Recent development of fast timing PMT

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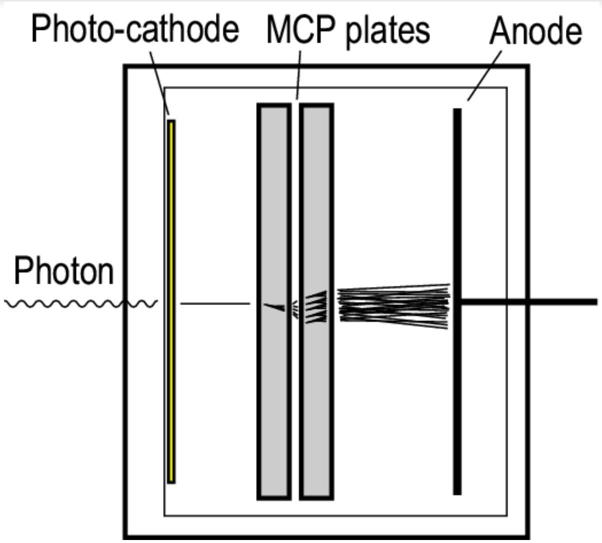
MCP-PMT for fast timing measurement

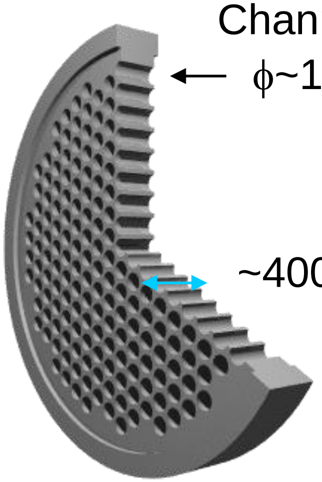
- Micro-Channel-Plate
  - Tiny electron multipliers
    - Diameter ~10μm, length ~400μm
  - High gain
    - ~10^6 for two-stage type

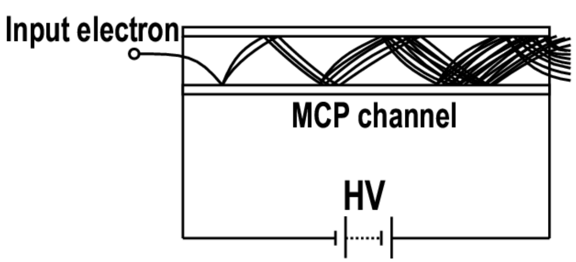
  → Fast time response

  Pulse rise time <400ps

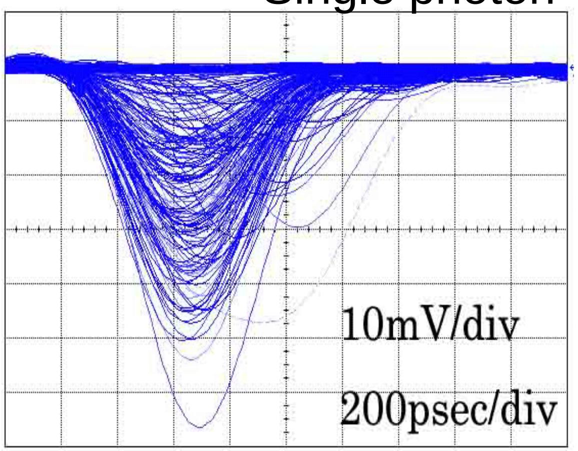
  Timing resolution < 50ps for single photon
  - can operate under high magnetic field (~1T)





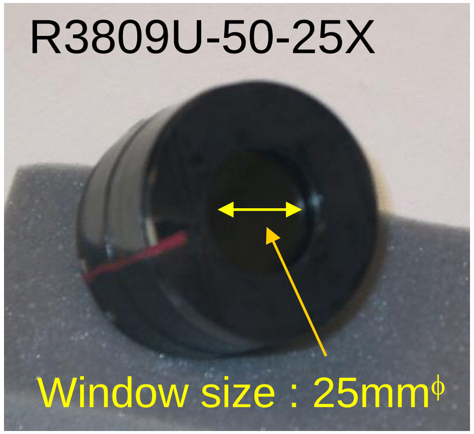


Single photon

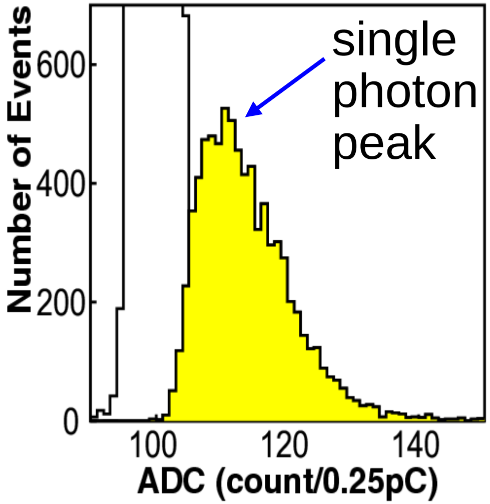


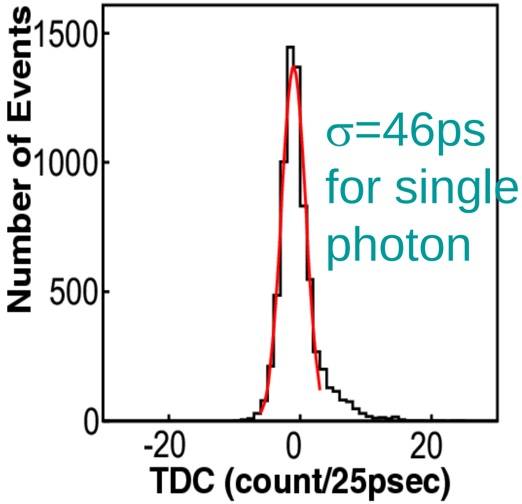
MCP-PMT output

- Hamamatsu R3809U-50 (multi-alkali photo-cathode)

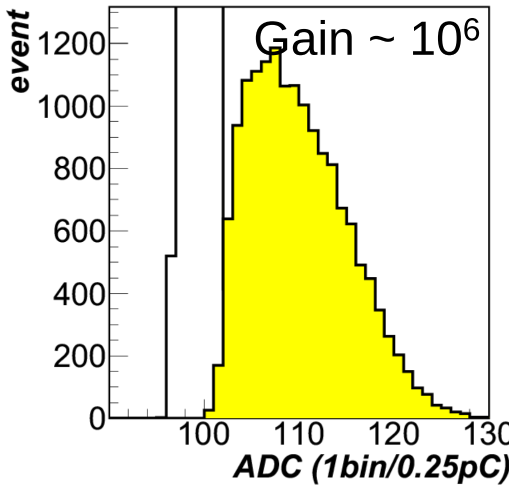


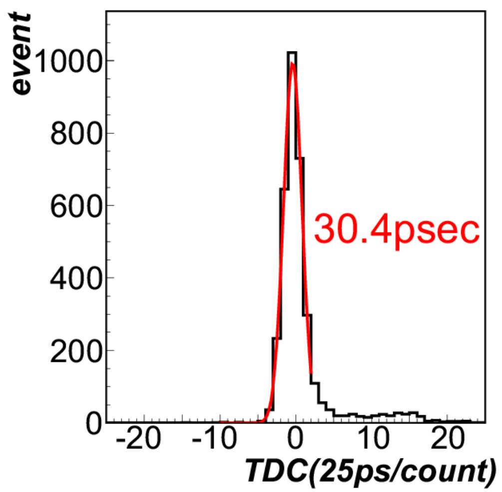
MCP hole 10μm$^{\phi}$





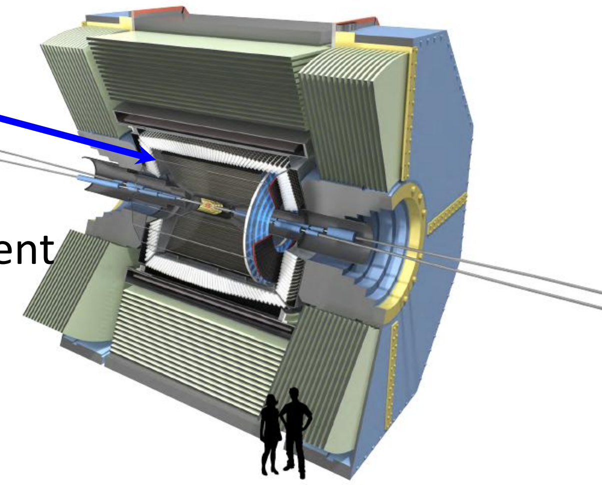
MCP hole 6μm$^{\phi}$



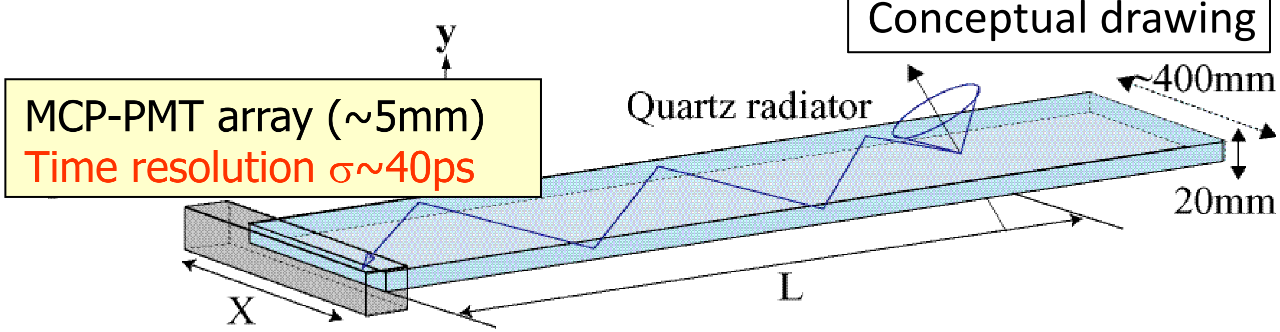


Application: TOP counter in Belle II

- TOP (Time Of Propagation) counter
  - Developing to upgrade the barrel PID detector
  - For Super B factory
    - L_{peak}~$10^{35\sim36}$/cm^2/s, 20~100 times higher than present
      - Need to work with high beam BG
  - To improve K/π separation power
    - Physics analysis: B→ππ/Kπ, ργ, Kνν etc.
    - Flavor tag, Full reconstruction, etc.
  - Measures Cherenkov radiation cone by 2D position + timing
    - Time of Propagation of internal reflected photons
    - + TOF from IP

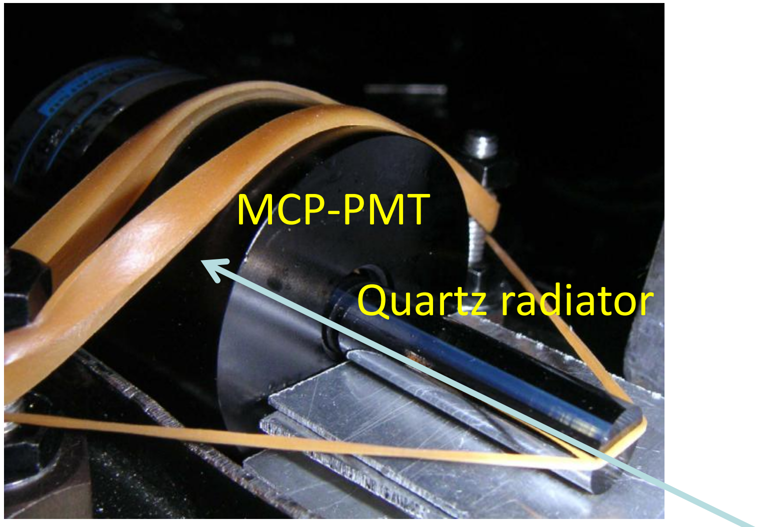


Conceptual drawing

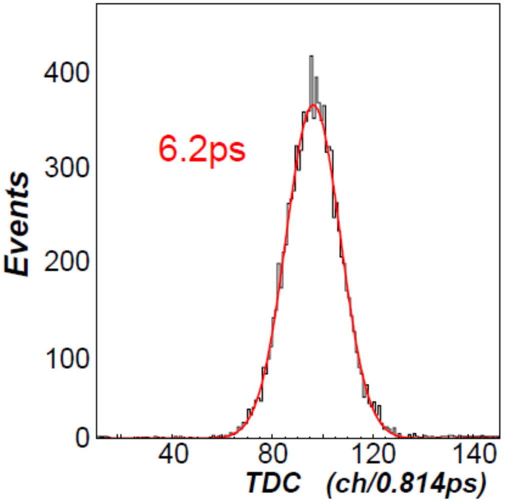


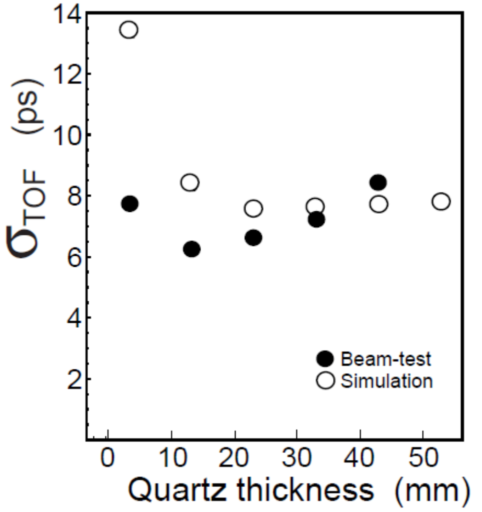
Application: High resolution TOF

- TOF with Cherenkov light
  - Small-size quartz (cm~mm length)
    - Cherenkov light (Decay time ~ 0)
      extremely reduce time dispersion compared to scintillation (τ ~ ns)
  - MCP-PMT (multi-alkali photo-cathode)
    - TTS < 50ps even for single photon
      gives enough time resolution for smaller number of detectable photons



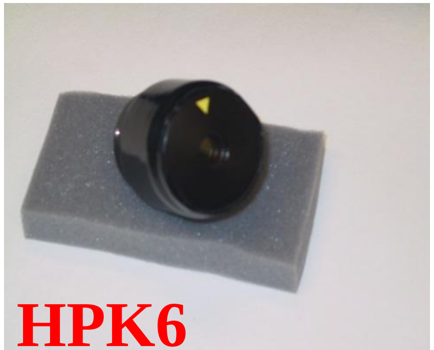
- Test results
  - Time difference between two counters
  - Timing resolution = 6.2ps
    - ~180photon detecton
  - Intrinsic resolution = 4.7ps

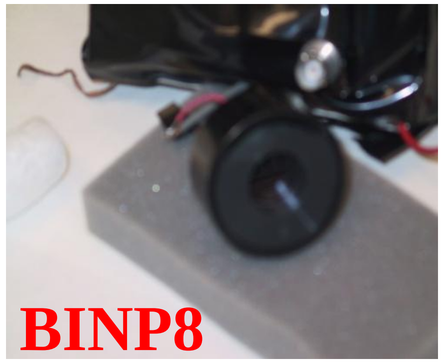


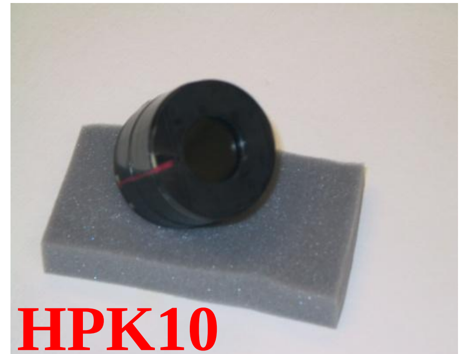


MCP-PMTs performance

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



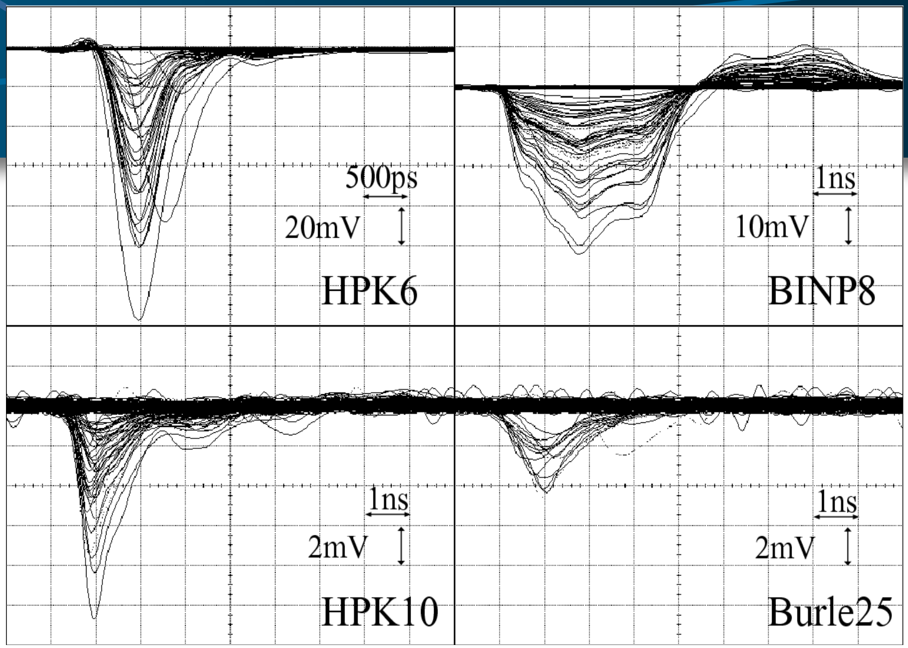


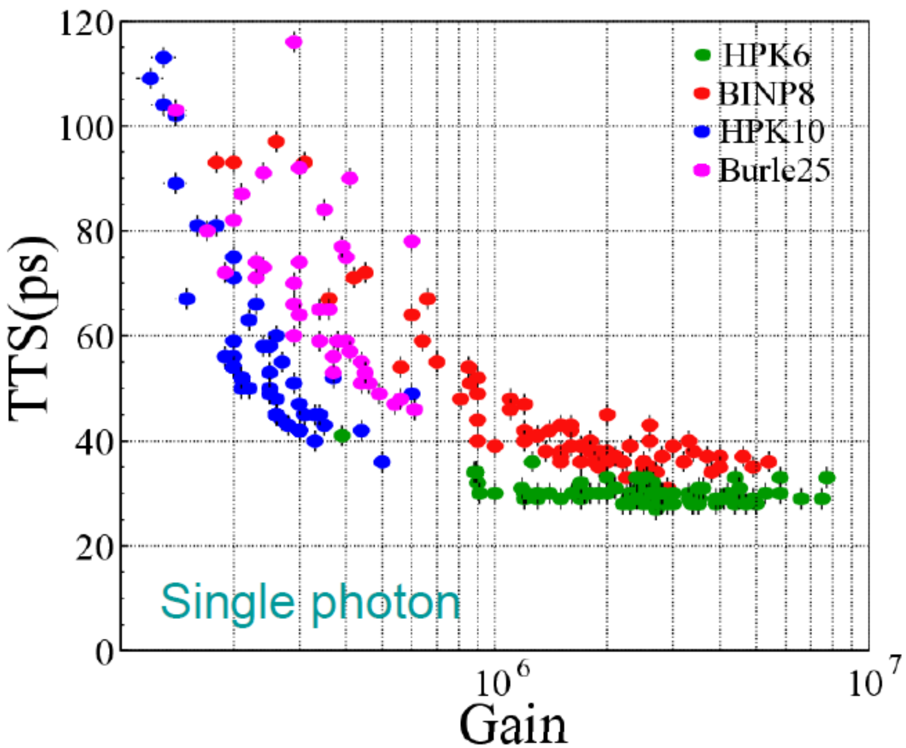


MCP-PMT	HPK6 R3809U-50-11X	BINP8 N4428	HPK10 R3809U-50-25X	Burle25 85011-501
PMT size(mm)	45	30.5	52	71x71
Effective size(mm)	11	18	25	50x50
Channel diameter(μm)	**6**	**8**	**10**	**25**
Length-diameter ratio	40	40	43	40
Max. H.V. (V)	3600	3200	3600	2500
photo-cathode	multi-alkali	multi-alkali	multi-alkali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

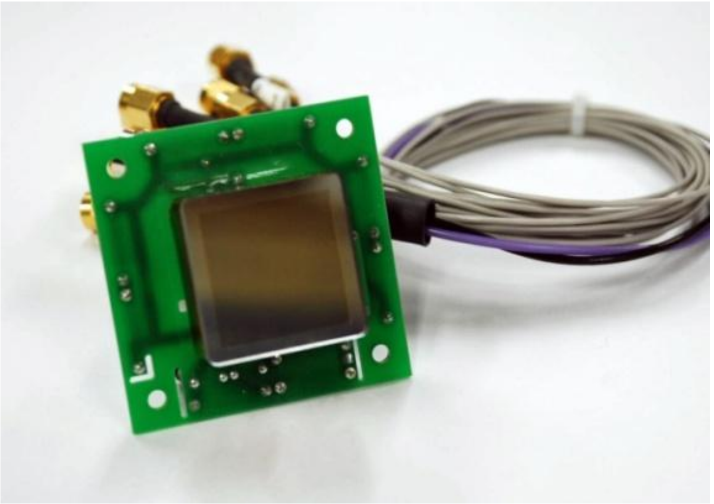
Pulse response

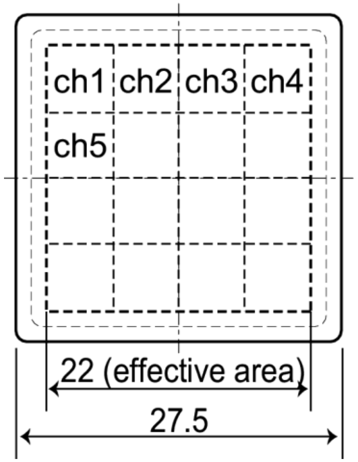
- Pulse shape (B=0T)
  - Fast rise time (~500ps)
  - Broad shape for BINP8
    - Due to mismatch with H.V. supply divider
    - No influence for time resolution
- TTS v.s. Gain
  - For several HV and B-field conditions
  - 30~40ps resolution was obtained for gain>10^6
- Narrower channel shows better TTS.

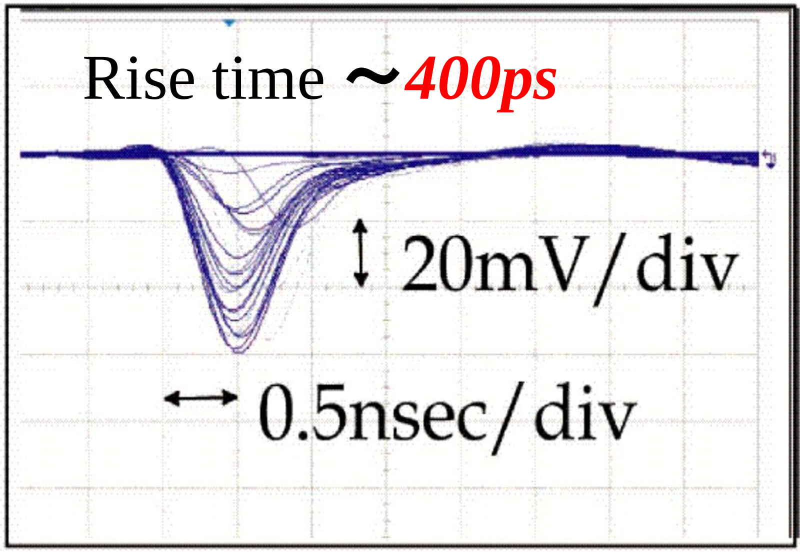




MCP-PMT for TOP counter



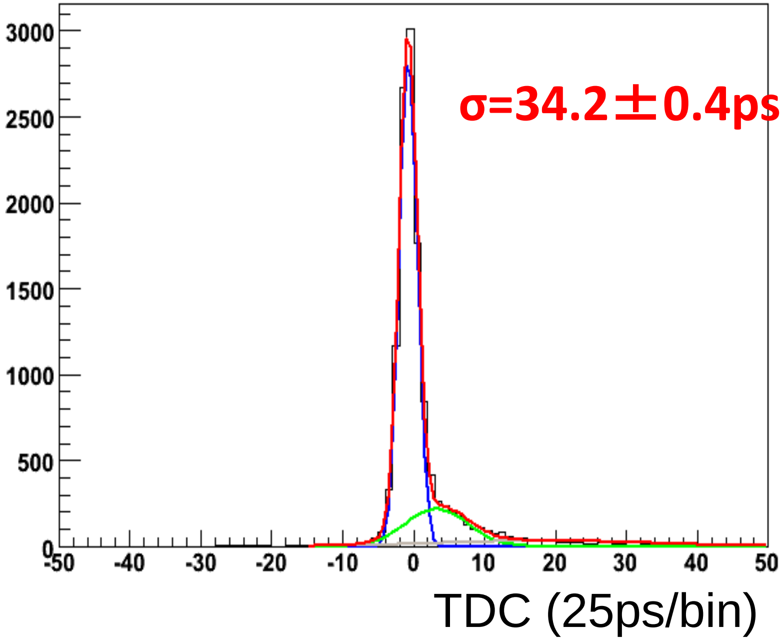




R&D with Hamamatsu photonics

- Large effective area 64%
- Position information 16ch
- 10μm channel size
- Single photon detection
- Fast rise time: ~400ps
- Gain: >1x10^6 at B=1.5T
- T.T.S.(single photon): ~35ps at B=1.5T
- Position resolution: <5mm

➔ Mass production (>500PMTs) done

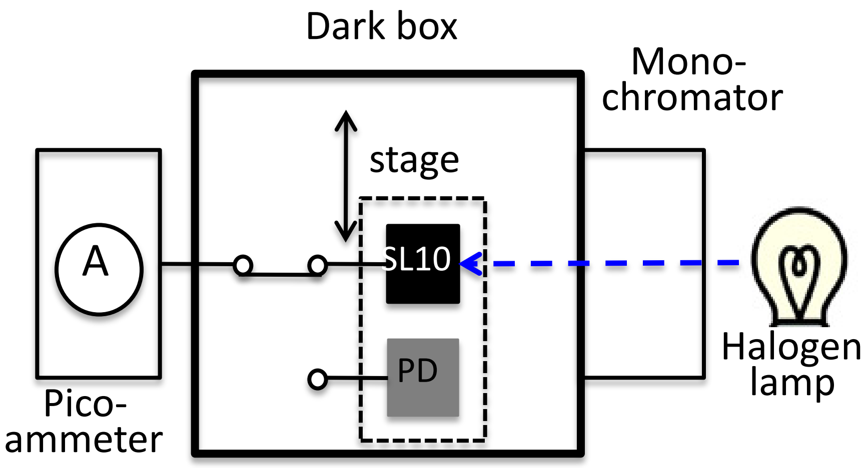


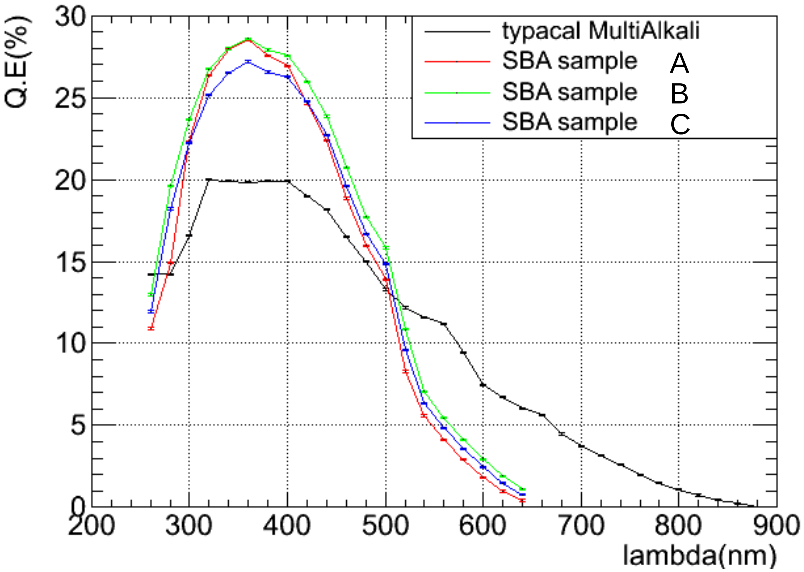
Photocathode efficiency

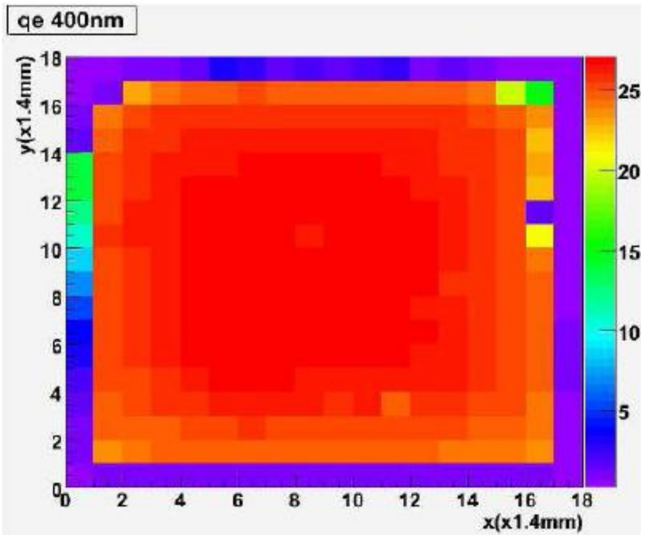
- Quantum Efficiency (QE)
  - With a reference photodiode.

    $QE_{PMT} = [I_{PMT} / I_{PD}] * QE_{PD}$

    I_{PMT}: photo-current between the p.c. and the front surface of the 1st MCP.
  - 2D scan on the PMT window.
  - λ scan: 350-700 nm is our interest.
- Super-bialkali technique tested

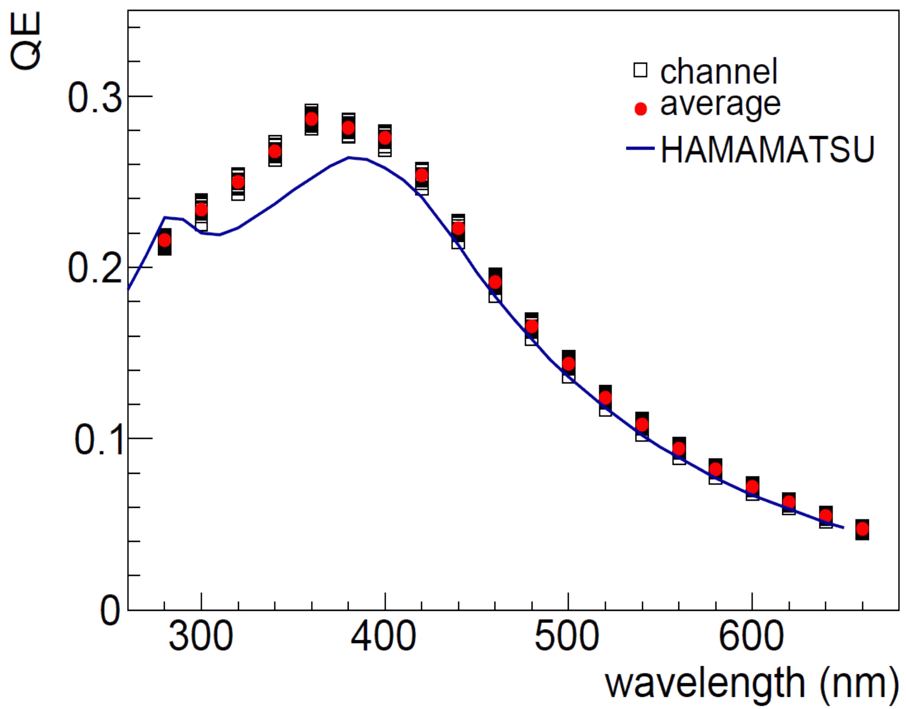






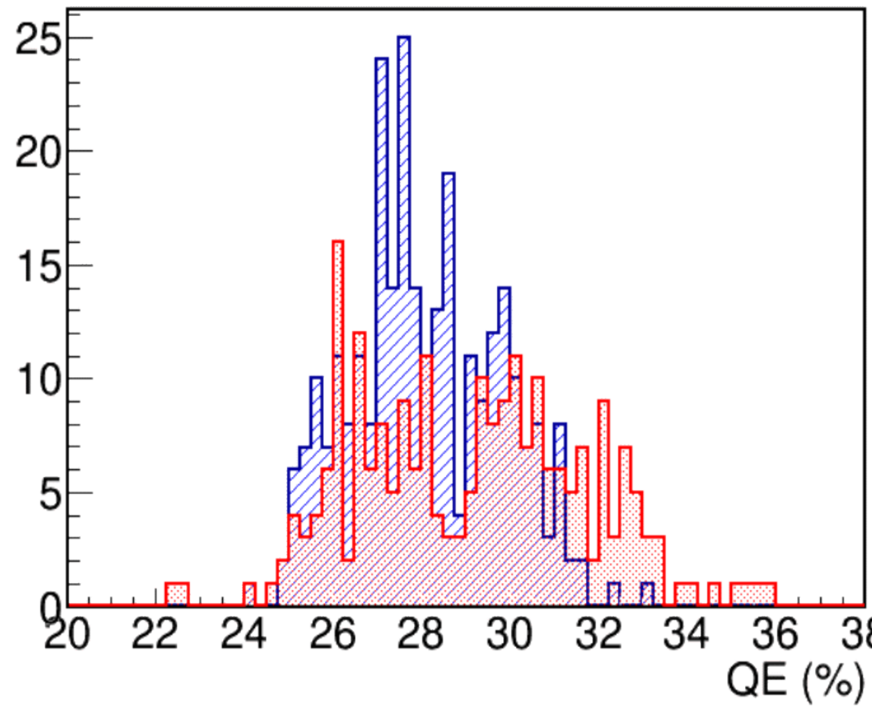
Photocathode improvement

- Apply similar method to multi-alkali photocathode
  - Major photocathode cathode for Hamamatsu MCP-PMT
  - QE Improved during mass production
  - On average, 28.1% of 283 conventional-MCP-PMTs and 29.1% of 231 ALD-MCP-PMTs at 360 nm.



QE peaks around 360 nm

QE at 360nm for mass-produced PMTs



Max QE = ~ 28%

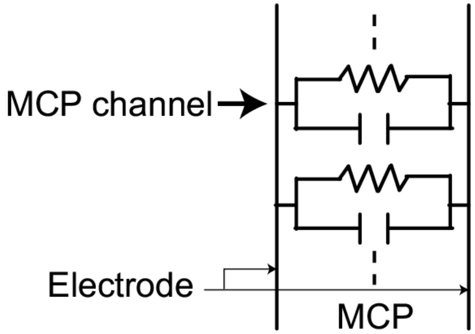
Issues under the high hit rate experiment

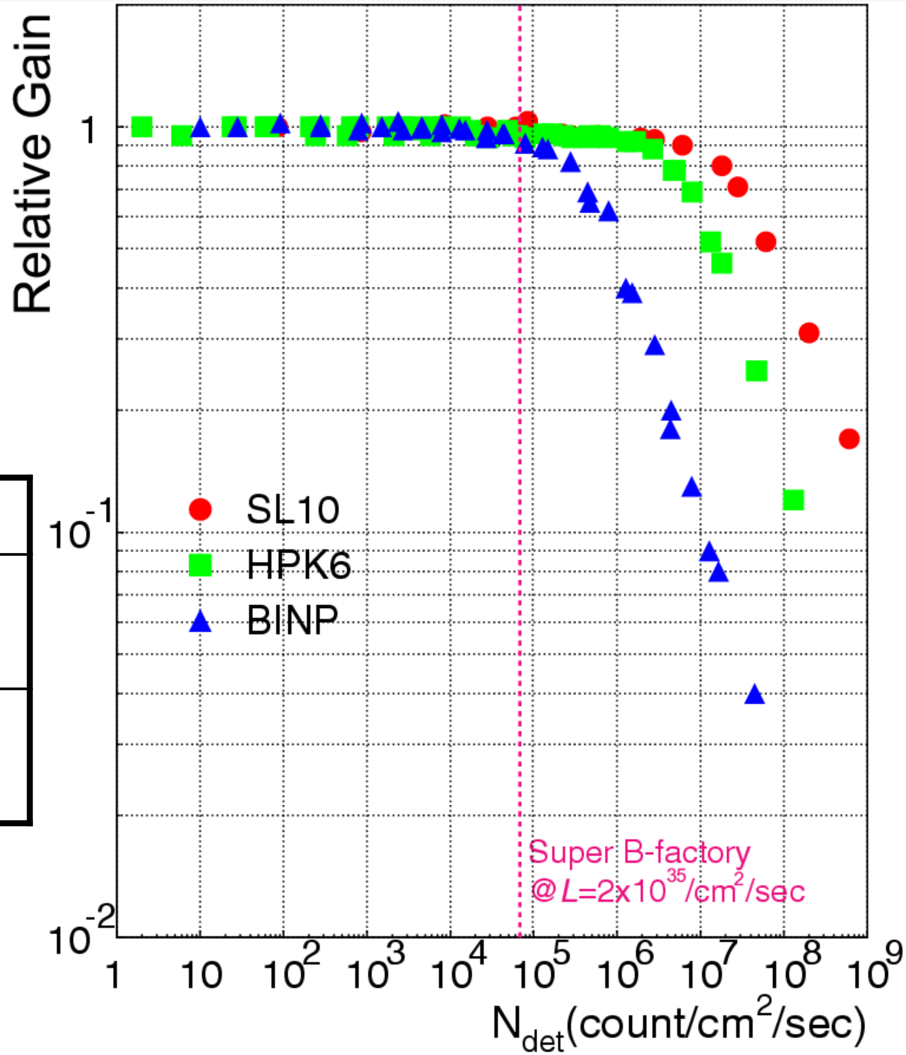
- Timing performance degradation
  - Gain drops when MCP current is saturated due to many electron multiplication in the channel.
- Photocathode aging
  - Electron multiplication causes out gas and ion feedback to photocathode.
  - Photocathode QE degrades

Rate dependence

- Gain drop for high rate
  - $>10^5$ count/cm^2/s
  - Due to lack of elections inside MCP holes
  - Dep. on RC variables

	SL10	HPK6	BINP
MCP resistance ($M\Omega$ cm^2)	96	143	380~1000
MCP capacitance (pF/cm^2)	16	31	24~39



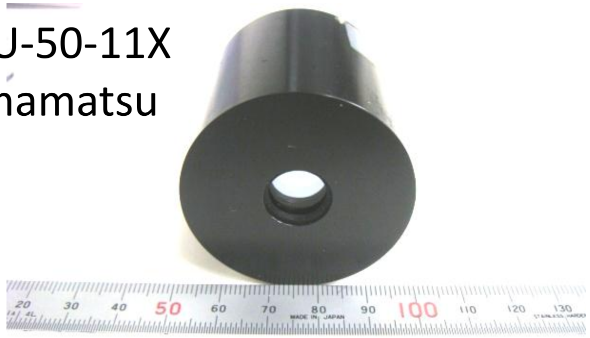


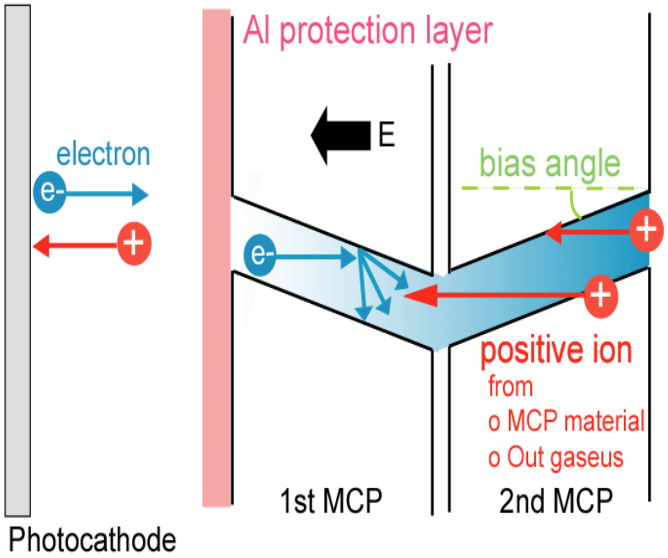
[SL10: Square-shaped MCP-PMT for TOP counter]

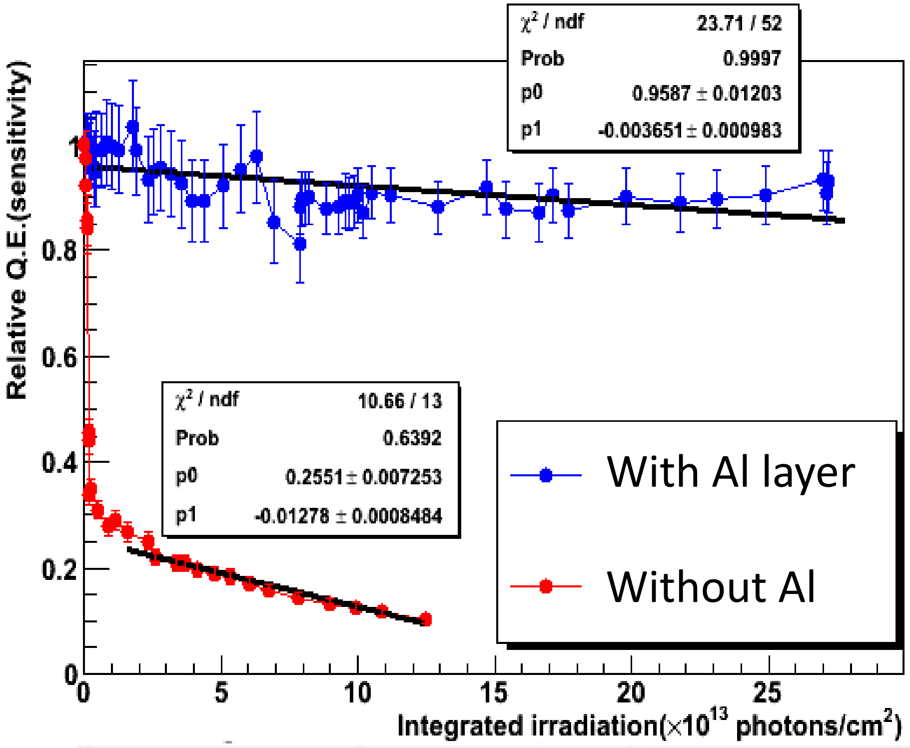
Aging of photocathode

- Round-shape MCP-PMTs
  - With and without aluminum layer on MCP
    - Protect feedback ions
  - Obtain sufficient lifetime, by putting Al on MCP
  - TTS is stable, if gain>~10^6

R3809U-50-11X
by Hamamatsu



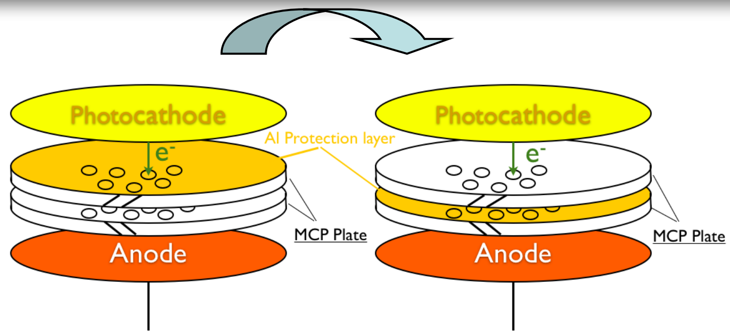




Nucl. Instr. Meth A564, 204 (2006)

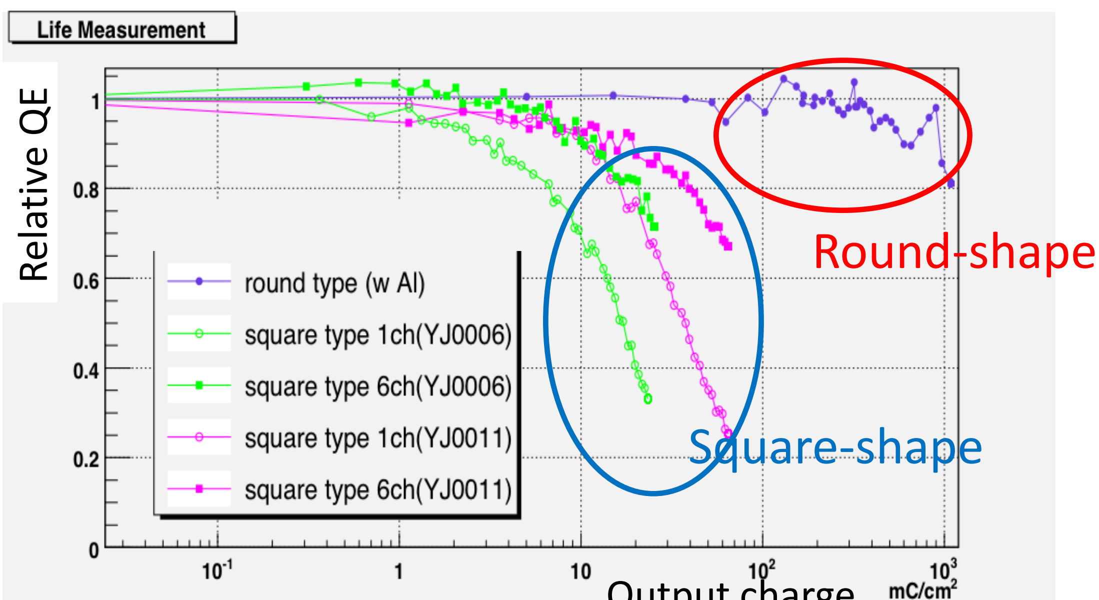
Lifetime for square-shape MCP-PMT

- Improvement for square-shape MT
  - With Al layer on MCP
  - Al protection layer on 2nd MCP
    - Recover collection efficiency (35%→60%)
    - Expect small effect to lifetime
      - Because of $1/10^3$ smaller number of electrons in 1st MCP compared to 2nd MCP



Measured PMT	YJ0006	YJ0011
Al protection layer	1st MCP	2nd MCP
Initial gain ($\times 10^6$)	0.41	1.1

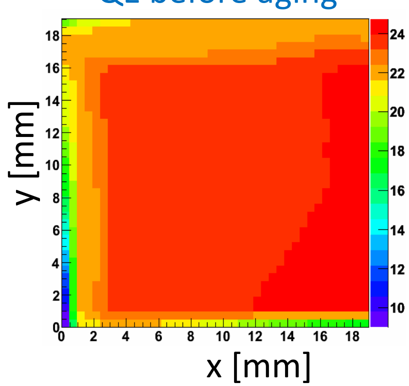
- Tested first prototype



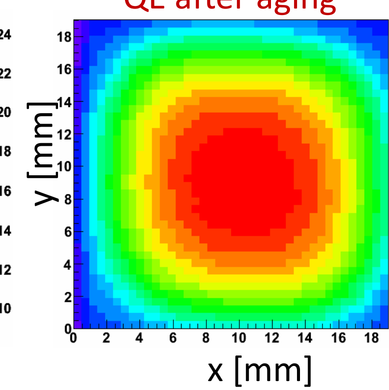
The QE drop becomes more significant toward the edges.

– Related to the structure?

QE before aging

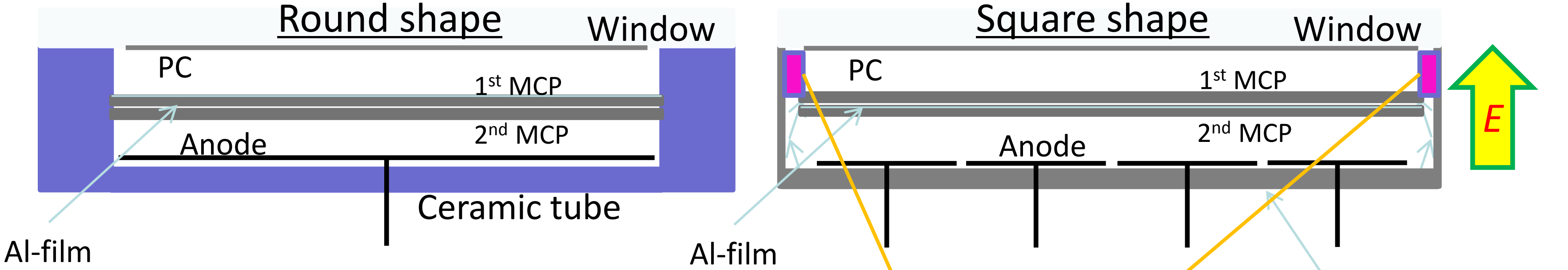


QE after aging



Cause of aging

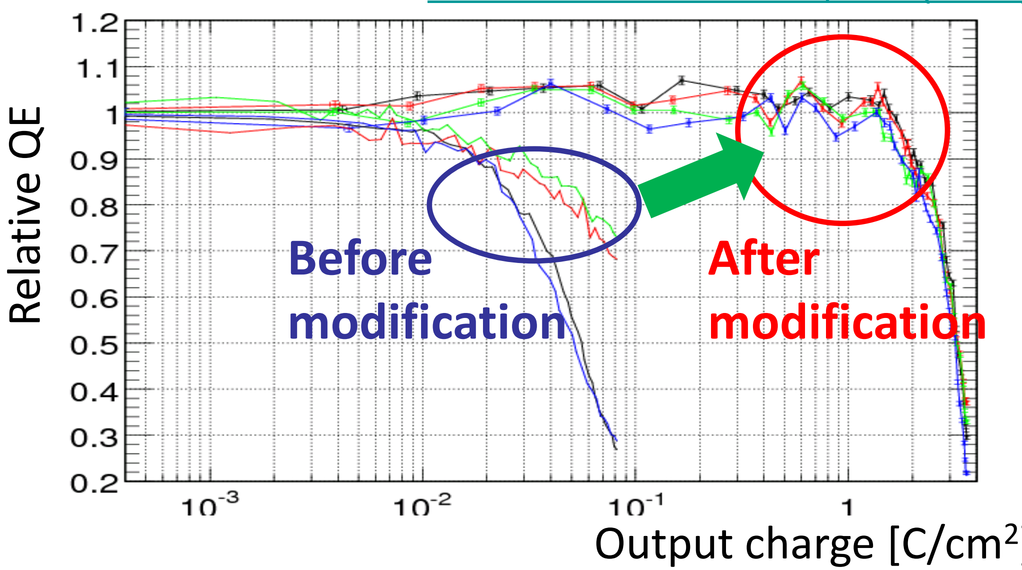
- Difference of inner structure btw round-shape and square-shape MCP-PMTs



- Neutral gas from 2nd MCP can pass through side gap.
  - We suspected that neutral gas through side gap causes QE degradation.
- Ceramic insulator added to block the path

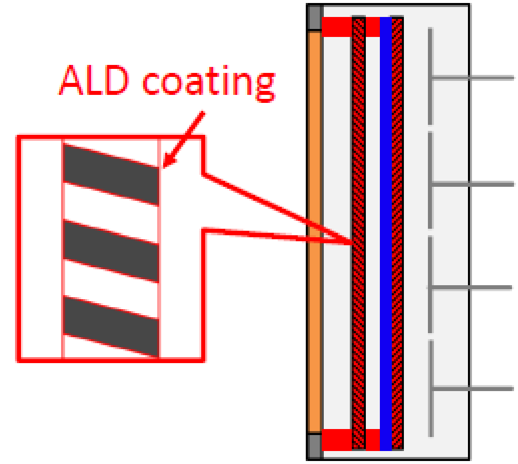
Nucl. Instr. Meth. A629, 117 (2011)

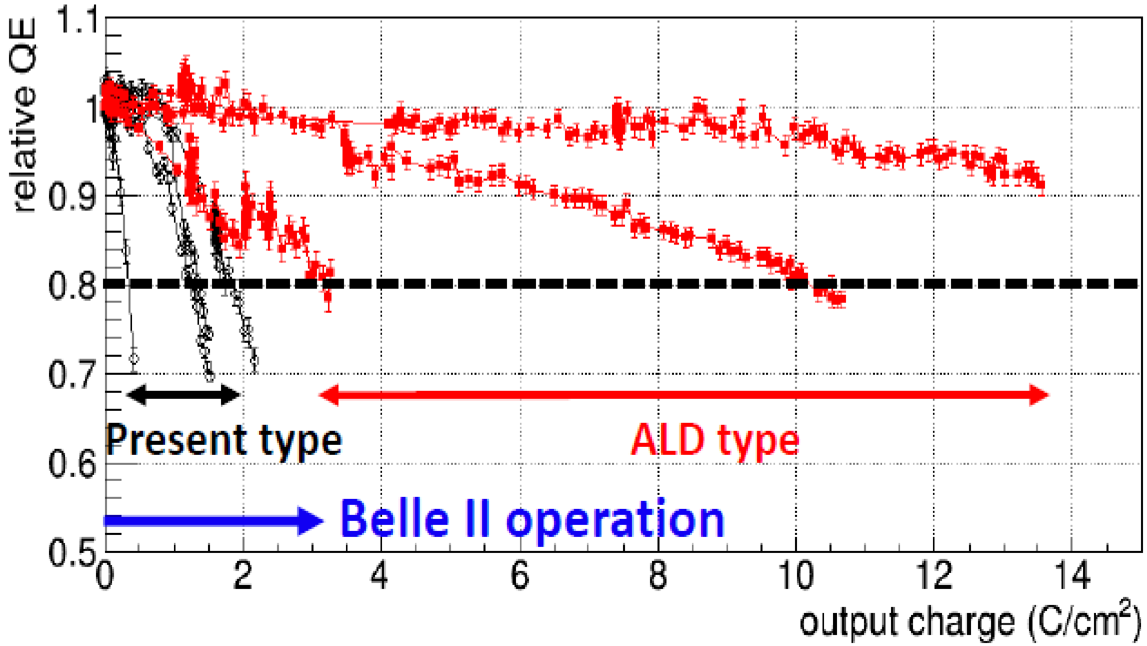
- Lifetime is significantly improved



ALD coated MCP-PMT

- During mass-production, we noticed lifetime improved PMTs are needed along with the progress of BG sim.
- ALD (Atomic layer deposition) technique applied to MCP production.
  - Higher gain compared with conventional type
  - Less outgas/ion emission for same gain operation
- Tested ALD MCP-PMT ➔Confirmed improved lifetime

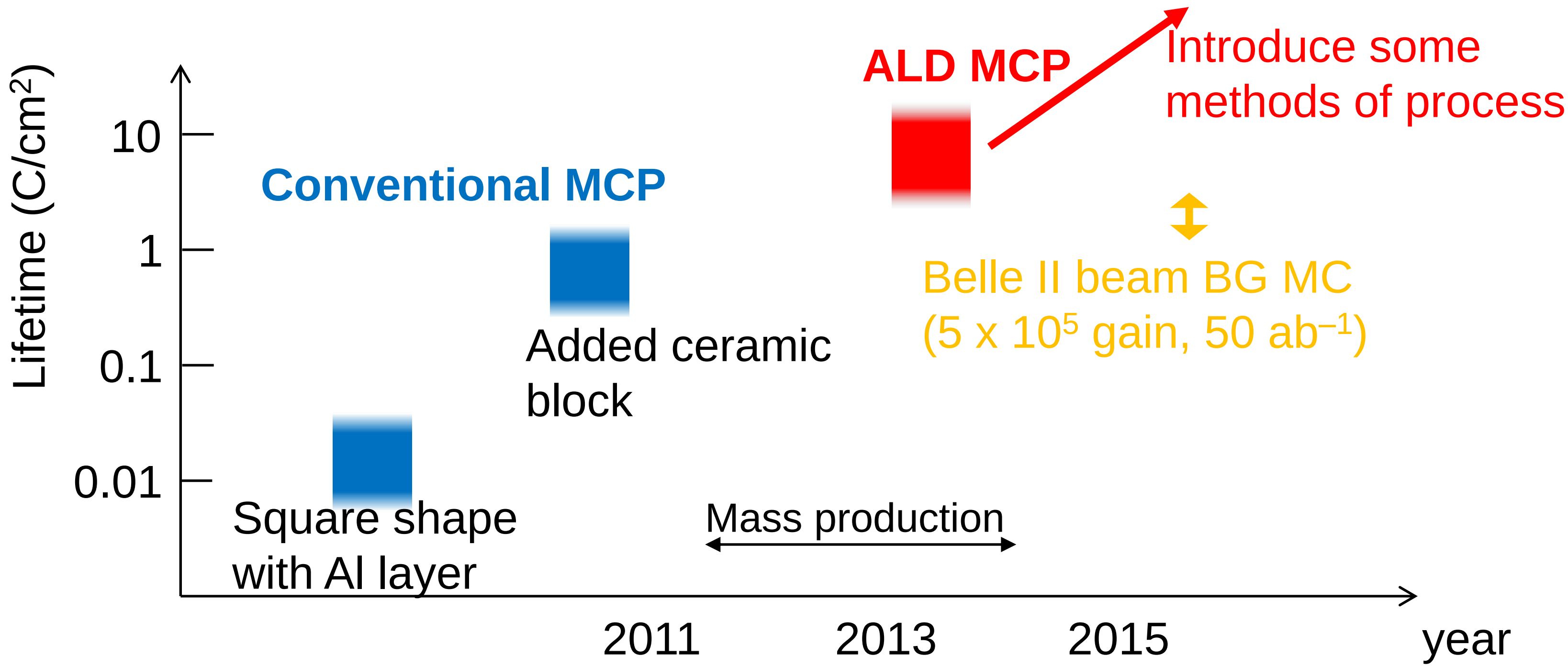




Nucl. Instr. Meth. A766, 148 (2014)

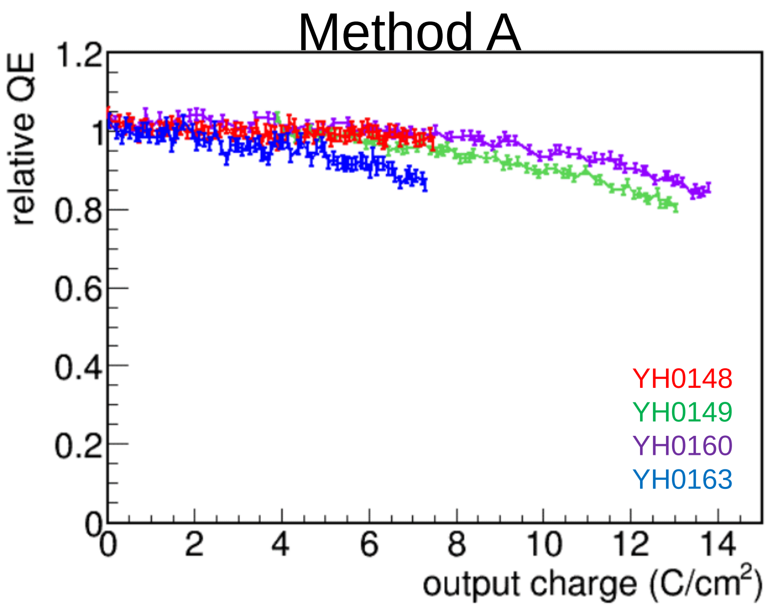
Further improvement for aging

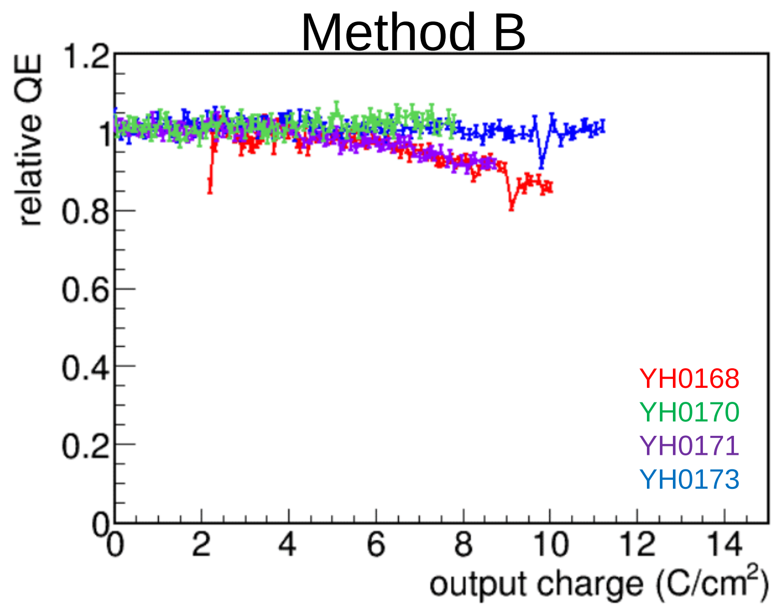
- ALD coated MCP improves lifetime, but it is close to the requirement

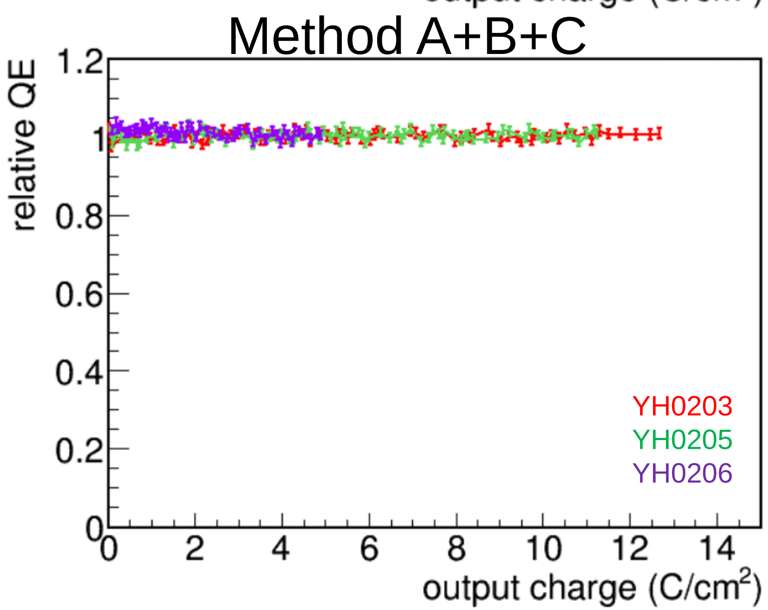


- Further improved PMTs developed with Hamamatsu.
  - Tried six methods of process to improve the lifetime.

Extended lifetime







- Three methods of process were found to be promising.
- 20 C/cm^2 or longer lifetime can be expected with Method A+B+C.

Summary

- MCP-PMT shows very fast timing response.
- We have developed square-shape MCP-PMT.
  - With Hamamatsu photonics
  - Gain~10^6, TTS<40ps for single photon detection

- Mass production for Belle-II TOP
  - Successfully; sufficient timing resolution <40ps
  - QE ~ 28% at 360nm with good flatness
- Lifetime has been improved.
  - By blocking the path, where an out-gas from the anode side can reach to the photo-cathode.
  - By introducing MCPs with ALD technique
  - Further improved ALD MCP-PMT developed
  - Finally, >20C/cm^2 lifetime was achieved.
  - Under production process for Belle-II TOP counter