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Progress in the development of large area sub-millimeter resolution CdZnTe strip detectors

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ABSTRACT

We report progress in ongoing measurements of the performance of a sub-millimeter pitch CdZnTe strip detector developed as a prototype for astronomical instruments. Strip detectors can be used to provide two-dimensional position resolution with fewer electronic channels than pixellated arrays. Arrays of this type are under development for the position-sensitive image plane detector for a coded-aperture telescope operating in the hard x-ray range of 20-200 keV. The prototype is a 1.5 mm thick, 64 x 64 orthogonal stripe CdZnTe detector of 0.375 mm pitch in both dimensions, approximately one square inch of sensitive area. In addition to energy and spatial resolution capabilities, as reported last year, we demonstrate the imaging capabilities and discuss uniformity of response across an 8 x 8 stripe, 64 "pixel", segment of detector. A technique for determination of the depth of photon interaction is discussed and initial results related to depth determination are presented. Issues related to the design and development of readout electronics, the packaging and production of strip detectors and the production of compact strip detector modules, including detector and readout electronics, are also discussed.

Keywords: CdZnTe, CZT, strip detector, x-ray astronomy, gamma-ray astronomy, imaging

1. INTRODUCTION

The next step in the development of hard x-ray telescopes for astronomical imaging will require improvements both in angular resolution and in energy resolution.^{1,2} A common approach to imaging at these energies involves coded aperture imaging techniques, where the angular resolution depends directly on the spatial resolution of the detector plane.³ Imaging detectors constructed of CdZnTe⁴, a high density, high atomic number material with a large band gap permitting room temperature detector operation, represent a strong candidate technology for achieving both improved angular and energy resolution. We have developed a concept for a new instrument, MARGIE (Minute-of-Arc Resolution Gamma Imaging Experiment), that will be capable of imaging with good energy and arc-minute angular resolution both steady-state and transient sources of cosmic gamma rays.¹ Initially, this is intended to be flown as a balloon payload. Eventually, however, this design could be employed on an orbiting platform. Motivated by the MARGIE concept and by encouraged by recent demonstrations of CdZnTe imaging detectors,^{5,6,7,8,9} we have continued to pursue the development of CdZnTe arrays for astronomical imaging.

2. PROTOTYPE STRIP DETECTOR

Figure 1 is a photograph of the prototype strip detector manufactured by DIGIRAD of San Diego, CA . It consists of a monolithic Cd_{0.9}Zn_{0.1}Te substrate measuring 28 × 28 mm by 1.5 mm thick with 64 gold stripe contacts and 2 guard stripes on each surface. The stripe pitch and thus pixel definition is 0.375 mm in both dimensions, with an effective imaging area of 576 mm². The CdZnTe array is mounted in a printed circuit board carrier with contacts to all stripes in a standard pin grid array pattern to facilitate safe handling and testing.

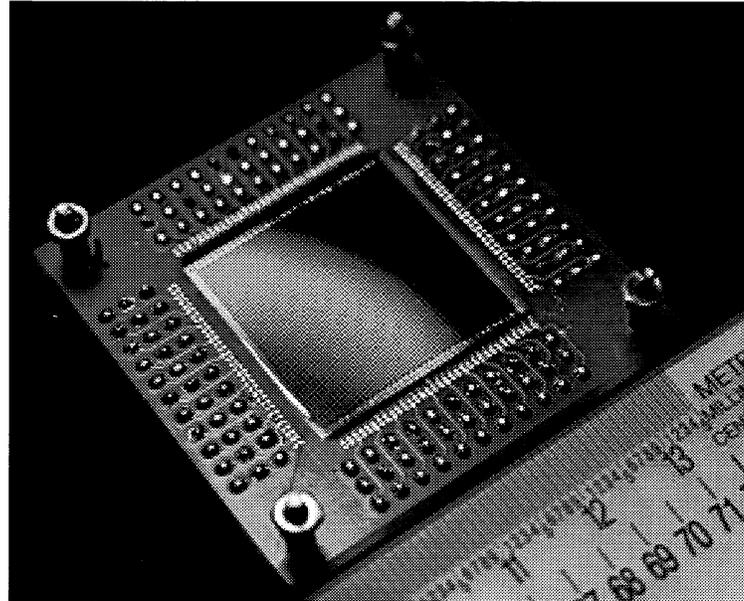


Figure 1. Photograph of prototype CdZnTe strip detector

3. STRIP DETECTOR OPERATING PRINCIPLES

Fig. 2 shows a schematic diagram of a small portion of the strip detector to illustrate the operational principles for the determinations of photon interaction site and energy deposit .

An incident gamma photon interacts at a point within the strip detector generating an ionization charge region whose extent is determined by the resulting scattering and fluorescence processes. Calculations and measurements with CZT pixel detectors at the University of Arizona have determined the extent of this ionization site to be ~200 μm.¹⁰ Charge signals in proportion to the deposited energy and related to the transport of these ionization charges (electrons and holes) are detected on each surface on the contact stripes near the photon interaction site. The electrons, transported along the Z dimension by the bias field, are collected on the nearest anode stripes. Except for interactions occurring at the cathode surface, the holes, with relatively poor charge transport properties, are not fully collected during the amplifier's integration time.¹¹ Rather, signals are induced on the individual cathode stripes in relation to the distance from the stripe and the amount of hole transport that takes place during the amplifier's integration time . Our measurements show that the size (pulse height) of this hole signal relative to the electron signal depends on the depth of the photon's interaction.

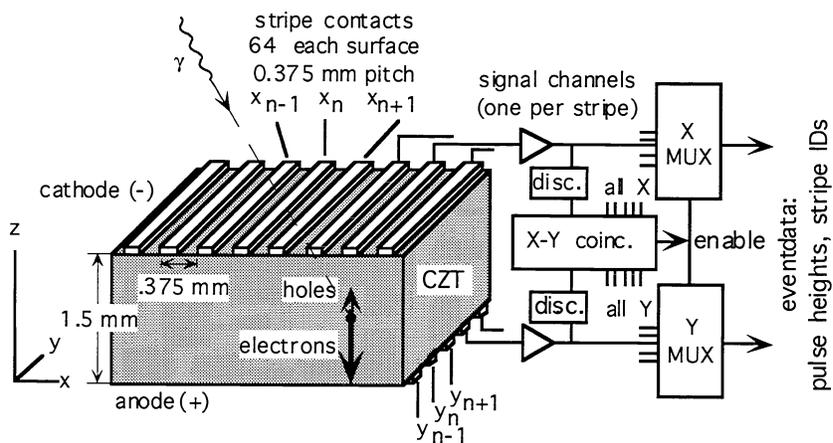


Figure 2. Strip detector operational principles.

measuring the relative X and Y pulse heights. A photon interaction site far from the cathode surface results in relatively lower cathode pulse height than is observed when the interaction site is close to the cathode. As with pixel detectors, pulse height analysis of the anode signals provides the optimum energy measurement.

4. TEST SETUP

Figure 3 illustrates the laboratory setup for the prototype strip detector tests. All stripes on each detector surface are biased to assure a uniform electric field in the CdZnTe. All untested stripes are ac coupled to ground. Eight consecutive contact stripes on each surface (X1 through X8 and Y1 through Y8) are selected and ac coupled to signal processing channels. This defines an 8 x 8 stripe, 64 "pixel", region of the prototype detector for study. Each channel utilizes an Amptek A225 charge sensitive preamplifier/shaper which provides both fast and slow (2.5 μ sec.) shaped outputs. Inverters and additional amplifiers are employed on the printed circuit board as required by the external NIM discriminators and CAMAC ADCs. Each fast channel (200 n.sec. shaping) has its own level discriminator, each slow channel its own peak sensing ADC. Any combination of X-discriminators firing in coincidence with any combination of Y-discriminators provides a strobe to the block of ADCs. Sixteen pulse heights are recorded for each registered event. The detector, its ZIF socket and the sixteen amplifier channels are mounted on printed circuit board enclosed in an aluminum box. The active area of the detector is open to illumination from either surface through thin windows in the aluminum box and holes in the ZIF socket and the printed circuit board. All measurements were performed at room temperature.

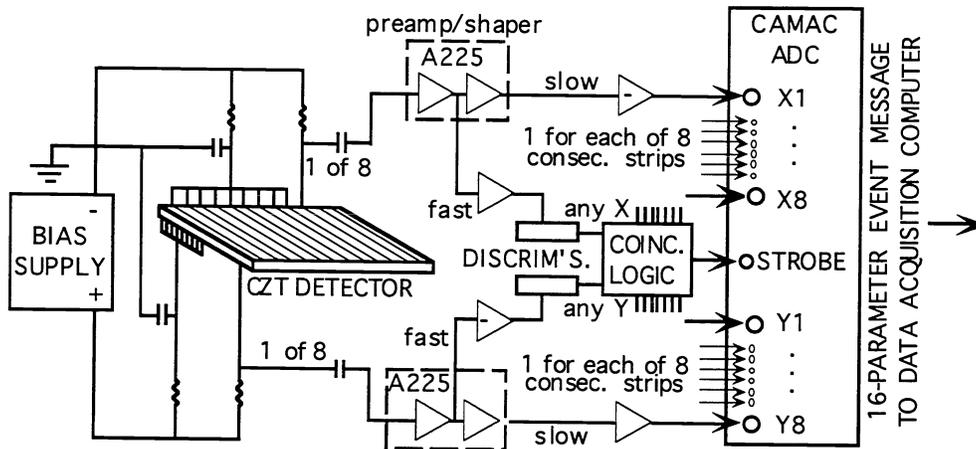


Figure 3. Test setup. 8 x 8 stripe, 64 "pixel", region of strip detector

5. PERFORMANCE

5.1 Spectroscopy and uniformity

It was previously demonstrated that signal charge for each detected event is shared by the triggering anode stripe and one, not more, of its neighbors.⁸ That result highlighted the importance of summing the signals from neighboring anode stripes when measuring the total energy deposit. Figure 4 illustrates this advantage with a comparison between trigger-channel-only and trigger-plus-neighboring-channel pulse height data. Figure 4a shows the response of a single "pixel" to 122 keV photons from a ⁵⁷Co source. Figure 4b shows the distribution of these same events when the pulse heights of the two adjacent anodes (Y1 and Y3) are added.

Figure 4. Response: single "pixel"

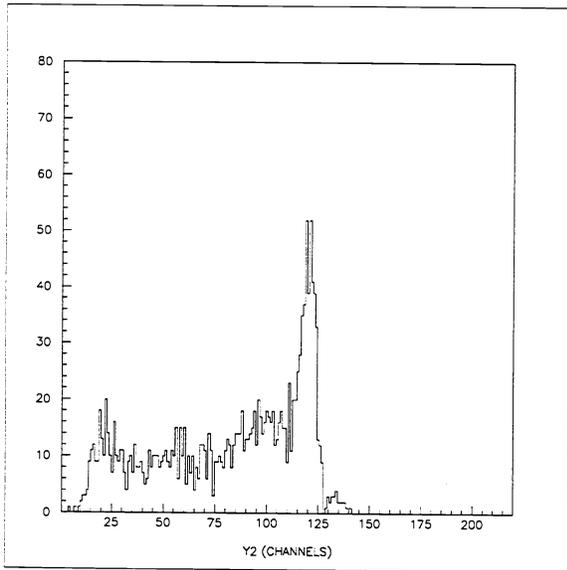


Figure 4a. ^{57}Co , 122 keV.
Trigger stripe (Y2) pulse height only.
Single "pixel" defined by X2-Y2 coinc.

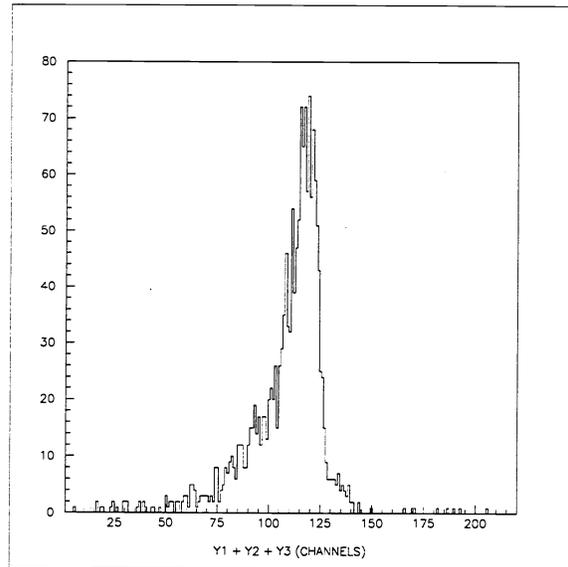


Figure 4b. ^{57}Co , 122 keV. Same events.
Sum of pulse heights,
trigger stripe plus adjacent stripes.

Figures 5a and 5b illustrate the uniformity of response across the 8 x 8 stripe, 64 "pixel", test region of our strip detector prototype.

Figure 5. Response: 64 "pixel", 8 x 8 stripe region. Flood illumination

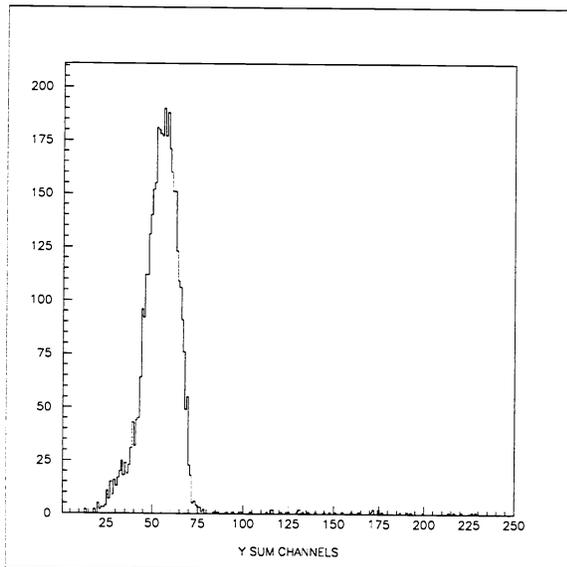


Figure 5a. ^{241}Am , 60 keV. Sum of 64 "pixels".

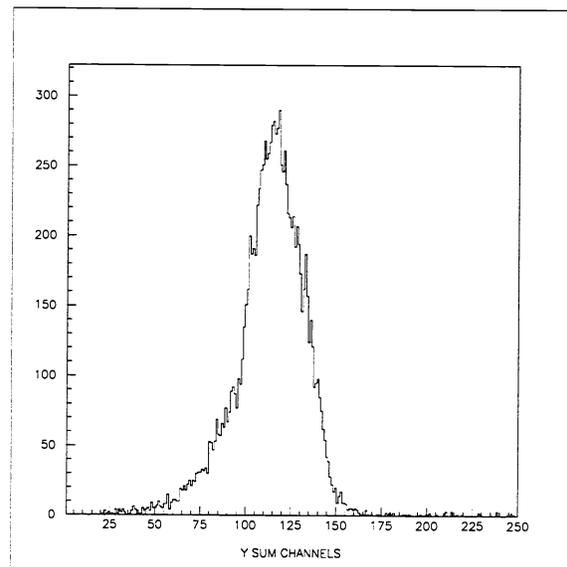


Figure 5b. ^{57}Co , 122 keV. Sum of 64 "pixels".

The detector was flood illuminated with 60 keV photons from ^{241}Am (Figure 5a) and 122 keV photons from ^{57}Co (Figure 5b). The response of the detector pixels is sufficiently uniform that the pulse height spectra accumulated by adding the contribution from all 64 pixels show clear full-energy peaks. Note that the responses of the individual amplifier channels were matched with a test pulse input and that no additional effort has been made in these examples to match photopeak peak pulse heights from the individual pixels before the sum histogram was computed. As with the single pixel example above (Figure 4), summing the signals collected for each event enhances the population of the photopeak and provides the better total energy measurement. The energy resolution is, however, degraded in this test since noise from all amplifier channels is present.

5.2 Imaging

A collimated beam of photons from a ^{57}Co source was directed at different locations across the 8 x 8 stripe test region of the strip detector. The beam spot size, determined by collimator geometry, is ~ 0.25 mm. The images in Figure 6 show the number of events located at each of the 64 "pixels" for two pointings of the collimator. Each event is located at the intersecting coordinates of the X and Y stripe recording the highest pulse height. In both cases a single "pixel" corresponding to the beam spot position registers the maximum number of events. The nature of the wing distributions which move along with the beam spot in these images is not yet understood. Recall, stripe pitch, and thus "pixel" size, is 0.375 mm in both the X and Y dimensions.

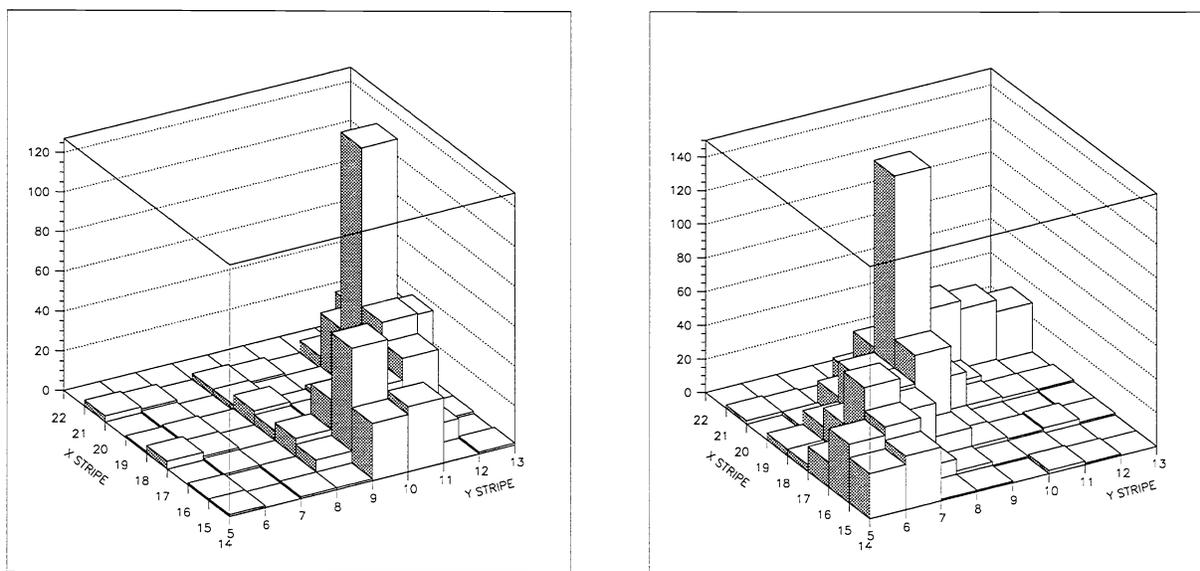


Figure 6. Images of 0.25 mm ^{57}Co beam spot at two locations within the 8 x 8 stripe test region. Stripe pitch, "pixel" size, is 0.375 mm in each dimension.

5.3 Interaction depth

As described above in the discussion of strip detector operational principles (section 3), the strength of the hole transport signal measured on neighboring cathode stripes is related to the depth of interaction, the Z-coordinate. Figure 7 illustrates the pulse height relationship between cathode (X-dimension, hole) signals and anode (Y-dimension, electron) signals for ~1600 detected events from 122 keV photons incident from a ^{57}Co source. The mean free path of these photons in CZT, 1.7 mm, assures that interactions take place at all depths within the detector. The flat distribution of pulse heights for photopeak events in the Y-dimension is evidence of CZT's good electron transport properties. The broad distribution of pulse heights for these same events in the X-dimension is evidence of widely varying cathode signal strength related to the depth of the interaction and the relatively poor transport of holes as predicted by the strip detector model.¹¹ Events with small relative X pulse height interacted farther from the cathode surface than those with larger relative X pulse height. To further demonstrate this effect we illuminated our prototype from opposite sides with 60 keV photons from an ^{241}Am source. The mean free path of these photons in CZT, 0.26 mm, assures that most interactions take place nearer the incident surface the detector. As predicted, the average cathode (X-dimension, holes) pulse height was higher (28% higher in our measurements) for the case where the detector was illuminated from the cathode side than when illuminated from the anode side.

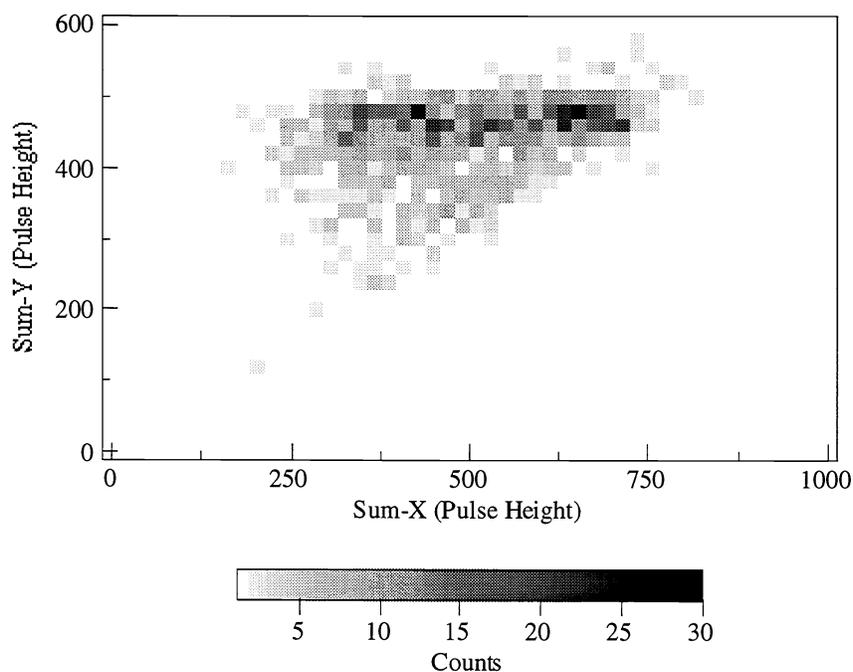


Figure 7. Distribution of X-dimension (cathode, holes) and Y-dimension (anode, electrons) pulse height sums for 122 keV photon events in our prototype CZT strip detector. The relative pulse height recorded for each event is a measure of the depth of interaction, the Z-dimension).

6. READ-OUT CIRCUIT ISSUES

As described previously, the strip detector contact geometry requires far fewer signal processing channels than does a pixellated array of the same pitch (128 vs. 4096 in this case).⁸ Event-triggered-processing facilitates recognition of the required X-Y coincidence, precise timing of the detection and the determination of relative timing with external events. For each detected event, only the pulse heights and IDs of the triggered stripes

and their neighbors need to be read out. Ideally each signal-processing channel should contain its own low-noise charge-sensitive preamplifier, discriminator and shaping amplifier and each detector in the image plane array should be controlled and read out by circuitry that occupies the same area or less.

We have demonstrated that by applying a relative pulse height technique we can achieve the discrimination of deep and shallow interaction depth for each detected event. The advantage of this technique for depth determination over techniques requiring pulse shape discrimination is the relatively simple and low power implementation in the readout electronics. Only one analog channel is required per stripe and only low noise relatively slow analog circuits would be required. Timing and/or pulse shape correction techniques may, however, be applicable to depth determination in CZT strip detectors and should also be studied.^{12,13}

7. FUTURE WORK

Finer imaging demonstrations and the evaluation of the uniformity of response across larger areas of the detector are important areas for study. Radiometry measurements are important for understanding the efficiency of the strip detector operating in the X-Y coincidence mode. Further characterization of the CZT strip detector signals and the optimization of the detector electronics for processing these signals is in progress. The goals of this effort are to fully understand the operational requirements and define appropriate detector and electronics specifications for developing compact modules that include the strip detector and signal processing electronics with appropriate analog, timing and digital functions.

8. CONCLUSIONS

The performance capabilities of CdZnTe strip detectors are well suited to applications in gamma-ray imaging spectrometers. They have good energy and spatial resolution as demonstrated with conventional laboratory electronics. Good energy response with clear photopeaks in the target energy range and spatial resolution in two dimensions comparable to the stripe pitch (≈ 0.375 mm) have been demonstrated for an 8 x 8 stripe, 64 "pixel" segment of our prototype. Relative anode and cathode pulse heights can be used to discriminate the third spatial dimension, the depth of interaction. An $N \times N$ orthogonal stripe detector module requires $2N$ signal processing channels and can achieve performance comparable to pixel detectors requiring N^2 channels.

9. ACKNOWLEDGMENTS

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