The R&D of Microchannel-Plate-Based Large Area Photomultiplier (MCP-PMT) at IHEP

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On Behalf of the Workgroup

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Outline

1. The Design of the new MCP-PMT;
2. The Research project;
3. The Challenge and Progress of the MCP-PMT;
4. The Prototypes and Summary;
1. The Design of the new MCP-PMT;

1.1 The relationship between the PMT and neutrino detection;

1.2 The Big demanding of PMT for DayaBay II;

1.3 The Conventional PMT and the High QE PC;

1.4 The R&D of the new type of PMT in the world;

1.5 The new design of a large area PMT in IHEP

Large Area; High QE (double photocathode); Low background
1.1 The relationship between the PMT and neutrino detection

- **Atmospheric neutrino exp.**
  - SuperK,
  - HyperK/UNO,
  - INO,TITAND,

- **Solar neutrino exp.**
  - SNO,
  - GALLEX/SAGE,
  - Borexino, XMASS,

- **Accelerator neutrino exp.**
  - T2K,
  - Nova,
  - Minos, OPERA,
  - MiniBooNE,

- **Reactor neutrino exp.**
  - KamLAND (Japan),
  - Daya Bay (China),
  - Reno (Korea),
  - Double Chooz (France)
  - …
1.2 The requirements of the PMT for the neutrino detection

<table>
<thead>
<tr>
<th>Detector</th>
<th>KamLAND</th>
<th>Daya Bay II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid Scintillator</td>
<td>~1 kt</td>
<td>10 kt</td>
</tr>
<tr>
<td>Energy Resolution</td>
<td>6%/$\sqrt{E}$</td>
<td>3%/$\sqrt{E}$</td>
</tr>
<tr>
<td>Light yield</td>
<td>250 p.e./MeV</td>
<td>1200 p.e./MeV</td>
</tr>
</tbody>
</table>

More photons, how and how many?

- Highly transparent LS: Attenuation length/D: 15m/16m $\rightarrow$ 30m/34m $\times 0.9$
- High light yield LS: KamLAND: 1.5g/l PPO $\rightarrow$ 5g/l PPO
  
  Light Yield: 30% $\rightarrow$ 45% $\times 1.5$
- Photocathode coverage : KamLAND: 34% $\rightarrow$ ~ 80% $\times 2.3$
- High Quantum Efficiency (or Photon Detection Efficiency) “PMT”:
  
  20” SBA PMT QE: 25% $\rightarrow$ 35% $\times 1.4$

  Or New PMT QE: 25% $\rightarrow$ 40% $\times 1.6$

  Both: 25% $\rightarrow$ 50% $\times 2.0$
The first PMT in the world in 1933
“Kubetsky’s tube”

Photon Detection Efficiency (PE) = QE_{Trans} \times CE = 20\% \times 70\% = 14\%
High QE PMTs: SBA (35%) and UBA (43%) are only available in small format (< 5" diameter ?)

Can we improve the Quantum Efficiency of Photocathode or Photon Detection Efficiency for the large area 20” PMT ?

?? 20” UBA/SBA photocathode PMT from Hamamatsu ? QE: 20% → 40%

?? 20” New large area PMT ? Quantum Efficiency > 40% ?

or Photon Detection Efficiency: 14% → 30%
1.4 The R&D of the new type of PMT

**HPD—of DUMAND European optical module**

**LAPPD project – ANL, Chicago**

**12” PMT with SBA photocathode--Hamamatsu**
1.5 The new design of a large area PMT

- High photon detection efficiency
- Single photoelectron Detection
- Low cost

1) Using two sets of Microchannel plates (MCPs) to replace the dynode chain
2) Using transmission photocathode (front hemisphere) and reflection photocathode (back hemisphere) 

\[ PD = QE_{\text{Trans}} \times CE + TR_{\text{Photo}} \times QE_{\text{Ref}} \times CE = 30\% \times 70\% + 40\% \times 30\% \times 70\% = 30\% \]

**Photon Detection Efficiency: 15% \(\rightarrow\) 30% ; \(\times 2\) at least !

Transmission rate of the glass: 40% 

Quantum Efficiency (QE): of Transmission Photocathode 30% ; of Reflection Photocathode 30% ; 

Collection Efficiency (CE) of MCP: 70% ;
2. The Research project;

2.1 Project team and Collaborators;

2.2 The Technical Workshop & Collaboration Meeting;

2.4 The R&D plan of MCP-PMT (schedule);

2.5 The R&D plan of MCP-PMT (method);
2.1 Project team and Collaborators

Institute of High Energy Physics, CAS

Microchannel-Plate-Based Large Area Photomultiplier Collaboration (MLAPC)

Collaboration Meeting

Program Executive committees

Advisory Committees

Program Industrialization committees

Spokespersons

(Yifang Wang)

Program Executive

(Shulin Liu)

Program secretary

(Qian Sen)

Design Group

Photocathode Group

Alkali metal & Glass Group

MCP Group

Packing Group

Test Group

effort by Yifang Wang;
2.2 The Technical Workshop & Collaboration Meeting

Technical Workshop

KM-- 20110911
PMT

XA-- 20120227
Vacuum Equipment

NJ-- 20120620
MCP

Collaboration Meeting

BJ-- 20111118

BJ-- 20121020
Photocathode

HK-- 20121212
2.3 The R&D plan of MCP-PMT (schedule)

- **2009~2010**: IHEP Beginning 5” MCP-PMT

- **2011 Prototype**
  - Collaboration 8” MCP-PMT QE=20%
  - Trans—photocathode
  - Ref—Photocathode

- **2012 Prototype**
  - Collaboration 8” MCP-PMT QE=20%
  - Trans—photocathode
  - Ref—Photocathode

- **2013 Prototype**
  - Collaboration 20” MCP-PMT QE=20%
  - Trans—photocathode
  - Ref—Photocathode

- **2014 Prototype**
  - Collaboration 12” Dynode PMT QE=20%
  - Trans—photocathode
  - Ref—Photocathode

- **2015 Prototype**
  - Collaboration 20” MCP-PMT QE=30%
  - Trans—photocathode
  - Ref—Photocathode

- **Mass production**
2.4 The R&D plan of MCP-PMT (method)
3. The Challenge of the Research Project;

3.1 The Photomultiplier Design;

3.2 The Low radioactive background glass;

3.3 The Low cost MCP;

3.4 The Base with Pre-Amplifier;
3.1 The Photomultiplier Design

- Simulate the possibility of the 20” spherical MCP-PMT
  - Electron Multiplier: small size MCP( φ =18(33)mm) → Dynode chain;
  - photocathode area: transmission+ reflection, nearly $4\pi$ effective area;
  - Could the small Electron Multiplier MCP collect all the photoelectron?

- Yes! Nearly all the photoelectrons could be collected by the small MCP!

- Simulate the properties of MCP-PMT (8”, 12”, 20”) with spherical and ellipse shell;
- Simulate the performance of different size MCP without the geomagnetic field (GM);
- Simulate the performance affected by the geomagnetic field;
The Photo current = Trans PC current + Ref PC current = 2 * Trans PC current

Situation: LED Source (duty factor = 1%, f=1kHz, Voltage=3.5V, Pluse signal)
3.2 The Low radioactive background glass

- Large (8”, 20”);
- Superb water-resistance characteristics;
- Low radioactive background glass;

<table>
<thead>
<tr>
<th>Glass</th>
<th>$DM-308$</th>
<th>$DM-305$</th>
<th>$CN-2#$ Glass</th>
<th>$CN-2#$ Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample Mass</td>
<td>211.0g</td>
<td>131.1g</td>
<td>335.2g</td>
<td>280.9g</td>
</tr>
<tr>
<td>Test Time</td>
<td>311023</td>
<td>424110</td>
<td>315394</td>
<td>359618</td>
</tr>
<tr>
<td>$^{238}\text{U}$</td>
<td>$21.50 \pm 0.10$</td>
<td>$42.40 \pm 0.14$</td>
<td>$14.96 \pm 0.08$</td>
<td>$&lt;0.1$</td>
</tr>
<tr>
<td>$^{232}\text{Th}$</td>
<td>$18.50 \pm 0.32$</td>
<td>$6.43 \pm 0.23$</td>
<td>$4.78 \pm 0.16$</td>
<td>$&lt;0.2$</td>
</tr>
<tr>
<td>$^{40}\text{K}$</td>
<td>$2.50 \pm 0.01$</td>
<td>$41.01 \pm 0.03$</td>
<td>$3.11 \pm 0.01$</td>
<td>$&lt;0.01$</td>
</tr>
</tbody>
</table>

radioactive background test of different PMT glass (unit: ppb)

Low background gamma spectrometer in IHEP
3.3 The Low cost MCP

Why the cost of the MCP is usually high?

--- optoelectronic imaging device
--- High timing resolution device

Low production yield! ~ 20%

The MCP production company, which is the one of our partner has over 20 years of experience in MCP production.

Could supply us the MCP with low cost.
3.4 The Base with Pre-Amplifier

The electron multiplier consists of two conventional MCP, ~ $10^5$ gains (in our group)

Current-sensitive preamplifier

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Equivalent noise charge</td>
<td>&lt; 2000 electron</td>
</tr>
<tr>
<td>Unity-Gain bandwidth</td>
<td>300 MHz</td>
</tr>
<tr>
<td>Rise time</td>
<td>1~2 ns</td>
</tr>
<tr>
<td>Amplification</td>
<td>$20 \times \sim 50 \times$</td>
</tr>
<tr>
<td>Output impedance</td>
<td>50 Ω</td>
</tr>
<tr>
<td>Signal polarity</td>
<td>negative</td>
</tr>
</tbody>
</table>

Electronics
4. The Status of the Prototypes;

4.1 The performance of 5” MCP-PMT;

4.2 The performance of 8” MCP-PMT;
4.1 Performance of the 5” MCP-PMT prototype

- The photoelectron spectrum of a prototype: 5” IHEP-MCP-PMT

- SPE? vs the Voltage of the PMT

- MPE vs the luminance of the LED light

**--adjust the working voltage of the LED to adjust the luminance of the LED light.
Rise time: ~2 ns;  
Fall time: ~3 ns;  
Signal amplitude ~7 mV;
4.2 Performance of the 8” MCP-PMT prototype
Test Situation:
LED Trigger = 1.766 (0.001%);

High Voltage:
Photocathode: 2100V
MCP1: 775V
MCP2: 875V
Anode: 150V

Fast Amplifier: X10
1. A new type of MCP-PMT is designed for the next generation neutrino exp.
   - Large ares: ~20”;
   - High photon detection efficiency: ~30%, at least ×2 than normal PMT;
   - Low coat: ~ low cost MCPs;

2. The R&D process is composing with 3 steps.
   ① 5”(8”) prototype with transmission photocathode;
   ② 5”(8”) prototype with transmission and reflection photocathode;
   ③ 20” prototype with transmission and reflection photocathode;

3. The R&D work is divided into 7 Parts to product the prototype to detect SPE:
   ① Photocathode; ② MCP; ③ Glass; ④ Photomultiplier;
   ⑤ vacuum equipment; ⑥ Electronic; ⑦ Test system;

There are lots of work to do!
We need any help from other institute and company!
Thank！谢谢！

Thanks for your attention!
Any comment and suggestion are welcomed!
## 2.5 The performance of the MCP-PMT

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>unit</th>
<th>R3809U-50 (Hamamatsu)</th>
<th>R5912 (Hamamatsu)</th>
<th>MCP-PMT-8 (IHEP)</th>
<th>R3600 (Hamamatsu)</th>
<th>MCP-PMT-20 (IHEP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>size</td>
<td>inch</td>
<td>2</td>
<td>8</td>
<td>8</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Spectral Response</td>
<td>nm</td>
<td>160~850</td>
<td>300~650</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>Bialkali</td>
<td>Bialkali</td>
<td>Bialkali</td>
<td>Bialkali</td>
</tr>
<tr>
<td>Electron Multiplier</td>
<td></td>
<td>MCP</td>
<td>Dynode</td>
<td>MCP</td>
<td>Dynode</td>
<td>MCP</td>
</tr>
<tr>
<td>Gain</td>
<td></td>
<td>2 × 10^5</td>
<td>≥1 × 10^7</td>
<td>≥1 × 10^5</td>
<td>≥1 × 10^7</td>
<td>≥1 × 10^5</td>
</tr>
<tr>
<td>Photocathode mode</td>
<td></td>
<td>transmission</td>
<td>transmission</td>
<td>reflection + transmission</td>
<td>transmission</td>
<td>reflection + transmission</td>
</tr>
<tr>
<td>Cathode Sensitivity</td>
<td>uA/Im</td>
<td>150</td>
<td>70</td>
<td>70</td>
<td>60</td>
<td>70 ~100</td>
</tr>
<tr>
<td>Quantum Efficiency (400nm)</td>
<td>%</td>
<td>--</td>
<td>22</td>
<td>20~40? ?</td>
<td>20</td>
<td>20~40? ?</td>
</tr>
<tr>
<td>Electron Multiplier Collection efficiency</td>
<td>%</td>
<td>~ 60%</td>
<td>~ 60%</td>
<td>~ 70%</td>
<td>~ 60%</td>
<td>~ 60%</td>
</tr>
<tr>
<td>Efficiency of detecting photoelectron</td>
<td>%</td>
<td>--</td>
<td>&lt; 13</td>
<td>&gt; 20</td>
<td>&lt;12</td>
<td>&gt; 20</td>
</tr>
<tr>
<td>Anode Dark Current</td>
<td>nA</td>
<td>100</td>
<td>≤700</td>
<td>≤100</td>
<td>≤1000</td>
<td>≤100</td>
</tr>
<tr>
<td>Anode Pulse Rise Time</td>
<td>ns</td>
<td>0.150</td>
<td>3.8</td>
<td>5</td>
<td>10</td>
<td>≤10</td>
</tr>
<tr>
<td>Transit Time Spread (TTS)</td>
<td>ns</td>
<td>≤0.025</td>
<td>2.4</td>
<td>≤1</td>
<td>5.5</td>
<td>≤2</td>
</tr>
<tr>
<td>Anti-Magnetic characteristics</td>
<td></td>
<td>Good</td>
<td>normal</td>
<td>normal</td>
<td>normal</td>
<td>normal</td>
</tr>
<tr>
<td>Glass</td>
<td></td>
<td>Low-Potassium Glass</td>
<td>Low-Potassium Glass CN-2#</td>
<td>HARIO-32</td>
<td>Low-Potassium Glass CN-2#</td>
<td></td>
</tr>
</tbody>
</table>

The performance of the MCP-PMT is summarized in the table above. Each parameter is measured and compared for different models of MCP-PMTs, providing insights into their performance characteristics such as size, spectral response, gain, and efficiency.