MCP-PMT for the Belle II TOP counter

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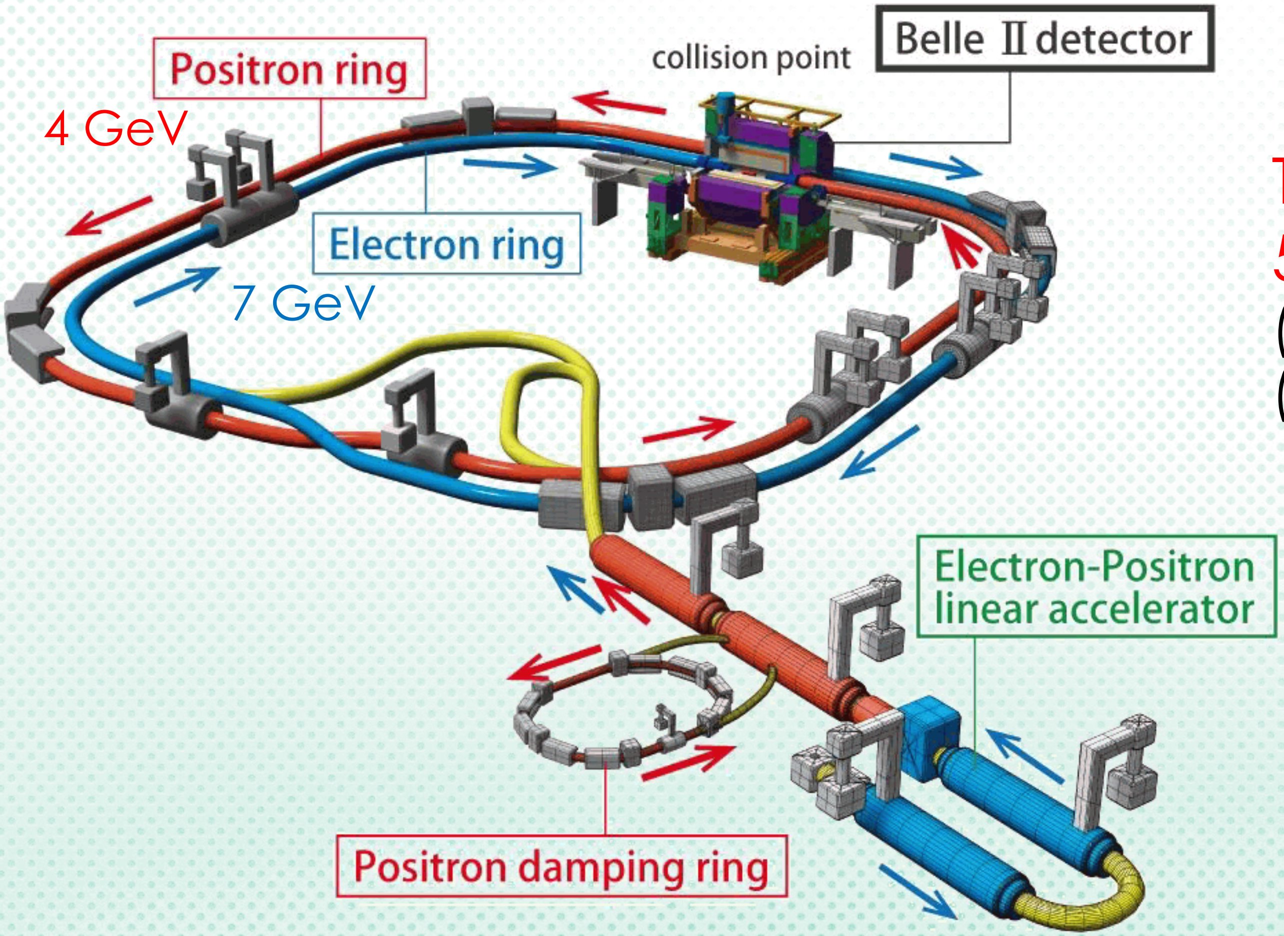
The Belle II experiment

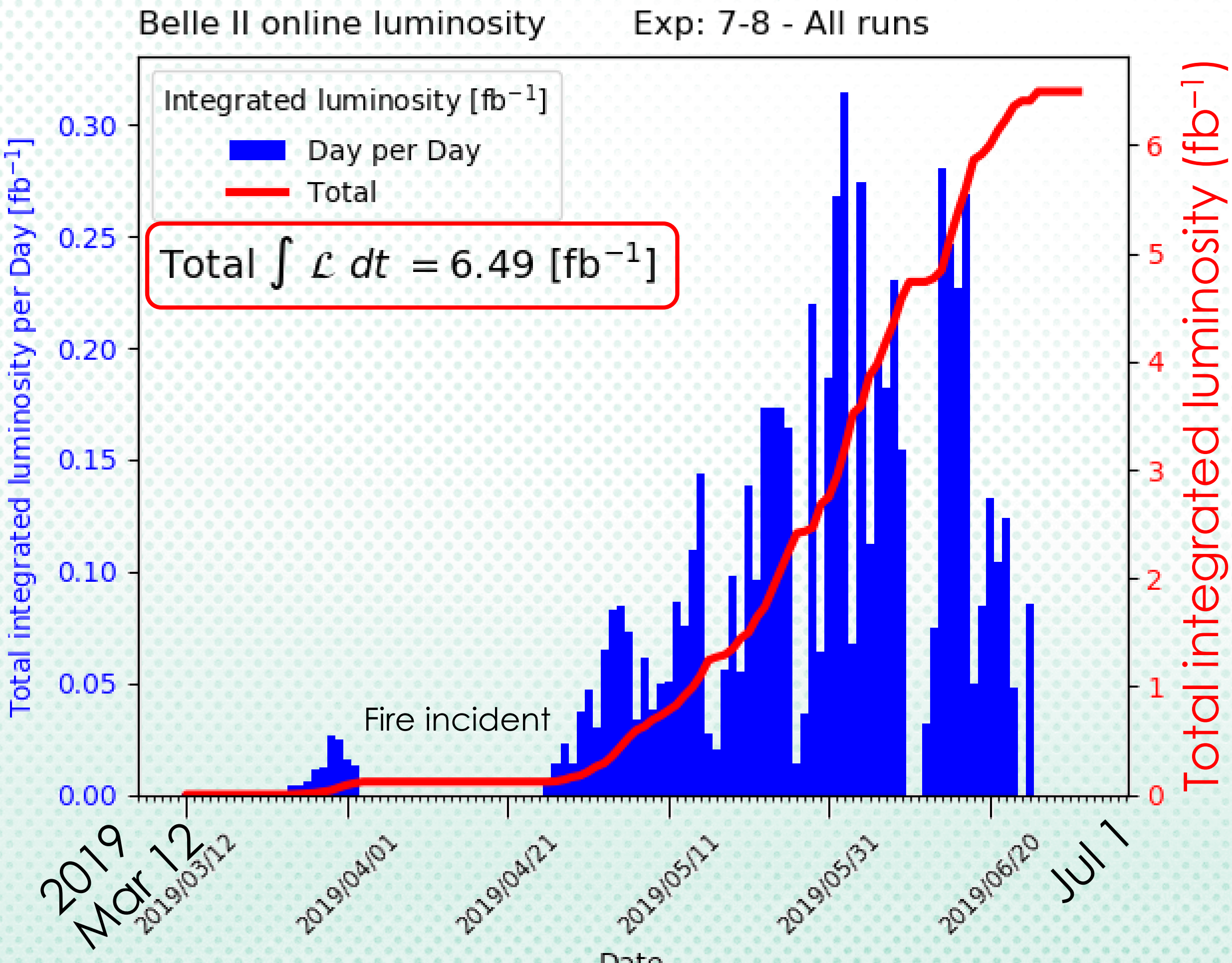
- Produce a large number of B, D, τ, etc. at Super-KEKB and extensively test the CKM paradigm to search for new physics.



Target:
50 ab^{-1} until 2027
(≈ 5e10 $B\bar{B}$ pairs)
(≈ x50 of Belle/BaBar)

Belle II status

- Started physics data taking with the full Belle II detector last March.



$\mathcal{L}$(peak) $\approx 5.5 \times 10^{33}$ /cm^2/s

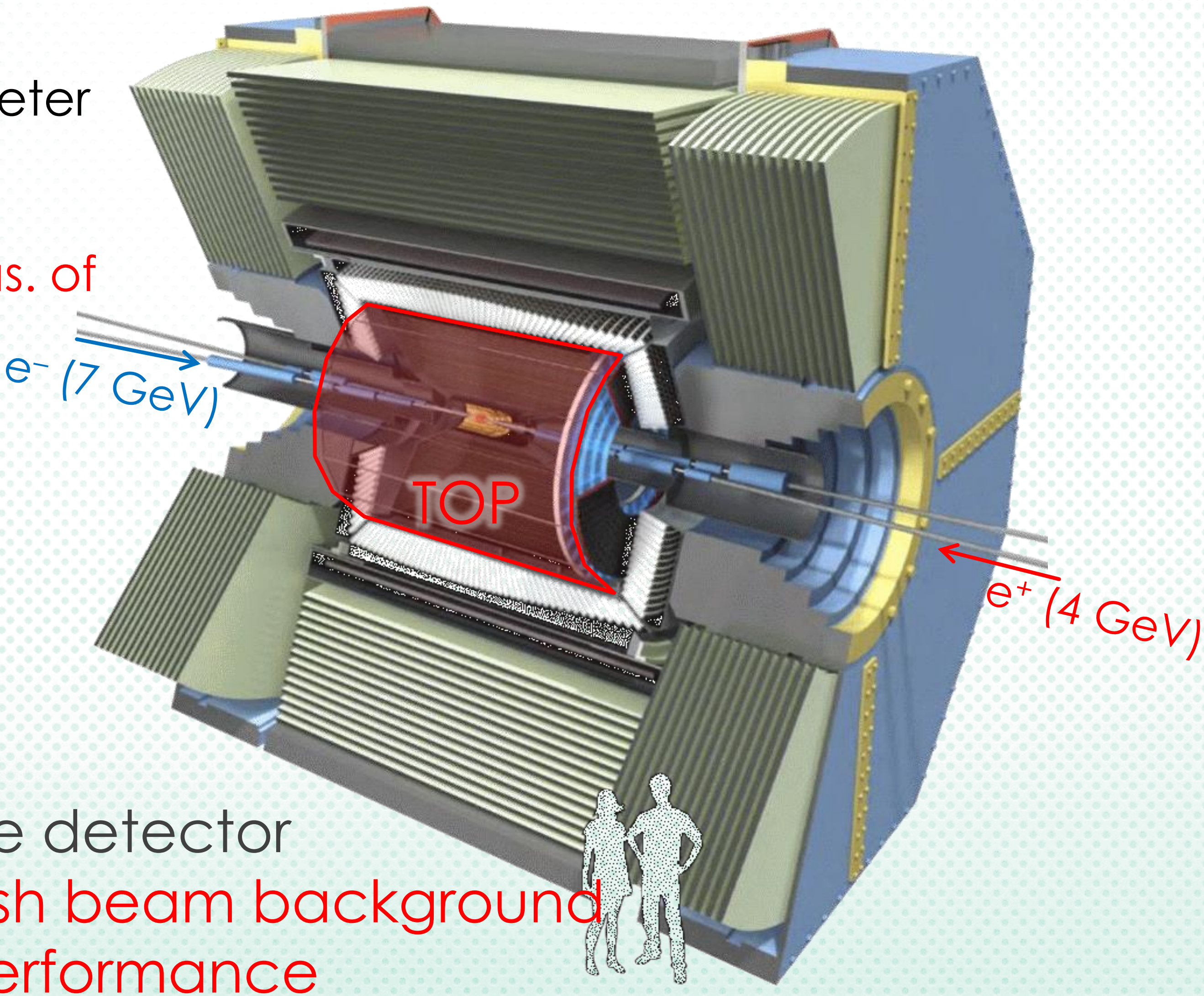
(design: 8×10^{35} /cm^2/s)

Accelerator and detector are being tuned up for the full-throttle performance.

The Belle II detector

Hermetic spectrometer capable of

- Tracking and momentum meas. of charged tracks
- Vertex meas.
- Particle ID
- γ energy meas.



Challenge on the detector

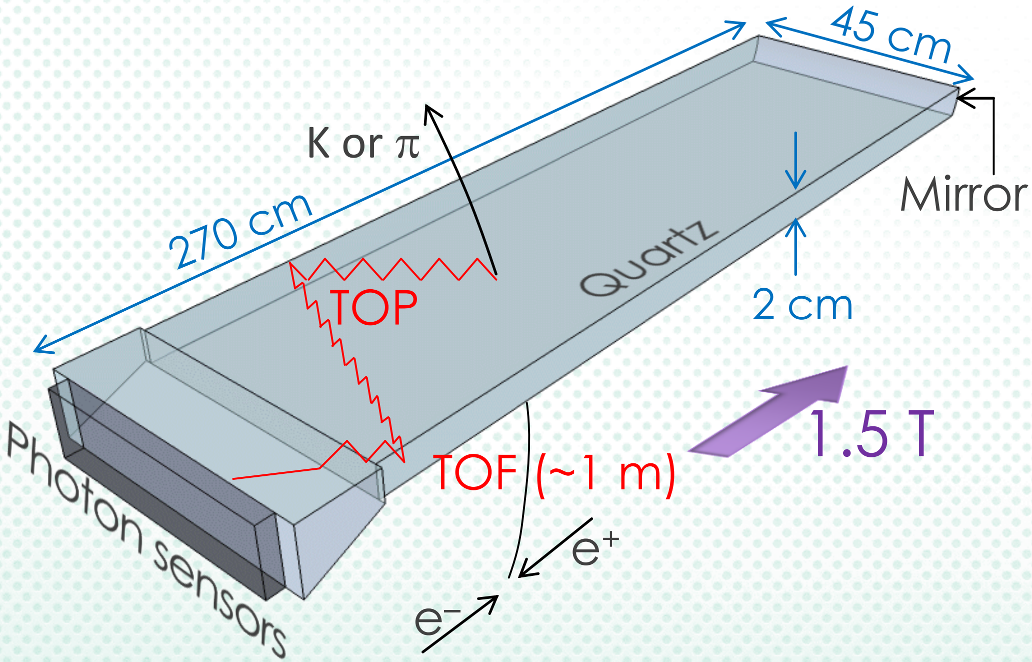
- Cope with harsh beam background
- Improve the performance

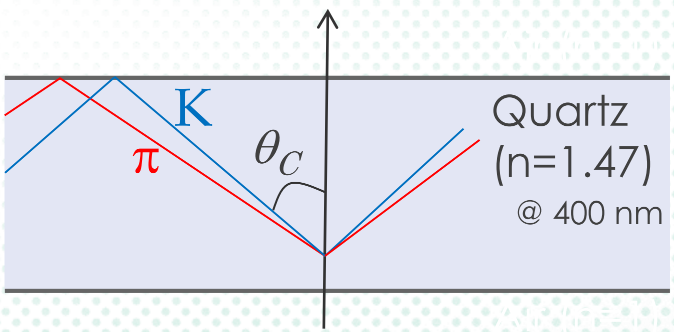
Barrel PID → TOP counter

TOP counter

→ Gary-san's talk in detail

- State-of-the-art Cherenkov ring imaging detector **in operation**
- K/π identification by means of β reconstruction using precise timing measurement of internally reflected Cherenkov photons





Time of propagation (TOP)

$$\propto \cos\theta_C = \frac{1}{n\beta}$$

Key techniques:

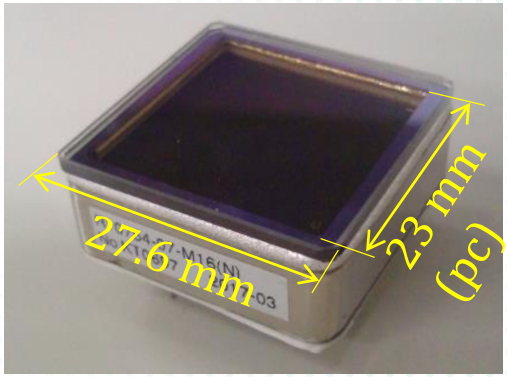
✓ Propagate the "ring" image undistorted

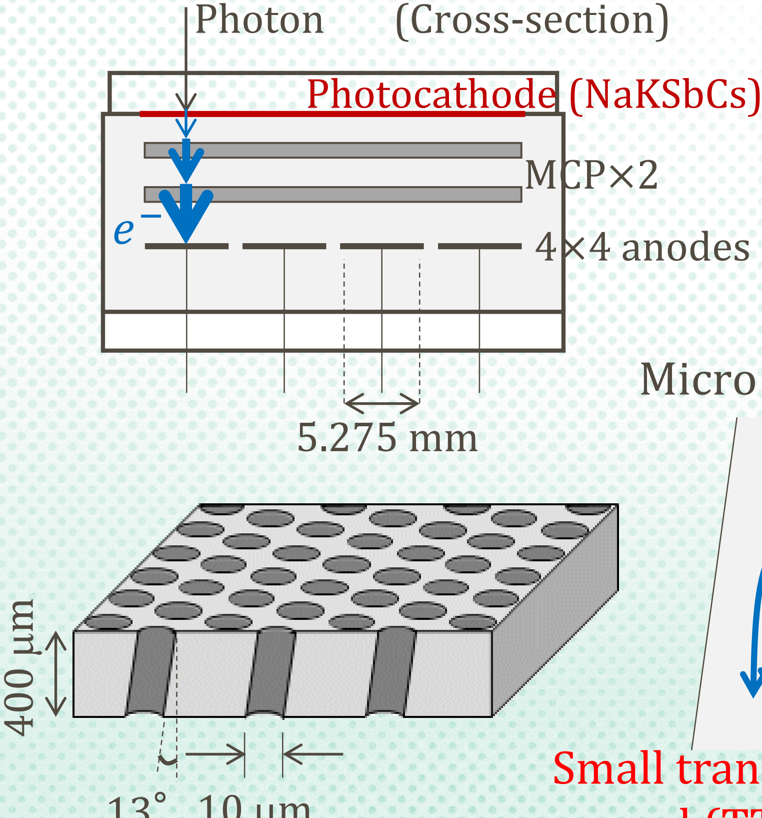
✓ Detect the photons with a high efficiency (~20 hits/track) and with an excellent time resolution (<50 ps)

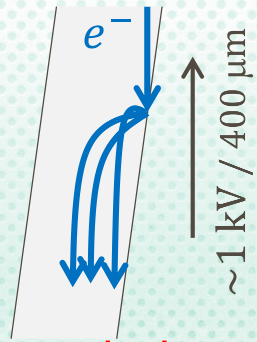
→ Only MCP-PMTs can meet the requirements.

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

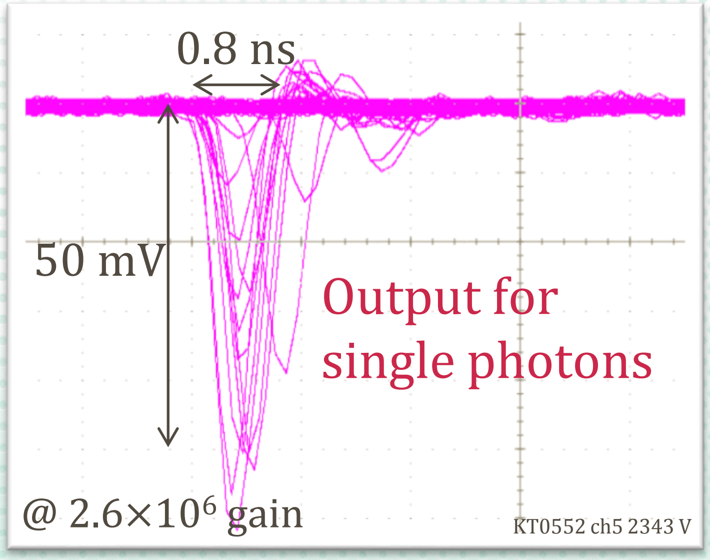






Small transit time spread (TTS)

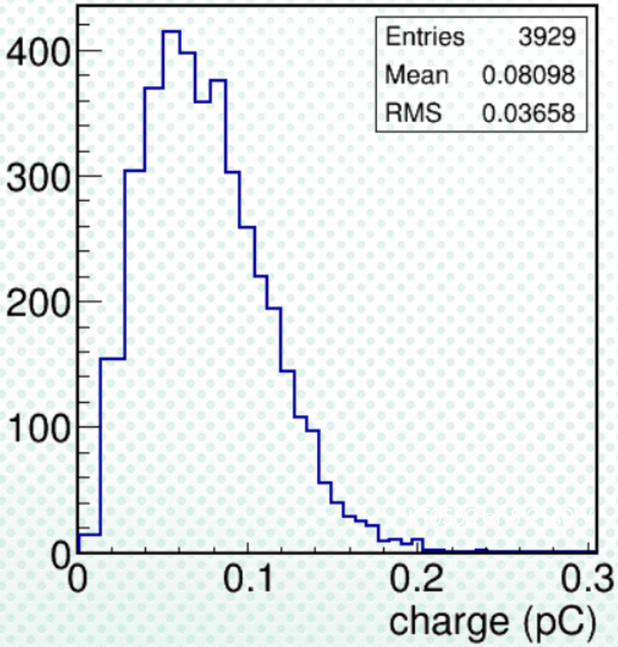
Oscilloscope (2.5 GHz bandwidth)



The best time resolution (σ~30 ps) of photon sensors

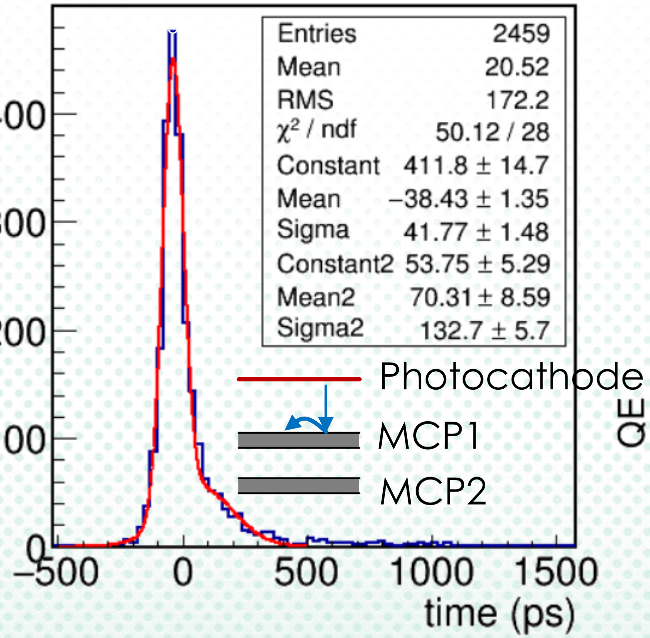
Performance of the MCP-PMT

ADC distribution for single photons



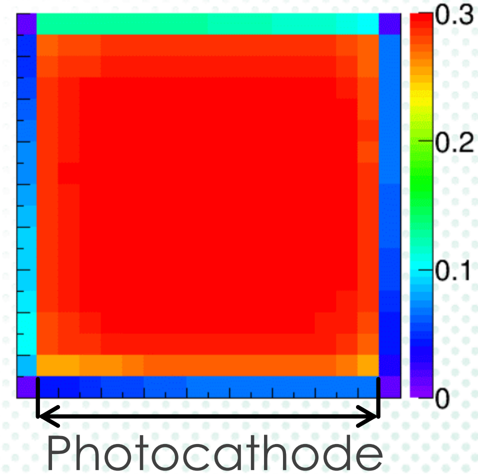
Gain
≡ mean of the distribution
$= 5.1\times10^5$

TDC distribution for single photons from picosecond pulse laser

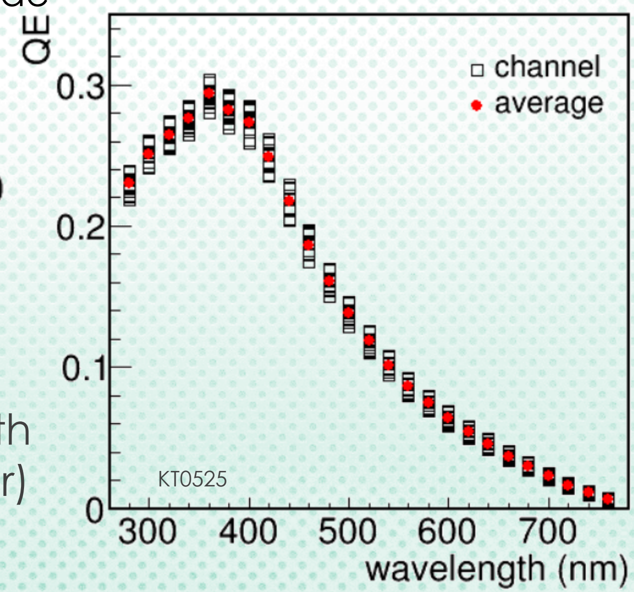


TTS ≡ σ of 1st Gaussian
= 41.8 ps
(incl. ~17 ps laser pulse width
and ~24 ps electronics jitter)

QE distr. at 360 nm

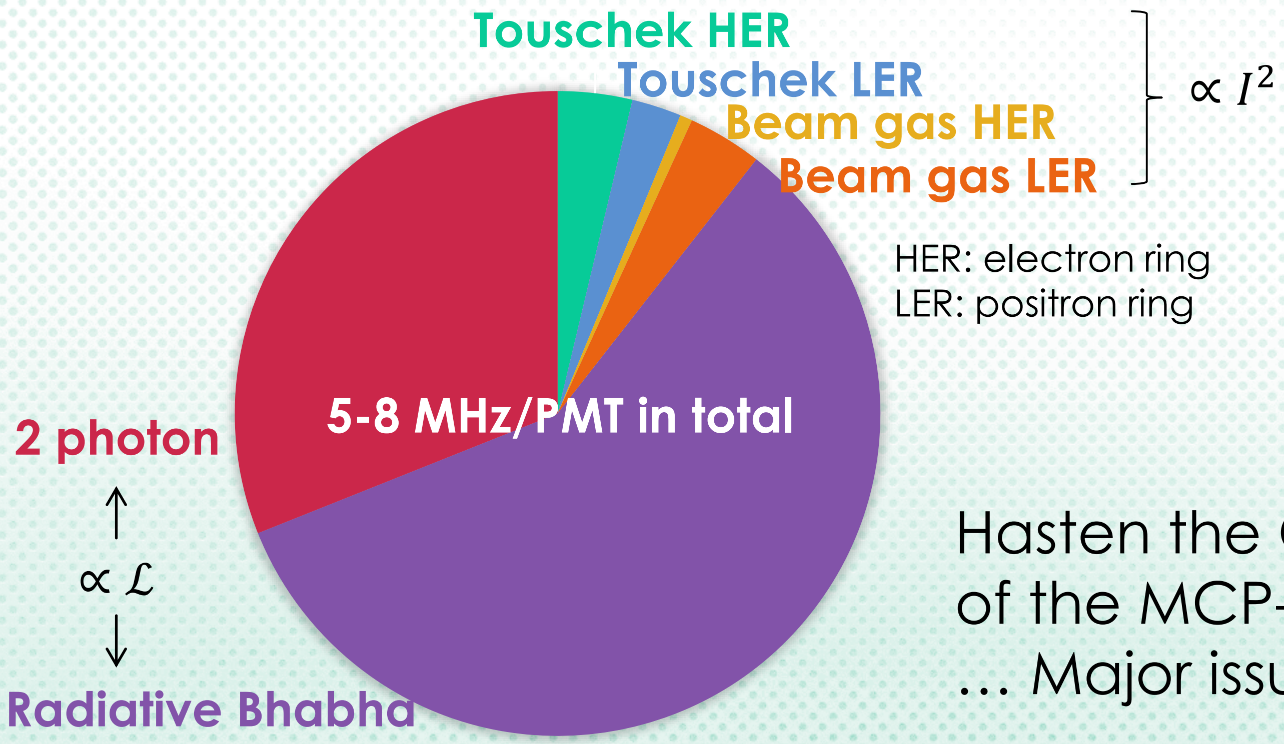


Typical QE spectrum



Background hits in the beam operation

- Dominated by γ rays from the accelerator
  - γ → Compton scattering / pair creation in the quartz bar → electrons → Cherenkov photons
  - MC estimation: 5-8 MHz/PMT at the design luminosity

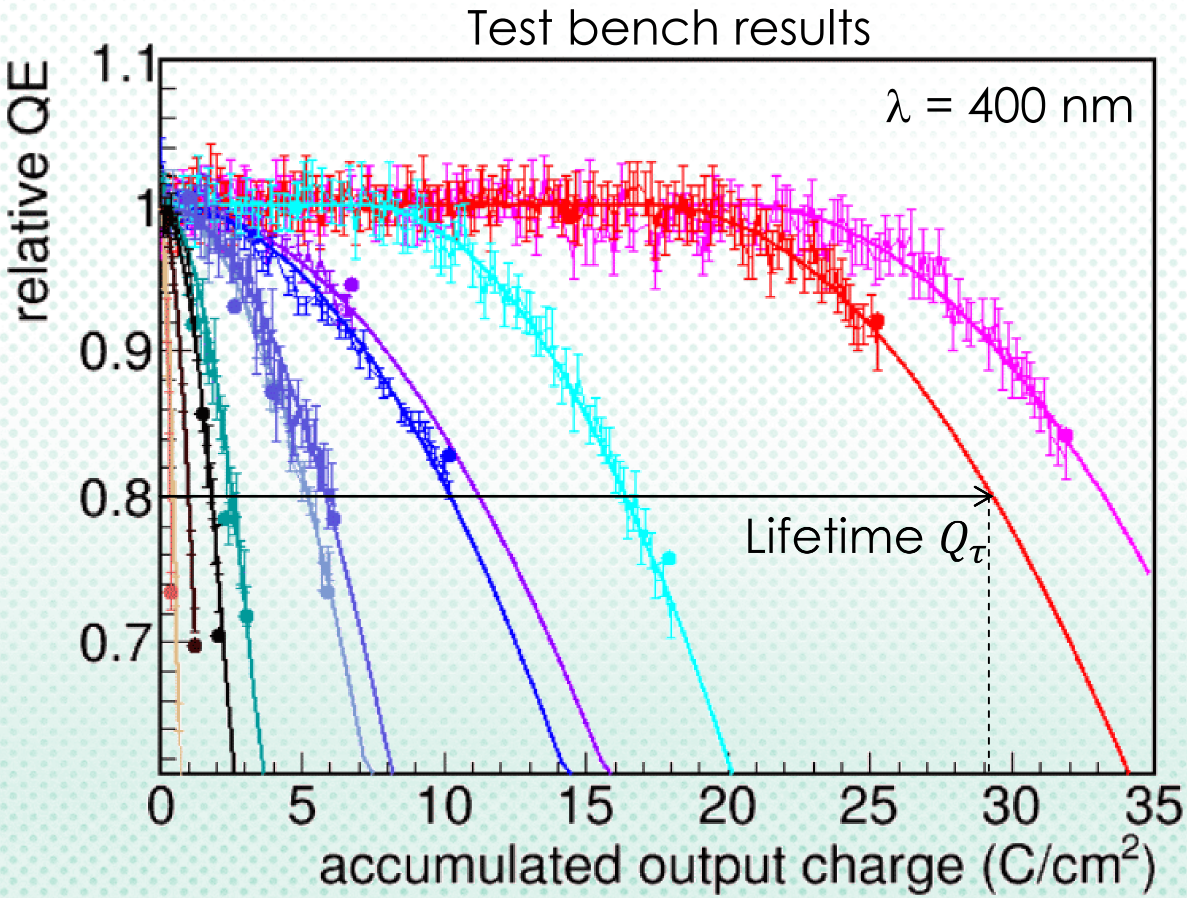


Hasten the QE degradation of the MCP-PMTs

… Major issue of TOP

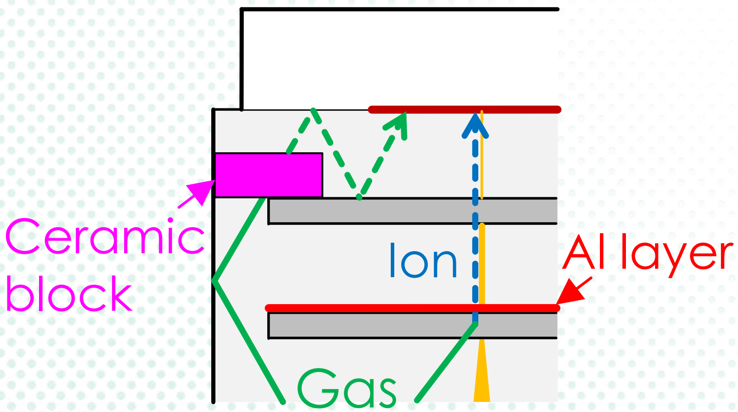
QE degradation

- Outgassing from the MCP deteriorates the photocathode and the QE drops as a function of the integrated output charge: $\frac{\mathrm{QE}(Q)}{\mathrm{QE}_{\mathrm{inital}}} = 1 - 0.2\left(\frac{Q}{Q_\tau}\right)^2$ for every MCP-PMT tested.

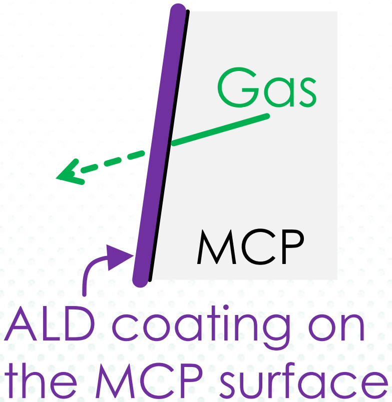


Lifetime extension of the MCP-PMT

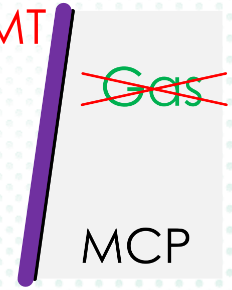
Step 1 (2011)
Conventional MCP-PMT



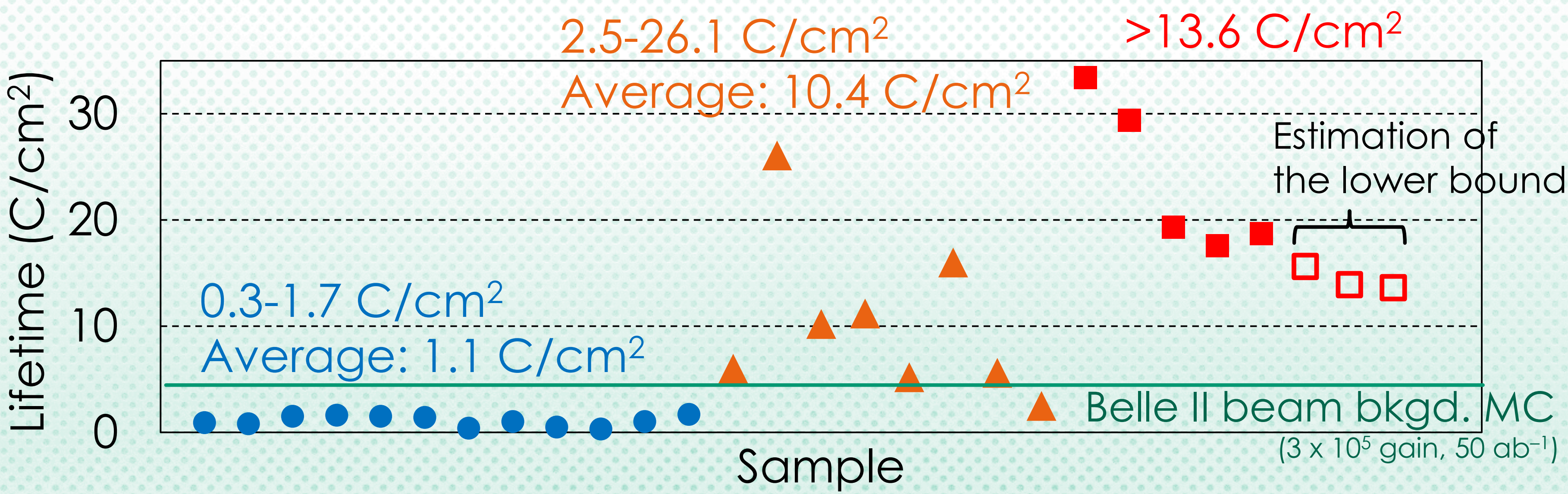
Step 2 (2013)
ALD MCP-PMT



Step 3 (2015)
Life-extended ALD MCP-PMT

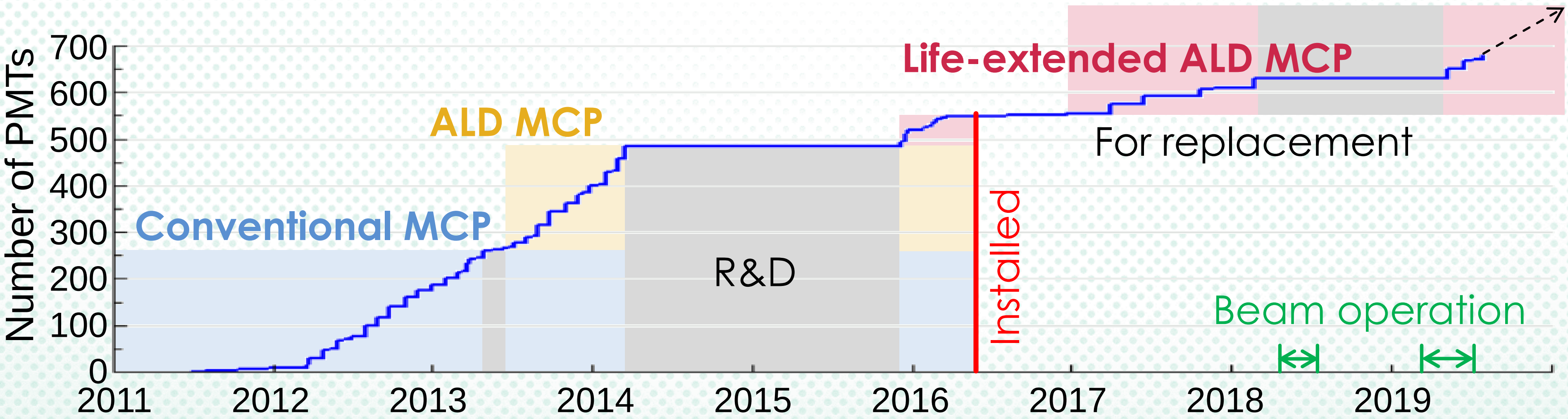


ALD: Atomic Layer Deposition



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



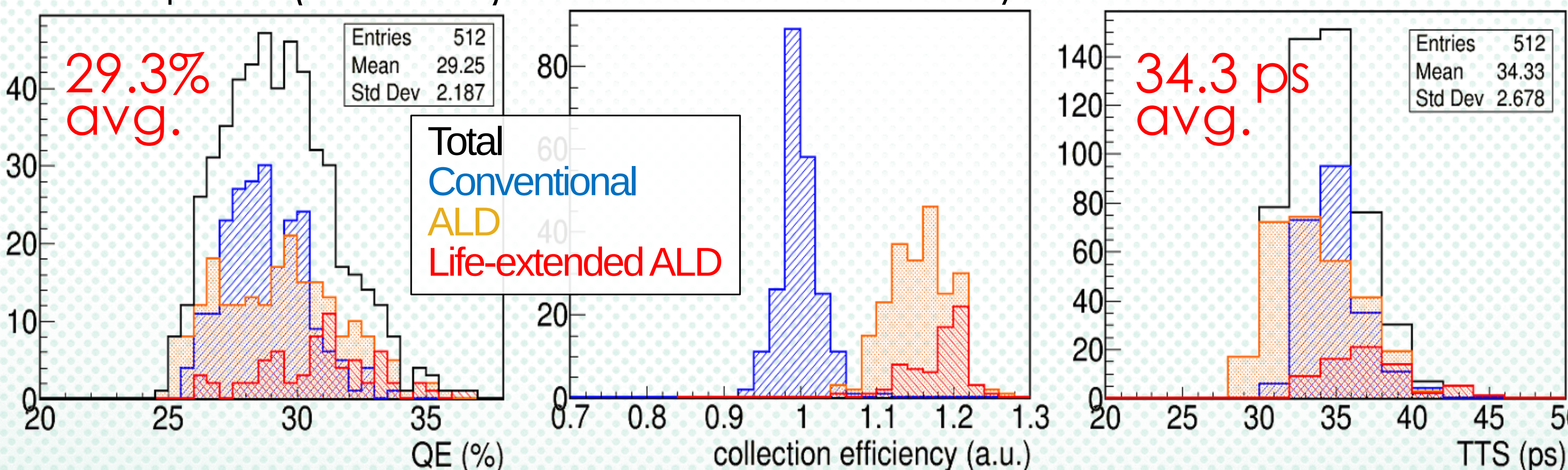
Succeeded in time for the TOP installation in May 2016.

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

Performance check at Nagoya

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

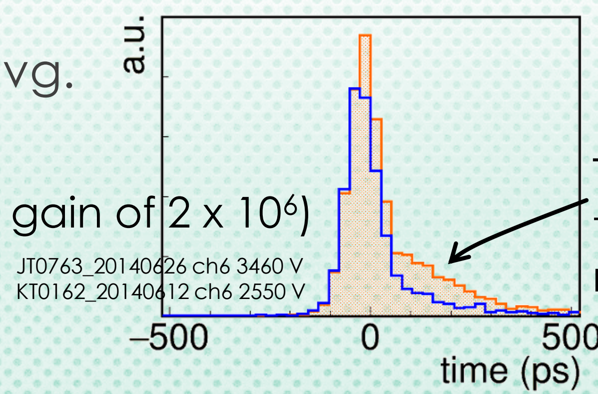
QE at peak (~360 nm) Collection efficiency TTS



Requirement:
24% min and 28% avg.

Requirement:
less than 50 ps

(same gain of 2 x 10^6)

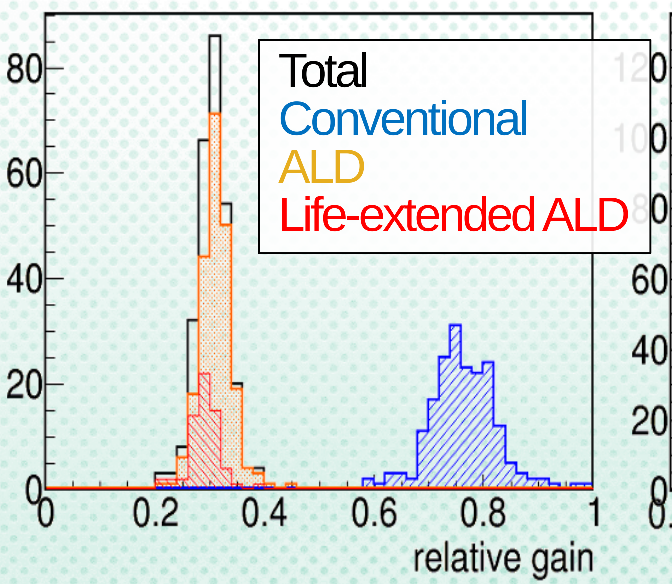


The difference only at the tail, where the recoil photo electrons contribute, makes the difference of CE.

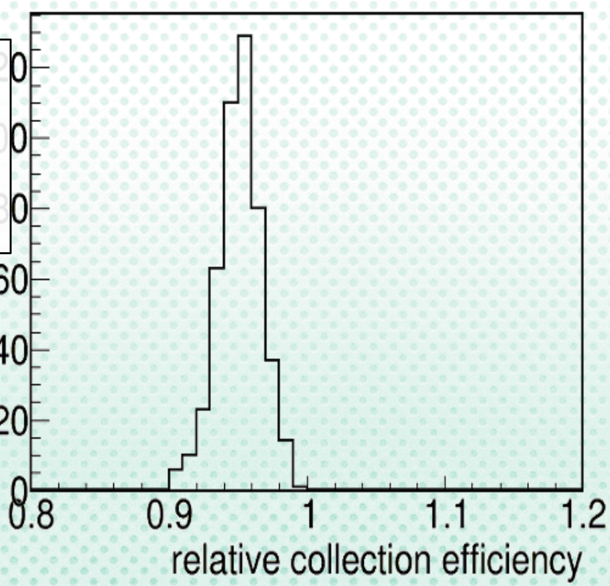
Performance check in 1.5 T

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

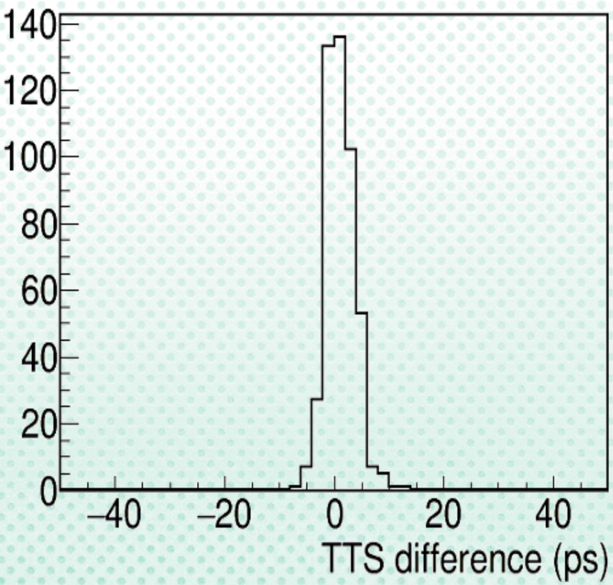
gain(1.5 T) / gain(0 T)



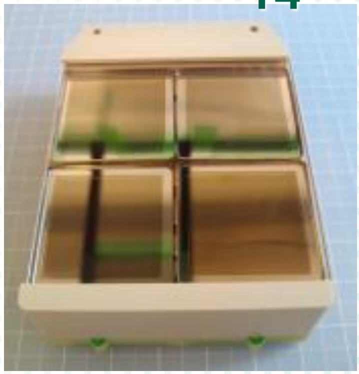
CE(1.5 T) / CE(0 T)



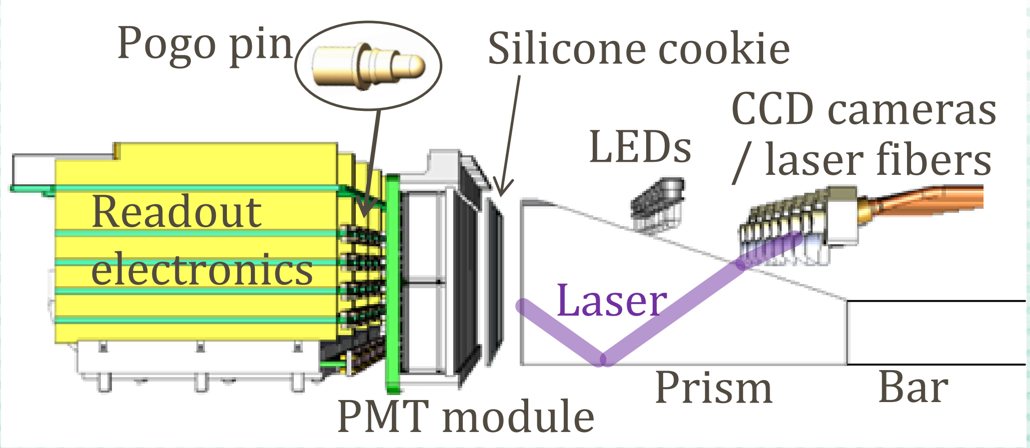
TTS(1.5 T) – TTS(0 T)

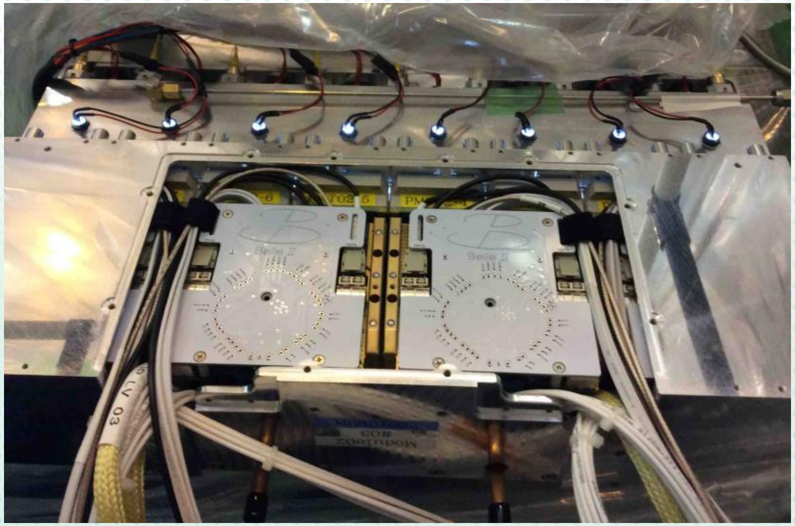


PMT module assembly / installation



- 4 MCP-PMTs are assembled in a module.
  - PMT window is glued on a wavelength filter, which cuts $\lambda \lesssim 340$ nm to suppress chromatic dispersion.
- Bubble free optical contact between the PMT module and the prism by a soft cast silicone cookie.
- 2.7 GSampling/s of PMT signal by switched-capacitor array ASIC (IRSX). → Gary-san's talk in detail
- Laser single photons for the in-situ calibration.

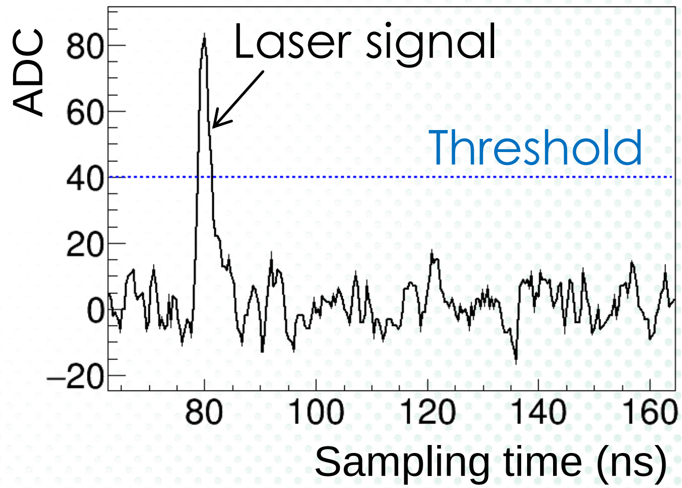




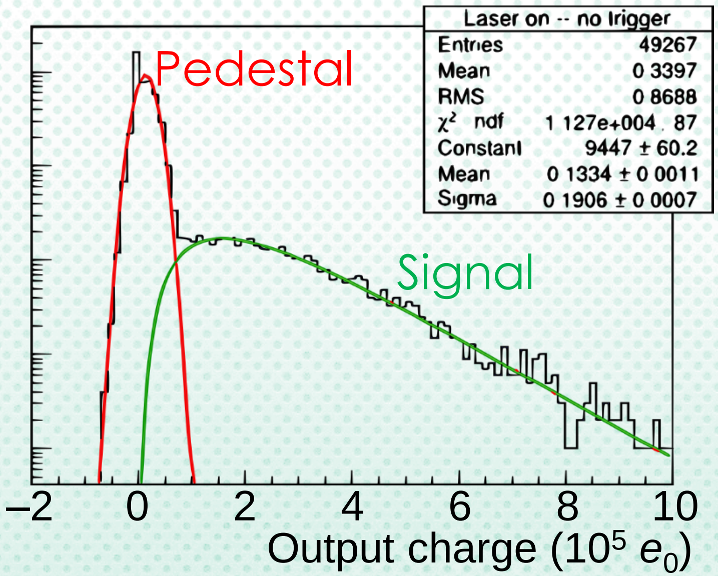
Installation of the TOP counter

Threshold efficiency

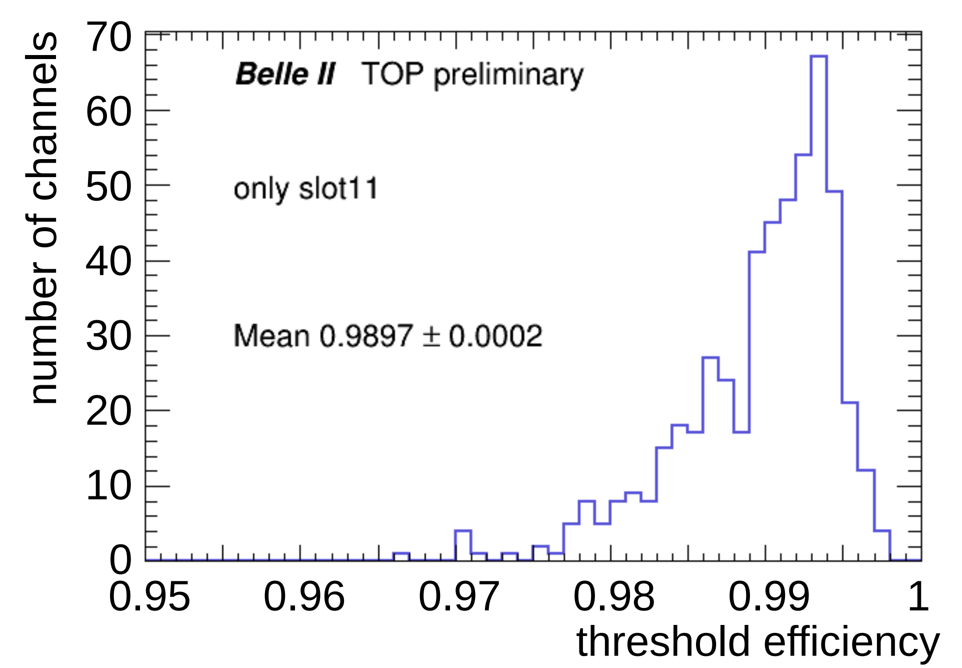
- The gain of every MCP-PMT was adjusted to 3 x 10^5.
  - Lower gain → longer lifetime but lower threshold efficiency
- Evaluated the efficiency with single photons from the laser.



Data taken without discrimination



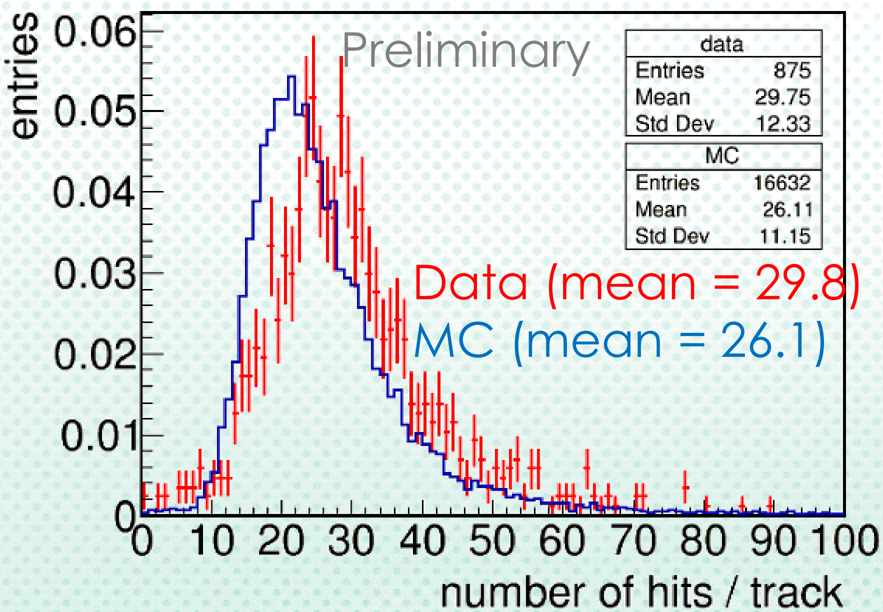
$$f(x) = p_0(x/x_0)^{p_1} \exp[-(x/x_0)^{p_2}]$$



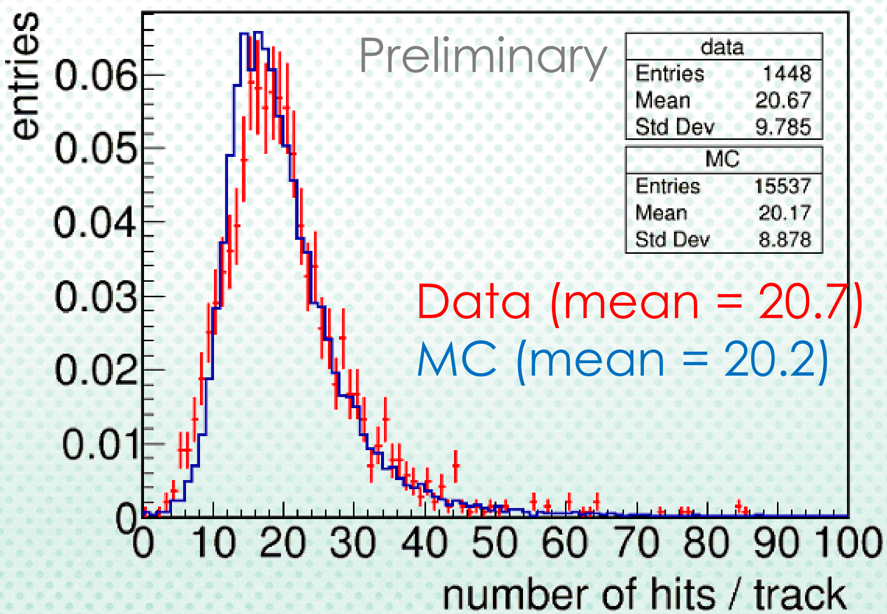
Evaluation of number of hits

- 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 and noise hits (a few %)
  - Beam background hits (~1 hits/slot)

Slot01 (life-extended ALD MCP-PMTs)



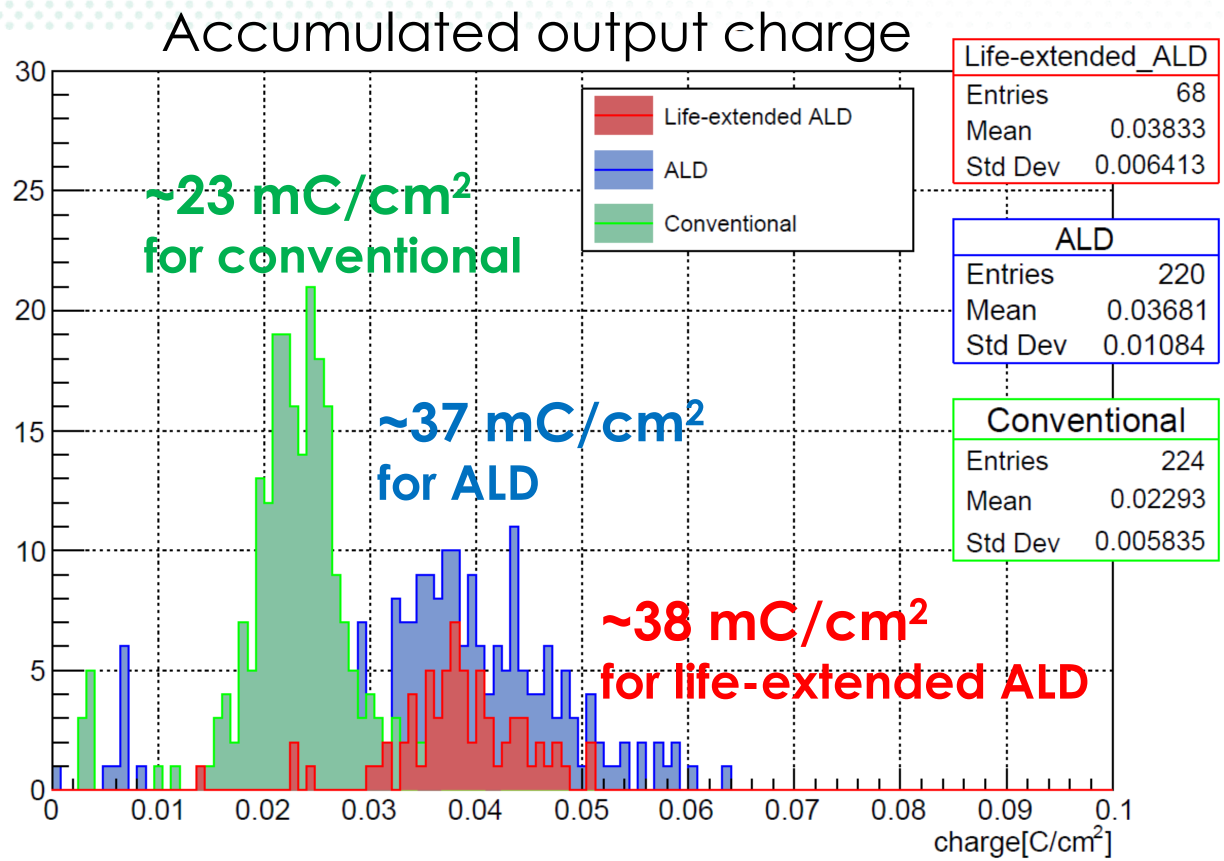
Slot11 (conventional MCP-PMTs)



The difference is under investigation.

PMT hit rate

- Kept below 2 MHz/PMT in the physics runs in 2019.
  - Dominated by beam gas scattering in the positron ring.
  - Much higher than anticipated. Has to be reduced.



Monitor the hit rate for the laser (∝ QE) and predict the lifetime of each MCP-PMT once the QE begins to drop.

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
- Succeeded in extending the lifetime to cope with the harsh beam background.
- Installation of the TOP counter finished in May 2016.
- The MCP-PMTs worked as expected in the first beam operation in 2018-2019.