Influencing factors of time resolution for LPMT for JUNO

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Abstract. Large area PMTs (LPMT) are widely used in neutrino experiments and cosmic ray detection. To meet the performance requirements for Jiangmen Underground Neutrino Observatory (JUNO), researchers at IHEP developed 20-inch MCP-PMTs which provide higher collection efficiency at a lower cost. 15k 20-inch PMTs produced by North Night Vision Technology Co., Ltd. (NNVT) has been delivered to Jiangmen and are to be installed as the central liquid scintillator detector of JUNO. Compared with prototype, though the collection efficiency (CE) and the quantum efficiency (QE) of the 15k MCP-PMTs get improved, the time performance gets worse. In this manuscript, the reasons for the deterioration of time resolution of the 15k MCP-PMTs are explored from several aspects. The optimized structure with great TTS of less than 5 ns is also introduced.

1. Introduction

Micro-channel plate photomultiplier tube (MCP-PMT) is a new type vacuum weak light detection device. Different from the traditional dynode-PMT where the dynode-chains are used as the multiplication structure, the MCP-PMT uses the MCP which is smaller in sized and faster in time response. In 2009, for the Jiangmen Underground Neutrino Observatory (JUNO) [1], the concept of 20-inch MCP-PMT was first put forward by the researchers [2] in IHEP (Institute of High Energy Physics). Cooperated with the North Night Vision Technology Co., Ltd.

(NNVT), the 20-inch MCP-PMT prototype with high detection efficiency which can meet the requirements for JUNO was produced in the middle of 2015, and got the 75% order (15k) of the JUNO PMT contrast. The mass production line for the 15k MCP-PMTs for JUNO was completed in 2016 and the corresponding batch test system was completed at the beginning of 2017. During the mass production process, the researchers in IHEP and NNVT still made effort to improve the QE of the photocathode and the MCP-PMTs with QE of more than 30% at 400 nm were successfully produced in 2017 [3]. The CE of the MCP-PMT is also improved to nearly 100% for the use of atom layer deposition (ALD) technology [4]. By August of 2020, all 15k MCP-PMTs are produced and delivered and ref [5] gives the average value for the typical performance parameters of the 15k MCP-PMTs for JUNO.

Table 1. Time characteristics of the 20-inch MCP-PMT for JUNO.

Parameters	Unit	Prototype	15k pieces
Rise Time	ns	1.2	1.4
Fall Time	ns	10.2	24
Transit Time Spread	ns	12	20

Table 1 gives the time performance for the MCP-PMT prototype and the average value for the 15k MCP-PMTs for JUNO. The results show that the time performance of the 20-inch MCP-PMTs for JUNO is worse compared with the MCP-PMT prototype. For large-area MCP-PMT, the time performance is mainly affected by the electron collection process between the large size photocathode and the MCP [6]. In this manuscript, the reason for the deterioration of the MCP-PMTs for JUNO compared with the prototype is analyzed from three factors, including the focusing electrode structure, the ALD technology used on MCP and the area of the photocathode. The time performance optimized structure is also introduced and a time resolution of less than 5 ns can be achieved.

2. Factors affecting the time performance of the 20-inch MCP-PMT

A schematic illustration of the structure of the 20-inch MCP-PMT for the JUNO project is shown in **figure 1**. The transit time (TT) is defined as the interval between the creation of a photoelectron in the photocathode and the arrival of the resulting anode signal. Repeated measurement creates a histogram of TT, which obeys Gaussian distribution and transit time spread (TTS) is defined as the sigma of the Gaussian function [7]. The total TTS characterizes the time resolution of the PMT. For the 20-inch MCP-PMT, the TTS_{total} is given by

$$TTS_{total} = \sqrt{TTS_{pc-mcp}^2 + TTS_{mcp}^2 + TTS_{mcp-anode}^2}$$

where the TTS_{pc-mcp} is the dominant factor for the 20-inch MCP-PMT which is on the order of tens of nanoseconds and the TTS_{mcp} and $TTS_{mcp-andoe}$ is on the order of hundreds of picoseconds. Therefore, the structure of the MCP is not considered in the time performance optimization of LPMT.

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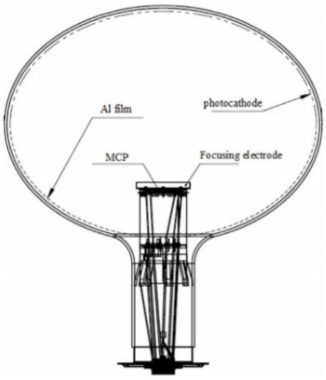

Figure 1. Schematic illustration of the 20-inch MCP-PMT for the JUNO project

2.1. The structure of the focusing electrode

For the 20-inch MCP-PMTs produced by NNVT, the distance between the photocathode and MCP is nearly 300 mm, the applied voltage is approximately 550 V, and the electrical field in the region between the photocathode and MCP is approximately 18 V/cm [8]. Due to the shape of LPMT, the electric field from the photocathode to the focusing electrode is inhomogeneous. The electric field near the PC is weak and gets stronger when closer to the focusing electrode. The inhomogeneous distribution of the electric field causes variation of the trajectories of photoelectrons from PC to MCP. Researchers from IHEP discovered that increasing the diameter of focusing electrode can significantly help reduce the inhomogeneity in LPMT, which improve the time performance of LPMT as illustrated in ref [8], but the collection efficiency (CE) is affected at the same time. For the 15k MCP-PMTs for JUNO, the CE is more important than the time resolution when detection the neutrino.

2.2. The ALD technology used on MCP

For the MCP-PMT prototype, the MCP has an opening ratio of about 70%, which means 30% of the electrons hitting the outer surface of the MCP is missing. In order to improve the CE of the MCP-PMT, the high-SEY material is deposited on the surface of the MCP using the ALD technology. As illustrated in ref [9], when the photoelectrons hit the outer surface of MCP, more secondary-electrons are emitted and collected by the MCP. Using the ALD technology, the CE of the MCP-PMT is improved from 70% to nearly 100%. However, the electrons impinge on the outer surface of the MCP induced extra time jitter compared to the electrons directly entering the micro-channel. Though the CE is greatly improved, the time resolution is also affected which is one factor affecting the time performance of the 20-inch MCP-PMT.

2.3. The area of the photocathode

Compared with the MCP-PMT prototype, the 15k MCP-PMTs for JUNO have larger photocathode to improve the CE, which makes the photoelectrons emitted form the PC to be collected by the MCP form a larger volume. This is also an important factor that affects the time performance of the 15k MCP-PMTs for JUNO.

3. The optimized structure

To improve the time resolution of LPMT a new 20-inch MCP-PMT with lotus-like focusing electrode was developed. Besides using a larger focusing electrode, the new MCP-PMT does not use the surface coated MCP as shown in **figure 2** and **figure 3**. The time resolution of the PMT using the lotus-like focusing electrode gets greatly improved from ~20 ns to less than 5 ns.

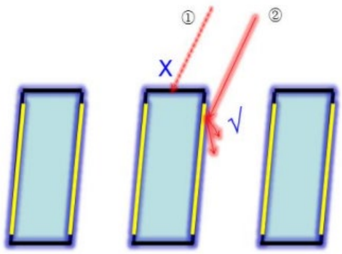

Figure 2. Electron trajectories for lotus like MCP-PMTs

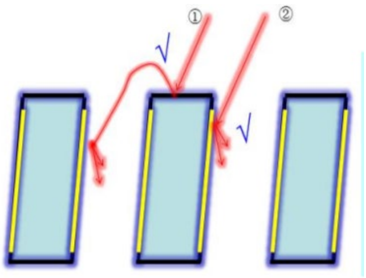

Figure 3. Electron trajectories for common MCP-PMT

4. Summary

In order to meet the requirements of high detection efficiency for JUNO, the 15k MCP-PMTs was modified from three factors, including the structure of the focusing anode, the MCP structure and the area of the PC, which also affect the time performance of these MCP-PMTs. However, the 20-inch MCP-PMT with time resolution less than 5ns can be produced with the structure optimized.

Acknowledgement

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