Development of the MCP-PMT for the Belle II TOP Counter

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TOP Counter for Belle II

- **Time Of Propagation** counter
  - $K/\pi$ identification on the barrel region with Cherenkov radiation

- For PID with TOP counters, photodetectors must have:
  - Good single photon detection efficiency
  - Excellent TTS (<50 ps)
  - Pixel size of $\sim 5$ mm
  - Large photo-coverage
  - Operable in 1.5 T

\[ \Delta t_{K-\pi} \sim 100 \text{ ps} @ 3 \text{ GeV/c } K \text{ or } \pi \]

\[ N_{\text{photons}} = O(10) \]
MCP–PMT Development

- Tested some samples in magnetic fields
  - HPK6 with φ6 um pores      HPK10 with φ10 um pores
  - BINP8 with φ8 um pores     Burle25 with φ25 um pores
- 10 um was the best selection
  - Good gain & TTS in 1.5 T
  - Reliable to produce 3 cm$^2$ size MCP compared to 6 um size

Nucl. Instr. and Meth. A528, 763 (2004)

Unable to measure in $B > 0.8$ T

Recover to ~30 ps with increasing HV
Square-shaped MCP-PMT (R10754)

Developed original MCP-PMT (R10754-07-M16) with HAMAMATSU

- Square shape to maximize photo-coverage in an array
  → 32 PMTs/TOP x 16 TOPs = 512 PMTs
- 4x4 anodes, one anode pad has a size of 5.6x5.6 mm²
- ~10⁶ gain in 1.5 T by 2-stage MCPs (t = 400 um)
- Fast raise time of ~200 ps, TTS of 30-40 ps
- Multi-alkali p.c., QE_{peak} ~28% around 360 nm

Excellent characteristics for TOP counter
Lifetime Improvement

- QE drops during operation
  - QE drop is a function of total output charge
  - \( \sim 80\% \) QE drop is acceptable
  - Estimated output charge is 2-3 C/cm\(^2\) in Belle II

- Al layer for ion feedback protection
  - Evaluated effect of Al layer with round-shape PMT
  - \( \sim 1 \) C/cm\(^2\) lifetime was obtained with Al layer
  - Usable with a few times of PMT exchanges in Belle II operation

* Result from round-shape PMT
Lifetime Improvement

- Lifetime of R10754 w/ Al layer
  - Only ~10 mC/cm², shorter than round PMT
- Improvements
  - Inserted ceramic parts to block path of neutral gas molecules
    → Lifetime was improved to ~1 C/cm²
  - Moved Al layer to 2nd MCP for increasing CE

QE drops from corners

Ceramic parts

Aluminum layer (Moved to 2nd MCP to keep CE)
**Successful Mass-production**

- MCP-PMT mass production for the TOP counter
  - Produced >500 MCP-PMTs
  - Measure QE and gain/TTS (0 T and 1.5 T) for all MCP-PMTs
    - Feedback to production/database of MCP-PMTs

- Further lifetime improvement with ALD-coated MCPs
  - ALD MCP had been available during production
  - ~50% MCP-PMTs are ALD type

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First MCP-PMT mass production for HEP experiment!

**ALD MCP-PMT**

ALD coating

![Graph showing MCP-PMT production timeline](image)
QE Measurement

- Irradiate monochromatic light to MCP-PMT and PD by turns
  - $Q_E_{PD}$ is well calibrated
  - $Q_E_{MCP-PMT} = (I_{MCP-PMT \text{ p.c.}} / I_{PD}) \times Q_E_{PD}$
- 473 PMTs have been measured
  - We use PMTs with $Q_E_{\text{peak}} > 24$
  - Averaged $Q_E_{\text{peak}} > 28$

$QE_{\text{mean}} = 28.7\%$

discard less than 340 nm to relax chromatic dispersion
Measurements with single photon

- Light from pulse laser with $\sigma_{\text{laser}} < 20$ ps
  - Intensity is reduced to single photon level
- Jitter on readout electronics $\sigma_{\text{jitter}} < 20$ ps
- All of 16 channels can be measured with moving the MCP-PMT position

No magnetic field (Nagoya) and 1.5 T magnetic field (KEK)
Gain/TTS in 1.5 T

- In 1.5 T (perpendicular to the PMT window)
  - ~100 PMTs have been measured (the measurement is ongoing)
  - Gain decreases down to 60% (conventional PMTs) or 30% (ALD PMTs)
  
    - Can keep > $5 \times 10^5$, which is enough for single photon detection
  - All PMT has TTS better than 50 ps in the magnetic field

- Slightly worse TTS of ALD PMTs is caused by lower gain in 1.5 T
  → Can be recovered by increasing HV
Beamtest @ SPring-8

- Constructed a prototype TOP counter for beamtest
  - 2x16 MCP-PMT array for full photo-coverage
  - Two types of readout electronics
    - IRS; waveform sampling ASIC for Belle II, still under development
    - CFD; traditional elec., only for beamtest because of large power consumption
Beamtest @ SPring-8

- Irradiated 2 GeV $e^+$ at the SPring-8 LEPS beamline
  - Good agreement between data and PDF

MCP-PMTs work very well as photodetectors of the TOP counter.

Data (CFD)

Calculated PDF (CFD)

* 4 anode channels are merged

for more details of the beamtest,
✓ Nucl. Instr. and Meth. A732, 357 (2013)
✓ K. Matsuoka, “Performance study of the TOP counter with the 2 GeV/c positron beam at LEPS” at TIPP2014
Lifetime of ALD MCP–PMTs

• Test setup
  – Illuminate LED to PMTs to obtain output charge
    \( \Rightarrow \sim 1 \text{ C/cm}^2 / \text{month} \), which is 1/2-1/4 of Belle II operation
  – Laser as a light source for single photon measurement
    \( \Rightarrow \) QE can be relatively monitored from the change of \( N_{\text{hit}} \) by the laser

![Image of test setup with LED, MCP-PMTs, Laser, and Ref. PMT]
Lifetime of ALD MCP–PMTs

- Lifetime of ALD MCP–PMTs
  - ALD MCP–PMTs have 3-14 C/cm² lifetime, which is 3-14 times longer than typical lifetime of present types with conventional MCPs.
  - We can avoid exchanging ALD MCP–PMTs in Belle II

- Lifetime variation is large
  - Further investigation is ongoing to suppress variation
Summary

• We developed original MCP-PMT (R10754-07-M16)
  – Peak QE of ~28%, excellent TTS of 30-40 ps, operable in 1.5 T
  – Square shape to increase effective area
  – ~1 C/cm² lifetime
  → We started to mass production

• Successful mass production
  – We produced >500 PMTs with excellent performance
  – While measurements are still ongoing, all of measured PMTs have $Q_E \text{peak} \approx 28\%$, and 30-60% gain drop & TTS < 50 ps in 1.5 T

• Lifetime improvement by ALD technique
  – Lifetime is extended to 3-14 C/cm²; possible to avoid PMT exchanges
  – Lifetime variation is large
  → trying to reduce the variation and will use them for future PMT exchange
Additional Slides
Photodetector Selection

- Photodetectors must work in 1.5 T
  - Candidates were fine mesh PMT, HAPD and MCP-PMT

<table>
<thead>
<tr>
<th></th>
<th>Gain(1.5 T*) (x10^6)</th>
<th>TTS</th>
</tr>
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<tbody>
<tr>
<td>FM-PMT</td>
<td>0.1-1</td>
<td>~100 ps</td>
</tr>
<tr>
<td>HAPD</td>
<td>0.5</td>
<td>~100 ps</td>
</tr>
<tr>
<td>MCP-PMT</td>
<td>1</td>
<td>30 ps</td>
</tr>
</tbody>
</table>

*Perpendicular to entrance face

From the viewpoint of TTS, we selected MCP-PMT

Nucl. Instr. and Meth. A460, 326 (2001)
Nucl. Instr. and Meth. A463, 220 (2001)
Nucl. Instr. and Meth. A528, 763 (2004)
Lifetime vs HV

- No clear correlation
Amplifiers

- We use 2-stage amplifiers

<table>
<thead>
<tr>
<th></th>
<th>Gali 39+ (1st amp)</th>
<th>Gali 84 (2nd amp)</th>
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<tbody>
<tr>
<td>Product</td>
<td>Mini-Circuits</td>
<td>Mini-Circuits</td>
</tr>
<tr>
<td>Gain at 1 GHz</td>
<td>21.1 dB</td>
<td>22.7 dB</td>
</tr>
<tr>
<td>Noise Figure at 1 GHz</td>
<td>2.4 dB</td>
<td>4.4 dB</td>
</tr>
</tbody>
</table>

- Noise level ~5 mV
Gain Uniformity Issue

• Gain Uniformity
  – Gain ratio = $\frac{\text{Gain}^{ch}_{\text{max}}}{\text{Gain}^{ch}_{\text{min}}}$ is about 6 at max.
  – For TOP operation, we may need to exclude large R PMTs

• Finer scan for some samples
  – Large R PMTs have characteristic structure
K. Matsuoka, “Performance study of the TOP counter with the 2 GeV/c positron beam at LEPS” at TIPP2014

Cherenkov image (IRS readout)

Data
Data ring image for $\cos\theta = 0.00$

MC
Simulated ring image for $\cos\theta = 0.00$

Good agreement

There are dead channels (90/512) due to some problems.
TOP (Time of Propagation) Counter

- New RICH counter
  - ID for K/π mesons
  - use “timing” of photon detection

\[ \beta = \frac{1}{n \cos \theta} \quad (n = 1.47) \]
\[ m = \frac{p \sqrt{1 - \beta^2}}{\beta} \]

PID is realized by measurement of “mass”

\[ \frac{2700 \text{ mm}}{} \]

16 modules

MCP-PMT

quartz bar

NDIP 2014 at Tours
• PID is performed by two different PDFs

compare which PDF is similar to the actual photon detection distribution

• To perform PID precisely, MCP-PMTs must have
  – QE >28%
  – Time resolution <50 ps (single photon detection)
Since CFD board could not be small, 4 channels were merged into a single channel.
MCP-PMT for single photon

- Timing properties under B=0~1.5T parallel to PMT

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</thead>
<tbody>
<tr>
<td>PMT size (mm)</td>
<td>45</td>
<td>30.5</td>
<td>52</td>
<td>71x71</td>
</tr>
<tr>
<td>Effective size (mm)</td>
<td>11</td>
<td>18</td>
<td>25</td>
<td>50x50</td>
</tr>
<tr>
<td><strong>MCP hole diameter (µm)</strong></td>
<td>6</td>
<td>8</td>
<td>10</td>
<td>25</td>
</tr>
<tr>
<td>Length-diameter ratio</td>
<td>40</td>
<td>40</td>
<td>43</td>
<td>40</td>
</tr>
<tr>
<td>Bias angle (deg.)</td>
<td>13</td>
<td>5</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>Max. H.V. (V)</td>
<td>3600</td>
<td>3200</td>
<td>3600</td>
<td>2500</td>
</tr>
<tr>
<td>photo-cathode</td>
<td>multi-alkali</td>
<td>multi-alkali</td>
<td>multi-alkali</td>
<td>bi-alkali</td>
</tr>
<tr>
<td>Q.E. (%) ((\lambda=408)nm)</td>
<td>26</td>
<td>18</td>
<td>26</td>
<td>24</td>
</tr>
</tbody>
</table>
QE

- MA; higher QE in red region, but peak is lower
- SBA; higher QE in blue region & wide peak, but difficult to obtain high QE in case of MCP-PMT
- new MA; higher QE in blue region. Although peak width is narrower than SBA, activation is very stable.
Radiation Hardness (γ rays)

Estimation: 30 krad for Belle II 10 years

Bolosillicate window

Fused silica window → good hardness
Radiation Hardness (neutrons)

- Estimation: $2 \times 10^{11}$ n/cm$^2$ for Belle II 10 years

**QE(ratio)-neutron irradiation**

- Bolosilicate window
- Fused sillica window → good hardness
Gain & TTS measurement

\[ \sigma_t = 34 \text{ ps} \]

back-scattered

Gain = $2.0 \times 10^6$
Exchange of MCP–PMTs

- Readout module

- How to change PMTs
  - Take off a module from a cutout → change a failed MCP-PMT

One module has 4 MCP-PMTs

Readout + PMT modules

Cutout here
Xe lamp

- L2195 by HAMAMATSU
Chromatic Dispersion

- Refractive index is a function of $\lambda$ (wavelength)
  - Therefore, light speed in material is also a function of $\lambda$
  - The shorter wavelength is, the slower propagation speed is.

\[
\text{Difference of TOP in quartz radiator}
\]

\[
\begin{align*}
t_{\text{def}}(\lambda) &= t_{\text{def}}(\lambda \rightarrow \infty) \\
\text{Wavelength (nm)}
\end{align*}
\]

- Time difference is relaxed.
Cherenkov Emission

• Wavelength dependence of Cherenkov photons is

\[
\frac{dN}{d\lambda} = 2\pi Z^2 \alpha L \left( 1 - \frac{1}{n^2 \beta^2} \right) \frac{1}{\lambda^2}
\]
B-field tolerant system

- A jig made of non-magnetic materials
- MCP-PMT is fixed tightly
- The jig is moved by the motorized stage located outside of B-field
- MPPC is used as an intensity monitor instead of a reference PMT.
Uniformity of the Magnetic Field

• Uniformity of B-field is good enough

![Graph showing the uniformity of the magnetic field](image-url)
Mechanical Inspections

• Visual inspection
  – Confirm PMT’s shape with a go-nogo gauge

- (1) Accepted
  Pins can be seen

- (2) Potting too thick
  Pins cannot be seen

- (3) Too short pin length
  Pins cannot be seen

Table

• HV application test

Normal

No output

HV discharge