3D-CZT Module for spectroscopic imaging, timing and polarimetry in hard X-/soft γ-rays satellite mission (3DCaTM).

E. CAROLI, INAF/IASF-BOLOGNA, SCIENTIFIC COORDINATOR

STUDIES FOR FUTURE SCIENTIFIC MISSIONS - PRESENTATION OF PROPOSALS

HEADQUARTERS OF THE ITALIAN SPACE AGENCY (ROMA, ITALY) - 17 NOV. 2017

Collaboration:

- **RU 1 - INAF/IASF-Bologna (Dr. Ezio Caroli)**
- **RU 2 - CNR/IMEM, Parma (Dr. Andrea Zappettini)**
- **RU 3 - DiFC/University of Palermo (Dr. Leonardo Abbene)**

- Participation of research personnel from DFST/University of Ferrara and INAF/IASF-Palermo as associated to RU 1.

- **Man power available to the project:** 10 Researchers for 48 man's months, 3 Technicians for 13 man's months.

Presentation outline

I. Scientific rationale and future mission requirements;
II. National and international scientific context, Technological heritage and status of the art;
III. Proposal objectives; Methods and Technical description;
IV. Conclusion: satellite mission perspective

Annex: Summary of deliverables of the project, temporal development schedule, financial request.

Scientific rationale and future mission requirements.

Science contest in hard X- and soft γ-rays astronomy

Hard X-/soft γ-ray astronomy is a crucial window for the study of the most energetic and violent events in the Universe as well demonstrated by past satellites (SAX, XTE), and still operating one's (INTEGRAL, Swift, NuSTAR).

In the range between 10 and tens of MeV, there are still several unanswered scientific key questions such as:

- The origin of the 511 keV annihilation line from the Galactic Center region
- The enigmatic shape of the high-energy spectra of AXPs and SGRs,
- The high-energy spectra of AGNs and their contribution to the high-energy Cosmic X-ray Background
- The physics and the origin of GRB’s, and their relevance in cosmology, and for gravitational waves electromagnetic counterparts.

Hard X- and soft γ- rays Astronomy: which is the future?

Main drivers for next decades space instruments.

- At least **a two–order of magnitude increase in sensitivity** and 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 fully understand the emission mechanism of several sources classes.

More general requirements

New space instruments shall be developed both for deep observations of point sources and for random transient events study and monitoring

Two different instrument approaches:

- High sensitivity narrow field instruments particular: 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 instruments requirements

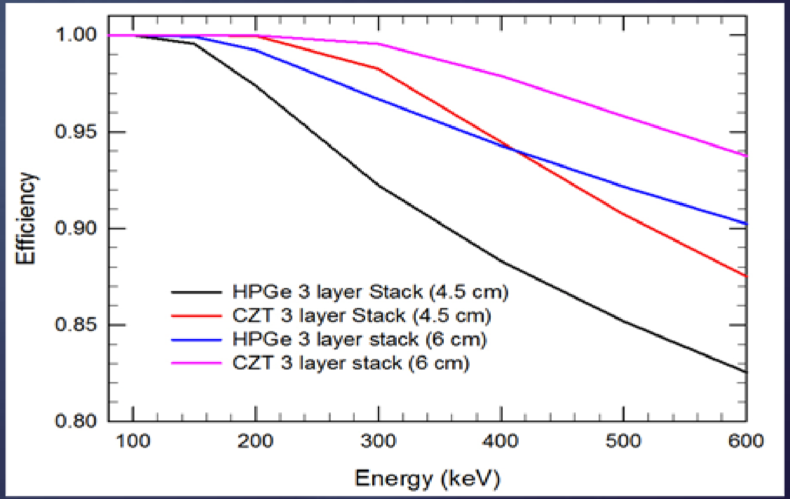
- Instruments suitable for a large variety of satellite class (from medium to micro/nano-satellite) in different mission scenarios (e.g. single or cluster type): i.e. high modularity and compactness.
- Detectors exploiting high dynamics to cover a large energy band and high performance in term of efficiency,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

New Detector Performance Requirements

- 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) (in particular for transient as GRB's)
- Scattering polarimetry in parallel to spectroscopy, imaging and timing

The detector that could fulfil contemporarily all the above requirements:

3D High Z spectro-imager

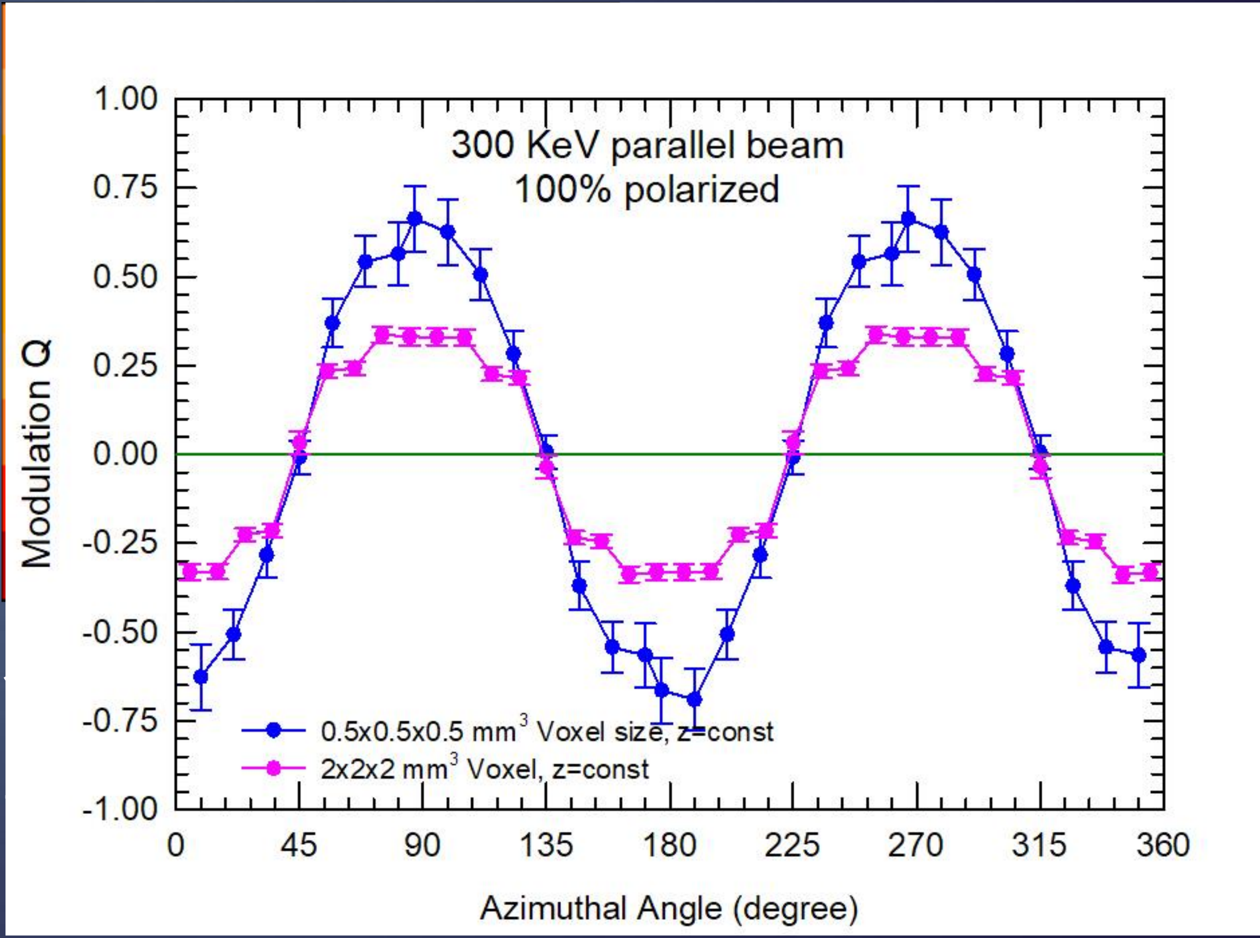


Why high spatial resolution is needed for high sensitive scattering polarimetry

POLCA experiments
4x4 cm^2, CZT 5 mm thick
11x11 pixels, 2.5 mm pitch

Caliste 256 experiment
16x16 pixels, 0.625 mm pitch
Schottky CdTe 1 mm thick/CZT 2 mm thick

LIP (Coimbra, Portugal) , CEA/Saclay (France), INAF/IASF-BO/PA (Italy)



3D Spectro-Imager Advantages

- **Improvement of the efficiency (i.e. the sensitivity)** using scattered events in addition to the photoelectric ones;
- **Rejection of environmental and instrumental background**, e.g. using Compton cinematic reconstruction;
- **Uniform response** over all the sensitive volume, achievable by means of signal compensation techniques;
- **Fine spectroscopy also for multiple events** because each hit signal come from a small sensitive volume (voxel)
- **Low degradation of the point spread function** of the flux focused by a Laue lens or similar optics with energy because of the possibility to identify the photon interaction points in scattered events.
- **High efficiency scattering polarimetry** in high energy astrophysics above 80/100 keV;

II

National and international scientific context, Technological heritage and status of the art.

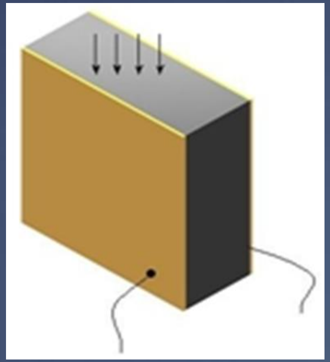
3D Spectro-Imager: on going worldwide developments

✓ Stack of several very thin detection position sensitive layers.
the vertical position is given by the address of the hit layer (Japan, USA)
Drawbacks: (a) complexity of electronics and mechanical assembling; (b) the presence of a lot of passive material between each layer (unwanted scattering);

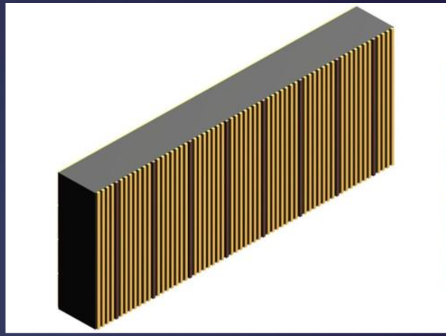
✓ Thick (10-20 mm) bulk CZT with pixelated electrodes:
the strong pixel effect allow the depth reconstruction of interaction– (USA).
Drawbacks: (a) high low energy threshold; (b) charge sharing strongly affect the spatial resolution at low energy

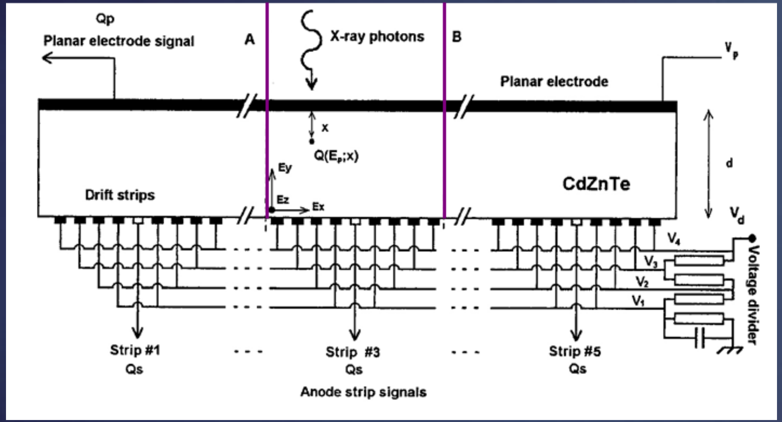
3D CZT Sensor Unit: the starting point (GRI ESA/M3 proposal framework)

PTF irradiation configuration: Decoupling between photon absorption thickness and charge collection distance

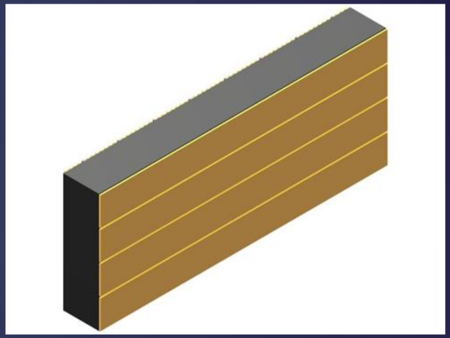


The Anode (top) side implement a drift strip configuration; The cathode segmented orthogonally (bottom)





The anode side electrodes are modified to make the detector more sensitive to electron collection and less sensitive to hole collection.



This configuration born as the result of an European collaboration between INAF/IASF (Italy), DTU-Space (Denmark), and CNR/IMM (Italy)

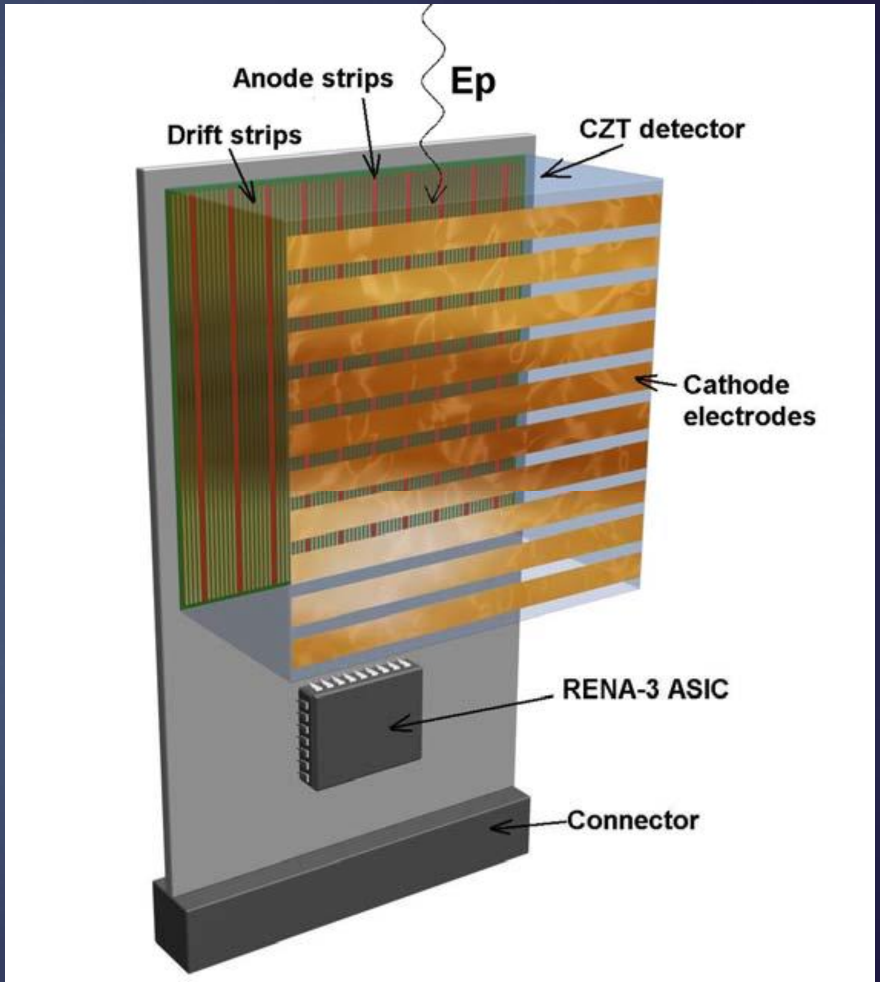
How this sensor type provide a 3D interaction position

Orthogonally segmented anode and cathode

2D position (X;Y)

Depth information can be derived from the ratio: R = Qp/Qs

3rd position (Z)



The Small Gamma-Ray Imager Prototype A first 3D CZT sensor implementation

The sensitive unit

CZT by Redlen

Dimension: 19×8×2.4 mm^3

Cathode:

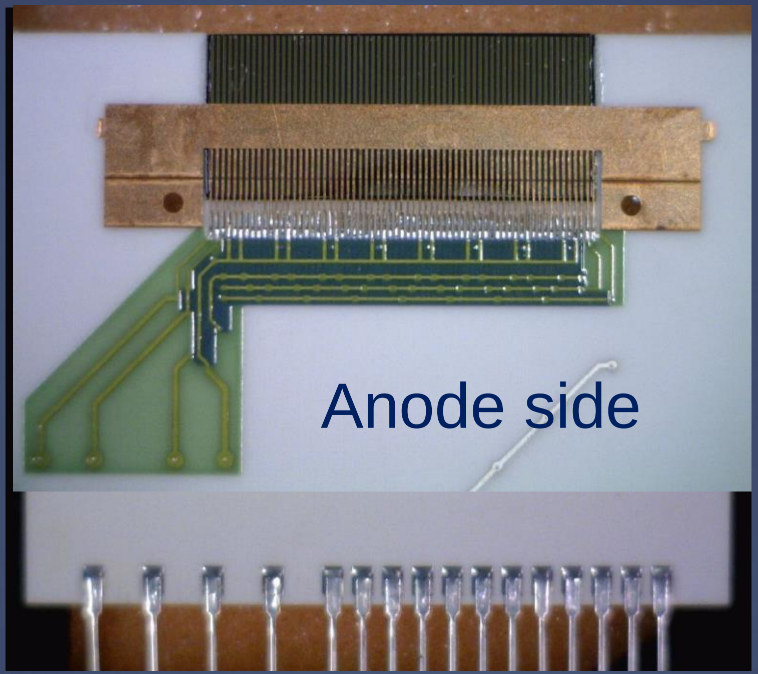
4 strips (2 mm pitch)

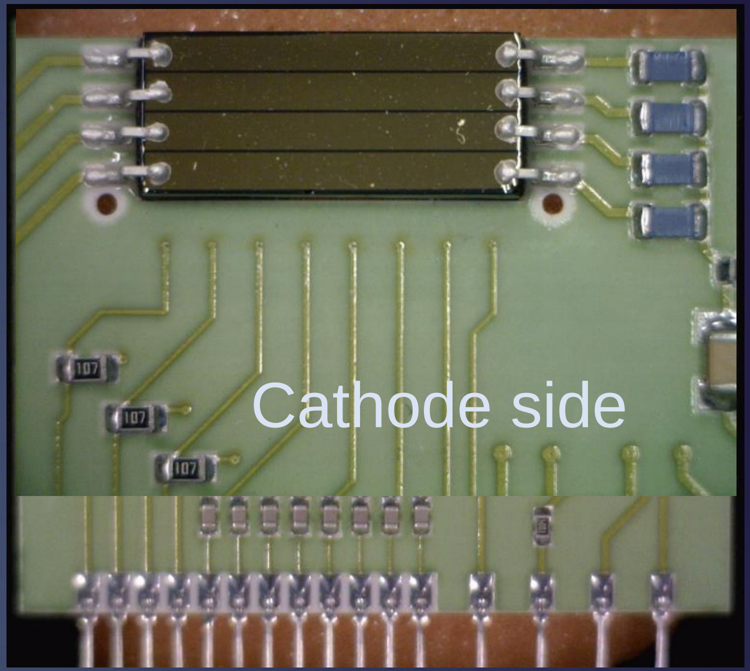
Anode:

8 collecting strips;

7 drift strips between each couple of collecting ones;

300 strips pitch (150 µm metallisation and gap).





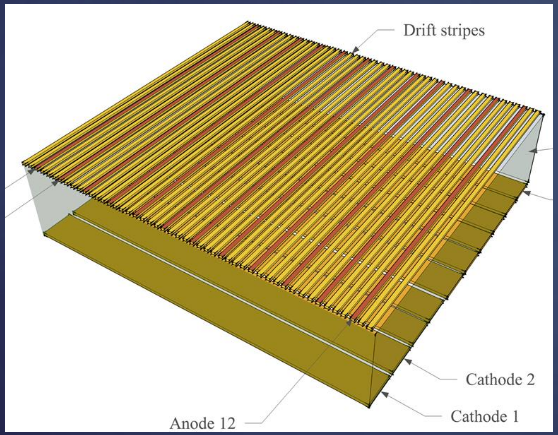
The bonding between the anode strips and the metallic pads on the alumina layer is realized by **a thin (50 µm) Cu comb** obtained by photo engraving technique. The Cu combs have the same fine µ-strips pattern with the metallic teeth 100 µm wide by AUREL SpA (Modigliana, Italy)

3D CZT sensor unit: the evolution

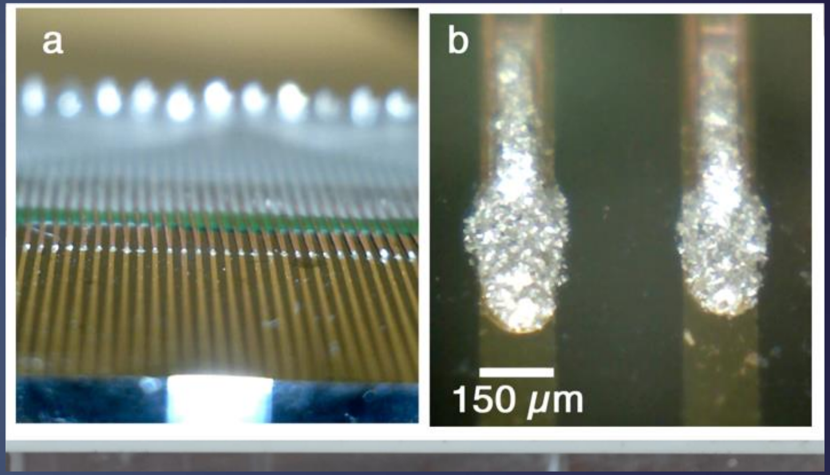
DTU-Space (Denmark) - ESA independent R&D development project
P.I.: DTU-Space, Denmark
"3D CZT High Resolution Detectors" Ref. 4000104191/11/NL/Cbi"

Sub-contractor: CNR/IMEM Parma

External partner: INAF/IASF-Bologna



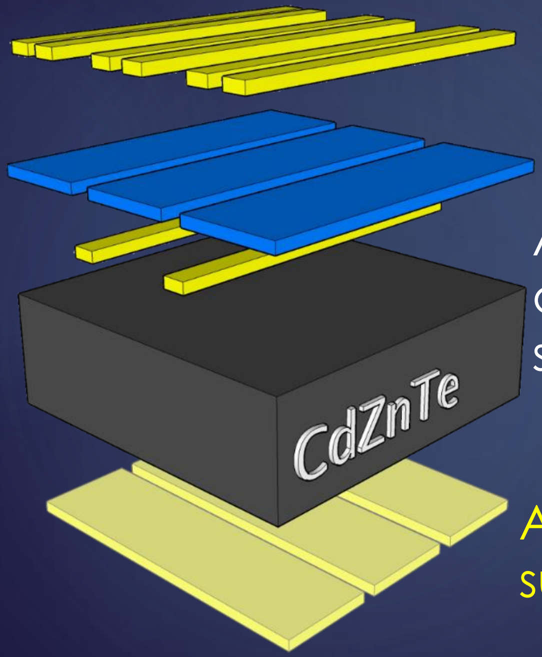
Redlen CZT Material
20 mm x 20 mm x 5 mm
Cathode: 10 strip, 2 mm pitch
Anode: drift strip configuration, 1.6 mm pitch
Drift strips: three between each collecting anode couple



The bonding made by thin copper combs techniques developed for the SGRIP prototype

Solving the problem of surface parasite currents

New passivation technique developed by CNR/IMEM (Italy)

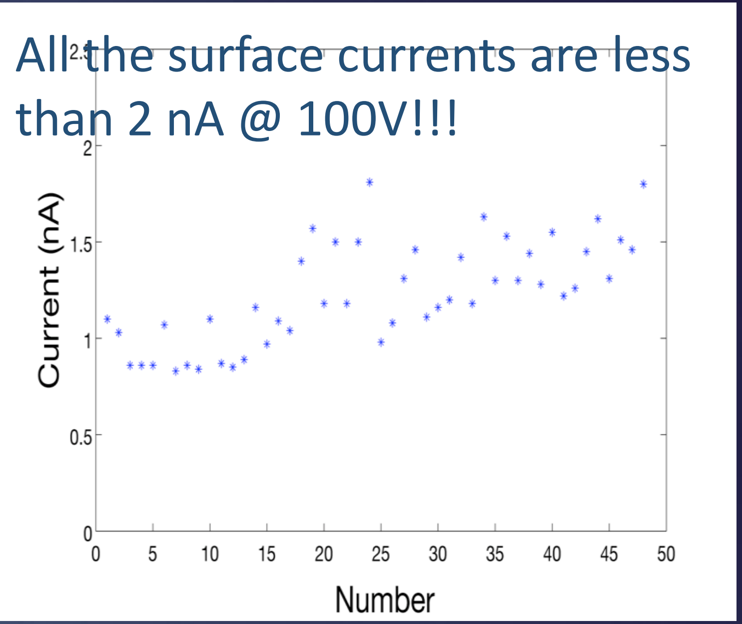


Cr/Au drift strip electrodes directly evaporated onto the Al_2O_3 layer

High resisitivity Al_2O_3 layer (150 µm thick)

Au collecting electrodes (anodes) deposited directly onto the CZT surface by electroless technique

Au catode strips deposited on the CZT surface by electroless technique.



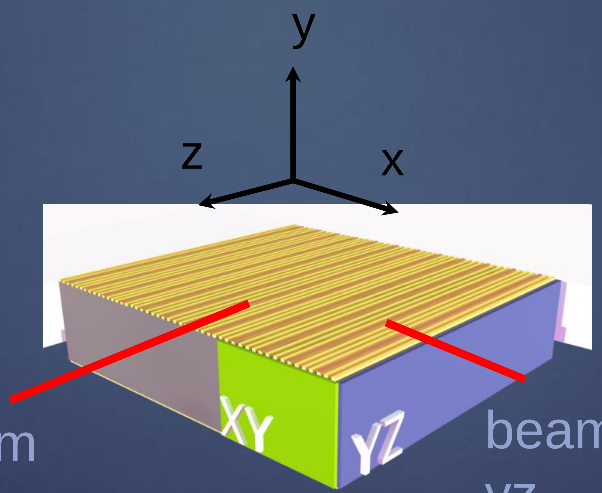
At least 10 time better with respect to SGRIP CZT units.

Very important step to guarantee high spectroscopic performance and fine 3D spatial resolution

Characterisation of the improved 3D CZT sensor unit design

ESRF ID 15 A: Test Campaign

Measurement in PTF configuration
Beam energy: 150, 300, 400, 580 keV
Beam spot: 50µm x 50µm
Scan steps: 0.15 mm



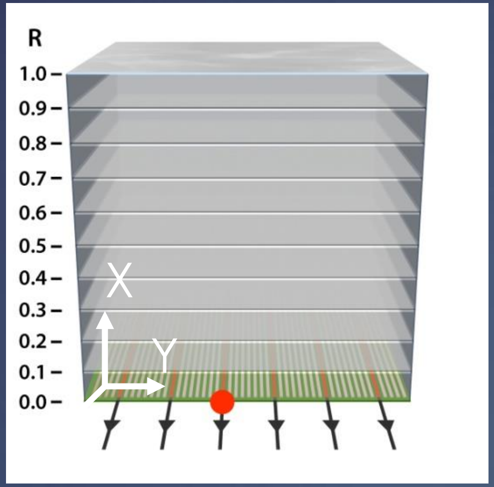
beam
xy scan

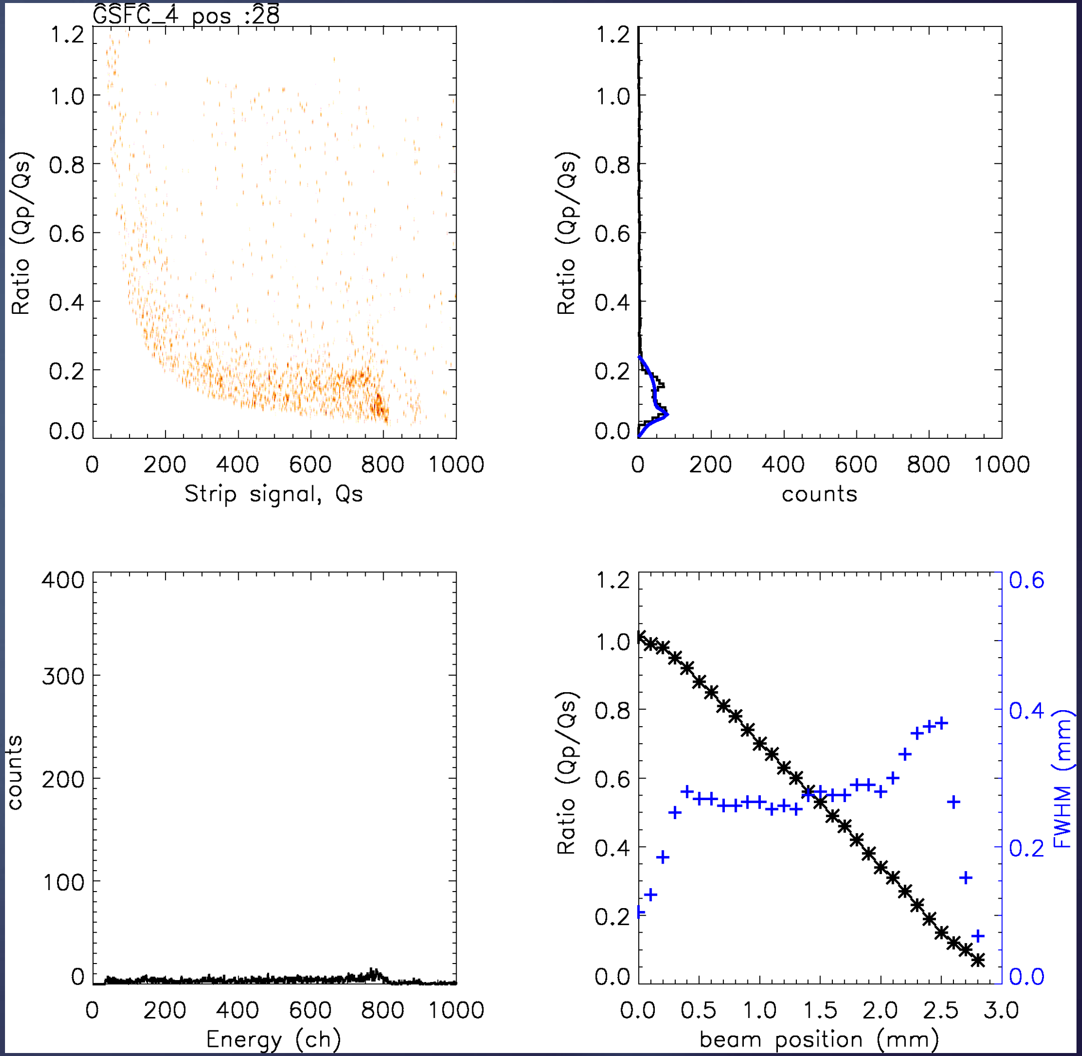
beam
yz
scan

Readout of:
10 cathode strips
2 collecting anodes
3 drift strips

The detector implement also the readout of drift strips signals by groups.

Deep scanning: the photon's third interaction coordinate





Co57, 1 μs shaping

Collimator height=14 cm

Beam size=230 μm

X-step=100 μm

Y-step=100 μm

Resolution in z (1 σ) ~150 μm)

3D Spectro-imager unit spatial resolution performance

The test demonstrated that the CZT sensor unit behave as a X/γ-ray detector with fine 3D imaging capability

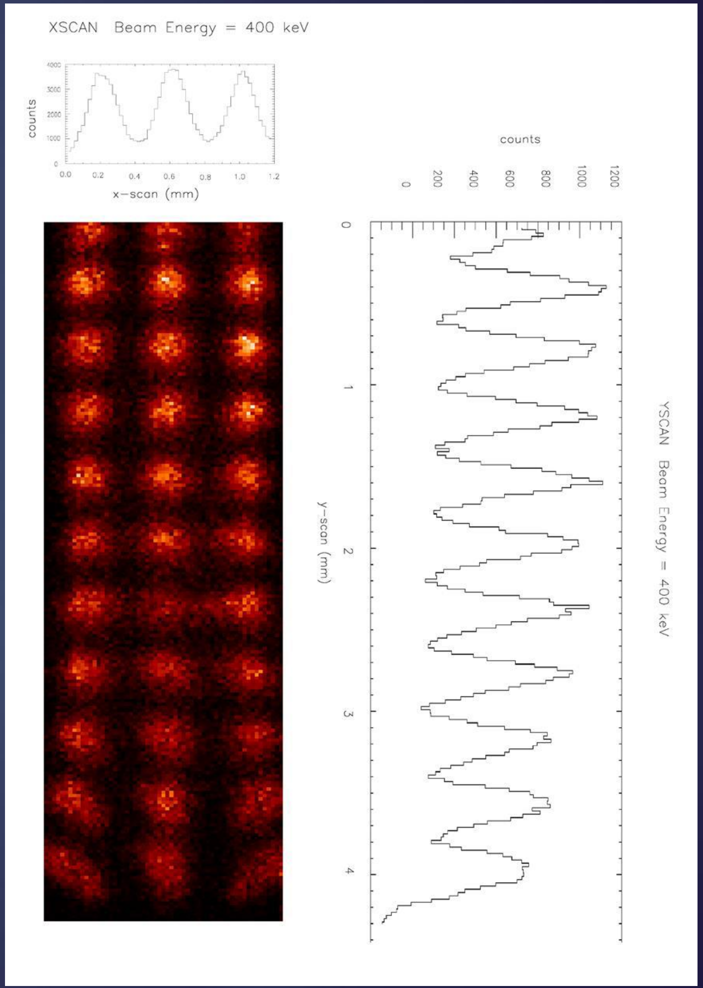
Best performances at 400 keV:

Δx = 0.15 mm

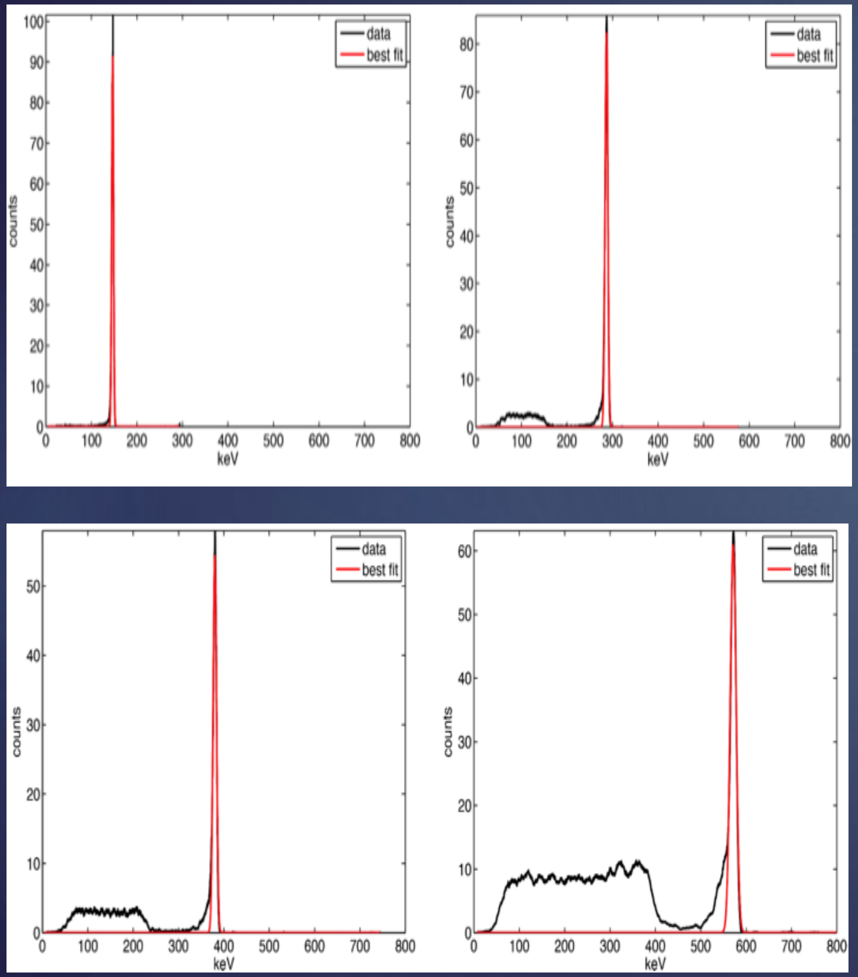
Δy = 0.26 mm

Δz = 0.65 mm

Few readout channels (~30) to obtain a sensor segmentation equivalent to: ~80000 "virtual" voxels (i.e. independent sensitive elements)



3D Spectro-imager unit spectroscopic performance

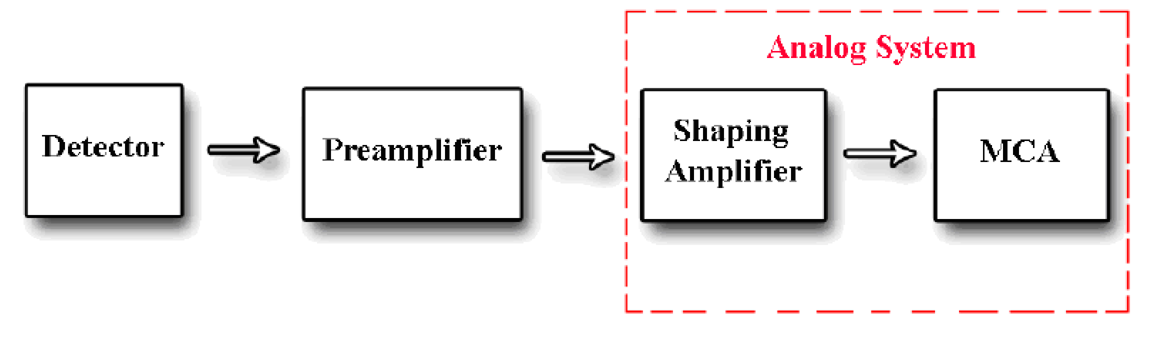


Results from ESRF demonstred that the CZT sensor units perform a a fine resolution spectrometer

$$\Delta E_{Tot} = \sqrt{\Delta E_{\det}^2 + \Delta E_{beam}^2 + \Delta E_{Elet}^2}$$

Energy keV	ΔE_{Tot} keV	ΔE_{Elet} keV	ΔE_{beam} keV	ΔE_{det} keV	ΔE_{det} (%)
150	4.2	3.67	0.73	1.91	**1.3**
300	6.1	3.67	1.88	4.5	**1.5**
400	7.4	3.67	3.18	5.58	**1.4**
580	10.8	3.67	6.7	7.63	**1.3**

Which kind of readout electronics we need?

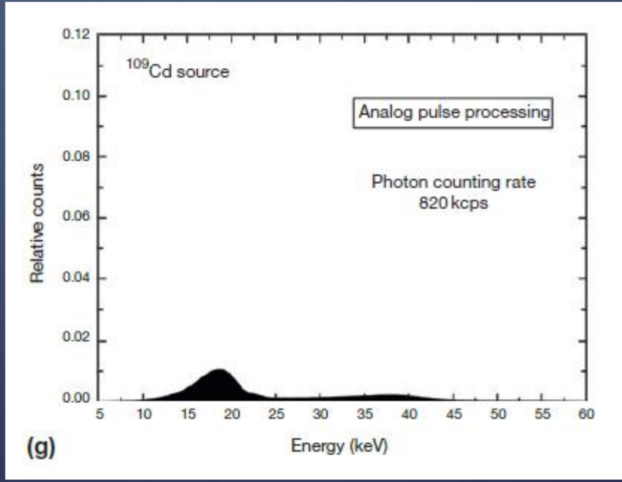


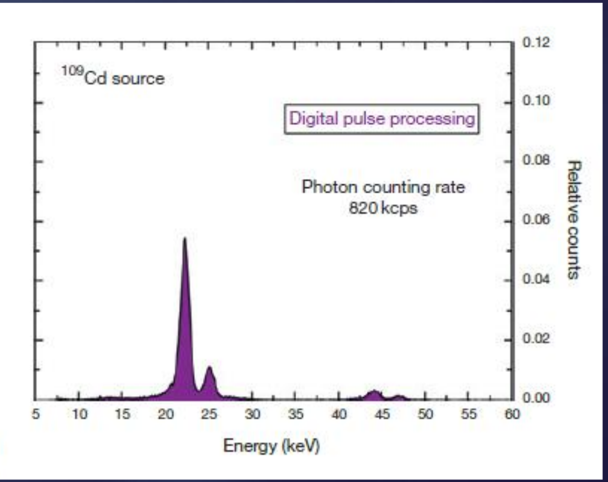
Standard approach for spectroscopy: Analog Shaping readout.
Large variety of ASIC available, but….
Fixed Analysis

We have chosen a new approach for readout: **Digital Pulse Processing.**
Digital Shaping, Digital Triggering, Digital Analysis……**Flexible Analysis**

820 kcps

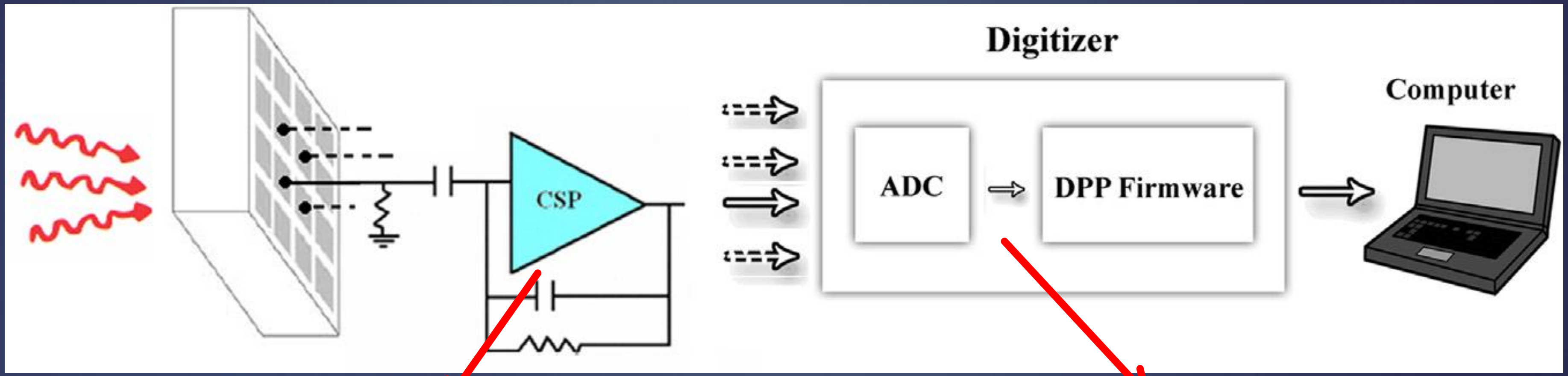
High-flux X-ray colour imaging for medical applications
PRIN Project 2014-2017 (P.I. L. Abbene, DiFC, Palermo)





An innovative spectrometer readout method: 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!

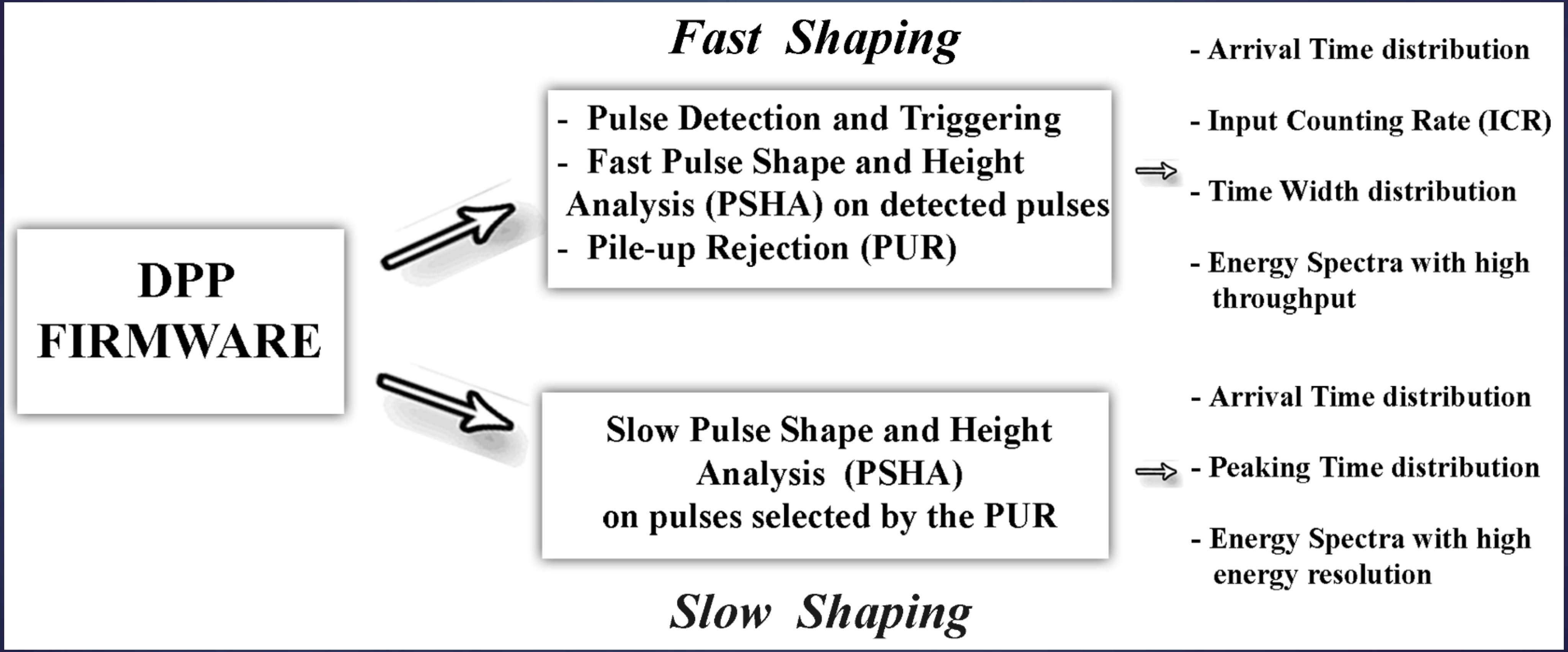


Analog Front-End:
the preamplifier (CSP) stage

Digital Readout Electronics for
Pulse Shape and
Height Analysis (PSHA)

Innovative Digital Strategy approach

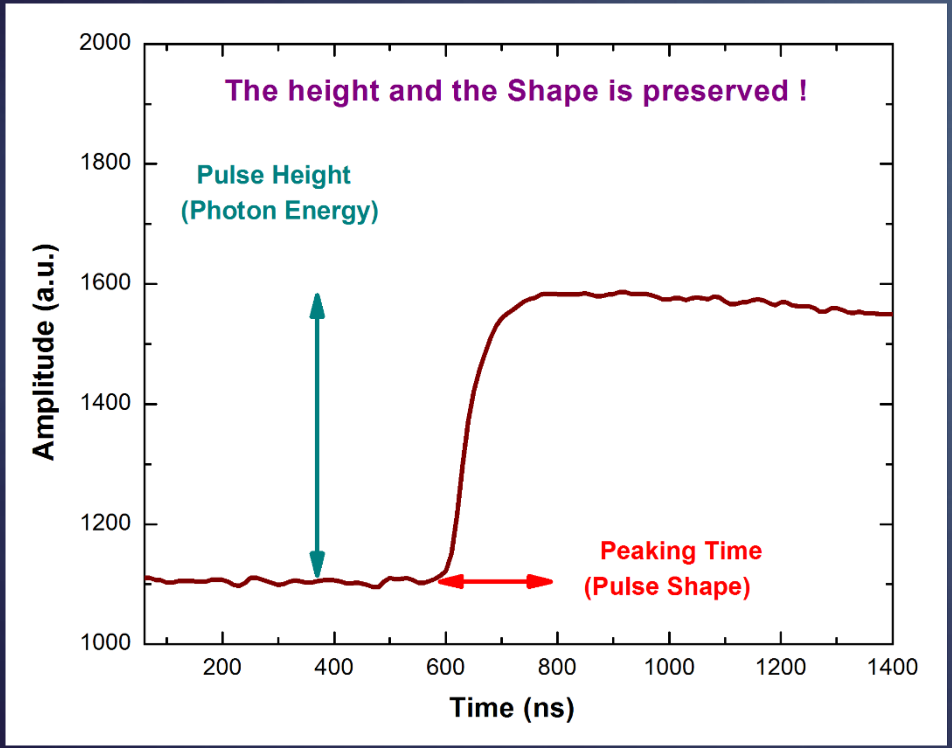
Each detector channel is analysed through two pipelined shaping: Fast (detection, rate) and Slow shaping (energy, peaking time)



Several operations for each channel

New Digital Pulse Processing Electronics: This approach advantege

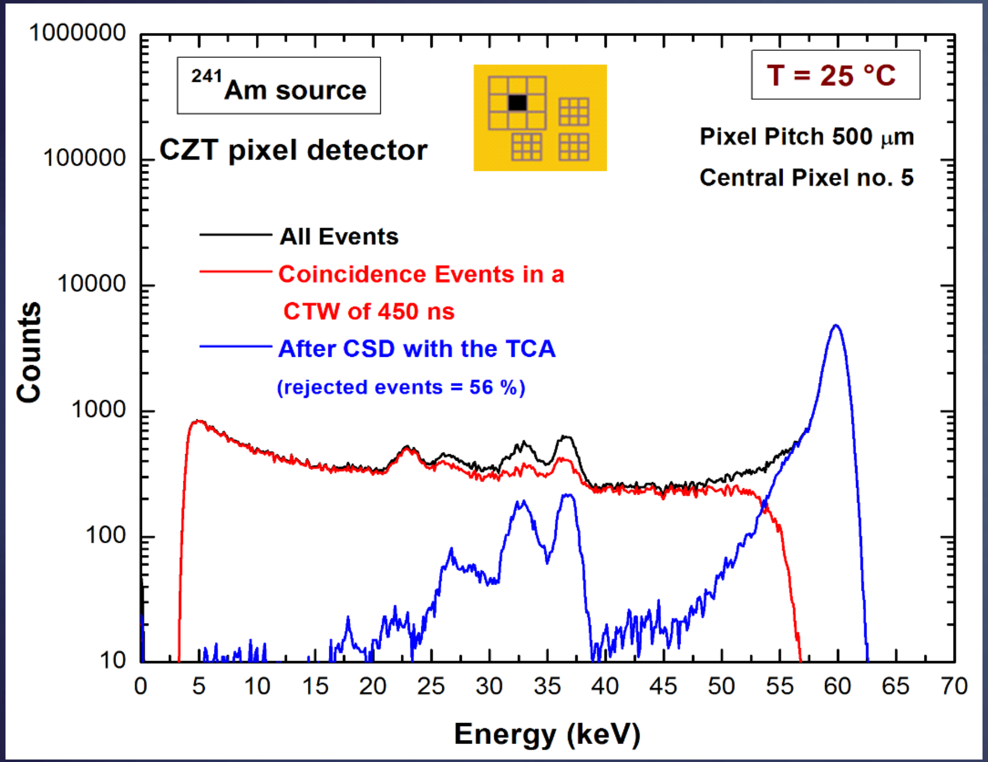
Digital readout allows better final performance, without changing hardware



- Implementation of custom filters and procedures. Challenging and high resource demanding to realize through the analog approach.
- Pulse detection and trigger time tagging with **high resolution (< 1 ns)** (for "slow" detectors)
- Implementation of bi-parametric techniques for each readout channel (e.g. shaping time/energy, fast/slow)
- Implementation of sub-pixel spatial resolution techniques (saving readout channels)
- Efficient techniques of charge sharing handling with coincidence time windows up to 10 ns (good for Compton event handling)

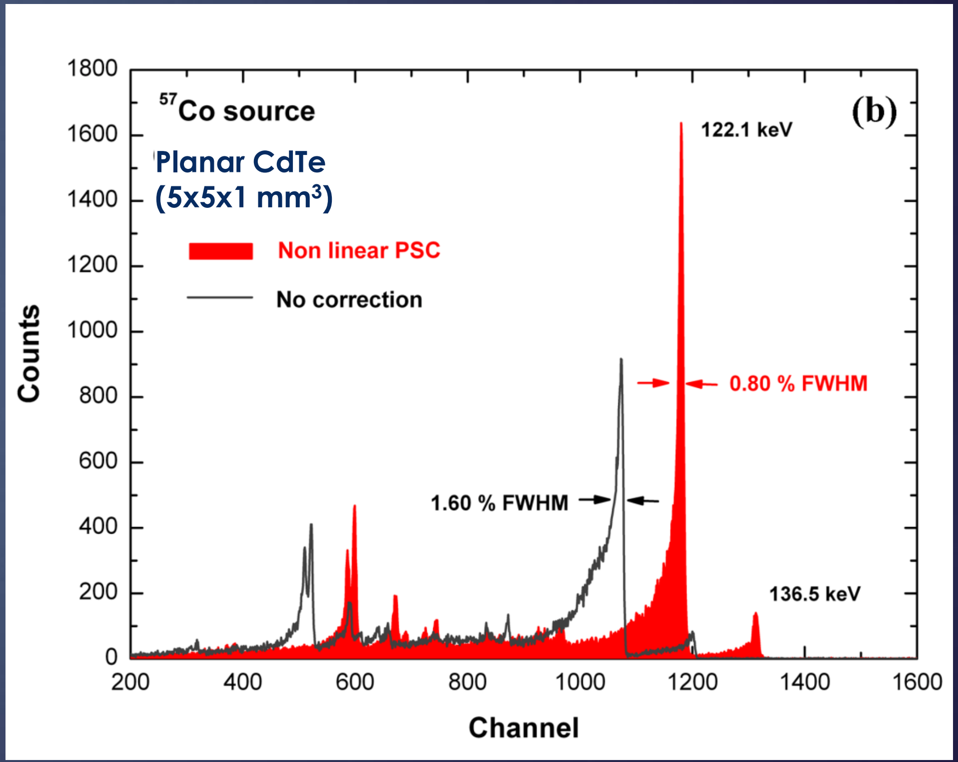
New Digital Pulse Processing:
Results on CZT/CdTe detectors at DIFC-Palermo

Charge Sharing Discrimination (time coincidence analysis)



L. Abbene, et al. J. Synchrotron Rad. (2017), in press

Pulse Shape Correction (energy-peaking time)



L. Abbene, et al. NIM A 730 (2013), 124-128.

III

Proposal objectives. Methods and technical description

The Objective

Development of a representative 3D new generation detection system prototype for high performance imaging, spectroscopy, timing and polarimetry operating between 5 keV and 1 MeV. This demonstrator includes two main subsystem:

- The demonstrator detector is based on a 20×20×20 mm^3 CZT module, realized by stacking four 20×20×5 mm^3 3D CZT PTF drift strip units, and the whole CSP boards for a total of up 120 readout channels.
- A Digital Pulse Processing electronics system to handle in real time all the preamplified signals.

For the first time, a fully digital approach will be implemented in a 3D spectro-imager to exploit its performance in term of spectroscopy (< 1% FWHM at 511 keV), 3D spatial resolution (<300 μm), polarimetry (Q > 0.5), timing (<10 ns) and Compton imaging capabilities (<10 degrees). **Only with 120 readout channels.**

The target is to improve the TRL from the current level 3 to level 5

The 3D CZT module

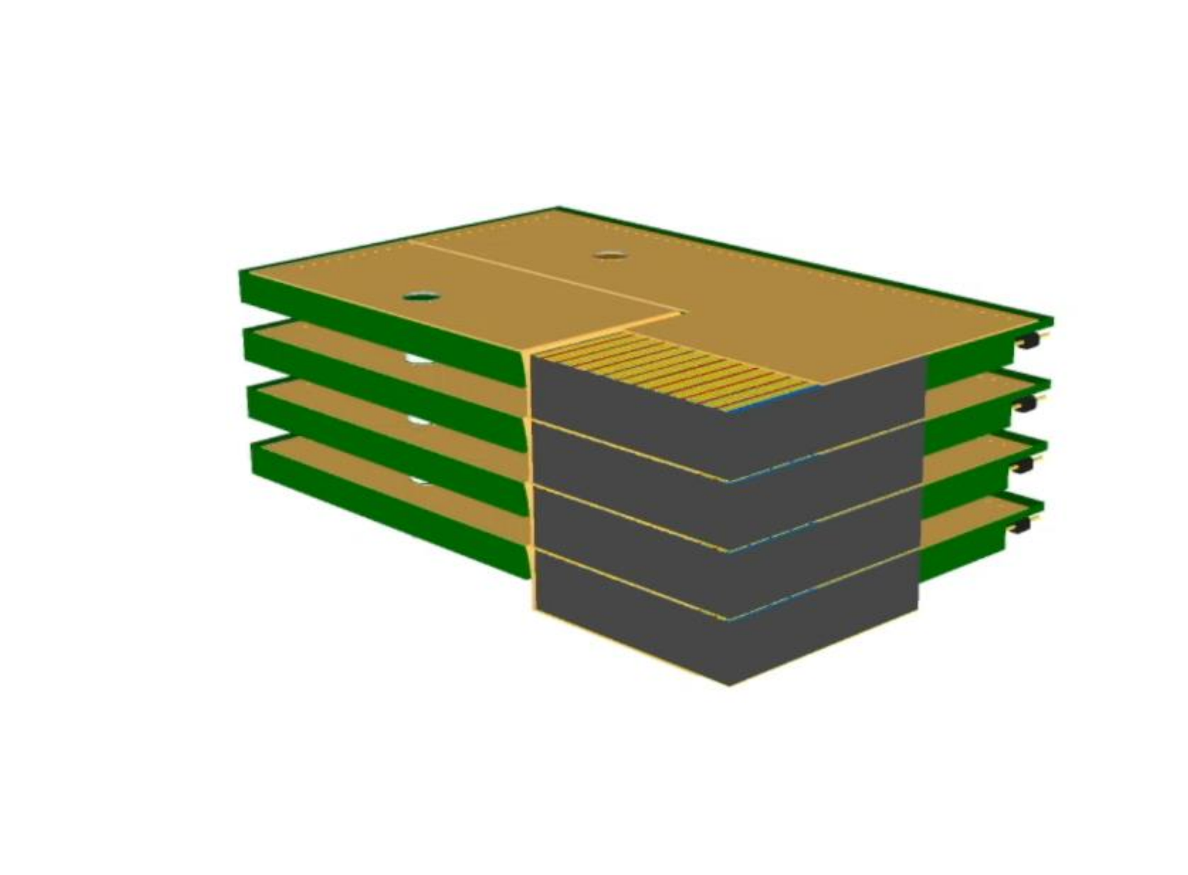
The detector module will be built by stacking four 3D CZT Sensor units.

- The 3D CZT sensor units will be based on 20x20x5 mm^3 bulk spectroscopic graded crystal. This choice rely both on: (a)our heritage concerning the achievable performance; (b) limitation of state of the art technology that does not guarantee optimal spectroscopic performances over volumes much larger.
- The sensor units will be processed to realize the optimized design, by using the technology developed along these years within the collaboration.
- The sensor units will be bonded on boards to allow the closest possible packing ((i.e. minimizing dead spacing) of the four sensor units;
- Each sensor unit is provided by about 25/30 independent read-out channels;
- The four detector boards are plugged on a main board with the readout charge sensitive preamplifier, the HV generator and other services

The 3D CZT module: the assembly

Relevant construction details:

- Space qualified components will be preferred when selecting insulating glues, bonding conductive epoxies, board material to built the single detector board. Capton technology for fan-outs;
- The CSP front-end board: implementation of a low noise **(<100 e^- rms)** and low power (**1 mW/channel**) hybrid design developed within the collaboration;



Views of he 3D CZT module detector

The Digital pulse processing electronics

A third level boards set will hosts Digital Pulse processing electronics that will include FPGA, ADC's, and ethernet connection for communication and I/O:

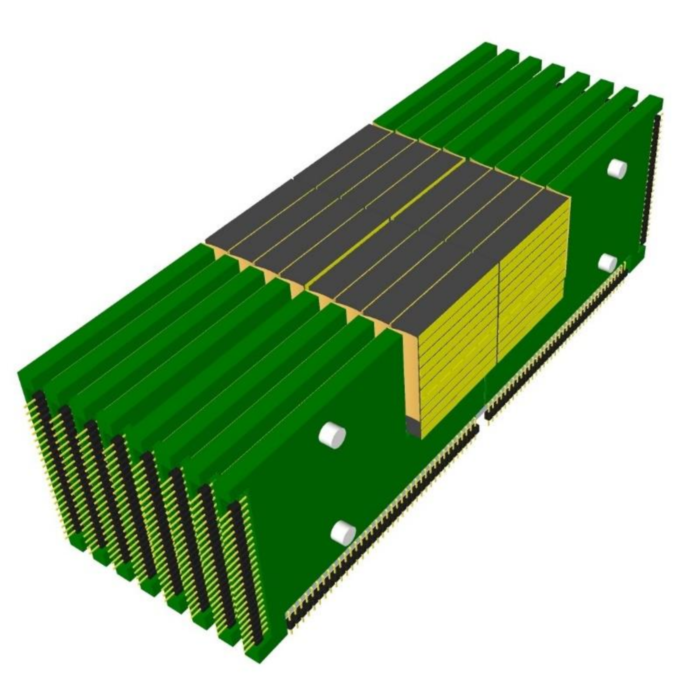
- ADCs at 100 MHz, 13-14 bit;
- One or more FPGA to handle the waveform acquisition from ADC units, to perform the data analysis and and to manage the data transfer to a PC by an ethernet connection.

Performance and Environmental «qualification»

- At **ESRF** (Grenoble, France), with polarized beam energy up to 700 keV and beam dimensions down to 10 micron. These measurement are mainly devoted to asses the achievable performance in term of spectroscopy, timing (high flux beam), Compton imaging capabilities and **polarimetry;**
- At **LARIX** facility (Ferrara, Italy), with X-ray beam from 50 to 200 keV, with bent laue crystal of Si, Ge and GaAs, or broad band laue lens prototype (if available), The target of these measurements is the evaluation of spectroscopic imaging performance in the contest of the use as focal plane in a broadband Laue lens;
- **Environmental tests** can be performed at SERMS facility in Terni (Italy), to prove and asses the response of the prototype under different space relevant environmental conditions (i.e thermo-vacuum and vibration).

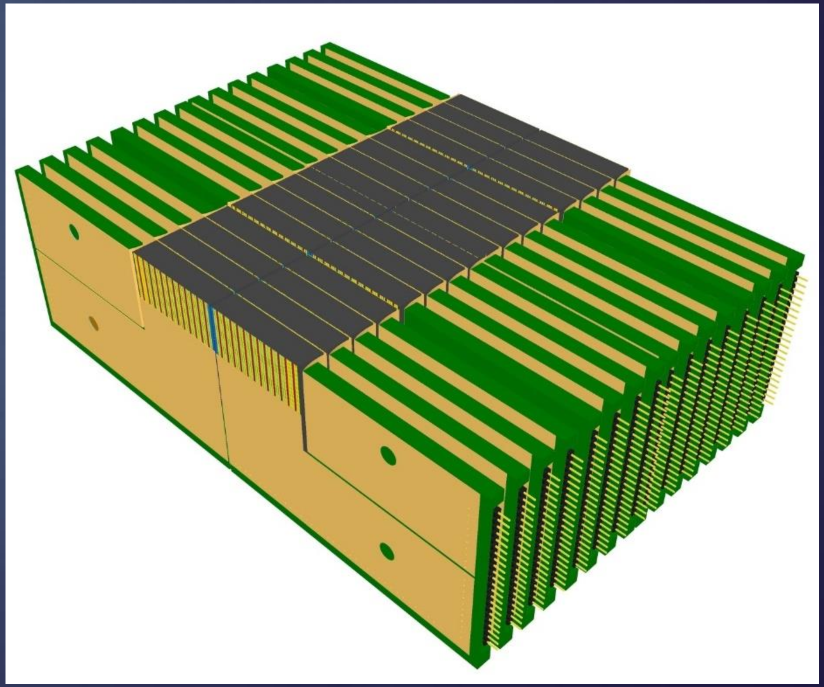
The 3D CZT module flexible design

The proposed design for the 3D CZT spectro-imager module already allow its use as a basic functional element for more complex and wider instruments. The chosen module assembly, that is three side abbutable, can be mosaiced to build 3D spectro-imager of 2 x n modules.



4 Modules
mosaic detector

8 Modules
mosaic detector



The 3D CZT detection system: Hot points

- The module will allow to fully exploit the achievable spectroscopic and spatial resolution performance using 3D CZT sensor implementing drift strips configuration for anode and segmented cathode.
- The sensitive volume (8 cm^3) and its geometrical sizes will allows to **prove and verify the capability in the Compton regime and therefore the performance as a scattering polarimeter and as a "compton imaging"**
- High modularity of the detector module (as shown in the slide before)
- The implementation for the first time of a digital pulse approach for readout electronics will allow to drastically improve intrinsic detector performance in term of spectroscopy, timing and imaging and therefore in polarimetry.
- The digital electronics readout approach will guarantee a very large flexibility and adaptability 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.**

IV Conclusion: Satellite mission perspectives

The proposed 3D CZT module represent an efficient solution to realize innovative high performance detectors for next generation of space instrument in hard X-/soft γ-rays astronomy. Its modularity will allow the implementation in a large variety of satellite mission classes able to answer a wide range of scientific topics.

- High performance focal plane detector for new broad band Laue lens high telescopes even in a cluster of mini satellite operating in different energy bands from 50 to 600 keV. This implementation will exploit in particular the polarimetry performance of such devices.
- Realisation of 4π FOV detectors in a high populated (50-100) cluster of micro-satellites for GRB's derived science as under study for the HERMES project. The high 3D spatial and spectroscopic resolution and the fine time resolution achievable by the digital readout system will allow a good discrimination of the background (both particles and photons) and a high source location accuracy through the possibility to use each detector as a small Compton telescope together with triggered satellite triangulations.

Annex
Deliverables of the project, temporal development schedule; summary of financial request.

Research Unit main reponsibility division

- **RU 1-INAF/IASF Bologna:**
  Project coordination
  Performance tests at single 3D CZT sensor unit
  3D CZT detection system performance tests at facilities
  3D CZT detection system environmental tests
- **RU 2-CNR/IMEM Parma**
  Realisation of 3D CZT sensor units
  Realisation of the CSP FE board
  Realisation of the 3D CZT module
- **RU 3-UNI/DIFC Palermo**
  Realisation of the DPP electronics
  Functional tests of the DPP electronics

Project Time Schedule

Yellow activities: under responsibility of the RU1-INAF,
but with direct participation of personnel from RU2 and RU3

RU	Work package description	Months																						
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	20	21	22	23	24
1	Design optimisation of CZT drift strip sensor units	■	■																					
1	Realisation of the laboratory set-up for testing CZT sensors			■	■	■																		
1	Laboratory performance test of CZT sensors & module						■	■	■	■	■	■				■	■	■						
1	Performance test at LARIX with laue crystals for spectro-imaging																			■			■	
1	Environmental Tests (Thermo-vacuum and vibrations)																				■	■		
1	ESRF polarimetry and spectro-imaging performance tests																				■	■		
1	Test campaigns final data analysis and final report preparation																							■
2	Procurement of spectrometer graded CZT crystals	■	■	■																				
2	Realisation of CZT drift-strip sensor units			■	■	■	■	■	■	■	■													
2	Design and realisation of the 3D CZT module packaging								■	■	■	■												
2	Realisation of the CSP FEE boards					■	■	■	■	■	■	■												
2	Integration of the 3D CZT module with CSP FE boards												■	■	■									
3	Design optimisation of the CSP FEE			■	■																			
3	Design and realisation of the DPP FPGA based system			■	■	■	■	■	■	■	■	■	■	■										
3	DPP FPGA functional and performance tests														■	■	■							
3	Integration of 3D CZT detection system with DPP electronics																	■	■					

Deliverables of the project after one year and at the conclusion

Deliverables at the end of the first year (KO+12 months:

- Reports on functional and performance tests of PTF drift strip CZT sensor units
- The complete 3D CZT module with 4 PTF drift strip sensors.
- The full sets of CSP boards required for readouts of the 100/120 module channels

Deliverables at the end of the project (KO+24 months):

- Complete and tested DPP system to acquire and handle 100/120 FEE channels;
- Complete detection system tested in laboratory with radioactive source;
- Performance report from LARIX test: focussed imaging and spectrometry in the 80-200 keV range;
- Performance report from ESRF tests: Compton imaging, polarimetry, spectroscopy and timing) in the 100-700 keV range.
- Report on the environmental (thermo-vacuum cycles and vibration runs)

Summary of the financial request

	RU 1-INAF	RU 2-CNR	RU 3-UNIPA	Totals
Personnel				
Equipment	€ 20000		€ 13500	**€ 33500**
Consumables	€ 7500	€ 47000	€ 35000	**€ 89500**
Travels	€ 16614	€ 10315	€ 9932	**€ 36861**
Others (*)	€ 37000	€ 43000	€ 23000	**€ 103000**
RU Totals	**€ 81114**	**€ 100315**	**€ 81432**	**€ 262861**

(*) Mainly external services