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Improvement of Compton imaging efficiency by using side-neighbor events

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In a pixelated detector, an electron cloud can be collected by and shared between several adjacent pixels. By including these charge-sharing events, the Compton-imaging efficiency can be improved for 3D position sensitive room-temperature CdZnTe gamma-ray detectors. Simulated photopeak events that trigger three separate pixels with two pixels being adjacent to each other, which are called three-pixel side-neighbor photopeak events, were divided into six categories based on interaction type. Analysis of this simulation shows that the most effective strategy is to treat all side-neighbor events as charge-sharing events and to combine all side-neighbor signals into a single interaction. By including these side-neighbor events in the Compton image reconstruction, we can improve the imaging efficiency by 45% and 160% for 662 keV and 1333 keV incident photons, respectively. The simulation also shows that 76% of these combined events reconstruct to rings that pass the source direction. Measured data is presented to validate the simulation results.

1. Introduction

Traditional spectroscopic gamma-ray detectors record the total energy deposited by each gamma ray in the active volume, producing a single energy spectrum. However, when the three-dimensional interaction positions of each gamma ray can be recorded, one can also produce an image of the source intensity around the detector using Compton imaging. A simple back-projection (SBP) image can be achieved by summing up the back-projection cones in the image space [1]. Maximum-likelihood deconvolution provides superior angular resolution by considering the probabilities that each measured event was produced by a photon originating from each direction in space [1,2].

Prior analysis did not include events that involve charge collection by adjacent pixels in the image reconstruction algorithm [1–5]. These events are defined as side-neighboring events and their probability of occurrence increases with gamma-ray energy. This work improves the Compton imaging efficiency by including side-neighboring events in the imaging reconstruction.

2. Charge-sharing events

In this work, we used a pixelated CdZnTe detector with dimensions of 2 cm $\times$ 2 cm $\times$ 1.5 cm. The anode of this detector is divided into an 11×11 array of pixels with a pixel pitch of 1.72 mm. The lateral positions of the interaction are determined by the anode pixel that collects the electrons. The interaction depth is found by the electron drift time. The depth uncertainty is about 0.5 mm.

The electron cloud from a single gamma-ray interaction can be collected by and shared between several neighboring pixels. This phenomenon, known as charge-sharing, can be produced for several reasons: a large electron cloud has a size comparable to the pixel pitch; the electron cloud is located directly over the gap between pixels; the electron cloud diffuses while drifting towards the anode; and the X-ray emission from a photoelectric interaction. However, it is also expected that some side-neighbor events will occur due to two gamma-ray interactions in adjacent pixels. The two mechanisms for generating side-neighboring events are difficult to distinguish and prior work did not include the events in the Compton image reconstruction.

Theoretically, charge-sharing interactions should be combined into a single interaction because they are produced from a single electron cloud. However, it is very challenging to differentiate charge-sharing events from side-neighbor Compton scattering events. To identify that two interactions took place the separation distance between the interactions must be greater than the spatial resolution of the device. The spatial resolution of the ASIC readout system used in this work [6] is limited to the pixel pitch. Thus, it is impossible to differentiate multiple interactions from charge sharing in side-neighbor pixels based on the separation information within the plane of the pixels. The only remaining possibility is to separate charge-sharing events from multiple-interaction events based on the depth of interaction in each pixel.

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Table 1
The definition and the event fraction for each category of three-pixel side-neighbor events at 662 keV.

	Charge sharing	Compton scattering	Others
First interaction is involved in the side-neighboring pixels	Cat. 1: 22.4%	Cat. 2: 18.5%	Cat. 3: 5.2%
First interaction is not involved in the side-neighboring pixels	Cat. 4: 16.5%	Cat. 5: 25.7%	Cat. 6: 11.7%

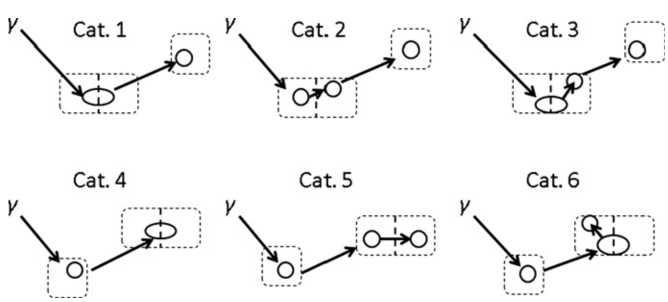

Fig. 1. Illustrations for each category in Table 1.

However, the average depth separation is shown in this work to be small relative to the depth resolution. Furthermore, the drift time measurement in a pixel may be distorted due to interference from the collection of a charge cloud in a neighboring pixel, further degrading the depth resolution of side-neighboring events.

Spatial resolution better than the pixel pitch, known as sub-pixel resolution, is achievable if the readout system can provide the charge induction as a function of time for each pixel. This has been achieved by sampling the preamplifier signal for each pixel at 80 MHz and analyzing the transient charge induction on the pixels that do not collect charge [7]. The capabilities of such a system will increase the probability of correctly identifying the number and the type of interactions as well as their respective locations.

The charge-sharing effect can be reduced by increasing the pixel pitch of the detector. However, increasing the pixel size will cause poorer energy resolution because it increases the position uncertainty, reduces the small pixel effect [8], and increases the leakage current collected by each pixel. As a consequence, the enlarged pixel size will improve the non-charge-sharing imaging efficiency while degrading the noise performance and angular resolution in the reconstructed image. With our current detector configuration, about 31% and 61% of the multiple-pixel events at 662 keV and 1333 keV

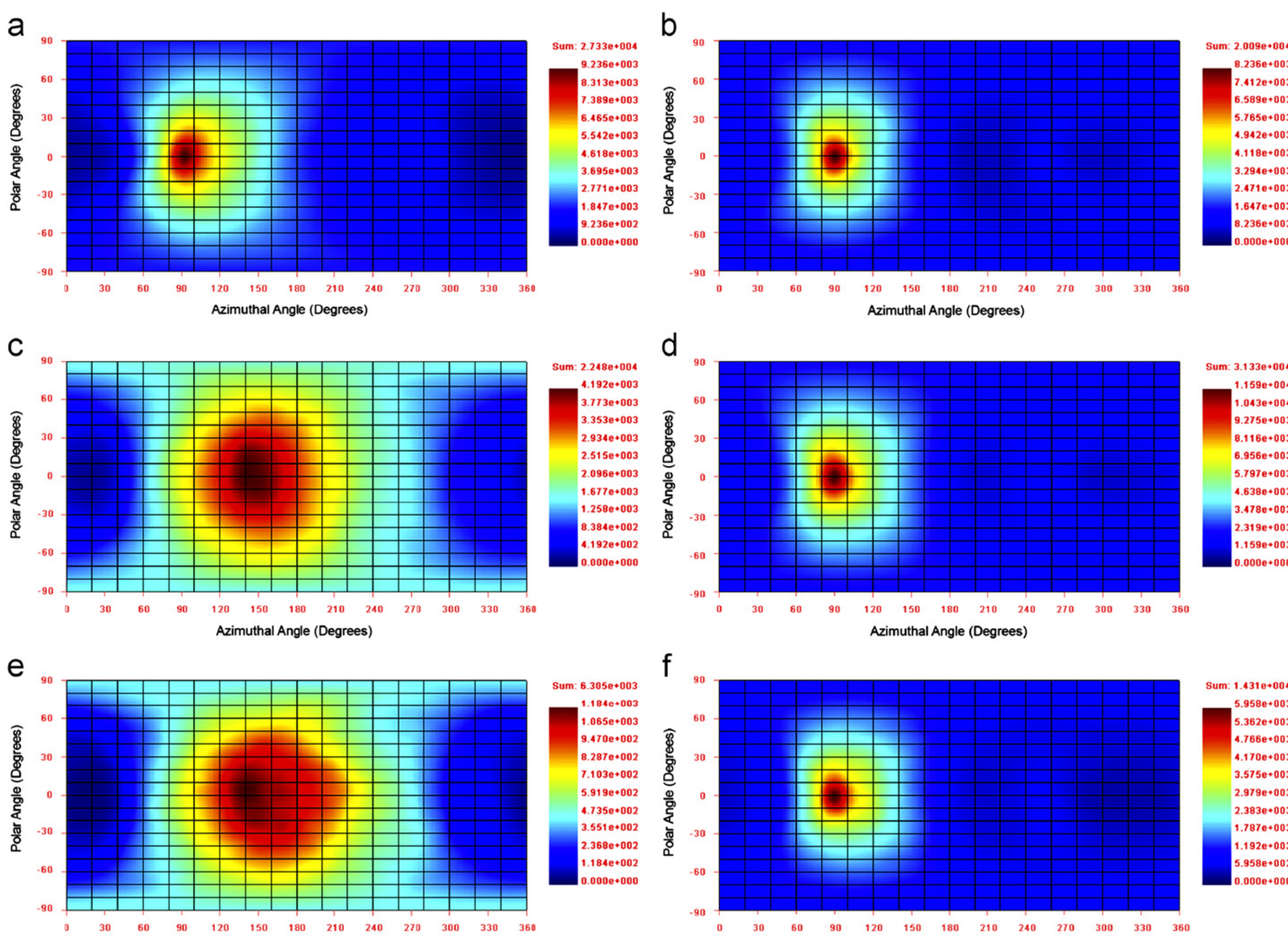

Fig. 2. All side-neighbor interactions are combined into a single interaction. The SBP image reconstruction is performed with these combined 2-interaction events (originally 3-pixel events) from six categories: (a) category 1; (b) category 4; (c) category 2; (d) category 5; (e) category 3; and (f) category 6.