V/eV), good **stability**.
- Satisfactory **agreement** between simulation and measurements.
- But **bad energy resolution (260 eV @ 13,4 keV)**, due to EM and vibration perturbations inducing **excess noises** ⇒ need to **improve** the test **setup**.

New experimental setup

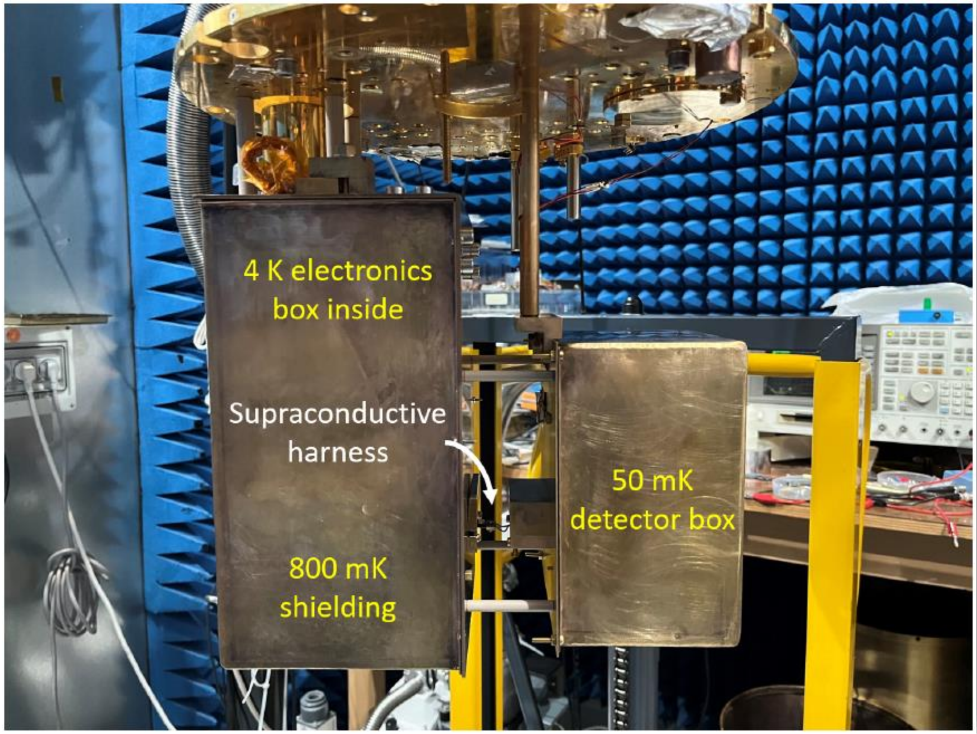
- Two **functions** : **mechanical holding** and **cooling at different temperatures** of the system.
- **Three temperature stages**, electrically interconnected by a shielded **superconductive harness** :
  - 50 mK : X-ray **source** (^{55}Fe), **detector**, **multiplexing electronics**.
  - 800 mK : Intermediate thermalization and IR screen.
  - 4 K : **amplification electronics**.
- Installed in the cryostat and in use : good robustness, modularity,

noise still not optimal : grounding work in progress.

37-tracks shielded superconductive harness.



3D drawing when EM and IR screen boxes are removed.



Photograph when the EM and IR screen boxes are closed.

Matrices (WP2 & WP3)

- Wire bonding technique cannot be used for matrices
  ⇒ use another technique : thin (5 µm) **Si membranes suspended by Si bridges**.
- Development in **two steps** :

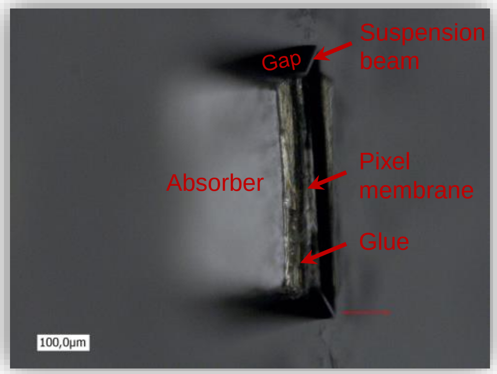
First step : mechanical matrices (WP2 : done)

- **Passive** matrices : no NbSi deposition on pixels ⇒ no thermometer nor heater.
- Aim : test **solidity** of membranes (fabrication process adjustments) and implementation of **absorbers**.
- Conclusion : membrane and beam **solidity validated, gluing absorber is achievable**.

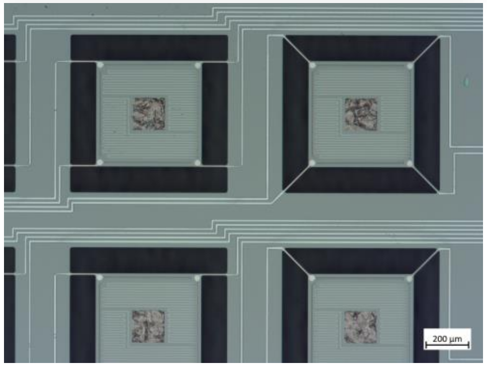
Second step : sensitive matrices (WP3 : done)

- 4x4 matrices with depositions of **HR-TES** (NbSi) on pixels
  and with **signal tracks (Al)** on beams and structure, bonding pads, TiAu hybridization pad.
- A set of matrix with different physical parameters are fabricated :
  - different lengths, sections and quantities of beams
    (→ set of thermal resistances and mechanical solidities),
  - different thermometer resistances and track widths.
  - Some matrices will be homogeneous, others heterogeneous (for comparison)
- Tests are still awaiting due to cryostat issues, matrices are bonded on mezzanine PCBs and successfully multiplexed by the ASIC

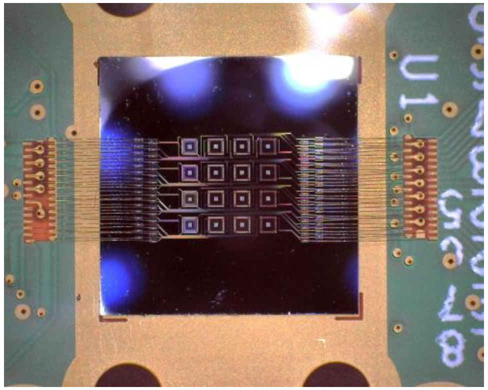
Side view of an absorber glued on a suspended pixel.



Microscope view of a matrix with different bridge configurations



A matrix fully bonded on its mezzanine PCB (interface with the 50 mK ASIC motherboard



Electronics (WP4)

Multiplexing 16 pixels at 50 mK to 1 amplifier at 4 K :

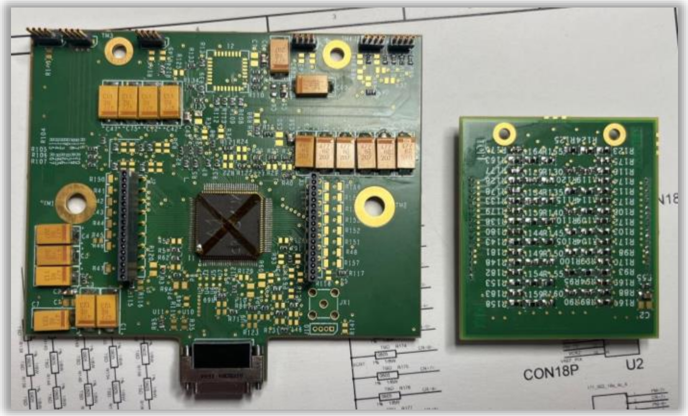
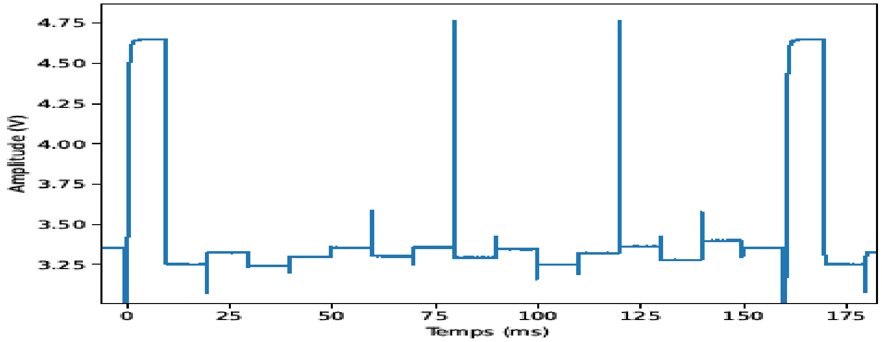


Image of the ASIC circuit PCB and resistive mezzanine.

50 mK stage

- Function : **multiplexing** 16 → 1 of : 1) the readout signal **AND** 2) the feedback links.
- Requirements :
  - For **signal** : high impedance detector ⇒ capacity compensation system (speed-up).
  - For **feedback** : holding between two updates when sampling ⇒ capacitive memory.
  - **Thermal budget** : consumption compatible with 1 µW for all channels.
- Status :
  - **Integrated circuit delivered and fully tested down to 150 mK**.
  - **Electronics boards designed and connected**.



Schematic of the elementary cell multiplexing signal and feedback.

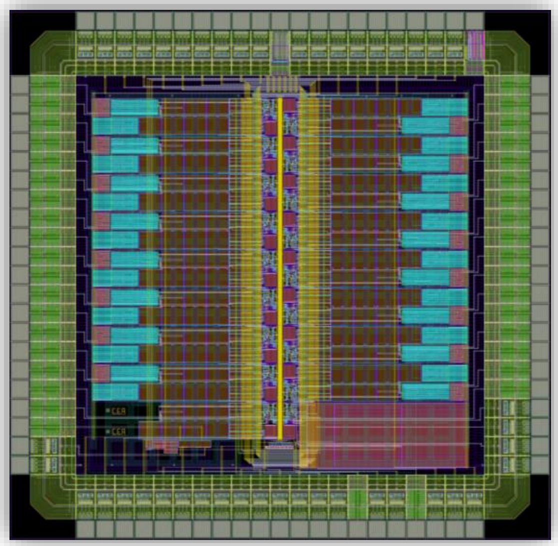


Image of the multiplexing integrated circuit.

4 K stage

- Function : low noise readout signal **amplification** and **feedback** signal generation.
- Status : A new HEMT+SiGe amplifier designed and used, noise around 10 nV/√Hz

Results

- The 16 to 1 multiplexing ASIC is functional and connected to matrices or dummy matrices (resistive mezzanine PCB) and read-out by the 4 K amplifier (see figure).

Conclusion

The HR-TES promises :

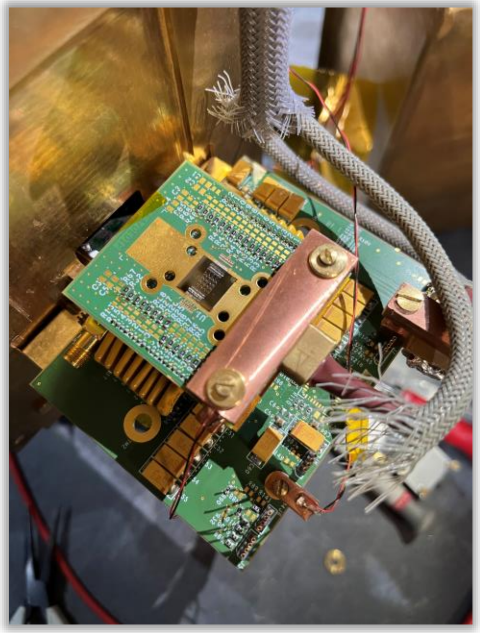
- An **ultra-low power dissipation** readout at 50 mK, allowing matrices of more than **50 000 pixels** ($\rightarrow$ today : 4000 max with LR-TES).
- A **spectral resolution** around **2 eV** ($\rightarrow$ today : 1-2 eV with LR-TES), according to our detailed model and **theoretical simulations**.

We demonstrated today :

- The strong diminution of the effects of the **electron-phonon decoupling**, which was the blocking point of HR-TES use for X-ray, thanks to the **active electro-thermal feedback**.
- The strong **linearity** of the system, proved thanks to our **calibration device**.
- The effective **detection** of ^{55}Fe **X-ray photons** on 0.5 mm pixels.
- **But** : for the moment we obtain a **bad** experimental **spectral resolution**, due to high **parasitic noises** in the setup.

We completed to date :

- The installation of our **new mechanical setup**
  $\rightarrow$ *should reduce the parasitic noises and improves modularity and robustness*.
- The design and manufacturing of **pixel-on-membrane matrices** (WP3 – IJCLab)
  $\rightarrow$ *should also improve the spectral resolution, and is an important step towards large matrices*.
- The design and test of the **new electronics boards** (50 mK and 4 k)



Future prospects

- A funding has been obtained to explore (starting now) in parallel an **new improvement way** :
  - Transformation of the mechanical structure by **replacing** the **suspended membranes** by a **planar structure**, thanks to a technological innovation : a **thermally super-insulating multilayer structure**.
  - $\Rightarrow$ this could transform the architecture of future low temperature detectors by facilitating their **manufacturing**, their implementation, and by improving their **robustness**.
- These developments are designed for X-ray spatial detection (beyond the Athena satellite project), but are **transposable** to other bands (sub-mm) and others contexts (ground instruments).