The performances of photomultiplier tube of WCDA++ in LHAASO experiment

Hengying Zhang[1], Yanhong Yu[1], Khuram Tariq[1], Zongkang Zeng[2,3], Xiurong Li[2], Cheng Liu[2], Dong Liu[1], Cunfeng Feng[1]

1. Shandong University, Qingdao266237, China

2. Institute of High Energy Physics, Chinese Academy of Sciences, Beijing100049, China

3. University of Chinese Academy of Sciences, Beijing100049, China

On behalf of LHAASO Collaboration

Introduction

The Water Cherenkov Detector Array (WCDA) is one of the major components of Larger High Altitude Air Shower Observatory (LHAASO at 4410 m a.s.l), which focuses on surveying the γ ray sources from 100GeV to 30TeV[1,2]. In order to extend the dynamic range of WCDA to 10PeV, an 1.5-inch photomultiplier tube (PMT) is placed aside the 8-inch PMT in each cell of WCDA. All(900) 1.5-inch PMTs constitute the WCDA dynamic extended system (called WCDA++).

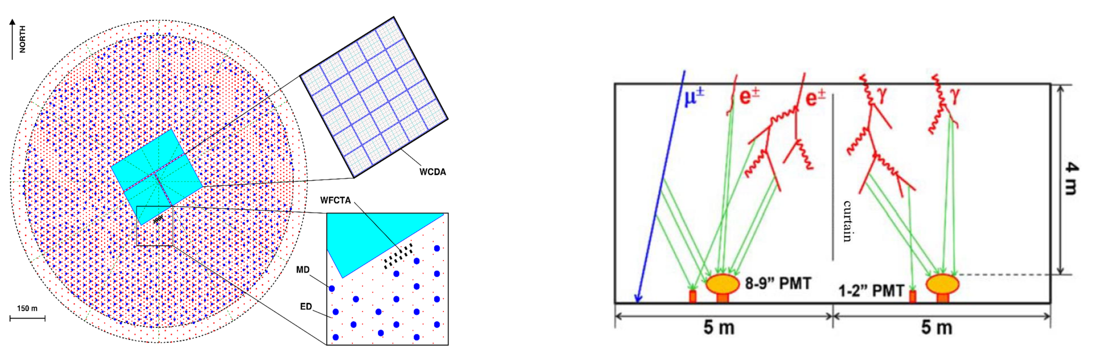

Fig. 1 Layout of the LHAASO experiment (left). profile of two adjacent WCDA pools(right).

XP3960 PMT and divider circuit design

Table 1. The performance of 1.5-inch PMT.

parameters	HZC's response
QE×CE@420 nm	25%
Dark rate@1mV	<200Hz
Nonlinearity	<5%@20-200kPEs
ADratio	90~150

XP3960 photomultiplier tube is manufactured by Hainan Zhanchuang Photonics Technology Co.,Ltd (HZC).
The divider circuit with bi-readout (anode and 6th dynode) was designed as shown in Fig.2.

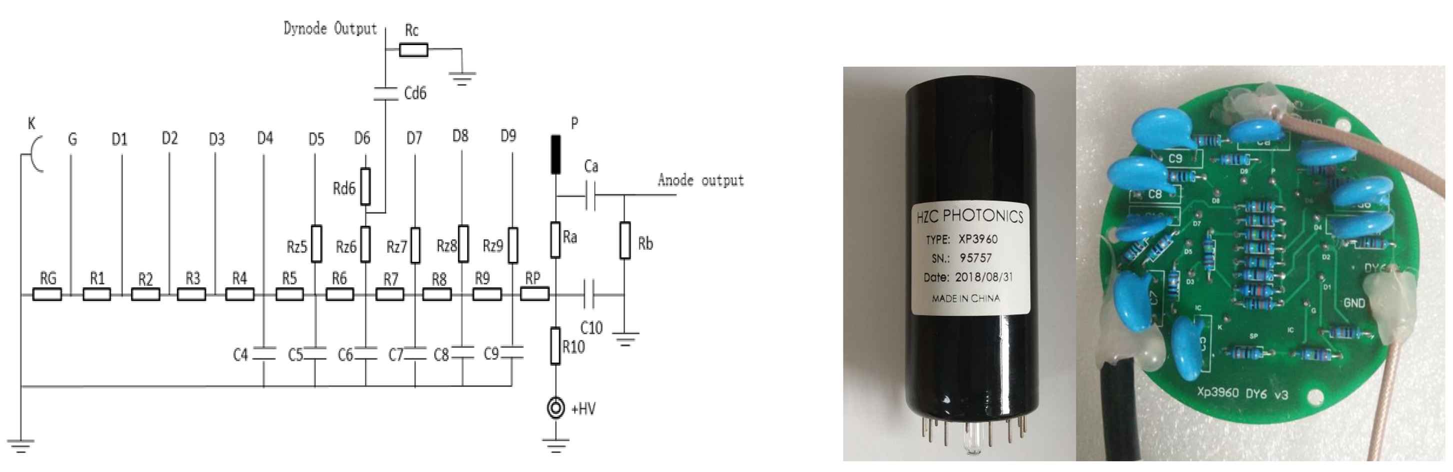

Fig. 2 Diagram of the divider circuit (left). The picture of the PMT and the divider (right).

The PMT test bench

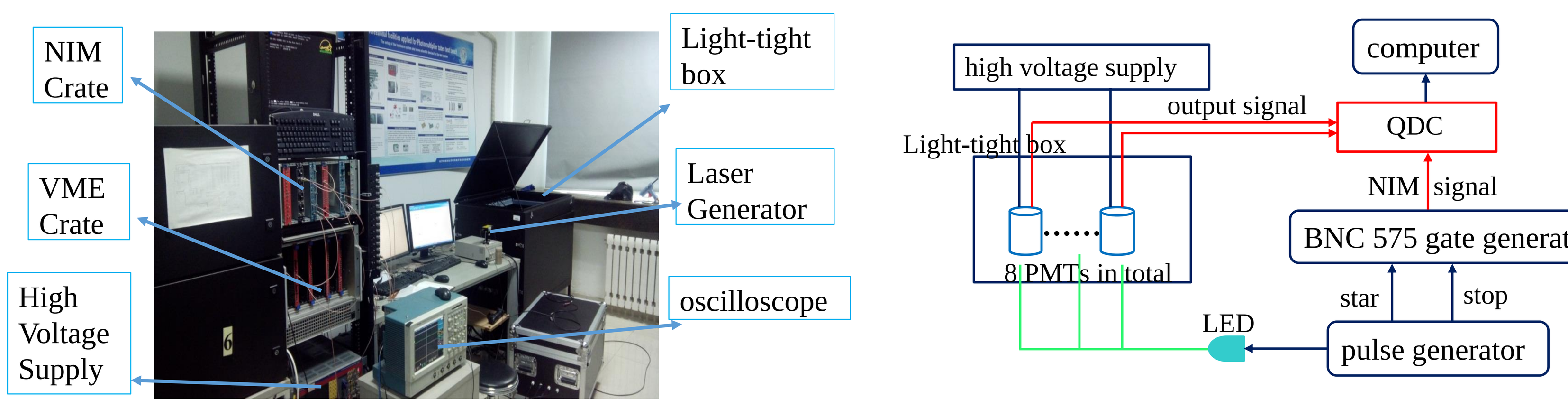

Fig. 3. The picture of PMT test bench (left) and the schematic of PMT test (right).

The batch test system was set up in Shandong University. The detailed information can be found[3]. Single photoelectron(SPE) spectrum, high voltage response and dark noise rate is tested by this system.

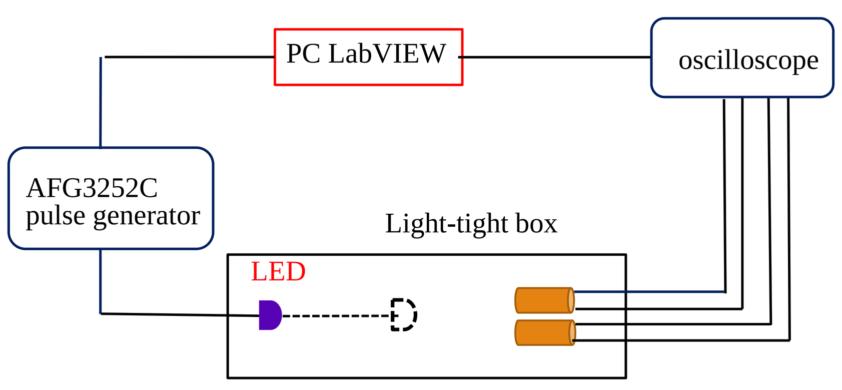

Fig. 4. Charge non-linearity test schematic.

The dynamic linearity range of anode and dynode was measured simultaneously by the bi-distance method. Non-linearity test system was set up as shown in Fig.4. Two PMTs' anode and 6th dynode output charge is read by PC LabVIEW. This charge is measured by oscilloscope.

1. The effect of pulse width on maximum number of photoelectrons (nPEs)

The pulse width of signal generator is set at 5.5ns, 15ns and 30ns, and the frequency is kept at 5kHz during the test process to study the pulse width effect on maximum nPEs. It turned out that the dynamic linearity range extend along with the increase of pulse width, as shown in Fig.5.
Since the arrival time of Cherenkov light is very narrow[4], 5.5ns pulse width was selected in the test process.

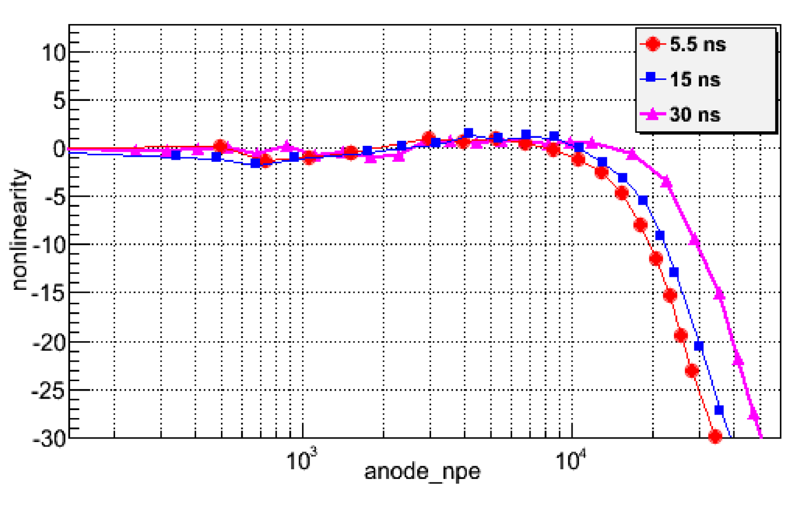

Fig. 5. The effect of pulse signal width on maximum number of photoelectrons.

2. The effect of driven voltage on the relation between Gain and high voltage

In the linear region, three LED driven voltages of signal generator are selected, the anode and 6th dynode output charge are measured under different high voltages. In linear region, the relation between Gain and high voltage does not change with driven voltage, in Fig.6. Light intensity did not affect β also. The exponential relationship between anode or dynode output charge with different high voltage is agree with the equations(1)(2).

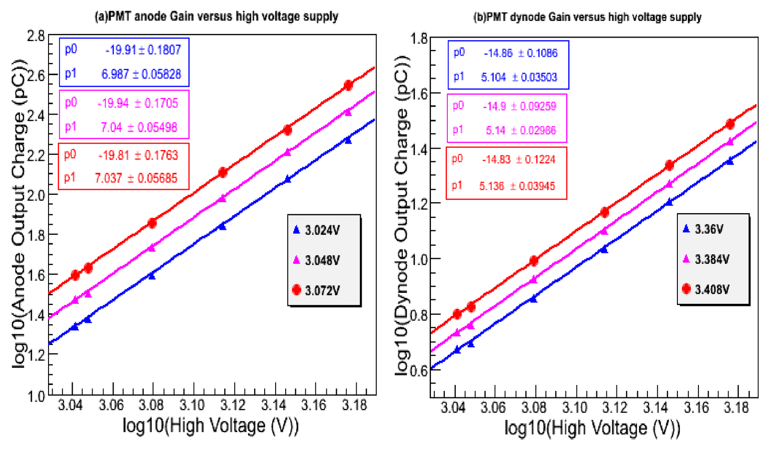

Fig. 6 The relation between Gain and high voltage under different driven voltage.

$$G = \prod_{i=1,n} c_i\,\delta_i = \left(\prod_{i=1,n} c_i\right)\left(\prod_{i=1,n}\frac{V_i}{V}\right)^k a^n V^{nk} = AV^{\beta} \quad (1)$$

$$G_d = \prod_{i=1,m} c_i\,\delta_i - \prod_{i=1,m-1} c_i\,\delta_i = \left(\prod_{i=1,m} c_i\right)\left(1-\frac{1}{c_m a V_m^k}\right)\left(\prod_{i=1,m}\frac{V_i}{V}\right)^k a^m V^{mk} = A'V^{mk} \quad (2)$$

3. The effect of high voltage on ADratio

The gain ratio of anode and dynode(ADratio) varied with the high voltage, as shown in Fig.7. Charge non-linearity test should be use the high voltage under the Gain at 2e+05. The equation(3) is the ratio of equation(1)&(2) called ADratio. There is a linear relation between log10(ADratio) and log10(high voltage).

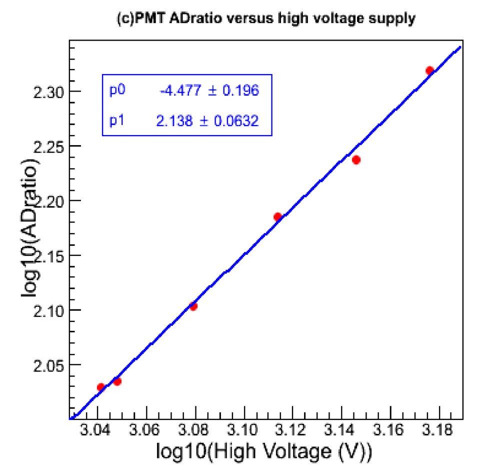

Fig. 7 The ADratio under different high voltage.

$$ADratio = \frac{G}{G_d} = \left(\prod_{i=m+1,n} c_i\right)\left(\prod_{i=m+1,n}\frac{V_i}{V}\right)^k a^{n-m}V^{n-mk} \Big/ \left(1-\frac{1}{c_m a V_m^k}\right) = A''V^{(n-m)k} \quad (3)$$

PMT test results

SPE, High voltage response, non-linearity

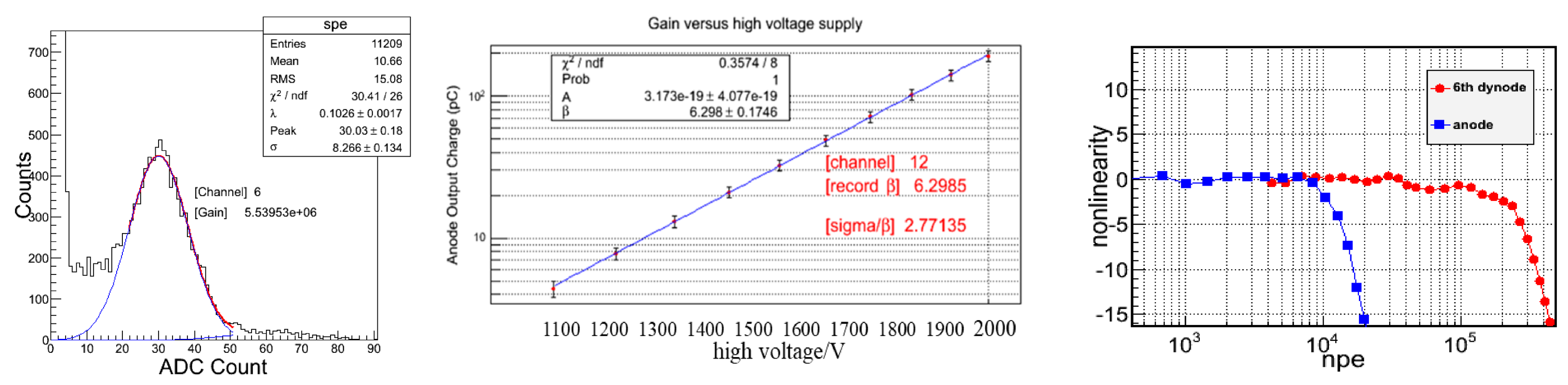

Fig. 8. PMT SPE spectrum(left), High voltage response(minddle), non-linearity curves(right).

The PMT SPE spectrum is tested at 2000V positive voltage, as shown in the left of Fig.8. The anode output charge is measured at different high voltage which varied from 1100V to 2000V with a step of 100V, as shown in the middle. The right part of figure shows the non-linearity result for both anode and dynode.

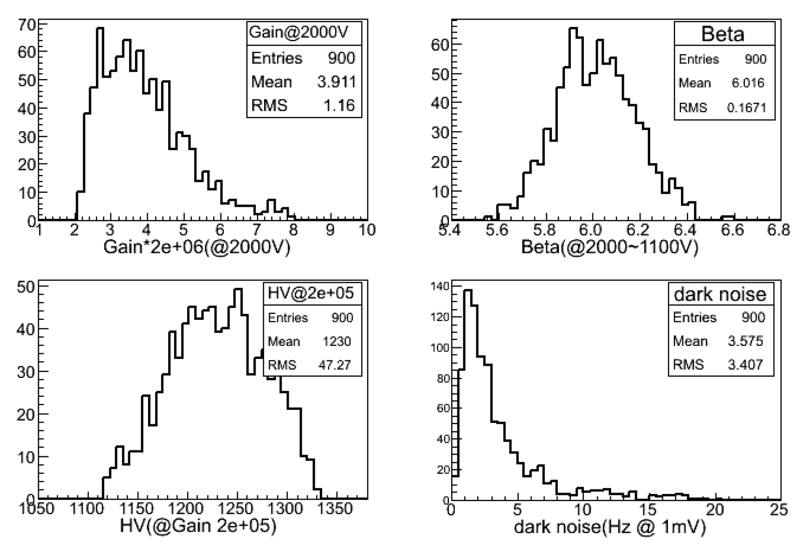

Fig. 9. gain, beta, working high voltage and dark noise rate distribution.

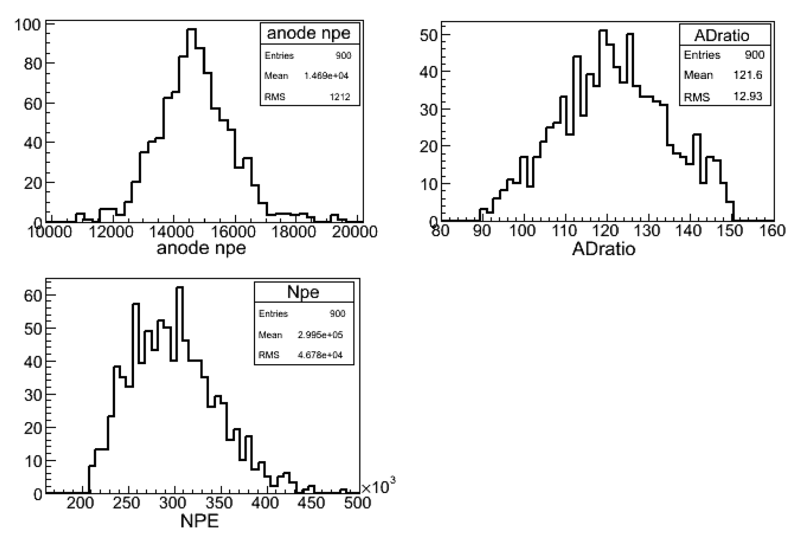

Fig.10. the distribution diagram of charge non-linearity test.

All distribution of test items are shown in Fig.9 and Fig.10. The results of all PMTs are meet the requirements of 1.5-inch PMT's performance listed in the Tab.1.

Conclusions

All 1.5-inch PMTs with special designed bi-readout voltage divider are tested by this PMT test system. The effect of working high voltage and signal width on the dynamic range of these PMTs are studied. The dynamic range within 5% charge non-linearity under signal width of 5.5ns is more than 200 kPEs (Photoelectrons). The dark noise count rate is less than 200Hz under the 1mV threshold at PMT gain of 2e+05. These results confirmed that PMTs' performance meet the WCDA++ requirements.

Reference

1. Zhen, Cao. *A future project at Tibet: The large high altitude air shower observatory (LHAASO). Chinese Physics C. 34. 249(2010). 10.1088/1674-1137/34/2/018.*
2. He, Huihai. *Design of the LHAASO detectors. Radiation Detection Technology and Methods. 2(2018). 10.1007/s41605-018-0037-3.*
3. Wang, Xu, et al. *Setup a photomultiplier tube test bench for use at LHAASO-KM2A. Chinese Physics C. 40(2015). 10.1088/1674-1137/40/8/086003.*
4. Zhao, X, et al. *Characterization of HZC XP1805 photomultiplier tube for LHAASO-WCDA with a high dynamic range base. Journal of Instrumentation. 11(2016). P10012-P10012. 10.1088/1748-0221/11/10/P10012.*