The Development of the BADG3R Prototype for a Stratospheric Balloon flight in the framework of the HEMERA Program

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Challenges for a new generation of hard X- and soft γ-rays astronomy telescopes.

***Main drivers for next decades space instruments*.**

- At least a two–order of magnitude increase in sensitivity with fine angular resolution, with respect to current instrumentations, in the energy band up to several hundreds of keV (600-700 keV) is required to be able to solve several still open hot scientific issues.
- Polarimetry shall become a "standard" observational mode of cosmic ray sources in the hard X- and soft γ- rays regime to better understand the emission mechanism of several sources classes thanks to the addition of two new observational parameters (just for example to clarify between the polar cap, the outer gap and the caustic model for the high energy Crab emission)

Two different observational approaches:

- High sensitivity narrow field instruments: e.g. Telescopes implementing new high energy focussing techniques (such as broad-band Laue lenses).
- Wide field instrument able to observe a large fraction of the sky: e.g. Advanced Compton detector (ACT) are particularly challenging and promising.

Further challenging instruments requirements

- Instruments suitable for a large variety of satellite class (from medium to micro/nano-satellite) in different mission scenarios (e.g. single or cluster type): i.e. high modularity and compactness.
- Detectors exploiting high dynamics to cover a large energy band and high performance in term of efficiency, spectroscopy, imaging and timing as well as polarimetry **and operating at room temperature**.

The need of a new generation of high performance detectors 1/2

- High detection efficiency, achievable with increased thickness (>80% at 500 keV);
- Fine spectroscopy (1% FWHM at 511 keV) achievable with small volume charge collection;
- Fine spatial resolution (<0.5 mm) achievable with high segmentation.
- Fine timing resolution (<1 μs) for background reduction
- Scattering polarimetry in parallel to spectroscopy, imaging and timing

The detector that could fulfil contemporarily all the above requirements:

3D High Z spectro-imager

- Improvement of the efficiency (i.e. the sensitivity),
- Rejection of environmental and instrumental background, (small size)
- Uniform response over all the sensitive volume by means of signal compensation techniques,
- Fine spectroscopy also for multiple events (hit signals come from a small sensitive voxel)
- Possibility of scattering polarimetry in high energy astrophysics above 80/100 keV;

The need of a new generation of high performance detectors 2/2

Our approach for the realisation of 3D CZT sensors:

- Planar Transverse Field (PTF) irradiation configuration;
- Anode with a drift strip configuration;
- Cathode segmented in strip orthogonally to the anode ones; almost electron only device

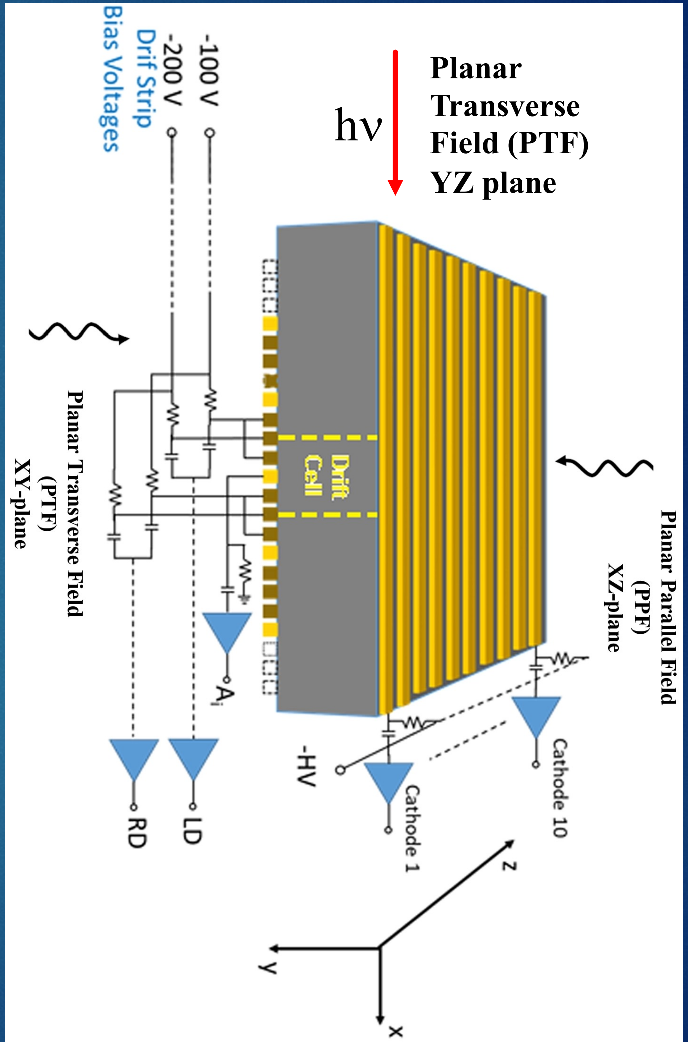
New signals readout scheme and handling system:

- For each 3D CZT unit, readout of collecting anode and cathode strips signal plus readout of grouped drift strip induced signal (low noise CSP);
- Digital pulse processing of readout signals.

PTF configuration allow to increase the thickness (i.e. efficiency) for photon absorption up to 40 mm (today is standard 20 mm);

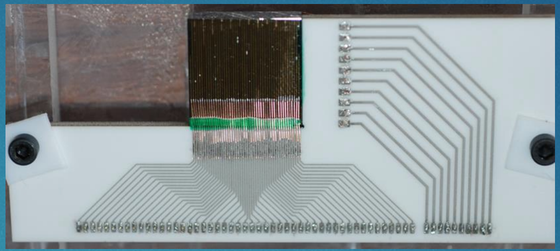
Few readout channels (25) to obtain high sensor segmentation (~30000 voxels, assuming ~0.4 mm spatial resolution in each direction).

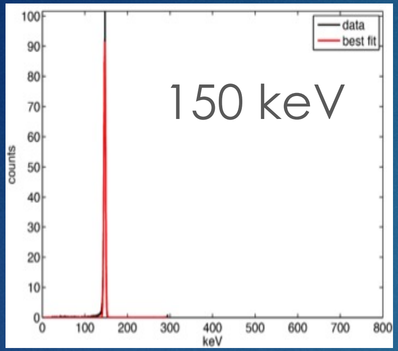
The digital processing approach will guarantee a large flexibility of the detection system to different operative condition. The detector performance can be tuned to the observational targets and space mission contest, without requiring change in its hardware.

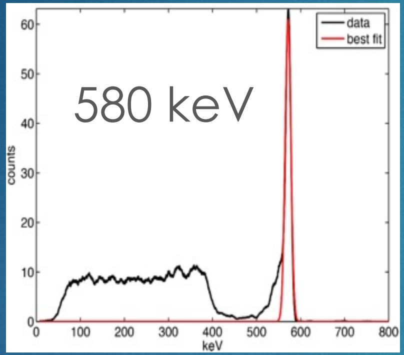


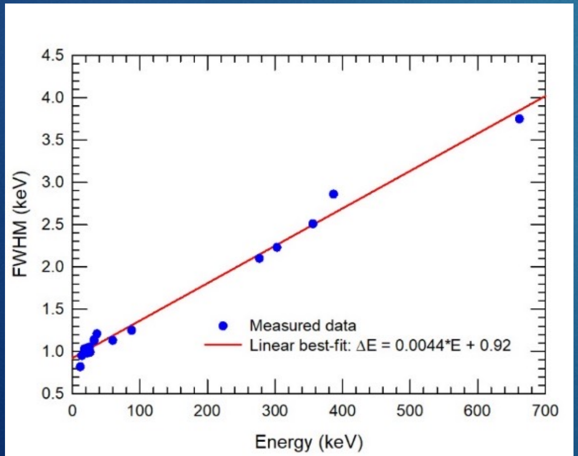
Development of 3D CZT spectro-imagers

Tests at laboratory and ESRF demonstrated that a 3D CZT sensor (20x20x5 mm^3) can achieve contemporarily fine energy resolution and 3D imaging capability.



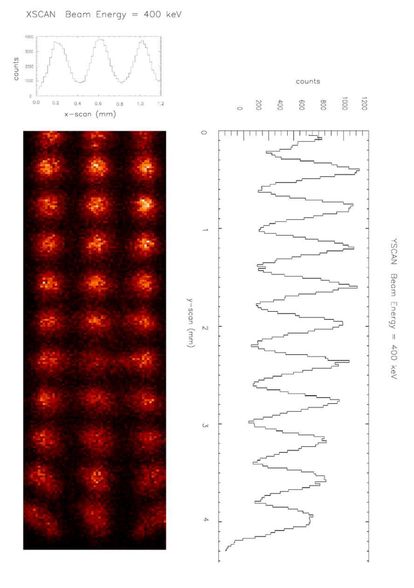


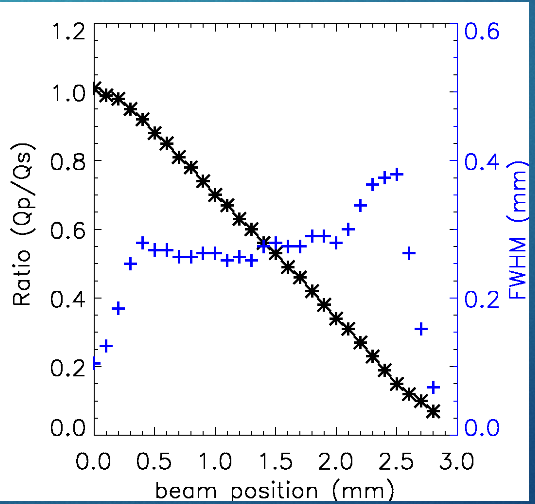




Measured spectroscopic performance:
(0.6 % at 661.6 keV) by a 3D sensor units in the 100 - 700 keV range using signals compensation technique allowed by the photon interaction 3D position knowledge.

3D spatial resolution: performances at 400 keV:
Δx = 0.15 mm,
Δy = 0.26 mm,
Δz = 0.65 mm



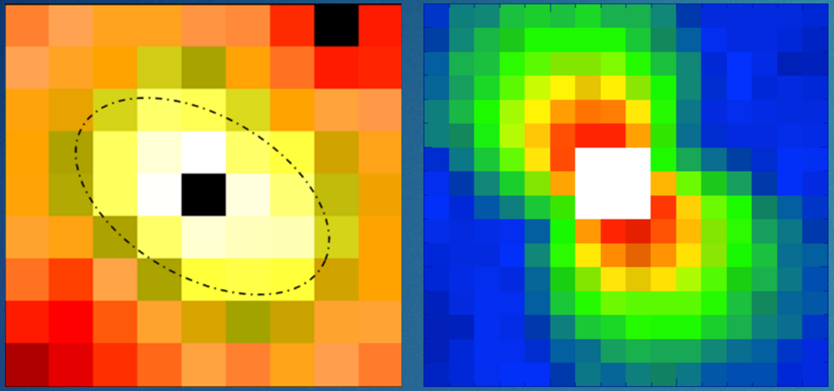


[black] The relation between the ratio of cathode (Qp) and anode signal (Qs) vs the beam position.
[blue] The spatial resolution in the same direction

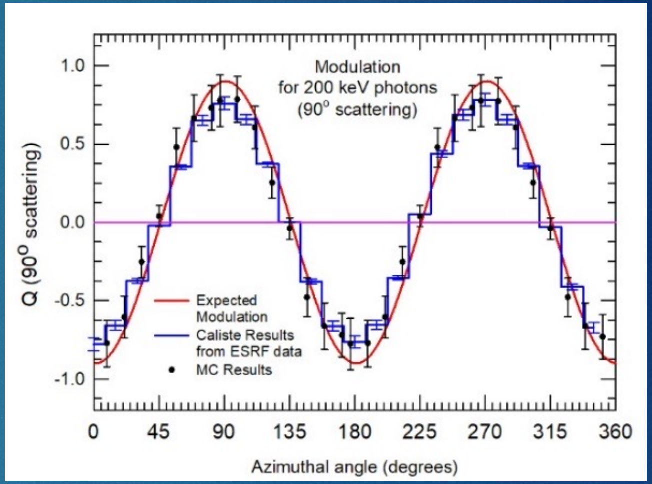
Development of 3D CZT spectro-imagers

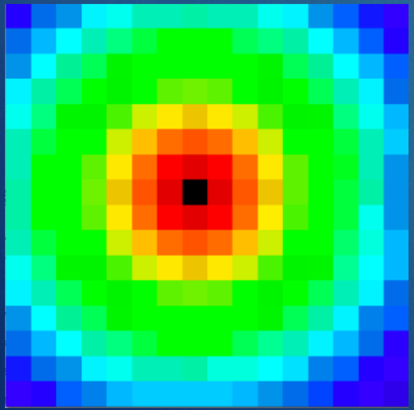
Segmented detectors are in principle able to operate as scattering polarimeter, relying on the asymmetry exhibited by the K-N Compton cross section with respect to the azimuth angle.

- The quality of the scattering polarimetry response strongly depend on the detector segmentation level (i.e. 2/3D spatial resolution) and on the spectroscopy performance



Scattering maps at 200 keV and with the polarisation plane 30° inclined with respect to the detector axes: (left) 2.5x2.5x5 mm^3 pixel detector; (right) 0.625x0.625x1 mm^3 pixel module.



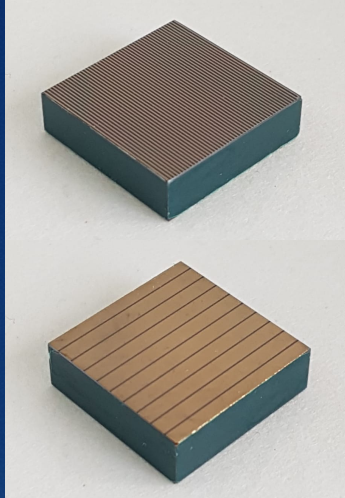


Scattering map for a un-polarized beam with the 0.625 x 0.625 x 1 mm^3 module

Scattering Polarimetry performance with both fine spatial resolution and spectroscopy.

The modulation curve (blue) obtained by the right map (Q=~0.78, very close to the expected values of 0.9 (red). This performance are equivalent to ones achievable with a 3D CZT spectro-imager, selecting events which scatter at large angles (close to 90°).

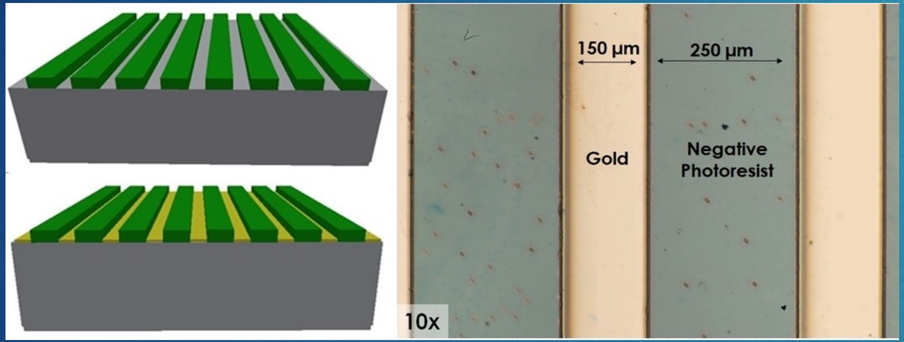
Development of 3D CZT spectro-imagers



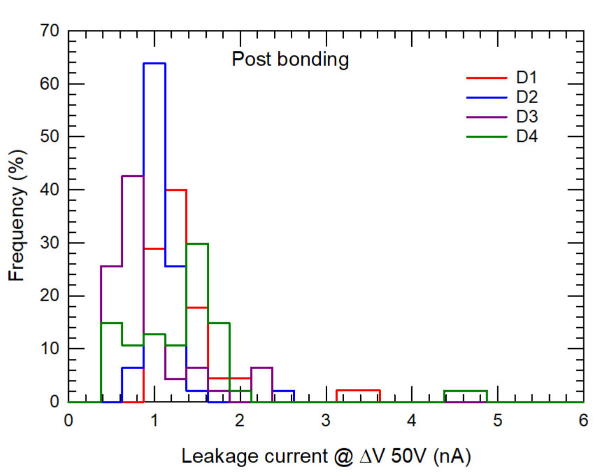
The 3D CZT unit:

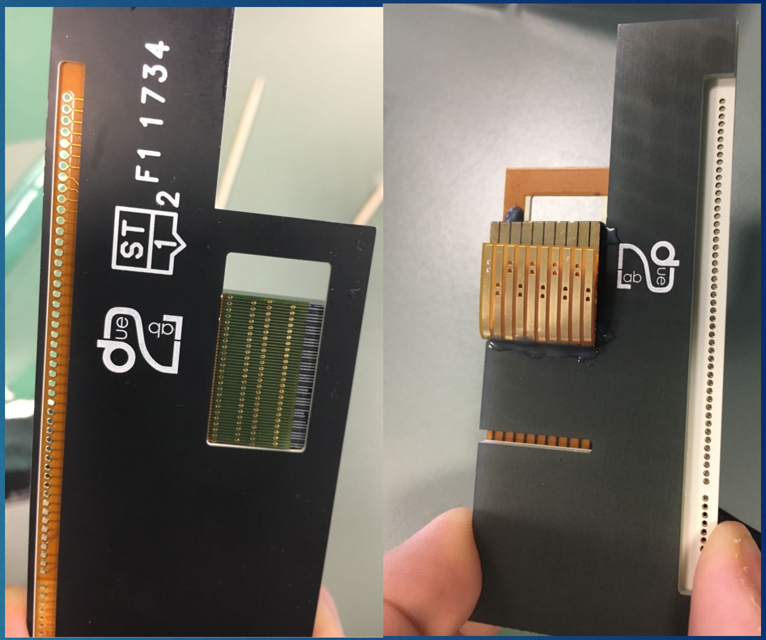
- Redlen spectroscopic graded CZT
- 19.6x19.6x6 mm^3
- Anode (top): 48 strips with 0.15 mm pitch (12 anode strips, 36 drift strip).

  The anode strips have 1.2 mm pitch. Between each anode strips there are 3 drift strips.
- Cathode(bottom): 10 strips with 2 mm pitch.



The new passivation require a 2 step process, with the deposition of negative photoresist on the anodic surface that is removed once the Au strip are deposited.

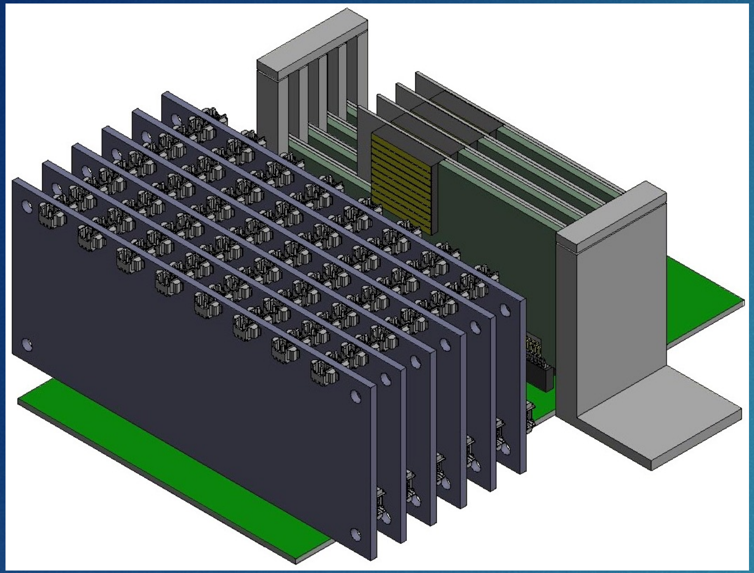




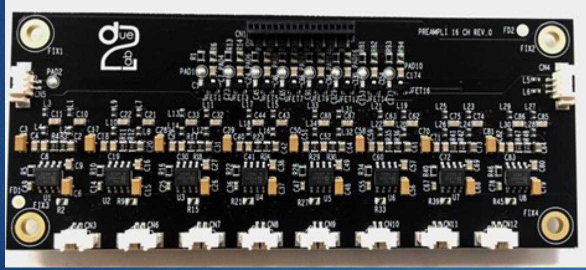
The 3D CZT unit mounted and bonded to the support I/F with the AFEE board. The I/F support is realized with 6 layers (FR4, Rogers, and Kapton). (left) anode side; (right) cathode side.

This technique allow a reduction of at least a **factor 10** with respect to other passivation techniques of the leakage currents (e.g. wet passivation, or Al_2O_3 layer)

Development of 3D CZT spectro-imagers



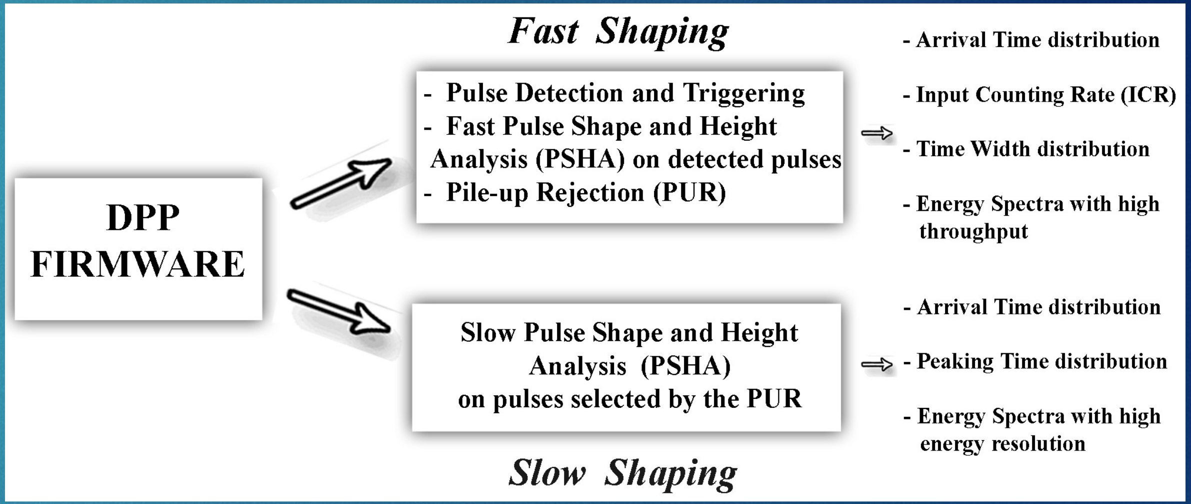
A possible configuration of the 3DCaTM detection module: the pack of the four 3D CZT sensors (at right) with the CSP front-electronics (six boards at left)



Charge Sensitive Preamplifier:
Hybrid design, 16 channels;
Bias: ± 5 V, Power: 1.4 Watt
Time constant: 250 µs,
Risetime: 0.2 µs
Gain: ~20

An innovative spectrometer readout approach: Digital Pulse Processing (DPP)

The detector output signals are directly sampled, digitized and processed with custom digital algorithms.
Original information on the event that generated the signal is preserved!



DPP will based on two units of new CAEN 2740 Digitizer family. This device will be equipped by fast digitizers (125 MHz, 16 bits ADC) and an open FPGA (Xlinx) system able to handle 64 channels with a power consumption of ~30 Watt.

Why a balloon experiment with the new 3D CZT spectro-imagers prototype ?

A balloon flight with a reduced version (only one detector module) of this detection system will be very important to integrate the information obtained at ground (facilities like: ESRF for photons, INFN/LNL for charge particles), to assess the reliability of some technological solution, and to verify the flexibility of the digital approach in a pseudo space environment. As the instrument is a quite sophisticated one these test are strongly suggested.

The available launch sites in the HEMERA project framework, are currently at very high latitude, implying operate our detector system in a quite "dirty" environment. In fact this represent a good situation to perform several interesting tests and measurements. Also a preliminary measurement of the charged particles background observed by a detector of this type is one of our goals.

- **Verification of the reliability** of the 3D CZT sensors **passivation, bonding, and packaging**, as well as of the custom CSP FEE designed electronics behaviour;
- **Measurements of background spectrum**, and using the digital approach **verify the capability of discriminating different type of particles** from the signals features.
- **Asses 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 logics in the firmware of the DPP system.

Overview the BADG3R prototype 1/3

In December 2019 we submit the BADG3R payload in the framework of the second call of the H2020/HEMERA program for a ZPB mission. The proposal was accepted for a flight in 2021. Due to the COVID-19 pandemic emergency the flight opportunity has been shifted to 2022.
The flight is currently scheduled for the begin of september 2022, from the SSC ESRANGE base in Kiruna (Sweden).

The BADG3R payload is constituted by two main subsystems:

1. **The detector module, made by one 3D CZT sensor unit and the 2 (16 ch) CSP analog front-end board;**
2. **The OBDH system operated by a dedicated computer which mainly manage three activities:**

- the data handling system (i.e. DPP), that provide the required real-time signal acquisition, coincidence and trigger logics;
- The data storage and TLM unit, providing the mass memory for on-board data storage and the interface with the gondola TLM system.
- Power unit, providing both the detector HV (150-500 V) and low bias for FEE, DPP, data storage and TLM unit.

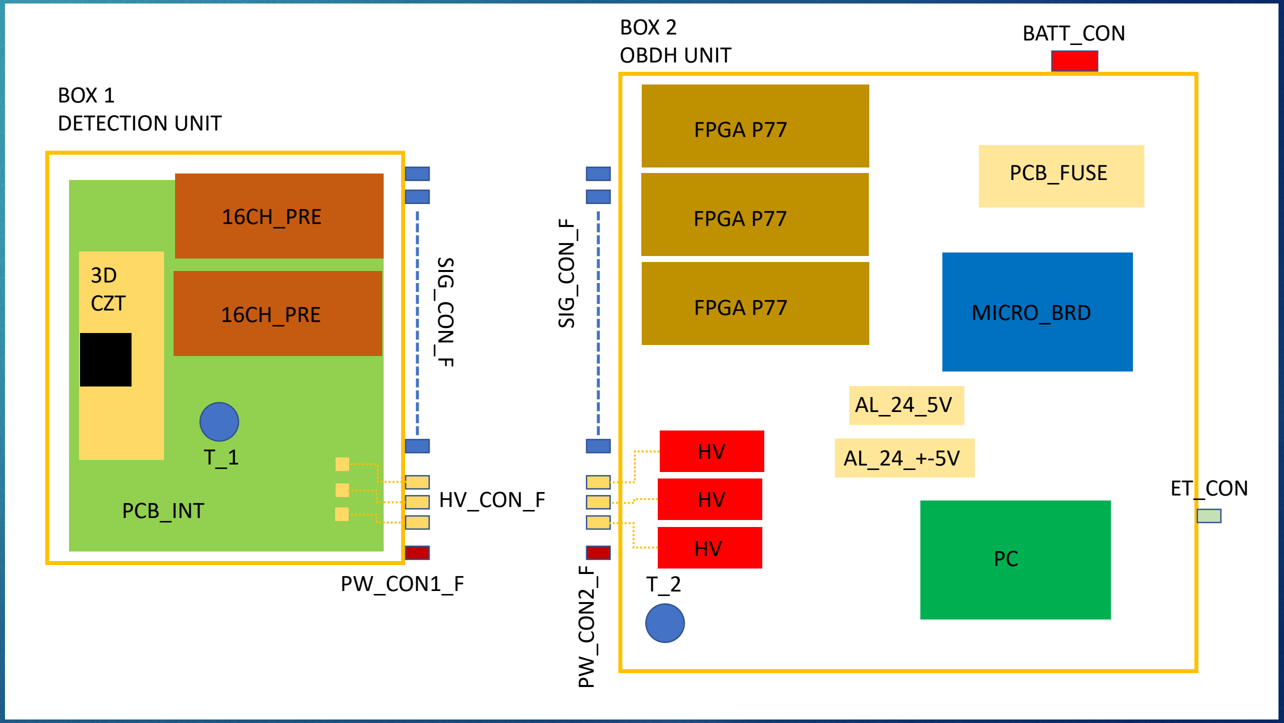
Overview the BADG3R prototype 2/3

The two main subsystems of the BADG3R payload are contained in two separate boxes mechanically linked together.

The detection system box will be placed on the top wall of the OBDH system box.

Between the two containers, made of aluminum, there are 24 cables for the output signals from the CSPs and the power cables (high and low voltages)

The OBDH is connected to the telemetry of the gondola via a LAN port, and receives the voltage from an external dedicated battery pack (24V or 12 V)



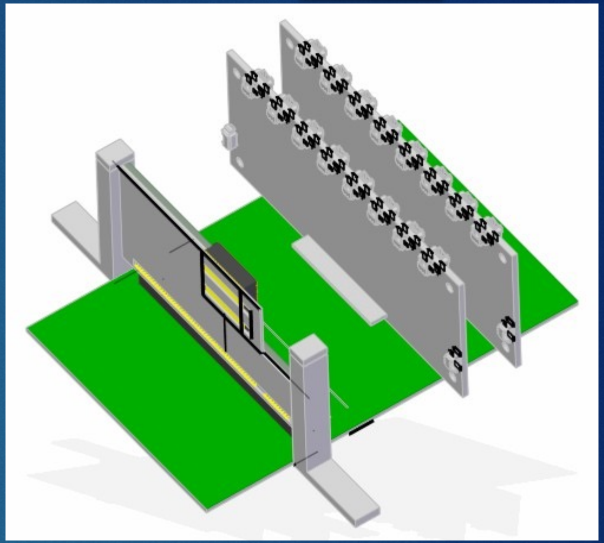
OBDH subsystems

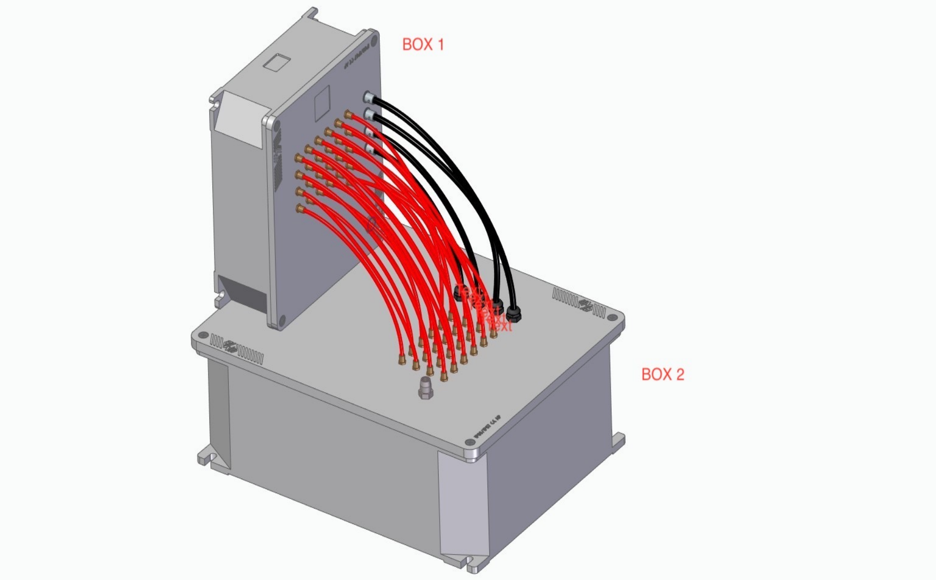
- 3 Digitzer/FPGA board: 8 ch, 100 MHz, 5W
- Microcontroller
- HV and LW distributor (by using DC-DC converters)
- Industrial board PC with SSD data storage: P1101, 10 W, 1.5 kg,
- On board data storage will be managed by a redundant system of two 1 TB SSD

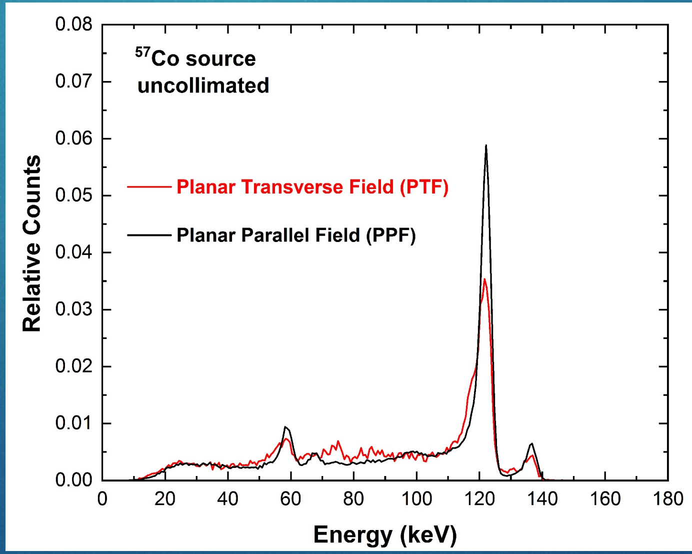
Overview of the BADG3R prototype 3/3

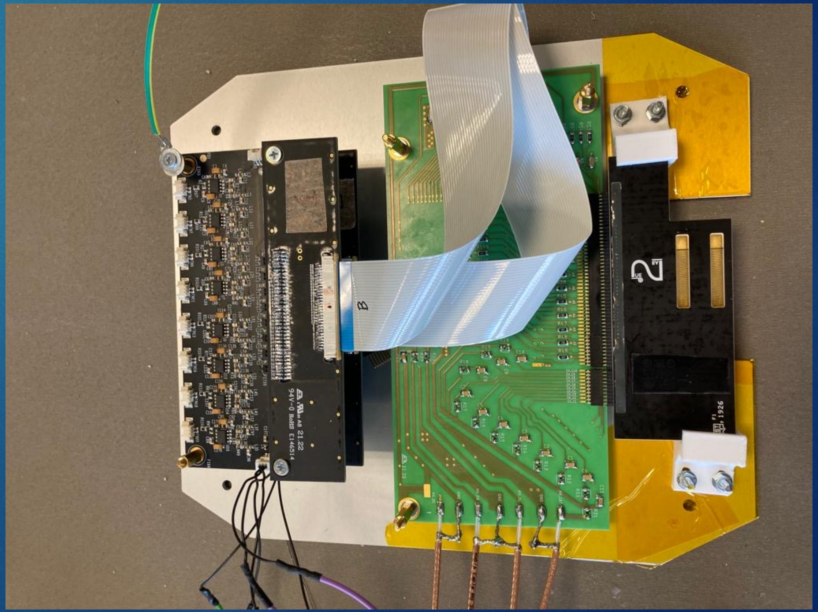
BADG3R detection system

- The detector module, made by one 3D CZT sensor and the two CSP Analog front-end board. The 3DCZT sensor selected for the payload is the **D4**
- Two small (5x5 cm^2, 2-3 mm thick) heavy metal plates (Pb and Ta) will be installed on the inner walls of the container and will be used as calibrators of the 3DCZT sensor through their fluorescence K-lines.
- Two small sensor prototype based on new organic semiconductors and perovskite, respectively, will be installed on the outer walls of the detection system container. Typically these sensor will be biased at 1 V, and will be connected to the on board PC by a USB link.









BADG3R prototype: Resources

Subsystem	Sizes (cm)	Weight (kg)	Power (W)
Detector Unit Box	20x30x20	5.0	3.0
OBDH Unit	40x40x20	10.0	30.0
Battery Pack	TBD	10.0 TBC	
TOTAL		25.00	33.0

- TLM Requirements are evaluated assuming a max rate of 1000 counts/s over the entire volume.
- Waweform snapshots mode produce 250 Mb raw. These data are stored only on board in a duplicated memory
- Scientific data will be downlinked only in spectroscopic mode (much more compact)

Data Type	*Trasmission Type*	*Expected Bit rate*
Housekeepings: Temperature Sensors, Bias (HV, low), FPGA/Digitizer status info's; Batteries charge status	Downlink/ Continuous	1 kbits/s
Science: Event in spectroscopic mode. i.e. [time, n. multiplicity, nx(energy, channels)] – Max 120 kb	Downlink/ Burst periodically	10-50 kbits/s
Telecommands: FPGA params, Bias, Science data downlink type, Safety TLC	Uplink/ Burst	1 kbits/s

BADG3R schedule and summary

Currently the BADG3R systems are under final integration. The detector crystal has been already qualified using radioactive sources.

In July 2022, the BADG3R payload will be carefully qualified using radioactive sources. An important outcome of this experiment will be a comparison of the performances of the detector after the flight in respect with the pre-flight calibration.

At the begin of August 2022, BADG3R and all relevant equipment's will be shipped to ESRANGE

The possibility of performing a balloon experiment with the developed detector prototype will allow us to obtain interesting results and technical information otherwise difficult to obtain in ground laboratories.

Moreover balloon experiments, due to the intrinsic prototypal nature of payloads and to their short development times, represent an excellent bench for the training of young researchers and technologists

In particular, we would highlight again that stratospheric balloon experiments represent an extremely important stage in research & development of new space instrumentations for high energy astronomy: balloon experiments as path-finder for satellite missions.

Future developments

- Based on the results of the BADG3R flight we foresee to ask, possibly in the framework of a new HEMERA call and with the support of ASI, for a more sophisticated and longer duration flight using the complete and improved version of the 3DCaTM Spectro-imager (4 detectors units, 100 ch) in a less ‘noisy’ environment (low latitude flight).
- Afterwards, on a longer time scale, we plan to realize a complete telescope (Laue Lens plus focal plane detector) to put on a dedicated flight capable of scientific observations of suitable sources. This experiment could be considered as a pathfinder for a high energy astrophysics mission like ASTENA

<< Thanks for your attention >>