# Design and performances of electromagnetic particle detector for LHAASO-KM2A *

ZHAO Jing(赵静)[1)] LIU Jia(刘佳) SHENG Xiang-Dong(盛祥东) HE Hui-Hai(何会海)
GUO Yi-Qing(郭义庆) HOU Chao(侯超) LÜ Hong-Kui(吕洪魁)
(The LHAASO collaboration)
Institute of High Energy Physics, Chinese Academy of Sciences, Beijing 100049, China

**Abstract:** In the Large High Altitude Air Shower Observatory (LHAASO) project, the one kilometer square extensive air shower array (KM2A) is the the largest detector array in terms of effective area. It consists of 5635 electromagnetic particle detectors (EDs) and 1221 muon detectors (MDs). Each ED is composed of 16 scintillator tiles readout by wavelength-shifting fibers that are bundled and attached by a 25 mm PMT. The design of the unit and its performances, such as photoelectron yield, time resolution and uniformity, are discussed in detail. An assembling scheme for the whole ED is established to guarantee the uniformity throughout all 16 tiles in a single ED and all EDs in mass production.

**Key words:** LHAASO, KM2A, electromagnetic particle detector, scintillator, uniformity

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## 1 Introduction

In the Large High Altitude Air Shower Observatory (LHAASO) project (Fig. 1) in China, a complex detector array will be built at high altitude (almost 4300 m a.s.l.). The LHAASO array consists of an extensive air shower array covering 1 km$^2$ (KM2A), four water chamber Cerenkov detector arrays covering 90000 m$^2$ (WCDAs), a shower core detector array covering 5000 m$^2$ (SCDA) and a wide field of view (FOV) Cerenkov/ fluorescence telescope array with 24 telescopes (WFCTA) [1]. With the highest sensitivity (1%$I_{\rm Crab}$) above 10 TeV and the highest gamma ray all sky survey power in the world, the LHAASO project aims at following three targets: 1) discovery of the Galactic CR sources; 2) discovery of numerous gamma ray sources in the energy range from several hundred GeV to 1 PeV by surveying the northern sky; 3) precise measurement of the cosmic ray energy spectrum and composition over a wide energy range from 5 TeV to 1 EeV by combining several cosmic ray detection techniques in the single project, etc.

KM2A, as the largest detector array of LHAASO in terms of effective covering area, is proposed to search for galactic gamma ray sources above 30 TeV in the northern hemisphere and study the primary cosmic rays in the energy range from 100 TeV to 100 PeV. It consists of 5635 electromagnetic particle detectors (EDs) and 1221 muon detectors (MDs) [2–4].

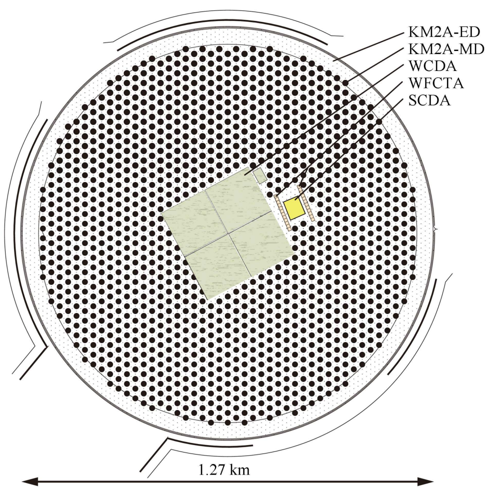


Fig. 1. The layout of LHAASO array.

The ED array is divided into two parts, a central part array and an outside ring for guarding the observed showers in the central part. 5341 EDs (15 m spacing) will be deployed in the central array in a circle with a radius of 560 m, while 294 EDs (30 m spacing) will be distributed in the guarding array encircling the central one. Once the extensive air showers (EASs) of cosmic rays arrive at the LHAASO site, the densities and arrival times

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1) E-mail: jzhao@mail.ihep.ac.cn

of the secondary charged particles in the fronts of the showers will be measured precisely by enormous number of EDs.

In order to provide basic guidelines for the design of KM2A to fulfill all requirements for very high sensitivity at high energies, a rather thorough air shower and detector simulation has been carried out. Many key factors, which are essential to guarantee the performance of the detector array and achieve all physical goals, have been validated in the detailed simulation study. Combining the simulation results and expertise on ground-based EAS detection at high altitudes for decades, we have optimized a baseline design of the ED. It is namely a plastic scintillator counter for passing through charged particles. The obvious advantages of this design are the following. First, a plastic scintillator is inexpensive and stable in the high altitude out-door environment. Second, the detector has a fast response to charged particles for high efficient counting of the numbers of particles and sufficient timing resolution. With the detecting efficiency higher than 95% of the charged particles in EAS, the ED has required timing resolution for the front of EAS as long as the effective area is not smaller than 1 m×1 m. To boost the detecting efficiency of secondary gamma rays in the EAS front, a layer of 5 mm lead is placed on the top of the ED as a convertor for the gamma rays to be detectable positron-electron pairs. Since a wide primary energy range from 10 TeV to 100 PeV needs to be covered, the ED has to have a very wide dynamic range spanning over four orders of magnitude. At the low energy end, the ED must be able to detect single particles with a resolution of 25%, while it is also able to measure 10000 particles with a resolution better than 5%. The arrival time of charged particles in the front must be determined to be better than 2 ns for reconstructing the geometrical orientation of the front. In addition, all EDs need to be uniform throughout the whole array within 10% to maintain an unbiased measurement of the EAS. In summary, all specifications of the ED play decisive roles in the detection efficiencies and reconstruction qualities of an EAS. They are crucial for the high sensitivity of KM2A.

## 2 ED unit design

In this section, the optimized design of the ED is described. Different plastic scintillator readout modes are used in many cosmic ray experiments, such as air guide readout (AS$\gamma$ experiment) and wavelength-shifting (WLS) fiber readout (YAC experiment [5]). After a study of the readout modes that are mentioned above, we find that WLS fiber is the best way to deliver the scintillation light to the equipped PMT and easy to get uniform detection and suitable time resolution over its whole effective area. Each ED consists of 16 independent scintillator tiles (25 cm×25 cm each) with wavelength-shifting fiber readouts, which are called “ED units”.

Once a minimum ionizing particle (MIP) passes through a scintillator tile, the energy deposited is about 2 MeV/cm. The scintillation light yield is in proportion to the energy deposit and the number of incoming charged particles. For EAS events induced by relatively low energy primary particles, the average density of secondary charged particles impinging on one ED is usually less than 1 MIP/m$^2$. The number of photoelectrons (p.e.) collected by the PMT's 1st dynode is required to be greater than 16 in the case of single particles. Thus the charge distribution of single particles follows approximately a Landau function, the sigma to most probable value (MPV) ratio is less than 25%. The ED's aging problem is mainly related to the critical time (the time when the light yield has decreased by 20%) of the scintillator. Considering the expected operating time of more than 10 years for KM2A, it is better for each newly assembled ED to obtain about 20 p.e.. Two kinds of domestically produced scintillators, ST-401 and HND-S2, are found suitable in our tests. They are selected for the ED prototype detectors and used in the experiments described in this paper.

### 2.1 Telescope system

A telescope system, with two small scintillator probe detectors (10 cm×10 cm×5 cm each, and one PMT XP2012B is equipped), has been set up to test the scintillator tiles, shown in Fig. 2. The two probe detectors work in coincidence mode to choose the incoming single MIPs and trigger the system. All signals from the detectors are transferred to the electronics and data acquisition system, which is based on one 9U VME crate. One FEE module with 16 channels is used to deal with the signals, where the signal arrival times are measured by FPGA-based TDC with a resolution of 1.56 ns and a jitter lower than 0.78 ns, while the signal charges are measured with the resolutions within 20%@1 pC and 1% above 5 pC.

### 2.2 Tile design optimization

As mentioned above, two kinds of scintillators are used for the tile design and their concrete properties are shown in Table 1. To optimize the light collection, the wavelength-shifting (WLS) fiber BCF-92 (1.5 mm in diameter, “core+ single cladding”, see Table 1) has been chosen because its absorption spectrum matches the emitting ones of the scintillators mentioned above. To hold the fibers in tiles steadily, eight grooves (3 cm spacing) are cut on one surface of the ST-401 type tile, while eight holes (3 cm spacing) are made in the middle of the HND-S2 type tile. The latter design aims at gaining light collection because the fiber in the middle of the tile has a bigger solid angle to receive the incoming light. Each tile is wrapped with a piece of Tyvek sheet (the 1082D, reflectivity is 92%).

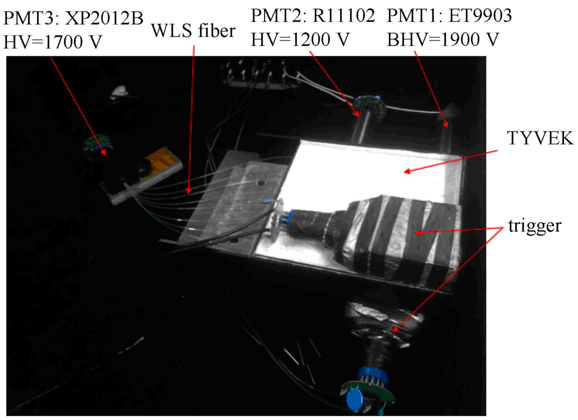


Fig. 2. The sketch map of the telescope system.

Table 1. Tables of the detector properties used in the simulation.

| scintillator | ST-401 | HND-S2 |
|---|---|---|
| H/C ratio | 1.0 | 1.1 |
| refractive index | 1.60 | 1.58 |
| scintillator yield (photons/MeV) | 8000 | 8000 |
| emission peak/nm | 418 | 420 |
| absorption length/cm | 200 | 244 |
| decay time/ns | 2.4 | 2.4 |
| WLS fiber (BCF-92) | | |
| core | | |
| refractive index | 1.60 | |
| emission peak/nm | 492 | |
| absorption length/cm | 350 | |
| decay time/ns | 2.7 | |
| diameter/mm | 1.38 | |
| cladding | | |
| refractive index | 1.48 | |
| diameter/mm | 1.50 | |

The detector simulation tool package GEANT4 [6] provides a convenient framework for the simulation of optical processes inside the tile. Based on this, a simulation package has been developed in this work to track the whole light collection processes once a single MIP passes through the scintillator tile. The quantity of scintillation light depends on the energy deposits, which is directly in proportion to the length of MIP's track in the tile. The light collecting efficiency depends very much on the optical properties of all materials used in the unit. Using the detailed simulation tool, all processes along the light paths are recorded and analyzed carefully. This helps the optimization of the design of the ED unit.

All required optical parameters of all the components mentioned above have been set normally in the simulation code. In this simulation work, single muons have the same incoming directions and hitting area as the ones selected with the telescope system at our laboratory (sea level). A standard electromagnetic process happens when a single muon hits the tile. The emitted scintillation photons undergo continuous light processes, such as photo transmission, bulk absorption, Rayleigh scattering, reflection and refraction at boundary and WLS process until they arrive at the cathode of the PMT at the other end of the fibers, where a photoelectric conversion occurs. It has to be pointed out that the light collection efficiency sensitively depends on the roughness of the tile surface and inside surface of the grooves or the holes [7]. Some parameters that describe the roughness of the scintillator surface have been presented here. The roughness index, $\alpha$, is 0.01 rad, while for the two main reflection modes, the percentage of specular spike is 70% and the one of specular lobe is 30%. Those parameters have been validated by the fine consistency between the simulation photon yields and the experimental ones in the tests of tiles attached to the PMTs directly.

The simulation work focuses on the design of the HND-S2 type tile. The tile size is 25 cm$\times$25 cm$\times$1.5 cm and eight holes are made in the middle, with eight WLS fibers (60 cm long each) embedded in the holes. The fiber end fixed in the tile is coated with a thin aluminium layer and the other end is connected to the PMT's cathode directly. As a MIP passes through the tile, about 24000 photons are produced along the track. Half of them may pass through the WLS fibers and about 40% of those photons in the WLS cores will be absorbed and re-emitted. As a result, the same number of photons with longer wavelengths will be emitted homogeneously in $4\pi$ solid angle. Only 8% re-emitted photons can be trapped in the cores because their propagations meet the requirements of total reflection and arrive at the cathode of the PMT. So it means that only $\sim$1.6% photons among all emitted photons in one tile can be received by the PMT's cathode in the case of single particles. Since the wavelengths of those photons reach the cathode range from 400 nm to 500 nm, an average quantum efficiency (QE), about 10%, is obtained at the cathode. Usually, 70% is set to be the average collection efficiency of one PMT when photons have wide incidence angles on the cathode [8]. Thus the average photoelectrons collected by the 1st dynode of PMT is about 27, which can meet the requirement indeed.

The length of a tile, paralleling the fiber holes, is one of the main contributions to the time resolution of the impinging particles that could hit any position along the fiber. The selection of 25 cm for the length is set to guarantee that this contribution is less than 2 ns [9]. In the simulation, the light yields in tiles with different widths are investigated with a fixed length (25 cm) and thickness (1.5 cm) and number of fibers per centimeter

(0.2/cm). The simulation results show that the obtained number of photoelectrons increases with the tile's width and it approaches stable once the width exceeds 15 cm. So it is suitable for each tile to have a width greater than 25 cm. The corresponding experimental results reveal a similar distribution. Both results are shown in Fig. 3.

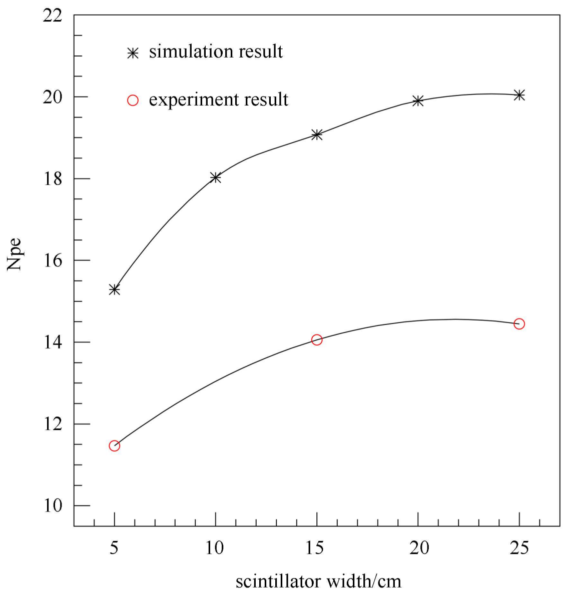


Fig. 3. The result of MIP signal vs. scintillator width. The tile's length and thickness are set to 25 cm and 1.5 cm respectively. The fiber density is 0.2/cm.

In Fig. 4, it shows that the number of obtained photoelectrons varies with the tile's thickness and the quantity of fibers. A tile with a thickness of 1.5 cm and eight WLS fibers could obtain more than 25 p.e.. As a summary, a HND-S2 type tile has the optimized size of 25 cm×25 cm×1.5 cm with eight fibers readout. Two kinds of HND-S2 type tiles are tested with the sizes of 25 cm×25 cm×1 cm and five fibers, 25 cm×25 cm×1.5 cm and eight fibers respectively, as shown in Fig. 4. It shows that there is about 30% decrease for the experimental values in both Fig. 3 and 4, which is attributed to the roughness of hole-making affecting scintillation light collection by the fibers. The technique of drilling the holes in the tile is still under development in order to solve all these problems.

At the same time, the design of ST-401 type 25 cm×25 cm×2 cm tile with eight grooves on its surface is found to be more stable and uniform. The average number of photoelectrons is about 25 in the case of single particles.

In fact, to obtain a better light collection efficiency, the shapes of grooves are also studied in detail. All tested tiles with optimized sizes and different groove shapes on the surface, are listed as follows, 1) 1.8 mm (depth)×1.6 mm (width), square bottom; 2) 1.8 mm (depth)×1.6 mm (width), round bottom; 3) 2.5 mm (depth)×1.6 mm (width), square bottom; 4) 2.5 mm (depth)×1.6 mm (width), round bottom. The experimental results are shown in Table 2. There is no distinct difference among these results and the non-uniformity (a deviation from the average over the units) is within 10%.

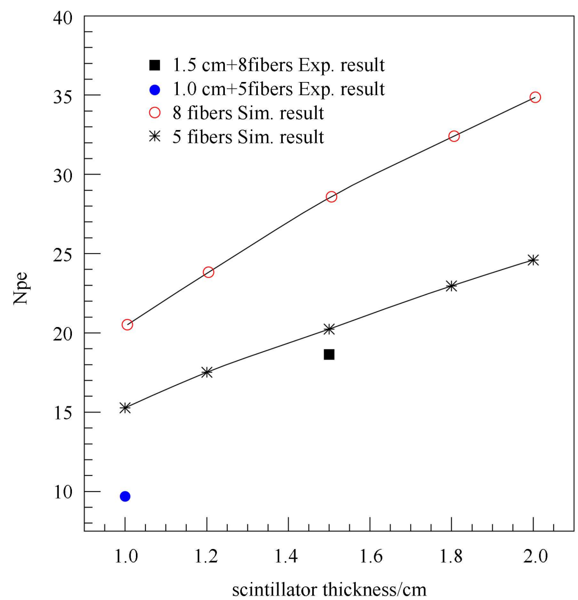


Fig. 4. The result of MIP signal vs. the thickness. The tile's length and width are set to 25 cm ×25 cm. The tile is wrapped with Tyvek.

Table 2. Comparison of different groove shapes.

| shape | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Npe | 25.05 | 22.32 | 24.85 | 24.39 |

Here, the ST-401 type tile with the size of 25 cm×25 cm×2 cm and eight grooves (1.8 mm (depth)× 1.6 mm(width), square bottom) on the surface has been chosen as the optimized one. 200 tiles of this design have been tested and are in storage at our laboratory, which will be ready for the assembly of ED prototypes.

### 2.3 Fiber placement in tile

As mentioned above, only 8% of scintillation photons can be trapped in the WLS fibers, it is very important for each fiber to transmit as many photons as possible to its far end, which is attached to the PMT. The traditional method is to coat the fiber ends with an aluminum layer (maximum reflection more than 90%). The problem is that the layer is easy to peel off because of the flimsy connection. This causes light loss and non-uniformity between tiles. Instead of using eight short fibers, four 3.2 m long WLS fibers are equipped with each tile, and each fiber is bent and placed in two grooves (12 cm spacing) in our new design (Fig. 5). In this case, most photons trapped in the fiber can reach its far end and the curvature does not cause light loss [10]. In addition, the light absorption length of WLS fiber is only 3.5 m, so there is 30% light loss in the WLS fiber.

### 2.4 Performances of ED unit

As mentioned above, the suitable design of the ED unit is the ST-401 type tile with the size of 25 cm×25 cm×2 cm and four 3.2 m-long WLS fibers embedded in eight grooves (1.8 mm (depth)×1.6 mm (width) each) on the surface (Fig. 5).

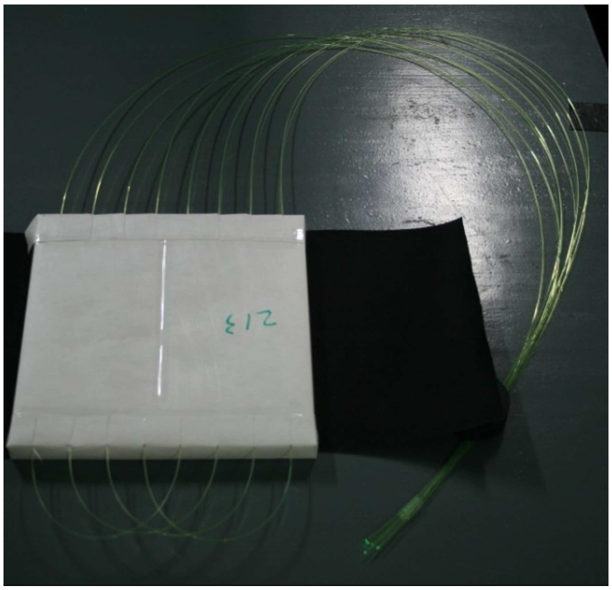

Fig. 5. One assembled ED tile.

The amplitude distribution in the case of a single MIP obeys the Landau function (Fig. 6 (a)). The MPV value is about 25 p.e. with a resolution of 17.6% and detecting efficiency of ∼97%. The distribution of time of flight (TOF) between the scintillator probe detector and the tested ED unit obeys a Gaussian distribution (Fig. 6 (b)). The time resolution is about 1.9 ns. In addition, the non-uniformity over the whole area of one tile is within 5% by selecting single muons hitting different regions with two probe detectors (10 cm×10 cm×4 cm each). The performances of ED units meet the requirements and will guarantee the stability of ED's performances actually.

## 3 Performance control of ED prototype

As mention above, there are altogether 5635 EDs in KM2A. So it is important to fulfill the required performances of massive EDs and guarantee the uniformity among them. Of course, the best solution is related to strict selections of all components and concrete assembling techniques of EDs. Then a set of strict criteria for EDs assembly have been studied.

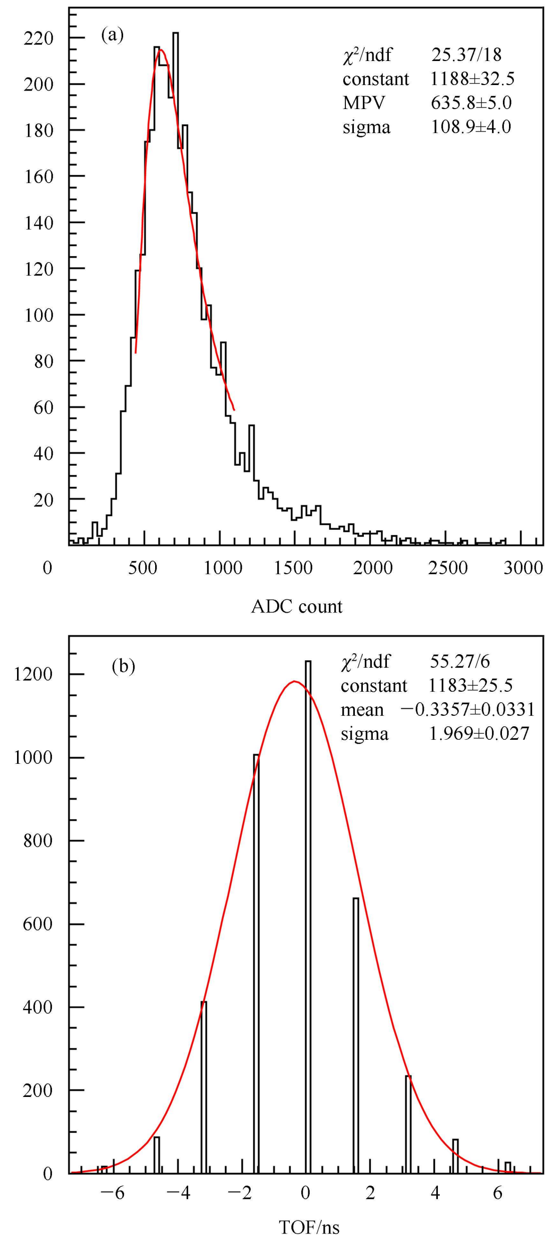


Fig. 6. The amplitude distribution and the time of fight distribution in the case of a single incoming MIP.

### 3.1 Tiles' uniformity

To choose the qualified scintillator tiles for ED, a measurement system has been installed (Fig. 7). 16 R11102 PMTs are fixed in the panel of a black box (1.2 m×0.8 m×0.6 m). Eight WLS fiber ends from each tile are connected to one PMT, thus 16 tiles could be tested in each batch (Fig. 7). The top tile and bottom one work in coincidence mode to choose the single particle events.

The system stability is within 2%. 200 ST-401 scintillator tiles are tested in the system. Their non-uniformity is within 6% excluding the fibers' contribution, which shows good quality and stability of these scintillator tiles. Based on these, the sampling test is a feasible way to avoid measuring a large quantity of tiles in the future.

Fig. 7. The tile light yield test system.

### 3.2 Polishing of fiber ends

Four WLS fibers (BCF92, 1.5 mm diameter) with a length of 3.2 meters are embedded in one tile. So there are 64 WLS fibers being used in one ED. To ensure fine uniformity and good light transmission, two steps are adopted for the polishing process of the WLS fiber ends. Firstly, 12 fibers are fixed in the clamp and there is about 3 mm long part of each fiber left at the clamp bottom. Placing the clamp in the muller (Fig. 8). Those 3 mm long fiber ends are rubbed down by a piece of P2000 paper fixed on the rotating board with a rotating frequency of 2.5 Hz for 200 seconds. Then all ends are level with the clamp bottom. Secondly, the fiber ends are polished by the liquid grind (3M 81235 type) on the rotating board with the rotating frequency of about 1Hz for 10 minutes. Then the ends are cleaned with water. The ends of each fiber are tested in the way that one end is irradiated with LED light and another end is connected to one PMT. The test results of more than 80 WLS fibers show that the non-uniformity is about 7% (Fig. 8). Furthermore, once they are grouped into 20 four-fiber-bundles, the non-uniformity is 2.7% among the bundles tested on a single tile.

### 3.3 Studies of PMT's gain

To meet the detection requirements of large dynamic charged particle densities from $1/\mathrm{m}^2$ to $\sim 10000/\mathrm{m}^2$, the gain of PMT anode readout is set to $10^5$. The average charge of the anode readout is 0.32 pC for single particles. But for the maximum particle density, the anode readout would reach 3200 pC, which exceeds the limit of PMT pulsed linearity. The best way to solve this problem is to record the signals from the anode and one dynode. The signal from one dynode has a gain of a few percent of the anode's. This study is in progress and not mentioned in this paper.

In the ED design, all 128 fiber ends from 16 tiles are connected to one PMT. Thus the characteristics of PMTs influence the ability of EDs directly. Three kinds

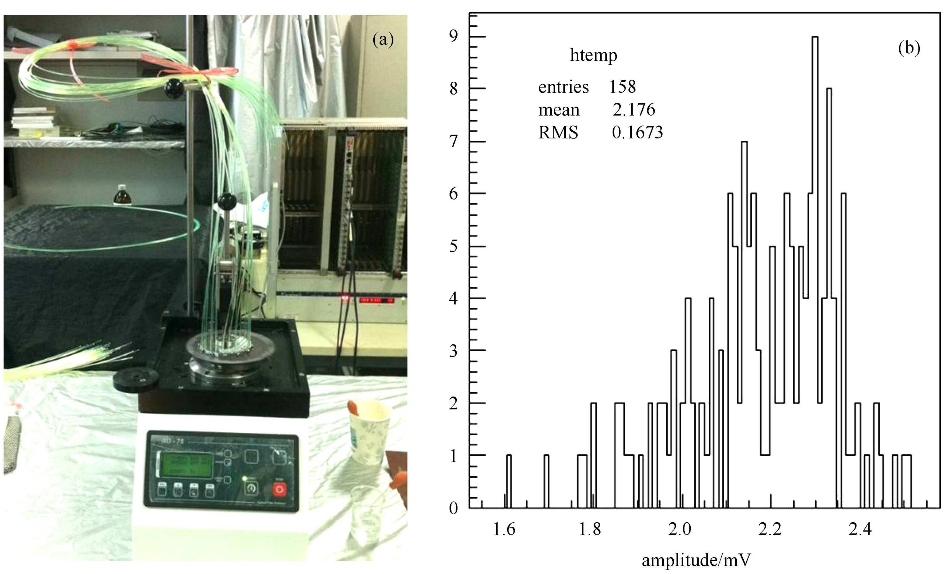


Fig. 8. Polishing of fiber ends (a) and the amplitude distribution of fiber ends' test (b).

of PMTs (1.5 inches in diameter), XP2012B [11], HAMAMATSU R11102 [12] and ET9903kB [13], have been studied.

The factors that affect the gain stability are concerned. Firstly, the gain varies with different placements of PMT in earth magnetic fields. Secondly, considering a large annual temperature variation (from −25 ℃ to 35 ℃) and 0.6 atm at local site, it is better for PMTs to have a temperature coefficient of less than 0.2%/℃. It also requires high voltage module supplies with a temperature coefficient of less than 0.01%/℃ and a ripple index of 0.01%, which ensure that the gain variation of each PMT is within ±5%.

The non-uniformity within a radius of 7.0 mm (coverage area of 128 fiber ends) in the PMT's cathode region is also considered because it contributes to the non-uniformity of the entire ED.

All the results of three PMTs are shown in Table 3.

Table 3. Comparison results of three PMTs.

| type | XP2012B | R11102 | ET9903kB |
|---|---|---|---|
| geomagnetic influence(%) | $<10$ | $<30$ | $<50$ |
| temperature coefficient(%/℃) | $<0.2$ | $<0.5$ | $<0.2$ |
| cathode non-uniformity(%) | $<6.9$ | $<9.4$ | $<17.0$ |

It is clear that R11102 and XP2012B PMTs have better uniformity which could have a smaller contribution to the whole uniformity of EDs. The comparison results show that R11102 and XP2012B are suitable for application in the ED.

### 3.4 Assembly techniques

Each ED consists of 16 units, which are placed in one 1.6 m×1.02 m×0.08 m steel and waterproof box. Before assembly, each tile is packed by a piece of black cloth to prevent scintillation light from passing through the Tyvek sheet and entering the WLS fibers, which ensures the uniformity of ED. Since there are two different unit designs, one universal assembling technique is applied as below. 16 units are divided into four batches. The first batch is placed in the back raw of the ED box and each corner of the units is lifted with one 5 mm high brace welded at the bottom panel. It needs to be emphasized that if the tiles with grooves were to be used, they should be reversed and the fibers should be close to the bottom panel and extend to the front. The second batch is placed close to the first one and each corner of units is lifted with one 15 mm high brace to avoid breaking the fibers. Then the third batch is placed in the same way as the first one. The last batch is placed in the same way as the second one, but it is rotated by 180 degrees to leave enough space for the bent fibers (Fig. 9).

The 128 fiber ends need to be level with each other before connecting to one PMT. To solve this problem, a suitable fixing tube is made, which consists of two parts. The first part is one tube (10 cm long, the inner diameter is 1.0 inch and the outer diameter is 1.5 inch), the two ends of which have fastening pieces to fix the fibers. The second part, a circular transparent glass window, is connected to the tube and is also easily separated from it. Once the fibers enter the tube, they are fastened a little with the fastening piece of one end. Each fiber is pushed to press the glass window. The next step is to fasten the fibers batch completely to prevent the fiber movement. Then the glass window is taken out. All fiber ends are in the same level with the fluctuation within 0.2 mm (Fig. 10). After connecting the fixing tube to one PMT, the connection part is wrapped with 3M of insulating tape to avoid the influence of the background light. In addition, the PMT is wrapped with a piece of magnetic shielding film to decrease the influence of the magnetic field.

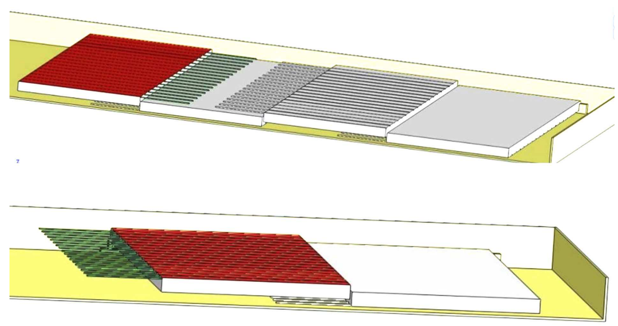

Fig. 9. The tile placement in ED box.


Fig. 10. (a)The fixing tube of WLS fibers; (b) the inner structure of ED box.

A modularize DC power supply followed by a high voltage module is fixed in the box. It is powered by a 220 V AC cord entering the box. The PMT signal is transmitted through a cable to the Front End Electric.

## 4 Performance tests and results

To study the performances and uniformity of ED, two scintillator probe detectors, i.e. a 25 cm×25 cm×2 cm scintillator plate equipped with a PMT, are put on the top and bottom of the ED, respectively. Moving the

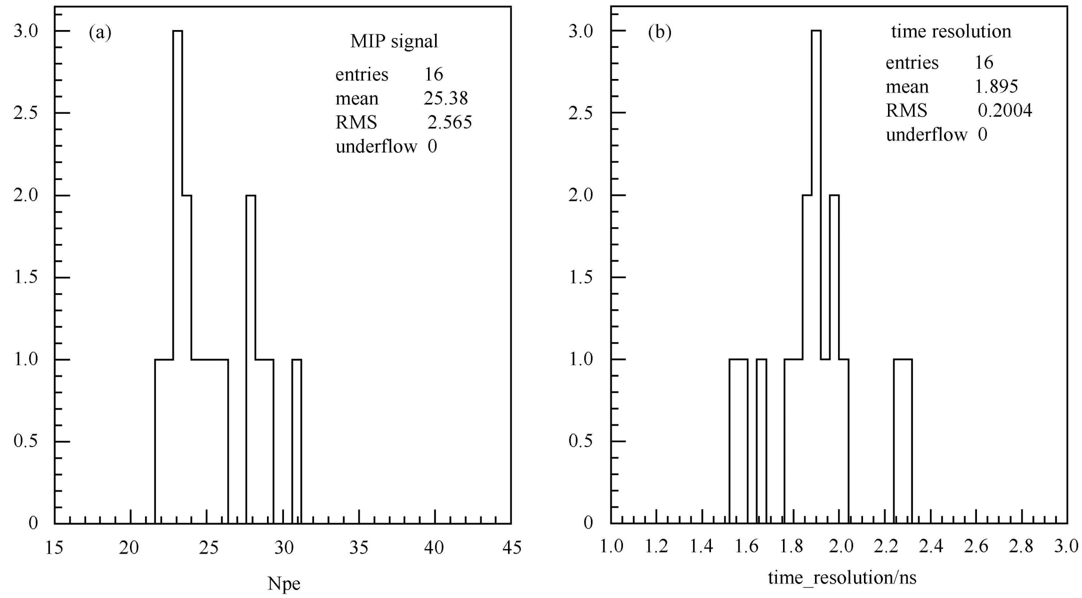


Fig. 11. The numbers of photoelectrons (a) and time resolutions (b) of 16 tiles in one ED.

probe detectors over all places on an ED, one can test every unit in the detector by using the vertical particles. Here, both the electronics and data acquirement system are mentioned above and the 5 mm thick lead layer is not used to cover the ED in the tests.

The performances of 16 units in one ED are shown in Fig. 11. The average number of photoelectrons is 25.4 and the non-uniformity is ~10%, while the average time resolution is 1.89 ns and the non-uniformity is also about 10%.

## 5 Conclusions and outlook

Two kinds of ED unit design have been presented. The ST-401 type tile of 25 cm×25 cm×2 cm with four WLS fibers is an eligible design. 25.4 p.e. are obtained for a single particle passing through. It results in a resolution of 20%. A timing resolution of 1.89 ns is achieved. The detection efficiency is higher than 95% for a passing through particle. The design with the scintillator HND-S2 and WLS fibers in holes is still in progress, which needs more study to solve the problem associated with the roughness inside the holes. The studies on ED assembling techniques give the criteria, which will be favorable for the ED assembly in mass batch. The detector has been thoroughly tested for its performances. It is found that all specifications of the prototype are satisfactory with the design using the scintillator ST-401.

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