A new design of large area MCP-PMT for the next generation neutrino experiment

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ABSTRACT
This manuscript discusses a new design of large area MCP-PMT for the next generation neutrino experiments. The main motivation of the design is to improve the quantum efficiency (photo detection efficiency) of the PMT. Two sets of small MCP units, the transmission photocathode coated on the front hemisphere and the reflection photocathode coated on the rear hemisphere are assembled in the same glass envelope to form nearly 4π viewing angle to enhance the efficiency of the photoelectron detection. The photoelectrons from the 4π photocathode are collected and amplified by two sets of MCP units. Our goal is eventually to produce 20 in. diameter PMTs following such an approach. We will report preliminary results of our photoelectronic simulation and the results of a 5 in. diameter prototype PMT. Future plans and prospects are discussed at the end.

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1. Motivation

The neutrino physics experiments commonly require detectors with large detector volumes. The area coverage and the quantum efficiency (QE) of the PMT photocathode are critical in such experiments in order to capture as much signal light as possible from neutrino reactions in the detection media.

The largest such an experiment, the Super-Kamiokande in Japan [1], uses 50 kt pure water as detector media and employs eleven thousands 20 in. diameter PMTs to detect Cherenkov light generated by neutrino reactions in water. The photocathode coverage is approximately 20% in the Super-K experiment. The KamLAND experiment [2] uses low energy neutrinos from nuclear power plants around Japan as sources and approximately 1 kt liquid scintillators as the detection media. The KamLAND detector also uses 20 in. diameter PMTs that covers approximately 38% of the detector surface.

The next generation experiments call for significantly increase the total detector volume. Inexpensive PMTs with large size and high efficiency photocathode are needed in order for these experiments to become reality.

2. The Daya Bay reactor neutrino experiment II

It is known that neutrino mass hierarchy can be determined by long baseline (more than 2000 km) accelerator experiment through matter effects [3,4]. A detailed Monte Carlo study [5,6] shows that if \( \sin^2(2\theta_{13}) \) is more than (1–2)%, a (10–50) kt liquid scintillator at a baseline of about 60 km with an energy resolution better than (2–3)% can determine the mass hierarchy at more than 90% C.L (in Fig. 1).

The Daya Bay Reactor Neutrino Experiment II is designed to build an underground laboratory 60 km from the Daya Bay [7,8]. The conceptual design of the detector shown in Fig. 2 is 30 m in diameter and 30 m high, filled with 20 kt liquid scintillator. The total number of the required 20 in. diameter PMTs is 15000, covering 80% of the surface area. Comparing with the detector of KamLAND, the number of detected photoelectrons per neutrino reaction should increase from 250 p.e./MeV to 2500 p.e./MeV.

There are actually two main technical difficulties for such purpose: the attenuation length of the liquid scintillator should be more than 30 m and the quantum efficiency (QE) of the large area PMTs should be more than 40% [9].

3. Concept and design of the large area MCP-PMT

Several manufactures have developed the high QE PMTs recently. High QE photocathode from Hamamatsu [10], the Super...
Bialkali (SBA) with QE about 35% and the Ultra Bialkali (UBA) with QE ~43% at efficiency peak are available for small size PMTs. These high QE PMTs use conventionally transmission photocathode. The QE improvements were believed to be accomplished by improved material composition, purity and thin film deposition technologies. The cost of the Hamamatsu high QE PMTs is quite high and it is not clear if the photocathode technology used can be transferred to large size PMTs. Currently, the peak QE of a 20 in. diameter PMT is approximately 20% [11] and since the photoelectron collection efficiency of its first dynode is about 70% [10], thus the overall photon detection efficiency is no more than 14%.

Because of the large size dynode chain electron multiplier, the large format PMT was only using the transmission photocathode in the front hemisphere glass envelope. As shown in Fig. 3, most area of back hemisphere was wasted even if using the aluminum mirror coating to reflect the traversing photon back to the photocathode. Improving the QE of the photocathode or increasing the photocathode area are the two possible methods to improve the photon detection efficiency of the PMT.

We have developed a conceptual design of large focusing type PMT aiming for improving the PMT photon detection efficiency. As shown in Fig. 4, the two sets of small MCP units, the transmission photocathode coated on the front hemisphere and the reflection photocathode coated on the rear hemisphere are assembled in the same glass envelope to form nearly 4π viewing angle to enhance the efficiency of the photoelectron detection. The photoelectrons from the 4π photocathode are collected and amplified by the two sets of MCP units.

The transmission photocathode with QE of approximately 20% and the reflection photocathode with expected QE up to 40% that detect the light transmitted are assembled in the spherical surface glass envelope to form nearly 4π viewing angle photocathode. Assuming 50%~70% of photons penetrating from the front hemisphere photocathode, potentially the total effective QE of such a design can reach 40%~50%. The photoelectron collection efficiency of the MCP is expected to be about 60%~70% mainly determined by the fraction of the area covered by the micro channels. As a result, the upper limit of photon detection efficiency in such a PMT is approximately 30% without any attempt to improve the photoelectron collection efficiency of the MCPs. On the other hand, this type of MCP-PMT could detect the single photoelectron with low cost.

### 4. The simulation results

Both the transmission and reflection photocathode generate photoelectrons in the 20 in. diameter spherical symmetry PMT, could they be collected efficiently by the small sets of MCPs that replace the large dynode chain?

As shown in Fig. 5a, the photoelectron could be generated from the whole photocathode in the module and be collected by the MCP unit along with the electric fluxline, but there is a blind ring in the spherical symmetry glass envelope for MCP to collect the photoelectron in Fig. 5b. The existence of this blind ring is mainly caused by the construction of the anode, forcing electrode and MCPs electron multiplier. Beside the blind ring, the glass joint

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**Fig. 1.** Impact of the energy resolution to the determination probability for sinon(θ13) in Daya Bay II.

**Fig. 2.** A conceptual design of a large liquid scintillator detector for the Daya Bay II project.

**Fig. 3.** Current PMT design, photomultipliers are constructed from a glass envelope with a high vacuum inside, which houses a photocathode, several dynodes, and an anode.
area should also be deducted to calculate the photoelectron emission efficiency ($Eff_{pe}$) from the 4π photocathode in ideal case.

The cost of the MCP depends on the size of the MCP, so it is very important to reduce the active area of MCP. The diameter ($D_{hit}$) of the hit area of the photoelectron in the MCP is used to describe the minimum size of MCP, which will not lose the photoelectron from the photocathode. The electric field intensity distribution and electric potential distribution could also be simulated to calculate the transit time spread (T.T.S.) of the signal.

The simulation work was finished within different large formats as described in Table 1. For all the large area PMT in 8–20 in. diameter, there are at least 96% photoelectrons generated from the 4π viewing angle photocathode could be along with the electric flux line to the MCP, whose active area diameter is less than 36 mm.

5. The R&D progress

It is impossible to produce the 20 in. diameter MCP-PMT at the beginning, even if some necessary simulation work has confirmed that this design is correct. The R&D process is divided into three steps: to produce 5 (or 8) inch diameter prototype with transmission photocathode at the primary time; to produce 5 (or 8) inch diameter prototype with both transmission and reflection photocathode secondly; to produce 20 in. diameter prototype with both transmission and reflection photocathode at the end.

With this roadmap, there are several key technical difficulties: the large area photocathode, the low cost MCP, the low background glass and the special preamplifier assembled with the PMT base. Our collaborators try to produce the standard alkali metal dispensers (AMD) to control the quality of the large area photocathode during the production process. On the other hand, the improvement of the photocathode quantum efficiency (or the cathode luminous sensitivity) also depends on the progress of this type of AMD.

Because of the low production yield ~20% for optoelectronic imaging device, the cost of MCP is usually high. The reasons of the disqualification MCP for the imaging device are mainly: the asymmetrical surface, the blind channels, non-uniform gain channels, and emission flash channels. Except the last problem, other disadvantage factors will not affect these MCPs used for the signal photoelectron detection. By this way, the cost of MCP used in our type of 20 in. diameter PMT will be lower than usual. On the other hand, the large active area MCP is more expensive than the smaller one. Considering simulation result, the MCP with 36 mm diameter of active area is chosen to be the candidate one.

The shape of the glass is designed to spherical envelope to form the spherical symmetry electrical field for better time characteristics. The size of the glass joint also affects the extent of the distorted electric field. After simulating calculation, the diameter of the glass joint is confirmed to 80 mm for better Mechanical strength. The 20 in. diameter MCP-PMT will be submerged in liquid for long periods in the experiment, the glass material should have the superb water-resistance characteristics. The concentrations of $^{238}$U, $^{232}$Th and all isotopes of K should be controlled to reduce the background radioactivity rates for the physics aim of neutrino detection in Daya Bay II.

The MCP electron multiplier consists of two pieces of conventional MCP, which could achieve only $\sim 10^5$ gains for the device,

![Fig. 4. Design of a new large area MCP-PMT in IHEP for the next generation neutrino experiment.](image)

| Table 1 | The properties of different inch MCP-PMT without the geomagnetic field (GM). |
| --- | --- | --- | --- |
| Size (inch) | Blind ring (mm) | Transmission photocathode | Reflection photocathode |
| Eff$_{pe}$ (%) | T.T.S (ns) | $R_{hit}$ (mm) | Eff$_{pe}$ (%) | T.T.S (ns) | $R_{hit}$ (mm) |
| 8 | 10 | 97.5 | 1 | < 24 | 95.4 | 4.8 | < 24 |
| 10 | 13 | 97.4 | 2.3 | < 24 | 96.2 | 5.1 | < 24 |
| 12 | 14 | 97.7 | 3.3 | < 28 | 96.8 | 8.5 | < 32 |
| 20 | 36 | 96.4 | 7.1 | < 32 | 96.1 | 10.1 | < 36 |

![Fig. 5. Photoelectron produced from the transmission and reflection photocathode (a), and could be collected by the electron multiplier MCP (b).](image)
so a preamplifier is needed for signal photoelectron detection. To restrain the noise, the preamplifier will be assembled together with the voltage divider in the base.

6. The prototypes

The MCP is always used in the PMT as an electron multiplier to form the normal Proximity-focus MCP-PMT. A same size photocathode is in front of the MCP and an anode readout behind. This type of construction could supply short and uniform electron paths for good timing resolution and magnetic field toleration.

Compared to this type of normal Proximity-focus PMT based on MCP, the 2 in. diameter prototype in Fig. 6 with transmission photocathode has larger distance from the cathode to the MCP. As shown in Fig. 7, the 5 in. diameter prototype has the large area transmission photocathode and small MCP with 25 mm outer diameter, whose diameter of active area is about 18 mm.

The signal of the 5 in. diameter prototype is shown in Figs. 8 and 9. The rise time and fall time of the signal are separately ~2 ns and ~3 ns, the amplitude is about 7 mV with the 2050 V operation voltage. The other characteristic of this prototype is shown in Table 2, with the characteristics of other typical PMTs [12] to contrast.

Because the gain of this 5 in. diameter prototype is only $1.01 \times 10^5$, it is impossible to detect the signal photoelectron spectrum (SPE) without the preamplifier. We only tested its multi-photoelectron spectrum by adjusting the luminance of trigger LED [13]. After the special preamplifier assembled in the PMT base is produced later, the SPE will be tested in time to check the performance of this prototype.

7. Summary and future prospect

For the next generation neutrino experiment, we have designed a large area PMT based on the MCP multiplier. The small conventional MCP unit multiplier replaces the large size dynode chain electron multiplier in the middle of the spherical symmetry glass. The transmission photocathode in the front hemisphere and the reflection photocathode in the back hemisphere are forming the nearly $4\pi$ viewing angle photocathode effective area, which could
obviously enhance the efficiency of the photoelectron detecting to 30% without the blocking of photons.

After the simulating calculation, the prototypes are produced according to the roadmap of this research project. The 8 in. diameter spherical symmetry glass envelope is produced with the low background glass material. The next 8 in. diameter prototype will have the transmission and reflection photocathode both, just as the concept above. The design of the base consisting of the voltage divider and preamplifier is unified for different size tube, and the primary version will be produced sooner for the 5 in. diameter prototype to test the signal photoelectron spectrum.

Acknowledgements

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Table 2
The characteristics of the PMTs.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>unit</th>
<th>R3809U-50</th>
<th>R3600-02</th>
<th>5&quot;-MCP-PMT</th>
<th>20&quot;-MCP-PMT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral Response</td>
<td>nm</td>
<td>160–850</td>
<td>300–650</td>
<td>300–650</td>
<td>300–650</td>
</tr>
<tr>
<td>Photocathode Material</td>
<td></td>
<td>Multialkali</td>
<td>MCP</td>
<td>Bi/ Multialkali</td>
<td>Bi/ Multialkali</td>
</tr>
<tr>
<td>Electron Multiplier (EM)</td>
<td></td>
<td>MCP</td>
<td>Dynode</td>
<td>MCP</td>
<td>MCP</td>
</tr>
<tr>
<td>Collection efficiency of EM</td>
<td>%</td>
<td>≥ 60</td>
<td>≥ 70</td>
<td>~ 60</td>
<td>~ 60</td>
</tr>
<tr>
<td>Gain</td>
<td></td>
<td>2 × 10^5</td>
<td>≥ 1 × 10^5</td>
<td>~ 1 × 10^5</td>
<td>≥ 1 × 10^5</td>
</tr>
<tr>
<td>Photocathode mode^a</td>
<td></td>
<td>T</td>
<td>T</td>
<td>R + T</td>
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<tr>
<td>Cathode Sensitivity</td>
<td>μA/Im</td>
<td>150</td>
<td>60</td>
<td>~ 100</td>
<td>~ 70</td>
</tr>
<tr>
<td>Quantum Efficiency (400 nm)</td>
<td>%</td>
<td>20</td>
<td>20</td>
<td>~ 20</td>
<td>~ 20</td>
</tr>
<tr>
<td>photoelectron detecting Eff.</td>
<td></td>
<td>14%</td>
<td>12%</td>
<td>~ 25%</td>
<td></td>
</tr>
<tr>
<td>Anode Dark Current</td>
<td>nA</td>
<td>≤ 100</td>
<td>≤ 1000</td>
<td>~ 20</td>
<td>≤ 100</td>
</tr>
<tr>
<td>Anode Pulse Rise Time</td>
<td>ns</td>
<td>0.15</td>
<td>10</td>
<td>~ 2</td>
<td>≤ 5</td>
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<tr>
<td>Transit Time Spread(TTS)</td>
<td>ns</td>
<td>≤ 0.025</td>
<td>5.5</td>
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<td>~ 2</td>
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<tr>
<td>Magnetic characteristics</td>
<td></td>
<td>good</td>
<td>bad</td>
<td>bad</td>
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</tr>
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</table>

R3809U-50 is a small proximity-focus PMT with MCP from Hamamatsu, R3600 is a 20 in. large format PMT from Hamamatsu. 5"-MCP-PMT is the real prototype in IHEP, 20"-MCP-PMT is the concept one in IHEP.


References