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A LYSO crystal array readout by silicon photomultipliers as compact detector for space applications

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A B S T R A C T

Precise measurements of GeV range gamma rays help narrow down among various gamma emission models and increase sensitivity for dark matter searches. Construction of precise as well as compact instruments requires detectors with high efficiency, high stopping power, excellent energy resolution, and excellent angular resolution. Fast and bright crystal scintillators coupled with small footprint photo-detectors are suitable candidates. We prototyped a detector array consisting of four LYSO crystals where each crystal is read out by a 2x2 SensL ArrayJ60035 silicon photomultipliers. The LYSO crystals were chosen because of their good light yield, fast decay time, demonstrated radiation hardness, and small radiation length. We used the silicon photomultiplier arrays as photo-detectors because of their small size, simple readout, low voltage operation, and immunity to magnetic fields. We studied the detector performance in the energy range of interest by exposing it to 2–16 GeV particles produced at the Test Beam Facility of Fermi National Accelerator Laboratory.

1. Introduction

Precise measurements of high energy gamma rays are very important for dark matter searches, gamma ray bursts, and understanding the gamma ray emission models [1–3]. The challenge however for these instruments is in how to improve precision while remaining small. To address this, deep and finely segmented detectors with excellent energy and angular resolution are needed. A deep detector can be achieved in the most compact manner by using high stopping power crystals, while small photodetectors help with fine segmentation.

In a previous paper [4], we examined the performance of the monolithic LYSO and $CeBr_3$ crystals readout by SensL 4x4 ArrayC30035 silicon photomultipliers (SiPMs) by irradiating them with low energy gamma rays. We found out they have potential as compact gamma ray detectors for use in space. In the current study, we built a mini-array consisting of four LYSO crystals where each crystal is read out by J-series SiPMs from SensL.

The emphasis of this work is on the performance of the detector when exposed to high energy positrons produced as secondary particles at the Fermi National Laboratory Test Beam Facility. The performance study serves as a milestone work towards full scale compact and granular electromagnetic calorimeters for space.

2. Setup

We constructed the detector prototype with four 16 mm x 16 mm x 40 mm LYSO crystals from EPIC-Crystal Co. and four 2x2 ArrayJ60035 SiPMs from SensL. The large number of micro-cells for this array of about 90 000 made it suitable for the desired large dynamic range. The LYSO crystals have proven to be radiation hard which is vital in a space environment. The LYSO crystal is characterized by a radiation length of ~1.2 cm, a decay time of ~40 ns, peak emission of ~420 nm, and a light yield of ~35 000 photons per MeV. We wrapped the LYSO crystals with Teflon tape and light proof black tape. We developed our own custom readout board based on the recommended readout from SensL but decreased the feedback resistance to 120 Ω to increase the dynamic range [5]. Fig. 1 (Top-Bottom) shows a photograph of the readout board and the crystals on top of the board respectively. We used a 3D printer to construct the mechanical enclosure for the whole detector. A neutral density filter with 10% transmission was inserted between the crystals and SiPMs to maintain operation in the dynamic range of transimpedance amplifier. The bias voltage of the SiPMs was set at 26 V all throughout our analysis. A DRS4 data acquisition board was used to capture the whole waveforms from the readout circuit [6]. To keep the signals in the dynamic range of the DRS4 board, 10 dB attenuators were used before the DAQ chain. The detector was placed

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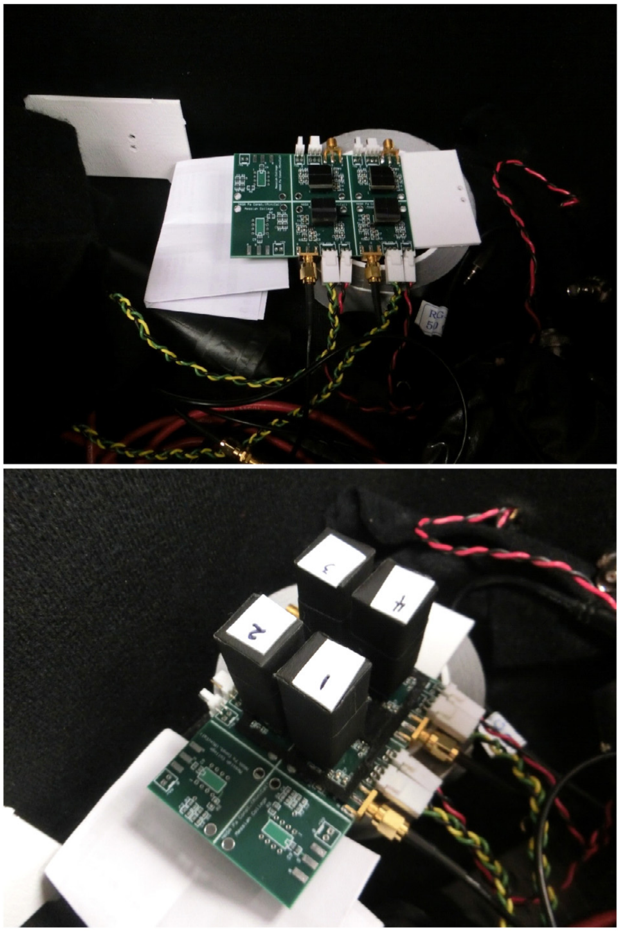

Fig. 1. (Top) custom readout circuit board with four SiPM arrays (Bottom) readout board with LYSO crystals on top of SiPMs.

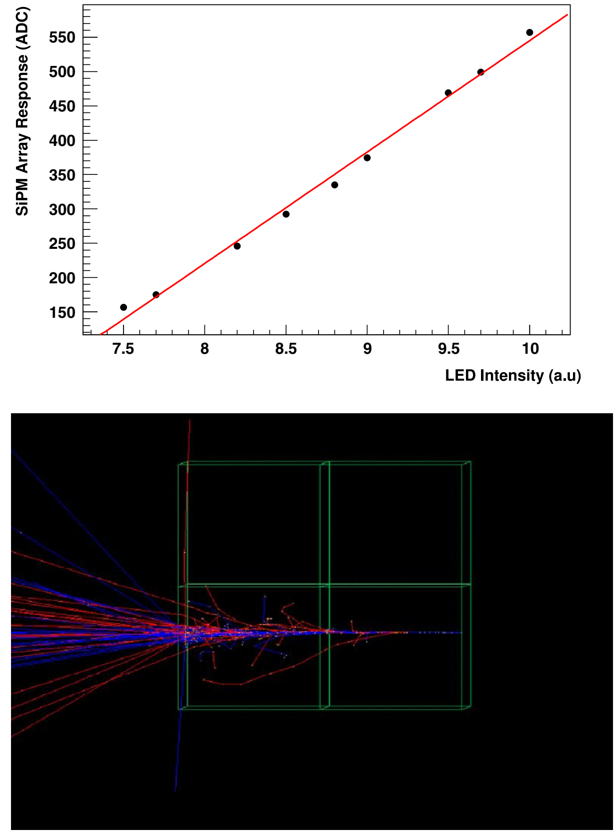

Fig. 2. (Top) SiPM arrays response to varied intensities of the CAEN driver, (Bottom) a Geant4 simulation of a 8 GeV positron in our detector as viewed from the top.

in the line of the Fermilab's Test Beam Facility (FTBF) [7]. The primary beam at FTBF is comprised of 120 GeV protons and by tuning a target and dipole magnets a momentum selectable beam of secondary particles is achieved. This beam consists of positrons, pions, kaons, and muons and we used the beam in the energy range 2–16 GeV. The trigger included three scintillator counters and a Cerenkov counter upstream of our detector with pressure tuned for positrons.

3. Results and analysis

3.1. LED runs

The large capacitance of the SiPM array made it difficult to extract single photon spectra directly due to pick up noise. Therefore the single photoelectron contribution of ∼0.33 ADC was calculated from the feedback resistor in the transimpedance amplifier, and the manufacture's parameters for this particular SiPM. We checked the linearity of SiPMs by using the SP5601 LED Driver from CAEN where we varied the driver's intensity and measured the SiPM array response. Fig. 2 (Top) shows a reasonably linear behavior indicating that in the expected signal ranges of our detectors we do not expect SiPM saturation effects to play a major role. The number of fired cells is much smaller than the maximum number of cells in this array.

3.2. Minimum ionizing particles & positrons

We used Geant4 [8] to simulate the energy loss of positrons, muons, and pions in our detector and found out that both pions and muons

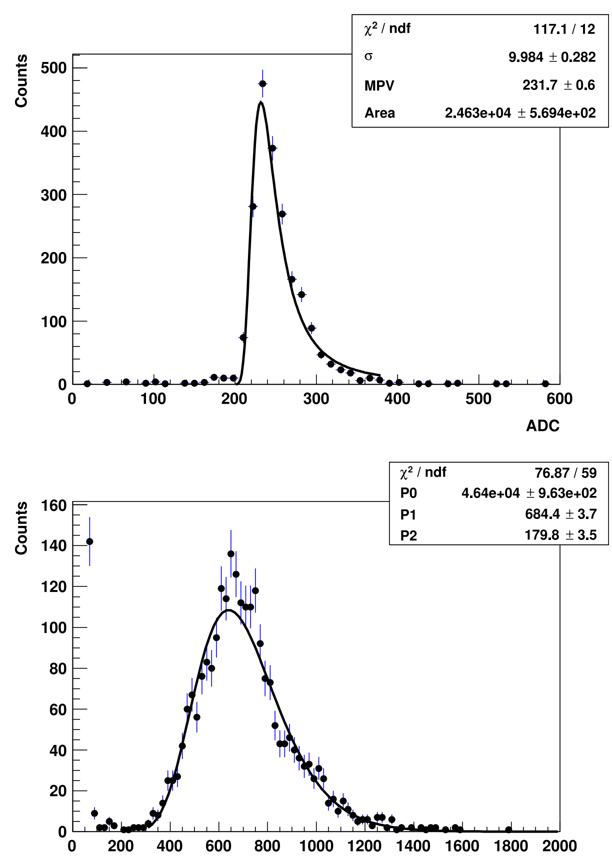

Fig. 3. (Top) ADC spectrum for the first crystal tower, (Bottom) ADC spectrum for the whole 2x2 array.

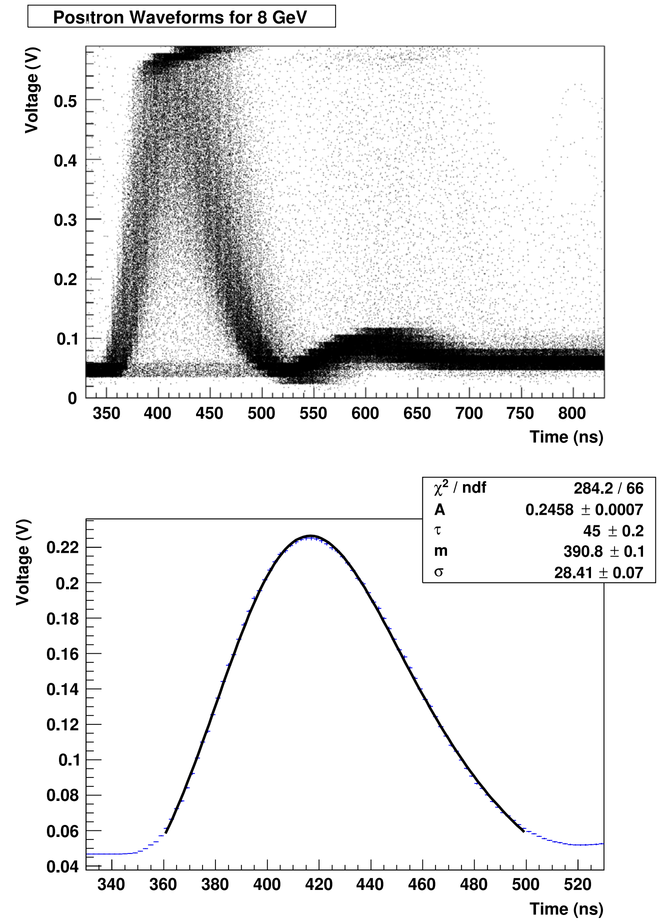

Fig. 4. (Top) mean ADC for different beam energies, (Bottom) waveforms for the crystal tower with the largest energy deposition.

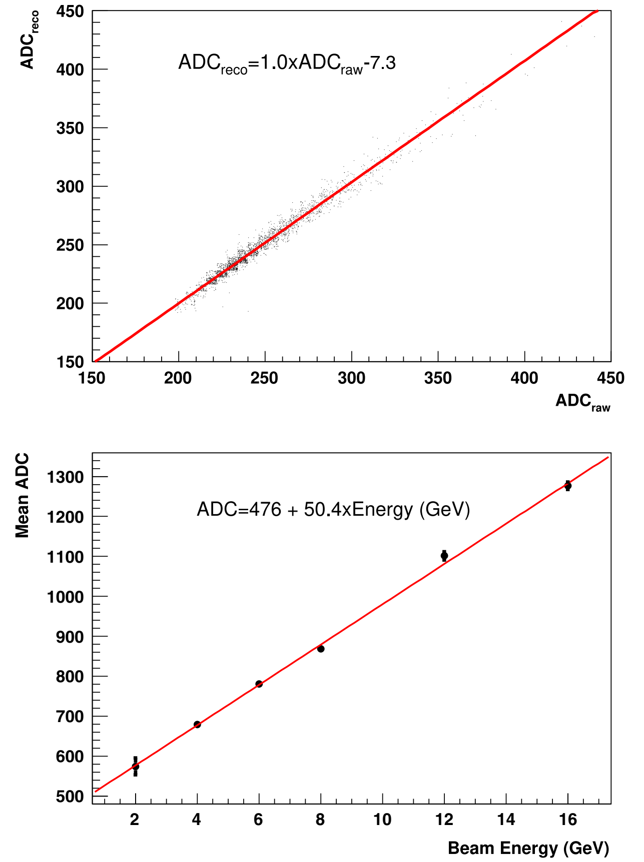

Fig. 5. (Top) scatter plot of reconstructed amplitudes from the fit versus the raw amplitudes from the pulses, (Bottom) reconstructed ADC counts versus the energy of the positron beam.

are minimum ionizing particles (MIPs) in the energy range considered: for MIPs ~69 ADC, and Pedestal is ~49 ADC. From Geant4 and MIPs spectrum we got the calibration constant of ~1.8 ADC per MeV energy deposited. Fig. 2 (Bottom) shows the simulation of an 8 GeV positron where the shower is mostly in the first crystal and the second crystal (the crystal behind). The second crystal tower is further along the particle path and therefore has larger energy deposition as expected. ADC spectrum for 4 GeV positrons is shown in Fig. 3 (Top-Bottom) for the first crystal tower where the shower starts and the whole 2x2 array respectively. The ADC spectrum of the first crystal is fit using a Landau distribution while the total ADC spectrum of the array is fit using a Log Normal Distribution. The resolution of our detector array is $\sigma(E)/E$ ~26% at 4 GeV as calculated from Fig. 3(Bottom).

As the energy of the particle beam was increased to 8 GeV we observed saturation effects in the second crystal tower as shown in Fig. 4 (Top). We identified that the saturation effects were due to limited amount of current (50 mA) that transimpedance amplifier can source or sink. We examined the possibility of recovering these saturated pulses by fitting with a predefined pulse shape. Initially, a profile of waveforms from unsaturated pulses is fit with variety of mathematical models and the best model is an exponentially modified Gaussian distribution as follows:

$$P(t) = \frac{A\sigma}{\tau}\sqrt{\frac{\pi}{2}}e^{(\frac{\sigma^2}{2\tau^2}-\frac{x-\mu}{\tau})}erfc(\frac{1}{\sqrt{2}}(\frac{\sigma}{\tau}-\frac{x-\mu}{\sigma})), \quad (1)$$

where A is the amplitude of the signals, τ is exponential component, μ is the mean of the Gaussian component, and σ is the width of the Gaussian component. Fig. 4 (Bottom) shows pulses and the exponentially modified Gaussian distribution. The non-saturated data points only were used to extract the fit parameters for the saturated pulses. In order to evaluate the fit performance we plotted the reconstructed amplitude versus the actual amplitude for the pulses from a non-saturated channel. As seen in Fig. 5 (Top) there is a strong correlation well described with this function $A_{reco} = 1.0A_{raw} - 7.3$.

A linear relationship is observed across the 2–16 GeV beam energies as shown on Fig. 5 (Bottom), where the mean ADC (counts) = 476 + 50.4x Energy (GeV). Neglecting the SiPM microcell saturation, the light yield for the energy ranges 2–16 GeV is from ~1700 to ~3900 photoelectrons respectively.

In order to scale the detector up to sizes that contain GeV energy gamma showers and have a reasonable geometrical factor, we simulated the performance of a calorimeter with dimensions of 60 cm x 60 cm x 30 cm and mass of ~500 kg constructed similarly to our prototype with small dead space for SiPMs in between. We found the resolution parameter $\sigma(E)/E$ ~1.5% for gammas with energy of 4 GeV which indicates potential for GeV range gamma ray astronomy. If a full scale calorimeter is constructed with the current readout scheme the dynamic range would be from about 30 MeV to 16 GeV, however the number of microcells in the SiPM arrays allows the dynamic range to be extended much further up by a better readout scheme.

4. Conclusion

A compact detector with LYSO crystals and SiPM arrays for readout was constructed and tested at Fermilab Test Beam Facility using positrons in the 2–16 GeV energy range. In addition to three scintillator counters a Cerenkov counter was used as a trigger to increase the purity of our positron beam. Positrons deposit much more energy compared to pions, kaons, and muons of the same energy in our detector. We used a fast transimpedance amplifier for readout of SiPM arrays and a neutral density filter of 10% transmission was inserted between crystals and SiPM arrays to operate in the dynamic range of the amplifier. The whole waveforms were recorded using the DRS4 evaluation board. Saturation effects were observed at 8 GeV in the crystal tower with the largest energy deposition which were due to 50 mA limit on the amplifier. Fitting the pulses however with an exponentially modified Gaussian proved to be a good fit and we recovered the amplitudes to 16 GeV. We observed a linear relationship between the measured ADC and the energy of the particle beam. The light yield in the energy range 2–16 GeV is from 1700 to 3900 photoelectrons, which is much smaller than number of microcells in the SiPM array, allowing room for exploration of a larger energy range with a carefully designed readout scheme. The resolution of our small detector array was ∼26% at 4 GeV, however simulations show a resolution of ∼1.5% at 4 GeV could be achieved when detector scaled up to a calorimeter with dimensions of 60 cm x 60 cm x 30 cm. This demonstrates potential for GeV range gamma ray studies.

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