2009/5/11-13

Workshop on fast Cherenkov detectors

- Photon detection, DIRC design and DAQ

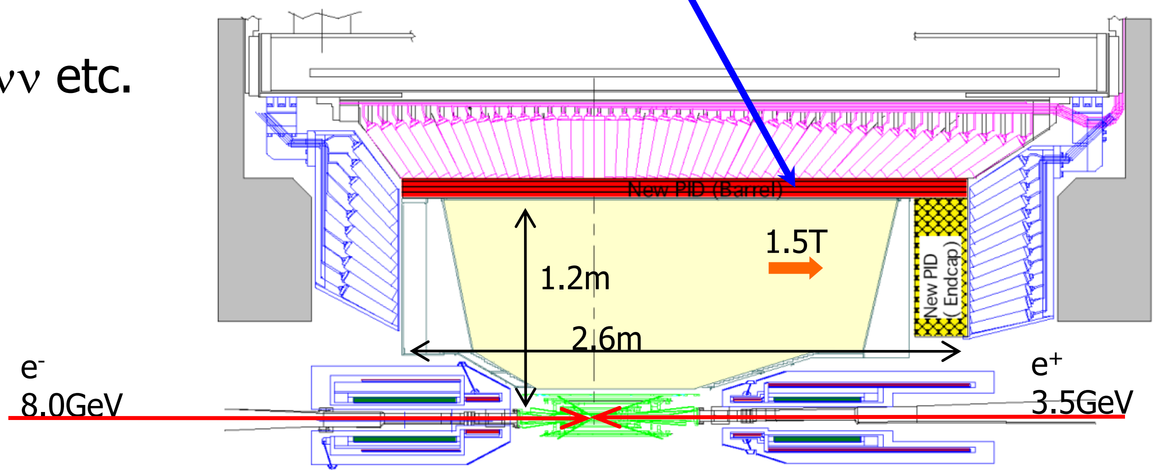
Development of TOP counter for Super B factory

- Introduction
- Design study
    - Focusing system
- Prototype development
    - Beam test
- Summary

K. Inami (Nagoya university)

Introduction

- 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→$\pi\pi$/Kπ, $\rho\gamma$, K$\nu\nu$ etc.
    - Flavor tag
    - Full reconstruction
  - Target; 4σ for 4 GeV/c

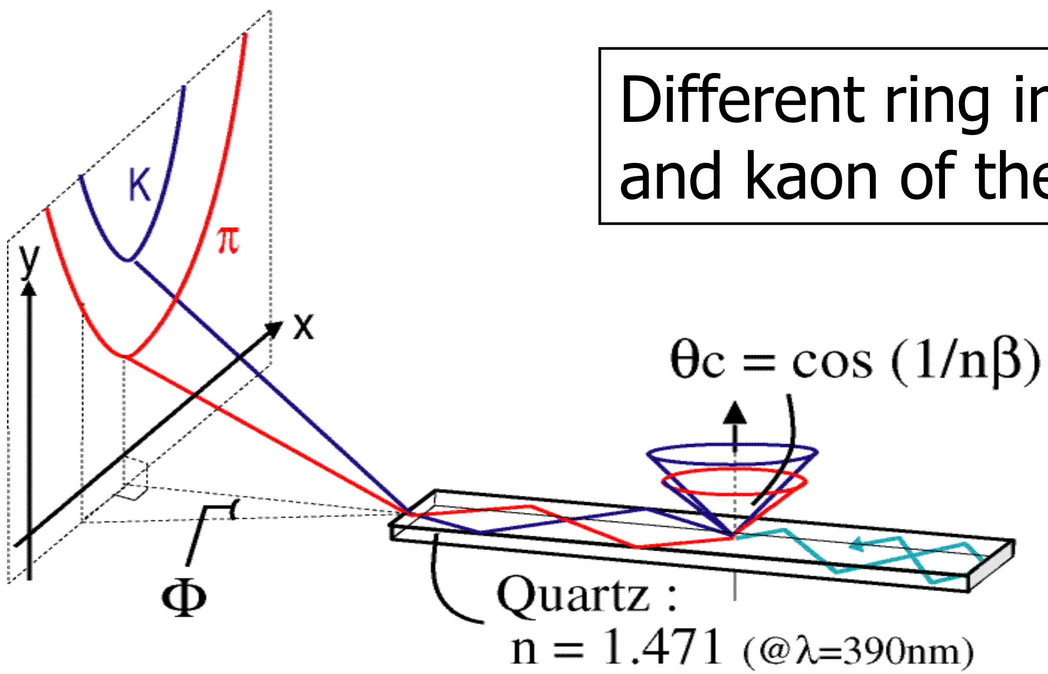


Side view of **Belle II** detector

TOP counter

- <u>Cherenkov ring in quartz bar</u>
  - Reconstruct ring image using ~20 photons on the screen reflected inside the quartz radiator as a DIRC.
    - Photons are detected with photon detectors.

Different ring image for the pion and kaon of the same momentum

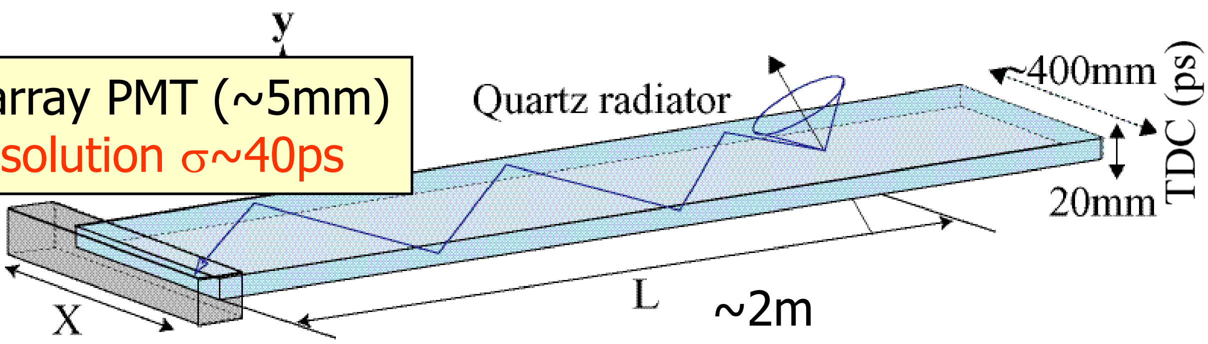


Need large screen...

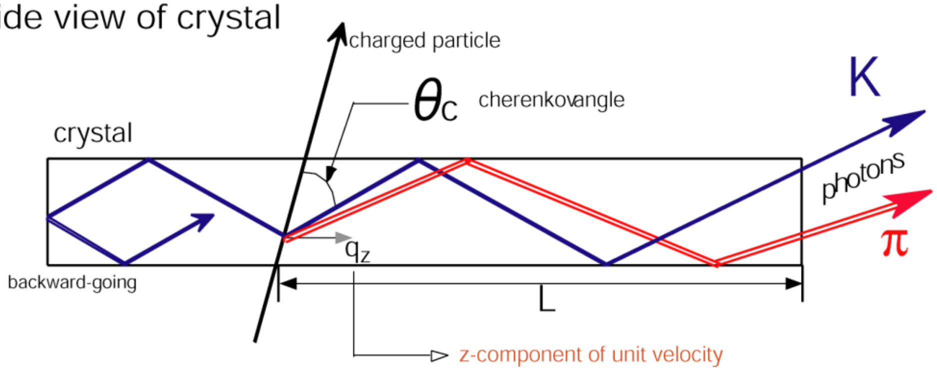
TOP counter

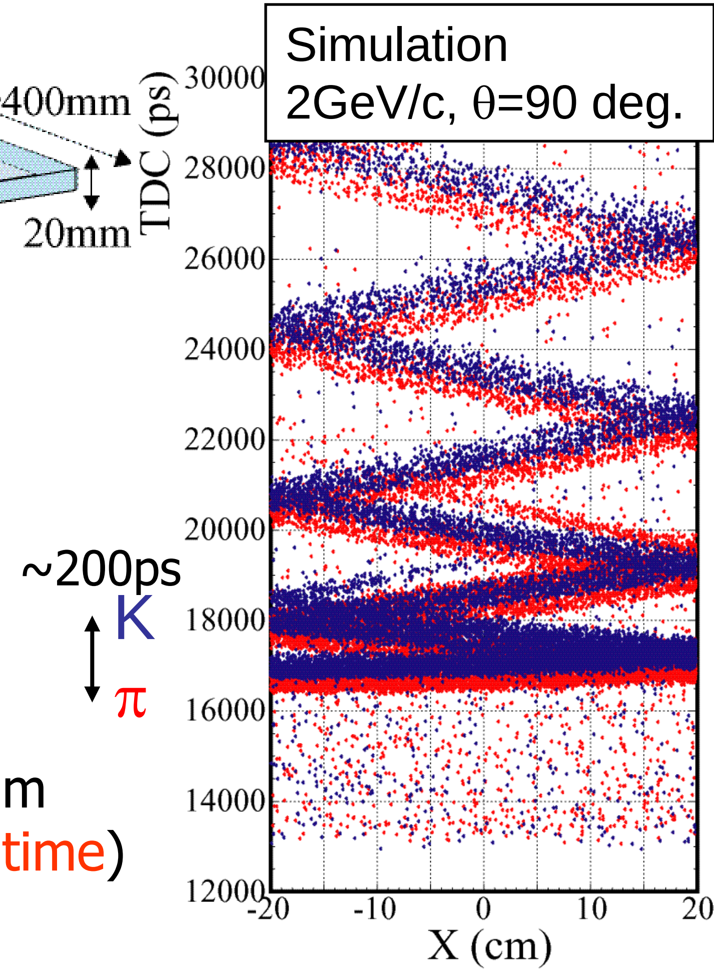
- 2D position information → <u>Position+Time</u>
  - Compact detector!

Linear array PMT (~5mm)
Time resolution σ~40ps



Side view of crystal



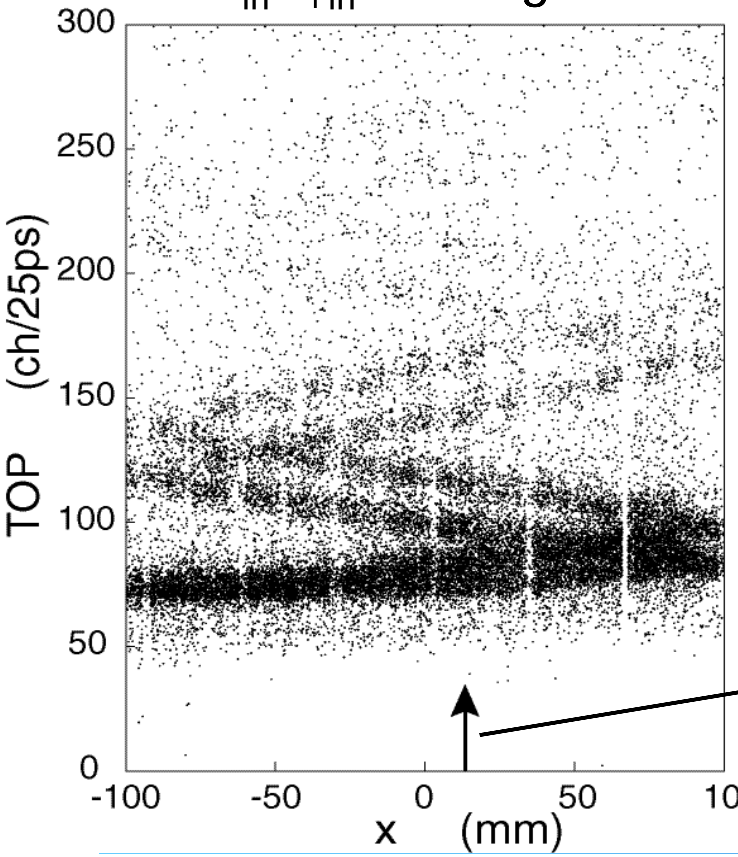


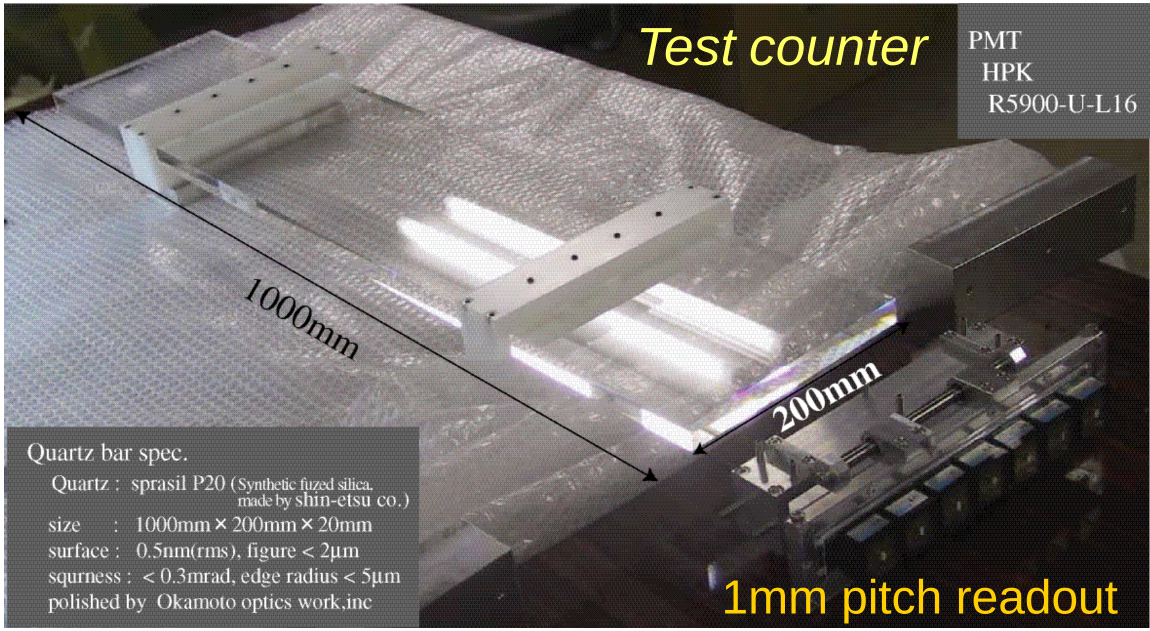
Different opening angle for the same momentum
→ Different propagation length(= propagation time)

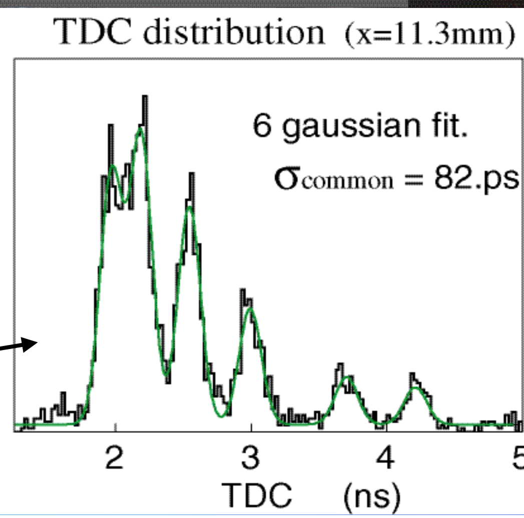
+ TOF from IP works additively.

Old test counter

Beam test
@ KEK PS $\pi 2$ line
3 GeV/c π^- beam
$\theta_{in}=\phi_{in}=90$ degree

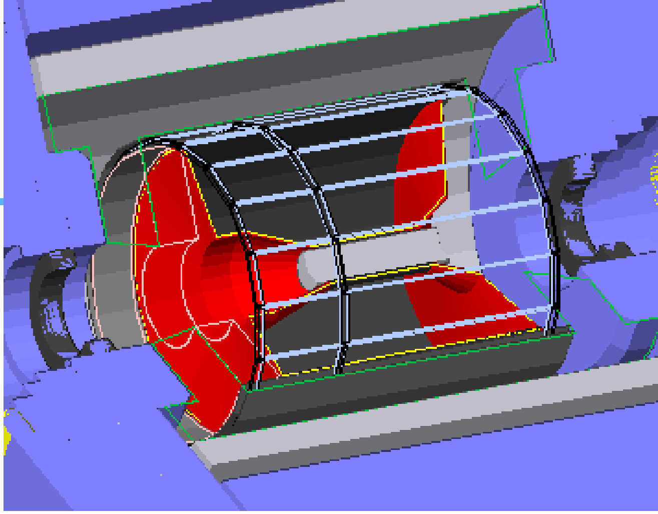




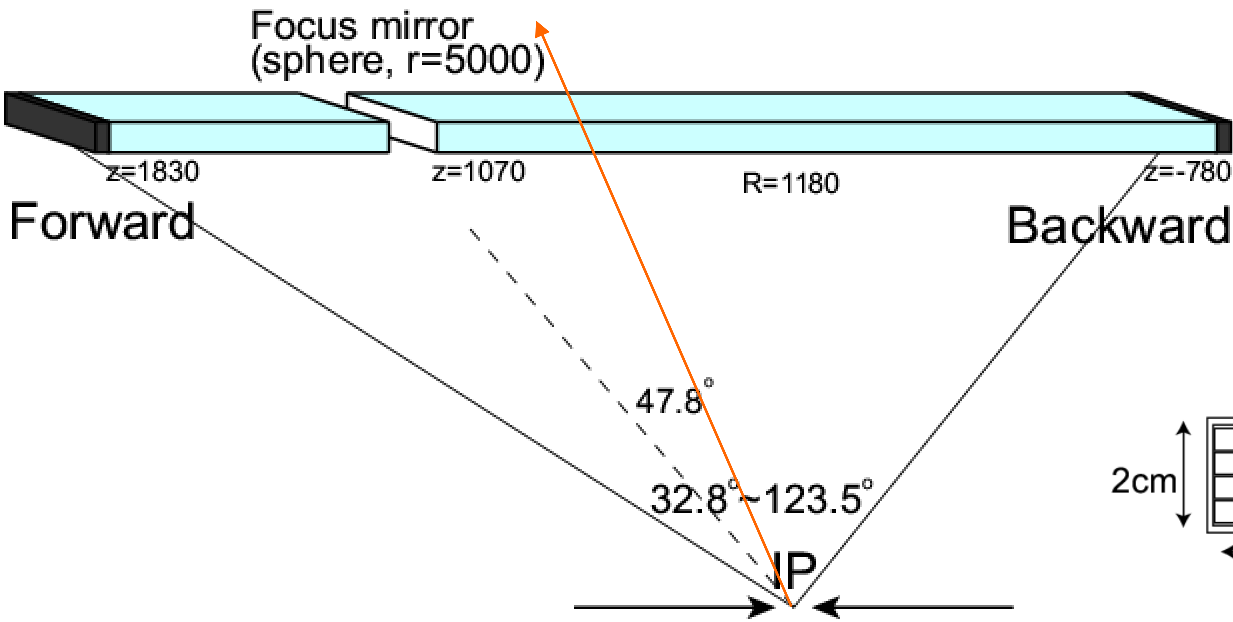


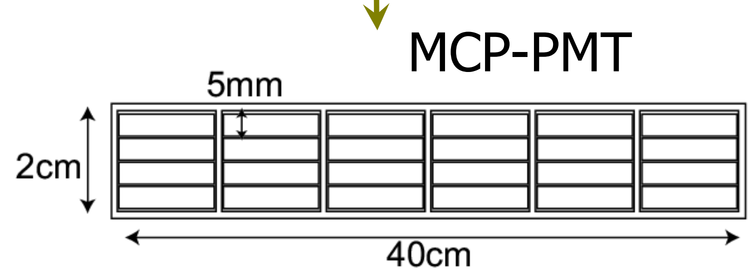
- Clear ring image
- Reasonable time resolution
- Enough bar quality

TOP counter

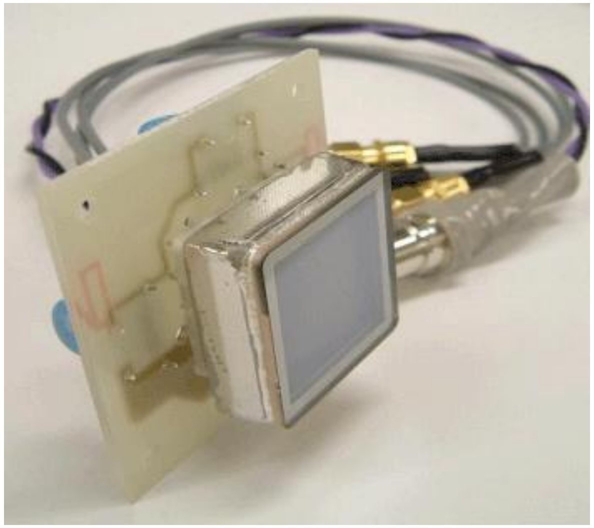


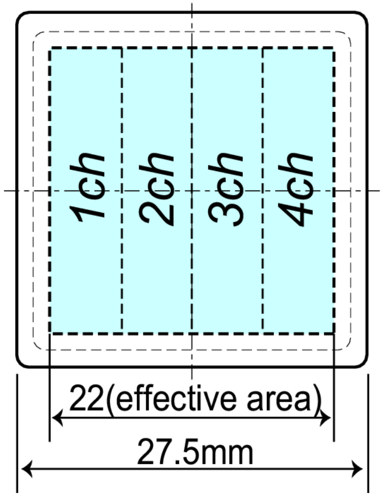
- Quartz: 255cm^L x 40cm^W x 2cm^T
  - Focus mirror at 47.8deg.
    to reduce chromatic dispersion
- Multi-anode MCP-PMT
  - Linear array (5mm pitch), Good time resolution (<~40ps)
  - → Measure Cherenkov ring image with timing information





Multi-anode MCP-PMT (1)





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

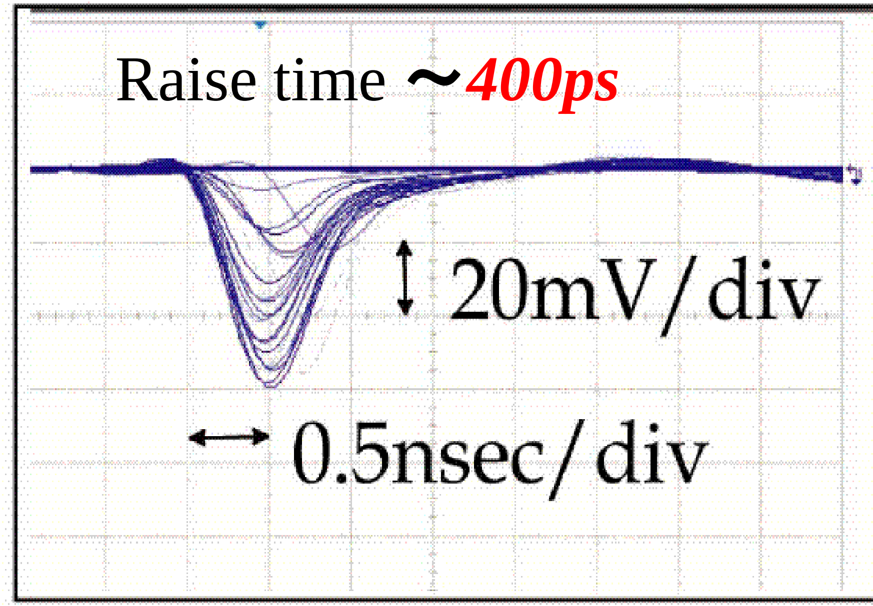
R&D with Hamamatsu
for TOP counter

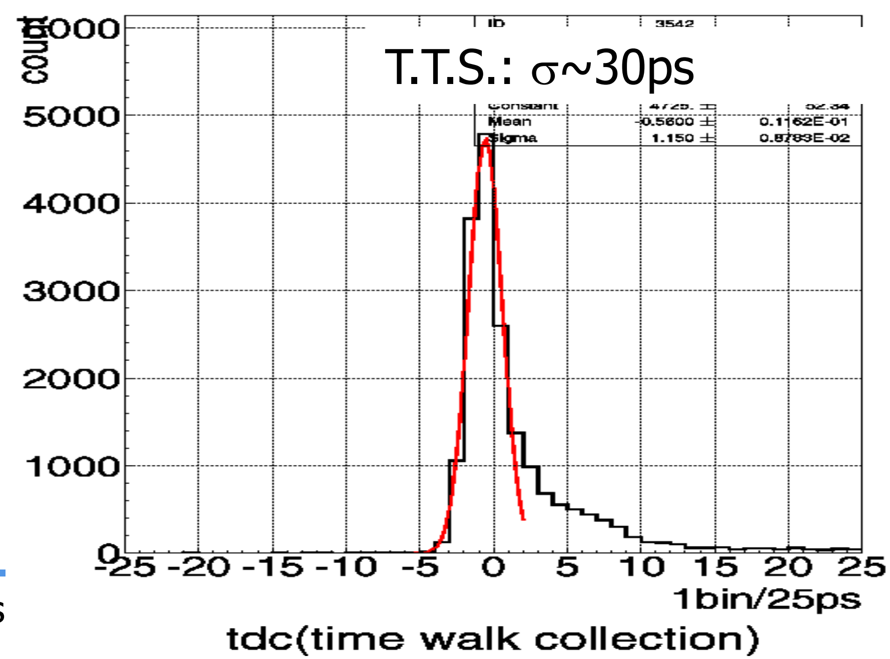
- Large effective area — 64% by square shape
- Position information — 4ch linear anode (5mm pitch)

Multi-anode (2)

- Single photon detection
- Fast raise time: ~400ps
- Gain=1.5x10^6 @B=1.5T
- T.T.S.(single photon): ~30ps @B=1.5T
- Position resoltion: <5mm
- Correction eff.: ~50%
  - Nucl. Instr. Meth. A528 (2004) 768.

- Basic performance is OK!
  - Same as single anode MCP-PMT

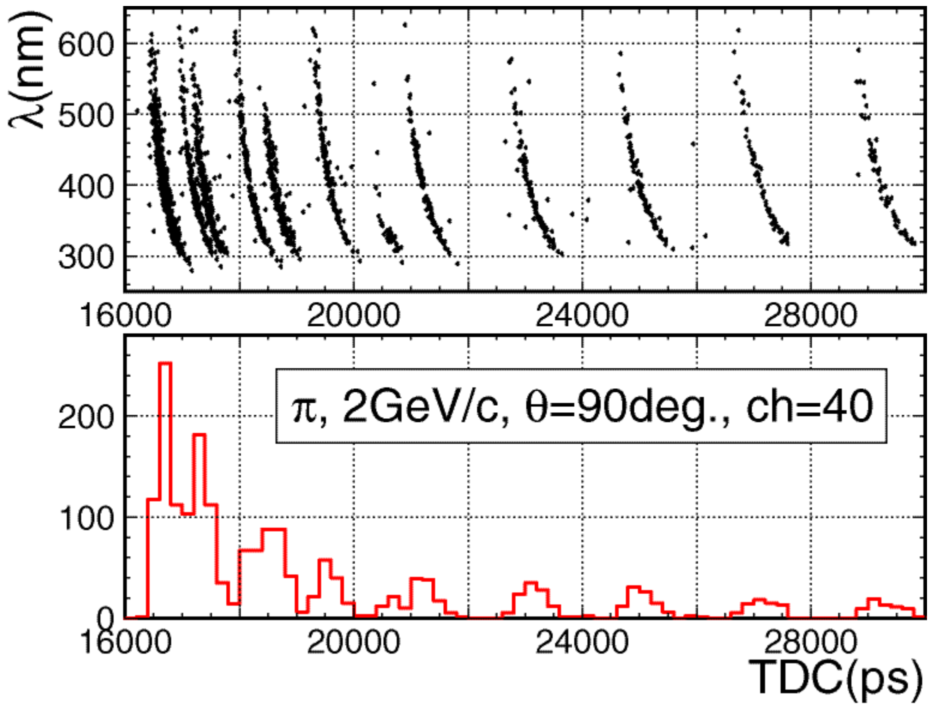


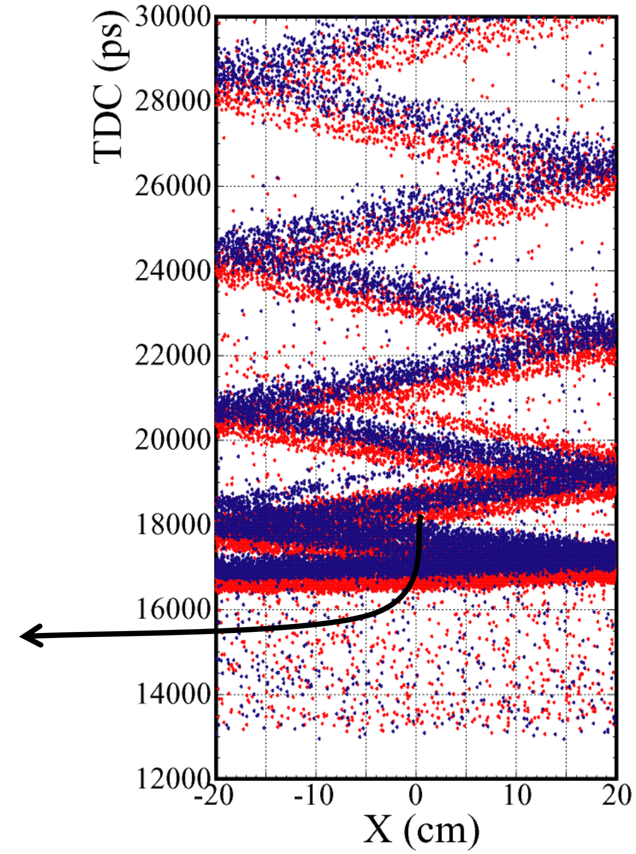


Chromaticity

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

    → Worse ring-image separation

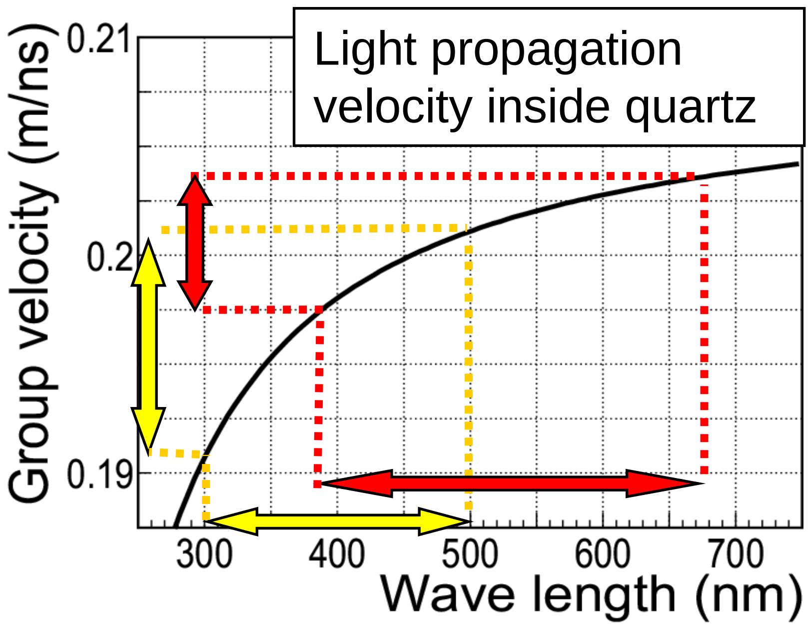


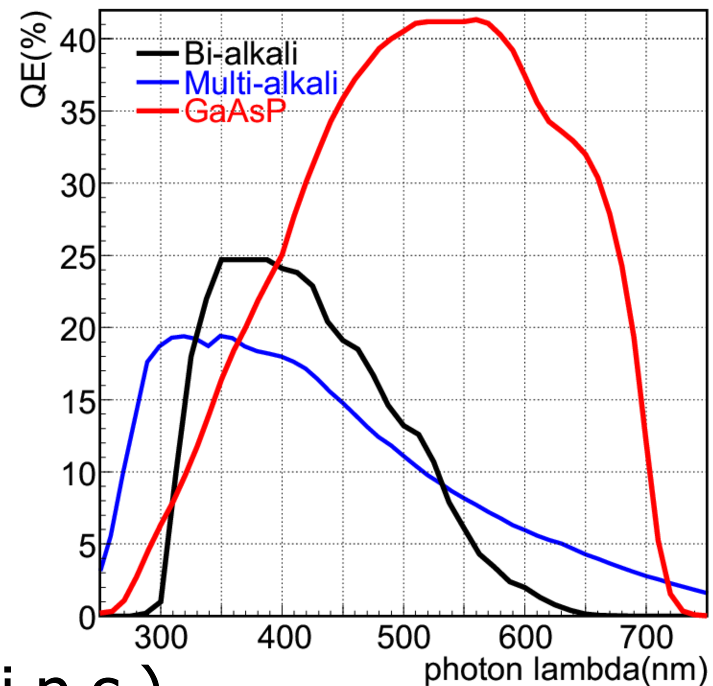


- ➔ Propagation velocity depending on λ in the quartz bar

Chromatic dispersion

Variation of propagation velocity depending on the wavelength of Cherenkov photons





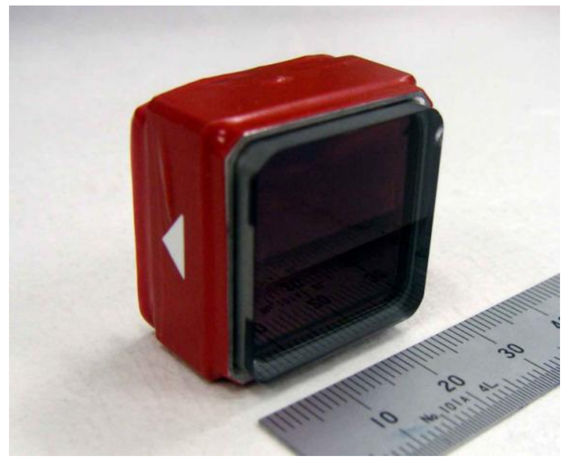
- GaAsP photo-cathode (←→ alkali p.c.)
  - Higher quantum-efficiency
  - at longer wavelength → less chromatic error

Photon sensitivity at longer wavelength shows the smaller velocity fluctuation.

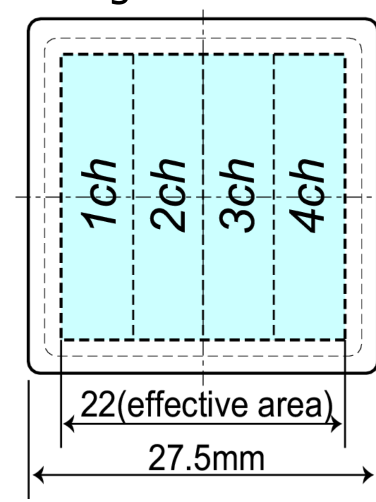
GaAsP MCP-PMT development

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

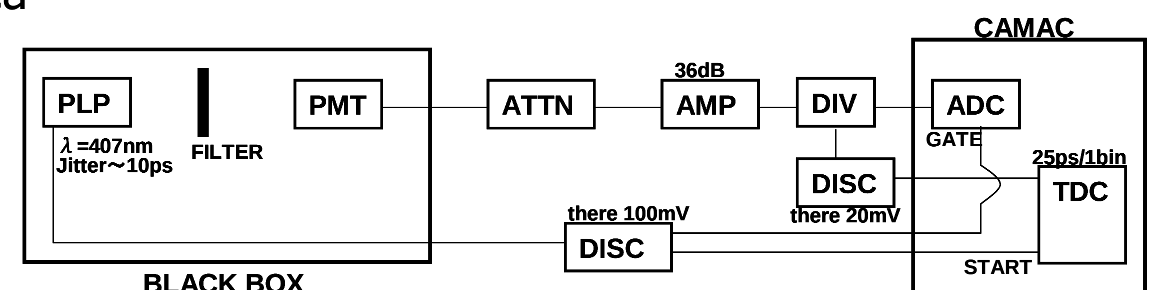
- Prototype
  - GaAsP photo-cathode
    - Al protection layer
  - 2 MCP layers
    - ϕ10μm hole
  - 4ch anodes
  - Slightly large structure
    - Less effective area



Target structure

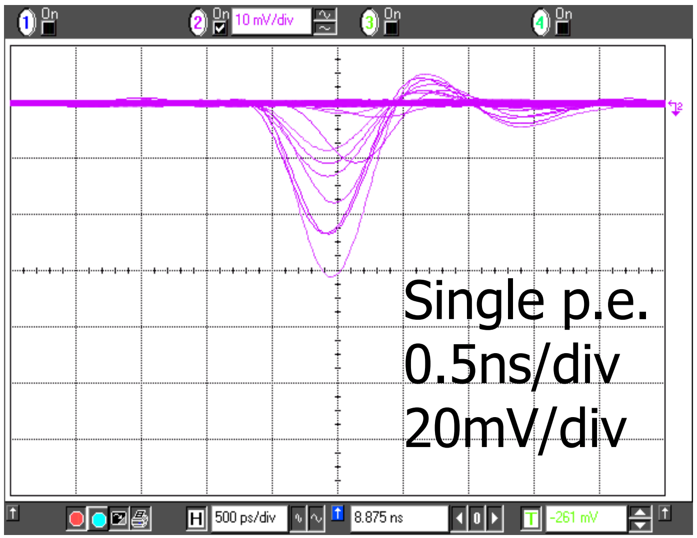


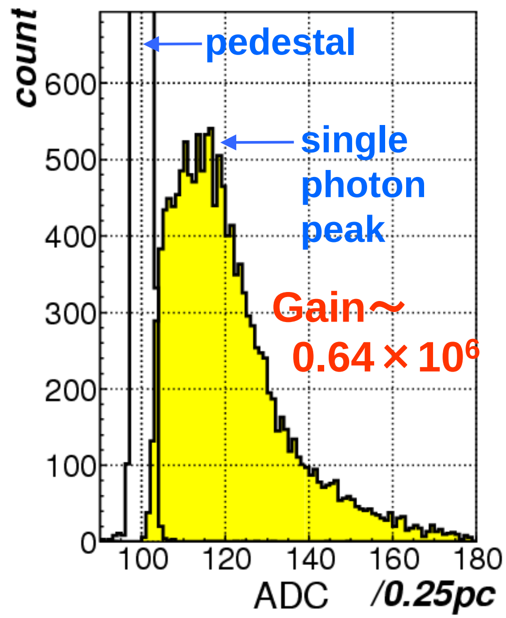
- Performance test
  - Time resolution

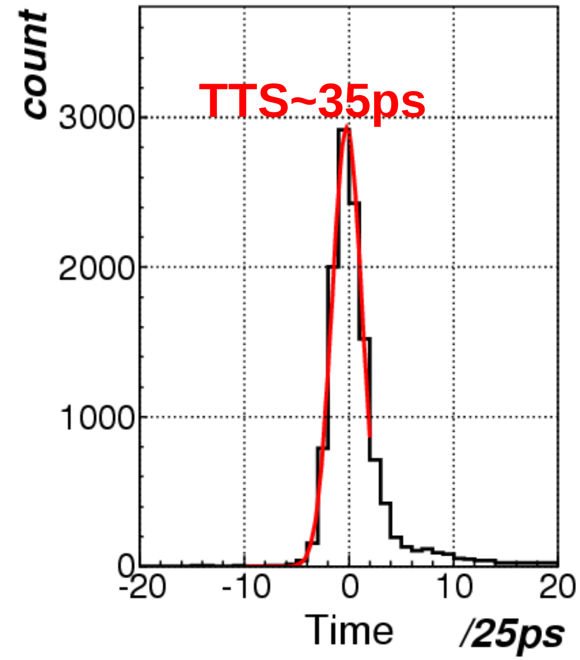


GaAsP MCP-PMT performance

- Wave form, ADC and TDC distributions for single photon







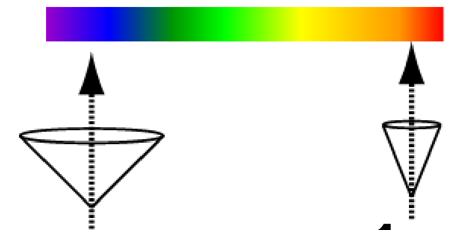
- Enough gain to detect single photo-electron
- Good time resolution (TTS=35ps) for single p.e.
- → Need to improve production rate

Focusing TOP

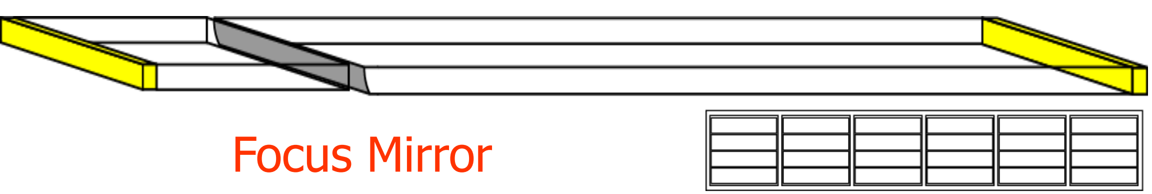
- Remaining chromatic effect makes ~100ps fluctuation for TOP.
- Use λ dependence of Cherenkov angle to correct chromaticity

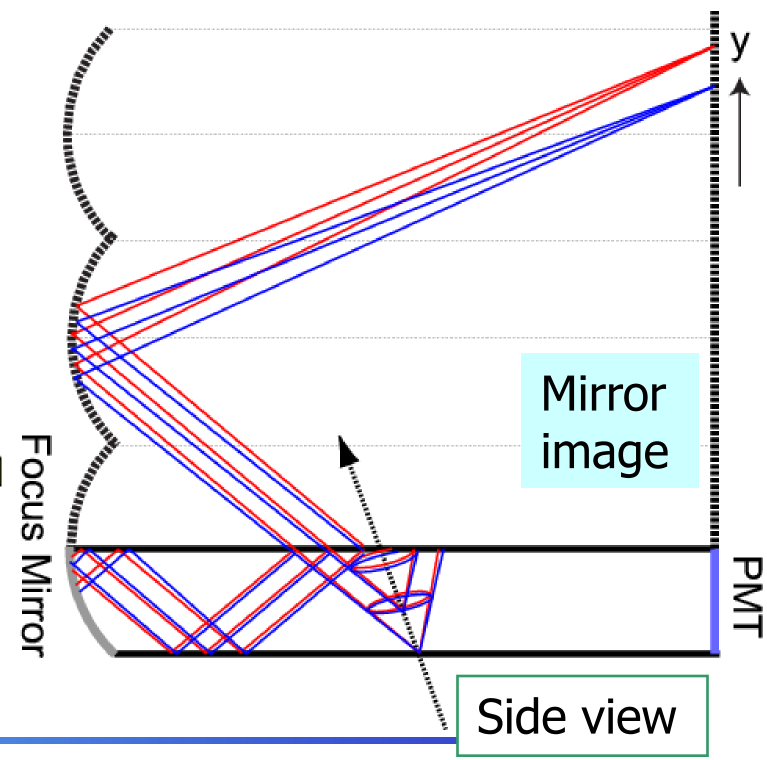
➔ Focusing system to measure θ_c

- $\lambda \leftarrow \theta_c \leftarrow$ y position
- Reconstruct ring image from 3D information (time, x and y).



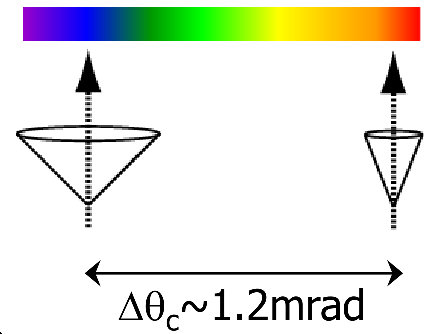
$$\theta_c(\lambda) = \cos^{-1}\left(\frac{1}{n(\lambda)\beta}\right)$$



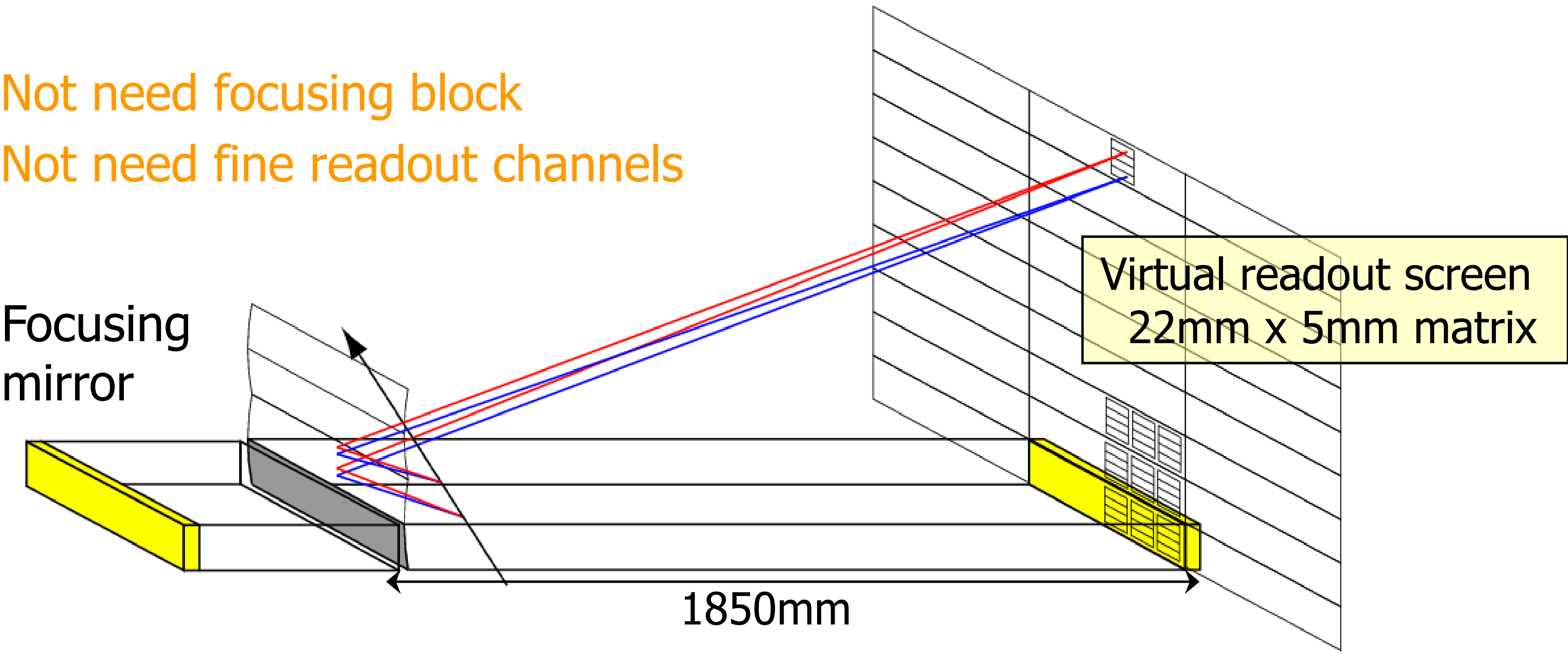


Focusing TOP (2)

- $\Delta\theta_c$~1.2mrad over sensitive λ range
- → Δy~20mm (~quartz thickness)
  - We can measure λ dependence and obtain good separation even with narrow mirror and readout plane, because of long propagation length.



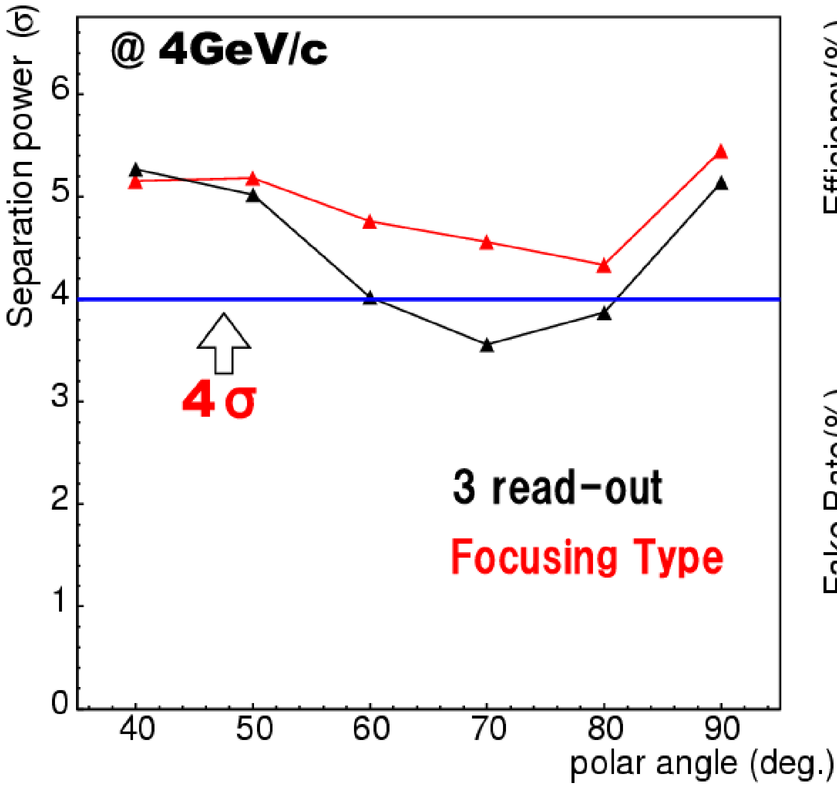
  - Not need focusing block
  - Not need fine readout channels



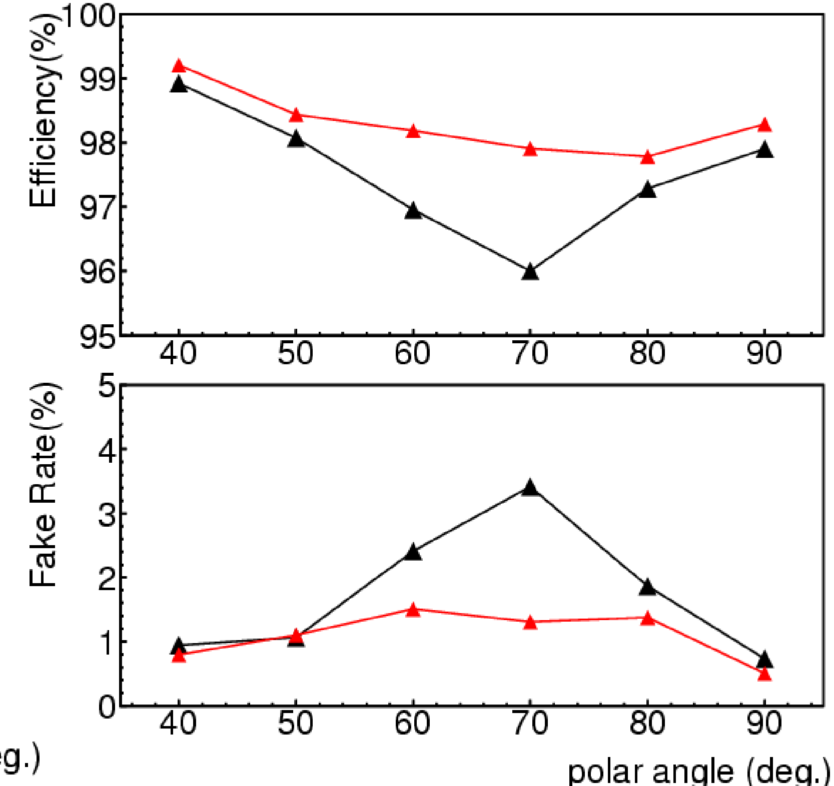
Performance of focusing TOP

- K/π separation power
  - GaAsP photo-cathode(+>400μm filter), CE=36%

Separation power

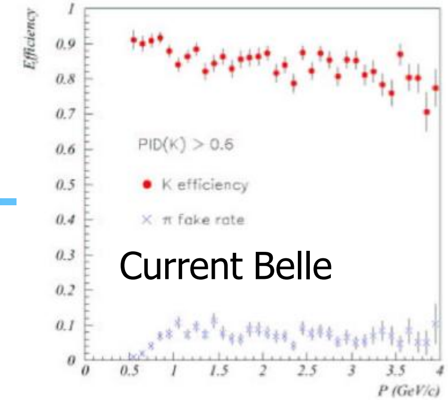


Efficiency,Fake rate

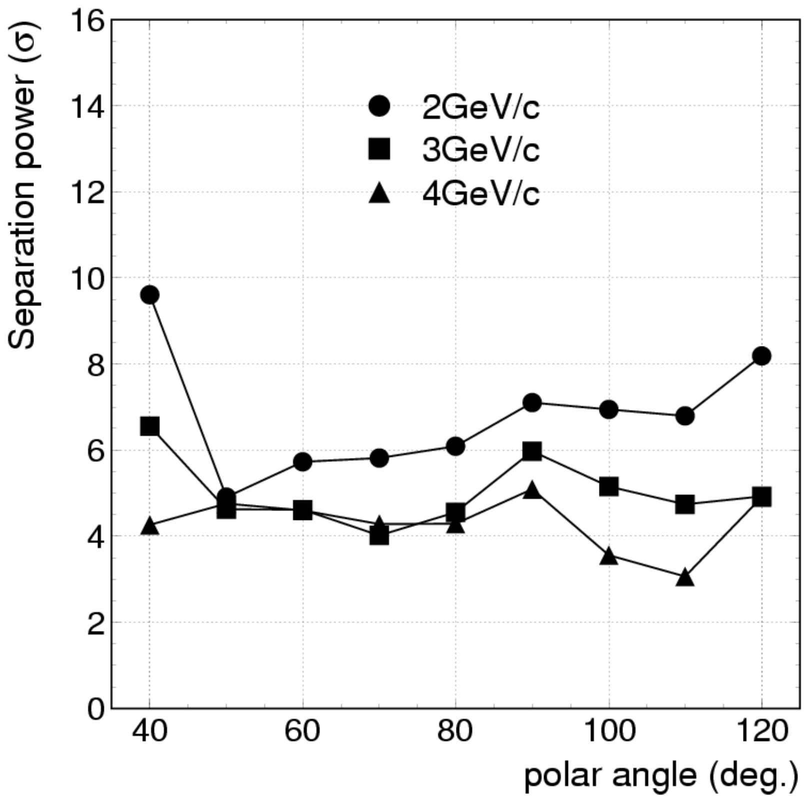


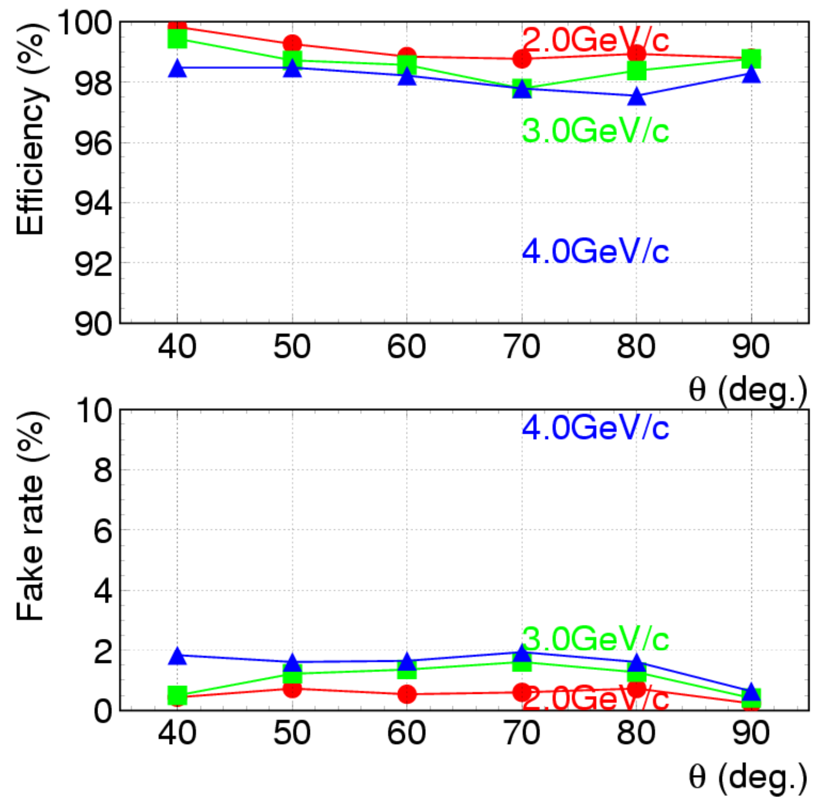
4.3σ separation for 4GeV/c

Expected performance



- K/π separation power
  - GaAsP photo-cathode + Focusing mirror

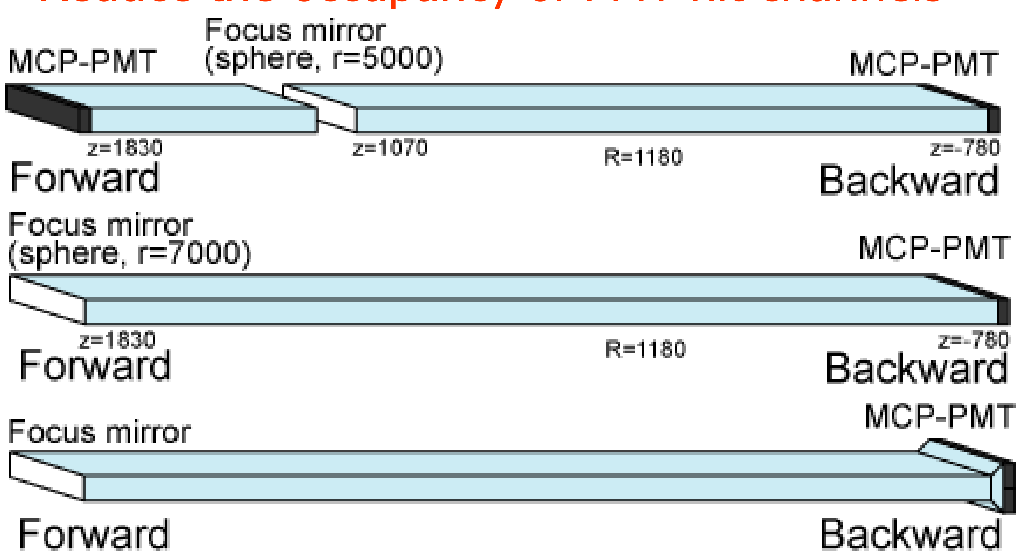




>4σ K/π upto 4 GeV/c, θ<90°, <2% fake rate

Design studies

- Better performance and robustness for additional fluctuation
  - Start timing T_0, tracking resolution, beam BG etc.
- Simple structure
  - Less systematic error for analysis
  - (Cost reduction)
- TOP with small standoff block (proposed by Hawaii univ.)
  - Larger readout plane
  - Relax the complicated ring image
  - Reduce the occupancy of PMT hit channels



2 readout

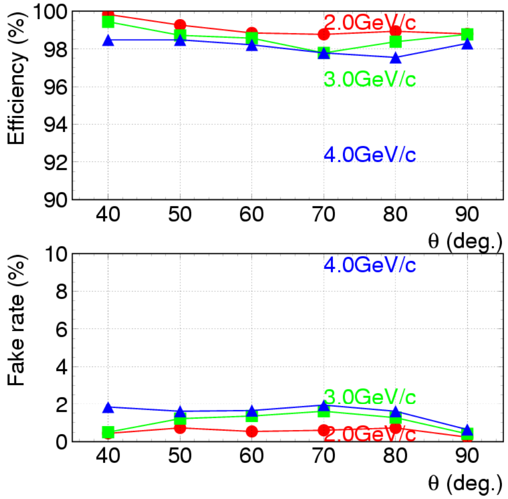
1 readout

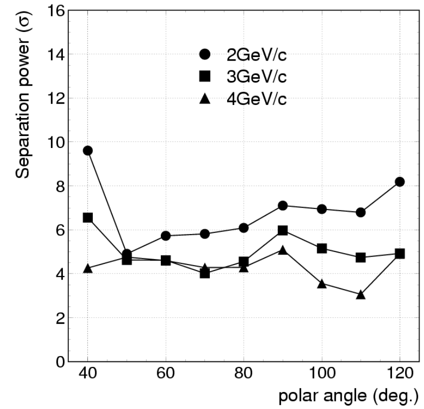
Standoff

Performance check

(Preliminary)

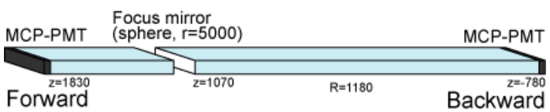
Ideal case

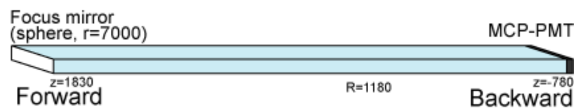




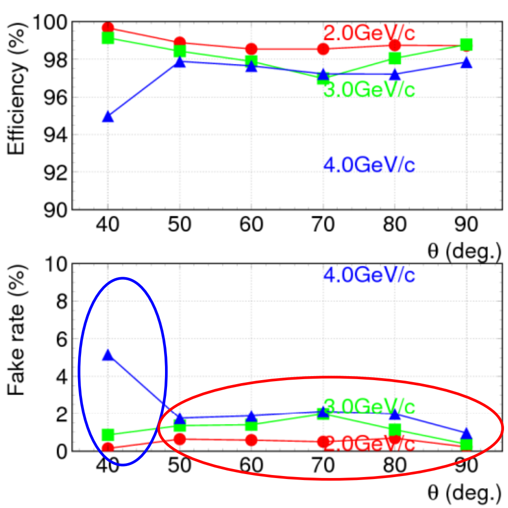
- MCP-PMT
  - GaAsP
  - CE=35%
  - λ>400nm

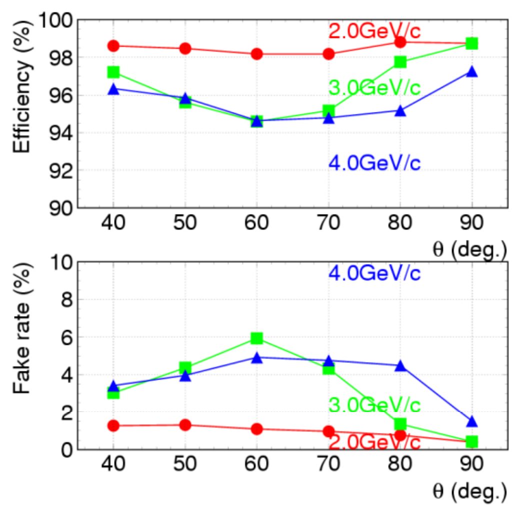
T_0 fluctuation; Robust for big ΔTOP region
(Time resolution is not good due to Chromaticity.)

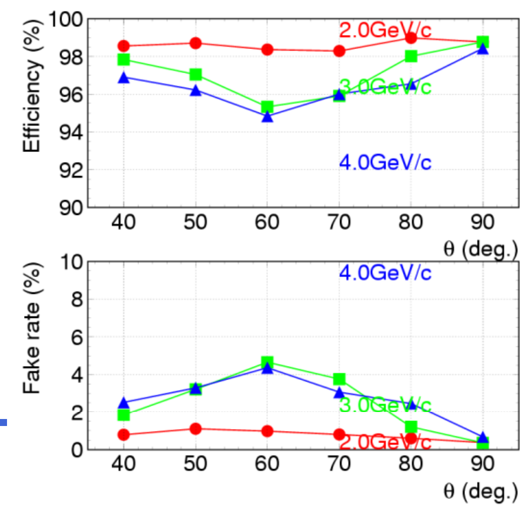




T_0: 10ps jitter







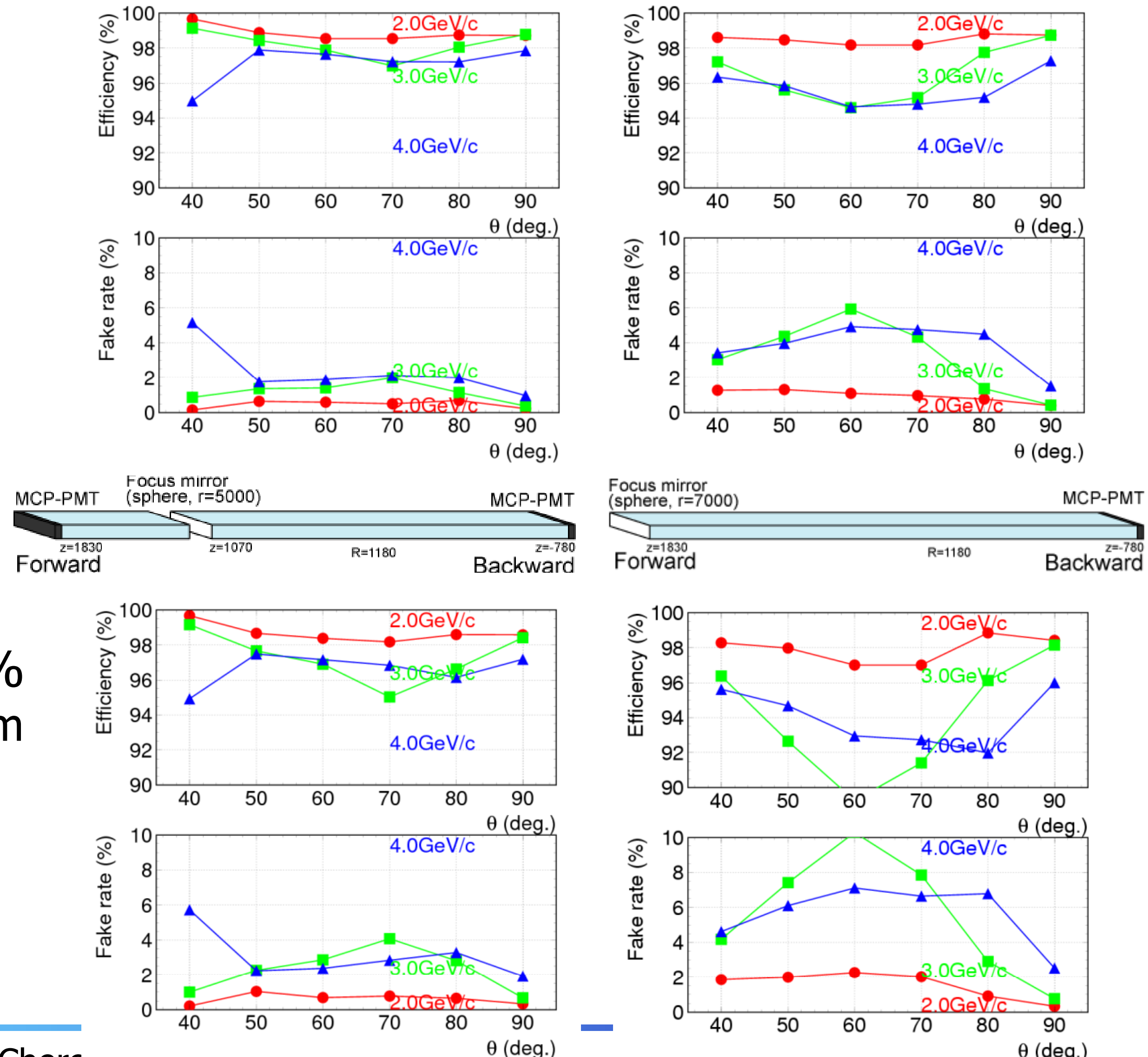
Performance check

(Preliminary)

With 10ps T_0 jitter

GaAsP, CE=35%

λ>400nm



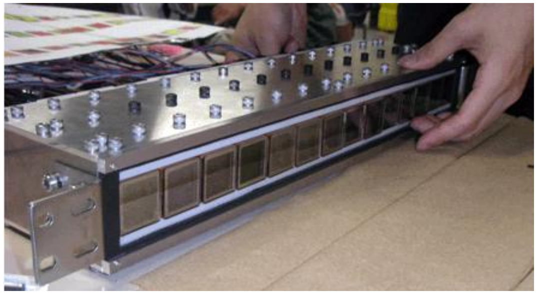
Multi-alkali, CE=60%

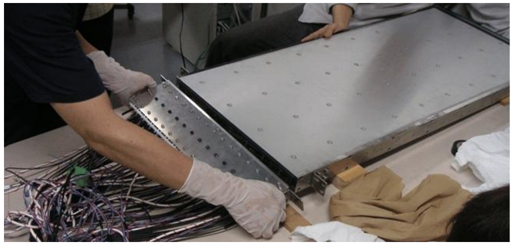
λ>350nm

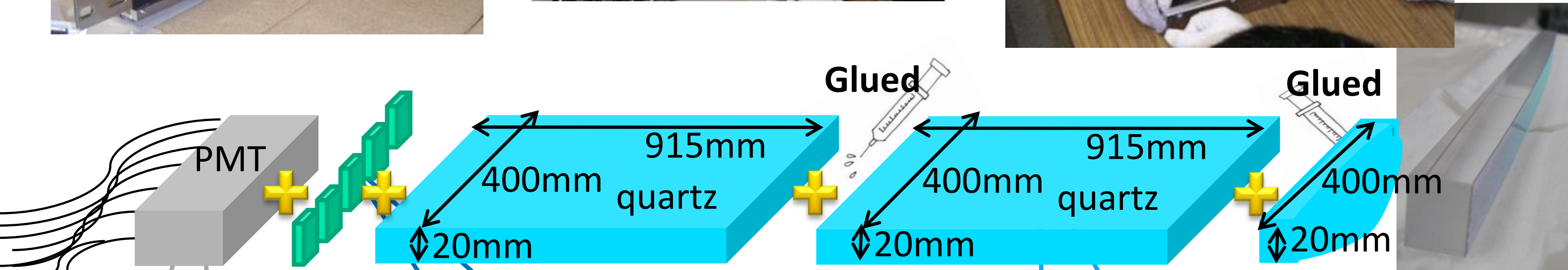
Propagation length optimized for QE variation is limited.

Prototype development

- Demonstration of the performance







Prototype overview

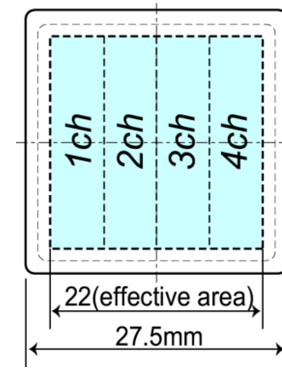
Photon detector
- **Time resolution**
- **Efficiency**

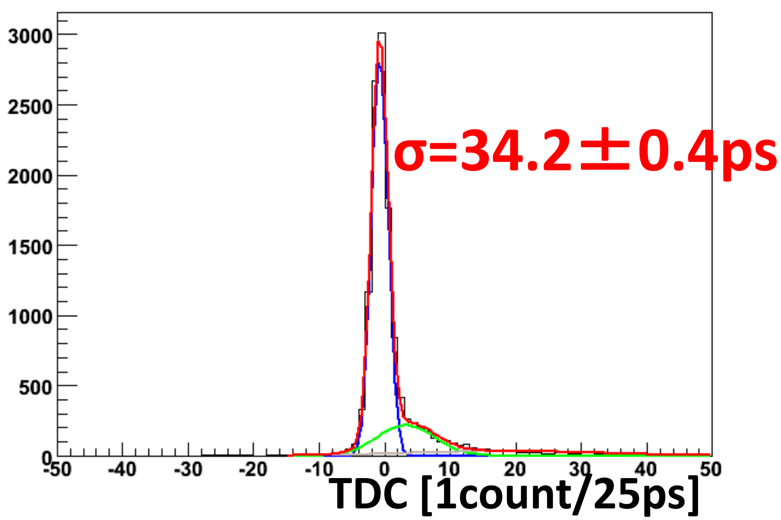
Filter (λ>400nm)
- **Suppression of chromatic dispersion**

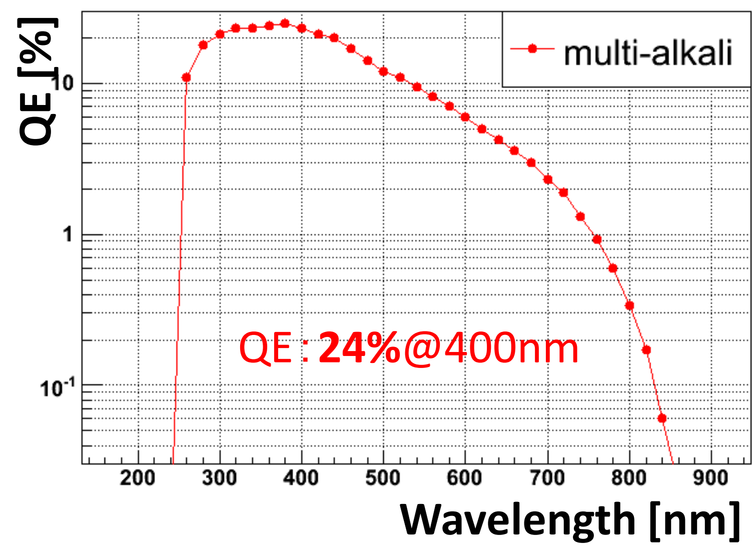
Quartz radiator (Fused silica)
- **Flatness:<1.2μm/m**
- **Roughness:0.5nm**

Photon detector

- Square-shape multi-anode MCP-PMT
  - Multi-alkali photo-cathode
  - Single photon detection
  - Fast raise time: ~400ps
  - Gain=1.5x10^{6} @B=1.5T
  - T.T.S.(single photon): ~35ps @B=1.5T
  - Position resoltion: <5mm
- Semi-mass-production (14 PMTs)





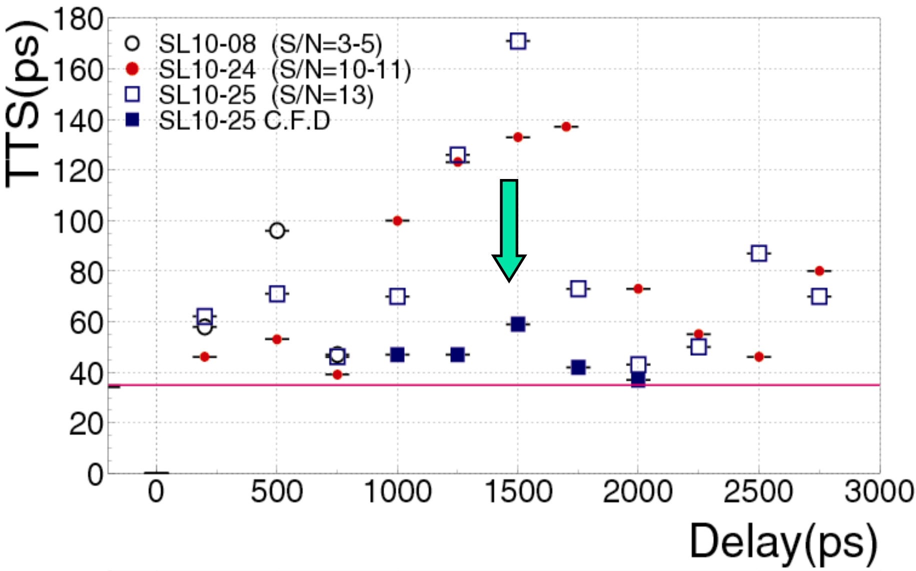


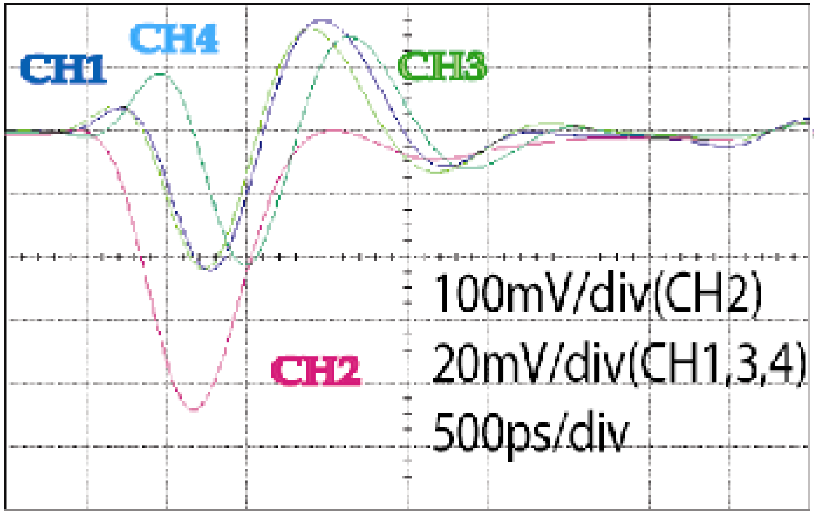
→ TTS＜40ps for all channels

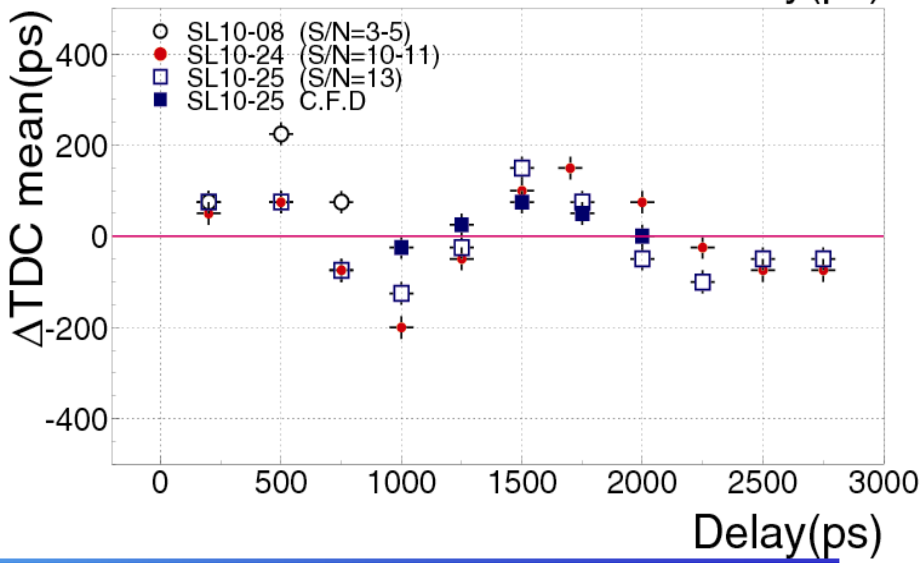
→ Ave. QE : **17%@400nm**

MCP-PMT + CFD

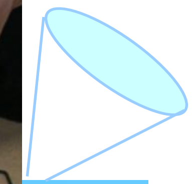
- CFD on PMT module
  - Digitize with low noise
    - Low PMT gain operation
  - Robust against cross-talk
    - Able to determine PMT timing by (approximately) pulse peak.

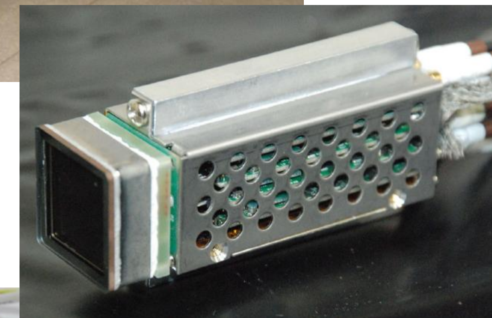




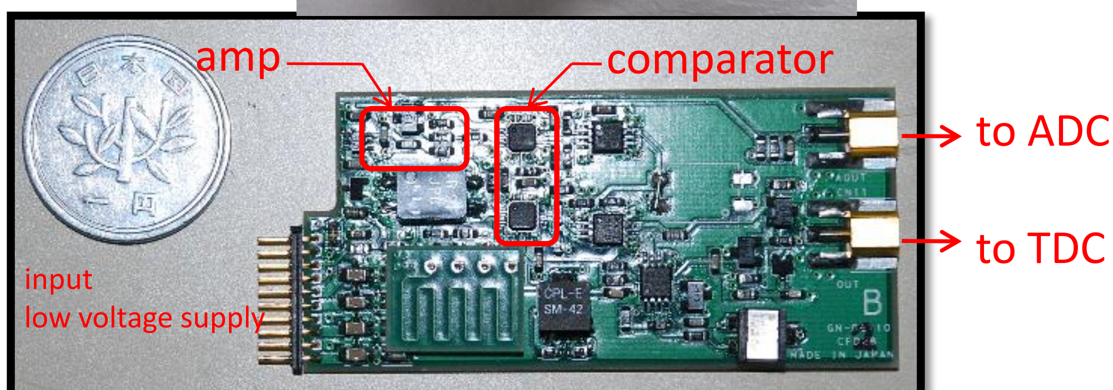


PMT module



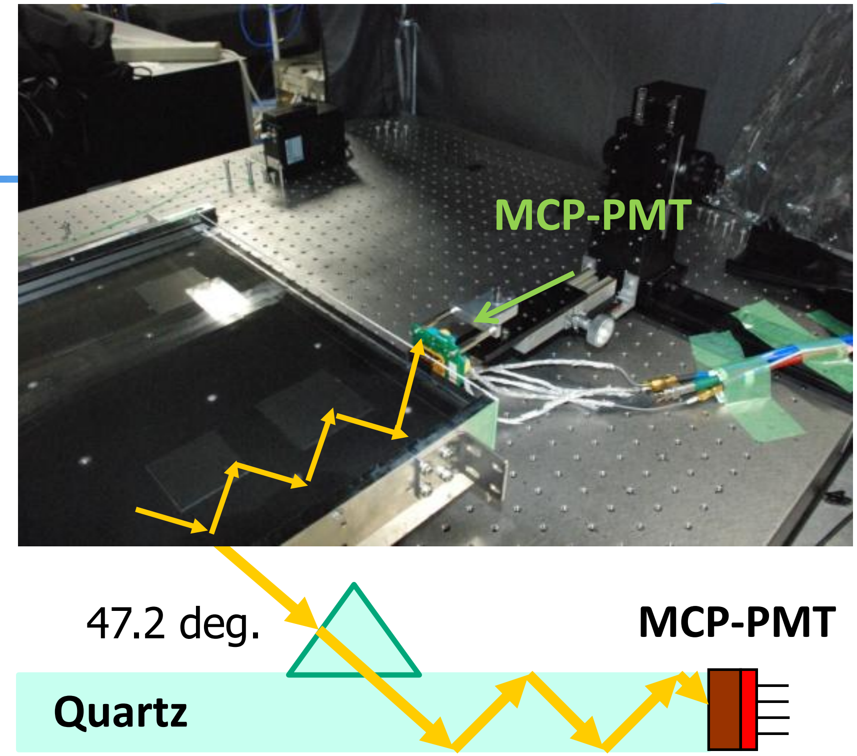


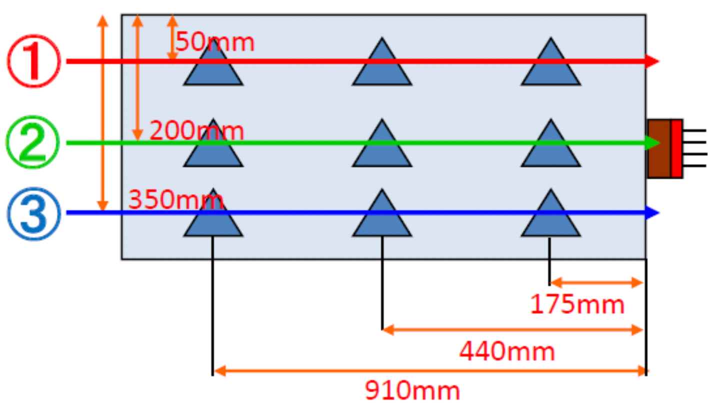
- HV divider + AMP + Discriminator
- Small size (28mm^{W})
- Prototype
  - Fast AMP (MMIC, 1GHz, x20)
  - Fast comparator (180ps propagation)
  - CFD with pattern delay
- Performance
  - Test pulse
    - ~5ps resolution
  - MCP-PMT
    - σ<40ps
    - Working well

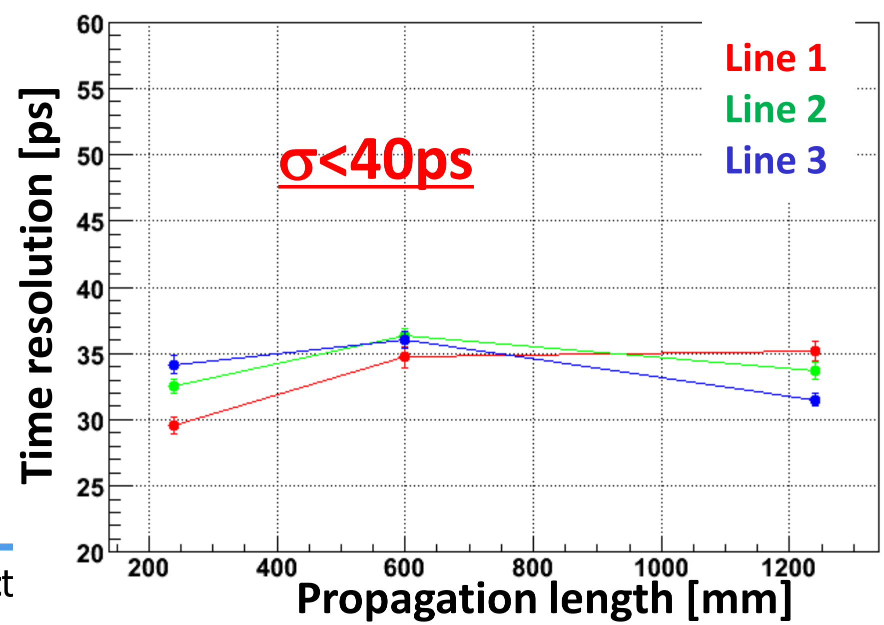


Quartz radiator

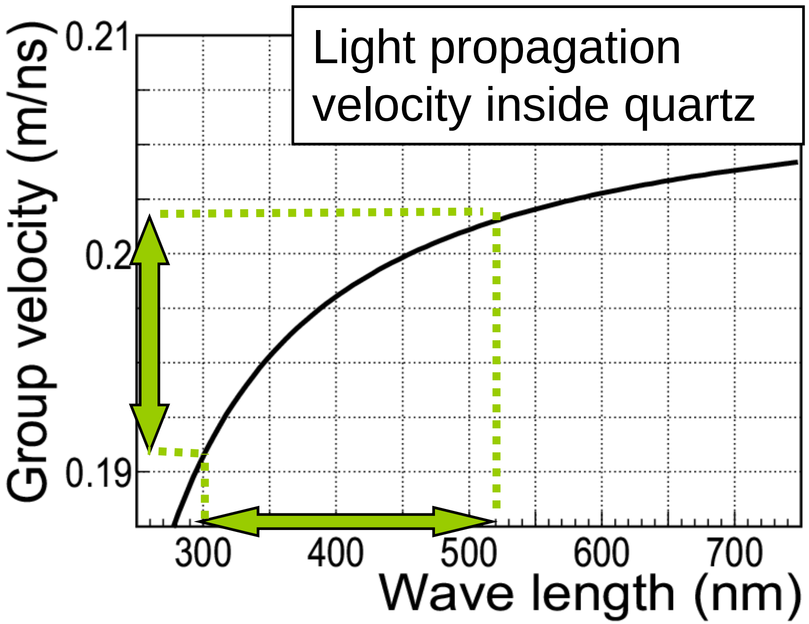
- Made by Okamoto optics
- Check the quality for time resolution
  - Single photon pulse laser
    - λ=407nm
  - MCP-PMT
  - Several incident position
- → No degradation of time resolution
  - Enough quartz quality

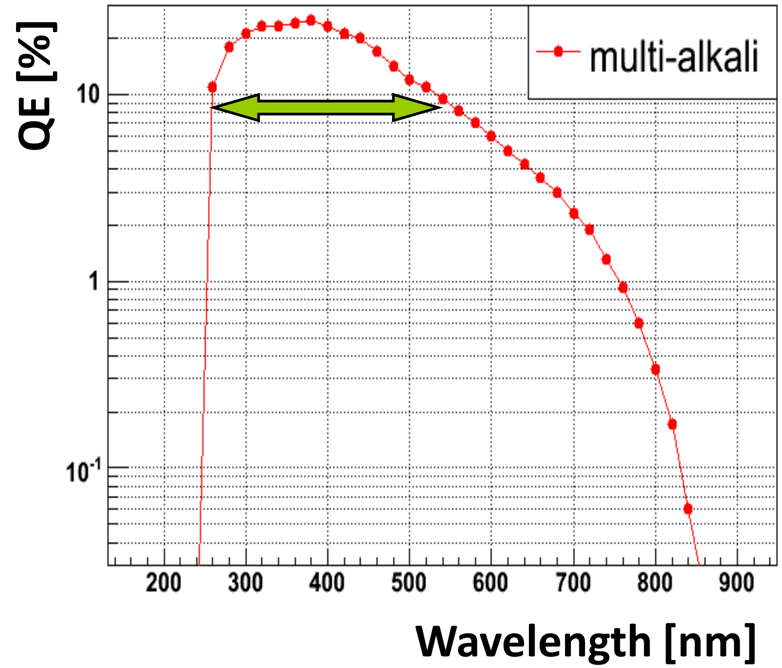






Check chromatic effect by beam test



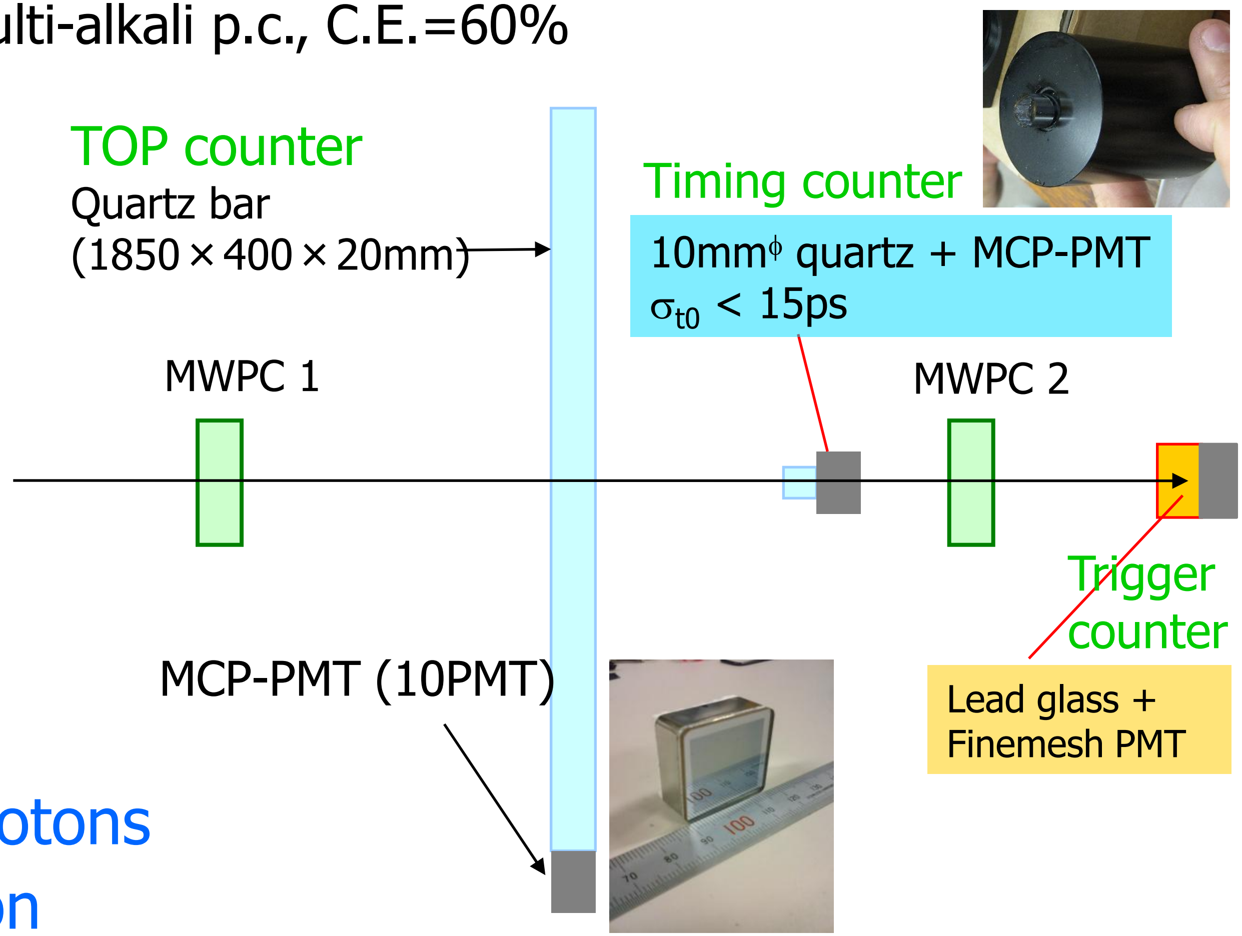


- Range of detectable wavelength of Cherenkov photons
  → Time fluctuation of the Cherenkov ring image
    → Time resolution depends on the propagation length.
- Check the degradation of time resolution by beam test

Beam test

- At Fuji beam line in June and Dec.
- Using real size quartz and MCP-PMT
    - MCP-PMT: Multi-alkali p.c., C.E.=60%

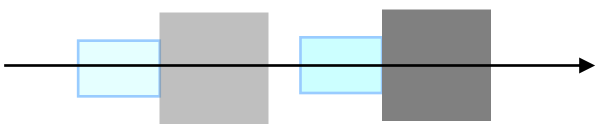
Quartz + support jig



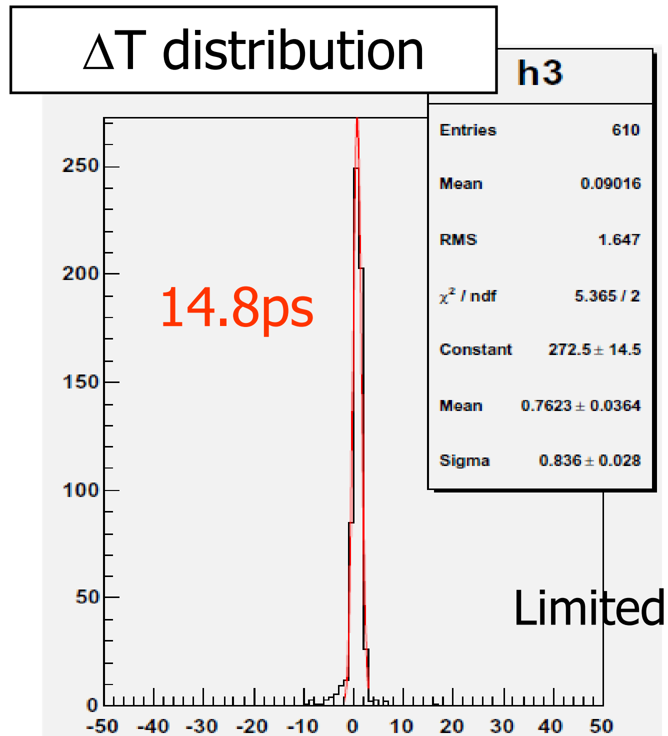
- Check
    - Ring image
    - Number of photons
    - Time resolution

Timing counter

- Based on our high resolution TOF
  - σ=6.2ps with 6μm MCP-PMT, Cherenkov light in quartz
  - and special electronics
- Time difference btw two counters
  - Check time resolution

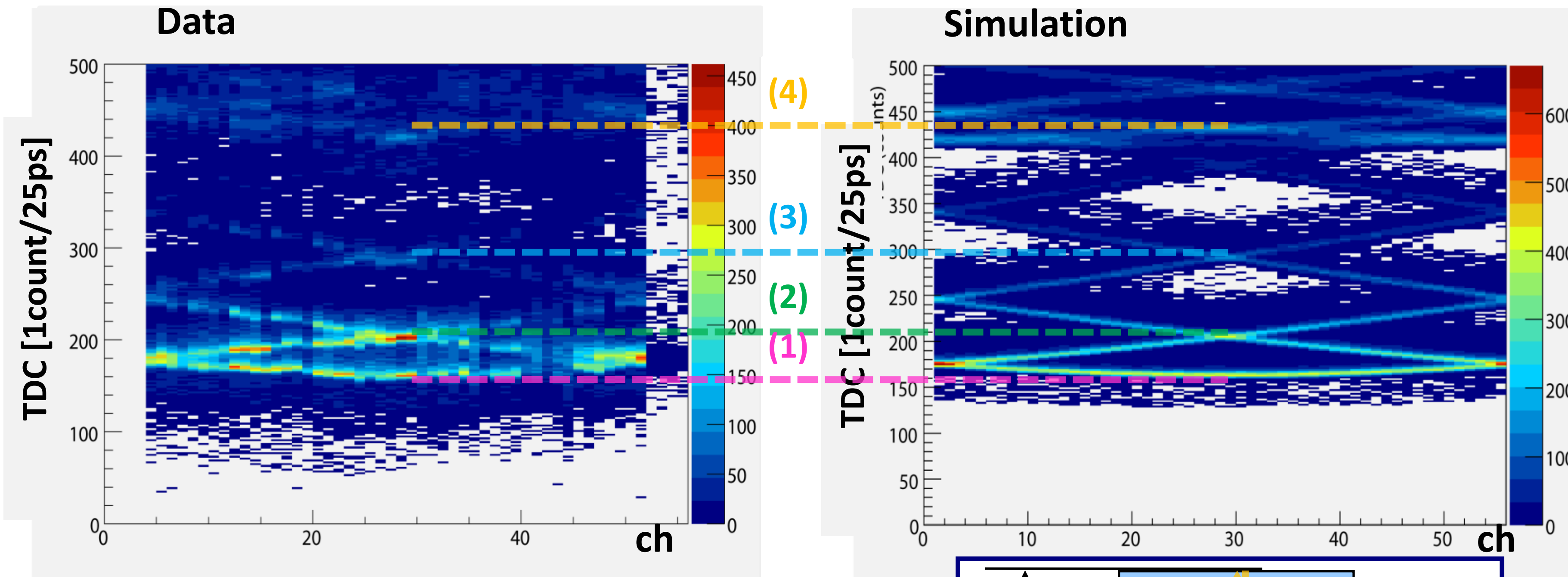


10mm$^{\phi}$ quartz + MCP-PMT

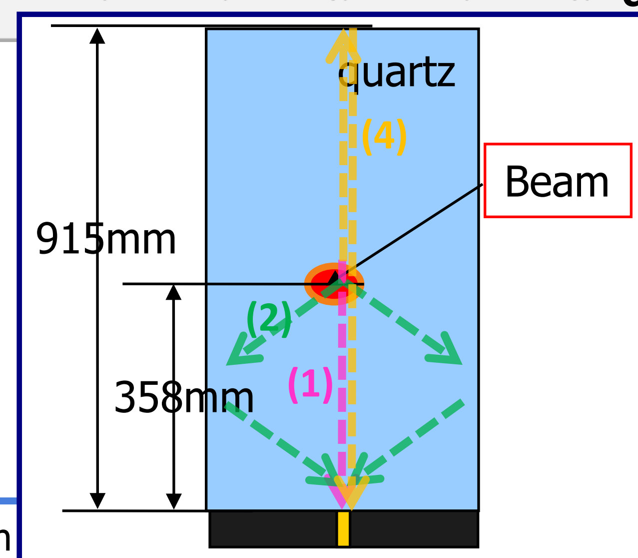


Limited by elec.

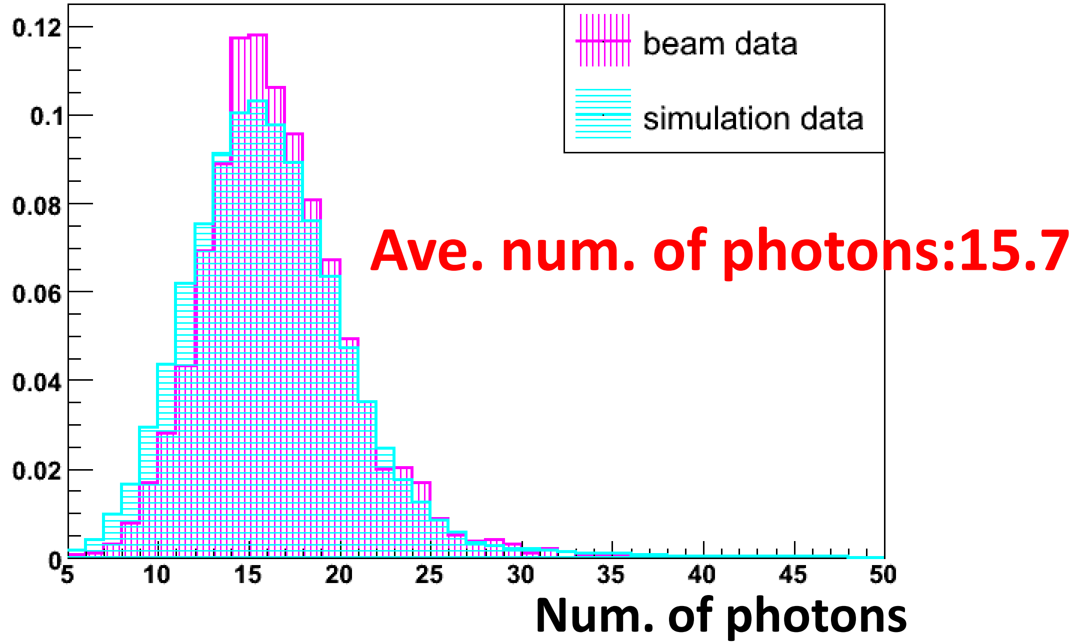
Ring image



- Proper ring image
  - Same time interval with simulation



Number of detected photons

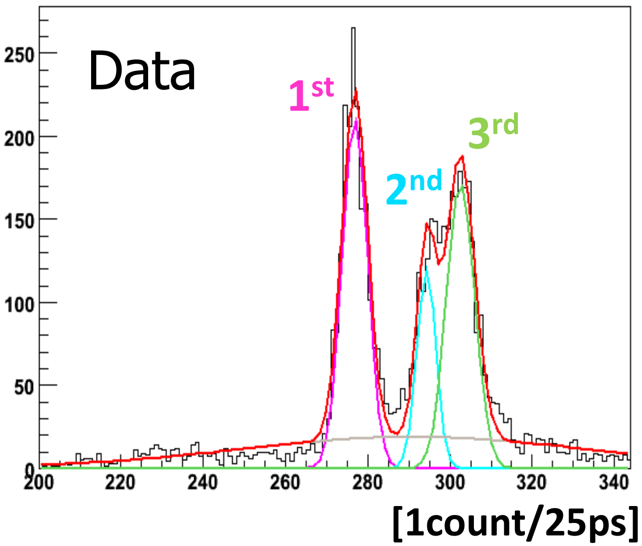


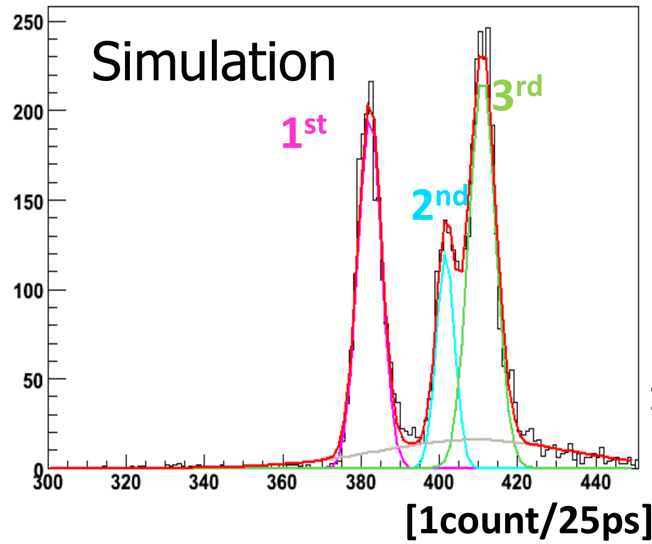
- Normal incidence (90 deg.)
- Obtained number of photons as expected

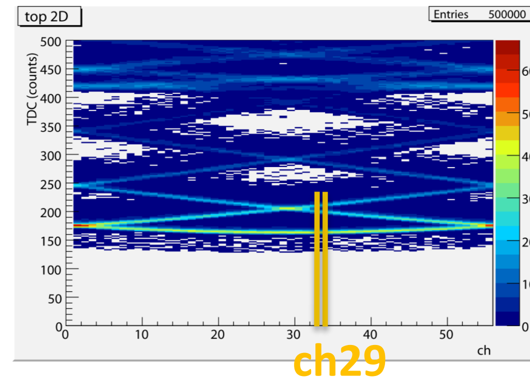
- → We can expect ~22 photons/event, if we use 14 PMTs.
  - Normalized by active area (10→14 PMTs)

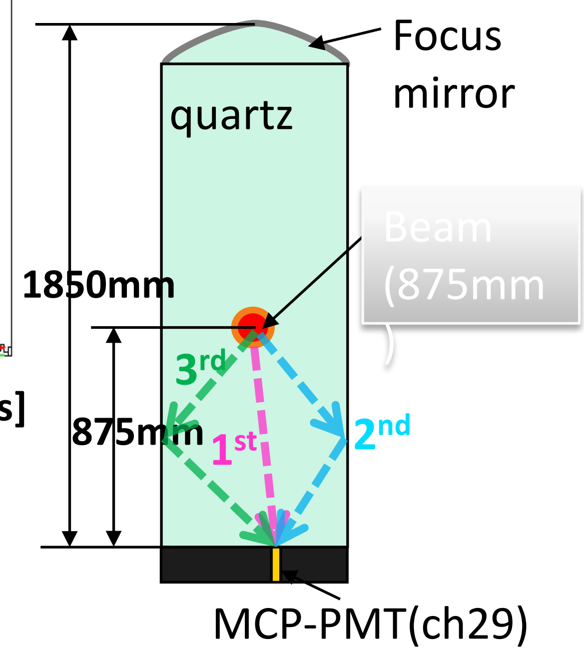
Time resolution

- TDC distribution of ch.29
  - Compare with the distribution expected by a simulation including PMT resolution and chromatic dispersion effect





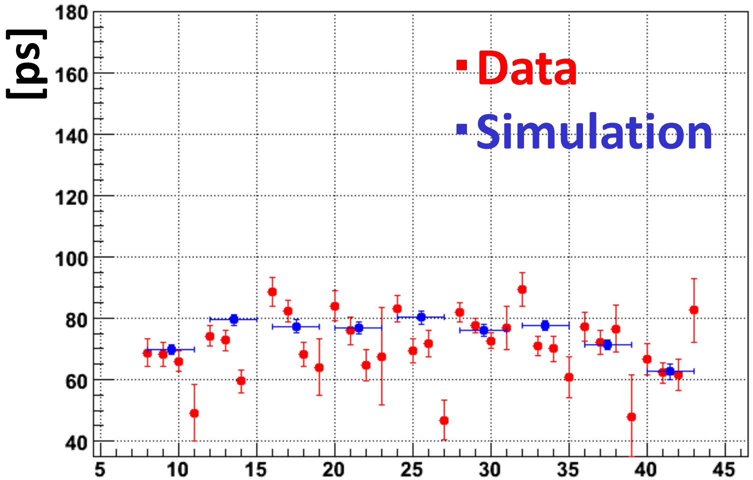




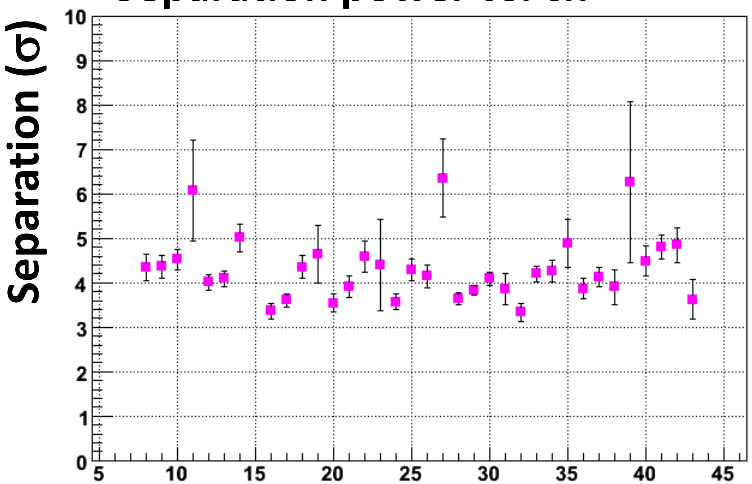
	Resolution(1st peak)
Data	76.0±2.0 [ps]
Simulation	77.7±2.3 [ps]

Time resolution

1st peak time resolution vs. ch

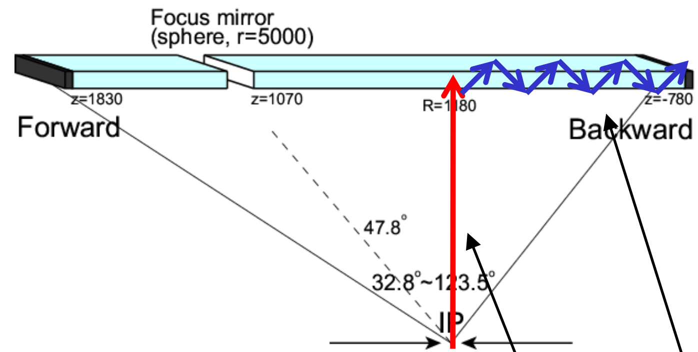


Separation power vs. ch



Ave. of data : 70.6ps

Ave. of simulation : 74.6ps

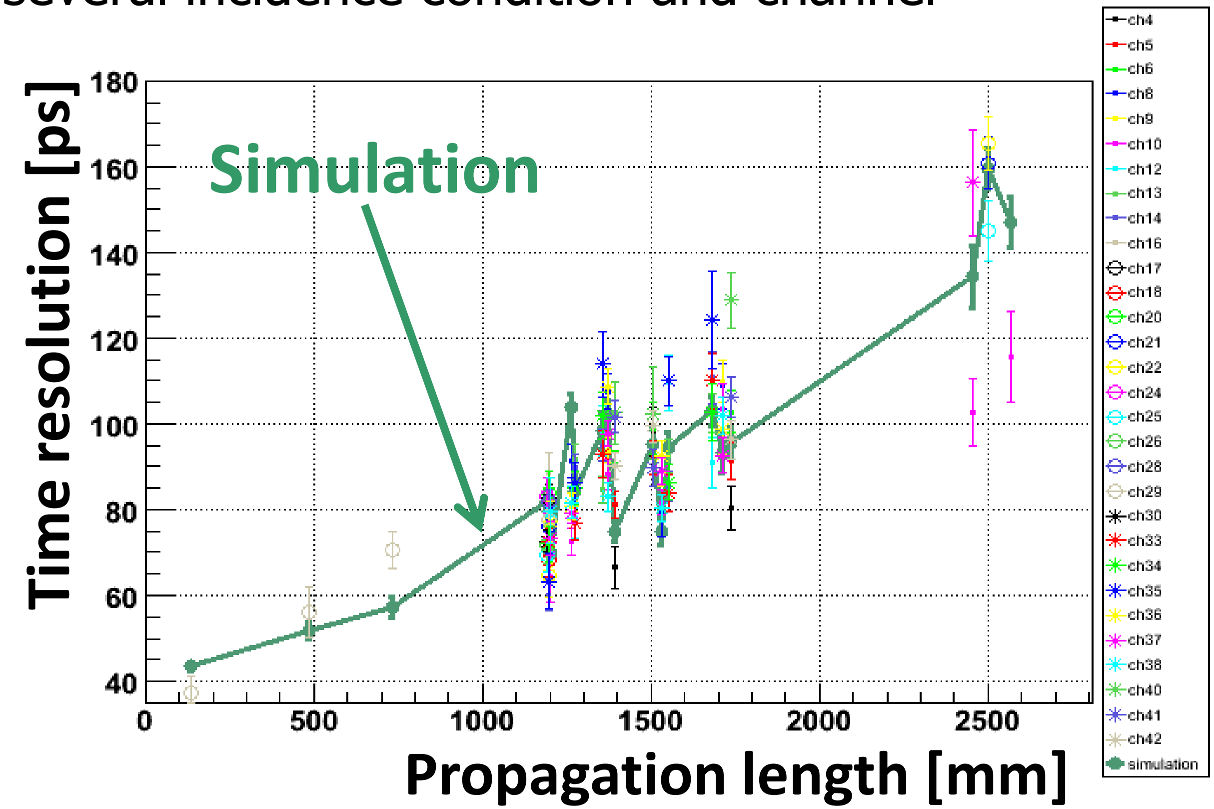


$$Separation\ Power(\sigma) = \frac{\Delta TOF + \Delta TOP}{\sigma_{top}} \sqrt{N_{det}}$$

- <u>4σ separation achieved</u>
  - If we calculate from time resolution and number of photons for normal incidence condition.

Time resolution vs. propagation length

- Check time resolution
  - For several incidence condition and channel



- Data agrees well with simulation expectation.
  → Confirmed the level of chromatic dispersion effect

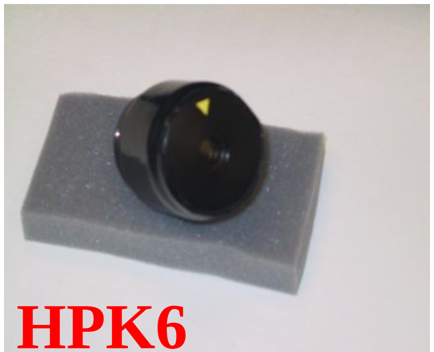
Summary

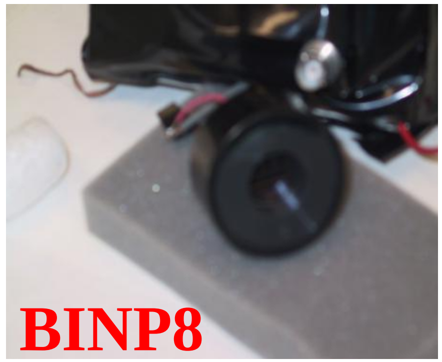
- R&Ds of Cherenkov detector are in progress!
  - TOP counter for barrel PID upgrade at Belle II experiment
  - Cherenkov ring imaging with precise timing information ($\sigma<40$ps)
  - Several design studies are going.

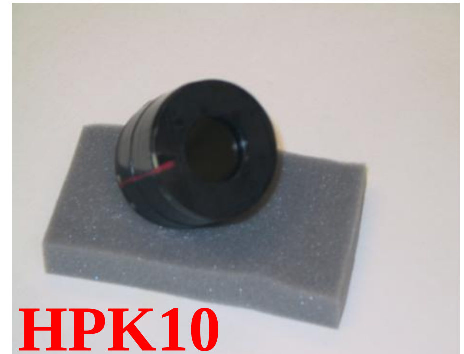
- MCP-PMT R&D with Hamamatsu
  - Enough performance for TOP counter
- Prototype development
  - Multi-anode MCP-PMT
    - Integrated module with amplifier and CFD
  - Quartz radiator
    - Enough quartz quality for single photon detection
- Performance test with beam
  - Proper ring image, number of detected photons (15.7 photons)
  - Time resolution as expected by simulation
    → Confirmed chromatic dispersion effect

MCP-PMT

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



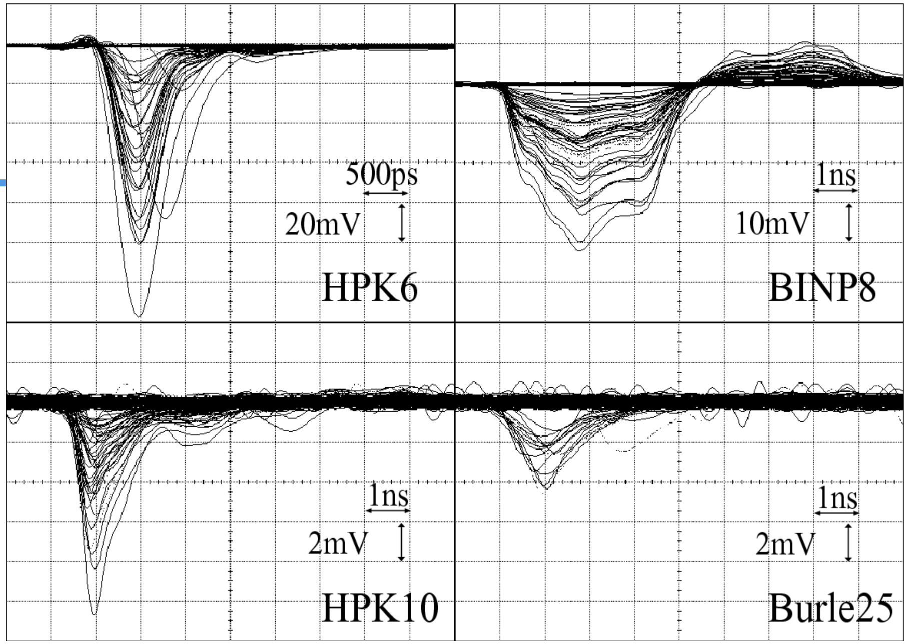


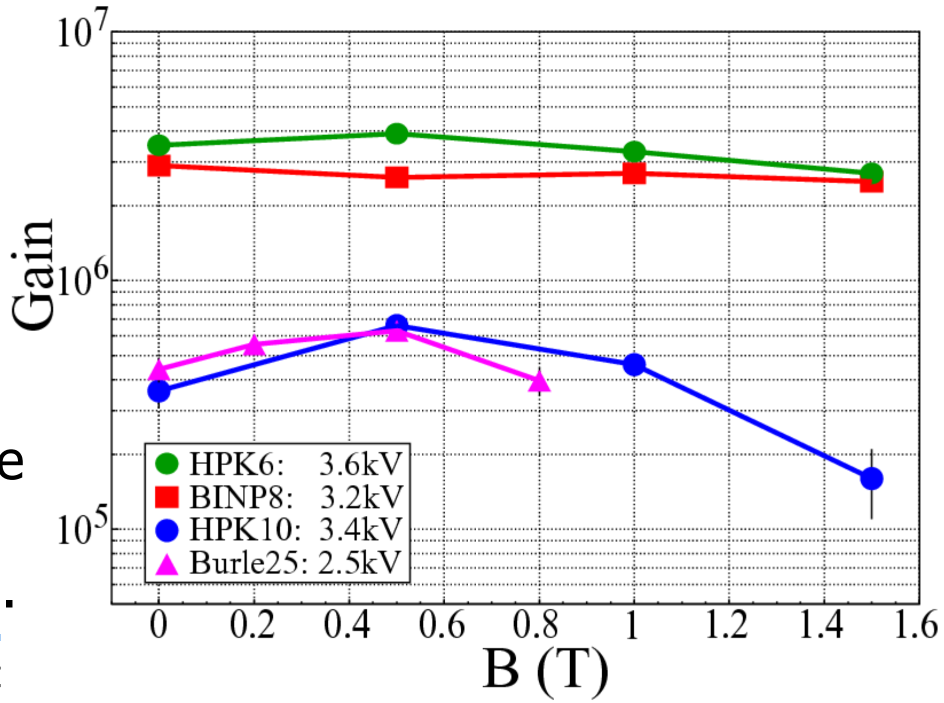


MCP-PMT	HPK6 R3809U-50-11X	BINP8 N4428	HPK10 R3809U-50-25X	Burle25 85011-501
PMT size(mm)	45	30.5	52	71x71
Effective size(mm)	11	18	25	50x50
Channel diameter(μm)	**6**	**8**	**10**	**25**
Length-diameter ratio	40	40	43	40
Max. H.V. (V)	3600	3200	3600	2500
photo-cathode	multi-alkali	multi-alkali	multi-alkali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

Pulse response

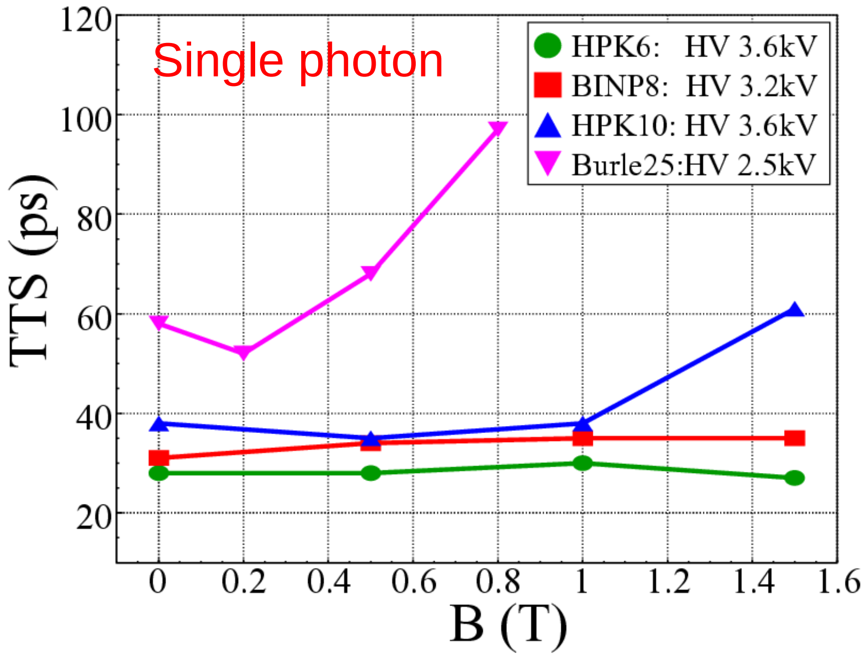
- Pulse shape (B=0T)
  - Fast raise time (~500ps)
  - Broad shape for BINP8
    - Due to mismatch with H.V. supply divider
    - No influence for time resolution
- Gain v.s. B-field
  - Small channel diameter shows high stability against B-field.
  - Explained by relation btw hole size and Larmor radius of electron motion under B-field.



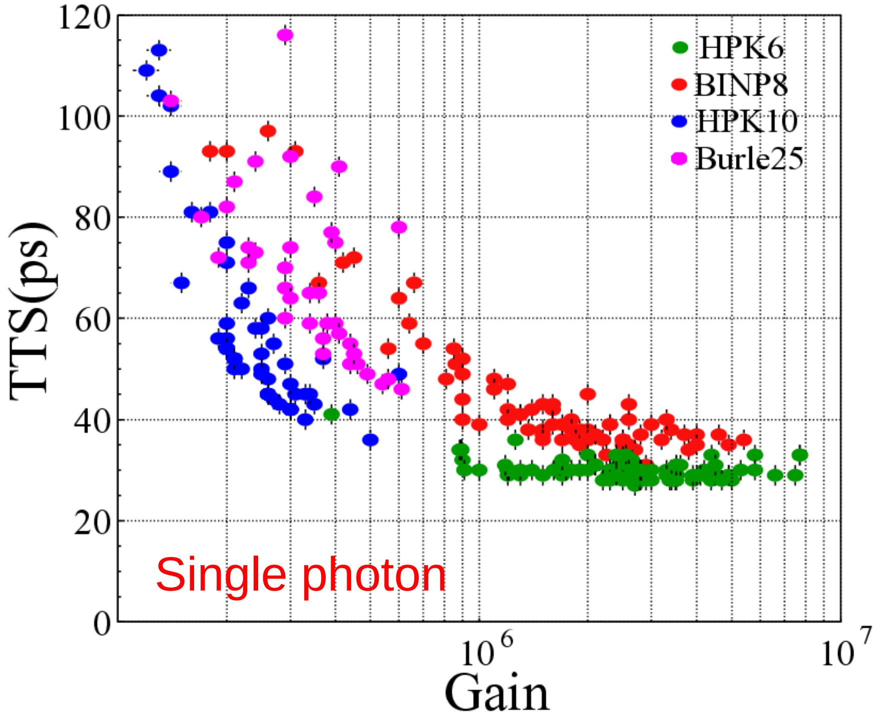


Time response

- 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

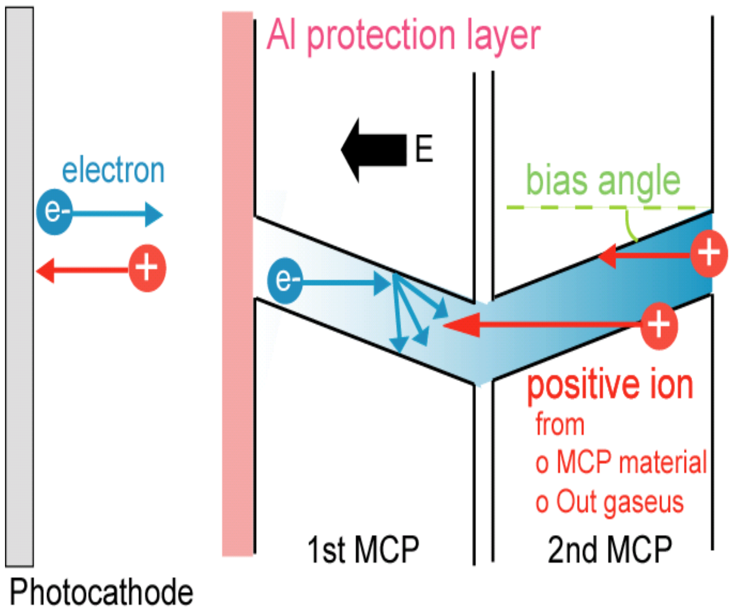


- Hole size need <~10μm
  - to get time resolution of ~30ps under 1.5T B-field.

Lifetime

- How long can we use MCP-PMT under high hit rate? (Nucl. Instr. Meth. A564 (2006) 204.)

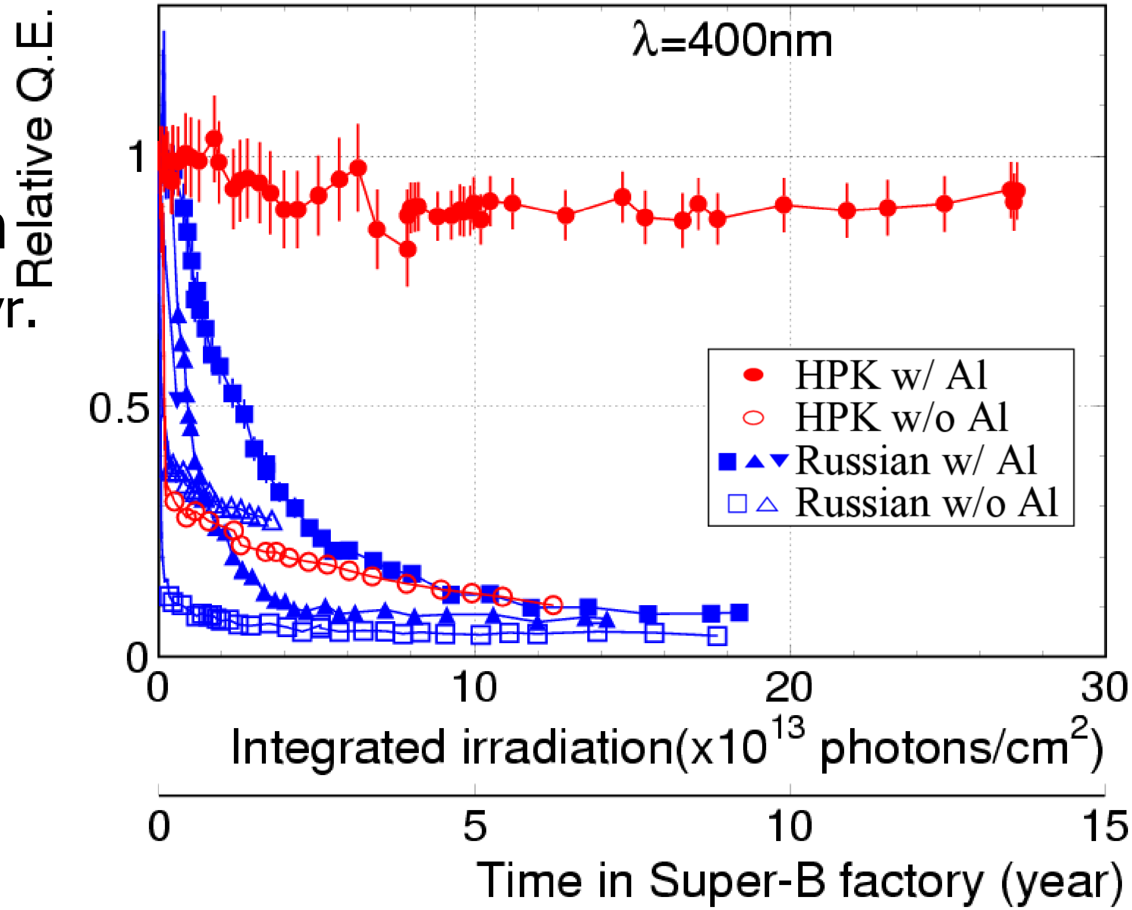
	HPK (x2)		Russian (x5)	
Al protection	**O**	**X**	**O**	**X**
Correction eff.	**37%**	**65%**	**40-60**	**55-60%**
Effective area	11mmϕ		18mmϕ	
Gain	1.9×10^6	1.5×10^6	$3 \sim 4 \times 10^6$	
TTS	34ps	29ps	30~40ps	
Photo-cathode	Multi-alkali (NaKSbCs)			
Quantum eff. at 400nm	21%	19%	16-20%	
Bias angle	13deg		5deg	



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

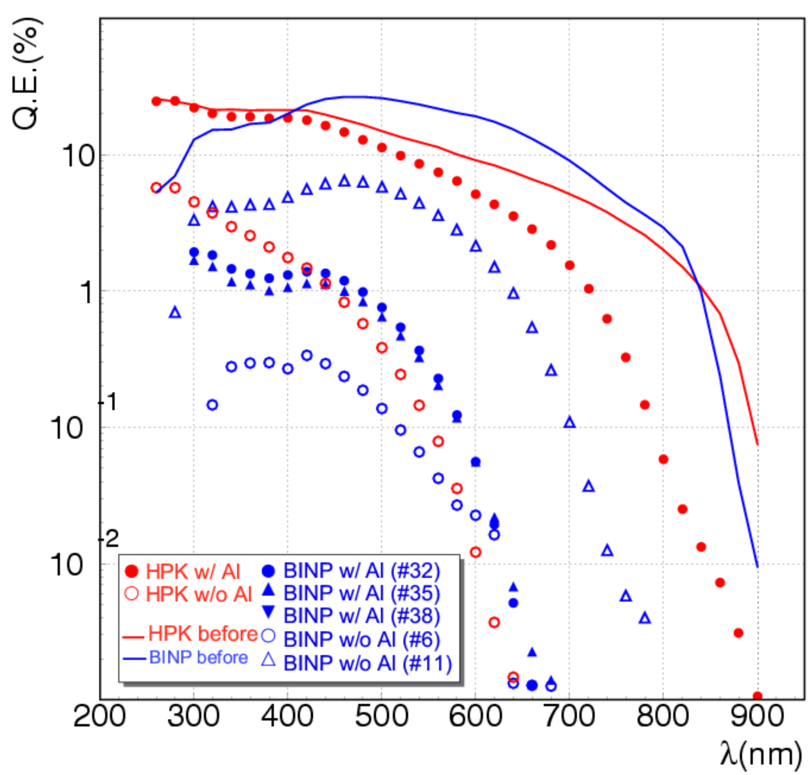
Lifetime - Q.E. -

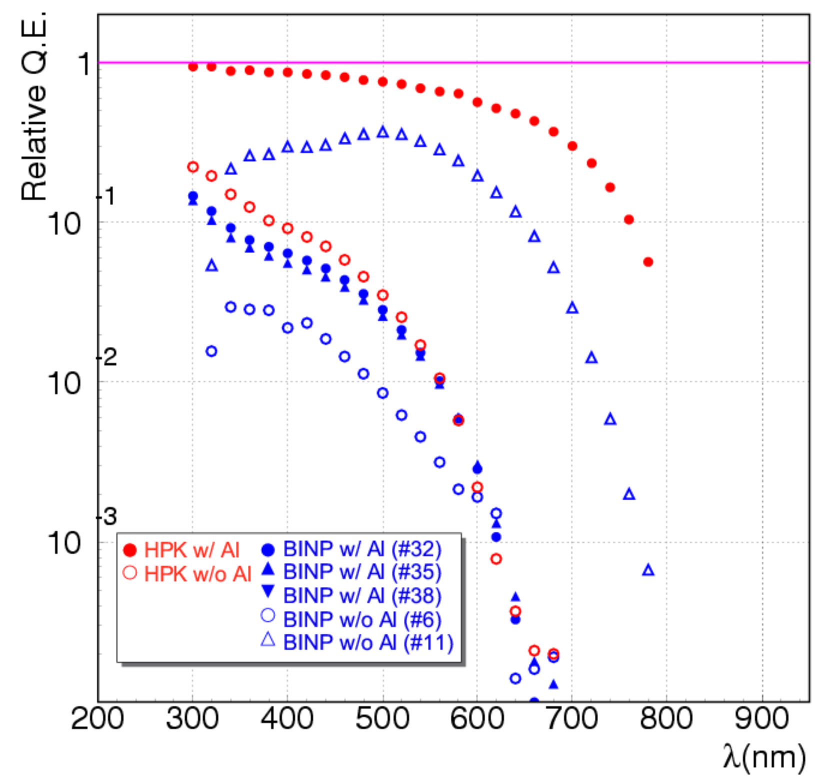
- Relative Q.E. by single photon laser
- Without Al protection
  - Drop <50% within 1yr.
- With Al protection
  - Long life
  - Not enough for Russian PMTs
- Enough lifetime for HPK's MCP-PMT with Al protection layer



Lifetime - Q.E. vs wavelangth -

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

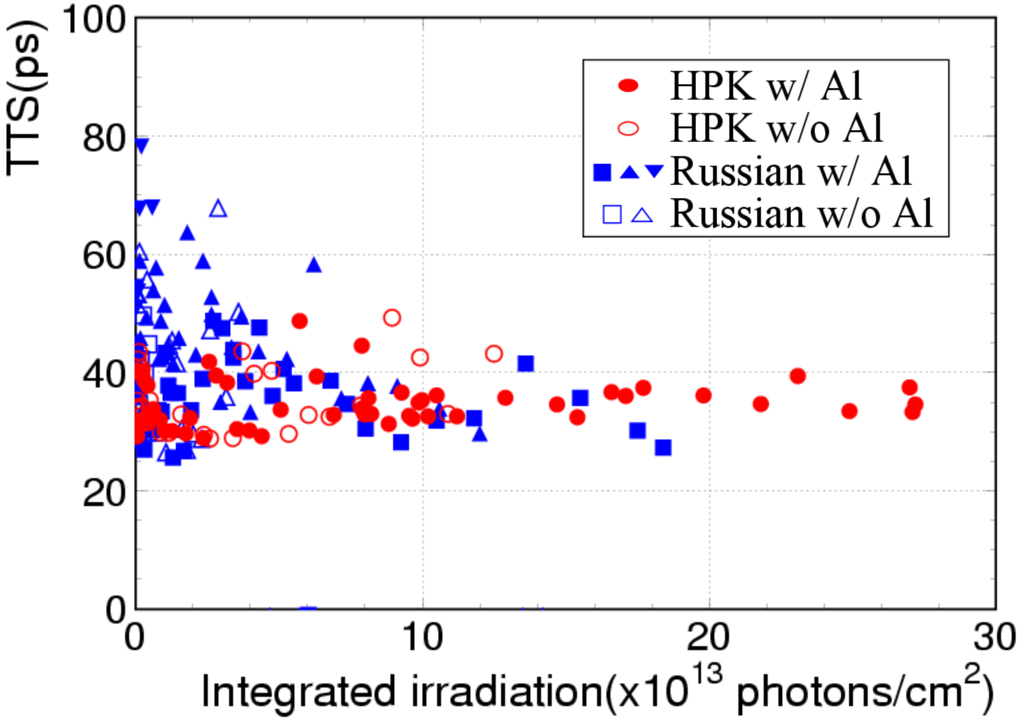


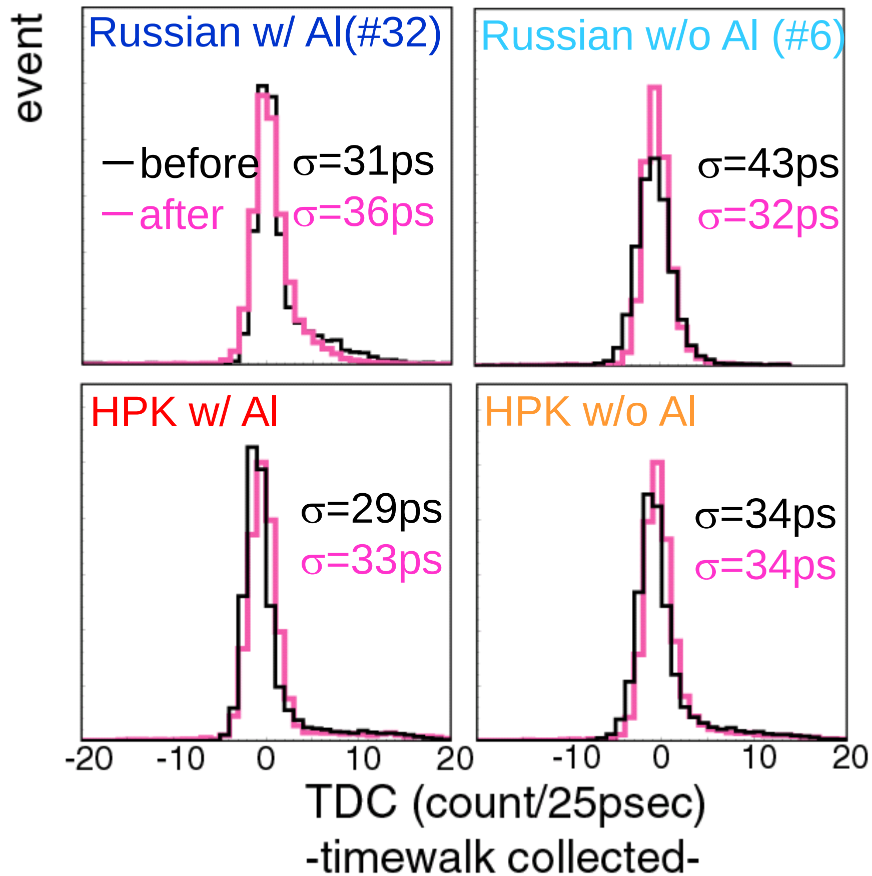


- Large Q.E. drop at longer wavelength
- Number of Cherenkov photons；only 13% less (HPK w/Al)
  - Number of generated Cherenkov photon:~$1/\lambda^2$

Lifetime - T.T.S. -

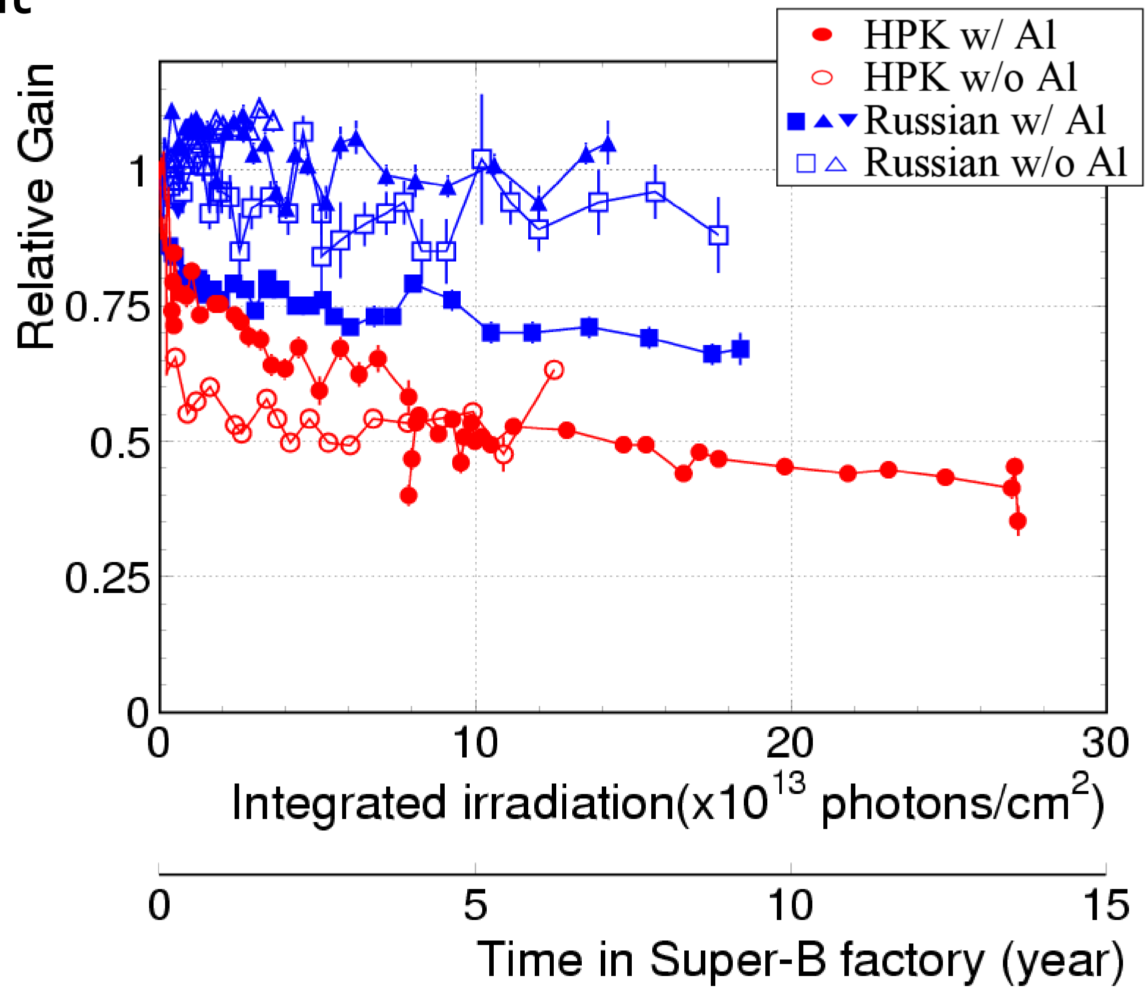
- Time resolution for single photon
  - →No degradation!
    - Keep ~35ps





Lifetime - Gain -

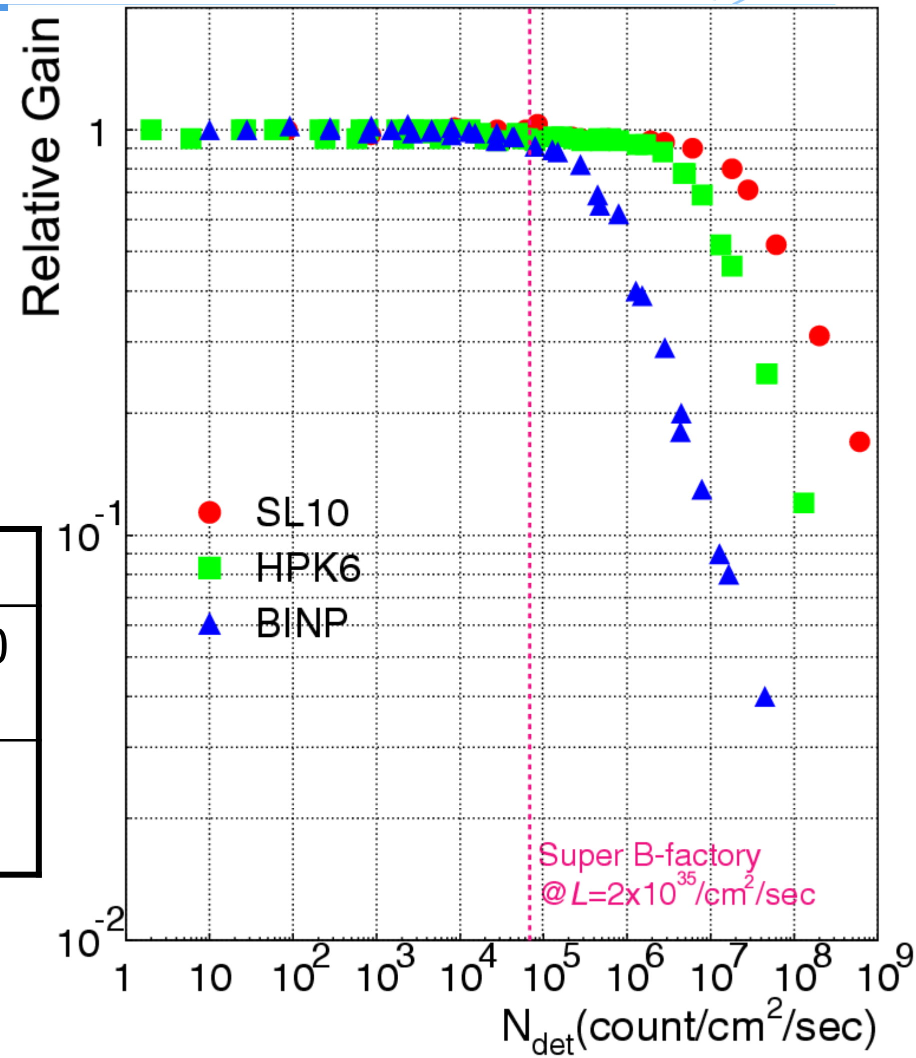
- Estimate from output charge for single photon irradiation
- $<10^{13}$photons/cm^2
  - Drop fast
- $>10^{13}$photons/cm^2
  - Drop slowly
- Single photon detection: OK
- Can recover gain by increasing HV

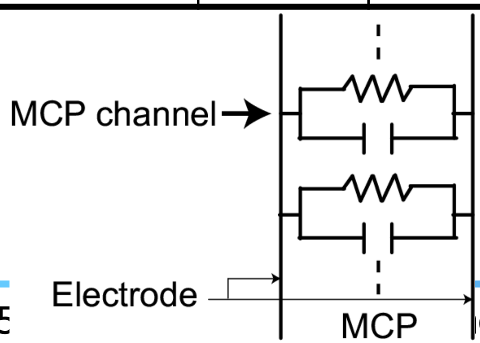


Rate dependence

- 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





Enough for TOP counter