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High-Energy 3D Calorimeter based on position-sensitive virtual Frisch-grid CdZnTe detectors for use in Gamma-ray Astronomy

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We present a concept for a calorimeter based on a novel approach of 3D position-sensitive virtual Frisch-grid CZT detectors. This calorimeter aims to measure photons with energies from ~100 keV to 10 (goal 50) MeV. The expected energy resolution at 662 keV is ~1% FWHM, and the photon interaction position-measurement accuracy is ~1 mm in all 3 dimensions.

Each CZT bar is a rectangular prism with typical cross-section of 6x6 mm^2 and length of 2-4 cm. The bars are arranged in modules of 4 x 4 bars, and the modules themselves can be assembled into a larger array. The 3D virtual voxel approach solves a long-standing problem with CZT detectors associated with material imperfections that limit the performance and usefulness of relatively thick detectors (i.e., > 1 cm). Also, it allows us to relax the requirements on the quality of the crystals, maintaining good energy resolution and significantly reducing the instrument cost.

Such a calorimeter can be successfully used in space telescopes that use Compton scattering of γ rays, such as AMEGO, serving as part of its calorimeter and providing the position and energy measurement for Compton-scattered photons. Also, it could provide suitable energy resolution to allow for spectroscopic measurements of γ-ray lines from nuclear decays. Another viable option is to use this calorimeter as a focal plane to conduct spectroscopic measurements of cosmic γ-ray events. In combination with a coded-aperture mask, it potentially could provide mapping of the 511-keV radiation from the Galactic Center region.

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1. Introduction

We are developing a three-dimensional, high-energy-resolution, high-efficiency calorimeter for photon energies 0.2 – 10 MeV, based on novel drift (Frisch-grid) bar CdZnTe (hereafter CZT) detectors recently developed at Brookhaven National Laboratory [1, 2]. This calorimeter will have a position resolution of <1mm along each of 3 axes and energy resolution of 1-3%, depending on the incident photon energy, with capability of operating in ambient conditions. The design features will allow us to correct the response non-uniformity caused by crystal defects, which means that standard grade (unselected) CZT material can be used. This will significantly increase the yield of acceptable detectors and consequently reduce the cost of the instrument. This technology represents a breakthrough, because it promises high performance with large-area detectors at a reasonable cost.

The immediate application of this technology is in medium-energy γ-ray space telescopes (e.g. AMEGO [3] or e-ASTROGAM [4]), whose high scientific potential has been emphasized by results at lower energies (Swift, NuSTAR) and higher energies (Fermi Large Area Telescope). In particular, the drift-grid CZT detector will enable a medium-energy γ-ray instrument to:

- provide incident photon energy measurement with high resolution, including the capability to measure cosmic nuclear lines;
- serve as a focal plane detector for Compton-scattered events to determine the direction and polarization of incident photons;
- enable a modular calorimeter of large area, which is critical for space instruments designed to measure low-intensity photon fluxes.

CZT is a promising medium for room-temperature γ-ray detectors and has several advantages over other semiconductor detectors (Si, Ge): a high atomic number, high density (important for γ-ray detection), a low Fano-factor 0.4, ability to operate at room temperature, and chemical and mechanical stability. The operational principle of CZT detectors is very similar to classic gas ionization chambers and to other semiconductor detectors. CZT detectors have been used in a number of space experiments, e.g. Swift, InFocus, and NuStar. The best energy resolution, approaching the electro-hole production statistic limit, 0.5% FWHM at 662 keV, has been demonstrated with large-volume pixelated detectors, up to 6 cm^3, made from the highest-quality CZT crystals [5]. The main challenge facing detector developers today is not how to make high-performance CZT detectors but how to make them less expensive and more widely available for practical applications. The main obstacle is the response non-uniformities caused by crystal defects that are present even in the best-quality commercial CZT material [6].

The low production yield of high quality crystals hampers the use of CZT detectors for γ-ray spectroscopy. Significant efforts have been directed towards improving the quality of CZT crystals to make them generally available for radiation detectors. Today, the most common defects still remaining in detector-grade CZT crystals are subgrain boundaries and Te inclusions or dislocation clusters left after annealing Te inclusions, which result in local variations in distributions of carriers trapping centers. These defects affect both the energy resolution and photopeak efficiency. The production yield of acceptable crystals is governing today the cost and availability of CZT detectors. It is clear that probability of finding "good" crystals decreases with volume, and it also depends on detector geometry.

One way to address this problem is to implement detector designs that would allow vendors to increase production yields and lower detector costs. Another possibility is to apply accurate and predictable correction of the response for the non-uniformities caused by the small defects. The latter approach is justified by the fact that the defect locations inside crystals are fixed, while the signal variations come about due to random distributions of interaction points and, thus, can be corrected by dividing the detector's active volume into sufficiently small voxels and equalizing responses from all voxels. Such detectors, called high-granularity position-sensitive detectors, can significantly improve the performance of CZT detectors fabricated from CZT crystals with wider acceptance boundaries, leading to an increase of their availability and expected decrease in cost.

Several types of CZT detectors were shown to achieve energy resolution close to the CZT material intrinsic limit determined by the statistics of the electron-hole pair production. Two detector designs: pixelated and coplanar-grid are particularly suitable for large-volume detectors. However, their performances were also shown to strongly depend on the quality of CZT crystals. Indeed, while the co-planar grid detector (CPG) device can offer drift-time (or interaction depth) correction, it has no position-sensitivity in XY directions, which means that the variations in the charge-collection efficiency over the device's area may degrade the spectral response. 3D devices have an advantage over CPG because they can correct large-scale response variations in 3-D coordinate space. However, because of rather coarse segmentations, they still rely on using the highest-quality CZT crystals.

2. Virtual Frisch-grid CdZnTe detectors

The proposed calorimeter is based on arrays of position-sensitive virtual Frisch-grid (PSVFG) detectors recently introduced by Brookhaven National Laboratory for imaging and spectroscopy of γ-ray sources. The array employs small area, currently 6x6 mm^2 (can be larger), but long, potentially up to 3-4 cm CZT crystals (bars) tightly packaged together. Each crystal is furnished with two gold contacts on the top and bottom surfaces (the anode and the cathode) and encapsulated inside an ultra-thin dielectric shell (or coating), which electrically insulates and mechanically protects the crystals. To make the detector position-sensitive, 4 metal pads are attached to the shell near the anodes (Fig. 1). The combination of high geometrical aspect ratio of the detector and the virtually grounded pads produces a strong shielding effect as if a real Frisch-grid were placed inside the crystal to shield the anode. Although, the virtual Frisch-grid design was originally proposed for a noble gas filled drift cells [7], this idea turned out to be more successful when applied to CZT detectors: CAPture^{TM} [8], hemispherical [9], Frisch-ring [10], and capacitive Frisch-grid [11].

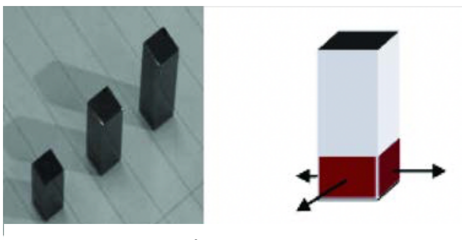

Figure 1. 6x6 mm^2 CZT bars of different length (left) and schematic of the detector (right).

The amplitudes of the signals read out from the pads are used to evaluate X-Y coordinates, while the drift time and the cathode-to-anode ratio, C/A, are used to independently evaluate the Z coordinate for the location of each interaction point. However, the design constrains dictate us to connect together the pads of adjacent detectors facing each other. Furthermore, we connect together the cathodes of 4 adjacent detectors. This also reduces the total number of readout channels, but it creates signal ambiguity when multiple interactions occur in adjacent detectors. In such cases, we cannot use the pads with signals generated by electron clouds in two adjacent but different detectors. The remaining signals from two orthogonal or three pads still can be used to evaluate the positions of the interaction points. We verified experimentally that two signals from two orthogonal pads are sufficient to locate the interaction point within a detector.

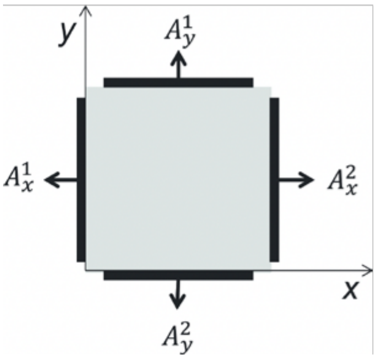

Figure 2. The coordinate associated with the detector

Fig. 2 shows the coordinate system associated with the PSVFG detector. The pads response function gives the amplitudes of the pad signal versus the *X-Y* coordinates of the electron cloud:

$$A = R(x, y) \tag{1}$$

Accordingly, the inverse R^{-1} function allows us to evaluate X and Y coordinates. There are several ways to construct the inverse response function. We assume that the amplitudes from the opposite pads define the position of the line along X (or Y) directions, while the amplitudes from the two orthogonal pads determine the point location on the line. For example, if the position of the line along the *X*-axis is defined by A_x^1 and A_x^2 amplitudes, then we can have two estimates for *X* where each depends on A_x^1 and A_x^2 :

$$X_1 = R^{-1}(A_x^1, A_y^1, A_y^2) \tag{2}$$

$$X_2 = L - R^{-1}(A_x^2, A_y^1, A_y^2) \tag{3}$$

where *L* is a distance between two opposite pads. Combining both estimates we can write:

$$X = \frac{X_1 W_1 + X_2 W_2}{W_1 + W_2} \tag{4}$$

where W_1 and W_2 are the weights defined as:

$$W = \frac{1}{\sigma_x^2} \tag{5}$$

where σ_x^2 is the standard deviation of the estimates:

$$\sigma_x^2 = \left(\frac{\partial R}{\partial A}\right)^2 \sigma_A^2 \tag{6}$$

The pad response functions have to be evaluated during the calibrations. In the first approximation, we can assume that they are identical for all detectors and all pads. We note that the above equations can be applied in the cases of using only 2- and 3-pad signals. Using a linear approximation for the response functions and taking the signal amplitudes as the widths, we can get a first-order estimate for *X* and *Y* coordinates:

$$X = \frac{A_x^1}{A_x^1 + A_x^2} \tag{7}$$

and

$$Y = \frac{A_y^1}{A_y^1 + A_y^2} \tag{8}$$

The first order (linear) estimates can be used for correcting the response non-uniformity, but they cause notable distortions near the detector edges when used for evaluating the real-space coordinates, especially in the case of 2- and 3-pad signals. As we demonstrated [12] the second order response functions provide good position estimates with accuracy of less than 0.5 mm in *X-Y* directions and less than 1 mm in *Z* direction. The accuracy is primarily limited by the local non-uniformity of the electric field, which is a common problem of CZT detectors.

The second-order response functions can be iteratively evaluated using measured pads signals from an uncollimated ^{137}Cs source during the calibration. For each set of measured pad amplitudes (interaction event) we can use Eqs. (7,8) to calculate the first-order approximations for *X* and *Y*.

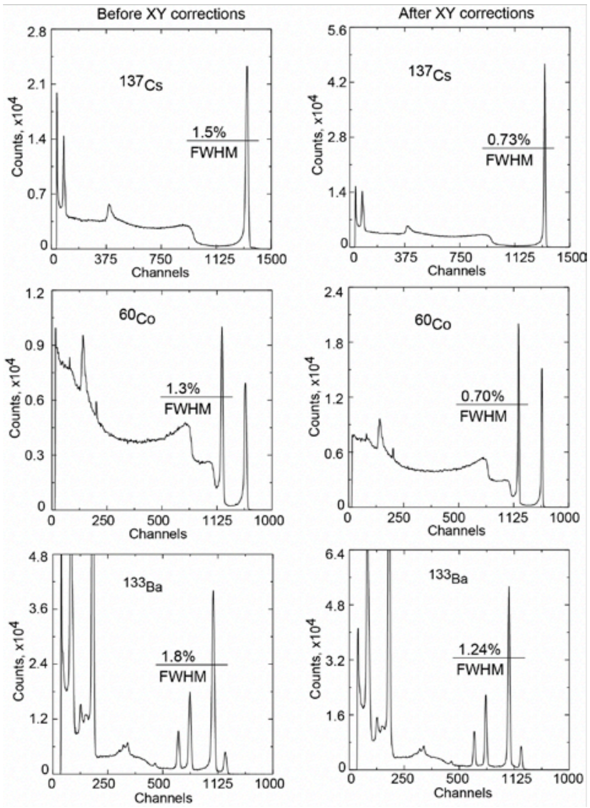

Figure 3. Performance improvements of a 20-mm thick position-sensitive virtual Frisch-grid detector before and after corrections for three γ-ray emitting sources [10]

Another advantage of using PSVFG detectors is that we can correct their response non-uniformities caused by crystal defects and local variations of the electric field inside the detectors. Despite significant progress in the technology and capabilities of CZT detectors, crystal defects (which exist even in the best quality CZT crystals) still remains the major factor that limits availability and increase costs of actual CZT instruments. Therefore, the main challenge facing detector developers today is not how to overcome these problems.

The proposed high-granularity position-sensitive detectors allow for more accurate and efficient charge-signal corrections to overcome non-uniformities in the devices' responses.

Using the position information, we can virtually divide a detector volume into small voxels and correct (equalize) responses measured from each of them by using a 3-dimensional correction matrix generated during calibration. Fig. 3 illustrates the performance of a 20-mm thick PSVFG detector before (left) and after (right) X-Y corrections measured with uncollimated ^{137}Cs, ^{60}Co, and ^{133}Ba sources. However we applied the drift-time (or interaction depth) corrections to the spectra shown on the left [12].

The main factor limiting the energy resolution of the PSVFG detectors is electronic noise related to the high leakage current, 5-25 nA, and large anode capacitance, ~3 pF. As we demonstrated, the detector's energy resolution stays below 1% FWHM at 662 keV for temperatures up to ~30 ^{0}C. Another potential problem in long-drift distance bars is the charge loss near the detector's side surfaces (edge effect).

These results demonstrate the feasibility of position-sensitive VFG CZT detectors and arrays of such detectors for high resolution γ-ray spectroscopic measurements. After applying the 3D corrections, we achieved an energy resolution below 1% FWHM at 662 keV with a majority of the CZT crystals that we either grew at BNL or obtained from commercial suppliers. The ability to use the majority of CZT crystals should bring down the cost significantly making this design useful in the manufacturing of commercial detectors.

3. Concept of the Calorimeter

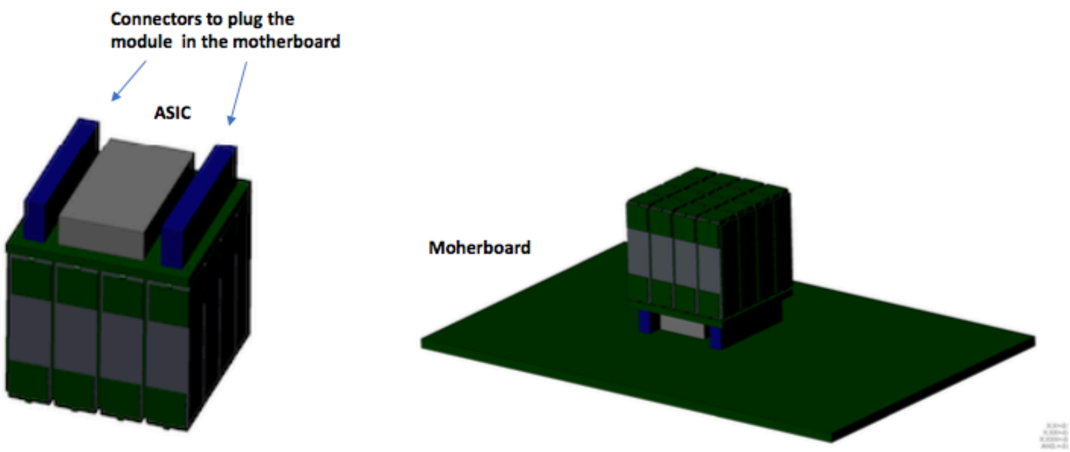

Figure 4. Individual 4x4 bar module (left, shown up-side-down), and plugged in the motherboard (right)

The base element of the calorimeter is a module made of 16 CZT bars, arranged in 4x4 bar array. Bars currently being tested are 6 x 6 x 20mm^3, which makes the module dimension 2.5 x 2.5 x 2 cm^3. The bars are encapsulated, tightly packaged and mounted on the printed circuit board (PCB). The module is served by a single ASIC positioned also there (Fig. 4). The modules (as many as a particular instrument design requires) are plugged into the "mother" PCB tightly to each other, making the array of the required area with practically no "dead" space (Fig. 4). The "mother" PCB distributes the signals to the appropriate electronics placed on its sides (FPGA etc.).

The best dimensions of the individual bars, and consequently the module size, are currently under investigation. Increase of the bar cross-section to 8x8mm^2 will reduce the number of needed bars to cover the same area, and also reduces the number of electronic channels. The cost of a larger size bar within these dimensions is roughly proportional to the detector volume, so the increased cross-section bar is probably the right approach. The increase of the bar length would be very good for the calorimeter performance because it would increase the detection efficiency (since the calorimeter thickness increases) and also the event containment. However longer bars experience larger leakage current and suffer from increased electric field distortion. Probably the optimal bar length is in the range of 30-35mm.

Ultimately we are targeting the following performance of the calorimeter:

a) extend detectable energy range down to ~100 keV;

b) energy resolution better than 1% for the photon energy 0.2 – 1 MeV and better than 3% for 1-5 MeV. Operation in "pair-production" range (above ~1.5 MeV) adds a problem of "escaping" annihilation 511 keV photons, so requires more work on the design and data analysis

c) spatial resolution (point of the first interaction) <1mm for E<1 MeV and 2-3mm for higher energy. Photons with energy >~1 MeV have several interactions before being fully absorbed, so more work is needed to identify the point of the first interaction. Possible solutions are the use of waveform sampling ASIC and developing smart analysis software. The high spatial resolution of such a calorimeter can make viable its use in the instruments utilizing a coded aperture mask and focused on accurate study of densily populated sky areas, e.g. Galactic Center or Cygnus region.

4. Summary

We are considering the use of such a calorimeter for the AMEGO Compton-Pair space telescope which is the NASA Probe-scale mission concept [3]. For that insrument the calorimeter array is 16 by 16 modules, making the area ~40 by 40 cm. AMEGO will comprise four such arrays, bringing the total area to ~80 by 80 cm. Extensive investigations are under way, which include numerous simulations, prototyping and testing. We are planning to run a beam test with photons of the energy 1 – 10 MeV to test our concept at higher energies than can be achieved with radioactive sources, as well as environmental tests to validate the design for space applications.

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