PROCEEDINGS OF SCIENCE

Calibration and Long-term stability of LHAASO Electromagnetic Particle Detector

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In the Large High Altitude Air Shower Observatory (LHAASO), the square kilometer array, with 5216 electromagnetic particle detectors (EDs) and 1188 muon detectors, is deployed to explore the gamma-ray sources above 30 TeV with unprecedented sensitivity and to measure primary cosmic rays in the energy range from 10 TeV to 100 PeV. The stability of detector performance is crucial for the physical research of LHAASO. In this paper, we present an established offline calibration technique for determining the crucial performance parameters of the EDs. This robust calibration also offers an ideal method to monitor the performance of thousands of EDs during their science exposure. According to the calibration results, the output charge of EDs has an average temperature coefficient of -0.33%/°C, and the detector relative time-offsets have no apparent correlation with temperature. Using the relationship between the output charge and temperature (dominant), the annual rate of performance degradation is studied after correcting the temperature effects.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

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PoS(ICRC2023)462

1. Introduction

One square kilometer array (KM2A) of the Large High Altitude Air Shower Observatory (LHAASO) consists of 5216 electromagnetic particle detectors (EDs) and 1188 muon detectors (MDs). EDs are designed to detect the particle density and arrival times of secondary particles (including $\mu^{\pm}$, $e^{\pm}$ and γ, etc.) in extensive air shower (EAS). 5216 EDs are uniformly distributed over 1.3 square kilometers (with a radius of 635 meters). The energy and direction of the primary particle can be reconstructed by the density and arrival time given by the all fired EDs in each event. For gamma ray detection, the angular resolution of ED array is 0.4° at 30 TeV and 0.2° at 1 PeV. The energy resolution is 28% at 30 TeV and 20% at 100TeV for gamma ray, 33% at 30 TeV and 25% at 100 TeV for proton [1]. The detection efficiency of an ED to MIPs (Minimum Ionizing Particles) is required to be > 95%, with a time resolution of better than 2 ns and a signal charge resolution of < 25% (defined as the sigma/mean of the signal charge distribution)[2]. The dynamic range for each ED is designed to be 1 to 10^4 particles, with the upper limit corresponding to the large number of shower secondaries near the shower core of the highest energy (up to 100 PeV)[2].

An ED is composed of four detection sensitive units, photomultiplier tube (PMT) (XP3960, 9 linear focused dynode stages, 1.5 inch end window), an electronics system and a power supply system. A sensitive unit is consists of a plastic scintillator tile (BC408, 100cm × 25cm × 1cm with length × width × thick) and 12 wavelength shifting (WLS) fibers (BCF-92SC,diameter of 1.5mm), a layer of tyvek wrapper (1082D) and black cloth. Twelve fibers with each length of 2.7 m are routed in 24 grooves (along the width of the scintillator) on the tile evenly to collect scintillation light generated by charged particles and guide the scintillation light to PMT. Four detection sensitive units are symmetrical to cover the 1 m^2 detection area. All ends of 96 fibers are bunched together coupled directly to the PMT photocathode. In order to increase detection efficiency for secondary gamma-rays and absorb charged particles with low energy to improve the angular resolution, a 5 mm thick lead layer is placed on the surface of each sensitive unit to convert gamma-rays into electron and positron pairs. Fig. 1 is a photo of the inside of an ED detector.

Once the PMT signal reaches a fixed amplitude threshold of 1.9 mV (approximately 0.25 times the equivalent pulse height of single particle), the arrival time and the integrated charge of this signal are digitized by the front-end electronics (FEE). Then the digitized data is transmitted to the data acquisition system (DAQ) via optical fibers within a White Rabbit network, which provides sub-nanosecond time synchronization among all ED FEE nodes [3, 4].

The performance of detection efficiency, time resolution and charge resolution of an ED to MIPs are tested by the ED batch test system before it is installed at LHAASO cite[5]. The test methods and results are described in detail in the article. The whole array will work for more than 20 years with good stability under severe environmental condition, with large temperature variation (±25°C annually), low atmospheric pressure (0.6 atm) and high humidity. In addition, In order to ensure that the charge resolution and dynamic range meet the design requirements, EDs should have a uniformity within 10%. The signal attenuation is required to be less than 20% in 10 years due to detector aging.

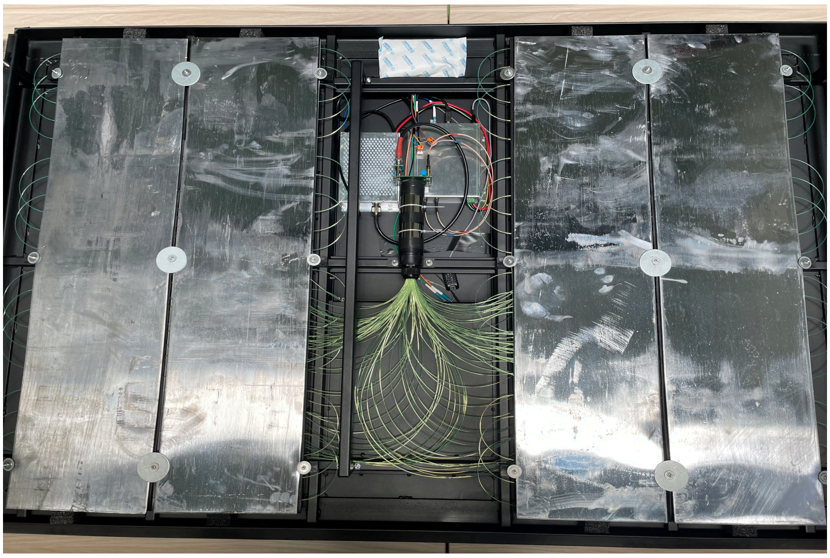

Figure 1: a photo of the inside of an ED detector.

2. ED calibration

2.1 Charge Calibration

In the LHAASO, thousands of EDs are designed to detect particle densities and arrival time of EAS charged particles produced by the primary particles, from which the primary energy and direction can be reconstructed. To calibrate the output charge of the PMT, a self-calibration technique that relies on the measurement of single particles within EASs has recently been applied.

Arising from the fact that the number of shower particles (irrespective of shower size and location of the shower core) detected by each detector during data taking follows an exponential distribution with a slope close to the energy spectrum index of the primary cosmic rays [6], the MPV of the shower particle spectrum is dominated by single-particle events, thus providing an estimation of the output charge corresponding to a single-particle [7].

The shower particle spectrum is obtained from the ED signals within a time window of ±150 ns from the trigger time. As an example, a shower particle spectrum of one ED during 4 hours of data taking is shown in Fig. 2. It should be mentioned that the high voltage of each PMT has been adjusted aiming to a the most probable value (MPV) of the charge distribution around 20 ADC channels, to ensure that the dynamic range of different detectors is approximately consistent.

The software-based calibration provides a robust method for monitoring detector performance during its science exposure. The stability of the single-particle response is an important parameter to monitor the detector performance (e.g., light yield, PMT gain and signal amplification) and its degradation through the lifetime. Fig. 3 shows the MPV of the shower particle spectrum of three EDs from June 2022 to May 2023. The single-particle response shows an inverse dependence on the temperature, a more detailed study will be mentioned in the following. During KM2A operation, the charge calibration is carried out once every 4 hours, and thus the diurnal variation can be easily calibrated.

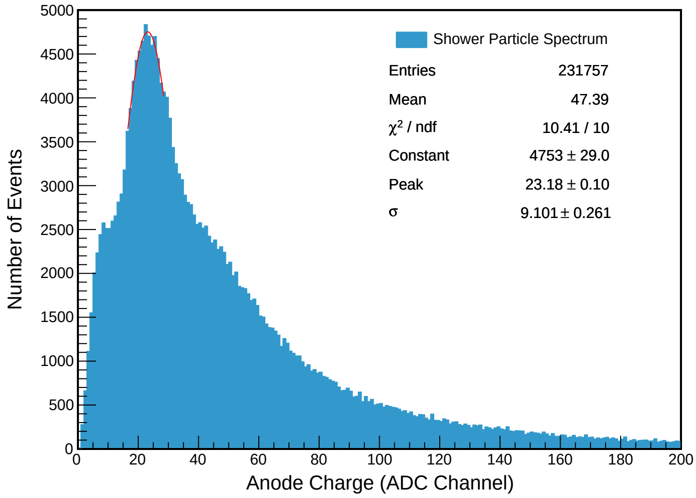

Figure 2: An example of a shower particle spectrum in ADC channel units for one ED (ID 998). Fitting this distribution with a Gaussian yields a peak value of 23.18 ± 0.10 ADC channels/particle.

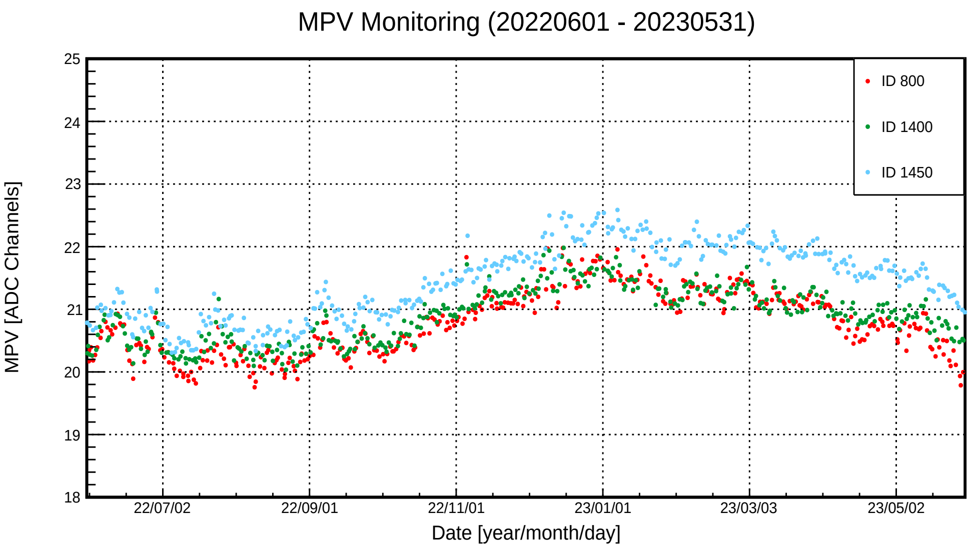

Figure 3: Variation of the shower particle spectrum peak of three EDs of three EDs (ID 800, 1400 and 1450) from June 2022 to May 2023.

2.2 Time Calibration

A reliable reconstruction of the primary cosmic ray direction requires the accurate determination of the arrival time of secondary particles on each detector. Keeping all the EDs time synchronized is critical for optimal pointing accuracy and angular resolution of the primary direction. To calibrate the relative time-offsets among the numerous detector units in the EAS array, an offline calibration named characteristic plane (CP) method is is applied [8]. Using the arrival time of particles recorded by each detector with respect to a reconstructed shower front plane, the detector time-offsets can be determined with accuracy within 1 ns [9].

Fig. 4 shows the distribution of calibration parameters for all EDs under operation on October 10, 2022. Some EDs have parameters that are higher than those of the majority because the PMTs in these EDs have 10 dynode stages (and consequently larger transition time), and the other PMTs have 9 dynode stages. Fig. 5 shows the variation of the calibration parameters of five EDs from January 2022 to December 2022. During the array operation, the time calibration is carried out once everyday. The detector time offsets remains stable and vary less than 0.5 ns in one year.

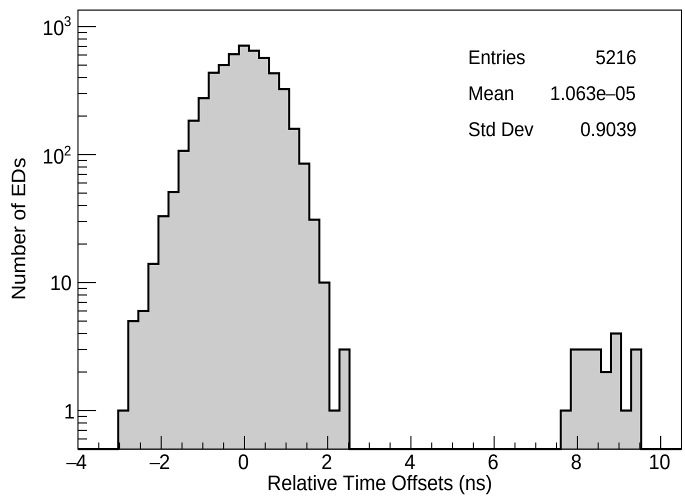

Figure 4: Distribution of time calibration parameters for all EDs under operation on October 10, 2022.

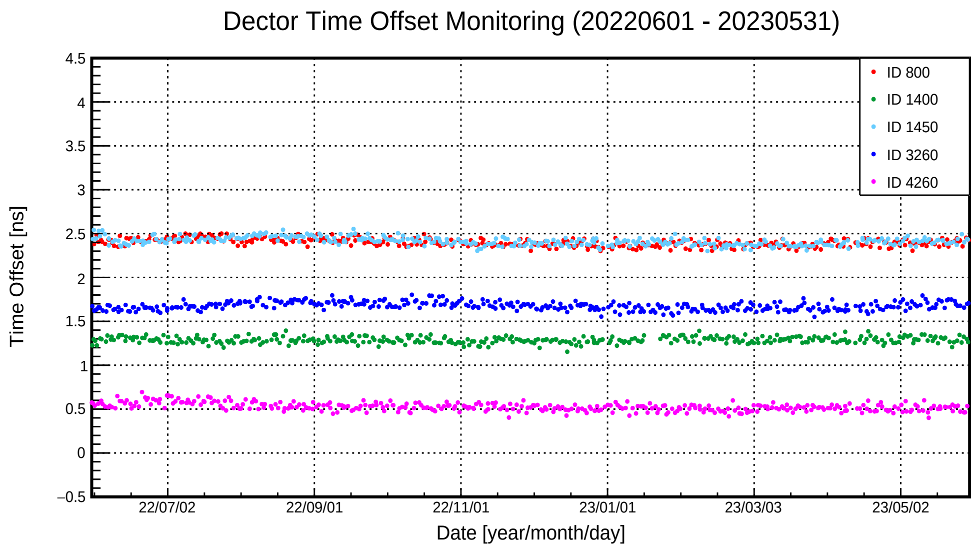

Figure 5: Variation of the relative time offsets of five EDs (ID 800, 1400, 1450, 3260 and 4260) from June 2022 to May 2023.

3. ED Long-term stability and aging

The whole array will work for more than 20 years with good stability under severe environmental condition, with large temperature variation (±25°C annually), low atmospheric pressure (0.6 atm) and high humidity. In addition, In order to ensure that the statistical error and dynamic range meet the design requirements, EDs should have a uniformity within 10%. The signal attenuation is required to be less than 20% in 10 years due to detector aging.

The number of ED is large, and there are many components in each ED. The dominant factors affecting the performance stability of the detector are temperature, aging of scintillator and WLS fiber. Changes in air pressure or humidity may also play a role.

3.1 Temperature Coefficient of EDs

The MPV of anode charge is used to analyze the temperature effect and long-term variation characteristics. An hour of data obtains a MPV value (the number of events > 15000), and each ED gets 24 mpv values per day. The relative error of MPV fitting value is about 0.8%. Fig. 6 shows the relationship between MPV and temperature of an ED for a month time. It is fitted by a linear function. The Temperature Coefficient (TC) is obtained by the slope dividing intercept of the function. Fig. 7 shows the TC distribution of all EDs for a month data. The average TC is about -0.33% per degree centigrade.

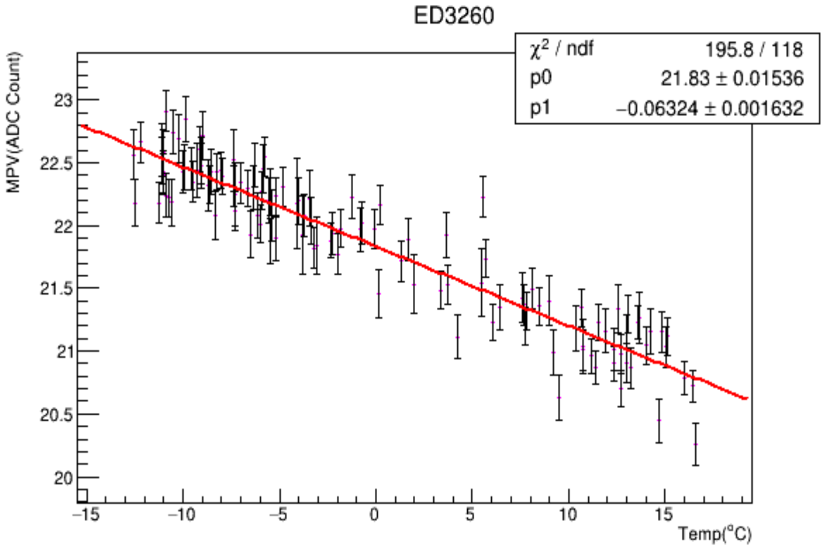

Figure 6: The two-dimensional distribution of MPV and temperature is fitted with a linear function.

The TC of PMTs and electronics are measured in the laboratory, the average value is about -0.085%/° C and 0.0075%/° C. The temperature drift of the power supply is less than 0.005%/° C. The effect on the gain is less than 0.03%/° C, which can be ignored. TC of plastic scintillators refers to temperature dependence of the plastic scintillator detector for DAMPE which is about (-0.037±0.042)%/° C. The TC of WLS fibers is (-0.094±0.007)%/° C which is measured in the laboratory. The remaining -0.14% come from the contribution of the coupling interface between the fiber and the scintillator. This value is confirmed by an experiment. The average temperature coefficient of 20 EDs made by large fiber groove holes (2mm) scintillators is about -0.2%/° C.

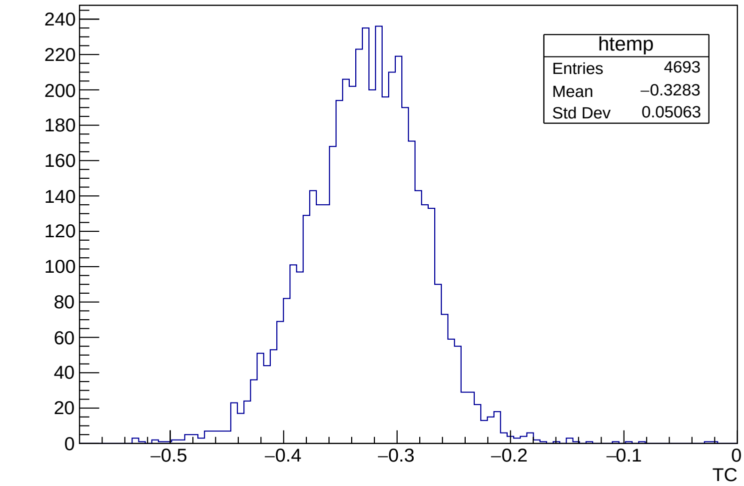

Figure 7: The TC(unit: %/° C) distribution of most of EDs for a month data.

3.2 Aging of EDs

For each ED, the short-term (one month) relationship between the temperature and MPV is used to make temperature compensation for the long-term MPV. Fig.8 shows an ED MPV before and after the temperature compensation for a month. Compared with a year ago, the MPV value has dropped by an average of about 1%.

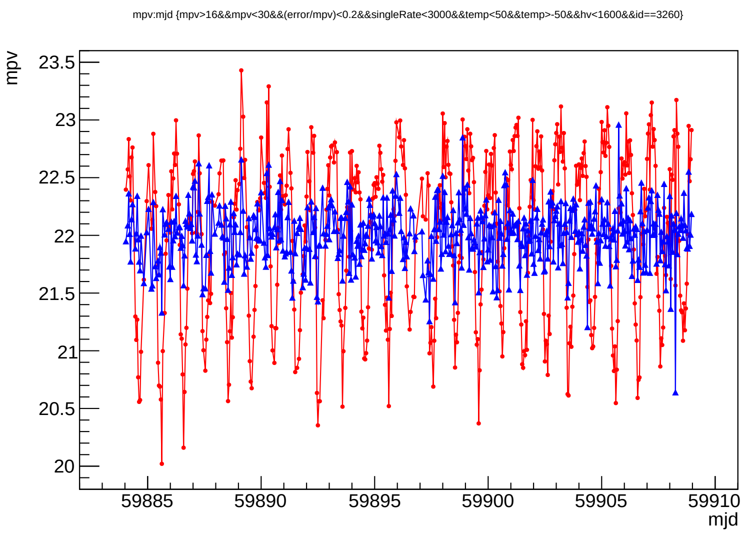

Figure 8: ED3260 before temperature compensation (red point), after temperature compensation(blue triangle), 2022.11, a point for an hour

4. conclusion

In the LHAASO, a robust calibration technique is applied to calibrate the output charge and time-offsets of 5216 EDs throughout their lifetime, according to which, the stability of the detector performance is investigated. It was found that the average temperature coefficient of the EDs is -0.33%/°C, indicating a small temperature dependence. Based on the data since the full array started running until now, the detector performance is observed to decrease by approximately 1% on average per year. These results demonstrate the suitability of the detector for long-term astronomical observations.

Acknowledgments

This work is supported by the National Natural Science Foundation of China (NSFC, No. 12105301).

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