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The status of the R&D of Ultra-Fast 8 times 8 readout MCP-PMTs in IHEP

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Based on the development of the 20-inch large-area MCP-PMT, the research of a small, ultra-fast MCP-PMT is carried out with the cooperation of Institute of High Energy Physics (IHEP), Chinese Academy of Sciences and Northern Night Vision Technology Co., LTD (NNVT). The structural simulation and optimization of the fast-time PMT was first performed by a Monte Carlo-based approach. Accurate measurements of the time performance of greatest interest are then tested and validated. IHEP and NNVT have successfully developed single-anode, 4 times 4-anode and 8 times 8-anode sample tubes suitable for different application scenarios. While maintaining the single-photon detection capability of the sample tube, the limiting time resolution of the sample tube can reach 30 ps.

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1. Introduction

Photomultiplier tube (PMT) is a kind of photoelectric conversion device. It has been widely used in various areas such as neutrino experiments, atmospheric motion detection and medical imaging for its great time resolution, energy resolution and single photon detection capability. The Institute of High Energy Physics (IHEP) of the Chinese Academy of Sciences, in collaboration with the Northern Night Vision Technology Co., LTD (NNVT) successfully developed a large-area 20-inch MCP-PMT [1-3], which was successfully applied in the Jiangmen Underground Neutrino Observatory (JUNO) [4]. Based on the experience of developing 20-inch MCP-PMT, IHEP and NNVT continue to develop fast time-resolved MCP-PMT, which we call this kind of small-sized PMT Fast-PMT (FPMT).

In the manuscript we will introduce the simulations made to optimize the structure and parameter configurations first. And in order to develop the small-sized MCP-PMT with great time resolution, improvements were made on the test facility to precisely obtain the transit time spread (TTS) of the FPMT. The effect of the data acquisition instrument on the TTS is explored and conclusions are made. Finally, the small-sized MCP-PMT prototypes with different anodes are tested and the test results including the rise time (RT), transit time spread (TTS) are given.

2. The Simulation of FPMT

Under different structure and parameter configurations, the small-sized MCP-PMT will show big difference in its overall performance. Simulations were made using CST STUDIO SUITE [5] to obtain the performance of FPMT with different structure or parameter configurations based on the Finite Integral Technique and Monte Carlo method.

A single-channel FPMT model was built with CST as shown in Figure 1 The model consists of eight parts, including the cathode, anode, two electrodes, two MCPs and two single channels. Some structures which will not affect the simulation results such as the insulating ceramics, the light window and the shield were not included in our simulation. And the area of the upper and lower surface of the MCP is adjusted so that the electric field inside the channel is almost even and the time taken to run a single simulation will not be too long.

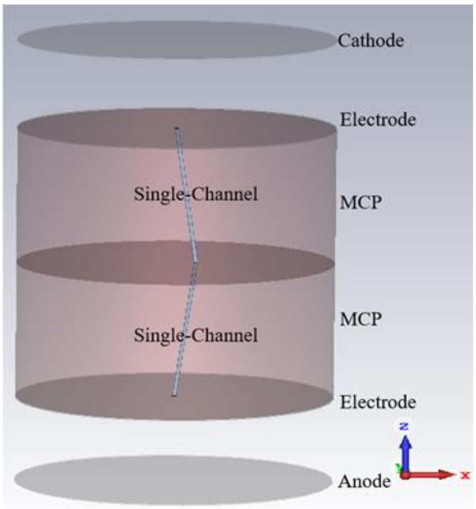

Figure 1 The single-channel FPMT model structure

The cathode, anode and two electrodes are made of nickel-chromium alloy. The two MCPs are set as some kind of electron multiplication material which obeys the Furman Model with a maximum SEY of 4 at 300 eV [6-7]. And all the other areas are vacuum including the area between and cathode and electrode and the area inside the MCP channel. In order to describe the model and optimize the structure for better overall performance, six parameters are defined, where d represents the diameter of each, θ represents the oblique angle for MCP channels, S_1 represents the distance between cathode and MCP-in, S_2 represents the distance between anode and MCP-out and L represents the penetration depth of electrode.

With the single-channel FPMT model, through online simulation and offline analysis we can obtain the performance parameters of the model under certain configuration including the gain, energy resolution (ER), transit time (TT), transit time spread (TTS), rise time (RT) and the angle distribution of the output electrons from the MCP. The trend of these parameter can be obtained with the change of model structure and related optimization can be made for specific parameters.

3.Time Performance Test Methods for FPMT

For the FPMT, the time resolution is our biggest concern among all the parameters and TTS is always used to evaluate the time performance of PMT [8]. TT represents the time interval between the synchronous signal which synchronize with light source pulse and the anode output signal. The spread of TT obeys Gaussian distribution and the sigma of Gaussian distribution shows the precision of time measurement which is defined as TTS. In order to obtain the TTS of the tested FPMT precisely, the instruments used to retrieve data and analyze performance should be selected appropriately and related tests on the effect of different data acquisition system on the TTS tested were conducted.

There are two main test methods for acquiring TTS, one is Time Digital Converter (TDC) based on the nuclear instrument module (NIM) bus, and the other is an oscilloscope with 4 GHz bandwidth and 40 Gs/s sampling rate based on waveform acquisition. As is shown in Figure 2, TDC only accepts the input of NIM standard signal, so both the FPMT signal and the sync signal need to be converted to NIM signal by a low-threshold discriminator, the sync signal as the TDC timing start signal, the FPMT signal as the timing end signal, the time difference is a TT. TTS is the distribution of TT.

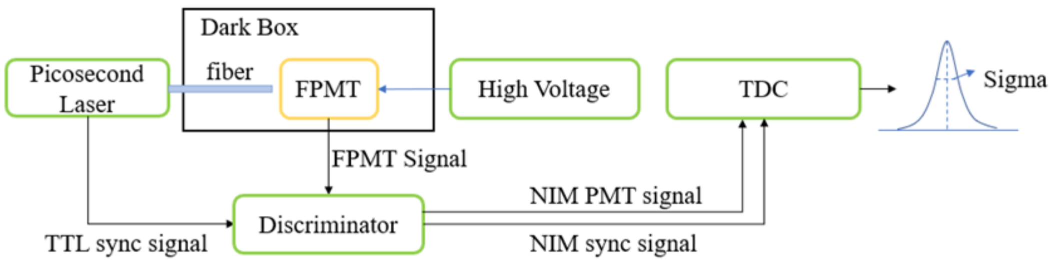

Figure 2 TTS test principle based on TDC

The oscilloscope has no input signal requirements, as shown in Figure 3, the TTL sync signal and the FPMT signal can be connected to the oscilloscope directly. Through the internal algorithm of the oscilloscope, the TTS can be accessed online. Compared with TDC, the oscilloscope measurement does not have the time fluctuation introduced by the low threshold discriminator plug-in, which can obtain more accurate measurement results. For the same single-anode FPMT signal, the TTS measured by TDC is 86 ps, while the oscilloscope is 20 ps. The oscilloscope was used for TTS testing in all subsequent time performance tests.

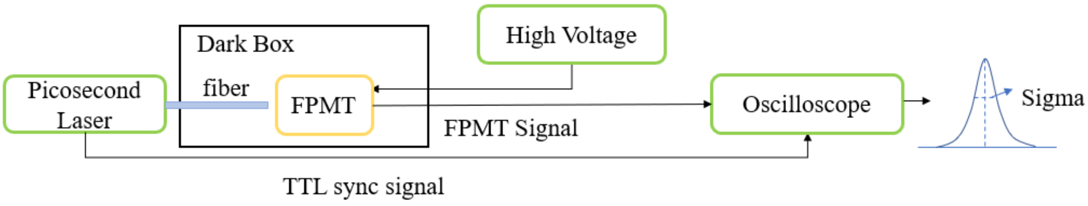

Figure 3 TTS test principle based on Oscilloscope

4.FPMT with different anodes

For different application scenarios, three different anode FPMTs are designed in our lab. Single anode FPMT is mainly used in application scenarios where time performance is prioritized, such as lidar [9-10], Time-Correlated Single Photon Counting (TCSPC) [11-12], etc. And 4 times 4 anodes and 8 times 8 anodes are more used in scenarios where time performance and position resolution performance are prioritized, such as Positron Emission Computed Tomography (PET) [13] and calorimeter.

Figure 4 shows the physical picture of the single-anode PMT protype. The photocathode size of single anode PMT is 1inch, which the quantum efficiency (QE) at 400nm wavelength can reach 17 %, the anode waveform rise time is 400 ps, the gain is 1×10^7, the TTS under single photoelectron (SPE) mode is 200 ps and its limited TTS is 25 ps. FPMT's time performance is measured with a 400nm picosecond laser source with less than 3 ps jitter. 4 GHz bandwidth, 40 Gs/s sampling rate oscilloscope is selected for the acquisition system.

Figure 4 Single anode FPMT protype

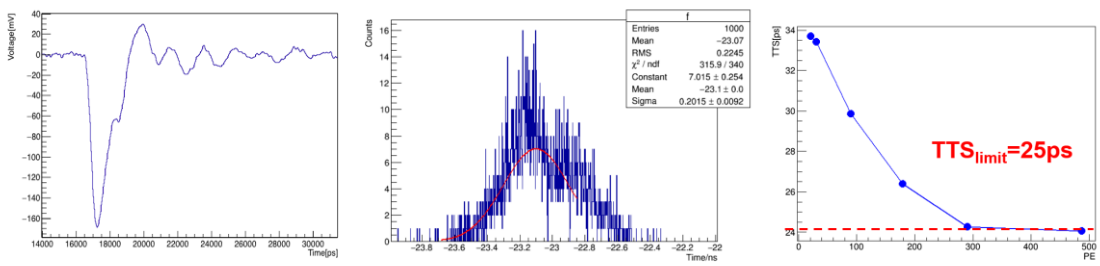

Figure 5 The waveform, TTS and limit TTS of single anode FPMT

The 4 times 4 anode and the 8 times 8 anode FPMT have the same size as the cathode, and both are square sample tubes with a side length of 50 cm. Figure 6 shows the protype of 4 times

4 anode FPMT, which the gain is 1×10^{7}, the rise time of the waveform is 250 ps, the TTS at SPE mode is 106 ps, at multi photoelectron (MPE) mode is 28 ps (Figure 7).

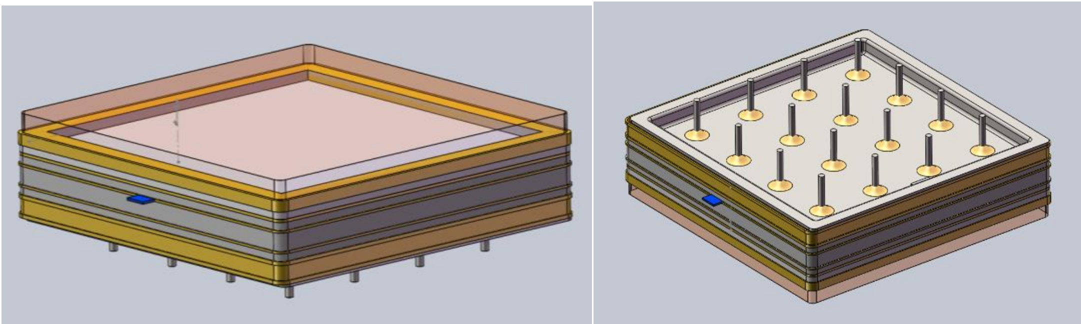

Figure 6 The diagram of 4 times 4 anode FPMT

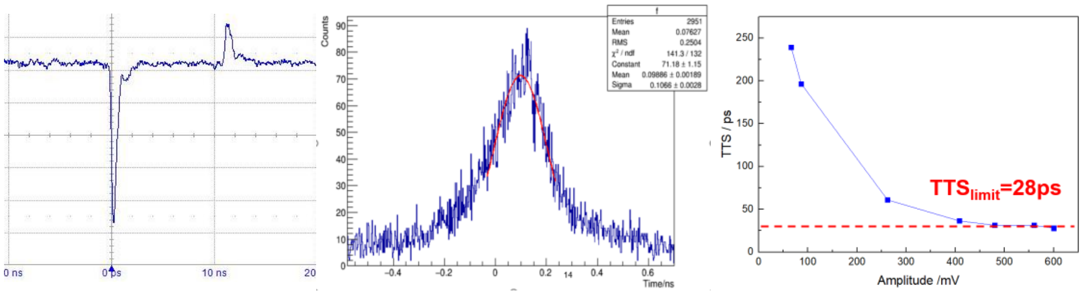

Figure 7 The Waveform and TTS of 4 times 4 anode FPMT at SPE and MPE modes

Figure 8 shows an 8 times 8 anode FPMT protype, which is in the development stage. At present, the waveform rise time of the first-generation sample tube is 500 ps, and the limited TTS is 30 ps. With a rise time of less than 100 ps and a single-photon TTS of less than 50 ps as the goal, the process is being improved.

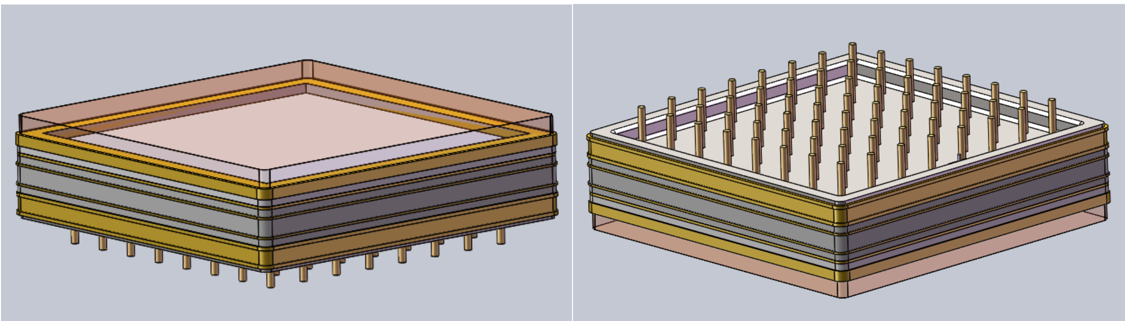

Figure 8 The diagram of 8 times 8 anode FPMT

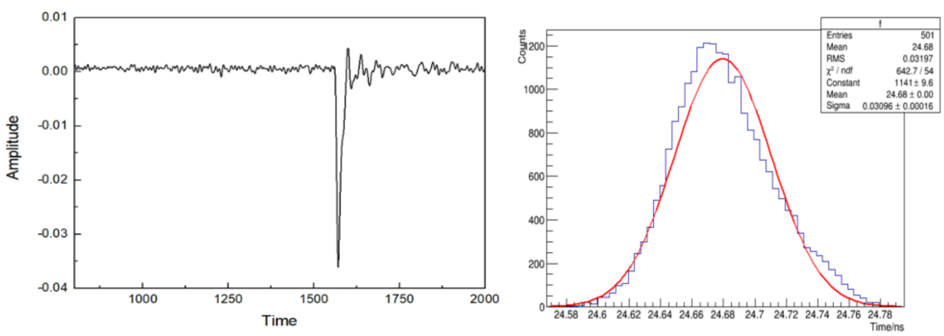

Figure 9 The Waveform and TTS of 8 times 8 anode FPMT

5. Conclusion

Three sample tubes with different anodes have been successfully developed. The single-anode sample tube can achieve a single-photon time resolution of 200 ps, the 4 times 4 anode single-photon time resolution can reach 106 ps, and the 8 times 8 anode sample tube TTS is less than 50 ps. The second-generation sample tube is currently being designed. Through structural improvement and process optimization, better time performance can be expected soon.

Acknowledgement

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