PERFORMANCE OF $PBWO_4$ CRYSTAL DETECTORS FOR A HIGH RESOLUTION HYBRID ELECTROMAGNETIC CALORIMETER AT JEFFERSON LAB

A. GASPARIAN

Department of Physics, NCA&T State University,
Greensboro, NC 27411, USA
E-mail: gasparan@jlab.org

(On behalf of the PrimEx Collaboration)

The PrimEx collaboration at Jefferson Lab is planning to perform a precision measurement of the neutral pion lifetime via the Primakoff effect. This will be a state-of-the-art experimental determination of the lifetime with a precision of less than 1.5%. Such a measurement requires an electromagnetic calorimeter with high resolution and high efficiency for detecting the photons from pion decay. A new electromagnetic hybrid calorimeter is under construction at Jefferson Lab consisting of 1200 lead tungstate ($PbWO_4$) crystal detectors and 600 lead glass Cerenkov modules. Recent beam tests were performed with few GeV electrons on the $PbWO_4$ crystals obtained from two different manufacturers (Bogoroditsk, Russia and Shanghai, China). Results from energy and position resolution studies, and the dependence of detector response on radiation rate are presented.

1. Introduction

The PrimEx Collaboration at Jefferson Lab (JLAB) is preparing to perform a high precision (1.4%) measurement of the neutral pion lifetime using the small angle coherent photoproduction of neutral pions in the Coulomb field of a nucleus, *i.e.*, the Primakoff effect[1]. This measurement will provide a fundamental test of the predictions of the axial anomaly in quantum chromodynamics. Photons from the Hall B photon tagging facility at JLAB will be used to produce neutral pions in the Coulomb field of a nucleus. At the incident photon energies of this experiment ($E_\gamma = 4.6 - 5.7$ GeV), the Primakoff cross section peaks at extremely small angles ($\theta_{peak} \simeq 0.02°$). In order to identify and extract the Primakoff amplitude, the experimental setup must have sufficient angular resolution for detecting forward produced pions. The pions will be identified by detecting the decay photons ($\pi^0 \to \gamma\gamma$) in the multi-channel electromagnetic hybrid calorimeter (HYCAL). Therefore, the angular resolution of the detected pions will depend strongly on both the position and energy measurement accuracies of the calorimeter. In addition, the kinematical constraints imposed by the knowledge of the initial photon energy provided by the tagging system results in an improvement of the angular resolution by about 30%[1].

Currently, we are constructing the HYCAL calorimeter (116 × 116 cm^2 area) consisting of two types of shower detectors: 600 lead glass Cerenkov modules located on the periphery of the calorimeter, and 1200 lead tungstate scintillating crystals in the central region with a hole (4×4 cm^2) in the middle for passage of the incident photon beam. In the past decade, $PbWO_4$ has became a popular inorganic scintillator material for precision compact electromagnetic calorimetry in high and medium energy physics experiments. The performance characteristics of the $PbWO_4$ crystals are well known mostly for high energies (>10 GeV)[2] and at energies below one GeV[3]. In this report, we are presenting results with few GeV electrons for the energy and position resolutions, as well as the dependence of the detector response on radiation rate. These measurements were done with crystals obtained from two different manufacturers: Bogoroditsk (BTCP), Russia and Shanghai (SIC), China.

2. Experimental Setup

In order to check the performance of the crystals and to select the manufacturer, we have done beam tests with a prototype detector. A 6 × 6 $PbWO_4$ crystal array (single crystal dimensions: $2.05 \times 2.05 \times 18.0$ cm^3) was assembled in a light-tight aluminum box maintained at a stable temperature of T = $5°C$. A front-view of the prototype calorimeter is shown in Figure 1. The upper

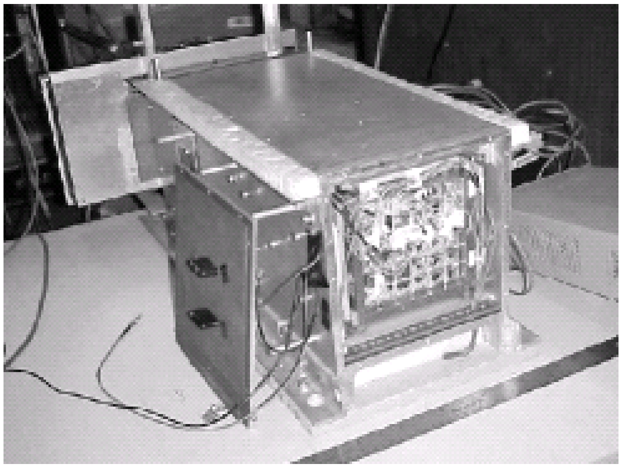

Figure 1. The prototype lead tungstate detector.

3×6 section of the array was assembled from crystals made by BTCP while the bottom section consisted of the ones made by SIC. The scintillation light from the electromagnetic shower in the crystals was detected with Hamamatsu R4125HA photomultiplier tubes (PMT) coupled at the back end with optical grease. Each crystal was wrapped with 100μm millipore paper which served both as a light reflector and as an optical isolator between the blocks. The anode signal from each PMT was digitized by means of a 14-bit charge-sensitive ADC (LeCroy 1881M, integration width=200 ns). The light yield of the crystal is highly temperature dependent ($\sim 2\%/^{\circ}$C). In order to keep the detector array at a very stable temperature, the crystal assembly was surrounded by thick copper plates with circulating coolants. Temperature stability at the level of $\Delta T = \pm 0.1^{\circ}$C was achieved during the entire period of data collection. Secondary electrons ($E_e \sim 4$ GeV) pair-produced by tagged photons in a thin radiator was incident on the crystal array. Signal from the PrimEx/Hall B pair-spectrometer system was used as the trigger for the data acquisition. For finer definition of the impact coordinates of the electrons on the crystal array, a pair of X-Y array of scintillating fibers with a fiber-width of 0.2 cm was used.

3. Energy Resolution

The energy calibration of the calorimeter was performed with 4 GeV electrons irradiating the centers of each crystal module. To measure the energy resolution, the centers of both the SIC and BTCP crystal arrays were irradiated and sufficient statistics was obtained. We found a slightly better energy resolution for the SIC crystals compared to those from BTCP. We attribute this to the relatively higher ($\sim 20\%$) light yield of the SIC crystals. For the final energy and position resolution, the central part of the prototype detector was irradiated with 2 and 4 GeV electrons. The reconstructed energy distribution for the 4 GeV electrons is shown in Figure 2 for three different calibrated ADC sums: the central module; the inner section comprising 3×3 array; and the total array of 6×6 crystals. The central module already contains $\sim 75\%$ of the total energy deposition. An excellent energy resolution of $\sigma_E/E = 1.3\%$ has been achieved by using a Gaussian fit of the line-shape obtained from the 6×6 array. After subtraction of the beam energy spread due to the finite size of the scintillating fibers, as well as multiple scattering effects in vacuum windows and in air, a level of 1.2% energy resolution was reached for 4 GeV electrons.

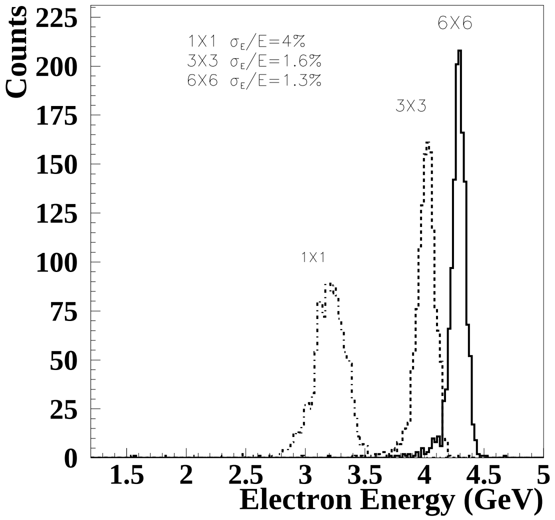

Figure 2. Energy response of a $PbWO_4$ crystal array to 4.25 GeV electrons. Left peak: single crystal; center peak: 3×3 array; right peak: 6×6 array.

4. Position Resolution

The impact coordinates of the electrons incident on the crystal array were determined from the energy deposition of the electromagnetic shower in several neighboring counters. In the case of the $PbWO_4$ crystals, the transverse size of the shower is about two times smaller than that in lead glass. As a result, the position resolution in the $PbWO_4$ detector with an optimal cell size should be about twice smaller than that of lead glass detectors. To maximize the position resolution, we have optimized the crystals' transverse dimensions, and have selected it to be 2.05×2.05 cm^2. This size is comparable to the Molière radius (2.2 cm) of the crystal material.

The distribution of the reconstructed coordinates for 4 GeV electrons hitting a crystal cell boundary is shown in Figure 3. The linear dependence of the reconstructed coordinates obtained from a logarithmically weighted average of the cell signals *versus* the impact positions determined by the fiber scintillator detectors is shown in Figure 4. As is well known, there is a rather strong correlation between the position resolution (σ_x) and the point at which the incoming electrons (or photons) hit the detector face. The bottom plot of the figure shows this dependence for the $PbWO_4$ crystals. The σ_x is smaller (1.28

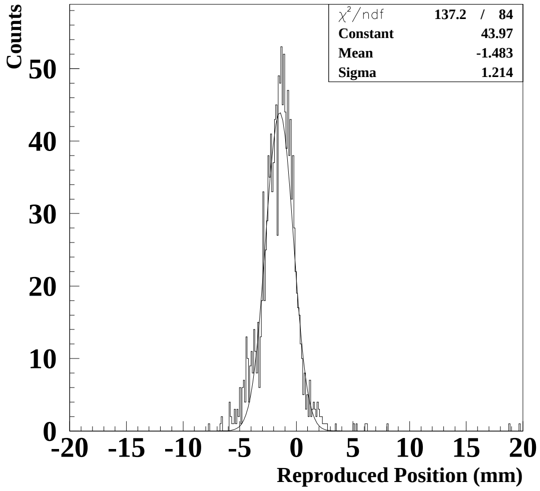

Figure 3. Distribution of reconstructed positions at the boundary between two lead tungstate crystal detectors.

mm) near the edge of the cell and increases to 2.1 mm at the cell center. These tests showed no measurable difference in the coordinate resolution for the two types of crystals produced by SIC and BTCP.

5. Detector Response *versus* Radiation Dose Rate

It is well known that all types of crystal scintillators are sensitive to integrated radiation dosage. In case of $PbWO_4$, one of the more important characteristics is the change in crystal response due to radiation dose rate. For crystals that were developed a decade ago, it was observed experimentally that even for a small dose rate ($\leq$ 1 Rad/hour), the gain changes were at the few per cent level. It was understood that this effect is not a result of the change of scintillation mechanism of the material, but the loss of light output due only to absorption by radiation-induced color centers[4]. A dramatic improvement of this effect has been achieved in recent years by both commercial producers of the crystals. We have done experimental studies of this effect for crystals produced in the past two years by SIC and BTCP. For these tests, several crystal centers were irradiated with 4 GeV electrons at different rates by changing the incident photon beam intensity and the radiator thickness. The duration

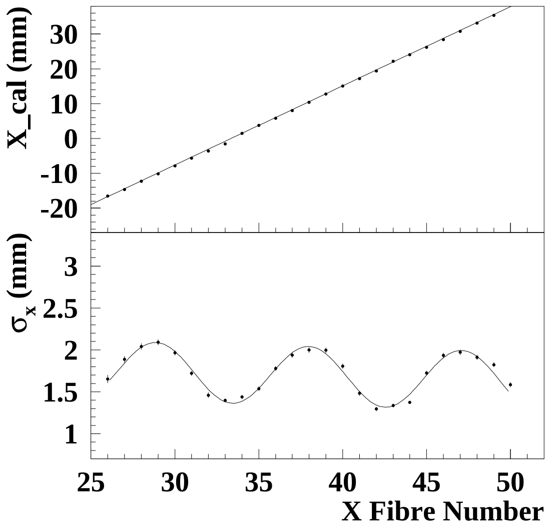

Figure 4. Reconstructed *versus* actual position (top) and position resolution (bottom) across the face of $PbWO_4$ crystal array.

of each irradiation was kept to about 30 minutes. The information from all channels of the 6 × 6 array prototype was recorded continuously during the irradiation process. Preliminary data of the normalized pulse-heights *versus* the relative beam rate for three typical crystals from each of the manufacturers is plotted in Figure 5.

It was observed that above the dose rate equivalent to 4 GeV electrons at ~ 50 kHz, the SIC and BTCP crystals show opposite behavior in detector response. This behavior could be caused by three different effects: (1) change of scintillation mechanism in the crystals; (2) change in the light transmission in the crystals; and (3) change in PMT gain due to rate variations. Currently, we are in the process of measuring performance of the PMT's at similar rates which will allow us to extract this contribution from the experimental data.

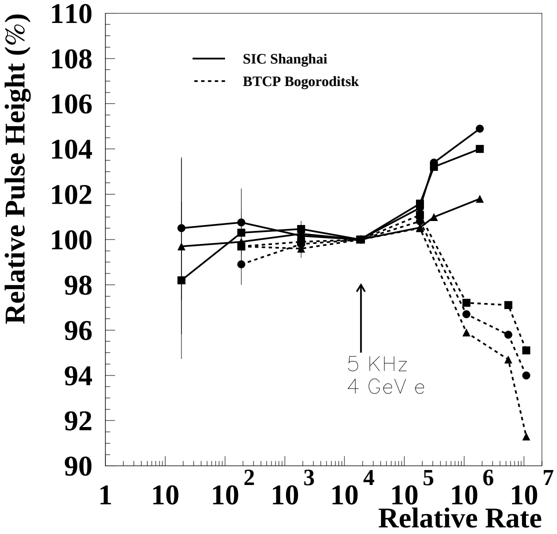

Figure 5. Relative pulse-height (preliminary) *versus* rate for SIC and BTCP $PbWO_4$ crystals. The location of the arrow indicates the dosage equivalent for 4 GeV electrons at 5 kHz obtained from GEANT simulations.

Acknowledgments

This project is supported by the National Science Foundation under a Major Research Instrumentation (MRI) grant (PHY-0079840).

References

1. PrimEx Conceptual Design Report, 2000 (http://www.jlab.org/primex/).
2. Compact Muon Solenoid Technical Proposal, CERN/LHCC 94-38, LHCC/P1 (1994).
3. K. Mengel *et al.* IEEE Trans. Nucl. Sci. **45**, 681-685 (1998).
4. R.Y. Zhu, *et al.* IEEE Trans. Nucl. Sci. **45**, 686-691 (1998).