# The R&D of the MCP based PMTs for High Energy Physics Detectors


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## Introduction


***Researchers at IHEP have developed two types of MCP-based PMTs for detecting weak light in particle physics. The 20-inch Large MCP-PMT (LPMT) utilizes small MCP units for electron multiplication in neutrino detection and has been successfully employed in JUNO, LHAASO, and JNE experiments. Building on this achievement, the small-sized Fast Timing MCP-PMT (FPMT) was created for radiation imaging purposes. The CA-FPMT provides a time resolution of 27 ps at single-photon events (SPE), while the 8×8 anode FPMT achieves 38.5 ps at SPE. To enhance timing accuracy and imaging precision, the CRW-FPMT was developed, incorporating a Cherenkov radiator as the optical window for the 8x8 anode FPMT, achieving a single-photon time resolution of 25.6 ps. The CTR of new CRW-FPMT prototypes measures < 50 ps (FWHM).***

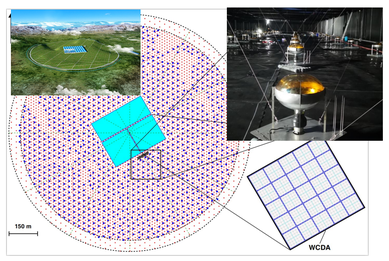

## 1.The 20inch LPMTs & lotus-like LPMT


• Design of LPMT • Prototype of LPMT • Mass production • Design of JUNO detector

The Core Technologies for PMTs

- High QE Photocathode
- High Gain and Low Noise MCP
- Low Radioactive Glass
- Vacuum Transfer Equipment

• Lotus-like LPMT




• Schematic of LHAASO-WCDA

- From 2010-2020，the MCP-PMT group produced the prototypes in 2”, 5”,8” and 20”, and the performance were also improved a lot during the process.
- By August of 2020, the 15K MCP-PMTs have been delivered to JUNO.

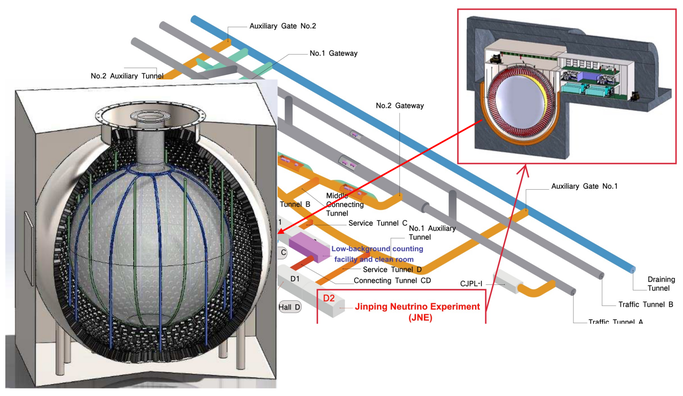
| PMTs | LPMT (Averaged) | Lotus-like LPMT |
|---|---|---|
| QE @ 400nm | 32 % | 30 % |
| CE | 100 % | 90 % |
| TTS@1pe | ~ 20 ns | 3.8 ns |
| DR | 40 kHz | 15 kHz |
| APR | 0.4 % | 0.2 % |

• Photograph of the electrode for the LPMT (left) and lotus-like LPMT (right)

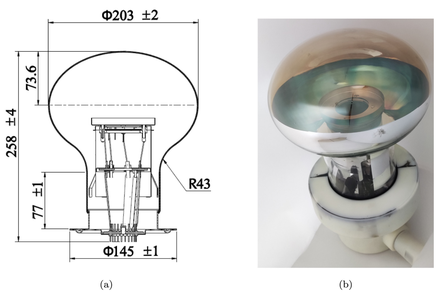
- By modifying the structure and processing of the PMT, a novel lotus-like LPMT was developed that shows improvements with respect to TTS and noise.
- The 20-inch MCP-PMTs are working well at LHAASO-WCDA and the waterproof potting failure rate is less than 1% as of June 31,2021


• Ref 1. 2012 NIM A 695 113-117 • Ref 2. 2021 JINST 16 C11003 • Ref 3. 2020 NIM A 977 164333


## 2. The 8inch MCP-PMT for JNE




• Design of Jinping Neutrino Experiment (JNE)



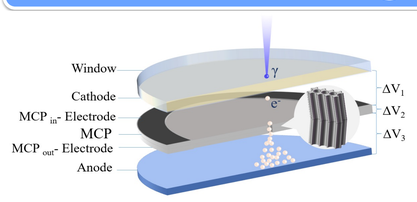

• Schematic of 8inch MCP-PMT for JNE

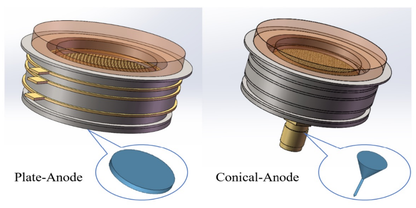
- The JNE (Jinping Neutrino Experiment ) under construction is a hundred-ton liquid scintillator detector with Cherenkov and scintillation light readout at CJPL II.
- With 2400m rock overburden, JNE will study for the targeting solar, terrestrial and supernovae neutrinos.
- JNE plans to deploy a new type of 8-inch MCP-PMT with high photon detection efficiency for MeV-scale neutrino measurements.

| PMTs | 8 inch MCP-PMT |
|---|---|
| DE @ 400nm | ~30 % |
| TTS@1pe | ~1.7 ns |
| P/V | ~5.9 |
| DR | ~5.8kHz |


• Ref 1. 2023 NIM A 1055 168506 • Ref 2. arXiv:2402.13266v2


## 3. Single-anode FPMT



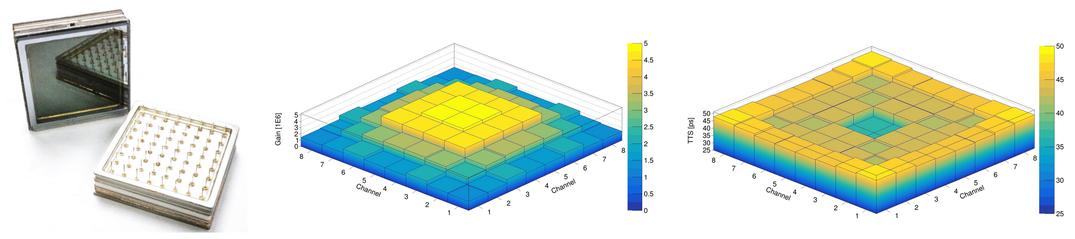

• Schematic diagram of the working principle of FPMT

| FPMT | HV/V | Gain | Amplitude | RT | FT | Width | TTS@SPE |
|---|---|---|---|---|---|---|---|
| PA-FPMT | - 2000 V | $1.9\times10^6$ | 7.6 mV | 1.4 ns | 1.4 ns | 1.8 ns | 71.0 ps |
| CA-FPMT | - 2052 V | $2.3\times10^6$ | 37.6 mV | 0.2 ns | 0.6 ns | 0.4 ns | 35.8 ps |
| CA-FPMT Voltage Optimized | - 3181 V | $2.6\times10^6$ | 53.0 mV | 0.15 ns | 0.4 ns | 0.3 ns | 27.2 ps |

- By optimizing the anode structure from plate-anode to conical-anode, the impedance matches well with the cable which significantly improve the time performance.
- The voltage applied in the FPMT is furtherly optimized and the TTS can reach 29.2 ps at SPE. The limit TTS with the amplitude over 1 V is 4.2 ps.

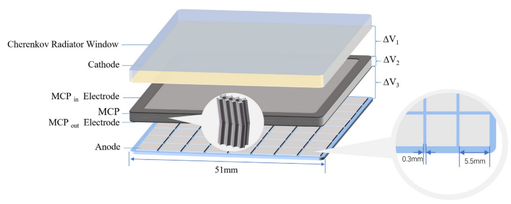

• Ref 2022 NIM A 1041 167333


## 4. Multi anode FPMT

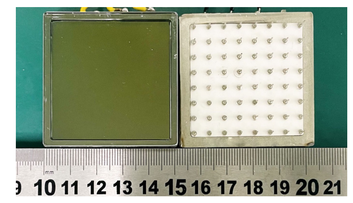



• 8×8 anode FPMT prototype • Gain scan result • TTS scan result

- The TTS@SPE for the middle anodes of the MA-FPMT is 38.5 ps，while limit TTS is around 7 ps.
- The average gain is $2.9\times10^6$ for all 64 anodes and $3.9\times10^6$ for the middle 32 anodes under 1500 V.
- The average TTS is 44.1±2.0 ps for all 64 anodes and 42.3±1.4 ps for the middle 32 anodes.

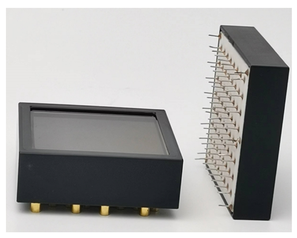



• Schematic diagram of CRW-FPMT structure

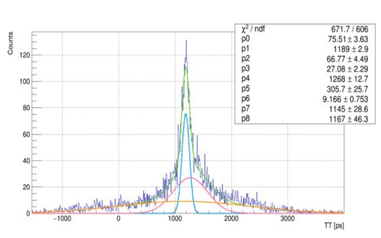


• Physical view of V4.0 CRW-FPMT

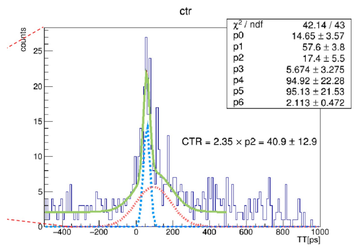
- To avoid the time jitter introduced by the light transmission process for the crystal coupled FPMT, the Cherenkov Radiator Window (CRW) FPMT has been developed.
- The CRW-FPMT uses the lead glass with large effective atomic number as its light window to directly detect the Cherenkov photons.
- Due to its 8×8 anodes readout structure, the CRW-FPMT is expected to have great temporal and spatial resolution at the same time.



• Physical view of V6.0 CRW-FPMT




• CTR：156.7 ± 10.6 ps FWHM




• CTR：40.9 ± 12.9 ps FWHM

- The performance of CRW-FPMT is continuously optimized, and V4.0/V6.0 were tested for CTR.
- Two CRW-FPMTs are placed face to face to directly detect the 511 keV photon from the $^{22}$Na radioactive source.
- The CTR of V4.0 CRW-FPMT is 156.7 ± 10.6 ps FWHM, while the CTR of V6.0 CRW-FPMT is 40.9 ± 12.9 ps FWHM .


• Ref 1. 2022 JINST 17 T04002 • Ref 2. 2023 NIMA 168089 • Ref 3. 2023 JINST 18 C12020 • Ref 4.2024 NIMA 169173


## 5. Conclusions

- ***The MCP-PMT groups in China successfully developed two types of MCP-based PMTs for weak light detection, including the LPMT and FPMT.***
- ***LPMTs have already used in JUNO, LHAASO and CJPL experiments and show good performance.***
- ***CA-FPMT can reach 27 ps TTS at SPE and the MA-FPMT also has a good time resolution and spatial resolution.***
- ***The CTR of two V6.0 CRW-FPMT prototypes is evaluated to be < 50 ps FWHM. CRW-FPMT has shown its great potential in high timing applications.***


## Acknowledgement

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