Performance evaluation of the 50 cm box-and-line dynode photomultiplier tube

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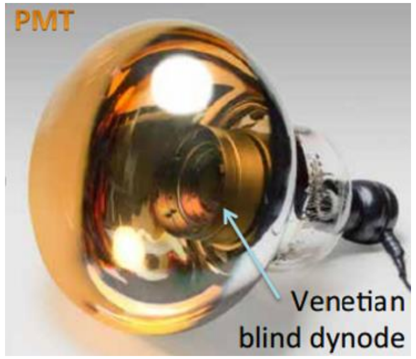
Outline

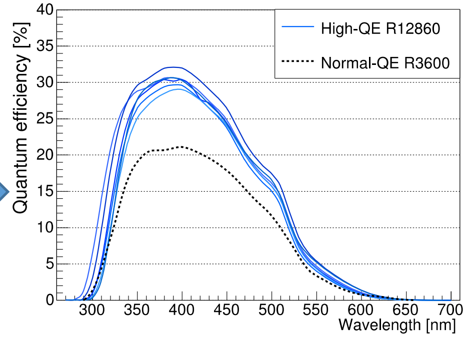
- Design
- Structure
- Performance evaluation
    - Signal & Time performance
    - Charge performance
    - Detection efficiency
    - Linearity
    - Rate tolerance
    - Gain recovery
    - Magnetic field tolerance
    - After pulse

Introduction

- Final Goal
  - Develop a 50cm high performance photodetector which can be used in a water Cherenkov detector for a long time.

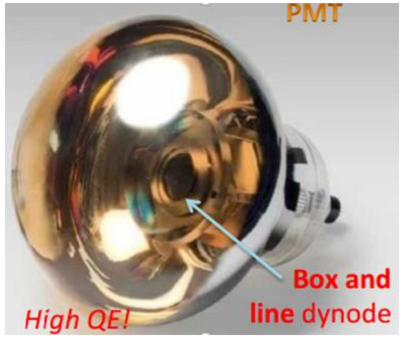


SKPMT: QE~22%
Well known

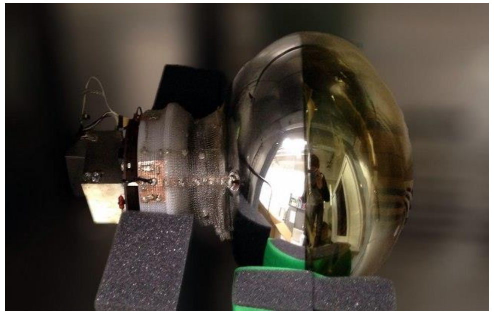


High QE SK PMT(22%->30%)

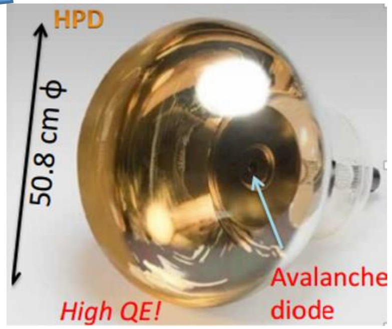
This talk



50cm Box & Line PMT

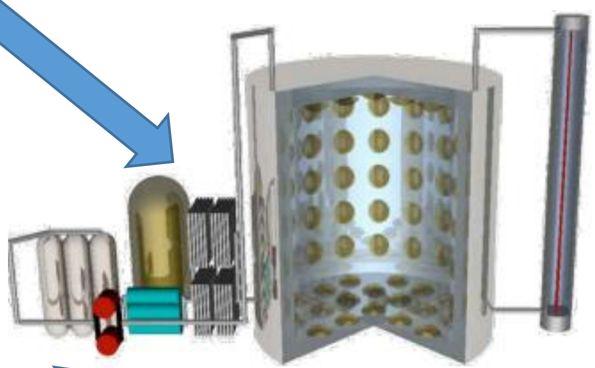


20cm HPD



50cm HPD

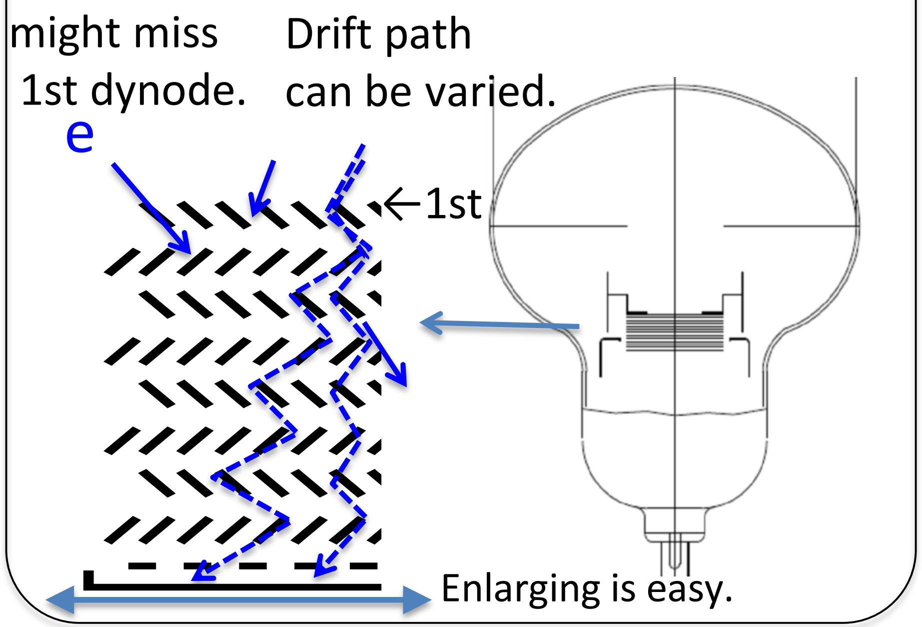
Test in 200ton tank
(Nishimura-san's talk)



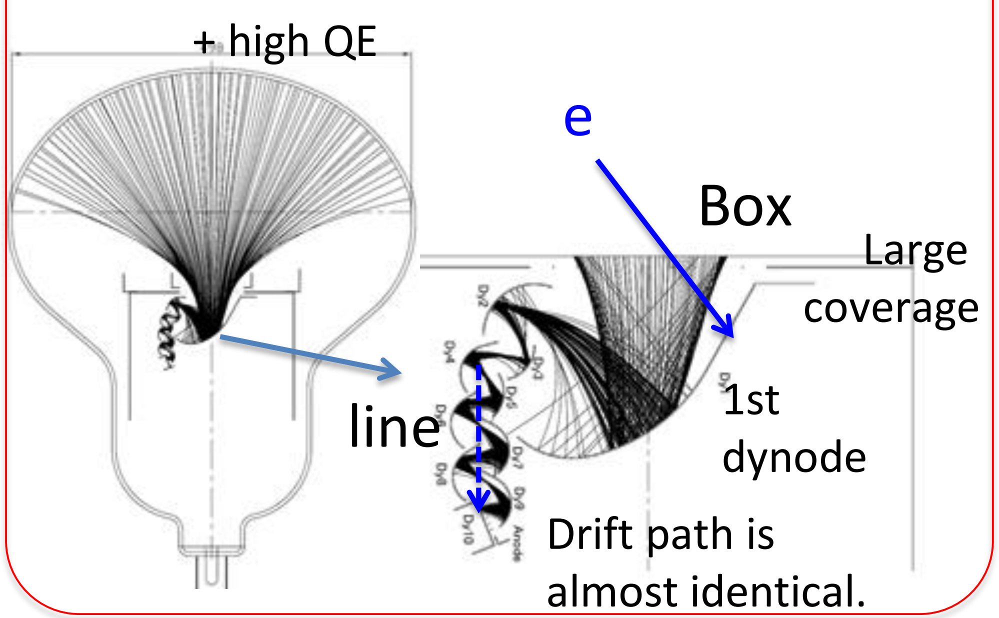
50 cm photomultiplier tube with box-and-line dynode

- Good photon collection by box shape 1st dynode
- Fast time response by line shape dynode

Venetian blind type (Super-K)



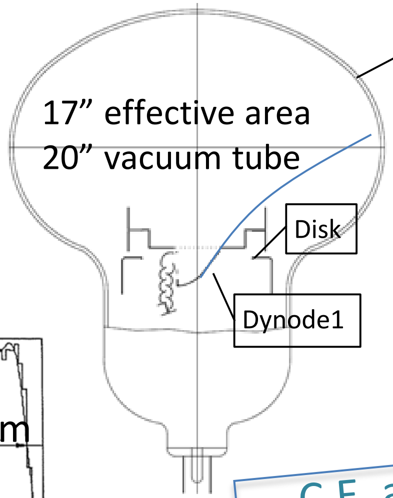
Box and line type (New for 50cm)



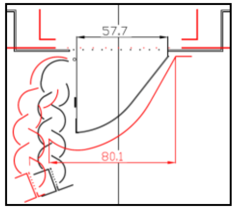
Structure

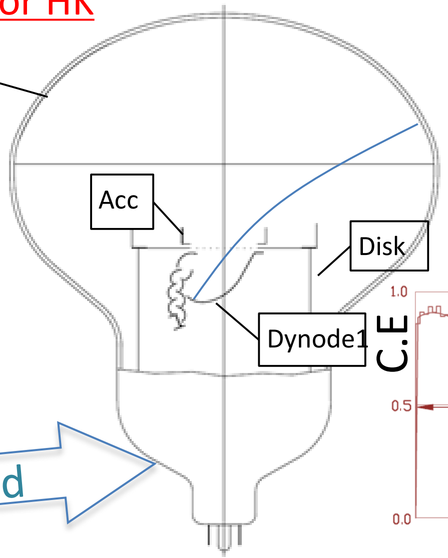
R7250 for KamLAND

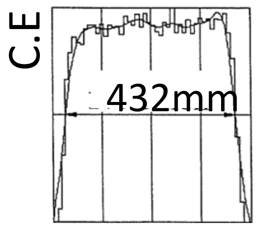
R12860 for HK

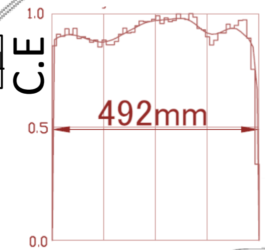


photoelectric surface









C.E. acceptance improved

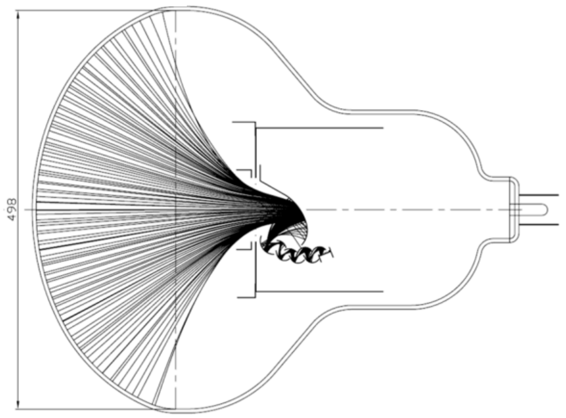
Effort to realize 50cm dia.

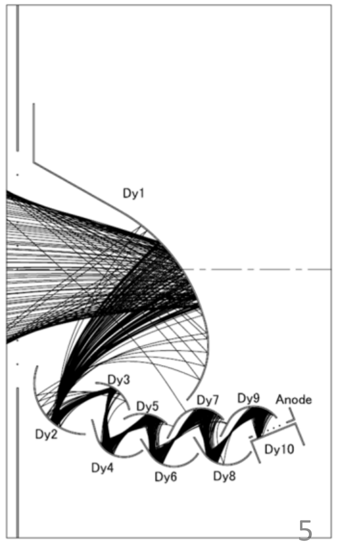
- Optimized curvature and dynodes’ alignment to improve collection
- Added focusing electrode
- Enlarged detection area of first dynode

S/N improved by a factor of 1.5 compared with SK PMT due to an increase of an effective gain in calculation.

K	Dy1	F	Dy2	Dy3	Dy4	Dy5	Dy6	Dy7	Dy8	Dy9	Dy10	P
11.3	0.6	3.4	3.7	3.0	2.0	1.0	1.0	1.0	1.0	1.0	1.0	

Ratio of voltage division



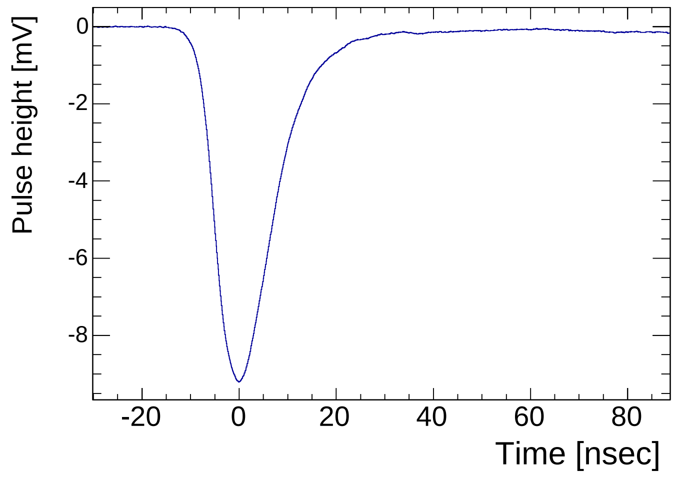


Signal

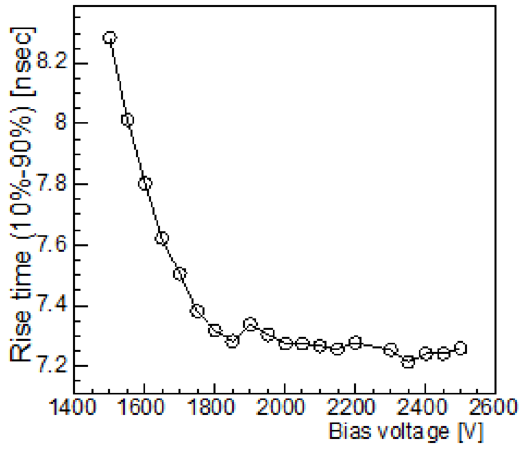
- The single photon signal is like left figure.

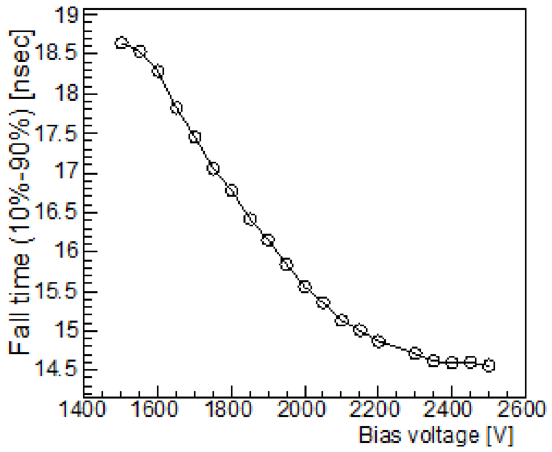
- We measured rise time, fall time in different bias voltage.

Single photon signal



Response as a function of bias V (~20pe)

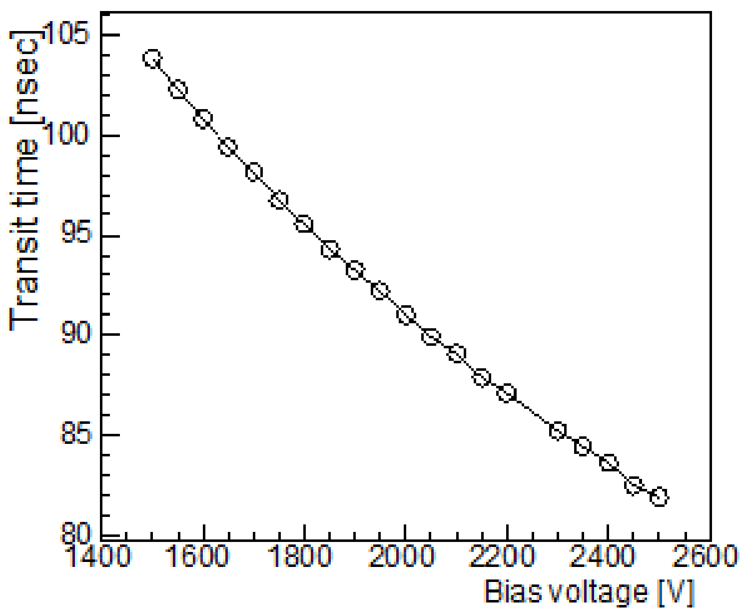




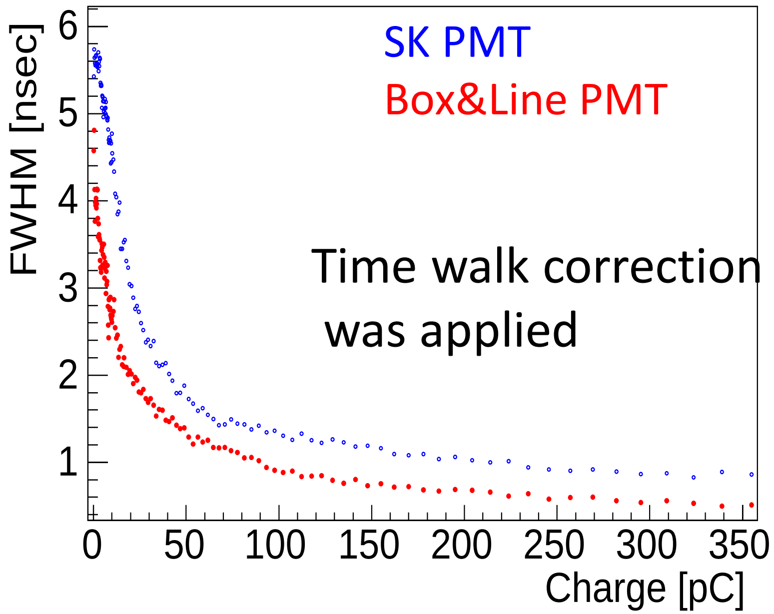
Transit Time

We also measure the transit time of PMT and its spread.
Obviously, Box&Line PMT has less spread than SK PMT, which means that the time resolution is better.

Transit Time



Transit Time Spread



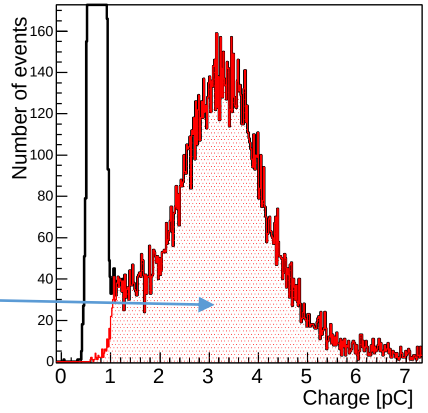
Charge distribution

σ/peak : 42%
FWHM/peak : 83%
Mean/peak : 0.86

σ/peak : 35%
FWHM/peak : 73%
Mean/peak : 0.92

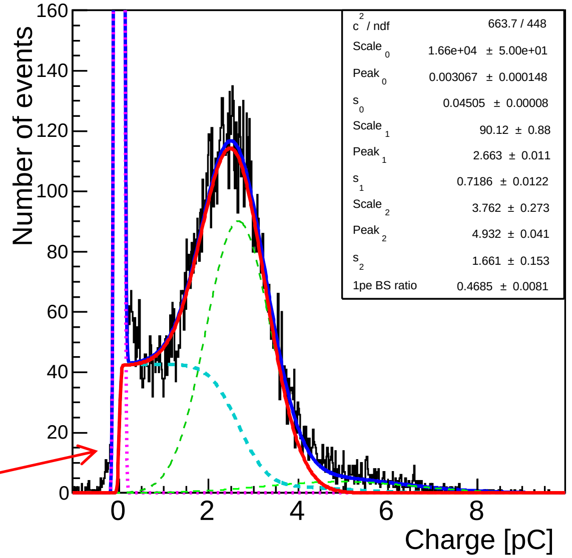
Analyze
from waveform

Charge w/ hit thre. cut

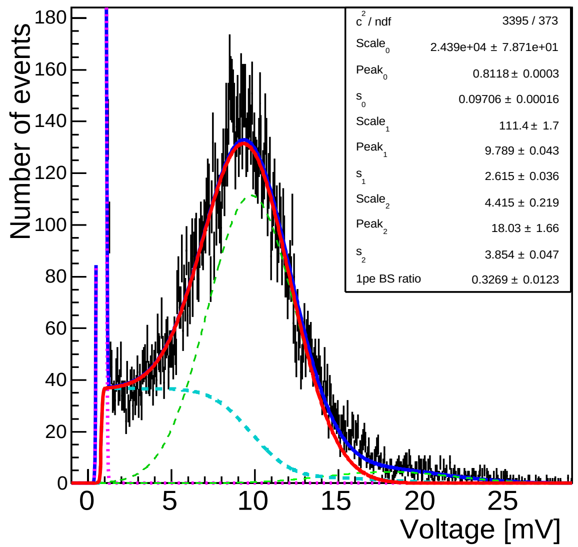


The distribution you
will see in real detector

Charge (100nsec integration)



Height

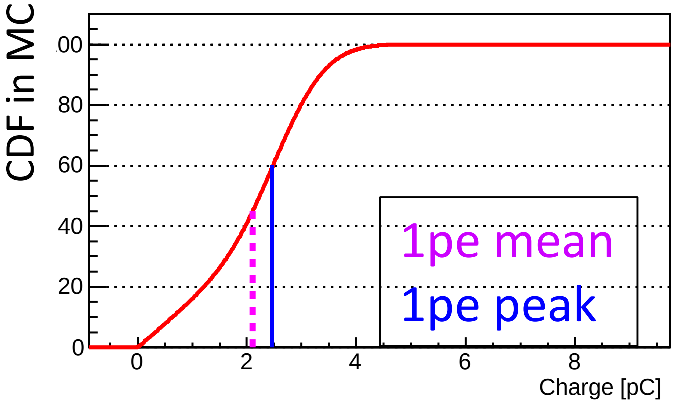


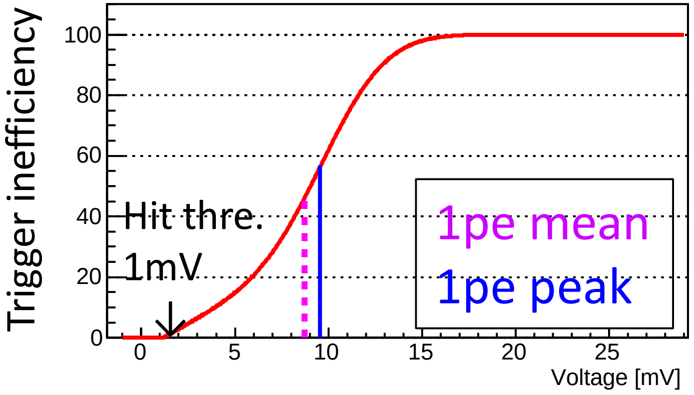
Func. model well represents
1pe component.

1pe=Peak+ Back scattering

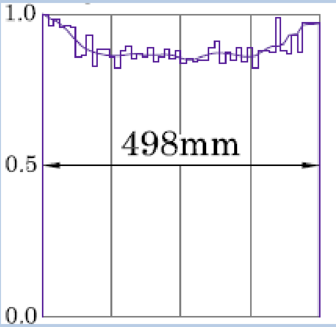
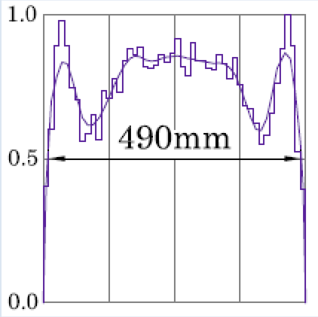
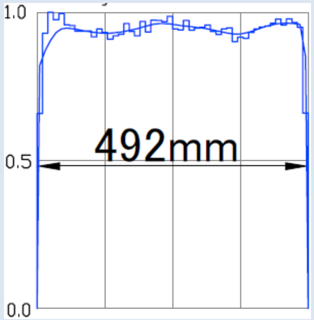
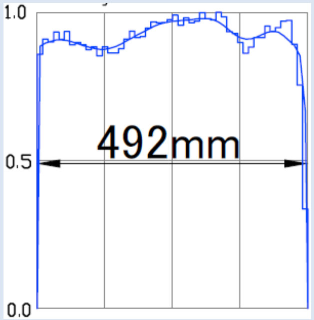
All=1pe+2pe+pedestal

Good 1pe detection efficiency in hit.
Would be provided to MC.

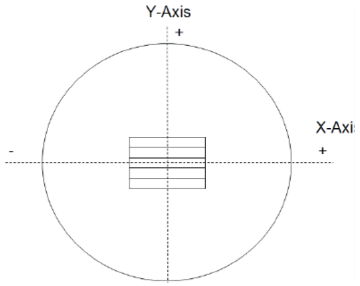




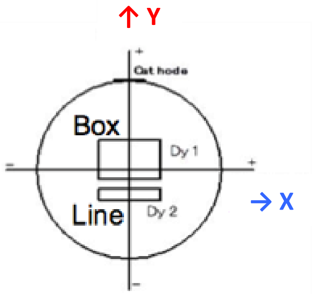
Uniformity of detection efficiency

Simulation (Hamamatsu)	**R3600 SK PMT**		**HQE Box&Line PMT**	
	Dynode Along (X)	Dynode Cross (Y)	Dynode Along (X)	Dynode Cross (Y)
Gain uniformity (not including C.E.)				
Overall C.E.[%]	86.0		98.2	

Measurement (Hamamatsu)

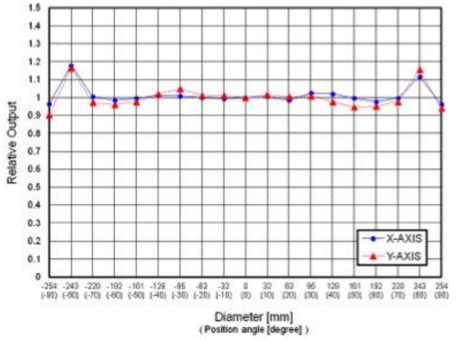


Topview: SKPMT

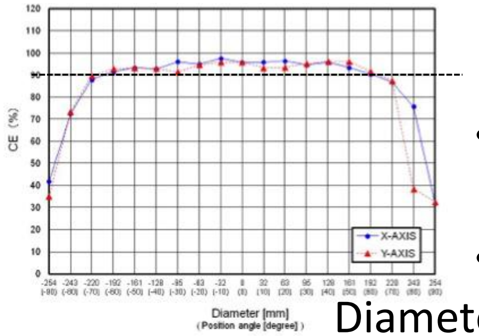


B&LPMT

B&L PMT Relative QE uniformity



B&L PMT Collection efficiency



Diameter

←90%

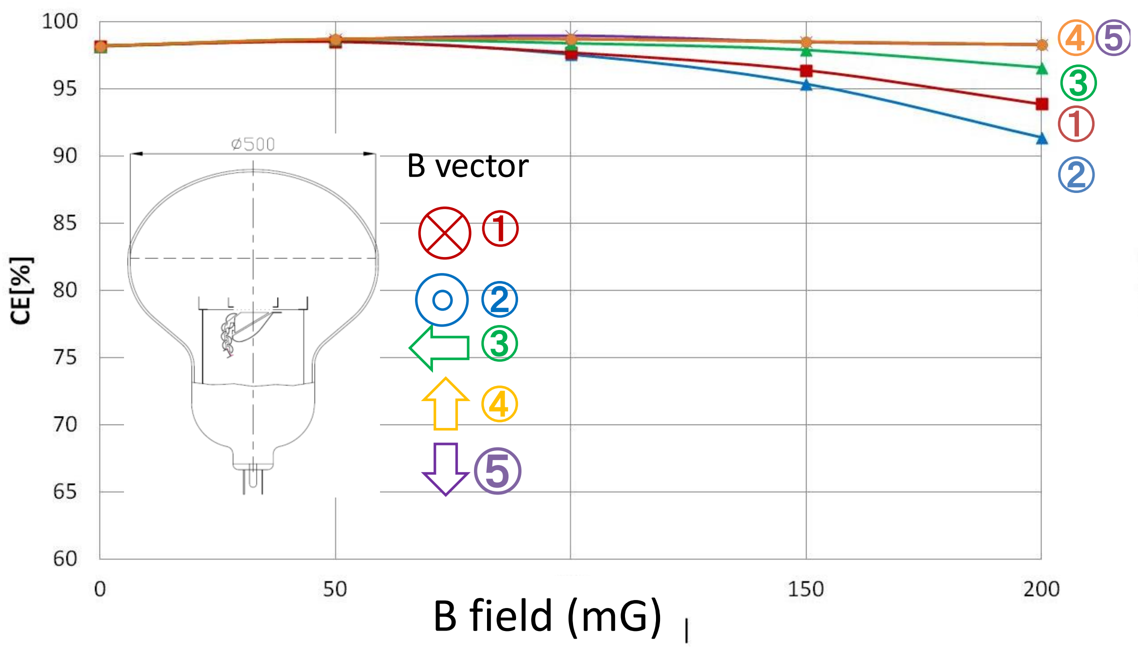
- Uniform response & high efficiency confirmed in measurement
- Better than SK PMT

Magnetic field tolerance

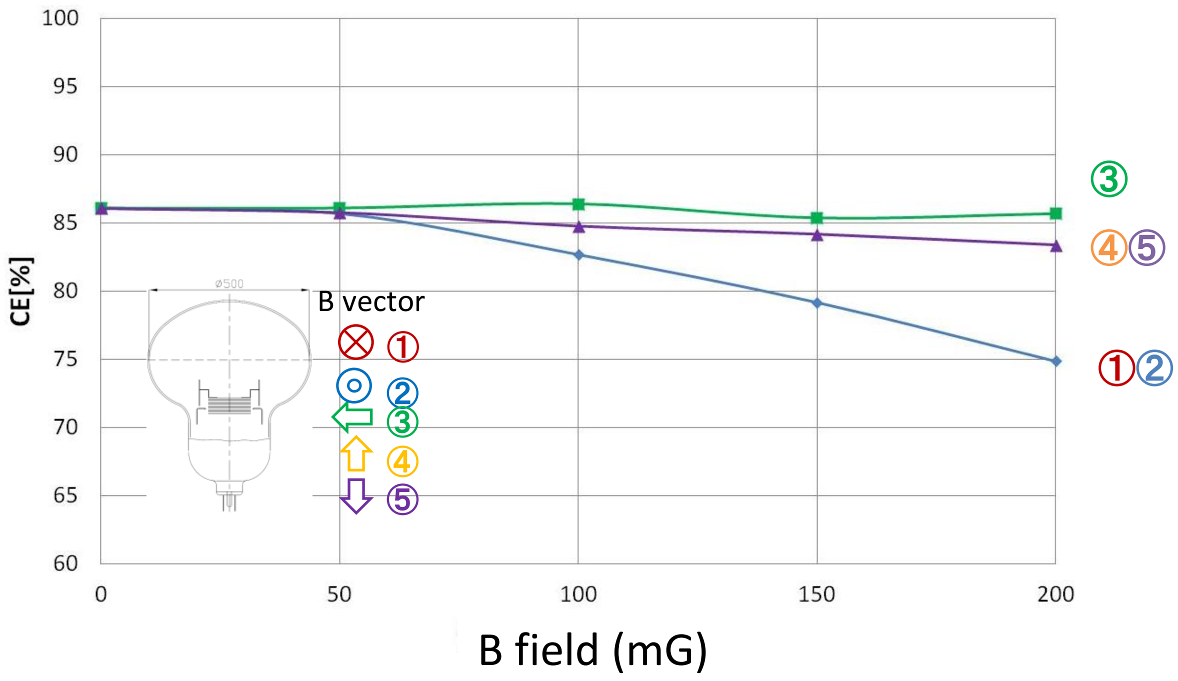
- For the photomultiplier tube, the magnetic field, even low as the geomagnetism, will influence the performance because the energy of the photoelectron in the vacuum tube is low while the path length is long.
- We measured the magnetic field tolerance of Box & Line PMT
- We also made a magnetic compensating shield prototype and evaluated the performance of Box & Line PMT in the shield.

Collection Efficiency
(By each B-direction, uniform injection, simulation)

Box&Line PMT



SK PMT



Comparing with SK PMT, the collection efficiency of Box & Line PMT is

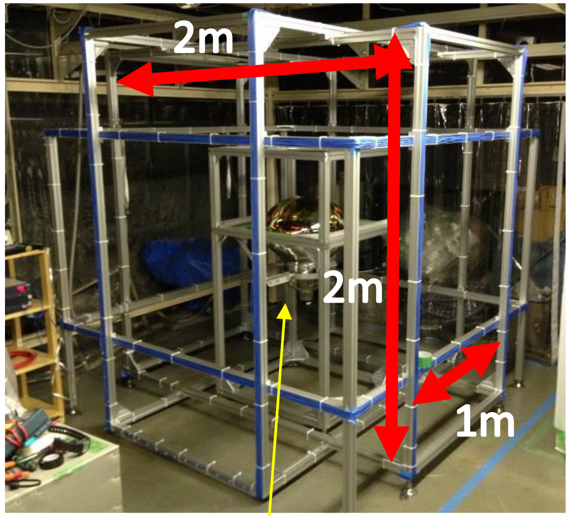
- higher
- not easily to be influenced by magnetic field

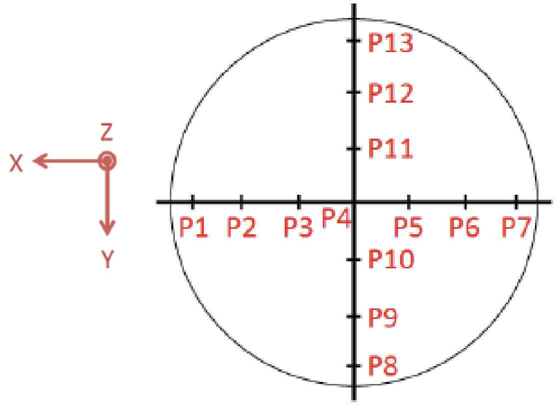
Measured by Changhao Zhao, Nakayama-san

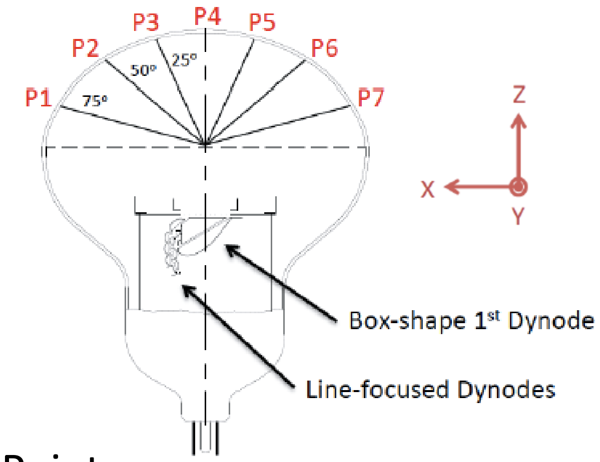
Setup for magnetic field tolerance measurement

- A 3D Helmholtz coil was constructed in Kamioka to compensate/control magnetic field.
- We check the collection efficiency in
  - different incident position
  - different magnetic field direction
  - different magnetic field intensity

3D coil

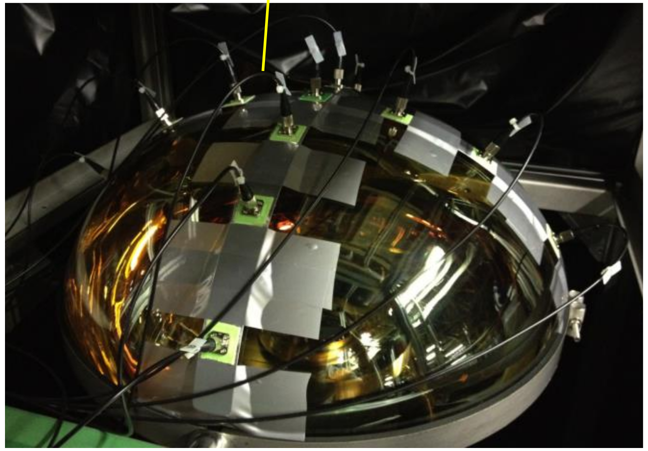




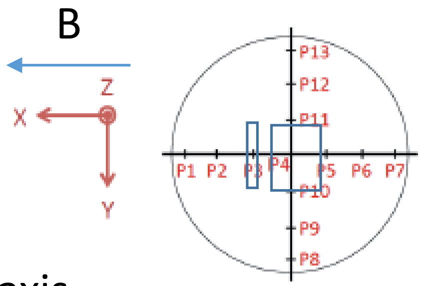


Incident Point

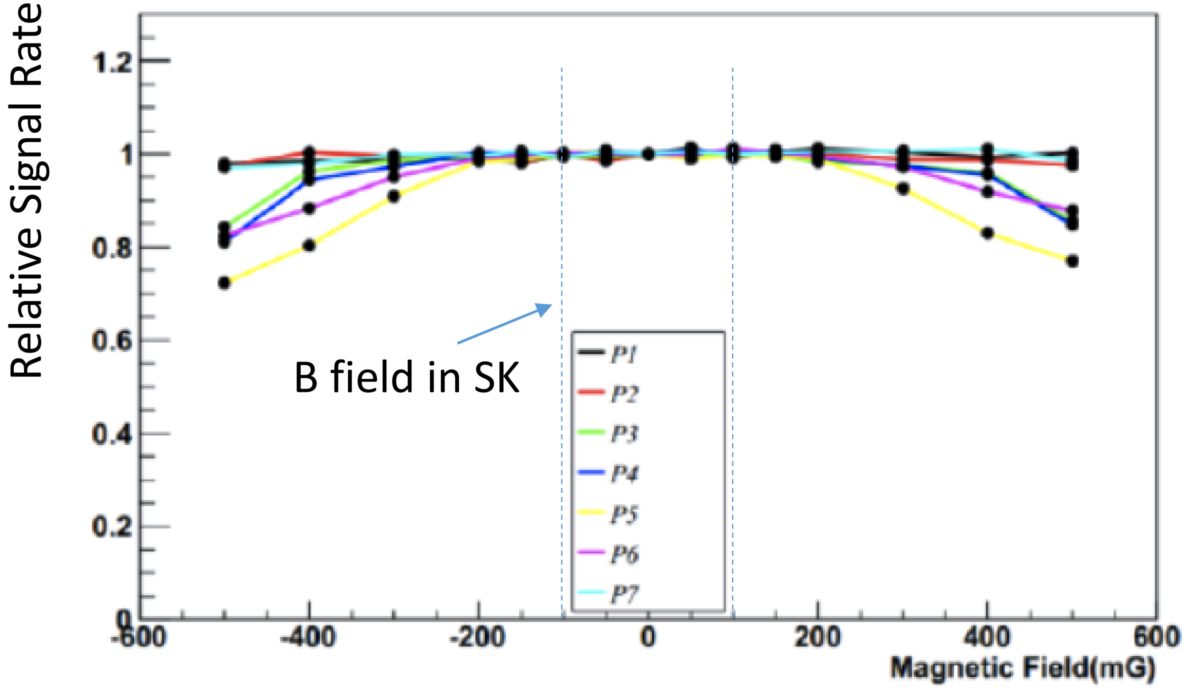
Photon Incident point



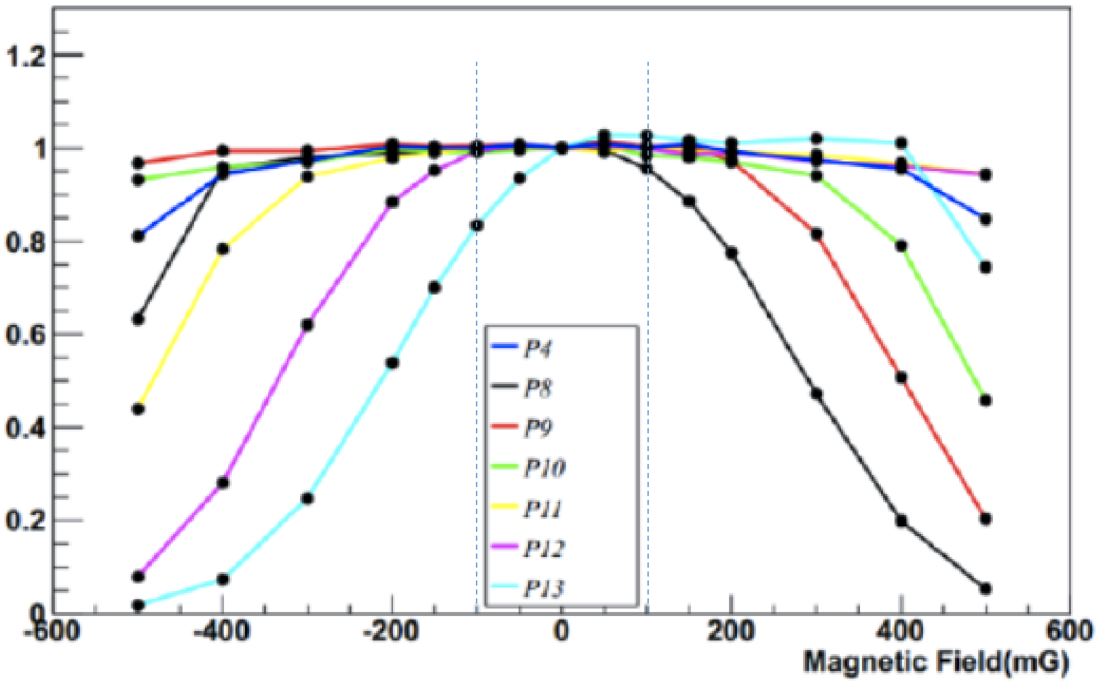
Relative Signal Rate in X direction B field



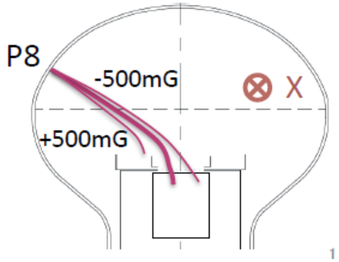
Incident Point on X axis



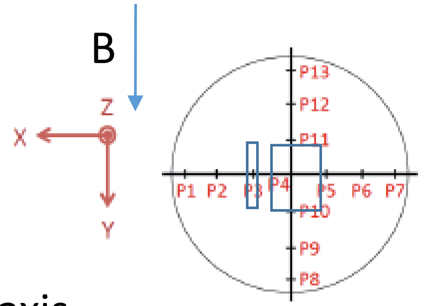
Incident Point on Y axis

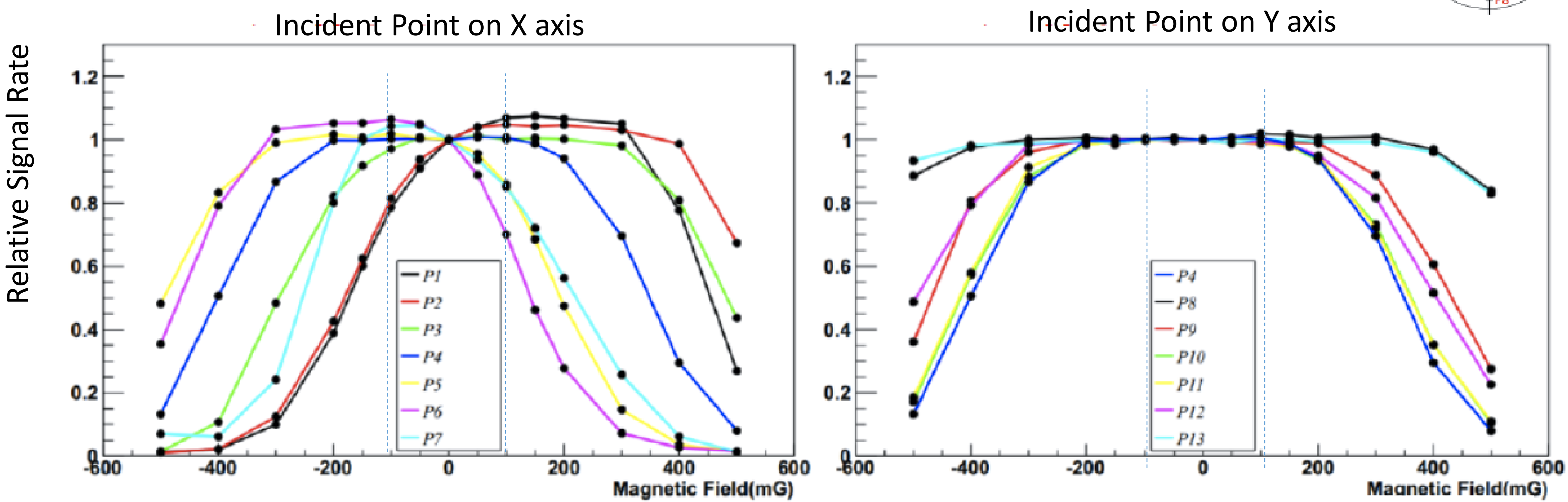


- It is easier to be influenced by magnetic field for the incident point on Y axis when B on X axis
- Detection Efficiency becomes lower about 20% at most in 100mG, which is the magnetic field in SuperK

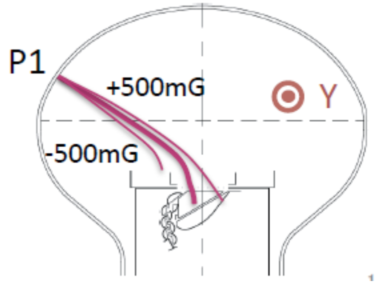


Relative Signal Rate in Y direction B field

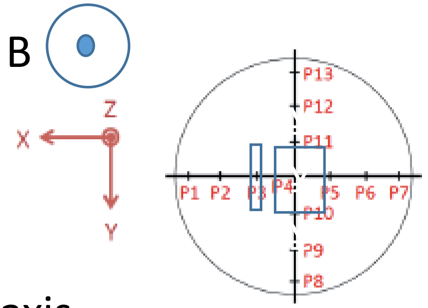


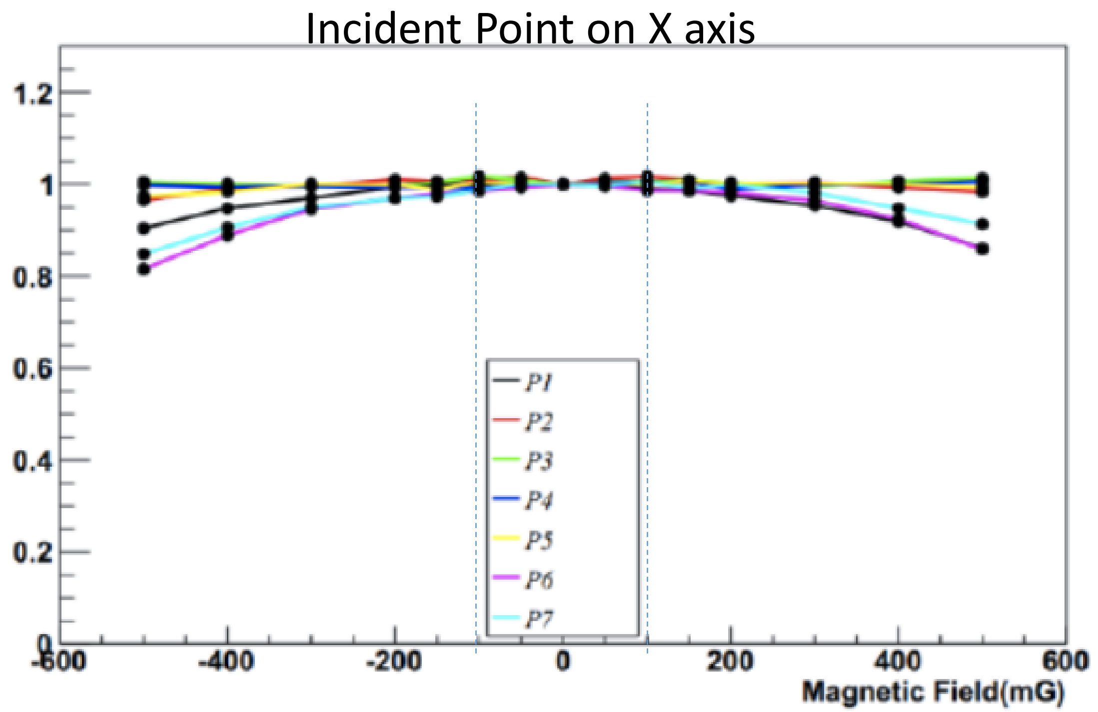


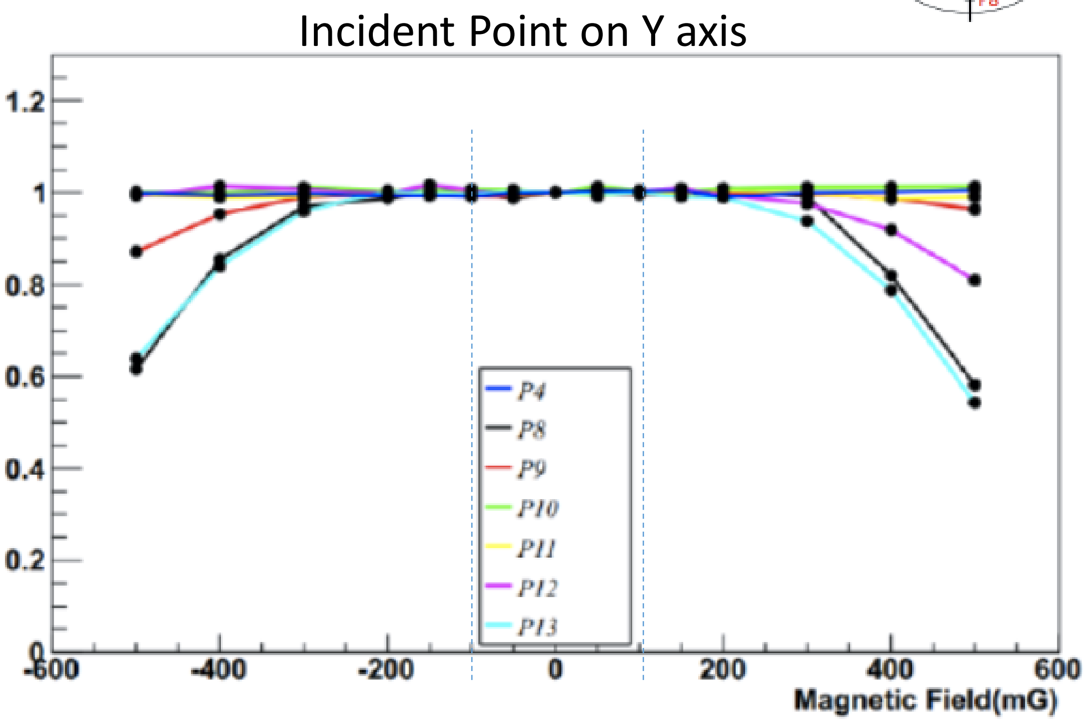
- It is easier to be influenced by magnetic field for the incident point on X axis when B on Y axis
- Detection Efficiency becomes lower about 30% at most in 100mG



Relative Signal Rate in Z direction B field



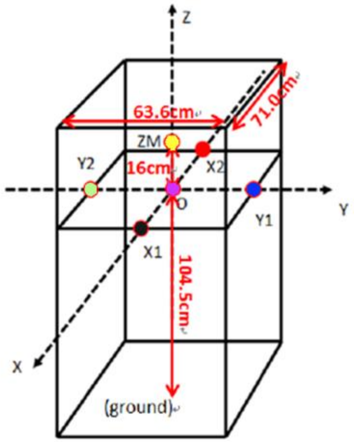




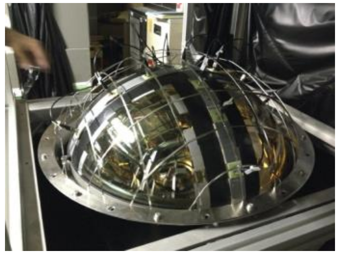
- The influence is small if magnetic field is on Z axis
- Detection Efficiency becomes lower about 5% at most in 100mG

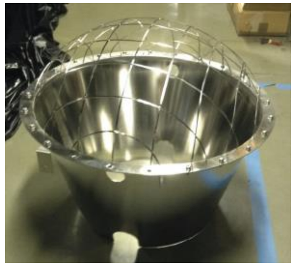
The way to compensating magnetic field

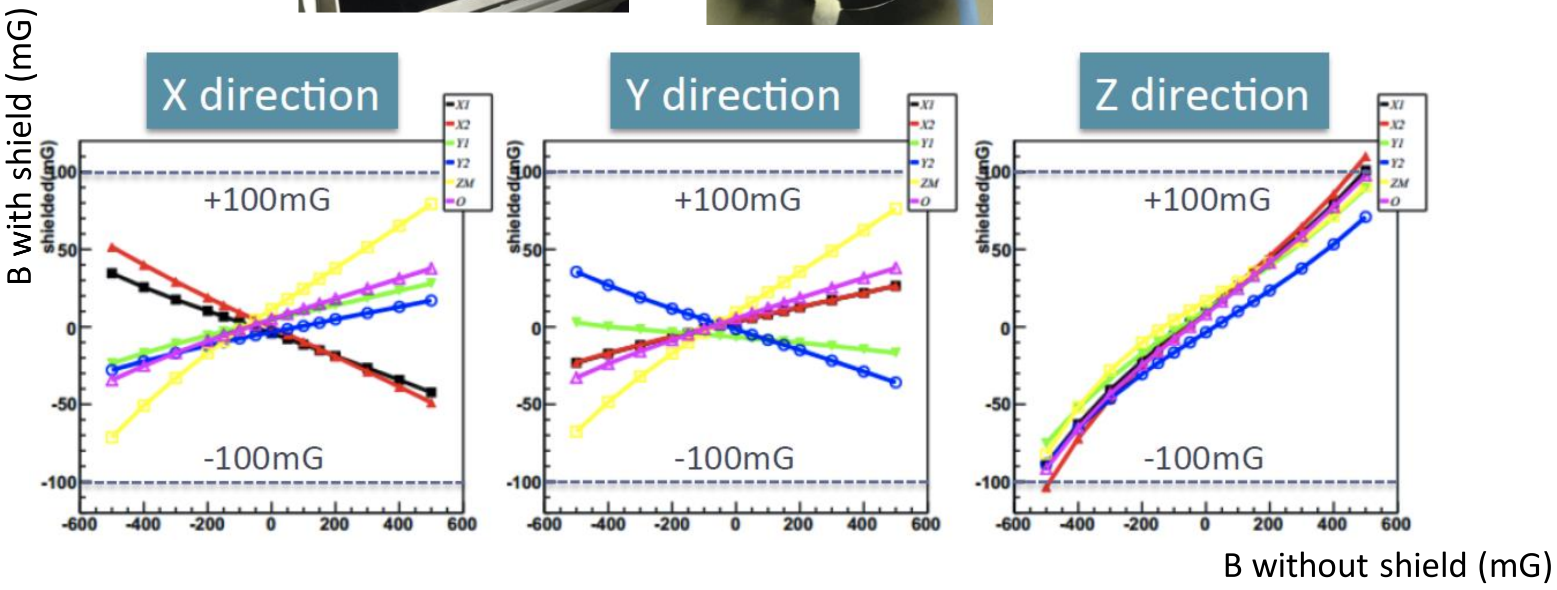
- Active shield
  - Put all the tank into a coil which generate a designed magnetic field to compensating geomagnetism.
  - Used by SuperK.
- Passive shield
  - Surround every photon sensor with high magnetic permeability metals
  - Used by Kamiokande, IceCube, Double Chooz
- We tested the performance of a passive permalloy shield prototype



Compensating field prototype

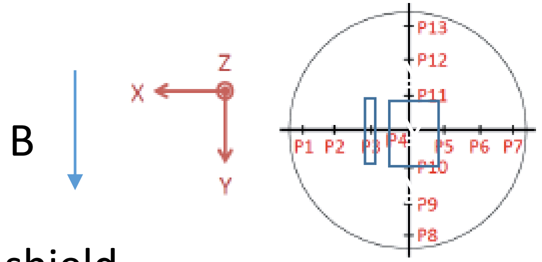






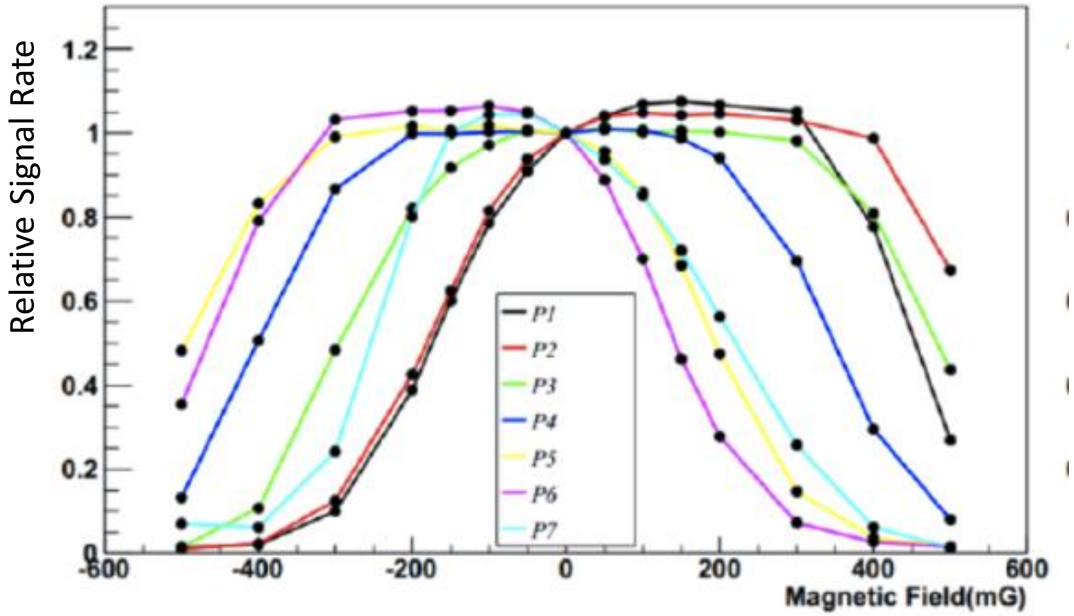
The magnetic field is reduced to 1/7 for X, Y direction, 1/5 for Z direction by compensating shield.

The effect of the compensating shield prototype

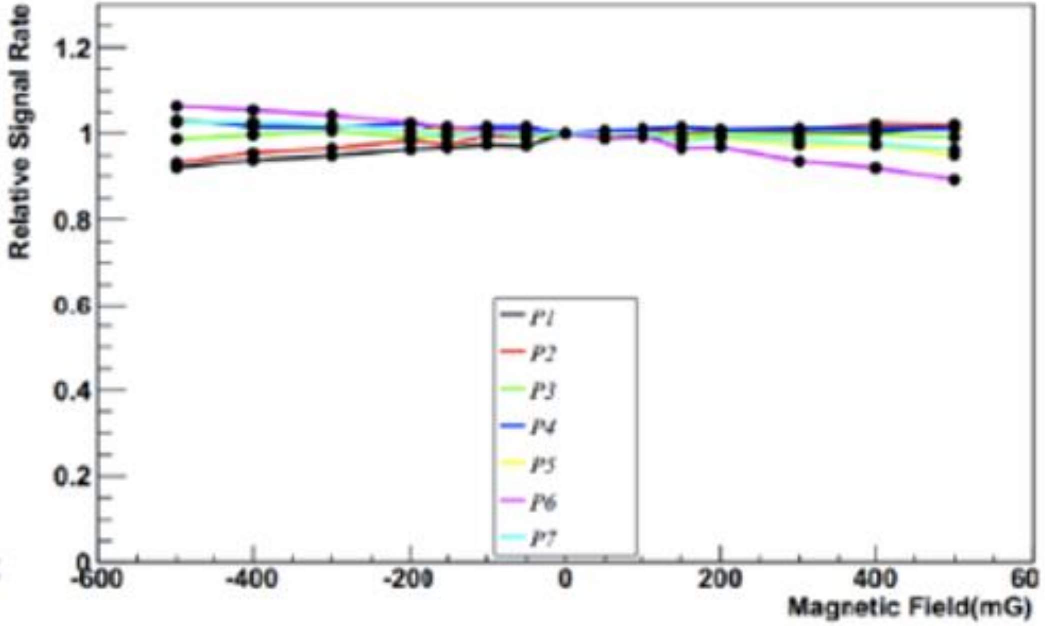


For the most influence from magnetic field situation

Without shield



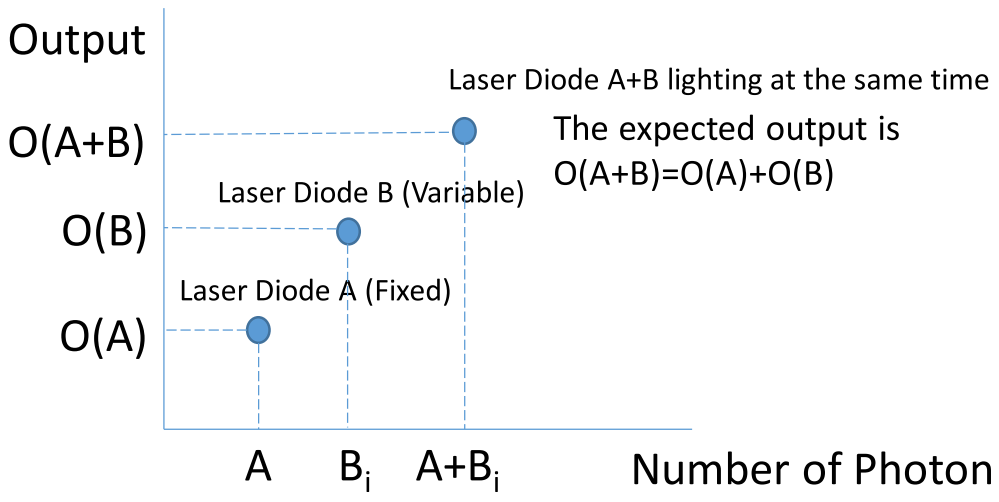
With shield



- The reduction of detection efficiency is small when the compensating shield is set
- For the most serious situation, (B direction perpendicular to the dynode), the effect of the compensating shield is significant
  - At geomagnetism in SK (100mG), reduction of collection efficiency is suppress to 5% from almost 20%

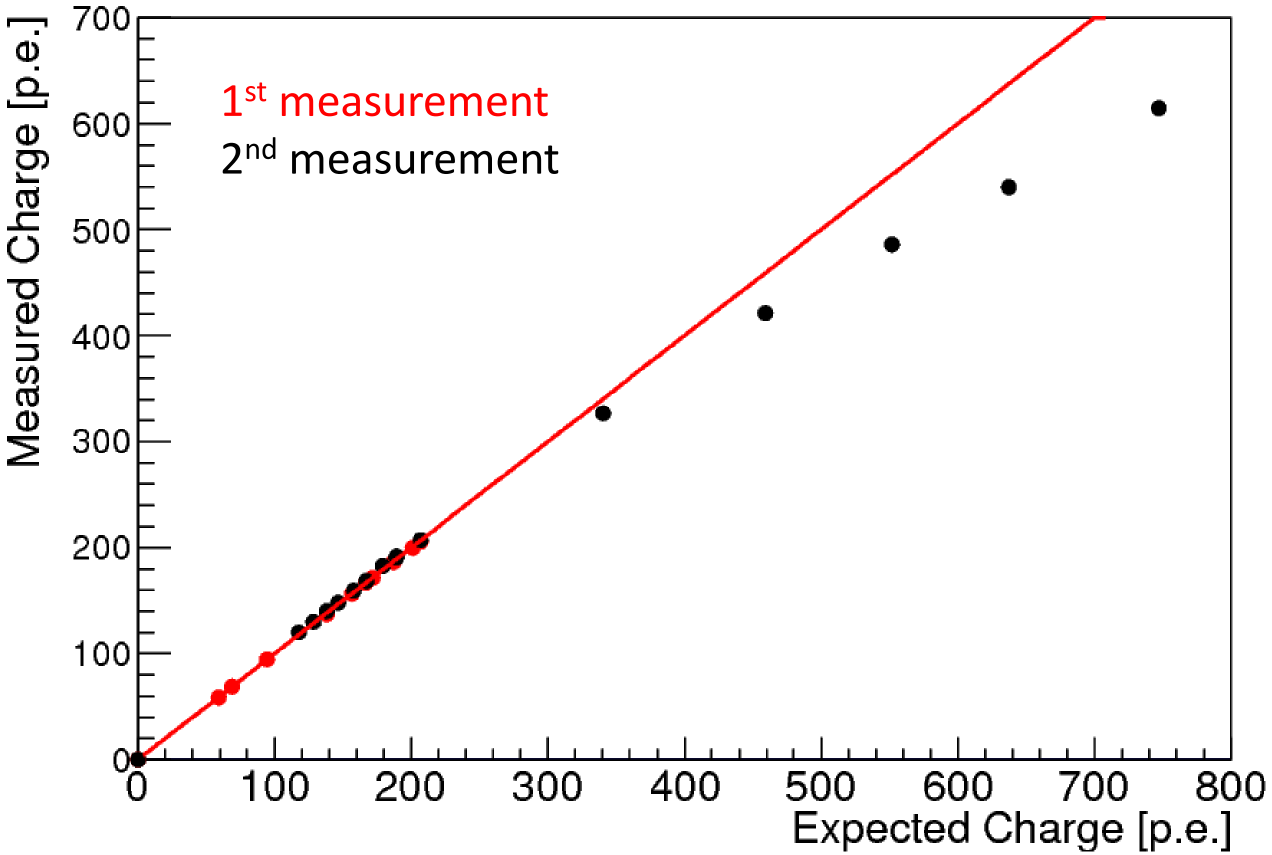
Gain Linearity

- The wide range of HK physical target, we need a PMT that can measure from 1 p.e. to several hundreds p.e. with a stable gain.
- When a large number of photons incidence to the PMT, there would be so many photoelectrons in the rear section of dynode to saturate. Then, the gain is not as high as expected – it drops.
- We use two laser diodes to evaluate the linearity of the output
  - We fixed the output luminosity of A and change the one of B from 1 p.e to several hundred p.e. by to check the linearity of wide region



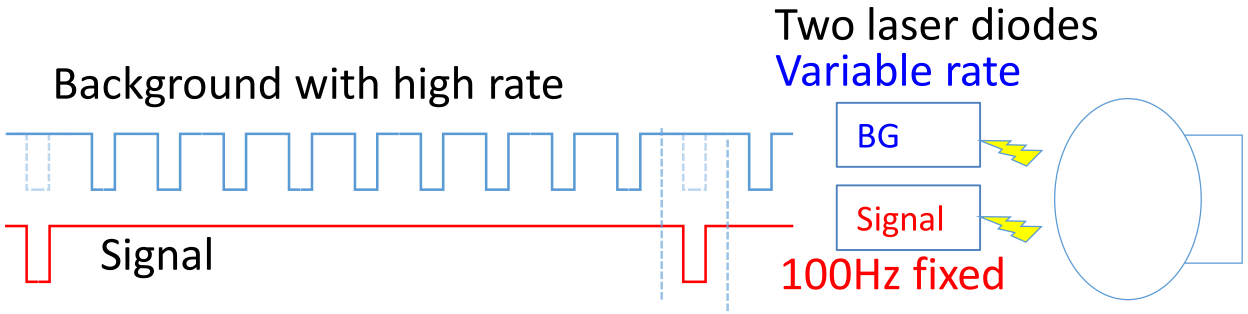
Gain Linearity

- The linearity is kept up to 400 p.e. with gain drop less than 5% when 1 p.e ~ 2.2pC.

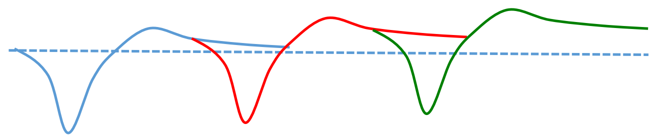


Rate tolerance

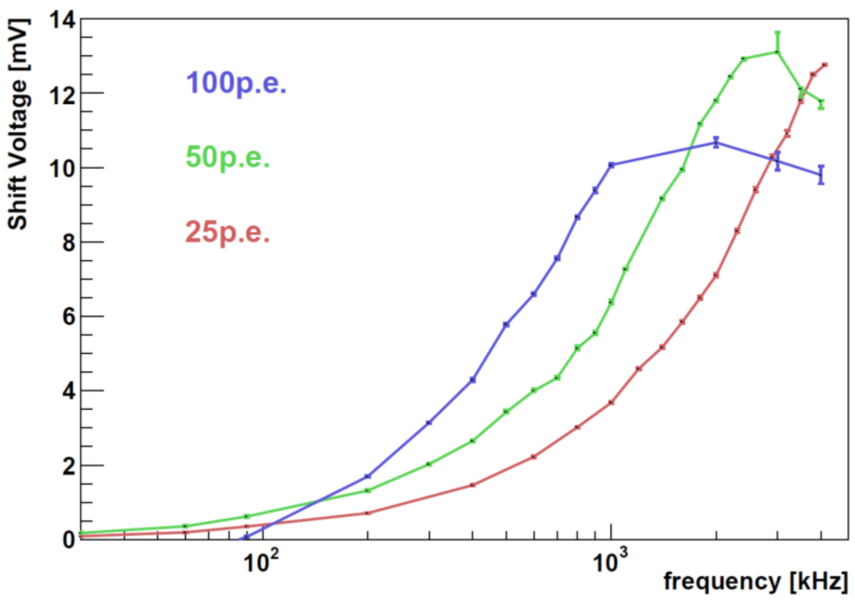
- For the supernova explosion, the photon-sensor might detect a large number of events in a short time
  - The response of the photon-sensor to the signal with a high hit rate might be different from the one when the hit rate of the signal is low because of the over-discharge on the dynode and cathode.
- We use two laser diode (LD) as light source at the same output in one pulse to evaluate the rate tolerance:
  - One for background, with a changeable rate
  - One for signal, with 100Hz
- We compared the pedestal and signal charge with background and the one without background.

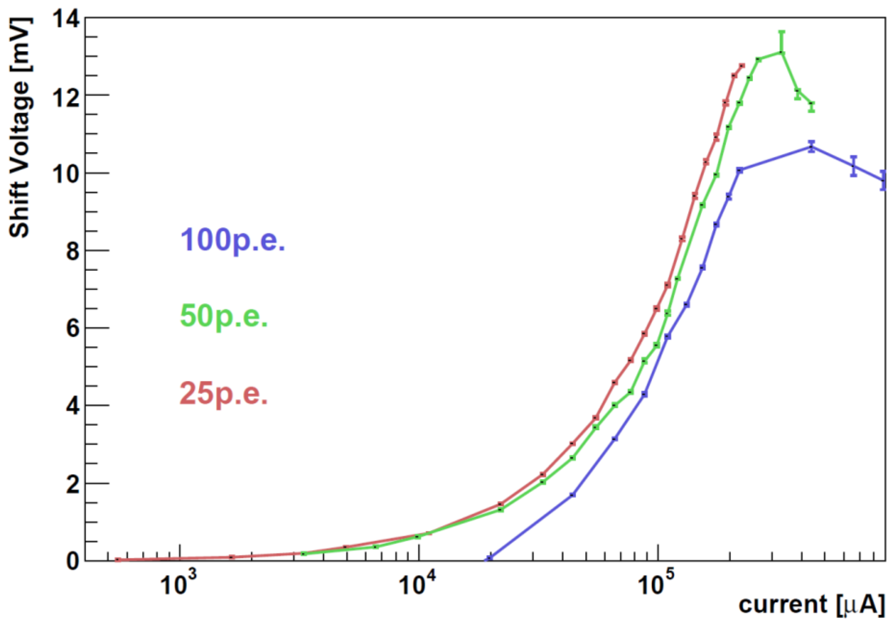


Rate tolerance – baseline shift



- Baseline is shifted due to RC in bleeder circuit.
  - For a high rate series of signals, the coupling capacitor in PMT cannot discharge fully before the next signal coming
  - →there are always current through the coupling capacitor, which means that the baseline changed
  - →Integration of charge and the “real threshold” would be influenced
- Comparable level with SK PMT.

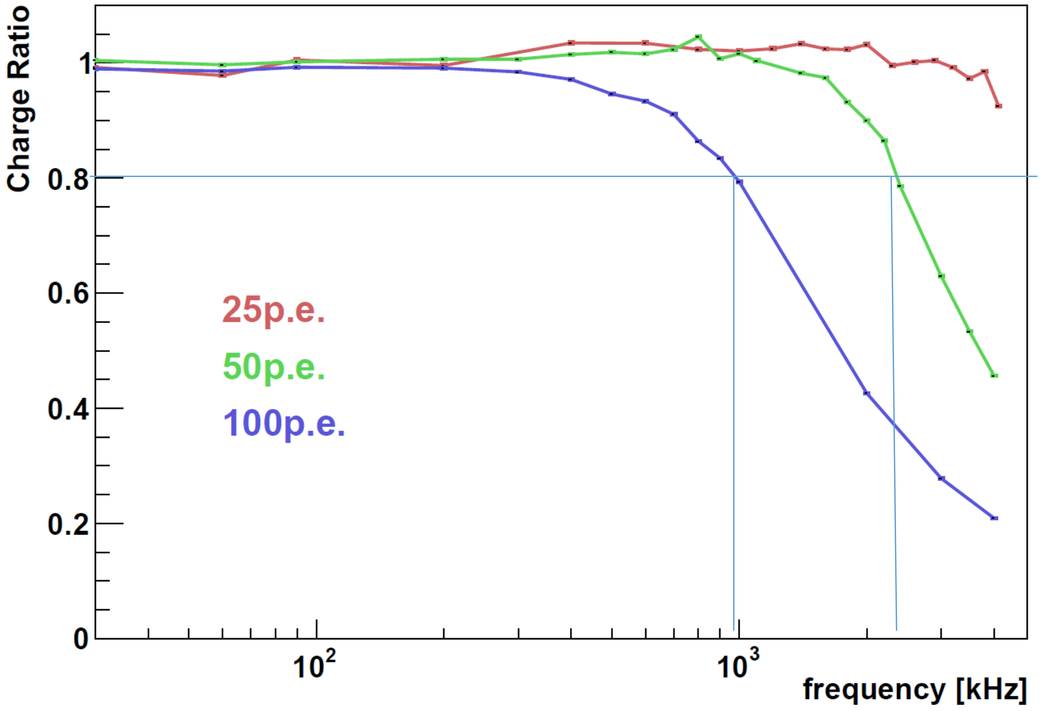


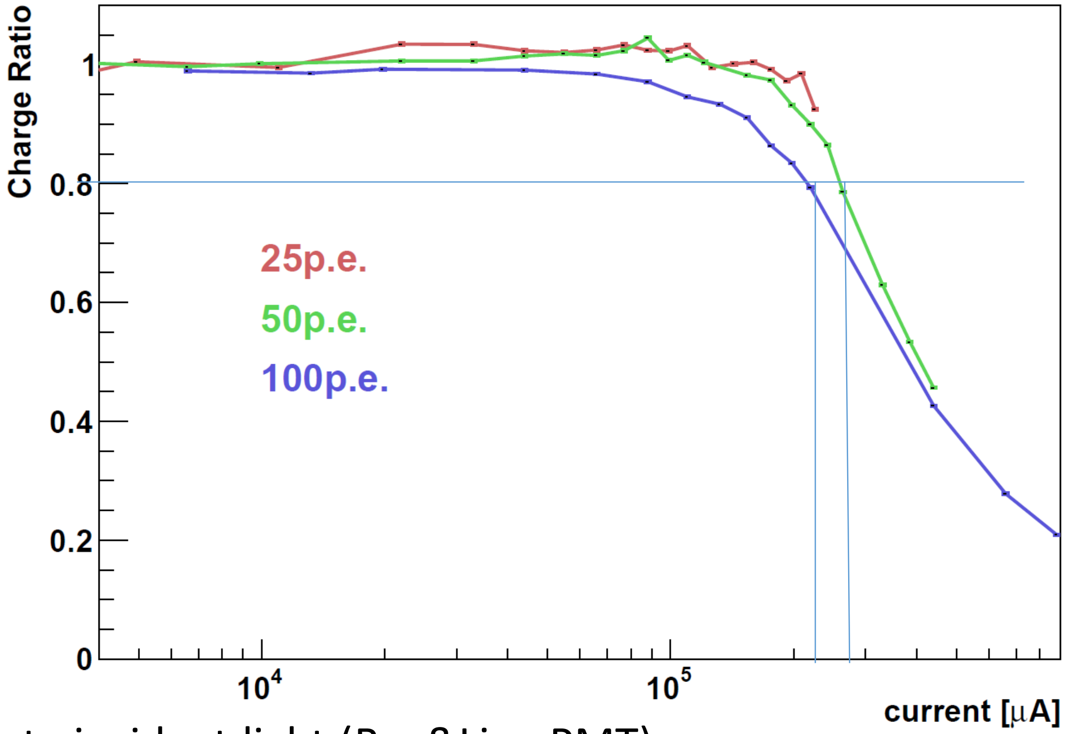


Rate tolerance

$$\text{Charge Ratio} = \frac{\text{Sig. charge w/ bkg}}{\text{Sig. charge w/o bkg}}$$

- Gain also drops in high frequency , or high output current situation
  - The voltage between dynode become lower due to over-discharge.
  - The gain kept stable (gain drop less than 20%) up to 1MHz for 100 p.e continuous signal
    - For 1 p.e. signal, the rate can be up to 100MHz (only consider the current limit)



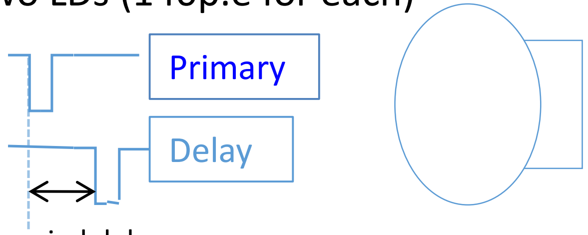


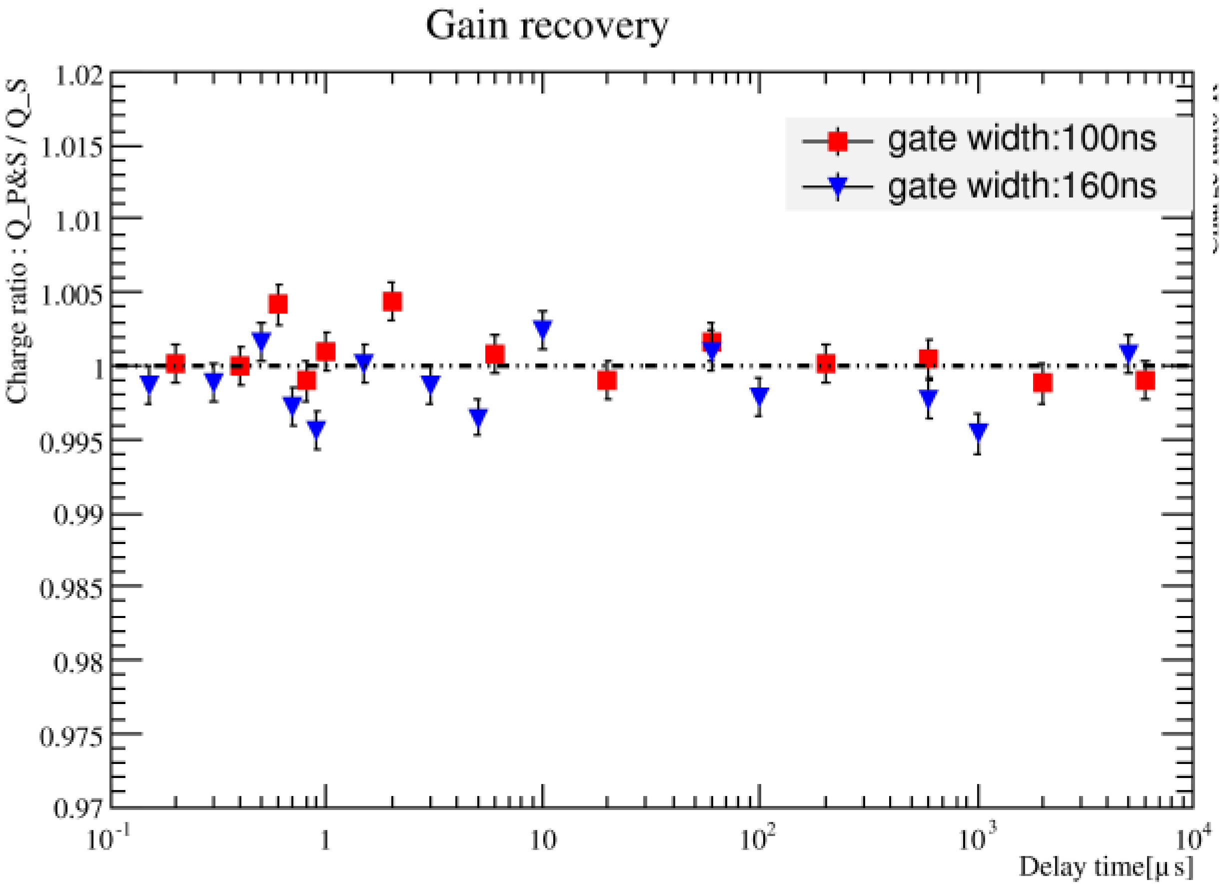
Gain drop for high hit rate incident light (Box&Line PMT)

Recovery

- For that events might happen quickly but not keeping so long time such as stopping cosmic muon decay, the performance of recovery is more important
- We used two continuous pulse to measure the gain recovery.
  - Observed change of delay pulse charge = (Delay w/ primary) / (Only delay pulse)

Two LDs (140p.e for each)



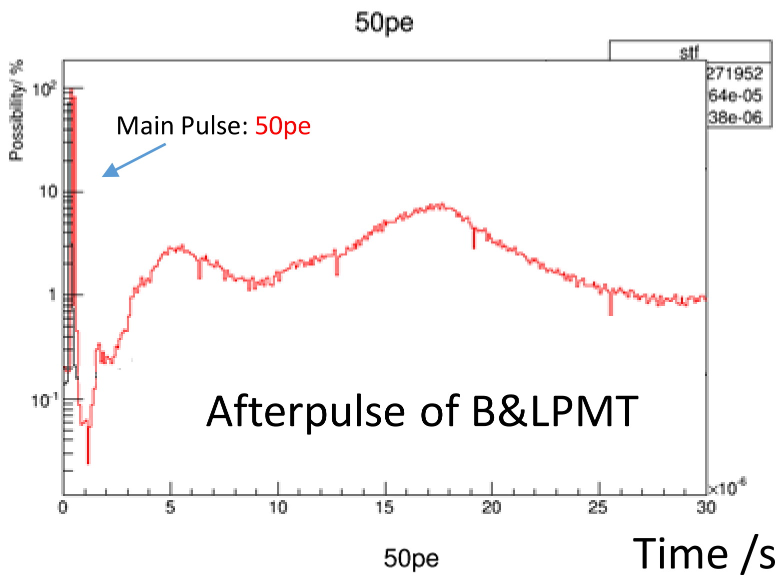


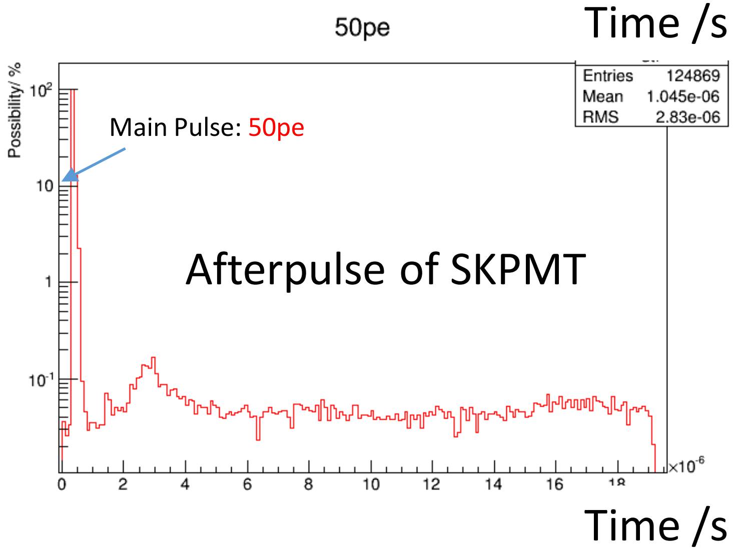
No significant change was observed so far, within 0.5%, which is the same level as measurement error

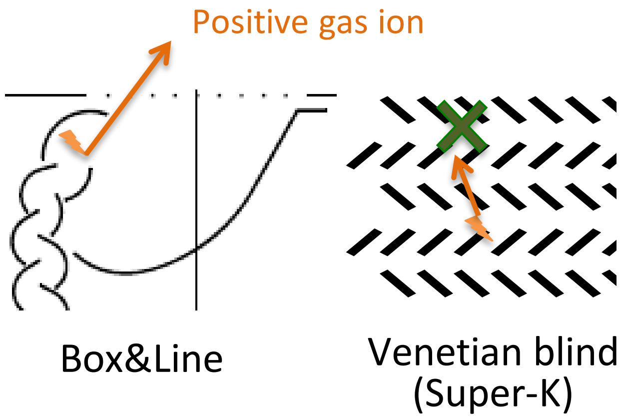
Measured by Jiang

Afterpulse (AP)

- Occurs some time after the initial photoelectron signal
- One of the main sources of undesired background noise signals, especially for low rate event detection
- It is more easier for the Box & Line PMT than the Venetian Blind PMT to generate the after pulse because of their dynode structure.





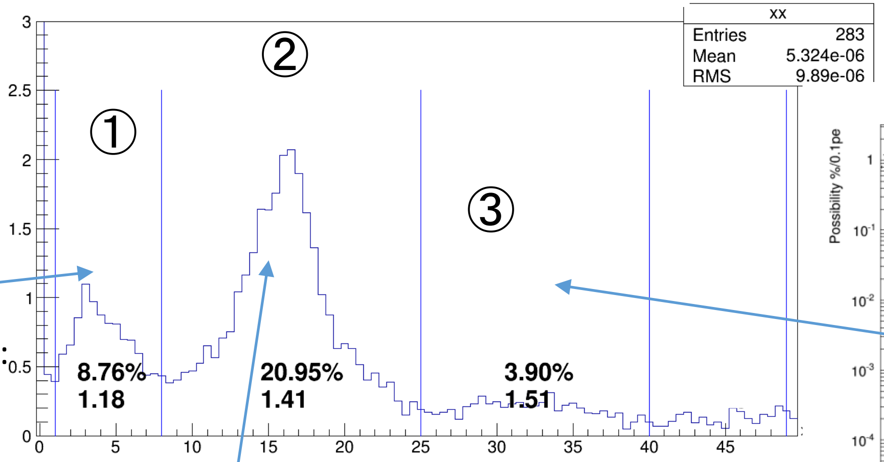


Afterpulse Time and Charge possibility distribution

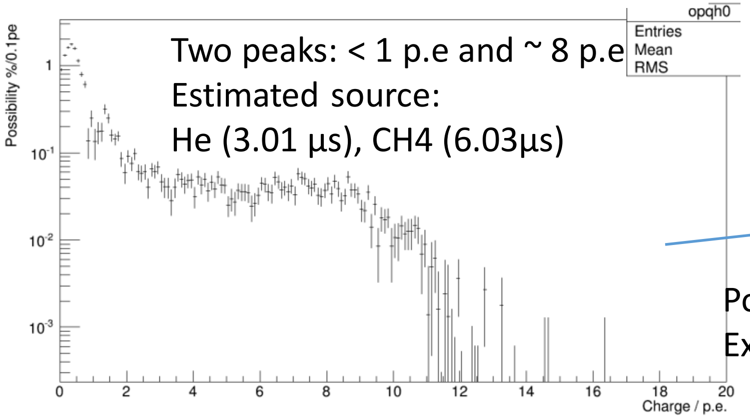
Overall Possibility (1μs~50μs): 30.8%
Overall Expected #: 1.49

Possi.: the possibility of more than 1 AP occurs
Exp.: expected value of # of AP per main pulse if more than 1 AP occurs
The influence of dark count has been removed

Afterpulse Time Distribution

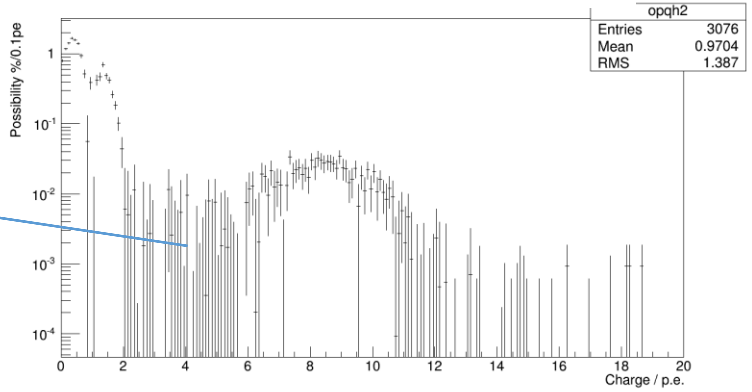


Charge Distribution in ①



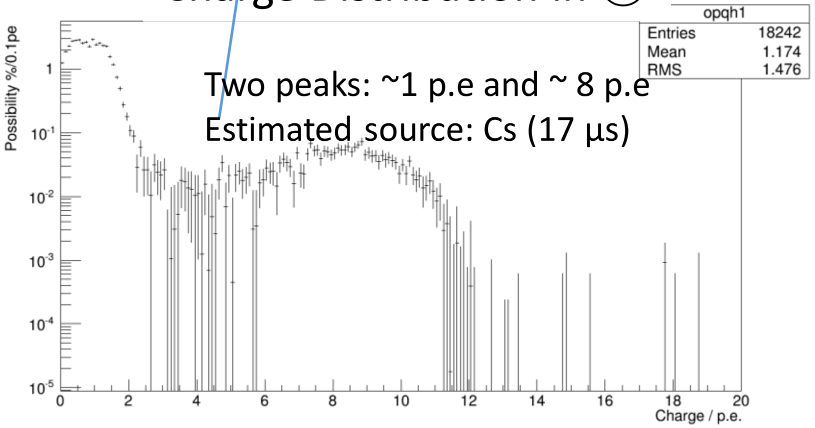
Two peaks: < 1 p.e and ~ 8 p.e
Estimated source:
He (3.01 μs), CH4 (6.03μs)

Charge Distribution in ③



Two peaks: ~1 p.e and ~ 8 p.e
Estimated source: Ion with Q/M ~ e/383u*

Charge Distribution in ②



Two peaks: ~1 p.e and ~ 8 p.e
Estimated source: Cs (17 μs)

- Most of the afterpulse is just 1 p.e pulse, although the rate is higher than that of SK PMT
- This distribution will be provided to MC so that its impact on physics can be analyzed

- incident light with luminosity about 1 p.e. at t = 0

Summary

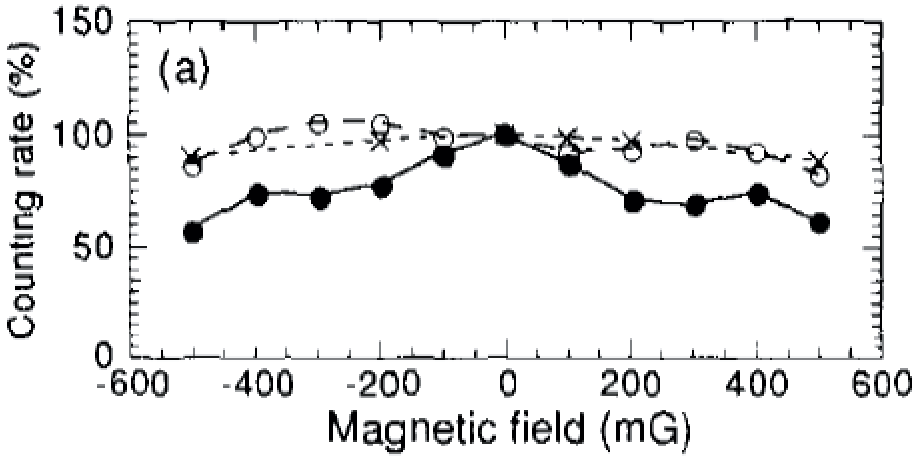
	R3600 (SK PMT)	R12860 (Box & Line PMT)
Dynode	Venetian Blind Dynode	Box & Line Dynode
Collection efficiency	70%	93%
Trans time spread	5.5ns	2.7ns
P/V of Single photoelectron	1.4	>2.5
High Voltage	2 kV	2 kV

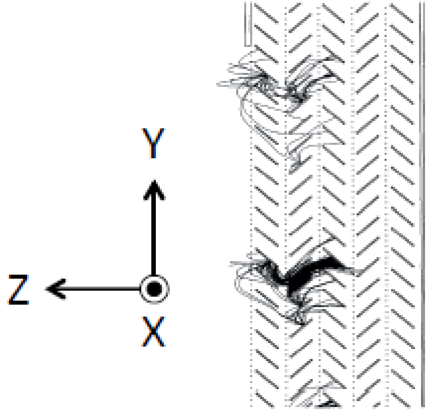
- We have developed the Box & Line PMT for Hyper-K
- The performance evaluation of Box & Line PMT is done in detail
  - Necessary data of B&L PMT is ready for HK simulation
- Further improvement and R&D of B&L PMT is ongoing
  - Suppress the afterpulse
  - Investigate the impact on event reconstruction and physical analysis from afterpulse

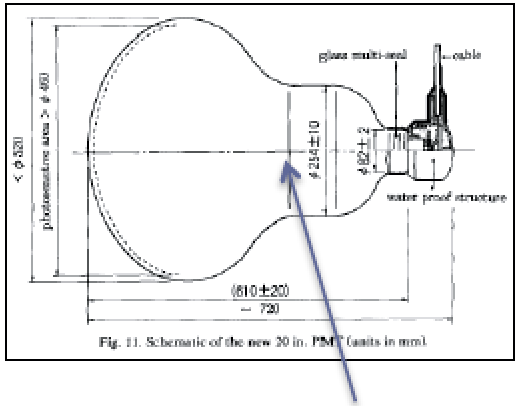
Back Up

A. Suzuki et al., NIM A329 (1993) 299-313

Performance of SK PMT in magnetic field





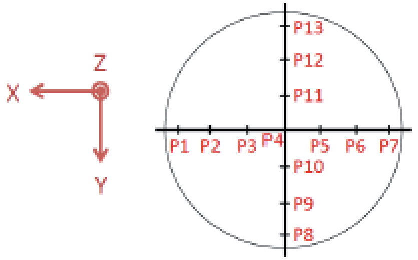


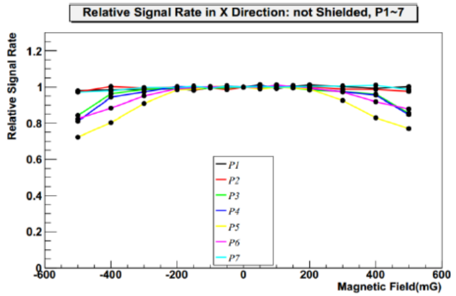
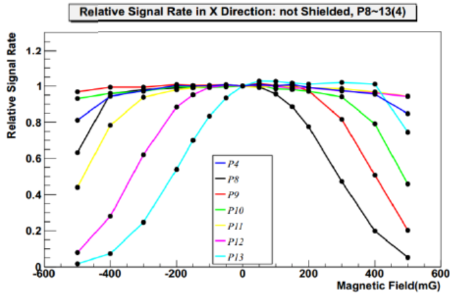
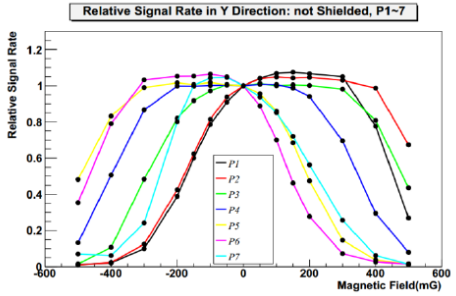
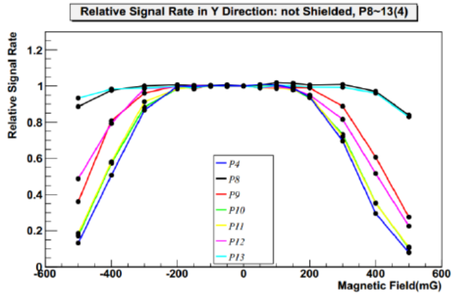
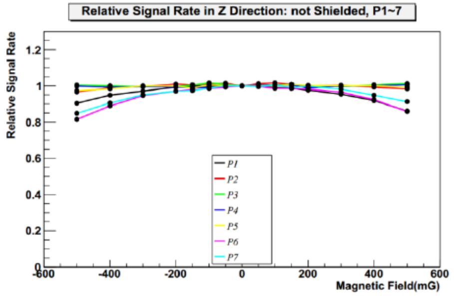
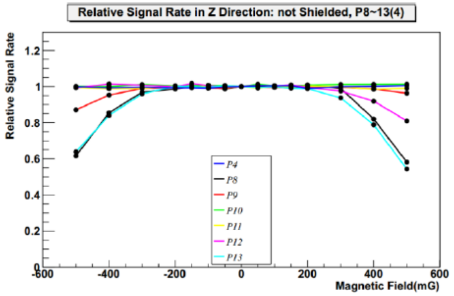
Venetian Blind Dynode

- ● Parallel to dynode (X)
- ○ Perpendicular to dynode (Y)
- × PMT facing direction (Z)

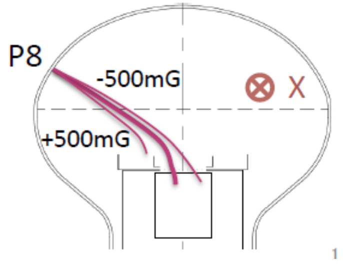
The detection efficiency would become lower 10~15% for the most strict situation (Parallel to dynode)

Relative Signal Rate in 3 direction magnetic field

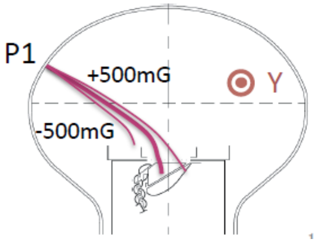


	Incidence Point on X	Incidence Point on Y
B Direction: X		
B Direction: Y		
B Direction: Z		

- It is easier to be influenced by magnetic field for the incident point on Y axis when B on X axis
- Detection Efficiency become lower about 20% at most in 100mG



- It is easier to be influenced by magnetic field for the incident point on X axis when B on Y axis
- Detection Efficiency become lower about 30% at most in 100mG



- The influence is small if magnetic field is on Z axis
- Detection Efficiency become lower about 5% at most in 100mG

For SK PMT, the detection efficiency would become lower 10~15% for the most strict situation (B Direction is Y) in 100mG, when incident point is on center.

Origin of afterpulse

- The mass of ion is much heavier than that of electron, so the drift of electron can be ignored when we talk about the afterpulse.

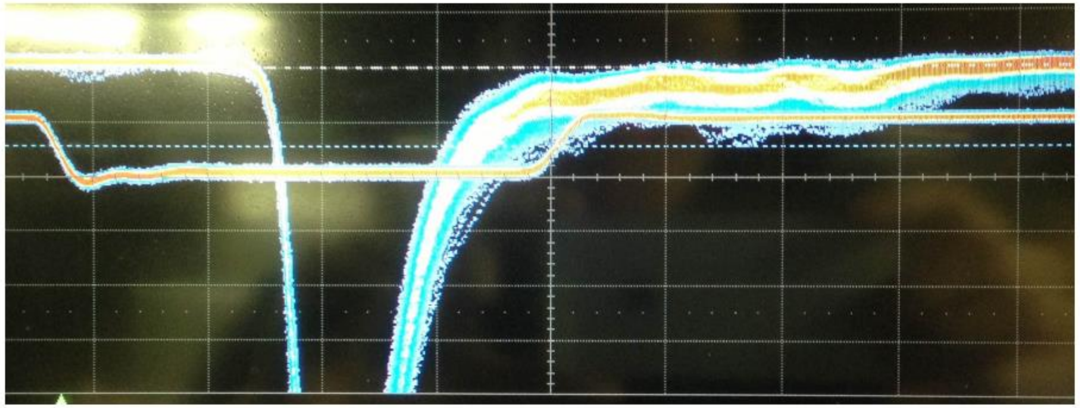
- We assume that the electric field in PMT follows an inverse-square law, the drift time is

$$t = \sqrt{\frac{m}{2qV_0}} L \int_{s_0}^{L} \frac{1}{(L-s_0)^2 - (L-s)^2} ds = \frac{4}{\pi}\sqrt{\frac{2m}{qV_0}} L$$

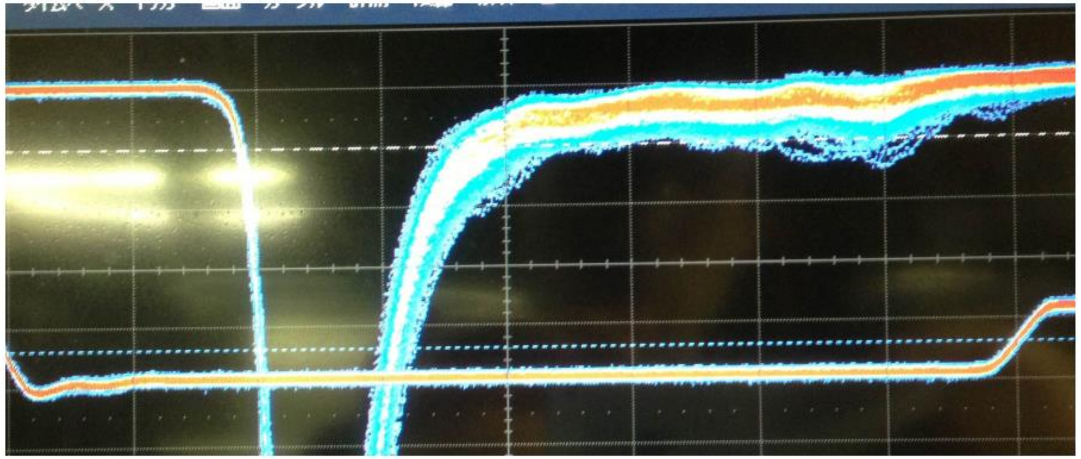
After Region	Qpeak p.e	T_{peak} µs	Source (Estimated Time µs)
AP0	< 1 p.e	3	H (3.08)*
AP1	~1 p.e	16	Cs(17.67)
AP2	~ 1 p.e	30	Ion with Q/M ~ e/383u*
AP3	7~8 p.e	5	CH_4 (6.15)
AP4	7~8 p.e	18	Ion with Q/M ~ e/138u* (Cs?)

*The reason that why the amplitude is different is under studying

Gate width
100 ns

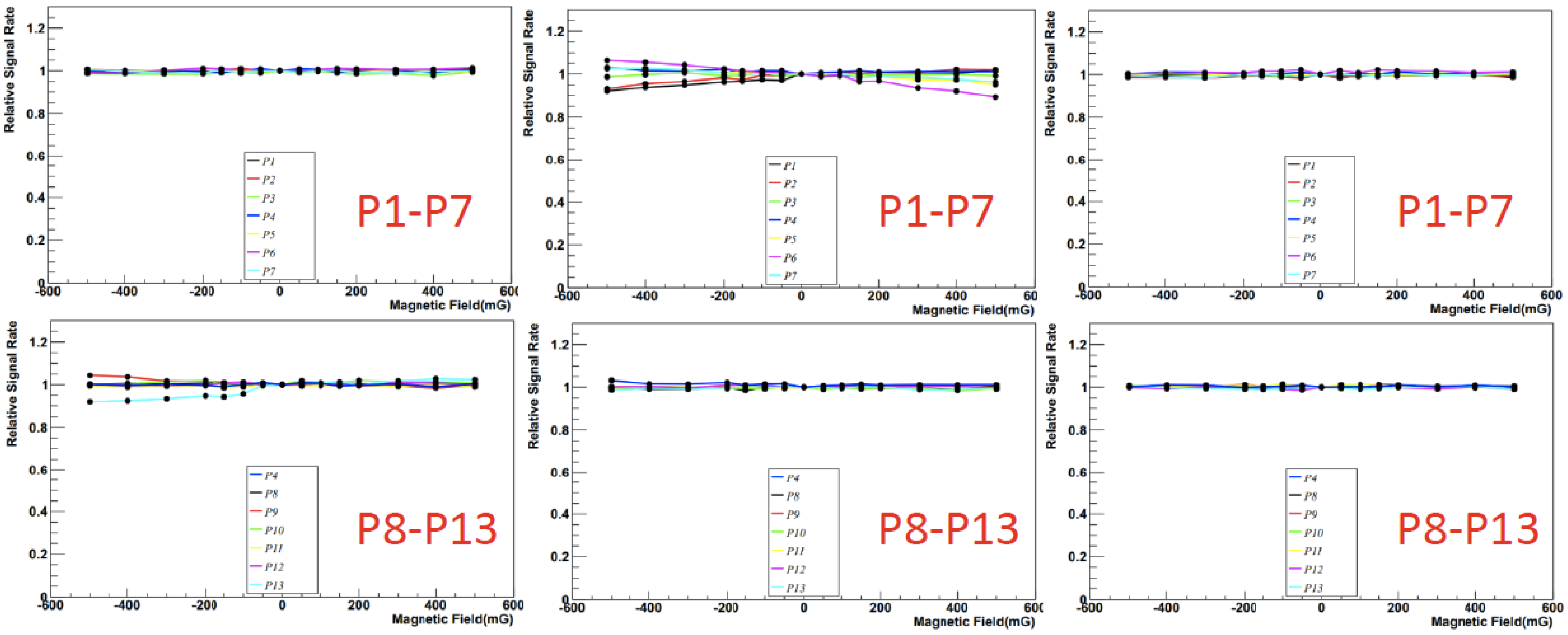


Gate width
160 ns

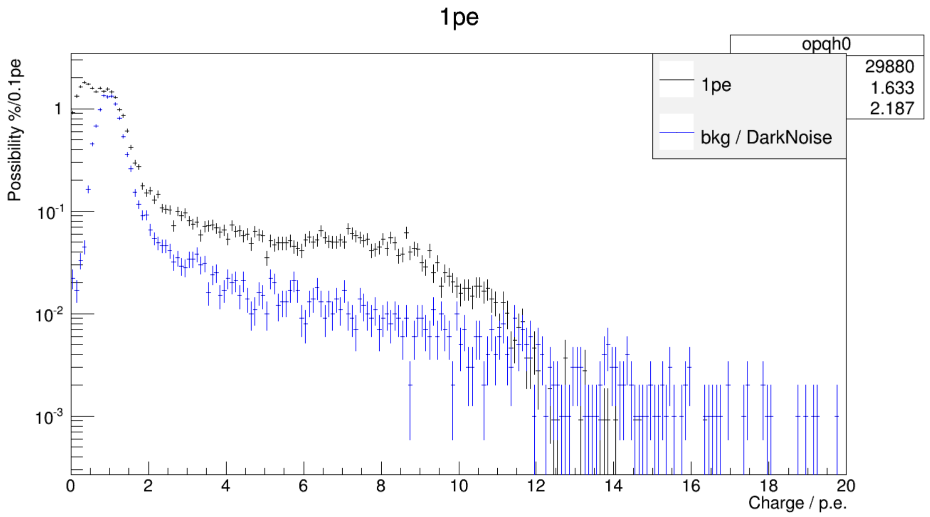


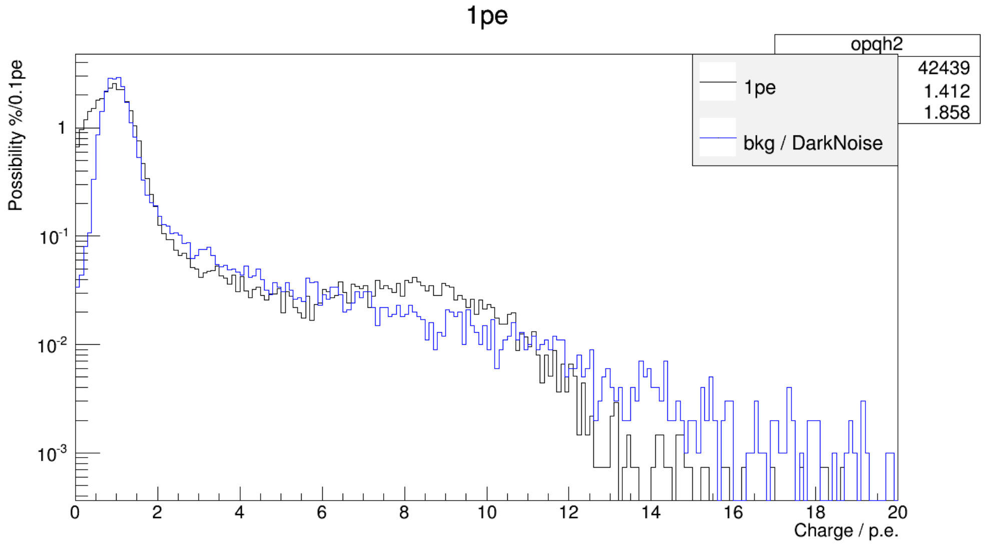
Relative Signal Rate in 3 direction magnetic field (with compensating shield)

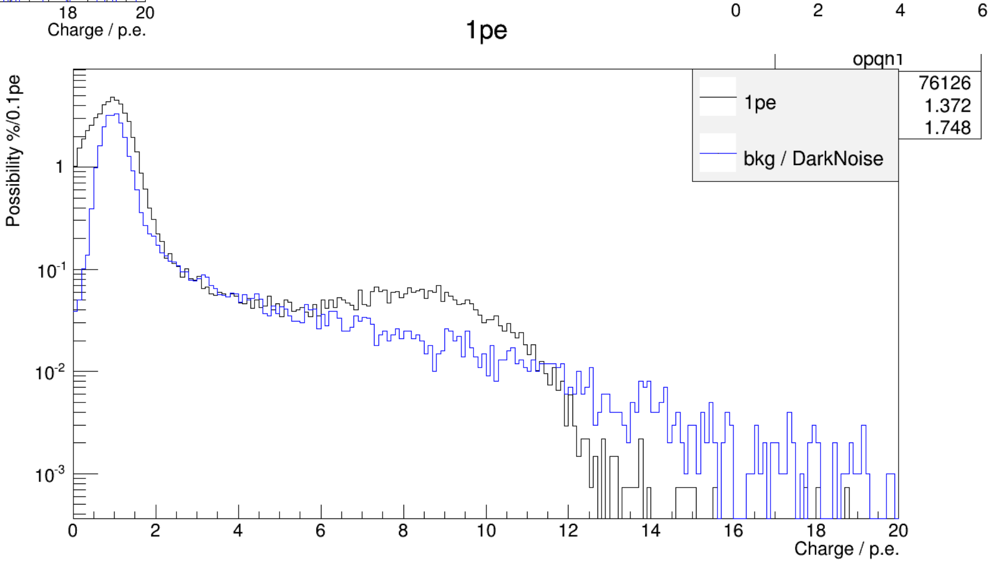
X direction | Y direction | Z direction



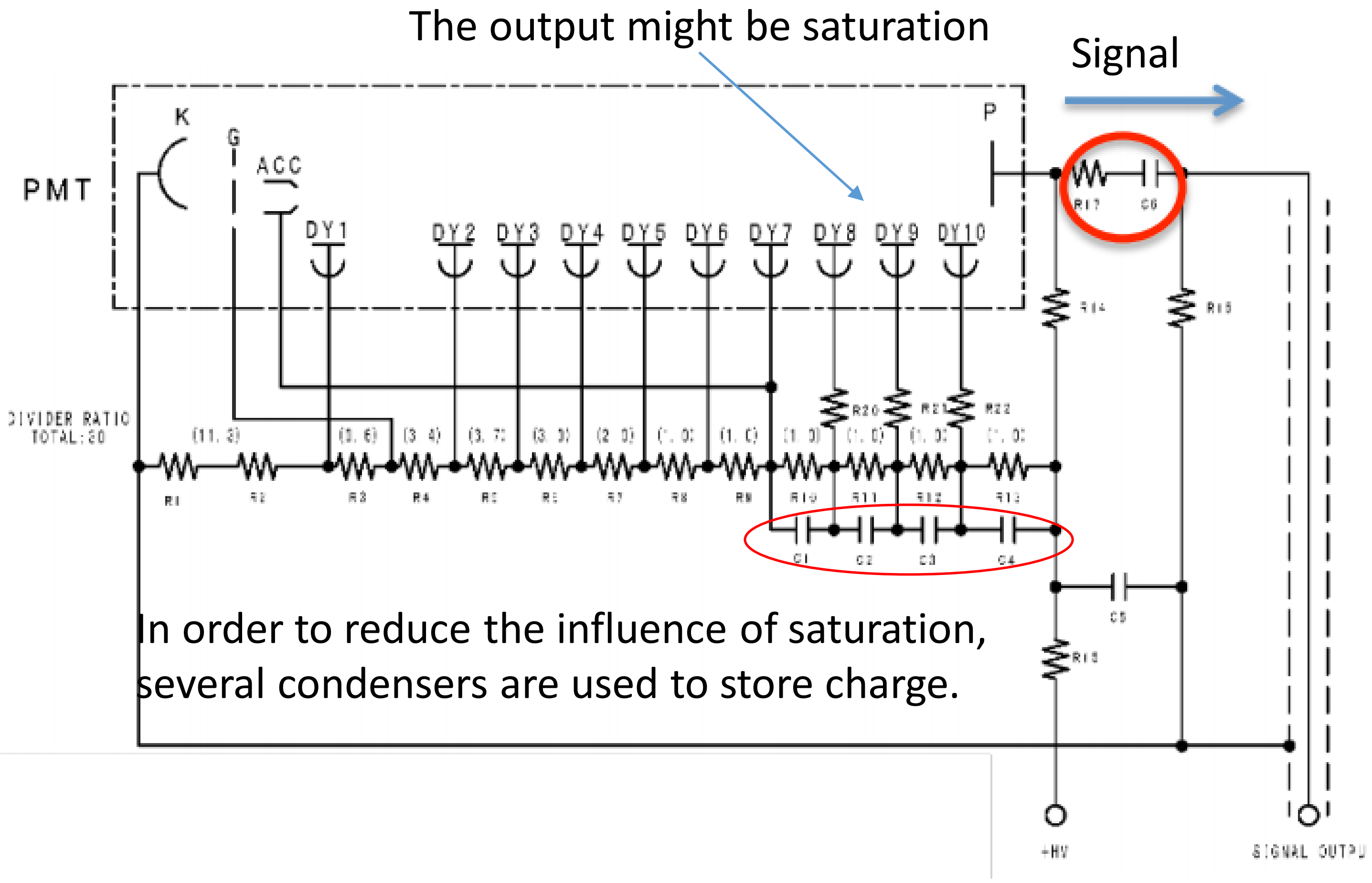
Charge Distribution







Circult of PMT



Other pulse related to B&L PMT

Pulse time distribution of B&L PMT (Main pulse ~ 1p.e)