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A study about effects of background light on the gain of Photomultiplier Tubes

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Photomultiplier Tubes (PMT) are mostly used in air Cherenkov light detection in extensive air shower of cosmic rays. The Cherenkov telescopes work at clear and moonless nights, therefore it is susceptible to the background of stars in the sky; and with the Earth's rotation and revolution, the affection of background is different yet. In this case, we conducted an experiment to evaluate the impact of night-sky background (NSB) to the gain of PMTs. By optimizing the voltage divider of PMT, one can decrease the influence brought by NSB on the gain of PMT.

35th International Cosmic Ray Conference — ICRC2017
10–20 July, 2017
Bexco, Busan, Korea

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PoS(ICRC2017)382

1. Introduction

Wide Field of View Cherenkov Telescope Array (WFCTA) is one of the main detectors of Large High Altitude Air Shower Observatory (LHAASO) [1]. Two telescopes prototype have been operated successfully at YBJ cosmic ray observatory in Tibet [2]. The WFCT works like Imaging Atmospheric Cherenkov telescope (IACT) which is widely used in many experiments, such as MAGIC [3], HESS [4], and CTA [5]. WFCTs detect the Cherenkov light in the extensive air shower initiated by cosmic rays.

The main parts of the telescopes are the spherical mirror and PMT array. The spherical mirror has a effective area of $5m^2$ to collect Cherenkov light and reflect it to the camera. The camera is composed of 1024 PMTs and the pixel of each PMT is 0.5°, watching a FOV of $14^\circ \times 16^\circ$. The electronic system follows the camera. All the parts of telescope are placed in a container for the convenience of movement and arrangement.

The PMT array as one of the most important parts of WFCTs, its performance need to meet various requirements, such as size, quantum efficiency, dynamic range and linearity, night-sky background (NSB) affect, and so on. In this paper, the variation of gain of PMTs at strong starlight background is discussed.

It was found that the gain of PMT varies with the size of background light, tube itself, and the voltage divider. The former two factors are easily to understand. Both background photons received by PMT and the structure and material of PMT have effects on the gain of PMT. The latter one is more interesting but it is not incomprehensible. Different dividers allow different gains of PMTs because they allow different voltage among dynodes of PMT. However, the occurrence of background light would cause a DC current which can change the voltage among dynodes. Therefore the gain of PMT varies.

In section 2, the description about the influence of DC background light on PMT gain is presented; section 3 is the mainly part for this measurement. Section 4 gives the conclusion.

2. Influences of background light on PMT gain

Take an iterative divider ($R = R_1 = R_2 = ... = R_N$) as an example, as shown in FIG. 1. R is the value of the resistors and N represents the number of dynodes.

At this divider, the gain is

$$G_m = KV_{ht}^{N\alpha} \tag{2.1}$$

where V_{ht} is the high voltage; α is usually between 0.6 and 0.8; and K is an constant;

For the divider current,

$$I_p = \frac{V_{ht}}{(N+1)R} \tag{2.2}$$

when there is no anode current I_a, the gain can be written to

$$G_m = K^{'} R^{N\alpha} I_p^{N\alpha} \tag{2.3}$$

When there is an anode current I_a, the divider current I_p changes to:

$$I_p^{'} = I_p + \Delta I_p = I_p + \frac{1}{N+1}\sum_{i=0}^{N} I_i \tag{2.4}$$

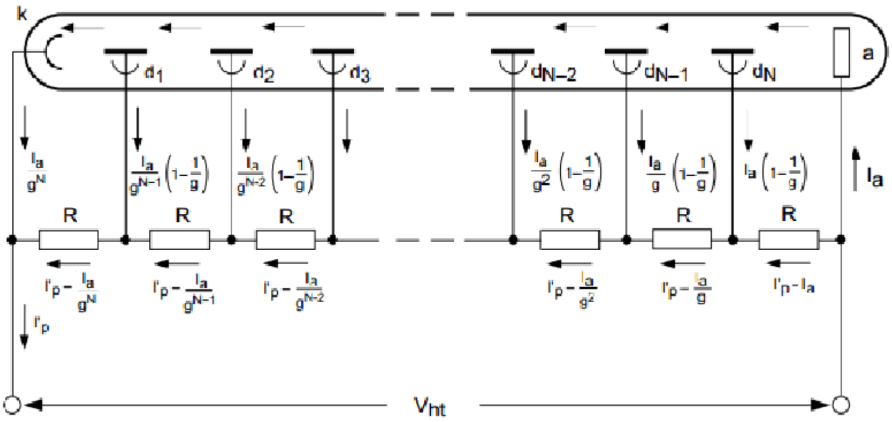


Figure 1: Current distribution in an iterative voltage divider

where $I_i = I_a/g^{N-i}$.

Then the gain changes to

$$G = K^{''} R^{N\alpha} \prod_{i=0}^{N-1} (I_p + \Delta I_p - I_i)^{\alpha} \tag{2.5}$$

Thus, the ratio of the gain is

$$\frac{G}{G_m} = \prod_{i=0}^{N-1} (1 + \frac{\Delta I_p - I_i}{I_p})^{\alpha} \tag{2.6}$$

If we neglect terms higher than the first order, Eq. 2.6 can be written to:

$$\frac{G}{G_m} = [1 + \sum_{i=0}^{N-1} (\frac{\Delta I_p}{I_p} - \frac{I_i}{I_p})]^{\alpha} \tag{2.7}$$

By Setting the gain of each stage g_i is the same $g_i = g$ and $g^N >> 1$, Eq. 2.7 can be simplified to

$$\frac{\Delta G^{'}}{G} = \frac{G - G_m}{G} \approx \alpha \frac{N}{N+1} \frac{I_a}{I_p} \tag{2.8}$$

As shown in formula (2.8), the occurrence of anode current I_a can make the divider current I_p change and cause an increase of gain. Moreover, the more background photons, the lager anode current. More detailed derivation process can be found in ref [6].

However, the actual situation is much more complicated. Firstly, the divider is usually not iterative so that the quantitative calculation would be much more difficult. Secondly, formula (2.1) is established at the assumption that the collection efficiency of all stages approaches 100% [6]. Finally, the setting $g_i = g$ means that the secondary emission coefficient (δ_i) of ith dynode and its collection efficiency (η_i) are the same because the gain of each stage is $g_i = \delta_i \eta_i$ theoretically.

Actually, because of the material, structure and manufacturing process of PMTs, the latter two conditions are difficult to meet. Furthermore, g_i varies with voltage of the ith dynode and the tendency of the variation is different yet. So the voltage divider is optimized in order to achieve the design requirements of WFCTA.

3. Measurements and Discussion

3.1 Introduction of measurement system

A test system was set up to measure impacts on the relative gain of tubes brought by these factors respectively. As shown in FIG. 2, a 3 m × 1 m × 1.5 m darkroom had been built up to place the PMT and light emitting diodes (LED). The LED is driven by a signal pulse generator. PMT is powered by negative high voltage power supply and its output signals are displayed by an oscilloscope and the waveform is recorded by the PC.

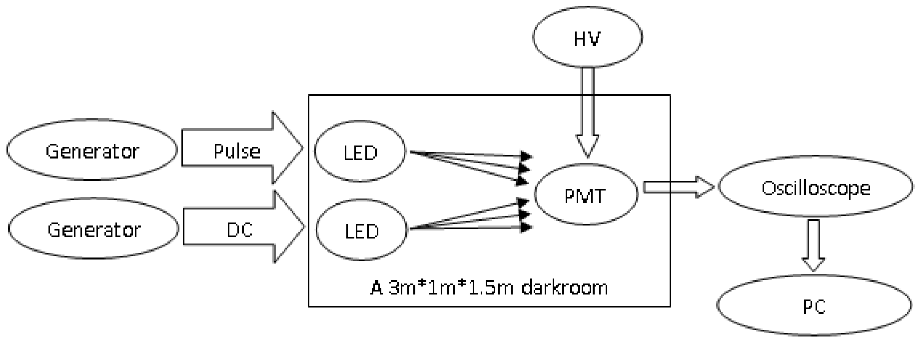


Figure 2: The measurement flow diagram

We used two signal pulse generators to drive two LEDs respectively. One is used to generate pulses with a Full Wave at Half Maximum (FWHM) 20ns and a frequency of 20Hz. This signal is used as the Cherenkov signal that produced in the extensive air shower of cosmic rays. The other is used to generate direct current (DC) signal as the night-sky background.

The PMT output charge at only pulse signal is recorded as Q_0 and charge at the same pulse signal plus DC signal is recorded as Q, so the variance of the relative gain can be defined as $\Delta G/G = (Q-Q_0)/Q_0 \times 100\%$. Ideally, $\Delta G/G=0$; however, it depends heavily on the strength of background light, PMTs and the high-voltage divider.

3.2 The ratio variation with different dividers

For the requirements of WFCTA, there are three voltage dividers. They are implemented with different resistances ($300K\Omega$ and $100K\Omega$) so five dividers need to be measured. As shown in Table 1.

Table 1: The specific ratio of voltage of different dividers. The voltage ratio of divider4 is the same as divider1 and divider5 is the same with divider2 but they are implemented with different resistances.

NO.	Ratio of voltage
Divider 0	3:1:1.5:1:1:1:1:2:3:3.6:3.3 $1 = 300K\Omega$
Divider 1	3:1:1:1:1:1:1:1.5:2:1:1 $1 = 300K\Omega$
Divider 2	3:1:1:1:1:1:1:1:1:1:1 $1 = 300K\Omega$
Divider 3	3:1:1.5:1:1:1:1:2:3:3.6:3.3 $1 = 100K\Omega$
Divider 4	3:1:1:1:1:1:1:1.5:2:1:1 $1 = 100K\Omega$

Two PMTs, NO.ZR5842 and NO.ZR5867 type of R7899, manufactured by Hamamatsu are used for testing.

Before test, the gain of PMT should be adjusted to 2×10^5 at different dividers. This is also the gain that WFCTA uses in the actual work.

First of all, the single photoelectron peak has been tested at divider1 at 1400V as shown in FIG. 3.

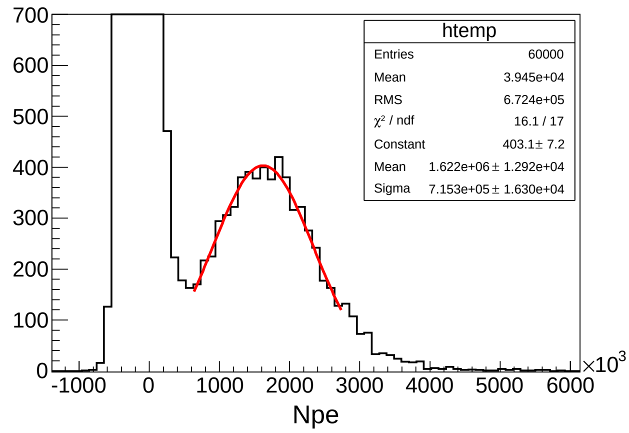


Figure 3: the single photoelectron peak of R7899-ZR5867 measured at 1400V.

Then, beta of this PMT is measured to be 6.753 through fitting by formula (3.1).

$$Q = KV^{\beta} \tag{3.1}$$

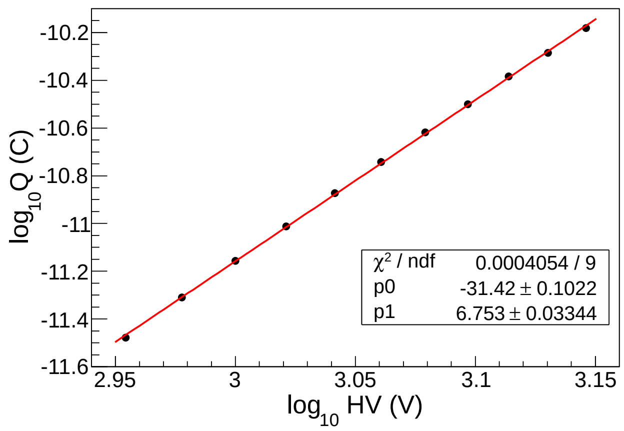


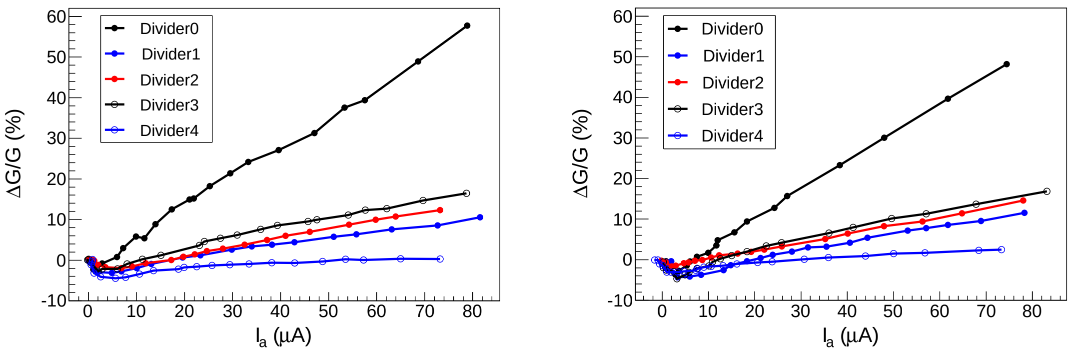
Figure 4: the fit of Q-V curve of R7899-ZR5867.

Furthermore, by formula (3.2) the operating voltage of ZR5867 at the gain of 2×10^5 is 1027V.

$$\frac{G}{G_0} = (\frac{V}{V_0})^{\beta} \tag{3.2}$$

At last, the operating voltage of ZR5867 at other dividers is determined through adjusting their relative gain consistent with divider1.

After determining the operating voltage, influences of the background light can be carried out. Test results are shown in FIG. 5. $\Delta G/G$ is increasing as a whole while declining when anode current caused by background light is small.



(a) ZR5876 (b) ZR5842

Figure 5: The gain of PMTs varies with anode current caused by background light at different dividers.

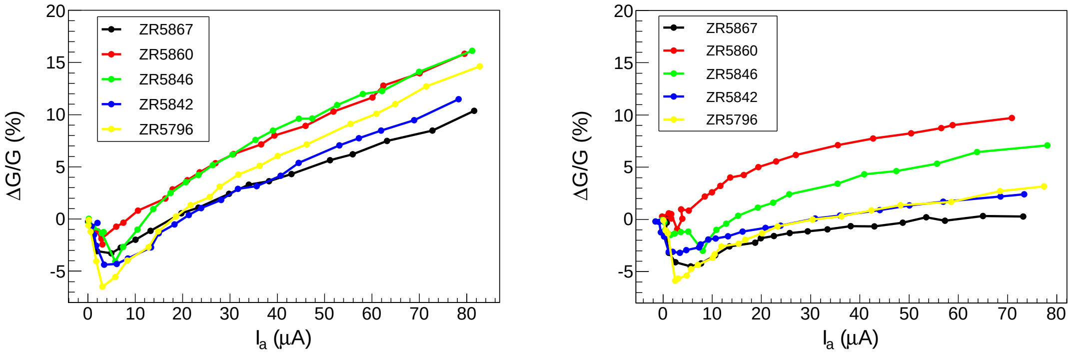
$\Delta G/G$ is larger at voltage ratio 3:1:1.5:1:1:1:1:2:3:3.6:3.3 (black line in FIG. 5 divider0 and divider3); and $\Delta G/G$ is smaller at voltage ratio 3:1:1:1:1:1:1:1.5:2:1:1 (blue line in FIG. 5 divider1 and divider4). Besides, the divider using $100K\Omega$ resistors (circle points in FIG. 5 divider3 and divider4) has a smaller $\Delta G/G$ than using $300K\Omega$ (solid points in FIG. 5 divider0 and divider1) at the same voltage ratio. Formula(2.8) gives the explanation for the latter result. The small resistance divider has a high divider current I_p, so $\Delta G/G$ becomes smaller.

While there are negative excess more than 2% when $I_a < 10\mu$A and even reach to 5%. The cause of this declining is not clear. But it doesn't affect the application of PMT on WFCTA so much. Since according to the measurement of two prototype WFCTs at Tibet, the NSB is about 1.3 photo-electrons/20ns, concerted to an 2.08 μA direct current of PMT output signal at a gain of 2×10^5. By cautious calibration, the gain can be corrected by increasing the high voltage.

3.3 The gain variation of the different PMTs

Five PMTs have been compared to estimate the difference of $\Delta G/G$ brought by background light. The measurement is carried out at divider1 and dicider4, that is $3:1:1:1:1:1:1:1.5:2:1:1$, where $1 = 300K\Omega$ and $1 = 100K\Omega$; and relative gain of different PMTs is also 2×10^5 at these dividers. This divider is designed to achieve large dynamic range by means of simultaneous readout of anode and the eighth dynode. FIG. 6 and FIG. 7 show variation of $\Delta G/G$ of anode readout and $8th$ dynode readout respectively.

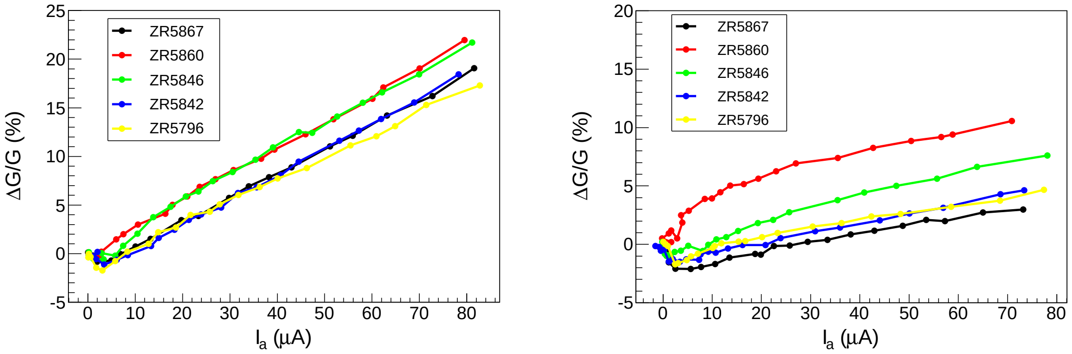
There are obvious distinctions of gain variance among different tubes. And $\Delta G/G$ of $8th$ dynode is larger than that of anode. Therefore the application of PMTs in the situation of strong background light must be strictly measured and cautiously calibrated.



(a) Anode readout at divier1

(b) Anode readout at divier4

Figure 6: the gain of anode varies with different intensity of background light of five PMTs measured at divider1 and divider4.



(a) Dynode readout at divier1

(b) Dynode readout at divier4

Figure 7: the gain of 8th dynode varies with different intensity of background light of five PMTs measured at divider1 and divider4.

4. Conclusion

Due to most of the PMT is applied in the case of completely darkness, the performance indicators of PMT provided by manufacturer do not contain the effects of background light on the gain of PMT. Therefore, the results of this measurement has a guiding significance for the application of PMT in WFCTA.

The gain of PMT at background light would change dramatically with the different tubes and different dividers. Therefore the Lab users can reduce the influence of direct background light by optimizing the voltage dividers. Taking static power and dynamic range into account, the design of divider1, 3:1:1:1:1:1:1:1.5:2:1:1, $1 = 300K\Omega$ has been adopted in the use of WFCTA.

In addition, through communication with manufacturer, it is found that the influence of background light can be reduced by improving the material processing of photocathodes and dynodes.

5. Acknowledgements

This work is supported by National Natural Science Foundation (NSFC) of China under contacts No. 11635011.

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