Initial Studies of a New Detector Design for Ultra-High Resolution Positron Emission Tomography

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***Abstract*--We are developing a novel detector concept for Positron Emission Tomography (PET) that will facilitate ultra-high spatial resolution, high sensitivity and optimal light collection efficiency. Spatial resolution in PET can be improved by using finer scintillation crystal array elements. Several groups are developing arrays with <2 mm crystal pixels for ultra-high resolution small animal PET systems. The challenge with finer crystals is extracting sufficient light to maintain a high detection signal-to-noise ratio (SNR), especially if the crystals are kept relatively long for good detection efficiency. Assuming the resulting light signals are sufficiently above noise, the finer crystals may be resolved in a flood histogram. However, the reduced detection SNR means lower count sensitivity since more pulses are now below a given threshold, and a loss in energy resolution, which can result in image contrast degradation. We propose scintillation detector concepts that use new avalanche photodiode (APD) arrays in novel readout configurations that promote very high light collection efficiency. These concepts exploit the high compactness of semiconductor photodetector arrays for tightly packed crystal readout schemes that are unavailable to PMTs. The schemes proposed have the potential to significantly improve detection SNR for ultra-high resolution PET. With a 1 mm wide LSO crystal coupled to a prototype APD array we obtained 13.7% energy resolution at 511 keV in a non-optimized measurement. Flood irradiation measurements with a 1 mm thick LSO crystal sheet coupled to the array prototype indicate that ≤1 mm intrinsic spatial resolution is available to the design with high spatial linearity out to the crystal edge.**

I. Introduction

We are developing a novel detector concept for Positron Emission Tomography (PET) that facilitates ultra-high spatial resolution, high sensitivity and optimal light collection efficiency [1]. Spatial resolution in PET may be improved by using finer scintillation crystal array elements. With 1 mm crystal pixels in principle sub-millimeter spatial resolution is possible for PET [2,3]. Several groups [e.g. 4-6] are developing scintillation arrays with <2 mm crystal pixels for ultra-high resolution PET systems designed for imaging small laboratory animals. The challenge with going to finer crystals is extracting sufficient light to maintain high detection signal-to-noise ratio (SNR). In particular, there is significant light loss in going from a 2 mm to 1 mm crystal pixel. If the crystals are kept long to maintain high detection efficiency, using finer crystals and reading light in the conventional manner results in much lower light collection efficiency.

Figure 1 shows the results of Monte Carlo simulations of light collection in various types of crystals commonly used in PET for a 1x1x10 mm^3 crystal size with ground or perfectly spectral surfaces and a white reflector. The perfectly spectral case is ideal and never achieved in practice and so the achievable light collection efficiency lies somewhere between that for the ground and perfectly spectral extremes. In most cost-effective designs the crystal surfaces tend toward the fine ground extreme (which corresponds to roughly 45% and 20% light collection efficiency, respectively, for a 2x2x10 mm^3 and 1x1x10 mm^3 LSO crystal) and only a relatively small fraction of the available light signal can be achieved. If the resulting light signals are sufficiently above noise, the finer crystals may still be resolved in a flood histogram and the desired high intrinsic spatial resolution may be achieved. However, the weaker light signals means lower sensitivity since more pulses are now below a given threshold, and a loss in energy resolution, which may result in image contrast degradation.

We propose scintillation detector concepts that incorporate new avalanche photodiode (APD) arrays in novel readout configurations that promote very high light collection. These concepts exploit the high compactness of semiconductors for tightly-packed crystal readout schemes that are unavailable to PMTs. We present some initial energy and positioning studies with minute LSO crystals coupled to a prototype APD array to demonstrate feasibility of the approach.

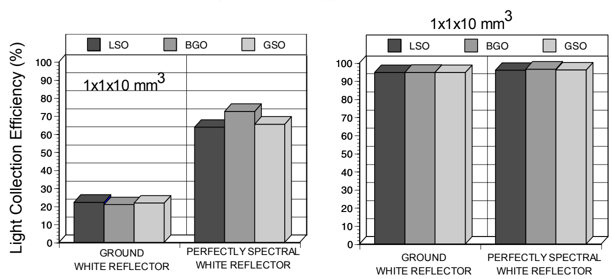

Fig. 1. Light collection efficiency from the ends (left) and side (right) of 1x1x10 mm^3 crystals used in PET for two different crystal surface treatments. For the conventional end readout only a relatively small fraction of light is collected, especially for non-ideal surfaces, and the light signal depends upon the scintillation light origin. For the side-readout, the light collection is nearly complete independent of crystal length, width and surface treatments and origin of the scintillation light.

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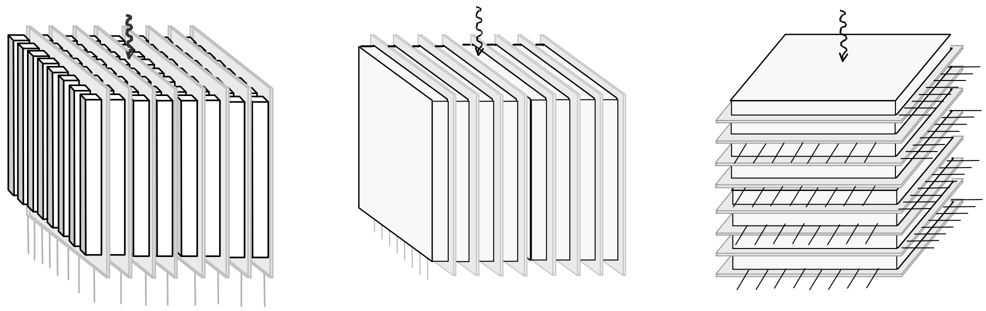

Fig. 2. Scintillation detector array designs with very high light collection efficiency. The left two "edge-on" schemes rely on very thin (≤300µm) photodetector arrays wedged between crystal layers to readout light from the long crystal faces. The right "face-on" approach does not rely on thin APD arrays. Photons enter from above as depicted.

II. MATERIALS AND METHODS

A. *High Light Collection Detector Array Configurations*

Figure 2 depicts three high light collection detector concepts available using highly compact APD arrays [1]. The first design (left) uses an array of very fine discrete crystals. The long sides of the crystals may be read out by very thin APD arrays that fit in between the crystal planes "edge-on" with respect to incoming photons. Any position sensitive array configuration may be used as long as it is ≤300µm thick in order to maintain a high crystal packing fraction. The advantage of reading out the long sides of the fine crystals is that the light collection aspect ratio is very high and the light extraction is nearly complete, independent of crystal length, width, and surfaces, and scintillation light origin. Fig. 1 (right) reflects these improved light collection properties for 1x1x10 mm^3 crystals in simulations, and identical trends hold for other crystal dimensions. The improvements with side over end readout are most significant for longer, less polished crystals.

A drawback of developing a system comprising many tiny discrete crystal elements as shown in Fig. 2 (left) is that they are expensive to cut and difficult to work with. Furthermore it is difficult to align these tiny crystals with the APD array elements, which could result in signal loss. The second design shown in Fig. 2 (middle) uses thin sheets of crystals that are easier to manufacture and incorporate without alignment problems with the photodetector array. Since there are no gaps in one direction with respect to incoming photons, the detection efficiency will be higher than in the first design. The packing fraction is 70% for a 300µm thick APD between 1 mm thick crystal sheets. The light collection aspect ratio is even higher for this design. Also, since the light created may involve multiple APD elements, a weighted mean position calculation may facilitate resolution better than the array pitch.

The third design in Fig. 2 (right) uses a "face-on" orientation of the crystal sheets and APD arrays with respect to incoming photons that does not require a thin APD array design. This third design has higher sensitivity since there are no gaps with respect to incoming photons and the interaction depth is easily determined by which crystal layer is hit. Some initial results of positioning capabilities of a very thin crystal sheet coupled to an APD array will be presented in this work.

B. *Prototype APD Array*

A prototype APD array for the configurations depicted in Fig. 2 that we are currently testing is shown in Fig. 3. The array has 41 rectangular pixels, each 0.7x7 mm^2 in area on a 1 mm pitch. This array was manufactured using a deep-diffusion process and standard planar silicon device technology [7]. The capacitance per element of the device is ~3 pf and the typical device gain is >200. Since the capacitance per pixel is small and the APD gain is relatively high, the dark noise is relatively low and determined by the bulk leakage current of the APD [1] and not by the preamplifier noise. The dark current per pixel is ~50 nA at the operating APD bias of ~1.1 kV. The prototype device dark noise, including parallel and series components is on the order of 250 eV FWHM (30 e^- rms) for each element [1]. This prototype is a standard thickness device mounted on a ceramic substrate (~1 mm thick). The bias and readout leads come out the backside. A very thin device may be achieved by significantly reducing the substrate and/or wafer thickness. The 300µm thick device has not yet been manufactured.

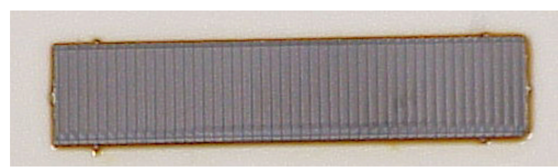

Fig. 3. Prototype APD "line" array has 41 rectangular elements, each 0.7x7 mm^2 in area on a 1 mm pitch. The elements cover ~ 4 cm in width.

C. *Energy Measurements*

Energy resolution studies were performed with the prototype APD array. We studied response to direct x-ray interactions in the silicon pixels using an ^{55}Fe point source (5.9 keV x-rays). We studied response to 511 keV annihilation photons using a ^{22}Na point source irradiating a 1x7x10 mm^3 Lutetium Oxyorthosilicate (LSO) crystal wrapped in white teflon tape on five sides and coupled through optical grease to APD array elements. The same crystal was coupled to a PMT for comparison energy resolution measurements. The individual APD array pixels were coupled to a low-noise charge-sensitive preamplifier (Canberra 4003). The output was amplified and shaped and split into two branches. One branch was delayed and sent into the digitizer card (PC6110E) that resides in a Macintosh G3 (330 MHz). The trigger for the digitizer was created by taking the other branch through a single channel analyser followed by a gate and delay generator. The acquisition was controlled by LabView (National Instruments).

D. *Positioning Measurements*

To test the positioning capabilities of one layer from the crystal sheet approach depicted in Fig.2 (middle and right), we coupled the large face of a 10x7x1 mm^3 LSO crystal covered in three layers of teflon tape to the prototype APD array as shown in Figure 4. Flood measurements were performed by irradiating the crystal with a ^{22}Na source. Narrow beam

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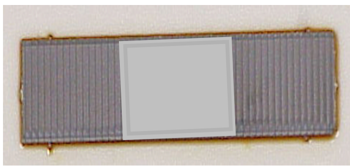
measurements were achieved by irradiating a 0.5-1.0 mm slit formed between two 3 cm thick led blocks. For positioning measurements, multiple channel acquisition was achieved through an application specific integrated circuit (ASIC) comprising integrated charge sensitive preamplifiers, shaping amplifiers, and trigger and sample-hold circuits (IDE AS) [8]. The simultaneously sampled data stream from all the channels for each scintillation event was digitized and acquired onto a 350 MHz PC through the parallel port interface and saved in list mode. The data acquisition was controlled by LabView.



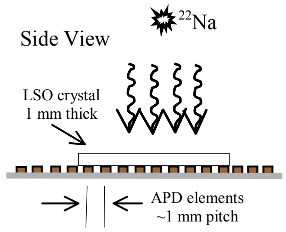


Fig. 4. Thin crystal sheet coupled to prototype APD array for positioning measurments.

III. RESULTS

A. Energy Measurements

Figure 5 shows an example ^{55}Fe x-ray flood energy spectrum measured with one of the rectangular array pixels connected to a discrete charge sensitive preamplifier. In this measurement the x-rays were directly absorbed in the silicon. Since the APD elements are long and there is a variation in gain along the length of an APD element, this flood spectrum does not provide optimum detection SNR. That is, this spectrum is a convolution of the lower gain ends with the higher gain center of the element. Better results are achieved when the x-rays are collimated on the center of a pixel. The fact that the 5.9 keV peak is still well-resolved in this non-optimal measurement is attributed to the high average gain and low noise of the device.

Since silicon on average requires 3.62 eV to create an electron-hole pair, the peak location of this energy spectrum allows us to calibrate the absolute number of electrons per pulse height measured by the APD. This will be useful to determine for example, the fraction of light collected experimentally from a scintillation crystal.

We coupled a 1x7x10 mm^3 LSO crystal to the array as shown in Figure 6 (left) and measured the ^{22}Na energy spectrum (middle) with 1 and 2 APD pixels connected to a single charge sensitive preamplifier. Since the 1x7 mm^2 crystal edge was coupled to the 0.7x7 mm^2 APD element(s), more light was collected into the APD array and better energy resolution resulted for the 2-pixel readout (13.7%) than for the 1-pixel readout (17.1%), even though the input dark noise to the preamplifier was twice as large with two pixels summed. This high resolution data demonstrates the low input capacitance, low series contribution to dark noise, and overall

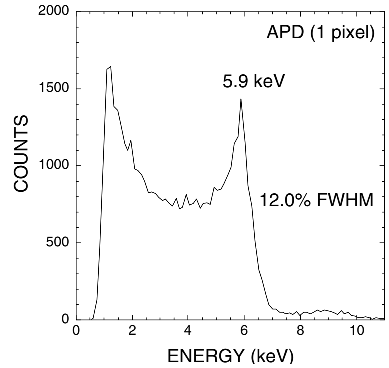


Fig. 5. ^{55}Fe x-ray (5.9 keV) spectrum measured by flood irradiating the array but reading out only one pixel, with the other pixels floating (this flood test does not provide optimal SNR for x-ray detection).

low APD noise. Note: these were not optimized studies and we expect better energy resolution results will be obtained.

Also shown (Fig. 6, right) for comparison is a ^{22}Na spectrum measured with the same LSO crystal and orientation coupled to a 1 cm diameter PMT. Comparable (~10% lower) resolution is measured for the LSO-PMT combination due to the high light collection aspect ratio (the 1x7 mm^2 crystal face) and the high SNR of the PMT. However, please note: the favorable coupling of the single crystal to the PMT for this measurement and the resulting high quality PMT spectrum shown would not be possible for an array of tightly packed crystals coupled to PMTs. In a PMT detector array only end-on coupling may be used, which significantly degrades the energy spectrum (>20% FWHM at 511 keV for a 1x1x10 mm^3 crystal-PMT coupling).

B. Positioning Measurements

A 10x7x1 mm^3 LSO crystal sheet was coupled to nine elements of the prototype array as depicted in Figure 4 and flood irradiated with 511 keV annihilation photons from a ^{22}Na source. Using the list mode data we formed a weighted mean of the digitized pulse heights for each scintillation event and plotted a 1-D position histogram for this measurement. The result is shown in Figure 7 (left). This flood histogram shows us the very important result that as far as positioning scintillation events goes, the crystal sheet coupled to the finely pixellated APD array responds like a discrete crystal system, except with the sharp peaks in sensitivity located over the APD pixel locations and a much higher peak-to-valley ratio. The reasons for this result are that the crystal is thin, the light spread is very confined, the APD array elements have a 1 mm pitch, and each pixel is most sensitive at its center.

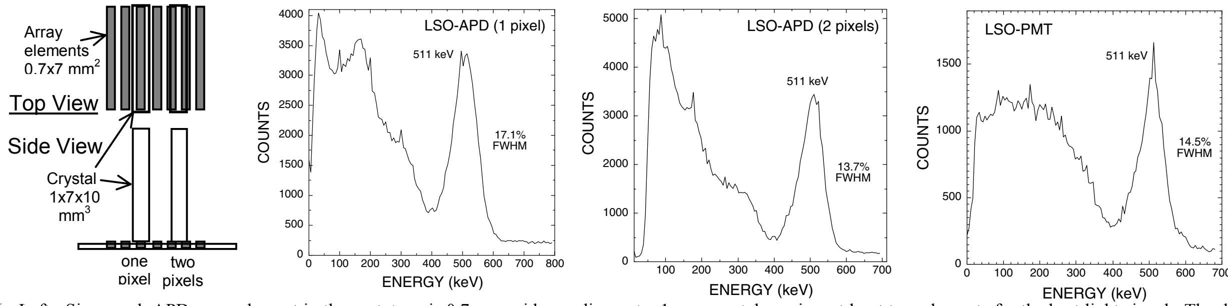


Fig. 6. Left: Since each APD array element in the prototype is 0.7 mm wide, reading out a 1 mm crystal requires at least two elements for the best light signal. The drawing shows a 1 mm LSO crystal coupled to one or two APD elements which are connected to a single preamplifier. Above: ^{22}Na (511 keV) energy spectra measured with the 1 mm wide LSO crystal coupled edge-on (1x7 mm^2 face) to one or two APD array element(s). Right: Also shown for comparison is an LSO-PMT spectrum for the same crystal and coupling aspect ratio. The measured 2-pixel APD energy resolution (13.7% FWHM) is better than that for the PMT (14.5% FWHM). Note: the high light collection aspect ratio achieved in the PMT measurement would not be possible for a compact array of very fine crystal rods coupled end-on to PMTs.

This semi-discrete nature is analogous to what happens in an Anger Camera if there is insufficient light diffusion from the crystal slab to the PMT array: The positioned activity in a flood field image concentrates at the PMT center locations. Note that the peaks seen correspond to the APD pixel locations and so there is excellent spatial linearity out to the crystal edge (Fig. 7 right). These results indicate that the spatial resolution for this prototype using crystal sheets is roughly 1 mm and events could be positioned in 1 mm bins.

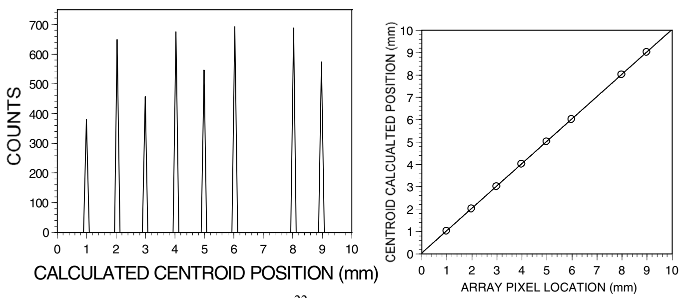


Fig. 7. Left: Measured 1-D ^{22}Na flood irradiation positioning histogram with a 10x7x1 mm^3 LSO scintillation crystal sheet coupled to 9 elements of the prototype APD array. Event positioning used a weighted mean on nine APD pixel signals (one pixel was disconnected). Right: Plot of 1-D flood histogram peak location versus APD pixel location shows a high degree of linearity out to the crystal edge.

As seen in Fig. 7 the dynamic range of positioning with the crystal sheet coupled to the prototype APD array extends all the way to the edge for this 1 mm thick crystal. Another way to see that is with results obtained from slit irradiation at the crystal edge. Figure 8 shows the results of irradiating the left and right most extremes of the crystal sheet shown in Fig. 4. In Fig.8, left, the slit was positioned over the center of the left most pixel under the crystal sheet. We see that indeed that the dynamic range extends out to the crystal edge.

For Fig. 8, right, the slit was positioned approximately in between the two right most pixels residing under the crystal sheet. We have previously studied light spread in a 1 mm thick crystal [1]. We learned that the light spread function is extremely narrow and relatively uniform across the face with a ~1-1.5 mm FWHM (3 mm FWTM), as extracted from a fit to a Lorentzian function. Due to the narrow, but finite light spread, when the source is collimated in between two pixels, they both light up (Fig.8, right). In this case, with 1 mm resolution bins, an intelligent decision of which bin to assign this dual-placed event must be made. Alternately, a 0.5 mm intrinsic resolution bin could be chosen and these in-between events could be assigned a bin in the center of the two pixels. Note that although this detector array responds to flood irradiation somewhat like a discrete crystal array, the array is not dead in betweem pixels as it would be in a discrete array (Fig. 2, left).

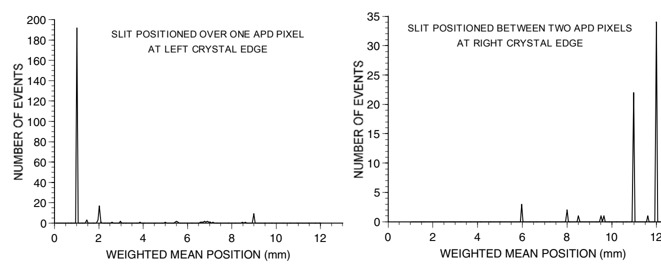


Fig. 8. Measured response of 511 keV photon collimated slit irradiation on left and right most extremes of LSO sheet coupled to APD array prototype. Left: The slit was positioned over the left most pixel. Right: The slit was positioned in between the two right most pixels.

IV. Discussion

For ultra-high resolution and sensitivity detector arrays for PET, the crystals must be very narrow and long. Extracting sufficient light from these minute crystal rods for good detection SNR is challenging. Reading out light in the conventional manner from the small crystal ends leads to significant light loss. Existing designs [4-6] use short crystals to improve the light collection efficiency, which significantly reduces coincidence detection efficiency (e.g. only 24% for 8 mm long LSO crystals). Low light collection may severely hinder the ability to resolve minute crystals in a detector flood image. Provided the light signal is sufficiently above noise, the minute crystals may be resolved and the desired intrinsic spatial resolution may be achieved. However, weaker light signals means lower sensitivity since more pulses are now below a given electronic threshold. Significantly reduced light collection efficiency also means poor energy resolution. Lower energy resolution means reduced Compton scatter rejection capabilities and at high data rates can lead to further degradation due to increased pile-up contamination in the energy window. Recent data [9] suggests that the scatter fraction may be as high as 30% for a 3-D acquisition of a rat. Thus, if light collection efficiency is low, the system will not perform as well as it could regarding important system parameters such as sensitivity and image contrast.

The main goals of our proposed design are to have ultra-high spatial resolution, optimal sensitivity and at the same time maintain high light collection efficiency. To do this we have proposed reading out the sides of the crystals for significantly improved light collection aspect ratio. Simulations show that collecting light in this manner yields nearly complete light collection, independent of crystal parameters and origin of the light within the crystal. This would be accomplished with the use of highly compact semiconductor photodetectors coupled to the crystals, which in addition to compactness have a factor of three better quantum efficiency than PMTs. For the edge-on design (Fig. 2, left or middle), the photodetector must be thin to maintain high crystal packing fraction and sampling frequency. If successful, the high light collection efficiency proposed, together with higher photodetector quantum efficiency should lead to significantly improved efficiency of converting absorbed annihilation photons into electrical signals.

The energy spectra measured with LSO coupled to the prototype photodetector array (Avalanche Photodiode or APD) were of high quality. When the signals from two APD pixels were summed the energy resolution was better than with that measured for one pixel alone since more light was detected. This fact indicates that the APD noise level is low. Due to a higher quantum efficiency, the energy spectrum measured with the APD was better than that for a PMT for the same crystal and orientation. Please note that the crystal orientation used had favorable light collection aspect ratio and allowed very high energy resolution. In our design this high aspect ratio would be available for the APD array, but would not be available for a PMT crystal array design. Thus the PMT energy spectrum would in reality be much worse for an array of crystals since the PMT can only access the crystal ends.

Due to complexities of working with minute (≤1 mm) discrete crystals, we proposed using 1 mm thick crystal sheets instead [1]. Thin crystal sheets have an even higher light collection aspect ratio. We have shown through simulations [1] and measured results in this report, that the light pulses created in a 1 mm thick LSO crystal coupled to a prototype APD array are extremely narrow with little variation across the crystal sheet face. Response to flood irradiation indicates that there is insufficient light spread among the APD pixels for continuous positioning. The 1-D flood histogram behaves in a semi-discrete manner, with discrete peaks appearing at the APD pixel locations in a perfectly linear fashion and with extremely high peak-to-valley ratio. This can actually work to our advantage in terms of simplifying event binning.

Unlike a discrete crystal array with dead gaps between crystals in both directions (Fig. 2, left), with the edge-on design proposed (Fig. 2, middle), only one direction has gaps. For 300µm thick APD arrays and 1 mm thick crystal sheets, the packing fraction would be roughly 70%. When the region over the middle of two APD pixels was irradiated, due to the small but finite light spread, both pixels light up and so the inter-pixel region is not dead. In the final system positioning events that occur between two APD pixels can be accomplished by either selecting the pixel with the higher signal, intelligently choosing one or the other pixel, or increasing the intrinsic resolution and actually positioning the event between pixels.

V. Conclusion

Preliminary results indicate that the proposed new design for an ultra-high spatial resolution scintillation crystal array will achieve high light collection efficiency for robust detector signals without compromising detection efficiency and sensitivity. The primary "edge-on" design we are testing uses 1 mm LSO crystals coupled to APD arrays. This design demonstrated very high energy resolution due to a significantly improved light collection aspect ratio. Using 1 mm crystal sheets will simplify construction and improve packing fraction and sensitivity. Through positioning measurements in one detector layer we showed that the crystal sheet-APD array detector behaves in a semi-discrete manner with sharp discrete peaks appearing at the APD pixel locations in a very linear manner. These properties will facilitate highly accurate event binning in a full detector system.

VI. Acknowledgment

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