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Extension of the MCP-PMT lifetime

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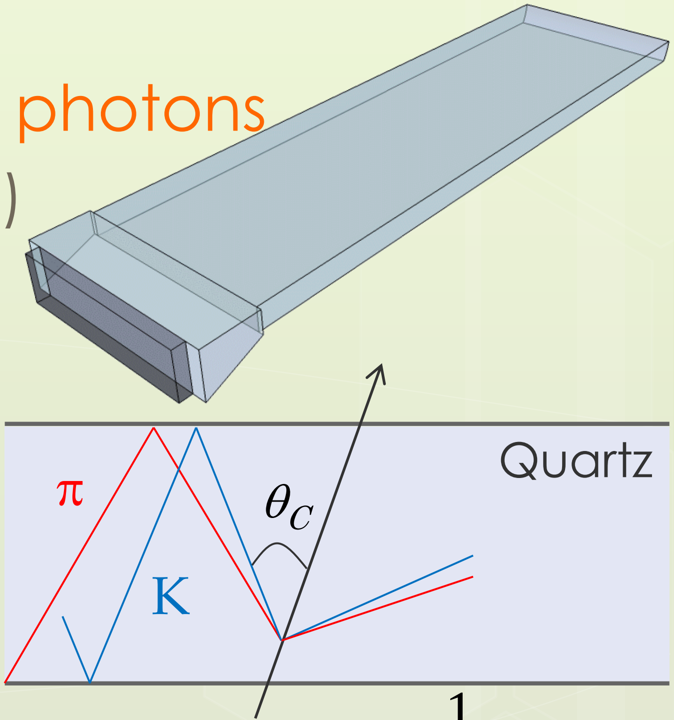
Photon sensors in novel RICH detectors

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

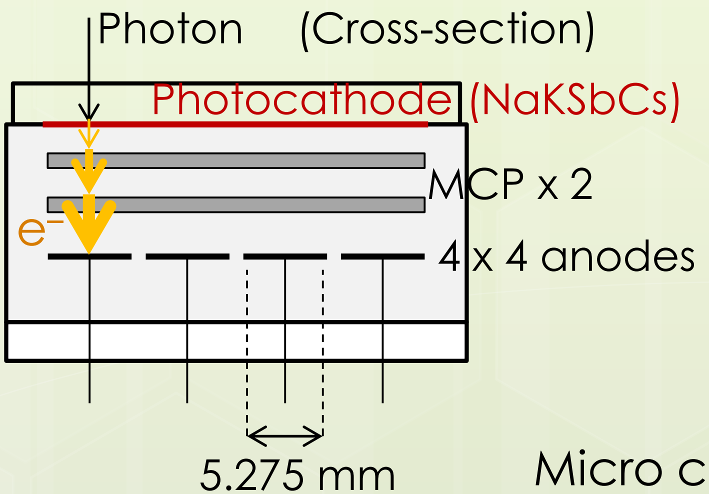


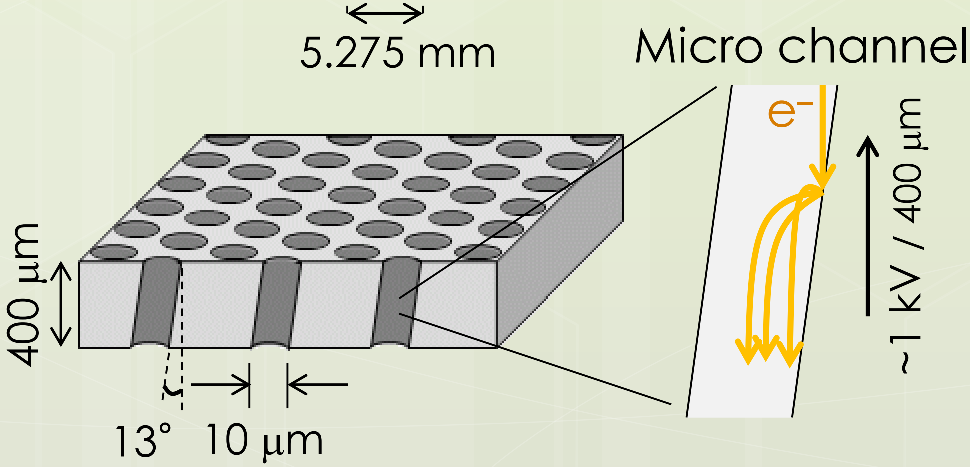
$$\mathrm{TOP} \propto \cos\theta_C = \frac{1}{n\beta}$$

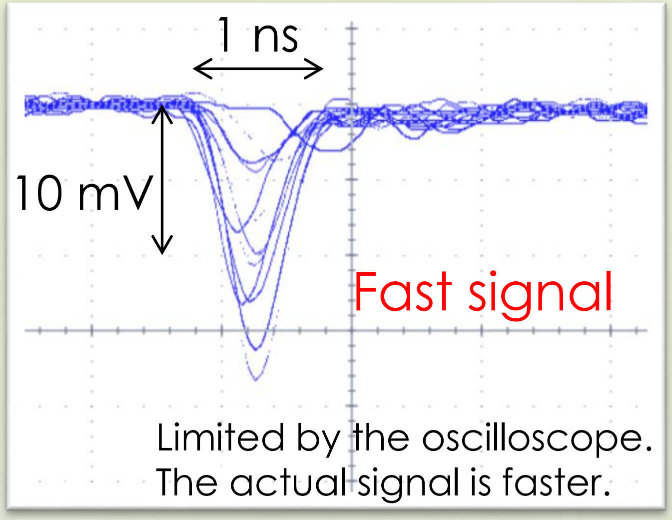
Only an MCP-PMT could meet every requirement.

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.

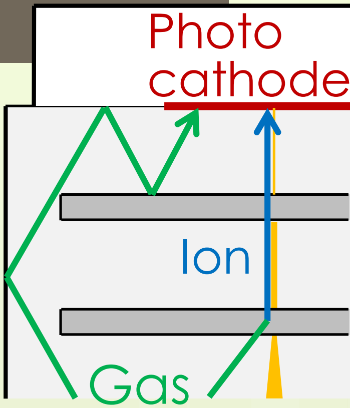






The best time resolution of photon sensors

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_τ at which QE(Q_τ)/QE$_{\text{inital}}$ = 0.8 at 400 nm.

- Estimated accumulated output charge for Belle II TOP dominantly due to beam bkgd.:

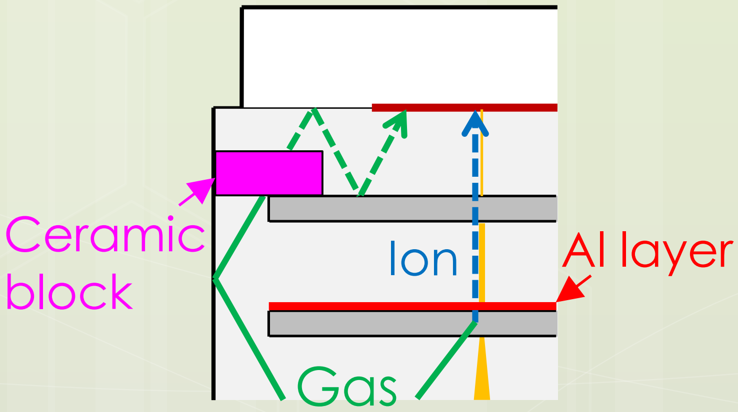
  ~3.7 C/cm^2 at 50 ab^{-1} with 5 x 10^5 gain

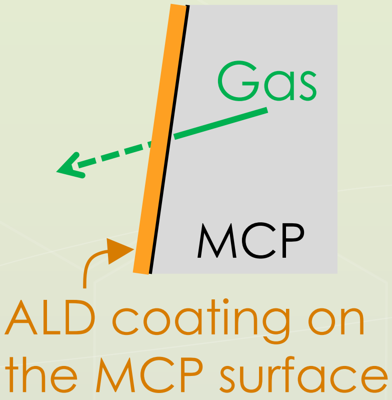
We have researched to achieve the lifetime longer than the estimated accumulated output charge.

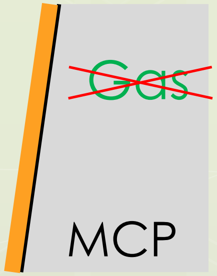
How to extend the lifetime

- 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~)

Step 1 + Step 2 + Step 3



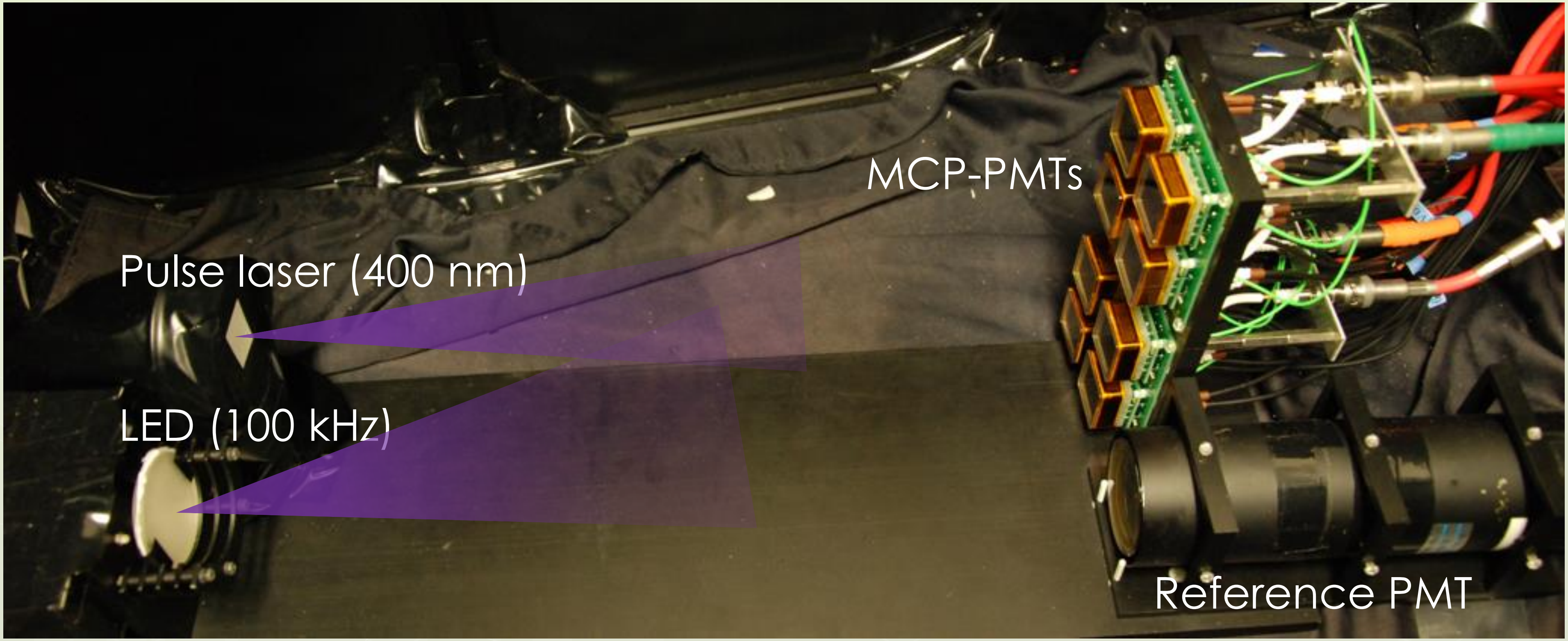




→ Evaluated the lifetime of each type of MCP-PMT

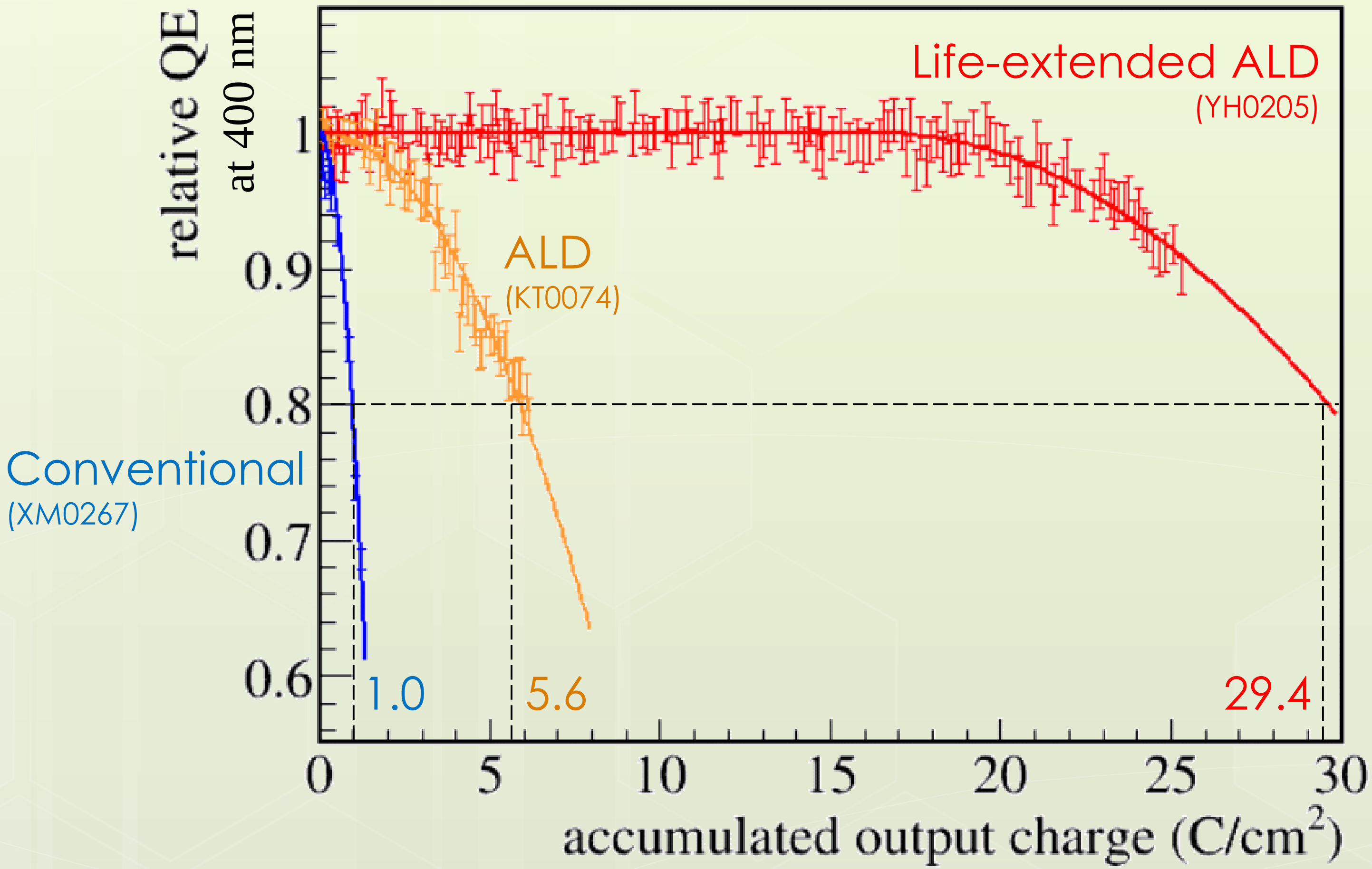
Test of the lifetime

- 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.



Result of the lifetime test

Result of typical sample of each type

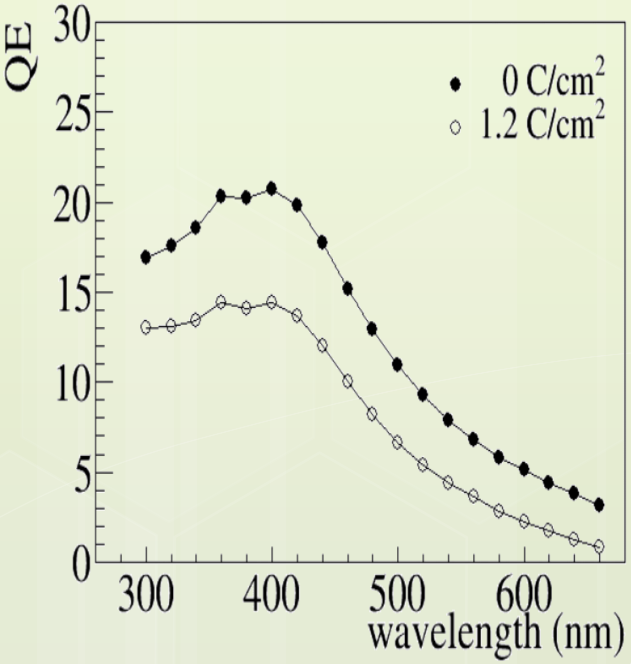


- The QE depression curve is represented by $\frac{\mathrm{QE}(Q)}{\mathrm{QE}_{\mathrm{inital}}} = 1 - 0.2(Q/Q_\tau)^2$
- Longer lifetime with ALD and much longer with life-extended ALD

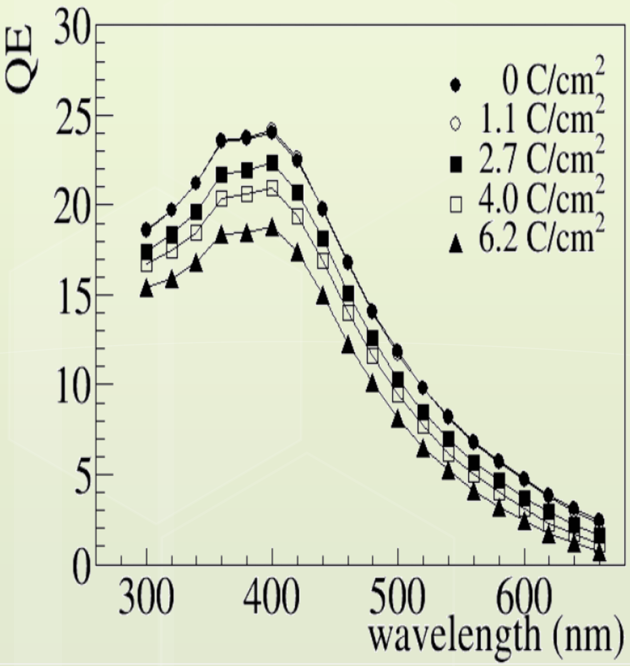
QE spectrum after the lifetime test

- Measured by Xe lamp + monochromator

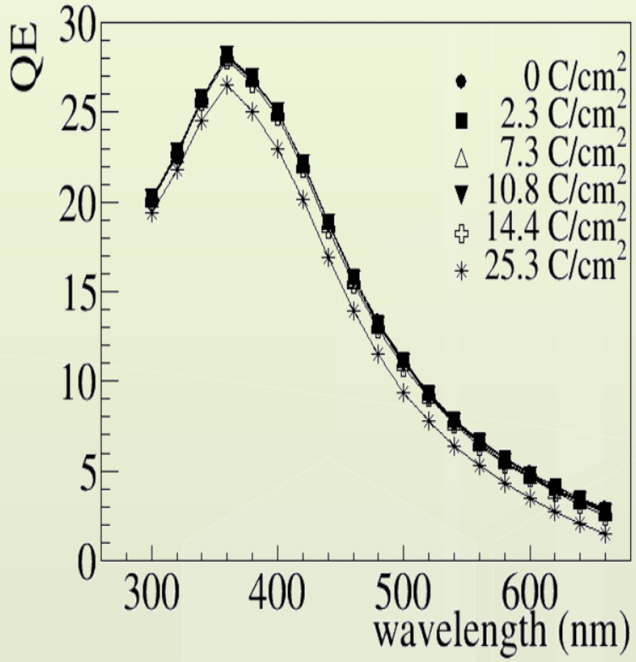
Conventional (XM0267)



ALD (KT0074)



Life-extended ALD (YH0205)

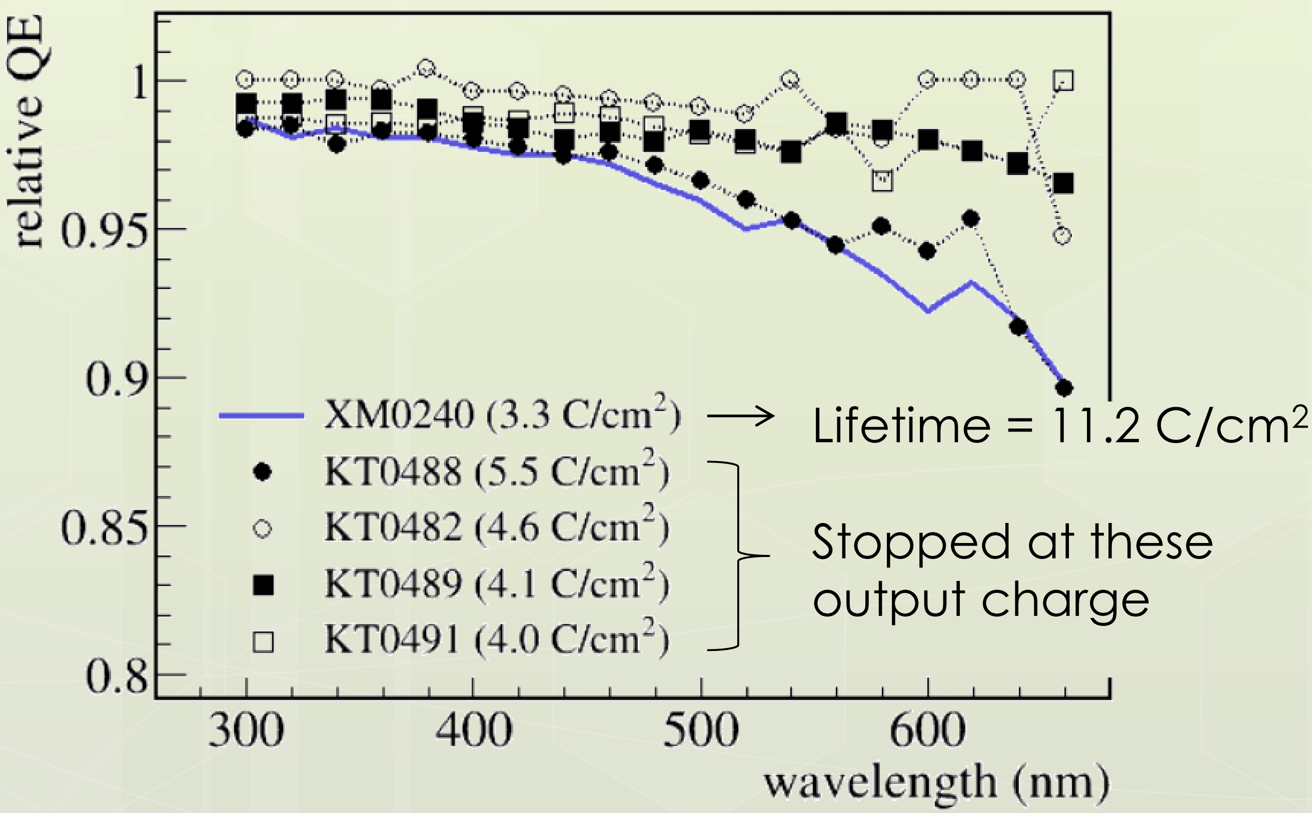


✓ Consistent with the in-situ QE measurement by the laser at 400 nm.

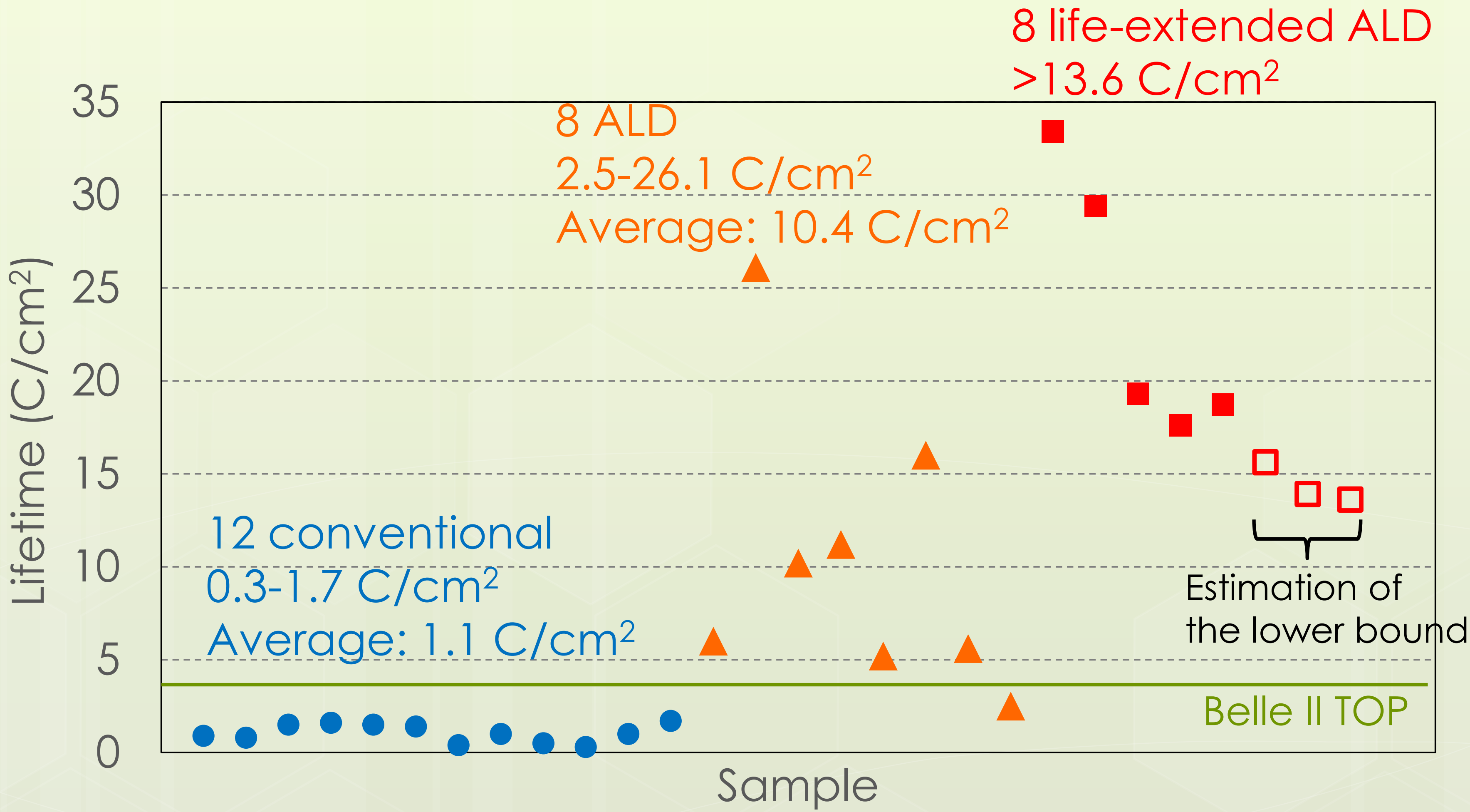
✓ The QE drops more significantly at longer wavelengths as the work function of the photocathode increases.

Lifetime estimation halfway through the test

- QE drop of 4 life-extended ALD MCP-PMT samples at 4.0-5.5 C/cm² 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/cm².
  - $\underbrace{1-0.2(Q/Q_\tau)^2}_{\text{Halfway sample}} \geq \underbrace{1-0.2(3.3/11.2)^2}_{\text{XM0240}}$ → $Q_\tau \geq Q/3.3 \times 11.2\ \mathrm{C/cm^2}$ $\geq 13.6\text{-}18.7\ \mathrm{C/cm^2}$



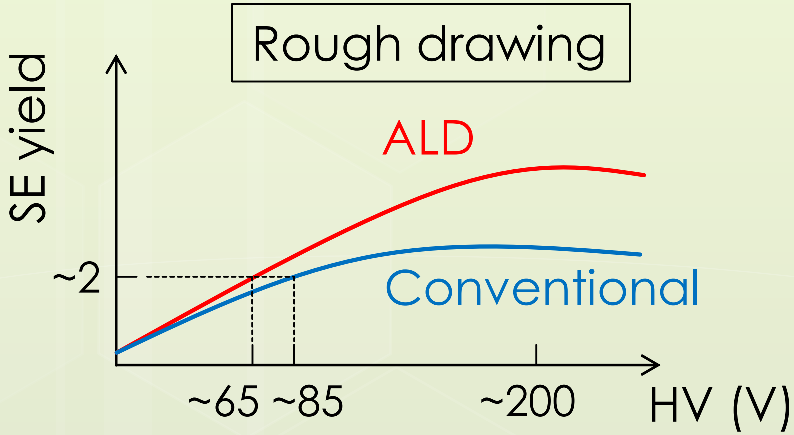
Summary of the measured lifetime



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

Performance of the ALD MCP-PMT

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

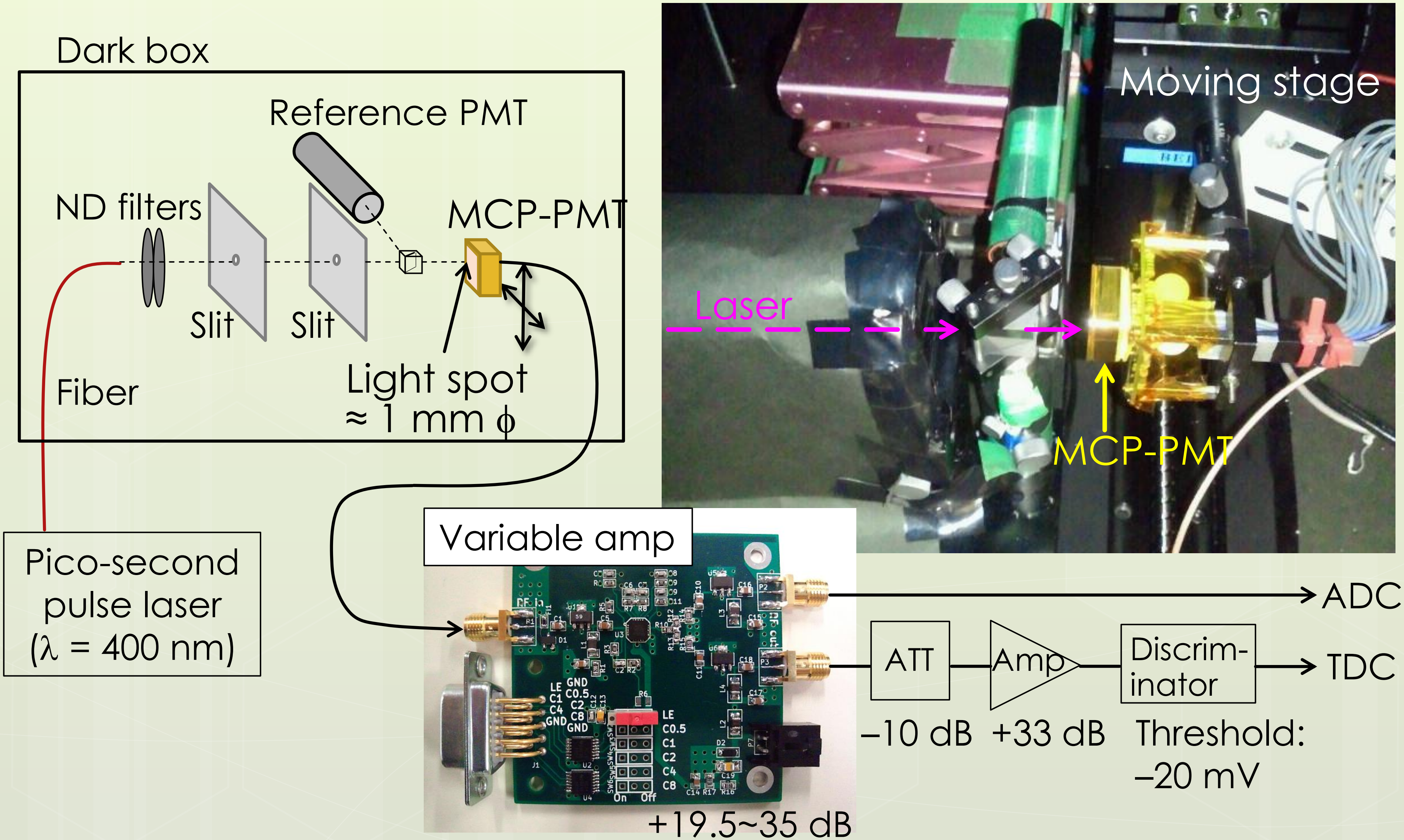


- We have 277 conventional, 231 ALD and 65 life-extended ALD MCP-PMTs for Belle II TOP.

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

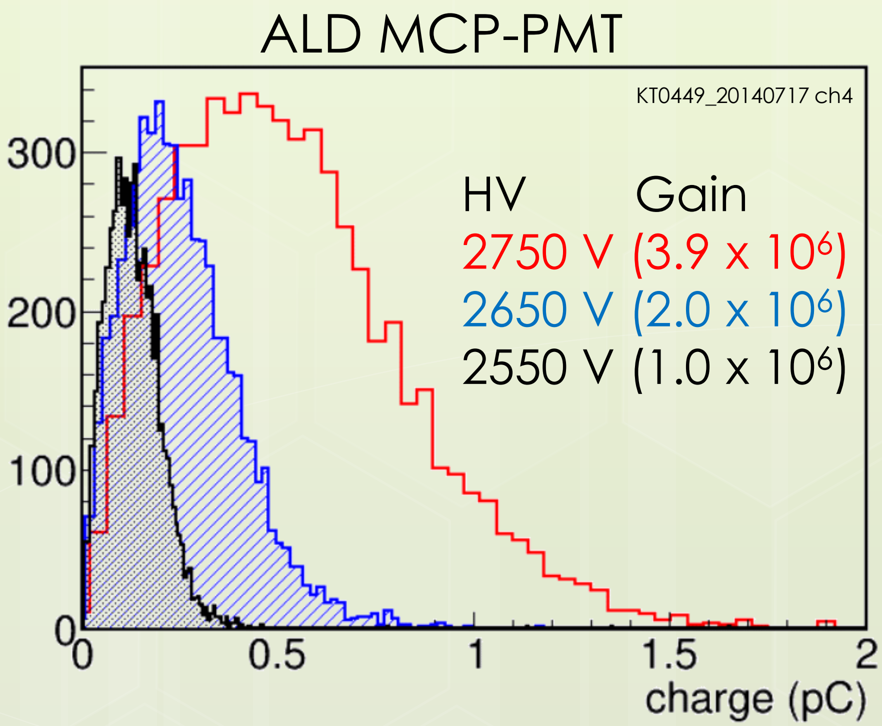
Setup of the laser test

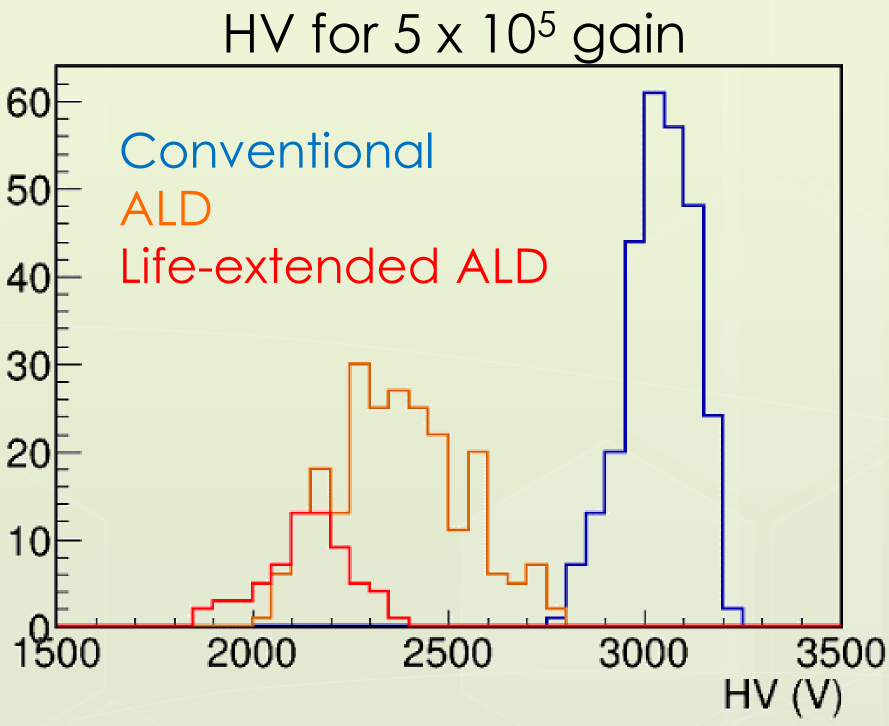
- Single photon irradiation to each anode one by one.



Gain

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

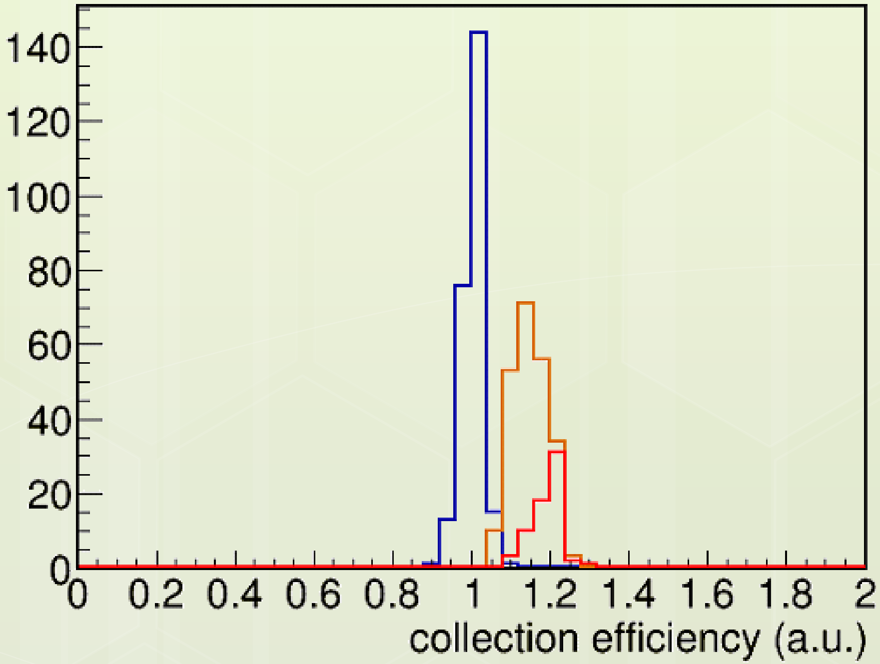


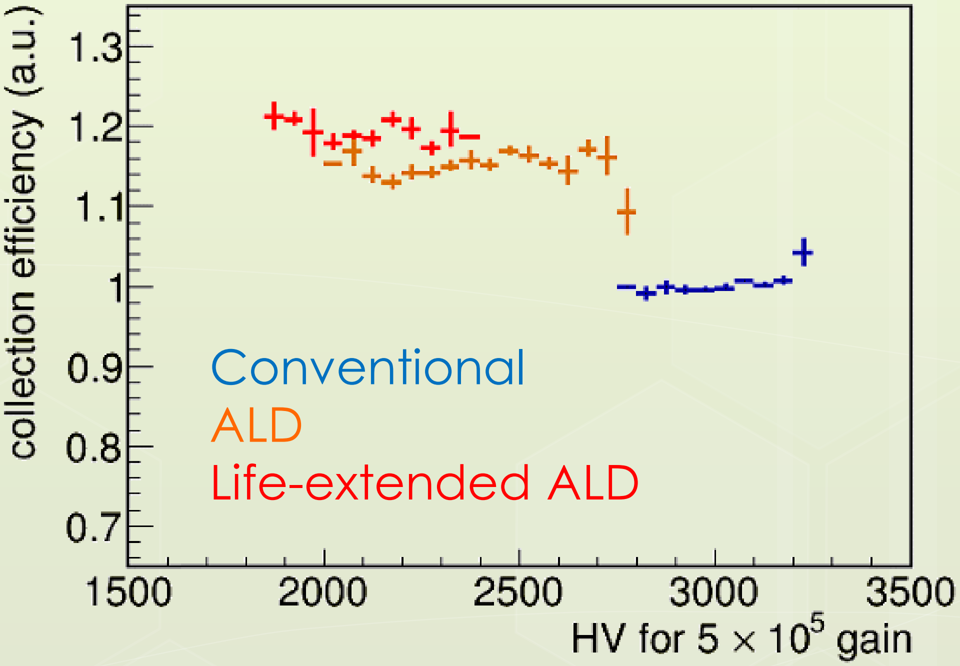


Lower HV for ALDs to have the same gain owing to the higher SE yield.

Relative collection efficiency

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



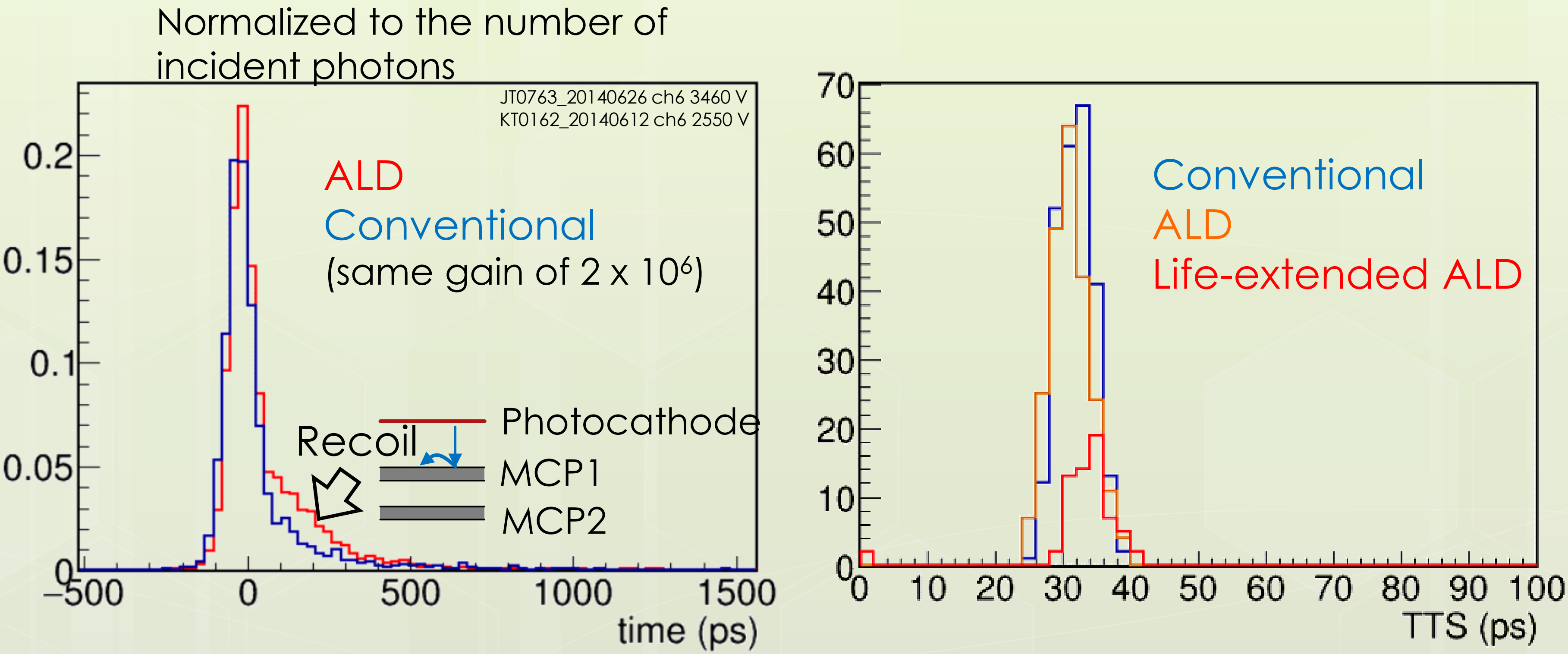


Higher collection efficiency of ALDs by ~15%.

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 σ of the primary Gaussian.

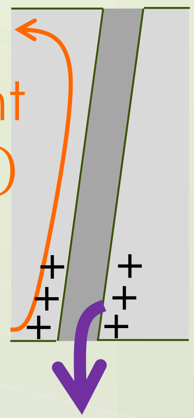


Higher collection efficiency is due to increase of the efficiency for the recoil photo electrons.

Performance under a high rate

- After a micro-channel fires, electrons are depleted on the channel wall.
- The channel wall $O(10^{-16}\ \mathrm{F})$ 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

  $\tau_d = RC = Q_{out}/I_s = O(10\ \mathrm{ms})$ for the 2nd MCP

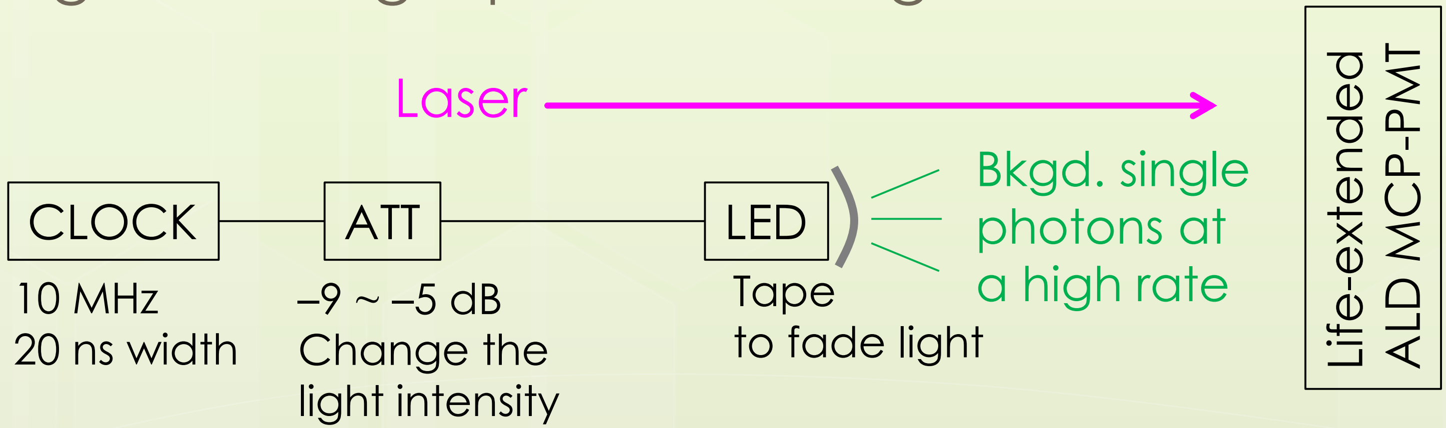


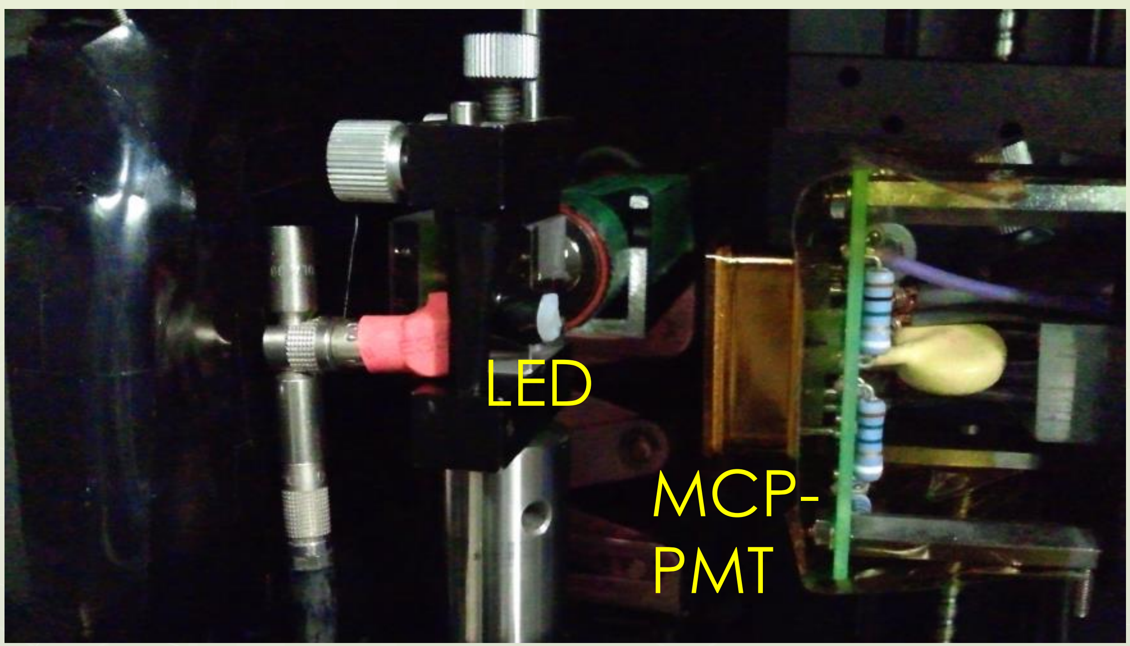
→Under a high rate of background, a large fraction of micro-channels could be dead.
(Belle II TOP: ~200 kHz/anode)

→Drop of the gain and efficiency, depending on the MCP resistance.

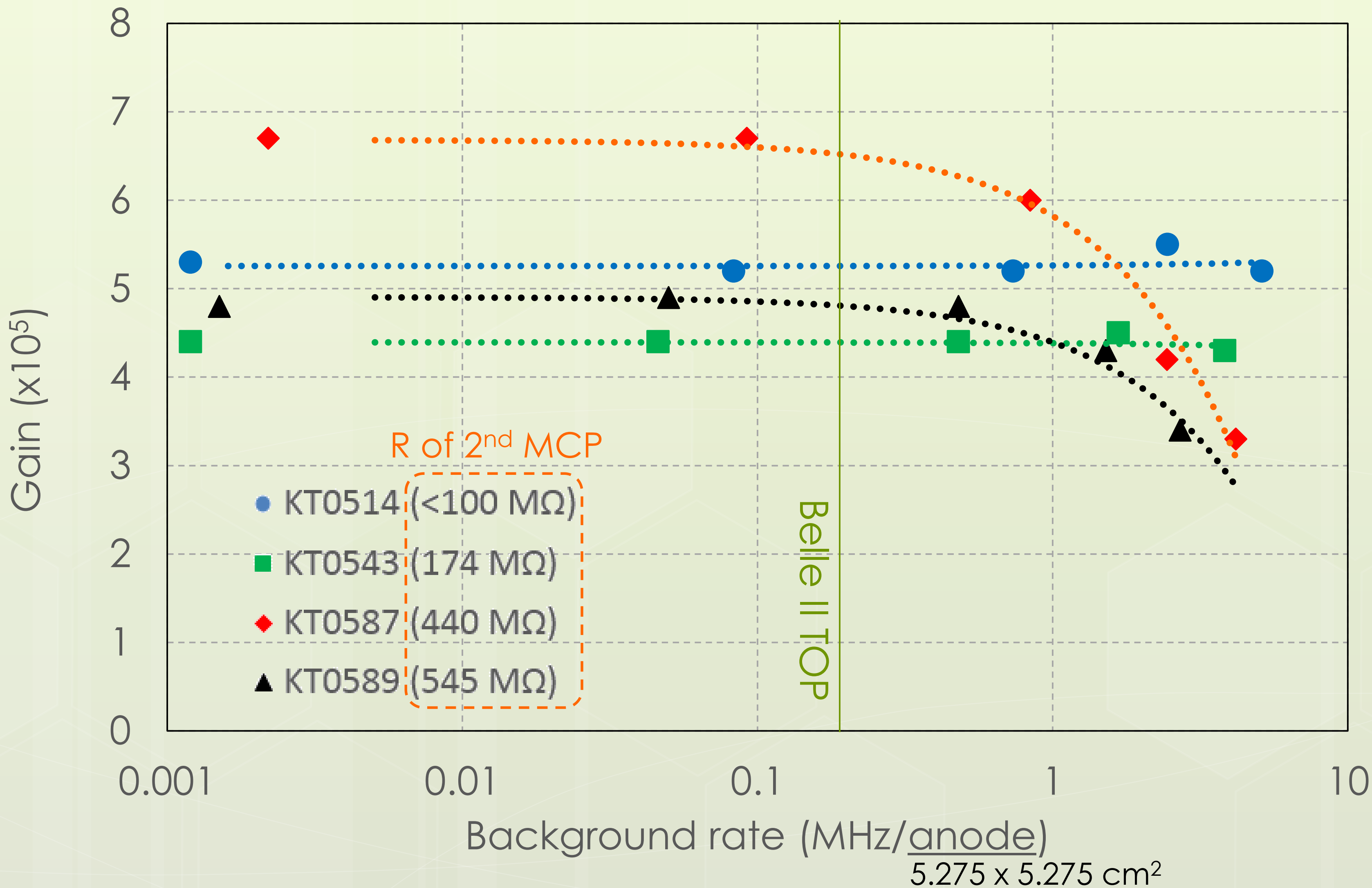
Test under a high background

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



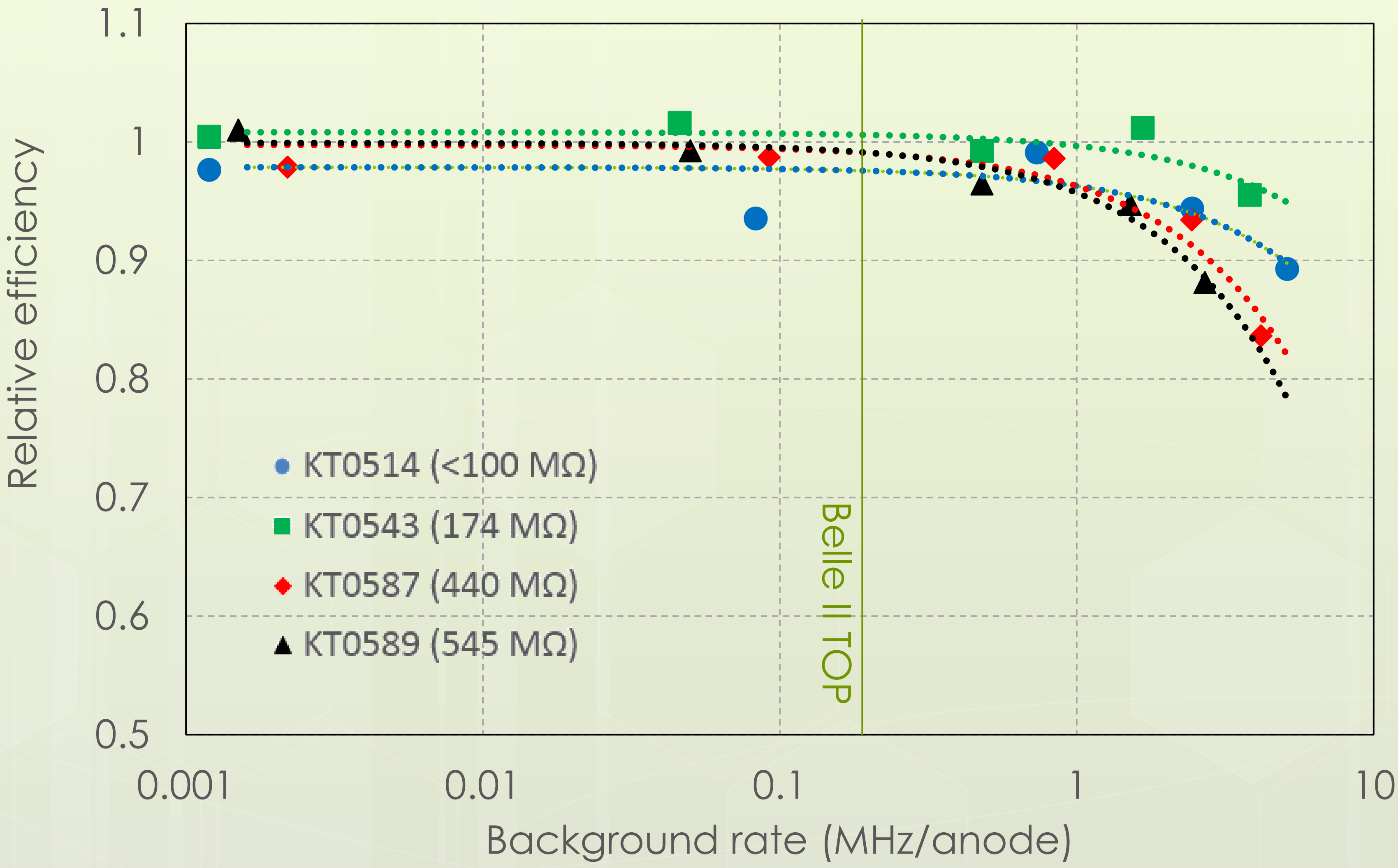


Gain under a high background



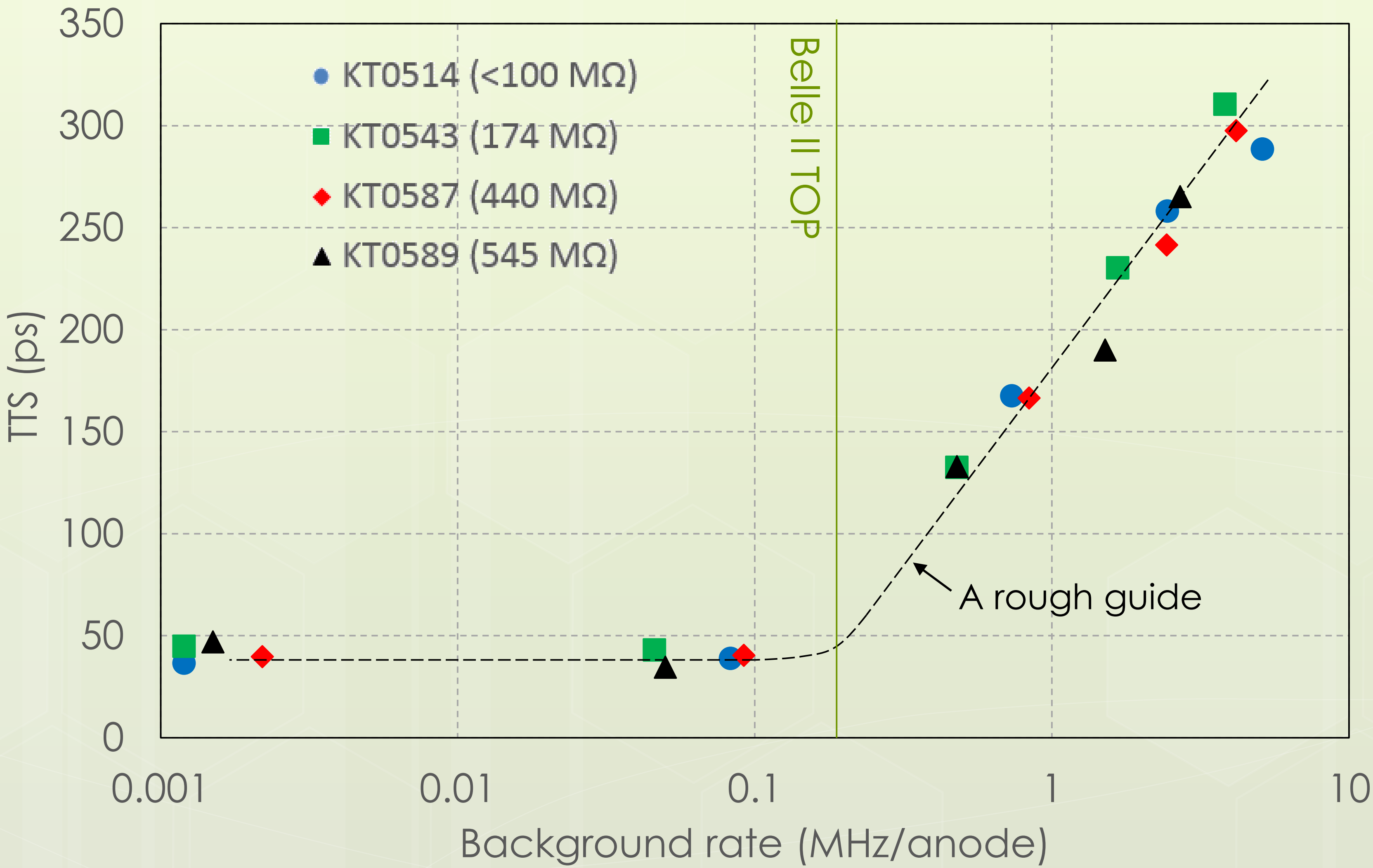
Gain drops above ≳100 kHz/anode for high R MCPs.

Efficiency under a high background



Efficiency drops above ~1 MHz/anode.

TTS under a high background



TTS deteriorates above ~200 kHz/anode.

Summary

- 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 $R_{MCP} \lesssim 174$ MΩ. (A smaller R_{MCP} is better.*)
    - TTS deteriorates above ~200 kHz/anode
      - Independent of R_{MCP}.
      - Correspond to 3.7 C/cm^2/50 ab^{-1} for 5 x 10^5 gain at Belle II TOP.
      - Current limit of background rate to use the MCP-PMT.

    * Cannot be much smaller to avoid thermal runaway.
- We succeeded in developing the MCP-PMT for Belle II TOP, but further R&D is necessary for next next generation experiments.