Performance of the MCP-PMTs of the TOP counter in the first beam operation of the Belle II experiment

K. Matsuoka (KMI, Nagoya Univ.)
on behalf of the Belle II TOP group

5th International Workshop on New Photon-Detectors (PD18), Tokyo, Nov. 29, 2018
The Belle II experiment

B-factory experiments

- BaBar
- Belle

Confirmed Kobayashi-Maskawa theory with $> 1 \text{ ab}^{-1}$ data

Search for new physics via precision measurements with $50 \text{ ab}^{-1}$ data

Next generation B-factory experiment

Belle II

Challenge on the detector

- Cope with harsh beam background
- Improve the performance

Barrel PID $\rightarrow$ TOP counter
TOP counter

- State-of-the-art Cherenkov ring imaging detector
- $K/\pi$ identification by means of $\beta$ reconstruction using precise timing measurement of internally reflected Cherenkov photons

Key techniques:
- Propagate the “ring” image undistorted
- Detect the photons with a high efficiency (~20 hits/track) and with an excellent time resolution (<50 ps)
  - Only MCP-PMTs can meet the requirements.

Mathematical relations:

\[ \text{Time of propagation (TOP)} \]
\[ \propto \cos \theta_C = \frac{1}{n\beta} \]
MCP-PMT for the TOP counter

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

Phatocathode (NaKSBcs)

Micro channel

Oscilloscope (2.5 GHz bandwidth)

The best time resolution ($\sigma \sim 30$ ps) of photon sensors
Performance of the MCP-PMT

ADC distribution for single photons

Entries 3929
Mean 0.08098
RMS 0.03658

TDC distribution for single photons from picosecond pulse laser

Entries 2459
Mean 20.52
RMS 172.2
χ² / ndf 50.12 / 28
Constant1 411.8 ± 14.7
Mean 38.43 ± 1.35
Sigma 41.77 ± 1.48
Constant2 53.75 ± 5.29
Mean2 70.31 ± 8.59
Sigma2 132.7 ± 5.7

Gain ≡ mean of the distribution
= $5.1 \times 10^5$

TTS ≡ $\sigma$ of 1st Gaussian
= 41.8 ps
(incl. ~17 ps laser pulse width and ~24 ps electronics jitter)
Performance in B-field

Shorter path in a higher B-field
→ More bounces / Lower energy
→ Higher gain
    / Lower secondary electron yield

Less divergence in a higher B-field
→ Rise and fall of the hole coverage
    or gain
Mass-production of the MCP-PMTs

- Unprecedented production of 512 (and spare) MCP-PMTs.
- In parallel, R&D for life extension.
  - Eventually three types of MCP-PMTs (Next talk by Muroyama-san)

Succeeded in time for the TOP installation in May 2016.

- Mass-production is continued for the replacement of the 224 conventional MCP-PMTs in 2020 summer.

ALD: Atomic Layer Deposition

Life-extended ALD MCP

For replacement

1st beam operation

Installed

Conventional MCP (short lifetime)

ALD MCP

R&D

Number of PMTs

0 100 200 300 400 500 600 700
Performance check at Nagoya

- The performance of every MCP-PMT was checked in automated test benches in a systematic way.

QE at peak (~360 nm)

- Requirement: 24% min and 28% avg.
- Avg. QE: 29.3%

Collection efficiency

- Requirement: less than 50 ps
- Avg. TTS: 34.3 ps

Total Collection Efficiency

- Conventional ALD
- Life-extended ALD

The difference only at the tail, where the recoil photo electrons contribute, makes the difference of CE.
Performance check in 1.5 T

- The performance of every MCP-PMT was checked in a large dipole magnet at KEK.
- Checked the difference between 0 and 1.5 T.

<table>
<thead>
<tr>
<th>gain(1.5 T) / gain(0 T)</th>
<th>CE(1.5 T) / CE(0 T)</th>
<th>TTS(1.5 T) – TTS(0 T)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conventional ALD</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Life-extended ALD</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
PMT module assembly / installation

- 4 MCP-PMTs are assembled in a module.
  - PMT window is glued on a wavelength filter, which cuts $\lambda \leq 340$ nm to suppress chromatic dispersion.
- Bubble free optical contact between the PMT module and the prism by a soft cast silicone cookie.
- Laser single photons for the in-situ calibration.
Threshold efficiency

- The gain of every MCP-PMT was adjusted to $5 \times 10^5$.
  - Lower gain $\rightarrow$ longer lifetime but lower threshold efficiency
- Evaluated the efficiency with single photons from the laser.

Data taken without discrimination

$$f(x) = p_0 \frac{(x/x_0)^{p_1}}{\exp[-(x/x_0)^{p_2}]},$$

Entries: 49267
Mean: 0.3397
RMS: 0.3688
$\chi^2$/ndf: $1.127 \times 10^4 / 87$
Constant: $9447 \pm 60.2$
Mean: $0.1334 \pm 0.0011$
Sigma: $0.1906 \pm 0.0007$

Belle II TOP preliminary

- only slot11
  - Mean $0.9897 \pm 0.0002$
Beam operation

- MCP-PMT HVs were turned on during luminosity runs in Apr-Jul 2018.
- TOP counter worked for particle identification.

Example of Cherenkov “ring” image
**Beam background**

- PMT hits are dominated by $\gamma$ rays from the accelerator
  - $\gamma \rightarrow$ Compton scattering / pair creation in the quartz bar $\rightarrow$ electrons $\rightarrow$ Cherenkov photons
  - MC estimation: 5-8 MHz/PMT at the design luminosity
- $\sim$0.5 MHz/PMT in the start-up luminosity runs in 2018
  - Much higher than predicted, but still tolerable.

Kept below 0.023 C/cm$^2$

Preliminary

Accumulated output charge of each MCP-PMT

cf. QE drops by 20% at 0.3-1.7 C/cm$^2$ for the conventional MCP-PMTs
Evaluation of number of hits

- Number of hits of Cherenkov photons for di-muon events
- MC based on the measured parameters of each component
  - Quartz internal reflectance and transmittance
  - MCP-PMT QE and collection efficiency (dark noise negligible)
  - Readout efficiency (~77%, to be improved) and noise hits (a few %)
  - Beam background hits (~1 hits/slot)

Slot01 (life-extended ALD MCP-PMTs)

- Data (mean = 29.8)
- MC (mean = 26.1)

Slot11 (conventional MCP-PMTs)

- Data (mean = 20.7)
- MC (mean = 20.2)

The difference is under investigation.
Summary

- The MCP-PMT is one of the key components which bring the Belle II TOP counter into life.
- Succeeded in developing and producing 512 (and spare) MCP-PMTs for the Belle II TOP counter.
  - ~34 ps TTS for every PMT
  - 29.3% avg. QE at ~360 nm
  - Work in 1.5 T
- Installation of the TOP counter finished in May 2016.
- The MCP-PMTs worked as expected in the first beam operation in Apr-Jul 2018.
QE measurement setup

- Measure the photocathode current with a picoammeter:

\[ QE_{MCP} = \frac{I_{MCP}}{I_{PD}} \cdot QE_{PD} \]
Laser measurement setup

- Single photon irradiation to each channel one by one.

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

- ND filters

- Slit

- Light spot $\approx 1 \text{ mm} \phi$

- Reference PMT

- Fiber

- Variable amp

- Laser

- MCP-PMT

- Moving stage

- ADC

- TDC

- ATT

- Amp

- Discriminator

- Threshold: $-20 \text{ mV}$

- $+19.5 \text{ to } 35 \text{ dB}$

- $-10 \text{ dB}$

- $+33 \text{ dB}$
Installation of the TOP counter

Installation of 16 TOP modules finished in May 2016.

Viewed from the backward to the forward.