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Caliste 64: detection unit of a spectro imager array for a hard X-ray space telescope

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ABSTRACT

In the frame of the hard X-ray Simbol-X observatory, a joint CNES-ASI space mission to be flown in 2014, a prototype of miniature Cd(Zn)Te camera equipped with 64 pixels has been designed. The device, called Caliste 64, is a spectro-imager with high resolution event time-tagging capability. Caliste 64 integrates a Cd(Zn)Te semiconductor detector with segmented electrode and its front-end electronics made of 64 independent analog readout channels. This $1 \times 1 \times 2$ cm^3 camera, able to detect photons in the range from 2 keV up to 250 keV, is an elementary detection unit juxtaposable on its four sides. Consequently, large detector array can be made assembling a mosaic of Caliste 64 units. Electronics readout module is achieved by stacking four IDeF-X V1.1 ASICs, perpendicular to the detection plane. We achieved good noise performances, with a mean Equivalent Noise Charge of ~65 electrons rms over the 64 channels. For the first prototypes, we chose Pt//CdTe//Al/Ti/Au Schottky detectors because of their very low dark current and excellent spectroscopic performances. Recently a Caliste 64 prototype has been also equipped with a 2 mm thick Au//CdZnTe//Au detector. This paper presents the performances of these four prototypes and demonstrates spectral performances better than 1 keV fwhm at 59.54 keV when the samples are moderately cooled down to -10°C.

Keywords: CdTe, Simbol-X, spectro-imager, X rays

1. SCIENTIFIC AND TECHNOLOGICAL CONTEXT

1.1 Simbol-X mission

The Simbol-X mission is a hard X-ray space telescope. It is currently undergoing a phase B with the French and the Italian space agencies. This telescope will fill the gap between X-ray telescopes with grazing mirrors, efficient until ~10 keV (XMM-Newton, Chandra missions) and hard X-ray and gamma-ray instruments using indirect imaging technique with coded masks to detect higher energies (INTEGRAL, SWIFT missions). Simbol-X will be a 20 meter focal length observatory, achieved by two satellites flying in formation. One carries the grazing incidence mirror to focus X-rays until 80 keV. The other satellite carries the detector payload. This focusing technique improves sensitivity and angular resolution by two orders of magnitude compared to the current instruments above 10 keV. As a consequence, a wide range of sources can be studied in detail, such as galactic and extra-galactic compact sources, supernovae remnants, cluster of galaxies, or young stellar objects. The core scientific objectives of Simbol-X are black holes physics and particle acceleration mechanisms [1, 2].

The detection set consists of three detector units [3]. The Low Energy Detector is a silicon drift detector with DEPFET readout, also called “Macro Pixel Detector” [4]. It covers the energy range from 0.5 to 20 keV. The High Energy Detector (HED) installed below the first detector is efficient from 8 to 100 keV. The third unit is an active shielding to reject background (unfocused photons and protons) by temporal coincidence.

1.2 The High energy detector (HED)

The sensors for the HED are Cd(Zn)Te detectors with segmented electrodes. CdTe and CdZnTe are semiconductors well suited for X and gamma rays detection, with excellent properties for imaging and spectroscopy. Contrary to silicon, a 2 mm-thick CdTe detector is still 97% efficient at 80 keV. Contrary to germanium, it can be processed with small pixels size for imaging and it can be easily operated at room temperature or moderately cooled. Requirements for the instrument come from both imaging and spectroscopy constraints. A pixel pitch of 625 µm is necessary to properly sample the ~3 mm diameter HEW point spread function. The 12 arcmin field of view requires a detector array of 64 cm2. Detector material uniformity is also essential to guarantee high imaging quality. The spectroscopic performance baseline of 1.2 keV fwhm at 60 keV over all the channels of the HED is driven by the study of supernovae. To build explosive nucleosynthesis models in young supernovae, a key parameter is the abundance of the ^{44}Ti isotope, visible through the 68 and 78 keV lines emitted in its decay chain. High resolution spectroscopy is not possible without very low noise electronics. The HED specifications are summarized in the table below.

Parameter	***Requirement***
Energy range	8-80 keV
Efficiency	100 % at 30 keV >90 % at 80 keV
Dimensions	8 × 8 cm²
Pixel pitch	625 µm
Detector effective area	> 90 %
Timing accuracy Science Anticoïncidence	 50 µs 100 ns rms
Energy resolution	< 1.2 keV fwhm at 60 keV
Effective HED threshold	4 keV
Duration of observations	~10 ks

Table 1: High Energy Detector specifications.

1.3 Caliste concept

Imaging requirements leads to a high energy detector with 16384 pixels. Each pixel has its own readout channel. One of the main technological difficulties is to integrate the front-end electronics. The solution contemplated is to put side by side 64 independent cameras of 256 pixels, with their front-end electronics below their 1 cm^2 detector. Caliste prototypes are designed to match Simbol-X scientific requirements while taking into account this strong constraint of integration.

Front-end electronics is achieved by full-custom IDeF-X ASICs. The solution to integrate the ASICs below the detector is to put the chips perpendicularly to the detection plane to read out two rows of pixels each. All the Caliste cameras are based on this principle of hybridization. The first Caliste 64 prototypes are resulting from a collaborative work between CEA/Irfu and 3D Plus company. Caliste 64 is equipped with four 16-channel ASICs to read out independently 64 pixels. The ASICs are mounted on mini printed circuits boards. The four PCBs are stacked and molded in an epoxy resin, according to 3D Plus technology [5]. The last step is the mounting of the detector on the top of the electronic block. The whole camera fits in a 1 × 1 × 2 cm^3 volume and is juxtaposable on its four sides. The whole fabrication respects space standards.

2. CALISTE 64 SUB-ASSEMBLIES

Caliste 64 is the hybridization of a 64-pixel Cd(Zn)Te detector with its front-end electronics. Detectors on one hand and ASICs on the other hand have been deeply studied before fabricating the camera.

2.1 Cd(Zn)Te detectors

Crystals for Caliste 64 are Cd(Zn)Te matrixes of 8 × 8 pixels of 900 µm side. Gap between pixels is 100 µm. The 64 pixels are surrounded by a 900 µm guard ring. Thickness is typically 1 or 2 mm.

CdTe and CdZnTe are very resistive semiconductors (10^9 to 10^{10} Ω.cm at room temperature). Their low dark currents enable to have low electronic noise and, as a consequence, potentially good spectroscopic performances. Samples from different families of detectors were mounted on substrates; current measurements in each pixel as well as spectroscopic measurements were realized at different temperatures with two dedicated test-benches [6]. Two kinds of detectors were identified as good spectrometers and possible candidates to cover the HED focal plane of Simbol-X:

- 2 mm-thick CdZnTe detectors processed by Bruker Baltic (Latvia) from raw material produced by eV-products (USA),
- 1 or 2 mm thick CdTe detectors with Al-Ti-Au anode from Acrorad (Japan).

Both kinds of detectors demonstrate extremely low dark current level of ~1pA per pixel when cooled down to −35°C and biased under −400V. This enables high spectroscopic performances.

First, we chose to mount CdTe detectors on Caliste 64 cameras because we got the best performances and highest uniformity [7, 8, 9 and 10]. However a couple of Caliste 64 has been also equipped with CdZnTe detectors and show good performances. In this paper, we illustrate the results obtained on Caliste 64 prototypes equipped with these two kinds of detectors.

2.2 Front-end electronics

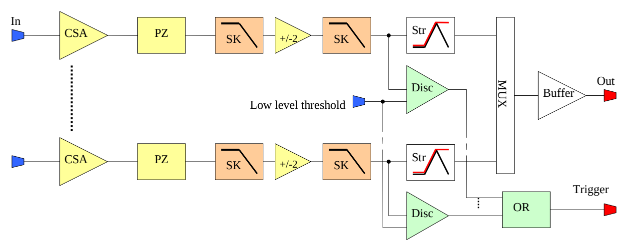

Figure 1: Schematic of the IDeF-X 1.1 circuit.

The front-end electronics use full-custom ASICs named IDeF-X 1.1. Each analog channel includes a charge sensitive preamplifier (CSA) with a continuous reset system, a pole zero cancellation system (PZ) and a variable peaking time fourth order Sallen & Key type shaping filter (SK). After the filters, the signal is a pulse whose amplitude is proportional to the incident charge. A stretcher realized with a peak detector plus a storage capacitor stores the amplitude, whereas a discriminator raises a trigger signal when the output is above the low-level threshold. Each stretcher is connected to the output buffer through an analog multiplexer, such as the channel outputs are read one by one. Each discriminator output contributes to the trigger signal output through a 16 inputs logical OR circuit, so as a trigger signal be sent outside the circuit as soon as at least a channel reaches the threshold value. The low-level threshold is adjustable and common to all channels. A schematic view of the circuit is illustrated in Figure 1. Noise can be as low as 35 electrons rms with neither capacitance load nor detector current at the channel input. Power dissipation is 2.8 mW / channel. Moreover, the circuit is radiation hard up to 1 MRad, and so, it is compatible with space applications [11].

IDeF-X 1.1 is a 16-channel readout chip. As a consequence, 4 ASICs are integrated in the hybrid component to read out the 64 pixels individually. To connect each channel to a pixel, ASICs are first stacked in a $10 \times 10 \times 18$ mm^3 block, perpendicularly to the detection surface. The top of this block is then prepared by laser ablation to get an 8×8 pixel pattern. The 16 pads of each ASIC are connected to 2 rows of 8 pixels.

3. ELECTRONIC PERFORMANCE

3.1 Set-up

Caliste 64 design was first validated without detector (see Figure 2). Charges generated by the interaction of a photon in the detector are simulated by a voltage step through a capacitance of 200 fF integrated in each channel. Since electronic performance depends on the dark current level of the detector, the device includes a tunable current source to produce leakage current at the input of each analog channel.

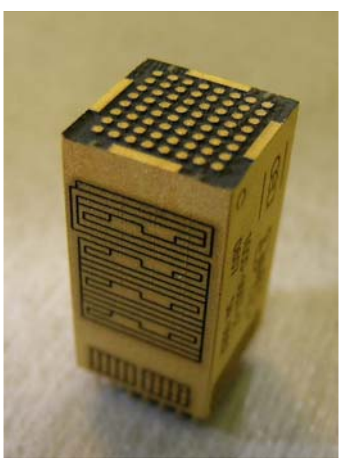

Figure 2: Electronic body of Caliste 64. Four ASICs are stacked inside a module and connected to the 8×8 pixel interface.

The acquisition is controlled by a printed circuit board with a FPGA. The readout sequence mode can be chosen (full-frame, hit pixels or hit pixels plus their neighbors), as well as the peaking time, the low-level thresholds, the frequency and the levels of the injections. The Caliste 64 sample, the FPGA and the computer communicate according a Spacewire protocol. For each event, the trigger time is recorded, as well as the pixel number and the amplitude of the differential output signal. That enables to perform imaging and spectroscopy with time tagging. The timing performances are described in details in ref. [13].

3.2 Electronic noise without detector

Noise performance is studied at different peaking times to know the minimum achievable noise and the associated optimal peaking time. For the shortest peaking times, the noise is dominated by the thermal noise of the preamplifier input MOSFET and increases linearly with the total capacitance connected at the channel input. The noise level for longer peaking times mainly depends on the dark current of the detector [12]. For a pixel current of about 7 pA, the minimum noise is ~65 e- rms for a peaking time value of 7.2 µs. This current level is typically what is expected with the Schottky CdTe detectors at -10°C. This noise level allows expecting spectral resolution of 816 eV fwhm at 60 keV assuming a Fano factor of 0.14.

The validation of electronics of a Caliste 64 sample consists in measuring gain and noise for different peaking times at room temperature to check that each of the 64 pixels have nominal performance.

3.3 Spectroscopy

3.3.1 Operations

After the electronic part of the Caliste 64 camera has been tested and validated, a 64-pixel detector is mounted on the top of the device (Figure 3).

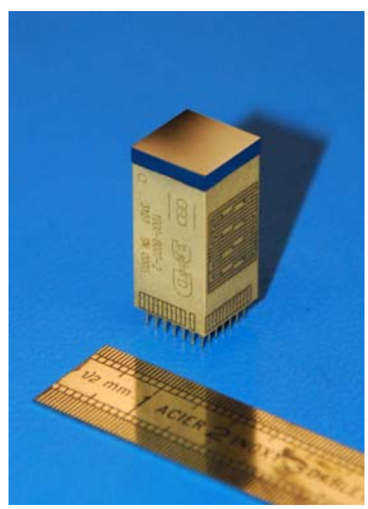

Figure 3: Caliste 64 complete camera. Prototype equipped with a 2mm-thick Schottky CdTe detector. The device fits in a $1 \times 1 \times 2$ cm^3 volume.

A 100 µm gold wire is installed on the planar cathode to provide the high voltage supply (Figure 4). The camera is placed in a thermal enclosure with a ^{241}Am source to perform spectroscopic tests at different temperatures. The set-up is exactly the same as the one for electronic characterization. Until now, the minimum achievable temperature is –15°C at the detector level.

Four complete cameras were tested. Three were equipped with 1 and 2 mm-thick CdTe Schottky detectors from Acrorad and one was equipped with a 2mm thick CdZnTe from Bruker Baltic. All of them have 64 pixels with good spectroscopic quality illustrated hereafter.

3.3.2 Spectral response

For a Caliste 64 sample, each pixel is precisely calibrated to obtain spectra with one ADC channel per 10 eV. Individual spectral response is derived and spectral resolutions are computed. Once calibrated, the sum spectra are generated from the data by summing the 64 individual spectra, channel by channel. Sometimes, one or two pixels are excluded from the sum because they show a bit too much dark current. Consequently, their spectra are out of global statistics. By cooling down to –30°C or lower, we should improve uniformity and include all the pixels in the sum.

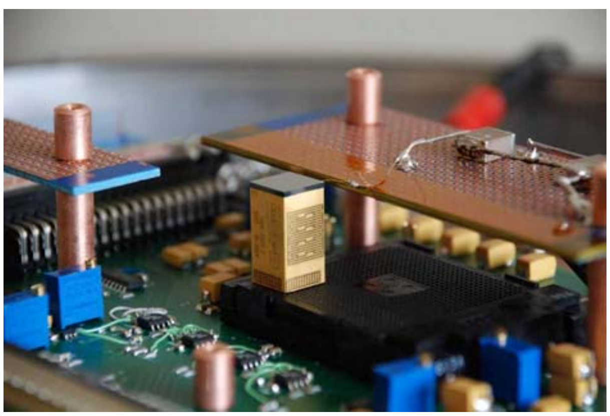

Figure 4: Integration in the thermal enclosure of a Caliste 64 prototype connected to the high voltage by a 100 µm gold wire and plugged into its test board.

Figure 5 and table 2 illustrates the spectral performances obtained with our four Caliste 64 prototypes. All the measurements reported here have been obtained at a temperature of approximately -10°C. The detectors are illuminated with an Am^{241} radioactive source. The spectral performances are resulting from the fit of characteristic lines.

Generally speaking, the performances look very similar from one sample to the other. However, looking at the spectra in further details, one can conclude the best performance is achieved with Caliste 64 equipped with 1 mm thick CdTe Schottky. In the case of CdTe crystals, the 60 keV line is almost symmetrical indicating that charge collection is complete while the asymmetry of the line with CdZnTe detectors indicates a small charge loss. In any case, all samples show performances compatible with the Simbol-X spectral response requirements of 1.2 keV fwhm.

	SN 3	***SN4***	***SN5***	***SN11***
Detector	CdTe	CdTe	CdTe	CdZnTe
Electrode	Al/Ti/Au	Al/Ti/Au	Al/Ti/Au	Au
Thickness	1 mm	1 mm	2 mm	2 mm
Active channels	63/64	64/64	62/64	64/64
Optimal peaking time	6 µs	9.6 µs	4.8 µs	7.2 µs
Bias Voltage	-400 V	-500 V	-800 V	-1000 V
ΔE @14 keV	694 eV	664 eV	735 eV	841 eV
ΔE @60 keV	851 eV	841 eV	905 eV	1177 eV

Table 2: Spectral performances of Caliste 64.

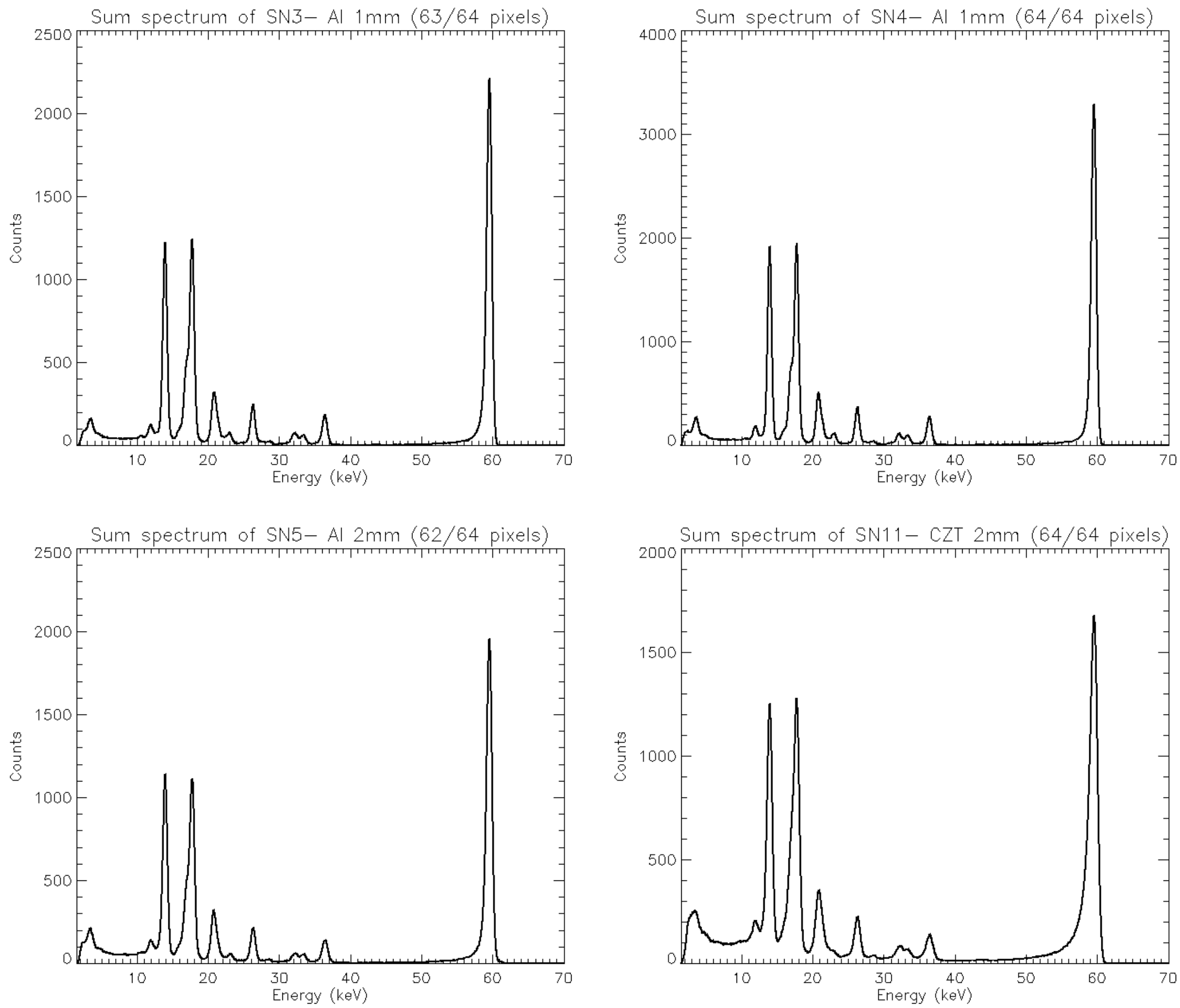

Figure 5: Best sum spectra obtained with the four first Caliste 64 samples. All spectra are sum of all pixel response at -10°C. Top Left: SN3 / 1 mm thick CdTe Schottky – Top Right: SN4 / 1 mm thick CdTe Schottky – Bottom Left: SN5 / 2 mm thick CdTe Schottky– Bottom Right: SN11 / 2 mm thick CdZnTe.

3.3.3 Split events

Caliste 64 enables to perform spectroscopy with time resolution. As a consequence, split events can be easily studied by selecting events in coincidence between neighbor pixels. Split events occur in case of charge sharing when a photon interacts in-between pixels and induces signals on several electrodes, or when the first interaction in a pixel with a Cd or a Te atom produces an X-ray fluorescence photon that escapes in the neighbor pixel. Figure 6 shows the correlation between the energies of any couple of pixels that triggered at the same time. The strong linear correlations indicate that there is very little charge loss, even when the photon interacts in the pixel gap. Consequently, double events may be combined to extract the impinging photon energy. Comparing the correlations between CdTe and CdZnTe detectors, one can conclude that residual charge loss is affecting the double event spectral response for CdZnTe. This is visible as the correlation plot is slightly bended and enlarged toward low energies.

The sum of the energies recorded in any couple of pixels that trigger simultaneously gives singular constants corresponding to the Americium lines. Computing the total energy, we derive the spectral response in case of split events (Figure 7). Here, it becomes obvious that the charge loss between two pixels affects severely the CdZnTe double pixel events spectral response while the performances are near to theoretical values for CdTe sample, assuming that the reconstructed spectrum is only limited by the combined noise of two independent readout channels, i.e., $\Delta E^{double} \approx \sqrt{2}\,\Delta E^{single}$. As a matter of fact, according to the 1177 eV fwhm spectral resolution for the CdZnTe sample, one should find 1.67 keV fwhm on the double event spectrum while we find 2.87 keV fwhm at 59.54 keV. On the other hand, the expected value for the CdTe sample is 1.28 keV fwhm at 59.54 keV while we find 1.38 keV fwhm.

Doing the same computation on thinner detectors (1 mm thick CdTe Schottky), the charge loss is even lower. In this case we find a double event spectral response of 1.23 keV fwhm at 59.54 keV, while the expected value of 1.2 keV fwhm. Note that, in this case, the energy resolution requirements for Simbol-X are achieved on double hits.

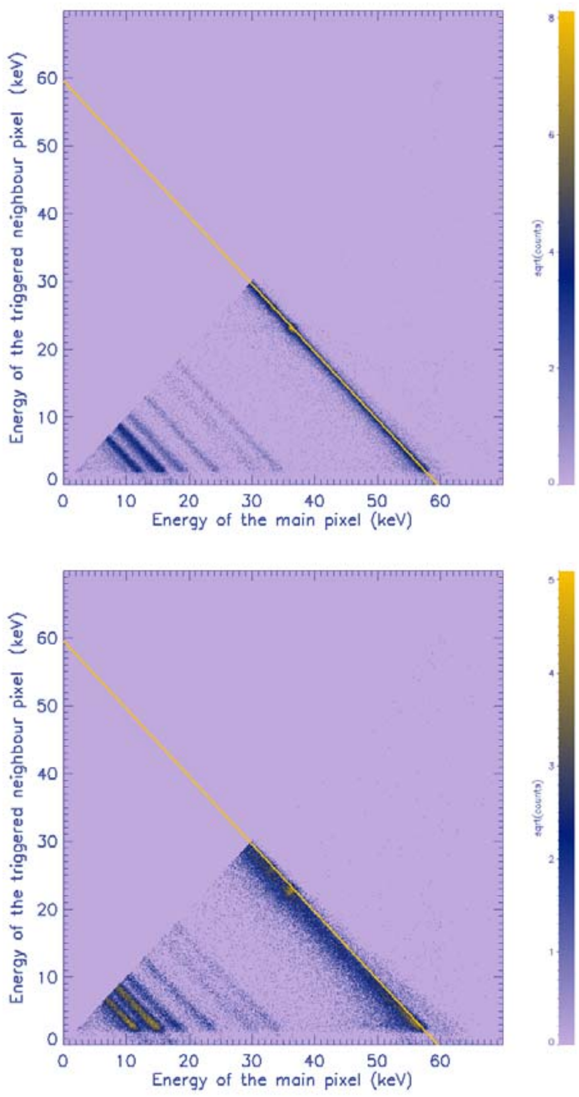

Figure 6: Correlation graphs of the energies of any couple of pixels that trigger at the same time. The energy is calibrated for each pixel from its single events spectrum. Top – Correlation graph for a 2mm thick CdTe Schottky detector. Bottom – Correlation graph for a 2 mm thick CdZnTe detector.

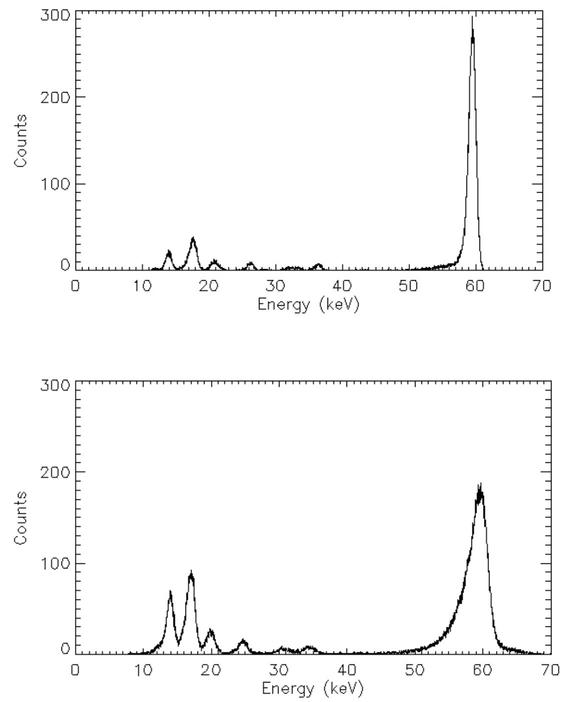

Figure 7: Spectrum built with only the split events between two pixels, at -10°C. Top – Split events spectrum in a 2 mm thick CdTe Schottky detector (Energy resolution is 1.38 keV fwhm at 60 keV). Bottom – Split events spectrum in a 2 mm thick CdZnTe detector (Energy resolution is 2.87 keV fwhm at 60 keV)

4. CONCLUSION

Caliste 64 is the new spectro-imager designed for space applications, in particular for large hard X-ray focal planes. Its high performance meets Simbol-X requirements in terms of spectroscopy and time-tagging accuracy. Spectral resolution is already excellent at -10°C, ~0.85 keV fwhm at 59.54 keV in case of 1 mm thick CdTe Schottky detector. CdZnTe detector gave also satisfactory results with ~1.17 keV fwhm at 59.54 keV, close to the CdTe performance except for double events where the performance is affected by residual charge loss between neighbour pixels. Cooling down the detectors to -35°C will guarantee uniformity and energy resolution better than 1.2 keV fwhm at 60 keV over all the channels.

Next challenge is a new prototype with 256 pixels in the same volume as Caliste 64 to reach the spatial resolution of 625 µm needed for Simbol-X mission. The fabrication of this micro-camera called Caliste 256 is being studied by CEA/Irfu and 3D Plus.

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