Performance of an array of 6 x 6 x 20 mm³ virtual Frisch-grid CdZnTe detectors with a waveform sampling readout system

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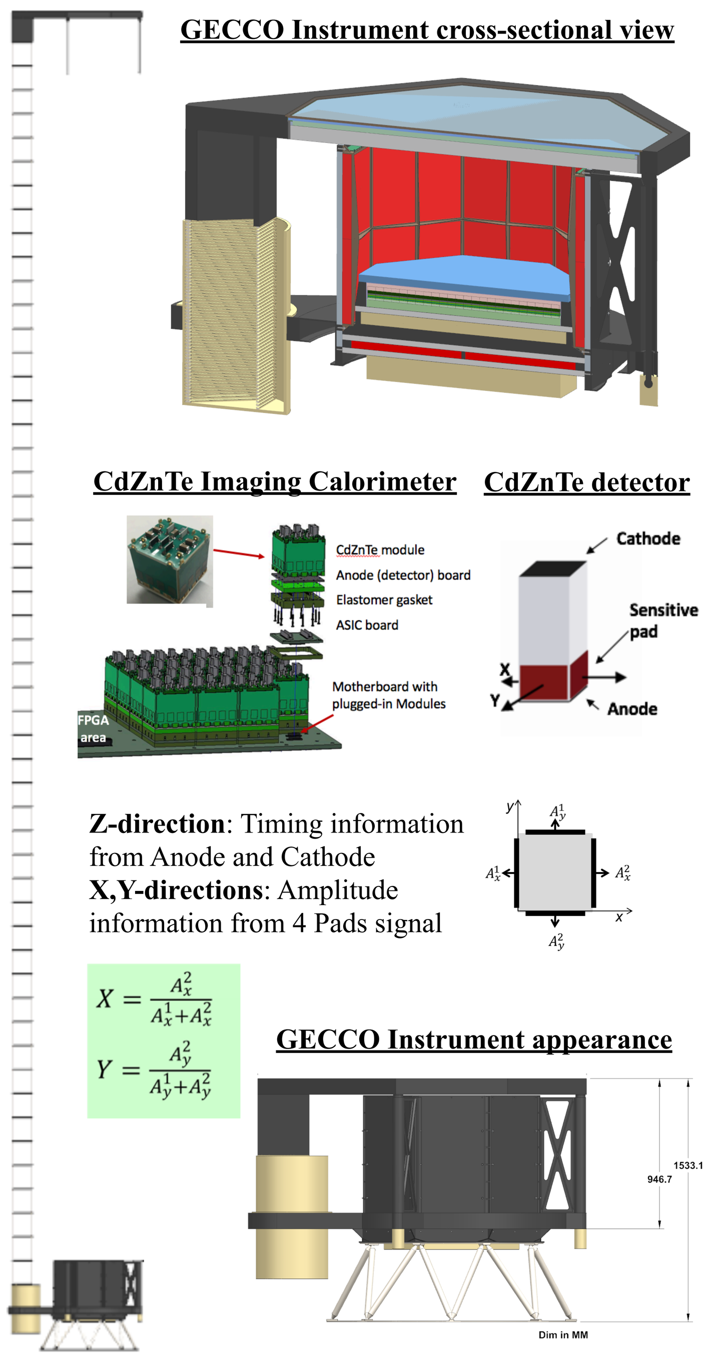
Abstract

Arrays of CdZnTe (CZT) bars with high spatial and energy resolution are an enabling technology for future space missions, such as the image plane detector of the Galactic Explorer with a Coded Aperture Mask Compton Telescope (GECCO). GECCO will explore the medium-energy (100 keV – 10 MeV) gamma-ray sky, which is among the least covered windows to the Universe with a massive potential for discovery. We have integrated an array of 6x6x20 mm³ virtual Frisch-grid (VFG) CZT detectors, measuring signals from the cathodes, anodes, and pads on each of the four sides of each bar. The VFG CZT detector is read out with an IDEAS GDS-100 waveform sampling readout system to optimize the signal processing and event reconstruction. We evaluated the energy and position resolution of the integrated VFG CZT array with a ^{137}Cs source and successfully demonstrated better than 1% energy resolution and finer than 1 mm position resolution at 662 keV. Furthermore, we carried out a beam test at the High Intensity Gamma-ray Source (HIGS) at Duke University to investigate the performance of the system for higher energy gamma-rays. Together with the basic performance obtained from the ^{137}Cs source, we present here those results from the beam test with various gamma-ray energies up to 8 MeV.

Detector & Readout Electronics

GECCO and Virtual Frisch-Grid CdZnTe Detector

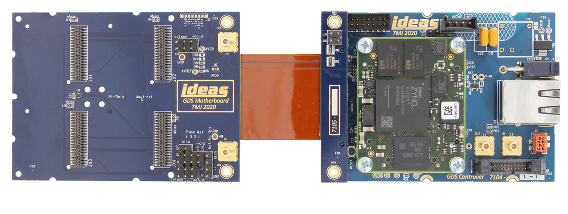


GECCO is a unique concept of combined dual mode γ-ray Compton telescope with coded aperture mask. It will conduct high-sensitivity measurements of the cosmic γ-radiation in the energy range from 100 keV to ~ 10 MeV and create intensity maps with high spectral and spatial resolution, focusing on sensitive separation of diffuse and point-source components [1]. GECCO utilizes a novel CdZnTe Imaging Calorimeter as a standalone Compton Telescope and as a focal-plane detector. A coded aperture mask modulates the incident photon flux and creates an image on the CZT detector plane. The mask is deployable and can be placed at a large distance from the detector for high-angular resolution.

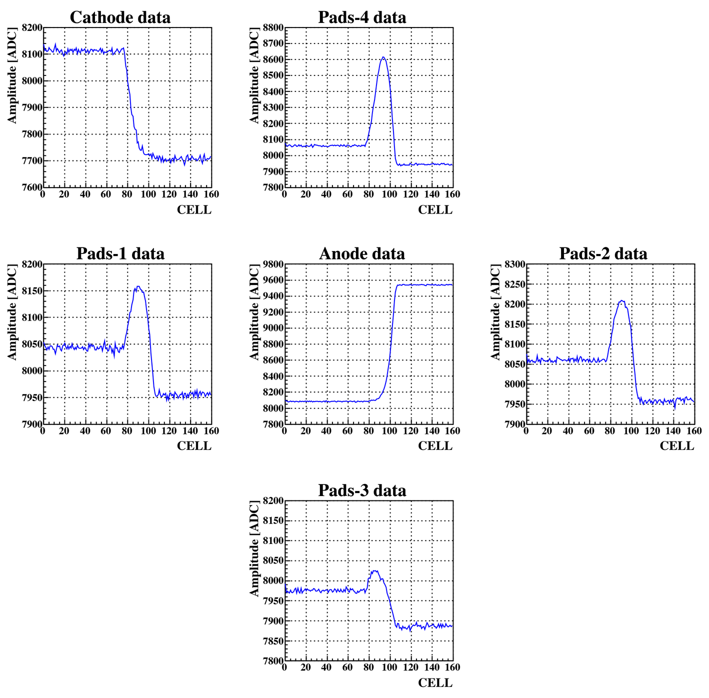
Virtual Frisch-Grid CZT detector developed by BNL group [3] has been adopted for the GECCO CZT Imaging Calorimeter. Copper pads placed near the anode screen out the induced signal from slow moving positive holes such that only the electron passing through the grid generates the signal on the anode,. This screening means that the position dependence on the anode signal is effectively suppressed and that the anode signal is related only to the energy deposited in the crystal. The relative signals induced on the pads are used to determine the X- and Y-positions of the interaction point, and the timing information or the ratio of the cathode signal to the anode signal is used to determine the Z-position. The dimensions of the CZT bars reported on in this work are 6mm x 6mm x 20 mm, and 16 such CZT bars are arranged into each crate as 4 x 4 array. The crates can be installed on a motherboard of any required geometry depending on detector design.

Waveform Sampling Readout System

IDEAS GDS-100 with IDM-121 waveform sampling ASIC is a newly developed CZT readout system [4]. Up to four IDM-121s can be installed on the GDS-100 motherboard, covering an active area of up to 64mm x 64mm. The figure below shows waveforms captured by GDS-100 system for a ^{137}Cs event from a CZT bar. The central panel shows the anode signal waveform, and the 4 pad signals are plotted above, below, left, and right on it. The top left plot is the cathode signal waveform

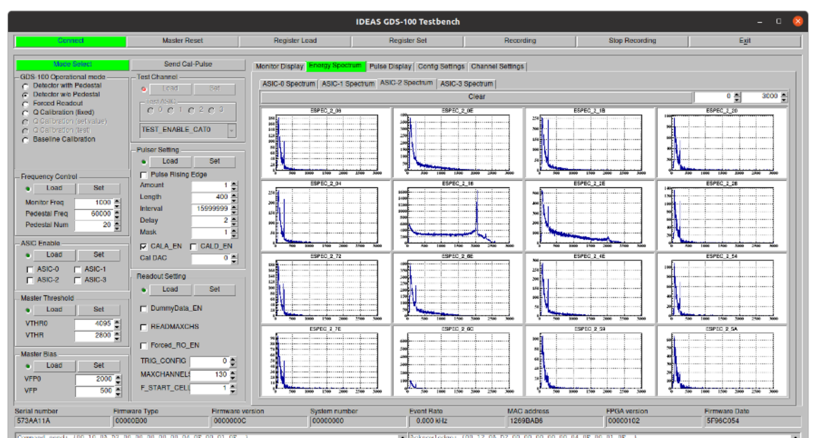


IDEAS GDS-100 system. The motherboard with 4 connectors for IDM-121 is on the left side and control board is on the right side interconnected by a flex circuit.



The deposited energy is determined from the anode signal and the 3D interaction position is determined from the 4 pad signals and the cathode to anode ratio as desired left column.

GDS-100 control GUI panel

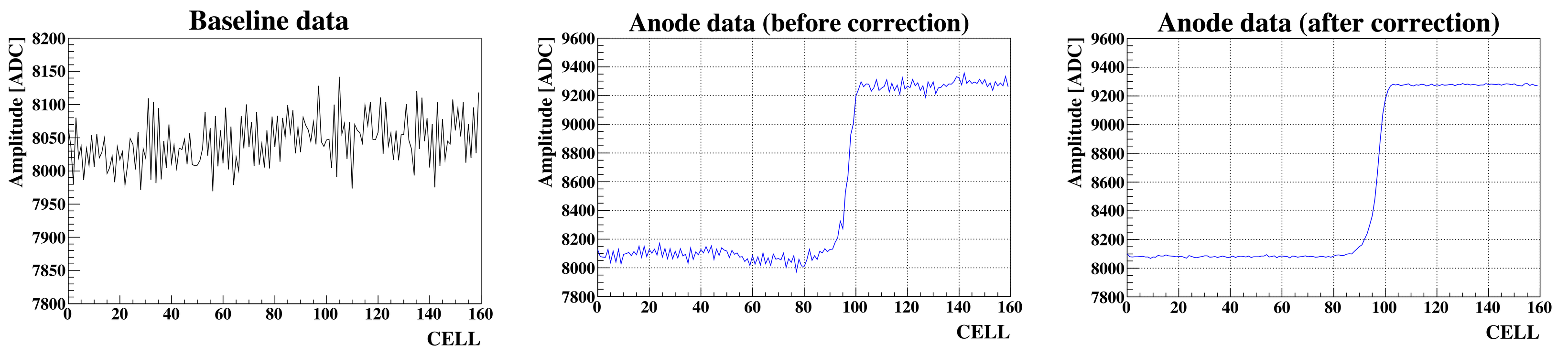


GUI-based DAQ program was developed using the CERN ROOT package. The figure above is a screenshot of the GUI control panel in operation during the HIGS beam test. The 4 x 4 histogram in the right pane shows processed anode signals from one of the CZT crates. The beam energy at the time of this screenshot was 5 MeV and the diameter of the beam profile was about 6mm, which corresponds to the cross-section of the CZT bar. The target bar can be easily identified on the plots (second from the left and second from the top). The 511 keV positron annihilation line is seen in the neighboring bars, and occurred due to incident photons creating electron-positron pairs.

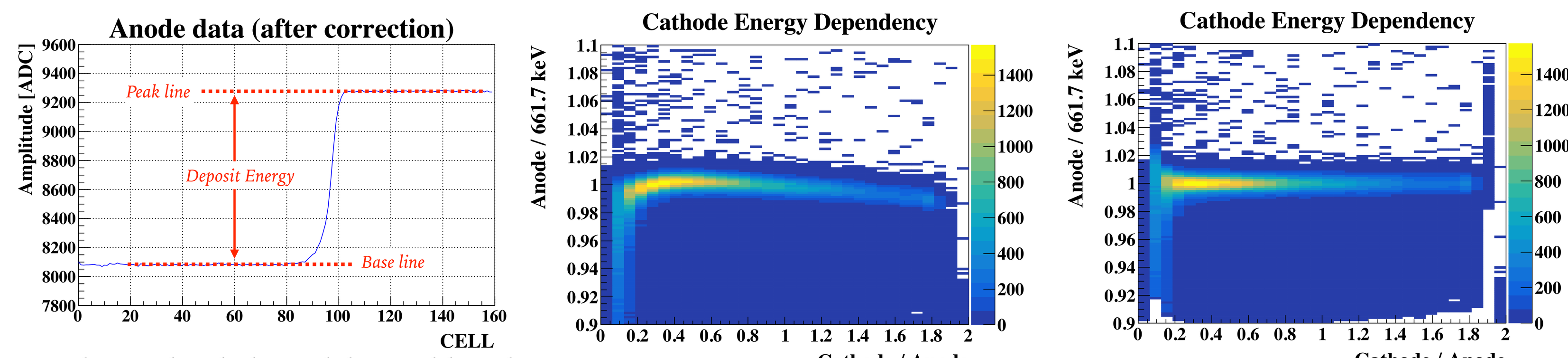
Performance

Data Corrections

Baseline correction: The IDM-121 wave form sampling ASIC has 121 (+2 special) input channels. Each channel having a pre-amplifier which is connected to a 160-cell analog pipeline. The analog pipeline is used as a ring buffer, and the signal from the pre-amplifier is continuously sampled into the pipeline until readout is triggered. Each cell has a different offset due to process variation in the hardware, and needs to be corrected the offset appropriately as shown in the following figures.



Depth correction: Although the position dependence of the output anode signal, which carries the energy information, is suppressed by the Frisch-grid design, some remains due to shielding inefficiency of the virtual grid and to the crystal non-uniformity. Therefore, to improve the energy resolution, the magnitude of the anode signal needs to be corrected by the depth of interaction, which can be estimated from the Cathode to Anode signal ratio, as shown in the following figures.

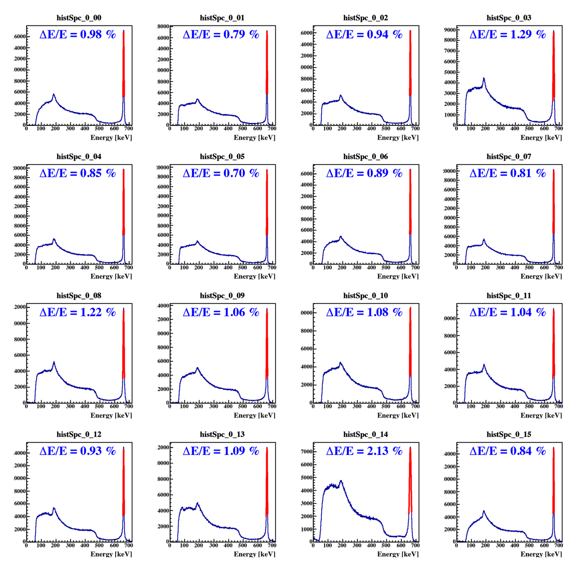


Anode signal with the peak line and base line indicated by dotted line. The deposit energy of the gamma-ray is proportional to the difference between the values of the two lines.

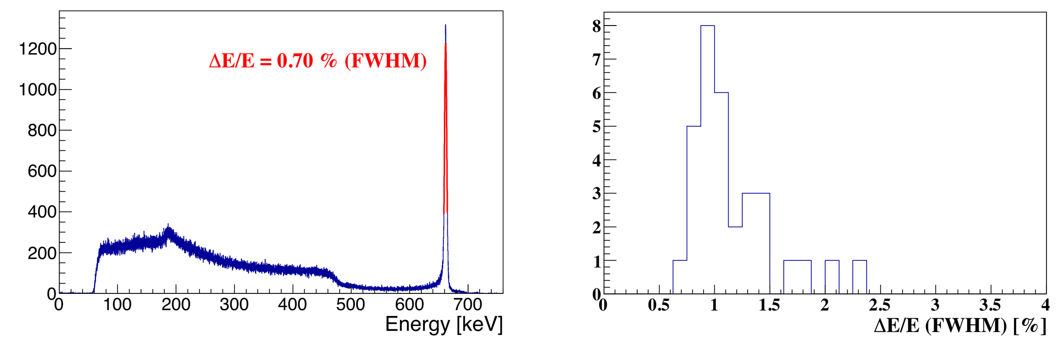
A cross plot of the Anode/661.7keV vs. Cathode/Anode for ^{137}Cs data before applying the depth correction.

A cross plot of the Anode/661.7keV vs. Cathode/Anode for ^{137}Cs data after applying the depth correction.

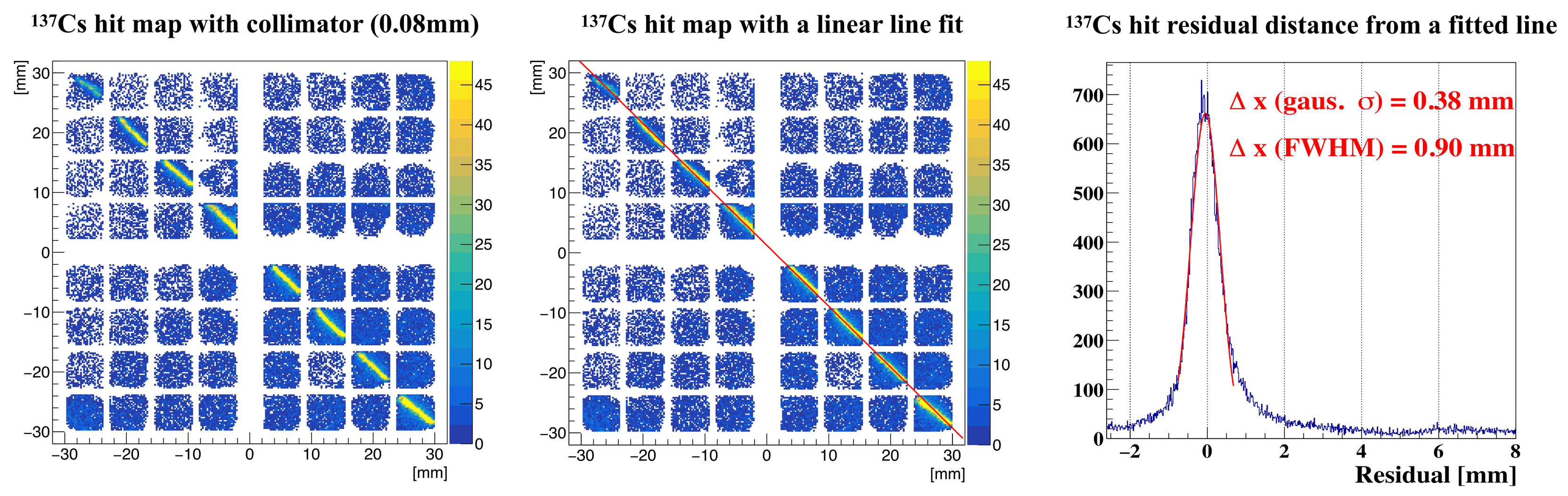
Energy Resolution and Position Resolution



Energy resolution: We used ^{137}Cs source to determine the energy resolution of the system. The left side figures (4x4) show the energy spectrum observed by one CZT crate. One of the histogram is enlarged and shown below along with the distribution of the energy resolution from two crates (32 bars). The peak value of the energy resolution distribution was less than 1%



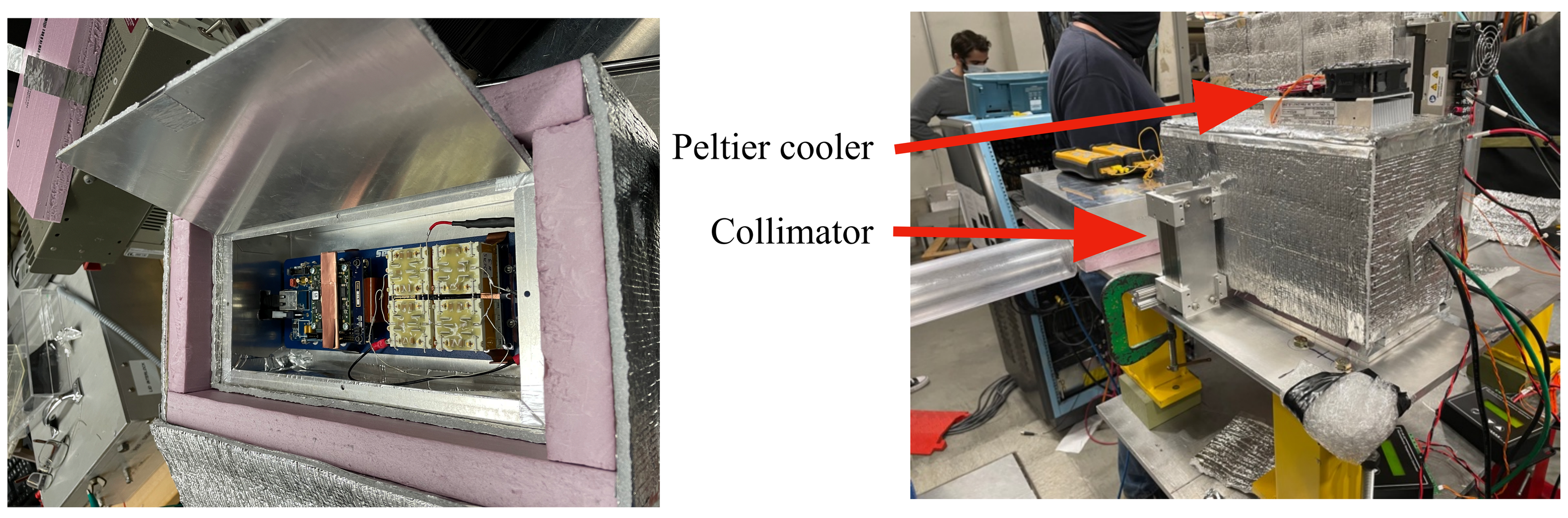
Position resolution: To determine the position resolution, we used ^{137}Cs source and a tungsten collimator with a 0.08 mm gap. The left figure below shows the reconstructed hit map of the detected events. The center figure shows the best linear fit line in red color, and the right figure shows the residual distance distribution between the reconstructed hit location and the fit line. As we expected, we obtained the position resolution (FWHM) of the system better than 1 mm.



HIGS Beam Test

Detector setup at beam line

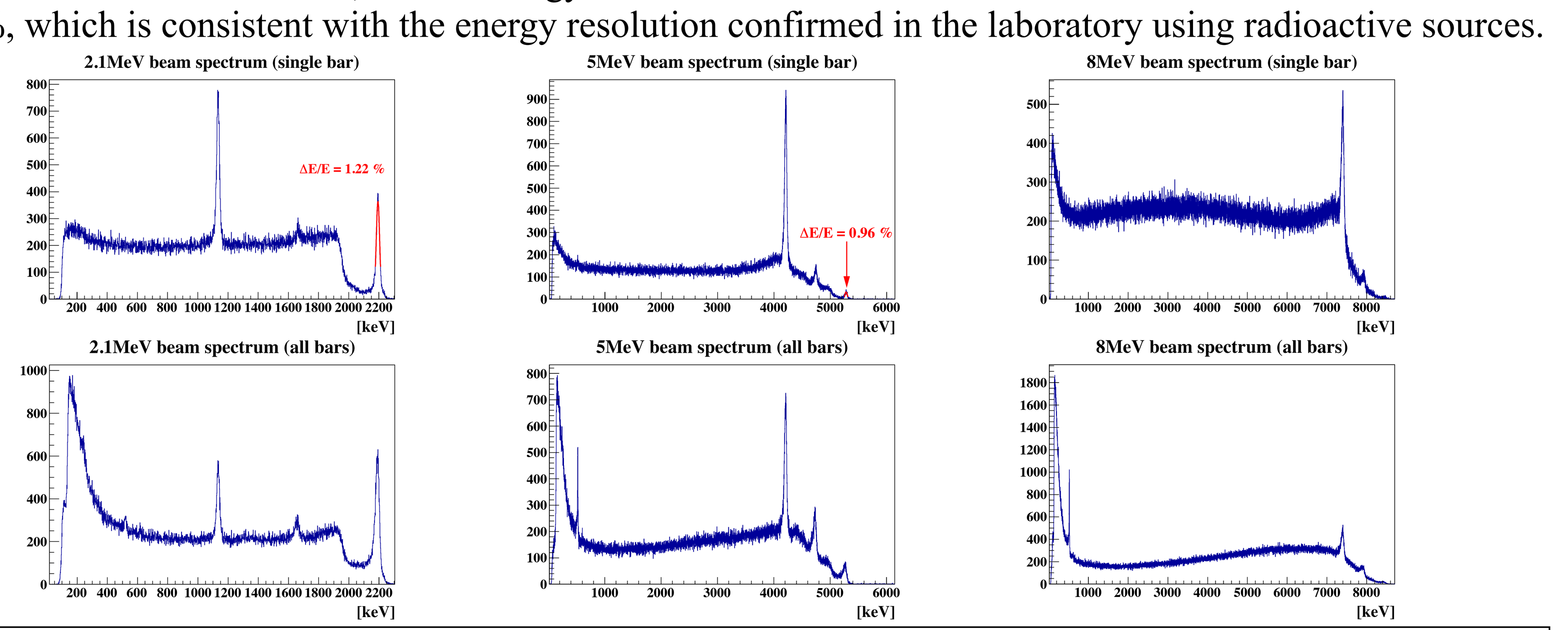
Test CZT detector we used at the beam is shown in the photo below, left. The GDS-100 system was installed in the small aluminum box with multiple thermal shields to keep the temperature stable during the beam test and to avoid moisture condensation. 4 CZT crates were attached to the system. A copper heat strap was attached to the FPGA on the control board for efficient cooling.



Peltier cooler (CP-040HT, TE technology, Inc.) was attached to the aluminum box to control the temperature inside the box. We kept the temperature around 18-20 degrees C during the beam test. The photo above, right, shows the test detector with the Peltier cooler at the top. A tungsten collimator was located at the front of the test detector to evaluate the position resolution of the detector. A HV cable, Ethernet cable, and power cable were connected to the detector through holes on the side wall.We carried out the beam test at the High Intensity Gamma-ray Source (HIGS) at Duke University on November 1 - 5, 2021 with total 20 hours of actual beam time to evaluate the performance of the CZT

HIGS beam test results

Energy spectra with various gamma-ray beam energies obtained at the HIGS beam test are shown here. The upper three figures show energy spectra from the single CZT bar targeted by the beam, and the bottom three figures show energy spectra after summing the signals from all bars. There were clear 511 keV lines in the bottom figures for 5 and 8 MeV, which appear to have come from photons which created the electron-positron pair outside of the CZT detector. The energy resolution of the CZT bars at the beam energy was obtained from a Gaussian fit for the 2.1 MeV and 5 MeV. There were too few events that absorbed all the beam energy for the 8MeV. $\Delta E/E$ (FWHM) at the full absorption peak for the 5MeV beam was 0.96%. The energy resolution of the beam itself has been measured separately and is estimated to be about 0.6%, so the energy resolution of the instrument itself is therefore estimated to be 0.7%, which is consistent with the energy resolution confirmed in the laboratory using radioactive sources.



SUMMARY.

We demonstrated the basic principles and benefits of the CZT imaging technology for γ-ray space telescopes and its ability to measure with high efficiency both the photon interaction sites and the deposited energy with 3D position resolution <1mm and energy resolution <1% FWHM. Arrays of such detectors have been recognized as promising for use in various γ-ray telescopes. The Imaging CZT calorimeter represents a Compton mission enabling technology and is being prepared for a balloon flight as a subsystem of the AMEGO [2] prototype ComPair.

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3. A.E. Bolotnikov, et al., "A 4x4 array module of position-sensitive virtual Frisch-grid CdZnTe detectors for gamma-ray imaging spectrometers", Nuclear Instruments and Methods in Physics Research A954, 161036, 2020
4. https://ideas.no/products/gds-100