Extension of the MCP-PMT lifetime

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Photon sensors in novel RICH detectors

Requirements for the photon sensors are

- Not only a spatial resolution to reconstruct Cherenkov images
- Very good time resolution for single photons
  - <50 ps for Time-Of-Propagation (TOP)
- Large photocoverage
- High efficiency
- Work under a high background
- Work in a high B-field

Only an MCP-PMT could meet every requirement.
MCP-PMT (Micro Channel Plate PMT)

- Square shape multi-anode MCP-PMT with a large photocoverage
  - Developed for the Belle II TOP counter at Nagoya in collaboration with HAMAMATSU Photonics K.K.

Photon (Cross-section)

Photocathode (NaKsBcCs)

MCP x 2

4 x 4 anodes

Micro channel

The best time resolution of photon sensors

Limited by the oscilloscope. The actual signal is faster.
Major problem of the MCP-PMT

Aging of the photocathode

- In the electron multiplication, gas/ion is desorbed from the MCP.
- The photocathode is deteriorated by the gas/ion and the QE is depressed.
  - The amount of QE depression depends on the accumulated output charge.
→ Define the lifetime of the MCP-PMT as an accumulated output charge $Q_\tau$ at which $\text{QE}(Q_\tau)/\text{QE}_{\text{initial}} = 0.8$ at 400 nm.

- Estimated accumulated output charge for Belle II TOP dominantly due to beam bkgd.:
  $\sim 3.7 \text{ C/cm}^2$ at 50 ab$^{-1}$ with $5 \times 10^5$ gain

We have researched to achieve the lifetime longer than the estimated accumulated output charge.
How to extend the lifetime

Three steps of approach

1. Block the gas/ion from reaching the photocathode
   ... Conventional MCP-PMT [NIM A629 (2011) 111]
2. Suppress outgassing from the MCP
   ... ALD (Atomic Layer Deposition) MCP-PMT (2013~)
3. Reduce residual gas on the MCP
   ... Life-extended ALD MCP-PMT (2015~)

Evaluated the lifetime of each type of MCP-PMT
Test of the lifetime

- Monitor the QE as a function of the accumulated output charge of the MCP-PMT.
  - LED is used to load the output charge, which is measured by a CAMAC ADC.
  - QE is monitored as the hit rate by the laser single photons.
The QE depression curve is represented by \[ \frac{QE(Q)}{QE_{\text{initial}}} = 1 - 0.2\left(\frac{Q}{Q_\tau}\right)^2 \]

- Longer lifetime with ALD and much longer with life-extended ALD
QE spectrum after the lifetime test

- Measured by Xe lamp + monochromator

Consistent with the in-situ QE measurement by the laser at 400 nm.

- The QE drops more significantly at longer wavelengths as the work function of the photocathode increases.
QE drop of 4 life-extended ALD MCP-PMT samples at 4.0-5.5 C/cm$^2$ was little. Stopped the test to keep them as spares for Belle II TOP.

Estimate the lifetime of those samples by comparing the QE spectrum with another sample of which lifetime was measured to be 11.2 C/cm$^2$.

\[
1 - 0.2 \left( \frac{Q}{Q_\tau} \right)^2 \geq 1 - 0.2 \left( \frac{3.3}{11.2} \right)^2 \Rightarrow Q_\tau \geq \frac{Q}{3.3} \times 11.2 \ C/cm^2 \geq 13.6-18.7 \ C/cm^2
\]
Summary of the measured lifetime

- The lifetime varies broadly sample-by-sample.
  - Need to measure many samples to evaluate the lifetime.
- Succeeded in extending the lifetime significantly.

### Lifetimes
- **12 conventional**
  - 0.3-1.7 C/cm²
  - Average: 1.1 C/cm²
- **8 ALD**
  - 2.5-26.1 C/cm²
  - Average: 10.4 C/cm²
- **8 life-extended ALD**
  - >13.6 C/cm²

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Belle II TOP
Due to the emissive coating of the ALD, the ALD MCP has a larger secondary electron yield (SE yield) than the conventional MCP.

We have 277 conventional, 231 ALD and 65 life-extended ALD MCP-PMTs for Belle II TOP.

Systematically studied the performance of the (life-extended) ALD MCP-PMTs compared with the conventional ones.
Setup of the laser test

- Single photon irradiation to each anode one by one.

- Pico-second pulse laser ($\lambda = 400$ nm)

- ND filters

- Slit

- Light spot $\approx 1$ mm

- Variable amp

- MCP-PMT

- Reference PMT

- Dark box

- Moving stage

- Laser

- MCP-PMT

- Fiber

- ADC

- TDC

- ATT

- Amp

- Discriminator

- +19.5~35 dB

- +33 dB

- Threshold: $-20$ mV
Gain

- Define the gain as the mean of the output charge distribution.

Lower HV for ALDs to have the same gain owing to the higher SE yield.
Relative collection efficiency

- Count the number of TDC hits.
- Correct the laser intensity variation with the reference PMT.

Higher collection efficiency of ALDs by ~15%.
The variation of the collection efficiency among PMTs of each type seems to be independent of the HV for the same gain or SE yield.
TTS (Transit Time Spread)

- Fit a double Gaussian to the TDC distribution after time-walk correction.
- Define the TTS as $\sigma$ of the primary Gaussian.

Higher collection efficiency is due to increase of the efficiency for the recoil photo electrons.
Performance under a high rate

- After a micro-channel fires, electrons are depleted on the channel wall.
- The channel wall $O(10^{-16} \, \text{F})$ is recharged by the strip current through a high resistance of the micro-channel $O(10^{14} \, \Omega)$.
- Dead time of a single micro-channel

$$\tau_d = RC = \frac{Q_{out}}{I_s} = O(10 \, \text{ms})$$

for the 2\textsuperscript{nd} MCP

- Under a high rate of background, a large fraction of micro-channels could be dead.
  (Belle II TOP: ~200 kHz/anode)
- Drop of the gain and efficiency, depending on the MCP resistance.
Test under a high background

- Added an LED to the laser test bench to emulate background single photons of high rate.

Laser

- CLOCK
  - 10 MHz
  - 20 ns width

- ATT
  - -9 ~ -5 dB
  - Change the light intensity

- LED
  - Tape to fade light
  - Bkgd. single photons at a high rate

Life-extended ALD MCP-PMT

MCP-PMT LED
Gain under a high background

Gain drops above $\gtrsim 100$ kHz/anode for high R MCPs.
Efficiency under a high background

Efficiency drops above ~1 MHz/anode.
TTS under a high background

TTS deteriorates above ~200 kHz/anode.
An MCP-PMT is a key photon sensor for novel RICH detectors.

A major concern is a use under a high background:

- **Lifetime of the photocathode**
  
  Lifetime has been extensively improved by three steps:
  
  1. Conventional MCP: 1.1 C/cm$^2$ on average of 12 samples
  2. ALD MCP: 10.4 C/cm$^2$ on average of 8 samples
  3. Life-extended ALD MCP: >13.6 C/cm$^2$ for all 8 samples

- **Performance degradation**
  
  - Drop of the gain and efficiency is little up to 1 MHz/anode for $R_{\text{MCP}} \leq 174$ M$\Omega$. (A smaller $R_{\text{MCP}}$ is better.*)
  - TTS deteriorates above ~200 kHz/anode
    - Independent of $R_{\text{MCP}}$.
    - Correspond to 3.7 C/cm$^2$/50 ab$^{-1}$ for $5 \times 10^5$ gain at Belle II TOP.
    - Current limit of background rate to use the MCP-PMT.

We succeeded in developing the MCP-PMT for Belle II TOP, but further R&D is necessary for next next generation experiments.

* Cannot be much smaller to avoid thermal runaway.