Testing a prototype of 8x8x32 mm^3 CdZnTe detector array

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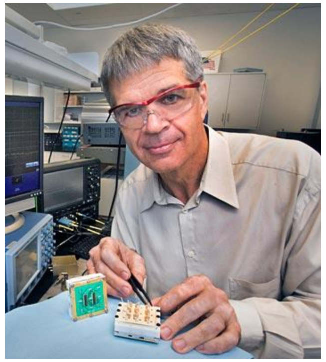

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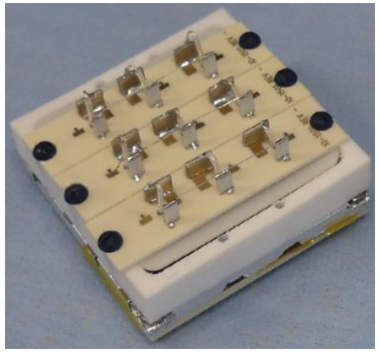
Introduction

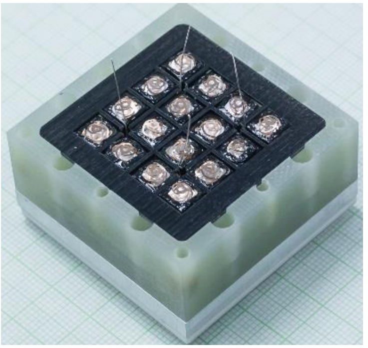
- Detection of gamma rays in the MeV region is important for nonproliferation and nuclear security missions
- It is also of great interest for gamma-ray astronomy: cosmic gamma rays in this range are least explored because of the low sensitivity of the existing instruments
- Achieving the high sensitivity in the MeV range requires detecting media with high Z and density, that can also provide high energy and position resolutions
- Today, CZT-based arrays can satisfy these requirements, and therefore, become attractive for ground and space telescopes
- In the past, we proposed CZT arrays for nuclear security and safeguards applications [1] and most recently, together with a NASA team, for the space telescopes GECCO [2]

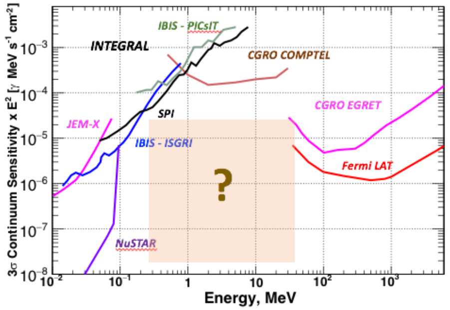
Arrays for nonproliferation

6x6 array of 5x5x15 mm^3 detectors



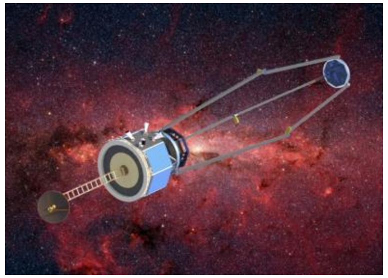
4x4 array of 6x6x20 mm^3 detectors





Gamma ray flux sensitivity limits achieved with space instruments

Artist's concept of the proposed Coded Aperture Mask Compton Telescope (GECCO)



[1] L. Ocampo et al., "Arrays of Position-Sensitive Virtual Frisch-Grid CdZnTe Detectors: Results from a 4x4 Array Prototype", IEEE Trans. Nucl. Sci., Vol. 64, no. 10, pp. 2698-2705, 2017.
[2] A. Moiseev et al., New mission concept: Galactic Explorer with a Coded Aperture Mask Compton Telescope (GECCO), 2021 International Cosmic Ray Conference (Berlin, 2021), PoS (ICRC2021) 648.

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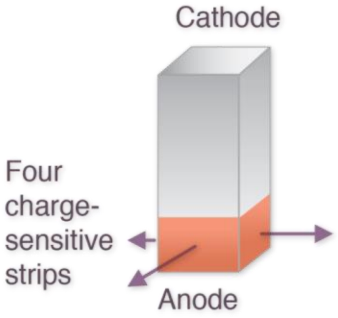
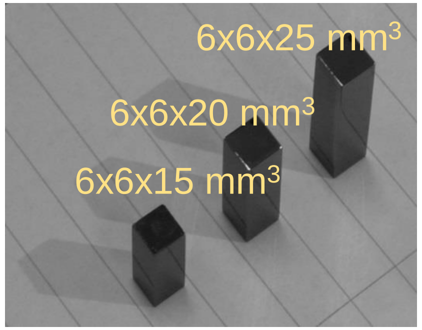
Arrays of position-sensitive VFG detectors

Schematics of a position-sensitive VFG detector



These images illustrate a progress in availability of CZT bars for VFG detectors



10x10x32 mm^3

- Our arrays are made up of CZT bars with cross-sections up to 10x10 mm^2 and thicknesses up to 32 mm
- The bars are configured as position-sensitive virtual Frisch grid detectors
- Pad signals provide X-Y coordinates, while the cathode signals are used to measure Z coordinates
- With this design, we demonstrated energy resolution of < 1% FWHM at 662 keV (limited by electronic noise) and position resolution < 1 mm for all three dimensions (limited by local electric field non-uniformity)
- We are moving to bigger detectors: 5x5x15 mm^3 -> 6x6x20 mm^3 -> 8x8x32 mm^3 -> 10x10x32 mm^3 (reflects progress in big CZT crystals availability)
- Smaller bars may also have advantages; the actual detector dimensions should be optimized depending on the applications

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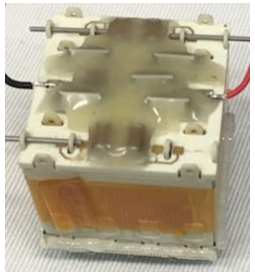
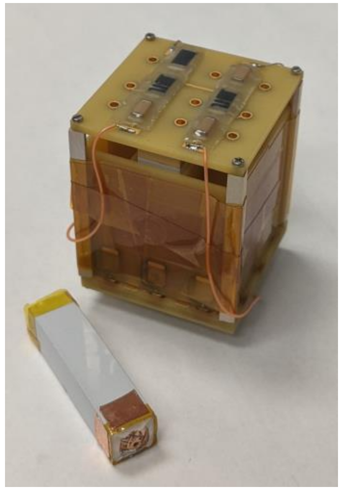
Array prototype based on 8x8x32 mm^3 CZT bars

- We proposed a modular approach
- Each module is a 3x3 detector array (or crate) with the same footprint as previously developed 4x4 modules -- this allows us to use the existing readout system
- Due to technical reasons, we were able to “load” inside the crate only 5 detectors
- 25 CZT bars were acquired from two vendors: Redlen and Kromek
- We also acquired 2 10x10x32 cm^3 bars from Redlen - the biggest available CZT crystals
- Before integration, each detector was tested individually using a single detector readout system, based on eV-Products hybrid preamplifiers and digital oscilloscope

Old 4x4 crate consisting of 6x6x20 mm^3



New 3x3 crate consisting of 8x8x32 mm^3



The new 3x3 crate with 5 8x8x32 mm^3 detectors slid inside

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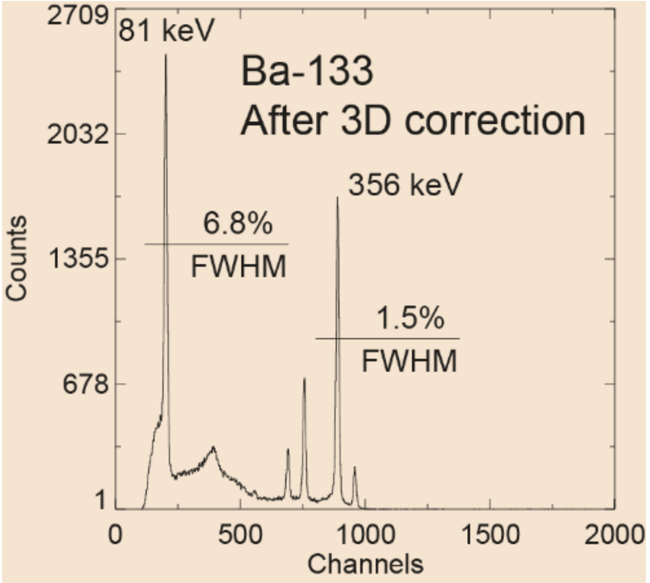
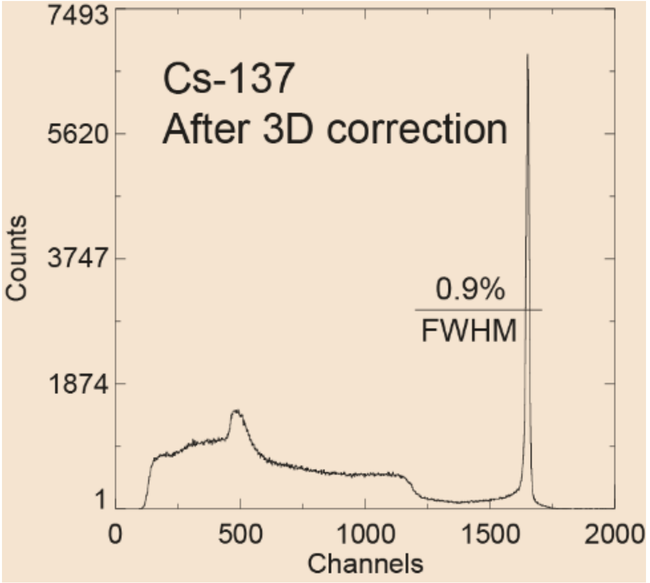
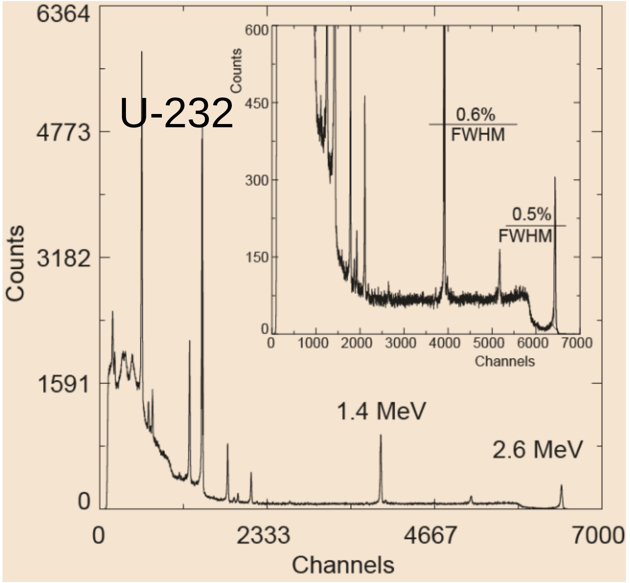
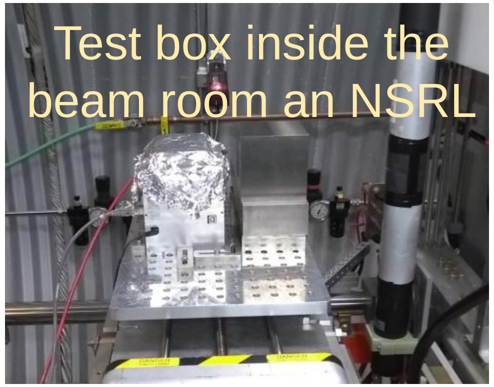
Results from testing an individual 8x8x32 mm^3 detector (from Redlen) before integration into array, bias 3500 V







- We demonstrated good performance of the detectors before integration
- An interesting fact: 4 Redlen detectors tested here were also used in radiation damage studies at the NASA Space Radiation Laboratory (NSRL) [3]. After exposure to 100 MeV proton flux with a total fluence of ~10^{10} p/cm^2, the detectors completely their responses
- After annealing at 80 ^{O}C for 3 weeks the detectors fully recovered



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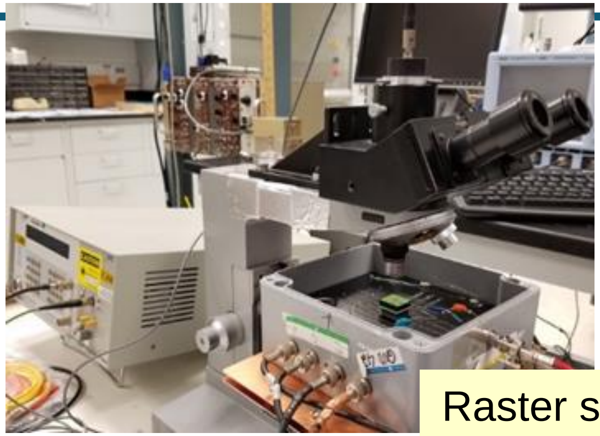
[3] A. Bolotnikov et al., “Radiation effects induced by the energetic protons in 8x8x32 mm^3 CdZnTe detectors”, NIMA, 1029, Article 166927, 2022

Testing position resolution using a focused pulsed laser beam



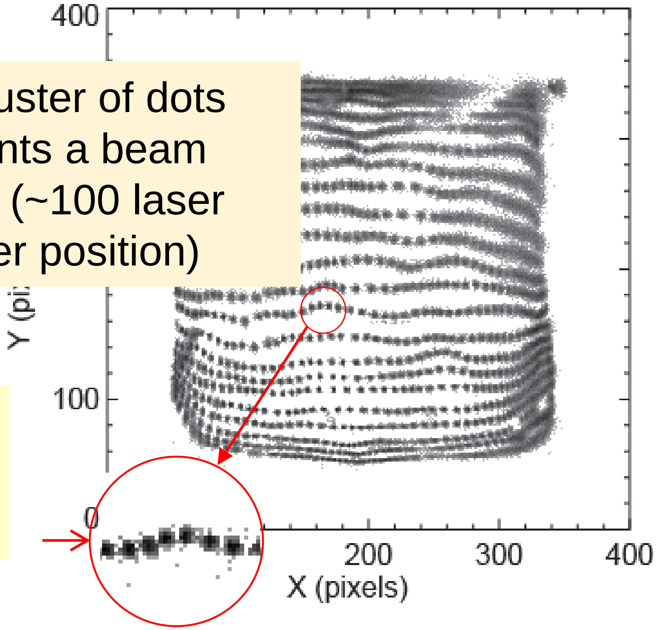
- Focused pulsed laser beam: ~10 µm, 100 µm steps
- An injected charge is equivalent to an energy of ~500 keV
- The center of gravity method was used to evaluate *XY* coordinates, which is the most robust approach

Center of gravity formulas (CG) to estimate positions (estimator)

$$X = \frac{A_x^2}{A_x^1 + A_x^2}$$

$$Y = \frac{A_y^2}{A_y^1 + A_y^2}$$

Raster scan of a 6x6x20 mm^3 director with 100 µm steps



Each cluster of dots represents a beam position (~100 laser shots per position)

The size of these clusters represents the <u>intrinsic</u> position resolution, < 50 microns

There are two kinds of distortions:

1) Dots wiggling, which is due to local variations of electric field (like polka dots)
2) Dots "clipping" near the edges caused by using the center of gravity formulas (we can correct these distortions using actual pad response functions)

Total = "Intrinsic" + "Electric field variations" + "Distortions due to using CG"

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Testing position resolution using a collimated Cs-137 source: 10x10x32 mm^3 detector

Geometry of the experiment

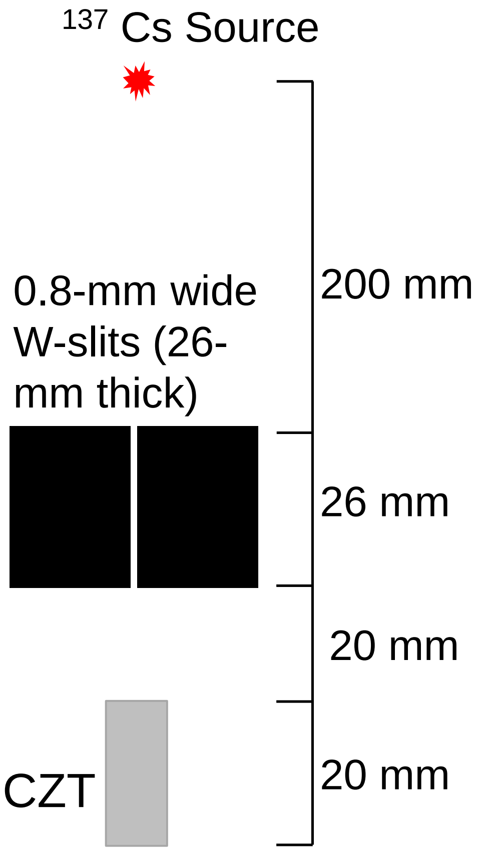
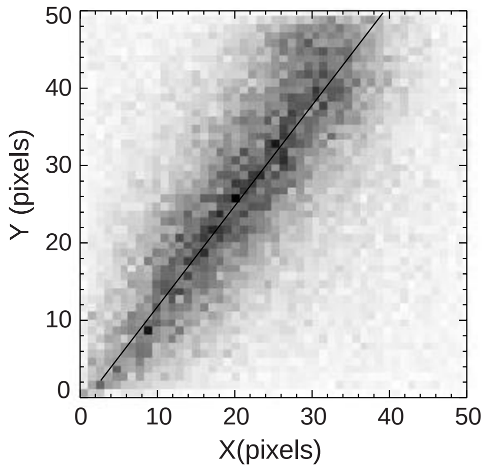
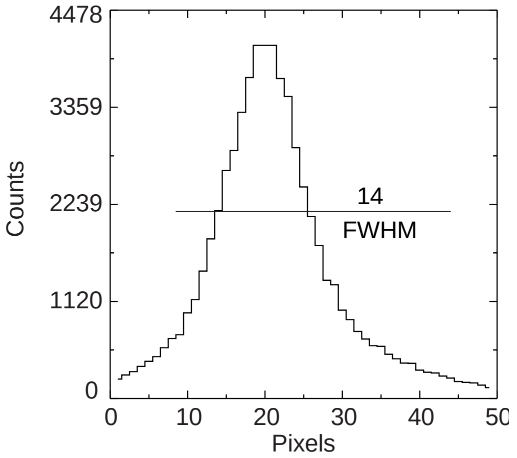


Image of the tungsten slits generated with a 10x10x32 mm^3 detector irradiated by the uncollimated Cs-137 source

10x10 mm^2



XY distribution of the interaction events inside a detector projected onto the *XY* plane after corrections



Distribution of the events with respect to the center of gravity line

Based on Monte-Carlo simulation we estimated the resolution to be < 1 mm

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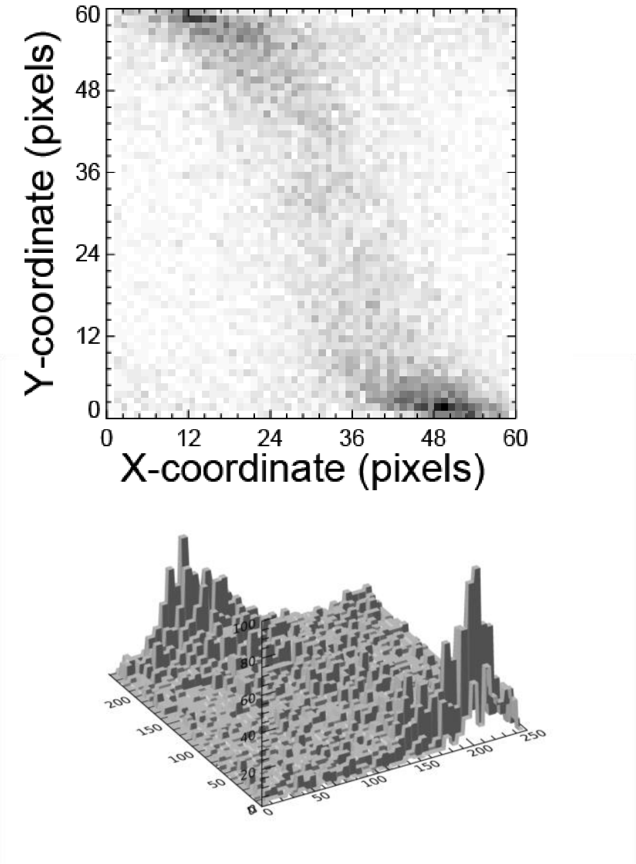
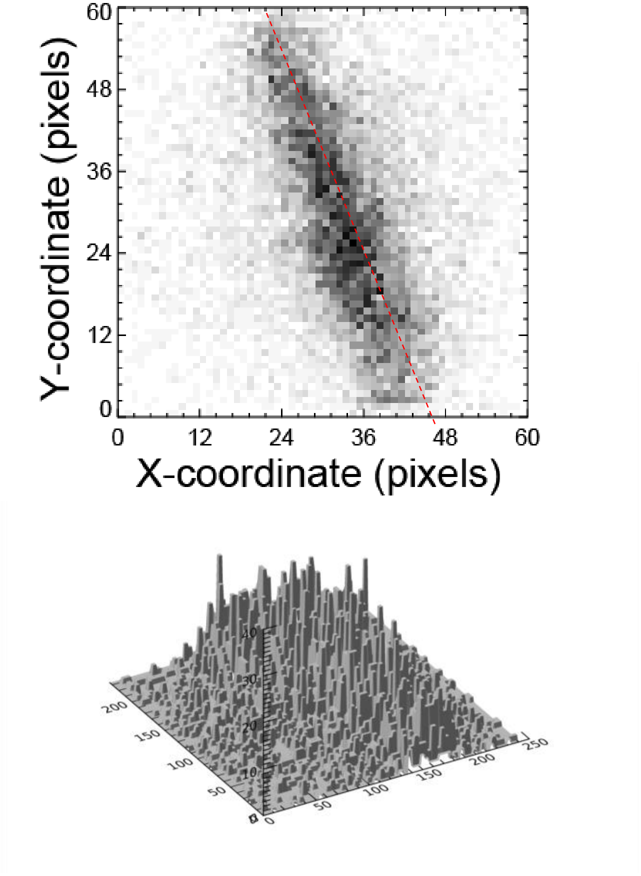
Correcting distortion due to the center of gravity formula

These images of the tungsten slits illustrate how corrections improve position resolution

Using the center of gravity formulas



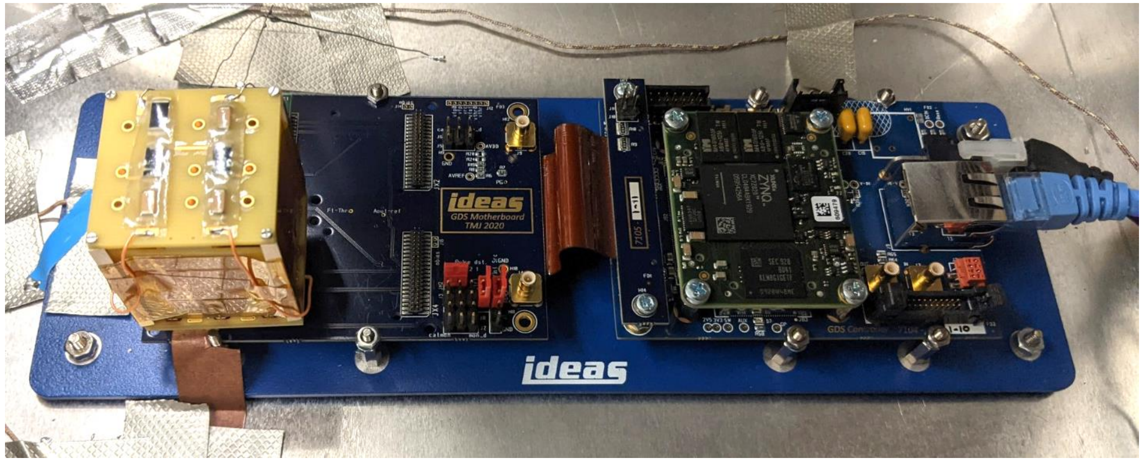
After applying corrections using the conformal maps



IDEAS's GDS-100 readout system developed for CZT arrays

- We use the IDEAS GDS-100 readout system developed by the company for CZT arrays
- It is based on a sampling ASIC optimized for CZT pixel detectors
- The system captures triggered 160-cell snippets from 121 preamplifier outputs
- The arrays and electronics were mounted inside an aluminum enclosure and placed inside the environmental chamber to maintain the temperature of the detector at around 15-16 ^{O}C during the measurements
- For more information visit the IDEAS website: https://ideas.no/successful-first-tests-in-development-of-czt-imaging-calorimeter/

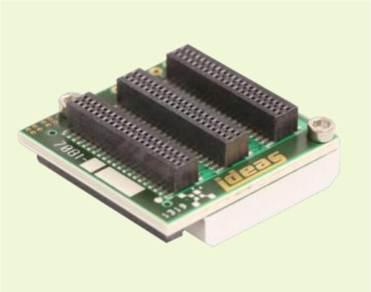
IDEAS GDS-100 readout system with a CZT crate



GDS-100 is a temporary solution for arrays prototyping

Limited dynamic range and slow readout

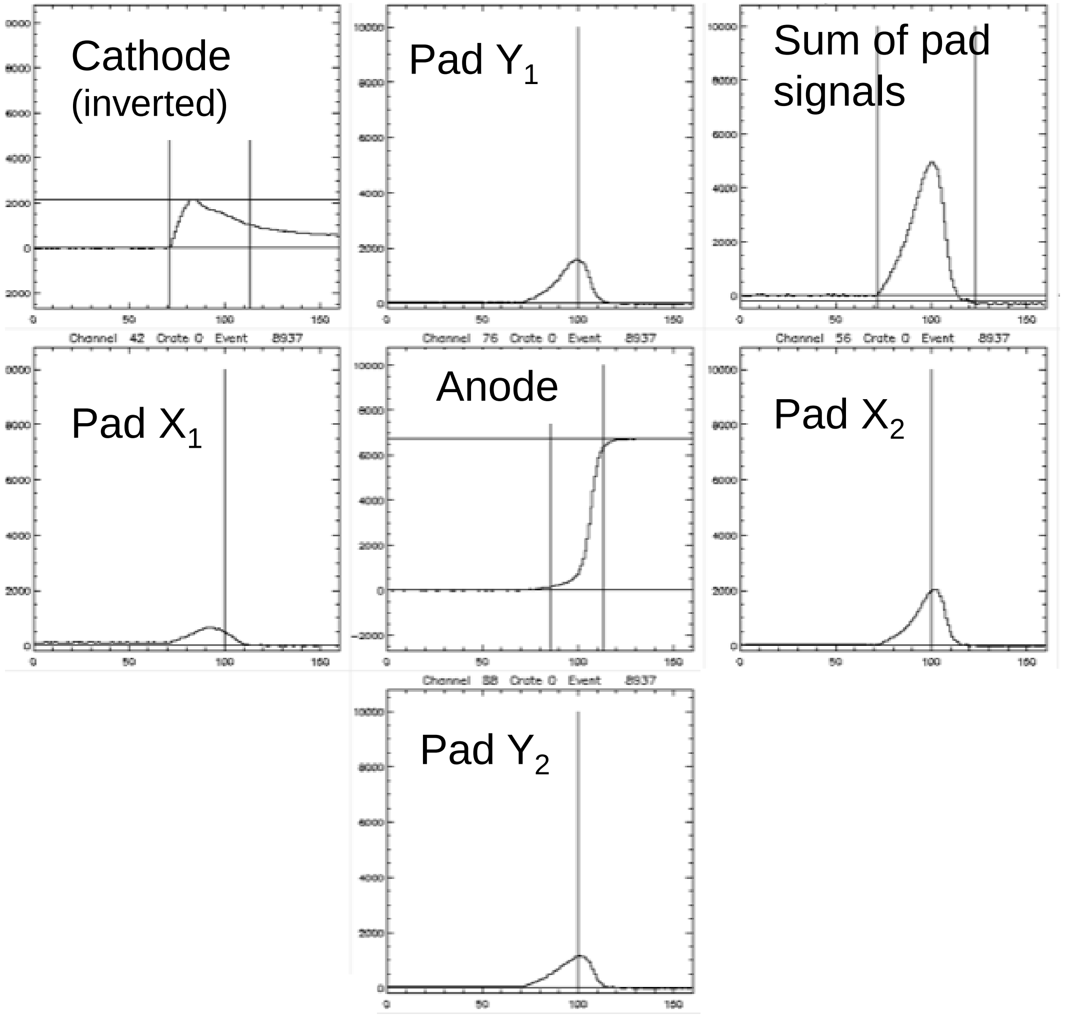
Signal sampling ASIC



The Instrumentation team is working on a new readout system with a wide dynamic range, faster, lower power for space applications

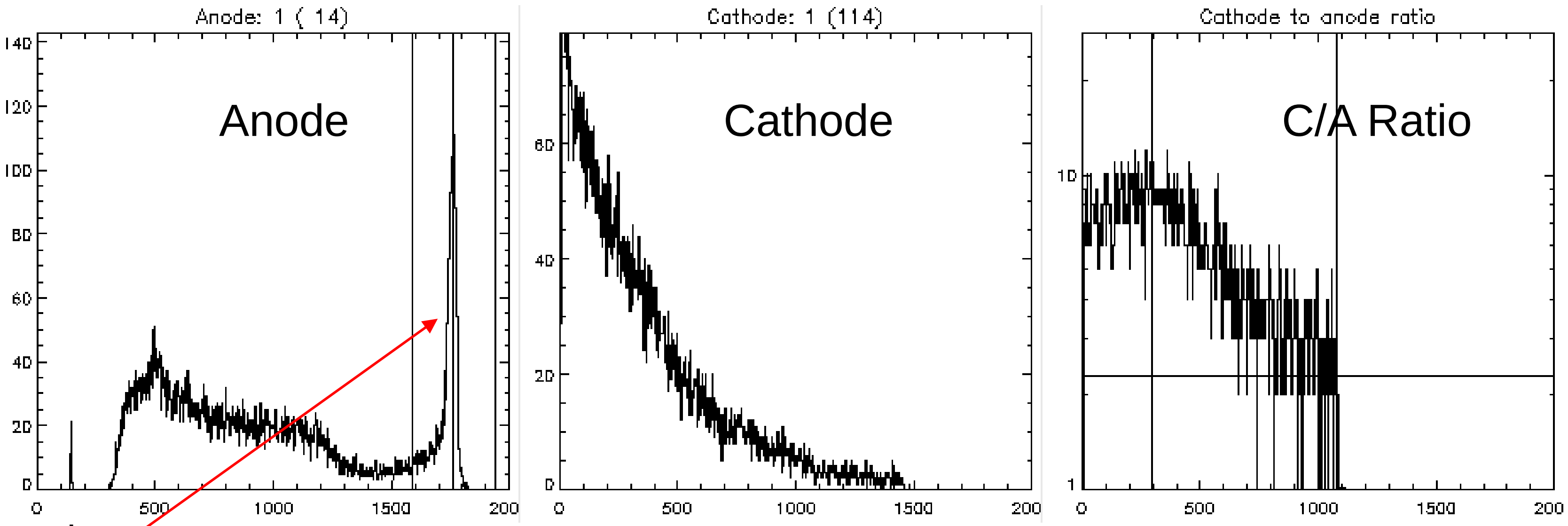
Example of the snippets captured by the readout system

Array was irradiated with a ^{137}Cs source



- We use the correlated double sampling to evaluate the anode and cathode amplitudes
- To evaluate the pad amplitudes, we use the samples taken at the same time for all pads (synchronized samples)
- This is very important for accurate *XY* coordinates reconstruction and minimizing geometrical distortions
- The sum of the pad signals can substitute the cathode signals

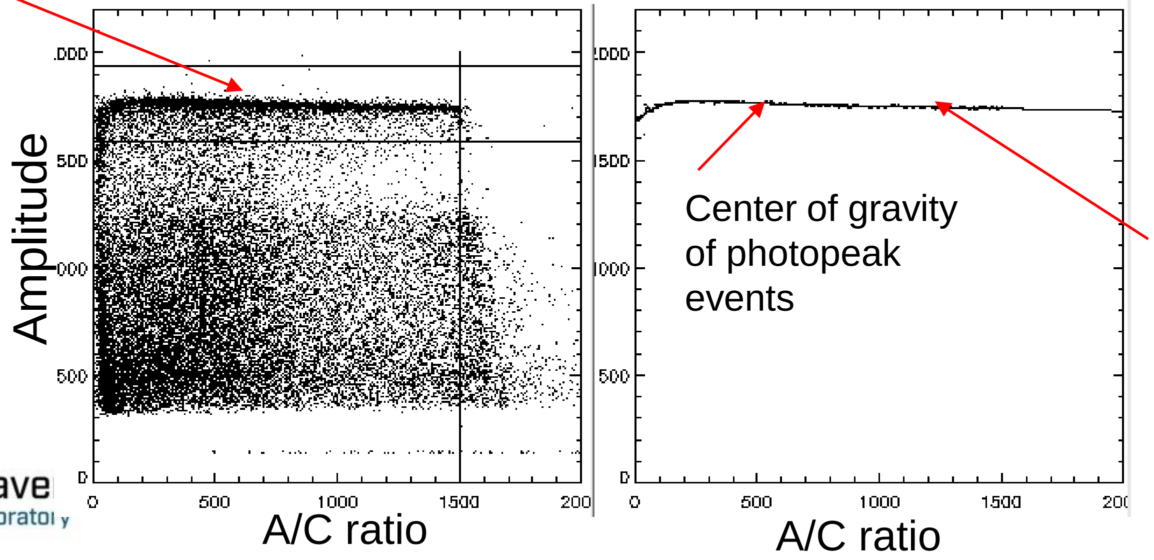
Examples of the anode, cathode and C/A ratio spectra measured with 8x8x32 mm^3 detectors from the array



8x8x32 mm^3 detector
Bias 3700 V, ^{137}Cs source

Photopeak events

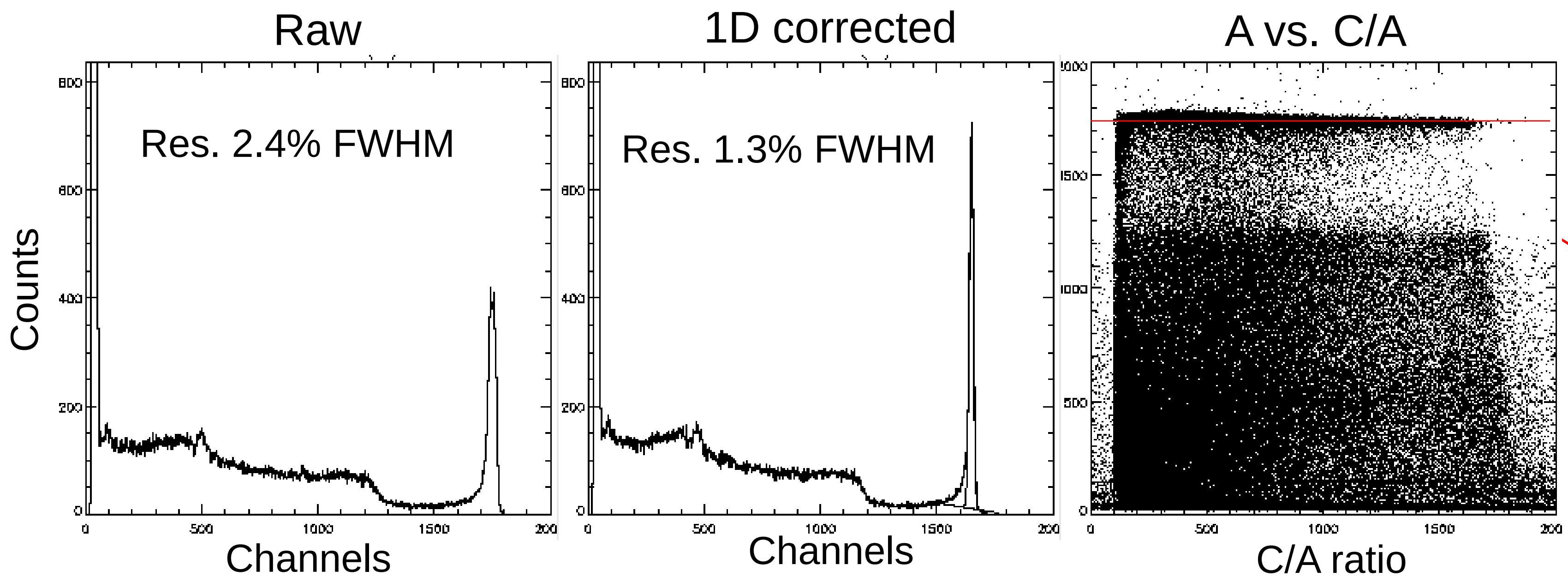
Evaluating *A vs. C/A* curve for 1D corrections



- This fitting curve is used for applying interaction depth, or 1D, corrections
- We note that <u>1D corrections are applied to all events regardless of *XY* coordinates</u>

Applying 1D (interaction depth) corrections

Example of the 8x8x32 mm^3 detector, bias 3700 V, ^{137}Cs source



The dependence of A vs. C/A is almost flat after 1D correction

- Further improvements can be achieved after 3D corrections

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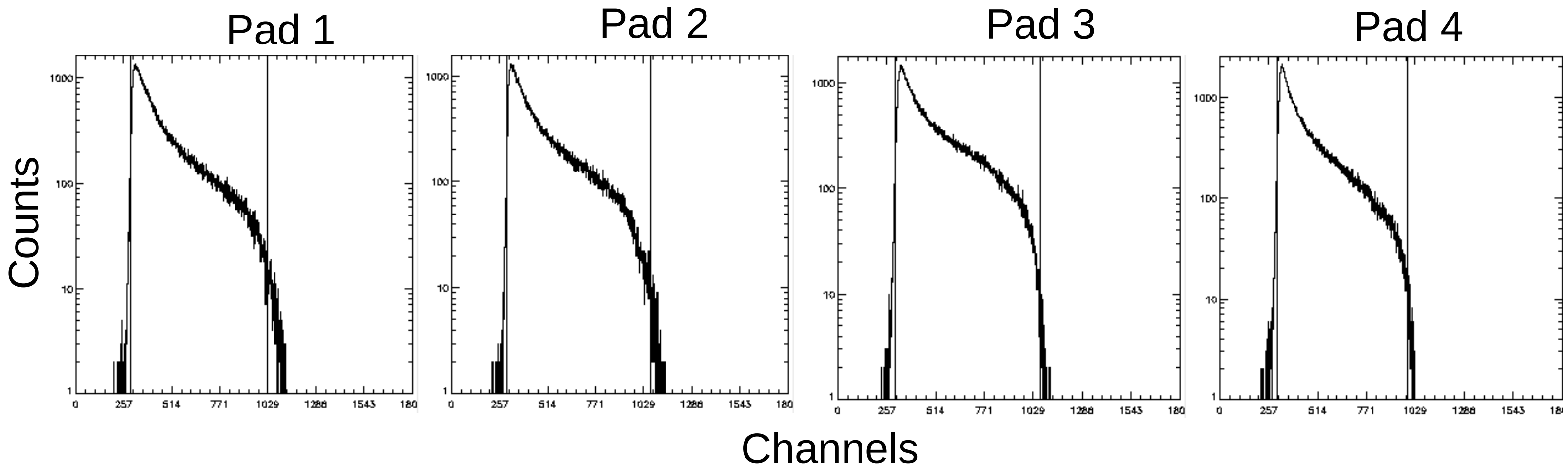
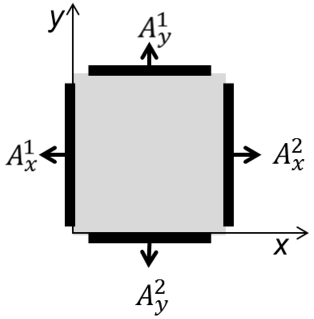
Pad signals calibration: baselines subtraction and gains calibration

Pad spectra are used to subtract offsets and equalize gains of individual pads
(we use pad-to-anode ratio, P/A)

8x8x32 mm^3 detector
Bias 3700 V, ^{137}Cs source



- Pad amplitudes are plugged into the center of gravity formulas to evaluate XY coordinates

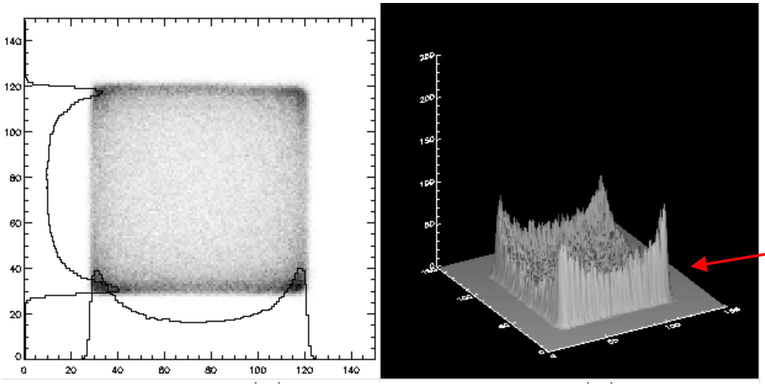


$$X = \frac{A_x^2}{A_x^1 + A_x^2}$$

$$Y = \frac{A_y^2}{A_y^1 + A_y^2}$$

Events distribution project on XY plane

The amplitude of the signal on the pad is roughly exponential with distance



- There are some geometrical distortions caused by using the CG formulas: coordinates are gradually compressed toward the edges
- This normally results in the apparent higher count rates near the edges

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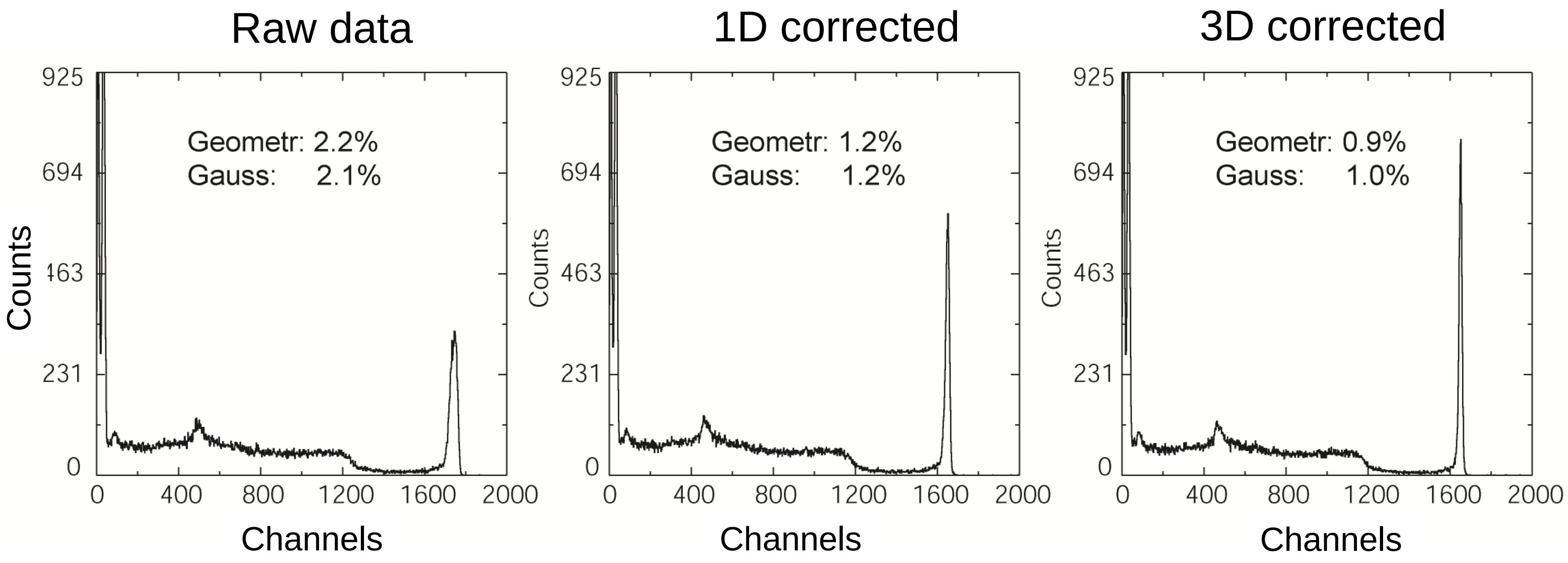
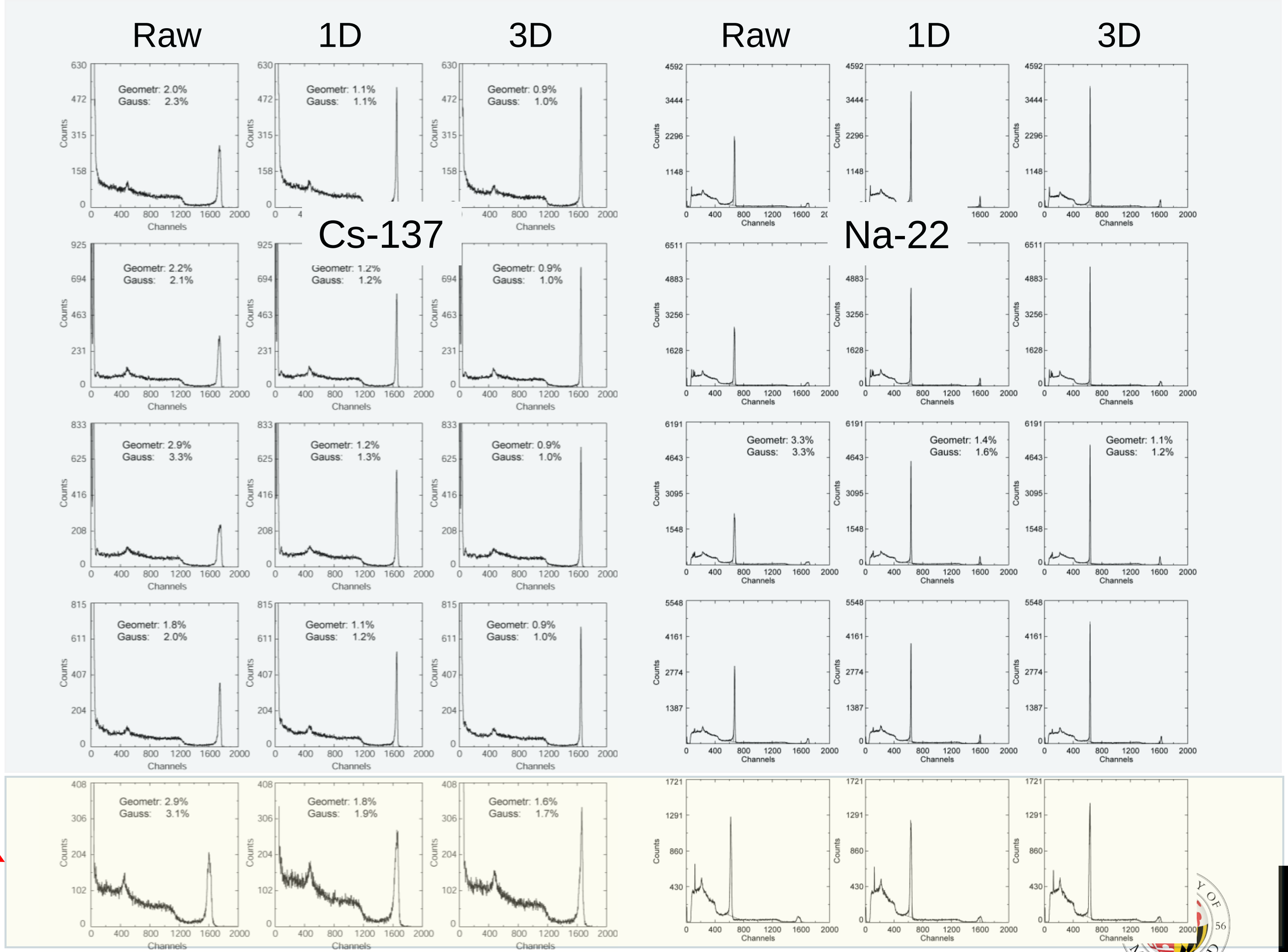
Applying 3D corrections

- Using position sensitivity, we virtually divide a detector into small voxels, typically 20x20x30 voxels
- During the calibration, we equalize spectral responses measured from each voxel by placing the photopeaks in the same channel
- The corrected gains are stored in a 3D look-up matrix used to **correct anode signals on the fly**



Spectra measured with 8x8x32 mm^3 detectors before and after corrections, bias 3700 V

- The energy resolution is ~1.0% FWHM at 662 keV, limited by electronic noise (additional coherent noise coming from the cooling system)
- We found two detectors with notably worse performances (one is shown here)

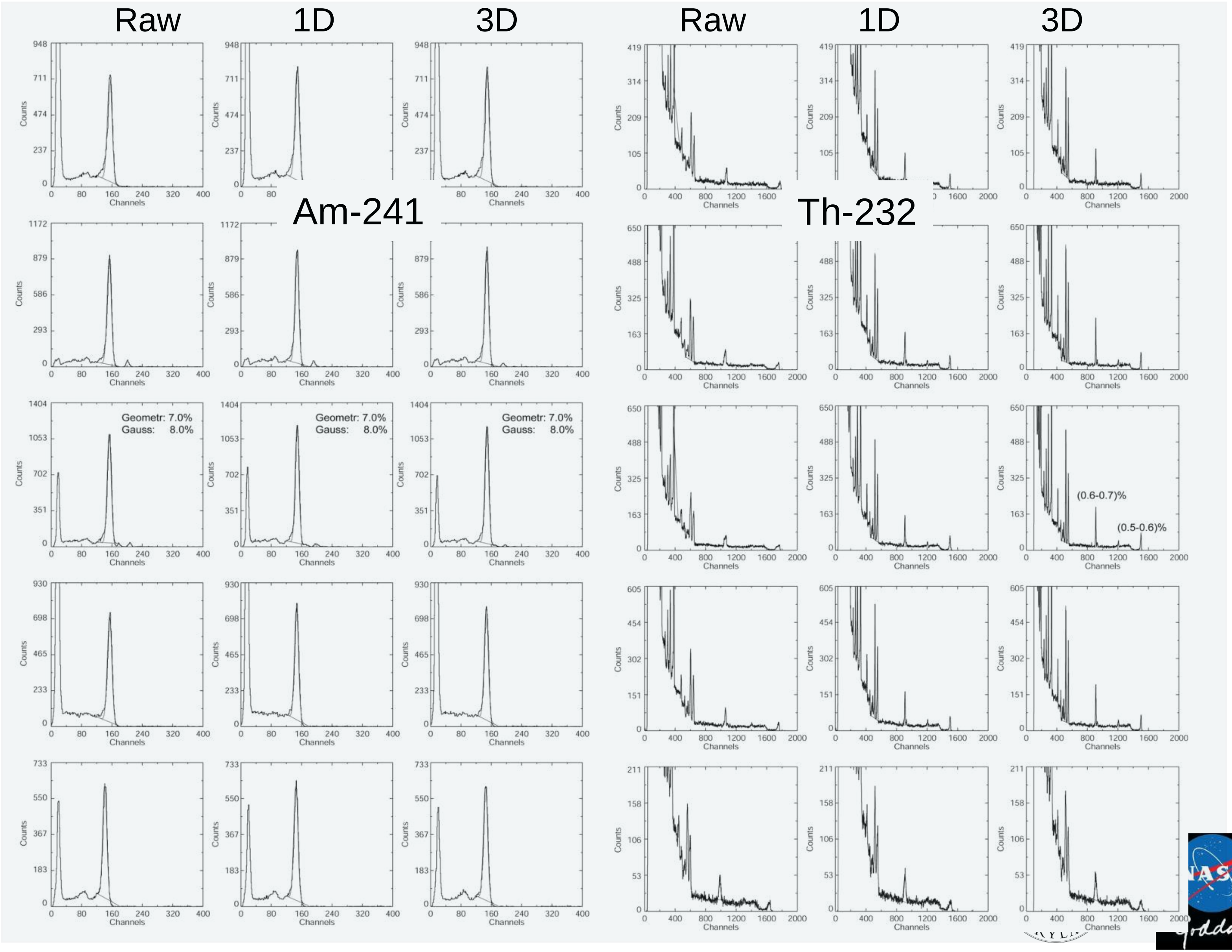


Am-241 and Th-232 spectra measured with 8x8x32 mm^3 detectors before and after corrections, bias 3700 V

- The energy resolution is 7-8% FWHM at 59.5 keV limited by electronic noise, ~4.5 keV
- The energy resolution is 0.5-0.6% at 2.6 MeV

- These results demonstrate a good performance of the array despite the fact that detectors have large anodes (capacitance)

- 2 detectors showed slightly poor performance
- To investigate this, we screen the crystals using a special technique that allowed us to reveal crystal defects



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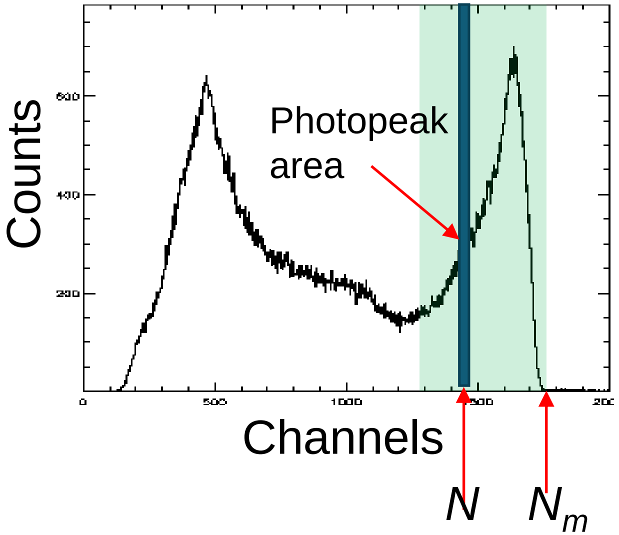
Using position sensitivity for revealing defects in VFG detectors (we applied this method for CZT and TlBr)

Example of the uncorrected spectra



- The charge collection efficiency (CCE) can be evaluated for the photopeak events as:

$$CCE = \frac{N}{N_m},$$

where N_m is the maximum collected charge and N is the energy bin of interest

Using position sensitivity, we can identify the locations of the events corresponding to particular magnitudes of CCE

There are several possibilities for plotting such events:

(1)

- Plot *XY* dependence of *CCE* (*CCE* map), which is equivalent to X-ray response mapping
- *CCE* must be first averaged over interaction depths, or a specific depth should be selected

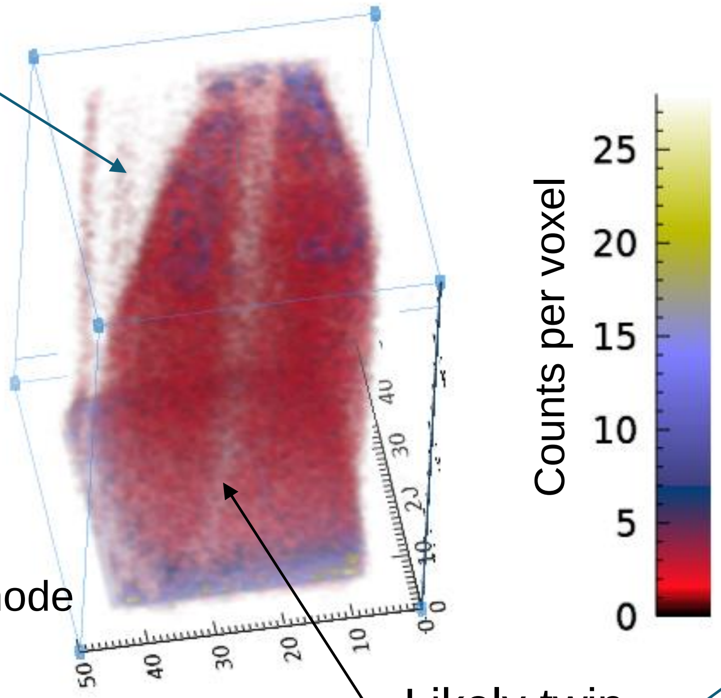
(2)

- Plot *volume* event distribution
- The events with a poor *CCE* will be missing in such plot, causing empty regions

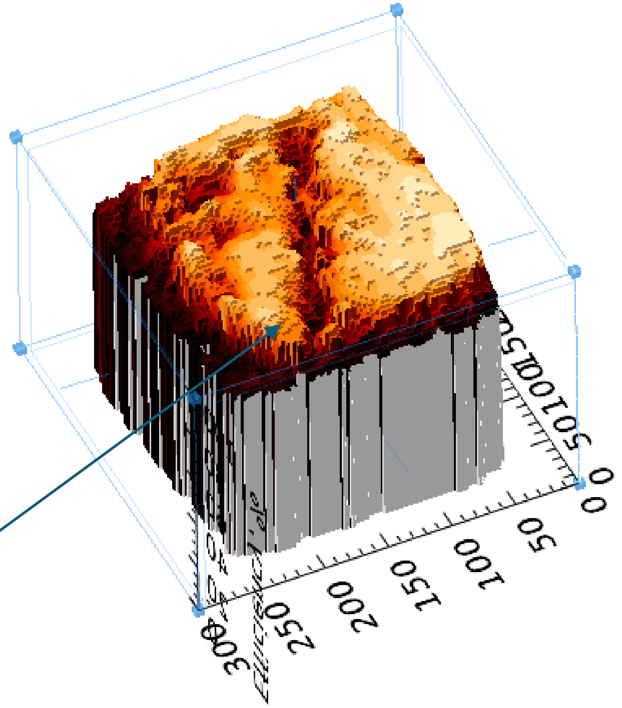
Both plotting methods complement each other (example of a 5x5x15 mm^3 TlBr detector)

Example of detectors with twin and sub-grain boundaries

Volume event distribution showing “empty” regions inside the detector



Charge collection efficiency map



Slide from a presentation at SPIE Optics + Photonics Conference this year “Performance Characterizations of Position-Sensitive Virtual Frisch-Grid TlBr Detectors”

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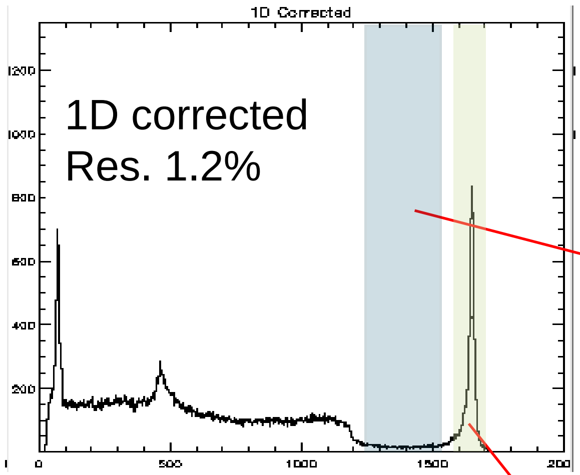
BTI BUBBLE Technology Industries

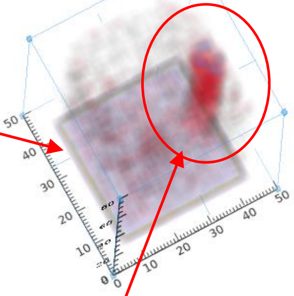
RMD A Dynasil Company

Example of a 6x6x20 mm^3 CZT detector with defects

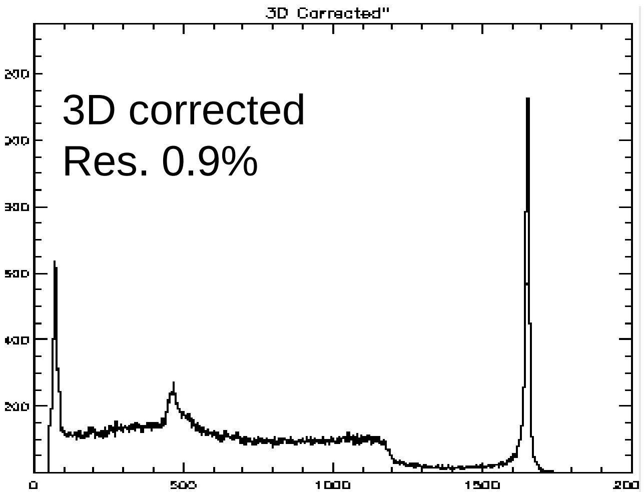


Plotted events are from the region between the Compton edge and photopeak

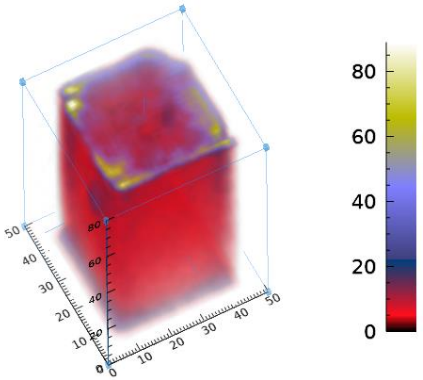
“Blue” events



Missing events from the photopeak are found in this region!

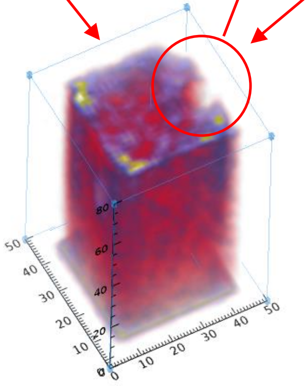


All events

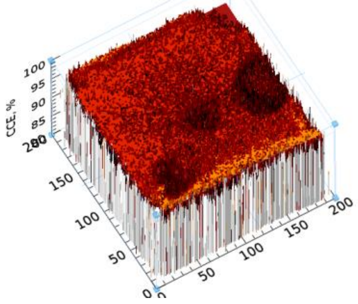


“Green” events

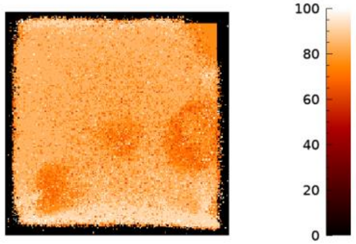
Photopeak events



CCE map

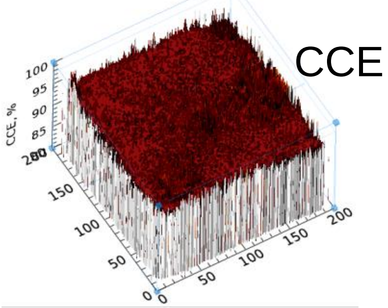


CCE

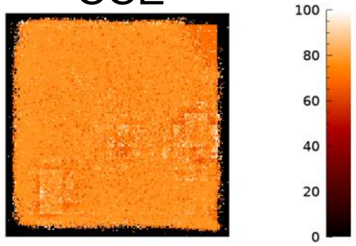


Charge losses correlate with coordinates, thus can be corrected

After 3D corrections



CCE



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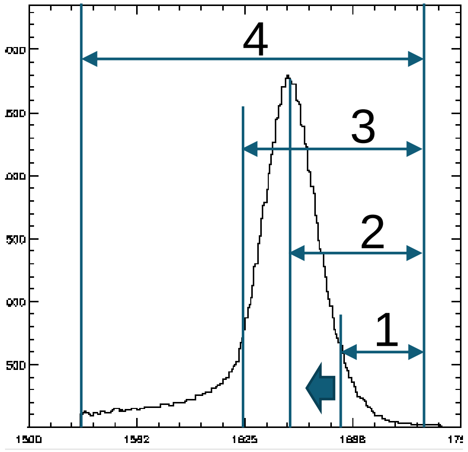
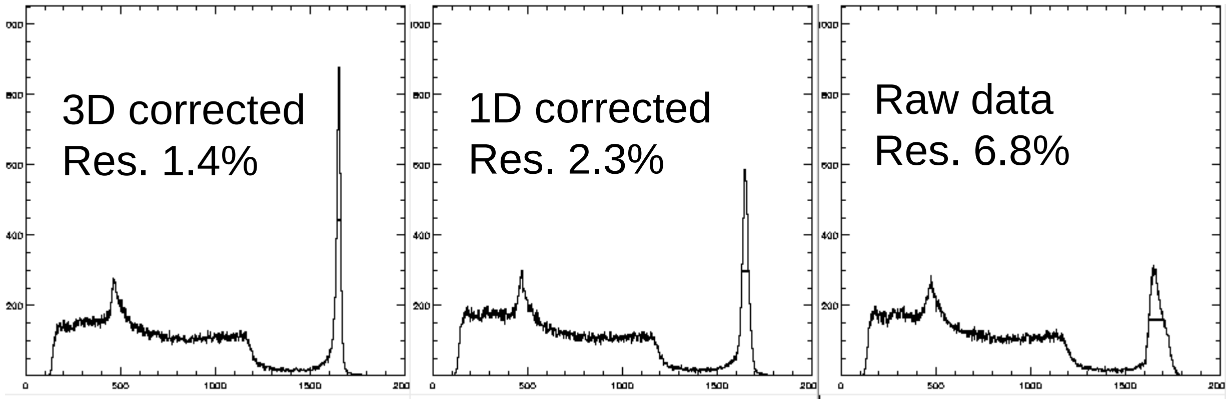
Example of a 6x6x20 mm^3 CZT detector with Te inclusions

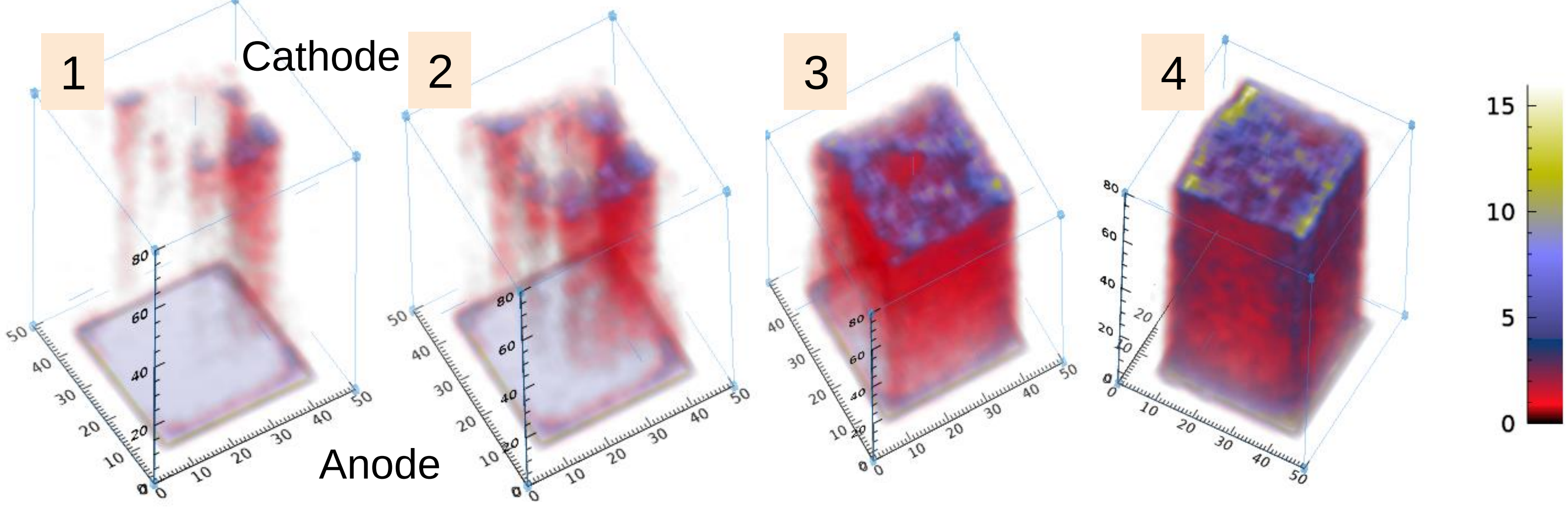


By moving the threshold to the left we ”fill” the detector volume with events

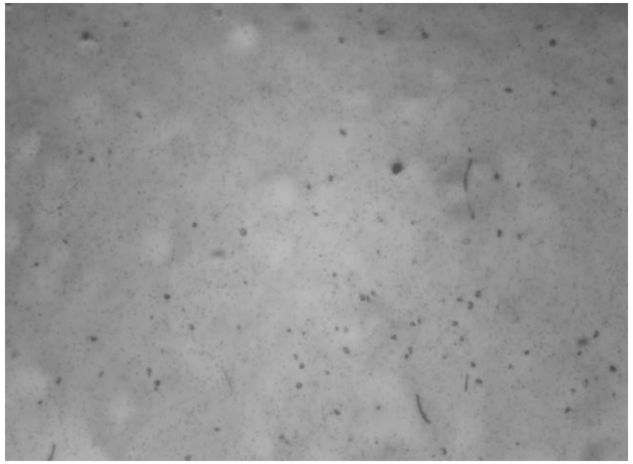
Cs-137 spectra



Photopeak events selected from different energy intervals



IR image 1x1.5 mm^2



Such pillar-like structures are caused by large defects, e.g., Te inclusions and defects at the anode surface damage

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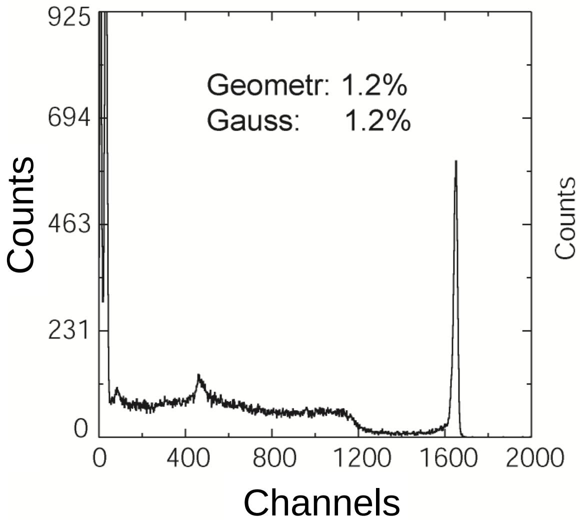
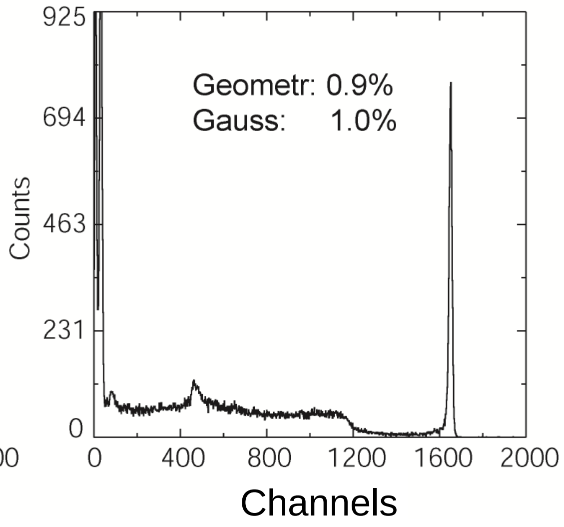
8x8x32 mm³ detector with good performance

After 1D corrections



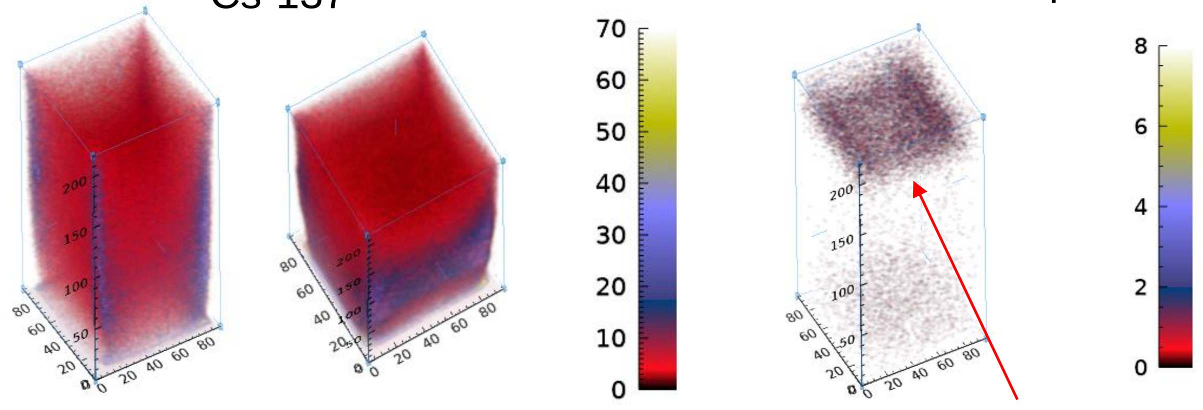
After 3D corrections



Volume distribution of the vents from the photopeak

Cs-137

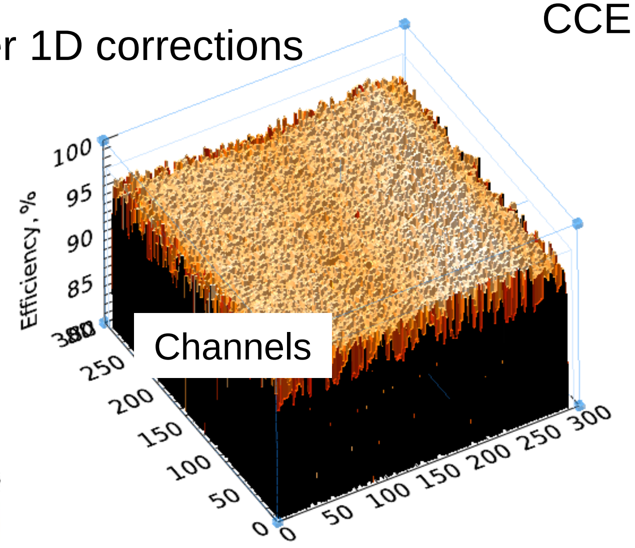
Am-241 on top



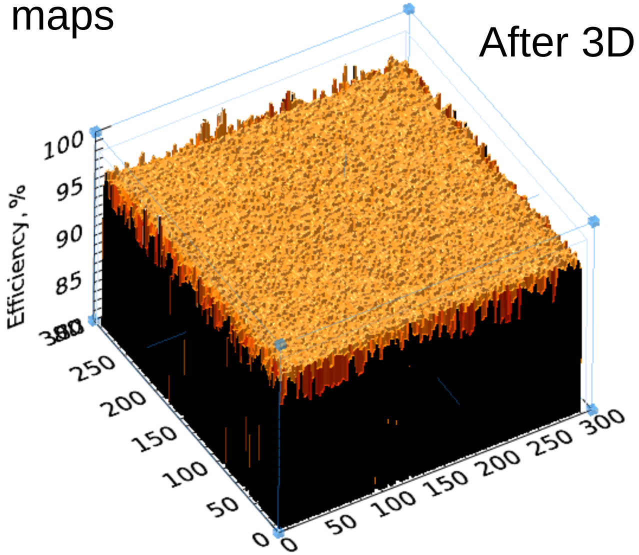
Events concentrated near the cathode

CCE maps

After 1D corrections



After 3D corrections



Variations of CCE correlated with coordinates can be corrected; however, small ripples are due to electronic nose

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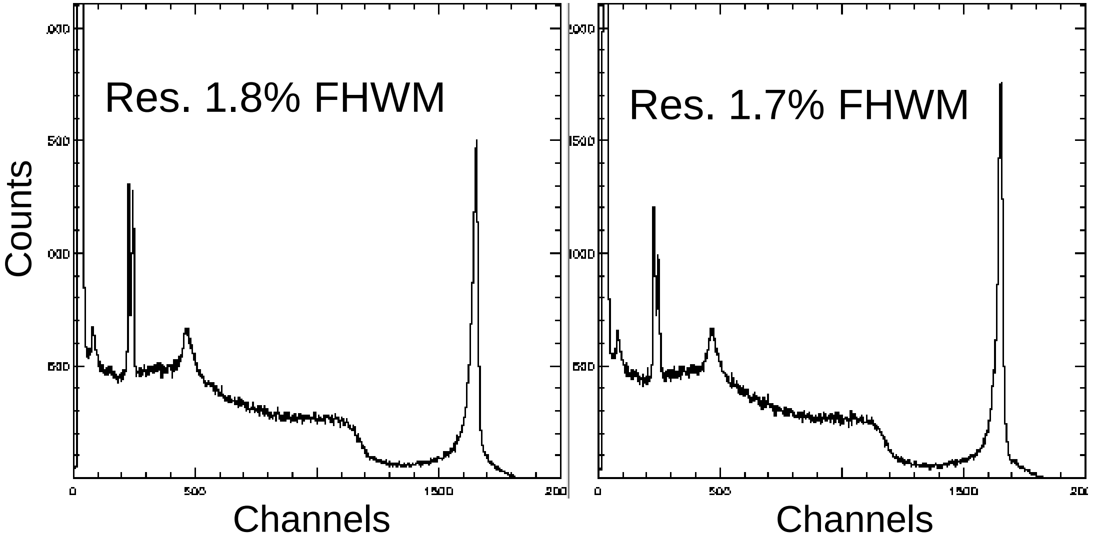
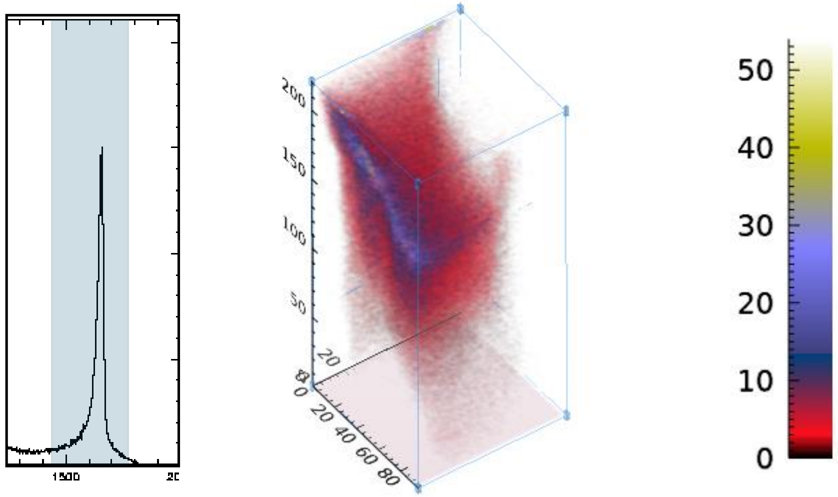
8x8x32 mm^3 CZT detector with poor performance

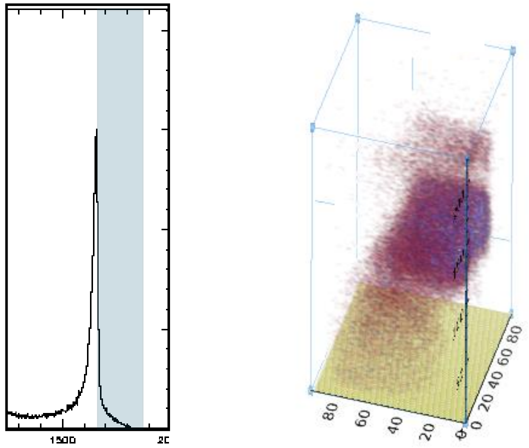
After 1D corrections   After 3D corrections



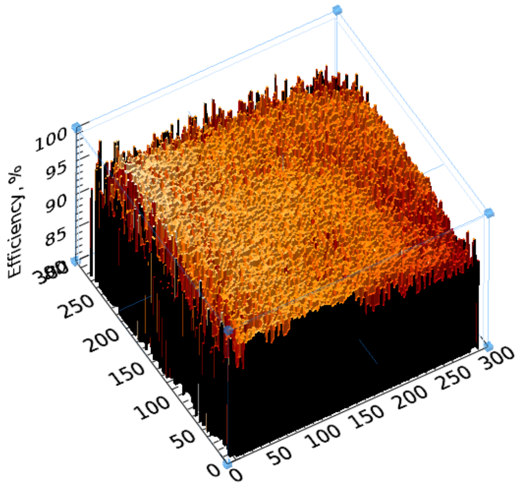
All events from the photopeak



Events from the tail



CCE map



- Volume plots indicate that the crystal has twin boundaries, which was confirmed with IR transmission microscopy
- The sample also has Te inclusions

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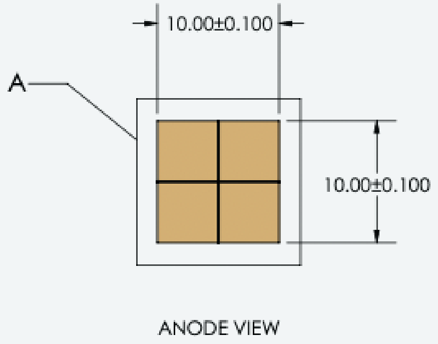
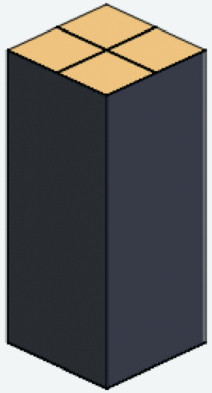
10x10x32 mm^3 detector with the 2x2 pixel anode

- In the past we demonstrated good performance of 10x10x32 mm^3 VFG detectors, however, the main drawback of using such big detectors is that it is difficult to handle multisite events whose probability increases with crystal dimensions
- A possible solution is to use a hybrid design: VFG with the 2x2 pixels or 3x3 pixels, taking advantage of both designs
- This design improves energy resolution (by *reducing the anode capacitance and the leakage current*) and helps to reconstruct multisite events

We tried to refabricate two 10x10x32 mm^3 VFG detectors; unfortunately, one sample (with best performance) was damaged during the fabrication

10x10x32 mm^3 detector with 2x2 pixels, 100-micron gaps





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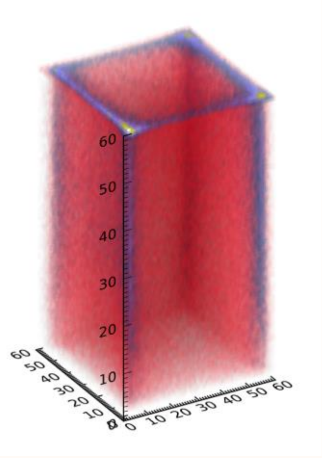
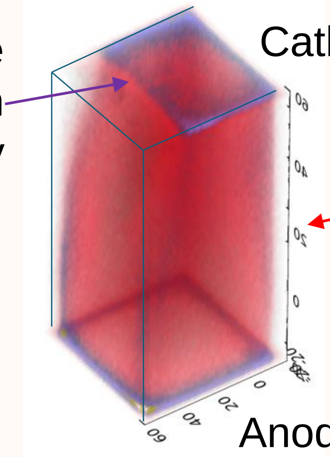
Volume events distributions plotted for two 10x10x32 mm^3 crystals used to fabricate



Likely the twin boundary



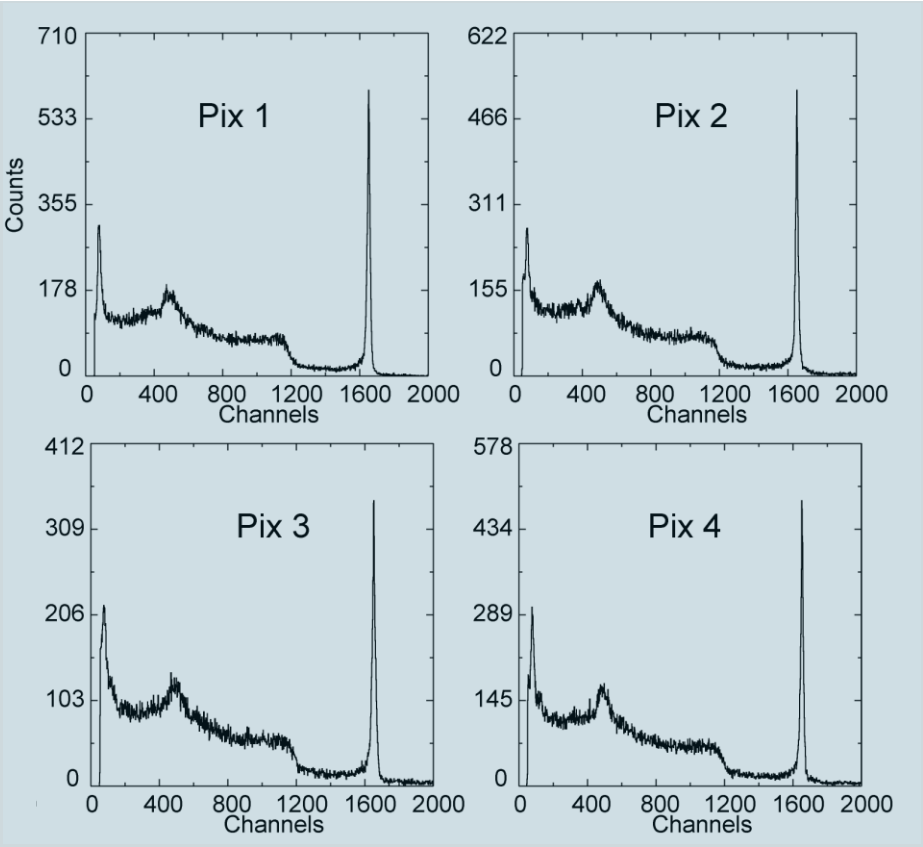
Cathode

The crystal was used for the fabrication
Also, the anode and cathode were switched

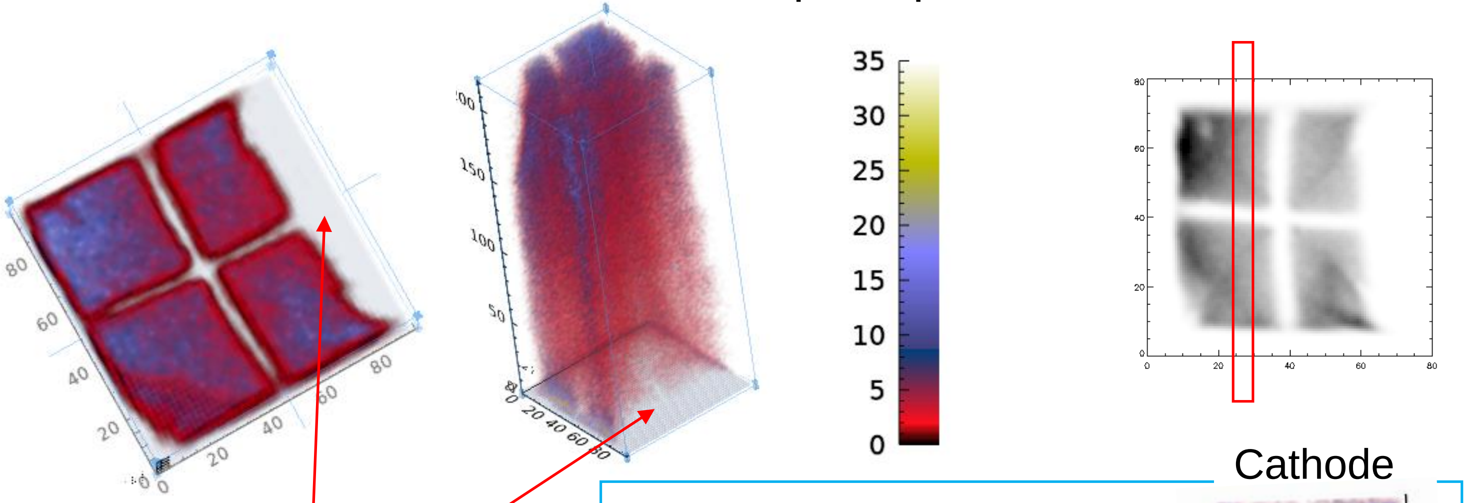
Anode

Results from testing 10x10x32 mm^3 CZT detector with the 2x2 pixel anode

Cs-137 spectra measured from 4 pixels, bias 3700 V
Energy resolution ~1.1% (el. noise limited)

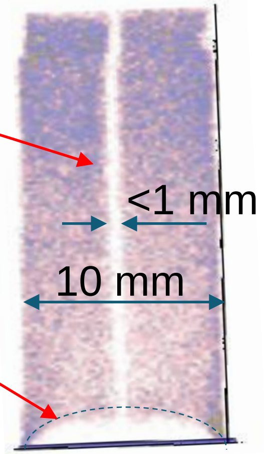


Volume distribution of photopeak events



The missing events are due to the twin boundary that tilts electric field lines toward the side of the detector

- Cross-section of the volume distribution
- 100-micron gap between the pixel contacts
- Curved surface identifying the virtual Frisch-grid



A 100-um gap between the pixels is clearly seen in the plots, demonstrating a good position resolution of < 1 mm

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Conclusions and future plans

- We tested a small CZT array prototype based on 8x8x30 mm^3 crystals and the DGS-100 readout system
- Good energy, < 1% FWHM at 1 and <0.6% at 2.6 MeV, and position, < 1 mm, resolutions
- Our next step is to fabricate 4 full crates and test them as an array with a DGS-100 readout system
- Develop a new readout system with a wide dynamic range, faster, lower power for space applications

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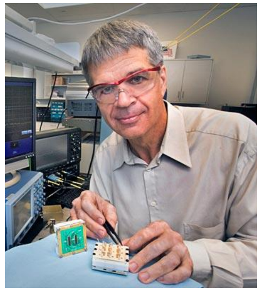

Acknowledgments

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