Status of the engineering array of LHAASO-WCDA

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Abstract: A Large High Altitude Air Shower Observatory(LHAASO) is proposed and to be built in next few years. The Water Cerenkov Detector Array(WCDA) plays an important role in the LHAASO project. An engineering array at 1% scale(3×3=9cells) of WCDA was constructed at YangBaJing in 2011. With the help of it, the relevant techniques, such as the waterproof potting of PMT, the counting rate, the light shielding, the water quality control, the data analysis, the engineering issues and so on, are well studied and to be presented in this paper. Furthermore, the combined analysis between the engineering array and ARGO-YBJ experiment has also been studied. This work will offer a great help for the future operation of the full array.

Keywords: Water Cherenkov, LHAASO, Gamma ray.

1 Introduction

The water Cherenkov detector[1, 2, 3] has been in largely used during the last 20 years in the high energy and comic ray physics, and this unique detector is capable of continuously surveying the TeV sky for steady and transient sources from 100GeV to 100TeV with a good gamma/hadron discrimination, high angular resolution and high background rejection power. The Water Cherenkov Detector Array(WCDA)[4] is the one of the major and important components of the Large High Altitude Air Shower Observatory (LHAASO)[5], which will be funded in the next few years. Furthermore, a one-fourth scale of WCDA, so called LAWCA project, is firstly planned to be constructed soon at YangBaJing, Tibet, China. The WCDA is configured with four neighboring $150m\times150m$ pools, and each pool is partitioned by the black curtains into $5m\times5m$ detector cells with an effective water depth of $4m$. Additionally, each detector cell has an 8-in PMT located at the center of the bottom that faces upward to receive the Cherenkov light produced in water by those secondary particles that are induced by the extensive air showers.

Because the construction of WCDA is a large scale engineering issue, the basic performance of the water Cherenkov technique should be well understood before construction begins. Therefore, in addition to a cell-sized prototype water Cherenkov detector[6] that had already been studied, a nine-cell-sized engineering water Cherenkov detector array has be built and operated at YangBaJing. In this paper, the setup of the engineering array is introduced, and then the measurement results are presented.

2 The engineering array

The engineering water Cherenkov detector array is located at the northwest of the ARGO-YBJ hall at an altitude of 4300 m a.s.l., which corresponds to a vertical atmospheric depth of 606 g/cm^2. The main part of the engineering array is a square water pool with dimensions of $25m\times25m$ on the surface, this pool has sloping angles of 45° on all four sides that lead to the bottom with $15m\times15m$ area, which has a depth of $5m$ (Figure 1). The roof of the pool is made of steel plates that can shield the pool from both the rain and external light. The whole array has 3×3 detector cells, and each cell has dimension of $5m\times5m$. And these cells are partitioned by the black curtains made of the polyethylene. The effective water depth is 4m. The layout of the detector cells is shown in Figure 2. At the center of the bottom of each cell, a 8-in PMT is deployed. In addition, the charge calibration setups[7] are used in cells No. 2 and No. 5 to study the charge calibration method. Each charge calibration setup is a $1m\times1m$ baffle that can be shifted horizontally by the manually dragging. When calibrating, the baffle is shifted 15cm above the PMT to exclude the Cherenkov light generated by most of the electromagnetic particles and muons that are far from the PMT. In addition to the above mentioned facilities, other equipments are set up, such as an electronics system, a data acquisition(DAQ) system, a water purification and recirculation system, a slow control system, and a time calibration system. These systems are either deployed in the pool or the control room.

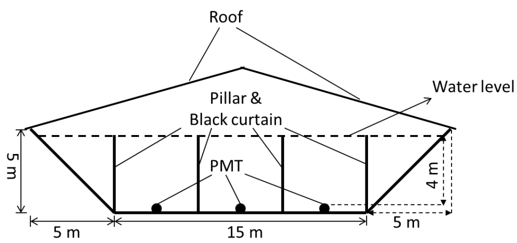

Fig. 1: The structure of the engineering array.

2.1 The photo-multiplier tube assemblies

In the engineering water Cherenkov detector array, nine 8-inch PMTs, including eight Hamamatsu R5912 and one(in the cell No. 6) ET 9354KB, are deployed. All of these

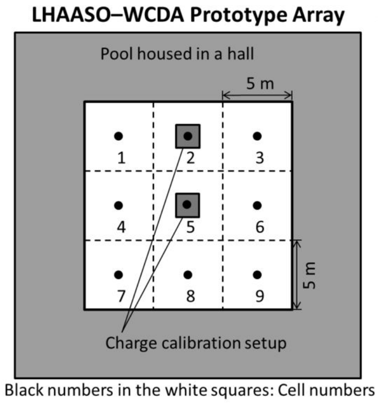

Fig. 2: The layout of the detector cells.

PMTs are operated at the high positive voltages to ensure that the photocathodes are at the same potential as the surrounding water. Based on the experience of the Milagro project and Daya Bay experiment, a new waterproof potting method[8] is developed to keep the PMT base dry. The pinout of each PMT is encapsulated in a PVC housing by the epoxy. These potted PMTs work well during the operation.

To accurately measure the time and the charge of the air shower, many characteristics of PMTs should be tested. Therefore, the single photoelectron spectrum, high voltage response, non-linearity, dark noise rate, transit-time spread(TTS), rise time and so on are measured[9]. Due to the compromised factors of the dynamic range and signal's amplitude, all the PMTs are operated at a gain of 2×10^6. In order to measure TTS and rise time, a picosecond laser source(Hamamatsu C10196) that typically emits ultra-narrow pulse with $\sim$70ps FWMH width is used. A TDC module(CAEN V775) records the fluctuation of the transit time and an oscilloscope(Tektronix 3054B) reads the rise time. The methods of other tests listed above are similar to the Auger project's[10]. The peak-to-valley ratios(P/V) of all measured PMTs are larger than 2.5, which indicate that these PMTs have an excellent charge resolution. According to the relation of gain vs. HV($Gain \sim (HV)^{\beta}$), the β values are all close to 8. In addition, the non-linearities reach 10% at $\sim$700PEs for the current base design. To extend the range of linearity, a new voltage divider circuit that adds the signal readouts from the eighth dynode and tenth dynode will be adopted in the future. The dark noise rates are all close to 1KHz when the thresholds at 1/3PE. Furthermore, the TTS values, which are equal to $\sim$2.4ns, are very close to the values in the Hamamatsu's datasheet and the rise time values are all around 3.3ns.

2.2 The electronics system and the DAQ system

The electronics system consists of nine double-gain preamplifiers and a VME 9U electronics board. Each PMT signal is firstly sent to a preamplifier through an 11-meter-long cable. Then, the preamplifier divides the signal into two channels with two different gains($\times$1 and $\times$25). Thirdly, the signals are transferred to the electronics board through two 100-meter-long cables. Finally, the information regarding the signals' amplitudes and times is handled by the analog circuit and digitalizing circuit. The functions of the digitalizing board also deal with the GPS time, trigger pattern and data readout[11]. The time resolution of the readout electronics system is 0.89ns with a RMS of 0.45ns, and the discrimination of multiple hits with an interval time of >25ns is capable. The charge resolution of the single PE measurement is $\sim$30%. The time window of one event is from 2μs to 4μs.

The DAQ software is based on the BESIII[12] software framework, which configures the electronics module, reads the hits information of PMTs from the board via the VME bus, and then transfers the data to the local PC by the TCP/IP protocol. The running status and online histograms that are sampled from the data stream can also be shown on the screen. The long-term operation shows that the electronics system and DAQ system can satisfy our requirements. The upper limit of the data readout reaches $\sim$70kHz.

2.3 The water purification and recirculation system

Due to the effects of the bacteria, dust and ions, the natural water attenuation length is usually less than 10m. To ensure that the loss of the Cherenkov light is less than 20%, the water attenuation length must be larger than 20m in the detector cell. Thus, the pool water should be purified and recirculated. Therefore, a water purification and recirculation system is designed and deployed in the control room and the pool, which consists of the following parts: 1) a multimedia filter, 2) a carbon filter, 3) a fine filtration of 5μm, 4) a storage tank, 5) a fine filtration of 1μm, 6) an ultra-fine filtration of 0.22μm, and 7) a sterilization setup with UV lamps that have wavelengths of 254nm and 185nm. The whole system has a filling capacity of 85L/min. Furthermore, the circulation speed of this system is $\sim$30 days per a pool volume.

To monitor the real-time water quality, a water attenuation length measurement device was used in the control room, which is controlled by the slow control system(more details in the next section). The mechanism of the measurement is that the different water depths under a constant light beam lead to the different attenuation ratios of the light intensity. And the light received by the PMT at the bottom of the device is emitted by the LED on the top. After a period of recirculation, the water attenuation length of the pool could be more than 20m.

The serious radon radioactivity is found in the fresh water pumped directly from the well. This radiation produces the fluorescent light, and some of this kind of light can ultimately reach and fire the PMTs. When the pool is being filled, the PMT single channel rate can be as high as 60KHz. Fortunately, the half-life of radon is only 3.8 days, and as a result, its influence does not remain for too long if no new fresh water is added to the pool. However, this issue means that the waterproof of the pool must be well constructed and the water recirculation system should not use too much fresh water during the daily operation.

2.4 The slow control system

The development of this system is based on a single board computer(Technologic Systems, TS-7350) and a microcontrol unit. One of the main functions of this system is to monitor the environment parameters, such as the humidity, air pressure and temperature of the control room as well as the water level and temperature of the pool. In the future, this system will be designed to control the HV value of each PMT. The other function of this system is to control the operation of the water attenuation length measurement device, and it supplies the powers to the LED and PMT, reads the PMT signal and the water level and controls the water volume in the device. Figure 3 shows the variations of the water temperature in the pool through the winter season, which hints that the water in the pool would not freeze during the whole winter.

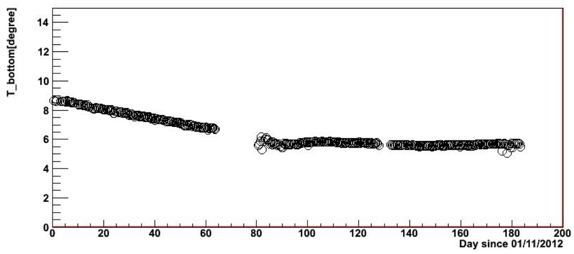

Fig. 3: The water temperature in the pool changes through the whole winter season.

2.5 The calibration systems

The measurement precision with respect to the time affects the angular resolution of the detectors. An optical system is applied to realize the time calibration. Nine equally long(30m) optical fibers which guide the uniformed LED light are separately attached near each PMT photo-cathode. All of the channels have nearly equal time offsets because the cable lengths of the PMTs, the electronics and the fiber lengths are nominally same. Moreover, one more set of fibers(45m) is added for the PMTs to verify the calibration with another LED light source. Consequently, the precision of the time calibration for the whole system (including the PMT and the electronics system) can reach 0.2ns[13].

Meanwhile, the measurement precision with respect to the charge affects the energy resolution of the detectors. A detailed description of the charge calibration system is given in the paper[7]. The precision of the charge calibration can be less than 5%.

3 Measurements and results

The engineering water Cherenkov detector array has been operated intermittently since August 2011. A series of experiment data have been obtained, such as the counting rates of the PMTs, the cosmic muon signals[7], the detected shower events and the angular resolution, which is estimated by the combined analysis with the ARGO-YBJ experiment.

3.1 The counting rates of the PMTs

When our experimental apparatus is submerged in water with an area of $25m^2$, the counting rate of each PMT increases because of the influence of the cosmic rays. Figure 4 shows the counting rate of each PMT at a threshold of $\sim$1/3PE when the water attenuation length is $\sim$7m. All of the PMTs have the counting rates of 22-30KHz. And deduced from these data, the counting rates at a 20m water attenuation length are estimated to be within the range 33-45KHz and averaged of 40KHz. The differences among the PMTs come primarily from the uncertainties of the thresholds. Unfortunately, this counting rate has not been exactly measured while the water quality is better than 7m because of the defect of the waterproof and the strong radon radioactivity. The counting rates of PMTs in the radon-contaminated water at a 20m attenuation length are $\sim$60KHz, which leads to a value of $\sim$40KHz after the radioactivity contribution subtracted. The single photoelectron signals dominate the counting rate in the detector cell, and the fitted values of single photoelectron peaks of each PMT are shown in Figure 4. And this peak position can be used to monitor the changes of the PMT gain and the stability of the electronics system[7].

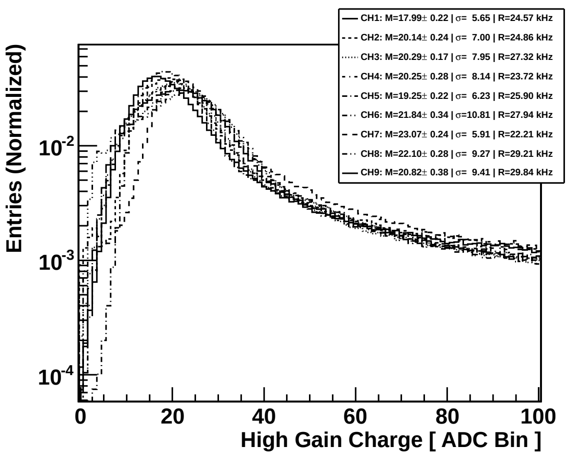

Fig. 4: The counting rate of each PMT in the pool.

In addition, no difference of the counting rates between measured in the day and night for each PMT is observed, which indicates that the light shielding of the engineering array is quite reliable.

3.2 The detected showers

When detecting the showers, the data is taken when the PMT multiplicity is ≥ 3 within the 100ns coincidence window. While the PMT multiplicity in the offline analysis is ≥ 5, the noise coincidence could be negligible. Therefore, under these conditions most of selected events should be the true shower events. By plane-fitting the arrival time of the photons from these events on each PMT, the distributions of the zeniths(theta) and azimuths(phi) of the shower directions can be derived as shown in Figure 5. The mean value of the distribution of the zeniths is 26°.

3.3 Combined analysis with the ARGO-YBJ experiment

Given that the area and the number of detector cells of the engineering array are very limited, the angular resolutions of the detected shower events are very difficult to estimate. Thus, the ARGO-YBJ experiment is used to aid this study. By matching the GPS times of events of the engineering array with the GPS times of ARGO-YBJ, the same showers that were simultaneously detected by these two experiments can be sorted out. The matching window of 1μs is chosen between these two GPS systems. After taking the trigger rate of these two experiments into account, it's obvious that the probability of the accidental trigger in a 1μs window is nearly close to zero. These shower cores are most likely distributed towards the north-west, where the engineering array is located at. This result confirms that

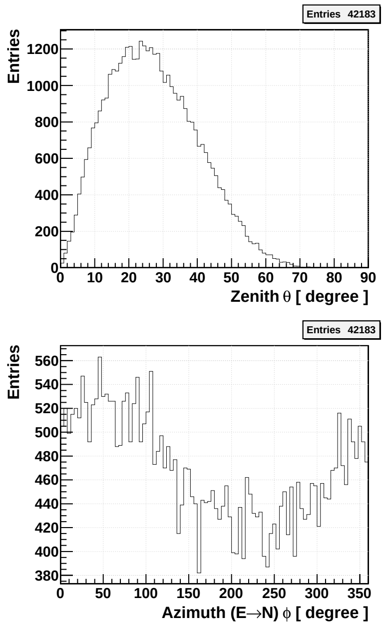

Fig. 5: The distribution of the zeniths(top) and azimuths(bottom) for the shower directions.

most of these matched signals from the two detectors came from the same showers.

The shower directions of the matched shower events from these two experiments are separately reconstructed. The space angles between these reconstructed shower directions are shown in Figure 6, whose peak is at 7.1°. These angles can be used to obtain the angular resolution of the engineering water Cherenkov detector array, which includes the contributions of the shower curvature($\sim 3.2°$) and the angular resolution of the ARGO-YBJ matched shower events($\sim 1°$). Subtracted from these two parts, the angular resolution of the engineering array is $\sim 6.3°$, which is approximately in agreement with the value of 6° by a simple estimation.

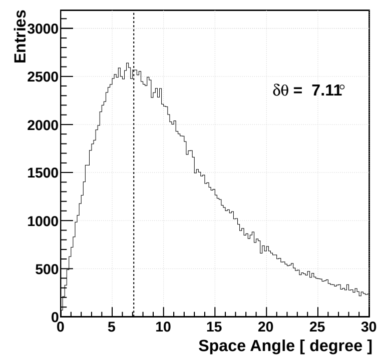

Fig. 6: The space angles of the reconstructed shower directions between the two experiments for the matched shower events.

4 Summary

After operating the engineering array of the LHAASO-WCDA project for more than one year, a great deal of important experience has been achieved. In addition, some related PMTs' characteristics are studied, a dedicated electronics board and a DAQ system for our experiment were developed, and the functions of a prototype slow control system were verified. Furthermore, a water purification and recirculation system was installed, and its preliminary running status shows that the pool water can be purified and maintained at a sufficient quality to satisfy the experiment.

The shower events have been detected by the engineering water Cherenkov detector array and reconstructed. Data analysis combined with the ARGO-YBJ experiment shows the angular resolution of the detecting showers is reasonable as expected, which also indicates the time measurement of the engineering array works well.

5 Acknowledgements

The authors express their gratitude to the ARGO-YBJ collaboration for providing their data for the combined analysis, and also thank the HAWC collaboration for many useful discussions.

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