Status of MCP-PMT for Belle II TOP

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2023/12/15

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Belle II

MCP-PMT for Belle II TOP detector

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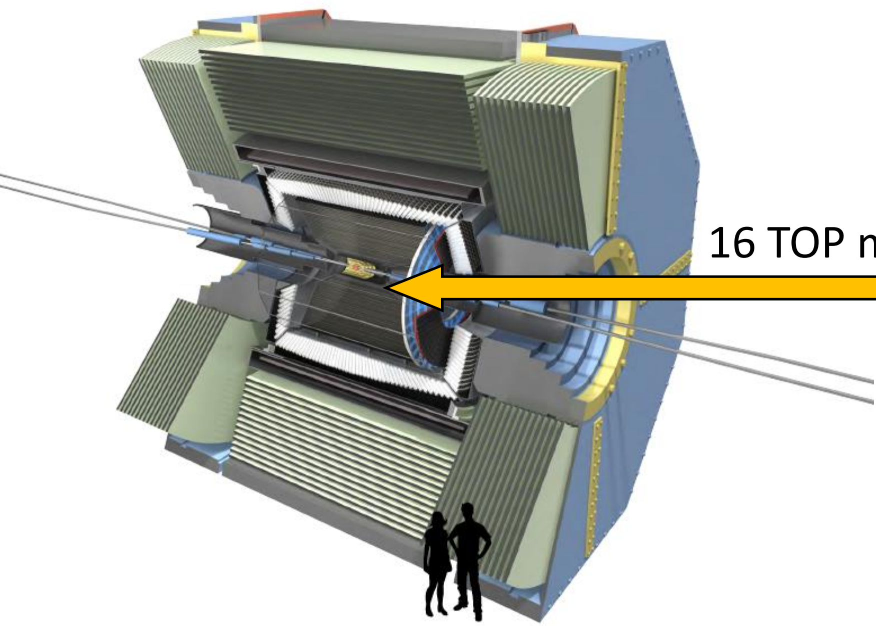
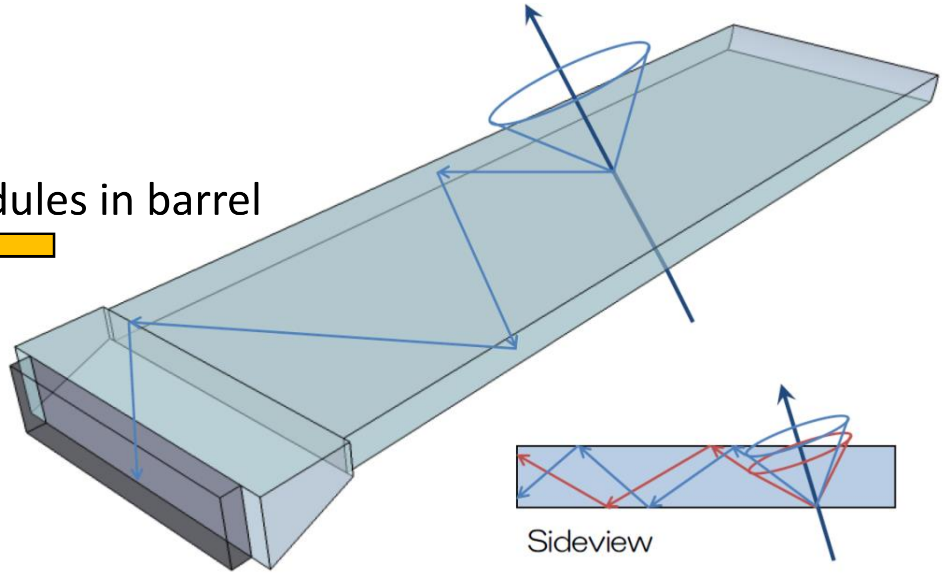
- Belle II experiment
  - Higher luminosity B-factory experiment; x50 integrated luminosity from Belle
- Particle identification; Ring Imaging Cherenkov detectors
  - A fake rate for K/π separation 2-5 times smaller than Belle
- TOP detectors are located in the barrel region outside of tracking device.
- MCP-PMT detects Cherenkov photons emitted and propagated in TOP detector with precise timing, then reconstructs particle velocity.



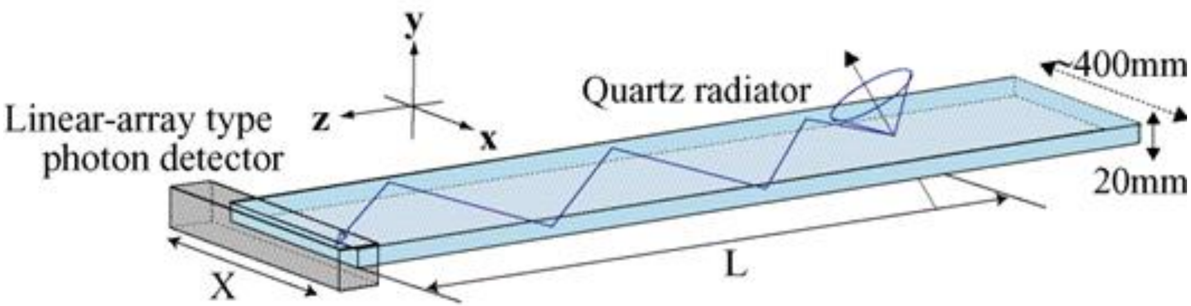
16 TOP modules in barrel

TOP（Time-Of-Propagation）detector

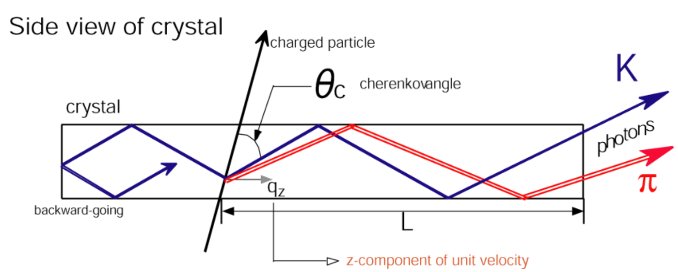


Basic concept

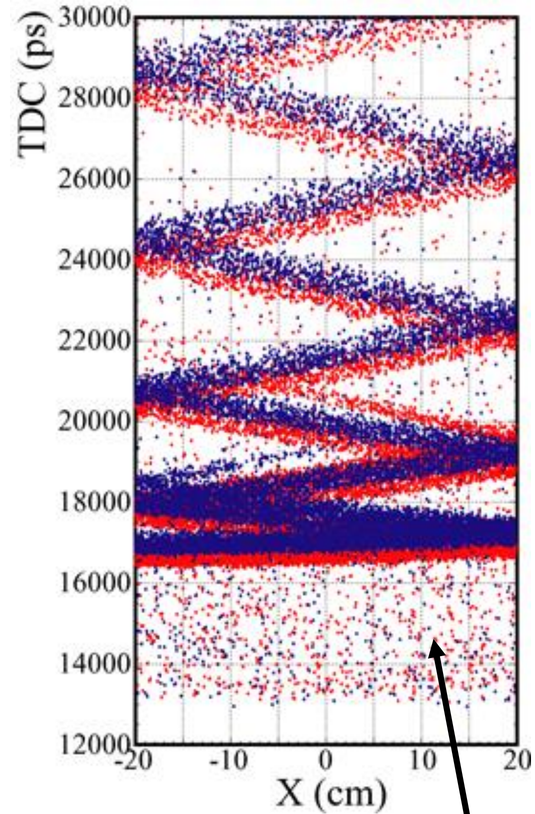
- Cherenkov ring imaging using timing information
- Very compact, suitable for detector geometry.
- Key technologies:
  - Single photo detection with precise timing
  - Accurately polished quartz bar



$$\cos\theta_c = \frac{1}{n(\lambda)\beta}$$



Simulation
2GeV/c, θ=90 deg.
~20photon/track

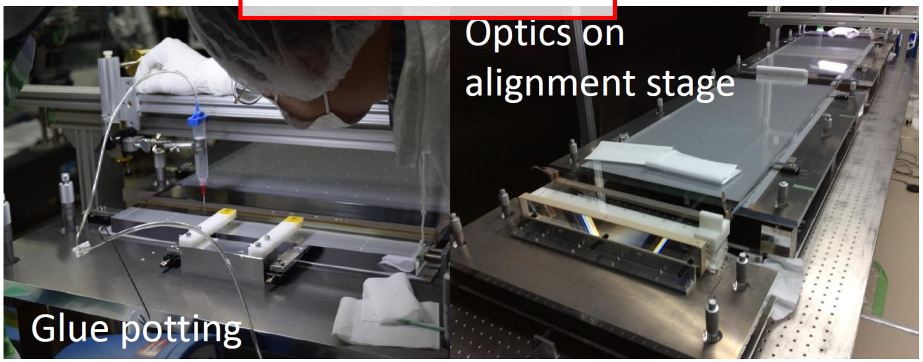


δ-ray, had. int.

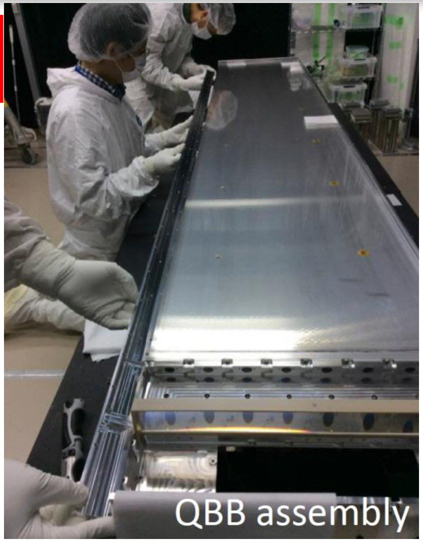
Difference of path length → Difference of time of propagation (TOP)
~150-200ps from TOP + TOF from IP
with precise time resolution (σ~40ps) for each photon

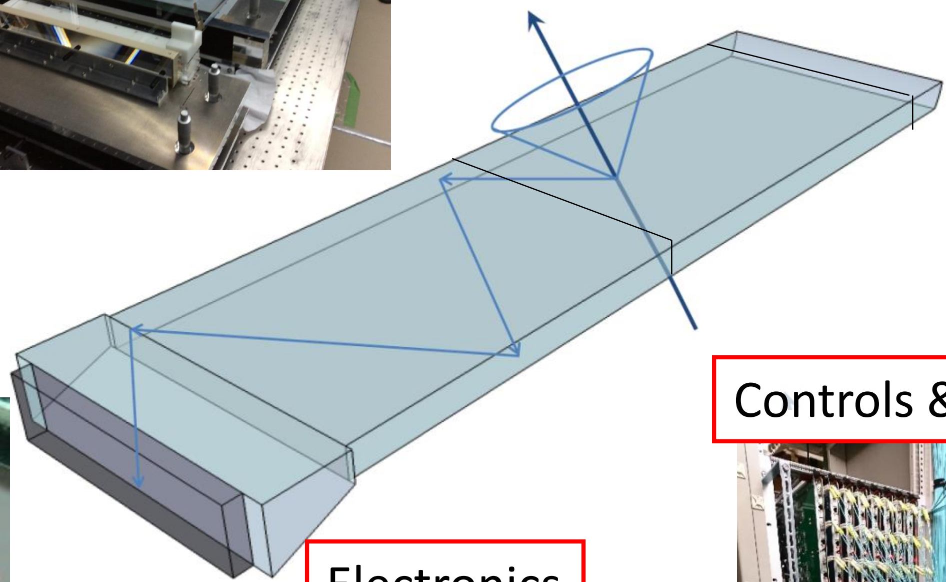
Detector components

Quartz radiator

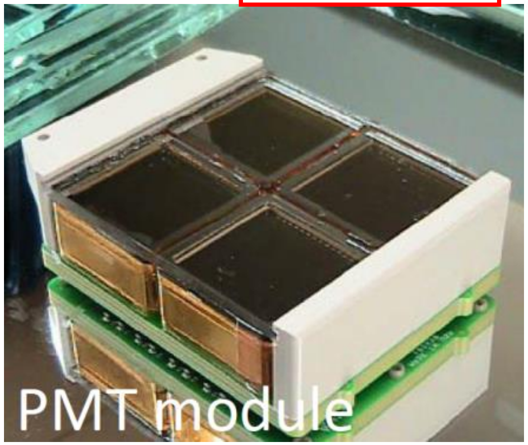


Mechanics



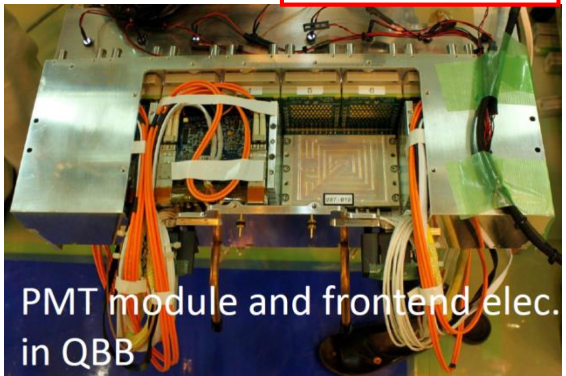


MCP-PMT



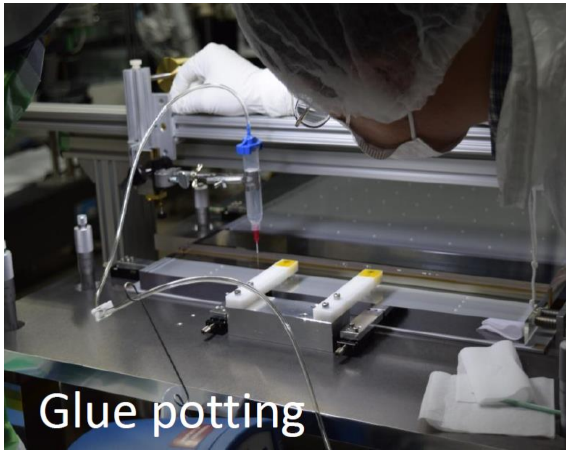
32 PMTs per TOP module installed with elec.

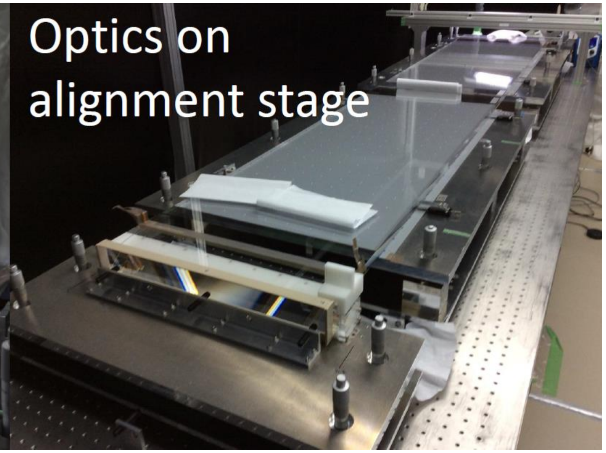
Electronics

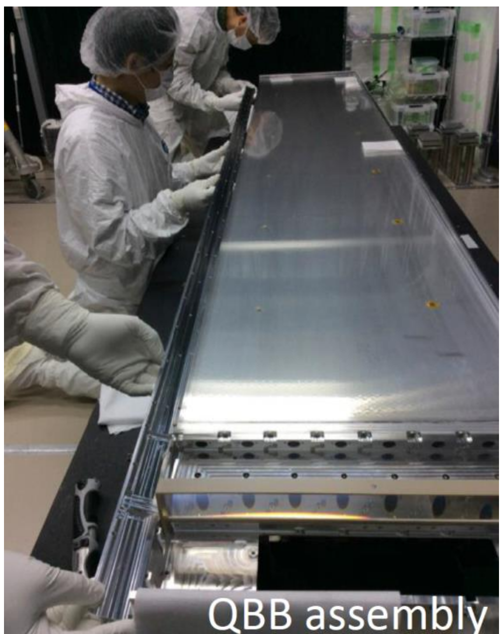


Controls & calibration system

Module construction/installation

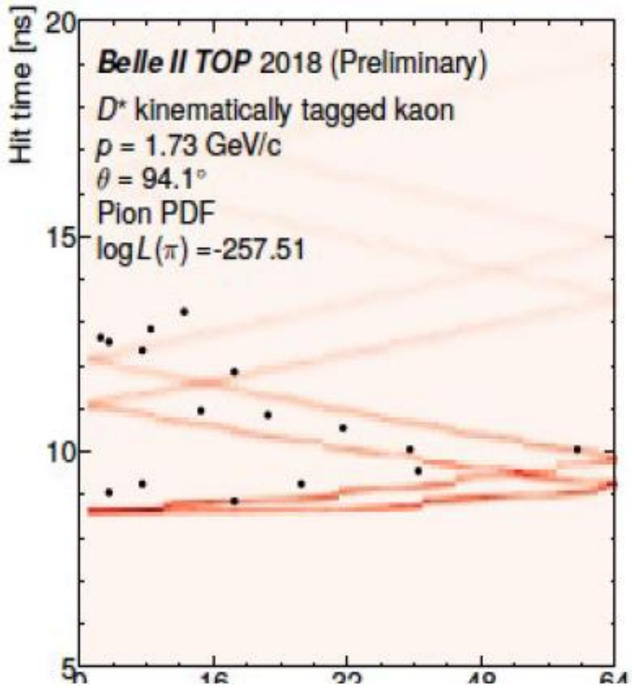


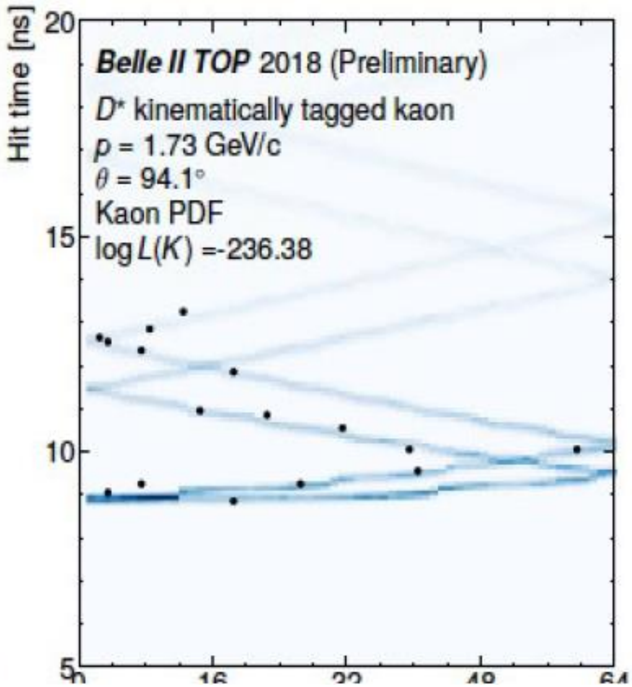


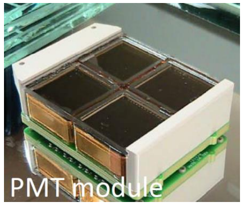


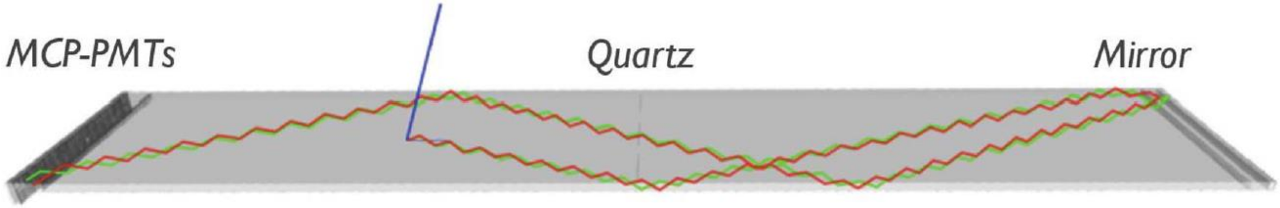
Ring image in TOP detector

- Using Kaon from D* decay
  - Well measured ring image



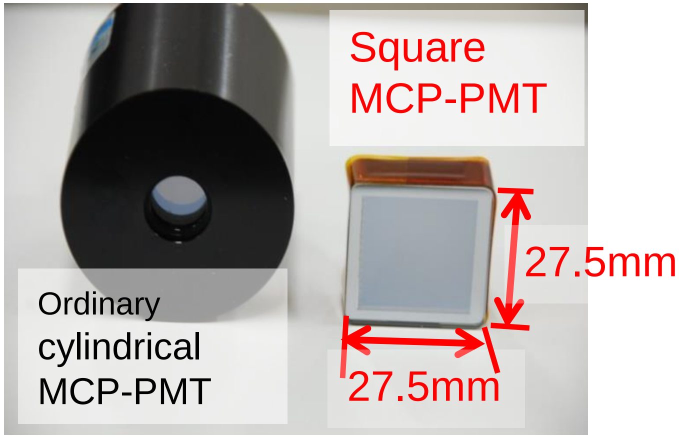




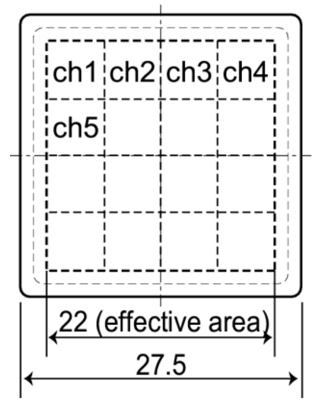


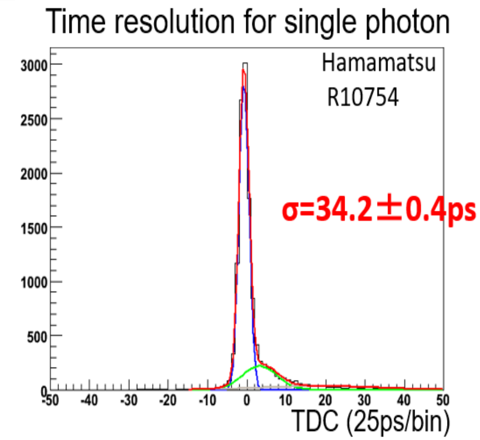
Example of Cherenkov-photon paths for 2 GeV/c $\pi^{\pm}$ and $K^{\pm}$.

Square-shaped MCP-PMT for Belle II TOP

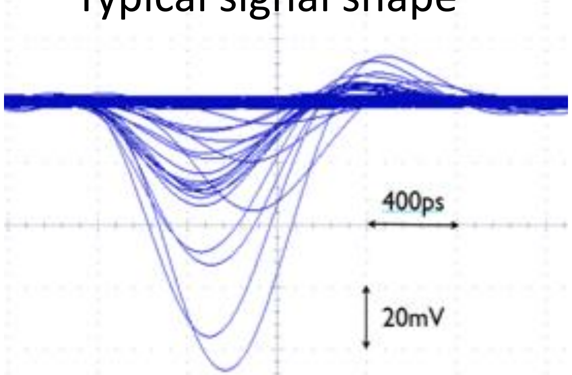


Co-development with
Hamamatsu Photonics K.K.





Typical signal shape

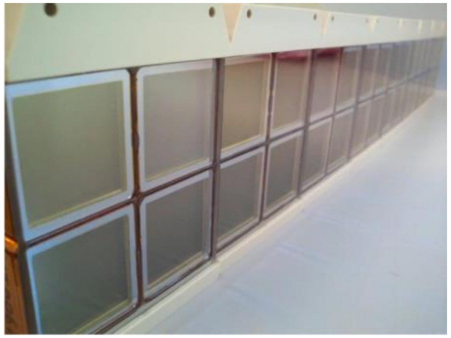


Single photon irradiation

Catalog spec	R10754-07-M16AN
Photo-cathode	Enhanced multi-alkali (>28% QE at peak)
MCP Channel ϕ	10μm
MCP bias angle	13°
MCP thickness	400μm
MCP layers	2
Al protection layer	On 2nd MCP
Anode channels	4×4
Sensitive region	64%
HV	~ 2000 – 3500 V

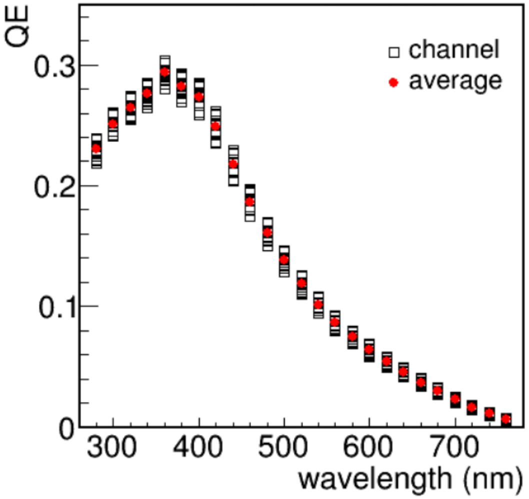
Mass production

- Three types produced from 2011
  - Conventional MCP (~250 PMTs) → ALD coated (~240) → Life-extended ALD
- QE improved during mass production
  - Apply super-bialkali technique to multi-alkali photocathode
  - 29% average of QE at ~360nm
- Stable gain, timing resolution
- Installed 512 MCP-PMTs (224+220+68)

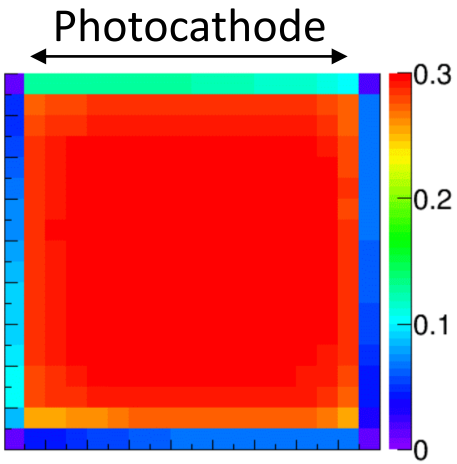


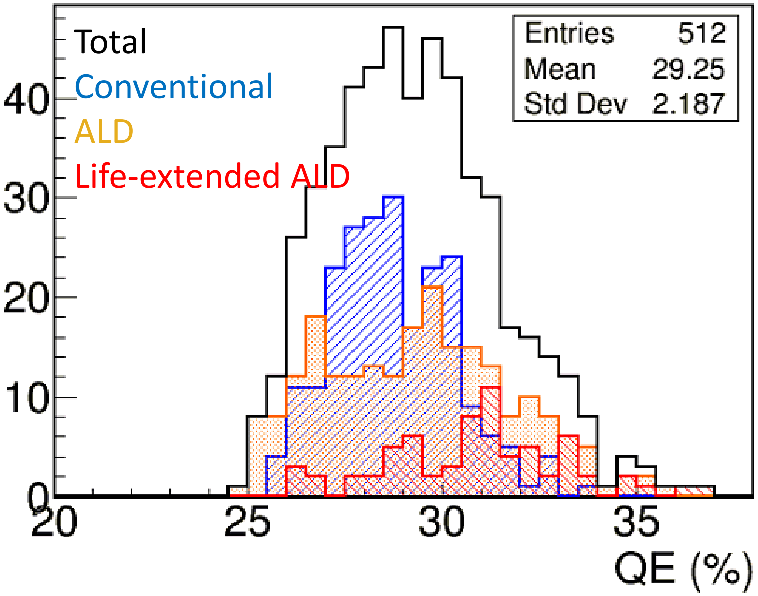
K. Matsuoka, DIRC 2019

Typical QE distribution



QE peaks around 360 nm



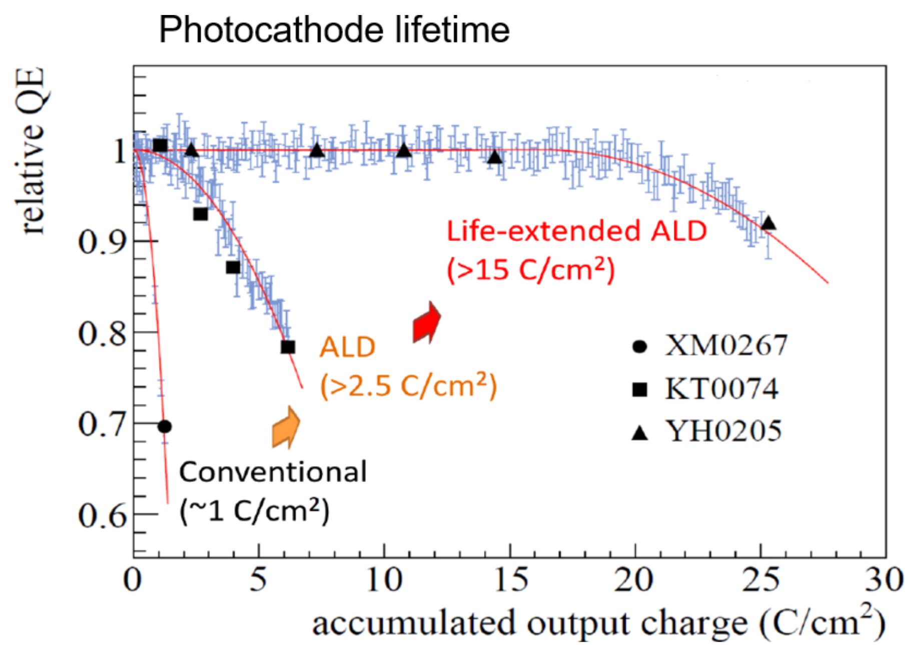


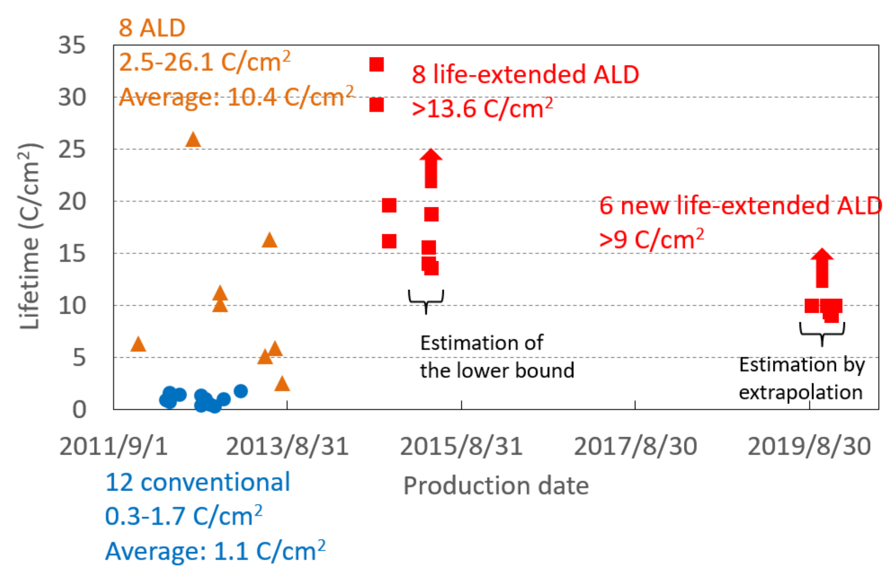
MCP-PMT lifetime

- PMT QE deteriorates following the output charge from anodes.
  - Thought to be due to the ion/gas feedback to photocathode by amplified electrons.
- TOP PMTs detects many Cherenkov photons by electron conversion of BG radiative gammas in radiator.
- Three types of MCP-PMTs installed.

MCP type	Lifetime for test samples
Conventional	1.1 C/cm² (Average)
ALD	10.4 C/cm² (Average)
Life-extended ALD	>13.6 C/cm² (Minimum) (>9 C/cm² for recent sample)

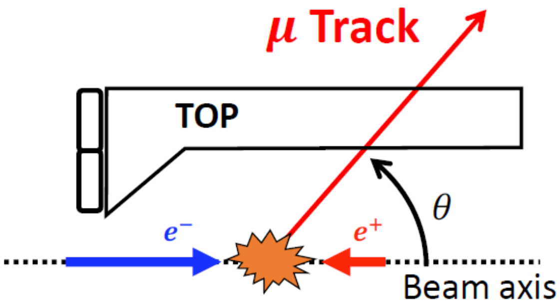
  - The conventional type will show QE degradation rather soon.

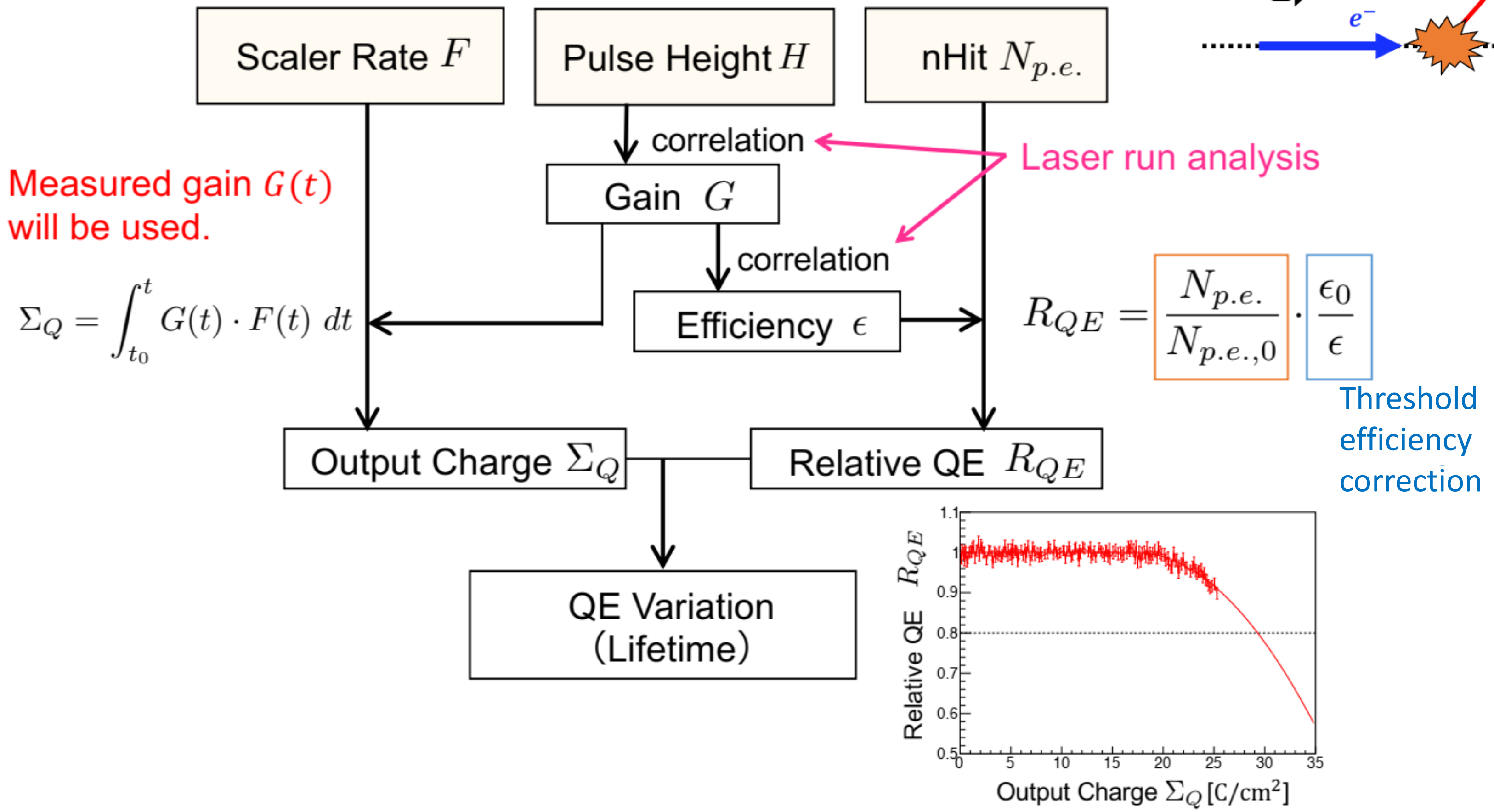




PMT monitoring

- Hit and gain monitoring during Belle II running
  - Hit rate monitored by trigger scaler output
  - Gain calculated from pulse height information
  - Number of hits per track evaluated using μμ events

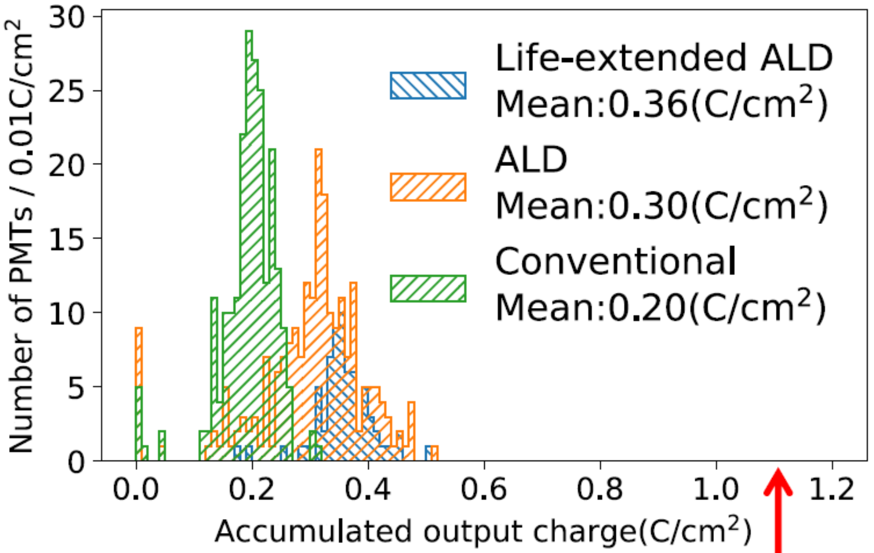




Output charge

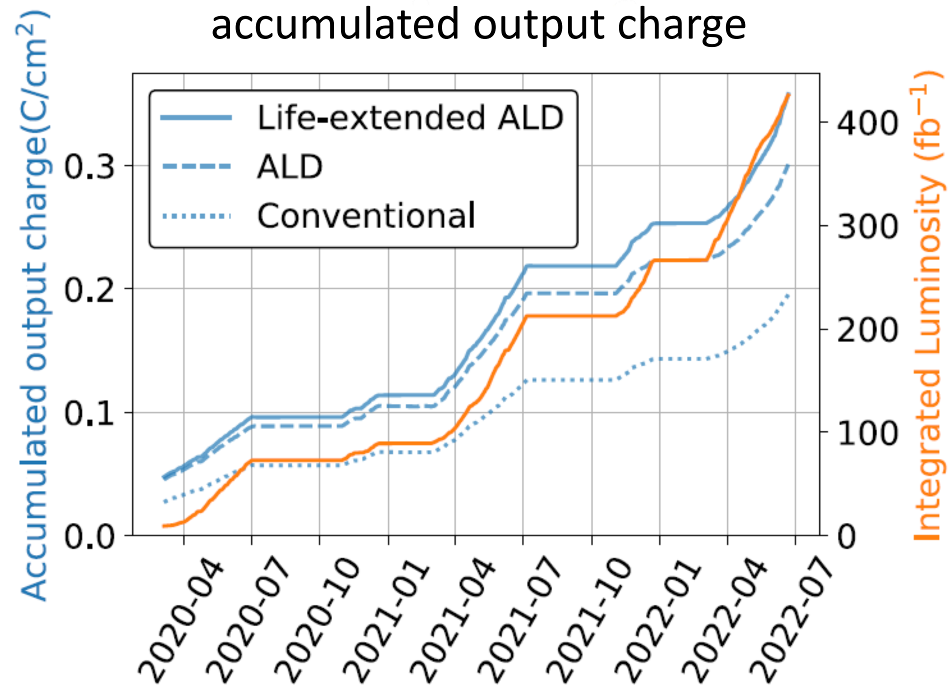
- Output charge from PMT is still much smaller than the lifetime.
  - Several conventional PMTs may shows the degradation of QE at this level.

Accumulated output charge of all MCP-PMT

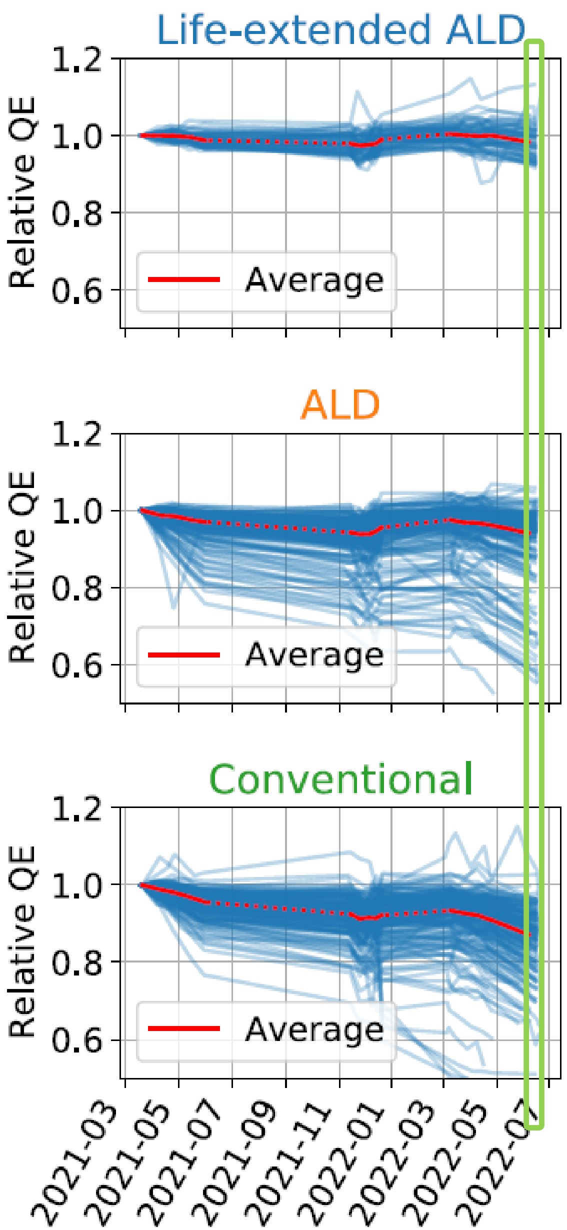


Average lifetime of conventional MCP-PMT

History of Luminosity and accumulated output charge



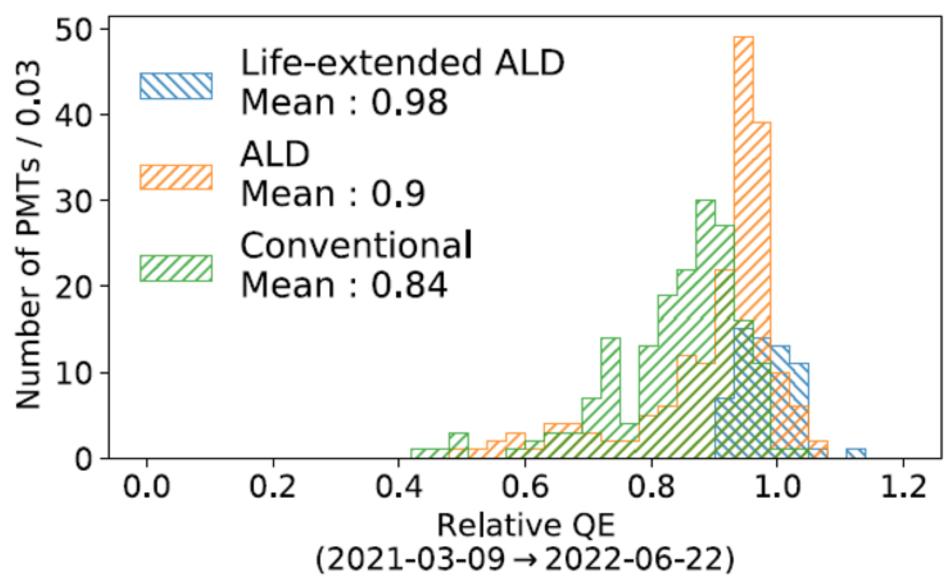
QE variation



- QE variation history from the beginning of 2021

$$\text{Relative QE} = \frac{\text{QE at the end of 2022}}{\text{QE at the beggining of 2021}}$$

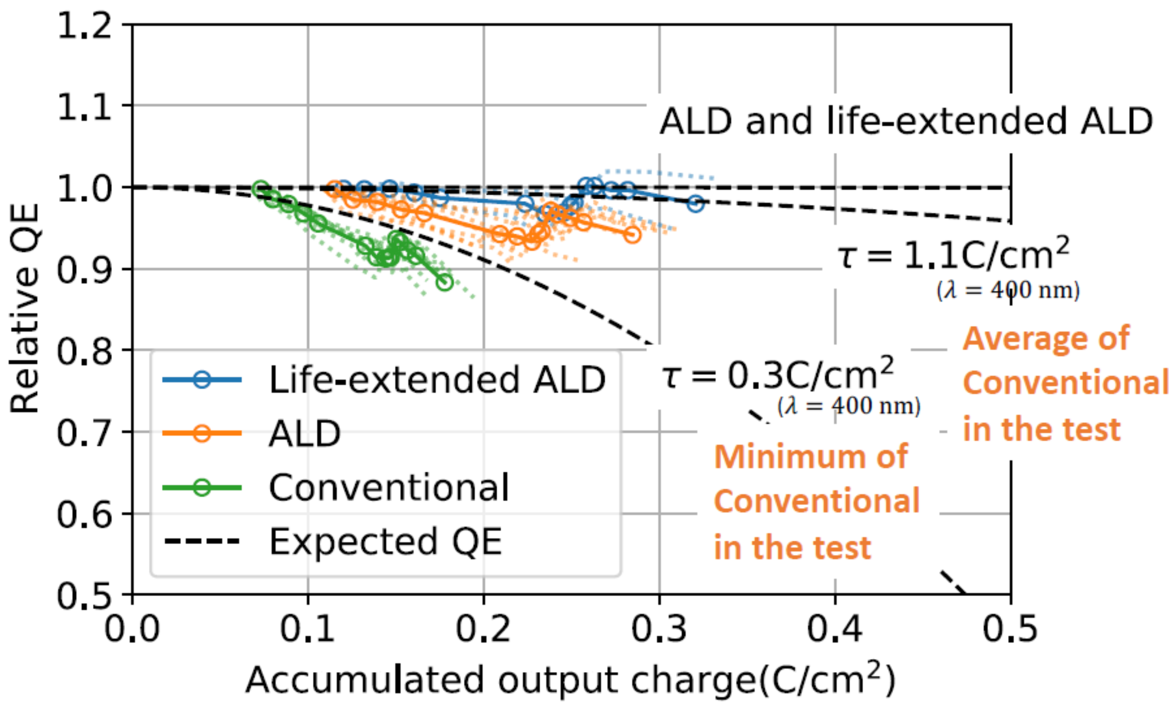
- Shows some QE degradation for conventional and ALD types, although the output charge is still small.



QE variation

- As a function of output charge
- Compare with the expectation from the R&D result

    → Follows curves for much short lifetime
- Need to study the reason of QE variation
    - Although there is strange fluctuation

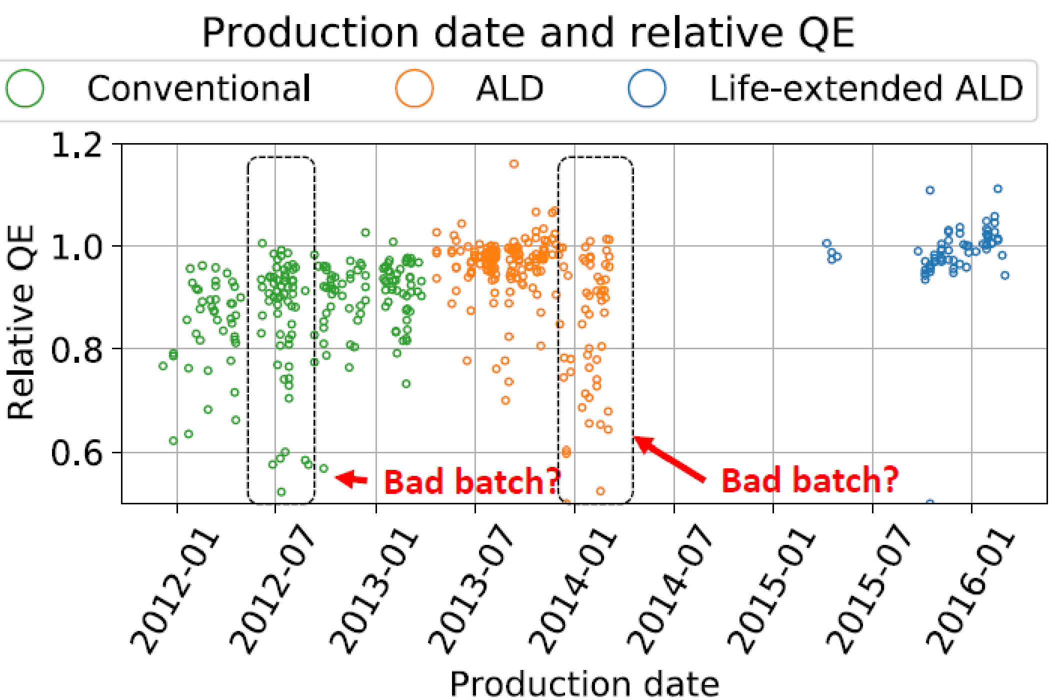


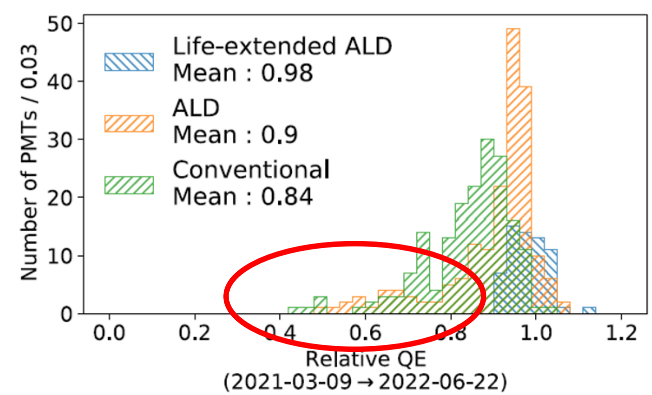
Dotted line : SLOT average

Solid line : Type average

Production date dependence

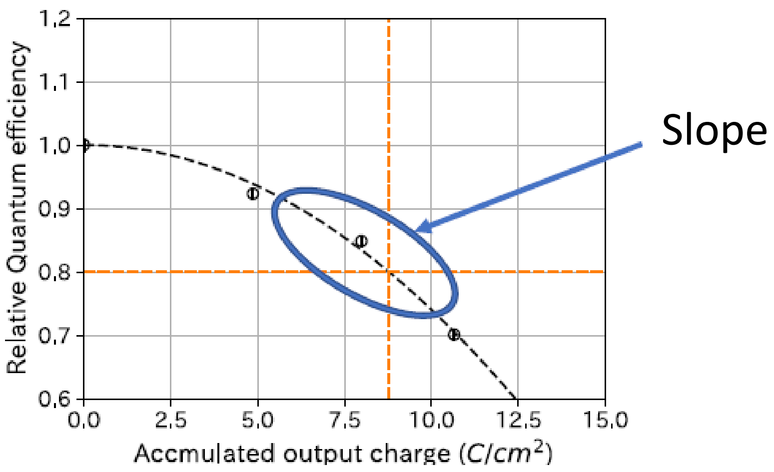
- There looks the production date dependence.
  - Very short lifetime seems due to the production method.



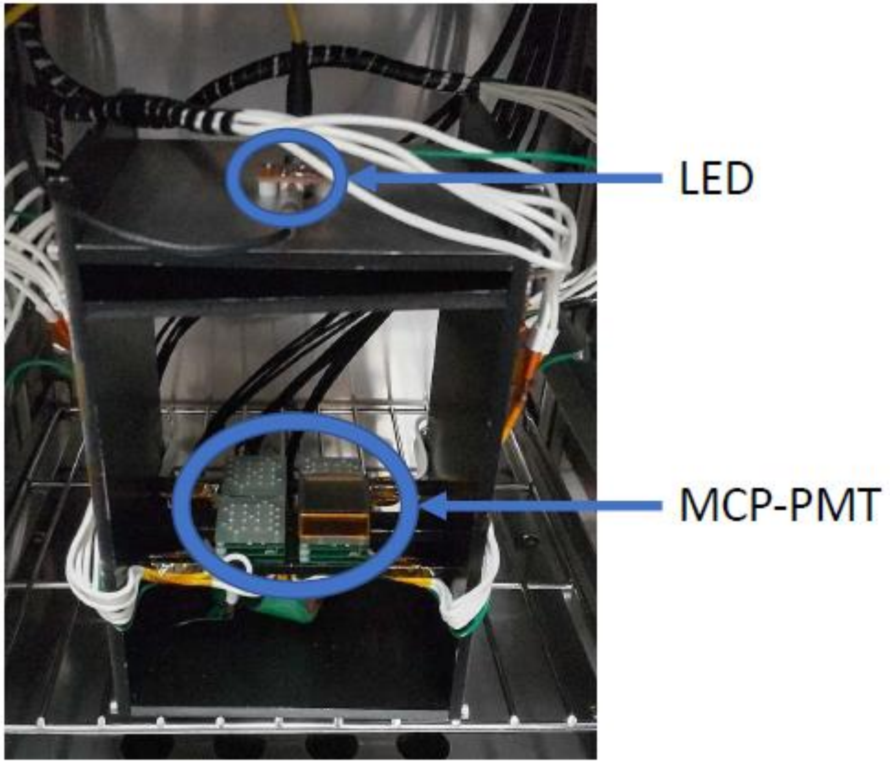


Lifetime test at higher temperature

- Environmental temperature is different between the detector (~40 deg-C) and test bench (room temp.)
- Checked QE stability under higher temperature
- Lifetime test with oven
  - LED irradiation in oven
  - Measure QE periodically by QE bench
  - Check the change of slope depending on the temperature



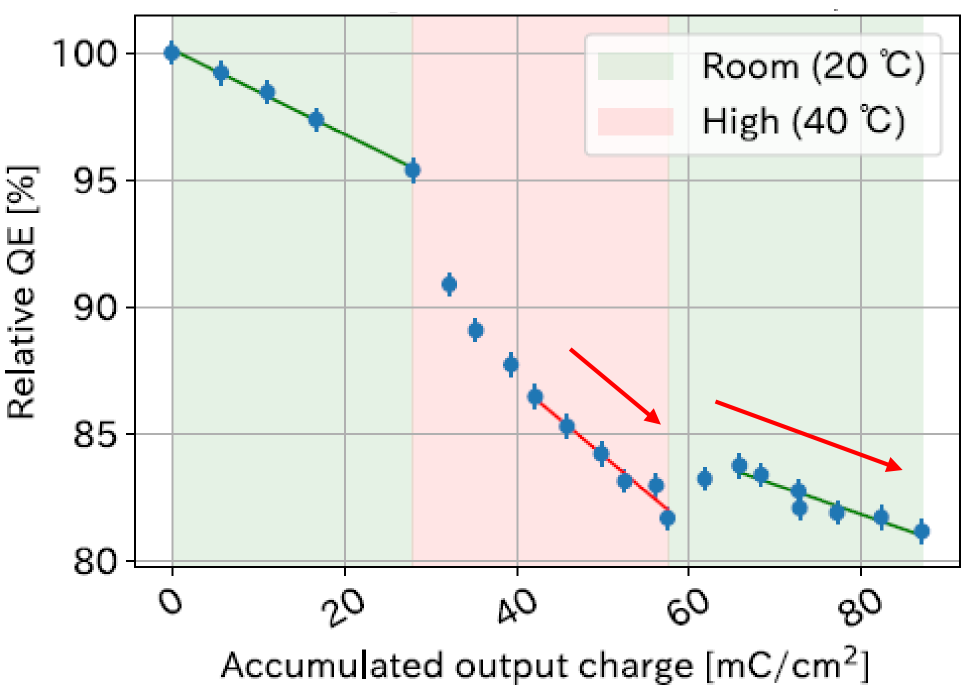
Setup inside oven



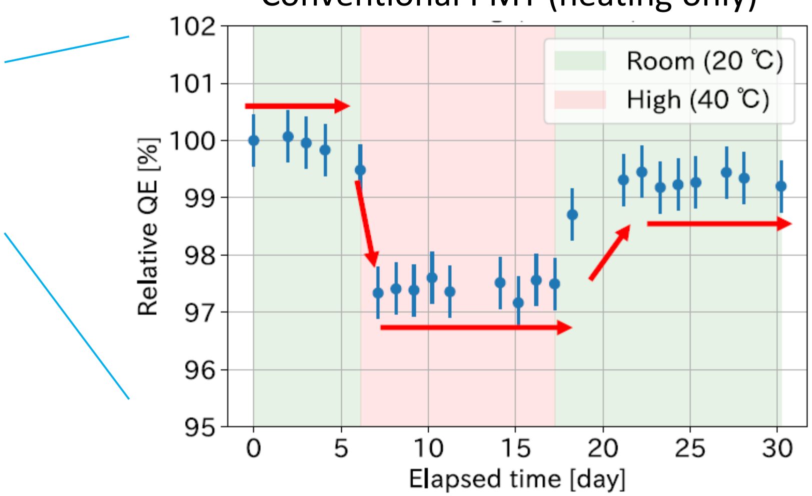
Lifetime test at high temperature

- Tested conventional PMTs
- There was a tendency of shorter lifetime for higher temperature
- Heating test without operation (no HV) performed as cross-check
  - Measured QE is stable under same condition
- Now , continue with other samples and different types.

Conventional PMT (JT0901)

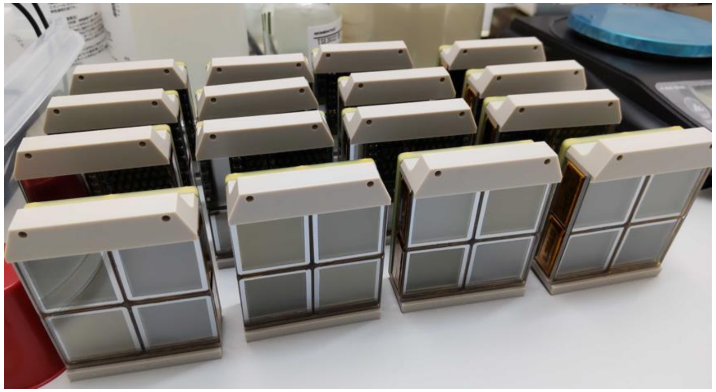


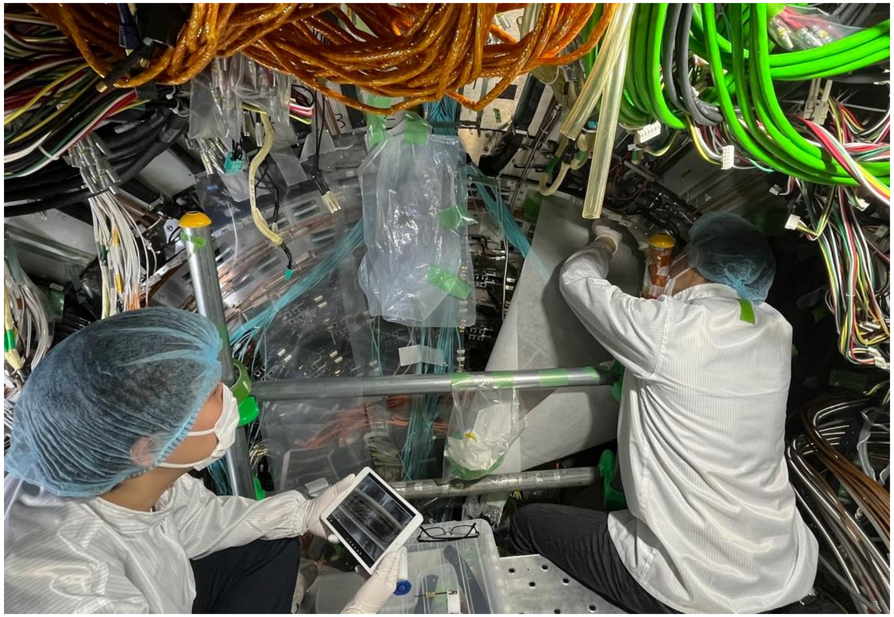
Conventional PMT (heating only)



PMT replacement

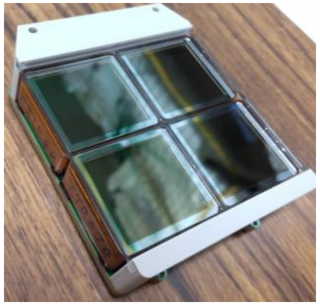
- During long-shutdown 1 from 2022 summer, we have performed the PMT replacement.
- Remove most conventional types
- Install new life-extended ALD PMTs for about half of whole detector
- Re-installed best PMTs from ALD and conventional ones.
  - Will replace again during next long-shutdown period

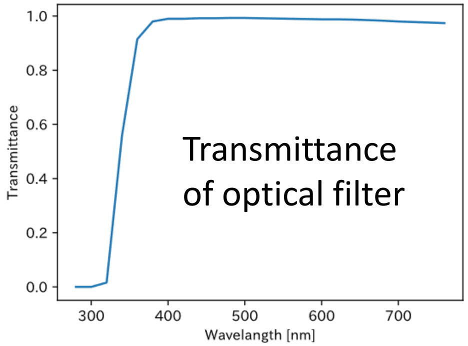


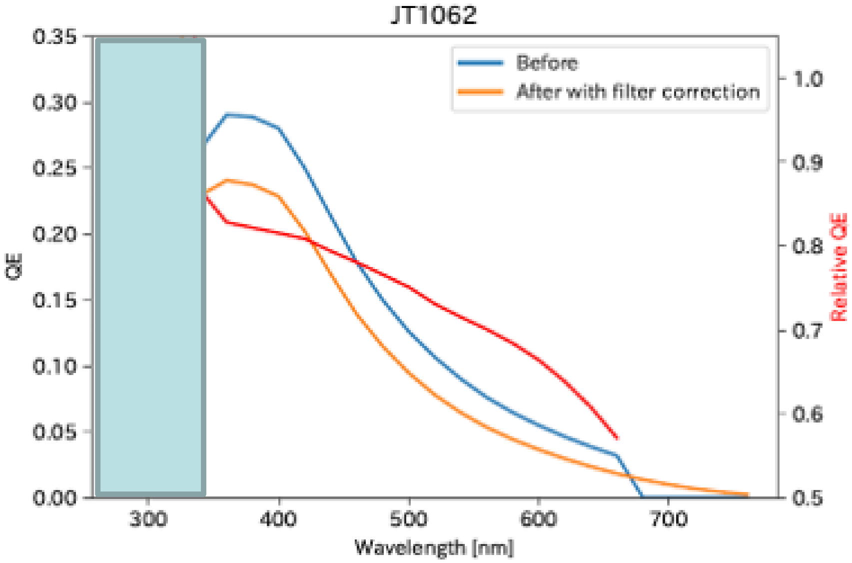


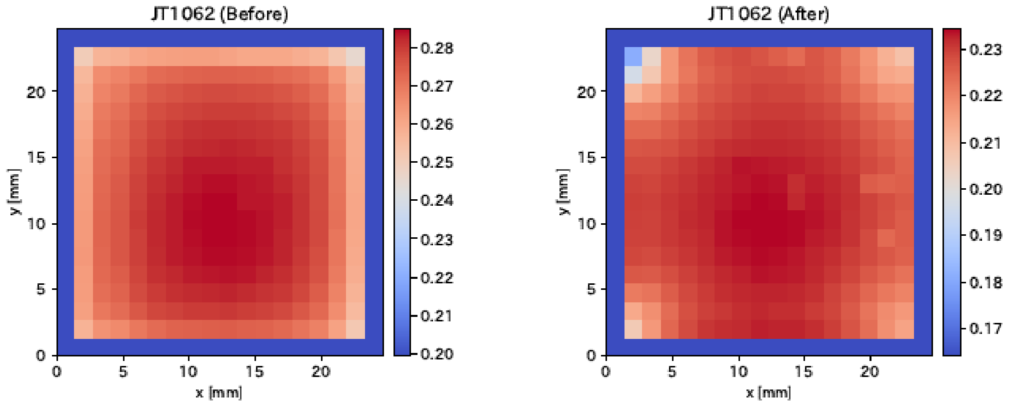
Check on uninstalled PMTs

- QE measurement in PMT module
  - Measurement with optical filter
  - Applied correction of transmittance and reflectance at boundaries (a few %)









  - Found actual QE drop
    - » Similar degradation with lifetime test

Summary

- Developed square-shaped MCP-PMT for Belle II TOP detector
- 512 PMTs have been installed and operated for ~3 years
- PMT performance is monitored during the Belle II runs
- Found faster QE degradation than expected for conventional and ALD type of PMTs
  - Much shorter PMTs are clustered in some of production batch.
- Tested the lifetime in higher temperature environment
  - Found a tendency of shorter lifetime for higher temperature
  - Continue the lifetime test with other type

- Check performance of un-installed PMTs
  - Feedback to the future production and operation