Chinese Physics C Vol. 38, No. 11 (2014) 116004

Test of the LHAASO electron detector prototype using cosmic rays *

XU Tong-Ye(徐统业) DU Yan-Yan(都艳艳) WANG Xu(王旭) SHAO Ruo-Bin(邵弱宾)
ZHANG Deng-Feng(张登峰) ZHU Cheng-Guang(祝成光)[1]
(for the LHAASO collaboration)
MOE Key Laboratory for Particle Physics and Particle Irradiation, Shandong University, Ji'nan 250100, China

Abstract: The LHAASO project is to be built in south-west China, using an array of 5137 electron detectors for the measurement of incident electrons arriving at the detector plane. For quality control of the large number of electron detectors, a cosmic ray hodoscope with two-dimensional spatial sensitivity and good time resolution has been developed. The first prototype of the electron detector has been tested with the hodoscope and the performance of the detector is found to be consistent with the design.

Key words: electron detector, Hodoscope

PACS: 07.77.Ka, 29.40.Gx **DOI:** 10.1088/1674-1137/38/11/116004

1 Introduction

The Large High Altitude Atmosphere Shower Observation (LHAASO) [1] is about to be constructed in south-west China. An array consisting of 5137 electron detectors (ED) [2] is an essential part of this experiment. These detectors are used to count the number of incident electrons arriving at the detector plane and to measure the incident angle of the original cosmic particles arriving at the earth. To achieve the required measurement precision for the incident angle of the original cosmic particle, the time resolution of the ED must be less than 2 nano-seconds. In the design, the energy resolution for a single electron is required to be less than 25%. However, in the testing, the main particles are muons whose energy distributes from several MeV to several GeV, which makes the muon the minimum ionization particle. The energy loss per single electron is at least double of this figure, so the required energy resolution in the test is relaxed to $35\%(25\%\times\sqrt{2})$.

Since the ED is a large area (1 square meter) scintillation detector, the uniformity of the responses to a single incident particle(such as detection efficiency, photon yield and time measurement) over the whole sensitive area is very important for the precision of measurements and for problem finding. The uniformity of the ED responses should, therefore, be tested thoroughly.

To achieve an efficient and robust quality control test for the large number of EDs used in a limited duration of time, a large COsmic RAy Reference System (CORARS) was developed, making use of the cosmic muons arriving at the laboratory. The system is designed to provide more precise time and position information for the arriving cosmic muons than those that are achieved by the EDs. The time resolution, energy spectrum and detection efficiency for a single particle can be measured for eight EDs in one run, within 10 hours of a cosmic muon event accumulation.

The one-square-meter ED consists of 16 plastic scintillation blocks, each with a size of 25 cm×25 cm×1.5 cm and eight light fibers to transmit photons to a PMT (photomultiplier tube). After the first ED prototype was produced, it was tested with CORARS. The time resolution, detection efficiency and photon yield, and their uniformity, were measured and compared to simulation results, showing that the prototype meets the design requirements.

In Section 2 we describe the CORARS system, including the structure, the electronics setup, the DAQ (Data Acquisition) system, and the system calibration procedure. Section 3 is devoted to its application in testing the ED prototype, and the results of the measurements are given in Section 4.

2 Description of CORARS

2.1 The detector system

CORARS is 325 cm high and has dimensions of 120 cm×120 cm in the horizontal plane, as shown in Fig. 1. Four rectangular plastic scintillation detectors

---

Received 25 December 2013, Revised 24 March 2014

∗ Supported by NSFC (11075095,11375210) and Shandong Province Science Foundation (ZR2010AM015)

[1] E-mail: zhucg@sdu.edu.cn

©2014 Chinese Physical Society and the Institute of High Energy Physics of the Chinese Academy of Sciences and the Institute of Modern Physics of the Chinese Academy of Sciences and IOP Publishing Ltd

with dimensions 1.2 m×25 cm×7 cm are placed at the top and bottom of the system, for trigger generation and muon hit time measurements. A Thin Gap Chamber (TGC) [3], in the shape of an isosceles trapezium with an area of around two square meters, is placed on the layer adjacent to each scintillation detector layer for position measurement, with a resolution of around 1 cm. The volume between the two TGC layers is divided into layers, into which the detectors being tested are placed. The design allows for a maximum of eight EDs to be inserted simultaneously for testing.

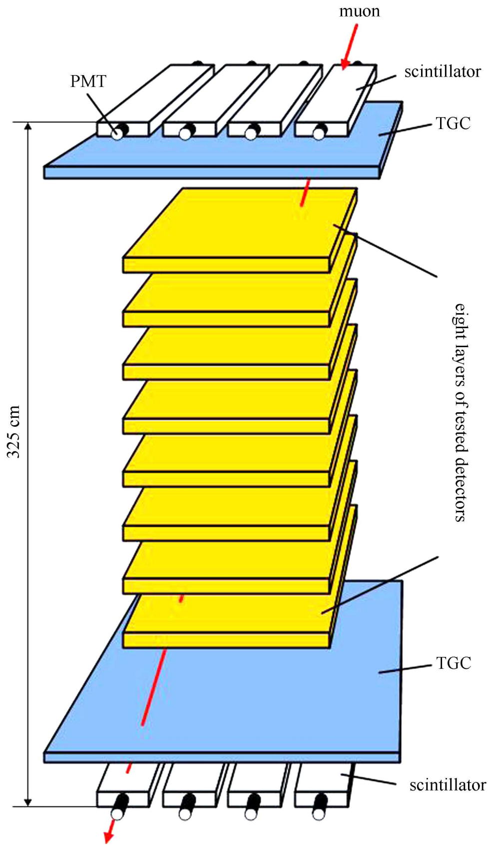

Fig. 1. (color online) Schematic layout of the detectors included in CORARS.

2.2 Electronics and DAQ

The analogue signals from the scintillation detector PMTs are discriminated by a Constant Fraction Discriminator (CFD). The NIM signal from the discriminator is then fed to a Time Digital Converter (TDC) for timing measurement. The four signals from the scintillation detectors on each layer are fed to an OR logic gate, and the outputs from the OR gates corresponding to the two scintillation detector layers are then passed to an AND gate to produce the trigger, as shown in Fig. 2. Because the trigger generation is constrained by the maximum time difference between the two OR gate outputs, we firstly measured the maximum time difference between the outputs of the two OR logic gates. We then set the widths of the output NIM signals from the CFD to be minimum (50 ns), which can effectively reduce fake triggers caused by noise.

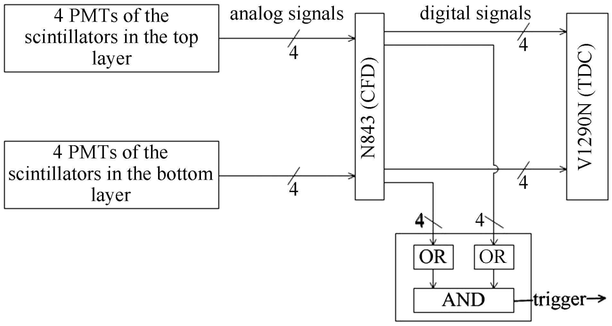

Fig. 2. The processing of the PMT signals from the eight scintillator detectors.

Two-dimensional spatial information on the incident muon is given by the TGC layers. On each TGC layer, 32 electronic channels are used for the X-dimension measurement and 32 channels are used for the Y-dimension measurement. The LVDS signals from the front-end electronics boards of the two TGCs are recognized and recorded by a 128-channel TDC module.

Once the system is triggered, the signals from the scintillation detectors and TGCs are read out, which happens at a rate of around 10 Hz at an altitude of about 50 meters. By reconstructing the muon tracks as straight lines, the particle hitting time and positions on the test layers are calculated.

For the detectors to be tested, the time and charge of the ED signals are measured. The ED signal is firstly fanned out into two identical analogue signals. One of these is sent to a charge-to-digital converter (QDC), with LSB of 100 fC. After a suitable delay, the other is sent to a CFD and then TDC for the time measurement.

A program has been developed using C# to collect and decode the raw data from the VME modules and then save in ROOT format. This software also does some rudimentary online data analysis to monitor the operation status of the system.

In order to eliminate the scintillation light propagation time offset in the scintillation materials due to the different hit positions, a timing calibration procedure was implemented. The sensitive area of each scintillation detector is divided into pixels of size 2.5 cm×2.5 cm, giving the required spatial sensitivity for the system. The mean time delay of every pixel relative to a selected reference point on the other scintillation detector plane was obtained. Although PMTs are mounted on both ends of the scintillation plastic, only one PMT is read out, due to the lack of electronics channels. The other PMT will be used for a system upgrade in the future. As a result of the one-sided detector readout, the time delay increases with the distance between the hit position and the PMT, as can be seen in Fig. 3. The width $\sigma_{\rm delay}$ of the distribution of the time delay for each pixel serves as a figure-of-merit for the time resolution of that scintillator pixel, as shown in Fig. 4. The $\sigma_{\rm delay}$ of most of the pixels (92%) is smaller than 700 ps. The pixels with $\sigma_{\rm delay}$ greater than 700 ps are mostly found around the end where the PMT is mounted. In order to obtain a better time resolution, these pixels were not used.

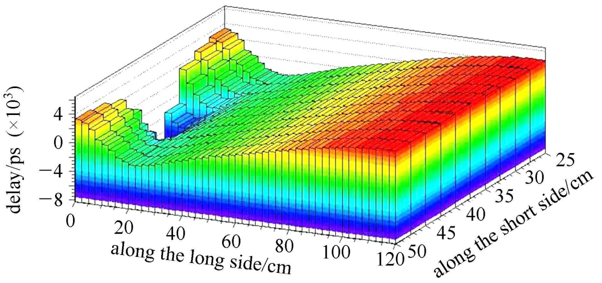

Fig. 3. (color online) The time delay distributions on one example scintillation detector relative to the selected calibration point.

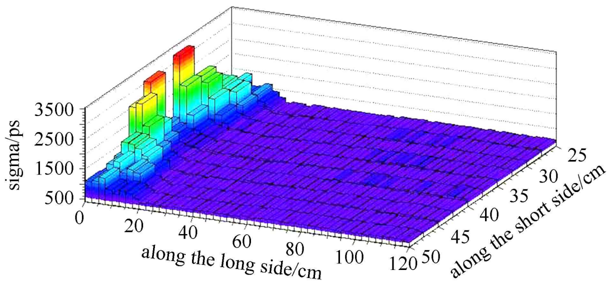

Fig. 4. (color online) The time resolution distributions on one example scintillation detector relative to the selected calibration point.

A test was then done to find the calibrated time resolution of each layer of the scintillation detectors. For a muon that passes through the entire detector system, the time of flight of that muon can be obtained using

$$tof_{\rm scin}=(t_{\rm btm}-t_{\rm top}),\tag{1}$$

where $t_{\rm btm}$ is the time when the muon hits the bottom scintillation detector layer, and $t_{\rm top}$ is the time it hits the top layer. The time of flight can also be obtained using

$$tof_{\rm dis}=d/v,\tag{2}$$

where d is the distance traveled by the muon between the top and bottom scintillator layers, and v is the velocity of the muon, which is assumed to be the same as the speed of light. Fig. 5 shows the distribution of

$$\Delta tof=tof_{\rm scin}-tof_{\rm dis},\tag{3}$$

and the width $\sigma_{\Delta\rm tof}$ of this distribution is 905 ps, with the main contributions coming from the time resolutions of the two scintillator layers. The resolutions of the two scintillator layers should be the same, so the time resolution of each scintillator layer after calibration is

$$\sigma_{\rm scin}=\sigma_{\Delta\rm tof}/\sqrt{2}\approx 640{\rm ps}.\tag{4}$$

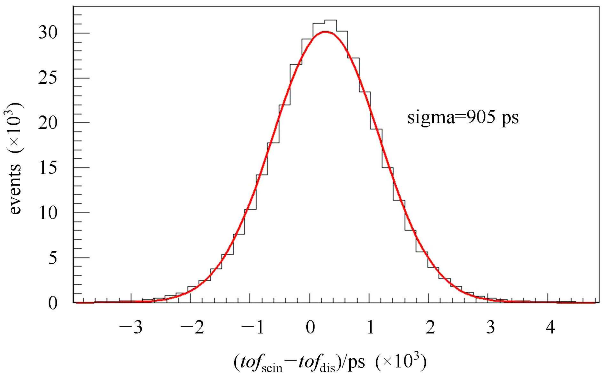

Fig. 5. The distribution of the differences between the time of flight measurements obtained using two methods.

3 ED prototype test

The performance of the first ED prototype was studied using this system. The method and the results are presented below.

3.1 Time resolution

Using the time $t_{\rm top}^{\rm initial}$ given by the top scintillator layer, $t_{\rm btm}^{\rm initial}$ given by the bottom scintillator, and the calibration constants of the scintillator detectors, the corrected hit time on the two scintillation layers

$$t_{\rm top}^{\rm corrected} = t_{\rm top}^{\rm initial}-t_{\rm top}^{\rm delay},\tag{5}$$

$$t_{\rm btm}^{\rm corrected} = t_{\rm btm}^{\rm initial}-t_{\rm btm}^{\rm delay},\tag{6}$$

can be obtained. The time when the ED is hit can then be reconstructed using the formula

$$t_{\rm ed}^{\rm reconstructed}=t_{\rm top}^{\rm corrected}+\frac{h}{H}\cdot(t_{\rm btm}^{\rm corrected}-t_{\rm top}^{\rm corrected}),\tag{7}$$

where H=325 cm is the vertical distance between the top and the bottom scintillator layers, and h=224.25 cm is the vertical distance between the top scintillator layer and the layer where the prototype ED is placed in the real test. On the other hand, ED also gives the time $t_{\rm ed}$ when it is hit by the muon. The time resolution of the ED can then be obtained from the width σ_Δ of the distribution of

$$\Delta=t_{\rm ed}-t_{\rm ed}^{\rm reconstructed}.\tag{8}$$

The histogram of this distribution is shown in Fig. 6, and σ_{Δ}=1805 ps is obtained, which has contributions from the time resolutions of both the ED and the CORARS system. According to Eq. (7), the time resolution $\sigma_{t_{\rm ed}^{\rm reconstructed}}$ is given by

$$\sigma_{t_{\rm ed}^{\rm reconstructed}} = \frac{\sqrt{(H-h)^2+h^2}}{H}\cdot\sigma_{\rm scin} \approx 487 \text{ ps}. \qquad (9)$$

The time resolution of the ED is then obtained as

$$\sigma_{\rm ed} = \sqrt{(\sigma_{\Delta})^2-(\sigma_{\rm ed}^{\rm reconstructed})^2} \approx 1740 \text{ ps}. \qquad (10)$$

In order to understand in more detail the uncertainties that contribute to the time resolution of the whole ED, the uniformity of the time walk effect and time resolution is scanned by dividing the ED area into 5 cm×5 cm pixels. The time resolution of each pixel is clearly less than 2 ns, but the time walk of each pixel, which is shown in Fig. 7, is not perfect. The calibration of the PMT transition time relative to photon injection position on the PMT window shows that the transition time is shorter in the center of the PMT window and longer at the edge. This shows us that the non-uniformity of the PMT transition time should be measured before a PMT is assembled into the ED.

3.2 Photo-yield and detection efficiency.

In this test, the charges of signals from the ED were measured. In the charge spectrum shown in Fig. 8, three peaks can be seen. The first peak is the electronic pedestal, the second peak is the charge from single-photon signals, and the third is the charge from single-muon signals. The mean charge of the pedestal is 9.3 pC, the mean charge of single-photon signals is 11.4 pC, and the average charge of single-muon signals is 46.6 pC. It can be calculated that an average of 17.8 photo-electrons are collected by the PMT when one cosmic muon passes through the ED; that is, the average photon-yield is 17.8 photons/muon. To fit the single particle charge spectrum with a Poisson distribution convoluted with a Gaussian function, we got the relative "energy resolution" as 26%.

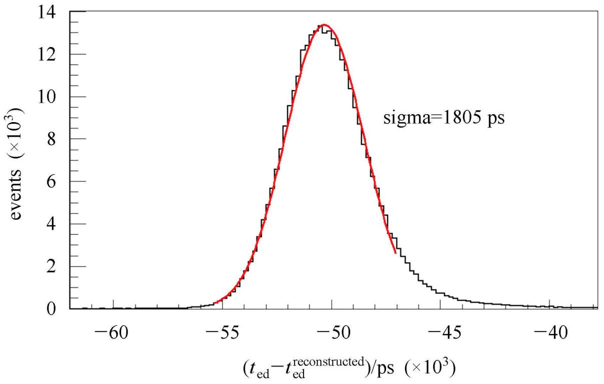

Fig. 6. The distribution of the differences between the ED measured time and the CORARS reconstructed time.

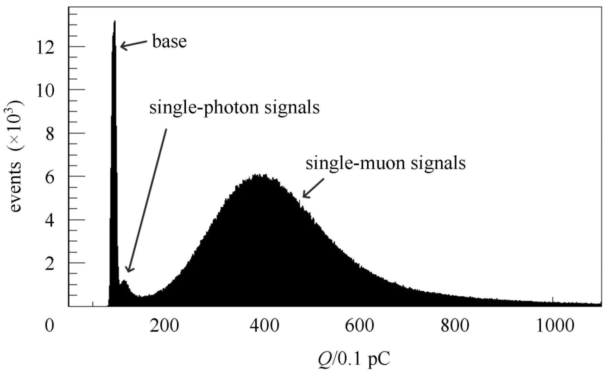

Fig. 8. The charge spectrum of the ED signals.

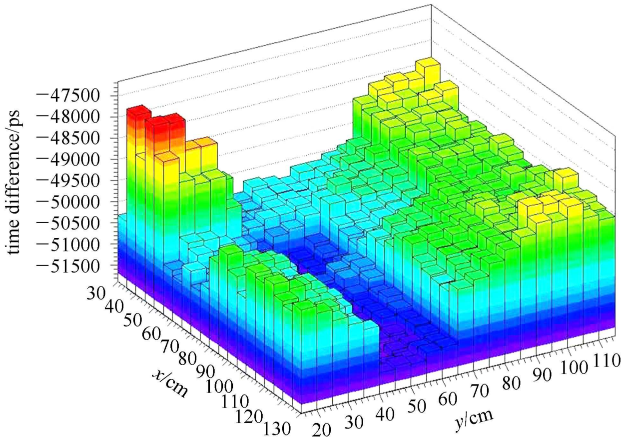

Fig. 7. (color online) The uniformity of the time walk relative to the trigger of each 5 cm×5 cm pixel of the ED.

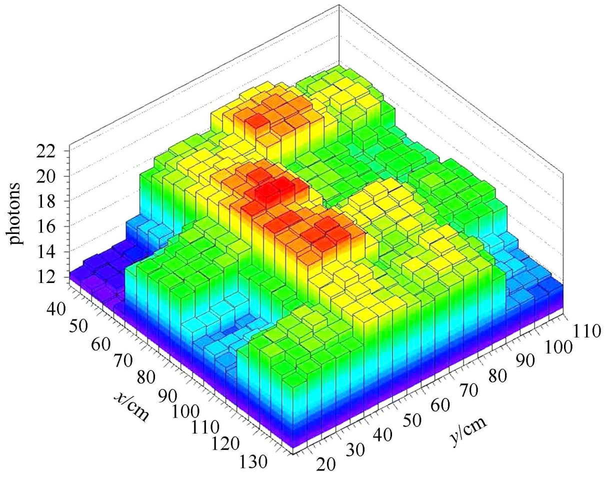

Fig. 9. (color online) The uniformity of the average photo-yield converted from the ED signal charge.

The photon-yield of each 5 cm×5 cm pixel of the ED was calculated and is shown on the right-hand side of Fig. 9, which shows the photo-electron collection efficiency differs between scintillation blocks, which can be explained by the non-uniformity of the PMT quantum efficiency over the whole PMT window. The scintillation block with lowest photon-yield is known to have one light fiber broken.

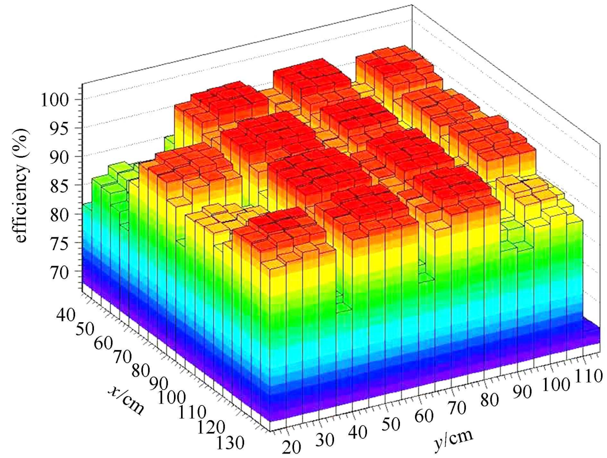

Fig. 10. (color online) The uniformity of detection efficiency of each 5 cm×5 cm pixel of the ED.

When a cosmic muon is confirmed by CORARS to hit the ED, the signal from the ED is checked. If the ED signal is present, this muon is considered as being detected by the ED, otherwise it is considered as being missed by the ED. The ratio of the number of events detected to the number of total events is the detection efficiency of the ED. An average detection efficiency of about 93.7% was obtained for the entire ED. The detection efficiency of each 5 cm×5 cm pixel was also calculated, and the result is shown in Fig. 10. This "lower" efficiency is partially due to the threshold definition of the electronic system, and can be adjusted later.

4 Summary

A CORARS system that has good time (~0.5 ns) and spatial (~1 cm) resolution has been built. It is clear that the scanning ability of CORARS is crucial in ED testing and problem finding, which is necessary for the quality control of a large quantity of detectors. The first ED prototype for the LHAASO project has been tested, showing good performance as designed. The time resolution is measured to be around 1.7 ns, which meets the design requirements. About 17.8 photo-electrons are collected on average by the PMT when a cosmic muon passes through the ED, which is consistent with the simulation results. The relative energy resolution is measured to be around 26%, satisfying the design. The mean detection efficiency of the entire ED is about 93.7%, which is lower than it should be due to the poor performance of a single scintillation block with a broken light fiber. We expect to obtain a higher efficiency in the future.

References

1 CAO Zheng Chin. Phys. C (HEP & NP), 2010, **34**(2): 249–252
2 ZHAO Jing, LIU Jia, SHENG Xiang-Dong et al. Chin. Phys. C, 2014, **38**(3): 036002
3 Atlas collaboration. ATLAS muon spectrometer: Technical design report, 1997. CEAN/LHCC/97-22