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Study of sub-pixel position resolution with time-correlated transient signals in 3D pixelated CdZnTe detectors with varying pixel sizes

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A B S T R A C T

We evaluated the sub-pixel position resolution achievable in large-volume CdZnTe pixelated detectors with conventional pixel patterns and for several different pixel sizes: 2.8 mm, 1.72 mm, 1.4 mm and 0.8 mm. Achieving position resolution below the physical dimensions of pixels (sub-pixel resolution) is a practical path for making high-granularity position-sensitive detectors, <100 μm, using a limited number of pixels dictated by the mechanical constraints and multi-channel readout electronics. High position sensitivity is important for improving the imaging capability of CZT gamma cameras. It also allows for making more accurate corrections of response non-uniformities caused by crystal defects, thus enabling use of standard-grade (unselected) and less expensive CZT crystals for producing large-volume position-sensitive CZT detectors feasible for many practical applications. We analyzed the digitized charge signals from a representative 9 pixels and the cathode, generated using a pulsed-laser light beam focused down to 10 μm (650 nm) to scan over a selected 3×3 pixel area. We applied our digital pulse processing technique to the time-correlated signals captured from adjacent pixels to achieve and evaluate the capability for sub-pixel position resolution. As an example, we also demonstrated an application of 3D corrections to improve the energy resolution and positional information of the events for the tested detectors.

1. Introduction

Large-volume, >1 cm^3, position-sensitive CdZnTe (CZT) gamma-ray detectors have been proposed and used in many applications [1]. Among them, a $20 \times 20 \times 15$ mm^3 3D position-sensitive detector developed by the Orion radiation measurement group at University of Michigan [2] demonstrated a record breaking energy resolution, high detection efficiency and advanced imaging capabilities. However, these kinds of detectors mainly rely on using premium-grade (selected) CZT material, which has a low production yield and high cost. The proliferation of this highly demanded technology is connected to the growing supply of low-cost material free from crystal defects. The steady supply of such material has yet not been achieved. An alternative (and more economical) approach is to employ more accurate charge-loss (or response non-uniformity) correction techniques, which rely on using high-granularity position sensitive detectors. These techniques allow for using standard-grade materials to reduce the device cost without compromising their performance. High position sensitivity allows us to virtually divide the detector active volume into small voxels and equalize the responses from each voxel. Recently, we demonstrated this approach for 3D pixelated detectors with small-pixel sizes, using charge sharing to enhance position resolution [3]. Using the collected-charge signals generated as a result of the charge sharing is an easy and straightforward approach for achieving sub-pixel resolution. However, its main drawback is that it requires using small pixels and readout channels, which makes this approach impractical for many applications due to system complexity and power consumption in the readout ASIC. A more practical approach involves use of the induced signals from the adjacent pixels to refine the position resolution. In this work, we investigated several commercial pixelated detectors with varying pixel sizes using the time-correlated transient signals.

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The approach of using the induced-charge signals from adjacent pixels to refine the position resolution of events was originally proposed (to the best of our knowledge) by Warburton and employed by several researchers [4–8]. It 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. In reality, both types of events occur in pixelated detectors with the relative number of shared events increasing with 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. In most cases, the researchers used a center-of-gravity algorithm to process the amplitudes of the shaped signals. More advanced algorithms have been proposed [9,10] using the signal waveforms and the maximum-likelihood method to find the best fit to the benchmark waveforms obtained from a calibration run or simulated theoretically and analyzing pulse shapes of strip signals.

Recently, we evaluated sub-pixel position resolution of a 3D pixelated detector with a pixel size of $1.72\times\ 1.72$ mm^2 and demonstrated the advantage of using the time-correlated approach for enhancing the position resolution [11]. This was done considering single-point interaction events only, which were generated by means of a pulsed laser. In this work, we investigated the position resolution of commercial pixelated detectors with standard patterns of varying pixel sizes (0.8 mm, 1.4 mm, 1.72 mm, and 2.85 mm) and illustrate the application of the response corrections in a pixelated detector. In this work we conduct systematic measurements to evaluate the energy dependencies of position resolution (%FWHM) using pixelated detectors with different pixel sizes. These data help to optimize the pixel size for achieving high-energy resolution (after response corrections) of large-volume CZT detectors, while using a minimum number of readout channels and standard (unselected) grade CZT crystals. Furthermore, this work aims to show the improvements in spectral resolution when applying 3D corrections to a pixelated crystal.

2. Experimental setup

The pulsed laser beam system is comprised of a 1 mW laser beam (650 nm wavelength) coupled with a single mode optical 9 μm fiber and microscope objective. The beam is manually focused on the surface of the detector over the pixels of interest using the same objective. We note, that the short light pulse (in these measurements we could vary the pulse width in the range 10–100 ns) cannot entirely substitute for actual gamma-ray events, but it has several advantages for the measurements conducted in this study; it provides precise timing and the original location of the injected charge, and ability to generate signals equivalent to gamma rays from a wide energy range (100 keV–2.5 MeV).

The detector being tested was plugged into the test box's motherboard containing 10 charge-sensitive preamplifiers (eV-5093), whose inputs were connected to the pixels of interest in the detector (3×3 area). The detector system was mounted on the motorized $X-Y$ translation stage controlled by a computer.

The detectors mounted on substrates were acquired from two vendors: Redlen Technologies, Inc. and eV Products, Inc. with a large fraction of working pixels (>50%) to ensure that we could scan over several 3×3 pixel areas for each detector. The pixel sizes varied from 0.8 mm to 2.85 mm as shown in Table 1. The socket board of the readout detector system allows selecting and reading out the signals from any of the pixels. The signals from the nine pixels and the cathode were recorded using two synchronized oscilloscopes: a LeCroy HDO 8058 oscilloscope and a LeCroy 6050 Waverunner. The charge signals, generated by the electron cloud as it drifted between the cathode and the anode, were sampled at 10 ns time intervals (bins) and stored in the oscilloscopes' memories for further analysis. The measurements were taken at room temperature around 21–22 °C. For the energy calibration, we used a standard ^{137}Cs source. The high-voltage values were 500 v per 5 mm in height for each detector.

For each event (laser pulse), we captured 10 waveforms from all 9 pixels (a central pixel plus 8 neighbors) and the cathode. The scan area was selected to ensure that the central pixel has the strongest signal, meaning that we covered the actual area of the central pixel. The boundaries of this area are not necessarily matched to the geometrical pixel boundaries because of the local non-uniformity of the electric field. After the carriers reach the anodes (collected by one or several pixels), all the waveforms plateau at either a close-to-zero level (if no charge has been collected at these pixels) or at some positive level proportional to the amount of collected charges (charge sharing). Using these levels we can identify the charge sharing versus single-pixel events and locate the actual physical boundaries between the neighboring pixels, i.e., when the levels measured from two adjacent pixels are equal. We also performed linear scans across the middle of the 3 pixels along the X and Y directions.

3. Data analysis

For each beam position we captured 500 sequential waveforms and evaluated their $X-Y$ coordinates using the time-correlated sample amplitudes from the recorded waveforms. For each coordinate, we selected two time-correlated samples: A_x^1 and A_x^2 for X and A_y^1 and A_y^2 for Y from the corresponding waveforms. Each pair was selected at a time at which the sample was the highest. In other words, one of A_x^1 and A_x^2 (and similarly of A_y^1 and A_y^2) is the maximum sample of the two corresponding waveforms. By selecting the highest amplitude of the time-correlated samples, we minimize the statistical (electronic) noise. As previously demonstrated [11] in our evaluation of one single pixel size (1.72) this gives the highest variation range, so we can expect to achieve the best position resolution.

As an example, Fig. 1 shows scans at three different energies for the largest pixel-size detector tested (eV Products, Inc., $15\times 15\times 10$ mm^3 volume and 2.85 mm pixel size). Each broad line consists of the overlapping Gaussian-like distribution of the estimated locations for each position of the laser beam. The FWHM of these distributions were used to estimate the position resolution at specific amounts of injected carriers. The amount of the locally injected carriers depends on the cathode contact and surface properties. The varying widths of the beam images display the different amounts of charge injected along the beam pass.

4. Results and discussion

Fig. 2 shows the dependencies of the spatial resolution, % FWHM, on the amount of injected charge (converted into the deposited energy equivalents) for different pixel sizes. As previously mentioned, we used a ^{137}Cs source to convert the signal amplitudes into the deposited energies, and based on geometrical consideration, the position resolution scales proportionally to the pixel sizes. The amplitudes of the signals induced on the adjacent pixels increase with larger pixel areas resulting in a higher signal-to-noise ratio. One could expect that the position resolution reaches a minimum at a certain pixel size. However, as seen from the plot, the largest pixel size (2.8 mm) yields a poor position resolution compared to the smaller pixel sizes. A high signal-to-noise ratio impacts the recorded waveforms and the amplitudes from the anodes, which affect the time-correlation technique and the position resolution. A small pixel size is affected by electron-cloud diffusion and electrostatic repulsion of the electrons, which alters the electron cloud before it reaches the anodes, whereas a large pixel size minimizes charge-sharing events.

Comparing the 1.72 mm and 1.4 mm pixel detectors with a corresponding nominal pixel size of 1.22 mm and 1.12 mm respectively,