Investigation of the Effects of Scintillator Pixel Shape, Surface Treatment and Optical Coupling on the Performance of Si-PM Based BGO Detectors

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Abstract—Positron Emission Tomography (PET) is based on the coincidence detection of annihilation photons, after their interaction with scintillator crystals. BGO produces less overall scintillation light compared to LSO and its variants. A considerable fraction of scintillation light becomes trapped and absorbed before it reaches the exit face of the BGO crystals. In order to improve the amount of optical photons that exit the crystal, we examined the performance of different scintillator geometries, surface treatments and interface material index of refraction for BGO crystals, coupled to solid state photodetectors. Simulations were performed to estimate the fraction of scintillation light detected by the photodetector (SiPM) as a function of the location of the source respect to the length of BGO crystals with different surface treatments and geometries (the standard rectangular block and crystals with an slanted face). In addition, the energy spectra for different crystal geometries and surface treatments were obtained through measurements of individual crystals coupled to a solid state photodetector, (Philips digital-SiPM DPC-3200). This work demonstrates that slight slanted geometry (120°) offers an advantage over conventional rectangular crystal shapes for light extraction for polished crystals, while there is no relevant difference in light extraction for non-polished crystals when changing the slanted angle.

I. INTRODUCTION

Positron Emission Tomography (PET) is commonly based on the detection of annihilation photons through their interactions with scintillator crystals. Traditionally, detection of scintillation light is achieved with multi-anode photomultipliers that have low noise and high gain but are bulky and have limited quantum efficiency. The new generation of solid state light detectors (SiPMs), offers similar gain with packaging advantages, but at the expense of increased device noise per surface area. Reliable triggering of solid state photodetectors, requires robust identification of a scintillation pulse, above the device dark current. Triggering becomes challenging, when the scintillator pixel geometry becomes elongated with a large aspect ratio, as is required for high resolution imaging. Furthermore, BGO, which is a scintillator with many appealing characteristics for preclinical PET (low background, high effective Z, high stopping power), produces less overall scintillation light, spread over a longer pulse time for each detected annihilation, compared to LSO and its variants, (Fig. 1). Scintillation photon flux rate is ~30 times lower for BGO than LSO. While the scintillator time constant is not very important when time of flight is not of concern, detector triggering and event position are dependent on both the total amount of light collected as well as on the time dependence of this process. Therefore, it is crucial that the small amount of light produced by BGO exits towards the light detector. Due to multiple internal reflections within the crystal and losses in the reflector, a considerable fraction of scintillation light becomes trapped/absorbed before it can exit towards the detection surface.

Fig. 1. Typical pulse for detected annihilation events using LSO and BGO crystals. Scintillation photons produced in the BGO crystal are spread over approximately seven times longer pulse duration than in LSO.

Factors influencing trapping of light within the crystal include its overall geometry, index of refraction, surface treatment as well as the index of refraction of the detection interface. Consequently, these factors pose an upper limit to overall system performance. Potential solutions to this problem have been examined before, based on the use of diffusive wrappings, optical contact agents, and crystal geometries, for
scintillators coupled to glass envelope photomultiplier tubes [1-7]. To address this issue, with the view of designing dense and contiguous crystal arrays coupled to solid state photodetectors for high resolution preclinical PET, we examined the performance of different scintillator geometries, surface treatments and interface material index of refraction for BGO crystals, coupled to solid state photodetectors. Simulations were performed by GATE, [8]. In addition, to validate the simulation results, the energy spectra for different crystal geometries were obtained through measurements of sample individual crystals coupled to a solid state photodetector. In agreement with previous work, preliminary results indicate that slant angle crystal geometry can significantly improve the light collection efficiency compared to conventional rectangular shaped geometries.

II. MATERIALS AND METHODS

The data acquired in this study were taken from two sources:

(1) To estimate the fraction of scintillation light detected by the photodetector (SiPM) after a number of scintillation photons are generated inside a BGO crystal, several combinations of crystal geometries and surface treatments were simulated using GATE. In all the simulations, 10000 isotropic emissions from a point source were generated. Each photon was followed starting at the emission site within the scintillator crystal, up to its absorption or detection.

Fig. 2. Gate simulation generic detector setup.

(2) To validate the results obtained in the simulations, measurements were taken using the setup in Fig. 3. The same geometries simulated in GATE for BGO crystals were used here. Coincidence measurements were performed between the BGO crystal of interest and an LSO crystal, to control the location of interaction within the crystal under investigation.

Fig. 3. (a) Side-view cartoon of the generic detector setup. (b) Front-view photo of the setup.

A. GATE Simulations

For all the geometries the exit face of the BGO crystal is 3x3mm² and the volume of the crystals is 144mm³, which was selected based on the dimensions of the original rectangular shaped crystal with dimensions of 3.0x3.0x16.0mm³, (Table I and Fig. 4). Two surfaces were simulated: one where all the crystal faces are polished and another where all the faces are non-polished, which is also named “as-cut.”

<table>
<thead>
<tr>
<th>Crystal ID</th>
<th>Slanted Angle (degrees)</th>
<th>Length Long Side (mm)</th>
<th>Length Short Side (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>165°</td>
<td>21.60</td>
<td>10.40</td>
</tr>
<tr>
<td>2</td>
<td>145°</td>
<td>18.14</td>
<td>13.86</td>
</tr>
<tr>
<td>3</td>
<td>120°</td>
<td>16.87</td>
<td>15.13</td>
</tr>
<tr>
<td>4</td>
<td>90°</td>
<td>16.00</td>
<td>16.00</td>
</tr>
</tbody>
</table>

Table I. BGO CRYSTAL GEOMETRIES
In all the simulations, 10⁴ isotropic emissions of optical photons from a point source were generated. Each photon was followed starting at the emission site within the scintillator crystal, up to its absorption or detection.

![Image](image1.png)

Fig. 4. Sets of four BGO crystals with dimensions showed in Table I. the slanted angle is shown in red.

The Unified model in GATE was used to define the surfaces between all the elements in the detector setup. The probability of micro-facet normals is proportional to a Gaussian of \( \sigma_\alpha \) given in degrees. Where \( \sigma_\alpha \) is the standard deviation of the Gaussian distribution of micro-facets around the average surface normal, [8]. In the case of polished surfaces, \( \sigma_\alpha \) was set to 1° with a ground finish. Therefore, this surface is flat enough to be considered polished but it has a small level of roughness to make it closer to what the manufacture could deliver.

![Image](image2.png)

Fig. 5. Gate Micro-facet definition, [8].

B. Measurements

We obtained energy spectra from two sets of three BGO crystals with dimensions showed in Table I and crystal ID 1, 3, and 4. One set of crystals has all the faces highly polished and the other set has all the faces “as cut”. Crystals were covered in VM2000 reflector, except at the exit surface. All BGO crystals have the light exit face with dimensions 3x3mm² and the volume of the crystals is 144mm³. These crystals were coupled with optical grease to approximately the centre of a 7.15x7.875mm² die of a Philips digital-SiPM sensor (DPC-3200). Each die includes four pixels and each pixel consists of 3200 cells; the discharged cells are summed up on a pixel basis to produce the photon count value, [9]. The dSiPM was equipped with a readout board that provided the number of cells that are triggered per die. All measurements were acquired inside an environmental chamber providing a constant temperature \( \sim \) 19°C for the dSiPMs. Several measurements were performed with each crystal with a 15uCi \(^{22}\)Na source. The signal obtained for coincidence measurements, from the dSiPMs coupled to BGO crystal and LSO crystal respectively, was analyzed with MATLAB. Each coincidence measurement was acquired for 10 minutes to acquire enough counts for a good spectrum. Repeated measurements were performed re-coupling the crystals with grease each time, to make sure any differences in the spectra were not due to poor coupling to the dSiPM die.

III. PERFORMANCE MEASUREMENTS

A. Light Output Dependence on Scintillator Geometry and its Surface Treatment from GATE Simulations

The effects of the scintillator geometry and its surface treatment where evaluated by positioning a source at several locations along the height of the BGO crystals; data was acquired through GATE simulations and measurements.

In the case of Gate simulations, the percent of optical photons that reached the SiPM out of the 10⁴ optical photons emitted inside the BGO crystal was recorded. This percent takes into consideration a quantum efficiency of 20% assigned to the SiPM as a generic value. Therefore, in case of a perfect detector, the percent of light output should be \( \sim \) 5 times that mentioned in the simulations results.

B. Light Output Dependence on Scintillator Geometry and its Surface Treatment from Measurements

In the measurements, the number of microcells triggered in coincidence in both SiPMs was recorded (Fig. 3a). As the number of microcells triggered could be considered proportional to the energy deposited in that specific die (assuming that the low light output of BGO is not saturating the SiPM), a spectrum as the one observed in Fig. 6 was obtained in MATLAB using the signal corresponding to every location of the \(^{22}\)Na source.

![Image](image3.png)

Fig. 6. Example of spectrum obtained through our measurements and MATLAB analysis.
The centroid of each spectrum as well as its spread was calculated by (1) and (2) respectively. Both, centroid and spread were plotted versus the source location.

\[
\text{Centroid} = \frac{\sum (\text{counts} \times \text{number of microcells})}{\sum \text{counts}} \quad (1)
\]

\[
\text{Spread} = \frac{\text{mean} [\sum (\text{counts} \times \text{number of microcells})]}{\text{stddev} [\sum (\text{counts} \times \text{number of microcells})]} \quad (2)
\]

C. Index of Refraction for the coupling material between a BGO crystal and the glass envelope of the dSiPM

The effect of the index of refraction of the epoxy shown in Fig.1 was examined through GATE simulations. In this case, the polished 90° crystal geometry was used and the index of refraction was varied starting at 1.0 until the light collected at the SiPM reached a plateau.

IV. RESULTS

A. Light Output for Polished Crystals

From Fig. 7 and Fig. 8, the results show that the 90° geometry is not affected by the location of the interaction inside the crystal. On the other hand, a change in light output is visible in the slanted regions of the other three geometries with respect to the portion of the crystal with rectangular faces. It is also observed that the 120° slanted geometry offers the best overall light output.

Fig. 7. GATE simulation: Light collection as a function of the photon emission location inside the crystal. Position z=0 mm refers to the exit face of the crystal (see Fig1). Red: 90° geometry, Magenta: 120° slanted angle geometry, Green: 145° slanted angle geometry, and Blue: 165° slanted angle geometry.

Fig. 8. A measure of the energy deposited as a function of the position of the \(^{22}\text{Na}\) source with respect to the height of crystal. Position z=0 mm refers to the exit face of the crystal (see Fig1). Red: 90° geometry, Magenta: 120° slanted angle geometry, and Blue: 165° slanted angle geometry.

Regarding the spread of the centroid from the energy spectrums obtained through simulations, the slanted regions show higher spread.

B. Light Output for “as-cut” Crystals

In the case of “as-cut” crystals, the results from both GATE simulation and measurements showed that the scintillation photons generated further from the exit face are less likely to escape the crystal, (Fig.10 and Fig.11).

The measurements in Fig. 11 suggest a lower light output for the “as-cut” crystals respect to the polished crystals in Fig. 8, even when the photons are generated near the exit face of the BGO crystals. However, this effect was not observed through GATE simulations (Fig. 10). A possible explanation to this relies on the fact that at this point we do not have details regarding the roughness of our “as-cut” crystals. Consequently, the values used to model this surface in the Unified model are not accurate.
Fig. 10. Light collection as a function of the photon emission location inside the crystal. Position z=0 mm refers to the exit face of the crystal (see Fig1). Red: 90° geometry, Magenta: 120° slanted angle geometry, Green: 145° slanted angle geometry, and Blue: 165° slanted angle geometry.

Fig. 11. A measure of the energy deposited as a function of the position of the 22Na source with respect to the height of crystal. Position z=0 mm refers to the exit face of the crystal (see Fig1). Red: 90° geometry, Magenta: 120° slanted angle geometry, and Blue: 165° slanted angle geometry.

The spread of the centroid corresponding to the crystals with “as-cut” surfaces shows similar patterns to that of the polished crystals; the slanted regions show higher spread.

Fig. 12. Spreading of the spectrum centroid as a function of the position of the 22Na source with respect to the height of crystal, (from the data in Fig11): Position z=0 mm refers to the exit face of the crystal (see Fig1). Red: 90° geometry, Magenta: 120° slanted angle geometry, and Blue: 165° slanted angle geometry.

C. Energy Spectrums

In this section a sample of the spectrums obtained in our measurements is shown, (Fig. 13 and Fig. 14). Each of these figures includes a pair of spectra per geometry corresponding to two source locations ~7mm and ~ 15mm from the bottom of the crystals, represented by line and dots curves respectively.

In the case of the polished crystals (Fig. 13), the two spectra corresponding to the 90° geometry overlap, while a shift is observed in the slanted regions (source location ~ 15mm) with respect to the rectangular regions (source location ~ 7mm), which confirms the results observed in Fig. 8.

In the case of the as-cut crystals (Fig. 14), a shift is observed in all the geometry pairs, which confirms the degradation on light output observed in Fig. 11.

Fig. 13. Energy Spectrum, as a function of the position of the 22Na source with respect to the height of crystal: Position z=0 mm refers to the exit face of the crystal (see Fig1). Red: 90° geometry, Magenta: 120° slanted angle geometry, and Blue: 165° slanted angle geometry. Line: Source ~ 7mm from bottom of the crystals. Dots: Source ~ 15mm from bottom of the crystals.

D. Index of Refraction for the coupling material between a BGO crystal and the glass envelope of the dSiPM

The polished 90° crystal geometry was used in this simulation. Considering the ~5% and ~7.7% light collection corresponding to index of refraction equal to 1 and 2
respectively; the light output could be improved in ~ 30% by going from a value of 1 to 2 in the index of refraction.

![Graph](image)

Fig. 11. Effect of the optical coupling between BGO crystal and the glass envelope of the SiPMs on the light detected.

V. CONCLUSIONS AND FUTURE WORK

We have examined the effect of scintillator geometry, and its surface treatment as well as the index of refraction of the material used to couple the crystal (BGO) to the glass envelope of SiPM. In the case of polished surfaces both GATE simulations and measurements agree that a slight slanted geometry (120°) offers an advantage over conventional rectangular crystal shapes for light extraction. Crystals with “as-cut” (non-polished) surfaces displayed a degradation of the light output as a function of how far from exit face the interaction occurred. For “as-cut” (non-polished) scintillator crystals the geometry does not seem to provide a relevant difference (if any).

The coupling material used to couple the scintillation crystals to the SiPM detectors has an impact on the amount of light detected. For index of refraction in the range 1.0 to 2.0, the percent difference could be as high as 30%.

This work demonstrates that non-standard geometries could be a promising factor for extracting BGO scintillation light and crystals with all faces polished offer a benefit over crystals with all faces as-cut.

Future work could involve:

1. Obtain the optimum slanted angle for the polished surface case by Gate simulations.
2. Examine the variation on light output from several crystals with “identical geometry and surface treatment”.
3. Obtain details from manufacturer regarding the specific roughness of our crystal in order to simulate them accurately (parameters used by the Unified model).

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REFERENCES