Performances and long-term stability of the LHAASO-KM2A prototype array *

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Abstract: A prototype array for the LHAASO-KM2A, which consists of 42 detector units and fully overlaps the ARGO-YBJ experiment, was set up at the Yangbajing cosmic ray observatory and has been in stable operation since Octoter 2010. The resulting performances of the KM2A electromagnetic particle detector prototypes fully meet the design requirements. Through hybrid observation of cosmic ray showers with the ARGO-YBJ experiment, the performances and long-term stability of the prototype array are tested and the results are consistent with expectation. The cosmic ray moon shadow observed by the prototype array is also presented.

Key words: LHAASO-KM2A, prototype array, performance, long-term stability

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1 Introduction

The Large High Altitude Air Shower Observatory (LHAASO) project focuses mainly on the study of sub-TeV–1 PeV gamma ray astronomy and 5 TeV–1 EeV cosmic ray physics by using a compound detector array distributed in one square kilometer [1]. It consists of an extensive air shower array covering an area of 1 km^2 (KM2A), 90000 m water Cherenkov detector array (WCDA), 5000 m^2 shower core detector array (SCDA) and 24 wide-field air Cherenkov/fluorescence telescopes (WFCTA). As the major array of LHAASO, KM2A [2] is comprised of 5635 electromagnetic particle detectors (EDs) [3] and 1221 muon detectors (MDs) [4]. The KM2A EDs are distributed with a spacing of 15 m in a large area of 1 km^2 at a high altitude of about 4300 m a.s.l., where the air pressure is about 60% of that at sea level and the annual air temperature variation is about ±30 ℃. Under such a harsh field environment, special considerations should be taken to keep such a huge detector array working properly in the field for an expected operation time of more than 10 years.

A prototype array of 1% the size of KM2A was built at the Yangbajing cosmic ray observatory, where the altitude is the same as that required by LHAASO, and has been in stable operation since October 2010 to test the validity of the design and to study the performances and long-term stability of the detector units and the array.

2 KM2A prototype array

2.1 Experiment setup

Figure 1 shows a schematic view of an ED prototype (1 m×1 m×1.5 cm) which consists of 4×4 plastic scintillation tiles (25 cm×25 cm×1.5 cm each). Eight single-cladding wavelength-shifting fibers (BCF92) 1.5 mm in diameter and 30 cm long are threaded into holes 1.6 mm in diameter in each tile to collect scintillation lights generated by charged particles that are interjecting in the tile. One end of each fiber is coated with an aluminium layer to reflect the collected scintillation lights, while the other end is connected to a single-cladding clear optical fiber (BCF98) of the same diameter and 180 cm long to guide the scintillation lights to a photomultiplier tube (PMT). For each ED, one XP2012B PMT with a temperature coefficient <0.2 %/℃ is used to collect scintillation lights from the total 128 fibers. Each PMT is supplied by a high voltage module with a temperature coefficient of <0.01 %/℃, thus the high voltage of each PMT can be adjusted independently. All the components of an ED are packed in an aluminium box.

For the KM2A prototype array, a total of 42 detector units are uniformly distributed in the central carpet of the ARGO-YBJ array [5] with the same spacing (15 m) as the one proposed for KM2A. The prototype array fully overlaps with the ARGO-YBJ central carpet, thus covering a total area of about 75 m×75 m and enabling cross-

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check between them by hybrid observation of cosmic ray showers (Fig. 2).

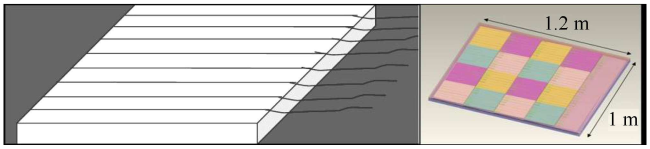

Fig. 1. Schematic of an ED tile (left) and an ED (right).

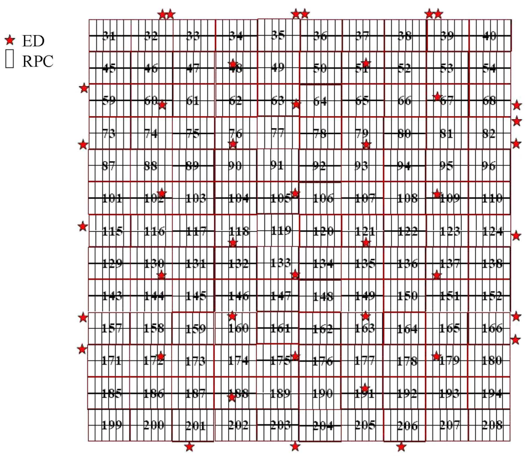

Fig. 2. Sketch map of the KM2A prototype array in the ARGO-YBJ array. Each red star represents an ED, black rectangle for an ARGO-YBJ RPC and red rectangle with a number for an ARGO-YBJ cluster.

2.2 Electronics and data acquisition

The PMTs are operated at a gain of about 4×10^5, under which the rise time of the anode pulse is about 3 ns and a typical maximum anode current of 60 mA can be reached with a pulsed linearity of 5%. Signals from PMTs are transferred through 45 m long coaxial cables to a so-called local station, where the front-end electronics (FEE) discriminates the signals according to a presetable threshold, which corresponds to 25% of the most probable value of the single particle spectrum. Once a single channel fires, the arrival of the PMT signal will be measured by a FPGA-based time-to-digital convertor (TDC) with a resolution of 1.56 ns and a jitter lower than 0.78 ns; at the same time, the signal charge is measured with a resolution of 20% at 1 pC and 1% above 5 pC by a shaping and peak-finding circuit based on 40 MHz-FADCs. With a high/low gain design for each channel, a dynamic range of 3.5 orders of magnitude is achieved for the signal charge measurement. A trigger board collects the single channel hit information and calculates the hit multiplicity in a time window of 400 ns. If the hit multiplicity exceeds 5, an event trigger signal will be generated, which fans out to the FEEs and the time and charge of all hits in a time window of ±5 microseconds are saved in a FPGA buffer for the data acquisition system to read. The event trigger time is recorded by a GPS-based timing system with an accuracy of better than 100 ns.

The data acquisition system for the KM2A prototype array is based on VME front-end modules [6]. We use a MVME5100 VME controller running Linux OS to configure and read out data from front-end electronics. The pedestal of each channel is also monitored online. Triggered events and pedestal data are sent to the back-end PC for online processing and storage.The software running on the back-end PC draws online histograms of the time and charge for each channel, monitors the status of the detector and electronic modules and also performs data acquisition tasks.

2.3 Calibration of detector units

For each ED, the time resolution, the relative time offset (due to the difference of the signal cable length, etc.) among ED detectors, detection efficiency and single particle spectrum in case of minimum ionization particles (MIPs) are measured through a telescope consisting of two small probe detectors (a 25 cm×25 cm×4 cm plastic scintillator and an XP2012B PMT) on top of the ED to be tested. The probe detectors work in coincidence mode to select MIPs in secondary comic rays, which act as the test beam and trigger the whole system. All the detectors are connected to the electronics and data acquisition system described above. The typical detector time resolution measured is about 2 ns. The single particle spectrum of each detector was measured both in Beijing and at Yangbajing. A slight difference due to transportation and the different environment can be seen from Fig. 3. The major difference among detector units comes mainly from the different PMT gains at the same high voltage. The high voltage of each PMT was then adjusted accordingly to achieve a uniform response from each channel (see Fig. 3).

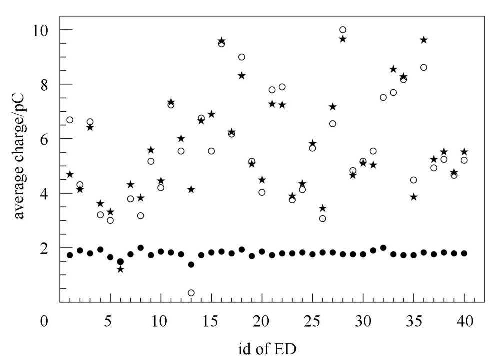

Fig. 3. Average charge of each detector unit in case of MIPs measured in Beijing (star), at Yangbajing (hollow) and after high voltage adjustment (solid).

The single channel counting rate of each channel was measured when we adjusted its trigger threshold. Fig. 4 shows an example. The final trigger threshold for each channel is set to 25% of the most probable value of the single particle spectrum. The resulting detection efficiency is higher than 95% and single rate is lower than 1 kHz.

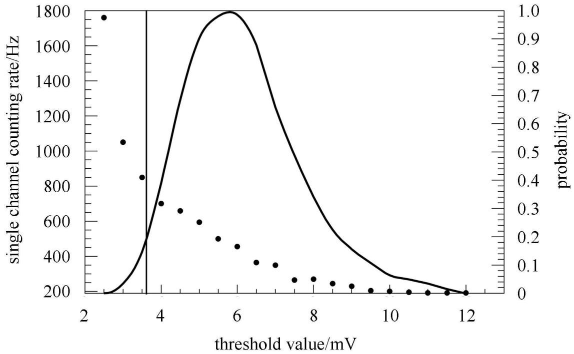

Fig. 4. Single channel counting rate vs. threshold. The trigger threshold for each channel is set to 25% of the most probable value of the single particle spectrum and single rate is lower than 1 kHz.

3 Performances of the KM2A prototype array

The prototype array of about 1% size of KM2A was built at the Yangbajing cosmic ray observatory and has been in stable operation since October 2010 to test the validity of the design and to study the performances of the detector units and the array. Each day about 1.5 GB data are generated and transferred to Beijing. The trigger rate is about 50 Hz with an event trigger threshold of $\geqslant$5 hits.

Since the prototype array fully overlaps with the ARGO-YBJ central carpet, we can match the event of the KM2A prototype array to ARGO-YBJ's according to the event time. These hybrid events are observed by both the ARGO-YBJ and the prototype arrays and are measured independently of the primary direction and shower size. More than 95% of the shower events of the KM2A prototype array match with the events of ARGO-YBJ in a time window of $\pm$500 ns, which allows a cross-check of the performances of the prototype array by the ARGO-YBJ experiment.

3.1 Energy response

For each hybrid event, the primary energy can be roughly estimated by the number of fired strips registered by ARGO-YBJ. The number of particles measured by the prototype array shows a linear correlation with the number of fired strips of ARGO-YBJ (Fig. 5).

Figure 6 shows the distribution of the number of hits registered by ARGO-YBJ for ARGO-YBJ events and hybrid events. With $\geqslant$5 hits, the mode energy of the prototype array is about 6 TeV and with 20 hits, it goes to about 50 TeV. Since KM2A is more than 100 times larger than the prototype array, its mode energy under the designed trigger threshold of $\geqslant$20 should be lower than that of the prototype array (the designed KM2A mode energy is 30 TeV).

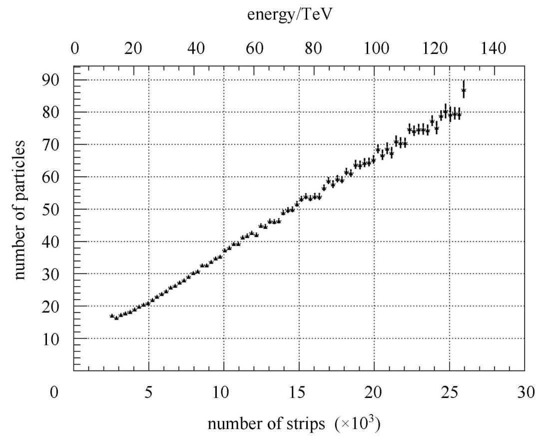

Fig. 5. Prototype array's number of particles vs. ARGO's number of strips. The reconstructed energy by ARGO-YBJ is indicated by the upper scale.

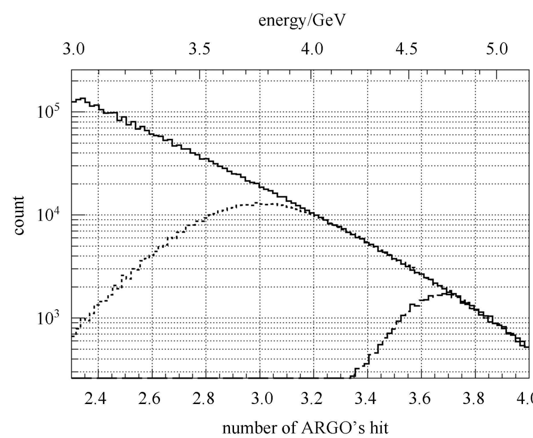

Fig. 6. The distribution of the number of hits (in log-scale) registered by ARGO-YBJ for ARGO-YBJ events (solid) and hybrid events with the prototype array's number of hits $\geqslant$5 (dotted) and $\geqslant$20 (dashed). The reconstructed energy (in log-scale) by ARGO-YBJ is indicated by the upper scale.

3.2 Angular resolution

The primary direction of an observed air shower is reconstructed by performing a planar fit to the space-time profile of the shower front measured by the prototype array with the hit time corrected according to the calibrated time offsets. Fig. 7 shows an example of a shower front observed by ARGO-YBJ and the KM2A prototype array.

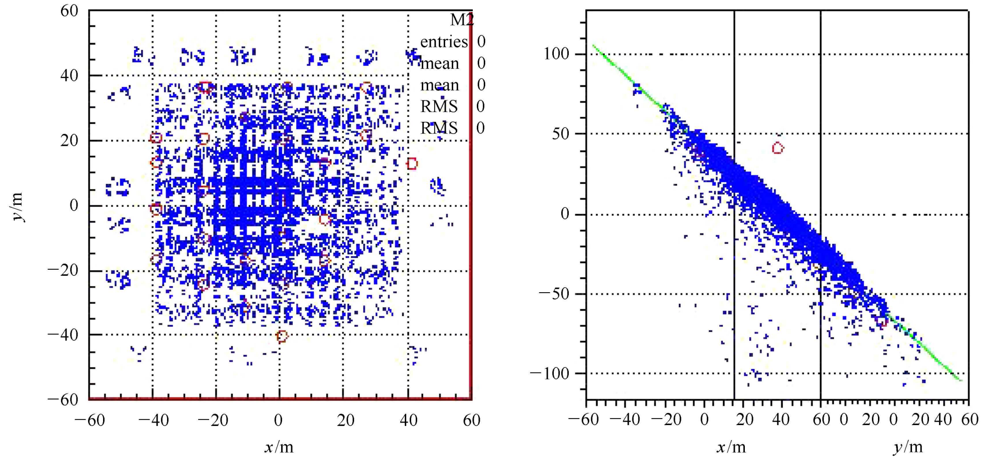

Fig. 7. (color online) An example of a shower front observed by ARGO-YBJ (blue) and the KM2A prototype array (red). The green line in the right shows the shower plane reconstructed by the prototype array data.

Since the angular resolution of the ARGO-YBJ experiment has been well checked by cosmic ray Moon shadow and gamma rays sources, the shower direction of hybrid events measured by the ARGO-YBJ experiment can be used to check the angular resolution of the prototype array. Fig. 8 shows the distribution of the space angle between the shower directions measured by the prototype array and directions measured by the ARGO-YBJ for events with more than 20 hits (the designed event trigger threshold of LHAASO-KM2A) in the prototype array and ARGO-YBJ reconstructed core location within 10 m of the center of the array.

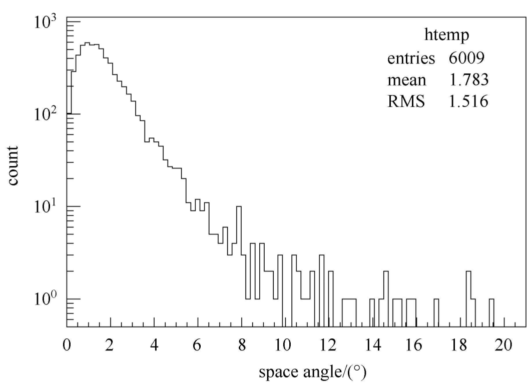

Fig. 8. Distribution of space angles between the shower directions measured by the KM2A prototype array and the ARGO-YBJ experiment.

The angular resolution of the prototype array is then estimated by:

$$\sigma_{\rm Km2a}=\sqrt{\sigma^2_{\rm spatial}-\sigma^2_{\rm ARGO}}. \tag{1}$$

Where $\sigma_{\rm spatial}$ is the peak value of the space angle distribution and $\sigma_{\rm ARGO}$ is the angular resolution of the ARGO-YBJ experiment. It should be mentioned that the above formula is correct only when the pointing errors of both arrays are negligible.

Table 1 shows the resulting angular resolution of the prototype array in different hit ranges. This is consistent with Monte Carlo simulation results [7]. For KM2A, the expected angular resolution should be better than that of the prototype array in the same hit range, since the fired detectors are expected to be distributed in a much larger area.

Table 1. Angular resolution in different hit range (energy is from ARGO-YBJ simulation).

$N\text{hit}_{\rm KM2A}$	$N\text{hit}_{\rm ARGO}$	energy/TeV	$\sigma_{\rm Km2a}/(°)$
⩾5	1900	13	2.0
⩾10	3470	35	1.4
⩾15	5040	50	1.2
⩾20	6610	100	1.1
⩾25	8180	140	1.0
⩾35	9680	180	0.9

3.3 Cosmic ray moon shadow

Based on the deficit profile and the peak shift from the Moon, the deficit analysis of cosmic rays from the direction of the Moon is a well known method to determine the angular resolution and the systematic pointing error of an extensive air shower array. The Direct Integral method [8] is used in the KM2A prototype array data analysis. Fig. 9 shows the cosmic ray moon shadow observed by the prototype array for events with $N\text{hit}\geqslant 5$ and zenith angle $<40°$. The maximum deficit is found at ($-1.4\pm1.0°$, $-1.0\pm1.3°$) from the Moon with a significance of 5.3 standard deviation, which is consistent with expectations according to the event rate, angular resolution and operation time. A Gaussian fit to the deficit profile of the Moon shadow results in an angular resolution of 2.6°, which is a little larger than that in Table 1. The events used for Table 1 are those with core locations within 10 m of the center of the array, thus they have a better angular resolution than the events used in the Moon shadow analysis (no core location selection).

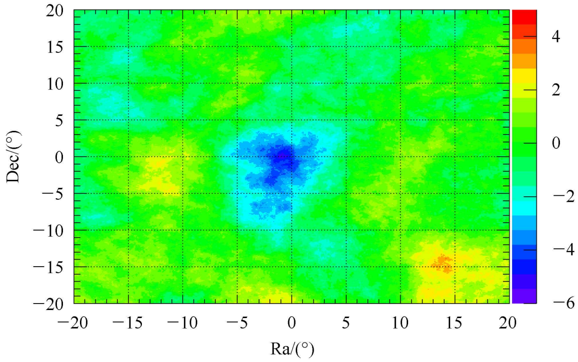

Fig. 9. The significance map of the sky around the Moon obtained in two years of observation, selecting the events with a number of ED larger than 5. Here (0, 0) is set to the Moon's position.

3.4 Long term stability

The prototype array has been continuously operated for about two years. The variation of event rate is less than ±1% and shows a linear correlation with air pressure with a barometric coefficient of about −1%, which directly reflects the atmosphere density that brings the variation of the shower size (see Fig. 10).

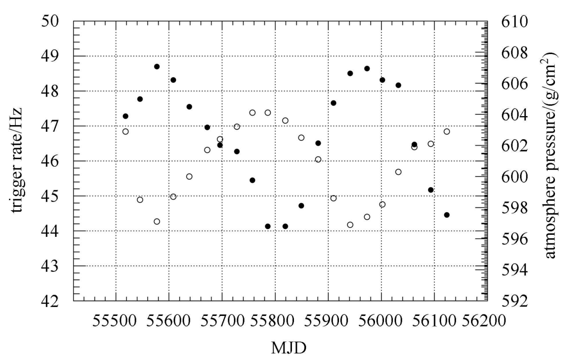

Fig. 10. The event rate of the KM2A prototype array (hollow) and the air pressure (solid) varying with time. Each point is an average over one month.

The average charge of each ED in case of MIPs can be used to monitor detector response and the gains of its PMT and electronics. Fig. 11 shows that the average charge of a typical ED varies with time and is very stable during the two-year operation. The variation is less than ±1% and is linearly correlated to the ambient temperature of ED. The resulting temperature coefficient of about 0.2 %/℃ is consistent with that of the PMT. Considering the annual ambient temperature variation of ±30 ℃ at LHAASO site, we have started to study the insulation of the PMT and the whole ED in order to lower the annual temperature variation to about ±15 ℃. By doing so, we can keep the stability of charge measurement to ±3%.

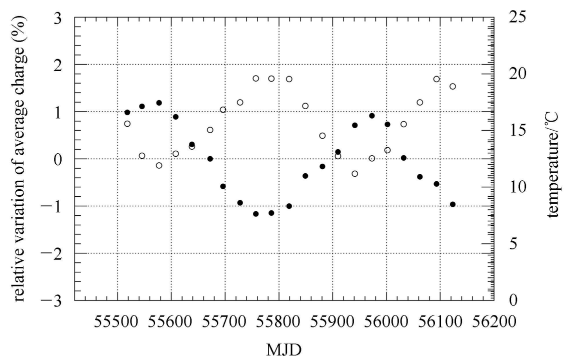

Fig. 11. The relative variation of average charge in case of MIPs for an ED (solid) and its ambient temperature (hollow) varying with time. Each point is an average over one month.

Monitoring of the time resolution of an ED by the telescope shows a variation of less than ±1% during the two-year operation, much better than the requirement.

4 Conclusions

Set up at the Yangbajing cosmic ray observatory, a prototype array with 1% size of the LHAASO-KM2A fully overlaps with the ARGO-YBJ array. The performances of the prototype array are studied through hybrid observation of cosmic ray showers with ARGO-YBJ. The results proved to meet the design requirements. Under the high altitude environment, the prototype array has been stably running for about two years, which is helpful to improve the design and optimize the whole array of LHAASO-KM2A.

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