THE BADG3R PROTOTYPE ON BOARD OF A STRATOSPHERIC BALLOON FLIGHT IN THE FRAMEWORK OF THE HEMERA PROGRAM

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ABSTRACT

New instruments for high energy astrophysics require detectors exploiting high dynamics, to cover a large energy band, and very high performance in terms of efficiency, spectroscopy, imaging and timing. In addition, the requirement to be suitable for a large class of satellites and different mission scenarios needs that these detectors have a high modularity and compactness.

In this perspective we had approved by ASI a project ("3D-CZT M*odule for spectroscopic imaging, timing and polarimetry in hard X-/soft γ-rays satellite mission - 3DCaTM"*). This project is dedicated to develop an innovative 3D spectro-imager for hard X- and soft γ-rays based on 3D-CZT drift trip sensor units and implementing an innovative digital readout of signals to obtain unprecedented performance with three-dimensional spatial resolution (<0.5 mm), fine spectroscopy (1% FWHM at 511 keV), and high response uniformity (few %'s) with a limited number of electronics channels.

In 2019 we proposed, in the framework of the H2020/ HEMERA program, a stratospheric balloon flight of a small prototype (BADG3R) derived from the detector described above. This flight, now approved and scheduled for September 2022 for a launch from the ESRANGE Space Center, will be very important to assess the reliability of some new technological solution we implemented in the 3D-CZT spectroscopic-imager module. Furthermore, this flight would verify the flexibility and reliability of the new digital approach in a noisy pseudo-space environment.

1. INTRODUCTION

For the development of next generation of hard X- and soft γ-rays astronomy space instruments, the main requirements can be identified in the followings: **(a)** a two–order of magnitude increase in sensitivity with fine angular resolution, in the energy band up to several hundreds of keV (600-700 keV) is required to solve several still open hot scientific issues; **(b)** polarimetry shall become a "standard" observational mode of cosmic sources in this energy regime to fully understand the emission mechanism of several sources classes. To fulfil these requirements two different observational approaches are possible, requiring two type of instruments: (i) high sensitivity narrow field instruments: e.g. telescopes implementing new high energy focussing techniques (such as broad-band Laue lenses) [1]; (ii) Wide field instrument able to observe simultaneously a large fraction of the sky [2].

The development of these high-energy telescopes, requires a step forward in the detectors technology. In particular: (a) high modularity and compactness to allow their use for a large variety of satellite class (from medium to micro/nano-satellite) in different mission scenarios (e.g. single or cluster type); (b) high operational dynamics and high performance in term of efficiency, spectroscopy, imaging and timing as well as polarimetric capability. This new generation of hard X/γ-rays detectors shall exploit high detection efficiency, (>80% at 500 keV), fine spectroscopy (1% FWHM at 511 keV), fine spatial resolution (<0.5 mm) in three dimension, good time resolution (<1 μs), and finally reliable scattering polarimetry capability simultaneously with spectroscopy, imaging and timing.

Detectors that could fulfil contemporarily all the above requirements can be realised using highly segmented CZT spectrometers units with fine three-dimensional spatial resolution, referred in the following as 3D CZT

sensor [3]. Such type of spectro-imager can allow further important advantages, such as operation at room temperature, good capabilities in the rejection of environmental and instrumental background, uniform response over the sensitive volume by means of signal compensation techniques, fine spectroscopy also for multiple events and high efficiency scattering polarimetry in high energy regime above 100 keV [4] .
Since about a decade, our group has been involved in the development of a high performance spectro-imager based on a particular configuration of 3D CZT sensor. In the following section, we report first, on the current development with a summary of achieved results and then we outline a small payload for a stratospheric balloon experiment devoted to test both the implemented technological solutions and achievable performance in a pseudo spatial environment.

2. THE 3D CZT SPECTRO-IMAGER

Our approach for the realisation of high performance 3D CZT sensors is mainly based on the following ideas: (a) Planar Transverse Field (PTF) irradiation configuration [5], (b) anode with a drift strip configuration [6], and (c) cathode segmented in strip orthogonally to the anode ones. Furthermore, we apply a new signals readout scheme that uses, together with signals from cathode and collecting anode strips, also the grouped drift strip induced signals.
The PTF configuration allows increasing the thickness (i.e. efficiency) for photon absorption up to 40 mm (today the standard is 20 mm). The adopted electrode configuration, together with the signal readout scheme, allow to obtain a high “virtual” segmentation of the sensor detection volume (e.g. 30000 voxels, for a spatial resolution of 0.4 mm in each direction) with few (25/30) electronics readout channels.
Tests performed at laboratory and at ESRF (Grenoble, France) demonstrated that a 3D sensor built using a 20×20×5 mm^3 CZT crystal, with the above-described electrode configuration and signal readout type, can achieve at the same time fine 3D imaging capability and fine spectroscopic performance [7].

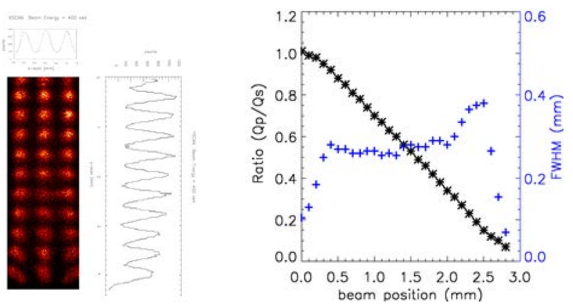

Figure 1. (left) spatial resolution in the photon impinging sensor surface; (right) the relation between the ratio of cathode (Qp) and anode signal (Qs) vs the beam position (black), the spatial resolution in the same direction (blue)

Fig. 1(left) shows the image of the collimated beam (0.05 mm in diameter) on the 3D CZT sensor surface where the beam itself impinges with the profile in the two orthogonal directions (*x* and *y*). As example, the spatial resolution achieved in these measurements at 400 keV in the three directions were respectively *x*=0.15 mm, *y*=0.26 mm, while across the cathode strip, *z*=0.65 mm. On Fig. 1(right) is shown the almost linear relation between the ratio of cathode and anode signal with respect to beam position across the two electrodes planes. This relation allows the reconstruction of the beam position along the charge collecting field direction, and thanks to this knowledge allows the compensation of the signals for trapping effect and therefore improves the spectroscopy.
The measurements confirmed that, together with the spatial resolution in three dimensions, this type of sensor exhibits excellent spectroscopic performance due to the signal compensation allowed by the reconstruction of the 3D interaction position.

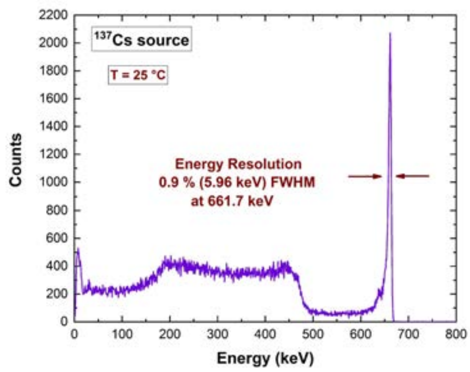

Figure 2. Measured spectroscopic performance of a 3D CZT sensor prototype after signal correction. The spectrum is obtained using all the event types.

As an example, Fig. 2 shows the spectrum obtained with an uncollimated 661.6 keV source after applying a new type of signal compensation [8].

2.1. CZT spectro-imager as scattering polarimeter

Segmented detectors are able to operate as scattering polarimeters, relying on the asymmetry exhibited by the Klein-Nishina Compton scattering cross section with respect to the azimuth angle. For such a type of measurement these detectors are quite efficient, because each pixel/voxel acts contemporary as scattering and detection element, and can perform at the same time spectroscopy, imaging and timing.
The quality of a scattering polarimetry response strongly depends on the detector segmentation level (i.e.

the 2/3D spatial resolution) and on their spectroscopic performance. As an example Fig. 3(left) represents the scattering map (i.e. the azimuth distribution of scattering angle for Compton events), and Fig. 3(right) shows the derived modulation curve obtained at ESRF (Grenoble, France) using a Caliste module [9] based on a 1 mm thick CdTe Schottky 16×16 pixels detector with fine pitch (0.625 mm).
The modulation curve (in blue) obtained by the right map exhibits a modulation factor Q=~0.78 that is very close to the value of 0.9 expected by the Klein-Nishina Compton scattering theory for linearly polarized photons (red). This performance is in fact equivalent to that achievable with a 3D CZT spectro-imager, selecting events which scatter at angles close to 90° (i.e. with the same z coordinate of the two hits) [10].
In perspective, 3D spectro-imagers will offer good polarimetric performance because of their improved scattering efficiency, due to higher thickness, and to the possibility to perform more event selection type, as well as to decrease background by means of Compton kinematics reconstruction.

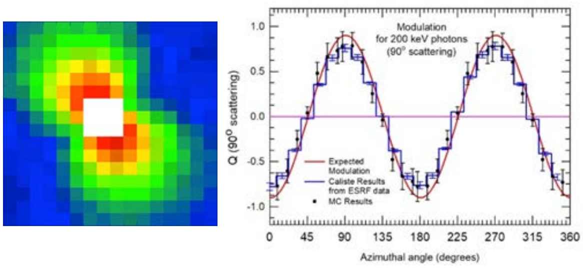

Figure 3. (left) Scattering maps at 200 keV and with the polarisation plane 30° inclined with respect to the detector axes measured with the Caliste module. (right) The modulation curve (blue) obtained from the left scattering map compared with the one from Compton scattering theory for polarised photons.

3. CURRENT DEVELOPMENTS

In the framework of a R&D project funded in 2018 by the Italian Space Agency (ASI) through INAF, our collaboration has developed a complete detection system based on a 3D CZT spectro-imager module with its own charge sensitive preamplifier (CSP) front end and readout by a multichannel digital systems based on high speed digitizers and FPGA.
The digital processing approach will guarantee a large flexibility of the detection system to different operative conditions. The detector characteristics can be tuned to the observational targets and space mission contest, without requiring a change in its hardware.
The 3D CZT spectro-imager module will be made of 4 3D CZT realised on single spectroscopic graded Redlen crystals of 19.6×19.6×6 mm^3.

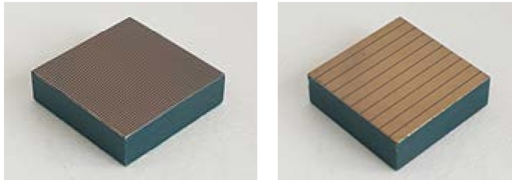

Figure 4. One of Redlen CZT used for 3D spectro-imager module; (left) anode side (48 stripes) and (right) cathode one (10 cathode stripes).

On one of the large crystal faces, the anode side, there are (Fig. 4 left) 48 strips with 0.15 mm gap (12 anode strips and 36 drift strips). These anode strips have 1.2 mm pitch. Between each anode strips, there are three drift strips. On the opposite crystal face, the cathode (Fig. 4 right), there are 10 strips with 2 mm pitch orthogonally oriented with respect to the anode ones.
The realisation of the 3D CZT drift-strip sensor units is extremely challenging for two reasons: a) the segmentation of cathode and anode requires a double patterning process on both sides of the CZT crystal; 2) the surface leakage current between the anode stripes must be drastically reduced by using special surface passivation techniques. After a delicate polishing of the CZT surfaces, a 100 nm gold film is deposited by wet-chemical electroless technique. The stripes on both cathode and anode are patterned using a standard photolithography process. Due to the small gap between strips in the anode side, it is mandatory to drastically reduce the surface leakage current in order to provide the correct sensor polarisation. We have implemented a passivation process that is an improved version of a technique developed for previous projects that rely on the deposition of a thin insulating film of Al_2O_3 between the strips. After this process, the average leakage current value is around 5.-6. nA, with a satisfying homogeneity over the whole anode surface.

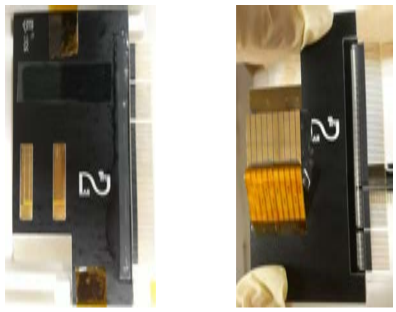

Figure 5. The 3D CZT unit mounted and bonded to the support interface with the AFEE board: (left) anode side; (right) cathode side.

The dark current between one anode stripe and cathodes increases linearly with potential and it is around 6-7 nA at 500V.
Each 3D CZT sensor will be bonded on a board that provides both the electrical and mechanical interface for

final module packaging and connection to the CSP front-end electronics. Fig. 5 shows the first prototype. The board consists of five superimposed layers of different materials (Roger, Kapton and FR4) rolled together. The 3D CZT sensor will be bonded to Au lines on Kapton film.

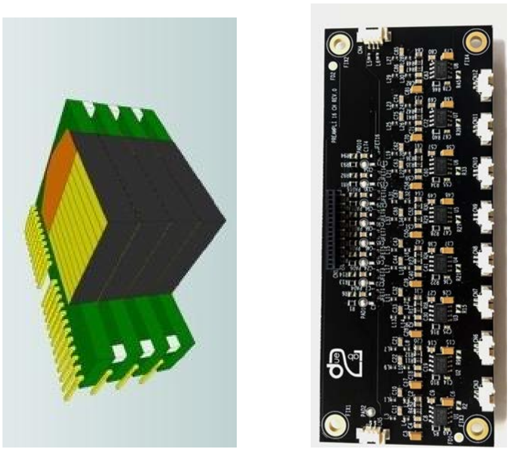

Figure 6. (left) The detector module: four CZT 3D sensors packaged together. The photon entrance window is the top black side; (right) the hybrid charge sensitive preamplifier board with 16 channels.

Four of these 3D CZT boards will be packed together to build an almost cubic detection module with a sensitive volume of about 8 cm^3 that will have the configuration shown in Fig. 6 (left). The detector module electrodes are analogically readout by seven 16 CSP hybrid boards (Fig. 6 right) for a total of 100 active channels (25 for each CZT sensor). The CSP boards implement a custom designed low noise and low power preamplifier circuit developed in the framework of the project. Each 16 CSP boards require 1.4 Watt from a single 5 V power supply. The 3D CZT sensors are biased with a HV between 150 and 500 V, that can be tuned to obtain the best performance.
The 100 pre-amplified signals are sent to the Digital Pulse Processing (DPP) system, which directly digitises and samples the detector output signals and processes them by means of custom algorithms implemented in its FPGA. Using this readout mode, the original information on the event that generated the signal is fully preserved. The DPP system, based on two pipelined shaping steps (a fast and a slow one), will allow an easy implementation of custom designed filters and procedures to handle detected events (Fig. 7).
This approach has already demonstrated its efficiency and reliability allowing it to achieve very high time (few ns) resolution even with quite intrinsically slow detectors such as CZT spectrometers [11].

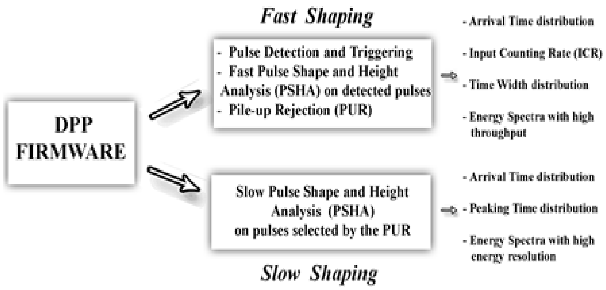

Figure 7. The main operations and output data of the DPP system under development.

Moreover, the DPP approach allows the easy implementation of: (i) bi-parametric techniques for signal compensation (e.g. shaping time/energy, fast/slow, cathode/anode signals ratio), (ii) sub-pixel spatial resolution techniques, and efficient techniques of charge sharing handling with coincidence time windows down to 10 ns (i.e. good for Compton event handling and polarimetry).
The DPP is based on two custom units of a device realised by the CAEN (Viareggio, Italy) company. Each unit is equipped with fast digitizers (125 MHz) and an open Xlinx FPGA able to handle 64 channels with a power consumption of 30 Watt.

4. THE BALLOON EXPERIMENT

A balloon flight opportunity for this detection system is very important to integrate the measurements obtained at ground facilities (like ESRF for photons, INFN/LNL for charged particles). In particular, to assess the reliability of some technological solution we implemented in the 3D CZT spectro-imager module, and furthermore to verify the flexibility and reliability of the digital approach in a pseudo space environment.
Based on the detection system developed, a payload configuration has been designed and proposed for a ZPB balloon flight in the H2020/HEMERA program. The proposal has been selected and the flight is now scheduled for September 2022 from the SSC/Esrange in Kiruna (Sweden) [12]. The launch site is at very high latitude (above the arctic polar circle), implying our detector system will operate in a rather “dirty” environment. In fact, this represents a good situation for us to perform several interesting tests and measurements.
First, a flight in this type of environment could allow the reliability verification of the 3D CZT sensors passivation, bonding, and packaging, as well as the custom CSP FEE designed electronics behaviour. Furthermore, by measuring the background spectrum, we can test our capability to use the digital readout approach to both discriminate different types of charged particles from the signals features and to reconstruct the unknown angular distribution of incoming photons by

using the Compton kinematics and the 3D spatial sensitivity of the detector.
Finally, a balloon experiment will allow assessing the flexibility of the readout digital approach to change the observational mode of the detection system during the flight, uploading different filters and event handling logic in the firmware of the FPGA on-board to the DPP system, or even simply by changing filter and logic setting parameters.
To simplify the payload without losing the significance of the achievable measurements we decide to use only one 3D CZT detector unit to limit the number of redouts channels. The balloon payload (BADG3R: BAlloon Detector for Gamma ray with 3 dimensional Resolution) is constituted by two main subsystems: (i) the Detector Module made by the CZT sensors module plus its CSP Front End Electronics); (ii) the On Board Data Handling (OBDH) system made by the DPP units and the onboard computer, that provide the required real-time signal acquisition, coincidence and trigger logics; the on board storage, providing the mass memory for on-board data storage and the interface with the gondola TLM system; Beside this there is the power unit that provide the bias of all the payload subsystems using an our own external battery pack. The expected main resources, in terms of dimensions, weight and power budget, required by the payload subsystems are summarised in Table 1. The complete payload scheme is illustrated in Fig. 8.

Table 1. BADG3R Payload required resources

Subsystems	*Sizes (cm)*	*Weight (kg)*	*Power (W)*
Detector Module	25×21×9	4.0	2.0
OBDH system	41×31×15	18.0	30.0
Battery pack	31×26×12	7.0	
Totals	48×49×45 *footprint*	28.00	32

We foresee transmitting to ground only few scientific information (e.g. channel count rates and energy spectra) together with health HK's information and parameters, requiring a continuous telemetry downlink that can be evaluated in less than 1-1.5 kbits/s. All the scientific data will be stored on a SSD mass memory on board. Assuming a maximum rate of 100 counts/s over the entire volume in the operation range (10-1000 keV), the real-time acquisition by the DPP system will produce ~10 MB/s. Therefore, a 1 TB solid-state disk would store about 30 hours of data.

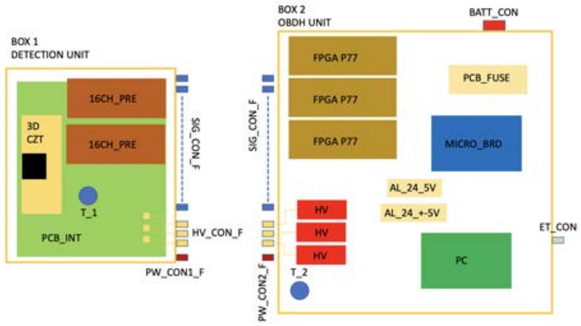

Figure 8. Payload scheme: (left) the Detector Module subsystem; (right) the OBDH subsystem

The scientific data are of two types: waveform snapshots and time stamp events. The waveforms snapshots are only recorded in the on board storage, while the timestamp event (spectroscopic mode) will be also transmitted to ground. The swap between the two scientific acquisitions modes will be controlled by telecommand from the ground station. Table 2 gives an overview of the required telemetry resources.

Table 2. BADG3R telemetry resources

Data Type	*Transmission Types*	*Expected Bit rate*
Housekeeping	Downlink/ Continuous	1.0 kbits/s
Science Data	Downlink/Burst periodically	10-50 kbits/s
Tele Commands	Uplink/Burst	1 kbits/s

5. PAYLOAD REALISATION STATUS

Currently we are working on the last stages of the payload systems realisation. After this phase, in July 2022 we will proceed to integrate all the systems and to perform extensive functional tests on the Detector Module operated by the OBDH. In Figure 9 are shown the Detector Module motherboard (top), and the OBDH inside its container.
Figure 10 (top) shows the open battery pack with the safety switch and fuse. The battery pack is composed of 160 1.5V AA cell units (Lithium/Iron Disulfide-Li/FeS2) supplying nominally 24V and guaranteeing about 16 hours of operation.
In the current configuration, the BADG3R subsystems will be finally implemented in a self-supporting mechanical structure that will provide an easy mechanical interface with balloon gondola (Figure 10, bottom).

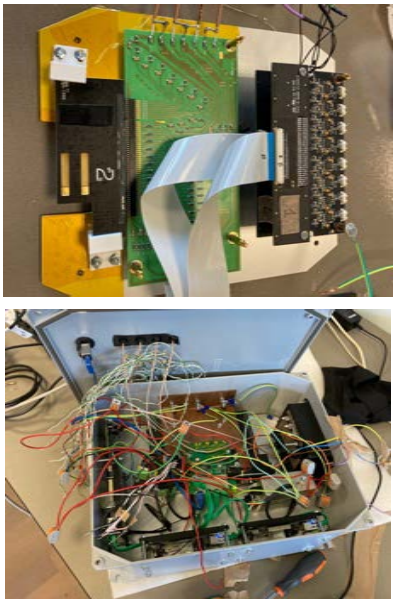

Figure 9. (top) The detector module motherboard: on the left the 3D CZT connected with the two 16 Channels hybrid board. (bottom) The OBDH system already assembled and cabled.

Figure 10. (top) An inside view of the open battery pack (bottom) The self sustaining structure helding dummy (empty) BADG3R subsystem container.

6. CONCLUSIONS

The possibility of performing a balloon experiment with the described detector prototype allows us to obtain important results and information otherwise impossible to obtain in ground laboratories.

We recognise that these kinds of experiments offer two main challenging opportunities: (a) Reliability verification in pseudo-spatial conditions of both advanced technological solution and instrument operations, essential for the implementation of new space missions; (b) Scientific values are always inherent, even in pure “technological” experiments like this. The stratospheric in-flight conditions allow us to obtain scientific information on detector performance in different observational conditions.

In particular due to the response dynamic of BADG3R, we foresee to make a measurement of the photons and particles background spectrum between several tens of keV up the one MeV at a stratospheric quote of 32-35 km.

Based on the results obtained from this flight we foresee to ask for, in the framework of a new HEMERA program, or to the ASI stratospheric balloon program, a more ambitious and longer flight using the complete prototype described above (4 detectors units and 100 electronic channels) to better explore the performance of the instrument in its full operative condition. This new flight could be considered a first step for the realisation of a pathfinder for a future high energy satellite mission equipped with a Laue lens telescope as the ASTENA concept proposed for the ESA Voyager 2050 program [13].

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UTILISATION OF BALLOONS FOR RESEARCH APPLICATIONS 1

WEDNESDAY 4 MAY 2022, MORNING SESSION – PART 1

ROOM 3

CHAIR: V. DUBOURG