

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

A. Kryemadhi^a, L. Barner^a, A. Grove^a, J. Mohler^a, A. Roth^a

^a*Dept. of Math, Physics, and Statistics, Messiah College, Mechanicsburg, PA 17055, USA*

Abstract

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.

Keywords: crystal calorimeter, silicon photomultipliers, GeV Gamma Rays

1. Introduction

Precise measurements of high energy gamma rays are very important for dark matter searches, gamma ray bursts, and understanding the gamma ray

Email address: akryemadhi@messiah.edu (A. Kryemadhi)

emission models [1–3]. The challenge however for these instruments is in how
5 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
10 LYSO and CeBr₃ crystals readout by SensL 4x4 ArrayC30035 silicon photomul-
tipliers (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.

15 The emphasis of this work is on the performance of the detector when ex-
posed to high energy positrons produced as secondary particles at the Fermi Na-
tional Laboratory Test Beam Facility. The performance study serves as a mile-
stone work towards full scale compact and granular electromagnetic calorimeters
for space.

20 **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
25 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 ~ 35000 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
30 from SensL but decreased the feedback resistance to $120\ \Omega$ to increase the
dynamic range [5]. Figure 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
 35 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 in the
 40 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
 45 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
 50 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 drivers intensity and measured the SiPM array response. Figure 2 (Top) shows a reasonably linear behavior indicating that in
 55 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
 60 in our detector and found out that both pions and muons are minimum ionizing particles (MIPs) in the energy range considered: for MIPs ~ 69 ADC, and

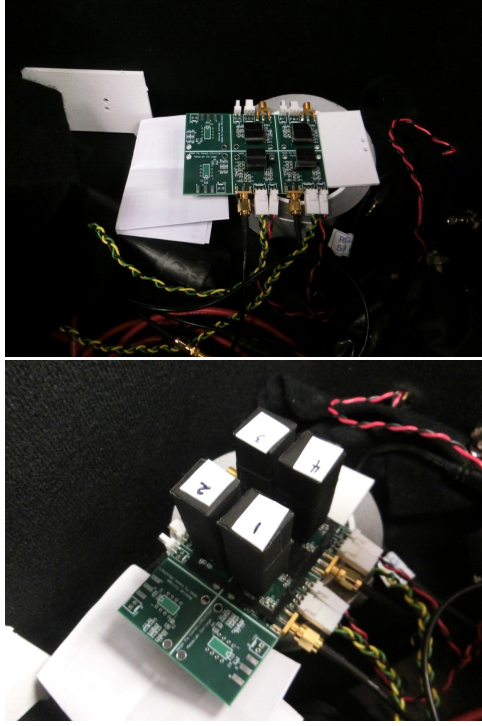


Figure 1: (Top) Custom readout circuit board with four SiPM arrays (Bottom) Readout Board with LYSO crystals on top of SiPMs.

Pedestal is ~ 49 ADC. From Geant4 and MIPs spectrum we got the calibration constant of ~ 1.8 ADC per MeV energy deposited. Figure 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 $\sigma(E)/E \sim 26\%$ at 4 GeV as calculated from Fig. 3(Bottom).

As the energy of the particle beam was increased to 8 GeV we observed

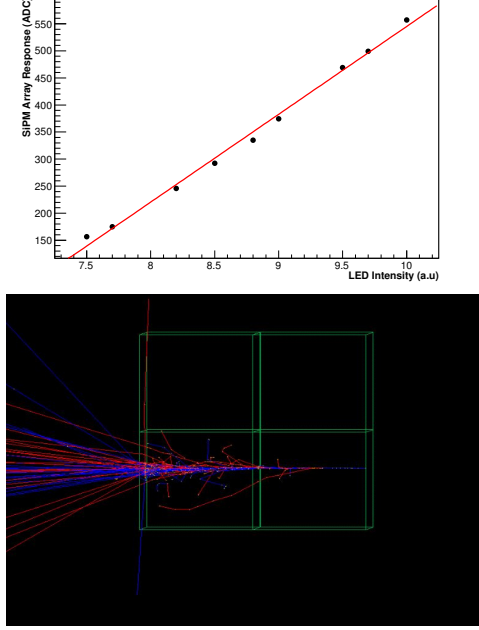


Figure 2: (Top) SiPM arrays response to varied intensities of the CAEN Driver, (Bottom) A Geant4 simulation of a 8 GeV positron in our detector as viewed from the top.

saturation effects in the second crystal tower as shown in Fig. 4 (Top). We
 75 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
 80 Gaussian distribution as follows:

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

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 compo-
 nent. Figure 4 (Bottom) shows pulses and the exponentially modified Gaussian
 distribution. The non-saturated data points only were used to extract the fit
 85 parameters for the saturated pulses. In order to evaluate the fit performance

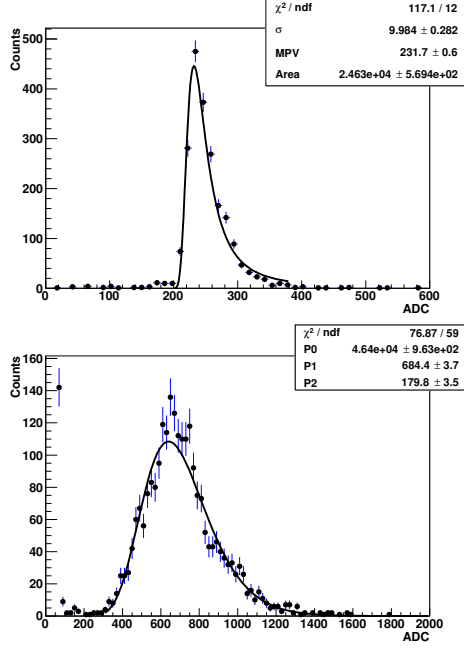


Figure 3: (Top) ADC Spectrum for the first crystal tower, (Bottom) ADC Spectrum for the whole 2x2 array.

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) = $476 + 50.4 \times \text{Energy (GeV)}$. 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 $\sigma(E)/E \sim 1.5\%$ 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

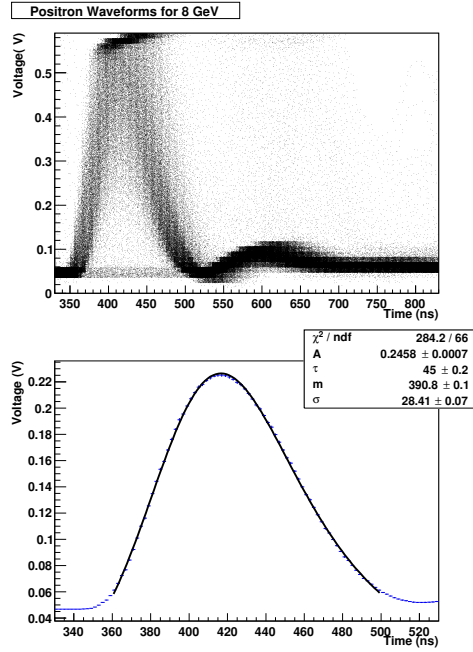


Figure 4: (Top) Mean ADC for different beam energies, (Bottom) waveforms for the crystal tower with the largest energy deposition

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

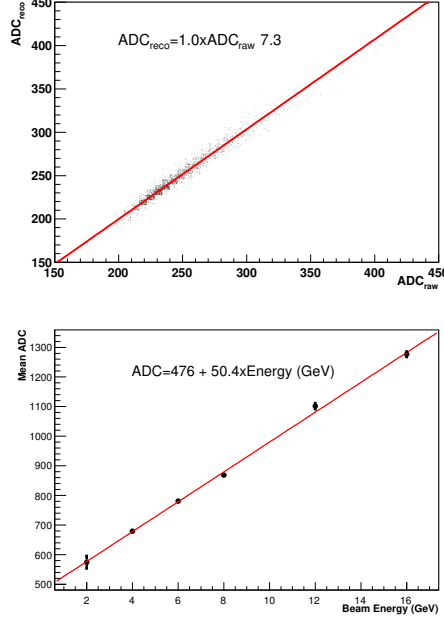


Figure 5: (Top) Scatter plot of reconstructed amplitudes from the fit versus the raw amplitudes from the pulses, (Bottom) Reconstructed ADC counts versus the energy of the positron beam.

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 $\sim 26\%$ at 4 GeV, however simulations show a resolution of $\sim 1.5\%$ 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.

125 5. Acknowledgement

We acknowledge NASA Pennsylvania Space Grant Consortium, Messiah College Scholar Chair Program, Fermilab Test Beam Facility, and this manuscript has been authored in part by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science,
130 Office of High Energy Physics. The United States Government retains and the publisher, by accepting the article for publication, acknowledges that the United States Government retains a non-exclusive, paid-up, irrevocable, world-wide license to publish or reproduce the published form of this manuscript, or allow others to do so, for United States Government purposes.

135 References

- [1] B. Degrange, G. Fontaine, Introduction to high-energy gamma-ray astronomy, *Comptes Rendus Physique* 16 (6-7) (2015) 587–599. doi:<https://doi.org/10.1016/j.crhy.2015.07.003>.
- [2] S. Funk, Ground- and space-based gamma-ray astronomy, *Ann.Rev.Nucl.Part.Sci.* 65 (2015) 245–277. doi:<https://doi.org/10.1146/annurev-nucl-102014-022036>.
140
- [3] J. Knudsen, The future of gamma-ray astronomy, *Comptes Rendus Physique* 17 (6) (2016) 663–678. doi:<https://doi.org/10.1016/j.crhy.2016.04.008>.
- [4] A. Kryemadhi, L. Barner, A. Grove, J. Mohler, C. Sisson, A. Roth, Performance of lyso and cebr₃ crystals readout by silicon photomultiplier arrays as compact detectors for space based applications, *Journal of Instrumentation* 12 (02) (2017) C02013. doi:<http://stacks.iop.org/1748-0221/12/i=02/a=C02013>.
145
- [5] SensL, J-Series User Manual, <http://www.sensl.com> (2017 (accessed August 10, 2017)).
150

- [6] S. Ritt, R. Dinapoli, U. Hartmann, Application of the drs chip for fast waveform digitizing, Nuclear Instruments and Methods in Physics Research A 623 (1) (2010) 486–488. doi:<https://doi.org/10.1016/j.nima.2010.03.045>.
155
- [7] M. Rominsky, Fermilab Test Beam Facility, <http://ftbf.fnal.gov/> (2017 (accessed August 10, 2017)).
- [8] S. A. et al., Geant4 a simulation toolkit, Nuclear Instruments and Methods in Physics Research A 506 (3) (2003) 250–303. doi:[https://doi.org/10.1016/S0168-9002\(03\)01368-8](https://doi.org/10.1016/S0168-9002(03)01368-8).
160