20-inch photomultiplier tube timing study for JUNO

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Abstract. Jiangmen Underground Neutrino Observatory (JUNO) is a large liquid scintillator neutrino detector now under construction at Jiangmen, Guangdong, China for determination of neutrino mass ordering with 3% energy resolution at 1 MeV, a precise measurement of neutrino oscillation parameters, and other neutrino physics. The central detector is made up of a 35.4-meter diameter acrylic sphere which contains 20 kton of liquid scintillator and is surrounded by about 18k 20-inch photomultiplier tubes (PMTs). The PMTs performance is one of the JUNO's key successes to reach the high resolution goal. In this study, the PMT characteristic and its timing related responses were determined via the PMT generated signals, extracted from the PMT in a scanning station system. About 2,400 of micro-channel plate PMTs (MCP-PMTs) and dynode PMTs were analyzed for their responses with LED source such as rise time, fall time, transit time spread (TTS), gain, etc., which relate to photon incident on different positions of PMT's glass surface. Furthermore, we also observed the fluctuation of PMT performance under magnetic field which can decrease the PMT photon detection efficiency (PDE).

1. Introduction

JUNO aims to study the neutrino mass hierarchy with 3% energy resolution at 1 MeV, a precise determination of neutrino oscillation parameters, and other neutrino physics. The JUNO detector will detect the interactions between the incoming neutrinos and 20 ktons liquid scintillator (LS), contained inside a 35.4-meter diameter acrylic sphere as shown in figure 1.

An incoming neutrino will interact with the LS via the inverse beta decay (IBD): $\overline{\nu}_e + p \rightarrow e^+ + n$ which produces a positron and a neutron as the result. The positron will annihilate with an electron, generating a pair of photons in a few ns and these photons will be defined as a prompt signal. About 200 μs later on average, a delayed signal will be produced, represented by another photon from neutron captured with hydrogen atom of LS. There are over 20,000 of 20" photomultiplier tubes (PMTs) (figure 2) and 25,000 of 3" PMTs on the surface of acrylic sphere with over 75% coverage to detect light signals of IBD interaction. JUNO PMT testing system was designed to determine the PMTs characteristic before the installation [1].

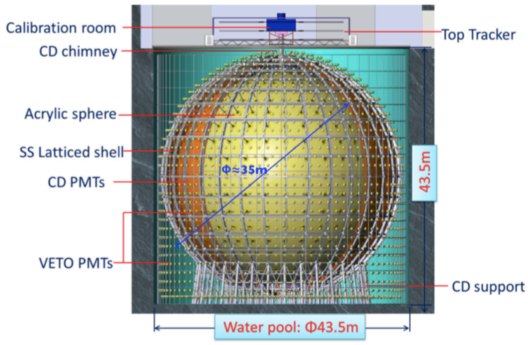

Figure 1. JUNO configuration [1].

Figure 2. 20” photomultiplier tubes.

2. PMT testing system

An incoming photon impinging on the PMT’s glass surface interacts with the photocathode material and produces a photoelectron. This photoelectron will be accelerated under supplied voltage into the electron multiplier for amplifying the number of electron and then convert into an electrical pulse. The 20” PMTs used in this experiment were designed with different inner structure of electron multiplications: micro-channel plates PMT (MCP PMT) and dynode PMT. The structure of MCP PMT is formed as thin disk of tiny channels bundled in parallel which electron will pass through and increase a number of electron by striking with an inner surface of these tiny channels. However, the electron multiplication of dynode PMT is caused by an electron collision on several stages of dynode to gain a number of electrons [2].

To verify the PMT performance before the JUNO operation, PMTs have been tested and analyzed their performances since 2017. The PMT testing procedure is divided into two testing steps: PMT container station and PMT scanning station. In this study, we focus on the scanning station which was designed to study the PMT uniformity on its entire surface. In the scanning station, PMT will be placed among the rotating machine with 7 LED light sources located on the rotating frame which will be rotated 15° each step for 24 steps to cover its entire surface as shown in figure 3. Therefore, the PMT surface will be divided into 168 testing grids (figure 4), follows these LEDs and rotating steps [3].

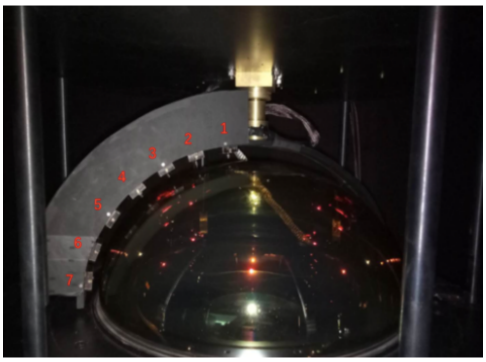

Figure 3. The rotating machine with 7 LED sources located on the rotating frame in the scanning station [3].

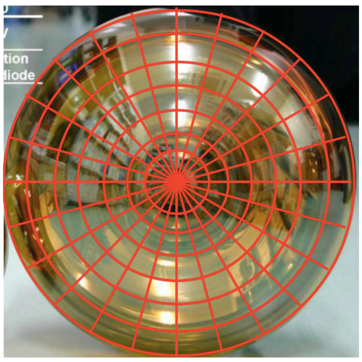

Figure 4. The top view of PMT, divided into 168 testing grid over its surface.

Besides, the trajectory of photoelectron from photocathode might be bent by the external magnetic field before reaching the electron multiplier and this might decrease the PMT efficiency. The PMT scanning station is also designed to adjust the magnetic field of the experimental area which can help us to understand the PMT's characteristic in the presence of magnetic field [4].

3. Result and discussion

The PMT's pulses generate a signal waveform as shown in figure 5 which has been used to extract several timing parameters such as:

- Rise time : Time spent when signal rises from 10% to 90% of the amplitude
- Fall time : Time spent when signal drops from 90% to 10% of the amplitude
- Full width at half maximum (FWHM) : Time spent when signal rises from 50% of the amplitude to its maximum then drops to 50% of the amplitude
- Signal's amplitude and hit time
- Transit time spread (TTS) : This parameter represents the time fluctuation of PMT starting when the light is detected till the signal is generated. This parameter can be calculated by averaging the fluctuation of hit time distribution which contains the hit time of hundreds of waveform (not shown in figure 5)

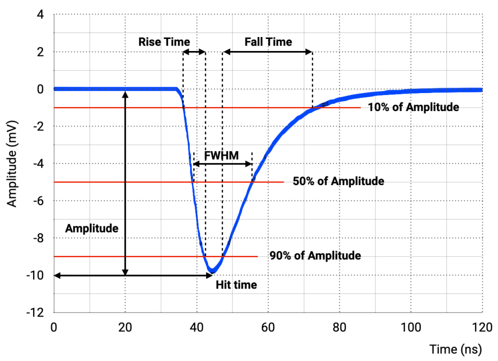

Figure 5. A signal waveform, labeled with parameter definitions.

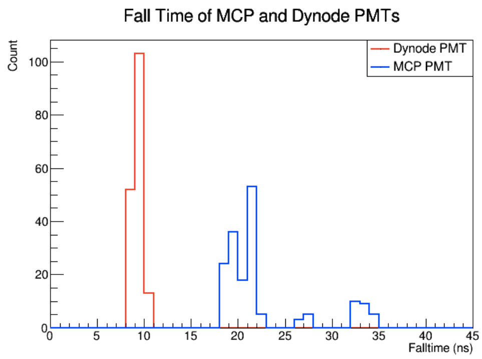

Figure 6. Fall time distribution of both PMT types.

We analyzed about 2,400 PMTs (2,131 MCP and 268 dynode PMTs), tested from the PMT scanning station to study the timing parameters and other information. We found that the signal characteristic of MCP PMT has a long-tailed waveform, compared to the signal measured from dynode PMT. This results in the fall time and FWHM from MCP PMT having higher values than dynode PMT. Figure 6 is an example of fall time distribution, averaged over 168 points on the surface of both PMT types. The result shows that the signal of MCP PMT can reach the fall time up to 35 ns at some position on its surface.

We studied the PMT's uniformity according to the LED light sources and the step of rotating frame around its surface, which will be determined as zenith angle and azimuthal angle, respectively. These timing parameters of both PMT types increase as PMT's zenith angle increases. The results suggests that the PMT responds better for forward incident photons. While the comparison on azimuthal angle shows the uniformity on these timing parameters over its surface as shown in figure 7.

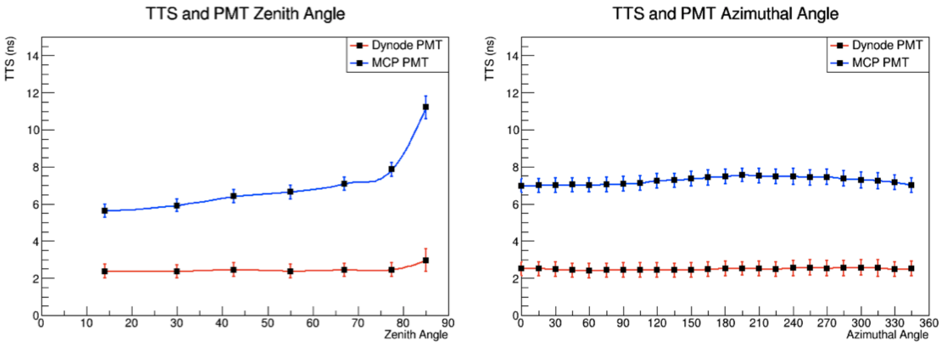

Figure 7. TTS of both PMT types, determining in PMT zenith and azimuthal angles.

The TTS is involved in the time likelihood function which is used to optimize the event vertex reconstruction inside the LS sphere. The time likelihood function is based on the time residual propagation of scintillating photon through the LS and the first hit time of each PMT which TTS is included [5]. Thus, PMT timing response can effect the performances of vertex reconstruction.

Furthermore, we also studied the PMT performance under the magnetic field by canceling the EMF down to 0-20 μT during the process of scanning station. The result shows that the PMT efficiency decreases since the residual magnetic field interferes the trajectory of photoelectron to reach the electron multiplier. Those timing parameters are significantly increased, resulting from the fluctuation of generated waveform by PMT which is spreading out.

To minimize the effect from magnetic field to PMT, a 16-pair-coil system will be installed to cancel the EMF in the detection region and help all PMTs to reach their excellent efficiency. Thus, the PMT performance and characteristic could be now used for the calibration and improvement for event energy and vertex reconstruction for JUNO experiment.

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References

[1] An F *et al.* 2016 *J. Phys. G: Nucl. Part. Phys.* **43** 030401
[2] Zhang H *et al.* 2020 *J. Phys.: Conf. Ser.* **1468** 012197
[3] Anfimov N 2017 *J. Instrum.* **12** C06017
[4] Payupol T, Suwonjandee N and Asavapibhop B 2018 *J. Phys.: Conf. Ser.* **1144** 012092
[5] Li Z *et al.* 2021 *Nucl. Sci. Tech.* **32** 1–12