Development of the MCP-PMT for the Belle II TOP Counter

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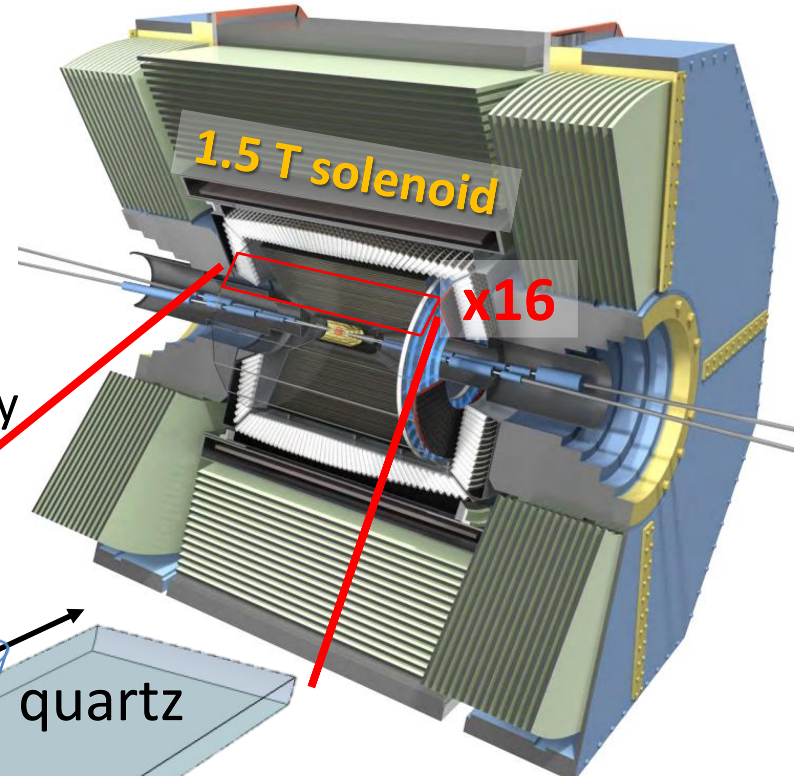
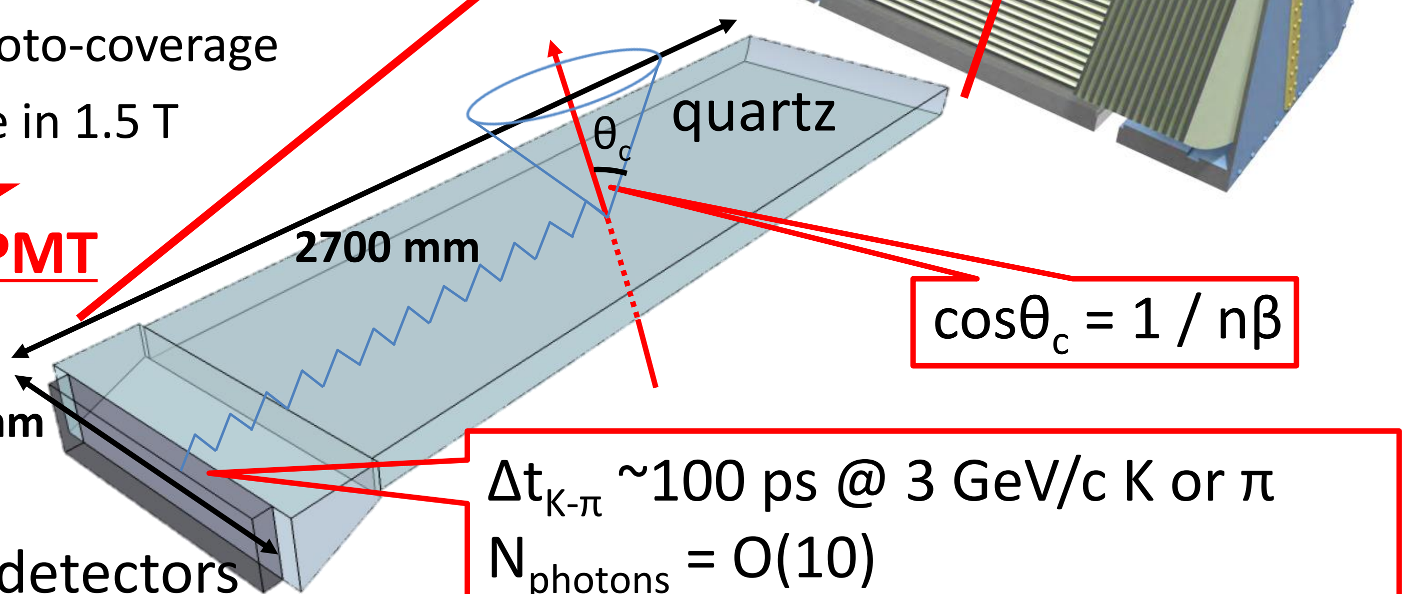
■ TOP Counter for Belle II

- Time Of Propagation counter
  - K/π identification on the barrel region with Cherenkov radiation
- For PID with TOP counters, photodetectors must have:
  - Good single photon detection efficiency
  - Excellent TTS (<50 ps)
  - Pixel size of ~5 mm
  - Large photo-coverage
  - Operable in 1.5 T

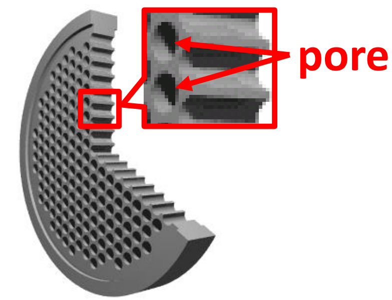
MCP-PMT

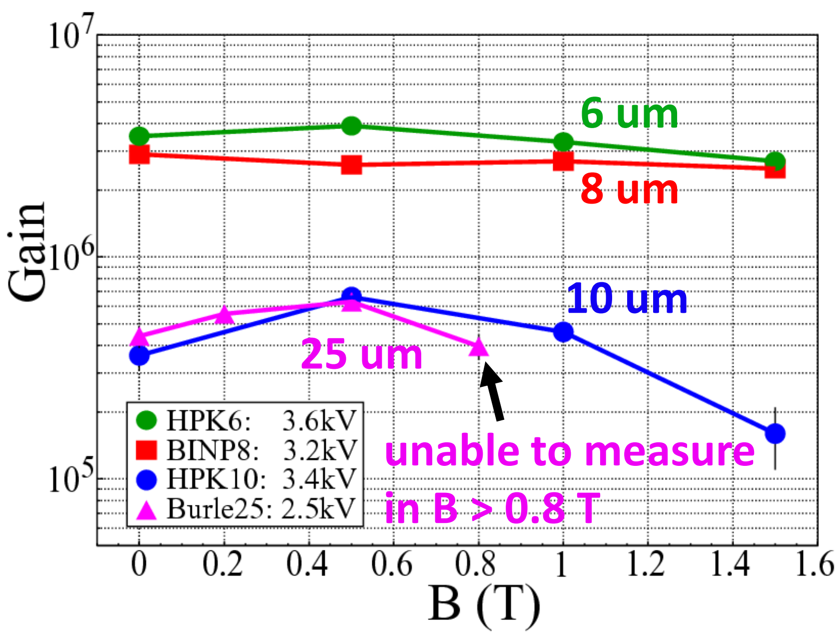


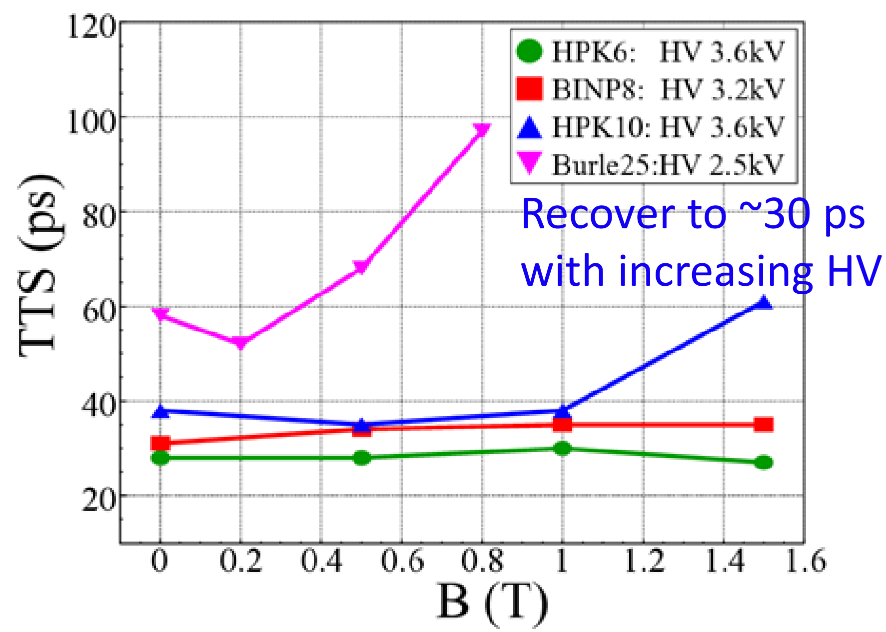


■ MCP-PMT Development

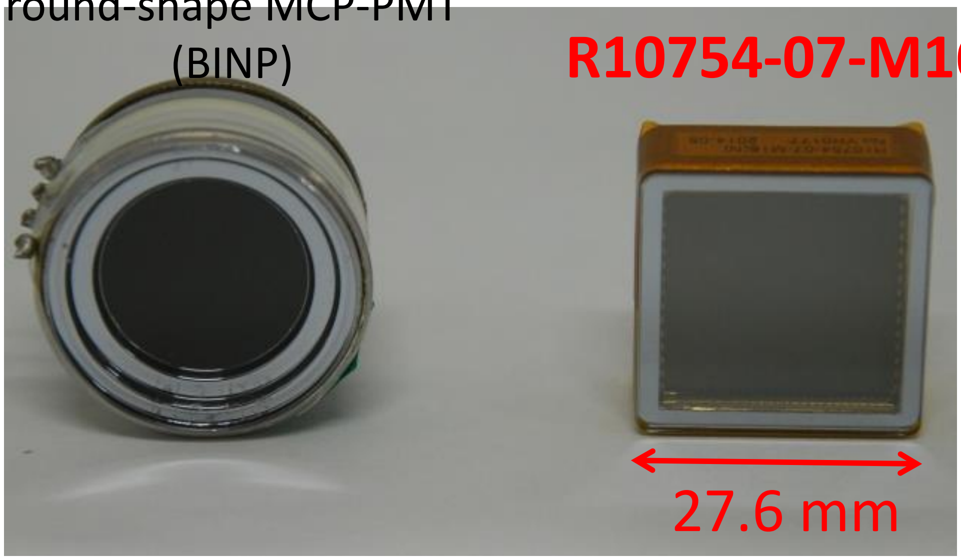
- Tested some samples in magnetic fields [Nucl. Instr. and Meth. A528, 763 (2004)] [Nucl. Instr. and Meth. A592, 247 (2008)]
  - HPK6 with ϕ6 um pores   HPK10 with ϕ10 um pores
  - BINP8 with ϕ8 um pores   Burle25 with ϕ25 um pores
- 10 um was the best selection
  - Good gain & TTS in 1.5 T
  - Reliable to produce 3 cm^2 size MCP compared to 6 um size

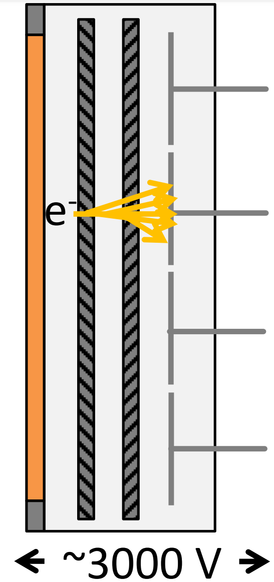


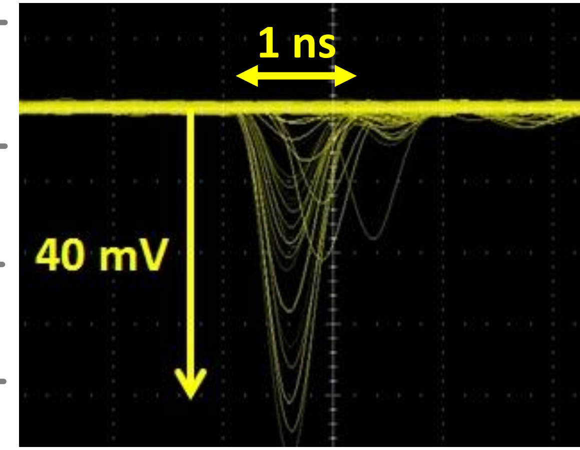




■ Square-shaped MCP-PMT (R10754)







<u>Developed original MCP-PMT (R10754-07-M16) with HAMAMATSU</u>

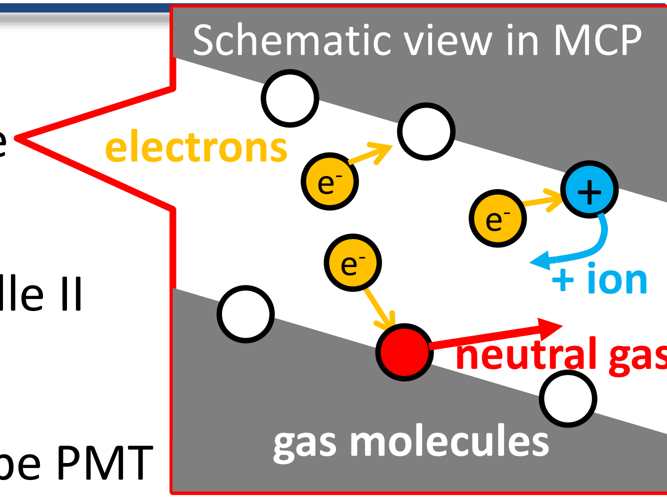
- Square shape to maximize photo-coverage in an array
  → 32 PMTs/TOP x 16 TOPs = <u>512 PMTs</u>
- 4x4 anodes, one anode pad has a size of 5.6x5.6 mm^2
- ~10^6 gain in 1.5 T by 2-stage MCPs (t = 400 um)
- Fast raise time of ~200 ps, TTS of 30-40 ps
- Multi-alkali p.c., QE_{peak} ~28% around 360 nm

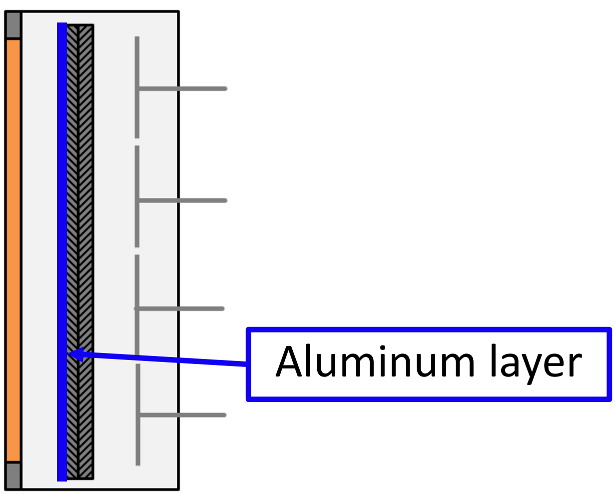
Excellent characteristics for TOP counter

■ Lifetime Improvement

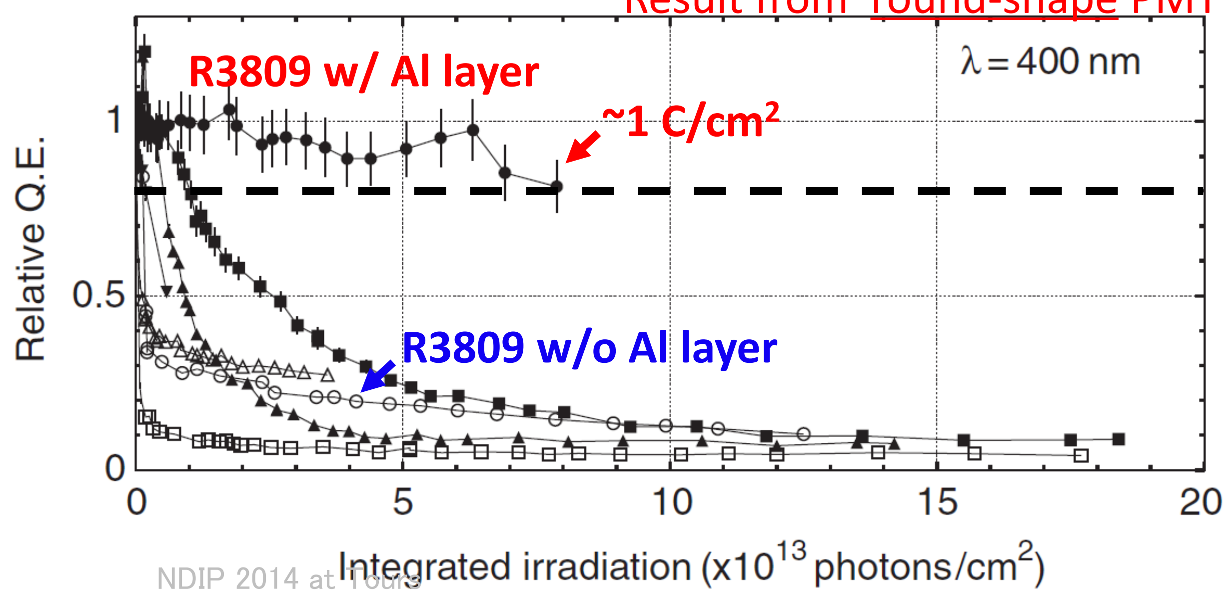
Nucl. Instr. and Meth. A564, 204 (2006)

- QE drops during operation
  - QE drop is a function of total output charge
    → ~80% QE drop is acceptable
  - Estimated output charge is 2-3 C/cm^2 in Belle II
- Al layer for **ion feedback** protection
  - Evaluated effect of Al layer with round-shape PMT
  - ~1 C/cm^2 lifetime was obtained with Al layer
    → Usable with a few times of PMT exchanges in Belle II operation



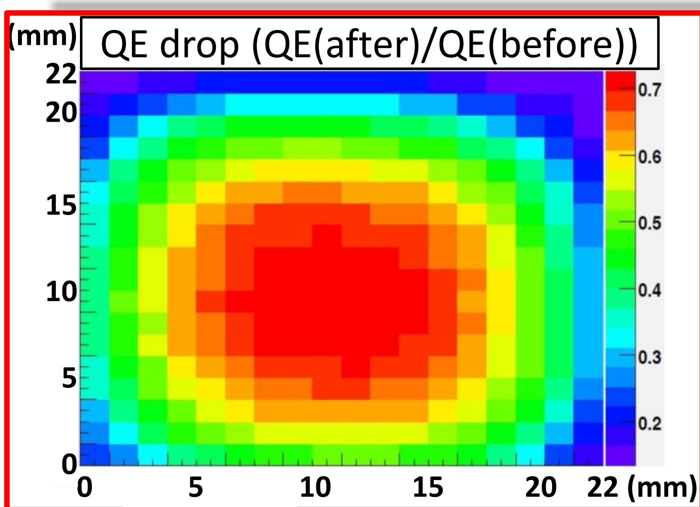


* Result from round-shape PMT

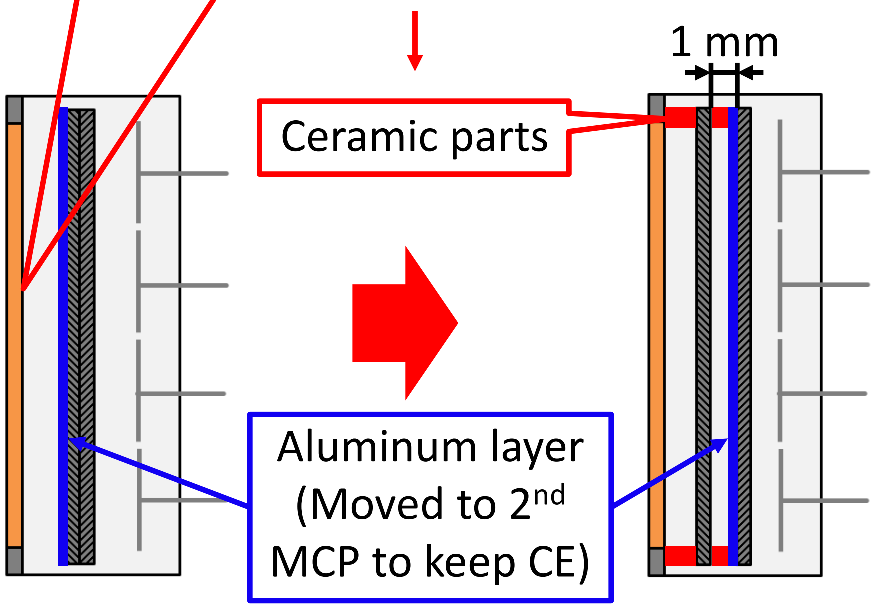


■ Lifetime Improvement

Nucl. Instr. and Meth. A629, 111 (2011)

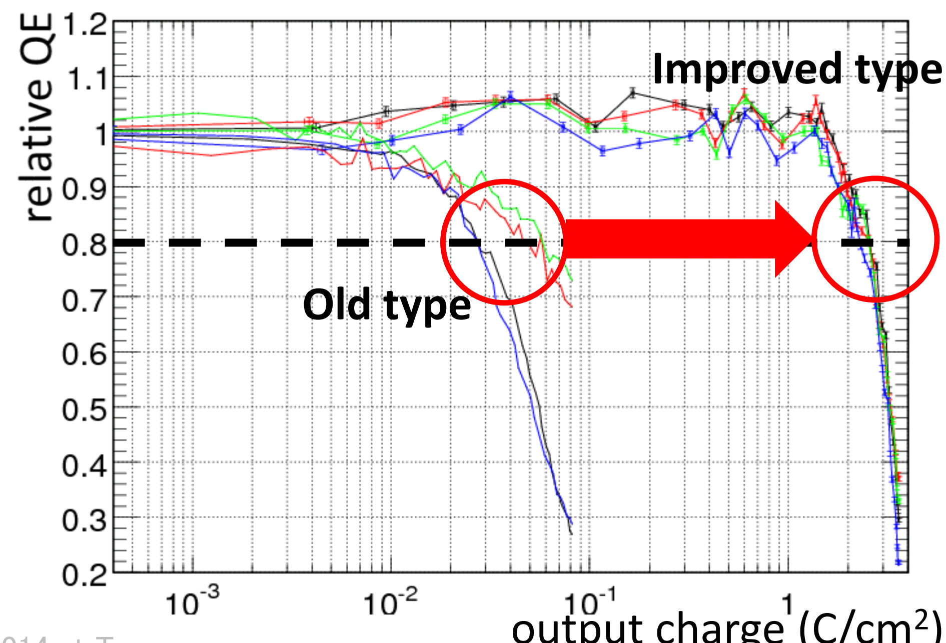


QE drops from corners



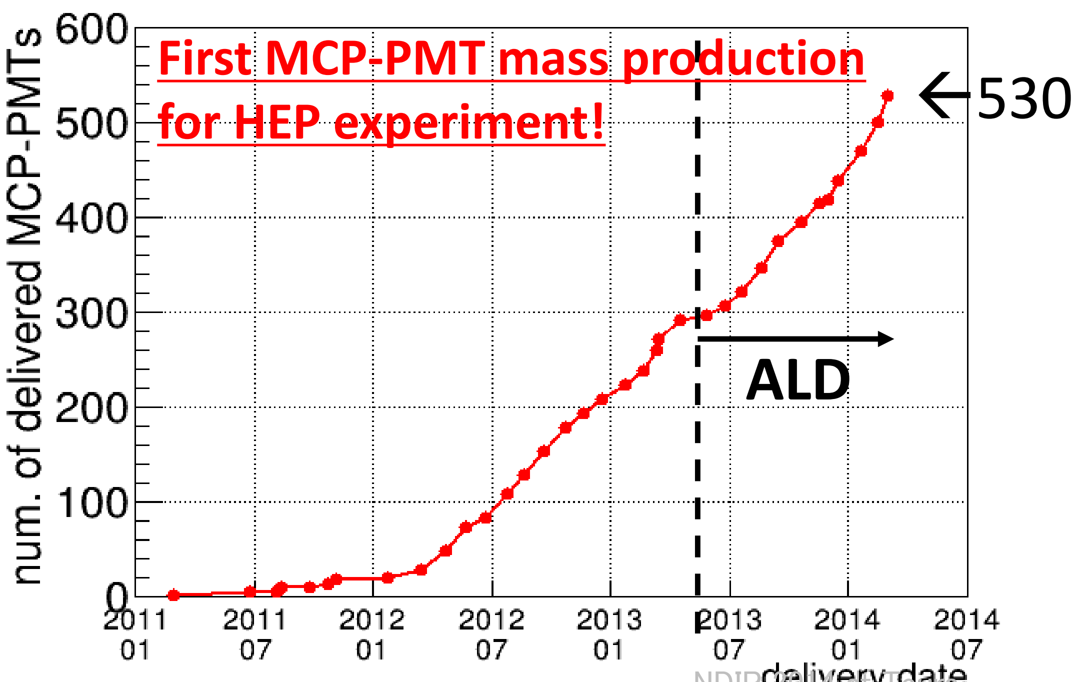
- Lifetime of R10754 w/ Al layer
  - Only ~10 mC/cm^2, shorter than round PMT
- Improvements
  - Inserted ceramic parts to block path of **neutral gas** molecules

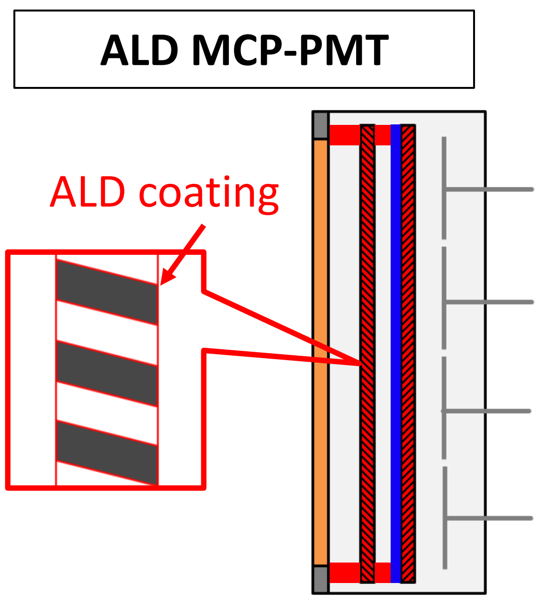
    → Lifetime was improved to ~1 C/cm^2
  - Moved Al layer to 2^{nd} MCP for increasing CE



■ Successful Mass-production

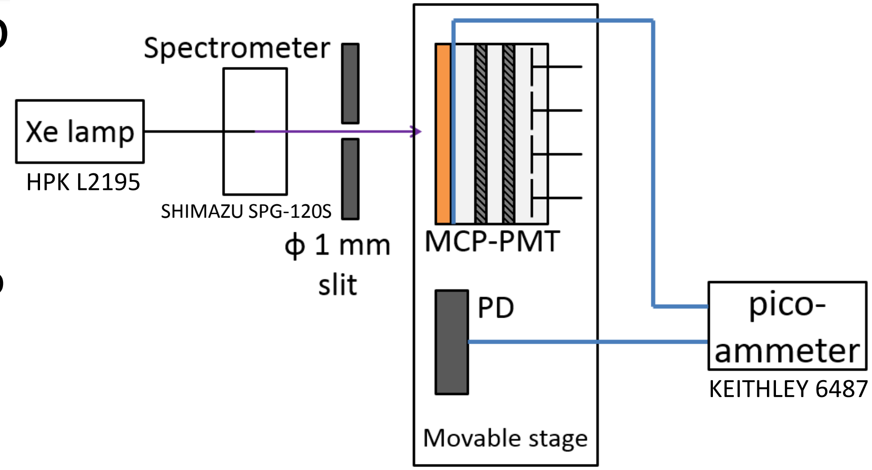
- MCP-PMT mass production for the TOP counter
  - Produced >500 MCP-PMTs
  - Measure QE and gain/TTS (0 T and 1.5 T) for all MCP-PMTs
    → Feedback to production/database of MCP-PMTs
- Further lifetime improvement with ALD-coated MCPs
  - ALD MCP had been available during production
    → ~50% MCP-PMTs are ALD type

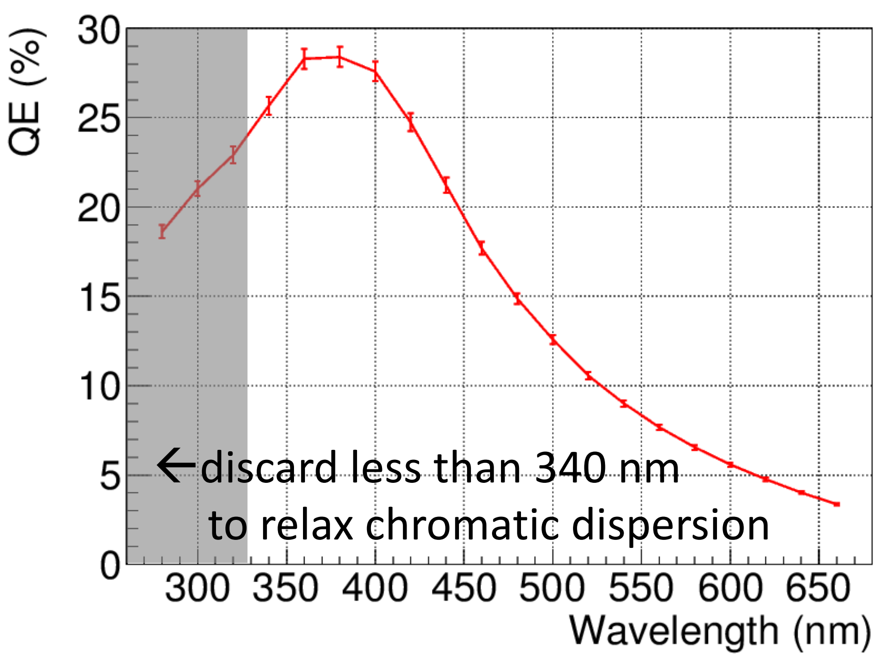


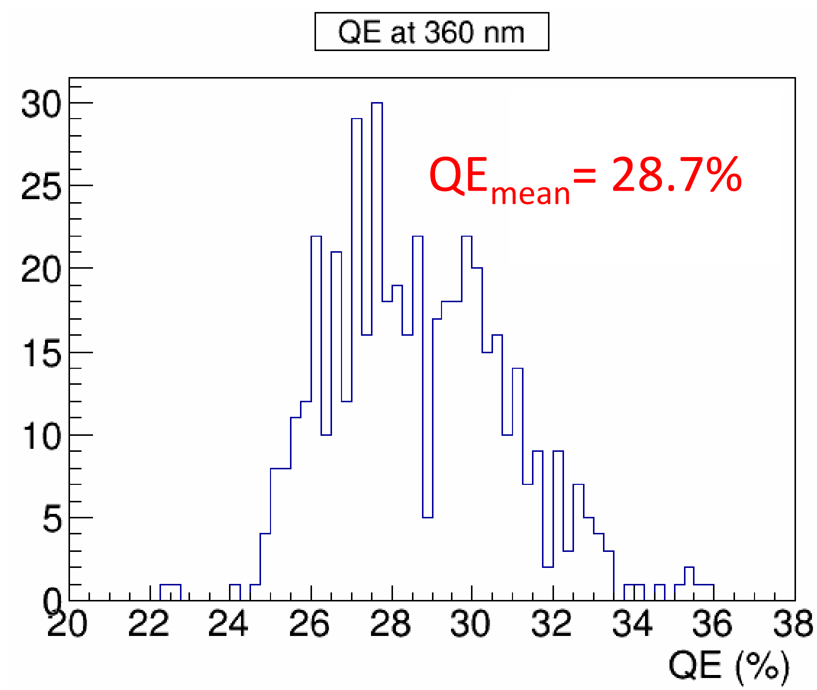


■ QE Measurement

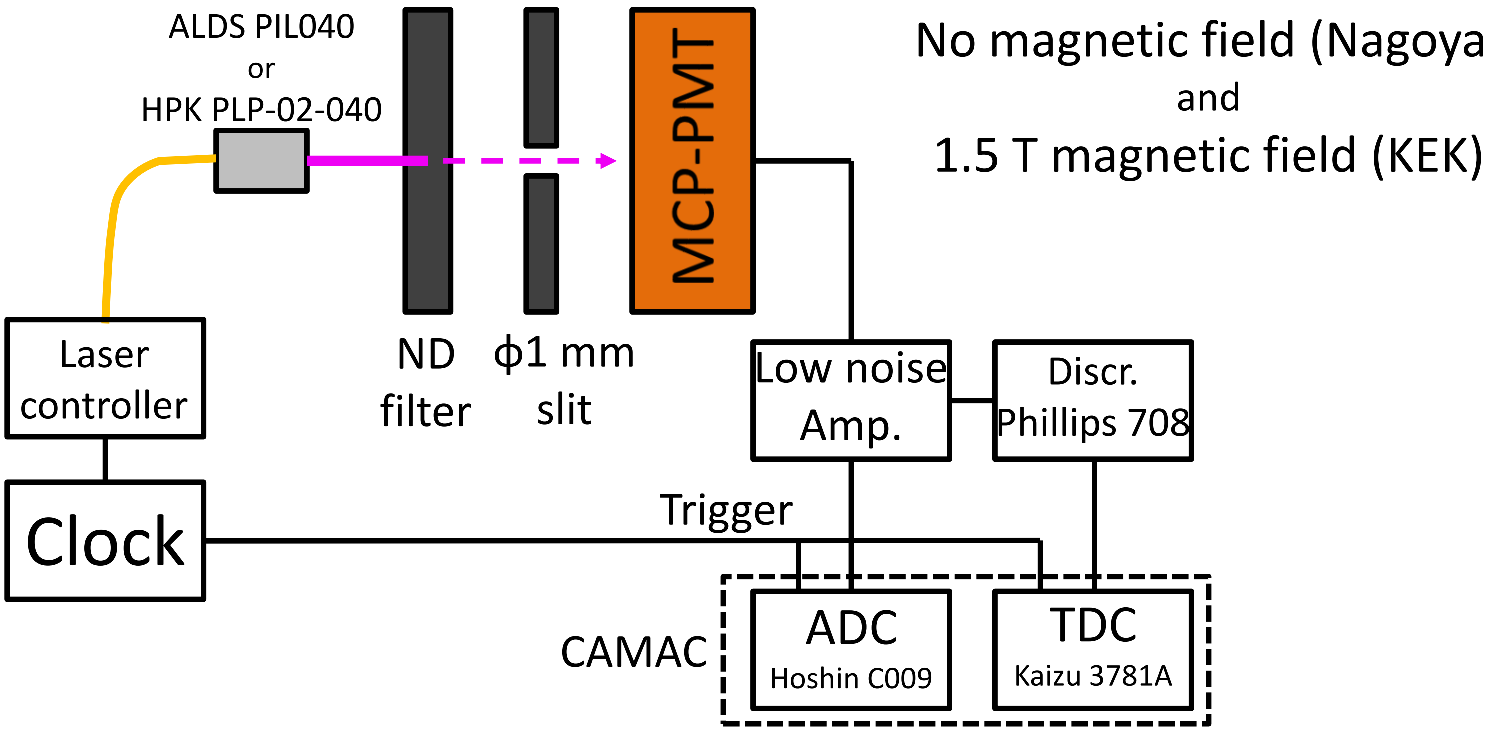
- Irradiate monochromatic light to MCP-PMT and PD by turns
  - QE_{PD} is well calibrated
  - → $QE_{MCP\text{-}PMT} = (I_{MCP\text{-}PMT\ p.c.} / I_{PD}) \times QE_{PD}$
- 473 PMTs have been measured
  - We use PMTs with QE_{peak} > 24%
  - → <u>Averaged QE_{peak} >28%</u>







■ Measurements with Single Photon

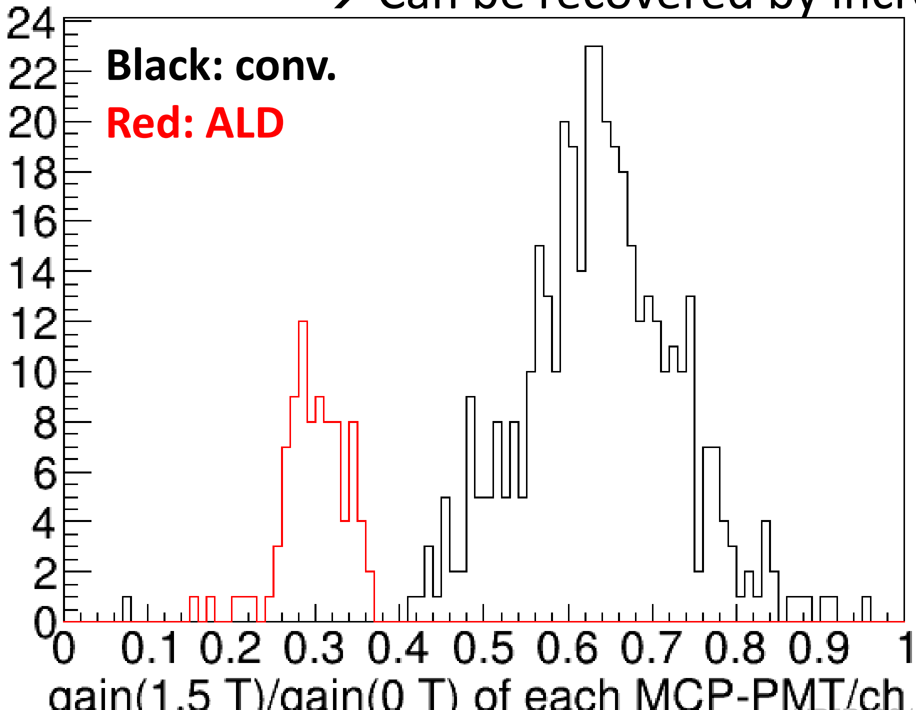


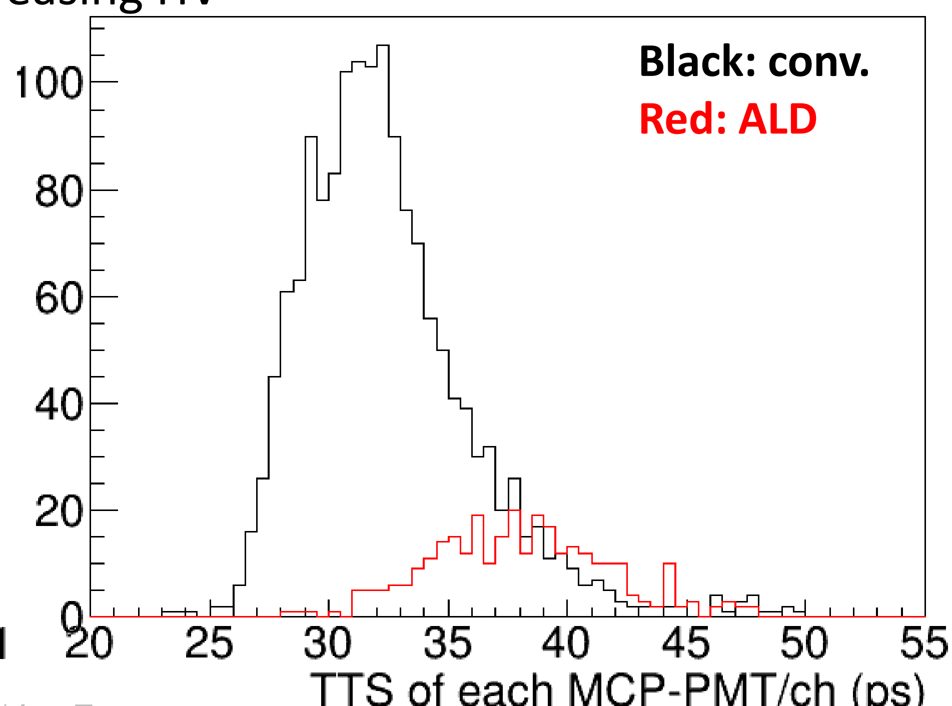
- Measurements with single photon
  - Light from pulse laser with σ_{laser} <20 ps
    →Intensity is reduced to single photon level
  - Jitter on readout electronics σ_{jitter} <20 ps
  - All of 16 channels can be measured with moving the MCP-PMT position

■ Gain/TTS in 1.5 T

- In 1.5 T (perpendicular to the PMT window)
  - ~100 PMTs have been measured (the measurement is ongoing)
  - Gain decreases down to 60% (conventional PMTs) or 30% (ALD PMTs)
    - Can keep > 5×10^5, which is enough for single photon detection
  - All PMT has TTS better than 50 ps in the magnetic field
    - Slightly worse TTS of ALD PMTs is caused by lower gain in 1.5 T

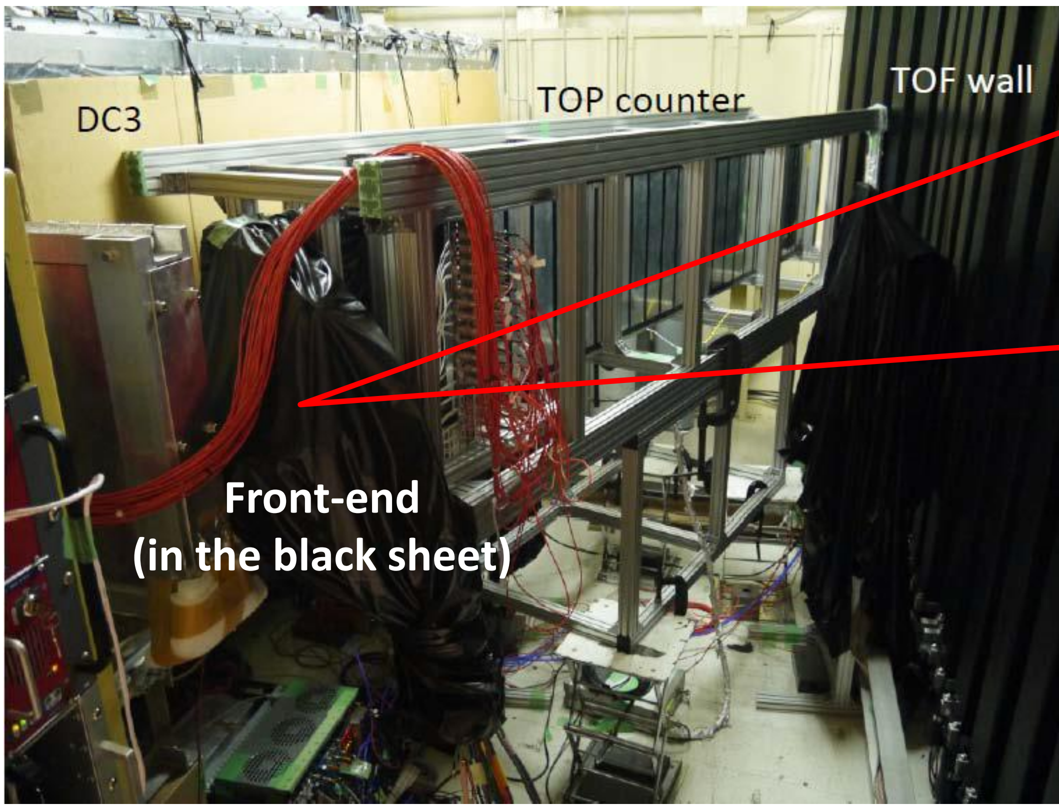
      → Can be recovered by increasing HV

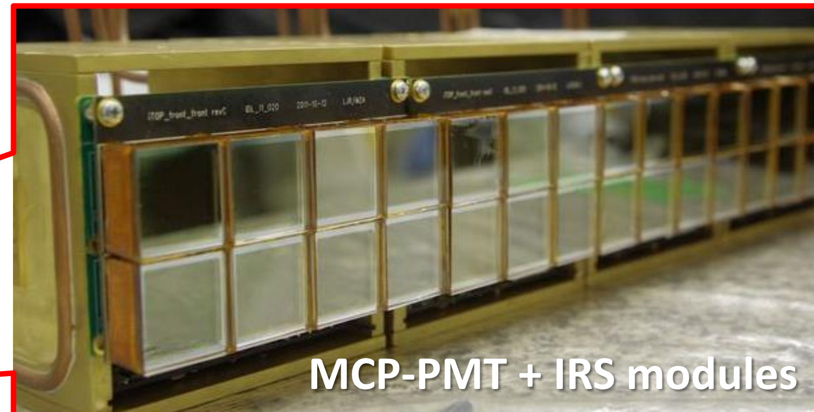


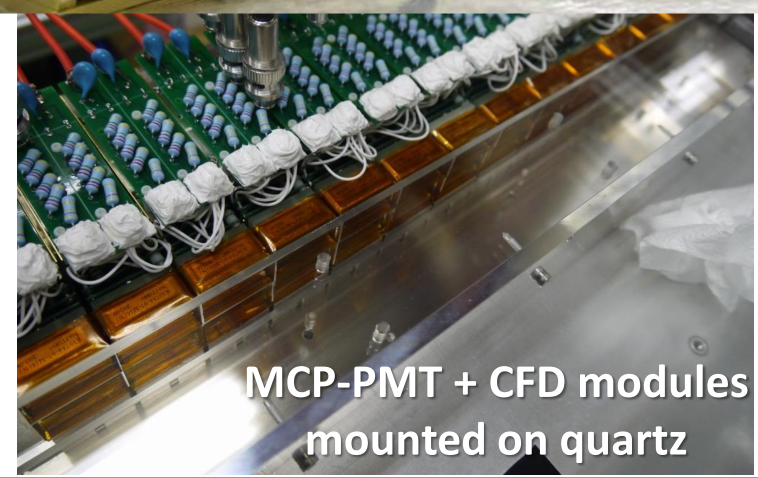


■ Beamtest @ SPring-8

- Constructed a prototype TOP counter for beamtest
  - 2x16 MCP-PMT array for full photo-coverage
  - Two types of readout electronics
    - IRS; waveform sampling ASIC for Belle II, still under development
    - CFD; traditional elec., only for beamtest because of large power consumption





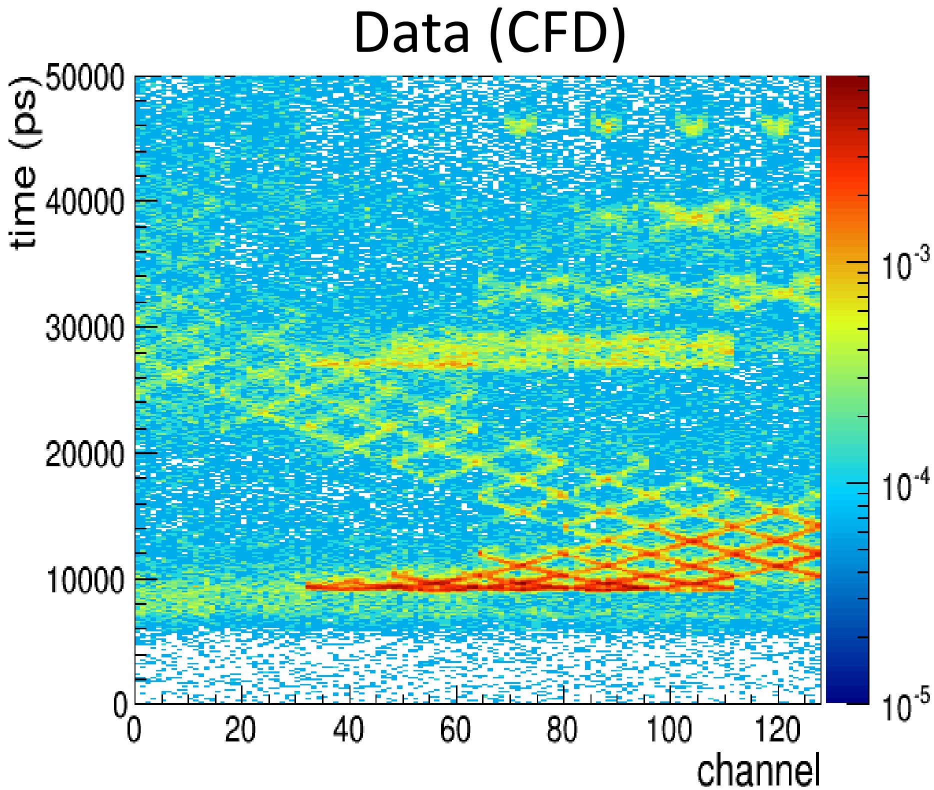


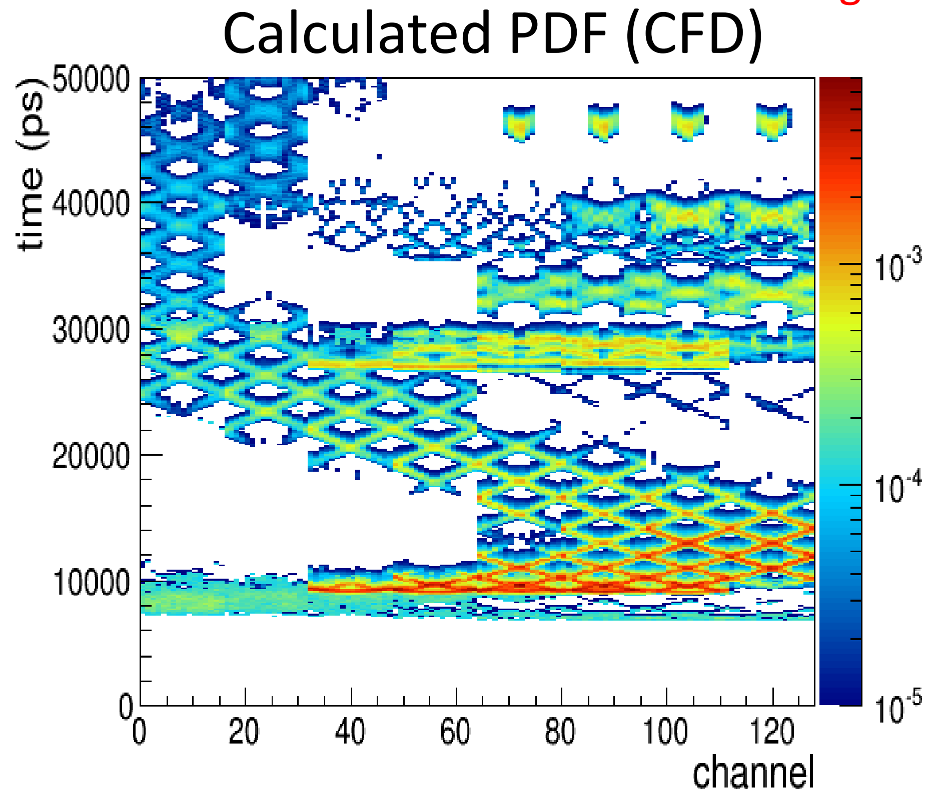
■ Beamtest @ SPring-8

Belle II PID group

- Irradiated 2 GeV e^+ at the SPring-8 LEPS beamline
  - Good agreement between data and PDF

* 4 anode channels are merged





MCP-PMTs work very well as photodetectors of the TOP counter

for more details of the beamtest,

✓ Nucl. Instr. and Meth. A732, 357 (2013)

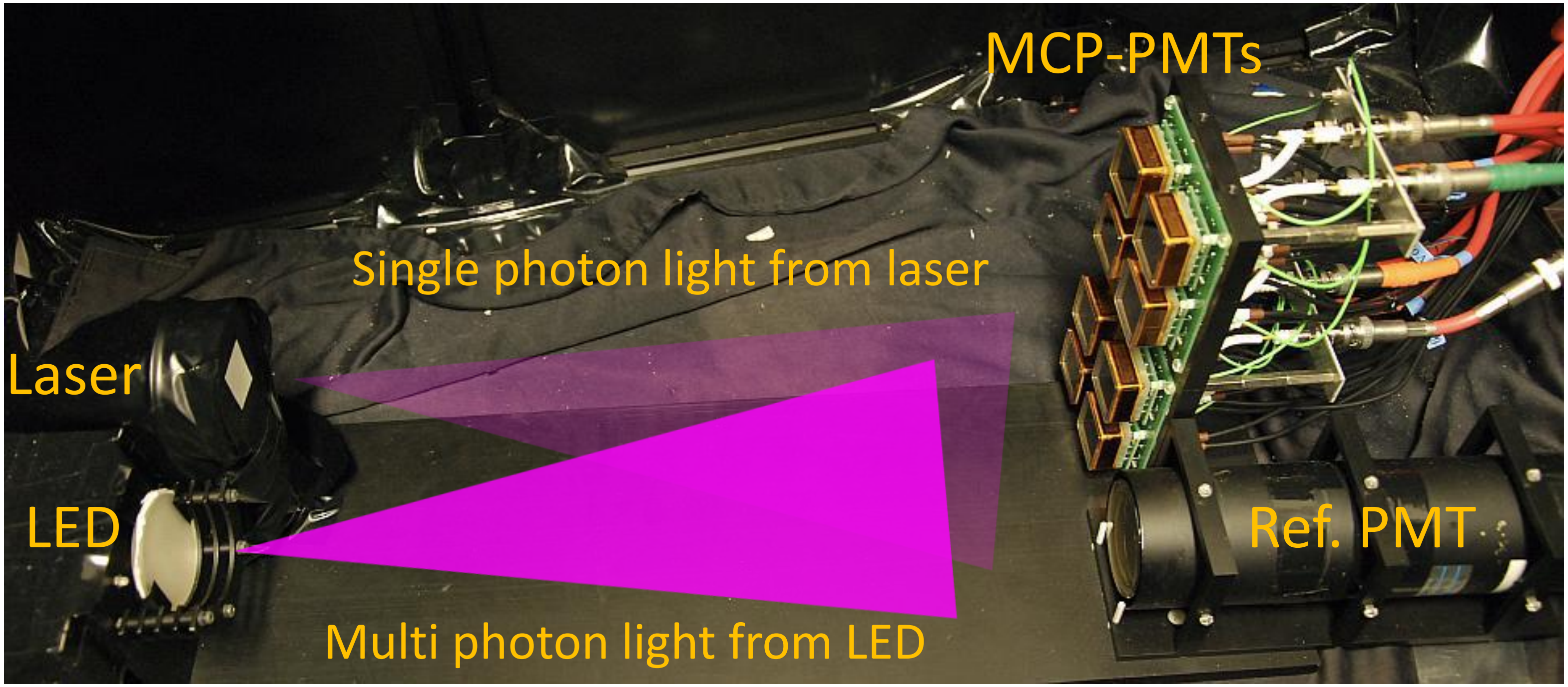
✓ K. Matsuoka, "Performance study of the TOP counter with the 2 GeV/c positron beam at LEPS" at TIPP2014

■ Lifetime of ALD MCP-PMTs

- Test setup
  - Illuminate LED to PMTs to obtain output charge

  →~1 C/cm^2/month, which is 1/2-1/4 of Belle II operation
  - Laser as a light source for single photon measurement

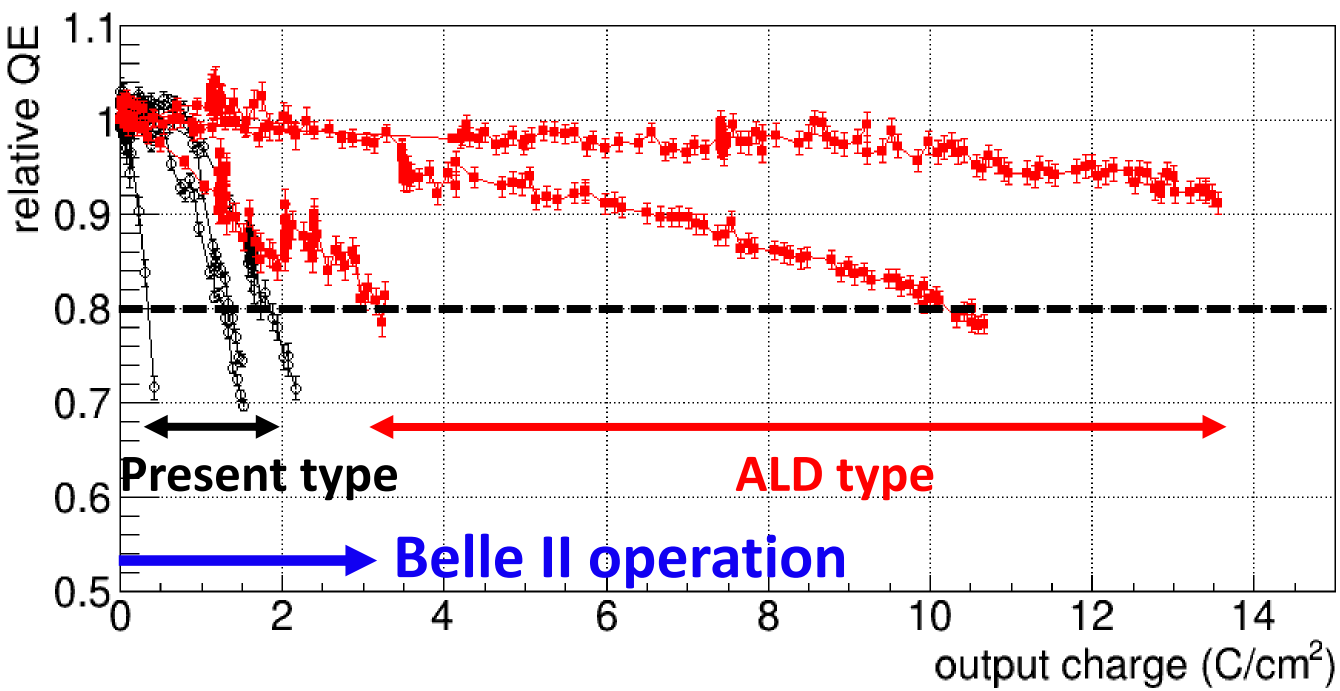
  →QE can be relatively monitored from the change of N_{hit} by the laser



■ Lifetime of ALD MCP-PMTs

- Lifetime of ALD MCP-PMTs
  - ALD MCP-PMTs have 3-14 C/cm^2 lifetime, which is 3-14 times longer than typical lifetime of present types with conventional MCPs.

    → We can avoid exchanging ALD MCP-PMTs in Belle II
- Lifetime variation is large
  - Further investigation is ongoing to suppress variation



Summary

- We developed original MCP-PMT (R10754-07-M16)
  - Peak QE of ~28%, excellent TTS of 30-40 ps, operable in 1.5 T
  - Square shape to increase effective area
  - ~1 C/cm^2 lifetime
  - → We started to mass production
- Successful mass production
  - We produced >500 PMTs with excellent performance
  - While measurements are still ongoing, all of measured PMTs have QE_{peak} ~28%, and 30-60% gain drop & TTS < 50 ps in 1.5 T
- Lifetime improvement by ALD technique
  - Lifetime is extended to 3-14 C/cm^2; possible to avoid PMT exchanges
  - Lifetime variation is large
  - → trying to reduce the variation and will use them for future PMT exchange

Additional Slides

Photodetector Selection

- Photodetectors must work in 1.5 T
  - Candidates were fine mesh PMT, HAPD and MCP-PMT

	Gain(1.5 T*) (x10^6)	TTS
FM-PMT	0.1-1	~100 ps
HAPD	0.5	~100 ps
MCP-PMT	1	30 ps

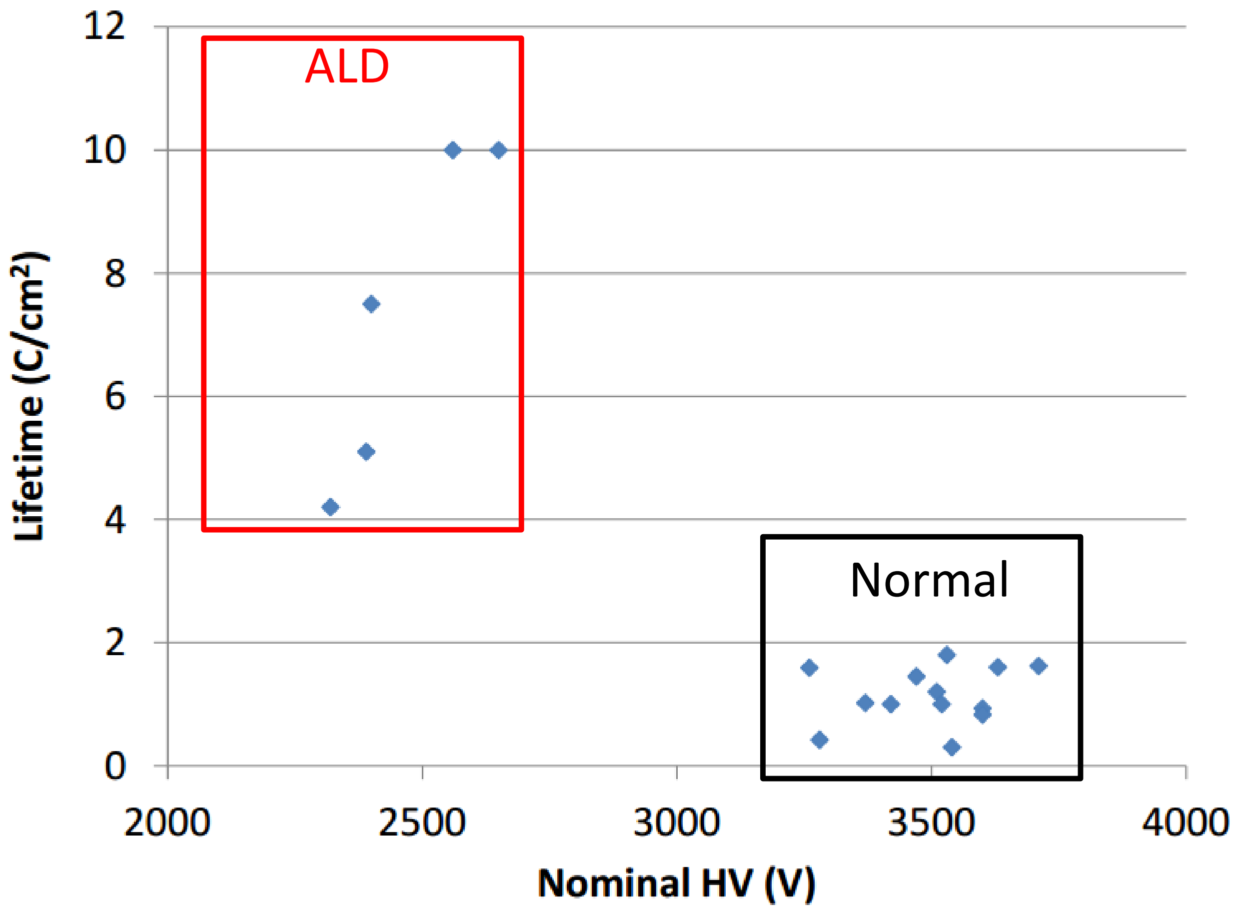
*Perpendicular to entrance face

From the viewpoint of TTS, we selected MCP-PMT

Nucl. Instr. and Meth. A460, 326 (2001)
Nucl. Instr. and Meth. A463, 220 (2001)
Nucl. Instr. and Meth. A528, 763 (2004)

■ Lifetime vs HV

- No clear correlation



■ Amplifiers

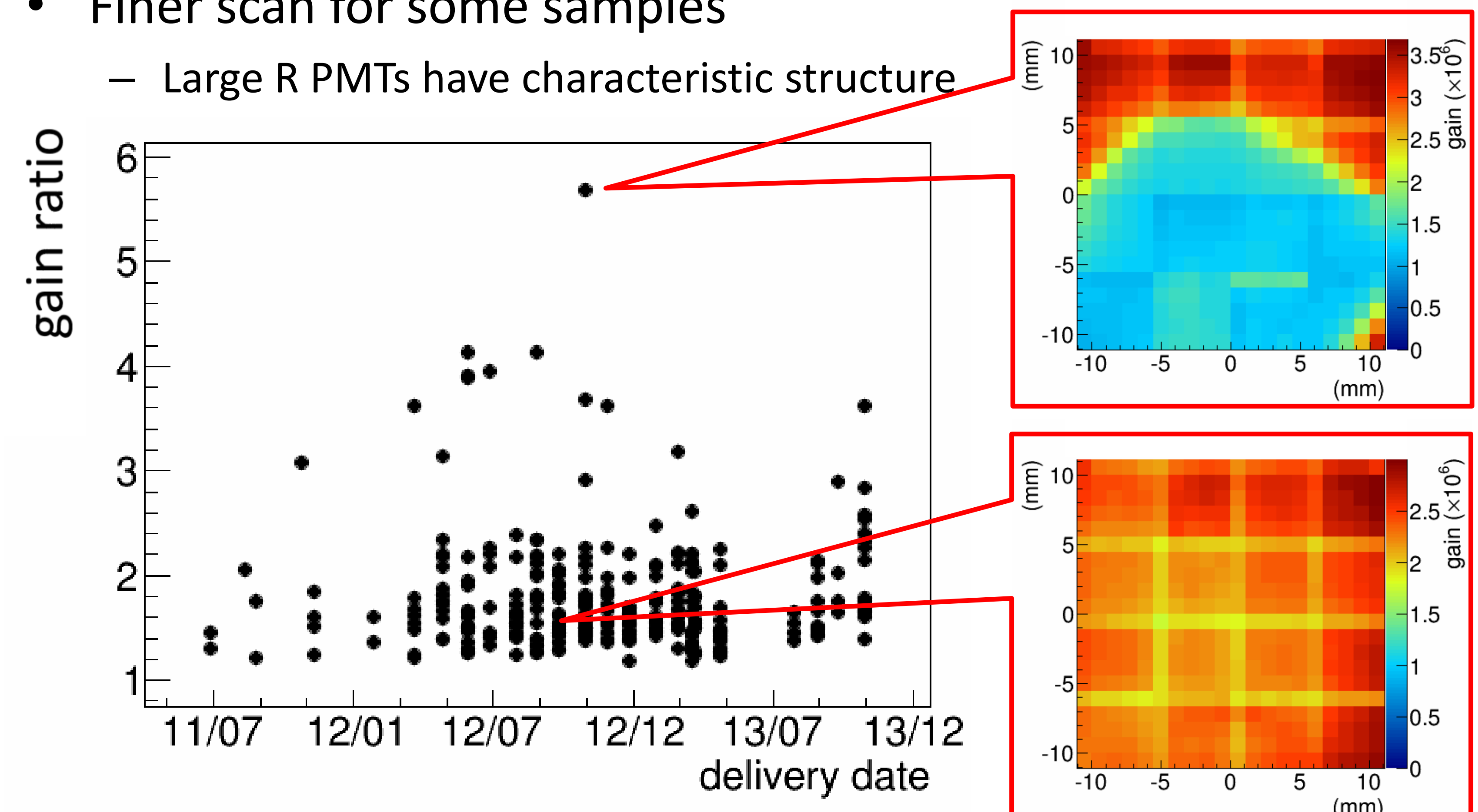
- We use 2-stage amplifiers

	Gali 39+ (1st amp)	Gali 84 (2nd amp)
Product	Mini-Circuits	Mini-Circuits
Gain at 1 GHz	21.1 dB	22.7 dB
Noise Figure at 1 GHz	2.4 dB	4.4 dB

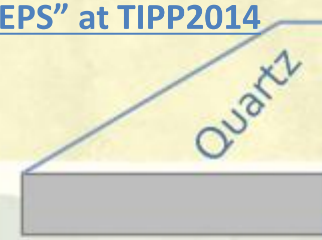
  – Noise level ~5 mV

■ Gain Uniformity Issue

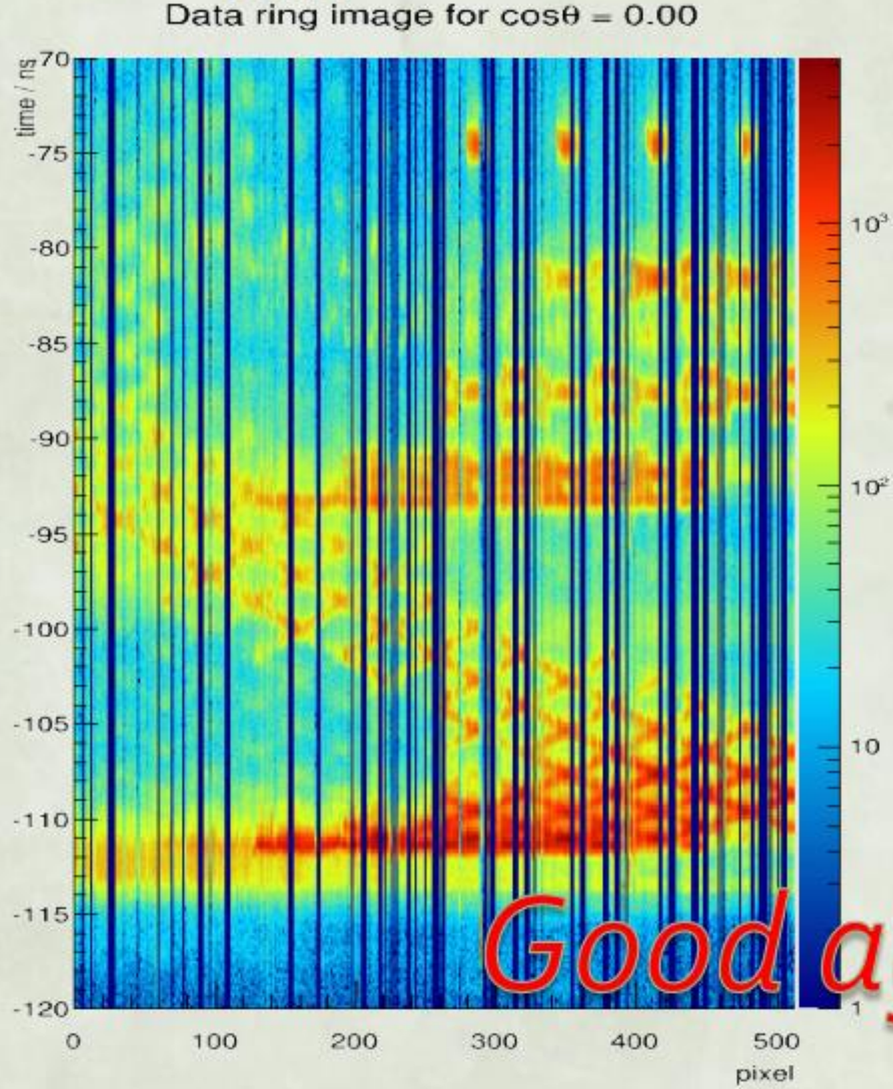
- Gain Uniformity
  - Gain ratio = $Gain^{ch}_{max}$ / $Gain^{ch}_{min}$ is about 6 at max.
  - For TOP operation, we may need to exclude large R PMTs
- Finer scan for some samples
  - Large R PMTs have characteristic structure



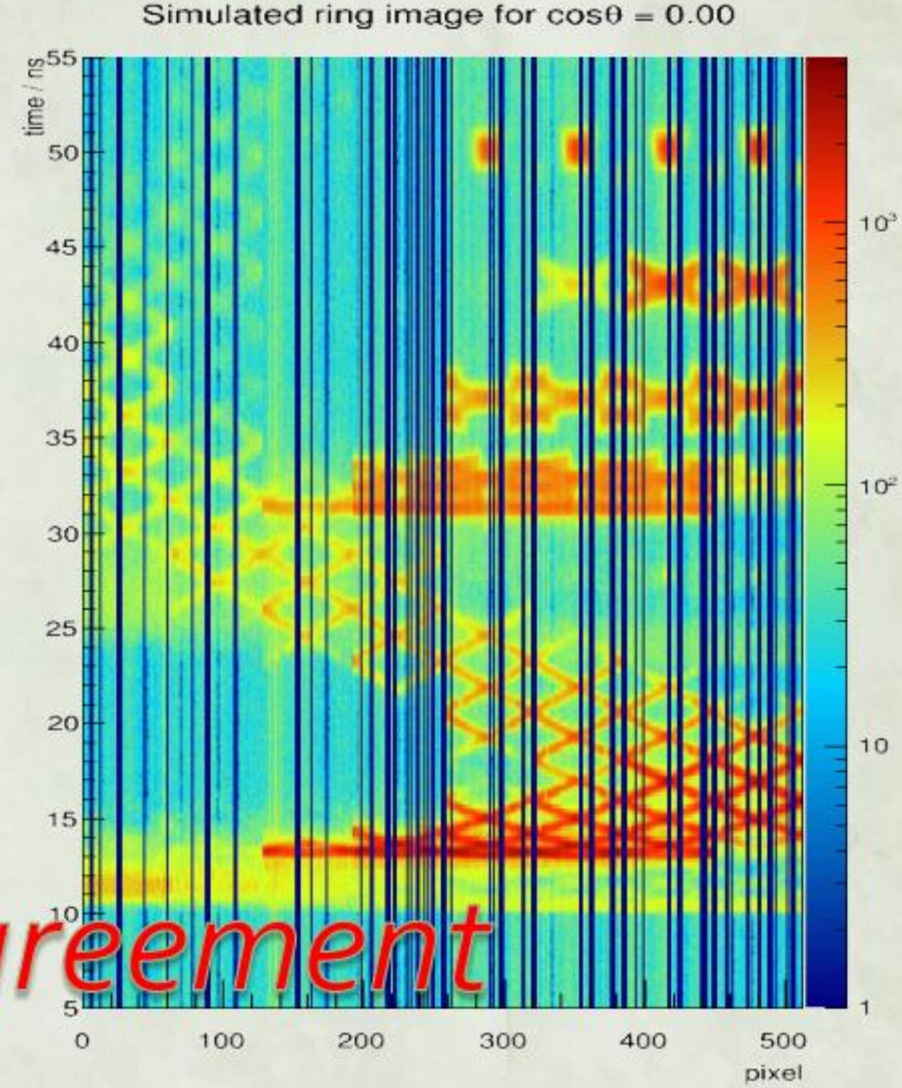
Cherenkov image (IRS readout)



Data



MC

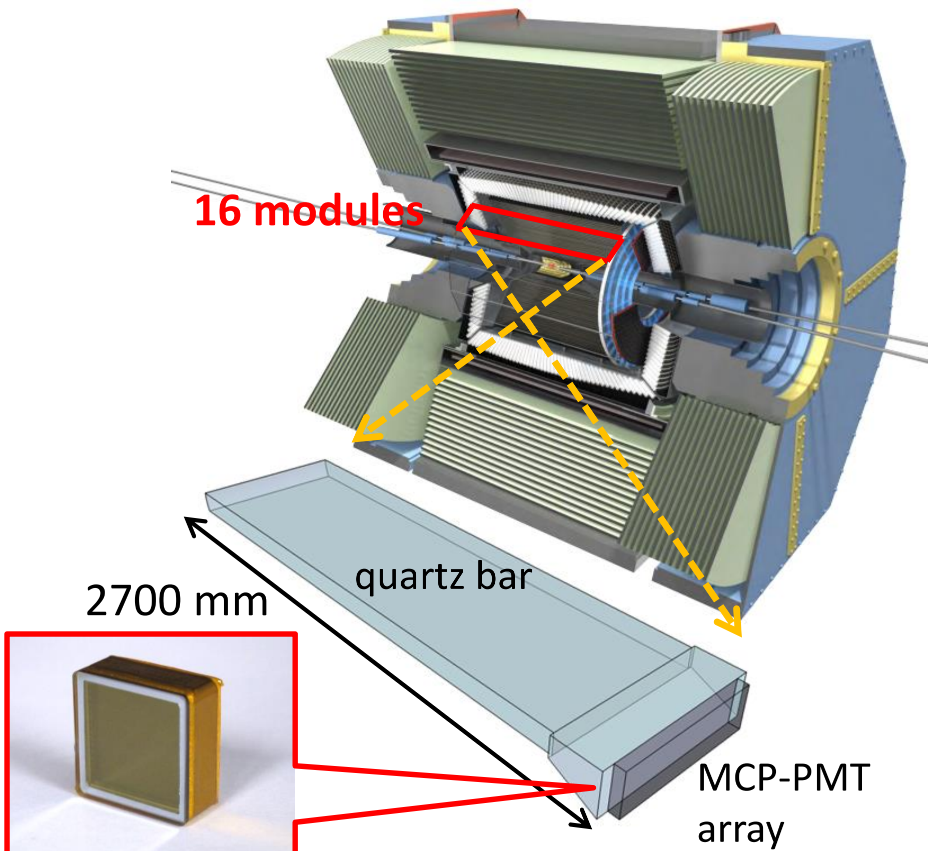


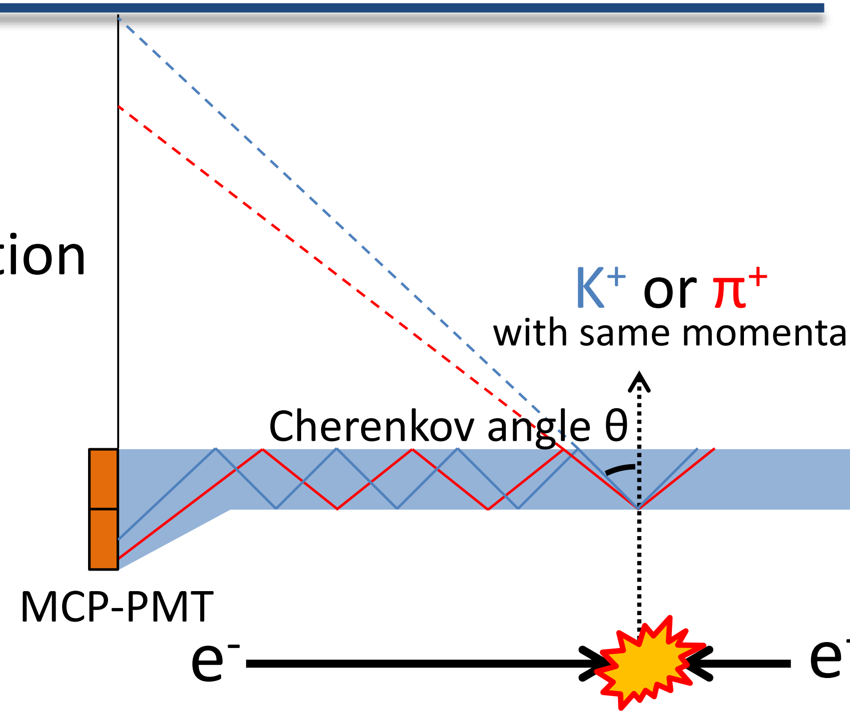
Good agreement

There are dead channels (90/512) due to some problems.

■ TOP (Time of Propagation) Counter

- New RICH counter
  - ID for K/π mesons
  - use "timing" of photon detection





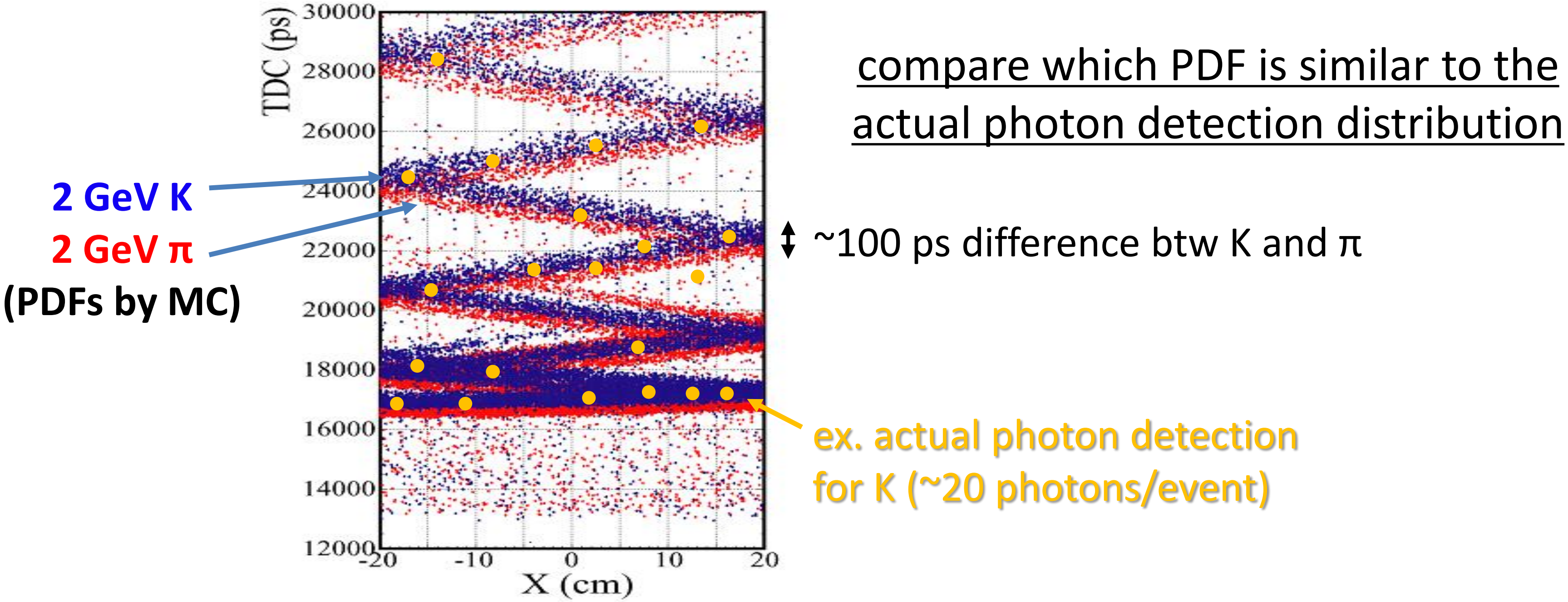
$$\begin{cases} \beta = \dfrac{1}{n\cos\theta} \quad (n = 1.47) \\ m = \dfrac{p\sqrt{1-\beta^2}}{\beta} \end{cases}$$

measured by drift chamber

PID is realized by measurement of "mass"

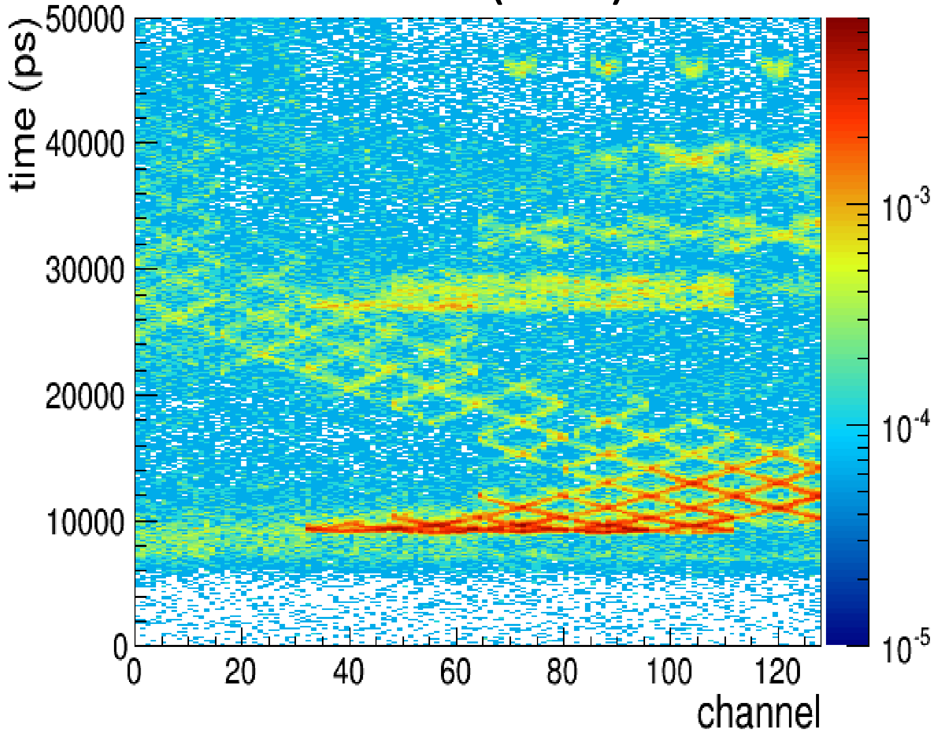
■ TOP（Time of Propagation） Counter

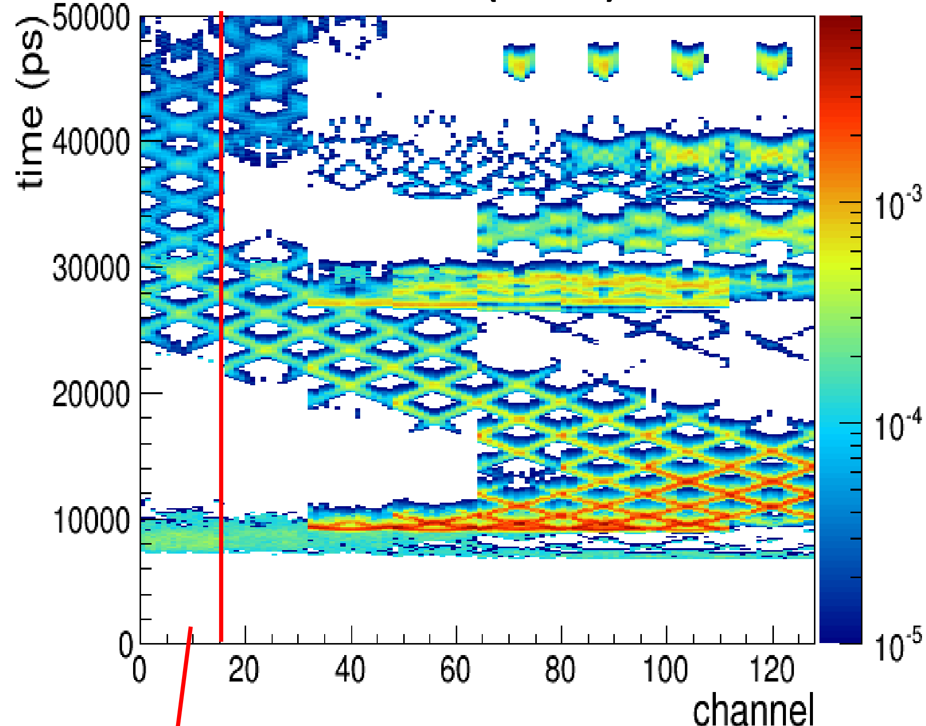
- PID is performed by two different PDFs



- To perform PID precisely, MCP-PMTs must have
  - QE >28%
  - Time resolution <50 ps (single photon detection)

■ How to See the Beamtest Result



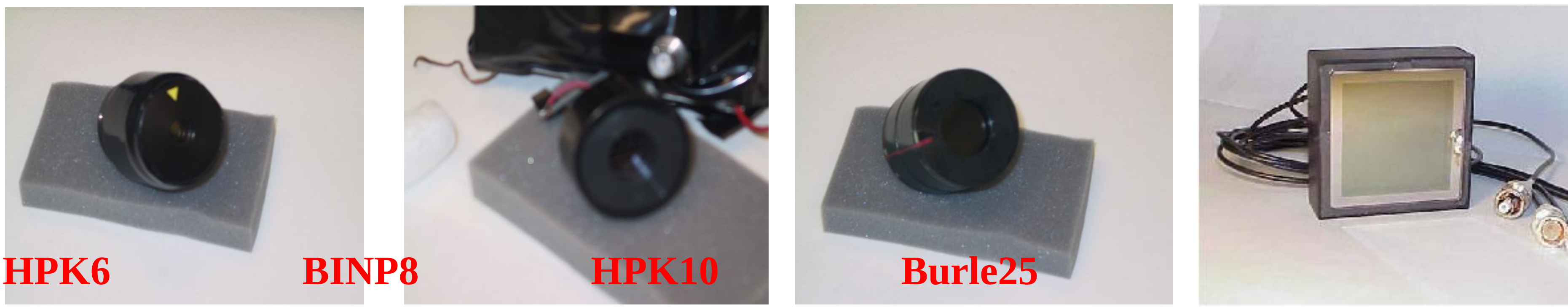


112	113	114	115	...	127
96	97	98	99	...	111
80	81	82	83	...	95
64	65	66	67	...	79
48	49	50	51	...	63
32	33	34	35	...	47
16	17	18	19	...	31
0	1	2	3	...	15

Since CFD board could not be small, 4 channels were merged into a single channel

MCP-PMT for single photon

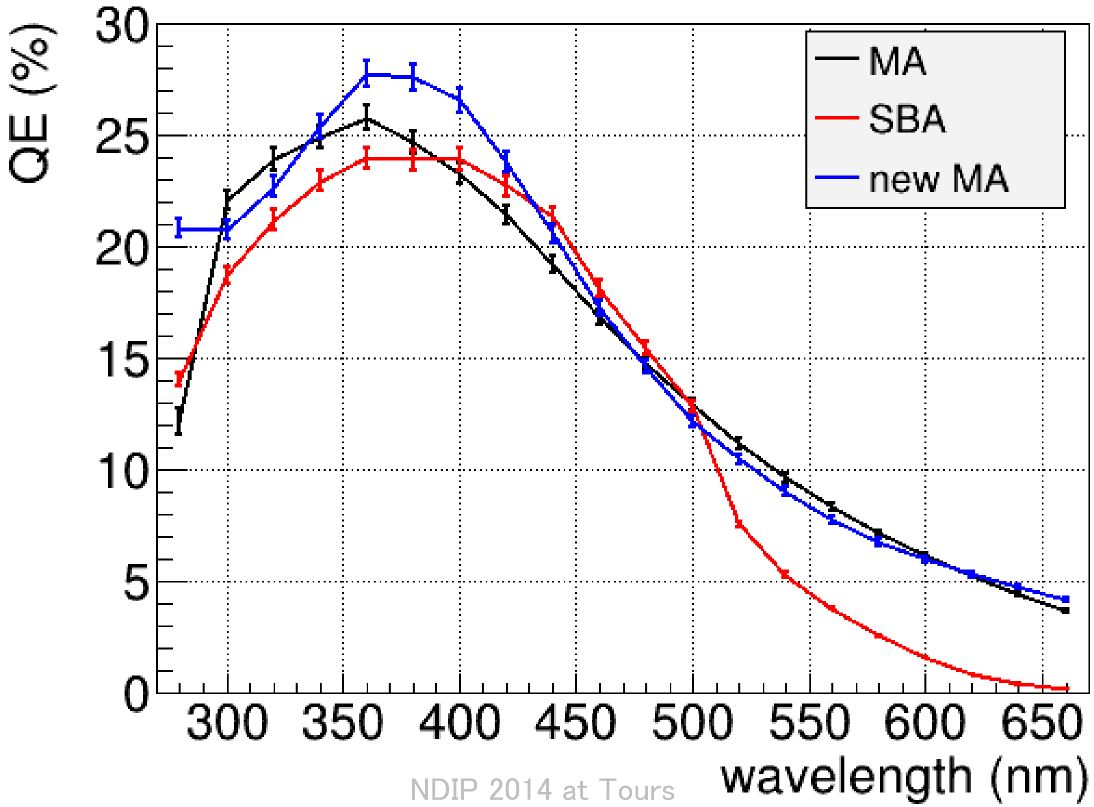
- Timing properties under B=0~1.5T parallel to PMT



MCP-PMT	HPK6 R3809U-50-11X	BINP8 N4428	HPK10 R3809U-50-25X	Burle25 85011-501
PMT size(mm)	45	30.5	52	71x71
Effective size(mm)	11	18	25	50x50
MCP hole diameter(μm)	**6**	**8**	**10**	**25**
Length-diameter ratio	40	40	43	40
Bias angle (deg.)	13	5	12	10
Max. H.V. (V)	3600	3200	3600	2500
photo-cathode	multi-alkali	multi-alkali	multi-alkali	bi-alkali
Q.E.(%) (λ=408nm)	26	18	26	24

■ QE

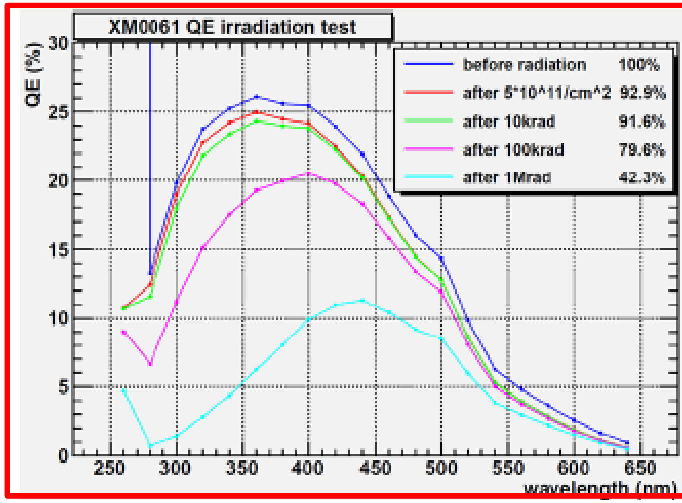
- MA; higher QE in red region, but peak is lower
- SBA; higher QE in blue region & wide peak, but difficult to obtain high QE in case of MCP-PMT
- new MA; higher QE in blue region. Although peak width is narrower than SBA, activation is very stable.

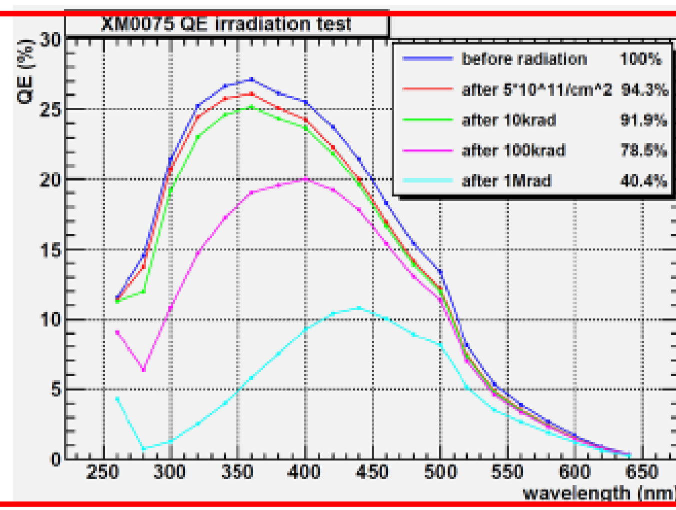


■ Radiation Hardness（γ rays)

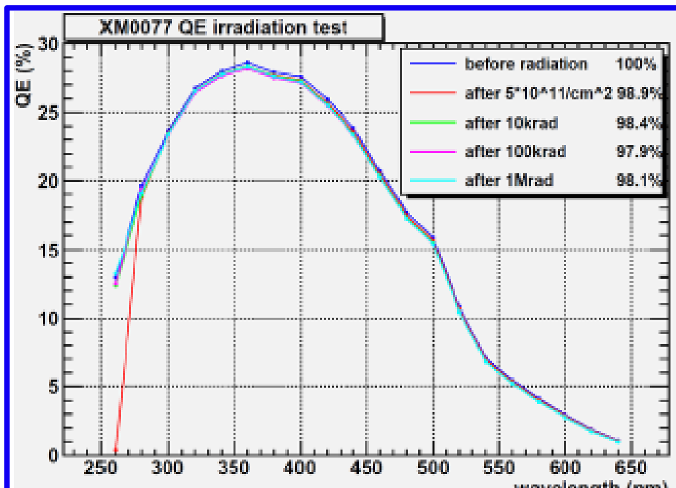
- Estimation: 30 krad for Belle II 10 years

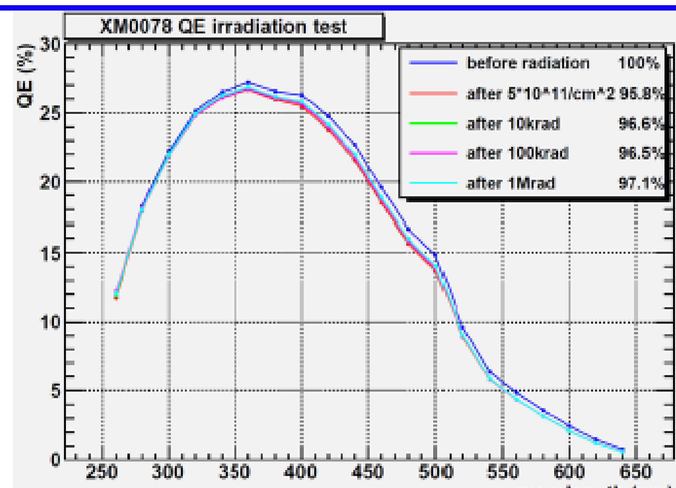
QE





Bolosillicate window



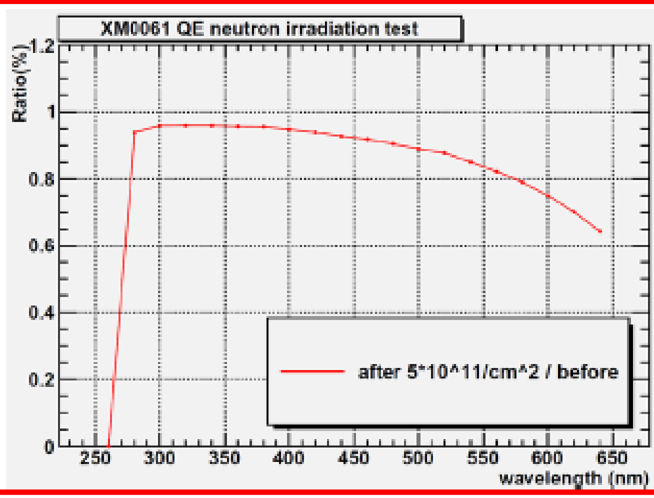


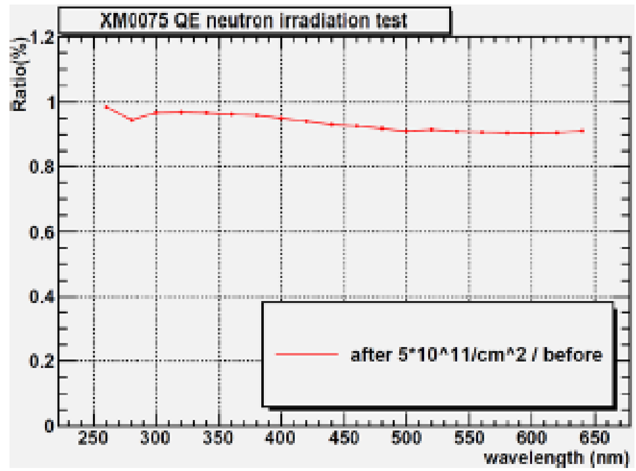
Fused sillica window
→ good hardness

■ Radiation Hardness（neutrons）

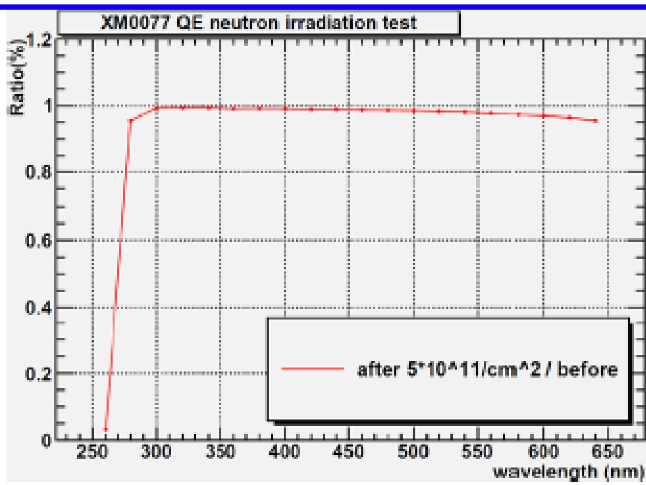
- Estimation: 2×10^{11} n/cm^2 for Belle II 10 years

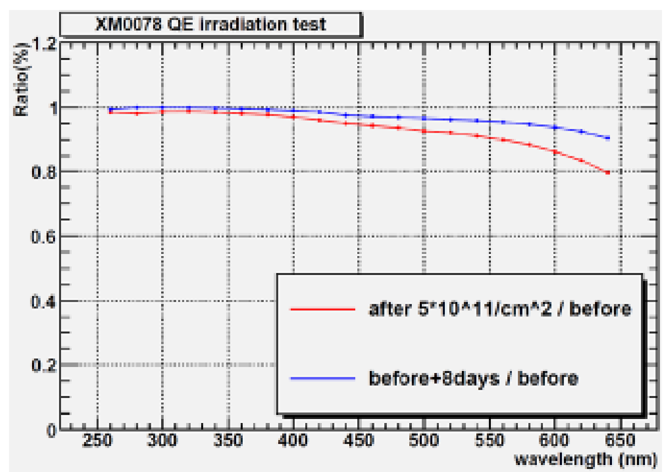
QE(ratio)-neutron irradiation





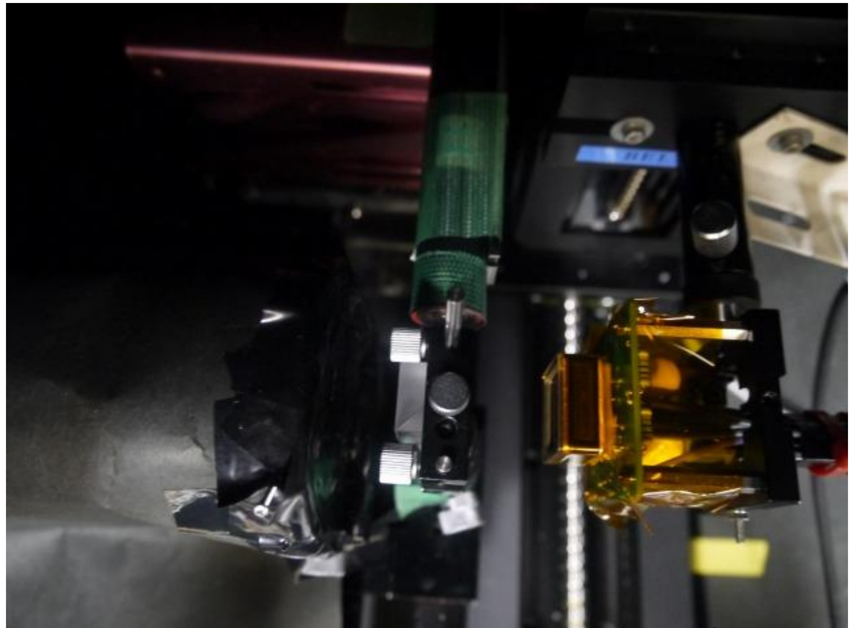
Bolosillicate window

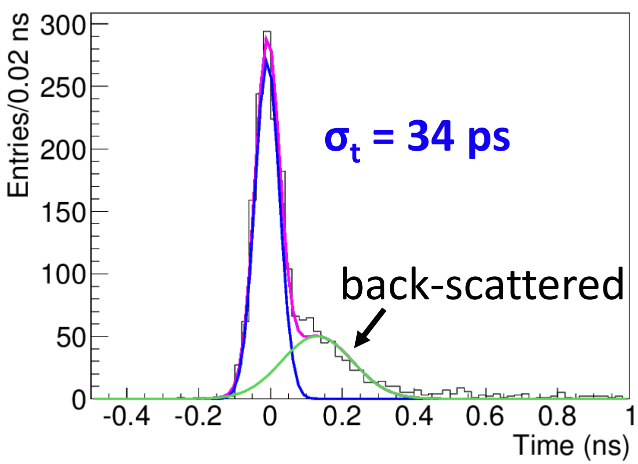


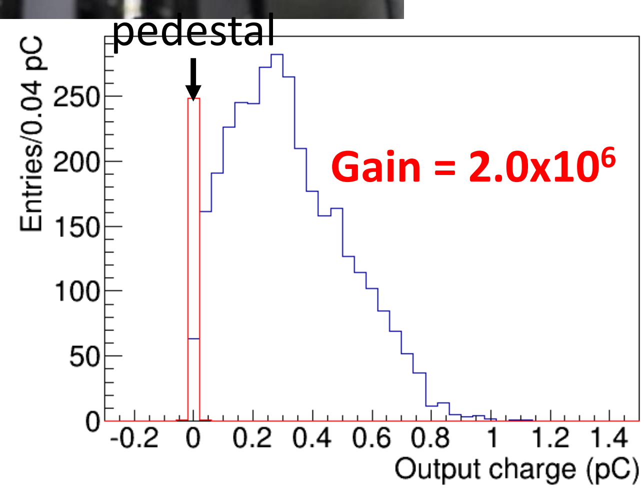


Fused sillica window
→ good hardness

■ Gain & TTS measurement

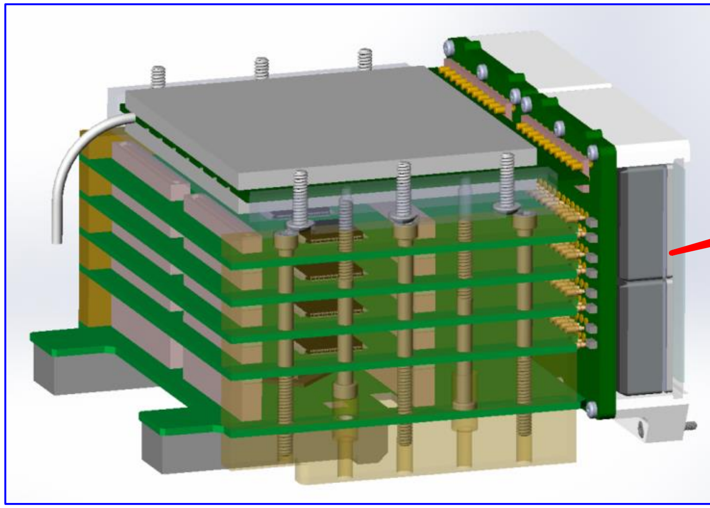






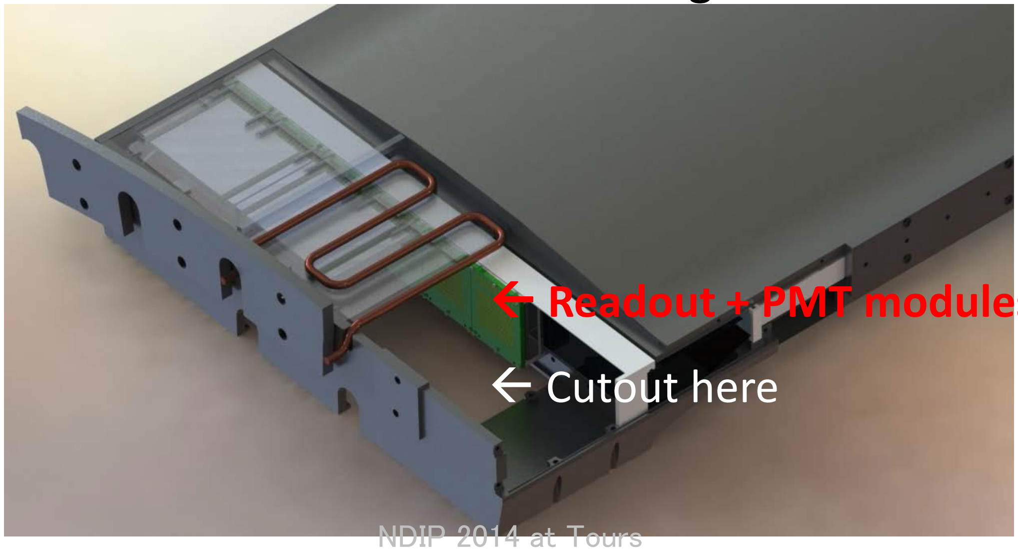
■ Exchange of MCP-PMTs

- Readout module



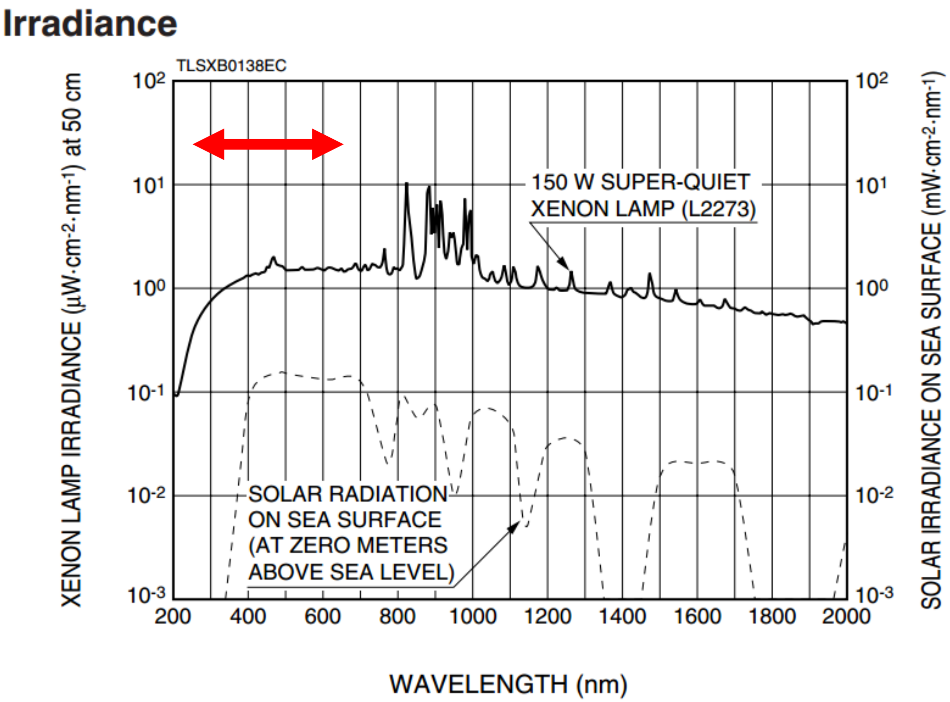
One module has
4 MCP-PMTs

- How to change PMTs
  - Take off a module from a cutout → change a failed MCP-PMT



■ Xe lamp

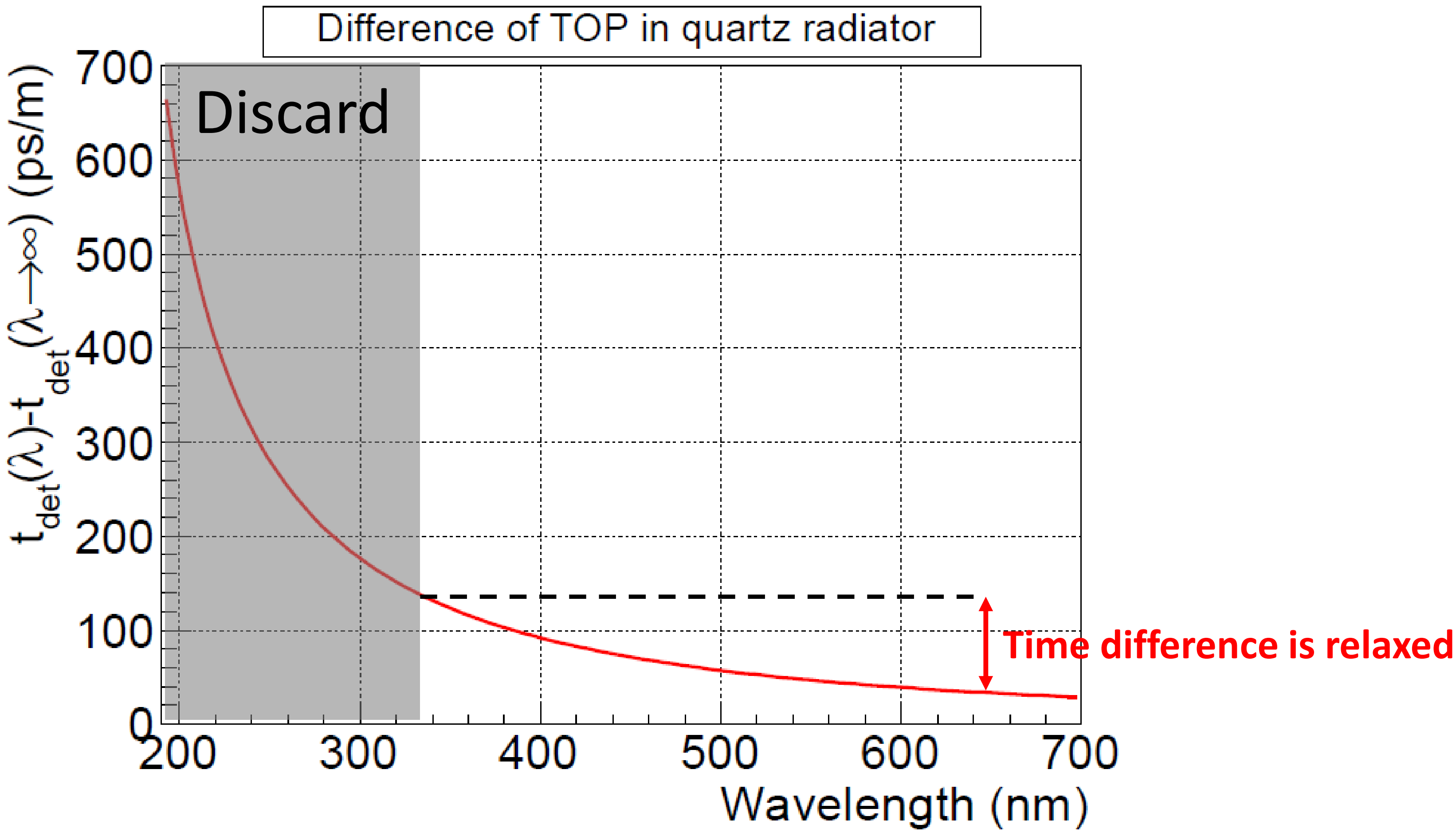
- L2195 by HAMAMATSU



■ Chromatic Dispersion

- Refractive index is a function of λ (wavelength)
  - Therefore, light speed in material is also a function of λ

    → The shorter wavelength is, the slower propagation speed is.

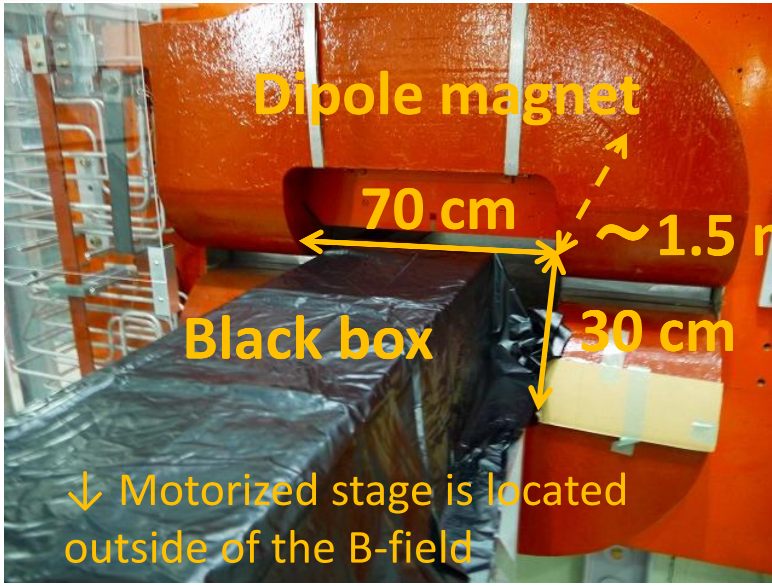


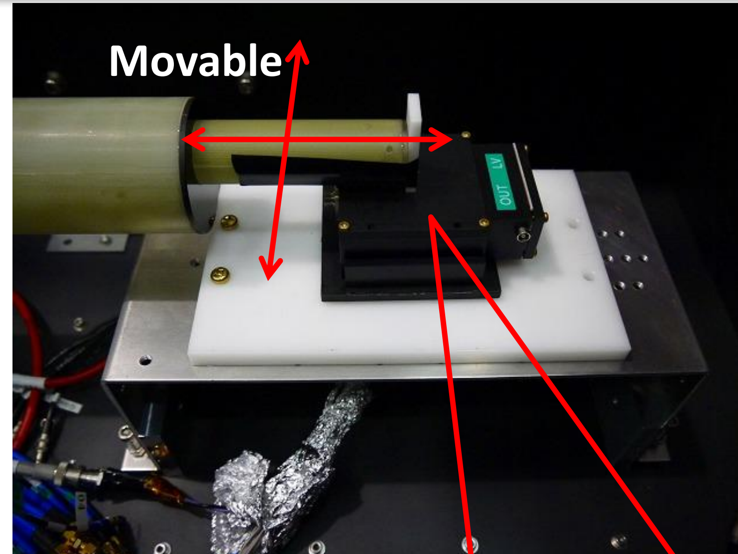
■ Cherenkov Emission

- Wavelength dependence of Cherenkov photons is

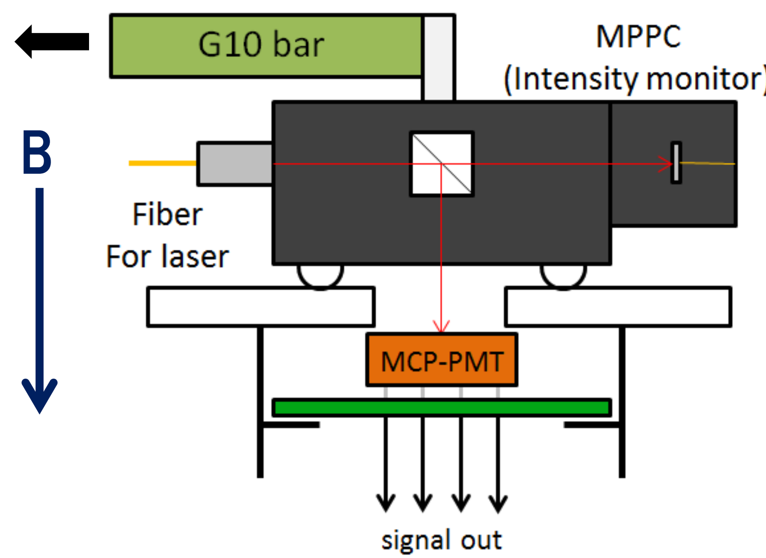
$$\frac{dN}{d\lambda} = 2\pi Z^2 \alpha L \left(1 - \frac{1}{n^2\beta^2}\right) \boxed{\frac{1}{\lambda^2}}$$

■ Measurement System in 1.5 T





No magnetic materials in the jig

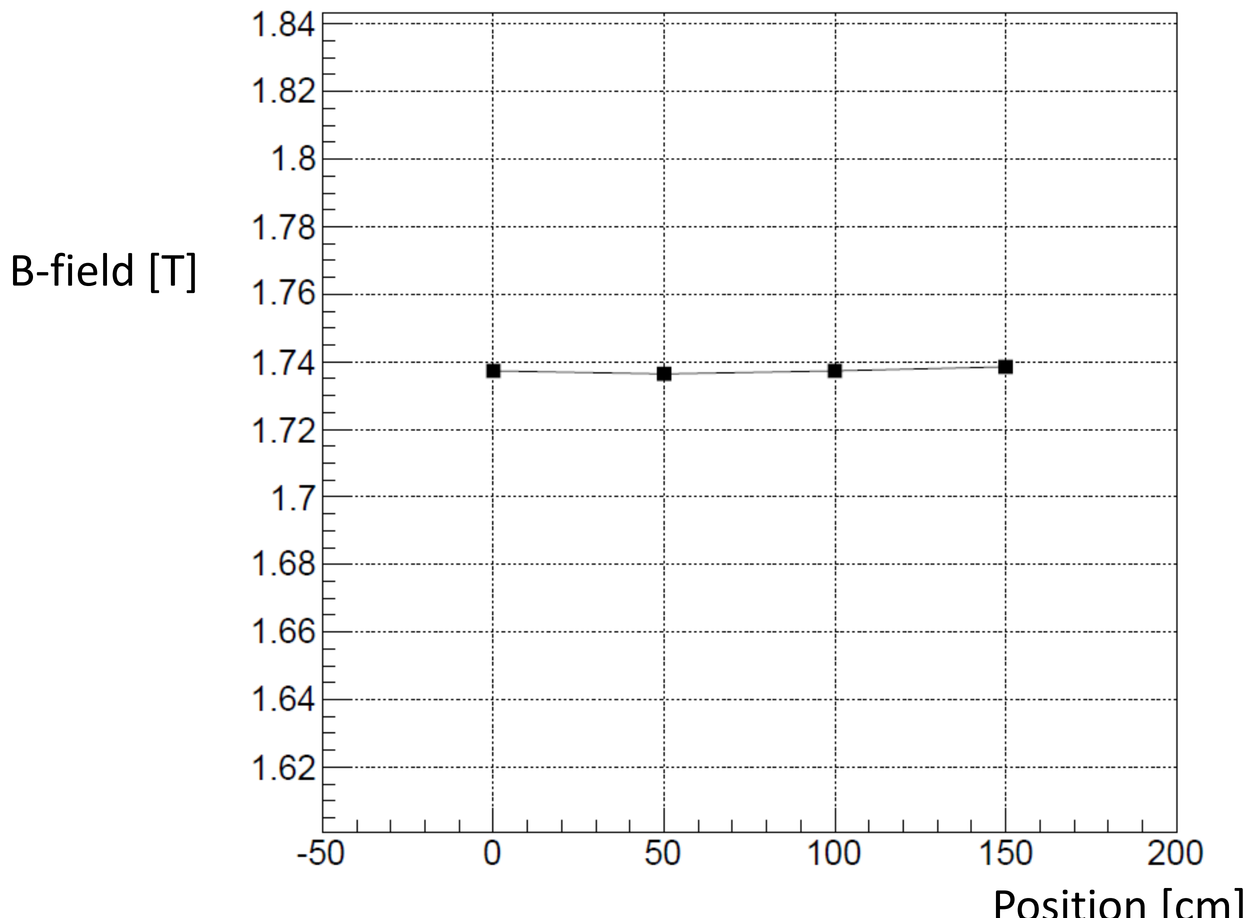


B-field tolerant system

- A jig made of non-magnetic materials
- MCP-PMT is fixed tightly
- The jig is moved by the motorized stage located outside of B-field
- MPPC is used as an intensity monitor instead of a reference PMT.

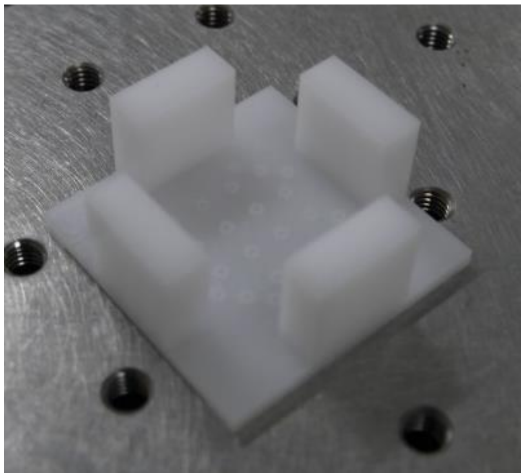
■ Uniformity of the Magnetic Field

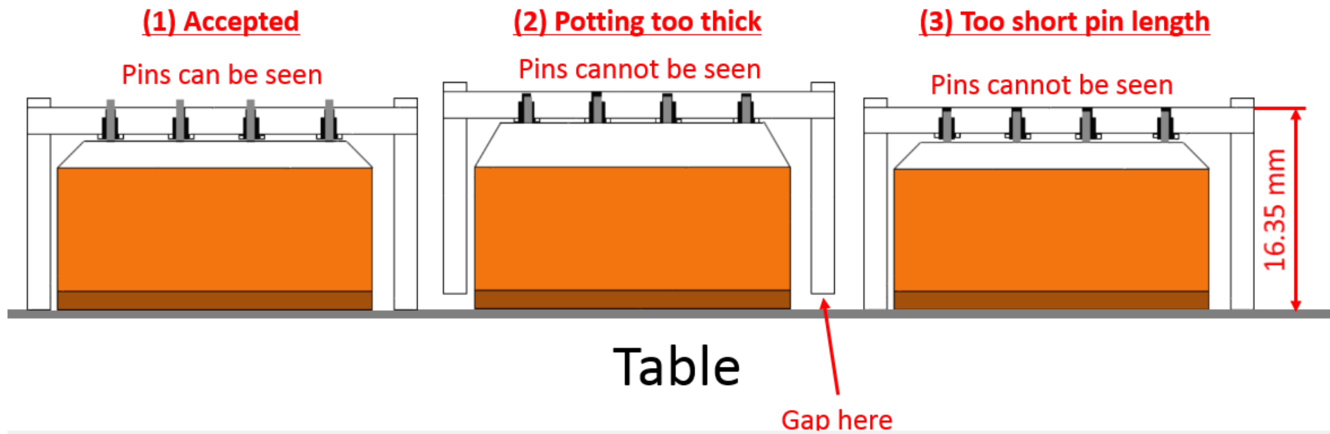
- Uniformity of B-field is good enough



■ Mechanical Inspections

- Visual inspection
  - Confirm PMT's shape with a go-nogo gauge





- HV application test