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This program is the development of germanium strip detectors for environmental remediation. It is a collaboration between the Naval Research Laboratory (NRL) and Lawrence Berkeley National Laboratory (LBNL). The goal is to develop detectors that are simultaneously capable of excellent spectroscopy and imaging of gamma radiation.

During the first phase of the program, a 2x2 array of germanium strip detectors was procured commercially. These detectors were each 5cm x 5 cm x 1 cm in size and were segmented into 2 mm strip on each side of the detector. The strips were daisy chained for electronic readout into a single chain for each direction. The detectors were manufactured using Li-doped contacts and Boron contacts. A similar single detector was manufactured using an amorphous contact technique developed at LBNL. This contact technique allow for finer pitch detectors that do not degrade over time at room temperature.

The 2x2 array, in conjunction with other germanium strip detectors available at NRL, was used to perform a range of gamma-ray spectroscopy and imaging experiments and demonstrations. A paper was presented at the IEEE Nuclear Science Symposium demonstrating the use of this technology for medical applications. It demonstrates the performance for Positron Emission Tomography (PET). The fine pitch of the detectors allowed us to image positron emitters with a volumetric position resolution that is ~30 times better than systems currently used in hospitals. A copy of the paper is included with this report.

More recently, the performance of these detectors has been shown to image special nuclear materials. The 375-414 keV lines from Plutonium-239 have successfully been detected and imaged remotely using a Compton imager setup consisting of germanium strip detectors. A similar experiment, in collaboration with Argonne National Laboratory, has demonstrated the detection and imaging of 2.6 MeV gamma rays. These gamma rays are present from small contaminants of U-232 in enriched U-235. They are the hardest to shield radiation from highly enriched uranium (HEU) and therefore one of the better candidates for the detection of shielded nuclear materials. The results of this experiment were presented at the IEEE Nuclear Science Symposium. A copy of the paper is included with this report.

The second phase of the program is to manufacture much larger detectors with finer pitch. The goal was to manufacture a 2x2 array of detectors, each with an active area of 8 cm x 8 cm x 2 cm. This required unique germanium crystals that extracted from the long direction of a germanium boule, as opposed to the normal perpendicular direction to the length of the boule. A first detector was manufactured. The active volume of this single detector is more than five times larger than each detector of the previous generation. The detector performs well, and a paper describing its performance was recently presented at the IEEE Nuclear Science Symposium. A copy of the paper is included with this report.

Unfortunately, the delivery of the first large crystal was delayed by almost a year from the original quoted schedule. This delayed the manufacturing and testing of the detector accordingly. The delivery of subsequent crystals was delayed even more. This caused us to cancel the contract with the original vendor and switch an alternative vendor. The alternative vendor could not make crystals of the original dimensions, which is why it was not originally selected. The new dimensions of the crystals are 14 cm x 7 cm x 1.7 cm. This is only ~ 10% smaller than the original crystal, but with a different aspect ratio. The tooling and the masks therefore had to be changed to manufacture detectors from the new crystals. Four crystals have been delivered from the new vendor, and detectors are currently being fabricated. We therefore still expect to finish the originally proposed program with a no cost extension.

Small Animal PET Imaging with Germanium Strip Detectors

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Abstract-- We have demonstrated a PET imaging system based on double-sided germanium strip detectors. The demonstration achieved an intrinsic position resolution of 1.35 mm FWHM. This performance was achieved with 2 mm orthogonal strips and a depth sensing capability of 0.5 mm based on timing the pulses at either side of the detector. The system could trigger at energies as low as 15 keV without any image degradation. By selecting events within the 2 keV-wide photopeak, events that scattered within the sampling volume were totally eliminated. If a detector is built with 1 mm strips, the position resolution for PET imaging will not be dominated by the position resolution of the instrument, but by the range of the positron in the sample.

1. INTRODUCTION

Over the last 50 years, Positron Emission Tomography (PET) has evolved from a curiosity into a common clinical and research tool. For the last 30 years, PET designs have mostly been based on rings of scintillating detectors read out by photomultiplier tubes. The evolution and improvements in PET scanners have followed the developments in scintillation materials and photomultiplier tubes. As scintillation materials are developed with better stopping power and faster response times, more sensitive PET systems can be built. With the development of position-sensitive photomultiplier tubes, a new regime of position resolution opened up. Photomultiplier tubes are now available with pixels of $\sim 2 \text{ mm} \times 2 \text{ mm}$. To optimally use these pixels, newer generation scintillation crystals are segmented into small pixel arrays. There are now a multitude of PET camera heads [1,2,3] with pixellated Bismuth Germanate (BGO), Gadolinium Orthosilicate (GSO), Lutetium

Orthosilicate (LSO), Yttrium Aluminum Perovskite (YAP), etc...

The common feature of these instruments is that there is a very fine two-dimensional square pixellization, typically 2 to 4 mm a side, and an unpixellized third dimension. As the size of the pixels shrinks, the cost in generating these crystals grows, and the fraction of the area taken up by gaps between the crystals grows significantly. The third dimension, the depth, is typically 20 mm. This depth is required to provide sufficient material to stop an annihilation photon with 511 keV of energy. When a gamma ray interacts in a crystal pixel, the location of the interaction is limited to a voxel, or three-dimensional pixel. The size of that voxel is roughly given by the dimensions of the small crystal.

For PET imaging, two such voxels are connected by lines to determine the origin of the radiation. If the radiation is perpendicular to the small face of a crystal, then the depth of the crystal does not contribute to the position uncertainty, and images with a very fine position resolution can be made. This is how on-axis two-dimensional (2D) PET works. Typically, as one moves off axis in a trans-axial plane, the image resolution starts to degrade. This is because the radiation is no longer perpendicular to the small face of the crystal and the long side of the crystal now causes a significant uncertainty in the position. Similarly, if one allows annihilations that are not in a trans-axial plane but have a significant component of their momentum in a sagittal or coronal plane, then the depth of the crystal again starts to contribute to the position uncertainty and the image quality degrades. This is typically the case for three-dimensional (3D) PET.

To overcome the effect of the depth of the crystal, or the depth of interaction (DOI) problem, several approaches can be taken. One is to restrict the imaging to 2D PET. This approach causes a clear loss of efficiency, and thus a similar loss of sensitivity. Another approach is to have a large distance between the ring of the detectors and the sample of interest. If the ring of detectors is large compared to the sample, then the gamma rays originate from near the axis of symmetry, or the center of the ring. The angle of incidence into the crystals is then nearly perpendicular, and the DOI problem decreases. The quantity of detectors required, and therefore the cost, in a

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PET system is proportional to the circumference of the ring. Worse though, is the fact that the solid angle coverage of a certain axial length of detector shrinks as the ring diameter grows. The efficiency then decreases sharply as the ring diameter grows.

Fig. 1. Schematic diagram of the experimental setup. Detectors 1 and 2 are double-sided germanium strip detectors with 2 mm pitch and 0.5 mm depth resolution. The detectors are 5 x 5 x 1 cm in size and the detector separation was ~9 cm.

New approaches to solving the depth of interaction problem are needed. This is particularly true for PET applications where a large instrument bore and large rings are not necessary, such as small animal PET or Positron Emission Mammography (PEM). Very recently, a number of groups have proposed approaches where some depth of interaction information could be obtained [4,5]. The techniques rely on changing the scintillation properties at different depths in the scintillator. The timing characteristics of the scintillation are altered for different depths. The light pulse collected by the photomultiplier tube from the end of the crystal is then processed with electronics with different time constants to extract the depth information. The scintillation properties are either changed by changing the dopants in the crystals, or by outright change of type of scintillator. The multi-scintillator approach is a pixellated version of the well known phoswich detector concept. The total depth of the crystal can be segmented in 2-4 pieces based on these techniques. These approaches are very laborious, and they can not be extended to much finer depth resolution.

We propose a new approach to PET based not on scintillation detectors but on germanium semi-conducting detectors. Semi-conducting detectors offer multiple advantages over scintillation detectors. The two-dimensional pixellization achieved with mechanical gaps and grooves in scintillators can be achieved by electrical segmentation on a single substrate. This means much smaller gaps can be achieved, and an arbitrarily small pitch can be achieved. Indeed, pixellized silicon detectors with 20-micron pixels are an everyday occurrence in commercial digital cameras. A less well-known feature of semi-conducting detectors is that the depth of interaction can be measured very accurately by timing techniques [6]. The time difference between the appearance of a signal on the top and bottom of a planar semi-conducting detector can be used to derive the depth [7] with great accuracy (< 0.5 mm). This technology is therefore intrinsically capable

of excellent three-dimensional localization of gamma ray interactions.

II. EXPERIMENTAL SETUP

We have built a prototype PET detection system based on germanium strip detectors [8,9] that have excellent energy resolution and three-dimensional position resolution. A schematic layout of the prototype is shown in figure 1. Two planar germanium detectors were used and the imaged volume is the region between the detectors. Each detector is a germanium double-sided orthogonal strip detector, with an active volume of 5 x 5 x 1 cm. Each surface of the detector has twenty five 2 mm wide strips. By combining the strip information from both sides of the detectors, 2 mm square pixels are generated. The third dimension is obtained by measuring the relative time between the arrival of the collected charge pulse at both electrodes [6]. Wulf et al. [7] showed a position resolution of 0.5 mm could be achieved using the technique in these detectors. The pair of detectors was partially instrumented with electronics reducing the actual sensing area to 8 cm² for the first detector, and 10 cm² for the second one. The data acquisition system was triggered on coincident events between both detectors with a coincidence window of ~500 ns. Even though the detectors have an excellent energy resolution of ~2 keV, a broad energy window was accepted in order to maximize the efficiency of the system. All events between a lower level discriminator of 15 keV and the 511 keV peak were accepted. All events with valid three-dimensional coordinates in both detectors can be used for image reconstruction.

Fig. 2. Reconstructed images of a Na-22 source. Both images are in a reconstructed plane that contains the source and is parallel to the detector planes. The left image has a 1 microCurie source in the plane of the detectors. The right image has the source perpendicular to the detector planes. The right hand picture shows a vertical thickness that corresponds to a position resolution of 1.5 mm Full-Width-at-Half-Maximum.

Since the main goal of this proof of concept was demonstrating the detector performance, only a very simple reconstruction algorithm was used. For each valid event, a line of pixels connecting the two interaction sites was incremented by 1 in the three-dimensional imaged volume. By collecting many events, three-dimensional images can be generated. More sophisticated algorithms can and should be used. Because of the total count limitations of PET, list-mode maximum likelihood reconstructions look the most promising.

Nevertheless, the simple reconstruction algorithm we used does demonstrate the excellent imaging capability of this technology.

III. RESULTS

Figure 2 shows a pair of images of a Na-22 source generated with the setup. The source was a standard calibration source with an unknown source distribution within the sealed capsule. Both images are generated by reconstructing the flux in a plane that both contains the source and is parallel to the detector plane. This plane is found by choosing the slice with the maximum counts per voxel. The left picture of Figure 2 shows that the source distribution is ~ 4 mm in diameter, with a very uneven source distribution. The position resolution is clearly better than the source distribution. The right hand picture of Figure 2 shows the same source rotated by 90 degrees into a roughly horizontal plane. The reconstructed vertical thickness of the source provides an upper limit to the position resolution of the system. Fits at various positions show an upper limit to the resolution of 1.5 mm Full Width at Half Maximum (see Figure 4). This is slightly larger than the resolution expected from the 2 mm pixellization of the detector, although it is also affected by the large third dimension of the source and the spread due to the motion of the positrons as they slow down in the source.

Fig. 3. Reconstructed images of a Ge-68 line source with a 1.5 mm active cross section. The images show the effect of increasing the lower level threshold on the energy of events allowed in for reconstruction. The left most picture has a threshold of 15 keV, followed by thresholds of 50 keV, 200 keV and 500 keV. The right most picture therefore only contains events where both 511 keV gamma rays underwent photoelectric absorption. No image degradation occurs when lowering the threshold, but the efficiency improves dramatically.

Figure 3 shows the reconstructed images from an Isotope Products line source of Germanium -68. The source activity is contained in a cylindrical cavity with a 1.5 mm diameter. The line source is clearly imaged. The four panels illustrate the effect of raising the lower level threshold on the energy deposited in a detector. The image quality is clearly unaffected by the decreasing threshold. The efficiency, on the other hand, is improved as the threshold is lowered. The events are as good as higher energy events in term of reconstructing positions, as clearly proven in Figure 3. Most scintillation-based detectors for PET need to put the threshold substantially higher, leading to a relative loss in efficiency. The right most picture of Figure 3 contains the fewest counts, but all the events are guaranteed to be caused by the photoelectric absorption of 511 keV

annihilation photons. This means that the gamma rays are guaranteed to not have interacted anywhere before entering the detector. Any coincidence events caused by scattered radiation are therefore totally eliminated. This mode can be useful when a very high-contrast image is required or when an unusually large amount of scattering material is present.

Fig. 4. Left: Vertical cross section through the right hand side image of Figure 2, the image of a side view of a Na-22 source. The Full Width at Half Maximum is 1.5 mm. Right: Horizontal cross section through the left hand picture of Figure 3, the image of a Ge-68 line source. The width is dominated by the size of the source (1.5 mm diameter) and the range of the positrons (~ 1 mm).

The position resolution in the image is measured by studying cross-sections of the images shown in Figures 2 and 3. Figure 4 (Left) shows a vertical cross section through the right side image of Figure 2, the side-view of a Na-22 calibration source. The full-width-at-half-maximum of the distribution is 1.5 mm. Cross sections taken at various other locations gave the same result. Some of this 1.5 mm is due to the distance the positron travels as it slows down before it annihilates. The 540 keV endpoint energy positrons from Na-22 beta-decay have a range of $.23 \text{ g/cm}^2$. This corresponds to a 0.85 mm range in any direction in aluminum, or a diameter of 1.7 mm. Since the bulk of the positrons have an energy closer to half the end point, the corresponding range is 0.09 g/cm^2 , or a corresponding diameter of 0.7 mm. Subtracting this in quadrature from the measured resolution results in an intrinsic position resolution of 1.3 mm. This corresponds to the expected resolution from the pixellization.

The cross section through the image of the Germanium-68 line source is also shown in Figure 4 (Right). It has a FWHM of 1.9 mm. The source is contained in a steel tube with an outer diameter of 4 mm and an active volume of 1.5 mm diameter. The endpoint energy of the positrons is ~ 1.9 MeV. The range of the positrons in the steel tube is ~ 1 mm. The range of the positrons therefore contributes significantly to the spread of positions from which annihilations can originate. The width shown in Figure 4 is a convolution of three things: the one-dimensional projection of the distribution of source material held in a circular pattern; the range of positrons emanating from the source material; and the position resolution of the imaging system. In order to better understand these issues, we modeled the source in a Monte Carlo simulation program. The GEANT-4 [10] simulation package was used to simulate the materials and particle transport. The package has

been extensively tested and fine-tuned in our laboratory to ensure a good performance for low energy processes [10s of keV to a few MeV]. The cross section of positions where positrons with the endpoint energy of ~ 1.9 MeV annihilated, when the entire circular source distribution is projected onto one axis, has a FWHM of 2.0 mm. When using a mean positron energy of ~ 1 MeV, the FWHM drops to 1.3 mm. If we subtract this in quadrature from the observed width of 1.9 mm, we again derive an instrument resolution of between 1.3 and 1.4 mm.

Fig. 5. Reconstructed images of a Ge-68 line source with a 1.5 mm active cross section and a 1 cm thick lead piece covering the bottom half of the field of view. The left hand picture has a threshold of 15 keV, whereas the right hand picture only contains events where both 511 keV gamma rays underwent photoelectric absorption. The photopeak-only image has very few scattered events, even though 1 cm of lead was present.

To demonstrate the rejection capability of the instrument for scattered events, we inserted a 1 cm thick piece of lead in the bottom half of the sensing volume and imaged the line source of Ge-68 (Figure 5). The attenuation due to the lead is clearly visible in the bottom half of the image. The left image shows the reconstructed image with a significant halo due to the events that scattered in the lead. The picture on the right shows the same setup but only includes events that deposited 511 keV in each detector. Almost all scattered events are rejected. This technique reduced the overall efficiency of coincidence detection by a factor of ~ 30 in our laboratory setup. In the proposed instrument, the thicker detectors and improved geometry will reduce this effect to a factor of ~ 8 loss in efficiency. Nevertheless, this mode of operation can be used when sharp contrasts are required and when the increase in radiation dose is not a problem.

IV. PROPOSED INSTRUMENT

We propose a prototype small animal PET system based on double-sided germanium strip detectors. A picture of the proposed instrument is shown in Figure 6. The instrument would consist of four rectangular germanium strip detectors. The detectors would be arranged in a box-type geometry creating an inside volume with a square cross section. The detectors would have an active detector volume of $6.5 \times 13 \times$

1.7 cm and a strip pattern of 64×128 strips, or a strip pitch of 1.02 mm. Each strip has its own read-out electronics for spectroscopy and timing. Each detector would be held in an aluminum frame that would also hold printed circuit cards. The four aluminum frames would be held onto a cold frame. The four detectors would be held in a common cryostat and cooled by a common cold plate.

Fig. 6. Artist's impression of the proposed instrument. The instrument consists of 4 germanium strip detectors with a position resolution of 1 mm. Not shown are the cryostat and ribbon cables. The sensing volume of the instrument is 6 cm in diameter, 10 cm long and is in an air environment. The position resolution of the instrument for images in the trans-axial plane will be ~ 0.7 mm FWHM.

Samples would remain in a regular air environment and be inserted in the volume between the detectors. The sensing volume would be a cylinder with a diameter of 6 cm and a depth of 10 cm. The central 4 cm in diameter and 8 centimeters in length would have an absolute coincidence efficiency of $>10\%$ (see Figure 7). Based on the 1.3 mm FWHM position resolution obtained in images made with our laboratory proof of concept demonstrator, we expect images in the trans-axial plane to have a position resolution of 0.7 mm FWHM. The position resolution in the third dimension will be somewhat degraded. The readout electronics for the instrument, based on proven commercial VME modules, will be able to operate at >100 kHz. With an average coincidence efficiency of $\sim 10\%$, this count rate is achieved with a total activity of ~ 30 microCi, or $\sim 10^6$ Bq. A more suitable activity to minimize accidental coincidences would be $\sim 10^5$ Bq. A 15 minute exposure could therefore collect ~ 10 million events. For a 25 gram mouse, if 10% of the volume elements contained all the activity, there would be 4 000 counts per active voxel. The statistical errors would therefore be small ($\sim 1.5\%$). Figure 8 shows a cutout of the detectors in their cryostat.

Fig. 7. Coincidence efficiency maps for the proposed instrument. The left hand picture is a trans-axial efficiency map; the right hand view is a sagittal or coronal efficiency map. Because of symmetries, the latter two are equivalent. The brightest regions correspond to 18% efficiency; the darkest regions correspond to 0% efficiency.

V. CONCLUSIONS

We have demonstrated Positron Emission Tomography imaging with a position resolution of 1.3-1.4 mm using germanium strip detectors with a 2 mm pitch. If we use detectors with 1 mm strip pitch, an imaging resolution of 0.7 mm should be obtained. At this level one can really start to explore the effect of the different endpoint energies the various possible isotopes. Another factor of two reduction in strip pitch might be possible before one encounters limitations due to the path-length of the conversion electron in the detector material itself.

Fig. 8. Cut out view of the proposed cryostat. The cryostat is ~ 30 cm long and 25 cm wide. The left plate is used to mount the gantry. It can also support a rotation stage to hold and rotate the samples. The cryostat can be mounted horizontally or vertically, but is assumed to be horizontal. Samples are inserted in the central hole.

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Development and Performance of Large Fine-Pitch Germanium Strip Detectors

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Abstract— We present the initial performance results obtained with a double-sided planar germanium strip detector with 1.25 mm pitch and 64 cm² of active area. The detector is 2 cm thick and was manufactured with an amorphous contact technology. The germanium crystal is 10 x 9 x 2 cm³ and was extracted from the long direction of a germanium boule. The detector has 64 strips on each side, with one side AC coupled to the front-end electronics and the other side DC coupled to the front-end electronics. An energy resolution of 2.4 keV and a pixellization of 1.25 mm are achieved. A depth resolution of 1 mm was obtained by using a timing technique. Gamma-ray imaging and spectroscopy are demonstrated using diffuse gamma-ray sources and collimators. Images created using coded apertures are also shown.

I. INTRODUCTION

HIGH resolution, position-sensitive germanium detectors offer excellent capabilities for the detection, identification and characterization of radioactive isotopes. These detectors provide enhanced capabilities over existing systems and have direct applicability in the areas of Decontamination and Decommissioning (D&D), Nuclear Materials, Spent Nuclear Fuel (SNF), Mixed Waste, as well as for basic laboratory nuclear physics and gamma-ray astrophysics. Germanium strip detectors are made by segmenting the contacts of a planar detector. The position of a gamma-ray interaction is determined in one dimension by which strip is collecting the electrons and in the orthogonal dimension by the strip collecting the holes. The location in the third dimension, the depth, is obtained by measuring the difference in the arrival time of the signals on both electrodes[1]. The energy measurement is obtained from the

amplitude of either the electron or the hole signal. We previously presented results from germanium strip detectors with 25 strips on each side and 25 cm³ of volume [2,3,4]. These detectors were either manufactured using lithium contact technology or amorphous contact technology. We have now constructed a detector with 128 cm³ of active volume using the amorphous contact technology.

Fig. 1. Photograph of large double-sided germanium strip detector. The detector has an active volume of 80 x 80 x 20 mm³. There are 64 strips on each side, with a strip pitch of 1.25 mm. There is a 5 mm guard ring around the perimeter of the active area.

II. AMORPHOUS CONTACTS

The amorphous contact technology was developed [5,6] to provide a simple process to fabricate segmented Ge detectors. Both single sided and double-sided strip detectors have been produced using amorphous-Ge contacts [7]. Amorphous contacts provide multiple advantages over the Lithium contact technology:

- It can achieve a finer pitch than possible with the Lithium diffusion technology
- The dead layer associated with the Lithium-diffused contact is eliminated
- Surfaces between electrodes are automatically passivated with the amorphous film

We have fabricated the third generation orthogonal strip detector with amorphous contacts and now have dimensions appropriate for field use. The detector has an active central volume of 80 mm X 80 mm X 20 mm and has 64 X 64 strips (see Fig. 1), resulting in a strip pitch of 1.25 mm. The crystal is

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90 mm x 100 mm x 20 mm and was cut along the long axis of a single crystal germanium boule. There is a 5 mm guard ring all around the active area and the remaining 5 mm of crystal on each side is machined into a lip to clamp the detector in a frame. The segmentation on both faces is obtained by evaporating an aluminum pattern of strips onto the amorphous-Ge film covering the full area of the detector. Since both sides of the detector are identical, either side can be used as a high-voltage contact. The detector started to deplete at ~ 300 Volts and was operated at 600 Volts or 700 Volts, with a typical leakage current of 60 nA. The strips are 1 mm wide by 80 mm long with 0.25 mm gaps between the strips. The energy resolution is ~ 2.4 keV Full Width at Half Maximum (FWHM, see Fig. 2), which is dominated by electronic noise.

Fig. 2. Energy spectrum of a strip on the high voltage side of the detector. The resolution for the 122 keV line from ^{57}Co is 2.4 keV.

III. READOUT ELECTRONICS

The signals from each side of the detector are connected from the pins shown in Fig. 1 to a separate board on each side of the detector. The board on the high voltage side contains decoupling capacitors and biasing resistors, whereas the board on the ground side acts as just a connector. From these boards, the signals are routed with flexible polyimide printed wire assemblies to preamplifier cards inside the cryostat. The preamplifier card contains 64 hybrid preamplifiers (eV Products model 5093, [8]). From the preamplifiers, the signals are routed by coaxial cable through a vacuum feed-through to 16-channel programmable shaping amplifiers (CAEN N568-B, [9]). The fast-shaped pulse (200 nanosecond shaping) is routed to 16-channel leading edge discriminators (Phillips model 7106, [10]) to generate triggers and timing pulses, and the slow-shaped pulse (2 microsecond shaping) is routed to 32-channel peak-sensing analog to digital converters (CAEN V785) for the spectroscopy measurements. The individual discriminator timing pulses are fed into TDCs, time to digital converters, (CAEN V775) to measure the timing of the pulses

from each side of the detector. The TDC is run in a common stop mode with the stop signal generated from the OR of all the strips delayed by 1 microsecond.

IV. DETECTORS SEGMENTATION

The segmentation of the detector was measured by scanning it with a finely collimated radiation source. A ^{57}Co source was collimated down to a line source with tantalum plates separated by 100 microns. The size of the beam at the detector is ~ 300 micron FWHM. Figure 3 shows the results of a scan in 125-micron steps across 2 strip boundaries on the high voltage side of the detector. The number of counts in the 122 keV photo-peak is plotted in three strips for each position of the scan. The strips are well separated, and the roll-off at the end of a strip is comparable to the size of the beam. The sharpness of the strip boundary is therefore < 300 micron and will be tested with even finer collimated scans.

Fig. 3. Scan of a collimated ^{57}Co source across 2 strips. The number of counts in the photo-peak is plotted for three strips versus the position of the source.

V. IMAGING DEMONSTRATION

To demonstrate the imaging capability of the detector, we made a shadowgram of a lead pattern. The shadow of a lead smiley face irradiated with a ^{57}Co source can be seen in Fig. 4. The dark region on the top and the right is due to the edge of our cryostat aperture. The dark strips in the image are due to troubled electronics channels, not the detector. This image is not of a radioactive mask, merely the shadow of a mask irradiated by a point source of radiation. To image a source of gamma rays, more complicated systems are required. Two examples are discussed below.

A. Collimator

A collimator can be used to image diffuse sources. Each pixel on the detector only detects photons from a specific part of the source. The detection efficiency is quite small, but the

imaging technique is quite robust. To demonstrate this technique, a ^{239}Pu cube was imaged by the detector using a 3.8 cm thick tungsten collimator with holes. The collimator is made by stacking 0.25 mm thick foils that had been etched with a pattern of square holes 0.4 mm a side on a 0.5 mm pitch. The image of the cube, which was 11 mm on a side, can be seen in Fig. 5. There is a dead vertical electronics readout channel corresponding to the lack of counts near $x = 6$ mm. This imaging technique allows one to make images of multiple sources within a field-of-view by selecting the emitted gamma ray based on its energy.

Fig. 4. Shadow of a lead mask illuminated by 122 keV photons from a ^{57}Co source. The dark area on the top and right hand side of the picture are due to a thick steel support structure for the vacuum window.

B. Coded Aperture

When sources are very faint, the effective area of the detector needs to be maximized. If the source is known to be point like, as is often the case in gamma-ray astrophysics, a coded aperture technique can be used. A known shadow pattern is located in front of the detector. By measuring the shadow of the pattern on the detector, the direction of the incoming beam can be determined. Uniformly Redundant Arrays (URA) and Modified Uniformly Redundant Arrays (MURA) are patterns that are optimized as masks for coded apertures [11]. The top image of Fig. 6 shows a 2 by 2 repetition of an 11 by 11 URA pattern. A coded aperture was manufactured with this pattern out of one millimeter-thick tantalum with a basic cell size of 3 mm and irradiated with 122 keV photons from a ^{57}Co source. The middle image from Fig. 6 shows the reconstructed shadow of the mask on the detector plane. The bottom picture from Fig. 6 shows the images that was reconstructed when combining the aperture pattern with the measured shadow.

VI. DEPTH SENSING

The previous section demonstrated the performance of this detector for two-dimensional imaging. There are a number of applications that require three-dimensional positional information of the gamma ray interaction. For example, Compton Imaging techniques require the three-dimensional coordinate of an interaction to reconstruct the event. Positron Emission Tomography (PET) can also be improved if full three-dimensional information is available. The third coordinate, the depth of interaction within the detector, is determined with a timing technique is used. The difference in the time of arrival of the signal on both faces of the detector is a measure of the depth of interaction of an event. All channels of electronics were therefore connected to a discriminator that was in turn connected to a time to digital converter.

Fig. 5. Reconstructed image of a cube of ^{239}Pu using a tungsten collimator. The cube is 11 mm a side. The image was generated by selecting the energy of the Pu lines.

Fig. 6. Coded aperture imaging of a point source. The top image shows the coded aperture pattern. The middle picture shows the imaged shadow of the aperture pattern on the detector, with a few dead electronic channels visible by the black lines. The bottom picture shows the image reconstructed knowing the mask and detector positions.

To characterize the depth sensitivity, the detector was illuminated from the side with a finely collimated fan beam of photons from a ^{133}Ba source. All signals from the source therefore occurred at the same depth. The width of the collimated beam is 0.3 mm at the edge of the detector. The beam covers the entire side of the detector in the other dimension. The collimated beam was then moved in steps of 2.5 mm along the depth of the detector. Figure 7 shows the resulting depth resolution at four different depths. The depth resolution is better than 1 mm. Near the edge, the depth resolution is slightly worse than towards the middle of the detector. This is due to inhomogeneity in the electric field lines near the gaps between the aluminum contacts of the strips.

Fig. 7. Time difference between the discriminator signals on the front and backside of the detector. This time difference is measure of the depth of the events. The four peaks are four individual runs using a finely collimated beam.

VII. CONCLUSIONS

Large double-sided germanium strip detectors can be successfully manufactured from wafers extracted from the long direction of a boule. Using the amorphous contact technology, a detector was manufactured with a performance that has remained stable over more than 6 months. The detector has been cycled many times between room temperature and liquid nitrogen temperature, as well as between air and vacuum without any performance degradation. A 2.5 keV energy resolution was achieved on the strips. A 1.25 mm strip pitch and 1 mm depth resolution were achieved. Therefore, three-dimensional positioning with an accuracy of ~ 1 mm has been demonstrated with this detector. Collimator and coded aperture imaging have been demonstrated. Compton imaging with this detector should provide interesting results in the near future.

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Strip Interpolation in Silicon and Germanium Strip Detectors

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Abstract—The position resolution of double-sided strip detectors is limited by the strip pitch and a reduction in strip pitch necessitates more electronics. Improved position resolution would improve the imaging capabilities of Compton telescopes and PET detectors. Digitizing the preamplifier waveform yields more information than can be extracted with regular shaping electronics. In addition to the energy, depth of interaction, and which strip was hit, the digitized preamplifier signals can locate the interaction position to less than the strip pitch of the detector by looking at induced signals in neighboring strips. This allows the position of the interaction to be interpolated in three dimensions and improve the imaging capabilities of the system. In a 2 mm thick silicon strip detector with a strip pitch of 0.891 mm, strip interpolation located the interaction of 356 keV gamma rays to 0.3 mm FWHM. In a 2 cm thick germanium detector with a strip pitch of 5 mm, strip interpolation of 356 keV gamma rays yielded a position resolution of 1.5 mm FWHM.

Index Terms—Silicon detector, Germanium detector, interpolation, Compton telescope.

I. INTRODUCTION

DOUBLE sided cross-strip detectors made from both silicon and germanium have been used to demonstrate excellent energy resolution and position resolution equal to their strip pitch. These properties have made them useful for gamma-ray imaging including Compton cameras and PET detectors [1]. Reducing the strip pitch to increase the position resolution increases the amount of electronics needed to readout the system and increases the number of events that are shared on multiple strips.

One way to get around this tradeoff is to digitize the preamplifier signal. The raw preamplifier signals contain information about the interaction site that is more accurate than the strip pitch. By digitizing the preamplifier signal of the strip and its neighbors, one can interpolate the position to less than

the strip pitch and determine the depth of the interaction within the crystal. This information was first exploited in segmented coaxial germanium detectors to locate interactions for nuclear experiments for GRETA [2]. This was then extended to germanium strip detectors first for GARBO [3] and then for a Compton telescope in a single detector [4].

II. DETECTORS

In this experiment, three detectors were used. One was a silicon detector manufactured by SINTEF which is 2 mm thick with 64 x 64 strips and a 0.891 mm pitch. The detector is DC coupled with external decoupling components. The energy resolution of the detector at room temperature using eV5093 preamplifiers and individual lab electronics is 4 keV FWHM [5].

Two germanium detectors were used as well. One detector was made by Eurisys Mesures for NRL and has 4 crystals in one cryostat arranged in a 2 x 2 array with lithium-drifted contacts on one side and boron implants on the other. The lithium contacts were made by diffusing the lithium through a photoresist mask. Each of the detectors is about 1 cm thick and has 25 x 25 strips with a pitch of 2 mm. The detector readout uses eV5093 preamplifiers and has an energy resolution of 1.5 keV FWHM at 60 keV. One of the four detectors was used in this work [6].

The other germanium detector was made by Ortec (Ametek) for Argonne National Laboratory. It is a 2 cm thick detector with 16 x 16 strips with a pitch of 5 mm. The boron contact is the same as in the NRL detector, but the lithium contacts are segmented by saw cuts. The detector uses preamplifiers from Ortec [3].

III. DATA ANALYSIS

The preamplifier signals from the detectors were digitized using Struck SIS3301 Flash ADC VME modules. They have a voltage range of ± 1 V, a 1 k Ω input impedance, 100 MHz maximum sampling frequency, and 14 bit voltage resolution. Each module contains 8 channels and 8 of these modules were employed. Their resolution combined with the conversion gain of the preamplifiers yielded approximately one ADC bin per keV of energy deposited in the crystal.

The energy of a gamma ray that interacts in the detector is directly proportional to the charge collected on the strip. Matching the energy collected on the front and back of the

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Fig. 1. These are preamplifier signals from three strips. The black line in the center plot, 1(b), shows that a signal from a ~ 500 keV gamma ray in this strip. The blue signal is the absolute value of the numerical derivative of the preamplifier signal. The energy deposited in the main strip induces a signal with a peak of about 50 ADC bins on the left strip, 1(a) and about 90 ADC bins on the right, 1(c). This means that the interaction point was closer to the right hand strip.

detector determines the location of the interaction, accurate to the strip pitch of the detector.

Fig. 1 shows three neighboring strips from one side of the NRL germanium detector connected to one Struck module. Fig. 1(b) shows the preamplifier signal in black for an interaction in the detector that has deposited approximately 500 keV in this strip. The signal is smoothed with a boxcar average over 9 points and is then numerically differentiated and the absolute value of this derivative is shown in blue above the black preamplifier signal. Fitting the derivative with a Gaussian yields the location of the 50% point and the width of the transition. The energy is determined by taking the average height before the transition point and after the transition point. The area within 10σ of the transition is excluded from this calculation. To determine the depth of the interaction, the difference between the 50% point of signals from either side of the detector are taken [7]. This yields an arctangent function when plotted against the actual depth of the interaction.

Fig. 1(a) and 1(c) show the signals induced in the strips to the left and right of the main strip respectively. These are shown around the 50% transition of the central signal in Fig. 1(b) and going out $\pm 10\sigma$ from this main transition. These peaks are fit with a Gaussian to determine the location of the peak and its width. The background subtracted amplitude of the neighboring signal is a measure of the induced charge. Taking the difference over the sum of the peak signals from the left and right yields the position asymmetry, see Equation 1.

$$Asymmetry_{Position} = \frac{P_{Left} - P_{Right}}{P_{Left} + P_{Right}} \quad (1)$$

This asymmetry is proportional to the position of the interaction within the strip.

IV. SILICON

A fan beam from a ^{133}Ba source was used to make strip measurements in the 64 strip silicon detector. The energy of

each interaction was extracted as described in the Section III. The resolution of the system was found to be 4 keV as shown in the Fig. 2 for a ^{133}Ba source.

Fig. 2. A spectrum from a ^{133}Ba source on a SINTEF silicon detector.

The source was then collimated into a fan beam that was 0.26 mm wide at the front face of the detector. This fan beam was stepped across the front face of the detector to measure the response as a function of position. Fig. 3 shows the response to two positions of the fan beam that are separated by 0.5 mm. The FWHM of the measured asymmetry is found to correspond to a resolution of 0.4 mm. Taking the width of the beam in quadrature yields a resolution of 0.3 mm FWHM or about 33% of the strip pitch.

V. GERMANIUM

Using the Flash ADCs, the energy resolution of the germanium detectors is ~ 4 keV FWHM at 356 keV. The energy spectrum summed over both detectors triggering in coincidence mode for a ^{60}Co source illuminating both detectors is shown in Fig. 4.

Fig. 3. The measured position asymmetry on one strip in the silicon with the two points separated by 0.5 mm on the silicon detector.

Fig. 4. A spectrum of a ^{60}Co source illuminating both detectors with a coincidence trigger.

The depth resolution was found to be 1.5 mm FWHM for the ANL detector (see Fig. 5) and 0.9 mm for the NRL detector.

Strip interpolation worked very well in both detectors. In the ANL detector, it was determined to be 1.5 mm (see Fig. 6) and in the NRL detector it was 0.9 mm.

One problem seen with the asymmetry measurement technique is that there are regions where the induced signal in the neighboring strips is too small to observe. The induced charge switches polarity at a certain depth as the predominate charge carrier switches from electrons to holes. Near these polarity changes the signal to noise is too small to be detectable using the current technique. This can be seen in Fig. 7. The black curve is the measured depth for all interactions in the thick detector. The blue curve is the measured depth where just the front face is required to have an asymmetry and the green curve is for just the back face. The red curve is where there needs to be a measurable asymmetry on both faces. There are two obvious regions in the depth of the detector where the signals for the asymmetry are not measurable out of the noise of the system. The same behavior is seen in the NRL detector but the effect is near the edges of the detector rather than near the middle.

Fig. 5. The ^{133}Ba collimated to a fan beam at two different depths on the ANL detector. The depth resolution is about 1.5 mm.

Fig. 6. The ^{133}Ba collimated to a fan beam at two different locations on the ANL detector. The strip position resolution is about 1.5 mm on the 5 mm strips.

VI. COMPTON TELESCOPE

A gamma ray that Compton scatters in one location and is fully absorbed in another location can be reconstructed to a cone of possible directions using

$$\cos(\theta_1) = 1 + \frac{511}{E} - \frac{511}{E - L_1}, \quad (2)$$

where θ_1 is the Compton scattering angle, E is the energy of the original gamma ray, and L_1 is the energy of deposited in the detector at the first scattering location. The position of the two interactions and their energies have to be measured accurately. Depth information and strip interpolation can be used to improve the resolution of a telescope.

The two detectors were placed parallel to each other, with the NRL detector in the front, and 10 cm apart. The NRL detector had 16 strips on both sides of the detector instrumented and the entire ANL detector was instrumented.

A ^{133}Ba fan beam was scanned across the detectors in all three dimensions to determine the exact location of the detectors with respect to one another. This was also done to calibrate the depth and strip interpolation for both detectors. This resulted in an ability to determine the source position in

Fig. 7. The measured depth for a ^{133}Ba source in the ANL detector is shown in black. The red is when both faces of the detector have a measurable asymmetry. The blue and green curves are when only one face or the other has an asymmetry.

the small detector to 0.9 mm in all three dimensions and to 1.5 mm in the ANL detector. The energy calibration for all strips was also determined.

Each detector had the strips from both sides ANDed together with a 200 ns coincidence window. Data were acquired with both detectors in coincidence with a 500 ns coincidence window.

Two different sources were placed 27.4 cm from the front face of the NRL detector. The acquired data were analyzed and events that interacted once in each detector were selected. The energy deposited in each detector was summed together to produce a spectrum. The events that summed to the energy peaks were selected and Compton reconstructed with and without strip interpolation.

A. ^{228}Th

A 60 μCi ^{228}Th source was placed 27.4 cm from the front face of the NRL detector. The 2614 keV line was chosen and the events that summed to this energy were reconstructed using the Compton scattering formula. This was done with and without strip interpolation. Using just the strip pitch, the resolution is 1.84 cm FWHM at a distance of 27.4 cm from the front of the detector. This corresponds to 3.8° . The source is 3 mm in diameter and at 2614 keV Doppler broadening contributes 1.0° . Subtracting these effects in quadrature results in a resolution of 3.7° . The predicted error from energy resolution and strip pitch is 1.0° .

Using strip interpolation the FWHM improves to 1 cm or 2.0° , see Fig. 8. Subtracting the other effects in quadrature gives a resolution of 1.7° . The predicted error due to energy and position resolution at this energy is 0.5° .

B. ^{60}Co

A 9 μCi ^{60}Co source was placed 24.5 cm from the front face of the NRL detector in two different locations. The ^{60}Co spectrum produced by summing the energy deposited in the

Fig. 8. The reconstructed ^{228}Th image using strip interpolation.

two detectors is shown in Fig. 4. The 1173 and 1333 keV line are clearly visible. Both the 1173 and 1333 keV lines were chosen and these events were reconstructed using the Compton scattering formula. This was done with and without strip interpolation.

Using just the strip pitch results in a resolution of 1.5 cm FWHM at a distance of 27.4 cm which corresponds to 3.2° . Subtracting the source size of 3 mm and the Doppler broadening effect of 1.8° yields a resolution of 2.5° .

The strip interpolation improves the resolution to 1.1 cm FWHM which corresponds to 2.3° , see Fig. 9. Subtracting the other effects in quadrature yields a resolution of 1.3° . The predicted resolution based on energy and position resolution is 0.5° . This difference corresponds to a 5.6 mm difference in the measured FWHM.

Fig. 9. The reconstructed ^{60}Co image using strip interpolation for two source positions.

VII. PET

One can use the same setup as the Compton telescope for doing simple PET. Instead of having the source on one side of the instrument or the other, the source is placed between the two detectors. The 511 keV gamma rays from the positron annihilation are emitted nearly back to back. A line can be

drawn between the locations of the gamma-ray absorption sites to locate the source.

A ^{68}Ge line source was placed between the two detectors at a diagonal. The line source is 1.5 mm in diameter and the positron has a range of 1 mm. The source was placed 3.7 cm from the back face of the NRL detector. The events that deposited between 100 and 400 keV in either detector were selected. The data using only the strip pitch showed a resolution of 4.7 mm FWHM. Using strip interpolation, see Fig. 10, the resolution was improved to 2.8 mm FWHM.

Fig. 10. The reconstructed ^{68}Ge line source using strip interpolation.

Selecting events that deposited the full 511 keV in each detector decreased the resolution to 4.0 mm and 4.7 mm, for interpolated and strip pitch reconstruction respectively, because of the increased range of the electron in the detector.

This method offers another advantage; the signals in the system can now be resolved to 10 ns improving the discrimination of true and accidental coincidences needed for high rate applications.

VIII. CONCLUSIONS AND FUTURE WORK

We have extended the strip interpolation to silicon strip detectors. In the SINTEF silicon detector, the strip interpolations is one third of the strip pitch. Also, strip interpolation in two germanium detectors has been demonstrated. There are certain interaction depths in the detector where the induced signal is too small in comparison to the noise to use for interpolation. Strip interpolation has been used to improve the resolution of a two detector Compton Telescope and a PET detector.

Further study needs to be done to model the electric field in the detector to determine the exact behavior of the induced signal at all points in the detector especially in the region where the signal becomes small and bipolar.

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