The 20 inch MCP-PMT R&D in China

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Outline

1. The JUNO and MCP-PMT;

2. The new design of the MCP-PMT prototypes;
   - the 4 $\pi$ design; the 8 inch prototypes; the 20 inch prototypes;

3. The High PDE MCP-PMT—2015;
   - the performance of the 20 inch prototypes;

4. The Special Behaviors of the MCP-PMT;
   - the High CE; The large TTS; the aging behaviors;
1. The JUNO and MCP-PMT

High QE 20” PMTs for JUNO:

- Hammamatsu PMT with SBA photocathode (2012)
- A new design using MCP: 4π collection (2009)

Requirement: High QE 20 inch PMT; Good SPE detection capability; Wide dynamic range; Low radioactive background; More than 20 years lifetime; Can withstand 0.4MPa Pressure; ≥ 20000 pieces;

2009: Design;  2011: Collaboration;  2012: DayaBay result;  2013: JUNO
15k MCP-PMT (75%)
Contract for JUNO
Signed with NNVT on Dec. 16, 2015
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   the High CE; The large TTS; the aging behaviors;
2.1 The new design of a large area PMT

High QE PMTs: SBA (35%) and UBA (43%)

are only available in small format (< 5" diameter ?) (2011)

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%
2.2 the primary design of the MCP-PMT in 2009

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)

Trans. Photocathode: 30% ; Reflection Photocathode: 30%

Collection Efficiency (CE) of MCP: 70%

Transmission rate of the glass: 40%

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

Photon Detection Efficiency: 15% → 30% ; ×~2 at least!
2.3 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;
2.4 The R&D plan of MCP-PMT (schedule)

The design of the IHEP-MCP-PMT

The project of Daya Bay II (JUNO)

Alkali metal
Low price MCP
Vacuum equipment
Prototype
Test system
SPE

Photomultiplier
Glass Shell
PreAMP & Base
2.5 The new design of the MCP-PMT prototypes 2013;

- 2009: the design of the MCP-PMT;
- 2010~2011: 5” MCP-PMT prototype without SPE;
- 2012: 8” MCP-PMT prototype without SPE;
- 2013: 8” prototypes with normal performance;
  QE ~ 25%@410nm; CE ~ 60%; P/V of SPE > 2.0;
- 2014: 20” prototypes with normal performance;
  QE ~ 25%@410nm; CE ~ 60%; P/V of SPE > 2.0;
- 2015: 20” prototypes with HDE performance;
  QE ~ 26%@410nm; CE ~ 100%; P/V of SPE > 3.0;
- 2016: for the high QE improvement.
  the mass production prepare;
### 2.5.1 8" prototypes with normal performance--2013

<table>
<thead>
<tr>
<th>HV</th>
<th>Gain</th>
<th>P/V</th>
<th>Rise Time</th>
<th>Fall Time</th>
<th>Dark rate @1E7 Gain(0.25PE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2100V</td>
<td>~1E7</td>
<td>~4</td>
<td>~1.3ns</td>
<td>~8.8ns</td>
<td>~3kHz</td>
</tr>
</tbody>
</table>
### 2.5.2 20” prototypes with normal performance--2014

<table>
<thead>
<tr>
<th>HV</th>
<th>Gain</th>
<th>P/V</th>
<th>Rise Time</th>
<th>Fall Time</th>
<th>Dark rate @1E7 Gain(0.25PE)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000V</td>
<td>~1E7</td>
<td>~3</td>
<td>~1.2ns</td>
<td>~15ns</td>
<td>~50kHz</td>
</tr>
</tbody>
</table>
Prototypes: Successful 8” and 20” prototypes with normal performance;

We could successfully produce the 8 / 20 inch MCP-PMT prototype for good SPE and QE.
And better for CE of the MCP; Uniformity of CE, QE, TTS, we also try to improve our design of the prototype.
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   the performance of the 20 inch prototypes;

➢ 4. The Special Behaviors of the MCP-PMT;
   the High CE; The large TTS; the aging behaviors;
3. The High PDE MCP-PMT--2015

| 20-inch Hamamatus PMT-Dynode Ellipsoidal Glass | 20-inch IHEP-MCP-PMT-Ellipsoidal Glass |

![Images of the high PDE MCP-PMT devices with captions.]
### 3.1 The QE of the Photocathode

<table>
<thead>
<tr>
<th></th>
<th>20 inch Prototype</th>
<th>R12860</th>
<th>MCP-PMT</th>
</tr>
</thead>
<tbody>
<tr>
<td>QE@410nm</td>
<td>~30%</td>
<td>~26%</td>
<td></td>
</tr>
</tbody>
</table>
## 3.2 Waveform of the Prototype

<table>
<thead>
<tr>
<th></th>
<th>Rise Time</th>
<th>Fall Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>R12860</td>
<td>~6.7ns</td>
<td>~17.7ns</td>
</tr>
<tr>
<td>MCP-PMT</td>
<td>~2.2ns</td>
<td>~10.2ns</td>
</tr>
</tbody>
</table>

![Waveform of the Prototype](image)
#### 3.3. The SPE of the Prototype;

<table>
<thead>
<tr>
<th></th>
<th>HV</th>
<th>Gain</th>
<th>P/V</th>
</tr>
</thead>
<tbody>
<tr>
<td>R12860</td>
<td>1650V</td>
<td>~1.1E7</td>
<td>~3.7</td>
</tr>
<tr>
<td>MCP-PMT</td>
<td>1930V</td>
<td>~9.6E6</td>
<td>~5.6</td>
</tr>
</tbody>
</table>

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**Hamamatsu R12860**

**MCP-PMT**
3.4. The TTS of the Prototype;

<table>
<thead>
<tr>
<th></th>
<th>HV</th>
<th>Gain</th>
<th>TTS @ top center</th>
</tr>
</thead>
<tbody>
<tr>
<td>R12860</td>
<td>1650V</td>
<td>~1.1E7</td>
<td>~2.8ns</td>
</tr>
<tr>
<td>MCP-PMT</td>
<td>1930V</td>
<td>~9.6E6</td>
<td>~12ns</td>
</tr>
</tbody>
</table>

Hamamatsu R12860

MCP-PMT
### 3.5. The Dark count of the Prototype;

<table>
<thead>
<tr>
<th></th>
<th>HV</th>
<th>Gain</th>
<th>Dark rate @ 0.25PE</th>
</tr>
</thead>
<tbody>
<tr>
<td>R12860</td>
<td>1650V</td>
<td>~1.1E7</td>
<td>~25kHz</td>
</tr>
<tr>
<td>MCP-PMT</td>
<td>1930V</td>
<td>~9.6E6</td>
<td>~ 30kHz</td>
</tr>
</tbody>
</table>

![Graph showing dark count over time for R12860 and MCP-PMT](image-url)
### 3.6. The After Pulse Rate of the Prototype

<table>
<thead>
<tr>
<th></th>
<th>Time distribution</th>
<th>After Pulse Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>R12860</td>
<td>4us, 17us</td>
<td>10%</td>
</tr>
<tr>
<td>MCP-PMT</td>
<td>4.5us</td>
<td>2.5%</td>
</tr>
</tbody>
</table>

**Hamamatsu R12860**

**MCP-PMT**
### 3.7. The Relativity Detection efficiency of the Prototype

<table>
<thead>
<tr>
<th></th>
<th>HV</th>
<th>Gain</th>
<th>Relativity PDE</th>
</tr>
</thead>
<tbody>
<tr>
<td>R12860</td>
<td>1650V</td>
<td>~1.1E7</td>
<td>100%</td>
</tr>
<tr>
<td>MCP-PMT</td>
<td>1930V</td>
<td>~9.6E6</td>
<td>110%</td>
</tr>
</tbody>
</table>

**Cut:**
- **cut@320** for Hamamatsu R12860
- **cut@248** for MCP-PMT
### 3.8 The performance of the 20 inch prototypes

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>unit</th>
<th>MCP-PMT (IHEP)</th>
<th>R12860 (Hamamatsu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron Multiplier</td>
<td>--</td>
<td>MCP</td>
<td>Dynode</td>
</tr>
<tr>
<td>Photocathode mode</td>
<td>--</td>
<td>reflection+ transmission</td>
<td>transmission</td>
</tr>
<tr>
<td>Quantum Efficiency (400nm)</td>
<td>%</td>
<td>26 (T), 30 (T+R)</td>
<td>30(T)</td>
</tr>
<tr>
<td>Relativity Detection Efficiency</td>
<td>%</td>
<td>~ 110%</td>
<td>~ 100%</td>
</tr>
<tr>
<td>P/V of SPE</td>
<td></td>
<td>&gt; 3</td>
<td>&gt; 3</td>
</tr>
<tr>
<td>TTS on the top point</td>
<td>ns</td>
<td>~12</td>
<td>~3</td>
</tr>
<tr>
<td>Rise time/ Fall time</td>
<td>ns</td>
<td>R<del>2 , F</del>10</td>
<td>R<del>7 , F</del>17</td>
</tr>
<tr>
<td>Anode Dark Count</td>
<td>Hz</td>
<td>~30K</td>
<td>~30K</td>
</tr>
<tr>
<td>After Pulse Time distribution</td>
<td>us</td>
<td>4.5</td>
<td>4, 17</td>
</tr>
<tr>
<td>After Pulse Rate</td>
<td>%</td>
<td>3</td>
<td>10</td>
</tr>
<tr>
<td>Glass</td>
<td>--</td>
<td>Low-Potassium Glass</td>
<td>HARIO-32</td>
</tr>
</tbody>
</table>
Outline

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4.1. The Transmission + Reflection QE of the Photocathode

Good situation:
- Improve the total QE;
- Improve the Detection Efficiency;

Bad situation:
- Larger Dark count;
- Larger TTS;
The Diameter of the MCP: 33mm; 50mm;
The Diameter of the Hole: 6um; 8um; 10um; 12um;
The Inclined Angle: 0°; 8°; 12°;
The Open Area Ratio: 60%; 77%;
The Depth of output electrode: .......

CE = 60%
The p.e. into the channel directly ~60%

CE = 100%
The p.e. into the channel directly ~70%
The p.e. from the electrode indirectly ~ 30%
➤ MCP: Large area PC (Rrf. + Tran.)

➤ Dynode: A mesh covering the dynode

➤ MCP: Special MCP for CE~100%

<table>
<thead>
<tr>
<th></th>
<th>Relativity DE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynode-PMT</td>
<td>100%</td>
</tr>
<tr>
<td>MCP-PMT</td>
<td>110%</td>
</tr>
</tbody>
</table>
4.2 Why the TTS is large?

The p.e. from where?
---> the Transmission Photocathode
---> the Reflection Photocathode

The p.e. to where?
---> to the channel of MCP directly
---> to the electrode and then reflect to the MCP channel indirectly

The contribution to the TTS
① The distance between the PC to the MCP;
   = = By adjusting the Electronic optical focusing
② The difference between the Trans. & Ref. PC;
   = = No way to adjusting; (for better QE)
③ The second electron emission part of the MCP;
   = = No way to adjusting; (for better DE)

The prototype
--> with Trans. + Ref. PC for better QE;
--> with special MCP for better DE;
But the TTS will be worse!
4.2.2 The second electron emission part of the MCP (channel or electrode);

➢ With the contribution of the second electron from the electrode (40%),

the spectrum of the TTS present several peaks, which made it’s TTS worse.
4.2.3 How to improve the JUNO PMT’s time resolution?

- optical coverage: 78%
  - 15,000 large PMTs (20"") → 75%
  - 36,000 small PMTs (3"") → 3%
  (double calorimetry + timing)

<table>
<thead>
<tr>
<th></th>
<th>TTS @ top center</th>
</tr>
</thead>
<tbody>
<tr>
<td>R12860 (20&quot;)</td>
<td>~2.8ns</td>
</tr>
<tr>
<td>MCP-PMT (20&quot;)</td>
<td>~12ns</td>
</tr>
<tr>
<td>3&quot; PMT</td>
<td>~1.5ns</td>
</tr>
</tbody>
</table>

HZC 3-inch XP53B20
Hamamatsu 3-inch R6091
MELZ 3-inch 10 dynodes
4.3 The aging behavior of the Prototype;

➢ High Voltage system SY1527

➢ Pulse Generator

➢ NIM Crate differentiator

➢ LT-Dis

➢ MCP-PMT

➢ Delay

➢ XP2020

➢ Delay

➢ Oscillograph

➢ VME-DAQ

➢ QDC V965

➢ USB-V1718

➢ TCP/IP

➢ Dark-Box

➢ 2inch XP2020 (Reference PMT)

----Monitoring the stability of the light and electronics.

➢ 20inch MCP81 (Test PMT)

----Monitoring the SPE; ----> the stability of Gain

----Monitoring the MPE (~1000p.e.) the stability of Gain

----Monitoring the pedestal; the stability of electronics;
➢ 8” MCP-PMT in 2014 with ~1000p.e. enhanced aging test,  
➢ the Gain of the PMT changed to 80%@7C@1X10^7 with MPE;

➢ 20” MCP-PMT in 2016 with ~1000p.e. enhanced aging test,  
➢ the Gain of the PMT changed to 90%@7C@1X10^7 with MPE;

➢ The aging behavior of the MCP better than before.
➢ 8” MCP-PMT in 2014 with ~1000p.e. enhanced aging test,
➢ the Gain of the PMT changed to 35%@14@1X10^7 with MPE;

➢ 20” MCP-PMT in 2016 with ~1000p.e. enhanced aging test,
➢ the Gain of the PMT changed to 80%@14C@1X10^7 with MPE;

➢ The aging behavior of the MCP better than before.
5" (8") prototype transmission

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>unit</th>
<th>MCP-PMT (NNVC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detection Eff. (QE * CE * area)</td>
<td>%</td>
<td>27%, &gt; 21%</td>
</tr>
<tr>
<td>P/V of SPE</td>
<td></td>
<td>&gt; 2.8</td>
</tr>
<tr>
<td>TTS on the top point</td>
<td>ns</td>
<td>&gt; 12, &lt; 15</td>
</tr>
<tr>
<td>Rise time/ Fall time</td>
<td>ns</td>
<td>R<del>2, Γ</del>12</td>
</tr>
<tr>
<td>Anode Dark Count</td>
<td>Hz</td>
<td>20K, &lt; 30K</td>
</tr>
<tr>
<td>After Pulse Rate</td>
<td>%</td>
<td>1, &lt;2</td>
</tr>
<tr>
<td>238U: 50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>239Th: 50</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Radioactivity of glass</td>
<td>ppb</td>
<td>10X: 20</td>
</tr>
</tbody>
</table>

30 pic/day for 2 years,

2009 Design

2010-2011
5" (8") prototype transmission

2012-2013
5" (8") prototype transmission + reflection

2014-2015
20" prototype transmission + reflection

2016
HQE Production line bunch test sys

2017-2018
Mass production

Bunch test

Test in NNVT:
MCP-PMT only

Test in JUNO:
MCP-PMT + Base + HV + Electronics
Thank! 谢谢！

Thanks for your attention!
Any comment and suggestion are welcomed!
Welcome to Kaiping
May 22-26, 2017 Beijing
X-PMT workshop
Dynode-PMT; MCP-PMT; Si-PMT; Gas-PMT; et.al

A visit to the **NNVT**, who produce the MCP-PMT for JUNO.
Thank! 谢谢!

If you are interesting about this workshop, please give me a e-mail.