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Development of position-sensitive Frisch-grid CdZnTe detectors for gamma-ray imaging

A. Bolotnikov[a], G. Carini[a], A. Dellapenna[a], J. Fried[a], G. Deptuch[a], J. Haupt[a], R. S. Herrmann[a], A. Moiseev[b], G. Pinaroli[a], M. Sasaki[b], E. Yates[b], R. James[c]

[a]Brookhaven National Laboratory, Upton, NY 11793, USA
[b]CRESST/NASA/GSFC and University of Maryland, College Park, MD 20771, USA
[c]Savannah River National Laboratory, Aiken, SC 29808, USA

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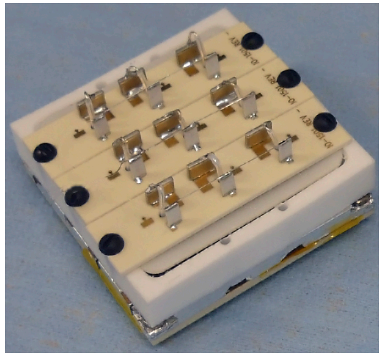
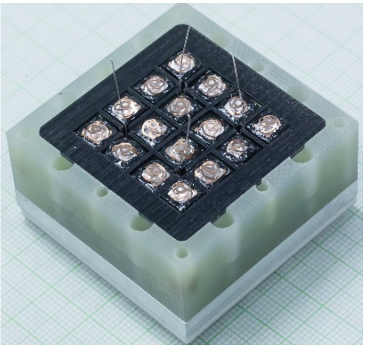
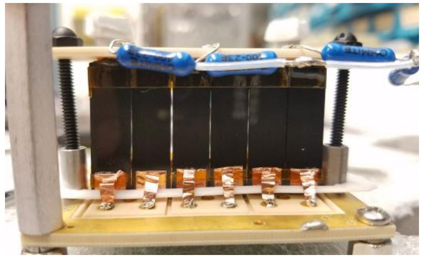
Position-sensitive virtual Frisch-grid (VFG) CdZnTe (CZT) detectors

6x6 array of 5x5x15 mm^3 detectors

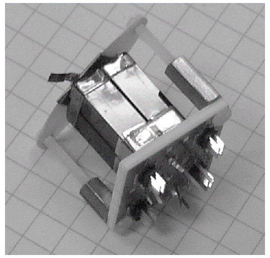


4x4 array of 6x6x20 mm^3 detectors





Linear array of 6 5x7x25 mm^3 detectors for low energy gamma rays (186 keV)



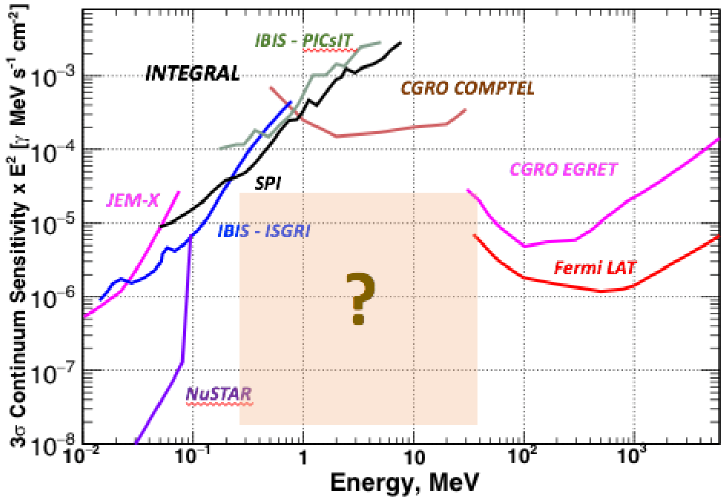
2x2 array of 6x6x20 mm^3 detectors for a handheld instrument

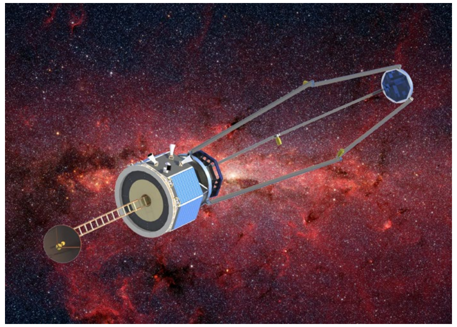
- The VFG design represents an economical way for making CZT detectors with good energy resolution, high detection efficiency and sub-mm position resolution
- Position-sensitive VFG detectors operate as mini TPCs
- 3D position sensitivity allows for correcting response non-uniformities often seen in large-volume CZT crystals, which is the main technological barriers limiting application of CZT detectors today

Arrays of position-sensitive CdZnTe for gamma-ray telescopes

- There is a growing interest in the development of gamma-ray telescopes operating in the MeV energy band (from 100 keV and up to 20 MeV) for astronomical observations
- The MeV energy range is the least explored because of the low intensities of cosmic gamma rays in this range and their high penetrating ability, which makes them difficult to detect
- Detection of the MeV photons requires high density and high Z
- In addition, the detectors should provide position sensitivity in order to be used in coded aperture or Compton telescopes
- Promising candidates for such telescopes are arrays of position-sensitive CZT detector elements, which sizes can be expanded today up to:
  - 40x40x15 mm^3 blocks in the case of pixelated detectors or
  - 10x10x35 mm^3 bars in the case of position-sensitive virtual Frisch-grid (VFG) detectors
- Pixelated and VFG detectors are two competing technologies available today for gamma ray telescopes

Gamma ray flux sensitivity limits achieved with space instruments





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

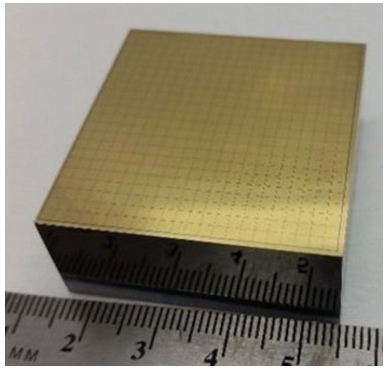
Progress in availability of CZT crystals for gamma-ray detectors

3-inch CZT ingots

- Both Redlen and Kromek can supply spectroscopic quality CZT slabs with a thickness of < 20 mm (current technological limit)
- This opens new opportunities for making large-volume detectors which were not possible before
- The charge loss corrections is a must-have feature of such big detectors, because of some non-uniformities present even in the best quality material
- Two detector designs are particularly suitable for such big crystals: H3D pixelated (University of Michigan) and position-sensitive VFG detectors (BNL)
- There are advantages and drawbacks of these devices used as building blocks in detection planes of the telescopes

CZT crystals possible for for the large-volume pixelated detector H3D detectors (developed by Michigan University)

40x40x15 mm^3



10x10x32 mm^3

CZT bars for position-sensitive virtual Frisch-grid detectors developed by BNL

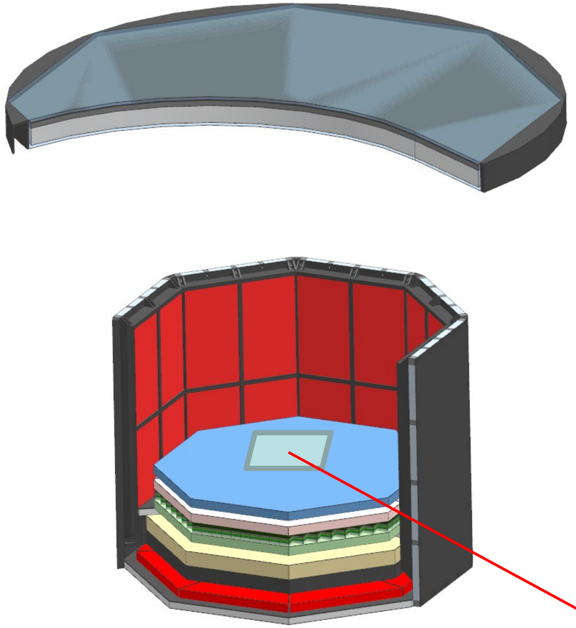
Comparison between pixelated and position-sensitive VFG CZT detectors

	Pixelated	Position-sensitive VFG
Max array thickness	15 mm	35 mm
Max area of a single detector in arrays	40x40 mm^2	10x10 mm^2
Energy resolution, % FWHM at 662 keV	0.5-0.7	0.9-1.1
3D position resolution	< 1 mm	< 1 mm
Number of readout channels	Larger	Smaller
Good crystals yield	Lower	Higher
Expected cost	Higher	Lower

- There are pros and cons of these two approaches
- Cost/availability/performance trade-offs

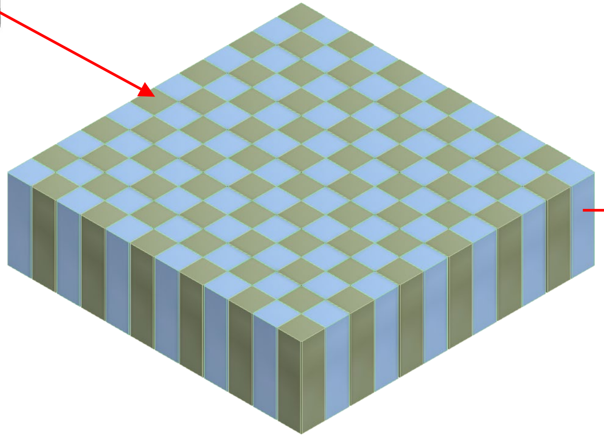
Position-sensitive VFG detectors are very suitable for the detection planes of gamma ray telescopes

GECCO schematics

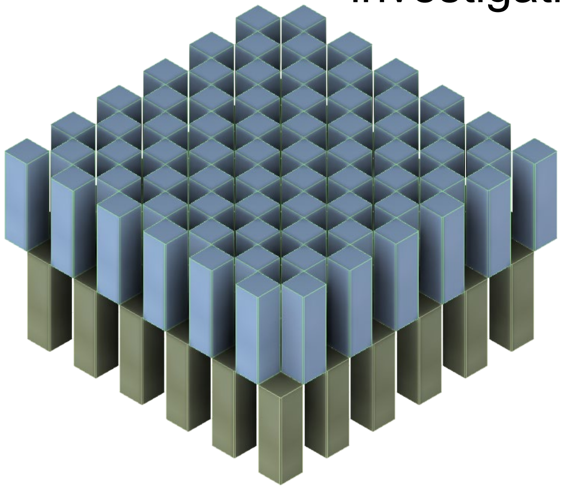


- GECCO is Coded Aperture – Compton telescope with a deployable mask
- Hexagonal detection plane has an area of ~1 m^2
- It consists of two layers of the detector bars separated from each other to increase photons scattering distances
- 8x8x30 mm^3 CZT bars are optimal for this design: a compromise between the bar separation and fabrication steps

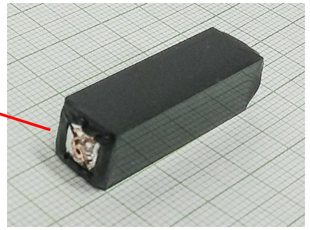
CZT detector plane



Two-layer calorimeter (with openings to increase scattering distances between interaction sites) is currently under investigation



8x8x30 mm^3

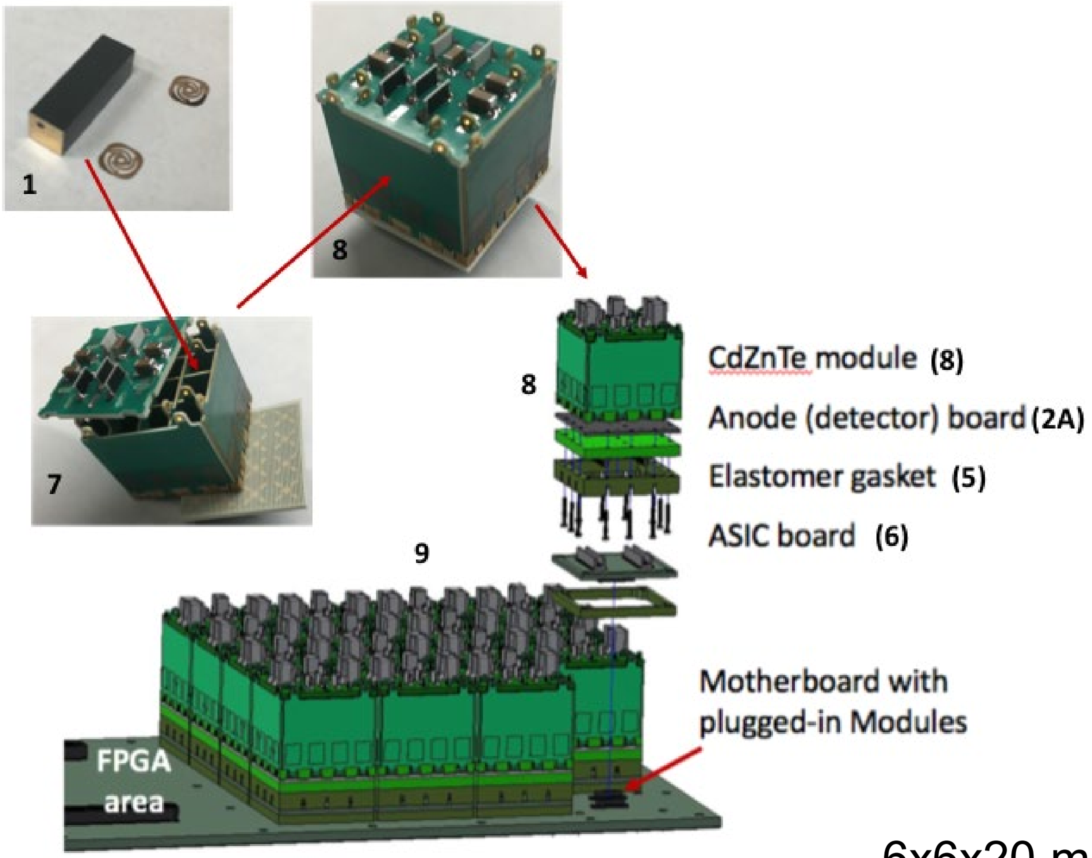


Angular resolution (FWHM) < 8 degrees in Compton mode and < 1 arc-min in coded aperture mode

Testing array prototypes for future detector planes

- Use modular approach: each module (crate) has 4x4 detectors
- Each crate is read out by a single ASIC

Artistic concept of the Lego-like block design



4x4 6x6x20 mm^3 CZT crate

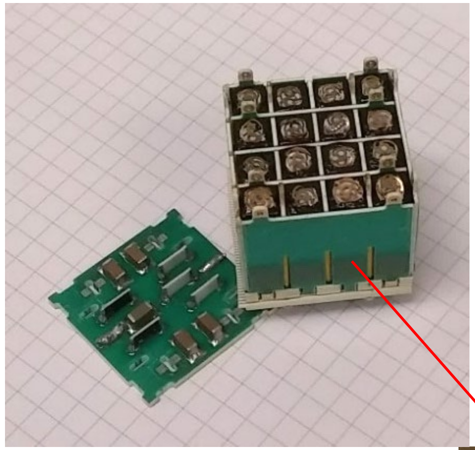
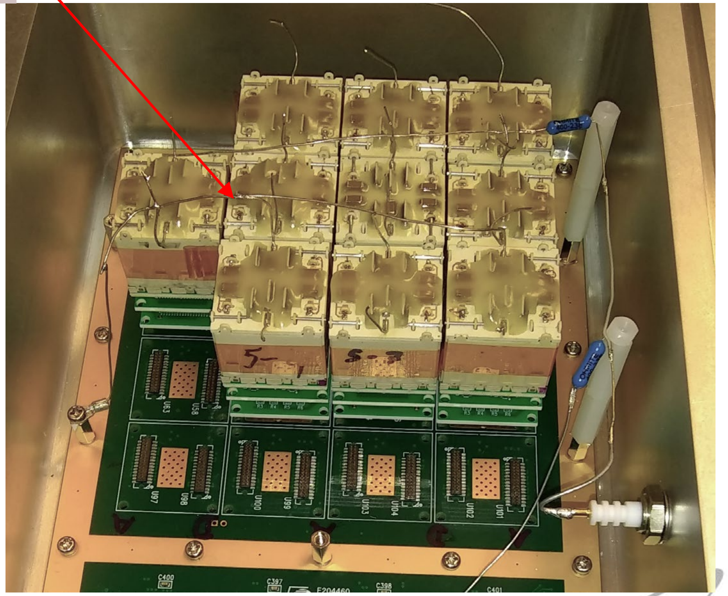


Image of 10 crates plugged into a motherboard

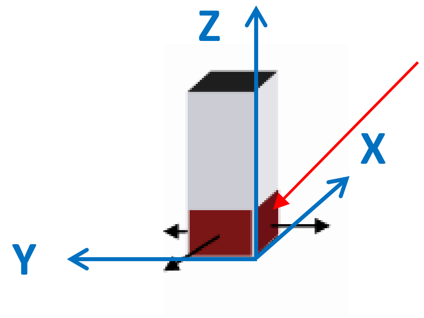


6x6x20 mm^3 -> 8x8x32 mm^3

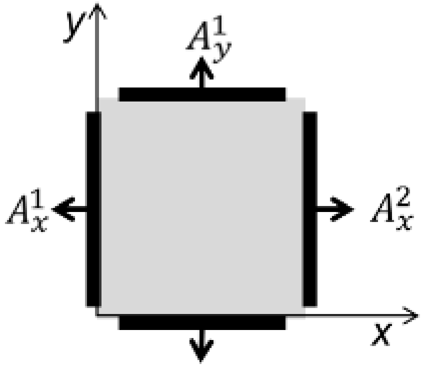
Position-sensitive VFG detectors: 3-D corrections

- Four position-sensing pads are placed around the anode and are used to measure the interaction location for each gamma-ray event
- The cathode, anode, and four pad signals are recorded for each PSVFG device
- The pad signals give X-Y coordinates, while the cathode signals provide Z coordinates
- The drift time and cathode-anode ratio give two independent estimates for Z
- The pads are virtually grounded to ensure the virtual Frisch-grid effect

Schematic of position-sensitive VFG detector-–mini TPC



Position sensitive pads



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

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

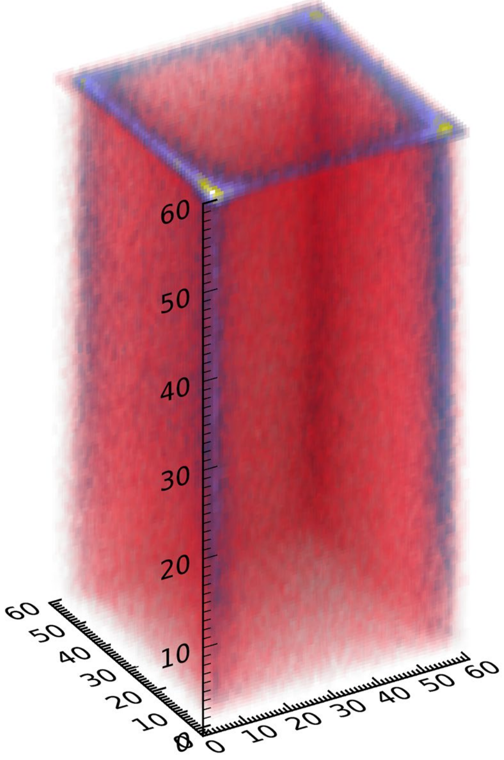
- The main advantage of position-sensitive VFG detectors is the ability to correct response non-uniformity caused by crystal defects
- Typical energy resolution is <2% at 200 keV and <1% at above 1 MeV
- Use unselected (standard grade) crystals to reduce the cost and improve performance

L.A. Ocampo Giraldo et al., IEEE Transactions on Nuclear Science 64(10), 2698 – 2705 (2017)

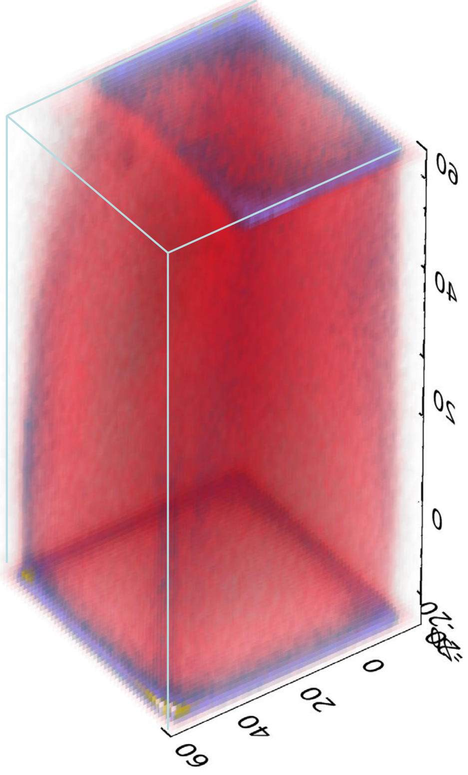
3D position reconstruction of interaction sites in 8x8x32 mm^3 detectors

Volume plots showing events distribution in 8x8x32 mm^3 detectors

Uniform crystal



Crystal with the extended defect (sub-grain boundary)

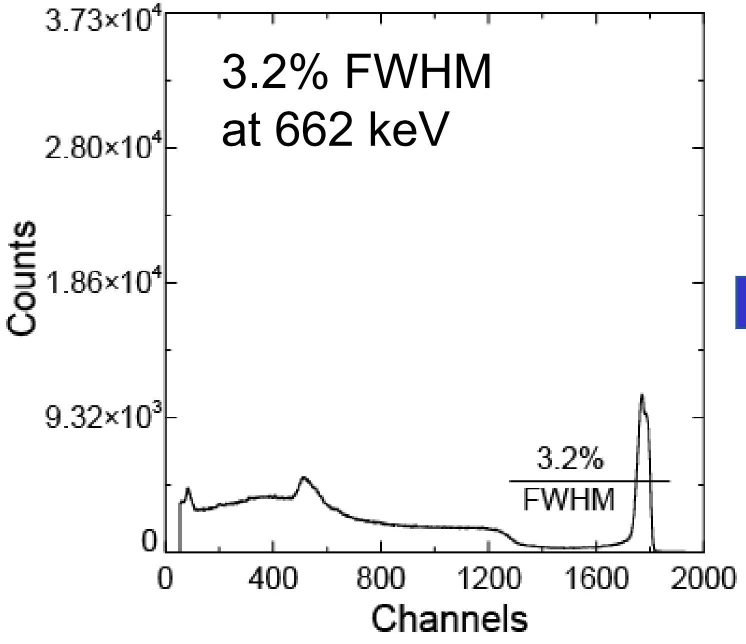


3D position sensitivity in combination with volume plotting provide good visualization of detector response uniformities

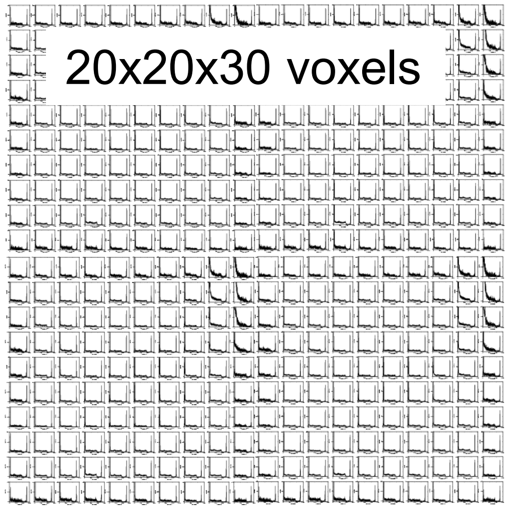
Correcting response non-uniformity: 8x8x32 mm^3 detector

Spectra measured from 8x8x32 mm^3 CZT detector
Bias: 3700 V, Waveform sampling, Cs-137 source, T=23C

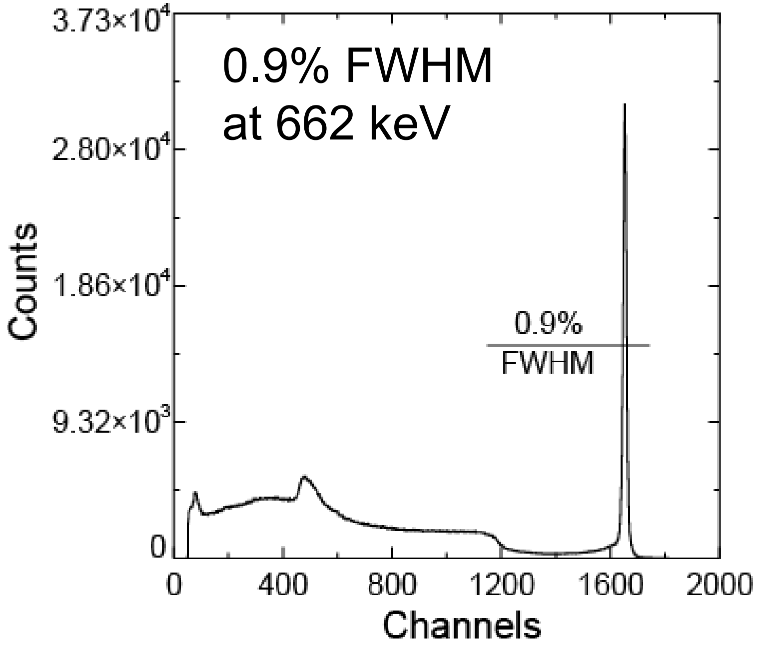
Raw spectrum



Spectra measured from individual voxels



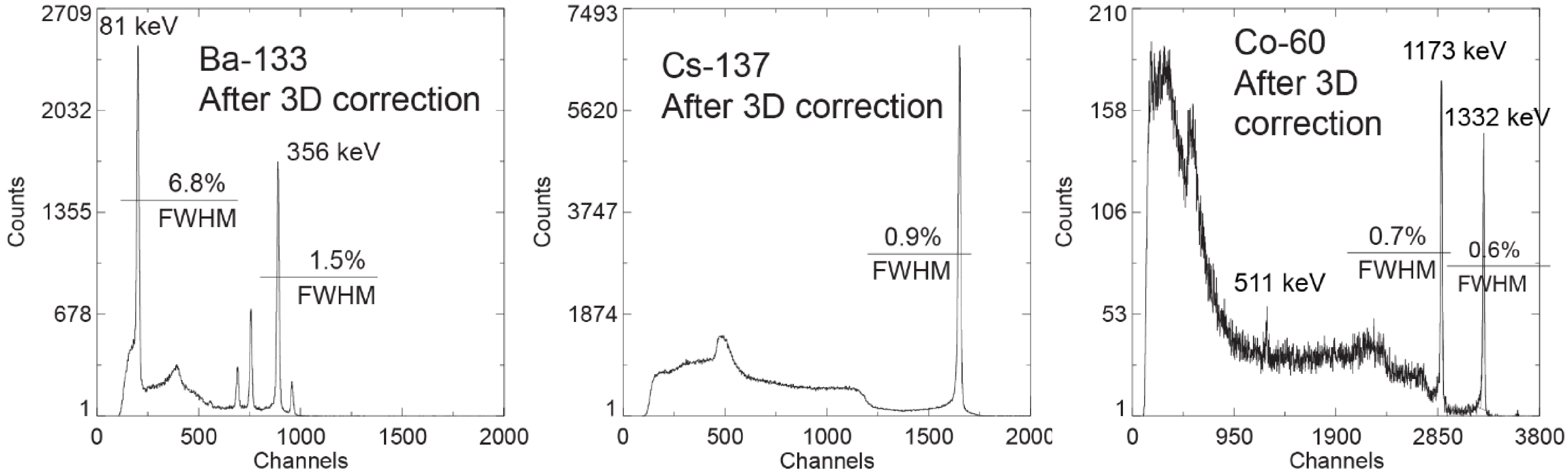
After 3D corrections



- Using position information, we can virtually segment a detector into voxels, equalize responses from each voxel, and add them together – 3D corrections

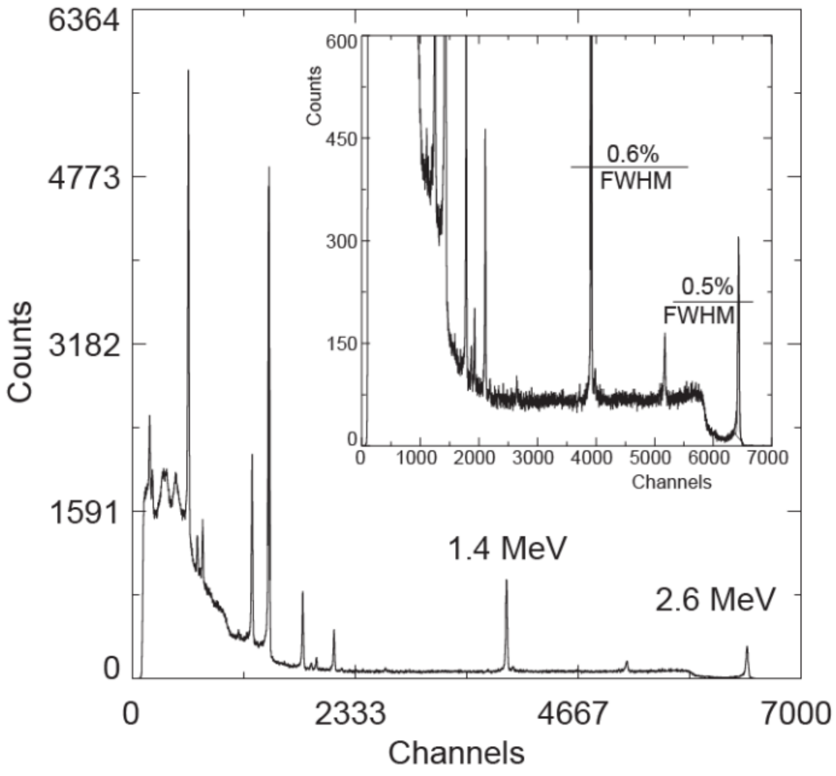
Testing 8x8x32 mm^3 CZT detector, bias 3200 V

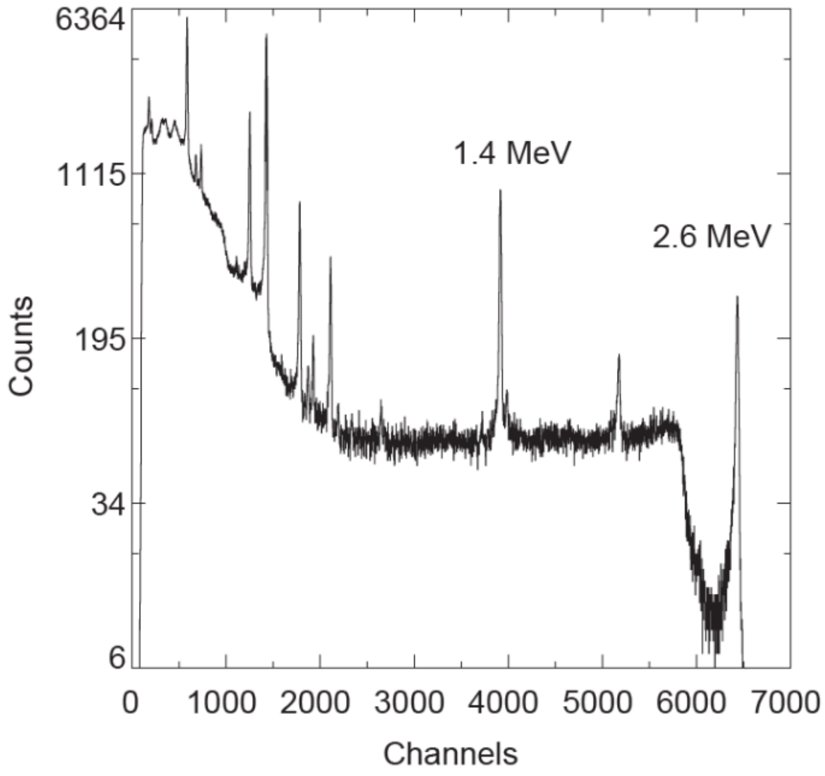
Spectra from Ba-133, Cs-137, and Co-60 check sources



Spectra measured with a large-volume 8x8x32 mm^3 Redlen detector

U-232 source through 5-mm lead (to reduce counting of low-energy photons), bias 3200 V
Gamma ray lines with energies up 2.6 MeV





- Thick CZT detectors are suitable for high-energy gamma rays

Evaluating position resolution: 10x10x32 mm^3 detector

Geometry of the experiment using 0.8-mm tungsten slits

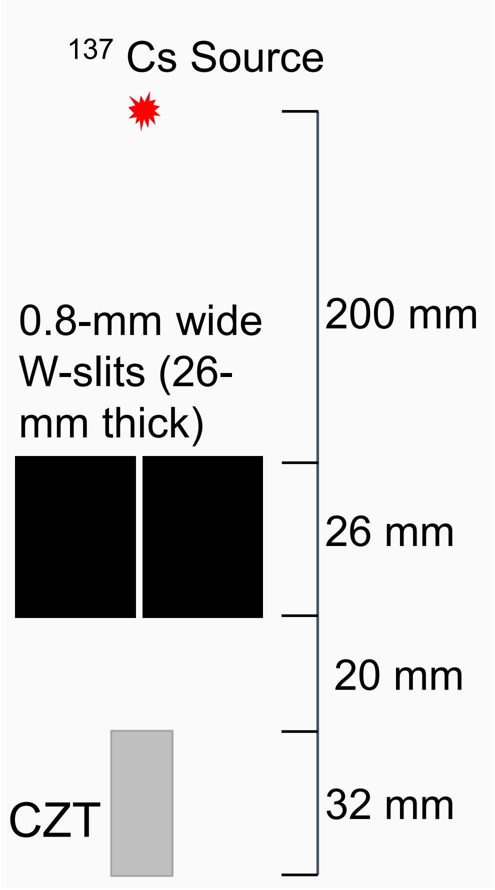
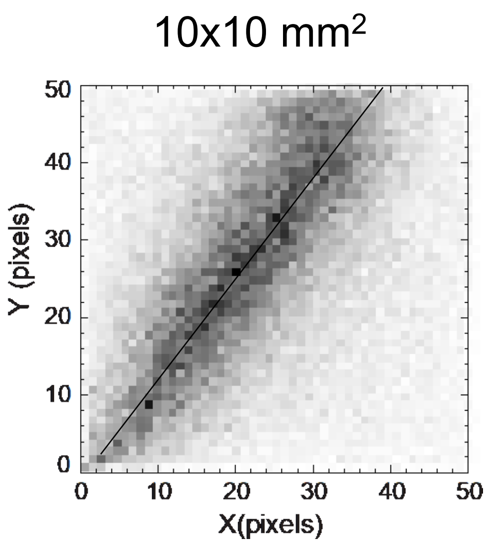
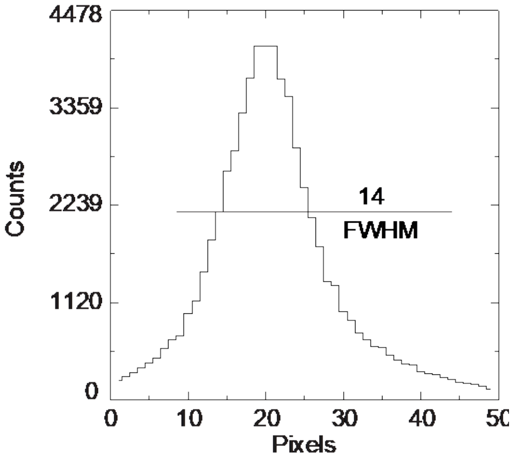


Image of the tungsten slits generated with a 10x10x32 mm^3 detector irradiated by the uncollimated Cs-137 source



X-Y distribution of the interaction events projected onto the *X-Y* plane after geometrical corrections



By comparing with Monte-Carlo simulation, we estimated the spatial resolution to be < 1 mm

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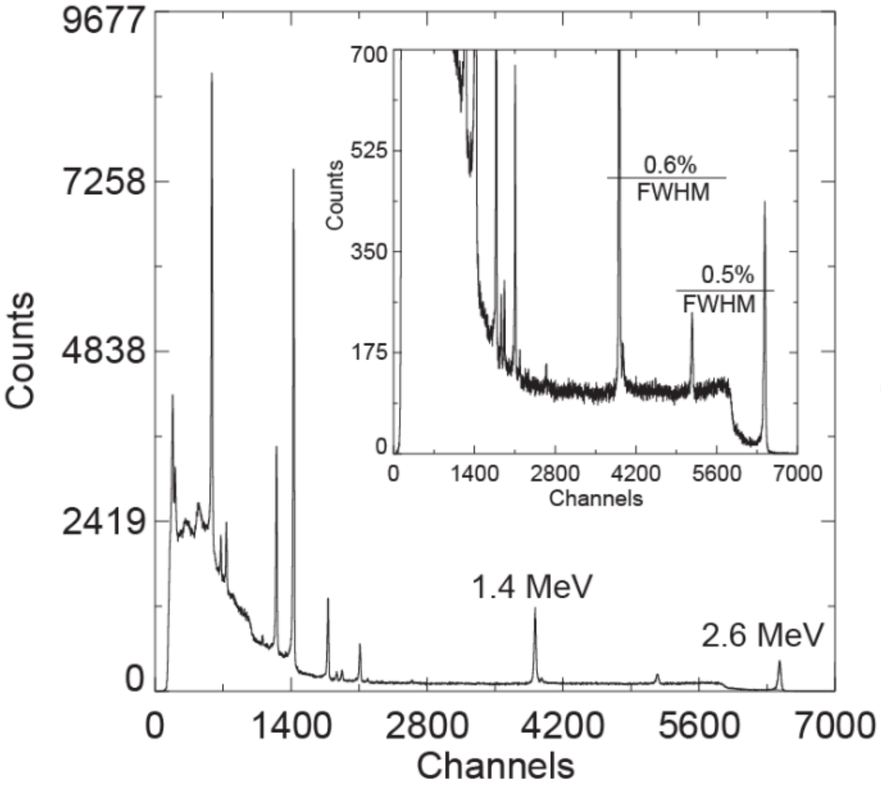
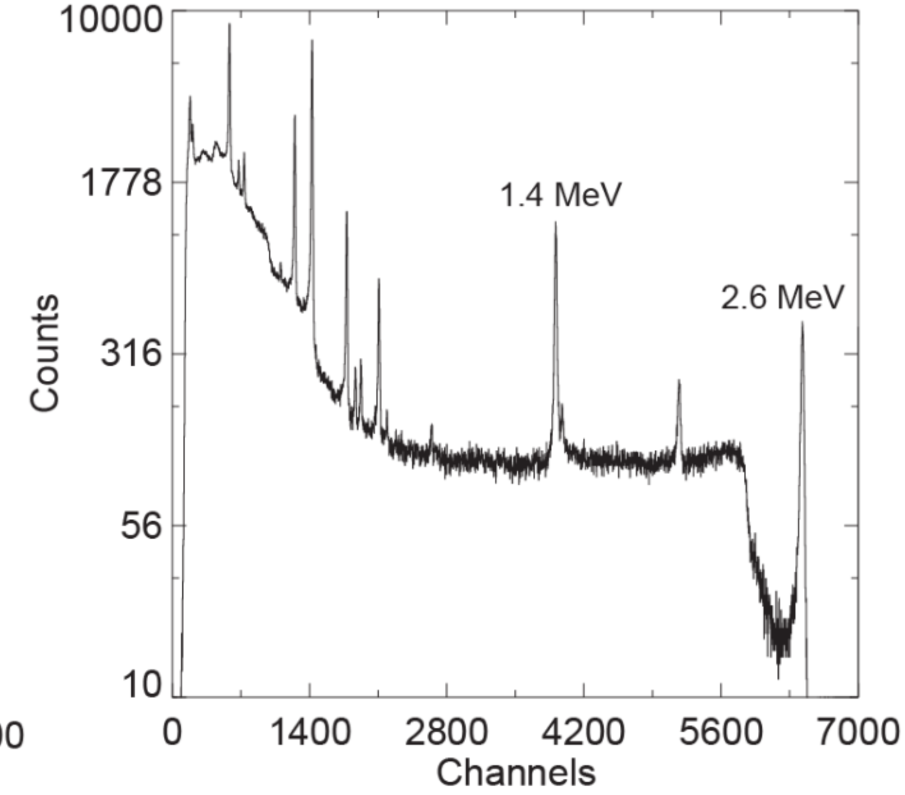
Testing 10x10x32 mm^3 CZT detector, bias 4000 V

U-232 source, bias 4000 V
Tested 2 such detectors:

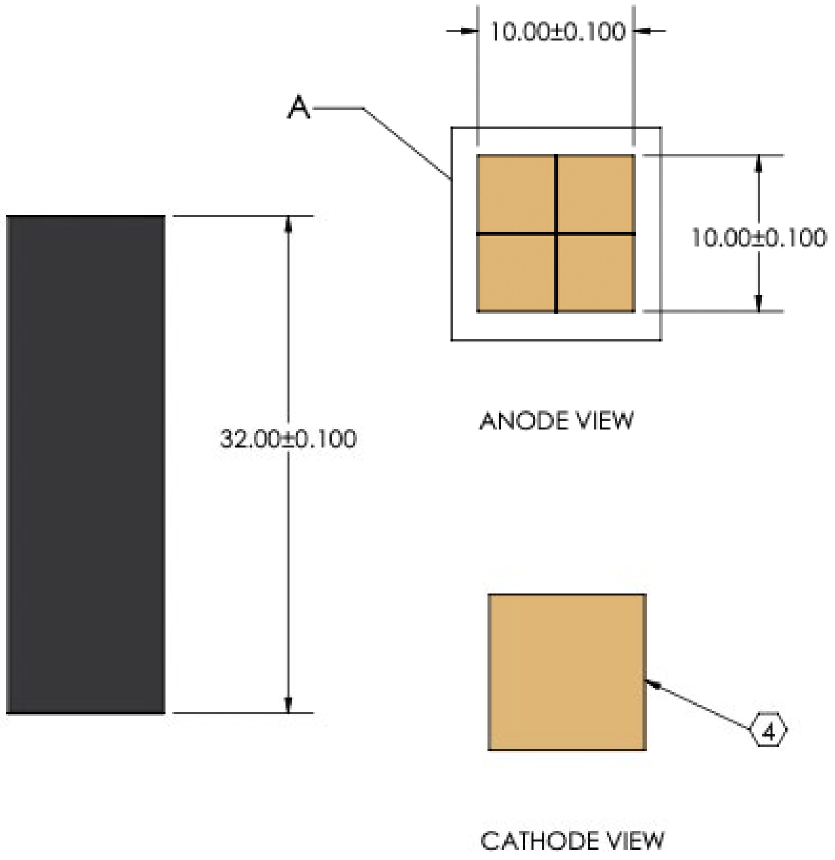
Spectra measured from the best of two detectors





Position-sensitive VFG detector with a 2x2 pixel anode

- Detector design with a 2x2 pixel anode
- We proposed this design to improve energy resolution of the detectors using the large area anodes, e.g., 10x10 mm^2 (by reducing the capacitances and leakage currents)

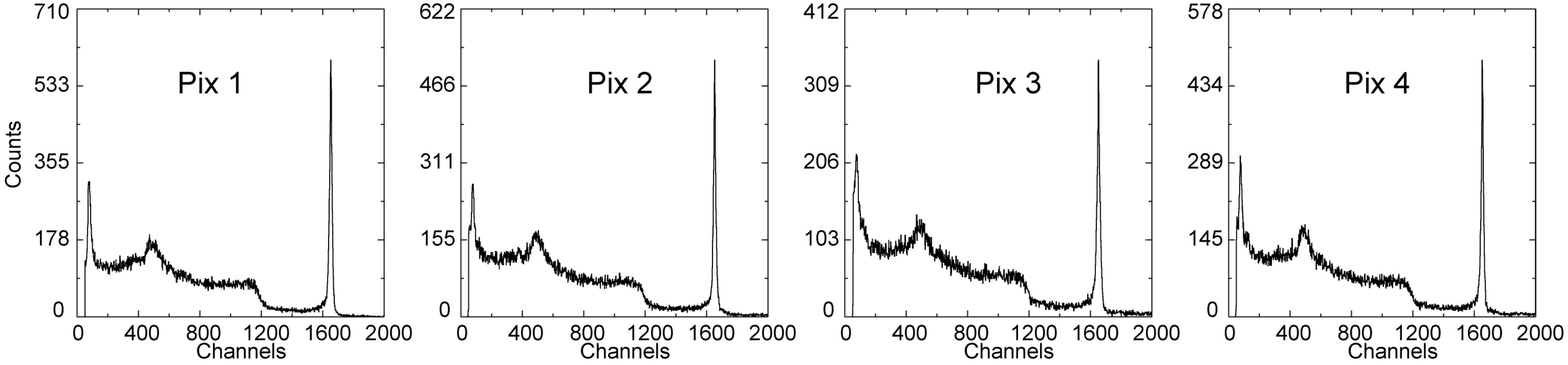


10x10x32 mm^3 detector

Another benefit of using this design: it simplifies reconstruction of the multiple site events (such events have high probabilities due to a large detector size)

Testing 10x10x32 mm^3 CZT detector with a 2x2 pixel anode

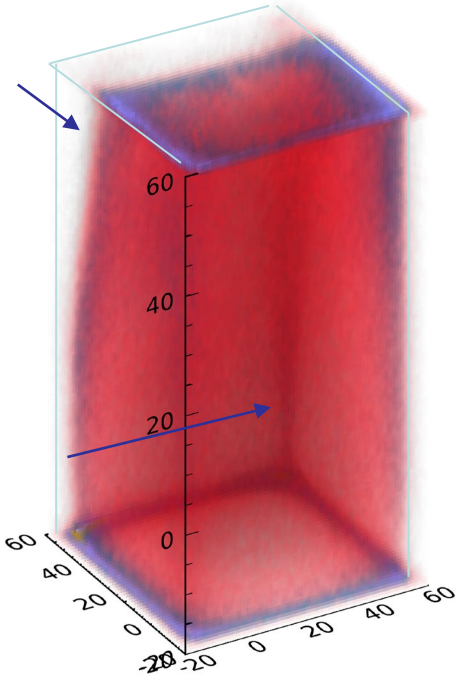
Cs-137 spectra measured from 4 pixels
Bias is 3000 V
Same energy resolution of 0.9-1.1% was measured for all quadrants
But the event count rates were different



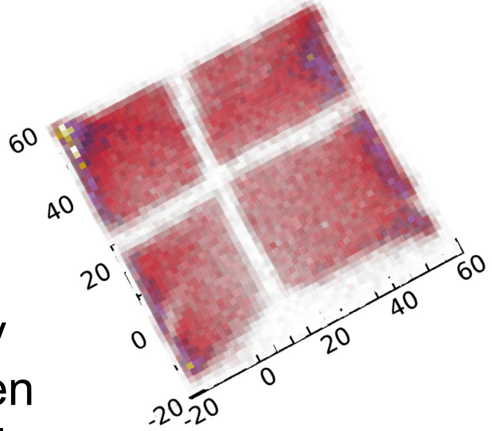
3D event distributions in 10x10x32 mm^3 with monolithic and pixel anodes

Response of the detector with the monolithic anode

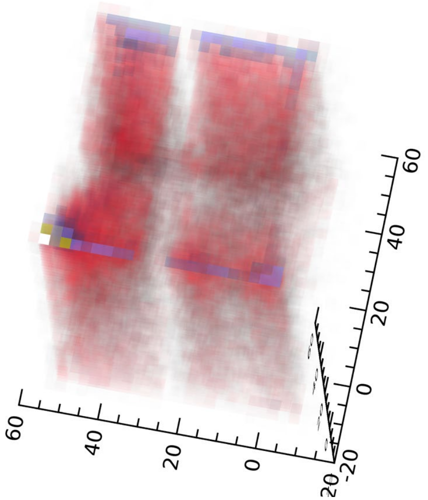
"Missing" portion of the crystal is likely caused by the defect

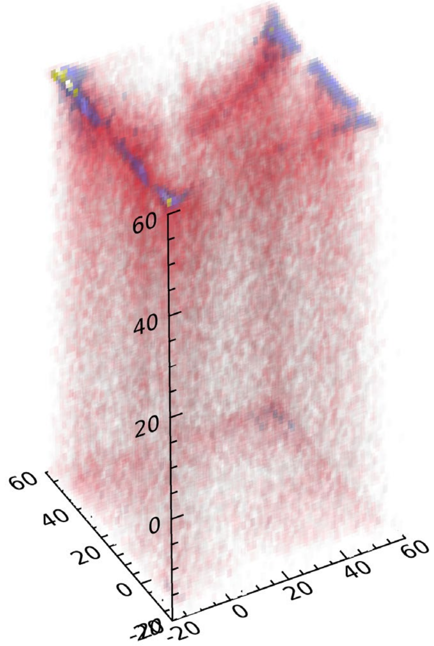


Same crystal with the 2x2 pixel anode
Single site events are selected
Charge sharing events are excluded
Tranches due to interpixel gaps are clearly seen



Despite the defect, the detector response is very uniform: the gaps between the pixels extend vertically from the anode to the cathode



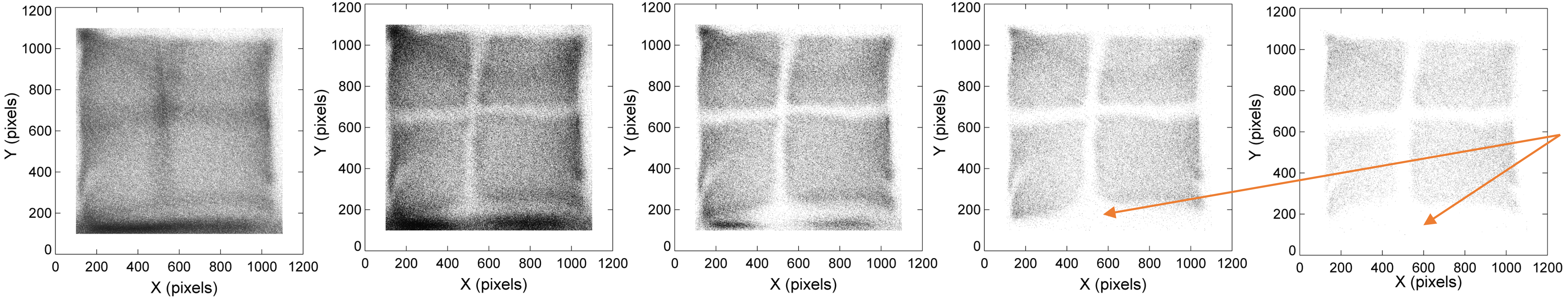


Testing 10x10x32 mm^3 CZT detector with the 2x2 pixel anode

100-micron gaps separating pixels gives us another opportunity to evaluate position resolution
X-Y distributions of the single site events generated at different distances from the anode

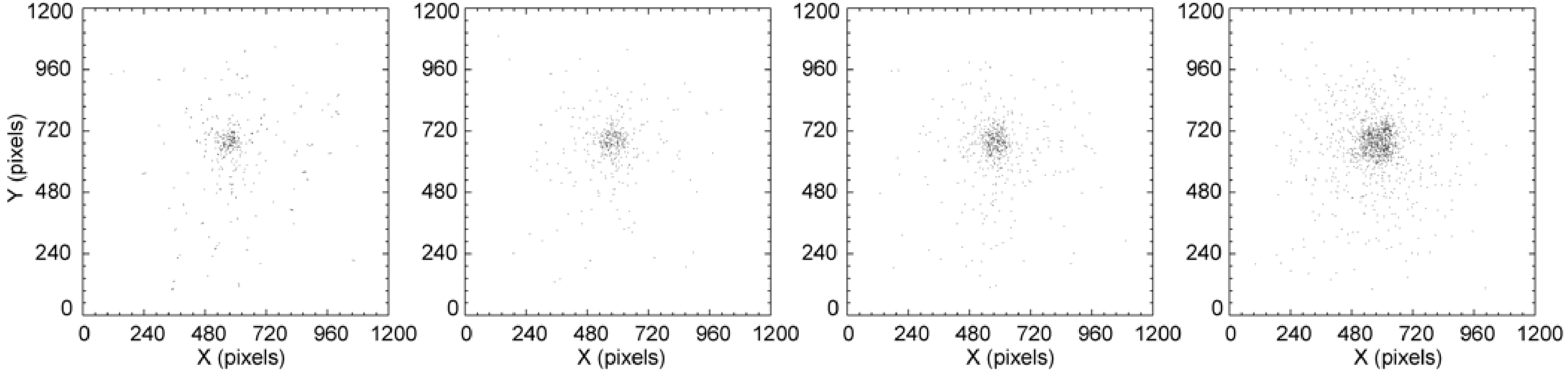
Charge sharing events are excluded

All events | 0.4 mm | 1.4 mm | 2.2 mm | 2.6 mm



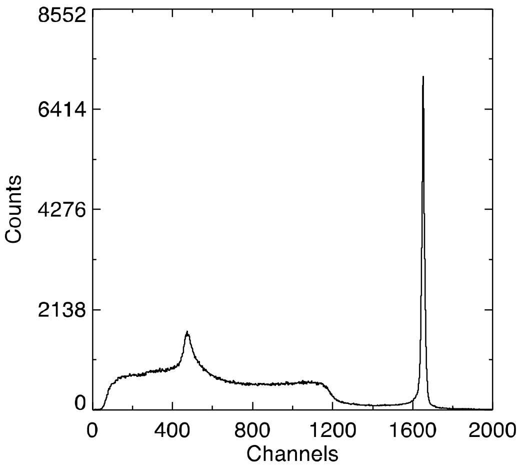
Crystal defect (twin or sub-grain boundary)

Only charge sharing events between 4 pixels are kept (illustrates diffusion in CZT)



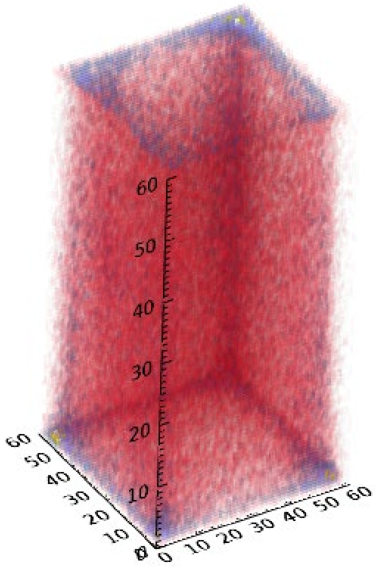
8x8x32 mm^3 detectors fabricated by eV Products (now Kromek)

We acquired 20 8x8x32 mm^3 detectors; so far, we tested 2 samples

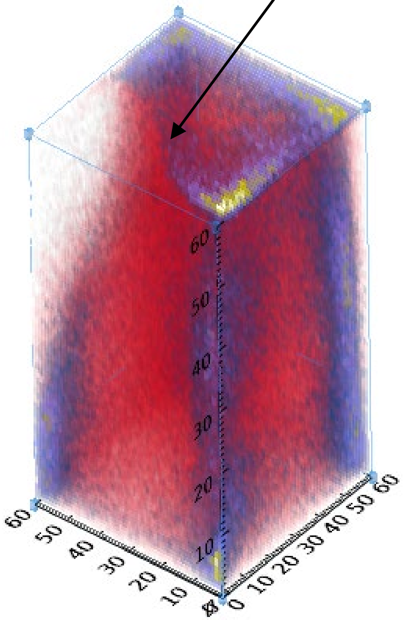


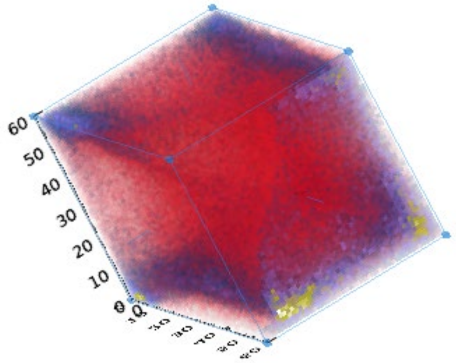
Cs-137 spectrum
Bias 3000 V
Energy resolution is 1.0% FWHM

The second tested detector has ~1.5% resolution
Volume plot revealed a crystal defect: likely a sub-grain boundary



Volume plot of the event distribution: Shows uniform distribution of the events



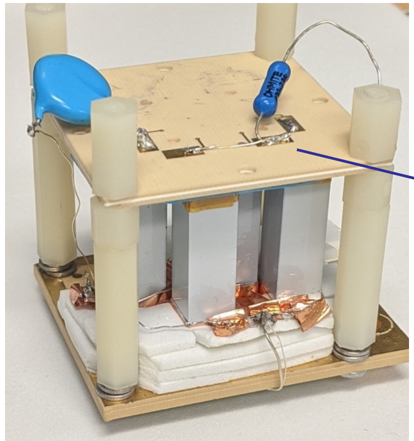


Investigating potential radiation effects in 8x8x32 mm^3 CZT bars induced by 150-MeV protons

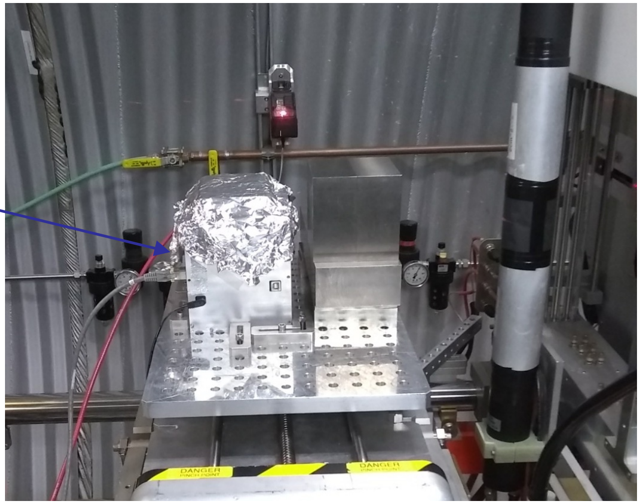
- An expected proton flux on the low Earth orbit in the broad energy range is ~1 cm^{-2}s^{-1} or 1 proton per sec crossing each CZT bar per sec
- These protons can induce polarization in operating detector and cause radiation damage
- Both effects will degrade the detector performance over time

- We used the NSRL proton beam at BNL to investigate the potential polarization effects and radiation damage
- 4 8x8x32 mm^3 detectors in the virtual Frisch-grid configurations were tested at the 150 MeV proton beam
- Potential polarization effects inside the detectors were monitored by measuring the 662 keV peak positions in the pulse-height spectra generated by ^{137}Cs source

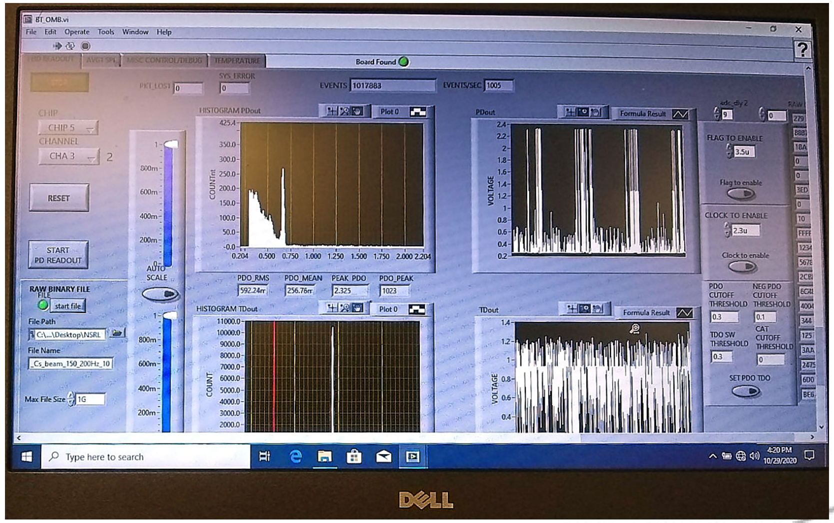
4 8x8x32 mm^3 detectors



Detector mounted in the 150 MeV proton beam



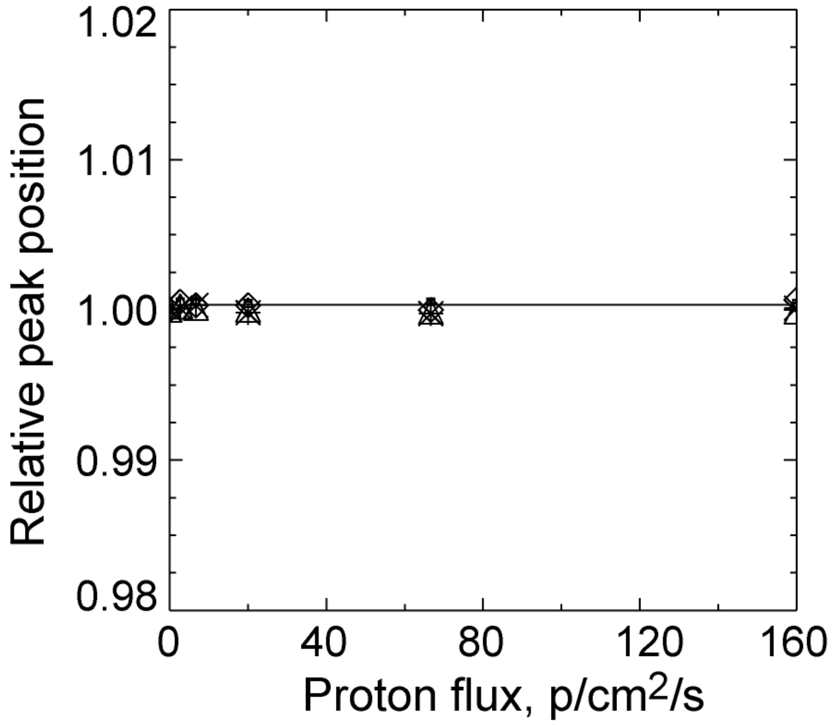
DAQ window



Potential polarization effect due to proton interactions in 8x8x32 mm^3 CZT detectors (Redlen)

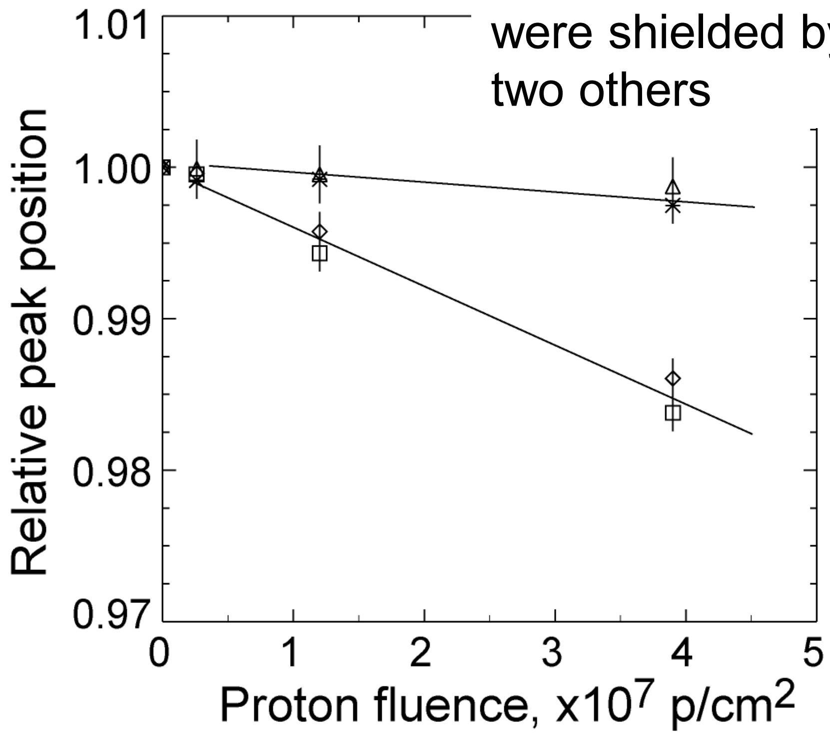
- Potential polarization effects were investigated by monitoring of 662-keV peak positions in gamma-ray spectra acquired during the detector irradiation from a Cs-137 test source
- A broad aperture 150 MeV beam covered the entire area of the CZT detectors
- Beam flux: 1-160 p/cm^2/s
- Expected flux of 1-200 MeV protons on Low Earth Orbit is 1-2 p/cm^2/s

662-keV peak position vs. proton beam flux



No polarization was observed up the maximum proton flux of 160 p/cm^2/s used in these measurements

Long term response degradation due to radiation damage caused by energetic protons



Two detectors were shielded by two others

- We observed < 2% decrease of the electron lifetime after exposing detectors to moderate proton fluxes, with a total fluence up 4x10^7 p/cm^2
- The exposure to a proton fluence of 10^{10} p/cm^2 affected the detector performance: No responses were observed after the exposure
- After annealing for ~10 days at the temperature of 80 C, the detectors recovered their performances (top spectrum), but the electron lifetime did not return to the initial level
- The initial lifetimes, measured for detector irradiation, were 60, 78, 89, and 89 us
- After irradiation they became 54, 58, 58, and 54 us, correspondingly

Conclusions and future plans

- We investigated the feasibility of using 8x8x30 mm^3 position-sensitive VFG detectors in detector planes for space gamma ray telescopes
- The detectors provide good energy and position resolution and potentially can withstand damage caused by cosmic radiation; however, more measurements are required to confirm this
- Two vendors (Redlen and eV Products) can potentially supply CZT bars with the required properties: the best choice is always a tradeoff between production yields and costs
- Our next step is to use a high-energy gamma-ray beam at the HIGS facility (Duke University) to evaluate detector responses and position resolution for several MeV gamma rays

Acknowledgments

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