HIGH RESISTIVITY TRANSITION EDGE SENSOR MODELLING AND EXPECTED PERFORMANCES

G. JEGO (galahad.jego@cea.fr), X. de la Broïse, J.-L. Sauvageot, X. Coppolani, X.-F. Navick – CEA/IRFU, Saclay, France

S. Marnieros – CSNSM, Orsay, France

Context

➢ **Goal:**
- **Development of a new approach for spatial x-ray spectro-imaging: 4096 pixels and 2 eV resolution**
- Propose an alternative solution to Athena X-IFU allowing in future larger matrices
- Our solution: high impedance sensors instead of TES and classical cryo-electronics instead of SQUID

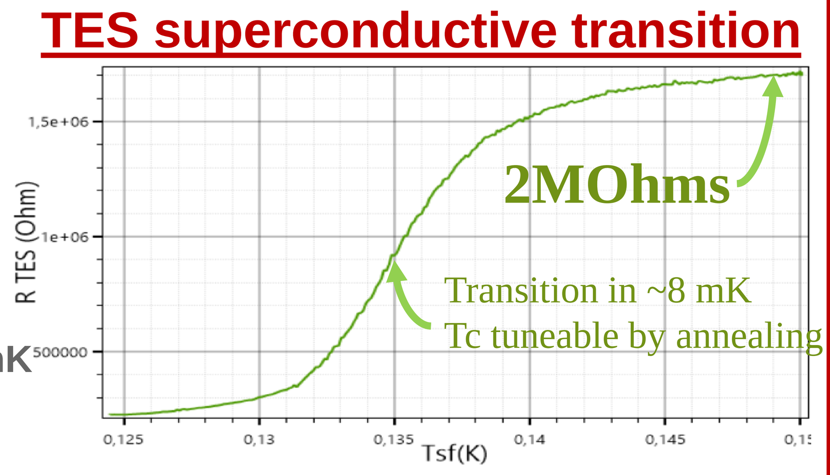
➢ **Current solution:**
- Low resistivity TES read by SQUID based electronics
- Great performances but **shows limitations in the making of very large matrices**
- High power consumption at cold stage of the cryocooler
- Multiplexing increasingly difficult with the number of pixel.

Sensor

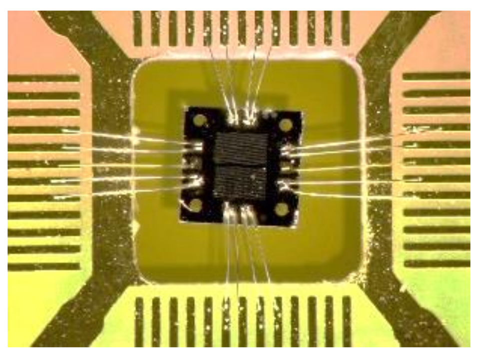
➢ **Materials:**
- NbSi co-evaporation on Si

➢ **NbSi performances:**
- Tc = 130mK (tuneable by annealing)
- **Transition in 8 mK**
- **Resistivity: ~400 Ω/□**

TES superconductive transition



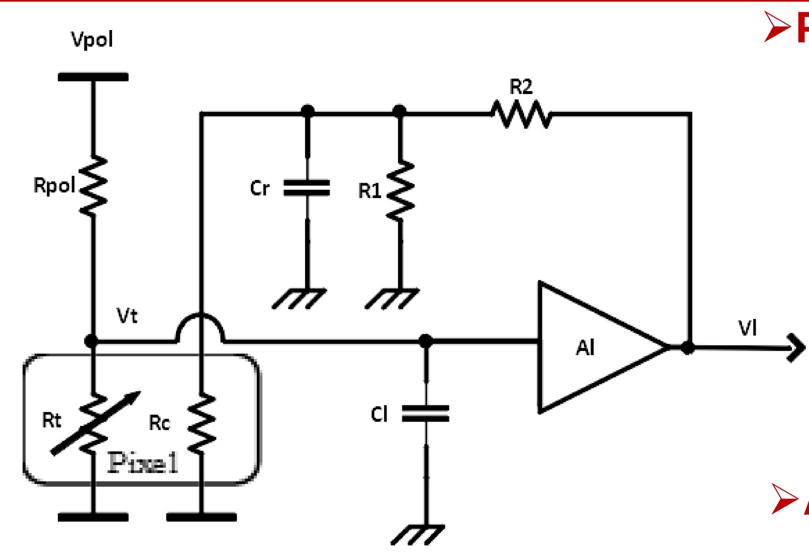
High impedance TES by CSNSM, Orsay



➢ **Tested geometry:**
- Meander width: 5 µm
- Meander length: 25734 µm
- Meander thickness: 50 nm
- Resistance after Tc = 2MΩ

➢ **Tested pixels:**
- Size: 2 mm x 2 mm
- Thickness: 300 µm
- 2 TES/pixel (one as a heater, the other as a sensor)

Problem and our solution



Active Electrothermal Feedback

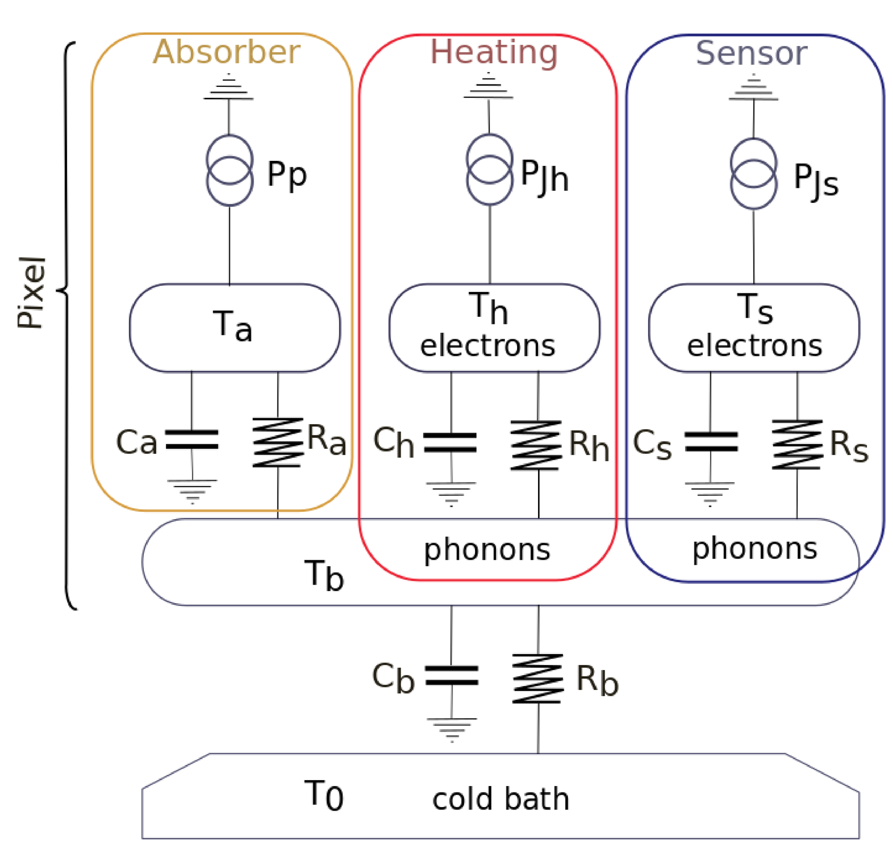
➢ **Problem:**
- Biasing needs to be high enough to have readable and usable signals and to induce passive electrothermal feedback for TES stabilisation.
- But high biasing induces an electron/phonon decoupling (resulting from self-heating)
- High decoupling means signal loss, and makes the sensor useless.

➢ **Action:**
- A Joule power is dissipated in the heater
- When a photon brings its energy, the Joule power in the heater is decreased in proportion by the negative feedback loop.

➢ **Effects:**
- The **thermometer temperature is held constant**, the signal then becomes the power decrease in the heater
- **The energy range (before saturation) is increased** without decreasing the TES high sensibility
- Electron/Phonon decoupling is negligible as the self-heating Joule power of the thermometer is very small compared to the Joule power of the heating device.

Thermal model

Thermal model



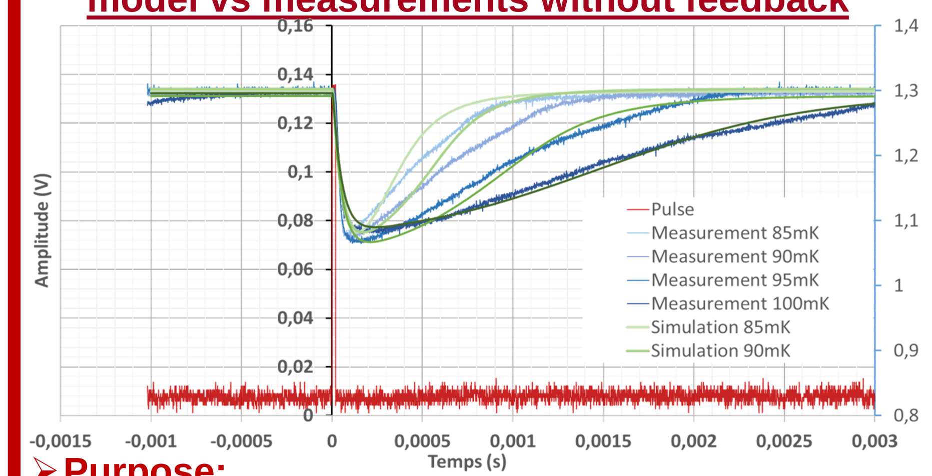
➢ **Five thermal baths:**
- Cold bath (T0), bulk phonon bath (Tb), absorber (Ta), sensor and heating device electron bath (Ts, Th)
- Every bath is exchanging thermal power through thermal resistance and is characterised by its thermal capacity
- Phonons of the sensor and the heating device are well thermally coupled to the silicon bulk.

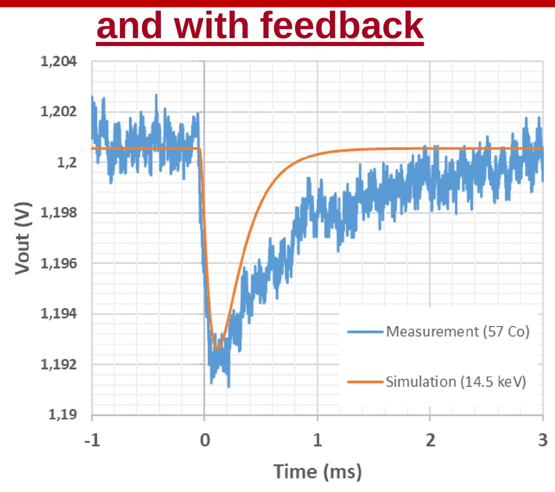
➢ **Three power sources:**
- The incident photon power on the absorber
- The Joule effect on the sensor caused by the bias
- **The heating Joule controlled by the active electrothermal feedback**

➢ **Links to the electrical feedback/readout:**
- The Ts bath is responsible for the signal and is directly **connected to the amplifier input**
- The **output of the electronics is connected to the heating** device which produces a large Joule effect responsible for the bulk temperature
- This model is translated into a fully electrical model with the electrical/thermal analogy
- It is resolved by a **SPICE simulator and analytically.**

Numerical study of the model

model vs measurements without feedback **and with feedback**





➢ **Purpose:**
- Numerical simulation to **compare model and measurements in time domain**

➢ **Model versus measurements:**
- Every parameter is expressed with literature definitions but controlled by the measurements. **The model gives very similar data as actual TES measurements.**
- Without feedback we observe the effect of the thermal capacities variations due to temperature. The same heat impulse gives longer signals as the temperature increase and therefore higher thermal capacities.
- With feedback we observe similar time behaviour for a 14.5 keV pulse, but this need to be perfected with less noisy measurements.
- A new campaign of measurements is planned with the great improvements in noise performances needed

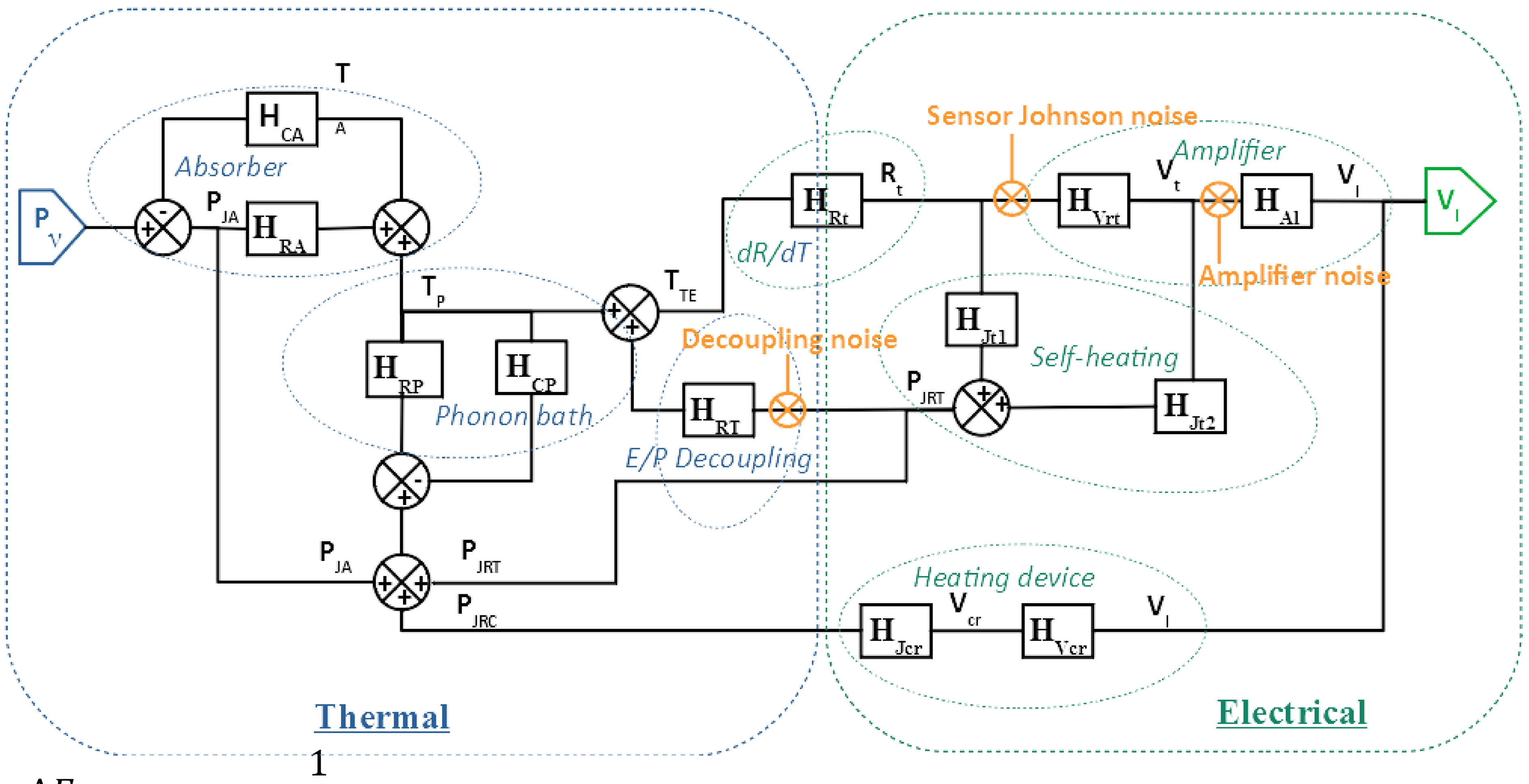
Analytical study of the model

➢ **Purpose:**
- **Have a better understanding of the frequency behaviour** of the system and its noises
- Tool to **enlighten parameters' influences** over the spectral resolution

➢ **Analytical model:**
- The electrothermal model is expressed as a block diagram
- Each block represents either a thermal component (capacity or resistance), an electrical function of the model (Joule effects or amplifier transfer function) or the dR/dT parameter of the NbSi measured.
- Every function is linearised and then transformed into the Laplace domain
- The diagram can be simplified and gives **the total transfer function** that expresses the voltage output with the input photon power.
- Every noise source is identified and placed on the diagram. It can be simplified again with the noise as input.

➢ **Noise:**
- A total **of 6 noises are identified**: sensor and heating Johnson noises, amplifier, thermal noises from the pixel to cold bath link and from the absorber to the pixel link, and the electrons/phonons decoupling noise.
- **We can derive the NEP** from the transfer function of those noises by dividing them by the total input transfer function.

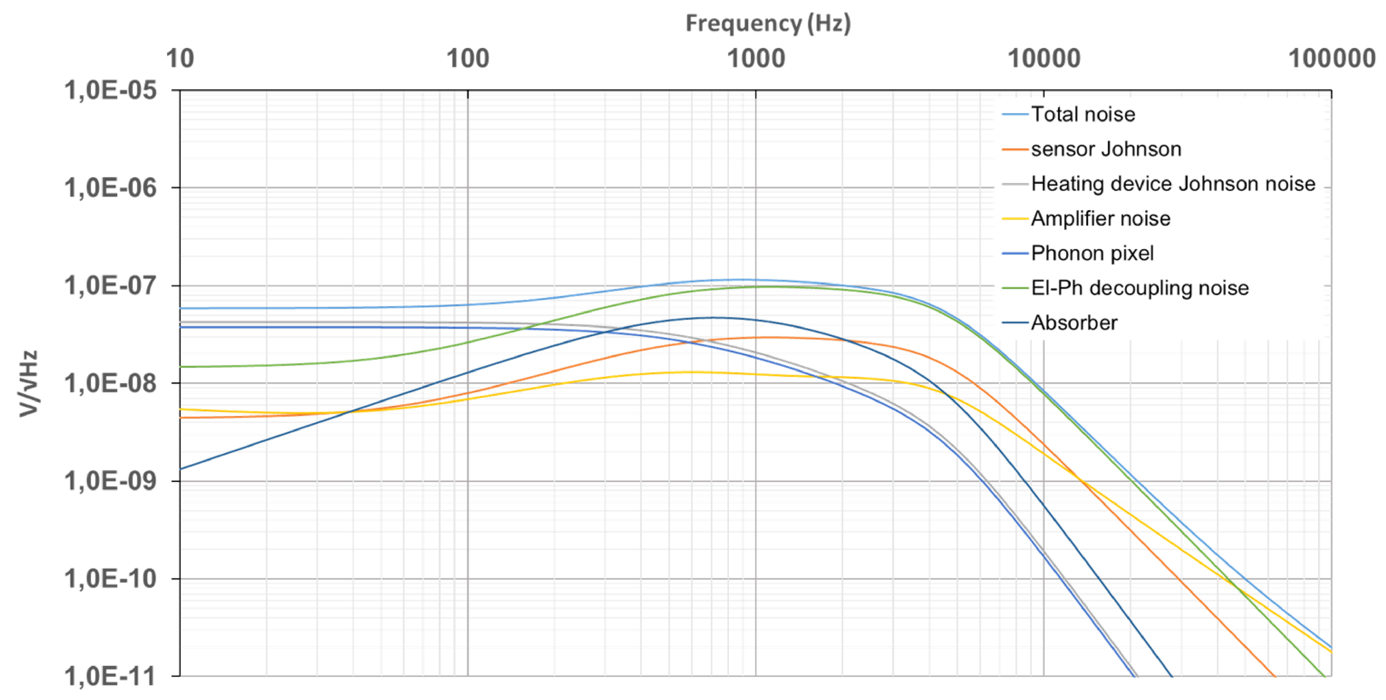
➢ **Spectral resolution:**
- The maximum performance that can be expected is directly derived from NEPs
- The model can then easily predict the best resolution for given parameters of our system.
- For the actual pixel, **we can expect 14.4 eV of spectral resolution as it is unoptimised**



$$\Delta E_{RMS} = \frac{1}{\sqrt{\int_0^{\infty} \frac{2d\omega}{\pi NEP^2(\omega)}}}$$

Analytical solving of the model

Pixel optimisation



Noise spectrum computed with the analytical tool

➢ **Optimisation:**
- The model **computes noise spectrum** for input parameters that are tuneable in the development of the detector.
- Every modification of any parameter is **automatically taken into account** on every other related parameters.
- It renders optimisation much easier and is necessary as the feedback loop have some very unintuitive effects.

➢ **Steps:**
- Lowering the temperature isn't necessarily the best option. Heat capacities decrease but el/ph decoupling increases and becomes too problematic. **An optimal temperature for the NbSi is found at 110 mK.** It helps improving the spectral resolution to **11.6 eV**
- Size can be of **500 µm x 500 µm for a pixel**, lowering the resolution to **5.56 eV**
- The volume of the NbSi deposition is a factor in both capacity and decoupling. And optimal is found at 2 e-9 cm^3. **The NbSi used as an heating device can be replaced by a lighter material too so we can achieve 4.13 eV.**
- The thermal link to the cold bath has to be lowered to a minimum before the signal becomes too slow. **All steps completed, a 1.54 eV resolution can be expected**

Conclusion

➢ **Expected resolution:**
- We have developed a complete and **accurate model** of our NbSi pixel which **fits measurements**.
- The model shows that we can achieve outstanding performances:

1,54 eV resolution for an average size pixel

- A new measurement campaign will soon start with great improvement in noise performances and with an iron source in order to compute a spectrum.
- Furthermore, preliminary simulation shows that such feedback can be integrated in the temporal multiplexing of 32 pixels.