PROCEEDINGS OF SCIENCE

TES Microcalorimeter for IXO: from Focal Plane to Anticoincidence detector

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The high resolution spectroscopy provides a unique technique to extract fundamental information in X-ray Astrophysics and Cosmology. In order to exploit at the best the capability of carrying out spectroscopy of faint sources, great care must be taken to reduce the background in the main detector. In this paper, we will present the working principle of a TES (Transition Edge Sensor) Microcalorimeter, its application for fine spectroscopy and a novel anticoincidence technique , based itself on a TES detector. Recent results from the first sample of the IXO-anticoincidence detector will be also shown.

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1.Introduction

The IXO (International X-ray Observatory) [1, 2] is a joined (ESA/NASA/JAXA) mission aimed at studying some of the most fundamental topics in contemporary astrophysics and cosmology:

- Black holes and matter under extreme conditions
- Formation and evolution of galaxies, cluster and large scale structures
- Life cycles of matter and energy

IXO will provide the advances in X-ray imaging, timing, spectroscopy and technology needed to address these goals.

One of the instrument on IXO is the XMS (X-ray Microcalorimeter Spectrometer). It is a 1K-pixel imaging-array based on TES (Transition Edge Sensor) microcalorimeter technology. It will provide high spectral resolution images in the 0.2-10 keV range: about 2.5 eV FWHM in the center of the field. In order to meet the scientific requirements, in particular for faint point or diffuse sources such as clusters of galaxies, it is necessary to reduce the background in the detector by almost two orders of magnitude below the value expected in the IXO orbit. This will require a high efficiency and fast anticoincidence detector.

In this paper the working principle of the TES-microcalorimeter, readout electronics, some state-of the-art results and XMS design will be briefly discussed. The anticoincidence detector [3], based on a novel approach employing a TES detector, will be presented, including preliminary tests.

2.TES Microcalorimeter

For a complete review see [4] and Ref. therein. Here, only the TES case will be discussed.

2.1 Working Principle

The microcalorimeter consists of (see Fig. 1 Top-Left):

- Absorber (C)
- Temperature sensor
- Thermal link (G) that connects the absorber to a heat bath of temperature T_b.

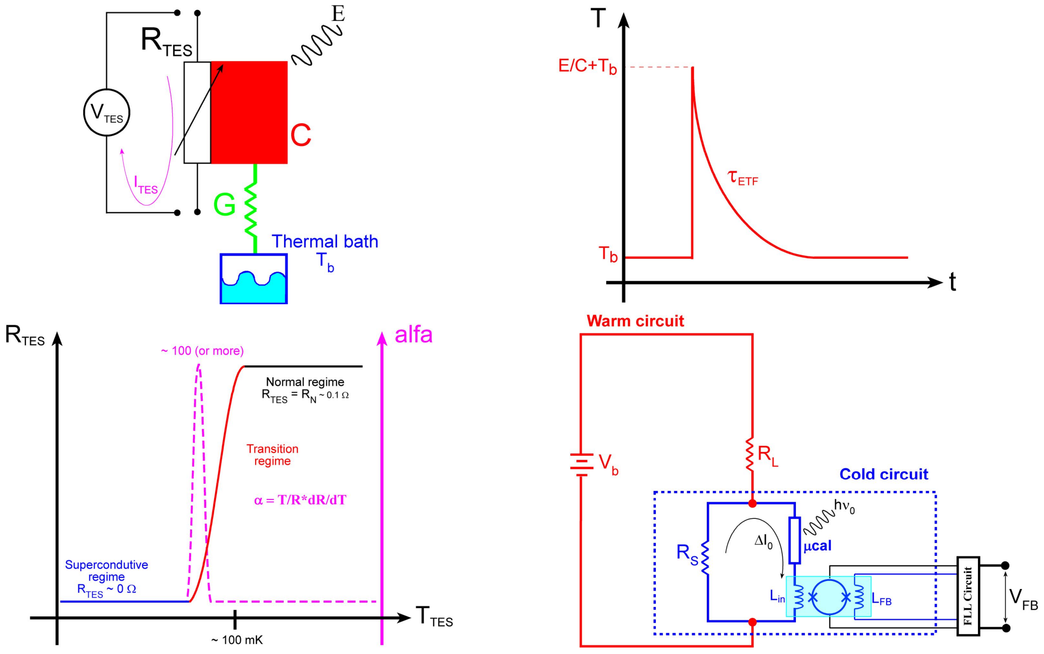

Fig. 1 - (Top-Left) Sketch of a microcalorimeter. (Top-Right) Thermal Pulse. (Bottom-Left) TES R-T, α-T curves. (Bottom-Right) Polarization circuit. (See text for details).

When a photon is captured in the absorber, its energy is swiftly converted in heat, which gives rise to a thermal pulse (Fig. 1-Top-Right) whose amplitude is inversely proportional to the heat capacity of the absorbing material. Then the temperature pulse is transformed in electrical measurable signal by a “thermistor”.

The TES-like thermistor uses the steep phase transition of the resistance between superconductive and normal regime, at which it has typical values of ~ 0.1 Ω. (Fig. 1-Bottom-Left). The transition temperature is usually set at about 10^2 mK. The practical parameter used to measure the sensitivity is related to the transition steepness $\alpha = T/R \cdot dR/dT$ (the logarithmic derivative of R(T) curve: $\alpha = d\log R/d\log T$): the greater the α, the greater is the sensitivity. For TES typical values for α are of the order of 10^2.

In order to speed-up and linearize the response of TES microcalorimeters, it is necessary to take the advantage of the electrothermal feedback by applying a voltage bias. This is typically provided by a current flowing through a small shunt resistance at low temperature (Fig. 1 Bottom-Right). The current pulse is generated by the rapid swing of the TES resistance following the photon absorption. The current pulse amplitudes are of the order of $10^{-6}/10^{-7}$ A with a noise level at 10^{-10} A or better. To read out these low current pulses with a so high dynamic range S/N=10^4-10^5 and with an optimal impedance matching, a special low-noise current amplifier is required: the SQUID Amplifier (Superconducting Quantum Interference Device Amplifier).

In the most simple thermodynamic model, the solution of the equations which rule the thermal budget among the deposited energy E, the Joule-power due to the electric bias, and the specific heat C, is an exponential pulse with a decay time constant $\tau_{ETF} \sim (C/G)/(1+\alpha/n)$, where ETF is the so-called ElectroThermal Feedback [4], and *n* a parameter related to the dominant mechanism responsible for the heat transport between thermometer and bath. In ETF regime, the greater the α the lower is the time constant (in ETF typically 10^2 µs for $\alpha \sim 100$). So, there is a strong reduction of the decay time constant which implies fast signals, that is high count rate (application related bright sources or large area optics). It has been demonstrated that, due to the voltage polarization of the TES, the ETF mode gives stability to the working point of the detector [4]. Further, two important parameters for designing a microcalorimeter detector are:

- The Energy Bandwidth → $E_{\mathrm{MAX}} = \dfrac{CT}{0.63 \cdot \alpha}$
- The Energy Resolution → $\Delta E_{\mathrm{FWHM}} \cong 2.35 \cdot \dfrac{1}{\sqrt{\alpha}} \cdot \sqrt{kT^2C} \cong \sqrt{kTE_{\mathrm{MAX}}}$

High Energy Bandwidth implies high C, low α (wide transition). On the contrary High Energy Resolution implies low T, so cryogenic detector, low C and high α (narrow transition), So, a trade off on the parameters is usually necessary to achieve the desired performances. Typical values for TES pixels are: C ~ 1 pJ/K and for G ~ 1 nW/K.

For information about cryogenics and SQUID see [5, 6] and Ref. therein.

2.2 Manufacturing, Single Pixel results, Array, Readout

The TES is usually a bi-layer metal film deposited onto SiN 1 µm thick suspended membrane, made of Ir/Au, or Ti/Au, or Mo/Au with a typical total thickness of about about 10^2 nm. The TES area depends on the pixel area. The Absorber (Au, Au/Bi, Cu/Bi, Sn) is few µm thick, depending on the maximum energy of the photons to be absorbed and grown on the TES. The area of each pixel is usually about 250x250 um. Presently, several groups [7, 8, 9, 10] have reached a resolution of few eV@6keV (E/dE $\gtrsim$ 2000) which fits the requirements of IXO.

A great efforts have been spent in developing an adequate readout electronics of large array by adopting Multiplexing techniques [11]. Such a technique allows to minimize the heat load caused by thermal conduction through the harness to the cold finger (thousand wires). The array is powered and read by rows or by columns using different Multiplexing methods:

- FDM (Frequency Division Multiplexing → Sinusoidal biasing functions)

- TDM (Time Division Multiplexing → boxcar readout function)
- CDM (Code Division Multiplexing → coded biasing function)

As an example, the FDM technique works as follows: the Pixels are AC-biased at different frequencies (line by line). Then, column by column, the signal is feed at a summing node and addressed to a single SQUID. After the summing signal is acquired, the electronics will perform the de-multiplexing. Several approaches have been realized in practise to implement this technique (see [12] and Ref. therein). At present, a 2x8 pixels array (TDM readout-based) has been tested getting an average resolution of 2.93eV@6keV [13].

3.IXO X-ray Microcalorimeter Spectrometer

The X-ray Micorcalorimeter Spectrometer (XMS) for IXO is being studied and developed by a consortium of institutes led by NASA/GSFC, SRON, ISAS-JAXA, INAF/IASF Roma, Genoa University Phys. Dept. The XMS instrument-layout that fits the scientific requirements is shown in Fig. 2.

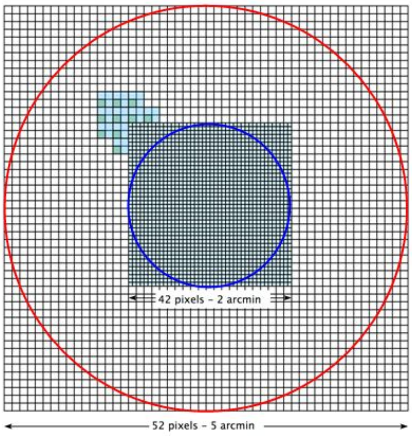

Fig. 2 - XMS-Layout. The blue and red circles define the FOV.

The XMS array is made of different arrays. The central core array achieves an exquisite energy resolution (2.5 eV) and is made of one absorber read out by a single TES, (42x42 with 2.9 arcsec, pxl area ~ 300x300 μm^2) reaching a 2.0 arcmin FOV. The time constant is ~ 300 μs. The outer array extend the FOV up to ~ 5arcmin by employing 4 absorbers for one TES (52x52 with 5.8 arcsec, pxl area ~ 600x600 μm^2). The required En. Resolution is < 10 eV, and the time constant < 2 ms. For all pixels the absorber is Bismuth 7 μm thick and the Energy Band is 0.2-10 keV. The cryogenics is a big issue, and the baseline technology is related to a dry-system (no consumables) [14].

4.The Cryogenic AntiCoincidence detector: CryoAC

The scientific requirements of IXO-XMS demand a Background better of $2 \cdot 10^{-2}$ cts/cm^2/s/keV [14]. In order to understand the background and to properly design the anticoincidence (CryoAC) a huge work is being put in simulations [15]. Without the CryoAC the background would be at least 10 or more times larger than required: from the preliminary simulations it can be seen that the contribution of the cosmic ray proton component should set to 0.15 cts/cm^2/s/keV. Therefore, it is necessary to place a CryoAC with at least > 95% rejection efficiency. From geometric simulation the CryoAC need to be placed at less than 1mm from the TES-microcalorimeter arrays: thus it has to lie in the same cryogenic environment of the main detector.

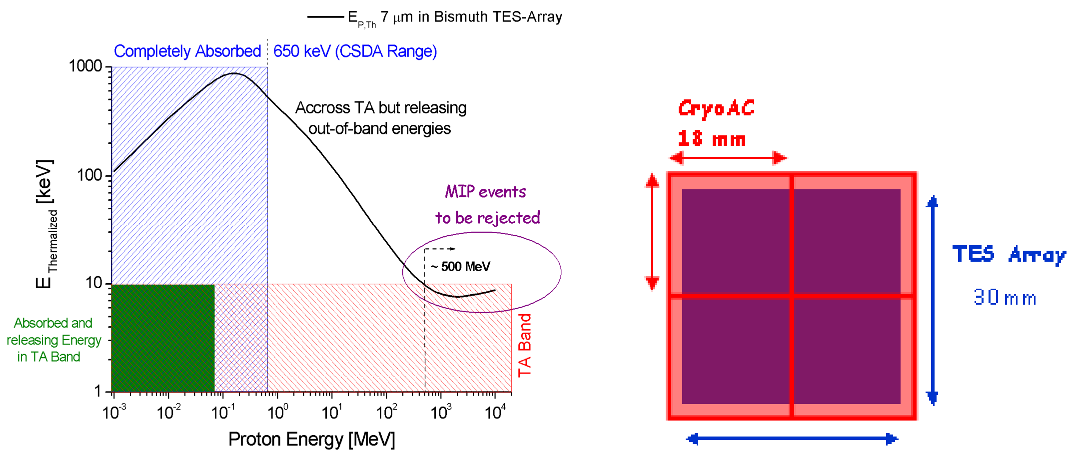

Fig. 3 - (Left) Thermalized energy in the XMS from protons. (Rigth) Sketch of the CryoAC.

The plot in Fig. 3-Left shows the thermalised energy inside the XMS for protons. As shown, the CryoAC must at least reject the so-called Minimum Ionizing Particles (MIP) events that release signals inside the XMS energy band (0.2-10 keV). Up to some tens of keV, protons are absorbed by the filters or deflected away by the magnetic diverter. Up to ~ 500 MeV they release energy out of XMS band (their rejection is hence achieved by out of range signal in the TES array). Protons above this energy will instead deposit energy in the instrument bandpass, and thus need to be rejected.

We have designed and produced a first prototype of anticoindence based itself on a Ir TES sensing a Silicon absorber due to the experience inside our collaboration. The baseline geometry is an assembly of 4 sub-unit (18x18 mm^2 each, Fig. 3-Right). For such a large area/volume detector, we expect to have both thermal and a-thermal pulses. In principle this will offer more room for parameter trade-off. The adoption of a TES-based detector, i.e. the same technology used for the main detector, gives several advantages, like simplifying the Electrical, Mechanical and Thermal I/F. By adopting a thickness up to 300 μm, a MIP is expected to deposit about 90 KeV. We set the minimum energy threshold by requiring for these events a S/N > 10, that means E_{min} ~ 5 KeV. The expected maximum deposited energy is ~ 4 MeV [3] but, in order to achieve a relatively fast duration for the thermal component the CryoAC maximum energy is about 0.5-1 MeV.

5.IXO-CryoAC Prototype measurements: Preliminary Test

During the summer 2009 preliminary tests have been carried out on a CryoAC prototype (see Fig. 4 and Ref. [3]). It is constituted by an Iridium TES (V = 3.7mm^2 x 90nm) directly deposited onto a Silicon n-type absorber (A ~ 16.5 mm^2, 300 µm thick). The absorber area is ~ 200 times the typical pixel area for a X-ray microcalorimeter. The expected total specific heat is ~ 16.5 pJ/K, and E_{MAX} ~ 0.45 MeV. The temperature transition is ~ 0.1 K, and the maximum expected α ~ 55 [3]. The detector has been irradiated by a ^{55}Fe source.

Fig. 4 – CryoAc prototype (Summer 2009). The Ir TES is visible.

For this test, the ETF was relatively mild. Fast pulses have been detected (Fig. 5-Left). The typical decay time constant is 100 µs. The rise time is ~ 2 µs. Sizable pulse amplitude spread has been observed (Fig. 5-Rigth), and is under investigation.

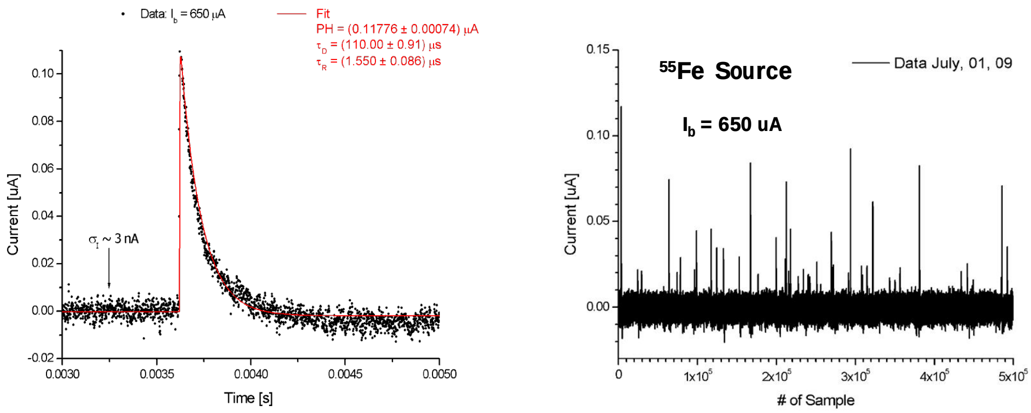

Fig. 5 - (Left) Typical Pulse acquired. (Rigth) Typical data stream.

The conclusion is that we have detected genuine events from a ^{55}Fe source (~ 6 keV close to the 5 keV for the requirement related the minimum energy to be detected) and observed fast signals (faster than the ~ 300 µs required for the XMS). In this respect, the system is not far from the goal but we need to consolidate these results on a second generation prototype, of larger area, closer to the flight detector. This is being currently manufactured, with an area of a 10x10 mm^2 , i.e. 6 times in Area of the present prototype (final size 18x18 mm^2). New tests will also include irradiating the prototype with α particles at ~ 5.4 MeV by ^{241}Am) to study the saturation regime and the dead time. Finally we will study the possibility to upgrade the CryoAC to make it sensitive to hard X-ray photons (up to ~ 50 keV). Enabling simultaneous

PoS(extremesky2009)086

observations of high resolution line emission in the keV range with correlated features in the hard X-ray range is an important scientific opportunity. TES-based single pixel and small array detectors working at 60-100 keV have been already produced [16, 17]. In our case, a solution with a minimum impact (n. of pixels, complexity of the design) on the system is in order.

Acknowledgement

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