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Use of high-granularity CdZnTe pixelated detectors to correct response non-uniformities caused by defects in crystals

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ABSTRACT

Following our successful demonstration of the position-sensitive virtual Frisch-grid detectors, we investigated the feasibility of using high-granularity position sensing to correct response non-uniformities caused by the crystal defects in CdZnTe (CZT) pixelated detectors. The development of high-granularity detectors able to correct response non-uniformities on a scale comparable to the size of electron clouds opens the opportunity of using unselected off-the-shelf CZT material, whilst still assuring high spectral resolution for the majority of the detectors fabricated from an ingot. Here, we present the results from testing 3D position-sensitive $15 \times 15 \times 10\ \text{mm}^3$ pixelated detectors, fabricated with conventional pixel patterns with progressively smaller pixel sizes: 1.4, 0.8, and 0.5 mm. We employed the readout system based on the H3D front-end multi-channel ASIC developed by BNL's Instrumentation Division in collaboration with the University of Michigan. We use the sharing of electron clouds among several adjacent pixels to measure locations of interaction points with sub-pixel resolution. By using the detectors with small-pixel sizes and a high probability of the charge-sharing events, we were able to improve their spectral resolutions in comparison to the baseline levels, measured for the 1.4-mm pixel size detectors with small fractions of charge-sharing events. These results demonstrate that further enhancement of the performance of CZT pixelated detectors and reduction of costs are possible by using high spatial-resolution position information of interaction points to correct the small-scale response non-uniformities caused by crystal defects present in most devices.

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1. Introduction

3D position-sensitive CdZnTe (CZT) pixelated detectors, developed by the team from the University of Michigan, offer significant enhancements in CZT detector spectral performance and the capability for gamma-ray imaging [1–4]. Further improvements of their position resolution will allow for more accurate corrections of detector-response non-uniformities, which will further increase the spectral and spatial resolution of CZT detectors and increase their acceptance for practical applications. Recently, we demonstrated the feasibility of correcting the small-scale response inhomogeneity and enhancing the performance of position-sensitive virtual Frisch-grid CZT detectors fabricated from unselected off-the-shelf CZT crystals [5]. By reading the signals from 4 strips placed on the device's side surfaces and using this information to measure the coordinates of the interaction points with an accuracy of $\sim 100\ \mu\text{m}$, we achieved high-granularity segmentation of these detectors, up to $60 \times 60 \times 150$ voxels. The measured signals generated in each of these voxels by interaction events were corrected before adding the events to the pulse-height spectrum. The three-dimensional response matrix, used to apply the in-fly corrections, was obtained by calibrating each of the voxels before measurements. As a result, we improved the energy resolution of different $6 \times 6 \times 15\ \text{mm}^3$ detectors from 1.5–2.5% to 0.6–1.1% FWHM at 662 keV.

The goal of the work presented here was to demonstrate that high-granularity position sensing could also be applied to enhance the performance of large-volume pixelated detectors fabricated from unselected off-the-shelf CZT crystals.

Signals measured in CZT detectors are always affected by carrier trapping in crystals. In high mu-tau product material, $> 10^{-2}\ \text{V/cm}^2$, the trapping centers have low concentrations and should not be a problem provided their spatial distributions are uniform inside the crystals. Unfortunately, the dislocations and subgrain boundaries, commonly present in commercial CZT material, cause non-uniformities in the trapping centers distributions and, thus, fluctuations

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of the collected-charge signals. We note that variations of the collected-charge signals are solely attributed to random distributions of the interaction points and therefore can be corrected by making high-granularity detectors.

Two approaches can be considered to enhance the spatial resolution in pixelated detectors by using the collected- and transient-charge signals. The first approach [6–10] is applied when the whole charge from the electron cloud is collected on a single pixel. In such cases, the electron cloud induces transient signals on neighboring pixels, and the *X–Y* coordinates of interaction points can be obtained from the amplitudes of the transient signals. Theoretically, this approach should provide a sub-pixel resolution, but only within a geometrical area limited by the size of the electron cloud. The second approach is applied when the total charge from the electron cloud is shared between two or more neighboring pixels. As in the previous approach, the signal amplitudes corresponding to these pixels can be used to refine the positions of the interaction points with accuracy better than the pixel size, but, as in the previous case, within a certain geometrical area limited by the size of the electron cloud. In reality, both types of events occur in pixelated detectors with the relative number of shared events increasing with a decreasing pixel size. The total charge from the electron cloud can be collected on a single pixel (single-pixel events), or it can be shared among several pixels (charge-sharing events). This means that both approaches should be combined to evaluate the coordinates of the interaction points in pixelated detectors. Recently, Montemont et al. [11] demonstrated a novel algorithm for processing waveforms captured after charge-sensitive preamplifiers to refine the positions of the interaction points. Its key feature is that it uses time-correlated (synchronized) sampling amplitudes from several pixels, regardless of whether the signals generated on the pixels are collecting or transient. We will discuss this approach in detail in Section 2.3.

For this study, we employed pixelated detectors with conventional contact patterns similar to the ones used in 3D devices, but with smaller dimensions, and relied on charge sharing for attaining high-granularity position resolution. We undertook three runs of measurements using pixelated detectors fabricated with progressively smaller pixel sizes from the same set of CZT crystals used for each consecutive run of measurements. For the performance baseline, we measured the pulse-height spectra from the 1.4-mm pixel size detectors, for which most of the electron clouds generated by the interaction events are collected on a single pixel. In contrast, for 0.8- and 0.5-mm pixel detectors, the majority of the events are shared between several adjacent pixels, allowing the high-granularity segmentation to improve the overall performance of these detectors.

2. Experimental

We conducted three runs of measurements to evaluate the performance of twelve $15 \times 15 \times 10\ \text{mm}^3$ 3D position-sensitive pixelated detectors fabricated from the same set of CZT crystals, but with progressively smaller pixel sizes, viz., 1.4, 0.8, and 0.5 mm. To read the signals generated in the detectors, we employed the data-acquisition system based on the H3D front-end ASIC developed in collaboration between BNL's Instrumentation Division and the University of Michigan [12–15]. By using the same crystals to fabricate the detectors for each next run, we were able to directly assess the effect of a reduction in pixel size (or higher granularity) on device performance.

Since the goal of this work was to demonstrate the feasibility of using high-granularity position sensing to correct the response non-uniformities in pixelated detectors, we were not concerned with reconstructing the multiple interaction point events caused by the Compton scatterings. Instead, for the analysis, we selected only single-point interaction events, which we used to plot the pulse-height spectra and evaluate the width of their photopeaks. We note that single-point interaction events still can be collected on several adjacent pixels. We set a limit of 4 on the maximum number of pixels per event; the events with a greater number of hit pixels would be an indication of multiple point interactions as will be explained in Section 2.3.

As mentioned in the Introduction, for the performance baseline we used detectors with a 1.4-mm pixel pitch. In these detectors, the majority of interactions produced single-pixel events, for which we applied the drift-time corrections (along *Z*-coordinate) only. Therefore, we anticipated that the energy resolutions of 1.4-mm pixel size detectors would be affected by small-scale non-uniformities. By comparing the energy resolution measured for the baseline detectors with those measured in the second and third runs, we could demonstrate the advantages of high-granularity pixelated detectors.

2.1. Detectors and front-end ASIC

Four $15 \times 15 \times 10\ \text{mm}^3$ CZT crystals, grown by the High-Pressure Electro-Dynamic-Gradient technique [16], were acquired from eV Products Inc. The crystals were cut from spectroscopy-grade material with a resistivity of $> 3 \times 10^{10}\ \Omega$-cm and a mu-tau product of $> 7 \times 10^{-3}\ \text{cm}^2/\text{V}$. Before fabricating the actual devices, we screened the crystals to reveal the presence and extent of extended defects, which are present inside the material, using white X-ray diffraction topography (WXDT) at BNL's National Synchrotron Light Source (NSLS).

Detectors with conventional contact patterns, comprising 11×11 square pixels (a 10×10 pattern was used for the first run) and 25-μm gaps between the pixel contacts, were fabricated by eV Products and mounted on the ceramic fanout boards using the reworkable conductive-epoxy bonding technology that allowed us to reuse the same crystals in the subsequent rounds of measurements. There was no interposing grid between the pixel contacts. For measuring the performance baseline (first run), we used detectors with a 1.4-mm pitch. For the second- and third-runs we used, correspondingly, 0.8- and 0.5-mm pixel pitches.

The readout system with the communication interface and low-voltage converters was enclosed inside a light-tight aluminum box that had a thin entrance window for the gamma rays. Fig. 1 shows the design of the 10×10 contact pattern, (a) the assembled detector mounted on the fanout substrate, and (b) the test box with a detector plugged into the motherboard (c). During the measurements the test box was placed inside an environmental chamber, where heat generated by the ASIC was drawn out, maintaining the temperature of the detector at around 18 degrees Centigrade. An uncollimated ^{137}Cs source with an activity of $\sim 10\ \mu$Ci was placed ~ 1 cm above the detector's cathode. Each measurement run usually took 2–3 days, the time needed to accumulate several gigabyte-size files containing a continuous data stream of the captured signal amplitudes and timing. For these measurements, we used the following ASIC settings: 1-μs peaking time for the anodes and the cathode's energy, and 0.2 μs for the cathode's timing. The cathode's bias was set at 2000 V.

Strong diffusion and electrostatic repulsion of the electrons in CZT cause significant broadening of electron clouds before they reach the anodes. This is particularly important in pixelated detectors with their higher probability of charge-sharing events, which can degrade the device's performance. One problem associated with such events is the charge loss in the gaps between the pixel contacts. Because of the high conductivity of a CZT surface, the electric field lines are virtually perpendicular to the crystal's surface between the contacts, meaning that a small fraction of the

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