Improvement of the MCP-PMT performance under a high count rate

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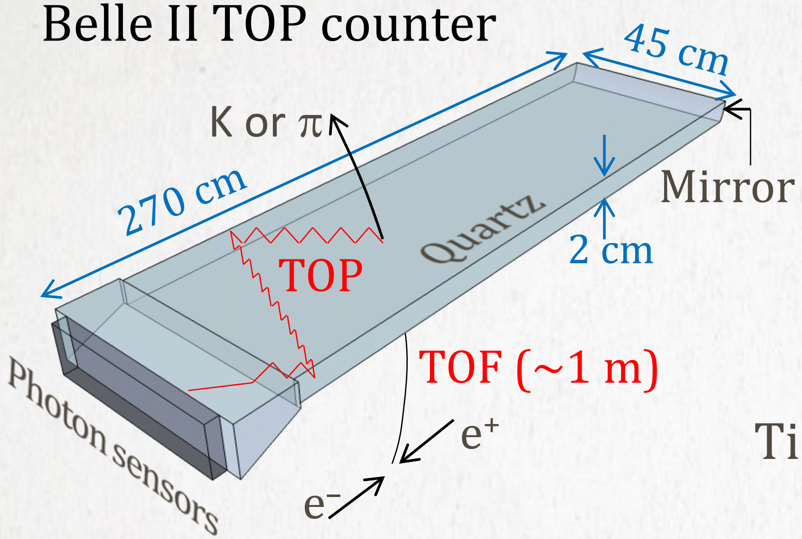
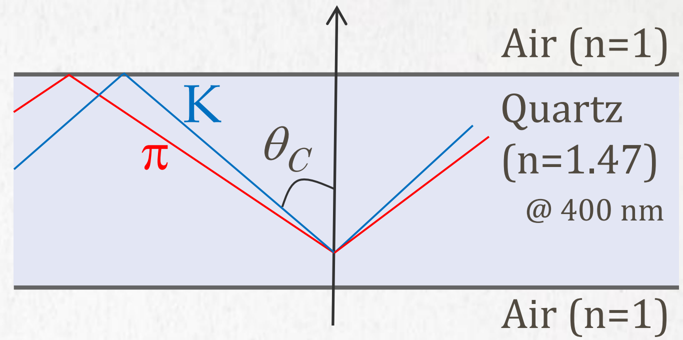
Novel PID detectors in the next generation experiments

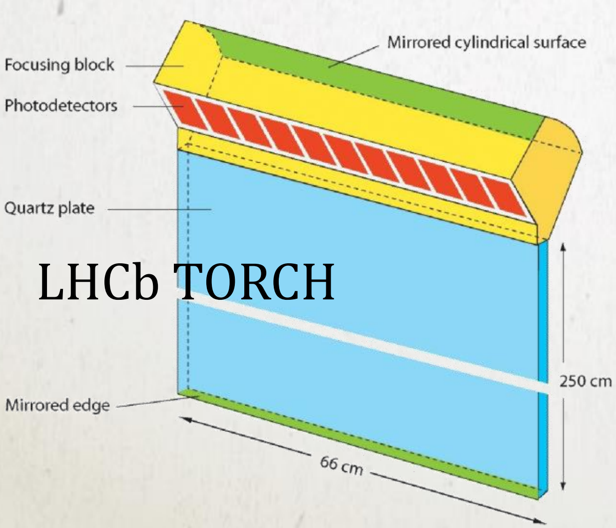
- Quartz-based "ring imaging" Cherenkov detectors

Belle II TOP counter



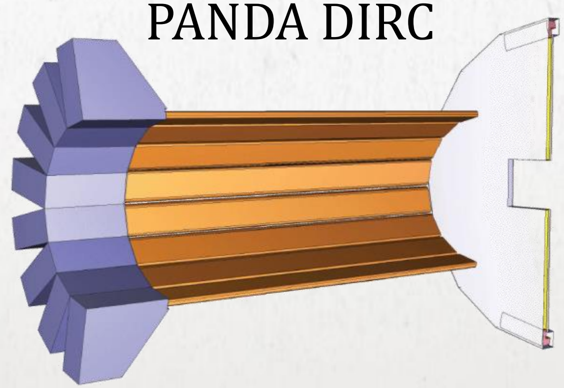


Time of propagation (TOP) $\propto \cos\theta_C = \frac{1}{n\beta}$

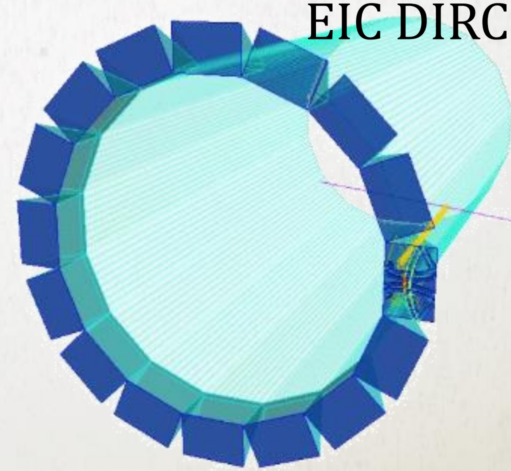


LHCb TORCH

PANDA DIRC



EIC DIRC



Photon sensors in novel RICH detectors

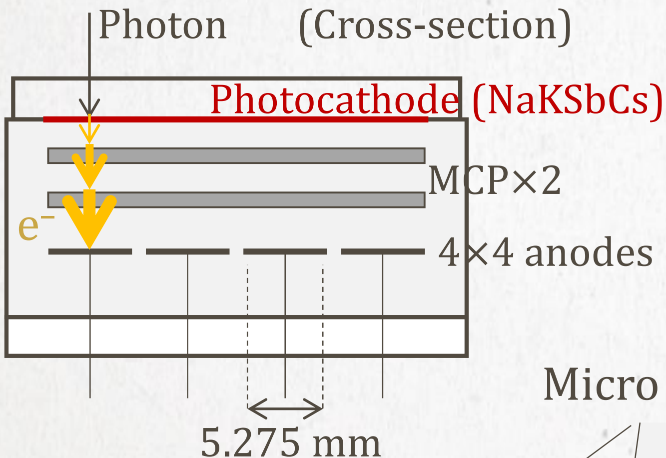
Requirements for the photon sensors:

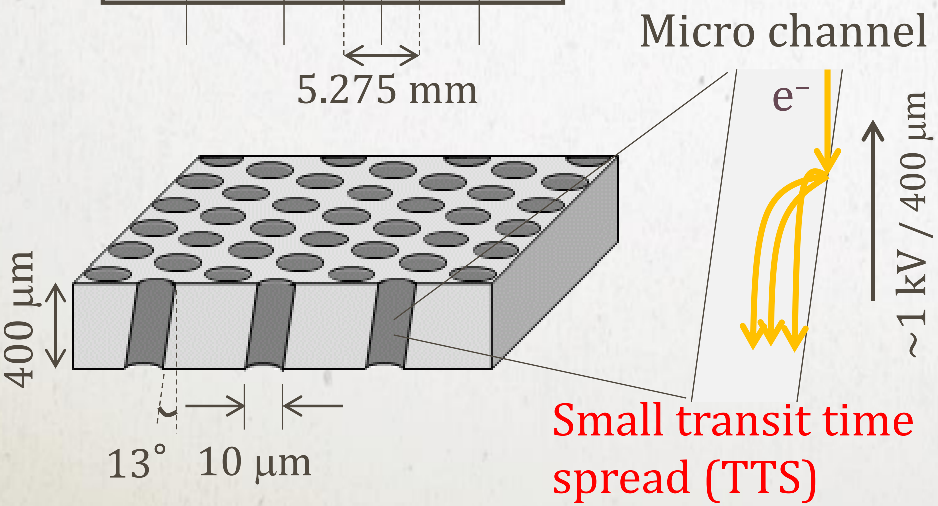
- Not only a spatial resolution to reconstruct Cherenkov images
- Very good time resolution for single photons
  - <50 ps for the TOP counter
- Large photocoverage
- High efficiency
- Work under a high background from the accelerator
- Work in a high B-field

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

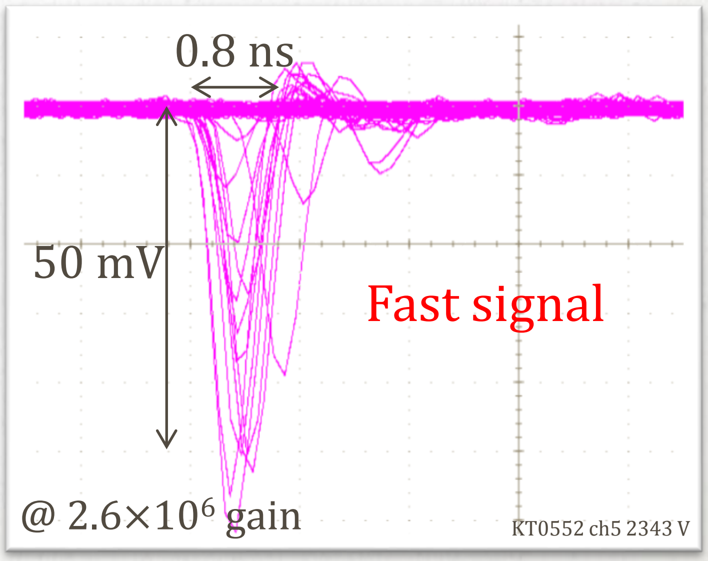
MCP-PMT for the TOP counter

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





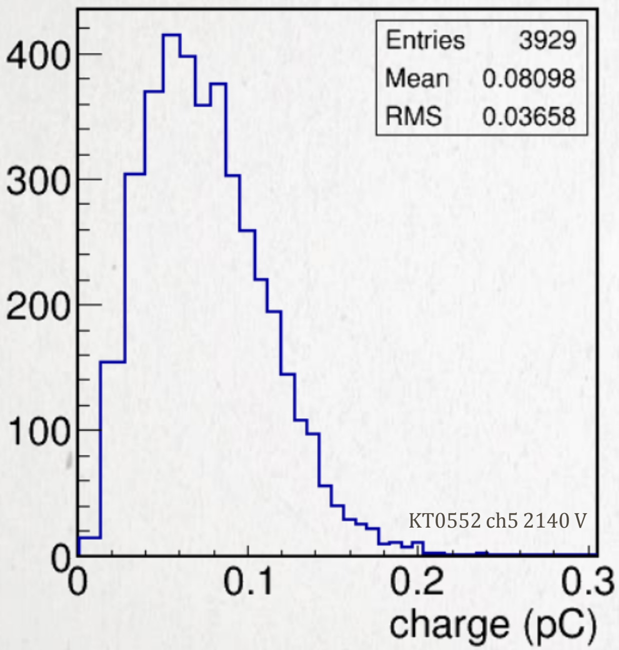
Oscilloscope (2.5 GHz bandwidth)



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

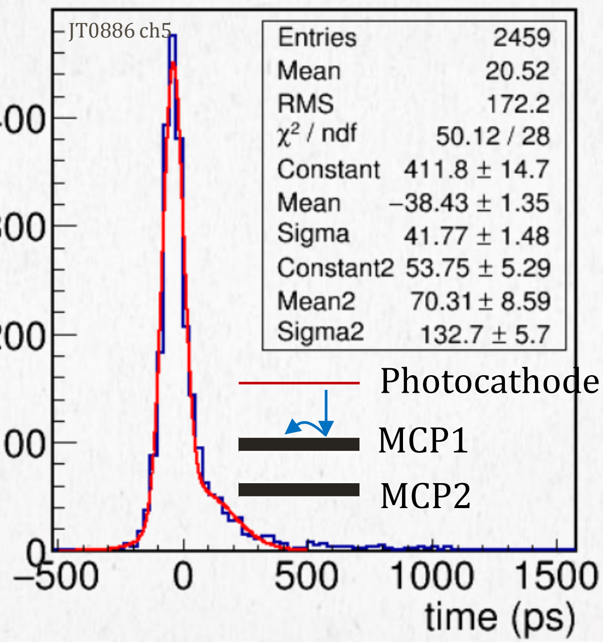
Performance of the MCP-PMT

ADC distribution for single photons



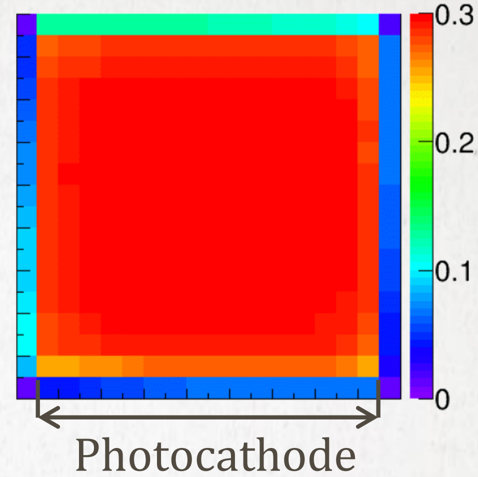
Gain
≡ mean of the distribution
= 5.1×10^5

TDC distribution for single photons from picosecond pulse laser

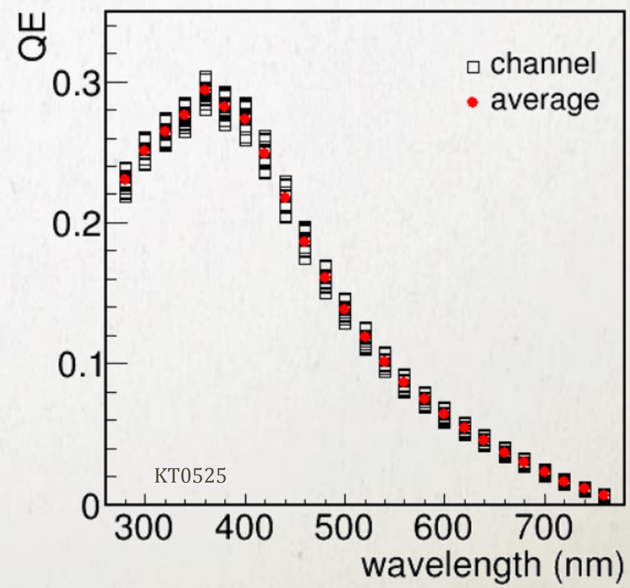


TTS ≡ σ of 1st Gaussian
= 41.8 ps
(incl. ~17 ps laser pulse width and ~24 ps electronics jitter)

QE distribution at 360 nm

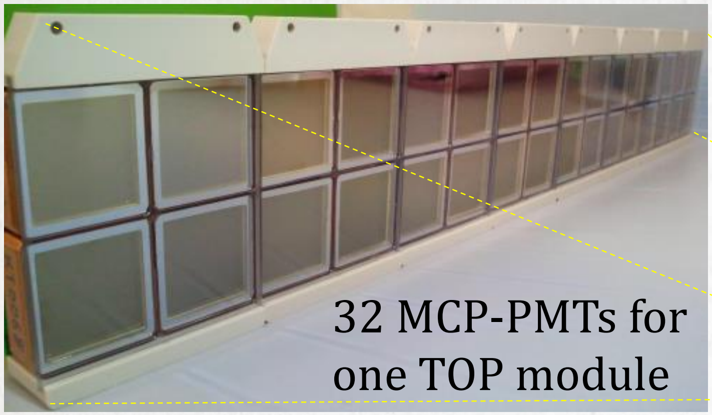


Typical QE spectrum

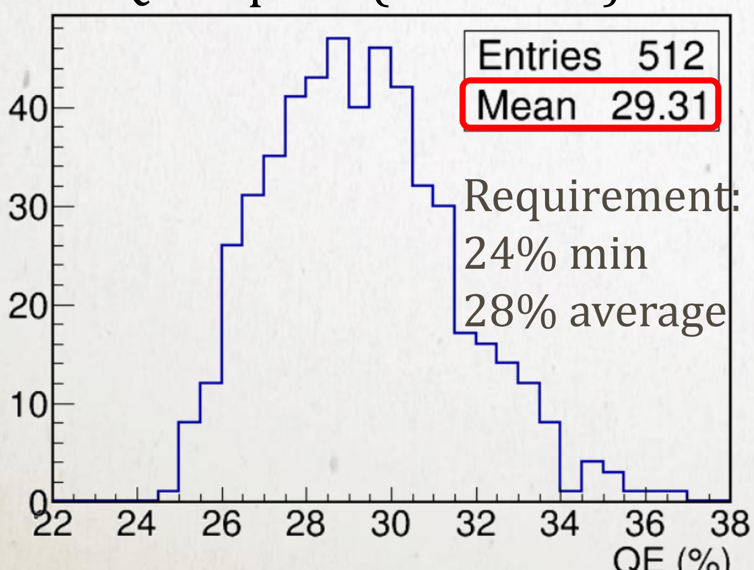


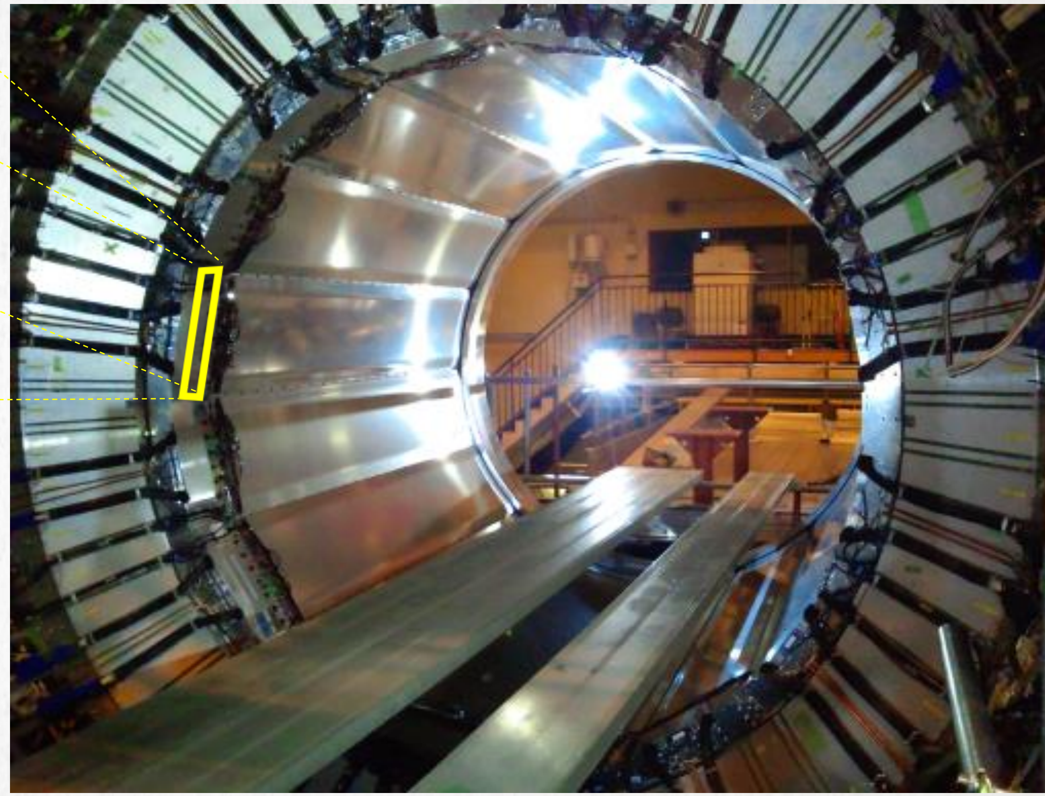
Mass production and installation

- Successfully mass-produced 512 (and spare) MCP-PMTs in 5 years from 2011.



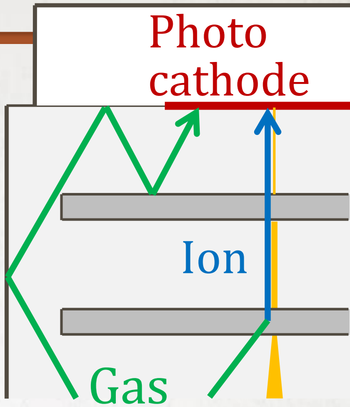
QE at peak (~360 nm)





Installation of 16 TOP modules finished in May 2016.

Major problem of the MCP-PMT



Aging of the photocathode

- In the electron multiplication, gas/ion is desorbed from the MCP of quite a large surface area. The photocathode is deteriorated by the gas/ion, and the QE is depressed.
  - Specific mechanism of the deterioration is unknown.
  - 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 $\mathrm{QE}(Q_\tau)/\mathrm{QE}_{\mathrm{inital}} = 0.8$ at 400 nm.

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

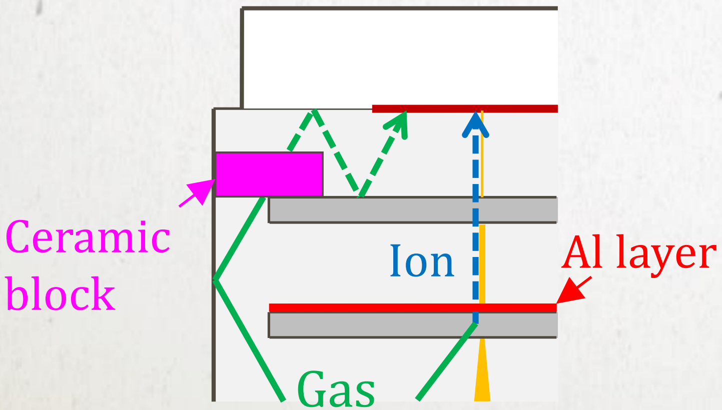
  ~8 C/cm^2 at 50 ab^{-1} with 5×10^5 gain by the latest simulation

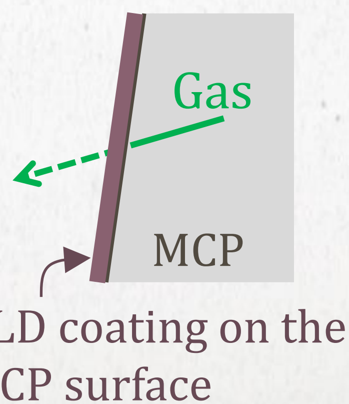
→ We have researched to achieve the lifetime longer than the estimated accumulated output charge.

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

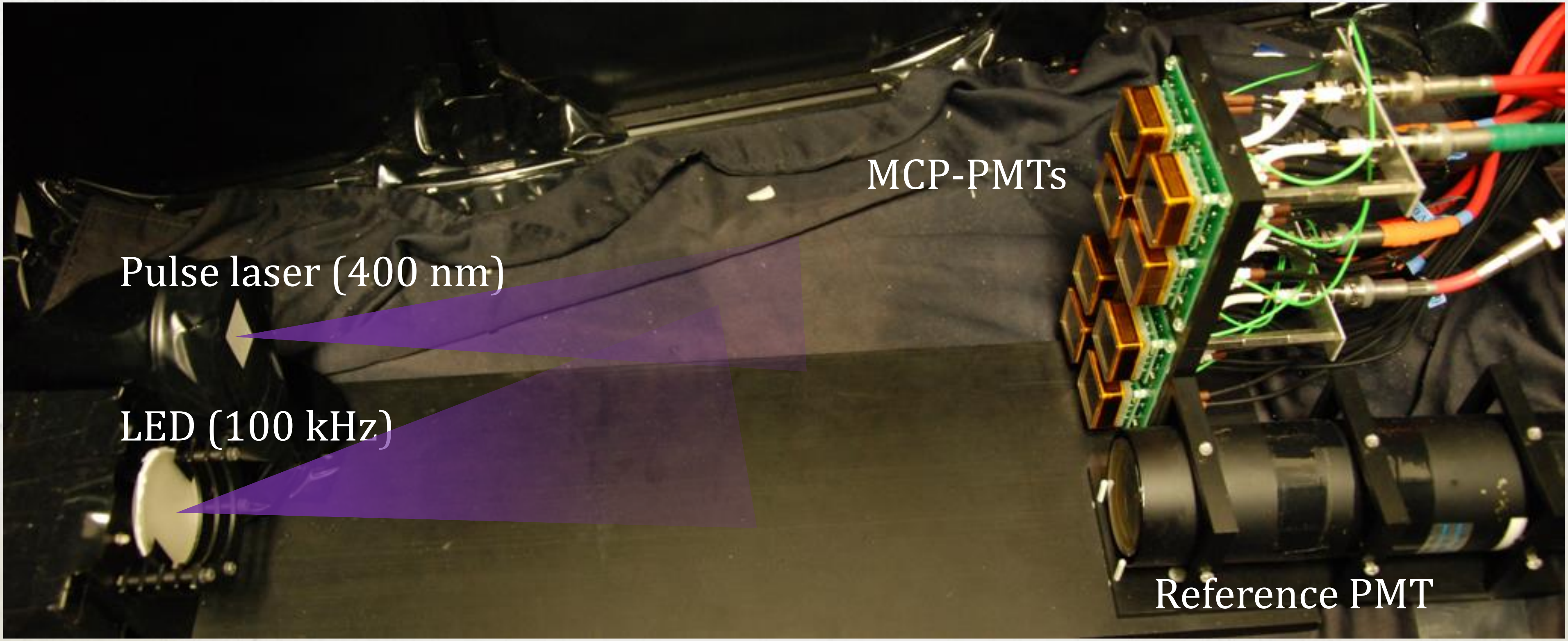




→ Evaluated the lifetime of each type of MCP-PMT

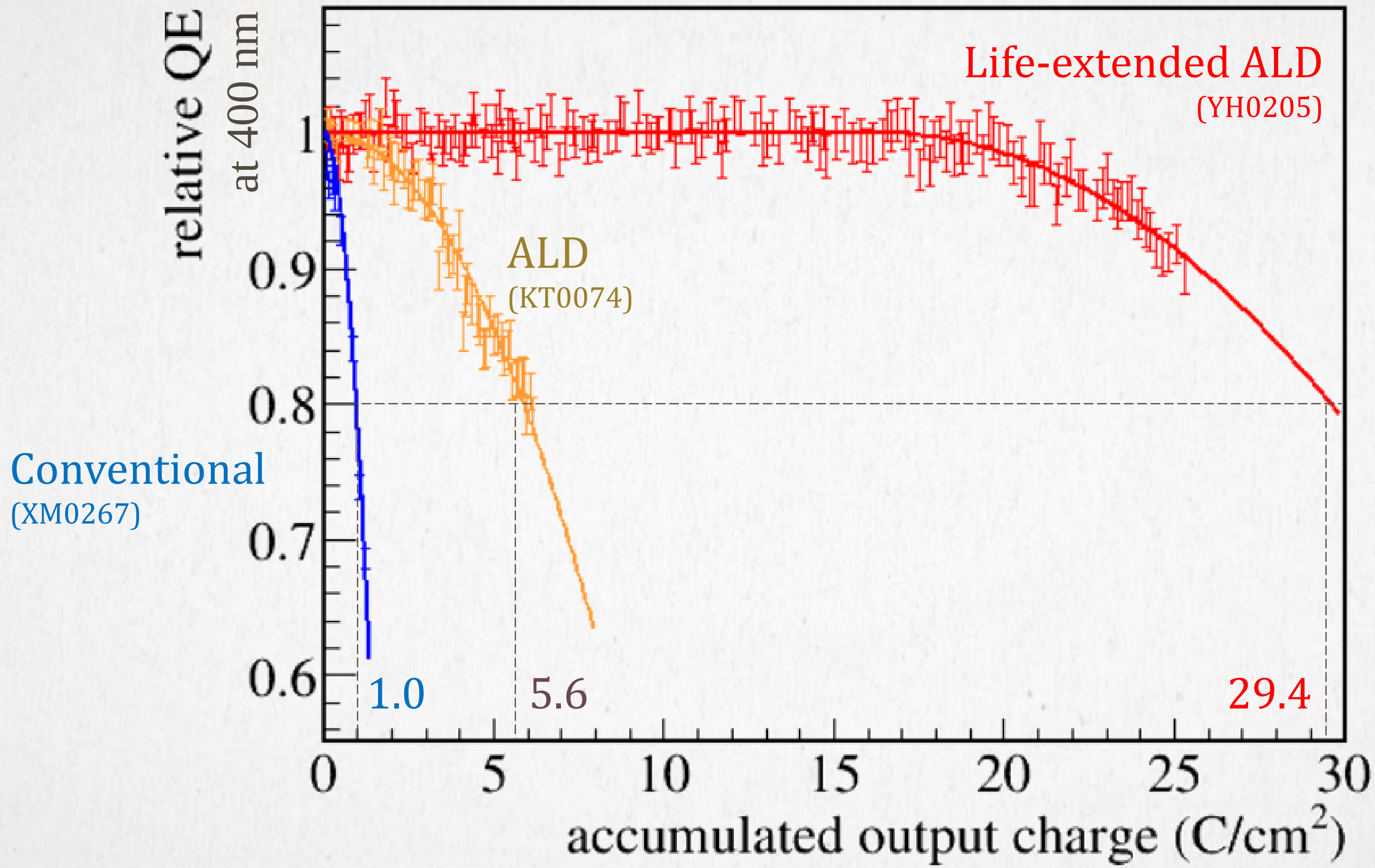
Lifetime test

- 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

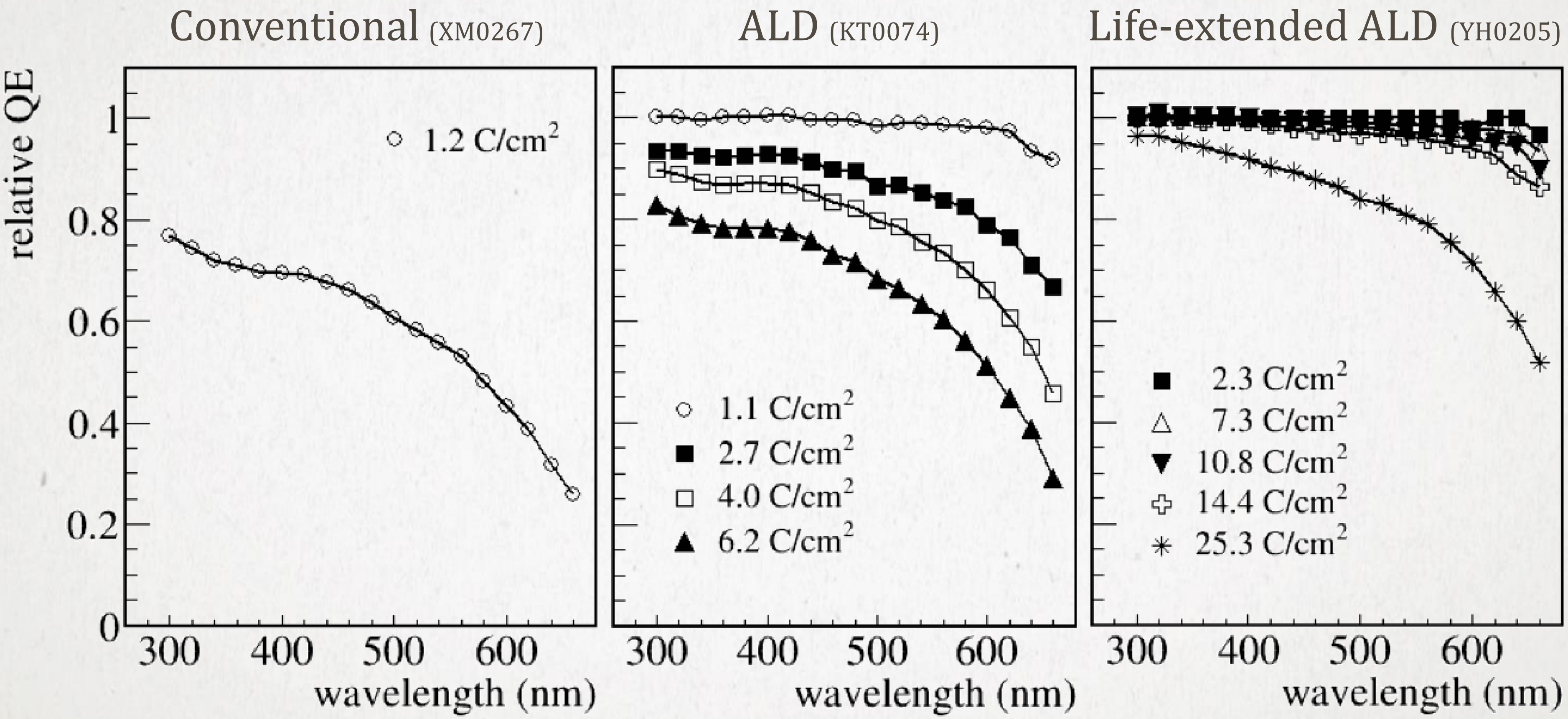
Typical examples of each type



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

Spectral dependence of QE depression

- Got off and on the lifetime test to measure the QE spectrum.

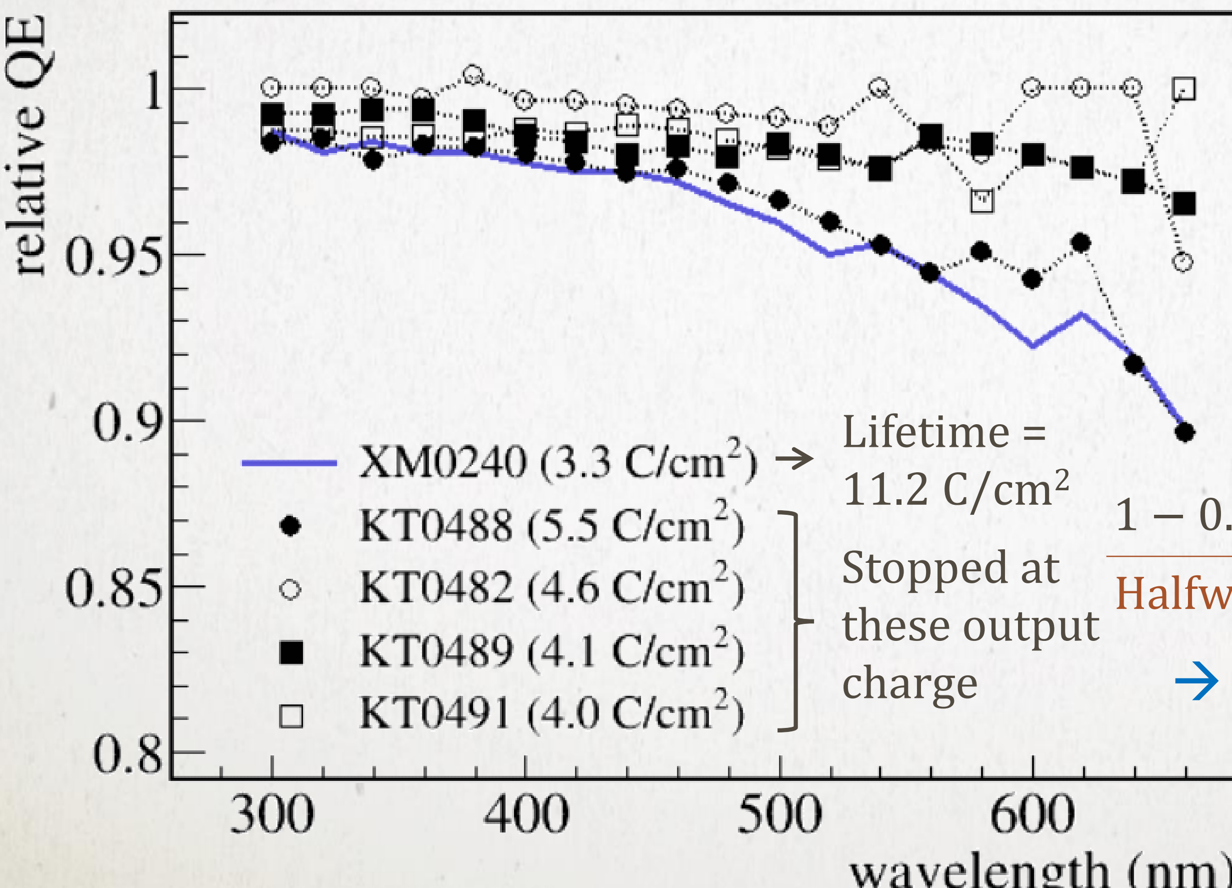


✓ Consistent with the in-situ QE measurement by the laser at 400 nm.

✓ More significant depression of QE at longer wavelengths.

Lifetime estimation halfway through the test

- 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.



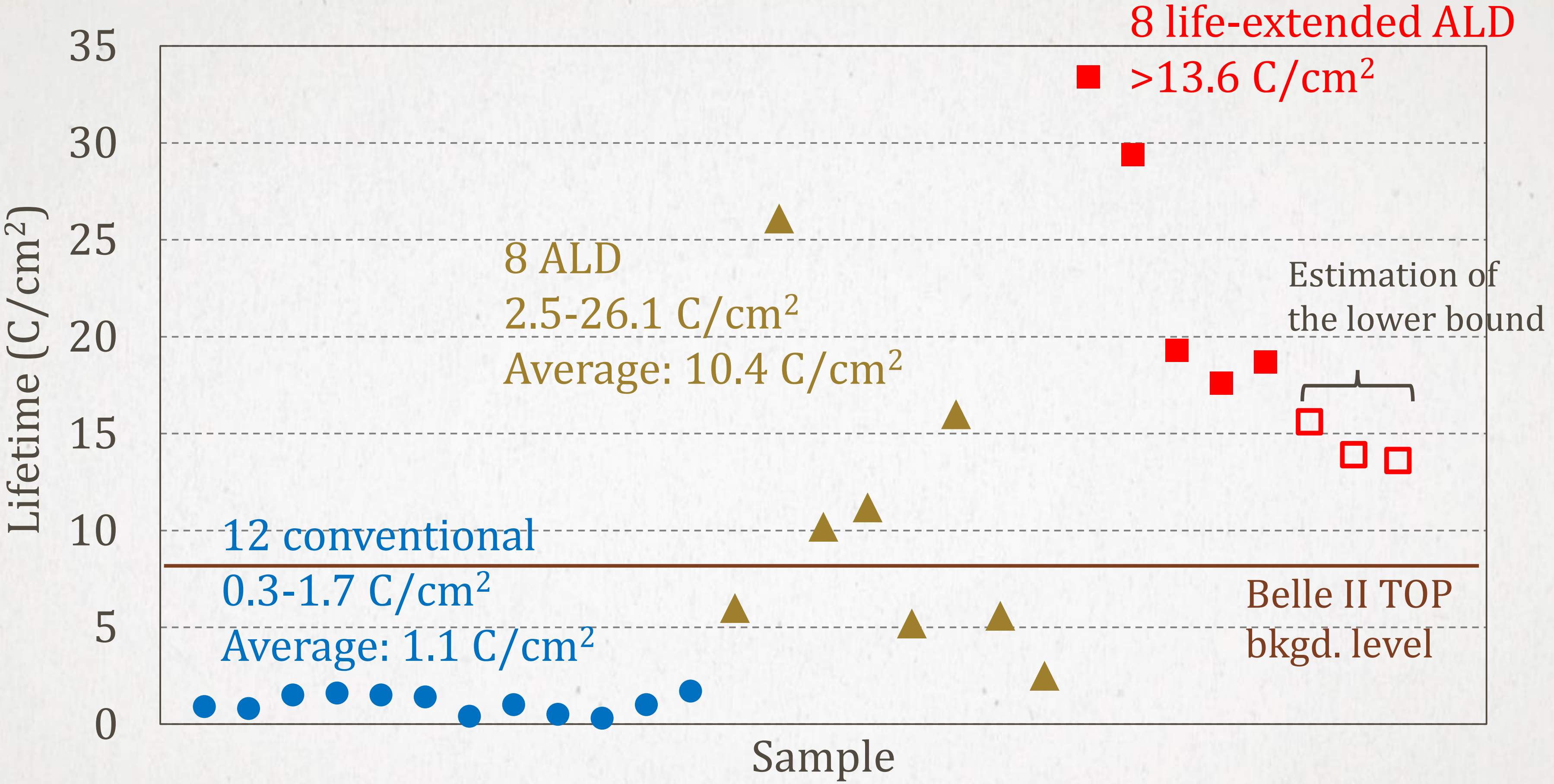
→ Lifetime = 11.2 C/cm^2

Stopped at these output charge

$$\underbrace{1-0.2(Q/Q_\tau)^2}_{\text{Halfway sample}} \geq \underbrace{1-0.2(3.3/11.2)^2}_{\text{XM0240}}$$

$$\rightarrow Q_\tau \geq Q/3.3 \times 11.2\ \mathrm{C/cm^2}$$
$$\geq 13.6\text{–}18.8\ \mathrm{C/cm^2}$$

Measured lifetime



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

Summary (and prospect)

- An MCP-PMT, which has the best time resolution of ~30 ps, is a key photon sensor for novel RICH detectors.
  - Belle II TOP counter uses 512 MCP-PMTs, which were successfully produced and installed.
- A major concern was a use under a high background, because the lifetime of the photocathode was very short due to outgassing from the MCP.
- Lifetime has been extensively improved by three successive countermeasures against the gas/ion:
  1. Block (conventional) 1.1 C/cm^2 on average of 12 samples
  2. Suppress (ALD) 10.4 C/cm^2 on average of 8 samples
  3. Reduce (life-extended ALD) >13.6 C/cm^2 for all 8 samples
- For further improvement, probably need a specific countermeasure based on understanding of the QE depression mechanism.