Design of the photomultiplier tube bases for high dynamic range readout in WCDA *

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Abstract: The photomultiplier tube (PMT) used in the water Cherenkov detector array (WCDA) of the Large High Altitude Air Shower Observatory (LHAASO) requires a good single photoelectron (SPE) spectrum and a charge dynamic range from 1 to 4000 photoelectrons. In this paper, the bases design and improvement of the photomultiplier tube R5912 are presented. The results show that at the gain of 2.6×10^6, the anode output has a good single photoelectron spectrum, and its charge non-linearity is within 5% when the number of photoelectrons (nPE) is 3500. The charge non-linearity of the 8th dynode output is within 2% when the number of nPE is 4000, which satisfies the dynamic range requirement.

Key words: PMT, WCDA, charge non-linearity, SPE spectrum

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1 Introduction

The LHAASO project is planned to be built in China. As a large scale complex of many kinds of detectors, the origin of the cosmic ray, the search of very high energy gamma ray sources, and the precise measurement of the components at the knee region are the main scientific goals of the LHAASO [1]. The proposed detector consists of the following components:

1) a 1 km^2 extensive air shower array (KM2A), including 5137 scintillation detectors (ED) and 1161 muon detectors (MD);

2) 4 water Cherenkov detector arrays;

3) a 5000 m^2 shower core detector array (SCDA); and

4) a wide field of view Cherenkov/fluorescence telescope array (WFCA).

The water cherenkov detector has been proved to be an efficient technique in detecting air showers induced by cosmic rays. The WCDA is proposed to be constructed with the aim of gamma ray astronomy at energies between 100 GeV and 30 TeV. The whole WCDA will cover an area of 90000 m^2, configured as a whole octagonal pond or four individual small octagonal ponds depending on the engineering factors and the sensitivity optimization. The baseline detector design calls for 780×4 cells (5 m×5 m×4 m depth) each instrumented with a single 8-in PMT looking up at the bottom center to collect the cherenkov light produced by the shower particles in water [2].

The number of photoelectrons distribution for each PMT, obtained from a Monte Carlo simulation of gammas from the Crab nebula, which is shown in Fig. 1, is mainly concentrated on 1 photoelectron (43%), 2 photoelectrons (18%), and 3 photoelectrons (10%). For nPE>4000, the probability of occurence is less than 10^{-4}. Even for high energy gammas ($E>5$ TeV), this probability is also less than 4×10^{-4} [2, 3].

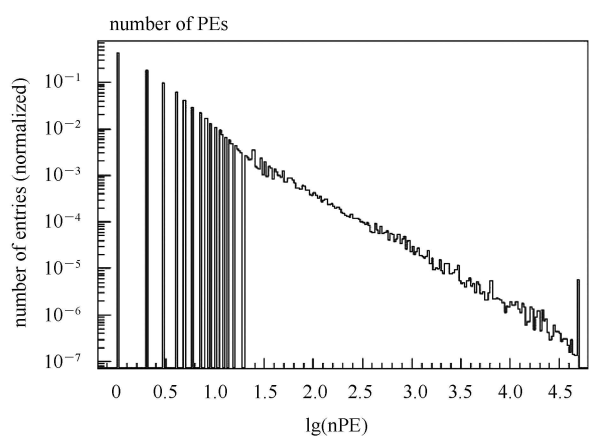

Fig. 1. The nPE distribution for each PMT.

Based on the simulation results, a good SPE spectrum and high dynamic range for PMT is required. Con-

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sidering the requirements of the experiment instrument and the scientific goal at the same time, the dynamic range demand is that the PMT charge non-linearity should be less than 5% from 1 to 4000 PEs. In view of the above requirements, the 8-inch hemispherical PMT R5912 [4], with 10 dynodes, produced by Hamamatsu, is chosen for testing.

Since the PMT base provided by Hamamatsu is designed for general use and its dynamic range is not satisfactory, a new PMT base should be designed to meet the needs of the WCDA. To determine the performance of the PMT, the SPE spectrum, high voltage response and charge non-linearity of the PMT are tested and analyzed.

2 Design and improvement of the base

In both direct current and pulse mode, when the light incident on the photocathode increases to a certain level, the relationship between the incident light and the output current begins to deviate from the ideal linearity, which is the so-called non-linearity. In pulse mode, the cause of non-linearity is mainly a space charge effect in the last several dynodes and anode. This space charge effect depends on the pulse height of the PMT output current and the strength of electric fields between electrodes. Two methods are applied to reduce the space-charge effect. One is to use decoupling capacitors, and the other is to use a tapered voltage divider circuit [5].

Since the base produced by Hamamatsu is not suitable for the WCDA, a new PMT base is designed and improved to ensure a larger dynamic range. The improvement is made as follows.

1) Using tapered voltage and adjusting the voltage ratio. The voltage of the first and later dynodes is stepped up while the voltage of middle dynodes is stepped down.

2) Using larger decoupling capacitors. The connection between decoupling capacitors is both serial and parallel.

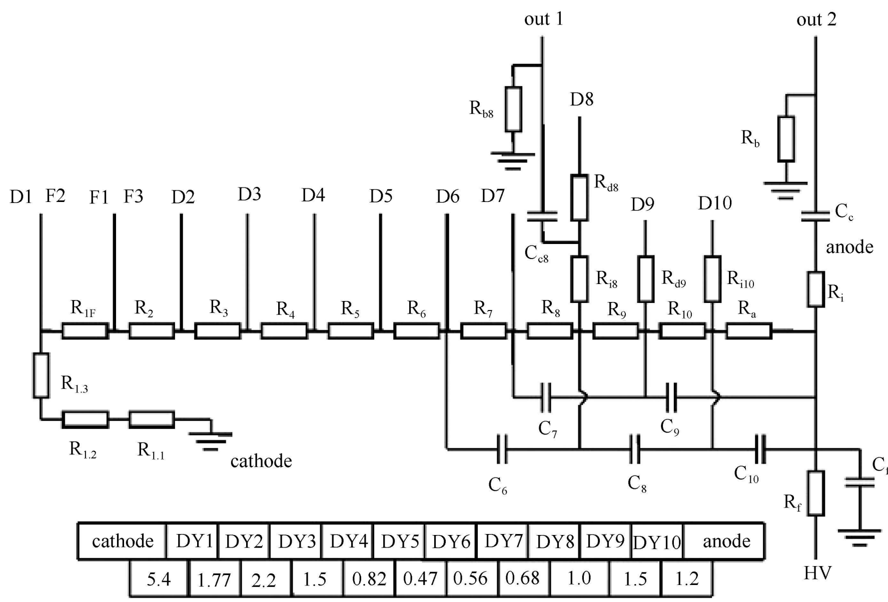

Fig. 2. Schematic of the PMT base.

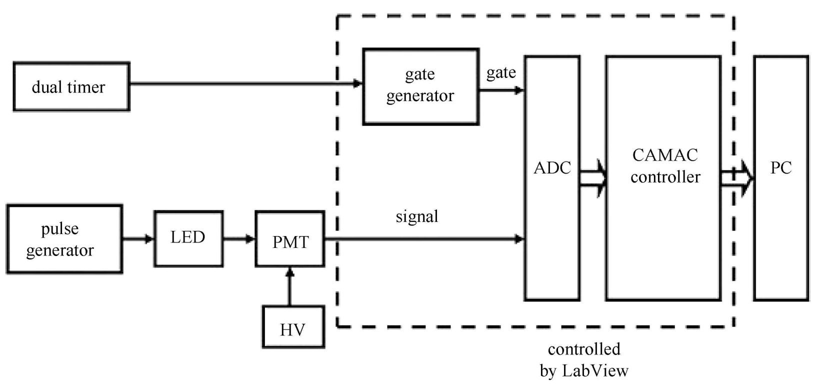

Fig. 3. The experimental setup.

3) With a view to the single photoelectron spectrum and the dynamic range, the anode signal and the 8th dynode signal are outputted at the same time. When one is tested, the other will be terminated by 50 Ω resistance. The improved PMT base is shown in Fig. 2. The division ratio in the dynodes resistance chain is shown in the table of Fig. 2.

3 The experimental setup

To test the performance of R5912, an experimental setup is built, shown in Fig. 3. A dual timer generates two synchronous NIM level signals, one is fed into a pulse generator and another into a programmable gate generator LRS/2323A. Photons are generated by a light source made with a blue LED, which is driven by a pulse from the pulse generator. The pulse width is 30 ns and the height of the pulse is varied to control the light intensity from the LED, which is an L-53MBC blue LED produced by the Kingbright Company [6]. The PMT's signal is fed to the ADC module to measure the total charge Q. The ADC module used in the exparement is LRS/2249W and the integral gate of 300 ns is controlled by the programmable gate generator. A homemade amplifier whose amplification is determined to 31 is used in the experiment [7]. The data transfer and control between the Computer Automatic Measurement And Control (CAMAC) system and the computer is realized by using LabView software.

The stability of the LED is determined before the test. Fig. 4 shows that the LED's stability is better than 1%.

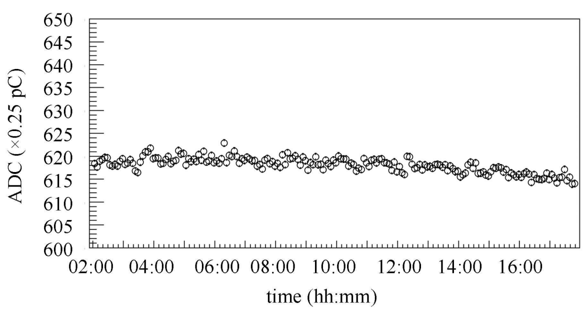

Fig. 4. Stability of the LED.

4 Results

4.1 Single photoelectron spectrum

The SPE spectrum is measured in order to get the absolute gain of the PMT.

Under real circumstances the number of photons hitting the photocathode is not a constant but a Poisson distributed variable. The conversion of photons into electrons and their subsequent collection by the dynode system is a random binary process. Therefore the distribution of the number of photoelectrons can be expressed as a convolution of Poisson and binary processes. This again gives a Poisson distribution:

$$p(n;\lambda)=\frac{\lambda^n e^{-\lambda}}{n!}, \quad (1)$$

where λ is the mean number of photoelectrons collected by the first dynode, $p(n;\lambda)$ is the probability that n photoelectrons will be observed when their mean is λ.

The response of a multiplicative dynode system to a single photoelectron can be approximated by a Gaussian distribution:

$$G_1(x)=\frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{(x-\mu)^2}{2\sigma^2}}, \quad (2)$$

where x is the variable charge, μ is the average charge at the PMT output when one electron is collected by the first dynode, and σ is the corresponding standard deviation of the charge distribution.

The PMT output charge distribution when more than one photoelectron is collected by the first dynode can be derived from Formula (3) if one assumes that the amplification processes of the charges initiated by different photoelectrons are mutually independent. In this case, the charge distribution when the process is initiated by n photoelectrons is a convolution of n one-electron cases:

$$G_n(x)=\frac{1}{\sigma\sqrt{2\pi n}}e^{-\frac{(x-n\mu)^2}{2n\sigma^2}}. \quad (3)$$

In the SPE spectrum, an additional Gaussian function is fitted to describe the pedestal. Then the resulting spectrum is a convolution of Formula (1), (3) and pedestal [8].

Figure 5 shows the R5912 anode SPE spectrum at 1400 V with the amplifier while Fig. 6 is without the amplifier. Fig. 7 is the anode SPE spectrum at 1000 V with amplifier. In each SPE spectrum, the leftmost Gaussian distribution is the pedestal and the right Gaussian distributions correspond to 1, 2 and 3 photoelectrons.

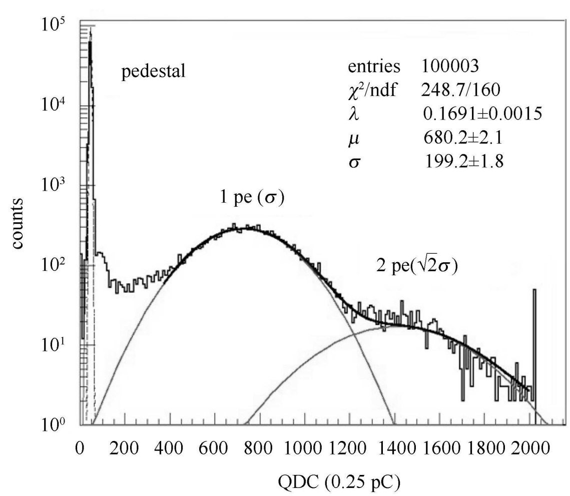

Fig. 5. The SPE spectrum at 1400 V with an amplifier.

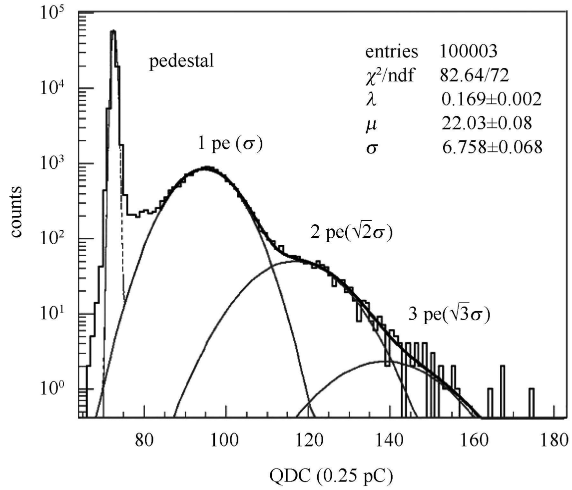

Fig. 6. The SPE spectrum at 1400 V without an amplifier.

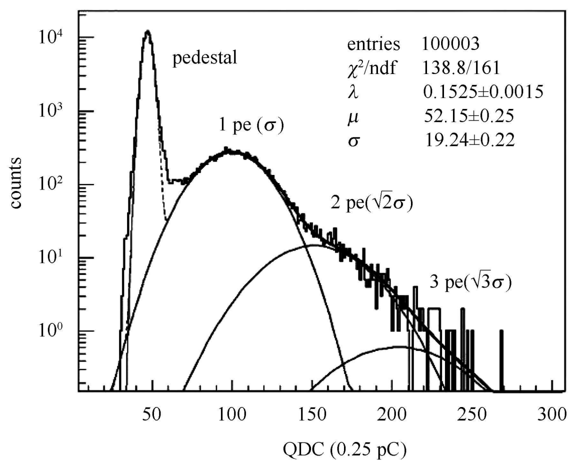

Fig. 7. The SPE spectrum at 1000 V with an amplifier.

4.2 Gain

The voltage dependance of the PMT gain (high voltage response) can be formulated with the following function:

$$\text{gain}=A\times V^{\alpha}. \tag{4}$$

where A is a constant and α is called the amplification voltage coefficient related to dynode material and geometric structure. The SPE spectrum at different voltage, which is from 1000 V to 1400 V with a step of 50 V, is acquired with the amplifier to calculate the corresponding gain. Then α can be obtained through the fit of Formula (4), shown in Fig. 8. The result shows that α is 7.445±0.021, then the working high voltage is selected at 1000 V to get the gain of 2.6×10^{6}. Fig. 9 shows the energy resolution at each voltage.

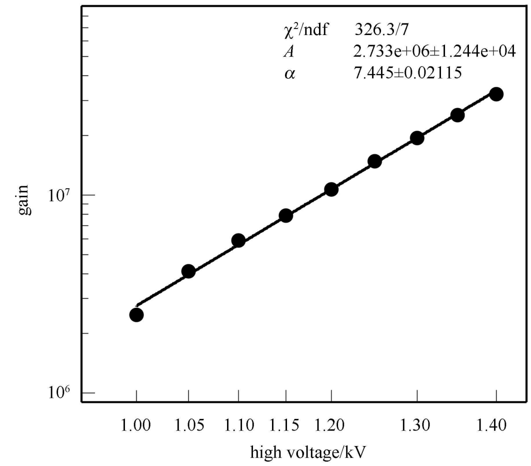

Fig. 8. High voltage response.

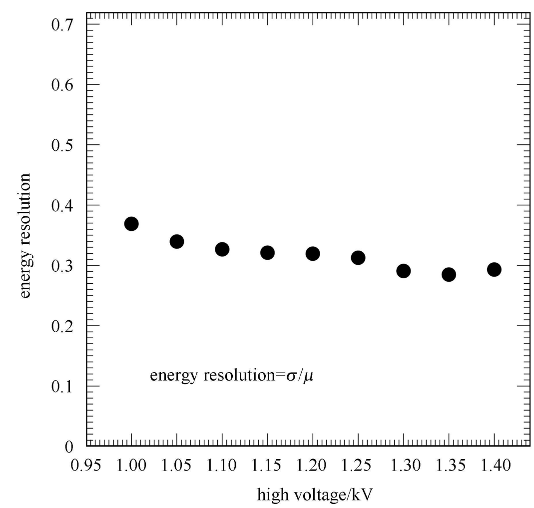

Fig. 9. Energy resolution.

To obtain the gain of the 8th dynode, the ratio of anode output and the 8th dynode output is attained. Fig. 10 shows that the ratio is 36.4 at 1000 V.

4.3 Non-linearity

The A-B method is used to determine the non-linearity of PMT [9]. An array of two LEDs, $L_{\rm A}$ and $L_{\rm B}$ is deployed, with the two LEDs acting as the light sources. These two LEDs can be lit individually or together at the same time, while the charge of the PMT pulse is measured, marked with $Q_{\rm A}$, $Q_{\rm B}$ and $Q_{\rm C}$ for cases of $L_{\rm A}$, $L_{\rm B}$ and both together, then the charge non-linearity is defined as follows:

$$\text{non-linearity}=\frac{[Q_{\rm C}-(Q_{\rm A}+Q_{\rm B})]}{Q_{\rm A}+Q_{\rm B}}. \tag{5}$$

The charge non-linearity of the anode and the 8th dynode at 1000V is tested with the A-B method. The result shows that the anode charge non-linearity exceeds

−5% when the nPE is 3500 and the 8th dynode non-linearity is within 2% when the nPE is 4000, which is shown in Fig. 11. When non-linearity is calculated with Formula (5), there is non-linearity in $Q_{\rm A}$ and $Q_{\rm B}$, so the corrected $Q'_{\rm A}$ and $Q'_{\rm B}$ should be used to replace $Q_{\rm A}$ and $Q_{\rm B}$. For the anode output, the correction shows that the charge non-linearity is −3% at 3500 PEs. For the 8th dynode, as the non-linearity is always within 1%, the correction shows that the charge non-linearity is still within 2%.

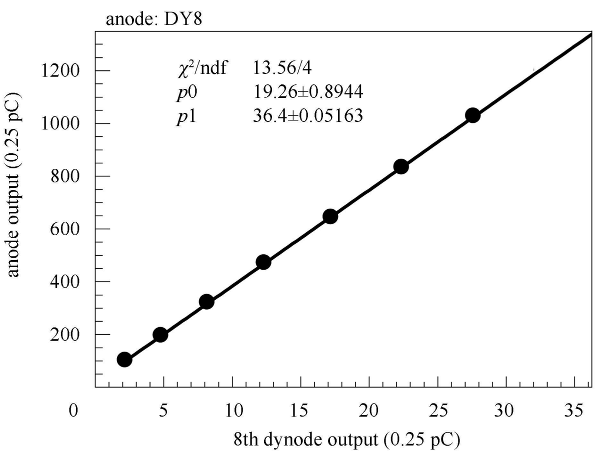

Fig. 10. The ratio of anode and the 8th dynode output at 1000 V.

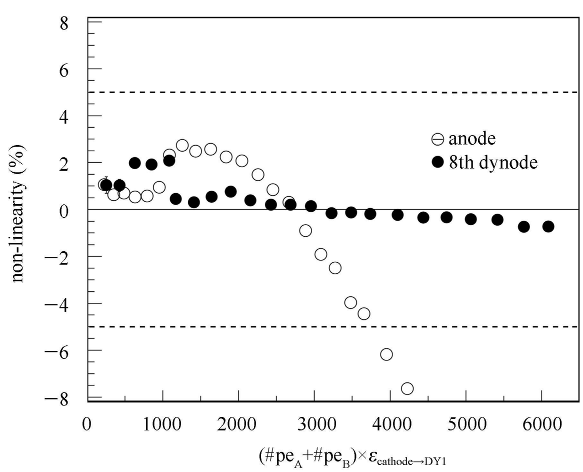

Fig. 11. The charge non-linearity of the anode and the 8th dynode. The x axis is the mean number of photoelectrons collected by the first dynode.

Figure 12 shows the anode current non-linearity. The current non-linearity exceeds −5% when the anode current is about 54 mA. The nPE is 3000 when the anode current is 50 mA, which indicates that the current non-linearity is worse than the charge non-linearity.

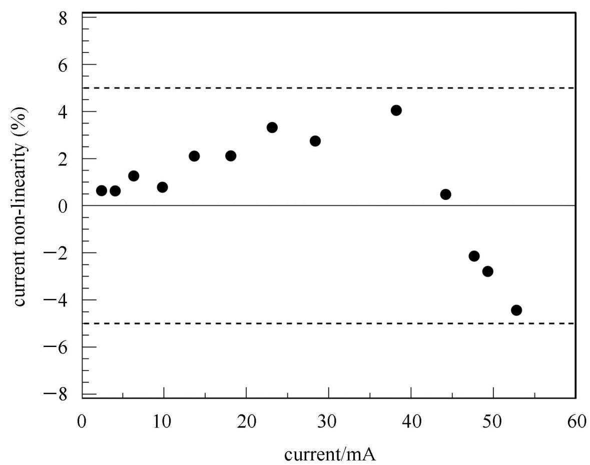

Fig. 12. Anode current non-linearity.

5 Conclusion

A PMT base is designed and improved for a good SPE spectrum and a large dynamic range readout in WCDA. The SPE spectrums at various voltages are measured to obtain the gain. The working voltage of the PMT is selected at 1000 V for a gain of 2.6×10^6 and a good SPE spectrum can be acquired at this gain with the amplifier. Meanwhile, the charge non-linearity test shows that the anode non-linearity is within 5% at 3500 PEs and the 8th dynode non-linearity is within 2% when the nPE is 4000, which meets the dynamic range demand in the WCDA.

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