Annual Report

Crystal Compton Camera

OR11CRYSCOMPCAMPD2JE

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Date:	**9/26/13**

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1. INTRODUCTION

Stand-off detection is one of the most important radiation detection capabilities for arms control and the control of illicit nuclear materials. For long range passive detection one requires a large detector and a means of "seeing through" the naturally occurring and varying background radiation [1], i.e. imaging. Arguably, Compton imaging is the best approach over much of the emission band suitable for long range detection. It provides not only imaging, but more information about the direction of incidence of each detected gamma-ray than the alternate approach of coded-aperture imaging. The directional information allows one to reduce the background and hence improve the sensitivity of a measurement. However, to make an efficient Compton imager requires localizing and measuring the simultaneous energy depositions when gamma-rays Compton scatter and are subsequently captured within a single, large detector volume. This concept has been demonstrated in semi-conductor detectors (HPGe [2], CZT [3], Si[4]) but at ~ $1k/cm^3 these materials are too expensive to build the large systems needed for standoff detection. Scintillator detectors, such as NaI(Tl), are two orders of magnitude less expensive and possess the energy resolution required to make such an imager. However, they do not currently have the ability to localize closely spaced, simultaneous energy depositions in a single large crystal. In this project we are applying a new technique that should, for the first time ever, allow cubic-millimeter event localization in a bulk scintillator crystal.

2. BACKGROUND

To make a Compton imager out of detectors based on bulk scintillators, one needs to separate and localize the simultaneous energy depositions in the crystal to voxels of order a cubic millimeter. If the voxels become too large, then one loses efficiency because the scatter and capture happen in a single voxel. One also loses directional information with poor spatial resolution since the direction of the opening angle of the cone cannot be well determined. The difficulty in making such a detector is that one can only instrument the outer surfaces of the crystal and, by the time the expanding sphere of light reaches a surface, it can be quite large (~ centimeters in diameter). Because the scintillation light from a crystal is faint (only hundreds of scintillation photons reach the detectors) one cannot precisely determine the center of the broad light distribution reaching the surface. The best reported results are ~ 2 mm spatial resolution per cm of crystal thickness at 500-keV deposited energy [5]. We need crystals that are 3 to 5 cm thick, and an approach that also works with lower energy depositions.

To solve this problem we use a 50% open shadow mask in the light pipe connecting the crystal with a pixelated readout system. The shadow of the mask cast by the scintillation event adds high frequency spatial information to the light reaching the readout; allowing us to determine both the depth and lateral location of an event. Extensive light transport simulations show that this approach should allow us to achieve millimeter-scale event localizations in thick crystals [6, 7].

3. EXPERIMENTAL RESULTS

As a first step to realizing a laboratory prototype of the technique, we constructed an apparatus that provided an analog for energy depositions at known locations within a thick crystal. This comprises a collimated radiation beam from a sealed source intersecting a thin scintillator crystal mounted on a light pipe with a variable thickness (Fig. 1). By changing the light pipe thickness, we can explore events at different "known" depths within a crystal. This approach was used to validate that a shadow mask can be seen with the faint light output from a scintillator crystal. Further, it allowed us to show that one can see the magnification of the pattern for events at different depths in a crystal (events closer to the shadow mask project an enlarged pattern on the multi-anode phototube (MAP)—see Fig. 2.)

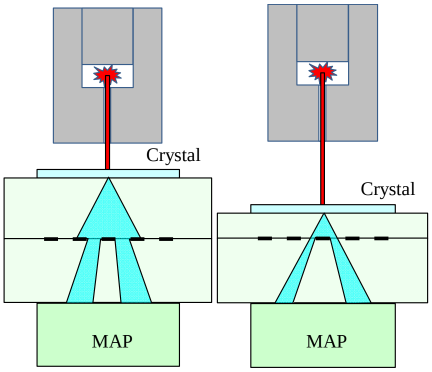

Fig. 1. Concept of experimental setup. The shadow pattern projected onto the MAP depends on the light pipe between the crystal and the shadow mask.

More recently, we have made a small 2D-version (depth and 1D transverse to the readout plane) of the system that uses a 1D coded-aperture pattern. This has been used to show we can localize events as predicted. By varying the distance of the thin crystal to the shadow mask from 6 to 20 mm, we simulate a crystal thickness of 20 mm (the difference is due to the higher index of refraction of the crystal compared to the light pipe.) In Fig. 3 (left) we show histograms of reconstructed event depth for events occurring at the bottom, one third of the way from the bottom, and at the top of our crystal analogue. The measured depth resolution is < 0.7 mm at the top of the “crystal.” In Fig. 3 (right) we show results for the spatial resolution transverse to the readout plane for the middle depth. After deconvolving the beam width, we obtain a 1.1 mm spatial resolution in this dimension.

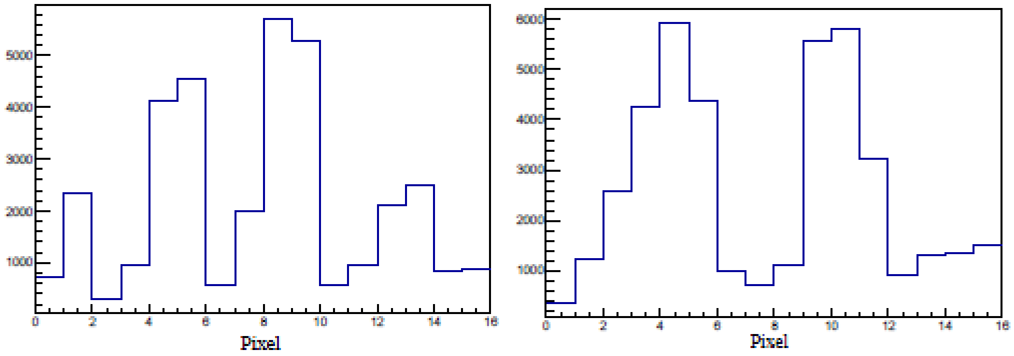

Fig. 2. Two single-event (80 keV) shadow mask images. On the left the magnification is four-pixels per cycle, on the right six.

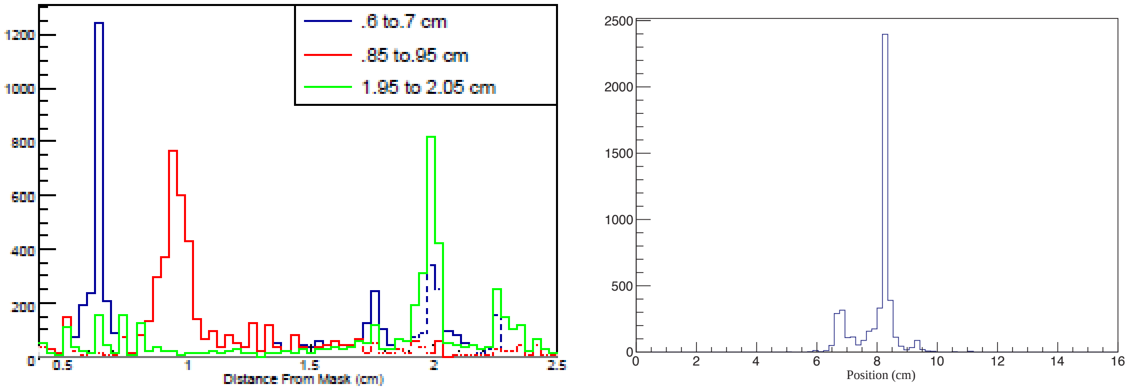

Fig. 3. Left: Event depth determination for many events at 3 different depths in the pseudo crystal. Right: X-position determination for the events at ~ 1 cm depth (red on left).

4. RESULTS, DISCUSSION AND CONCLUSIONS

The results presented above indicate that the approach works as predicted for single energy depositions. By itself this is a major achievement and has potential programmatic applications for use in coded-aperture gamma-ray imagers. It could also be of value to other communities including nuclear medicine, where the limiting resolution of PET scanners is the unknown depth of interaction. This is frequently of order centimeters! It is also of interest to the astrophysics community where a large, coded-aperture, x-ray telescope capable of mapping the x-ray sky once per orbit is a recognized mission concept at NASA.

5. PATH FORWARD

We are currently working to refine the results obtained with the 1D coded-aperture and are using this to inform the next step in our research plan; to build a prototype Compton imager. This more advanced instrument is nearing completion and will have a 25 x 25 cm^2 active area. We are currently waiting for delivery of the rest of the custom electronics that will be used to readout the individual anodes of our 25 MAPs. With this system we will both demonstrate full 3D spatial resolution of single events and explore the ability to generate Compton images with multi-site interactions.

6. PRESENTATIONS AND PUBLICATIONS

- An invited talk on extensive simulations for the system at 500 keV was presented at the 2012 SPIE Security and Defence meeting held last fall in Edinburgh, Scotland.
- A paper on the basic concept and initial simulation results was published in the refereed journal, IEEE Transactions of Nuclear Science.
- A paper on an analytic expression for the distribution of the light expected at a phototransducer was presented by the graduate student working on the project at the 2012 IEEE Nuclear Science Symposium last fall.
- An oral presentation on the results presented above will be given at the 2013 IEEE Nuclear Science Symposium.

REFERENCES

1. K.P. Ziock, J. Collins, M.F. Cunningham, L. Fabris, F. Habte, T. Karnowski, “A Fieldable-Prototype, Large-Area, Gamma-ray Imager for Orphan Source Search,” *IEEE Trans. Nucl. Sci.*, vol. 55, pp. 3643-3653, 2008.
2. S. Boggs, et al., “Performance of the Nuclear Compton Telescope,” *Exp. Astron.*, vol. 20, pp. 387-394, 2005.
3. D. Xu and Z. He, “Filtered Back-Projection in 4π Compton Imaging With a Single 3D Position Sensitive CdZnTe Detector,” *IEEE Trans. Nucl. Sci.*, vol. 53, pp. 2787-2795, 2006.
4. E.A. Wulf, B.F. Phlips, W.N. Johnson, J.D. Kurfess and E.I. Novikova, “Thick Silicon Strip Detector Compton Imager,” *IEEE Trans. Nucl. Sci.*, vol. 51, no.5, pp. 1997-2003, 2004.
5. P. Antich, N. Malakhov, R. Parkey, N. Slavin, E. Tsyganov, “3D position readout from thick scintillators,” *Nucl. Inst. Meth. in Phys. Res. A*, vol. 480, pp. 782-787, 2002.
6. K.P. Ziock, M.A. Blackston, T. Van Vuure, “3D Millimeter Event Localization in Bulk Scintillator Crystals,” *IEEE Trans. Nucl. Sci.*, vol. 60, pp. 1390-1399, 2013.
7. K.P. Ziock, J.B. Braverman, L. Fabris, M.J. Harrison, “The other end of the scale: Coded apertures in the near field for high resolution 3D gamma event localization in bulk scintillators,” *Proc. SPIE.* Vol. 854210, DOI 10.1117/12.979787, 2012.