Performance of Large BGO Arrays Coupled to SiPM Photosensors – Continued Study

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Abstract—Recently, several studies have been carried in order to determine potential capabilities of BGO scintillator crystals coupled to SiPM photosensor devices for PET and SPECT applications. The prior studies have been typically done on small size BGO samples. Despite the fact that timing capabilities for devices based on BGO are worse than those based in commonly used fast scintillators, such as LYSO and LSO, the price of BGO material is considerably lower and, thus, BGO could be an option for systems where the required scintillator volume is significantly higher.

In this report we present results of further studies using 12×12 SiPM arrays of the 3 mm C-Series SensL sensors, placed at a pitch of 4.2 mm, and coupled to the readout recording the 12 row and 12 column SiPM array signals. Two types of pixellated BGO crystals were tested: an array of 10×10 elements with 2.5 mm pitch and 10 mm thickness and an array of 30×30 pixels with 1.67 mm pitch but only 3 mm thick. A staggered depth-of-interaction (DOI) configuration was also evaluated using two layers of 2.5 mm pitch BGO pixels, with 10×10 (top) and 11×11 (bottom) elements with a total thickness of 20 mm. An energy resolution as good as 12% FWHM has been obtained. Our new results confirm that either single layer crystal arrays with pitch values as low as 1.67 mm or two staggered layers of 2.5 mm pitch could be well suited for PET applications, especially for large systems or low cost dedicated PET systems.

I. INTRODUCTION

RECENTLY, several efforts have been focused on the reintroduction of BGO based detectors in combination with Silicon Photomultipliers (SiPMs). These initial efforts suffered from poor photodetection efficiency and high noise resulting in poor signal to noise ratio (SNR) performance, in turn producing poor energy resolution results. Very recently due to a significant progress on SiPM technology, the performance parameters achieved in pilot studies approach the performance of systems with standard PMTs (and also performance parameters achieved in pilot studies) producing poor energy resolutions in the range of 12% FWHM. Moreover, the timing performance was also studied obtaining values below 1 ns using small cubic crystals (3×3×3 mm$^3$), but worsening to 1.33 ns with the 20 mm thick samples. These studies have been done so far on small size BGO arrays.

Despite the fact that timing capabilities for devices based on BGO are worse than those based in the commonly used scintillators, such as LYSO and LSO, the price of BGO is considerably lower than Lutetium based scintillators and, thus, it could be an option for systems where the required volume of scintillators is significantly high, as in the case of Nuclear Medicine scanners. Several other BGO advantages, such as high stopping power, high photoelectric event fraction, and no internal radioactivity, which is observed in the case of LSO and LYSO due to naturally occurring (2.6%) Lu isotope, have been pointed out by other authors. It is noticed that BGO can be interesting for specific applications where timing and/or rate capabilities are not crucial parameters. In this work we have considered three different large sized BGO configurations coupled to a new generation of SiPMs.

II. MATERIALS AND METHODS

In these studies we have used two types of BGO crystal arrays (Proteus, Ohio, USA) with different pitch coupled to C-Series 12×12 SiPM arrays from SensL (MicroFC-30035-SMT [6]), similar to those tested in the MindView project [7]. The microcell size of the SiPM array is 35µm and the pixel has an active area of 3×3 mm$^2$ with a pitch of 4.2 mm producing a total photosensor area of 49.2×49.2 mm$^2$ (53.4% active area).

Two types of pixellated BGO modules were tested. The first BGO configuration uses a crystal array of 10×10 elements with 2.5 mm pitch (10 mm thick), while the second one is a crystal array of 30×30 pixels with 1.67 mm pitch and 3 mm thickness. A staggered depth-of-interaction (DOI) configuration was also evaluated using two staggered layers of 2.5 mm pitch BGO pixels, with 10×10 (top) and 11×11 (bottom) pixels with a total thickness of 20 mm (Fig. 1). This configuration uses the relative offset method in order to test DOI capabilities of future PET detector modules based on BGO crystals.

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Fig. 1. Two pixellated BGO staggered layers coupled to the 12×12 C-series SiPM array from SensL through 1 mm thick acrylic spreader window. Pixels were polished and covered with ESR (Enhanced Specular Reflector, 3M™). The SiPM array is coupled to the BGO through 1 mm thick acrylic spreader window. Optical coupling was done by optical grease BC-630 from Saint Gobain (index of refraction of 1.47). The SiPM array was operated at a bias voltage of 29V, ~5V over the breakdown voltage. A special charge division network providing information for each row and column output of the SiPM array has been used. All these signals are transferred to custom analog to digital converter (ADC) boards. The ADCs have 12 bit precision and the integration time window can be varied from about 50 to 670 ns. For each event the number of digitized signals is 24 (12 rows + 12 columns) and a center of gravity algorithm used to determine the gamma ray impact position [8]. In order to avoid SiPM signal degradation and instability due to temperature changes [9][10], thermal control by air cooling was done, assuring a stabilized temperature within the photosensor area during the measurements (ΔT detector=0.5ºC). The temperature was stabilized at 20ºC for all the tests carried out with the 2.5 mm pitch BGO crystals, while the measurements carried out with the 1.67 mm pitch were carried out at both room temperature (no cooling, 29ºC) and at 6ºC to study the performance differences. In all these experiments we have used an extended 22Na source.

III. RESULTS

In order to select the proper integration time window of the ADC, since this can impact both the spatial and the energy resolution performance, initial tests were done with the 2.5 mm pitch BGO array. The energy resolutions for the 511 keV peak varied from 16% FWHM at 400 ns integration window to 14% at 670 ns. Due to the observed BGO pulse duration of about 1 microsecond, larger integration windows could even produce better values for the energy resolution. However, larger integration windows would deteriorate counting rate capabilities, by increasing the pile-up event rate. In Fig. 2 we show the measured 2D contour plot and energy spectrum for 400 ns integration window. The energy ratio of the 1274 to 511 keV peaks was on average about 2.45.

Fig. 2. 2D contour plot (left) of the 10×10 BGO pixel array 2.5 mm pitch, 10 mm thick for 400 ns integration window. Energy spectrum (right) for the pixel marked with a yellow box on the flood map.

A. 2.5 mm pitch, 10 mm thick 10×10 crystal array

The flood image and the profile of one column of the 10×10 BGO pixel array 2.5 mm pitch, 10 mm thick, is shown in Fig. 3, but at an integration time window of 670 ns. We obtained an averaged energy resolution of 14% FWHM, improved with respect to data obtained at 400 ns integration window. All pixels are well resolved including the corners.

Fig. 3. 2D contour plot (left) of the 10×10 BGO pixel array 2.5 mm pitch, 10 mm thick for 670 ns integration window. Profile (right) for the column marked with a yellow line on the flood map.

B. 1.67 mm pitch, 3 mm thick 30×30 crystal array

We have obtained flood maps for the 30×30 BGO crystal array of 1.67 mm pitch and 3 mm thick, at two different temperatures, namely 29ºC and 6ºC. The time integration window was also set to 670 ns. In Fig. 4 we depict the flood image of the 30×30 elements crystal array at 6ºC. As in the case of the 2.5 mm pitch array, all pixels are well resolved including those placed at the photosensor corners. The effect of temperature variations on the energy resolution is showed in Fig. 4 right. We have observed a worsening of the energy resolution from 12% FWHM at 6ºC to 17% at 29ºC for the 511 keV peak. That data acquired at 6ºC showed the photopeak energy distribution at higher ADC channels due to the increase in the gain (PDE) of the SiPM output signal when decreasing the temperature. We have also studied the temperature effect on the spatial resolution. In Fig.

Fig. 4. 2D contour plot (left) of the 30×30 BGO pixel array 1.67 mm pitch, 3 mm thick for 670 ns integration window. Profile (right) for the column marked with a yellow line on the flood map.
5 we show the profile of one column, marked with a yellow line in Fig. 4 left, at the two different temperatures (29ºC and 6ºC). In spite of the fact that all pixels are well resolved at both temperatures, the estimated spatial resolution (P/V) resulted on significant differences with respect to the temperature.

Fig. 4. 2D contour plot (left) of the 30×30 BGO pixel array 1.67 mm pitch, 3 mm thick for 670 ns integration window. Energy spectra for the pixels marked with a yellow square on the flood map at 6ºC (upper right) and 29ºC (lower right).

P/V values in the range of 6-7 were determined at 29ºC while these values improved to 8-11 at 6ºC. Notice that the measured P/V for the 1.67 mm pitch array at 6ºC are comparable to those we obtained for the 2.5 mm pitch array at 20ºC.

C. 2.5 mm pitch staggered arrays

Figure 6 left shows the flood image of the two staggered crystal arrays. On the right hand side the profiles of two adjacent rows, corresponding to different array layers, are plotted. The integration time window was also set to 670 ns. Both staggered layers are spatially resolved, suggesting an intrinsic resolution close or better than 1.5 mm. Moreover, Fig. 6 suggests the feasibility of discriminating between the two BGO layers, thus providing a discrete DOI of the detected events.

Fig. 5. Profiles for the column marked with a yellow line on the flood map of Fig. 4 and zoom in (bottom) to a centered region. Data are showed at two different temperatures: 6ºC (solid red) and at 29ºC (black pattern).

This DOI capability of the staggered configuration allowed us to obtain separated energy spectra for both layers. Figure 7 depicts the energy spectra for the DOI configuration for pixels belonging to the top and bottom layers. A 16% FWHM energy resolution was obtained for the top/entrance layer, slightly deteriorating to 18% for impacts taking place on the bottom layer. The degradation on the bottom BGO layer is due to scattered events in the top layer. Moreover, as there is no reflector on the entrance face of the bottom layer, some amount of light produced at the bottom layer can reach the top layer.

Fig. 6. 2D contour plot (left) of the 2.5 mm pitch staggered arrays with a total thickness of 20 mm for 670 ns integration window. Profile (right) for two adjacent rows marked with yellow lines on the flood map.

IV. CONCLUSIONS

In this work we have presented results of additional measurements with large (up to 5×5 cm$^2$) BGO crystal arrays coupled to 12×12 SiPM photosensors of the matching coverage. We have found that energy and spatial resolutions can be significantly improved by cooling down the SiPM photosensor area, reaching peak-to-valley ratios for the 1.67 mm pitch array at 6ºC comparable to those we found for the 2.5 mm pitch array at 20ºC. Energy resolution values as low as 12% FWHM at 511 keV has been obtained.

Fig. 7. Energy spectra in the staggered approach for pixels located in the bottom and top layer.

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DOI capabilities of staggered BGO crystal layers coupled to SiPMs photosensors have been also tested, allowing data discrimination in 20 mm thick BGO modules separated in two layers each 10 mm thick. The achieved good results were possible because of good BGO crystal material, low noise C-Series SiPM photosensors with additional cooling, but also due to our new high granularity optimized readout.

Our new results confirm the previous conclusion, that single layer crystal arrays with pixel sizes as low as 1.5 mm or staggered two layers of 2.5 mm pitch pixels will be well suited for PET applications, especially for large systems or in specific applications, such as low-cost dedicated PET systems, where timing capabilities might not be a crucial parameter. A human body PET covering a patient torso might be a realization example of a PET system where we could apply these detectors configurations. As sketched in Fig. 8, such an imager development would require a high volume of scintillation material, more than 700 detector blocks of 5×5cm². The dynamic Torso PET will be able to provide dynamic multi-organ correlations with exception of the legs that however could be imaged in the second bed position. When centered on the brain, the Torso PET will provide an order of magnitude higher sensitivity than standard whole body PET scanner from the PET/CT combo.

Fig. 8. Example of realization of a Torso PET imager.

Alternatively to the crystal BGO arrays, we plan measurements using monolithic scintillators, with lateral faces covered with white Teflon or ESR. These surface treatments would increase the amount of transferred light to the photosensor array when compared to black painted approaches.

REFERENCES


