Development of MA-MCP-PMT
for Belle-II TOP counter

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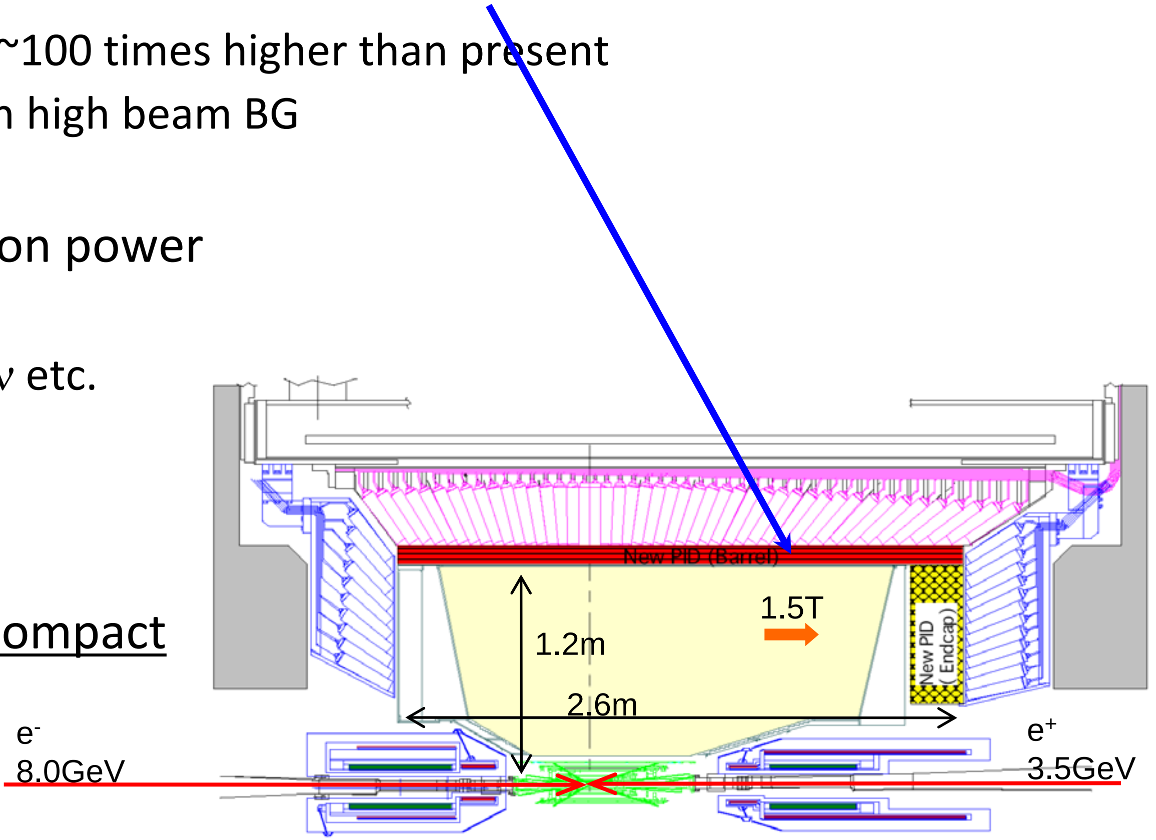
2014/12

TOP counter in Belle II

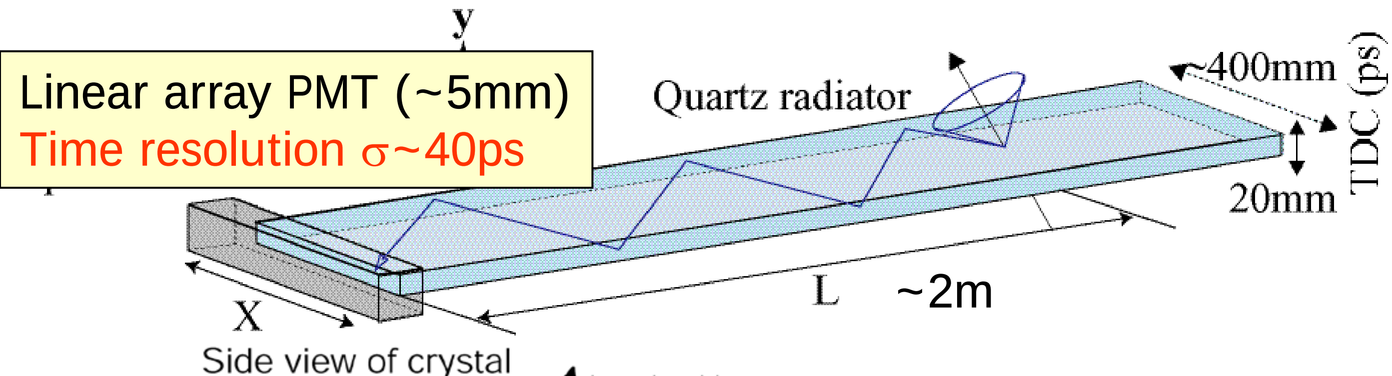
- TOP (Time Of Propagation) counter
  - Developing to upgrade the barrel PID detector
  - For Super B factory
    - L_{peak}~$10^{35\sim36}/cm^2/s$, 20~100 times higher than present
      - Need to work with high beam BG
  - To improve K/π separation power
    - Physics analysis
      - B→ππ/Kπ, ργ, Kνν etc.
    - Flavor tag
    - Full reconstruction
  - TOP counter should be compact

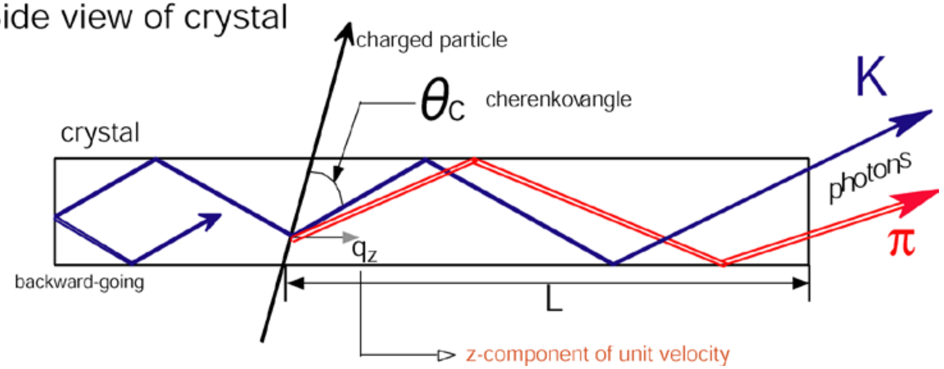


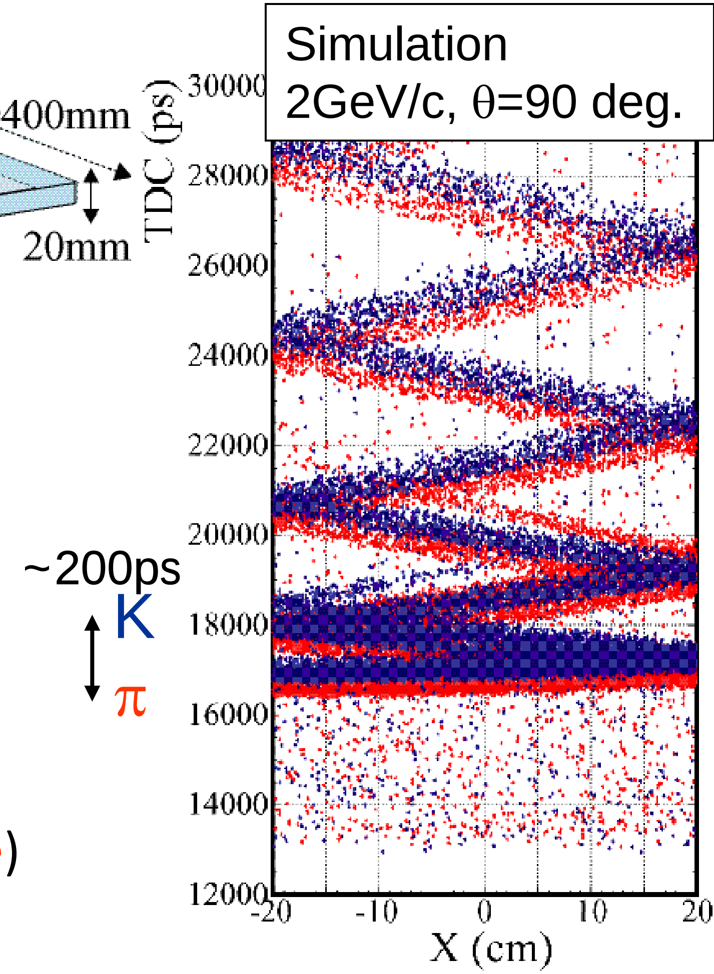
Side view of Super Belle detector

TOP counter

- <u>Position+Time</u> of arrival Cherenkov photons
  - Compact detector!







Different opening angle for the same momentum
→ Different propagation length(= propagation time)

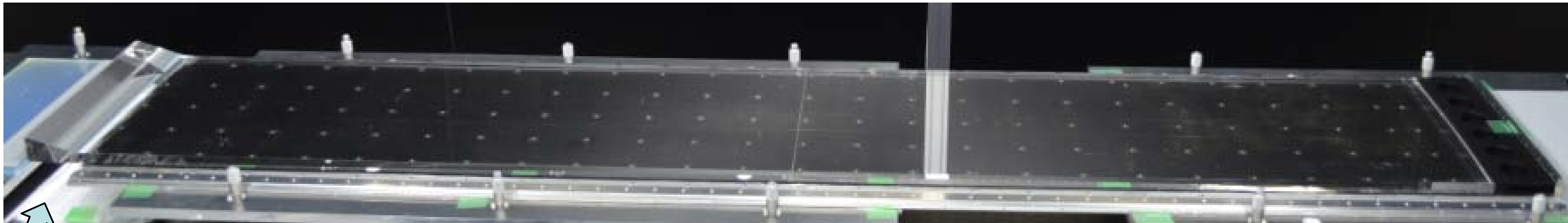
+ TOF from IP works additively.

TOP prototype test

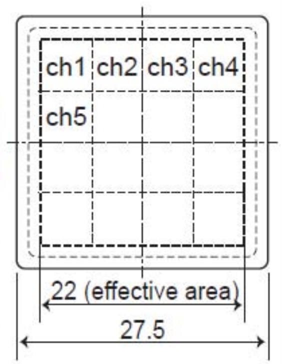
Expansion block

Quartz bar

Focusing mirror



MCP-PMT

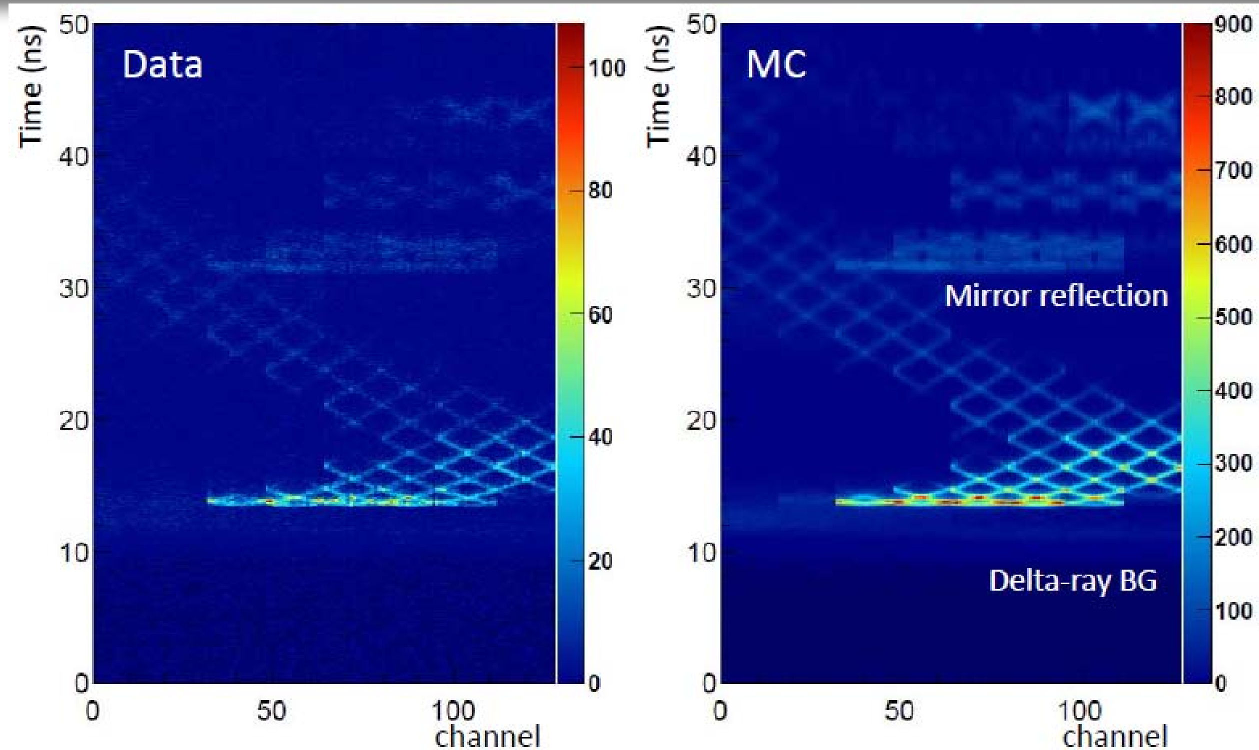


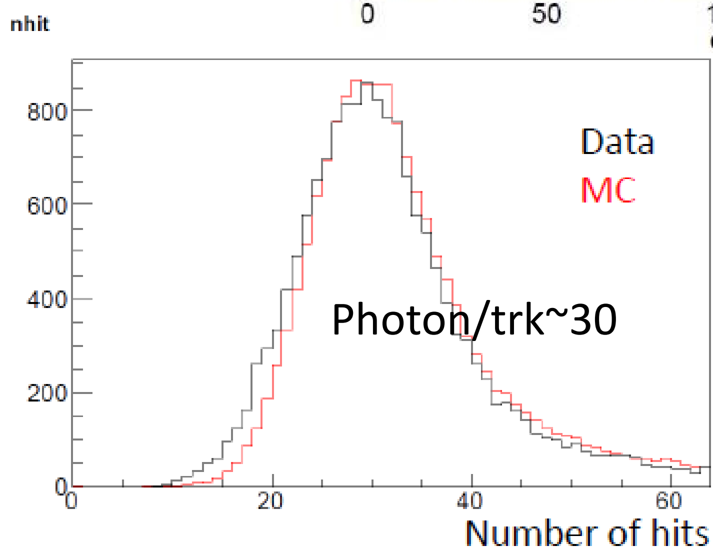
PMT modules mounted

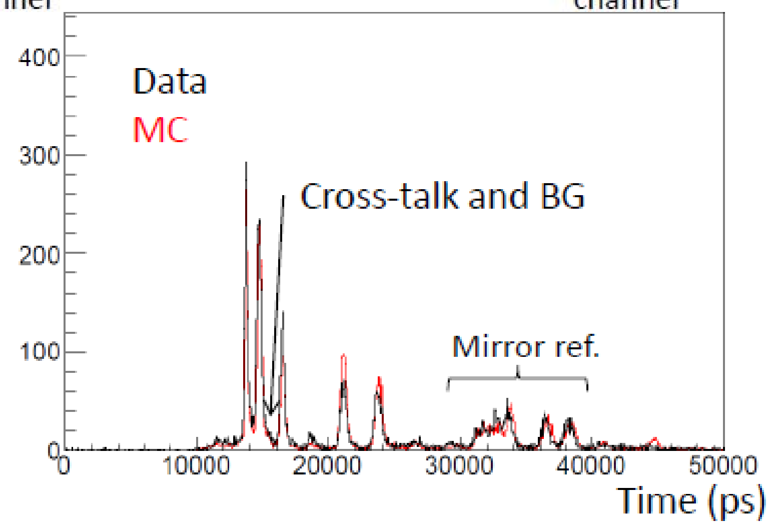
Beam test at Spring-8 LEPS line

Beam test result

- Sharp ring image as expected.
- Number of observed photons and time distributions are OK.
- Velocity reconstruction was succeeded.







TOP performance

- Performance dependence

Separation power : $S = \frac{\Delta TOF + \Delta TOP}{\sigma_{\text{top}}} \times \sqrt{N_{\text{det}}}$

$$\sigma_{\text{top}} = \sqrt{\sigma^2_{\text{photodetector}} + \sigma^2_{\text{radiator}}}$$

> ~ 50ps (Chromatic)

- $\sigma_{\text{photodetector}}$: Time Transit Spread (TTS)
- N_{det}: number of detected photons

MCP-PMT

- Requirements
  - TTS : <50ps
  - Gain : 1.0×10^6
    - Single photon detection
    - Enough statistics for TTS
  - QE : >20%@λ=400nm
  - Available in *B* -field

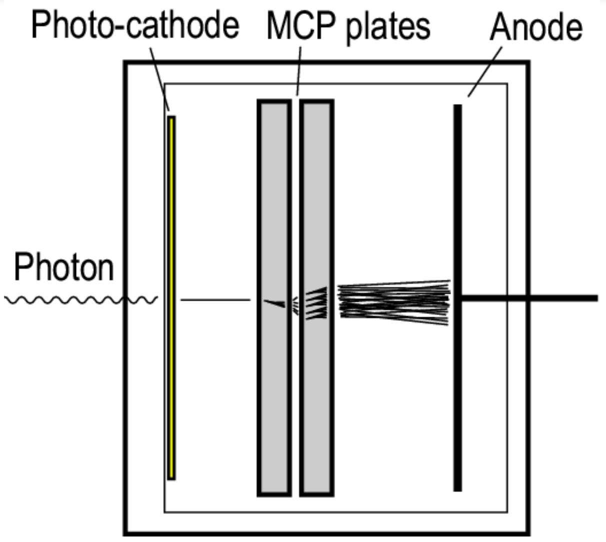
MCP-PMT

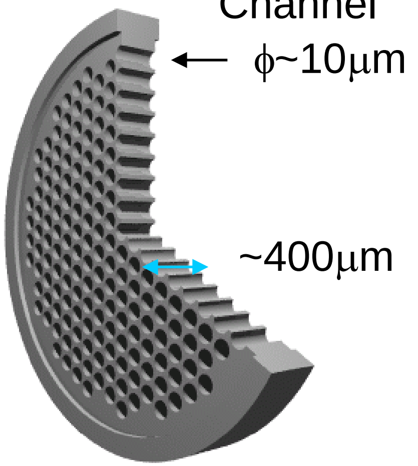
- Micro-Channel-Plate
  - Tiny electron multipliers
    - Diameter ~10μm, length ~400μm
  - High gain
    - $\sim 10^6$ for two-stage type

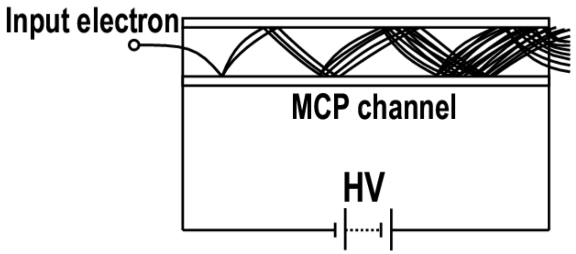
  → Fast time response

  Pulse raise time <400ps, TTS < 50ps

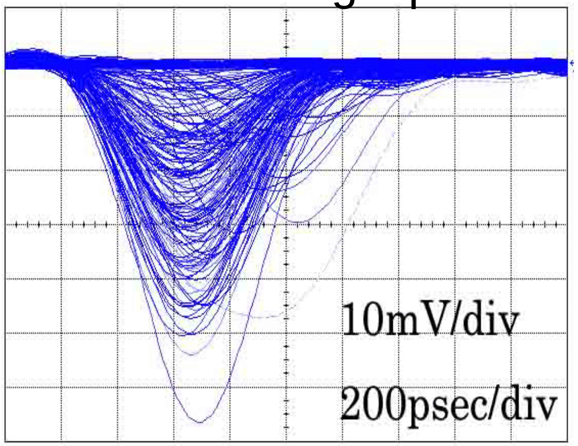
  - can operate under high magnetic field (~1T)







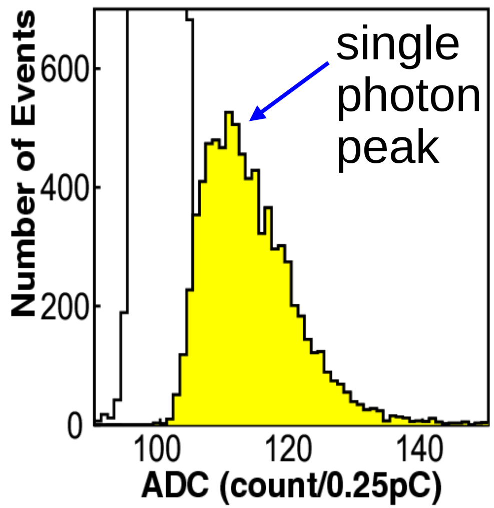
Single photon

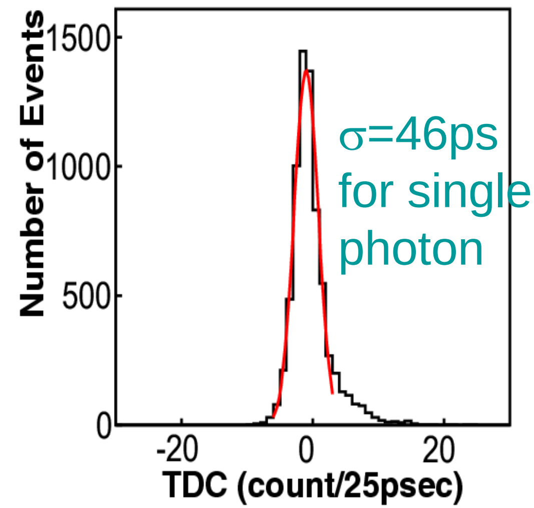


MCP-PMT output

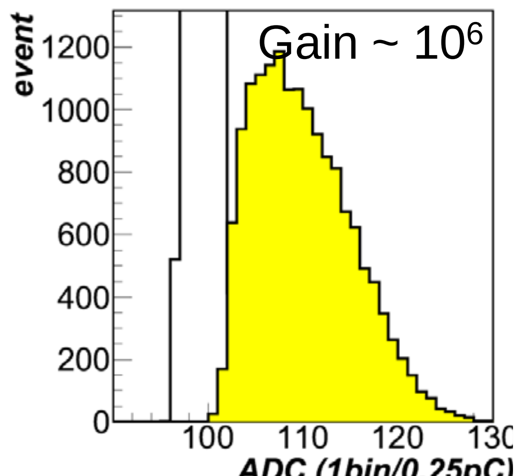
- Hamamatsu R3809U-50 (multi-alkali photo-cathode)

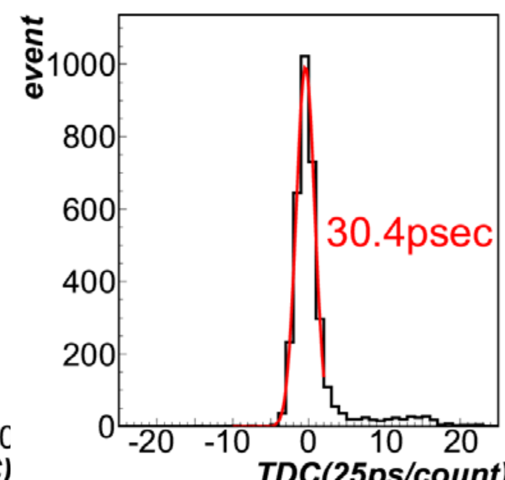
MCP hole 10μmφ





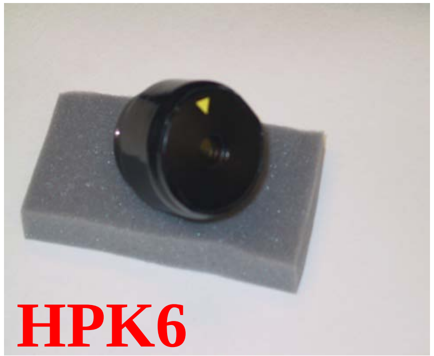
MCP hole 6μmφ

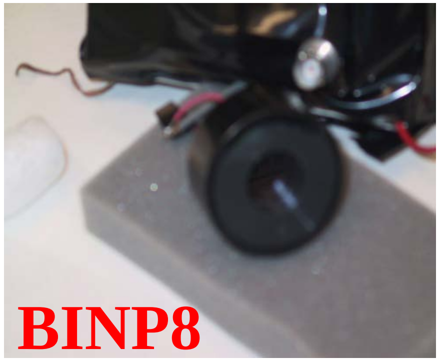


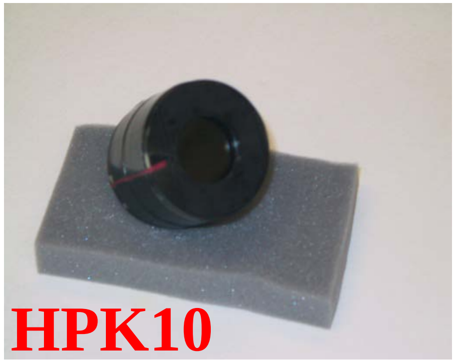


MCP-PMT

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



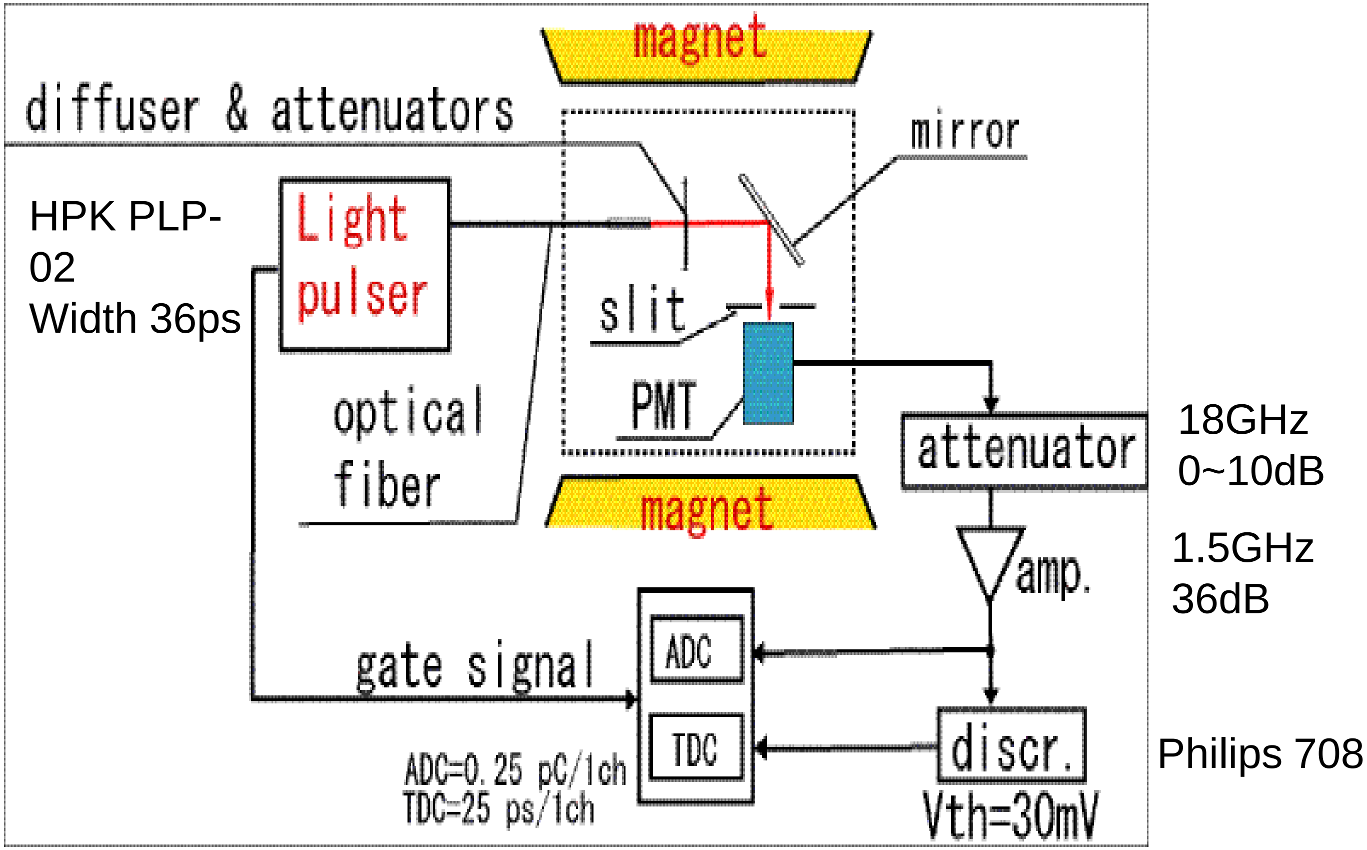




MCP-PMT	HPK6 R3809U-50-11X	BINP8 N4428	HPK10 R3809U-50-25X	Burle25 85011-501
PMT size(mm)	45	30.5	52	71x71
Effective size(mm)	11	18	25	50x50
Channel diameter(μm)	**6**	**8**	**10**	**25**
Length-diameter ratio	40	40	43	40
Max. H.V. (V)	3600	3200	3600	2500
photo-cathode	multi-alkali	multi-alkali	multi-alkali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

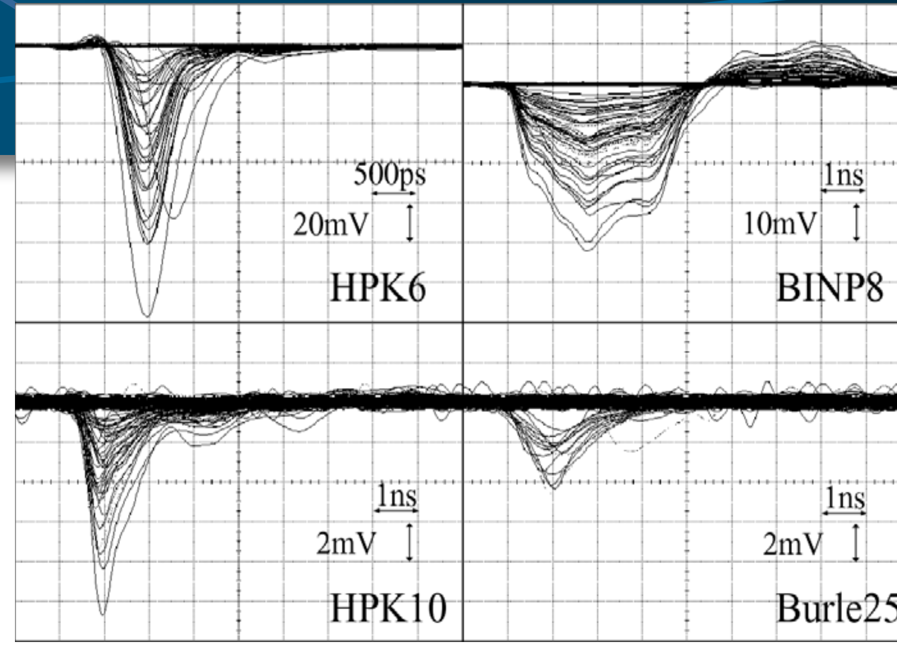
MCP-PMT for single photon (2)

- Setup
  - Single photon is generated by laser (408nm).
  - B-field is parallel to tube axis.

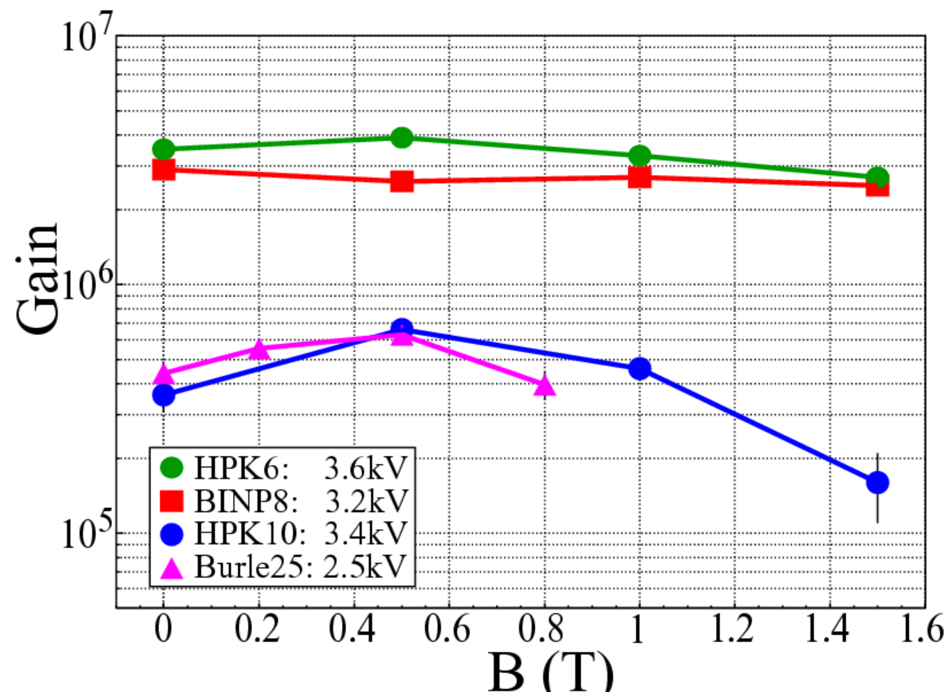


Pulse response

- Pulse shape (B=0T)
  - Fast raise time (~500ps)
  - Broad shape for BINP8
    - Due to mismatch with H.V. supply divider
    - No influence for time resolution

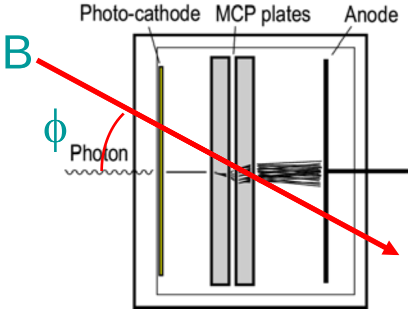


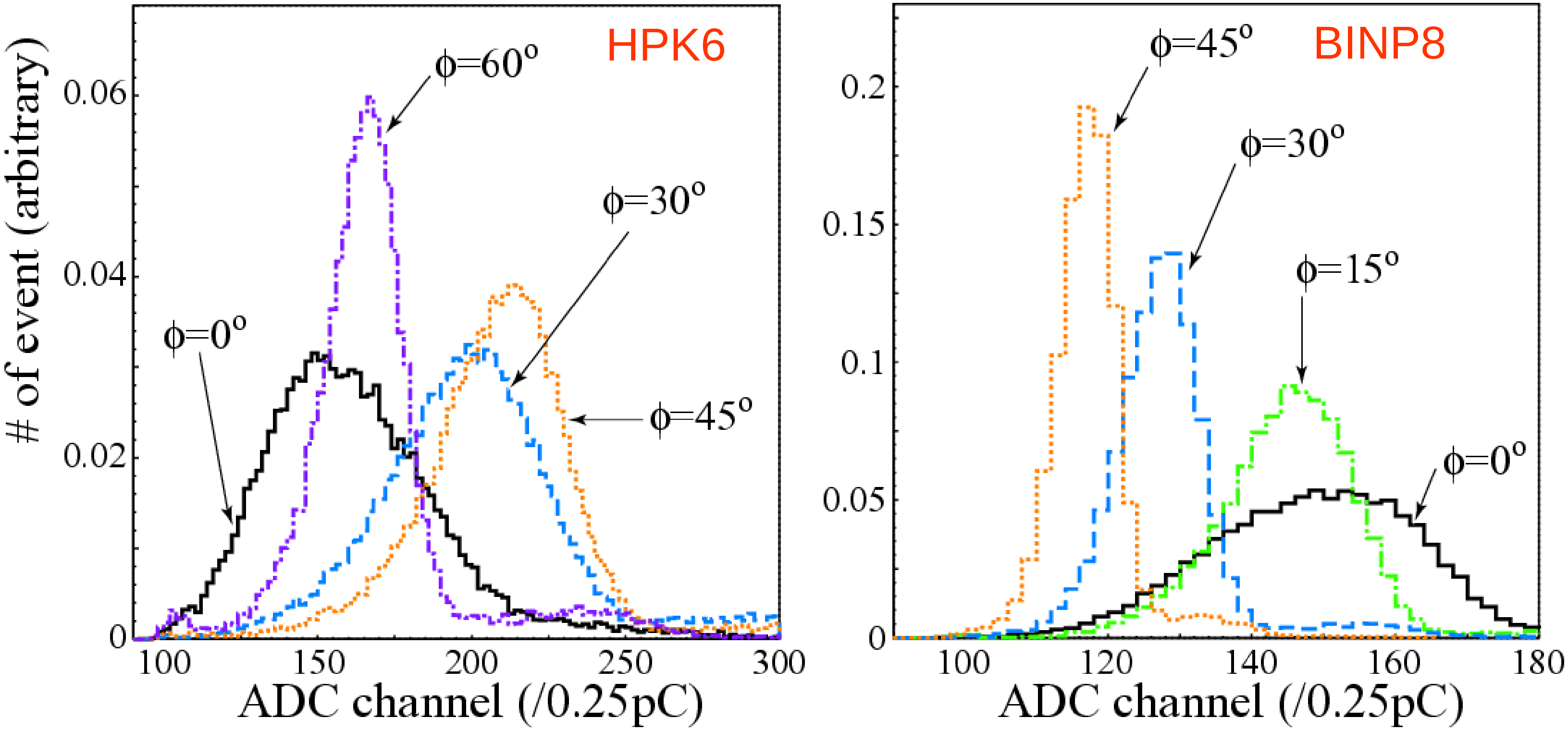
- Gain v.s. B-field
  - Small channel diameter shows high stability against B-field.
  - Explained by relation btw hole size and Larmor radius of electron motion under B-field.



MCP-PMT in B-field

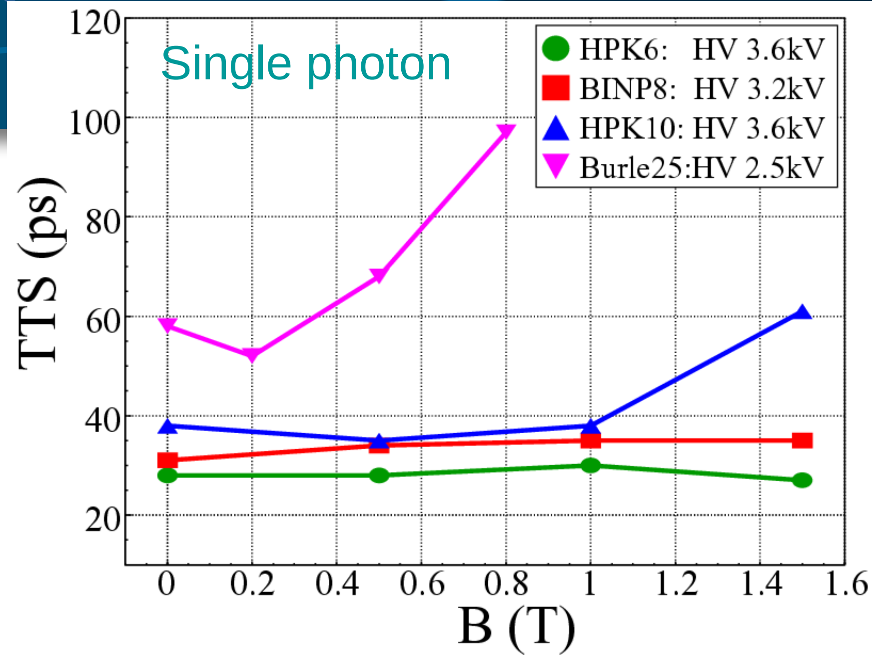
- ADC spectra with different angles under B=1.5T
  - Gain depends on the angle.
  - Behaviors are slightly different.
    - Because of the different bias angle of MCP hole
      - HPK6: 13deg, 6μm, BINP8: 5deg, 8μm



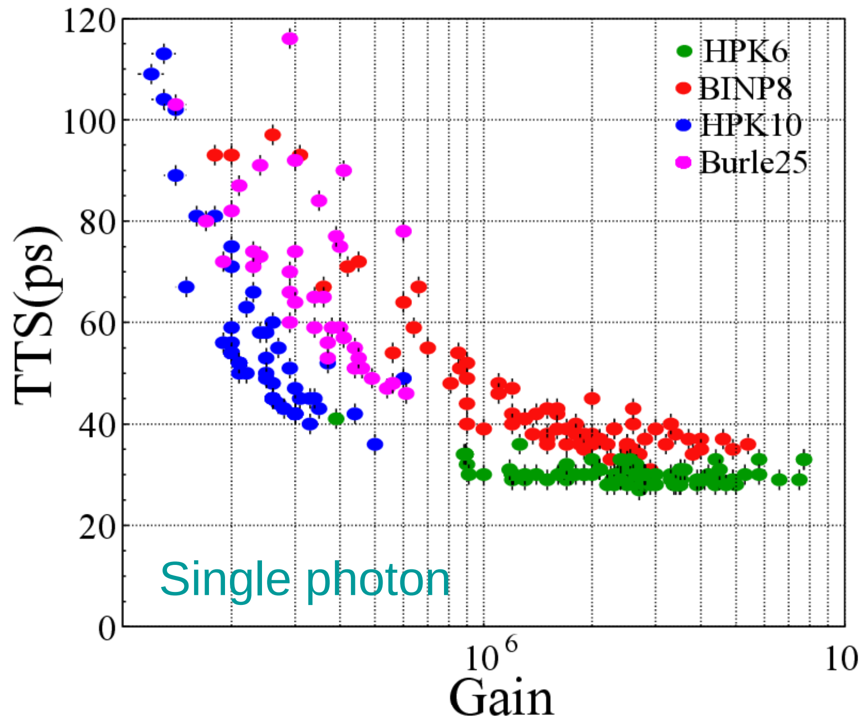


Time response

- TTS v.s. B-field
  - Small channel diameter shows high stability and good resolution.



- TTS v.s. Gain
  - For several HV and B-field conditions
  - 30~40ps resolution was obtained for gain>10^6

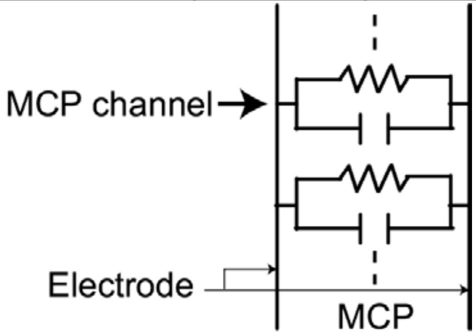


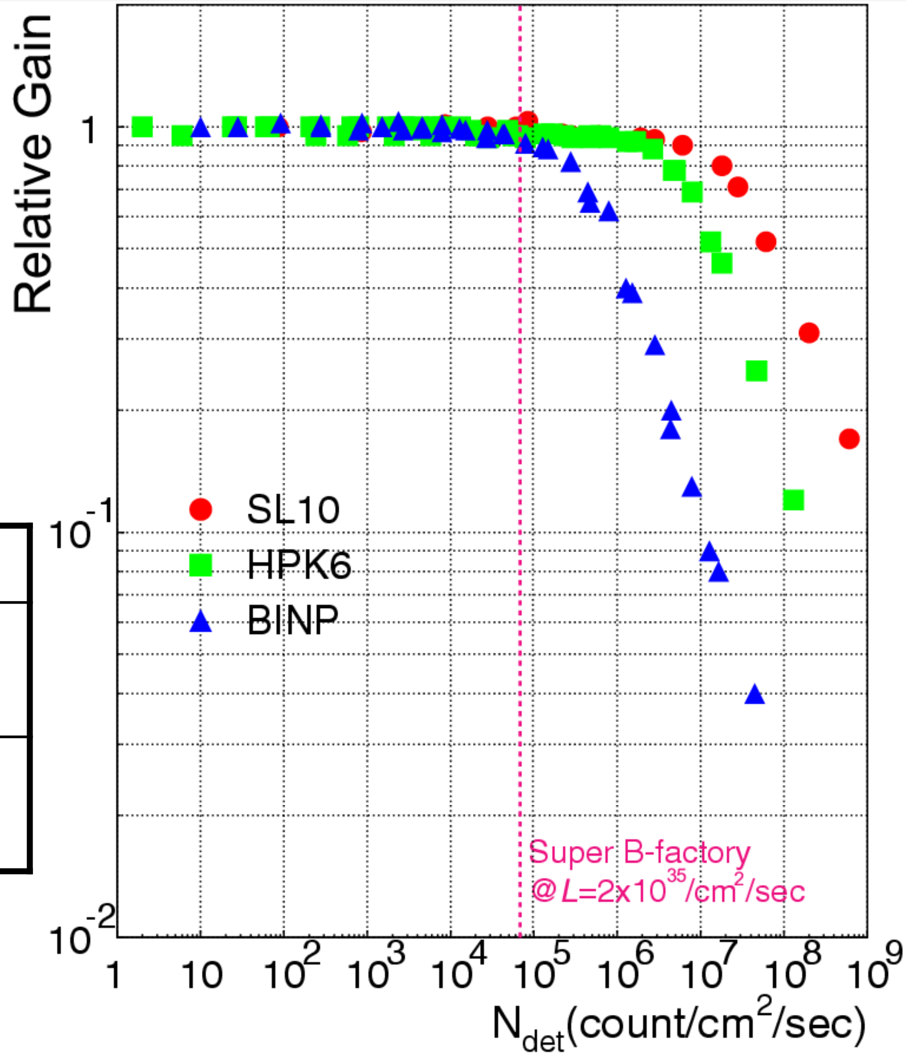
- Hole size need <~10μm
  - to get time resolution of ~30ps under 1.5T B-field.

Rate dependence

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

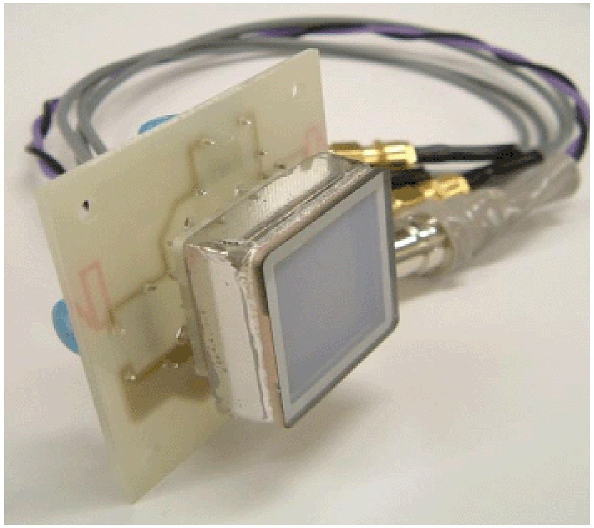
	SL10	HPK6	BINP
MCP resistance (MΩ cm^2)	96	143	380~1000
MCP capacitance (pF/cm^2)	16	31	24~39

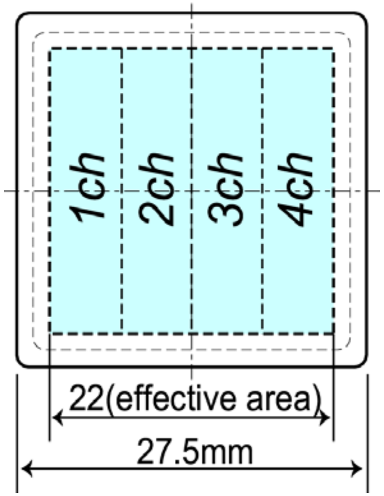




[SL10: Square-shaped MCP-PMT shown later]

Multi-anode MCP-PMT





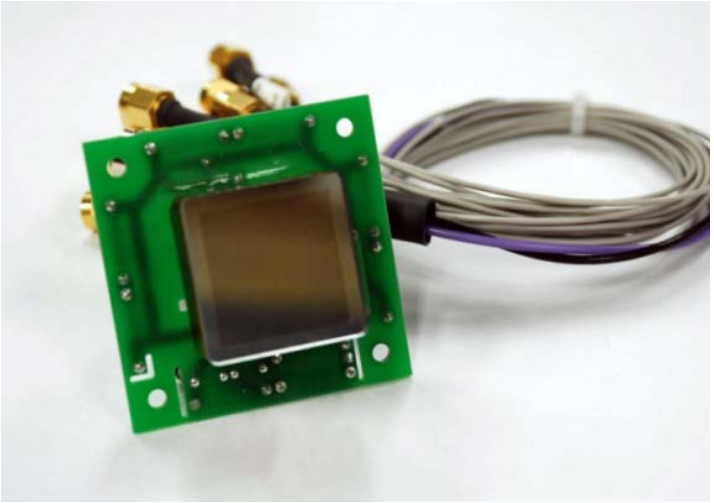
Size	27.5 x 27.5 x 14.8 mm
Effective area	22 x 22 mm(**64%**)
Photo cathode	Multi-alkali
Q.E.	~20%(λ=350nm)
MCP Channel diameter	10 μm
Number of MCP stage	2
Al protection layer	No
Aperture	~60%
Anode	4 channel linear array
Anode size (1ch)	5.3 x 22 mm
Anode gaps	0.3 mm

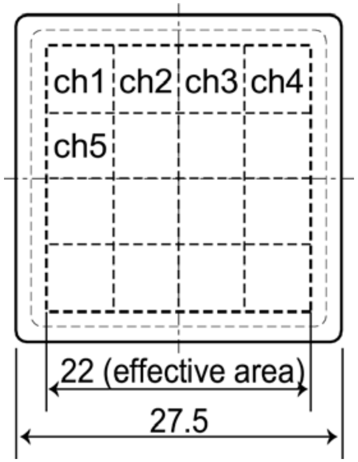
SL10

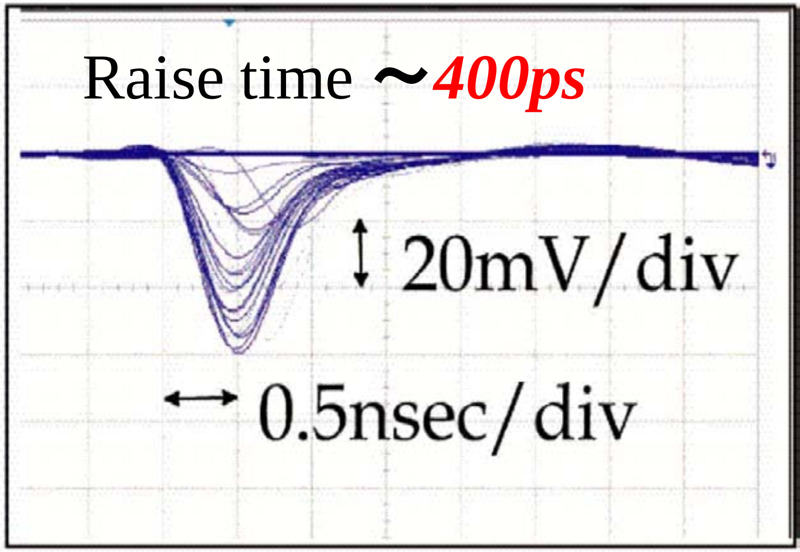
R&D with Hamamatsu for TOP counter

- Large effective area — 64% by square shape
- Position information — 4ch linear anode (5mm pitch)

MCP-PMT for TOP counter

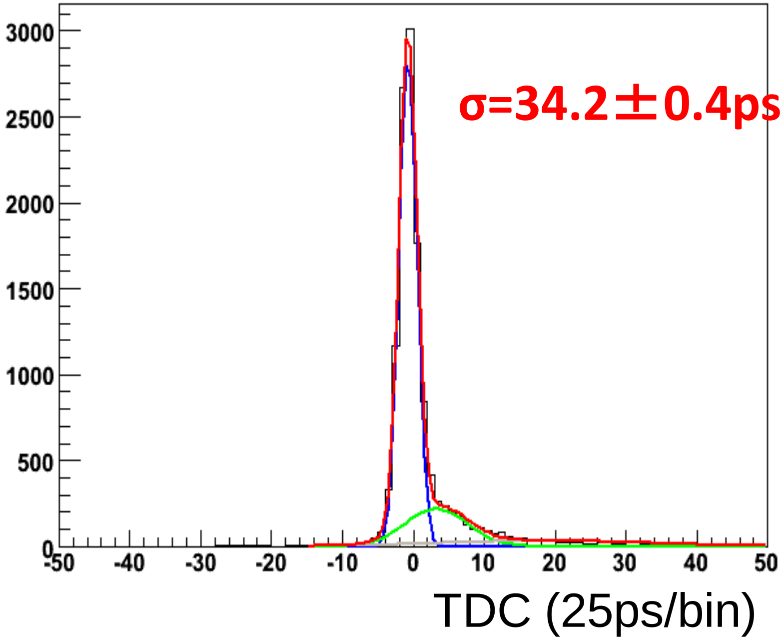






R&D with Hamamatsu photonics

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

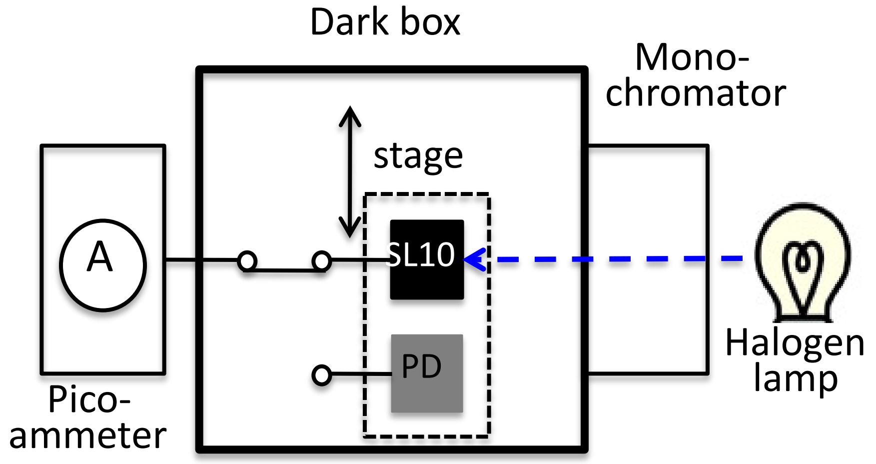


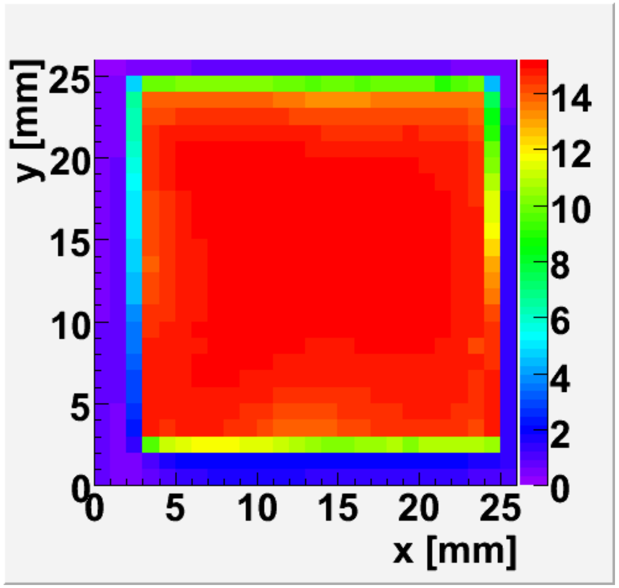
MCP-PMT for TOP counter

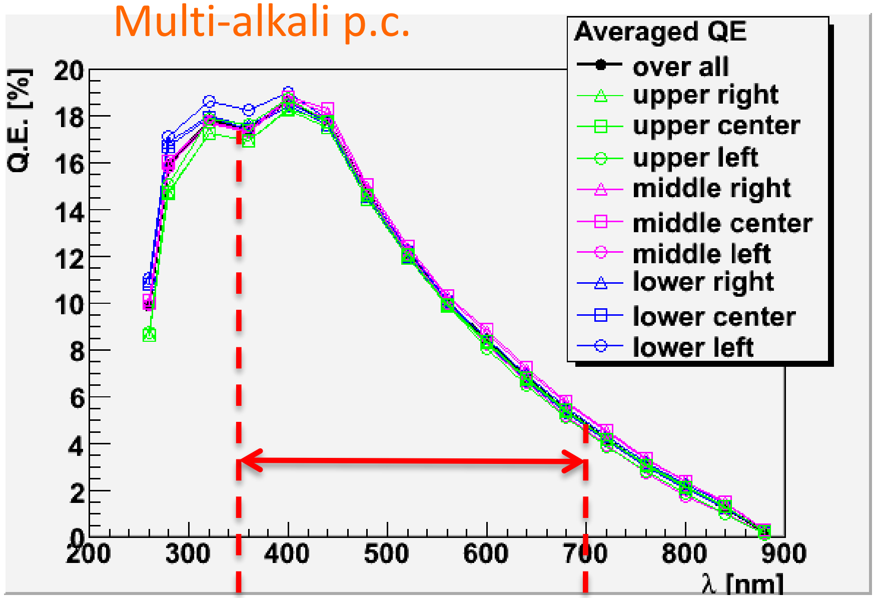
- Quantum Efficiency (QE)
  - With a reference photodiode.

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

    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.







Issues under the higher luminosity

- Basic performance meets our requirements.
- Higher the luminosity, higher the background rate gets.
  - Experience at Belle + Simulation:
    x40 higher luminosity => x20 higher backgrounds
  - Need to solve the issues for the long-term operation, e.g. 10 years.
- High photon rate
  - ~7x10^5 photons/cm^2/s => ~0.17 C/cm^2/year
  - Need to check the lifetime.

	Belle	Belle-II
Luminosity (/cm^2/s)	1×10^{34}	8×10^{35}
Num. of detected photons (/cm^2/s)	3400	68000
Output charge (mC/cm^2/year)	~6	~170

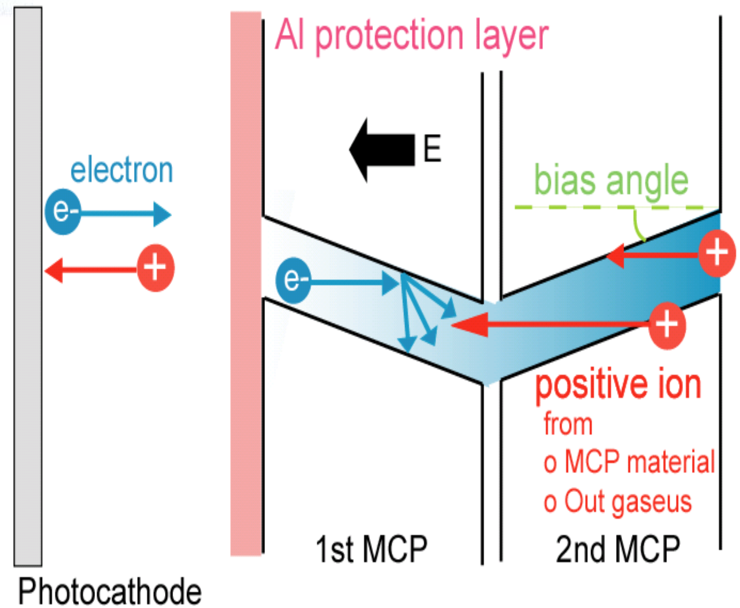
[Old estimation]

Lifetime of MCP-PMT

- How long can we use MCP-PMT under high hit rate?

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

	HPK (x2)		Russian (x5)	
Al protection	**O**	**X**	**O**	**X**
Correction eff.	**37 %**	**65 %**	**40-60**	**55-60 %**
Effective area	11mmϕ		18mmϕ	
Gain	1.9×10^6	1.5×10^6	$3\sim4\times10^6$	
TTS	34ps	29ps	30~40ps	
Photo-cathode	Multi-alkali (NaKSbCs)			
Quantum eff. at 400nm	21%	19%	16-20%	
Bias angle	13deg		5deg	

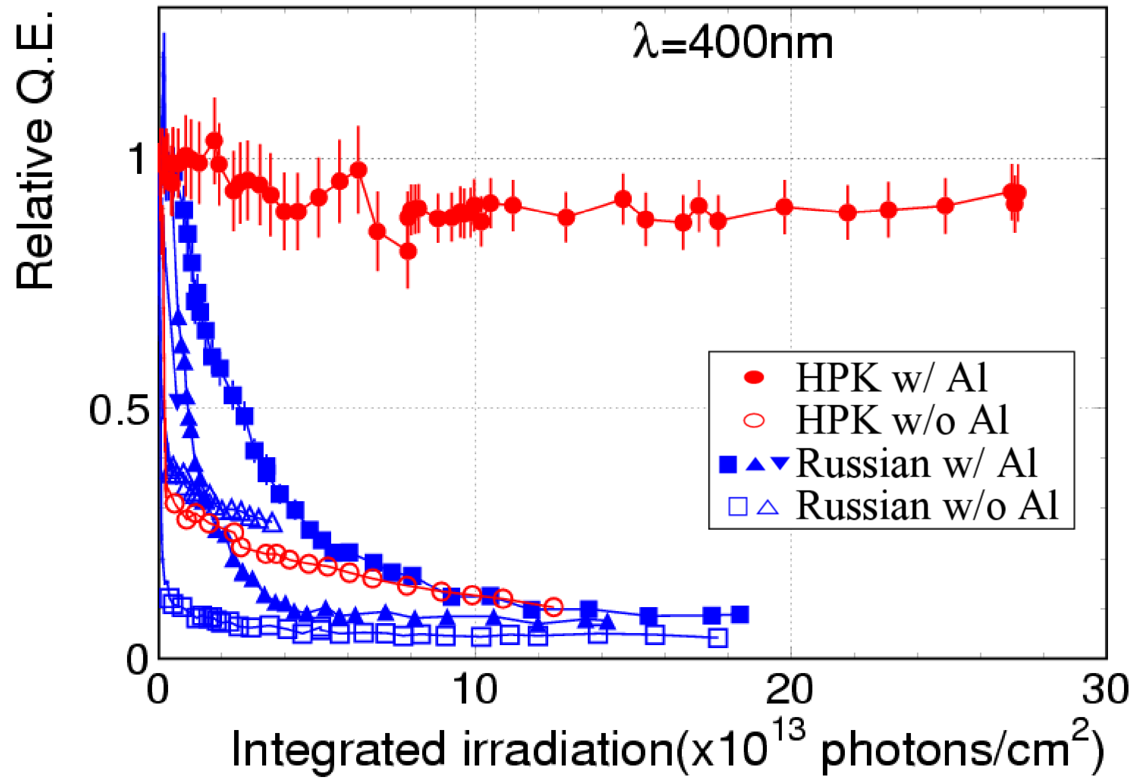


- Light load by LED pulse (1~5kHz)
  - 20~100 p.e. /pulse (monitored by normal PMT)

Lifetime - Q.E. -

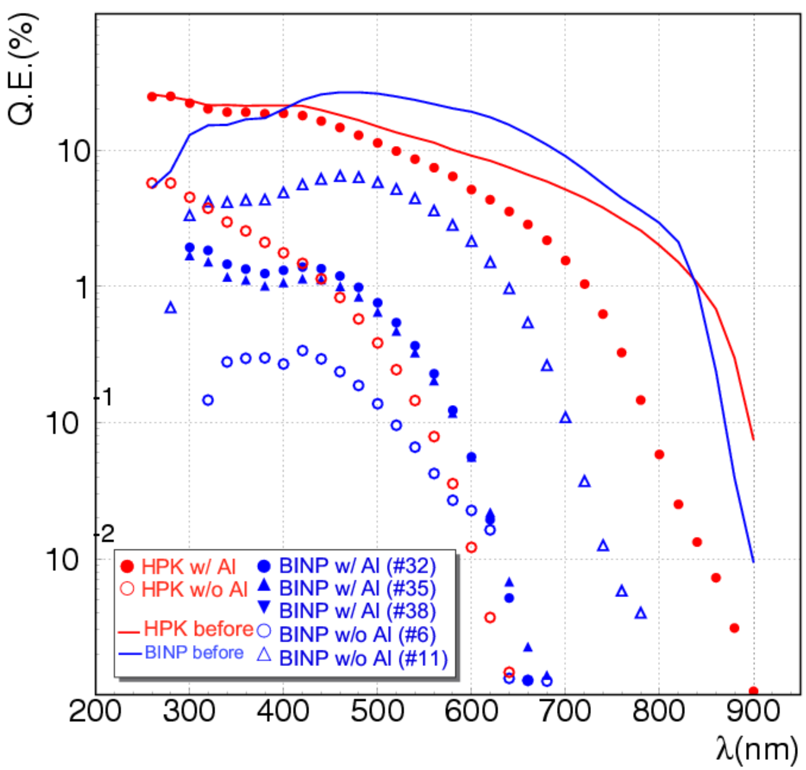
- Relative Q.E. by single photon laser

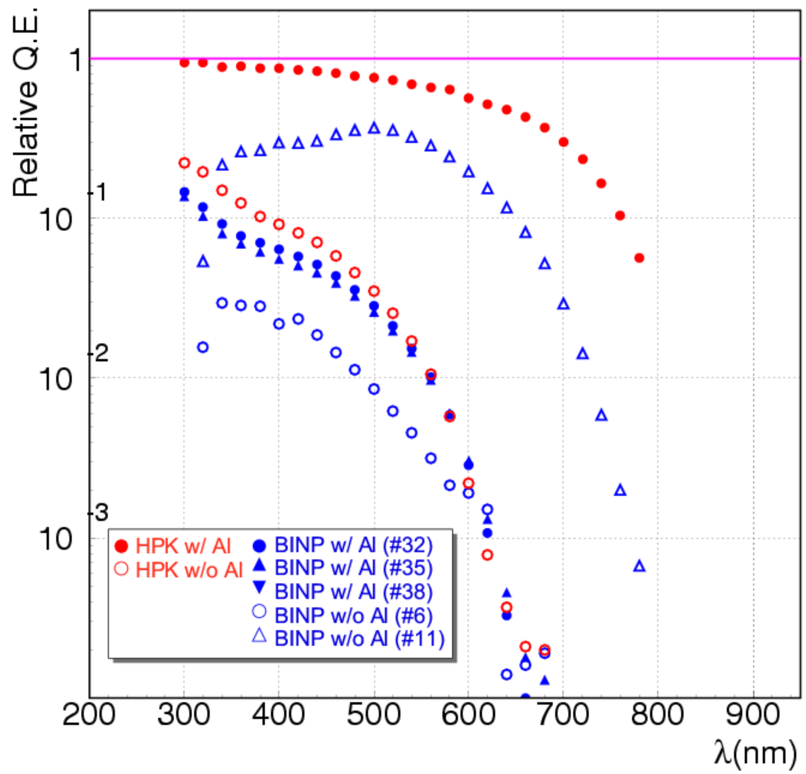
- Without Al protection
  - Drop <50% within 1yr.
- With Al protection
  - Long life
  - Not enough for Russian PMTs



Lifetime - Q.E. vs wavelength -

- Q.E. after lifetime test (Ratio of Q.E. btw. before,after)

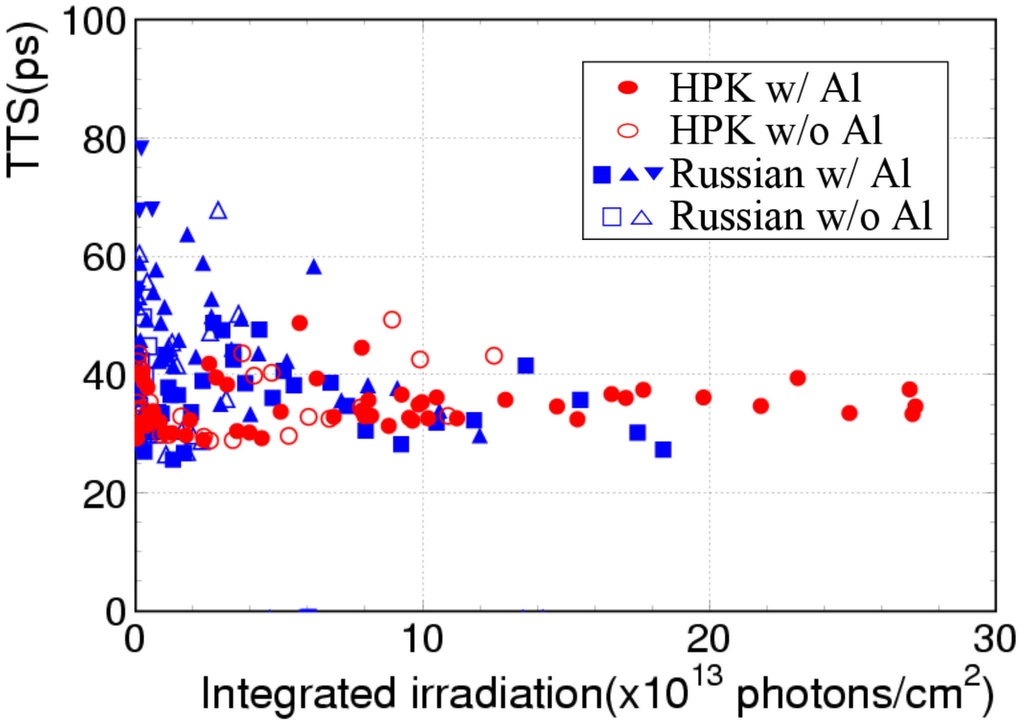


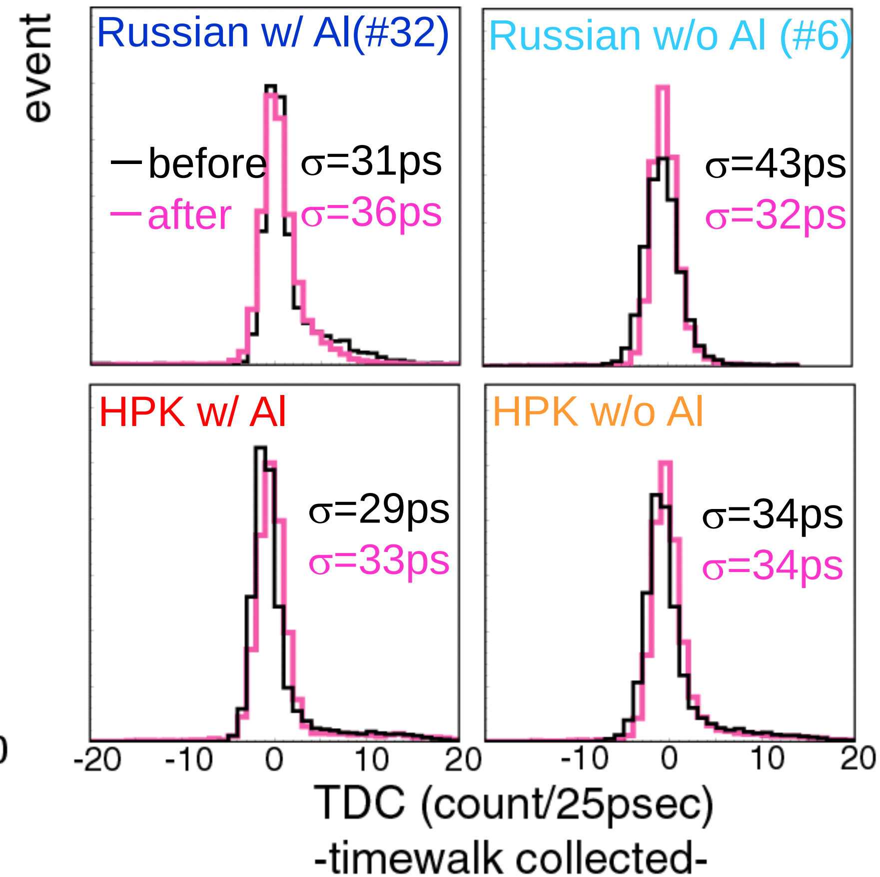


- Large Q.E. drop at longer wavelength
- Number of Cherenkov photons ; only 13% less (HPK with Al)
  - Number of generated Cherenkov photon:~$1/\lambda^2$

Lifetime - T.T.S. -

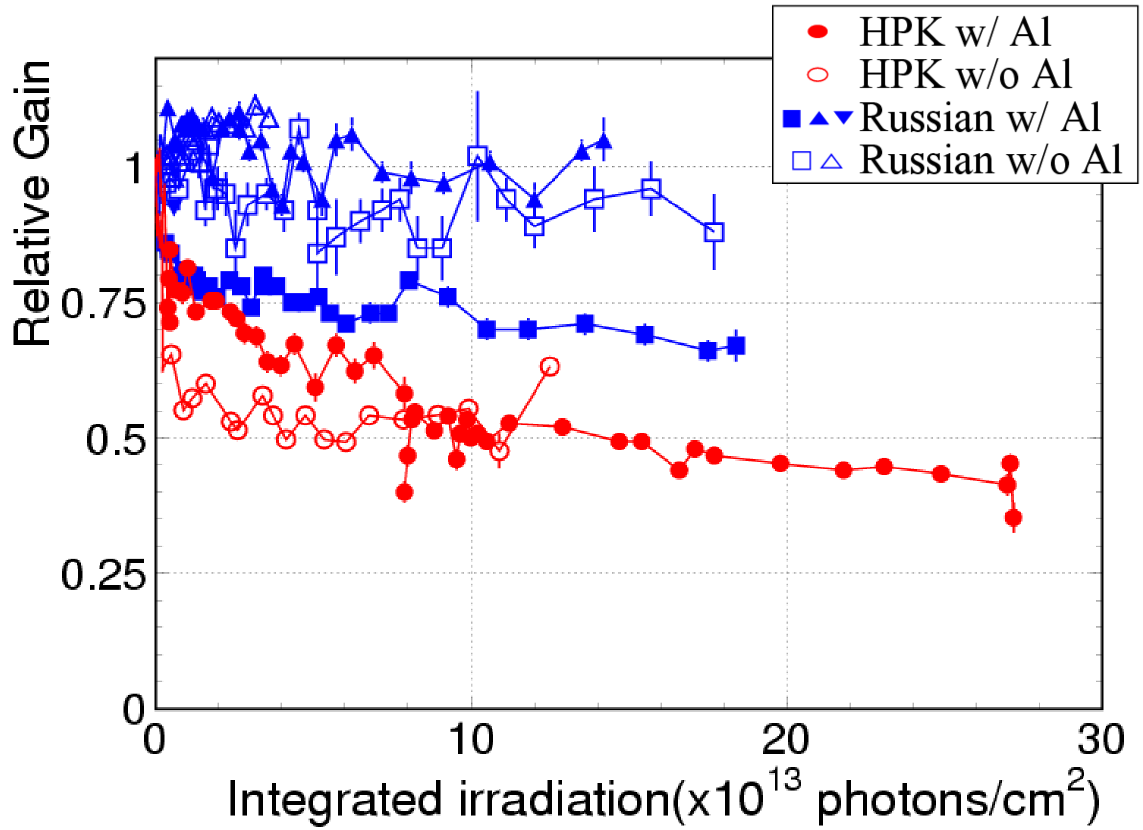
- Time resolution for single photon
  - →No degradation!
    - Keep ~35ps





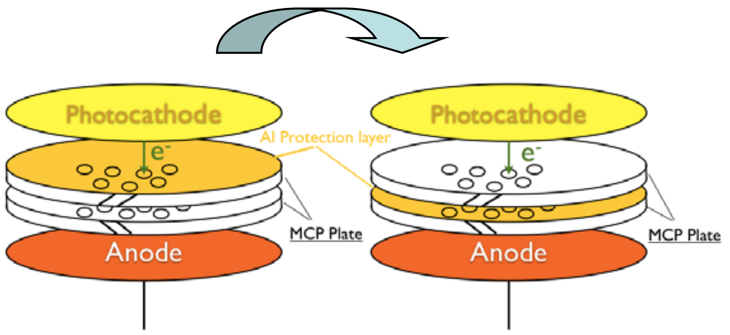
Lifetime - Gain -

- Estimate from output charge for single photon irradiation
- $<10^{13}$photons/cm^2
  - Drop fast
- $>10^{13}$photons/cm^2
  - Drop slowly
- Single photon detection: OK
- Can recover gain by increasing HV



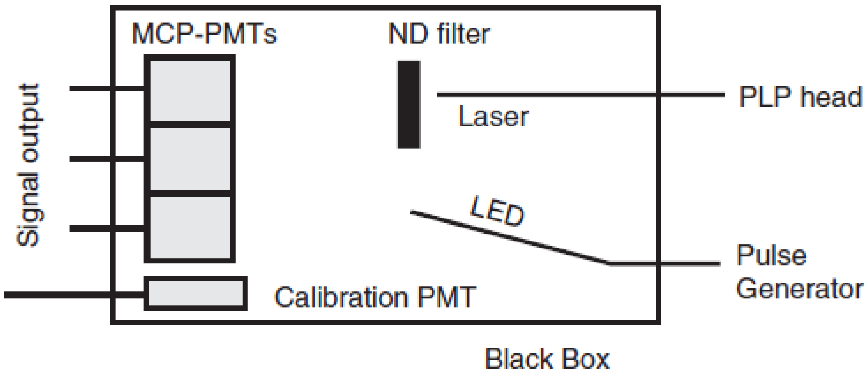
Lifetime for square-shape MCP-PMT

- Square-shape MCP-PMT
  - 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

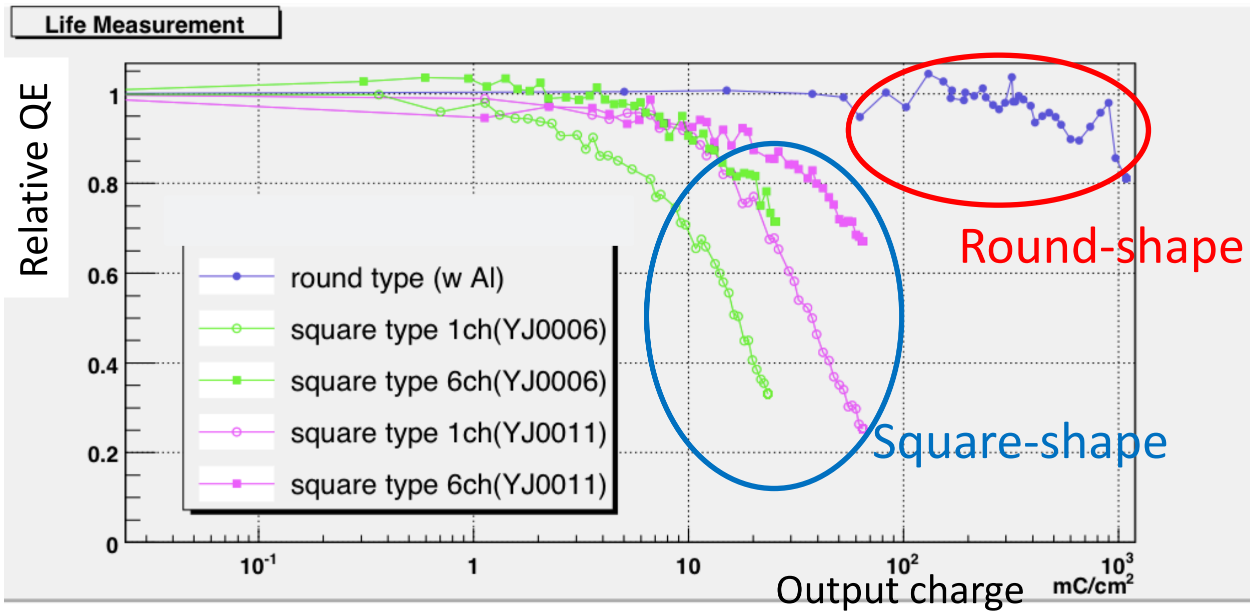


Measured PMT	YJ0006	YJ0011
Al protection layer	1st MCP	2nd MCP
Initial gain ($\times 10^6$)	0.41	1.1

- Lifetime measurement
  - Light load by LED pulse (1~20kHz)
    - 20~50 p.e. /pulse
  - Relative efficiency, gain and TTS
    - By pulse laser at single photon level
    - Periodically

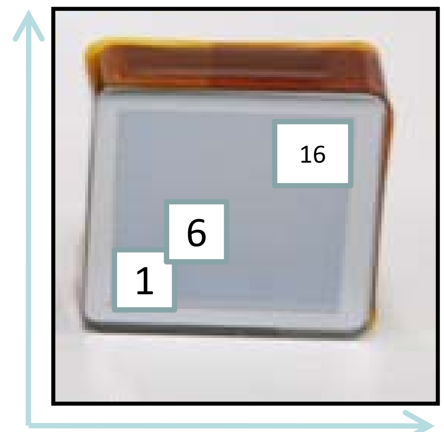


Lifetime test for square-shape MCP-PMT

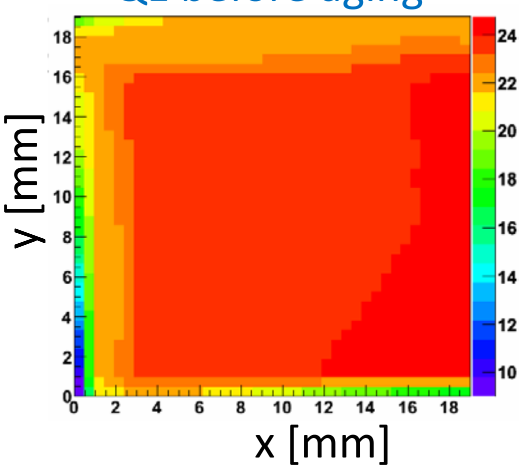


The aluminum layer is not enough!

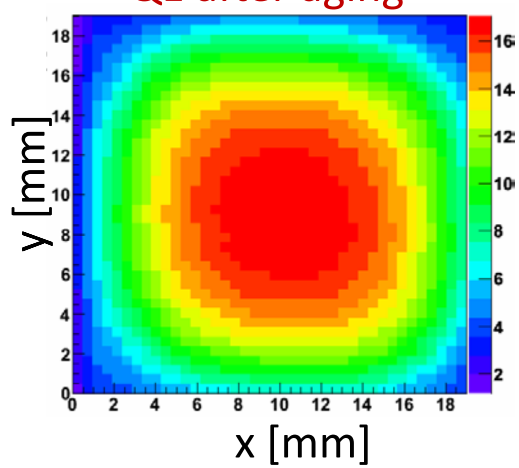
– Ch.1 drops more rapidly than ch.6?



QE before aging



QE after aging

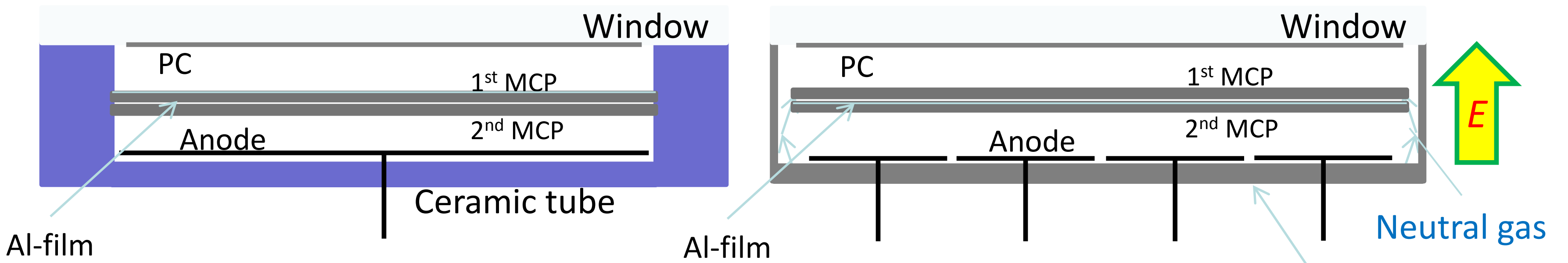


The QE drop becomes more significant toward the edges.

– Related to the structure?

Lifetime study

- Inner structure of round-shape and square-shape MCP-PMTs

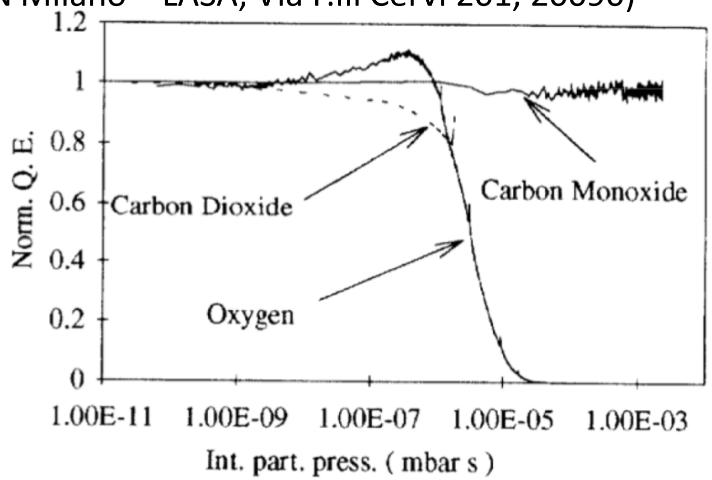


Round: separated

Square: connected

- Only NEUTRAL gas can pass through gap (due to electric field)

Poisoning of multi-alkali PC with different gasses
(INFN Milano – LASA, Via F.lli Cervi 201, 20090)



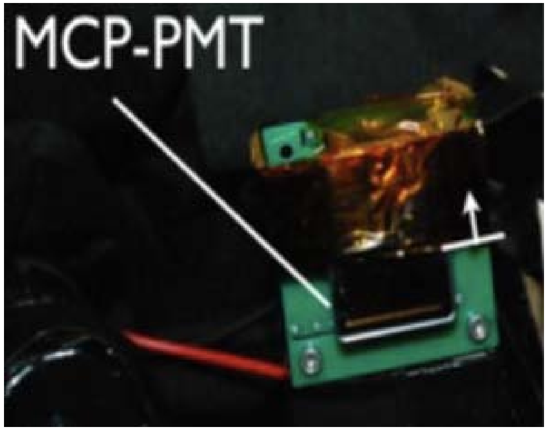
Too much oxidation of Cs
➔variation of band gap
➔increase of work function

We suspected that neutral gas through side gap causes QE degradation.

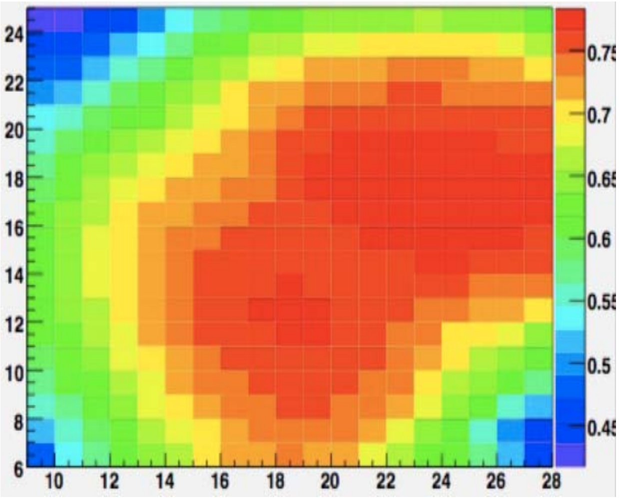
QE drop with mask

- Neutral gas vs. ion-feedback
  - Photon irradiation with mask
  - Check QE degradation
  - ➔ No change with/without mask

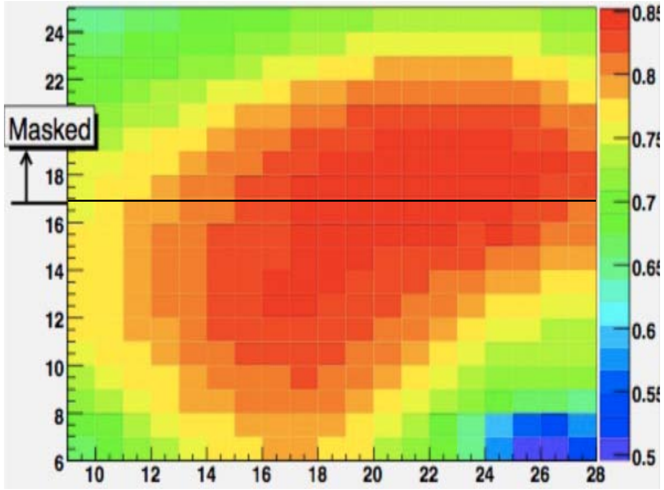
    This supports that the degradation is due to <u>residual gas from side gaps, not ions through MCP</u>



QE drop without mask (0.2C/cm^2)

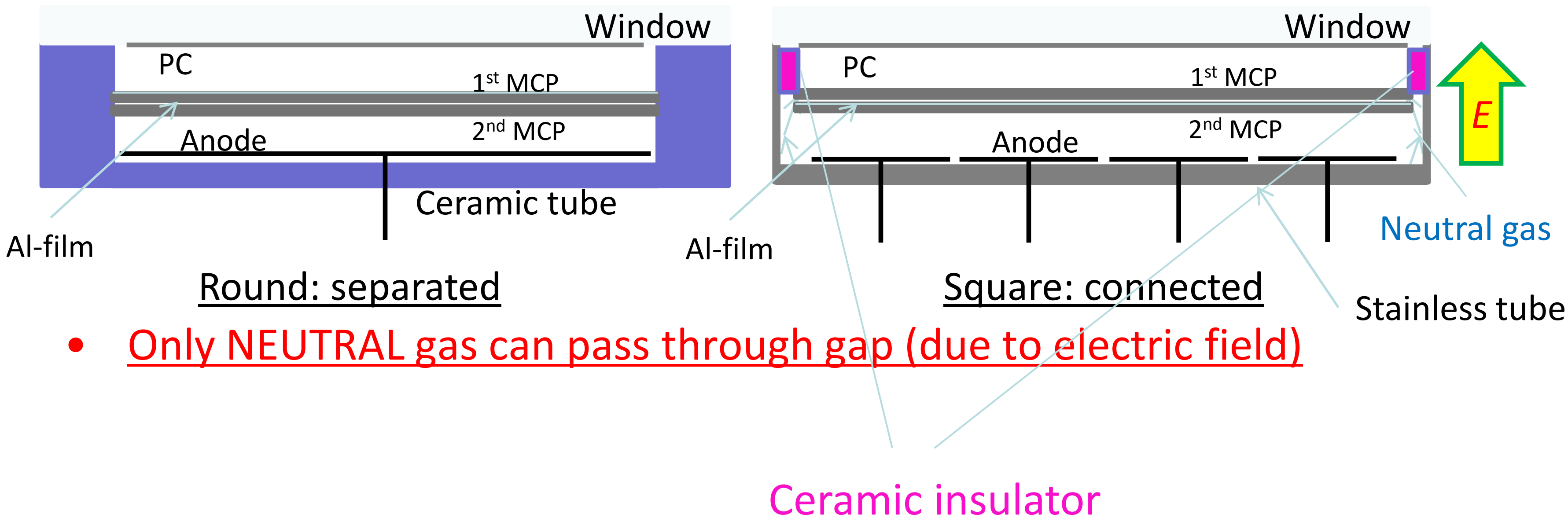


QE drop with mask (0.16C/cm^2)



Lifetime study

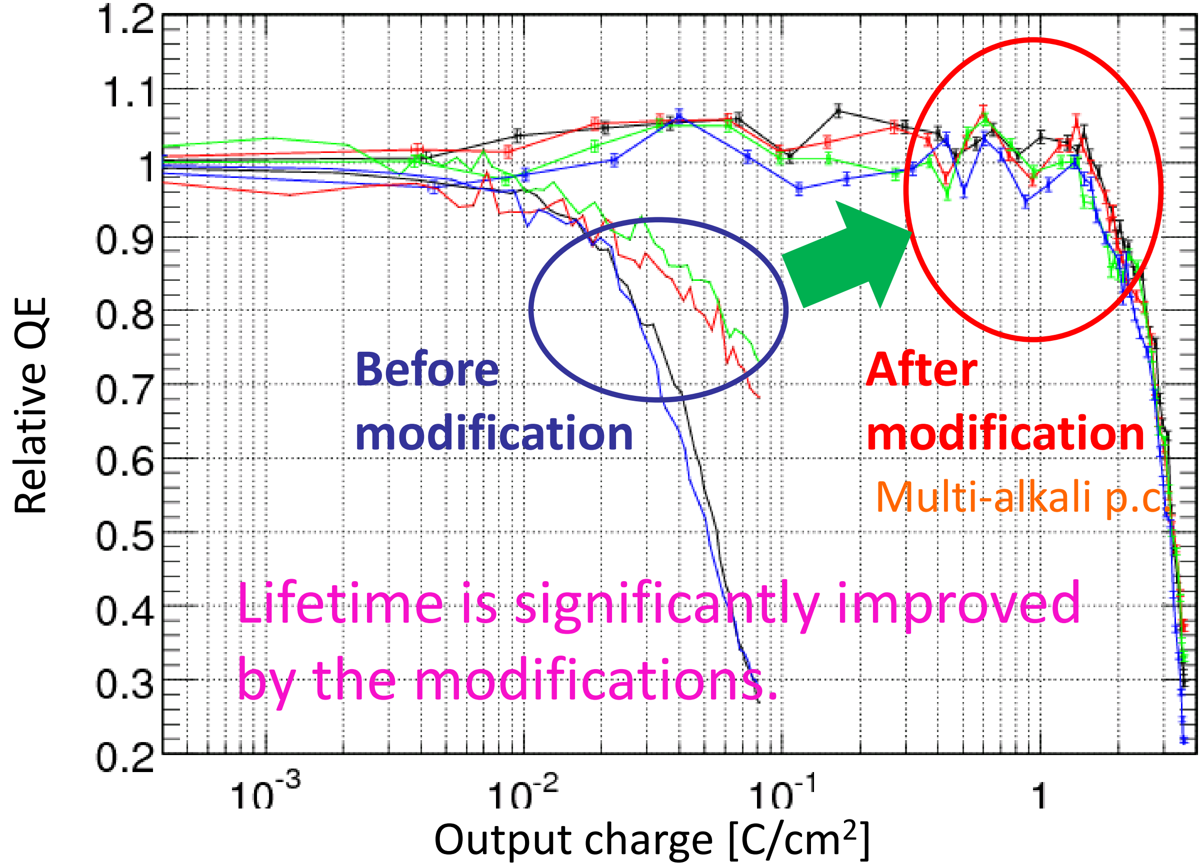
- <u>Inner structure of round-shape and square-shape MCP-PMTs</u>



- Only NEUTRAL gas can pass through gap (due to electric field)

- Following modifications are made.
  - Blocking the path that connects the p.c. and the anode sides,
  - Adopting a low out-gassing type of MCPs.

Lifetime test after modification

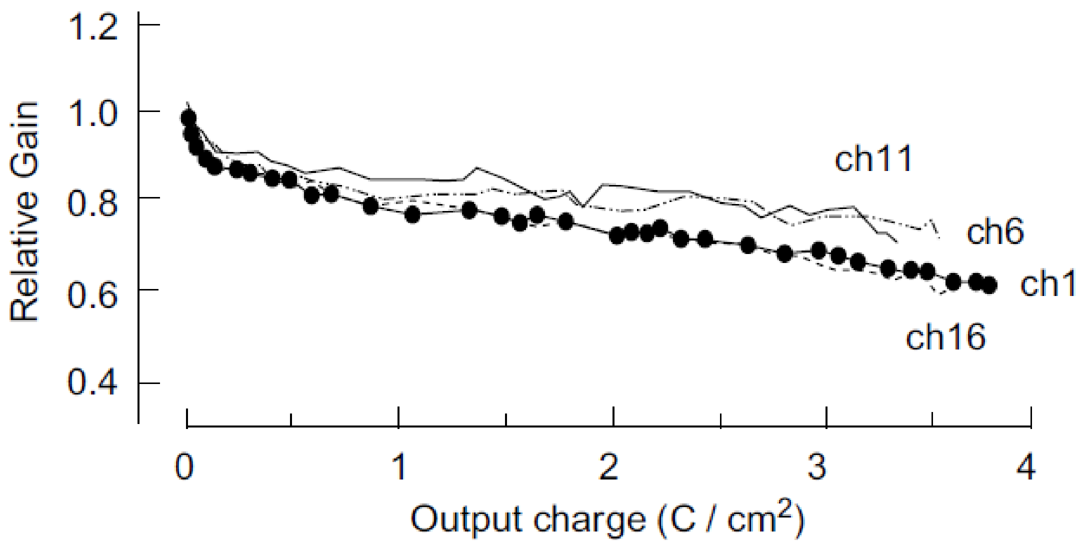


- 2.5 [C/cm^2] for relative QE ~80%
  - Corresponding to 1×10^{14} [photons/cm^2]

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

Lifetime result

- Gain
  - Same as previous results
  - Recover by applying higher HV



- Transit Time Spread
  - 41±4 ps
    - Slightly worse due to electronics
  - Stable as expected

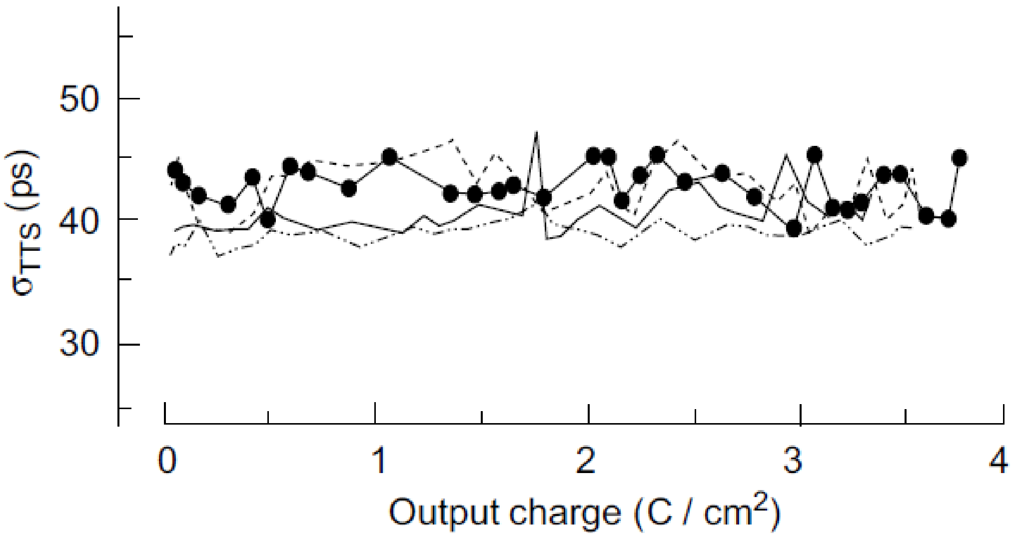
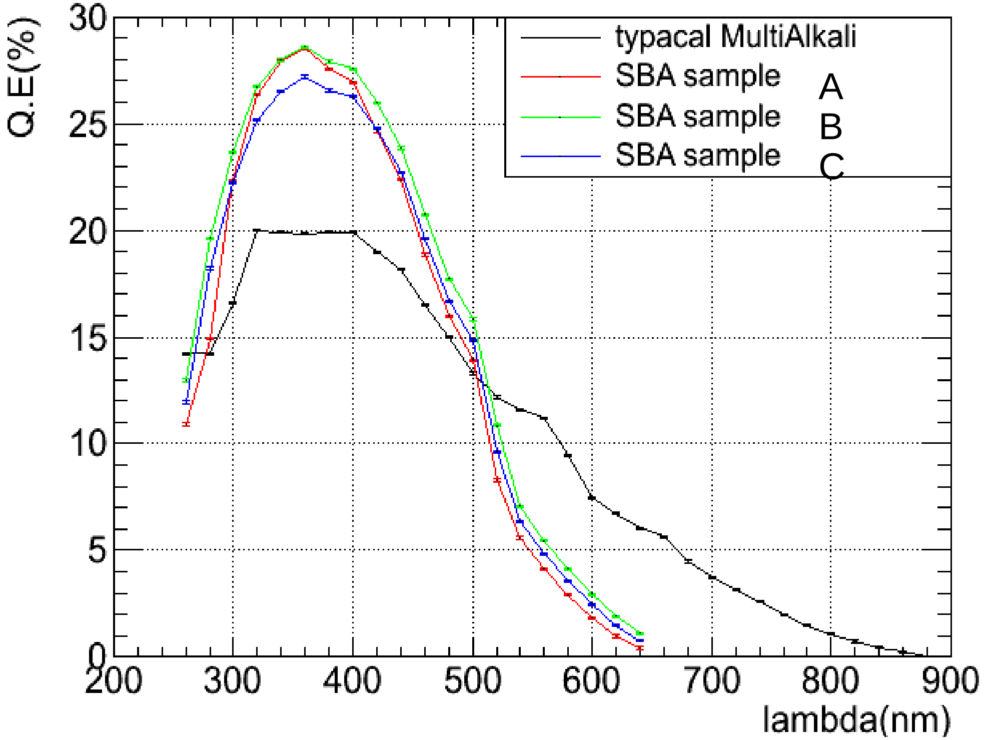
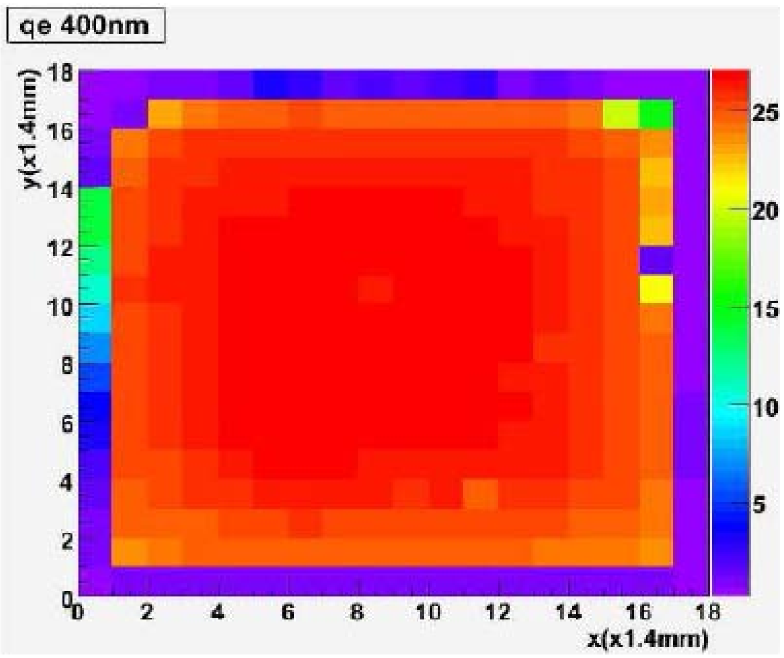


Photo-cathode improvement

- Super bi-alkali technique
  - 28% for bi-alkali and 24% for multi-alkali
  - Improve number of detected photons by 20%

QE distributions for recent samples

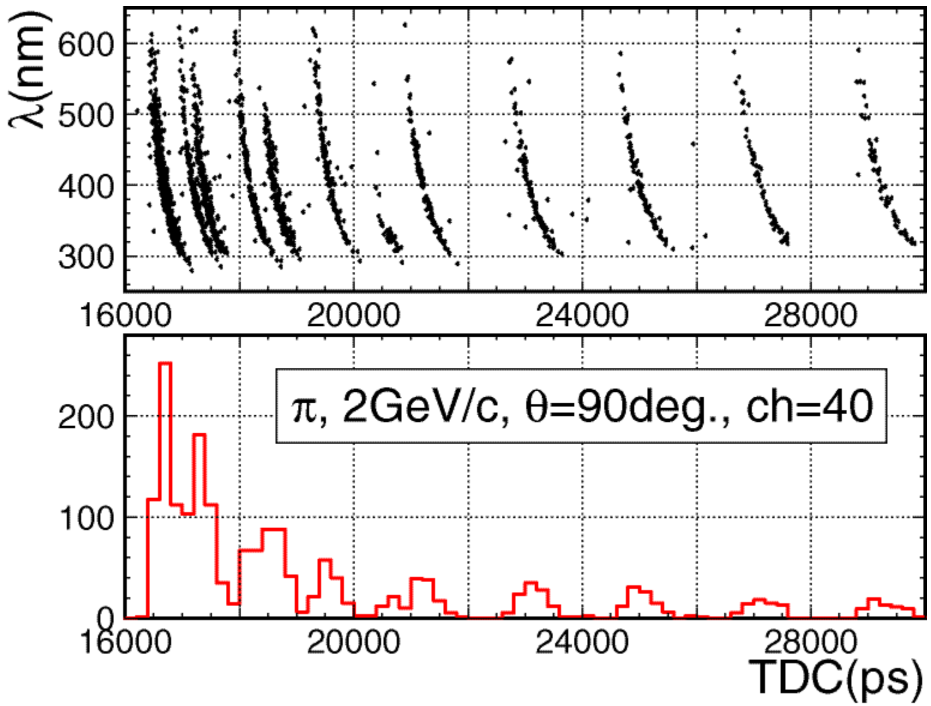


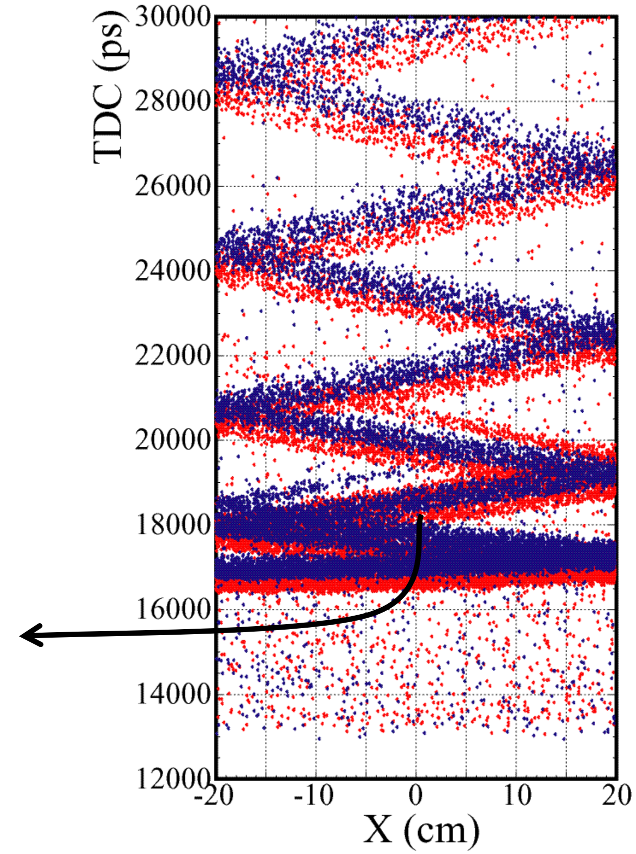


Chromaticity in TOP counter

- Detection time depending on the wavelength of Cherenkov photons
  - Worse time resolution

    → Worse ring-image separation

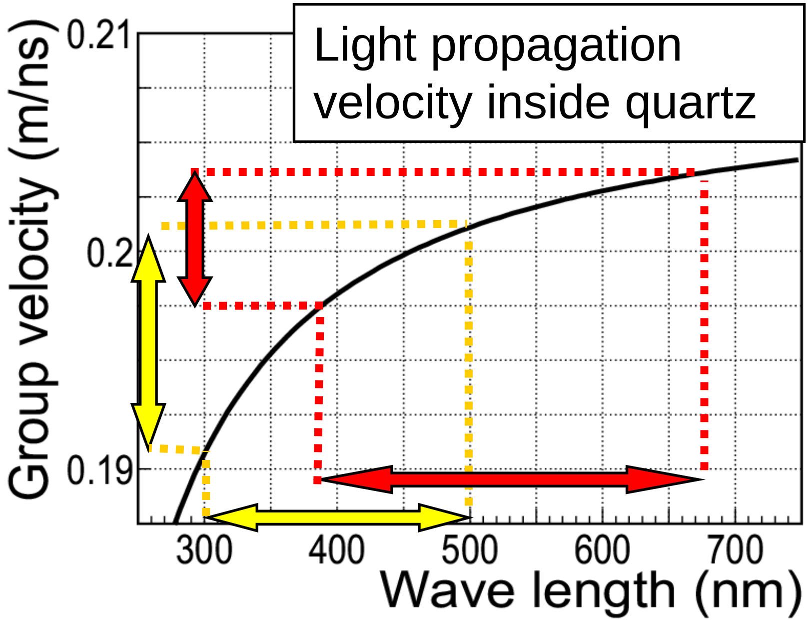


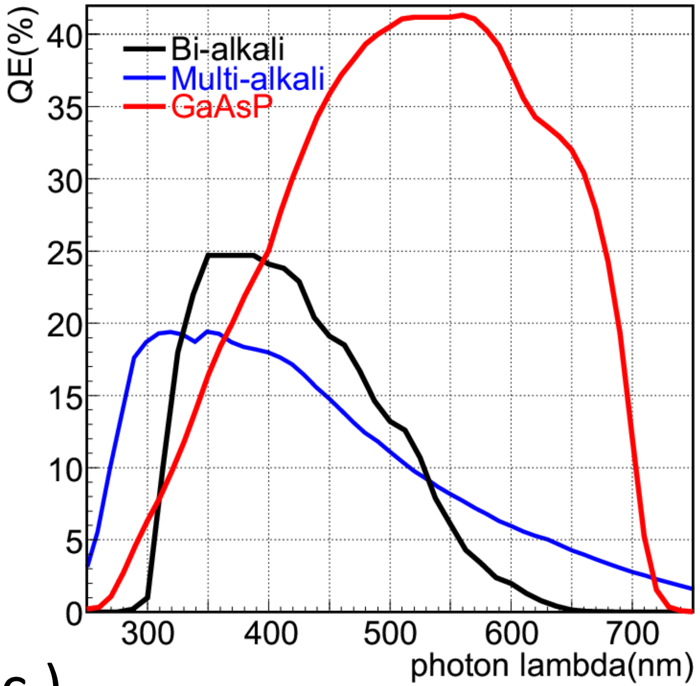


- ➔ Propagation velocity depending on λ in the quartz bar

Chromatic dispersion

Variation of propagation velocity depending on the wavelength of Cherenkov photons





- GaAsP photo-cathode (←→ alkali p.c.)
  - Higher quantum-efficiency
  - at longer wavelength → less chromatic error

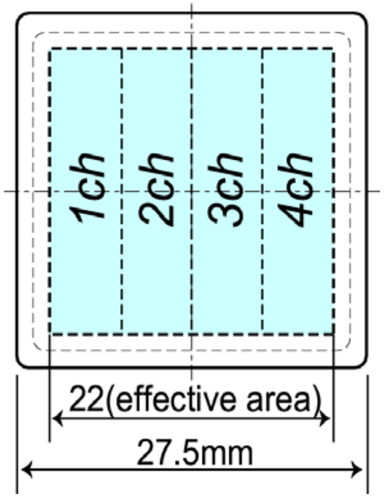
Photon sensitivity at longer wavelength shows the smaller velocity fluctuation.

GaAsP MCP-PMT development

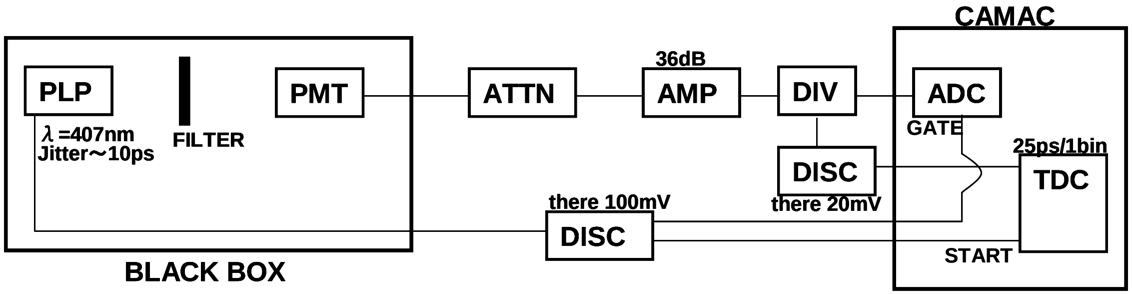
- Square-shape MCP-PMT with GaAsP photo-cathode is developed with Hamamatsu Photonics.

- Prototype
  - GaAsP photo-cathode
    - Al protection layer
  - 2 MCP layers
    - ϕ10μm hole
  - 4ch anodes
  - Slightly large structure
    - Less effective area

Target structure

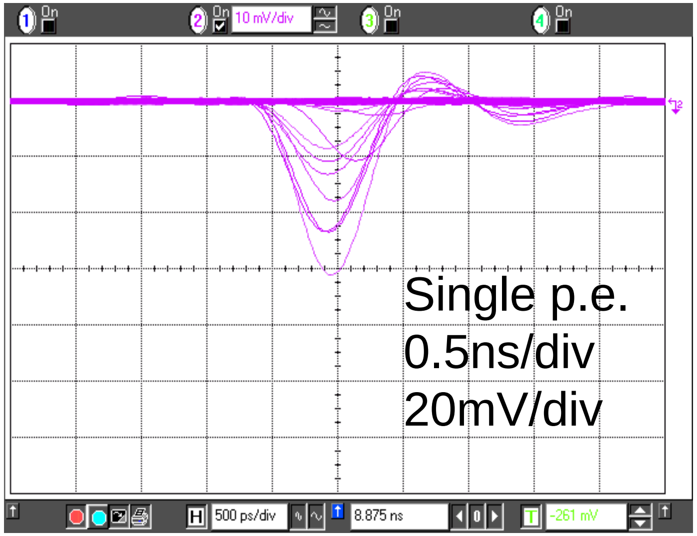


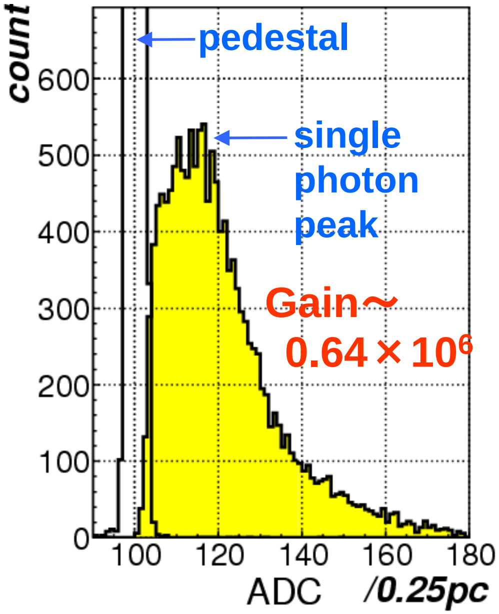
- Performance test
  - Time resolution

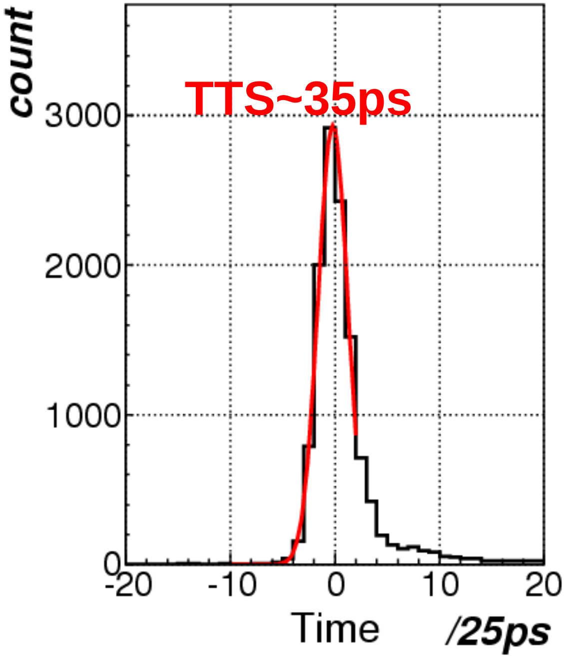


GaAsP MCP-PMT performance

- Wave form, ADC and TDC distributions for single photon







- Enough gain to detect single photo-electron
- Good time resolution (TTS=35ps) for single p.e.

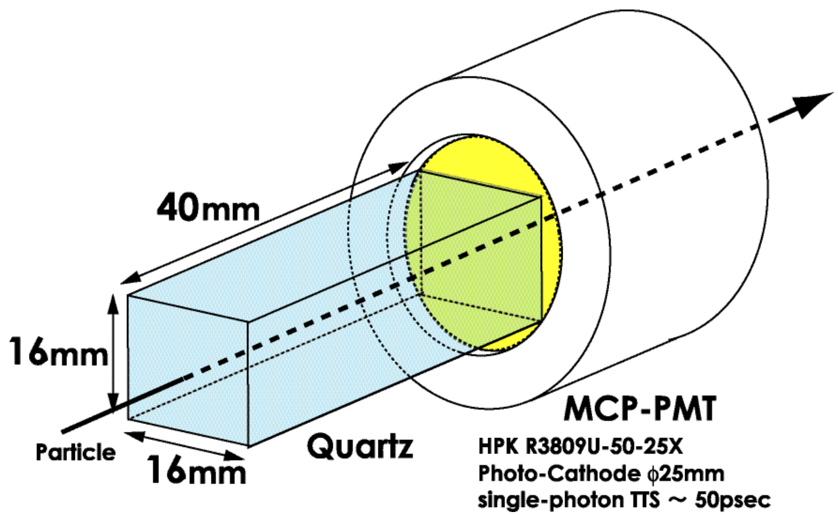
  → Need to improve production rate and lifetime

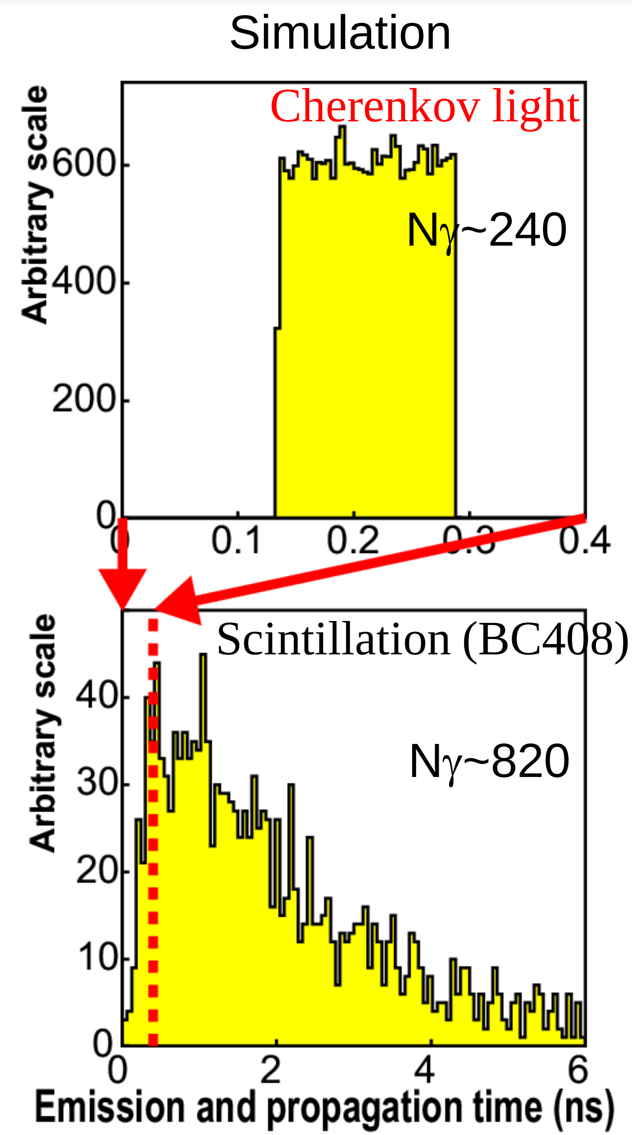
High resolution TOF

- Structure
  - 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

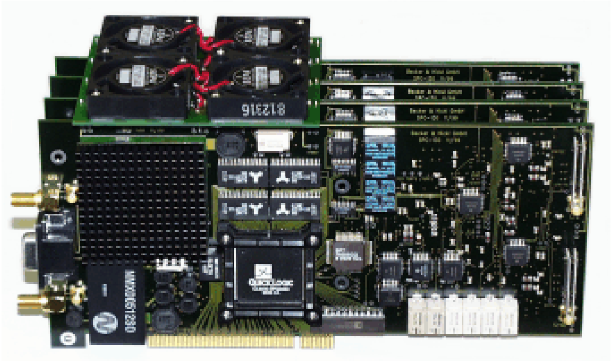




Beam test

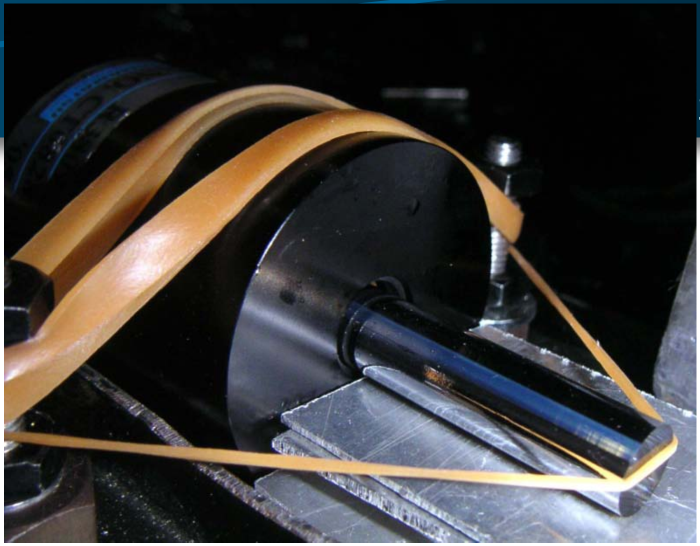
- MCP-PMT (HPK6, R3809U-50-11X)
  - TTS: ~30ps
  - 6μm hole

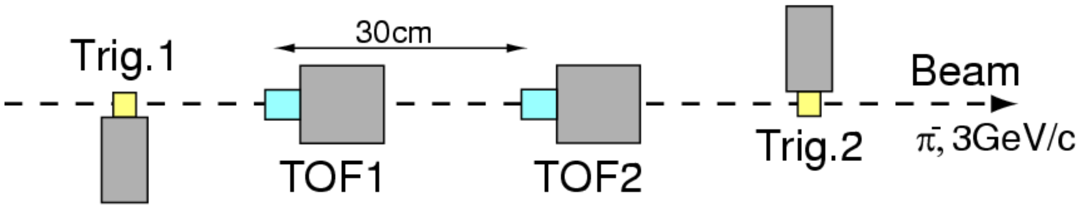
- Readout electronics
  - $\sigma_{elec.}$: 4ps
  - Time-correlated Single Photon Counting Modules (SPC-134, Becker & Hickl GMbH's)
    - CFD, TAC and ADC
    - Channel width = 813fs
    - Electrical time resolution = 4ps RMS

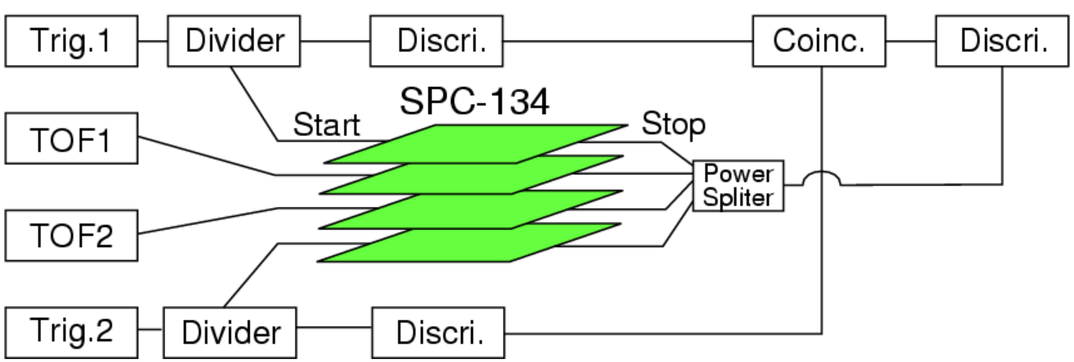


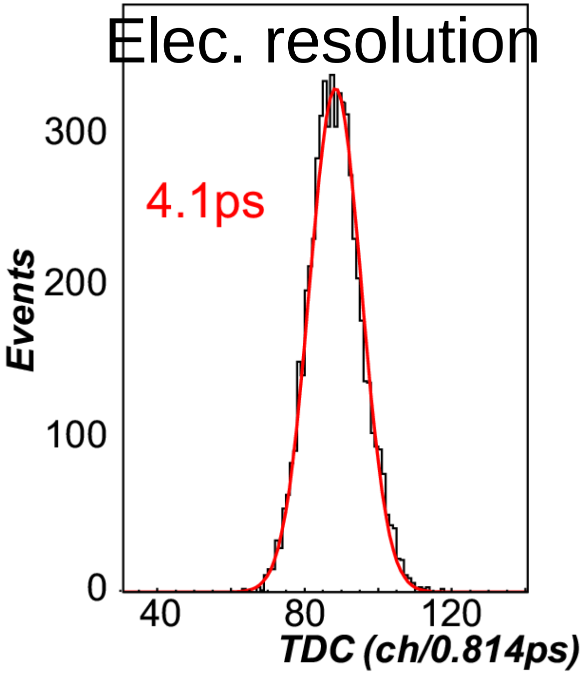
Beam test setup

- 3GeV/c π^- beam
  - at KEK-PS π2 line
- PMT: R3809U-50-11X
- Quartz radiator
  - 10^{ϕ}x40^{z}mm with Al evaporation



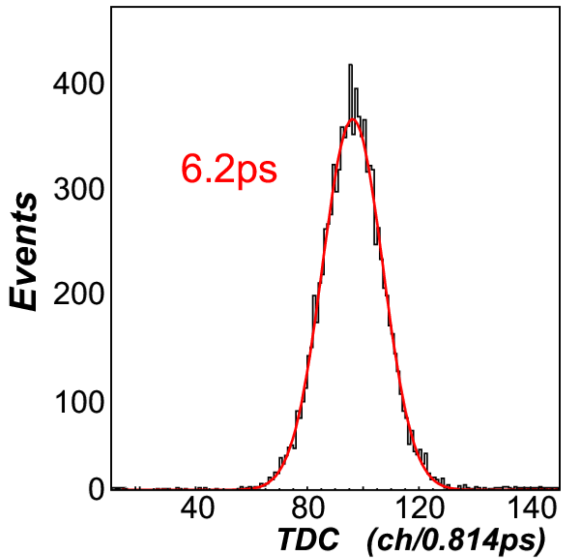




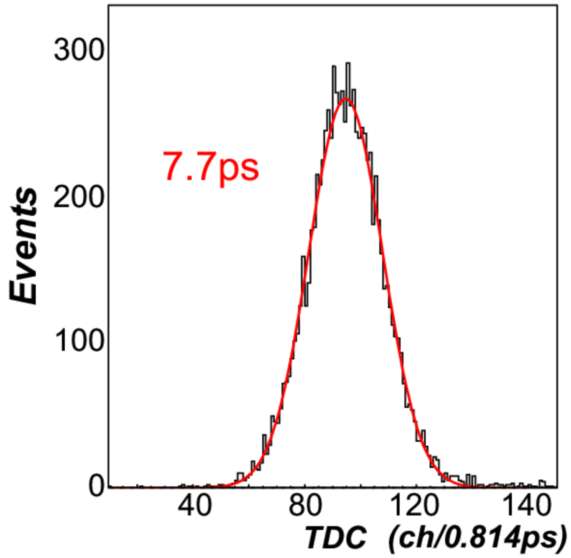


Beam test result

- With 10mm quartz radiator
  - +3mm quartz window
  - Number of photons ~ 180
  - Time resolution = 6.2ps
  - Intrinsic resolution ~ 4.7ps

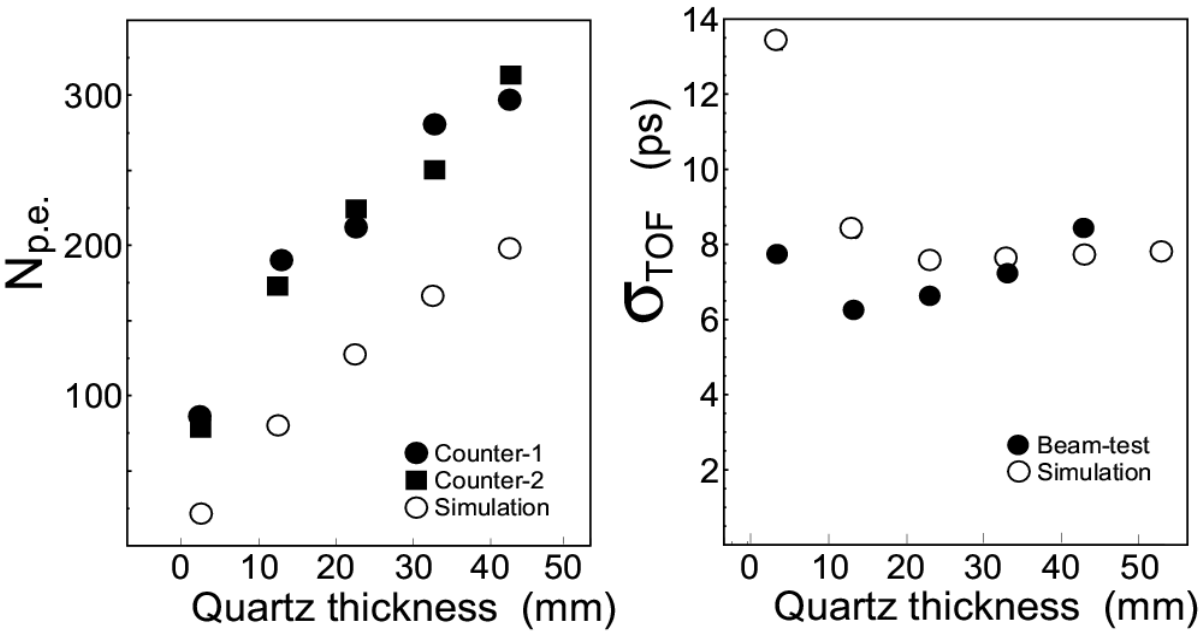


- Without quartz radiator
  - 3mm quartz window
  - Number of photons ~ 80
    - Expectation ~ 20 photo-electrons
  - Time resolution = 7.7ps



Beam test result

- $N\gamma$, σ_{TOF} v.s. radiator thickness



  - Extra photo-electrons
    - $N_{p.e.}$ from short distance is larger than that of expected.
  - Time-resolution behavior
    - Resolution is gradually worse.
    - → Extra p.e. would affect the resolution dependence.

Summary

- We have developed square-shape MCP-PMT.
  - With Hamamatsu photonics
  - Gain~10^6, TTS<40ps for single photon detection
  - QE>20% at 400nm, good flatness
    → Super bi-alkali technique adopted
      QE ~ 28% at 400nm
  - Lifetime has been improved.
    - >80% for 2.5 C/cm^2 for multi-alkali, >1 C/cm^2 for bi-alkali
    - By blocking the path, where an out-gas from the anode side can reach to the photo-cathode.
    - By reducing the out-gases of MCPs.
    - Neutral gases seem to be the possible cause of the QE degradation.

→ Mass production