Design and optimization of the electromagnetic particle detector in LHAASO-KM2A

JIA LIU1, XIANGDONG SHENG1, JING ZHAO1 ON BEHALF OF THE LHAASO COLLABORATION

1Key Laboratory of Particle Astrophysics, Institute of High Energy Physics, CAS, Beijing, 100049, P.R. China

shengxd@ihep.ac.cn

Abstract: In LHAASO project, there will be 5137 Electromagnetic particle Detectors (EDs) used to detect the densities and arrival time of secondary charged particles in the extensive air showers (EASs). As one kind of scintillator detector, the design of ED and its optimization have been studied in detail, including the optimized sizes of the tiles based on two kinds of scintillator types and corresponding scintillation light readout modes, etc. In addition, the critical times of scintillator tiles and characteristics of the operating photomultiplier tubes (PMTs) are also presented, as well as the temperature coefficients and ripple indices of the candidate module power supplies. 60 new ED prototypes will be assembled and take data at YBJ in the future.

Keywords: scintillator tile, extensive air showers, electromagnetic particle detector, photomultiplier tube

1 Introduction

In the Large High Altitude Air Shower Observatory (LHAASO) project [1], the whole detector array will be built at Yabangjai (YBJ) valley of Tibet with high altitude of 4300m. As a main detector array, one square Kilometer extensive air showers (EASs) array (KM2A) consists of 5137 electromagnetic particle detectors (EDs, 15m spacing) and 1209 muon detectors (MDs, 30m spacing) distributing within the region with a radius of 560m [2]. Obtaining the highest sensitivity (1%ICrab) at the highest Gamma ray energy, it aims at the following targets, 1) the discovery of the Galactic CR sources; 2) the survey of the northern sky, exploring the origin of galactic cosmic rays; 3) the study of Cosmic ray physics, etc.

Now, as a kind of scintillator detectors and based on the requirements of KM2A sensitivity, each ED will have an efficient detection area with 1m×1m to measure the densities and arrival time of secondary charged particles (above 5MeV) in the EASs with time resolution less than 2ns and detection efficiency better than 95%. Considering the large dynamic range of the primary cosmic ray particles, as well as the sizes and their lateral distributions of EAS events, it is required each ED should measure the charged particle densities in a large dynamic range from 1 particle(25% in resolution) to 4000 particles(<5% in resolution) per meter square. To realize their long-term operation in YBJ environment (4300m, 0.6 atm., -25ºC to 40ºC), the critical time of two kinds of scintillator tiles and gain variation of the photomultiplier tube (PMTs) have also been concerned and studied, as well as the appropriate EDs’ inner structures and crusts, which should be water-repellent and easy to maintain.

An ED prototype array, consisting of 42 old scintillator detectors (used in L3C+Cosmics experiment), has been taking data smoothly at YBJ for about one year. Compared with the results from ARGO data analysis, the performances of ED array have been validated to achieve good angular resolution and fine stability. More physics results are being studied in detail [3].

New studies in the design of ED and its optimization have been done, mainly concerning the sizes of each scintillator tile and scintillation light readout modes, as well as the characteristics of the operating PMTs and module power supplies, etc.

2 Design of ED and its optimization

Scintillator detectors are applied widely to many present cosmic ray experiments in the world, such as ASγ experiment [4], YAC and L3C ones [5][6], where the scintillation tiles with different sizes are used as detection effective region to convert the deposit energies of the incoming charged particles into scintillation light and the light will be collected and transferred to one PMT’s photocathode with some wavelength shifting (WLS) fibers or an air guide. Based on the above detection and readout modes, to obtain new designs of ED, the following factors are focused on, such as the characteristics of scintillator tiles, optimized tiles’ sizes, readout modes (WLS fibers or air guide), the requirements of operating PMTs and its power supplies, as well as the crusts of ED,

Vol. 4, 338
etc. Here, the contents of electronics and DAQ system aren’t presented in detail.

Two kinds of Chinese scintillator products (their sample units are called tiles, light outputs are both about 40% Anthracene), KEDI type and ST-401 one, are chosen as the candidate detection materials, while three types of PMTs, Electron Tubes 9903kB type, HAMAMATSU R11102 type and PHOTONIS XP2012B one, are chosen to be candidate PMTs used in the ED design and its optimization. In addition, WLS fibers (BCF92, Φ 1.5mm) and Tyvek sheet (0.27mm thick) are applied to the whole tests, as well as certain kind of silicon oil and optical cement (BC600), etc.

To study the performance of scintillator tile detectors composed by the above components, a telescope was set up with 2 small scintillator tile detectors (called trigger detectors, 10cm×10cm×5cm each, 2 XP2012B PMTs are equipped in them) to choose the incoming singly charged relativistic particles (minimum ionizing particles (MIPs)). The signals from the PMTs are processed with an electronics readout system, which is based on one 9U VME crate, where one FEE modules with 16 channels are used to measure the charge and time message with the charge resolution of 20%@1pC and time resolution of 0.5ns.

Furthermore, a GEANT4-based simulation package has been developed, with which the corresponding simulation work can be done to deal with those corresponding processes occurring in scintillator detectors, including scintillation light generation, transmission, collection and its conversion into photoelectrons at the PMT’s photocathode. Since the simulation results are consistent with the tested ones, it benefits the whole good progress in the ED design and optimization greatly.

2.1 ED’s design with air guide

Some tiles with different sizes and scintillator types, such as 50cm×50cm×5cm (ST-401 type, old scintillator), 25cm×25cm×2cm (ST-401 type, new tiles) and 25cm×25cm×1cm (KEDI type, new tiles), are applied to the detector prototypes with the area of a quarter of 1m2 and an infundibular air guide of 60cm high, where the inner surface of air guide is smeared with a layer of Titanium dioxide(TiO2). Here, an XP2012B type PMT is operated with the gain of 4.72×10^6 at -1600V in the whole test processes.

To study the uniformity of the whole prototype, an old scintillator tile of 50cm×50cm×5cm are used. Scanning the different positions by moving the telescope on top of it (see Fig.1), the testing results presents that the average value of photoelectrons obtained by PMT is about 18 and the average time resolution is about 1.5ns, while their ratios of RMSs to the mean values are less than 5% and 8%, respectively. Although there is good uniformity similarly, the average values of obtained photoelectrons are about 7 and 3.8 for two new tiles with size of 25cm×25cm×2cm and 25cm×25cm×1cm.

Now, the simulation work are being done to optimize the design of this kind of scintillator detector with 1m×1m, including the suitable sizes of air guide.

2.2 ED’s design with WLS fibers

Here, the ED prototype will consist of 16 scintillator tiles (25cm×25cm each). The optimized design will depend on the following factors, 1) the concrete size of each scintillator tile; 2) the size and quantity of WLS fibers; 3) fiber placement in scintillator tile; 4) optical coupling modes between different components, such as Fiber-scintillator coupling and Fiber-PMT’s window coupling, etc.

In the experiments, the tested tiles are produced with different sizes. Concretely, their lengths are fixed, 25cm, for both KEDI type tiles and ST-401 ones. The widths are 5cm, 15cm, 25cm for KEDI type tiles, while it is 25cm for ST-401 type ones. As to the thicknesses of different tiles, they are 1.0cm and 1.5cm for all KEDI type tiles, while it is 2cm for all ST-401 type ones. Another typical difference between KEDI tiles and ST-401 ones is that each KEDI type tiles is with 5 or 8 holes-making (25cm×Φ 1.5mm each) in the middle of it, while each ST-401 type tile is with 8 grooves (25cm×1.6mm×1.8mm or 25cm×1.6mm×2.5mm each )) at its surface. These holes and grooves are set for the placements of WLS fibers.

With the telescope choosing the single incoming MIPs, the above tiles and others components, the studies of performances of ED with fiber readout mode have been done in further detail (see Fig.2).
The photoelectrons obtained by the PMTs and the corresponding time resolution are concerned. Here, three kinds of PMTs are used in the tests, while each tile is covered with a layer of Tyvek sheet. The testing results of one KEDI tile are shown at Fig.3.

![Fig.3](image)

**Fig.3** the distribution of amplitudes (left) (Landau distribution) of the tested tile (5cm×25cm×1.5cm) and time of flight (right) between one trigger detector and tested one in case of single particle.

The results show that the photoelectrons increase once the width of a tile become larger, but it increases slowly and the time resolution becomes a little worse once the width exceeds 15cm. So it is suitable for the width to choose 25cm in present design. Validated by the simulation results, the optimized depths are 1.5cm for KEDI type tiles and 2cm for ST-401 type ones, respectively. Three kinds of methods to increase the collection efficiency of the trapped scintillation light in WLS fibers (polished ends) are applied in the tests, 1) one end of each WLS fiber coated an aluminium layer; 2) one end of each WLS fiber glued with a piece of enhanced specular reflector (ESR); 3) bending a double long WLS fiber and placing it in the two neighboring grooves or holes. The light collection efficiency increases are obtained to be 35%, 80%, 90% from the operation of the above 3 methods, comparing with the ones with only end polishing WLS fibers. So the method 3) will be chosen to be applied in the ED design.

As to the effects of the coupling between WLS fibers and scintillator tiles with different materials, such as optical cement (BC600) and air, it shows that there is more than 40% increase in the coupling with BC600 in either the grooves or the holes. In addition, it seems there is a little superiority in the light collection efficiency to use deeper grooves. In the coupling between WLS fibers and scintillator tiles with air and BC600, respectively, the obtained scintillation light efficiency increases are about 20% and 10% by comparing 2.5mm deep grooves with 1.8mm ones. Furthermore, in the coupling between WLS Fibers and the PMT’s window, the scintillation light collection efficiency is 30% bigger with silicon oils than with air.

Based on the above detailed studies, two suitable ED designs are shown in Fig.4. Concretely, for the design of ED with KEDI type scintillator tiles, the tile’s size is 25cm×25cm×1.5cm and 8 holes (25cm×1.6mm×1.8mm each) in the middle. A total 4 WLS fibers (310cm long and Φ 1.5mm) will be placed in the 8 holes of tiles with air coupling. Here, the average value of photoelectrons obtained in 1st anode of the PMT is about 16 and the time resolution is about 1.8ns. For the design of ED with ST-401 type tiles, each tile size is 25cm×25cm×2cm with 8 grooves (25cm×1.6mm×1.8mm each). A total 4 WLS fibers (310cm long and Φ 1.5mm) will be placed in the grooves with air coupling. According to this design, the average value of photoelectrons obtained in 1st anode of a PMT is about 21 and the time resolution is about 1.8ns for each ED.

![Fig.4](image)

**Fig.4** Two designs of scintillator tile with WLS fibers (KEDI type tile (left), ST-401 type tile (right))

A telescope detection system has been designed to scan the scintillator tiles in batch. To keep good uniformity of each ED, every 16 tiles with almost the same amplitude will be picked up and assembled in one ED. A total 128 WLS fibers will guide the scintillation light to the photocathode of one PMT (ET9903kB type or R11102 one). All the above scintillator tiles, one PMT and one module power supply are packed in one aluminium/plastic water-repellent box. On the top of the box, a layer of LEAD convertor with 5mm thickness are used to increase the detection efficiency, which is beneficial to improve angular resolution and position resolution of the KM2A.

## 3 Critical times of scintillator tiles

Considering the concrete environment at YBJ site and long operation time of open-air LHAASO array, the long term stability of scintillator tiles are concerned seriously. So their lifetime or critical time have been being studied with two accelerated aging experiments [7], dynamic temperature variation aging experiment and thermal aging one [8] at Institute of High Energy Physics (IHEP) recently. Here, the critical time is defined to be the time when its light output has decreased by 20%.

In the dynamic temperature variation aging experiment, two kinds of scintillator tiles (KEDI type and ST-401 one) were put in a simulation environment box, where the temperature varied from -30°C to 40°C alternately. The tiles’ light outputs are measured every 90 times. There is an accumulative 480 times in total. Assuming the scintillator tiles had undergone two days in one alternation, it shows that the critical times are about 9 and 15 years for ST-401 type tiles and KEDI ones.

In accelerated thermal aging experiment, KEDI type tiles were conducted at three high temperature points, 60, 70, 80°C. For each temperature point, the light outputs of the tested tiles are measured every 50hours. Considering that the logarithm of the critical time is in inversely proportion to the temperature, an Arrhenius plot will be obtained. So the critical time at 20°C will be extrapolated...
from the plot. Here, it is about 9 years for KEDI type tiles, while the critical time of ST-401 ones at 20°C will be obtained soon.

4 Characteristics of the PMTs

The operating PMTs’ characteristics are related to the EDs’ capabilities, especially in the detection dynamic range and particle number resolution. The characteristics of XP2012B type PMTs, R11102 type and ET9903kB type ones have been being studied in detail [9].

For required PMT, its pulse linearity must cover 3.6 orders of magnitude to detect the particle density in a large dynamic range from 1 to 4000 per square meter. It is suitable for one ED to obtain about 16 p.e. collected at 1st dynode of the PMT when single incoming particle impinges on it, which is consistent with the expected design of the scintillator tiles. Further, total 64000 p.e. (4000 incoming particles) should be measured linearly by the PMT within 5% deviation. Here, the pulse linearity of three kinds of PMTs, R11102 type, ET9903kB type PMTs and XP2012B type, have been measured and are about 3.1, 3.3 and 3.0 orders, respectively. New efforts are being made to modify their dividers or realize dynode readout modes to obtain 3.6 orders.

A two-dimensional scanning system has been constructed and operated to study the PMTs’ uniformities. With a purple LED light source scanning over each tested PMT photocathode millimeter by millimeter, the position response of the photocathode is measured and it shows that the non-uniformities (the ratio of RMS to the mean amplitude) within a radius of 7.0mm of each PMT’s center are about 6.9%, 9.4% and 17.0% for R11102, XP2012B and ET9903kB types respectively. Based on them, the possible effects on the pulse amplitudes resolution have been estimated and proved to be eligible. Here, it is emphasized that the position response is mainly caused by the photoelectron collection efficiency due to focus electrode and electric field distribution inside the PMT.

The effect from the electromagnetic field on the gain variation of one PMT without any magnetic field has been studied in an elaborate experiment operated at IHEP. By rotating one XP2012B type PMT around the normal of the horizontal and its axis, the measured results show that the earth’s Magnetic fields (~0.5G in Beijing or Tibet) affect the gains of PMTs with a maximum variation less than 10% (see Fig.5).

The effects from the electromagnetic field of ET9903kB type PMTs and R11102 ones are being studied.

Another important factor to affect the gain of PMT is related to the power supply sources equipped with each PMT. Considering a large annual temperature variation (from -25°C to 40°C) and 0.6 atm. at YBJ site, for the operating module power supply, it is required that a temperature coefficient is less than 0.01%/°C and the ripple index is less than 0.1%. Thus the variation of each PMT Gain can be limited within ±5%. Three kinds of candidate module power supplies, TIANJIN LION type, Dongwen type and Centre type, have been studied in Hebei Normal university. All of their parameters meet the present requirements [10].

5 Conclusion and outlook

Some progresses have been made on the design of ED by now. The characteristics of scintillator tiles, operating PMTs and their power supplies have also been studied in detail. But more effort is still needed to realize the pulse linearity of PMT with 3.6 orders, as well as the final design of ED.

60 new ED prototypes will be assembled in half a year. The corresponding quantities of two kinds of scintillator tiles have been ordered, as well as the PMTs and power supplies. The testing systems have been installed and being operated in Shandong University and IHEP, Hebei Normal University, respectively.

New 60 EDs will cover the top of one MD and take data at YBJ. By recording the EAS events, some studies on their performances will be done.

Acknowledgments

The authors would like to express their gratitude to the ARGO Collaboration for the powerful support. This work is partly supported by the Knowledge Innovation Fund (H85451D0U2) of IHEP, Beijing.

[9] Chao Hou et al. LHAASO collaboration, 32nd ICRC, Beijing, 2011