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Position-sensitive virtual Frisch-grid CdZnTe detectors for the future gamma-ray telescopes

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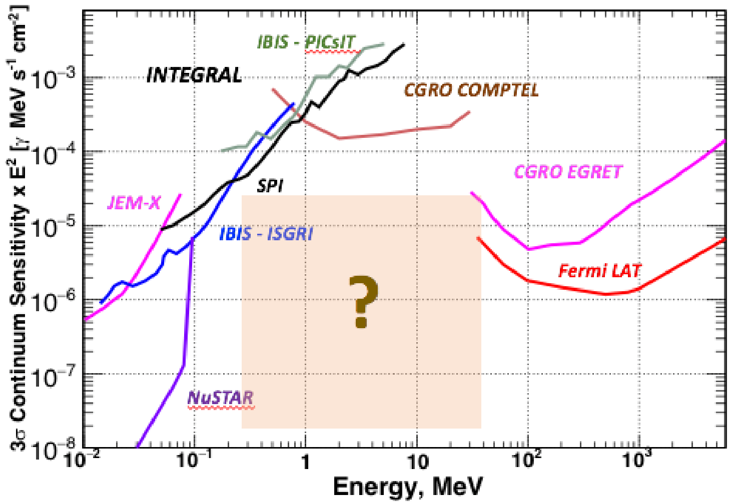
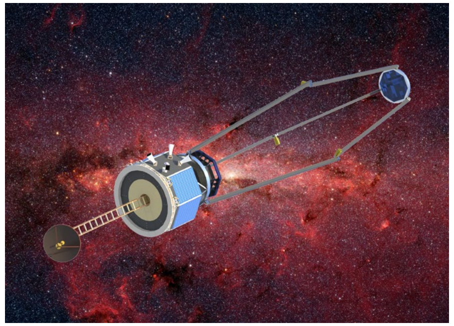
International Symposium on Room Temperature Semiconductor Detectors
October 31 - November 7, 2020

Introduction

- Position-sensitive virtual Frisch-grid (VFG) detectors are a mature technology that can be used in applications for imaging and spectroscopy of gamma-ray sources
- Originally these detectors were proposed for nuclear nonproliferation and national security tasks
- Recently, this technology attracted attention of gamma-ray astronomers interested in gamma rays from a particular energy range from 100 keV up to 50 MeV
- This is the least explored and most difficult energy range, which requires large effective area detectors with good position and energy resolutions
- Arrays of CdZnTe (CZT) position-sensitive virtual Frisch-grid (VFG) detectors with dimensions of the individual elements in the array up to 8x8x30 mm^3 are promising candidates for such instruments
- Such large size CZT bars have recently become available from commercial suppliers: Redlen and Kromek

Gamma ray flux sensitivity limits achieved with space instruments



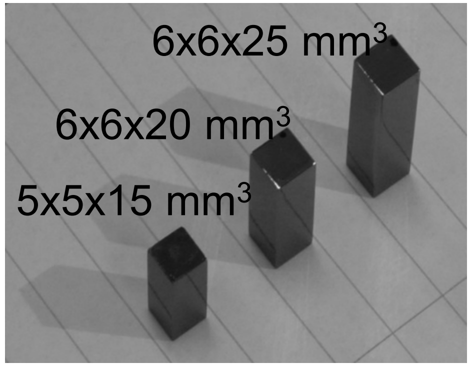


Artist concept of the proposed Coded Aperture Mask Compton Telescope (GECCO)

Advantageous features of CZT position-sensitive VFG detectors

- The VFG design represents an economical way for making CZT detectors with good energy resolution, high detection efficiency and sub 1-mm position resolution
- 3D position sensitivity allows for correcting response non-uniformities often seen in large-volume CZT crystals, which is one of technological barriers limiting application of CZT detectors (3D corrections)
- The bar shaped geometry is beneficial for making arrays to substitute big CZT crystals, which are more expensive to produce
- Good characteristics of VFG detectors make them capable to compete with H3D pixelated detectors in large-area arrays
- Previously, we reported spectroscopic performance of VFG detectors. Here, I concentrate on achieving high position resolution that is important for gamma-ray astronomy

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



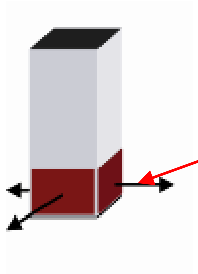
Bar-shaped crystals available 3-5 years ago

Crystals available today

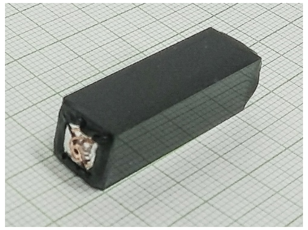
Such bars are available from Redlen and other vendors

Detector design

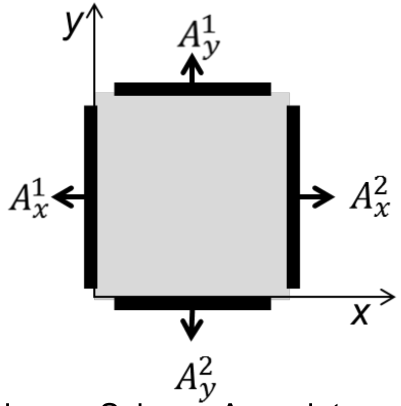
Schematic of position-sensitive VFG detector



Encapsulated detectors



Coordinate system



- Bar shaped CZT crystals are encapsulated inside insulating shells
- 4 position-sensing pads are attached to the sides near the anode
- The pads signals provide *X-Y* coordinates, while the cathode signals are used to measure *Z* coordinates: the drift time and C/A ratio give two independent estimates for *Z*
- The pads are virtually grounded to ensure the virtual Frisch-grid effect

- The simplest approach to evaluate *X-Y* coordinates is to use the center of gravity method
- This approach works well for correcting response non-uniformities, but causes some image distortion, especially near the edges

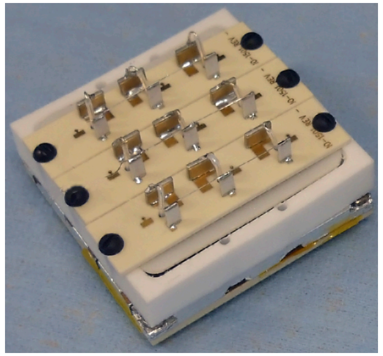
$$X = \frac{A_x^2}{A_x^1 + A_x^2}$$

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

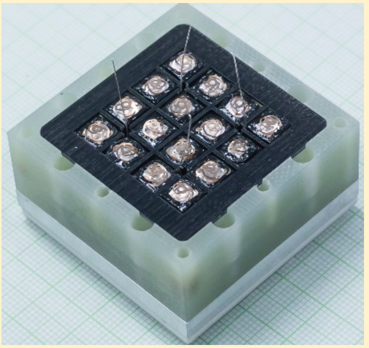
- The main advantage of position-sensitive VFG detectors is the ability to correct response non-uniformity caused by crystal defects
- Typical energy resolution is <2% at 200 keV and <1% at above 1 MeV
- Use unselected (standard grade) crystals to reduce cost and improve performance

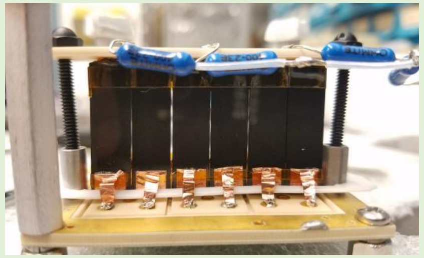
Examples of the arrays

6x6 array prototype of conventional VFG detectors, 5x5x15 mm^3

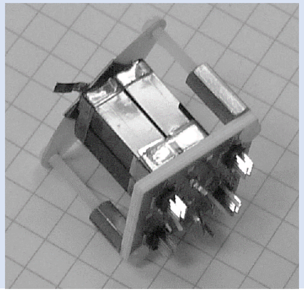


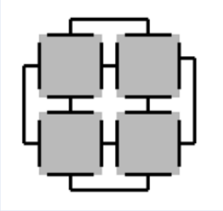
Array module of 4x4 position-sensitive VFG detectors, 6x6x20 mm^3





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

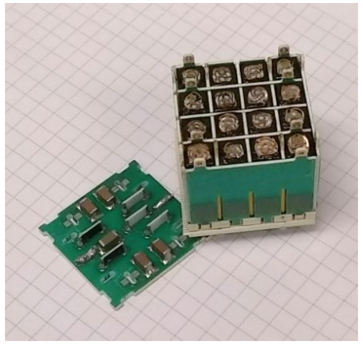


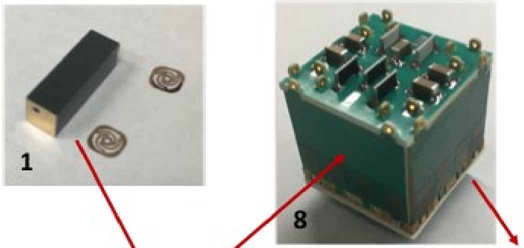


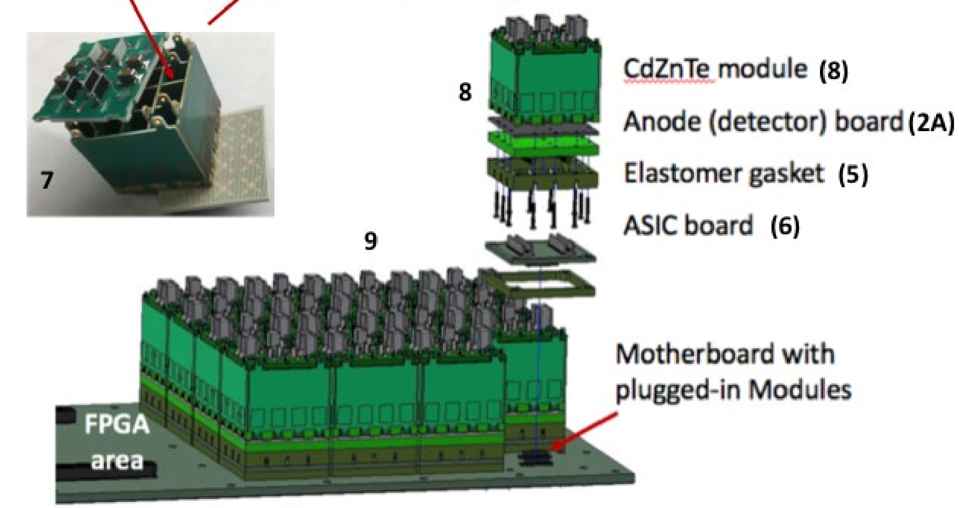
Small 2x2 array of 6x6x20 mm^3 detectors for a handheld instrument

Conceptual design of the array proposed for NASA Coded Aperture Mask Compton Telescope (GECCO)

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



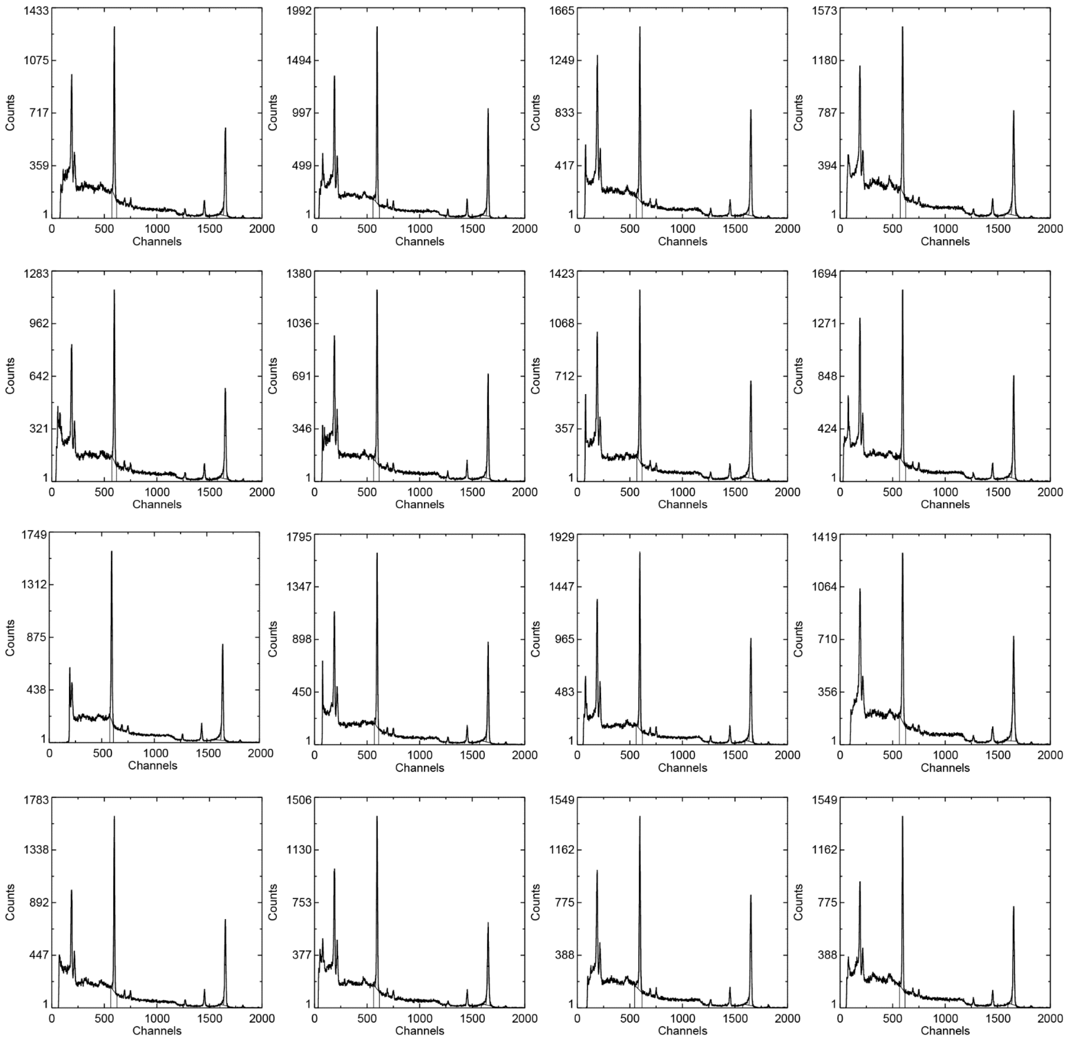




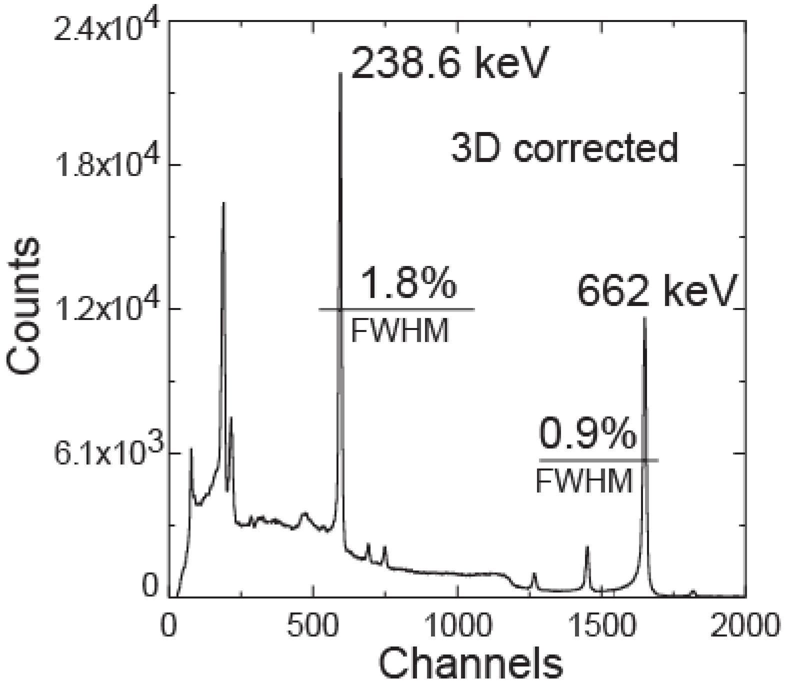
Artistic concept (like Lego blocks)

Spectra measured with the 4x4 array from ^{232}U and ^{137}Cs

4x4 array of 6x6x20 mm^3 detectors read out with AVG2 ASIC



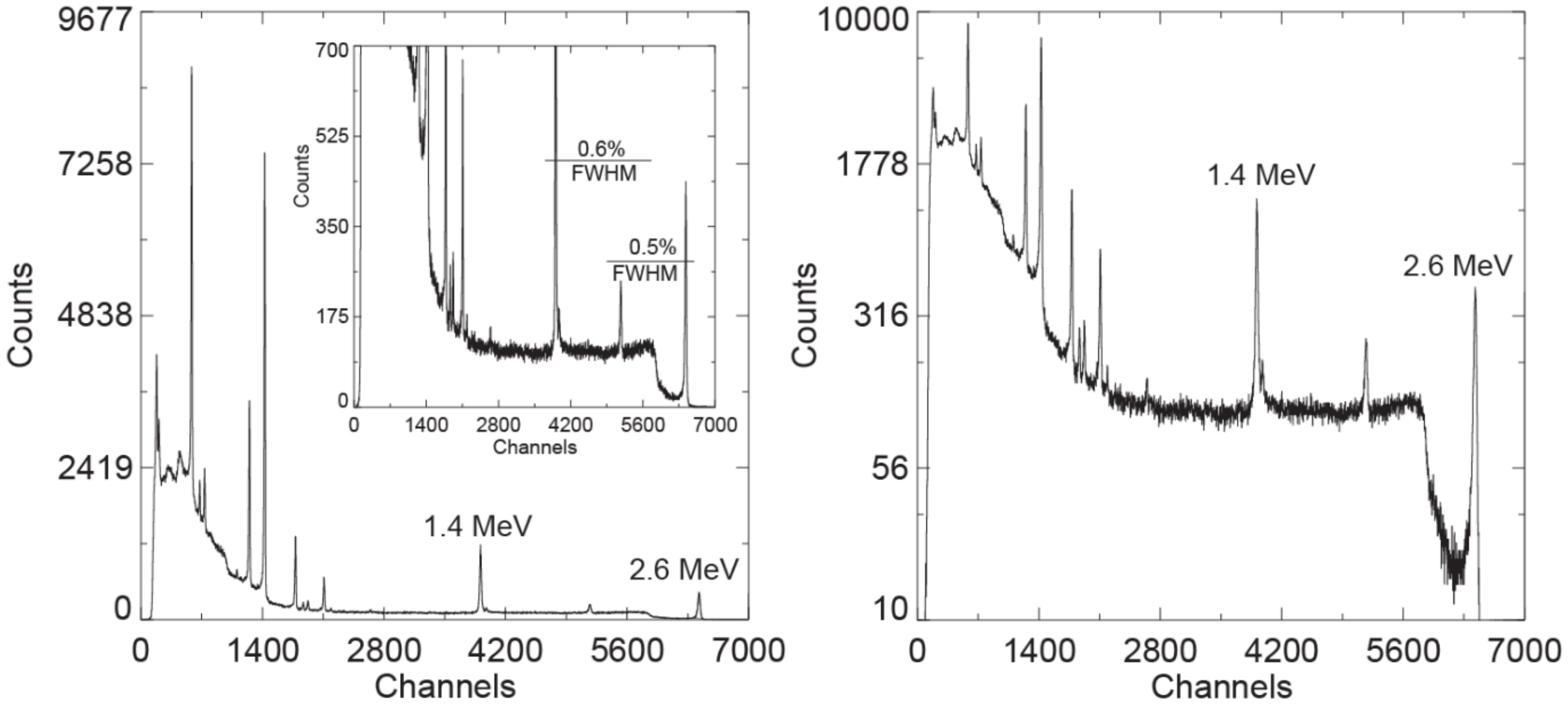
Combined spectrum



- Arrays show good performance in a wide energy range
- Resolution: < 2% at < 200 keV and <1% at 662 keV

Spectra measured with a large-volume 10x10x32 mm^3 detector

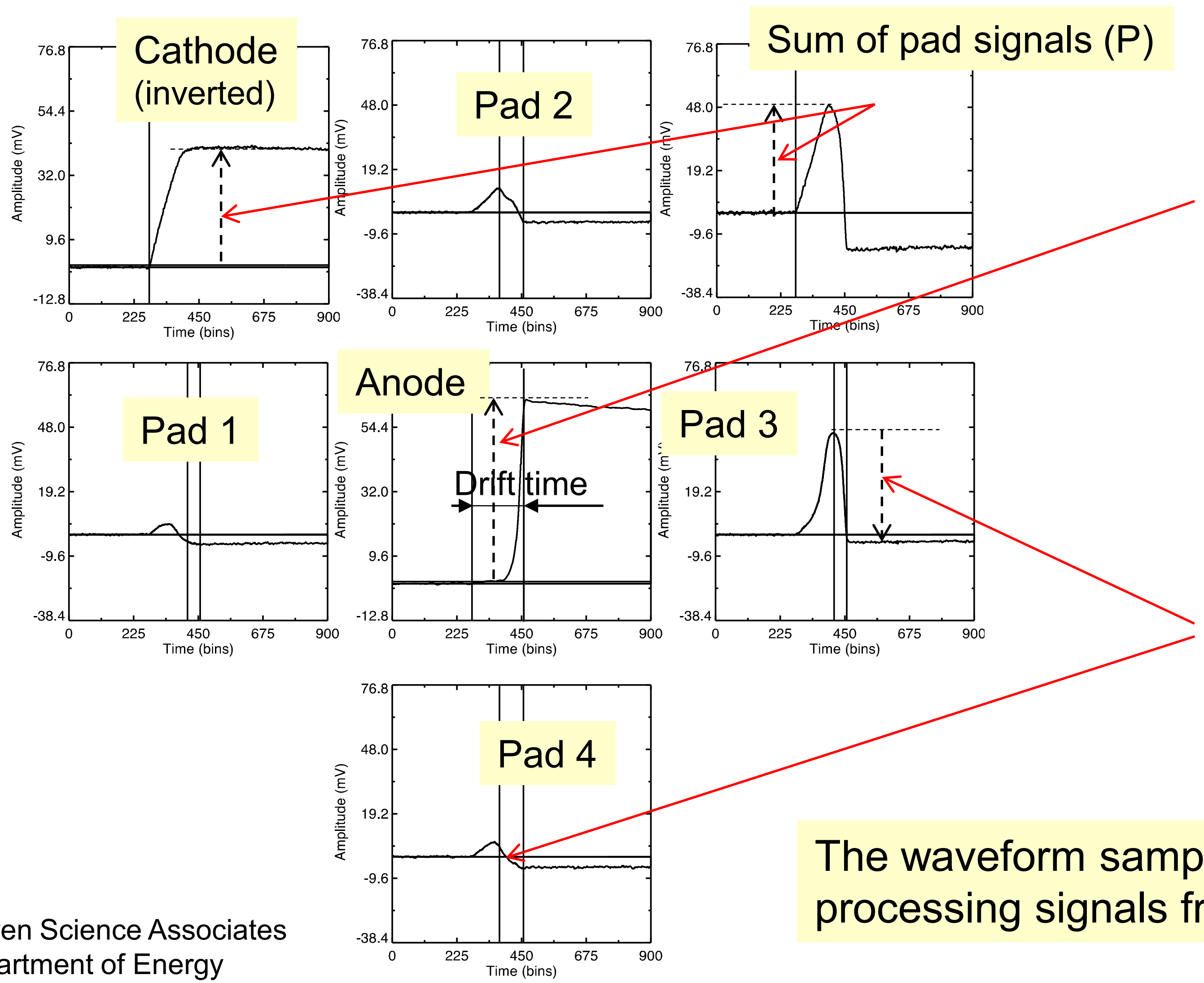
U-232 source through 5-mm lead
Gamma ray lines with energies up 2.6 MeV



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

Charge signals generated in position-sensitive VFG detectors

Charge signals generated in position-sensitive VFG detectors
(captured from the cathode, anode and 4 pads)

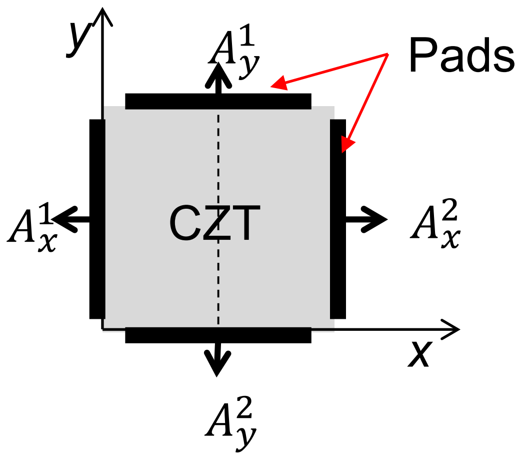


- Positive steps of the anode signals give the collected charge (deposited energy)
- Negative steps of the cathode signals gives Z coordinates
- The sums of the pad signals are equivalent to the cathode signals and can substitute them (simplify the design)
- Z coordinate can be evaluated by measuring: (1) drift time, (2) C/A ratio, or (3) P/A ratio
- Negative steps of the pad signals give *X*-*Y* coordinates; however, it is important to use time correlated samples of the pad signals

The waveform sampling is the best approach for processing signals from these detectors

Using pad signals to evaluate *X*-*Y* coordinates

Detector coordinate systems



Four amplitudes: A_x^1, A_x^2, A_y^1 and A_y^2 can be used to evaluate (x, y)

- We define a pad response function as the dependence of the pad amplitudes on (x, y) coordinates:

$$A_x^i = R_x^i(x, y)$$
$$A_y^i = R_y^i(x, y), \text{ where } i=1,2$$

- Each point from the space domain (x, y) corresponds to 4 points (A_x^i, A_y^i) from the amplitude domains formed by two orthogonal pads from each corner

- The reverse response functions give 4 estimates for (x, y):

$$\begin{pmatrix} x \\ y \end{pmatrix} = \begin{pmatrix} R_x^{-1}(A_x^1, A_y^1) \\ R_y^{-1}(A_x^1, A_y^1) \end{pmatrix} \text{ (for upper left corner)}$$

- Similar estimates can be obtained for each pair of orthogonal pads, but only 2 are independent. Combining two estimates from opposite corners:

$$\begin{pmatrix} x \\ y \end{pmatrix} = \sum_{i=1}^{2} \begin{pmatrix} x_i \\ y_i \end{pmatrix} w_i$$

- where w_i are the weights (proportional to pad amplitudes)

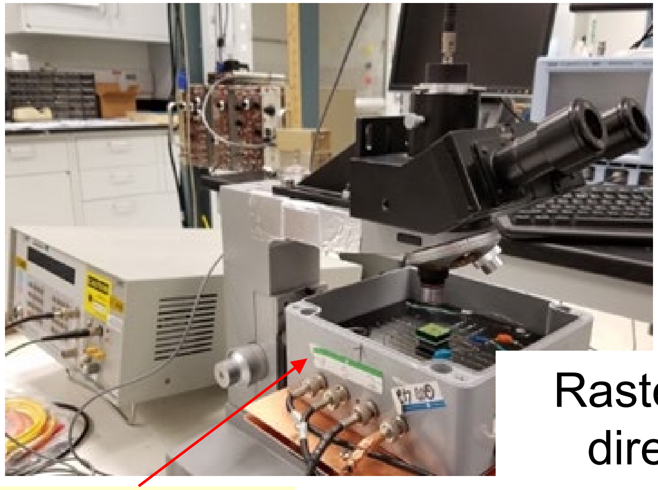
- If assume linear approximations for the response functions, we can get the center of gravity formulas:

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

- The center of gravity formular is a very robust estimator, but it causes geometrical distortions near the edges

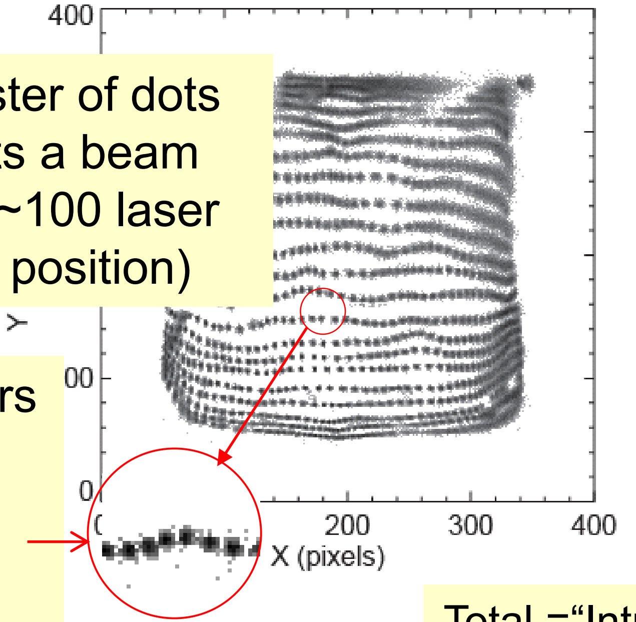
Using a focused pulsed laser beam to investigate position resolution of a VFG detector: Geometrical distortions caused by the center of gravity formula

- Focused lased laser beam: ~10 μm, 100 μm steps
- Injected charge is equivalent to an energy of ~500 keV
- Use a simple center of gravity formula to evaluate *X*-*Y* coordinates



Readout box

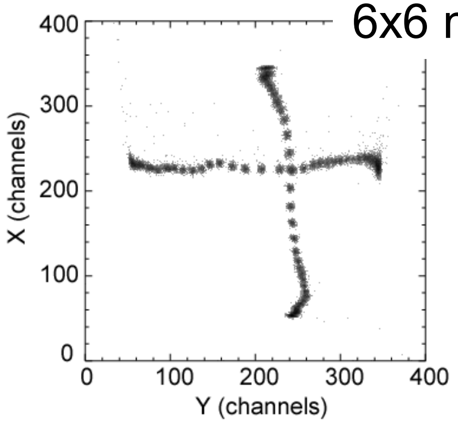
Raster scan of a 6x6x20 mm^3 director with 100 μm steps



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

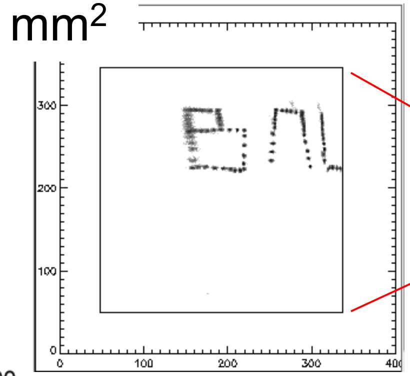
The width of these clusters represents the intrinsic resolution, < 50 μm (due to diffusion and electrostatic repulsion)

Cross scan



Use the laser beam to write "BNL"

6x6 mm^2



There are two kinds of distortions:

1) Dots wiggling, which is due to local variations of electric field
2) Image clipping near the edges caused by using the center of gravity formula

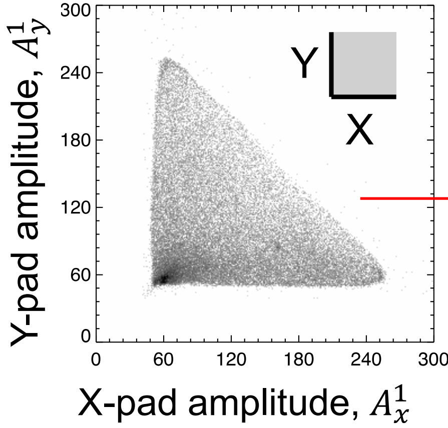
Total ="Intrinsic"+ "Electric field variations" + "Geometrical distortions"

Using analytical response functions to avoid distortion caused by the center of gravity formulas

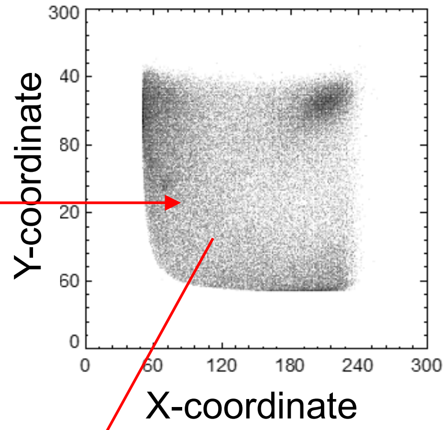
- Response functions can be calculated or measured experimentally during calibration
- Here, we used the analytical response functions to convert 4 pads amplitudes into (x, y) coordinates
- This approach helps to minimize geometrical distortions but not eliminates them completely, because it is not possible to accurately evaluate response functions near the detector edges

Use the conformal transformation matrix to correct the distortions

Events distribution in amplitude domain

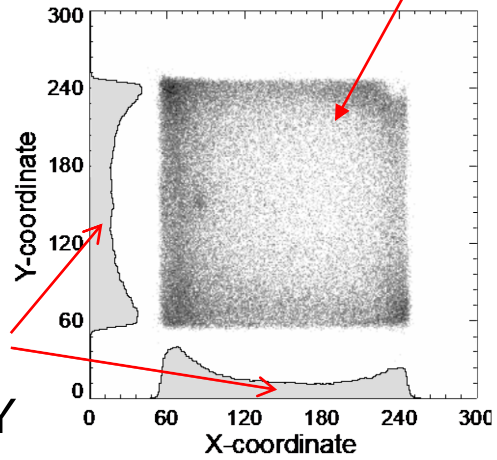


Same distribution in *X-Y* domain after applying the analytical response function



After averaging maps from 2 pairs of orthogonal pads

All events >200 keV from ^{137}Cs integrated over Z



Events distributions along X and Y directions

- We expected a uniform events distribution
- Events are still piling up around the detector edges

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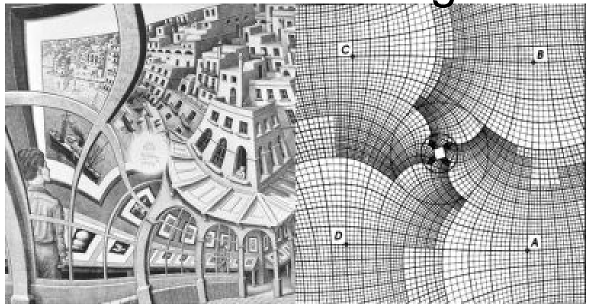
Using conformal transformation matrix to correct geometrical distortions

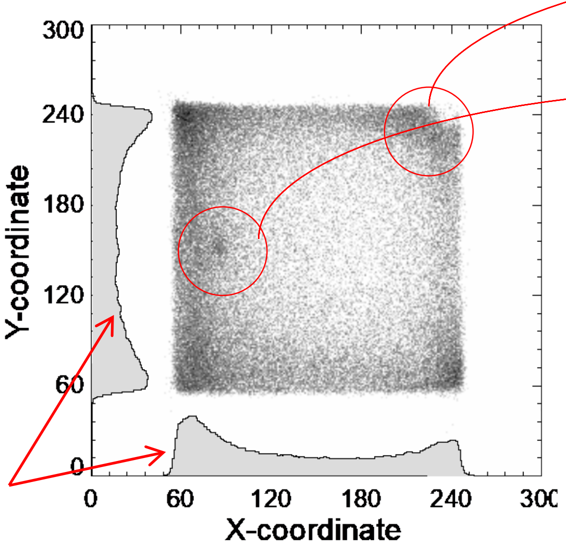
- First, we apply the *analytical response function* to convert amplitudes to positions
- Then, we apply the conformal matrix to correct the distortions
- With conformal transformation, we can avoid using the actual response functions by replacing them with the center of gravity formulas

Escher drawing

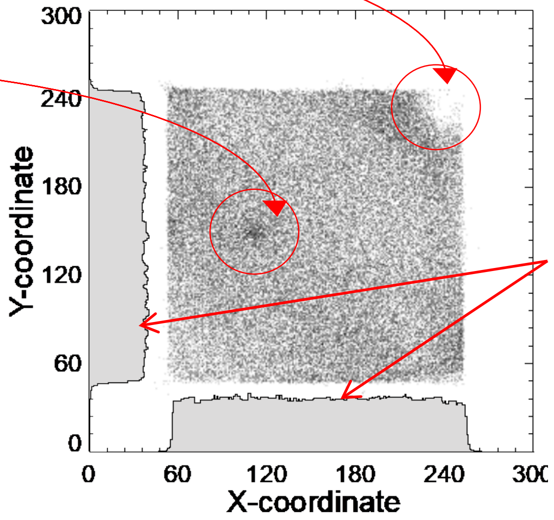


X-Y events distribution evaluated using the analytical response function (center of gravity formulas)

Same events after applying conformal transformation matrix



These details are preserved in the corrected map



Averaged events distributions along X and Y directions

Almost uniform event distribution after corrections

The maps contain all events >200 keV generated by 662 keV photons

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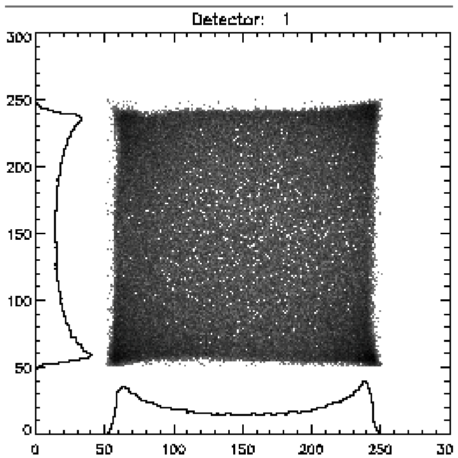
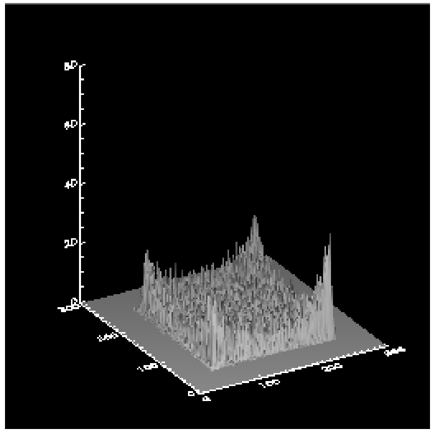
Correcting geometrical distortions caused by the center of gravity formulas

- A 6x6x20 mm^3 detector exposed to an uncollimated Cs-137 source (all events projected onto *XY* plane)

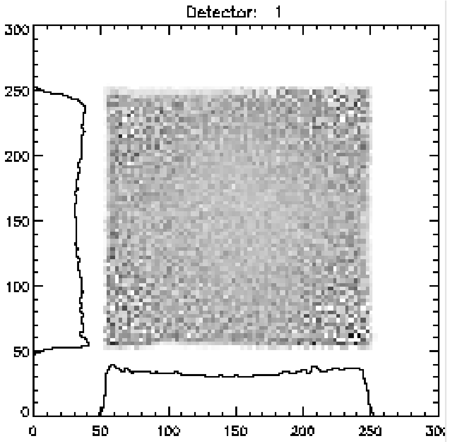
XY events distribution evaluated using the center of gravity formula

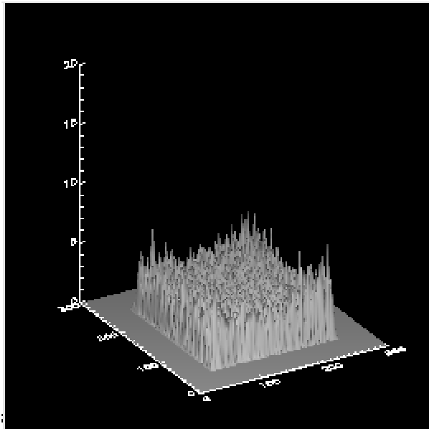




More counts are near the detector edges and corners

Same events after geometrical corrections using the conformal map





After corrections, the event distribution is almost flat

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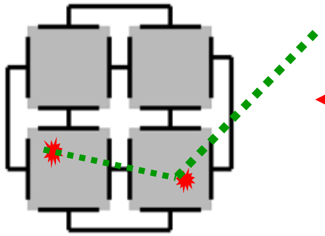
Using signals from 2 orthogonal pads to evaluate *X-Y* coordinates

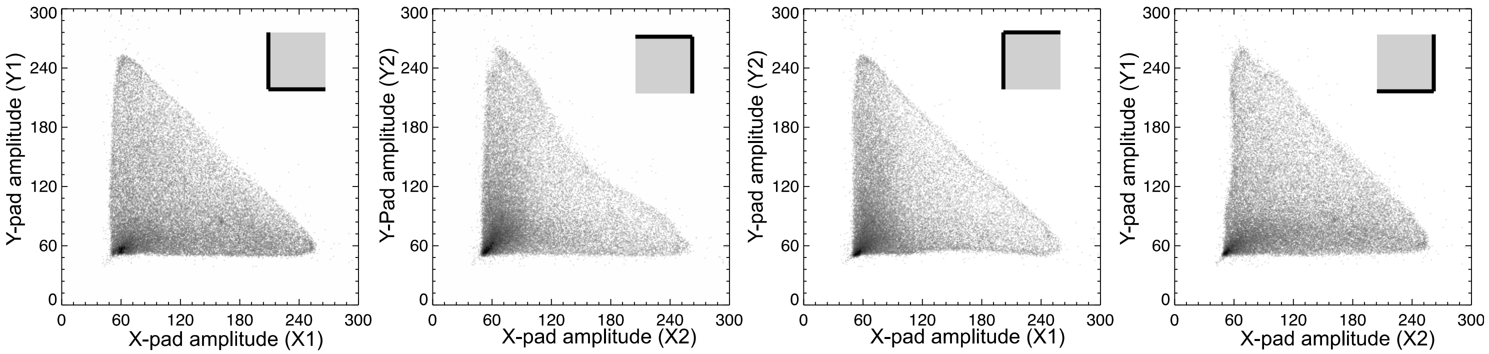
- Such situations happen when adjacent detectors in arrays share their pads
- If an interaction happens in two adjacent detectors, it creates ambiguity of using the signal generated by two electron clouds



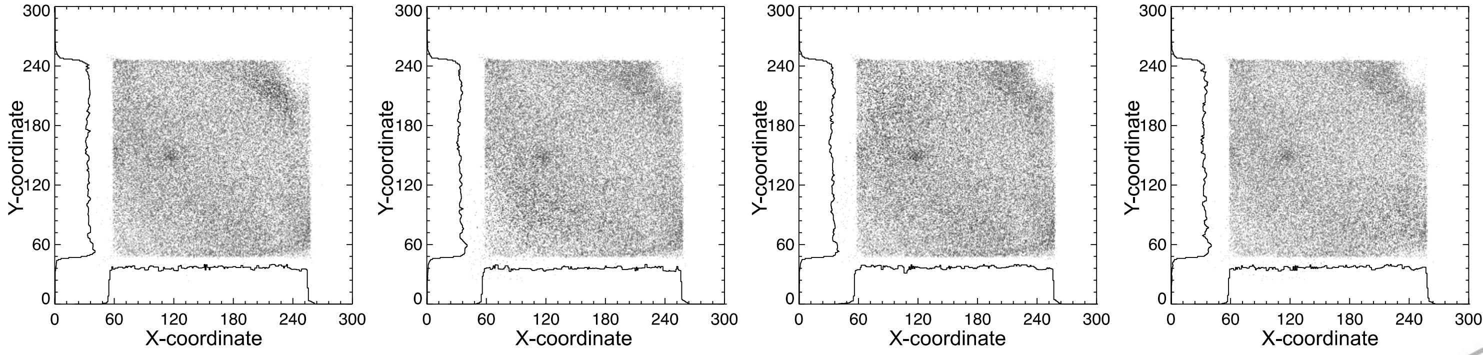
Example of a 2x2 array with interconnected pads

To deal with such events, we use the transformation matrices (generated during calibration) that convert the measured 2-pad amplitude distributions into the *X-Y* maps

Measured 2-pad signal distributions in the amplitude domains



Same distributions in the *XY* space domain after applying transformation matrices



Evaluating position resolution: 6x6x20 mm^3 detector

Geometry of the experiment using a tungsten collimator

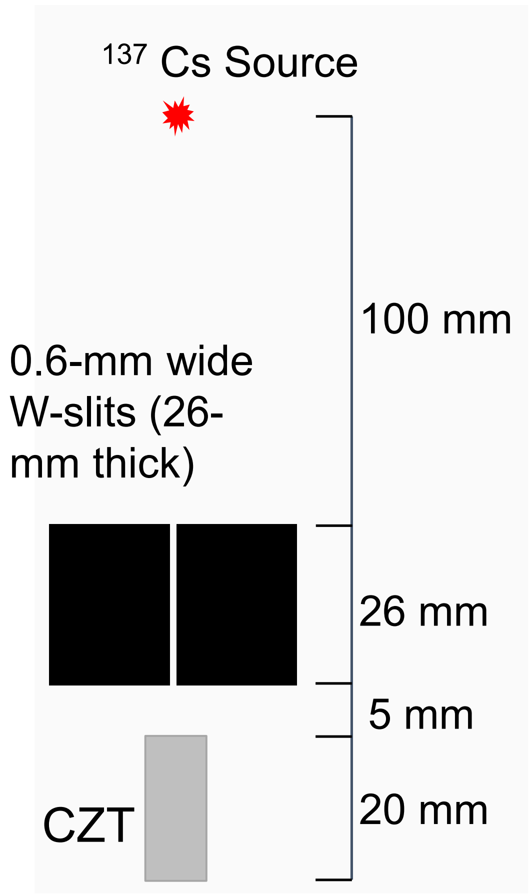
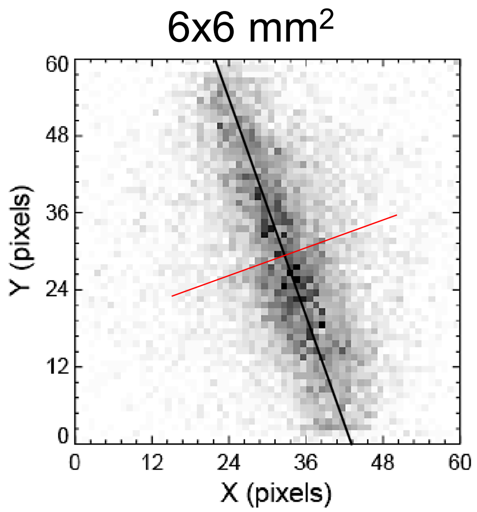
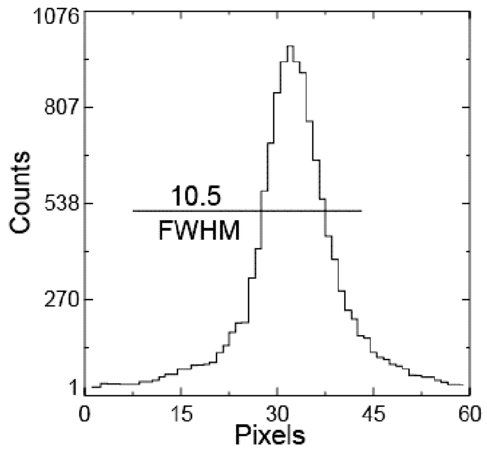


Image of the tungsten slits generated with a 6x6x20 mm^3 detector irradiated by the uncollimated Cs-137 source



X-Y distribution of the interactions over entire detector depth projected onto the *X-Y* plane after geometrical corrections



Events distribution projected onto a perpendicular plane

By comparing this distribution to Monte-Carlo simulations we estimated the spatial resolution to be < 1 mm

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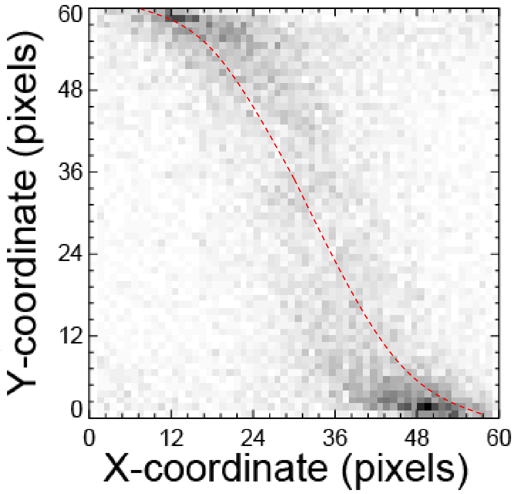
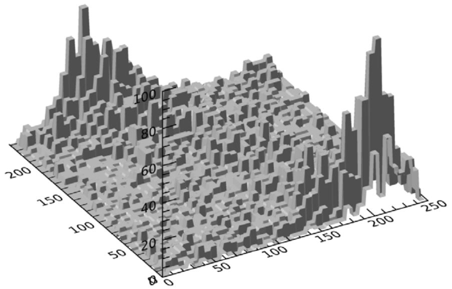
Correcting geometrical distortions

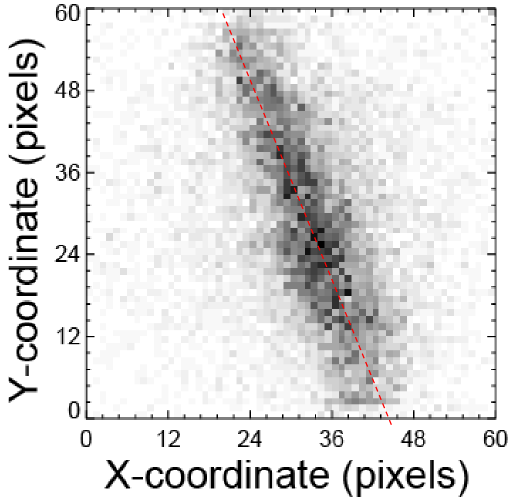
The image of the tungsten slits illustrates how the corrections improves position resolution, 6x6x20 mm^3 detector

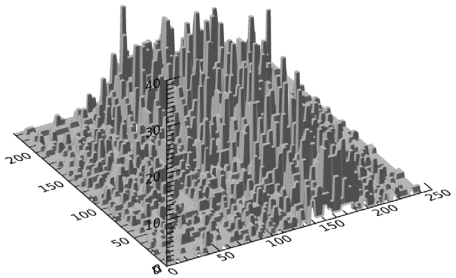
Response map generated using the center of gravity formulas





Same map after applying corrections using the conformal maps





Evaluating position resolution: 10x10x32 mm^3 detector

Geometry of the experiment using 0.8 mm tungsten slits

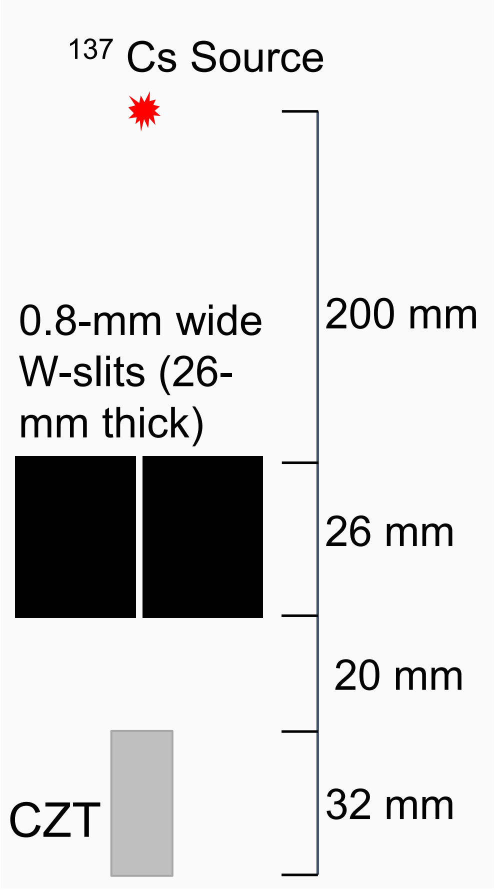
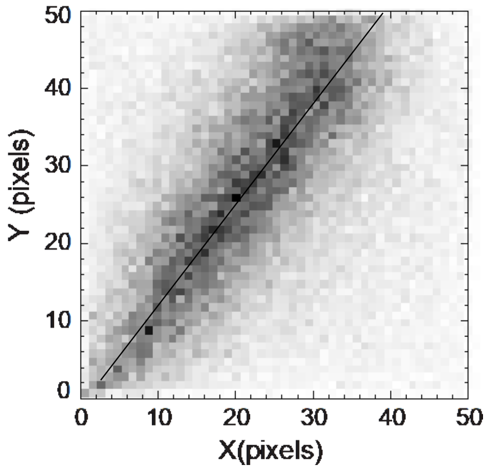
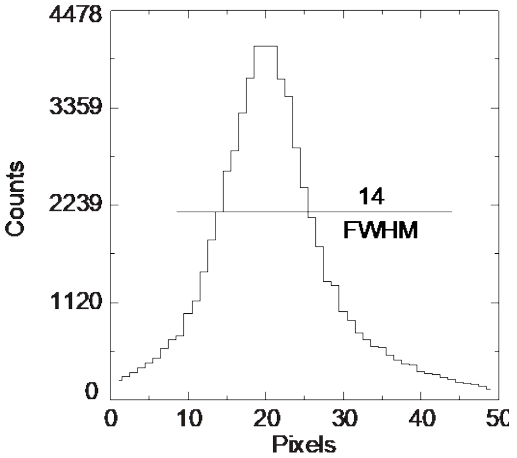


Image of the tungsten slits generated with a 10x10x32 mm^3 detector irradiated by the uncollimated Cs-137 source

10x10 mm^2



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

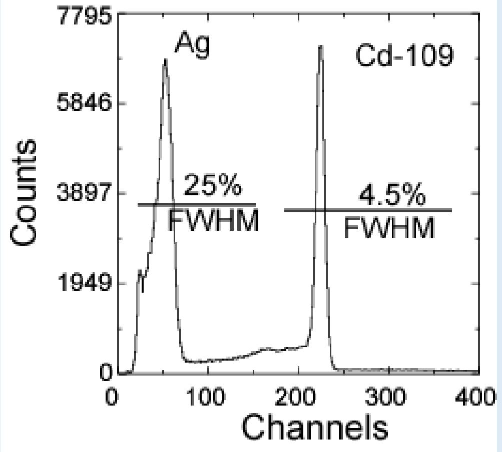


Based on Monte-Carlo simulation we estimated the spatial resolution to be < 1 mm

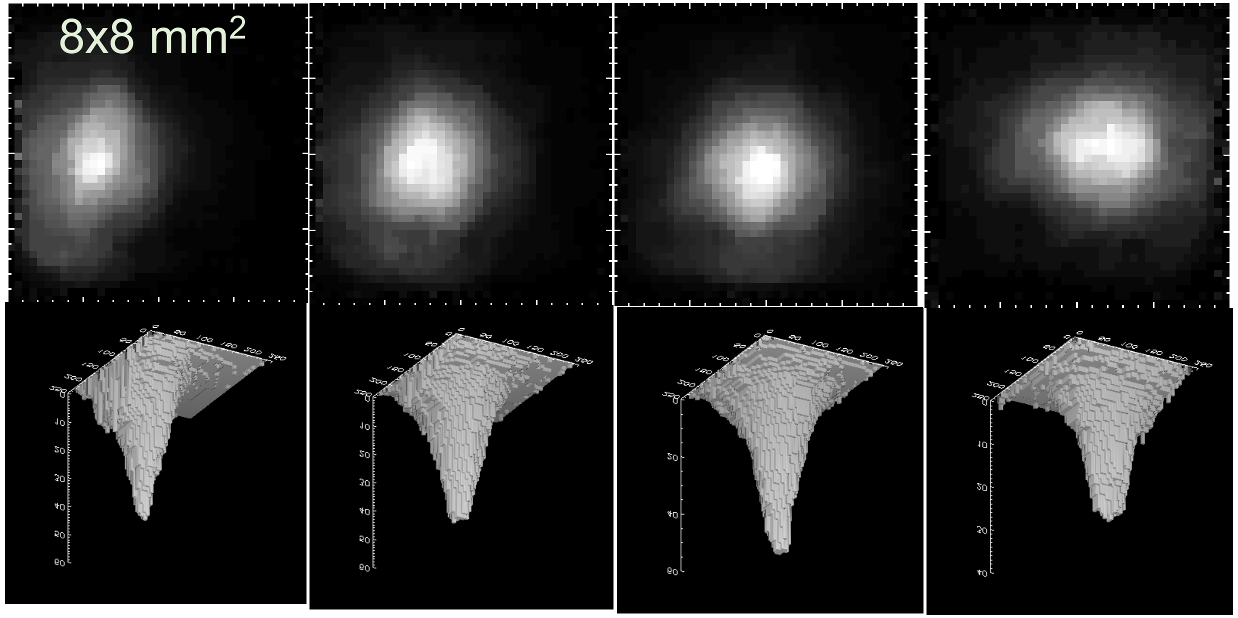
Position sensitivity measured with Ag X-Ray tube: 8x8x32 mm^3 detector

Collimated down to ~200 μm X-ray beam from Ag X-Ray tube, 22 keV

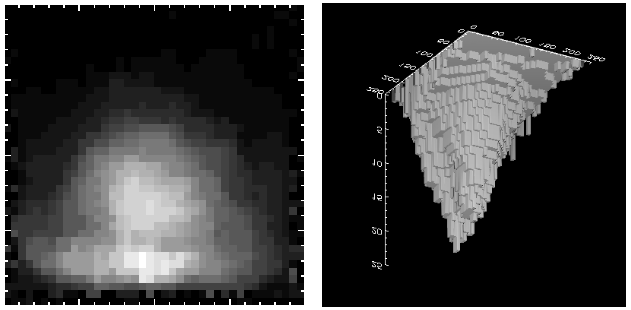
Cd source was used for calibration



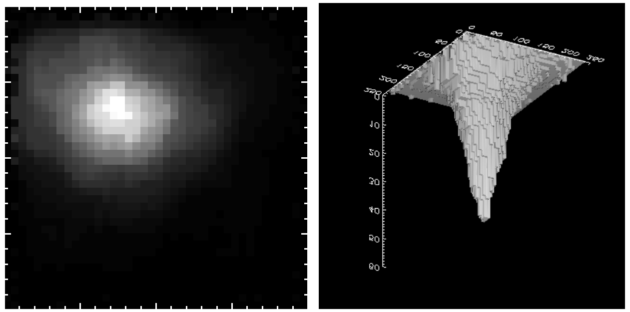
Linear scan from the left edge to the center



Beam splitting at the edge



Beam positioned close to the corner



Good position sensitivity despite the low X-ray energy, 22 keV

Conclusions and future plans

- We developed techniques for evaluating *X-Y-Z* coordinates in position-sensitive VFG
- We demonstrated the intrinsic position resolution of < 50 μm, while the actual resolution could be affected by local electric field variations and geometrical distortions caused by the signal processing method
- Overall position resolution measured with collimated sources was found to be < 1 mm
- Our next step will be to use the beam at the HIGS facility to evaluate detector responses and position resolution for several MeV gamma rays

Acknowledgments

We would like to thank Graham Smith for letting us use his X-ray system and Matthew Chekhov for helping with data analysis.

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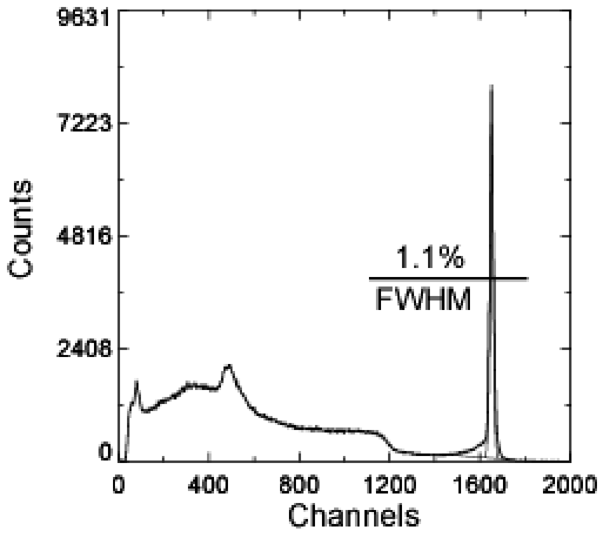
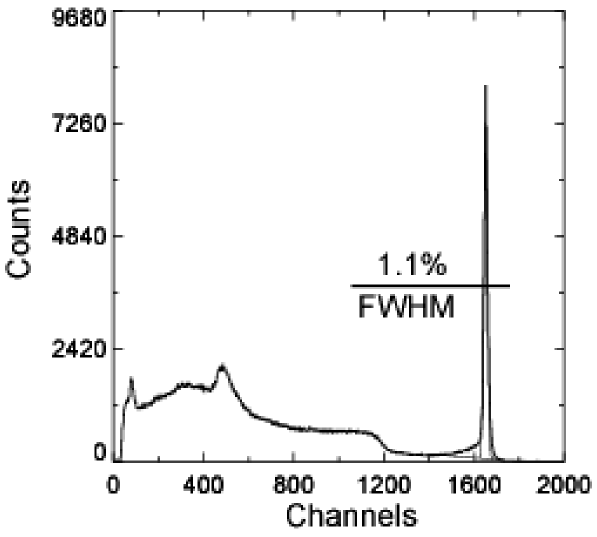
Comparison of using the cathode signals Vs. the sum of the pad signals

10x10x32 mm^3 detector
Cathode bias: 3700 V, ^{137}Cs source

Using C/A ratio



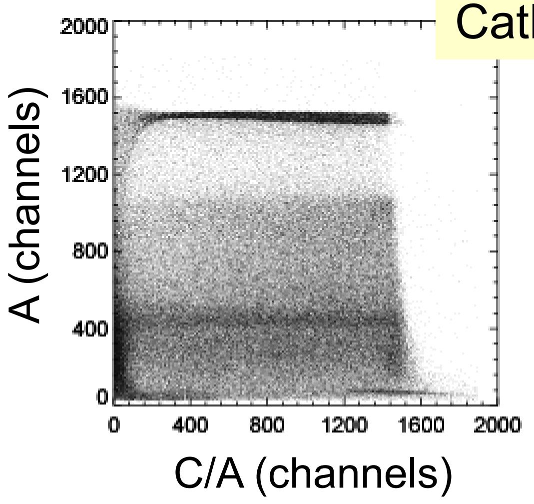
Using P/A ratio

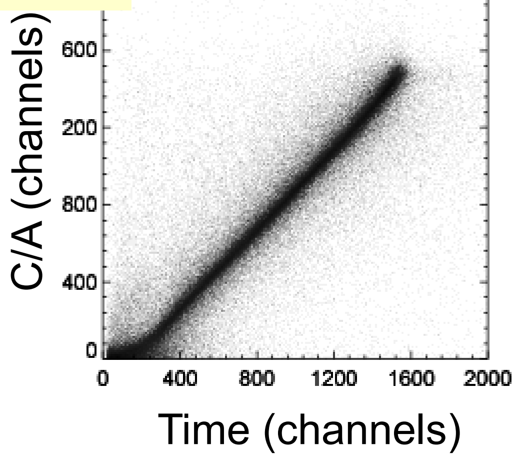


- The sum of the pad signals can be used to substitute the cathode signals

Correlation plot used to apply corrections

Cathode





Sum of pads