The Hyper-Kamiokande Photodetector System using new 50 cm Photomultiplier Tubes

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New and Enhanced Photosensor Technologies for Underground/underwater Neutrino Experiments

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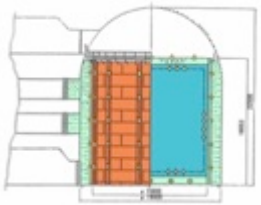
History of 50-cm Photosensors

Development of large aperture photo-detectors is a key to explore neutrino physics.

First 20-inch (50 cm) Photomultiplier Tube (PMT)

Hamamatsu R1449 (Venetian blind dynode) → IEEE milestone (2014)

For Kamiokande

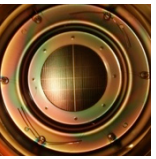


(1983-1996)

1k PMTs
/ 3 kton water

Supernova ν observation!

R3600 (Venetian blind dynode, improved)



For Super-Kamiokande (Super-K, SK)

(1996-)

11k PMTs
/ 50 kton water

ν oscillation discovery!

For Hyper-Kamiokande (Hyper-K, HK)

For other experiments

42 cm (17") Box&Line PMT

R7250
(Box&Line dynode)
with 50 cm bulb
of R3600

For KamLAND

50 cm MCP PMT
GDB-6201 by NNVT
(Micro-Channel Plate)

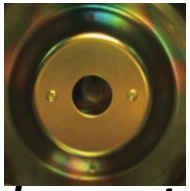
For JUNO

Recently developed in **China**

50 cm Box&Line PMT
R12860-HQE (Box&Line dynode)

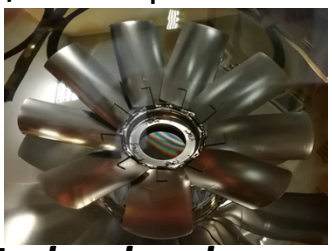
Developed
→ Hyper-K baseline

50 cm Hybrid Photo-Detector (HPD)
R12850-HQE (Avalanche diode)



Under development
→ Possible further HK improvement

50 cm MCP PMT
w/ TTS improved for HK



Under development

Photosensors for Hyper-K

New high-QE 20” Box&Line PMT → **Hyper-Kamiokande (HK)**

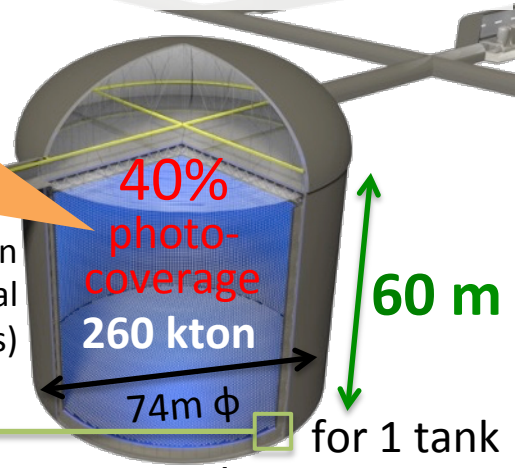
×2 high pressure bearing for 60 m height

×2 high detection efficiency

and half time&charge resolutions

compared to Super-K PMT (up to ~40m depth)

×40,000



(190 kton Fiducial Mass)

for 1 tank

×2 tanks

6,700 of 8” PMTs
for Outer Veto Detector

Requirements

- Rich physics programs
  - ν oscillations
    - Leptonic CP violation, ν mass hierarchy, …
  - Nucleon decay discovery
  - ν astrophysics
    - Supernova burst ν, …

→ Wide dynamic range

→ High time&charge resolutions, high detection efficiency, ..

→ ~nsec time resolution, low background

→ Clear photon counting,

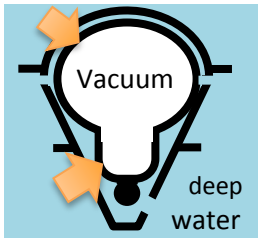
→ High rate tolerance

- *Large aperture photo-detectors are essential for physics sensitivities.*

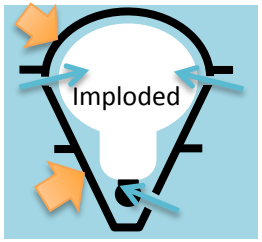
Hyper-K Photodetector System

Shockwave prevention cover

To avoid chain reaction of implosion



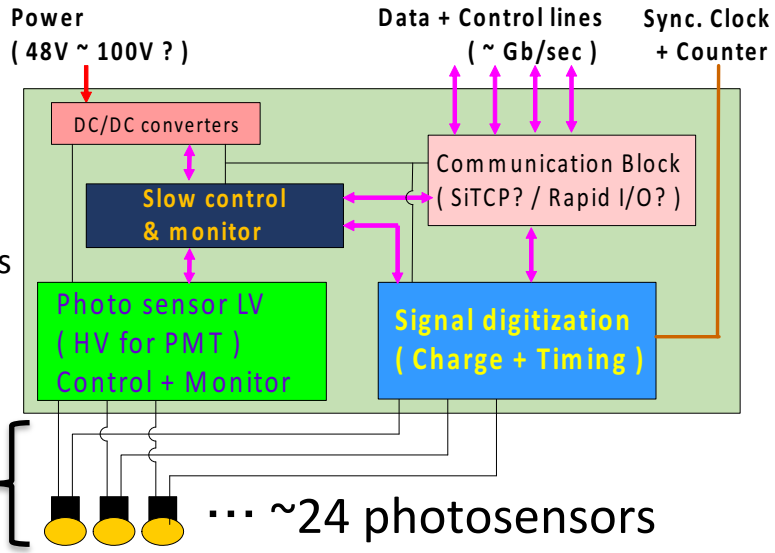
Usual case
Bulb is pressurized.



Implosion
Cover is pressurized.
Slow water flow through cover holes suppresses the shockwave.

Photodetector / Cover / Cable+Connector in this talk

Electronics in tank



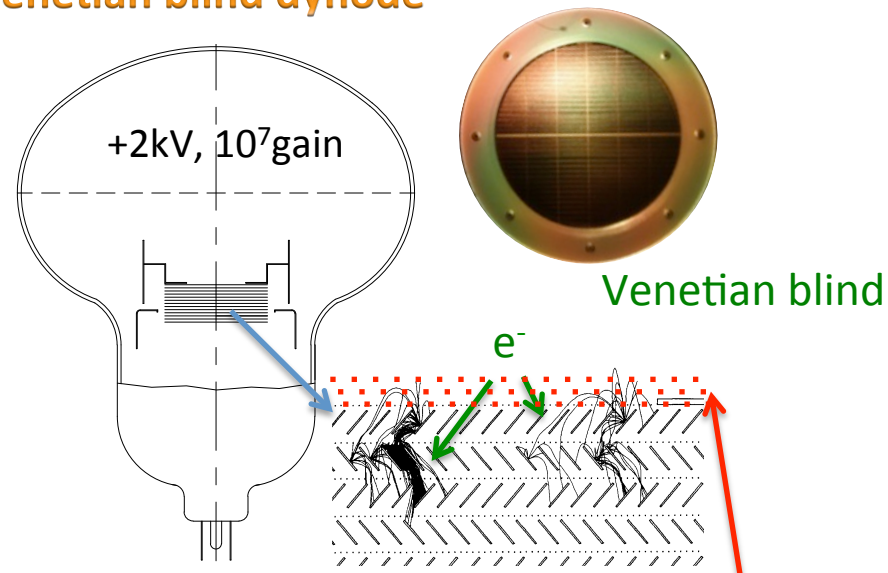
All hits are triggered simultaneously by setting a threshold below single photoelectron.

- Event Trigger
  - Sum of hits can be used to make events.
  - Dark rate has significant impact on the lowest energy in both trigger and reconstruction.
    - Essential to take low energy events with lowering dark rate and increasing detection efficiency
- Time at hit threshold is taken with Charge.
  - Time walk can be corrected using charge.

Dynode Structure Compared with SK PMT

Super-K PMT Hamamatsu R3600

Venetian blind dynode



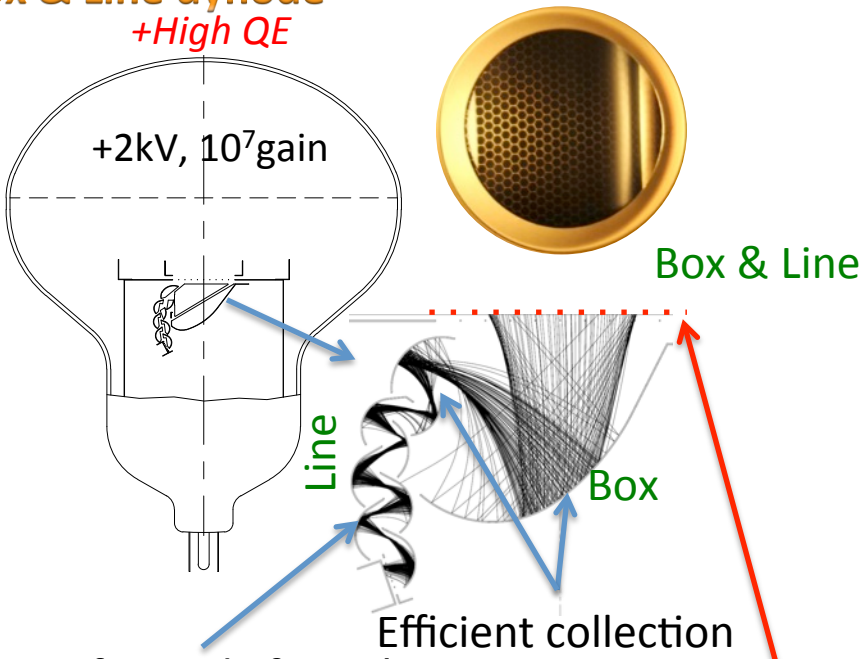
- Electron might miss dynodes
  → less collection efficiency
- Ambiguity of drift path limits charge and time response.

Meshes on 1st dynode control direction of electrons' path not to miss the 1st dynode with 74% aperture.

New Box&Line PMT Hamamatsu R12860

Box & Line dynode

+High QE



Uniform drift path
→ High charge&time resolutions

A mesh to make flat electric potential on surface has 95% aperture.

Effective gain(δ)

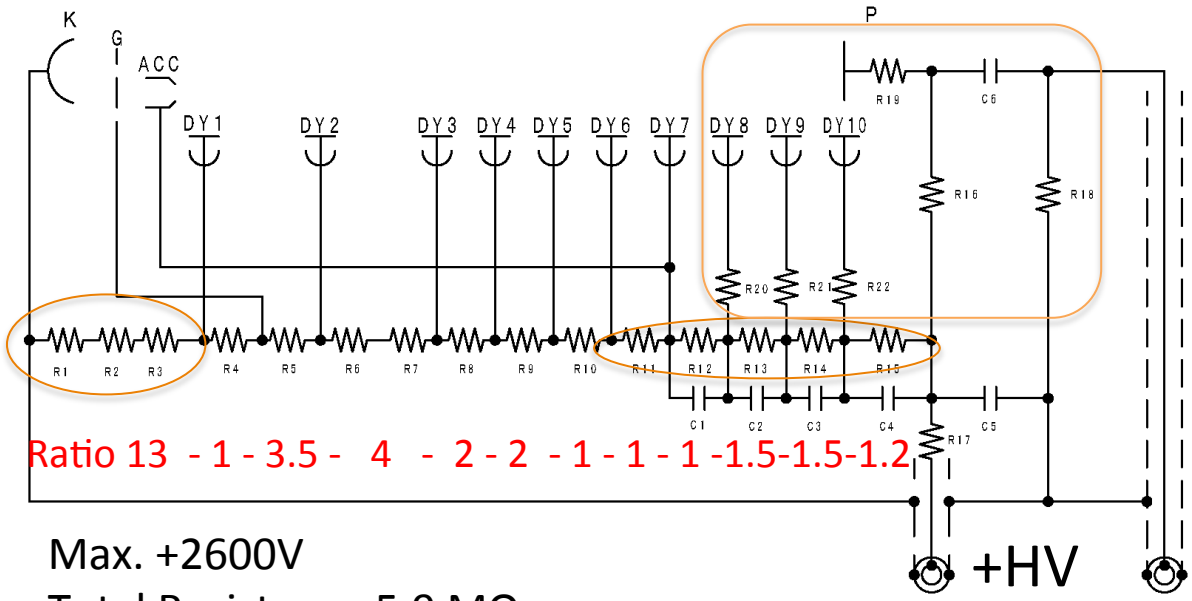
δ_1(Super-K PMT) = 8.3

δ_1(Box&Line PMT) = 18.6

δ_1 = (Bombardment gain on Dy1) × (CE of secondary electron from 1st to 2nd dynode)

Difference of effective gains, √(18.6/8.3) = 1.5,
explains improvement of 1PE charge resolution :
53%/35% (=1.5)

High Voltage Base



Max. +2600V
Total Resistance 5.9 MΩ
Typical Divider Current 339 μA at +2000V

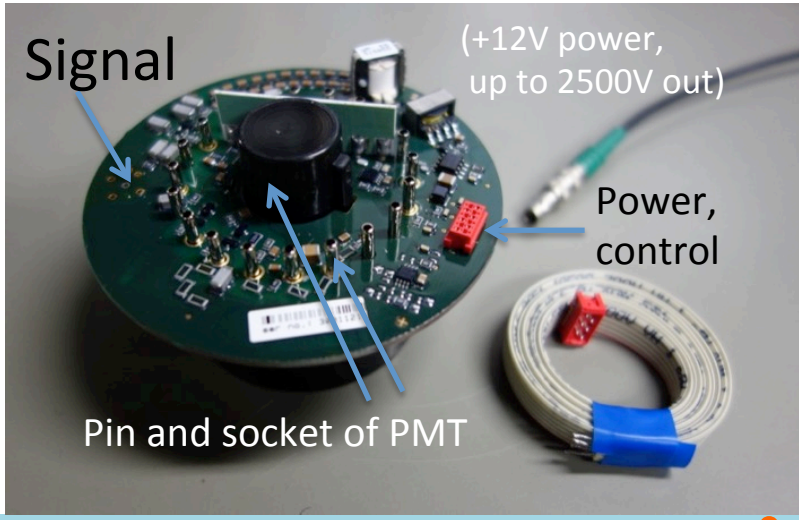
Passive divider base

- Positive HV is necessary to minimize dark rate.
- Parameters optimized for
  - Less ringing
  - Wide dynamic range
  - Constant collection efficiency
- Tuning finished.

(50Ω Termination is required.)

(Option) Built-in HV power base

Prototype is available for test,
operated by +12V with LV control.



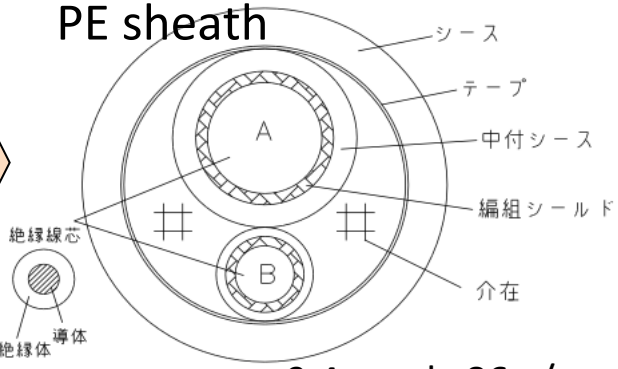
Waterproof Cable and Connector

Waterproof cable complex

Coaxial cable with
1-wire HV for SK

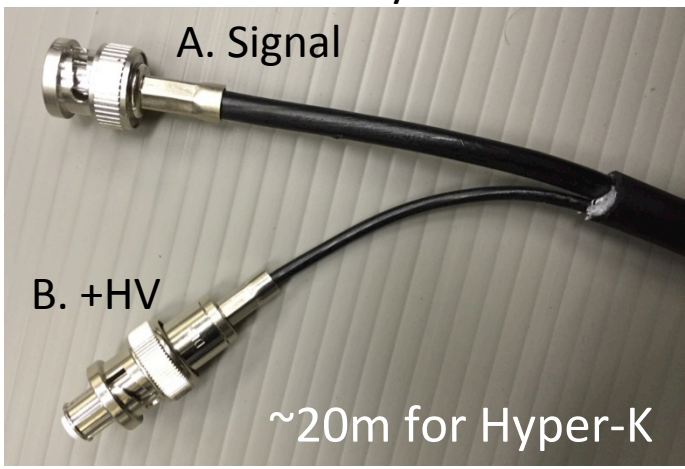
8.4 mmϕ, 68 g/m

Two coaxial cables for HK
PE sheath



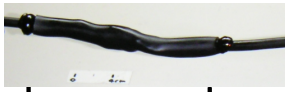
9.4 mmϕ, 86 g/m

By Hamamatsu



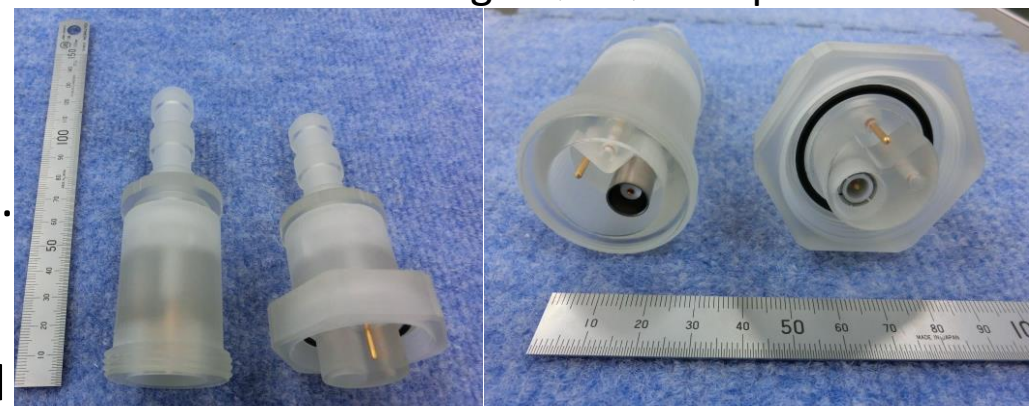
Watertight connector (up to 100m water)

- In Super-K, BNC + crimp in heat shrink tube for connection



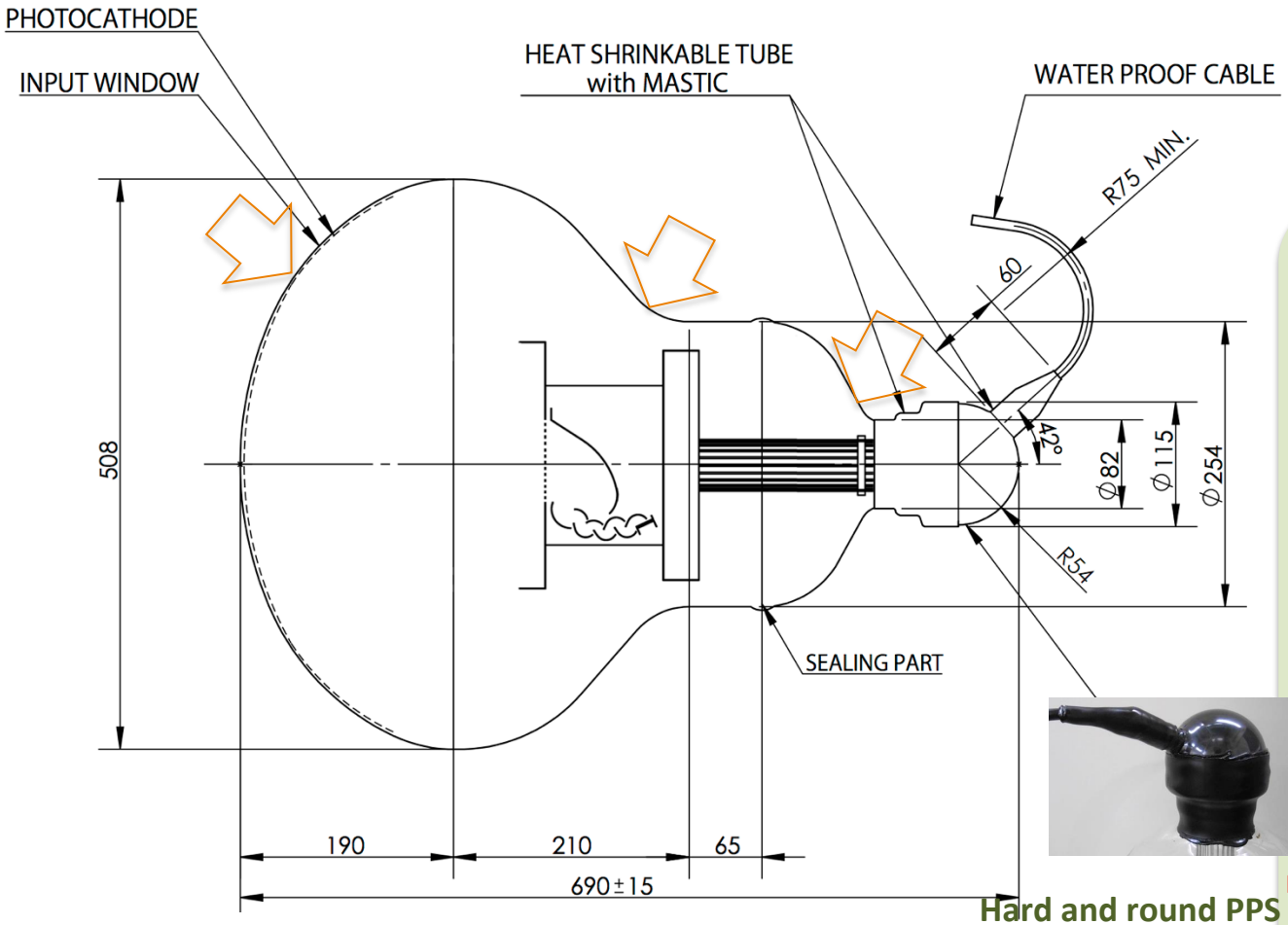
- Dedicated connecter was developed.
- Connected to electronics case in water, and can be disconnected.
- Test in high pressure water is planed this summer.

TNC coaxial signal (RG58C/U) + HV pins

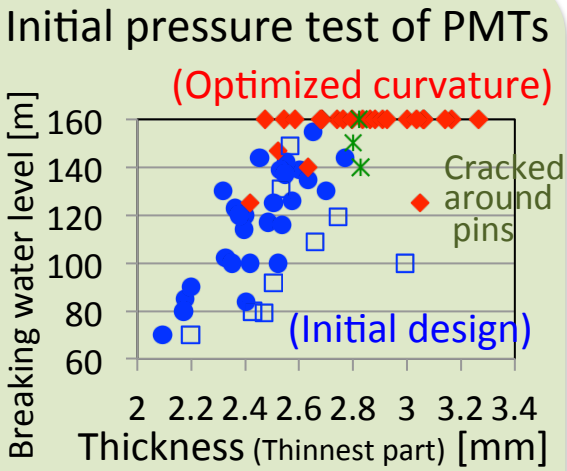


Improved noise shield and less failure of connection compared with SK.

PMT Design for High Pressure Water



Bulb curvature was optimized to achieve high pressure tolerance

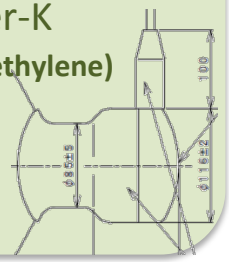


Hard and round PPS
(Poly Phenylene Sulfide Resin)

Reinforced

Waterproof case used in Super-K

Soft PE (polyethylene)



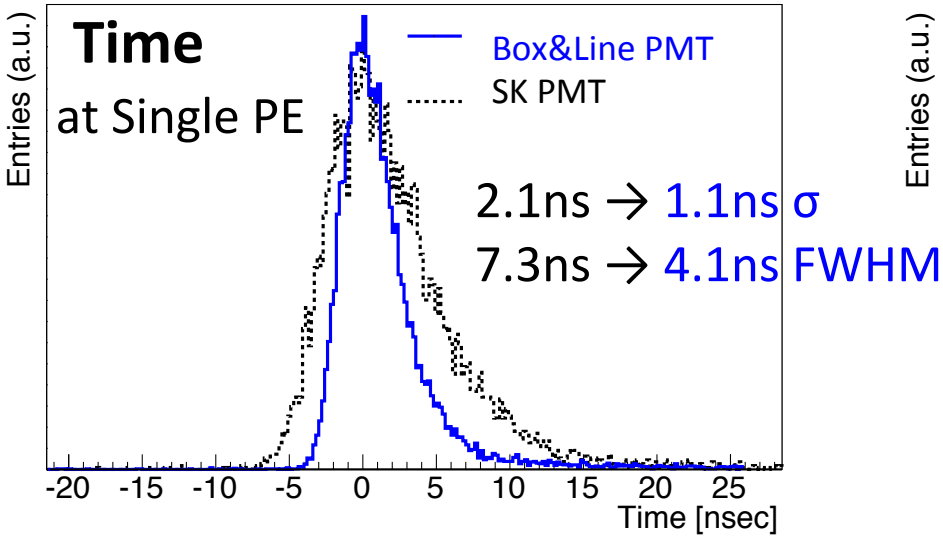
- For screening in production
  - Bulb thickness is scanned.
  - All PMTs are tested in high pressure water.

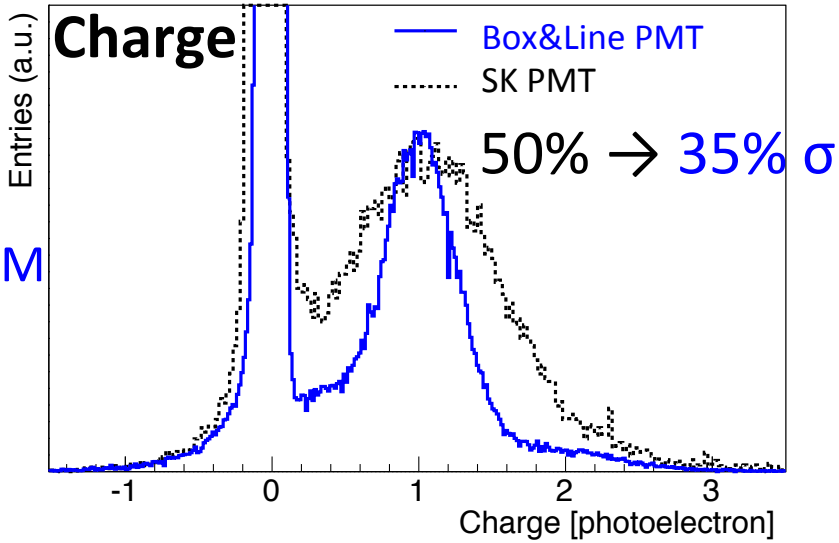
50 Box&Line PMTs were tested up to 1.25 MPa (125m).

■ No damage in all 50 samples.

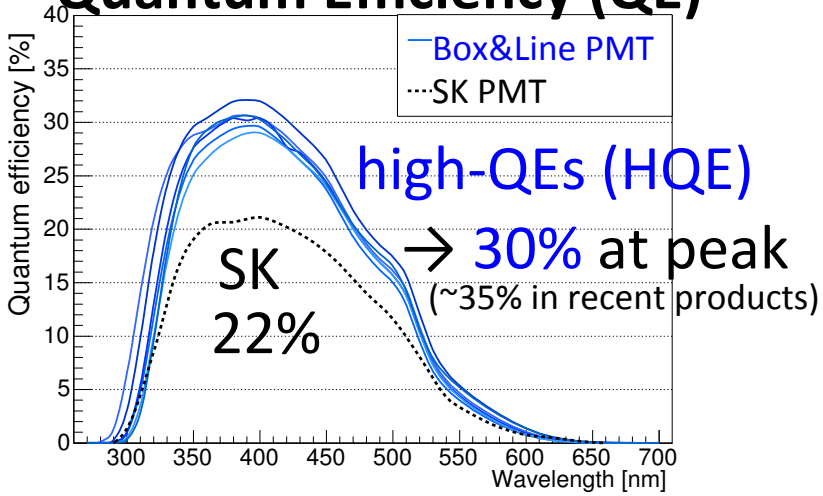
Performance

Confirmed sufficient performance in Hyper-K

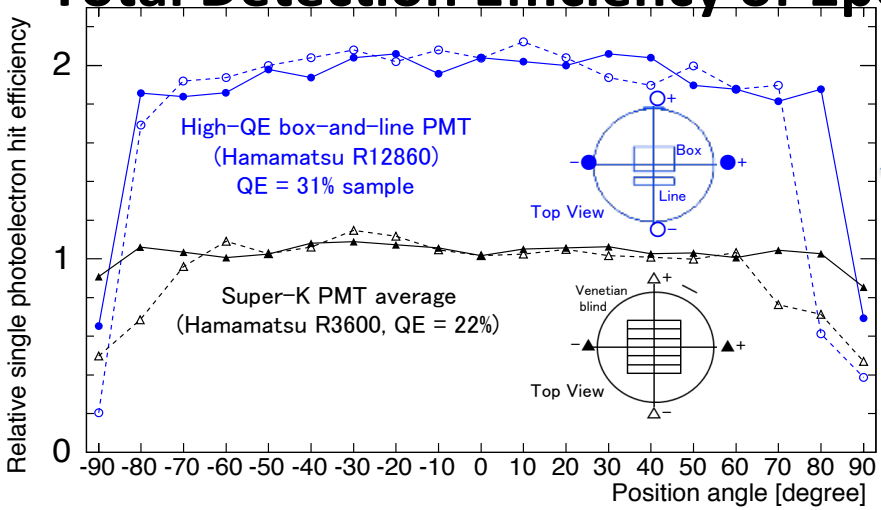




Quantum Efficiency (QE)



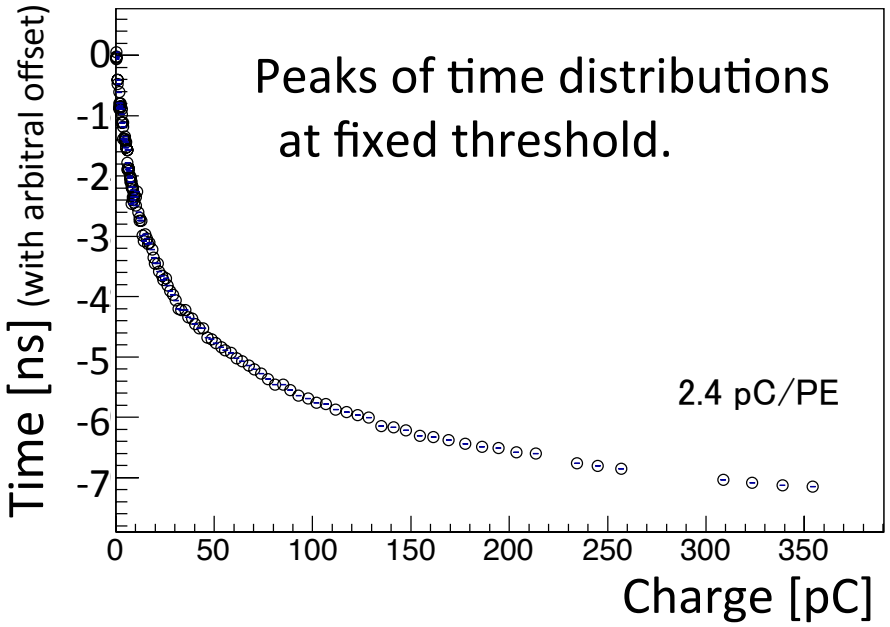
Total Detection Efficiency of 1pe



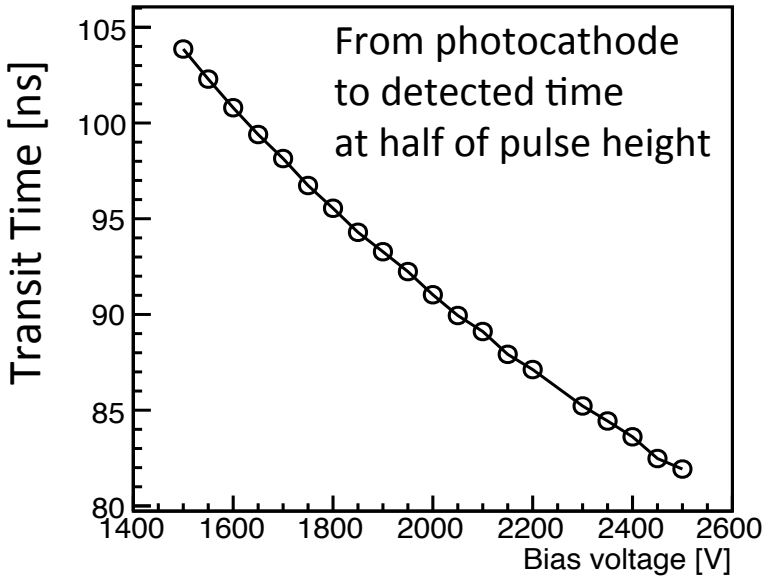
×2

Timing in Various Range

Transit Time Peak by Charge

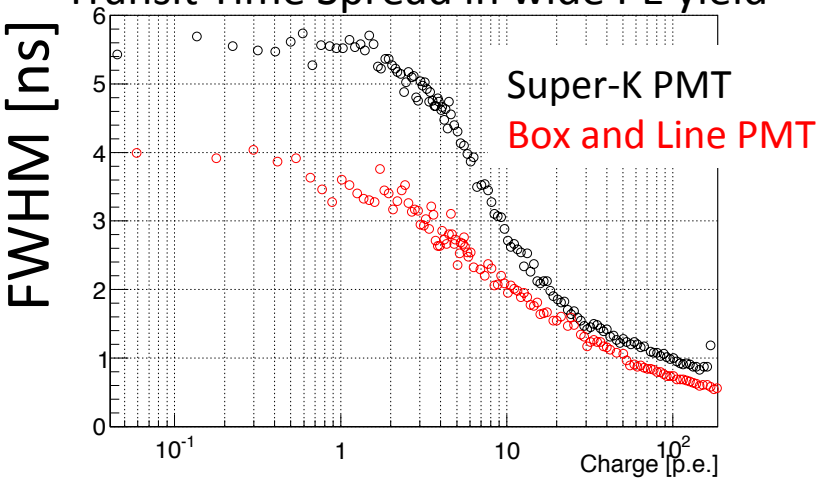


Transit Time by High Voltage Bias



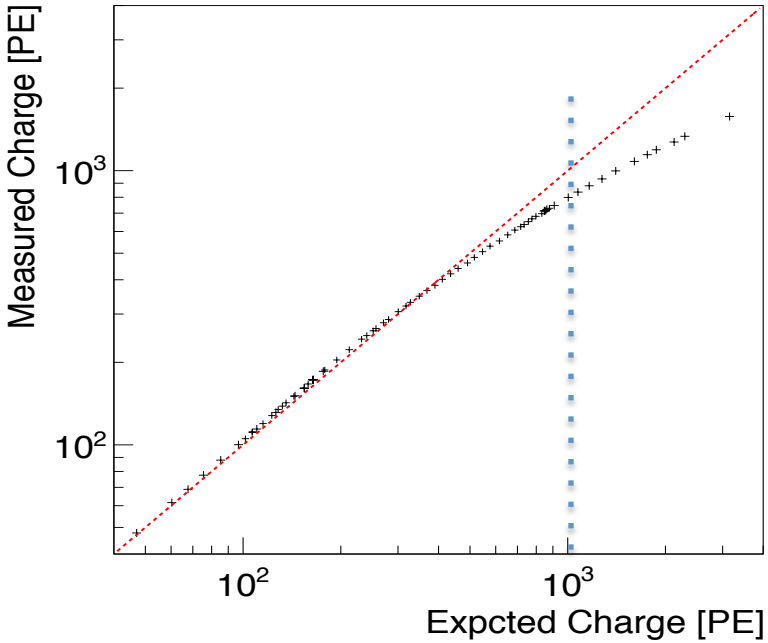
- Time offset is different by PMTs in various voltage and charge, while it can be corrected by calibration.
  - Time walk correction by charge is performed.
- Timing resolution (FWHM) is improved by the correction using charge.

Transit Time Spread in wide PE yield

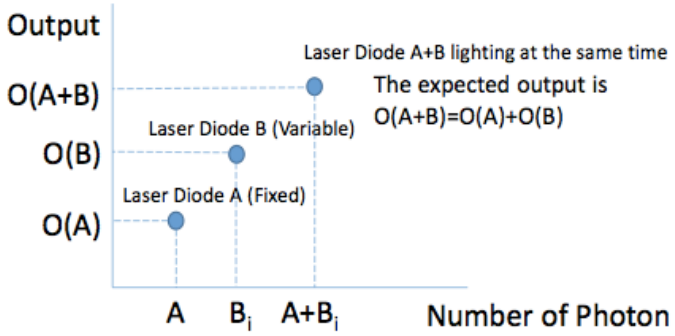


Output Linearity and Dynamic Range

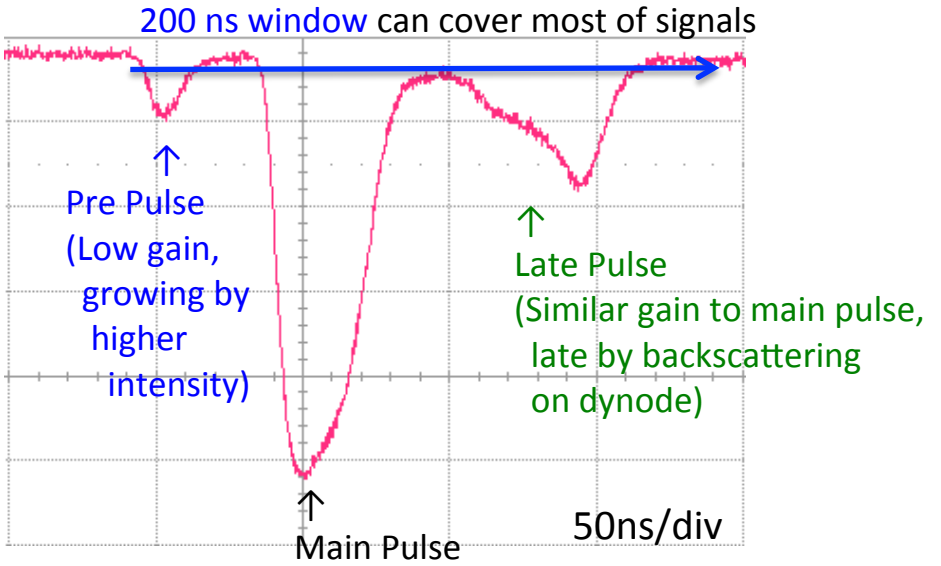
Good linearity over 1000 photoelectrons



Measured using two coincident light sources



Saturated waveform with high intensity

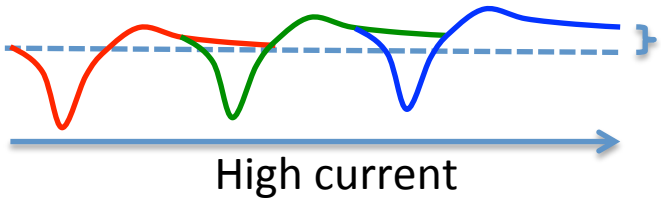


Pulse height of main pulse is saturated.

- Typical max. output voltage is ~7.5V in a measured sample.
- 200ns windows is necessary to integrate all peaks.

High Rate Tolerance

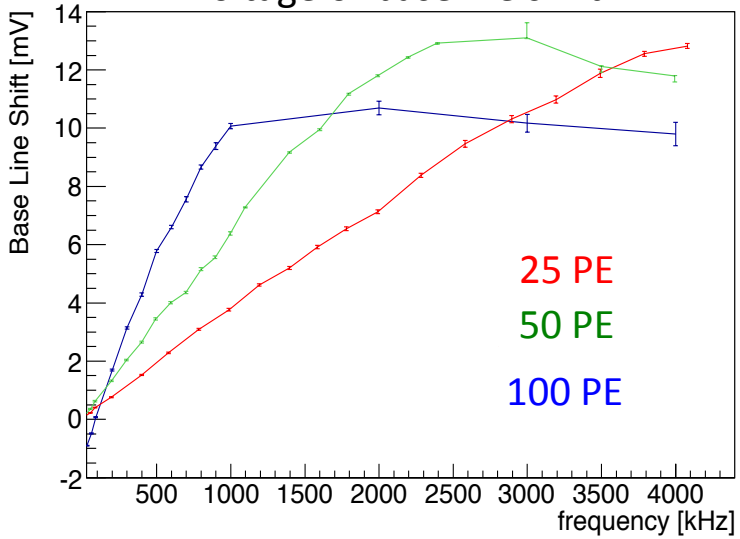
Voltage shift due to a coupling capacitor



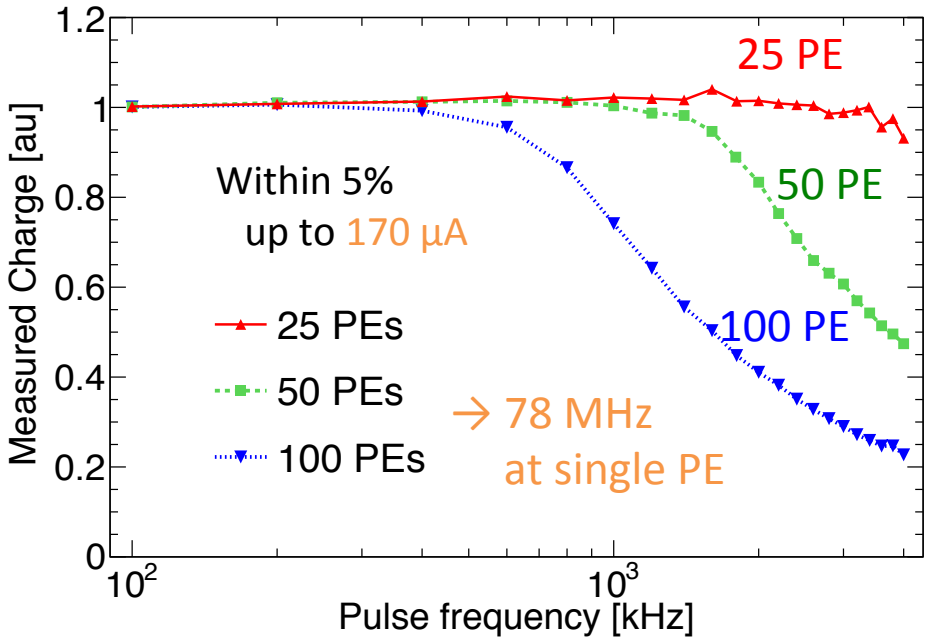
The shift is subtracted as well as in Super-K

Sufficient high rate tolerance
for supernova burst detection
(10MHz at max in low PE)

Voltage of baseline shift



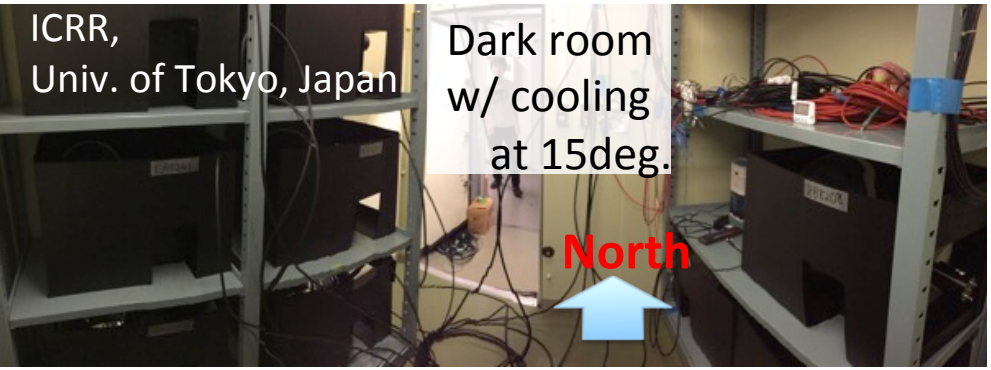
Rate Tolerance of Gain



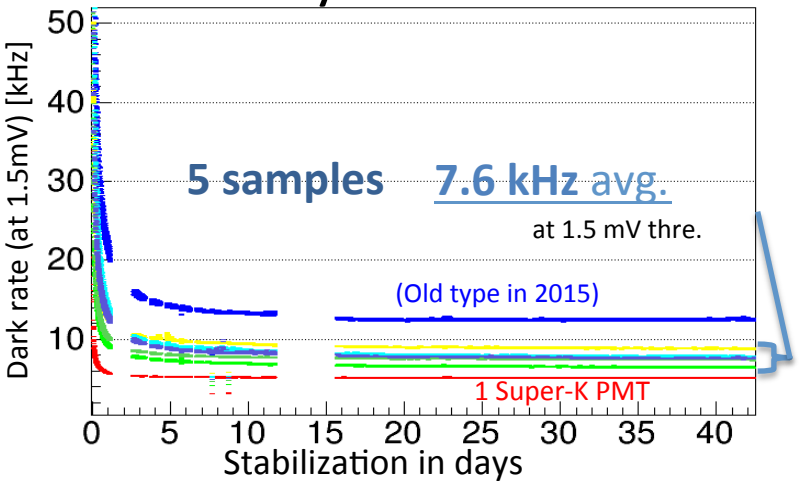
All demerits of positive bias can be solved in electronics, while lower dark rate by positive HV is essential for HK physics.

Dark Rate

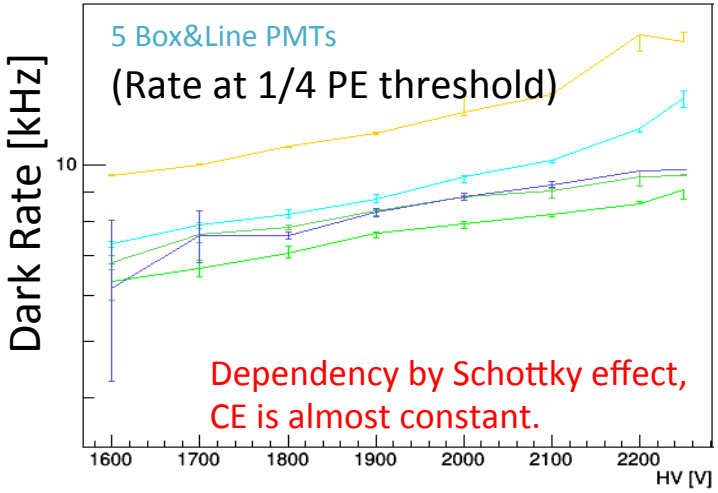
Measuring many ~20 PMTs for a long time to confirm stabilized performance.



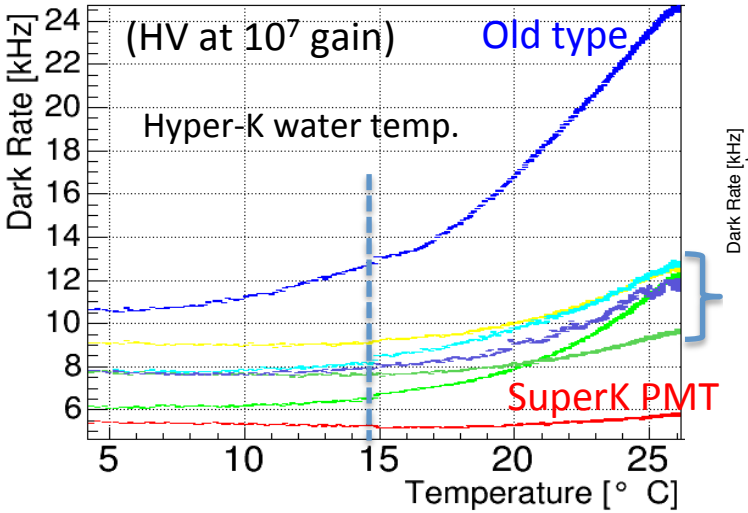
By time



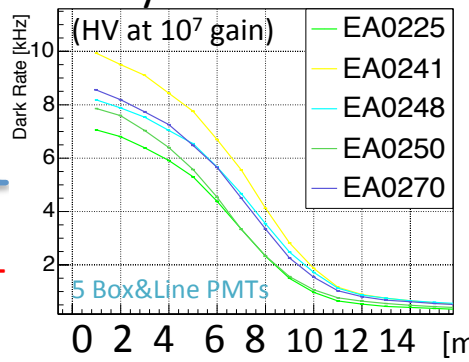
By bias voltage



By temperature



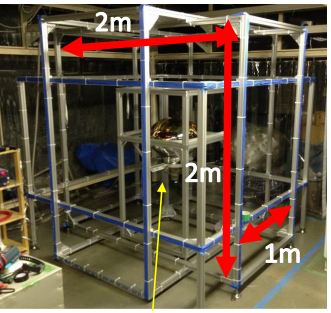
By hit threshold

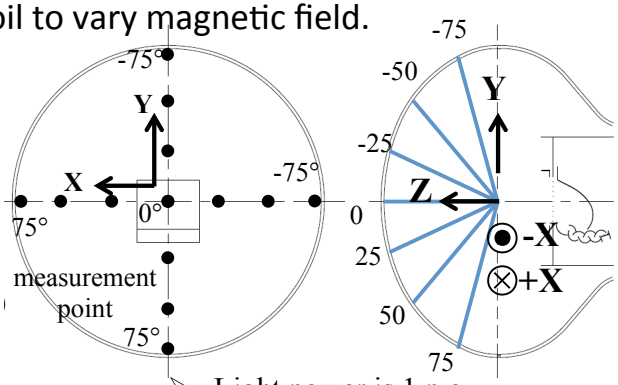


- Still trying reduction of achieved rate in a year with optimizing design/production.

Response Uniformity

Uniformity of various performance was measured in the Helmholtz coil to vary magnetic field.

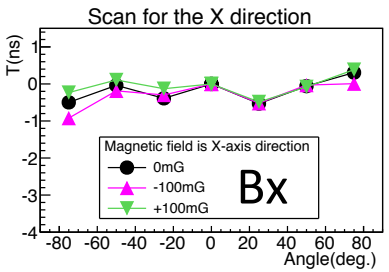


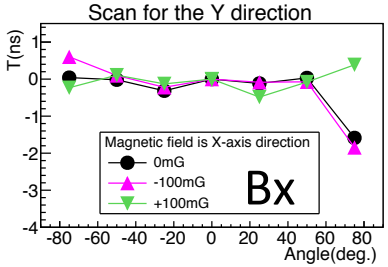


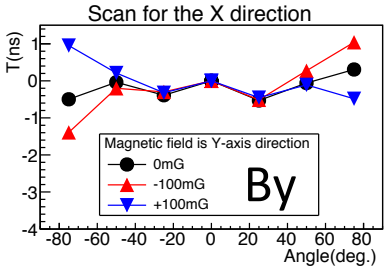
- Light power is 1 p.e.
- HV is 2000V

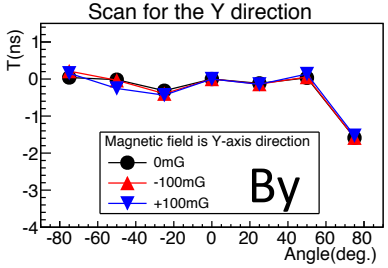
±100 mG is maximal residual range in HK.

Uniformity of relative transit time

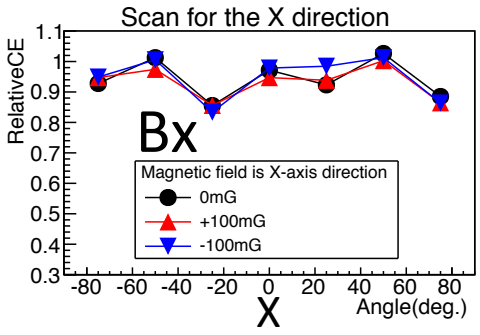


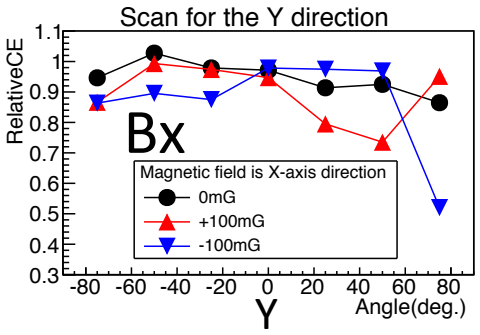


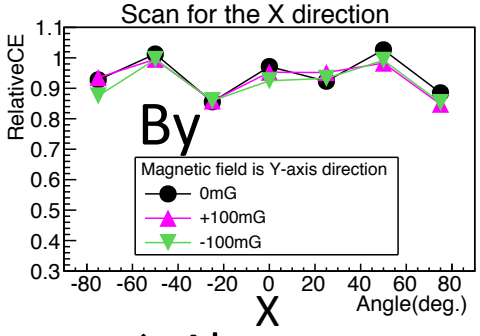


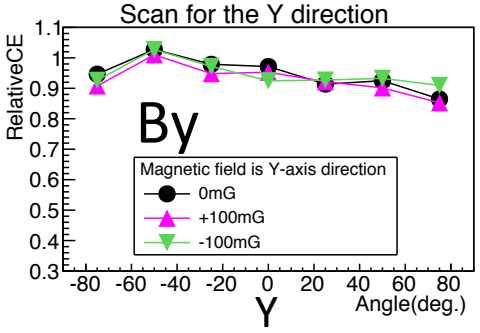


Uniformity of relative collection efficiency



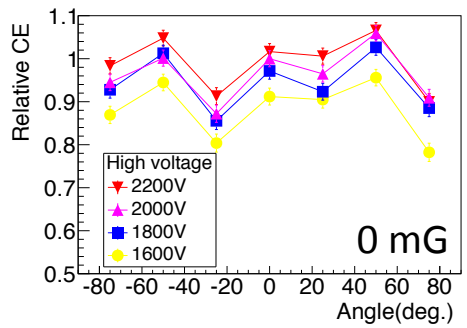


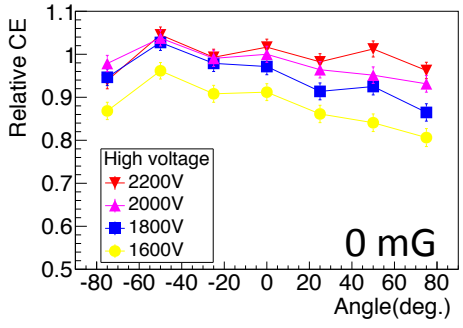




→ Almost constant in ± 100 mG range

2000V typical and varied volt. from 1600 to 2200V



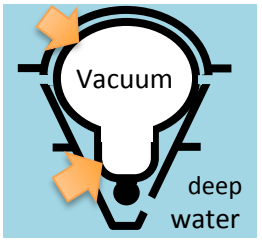


For Long-Year Operation

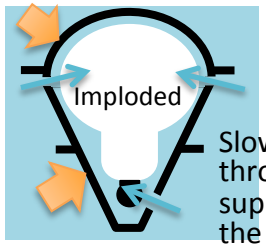
- Covers to avoid chain implosion in tank
  - With validation tests
- Proof test
  - 2.5 years' stability
- Operation in Super-K
  - Production and screening of Hyper-K PMTs
  - Status

Covers

- Accidental implosion of bulb in water might cause a chain implosion by a shock pulse.
  - A shockwave prevention cover made of FRP was developed for Super-K for 40m depth.



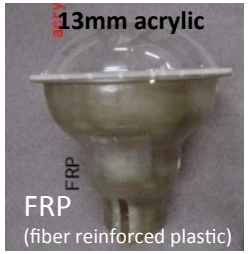
Usual case
Bulb is pressurized.



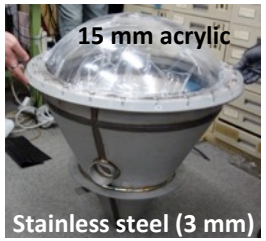
Implosion
Cover is pressurized.
Slow water flow through cover holes suppresses the shockwave.

- New covers were developed for a deep Hyper-K tank up to 60 m with clean materials.

Super-K cover for 40 m water depth

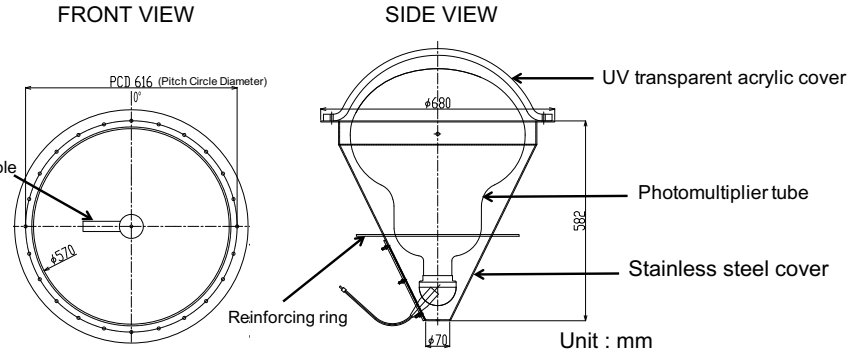


Hyper-K Cover



Cover pressurized test in water → 1.2-1.5 MPa

Weight w/o acrylic (~6kg) 22kg



Baseline design established by tests

Cover pressurized in vessel

Improved covers for light weight or low cost

1. Improved cover

Cover pressurized test in water → 1 MPa

17kg

2. Resin cover

0.5-0.57 MPa

Light weight, fast and easy mass production

6.4kg

3. Stainless steel tube cover

0.7 MPa

Cheap and simple, Developed in Spain

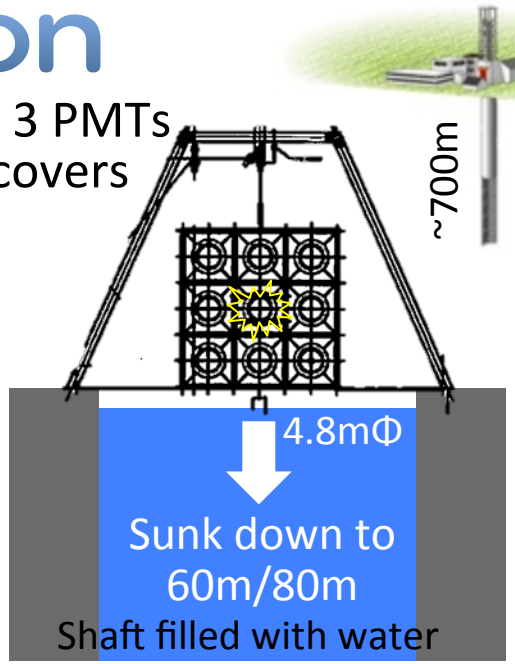
30kg

New 3 covers were also tested with bulb implosion inside in 2018.

Cover validation

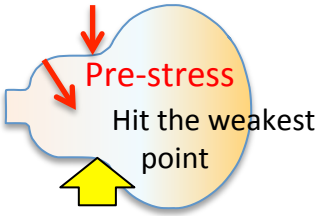
1st demonstration test was performed in 2016 and 2018.

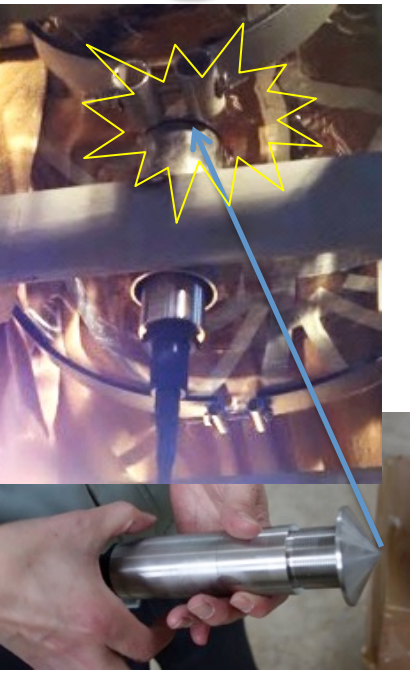
3 x 3 PMTs + covers



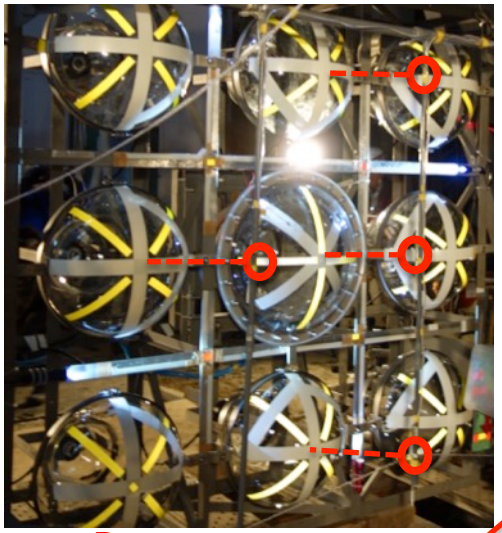
Procedure

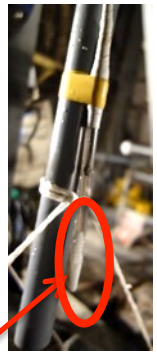
1. Center PMT is imploded by tool.
2. Confirm no damage of central PMT cover and surrounding PMTs with monitoring



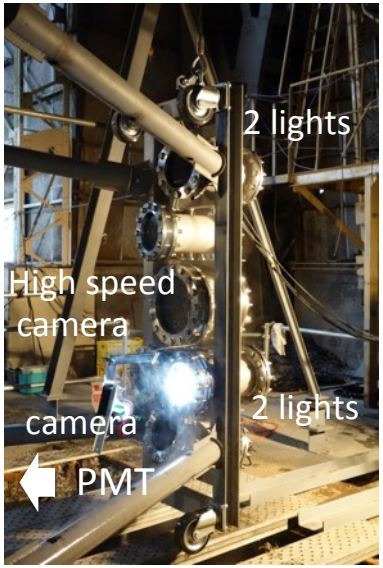


Shock wave monitor in water





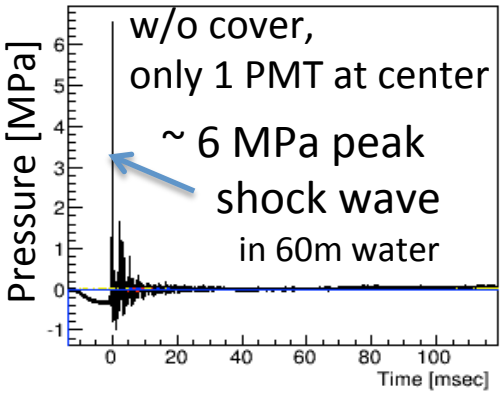
Pressure gauge



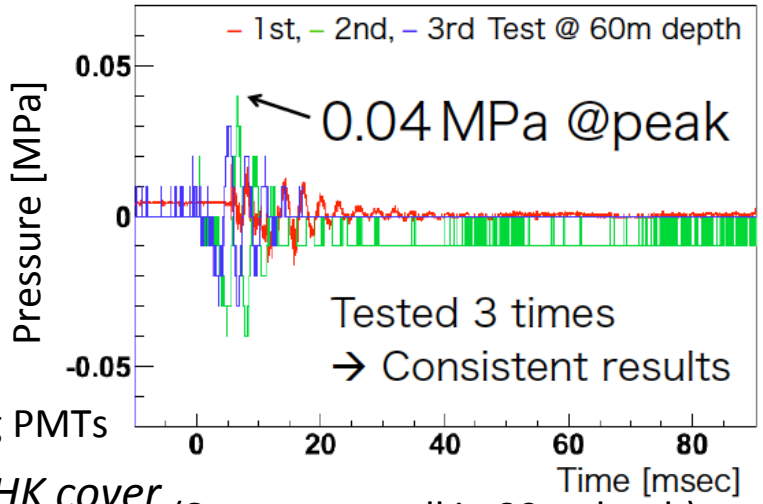
Strain gauges

Implosion Tests

Test in 2016 for baseline design



1/100 suppression
without any damage
for cover and neighboring PMTs



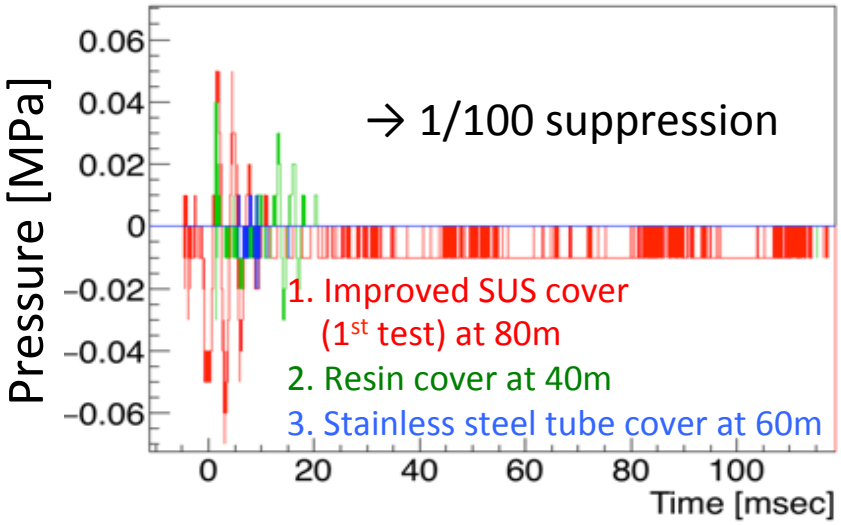
→*Established as HK cover*

(Success as well in 80m depth)

Test in 2018 for improved covers

1. Improved cover
(Stainless steel)

→ *Established*



2. Resin cover

Success at 40 m (1 test only),
but failed at 60 m

Next: To be reinforced with optimizing design and injection material.

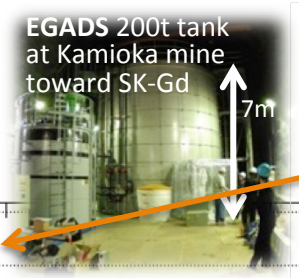
3. Stainless steel tube cover

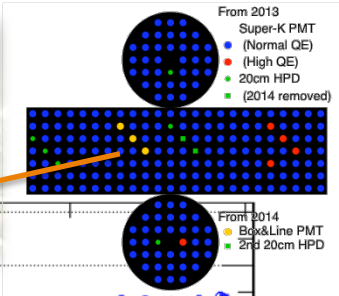
Success at 60 m (1 test only)

Next: Reduce weight,
reach easy mass production
/assembly design

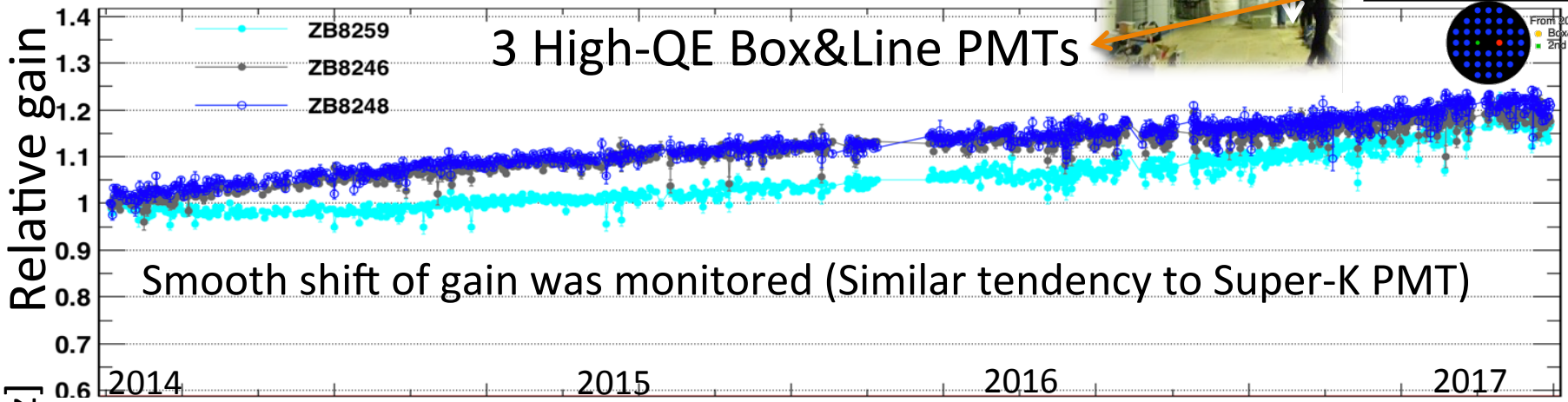
Stability of Gain and Dark Rate

Testing initial type of Box&Line PMTs
in 200-ton water Cherenkov detector since 2014.
Working for ~3 years!

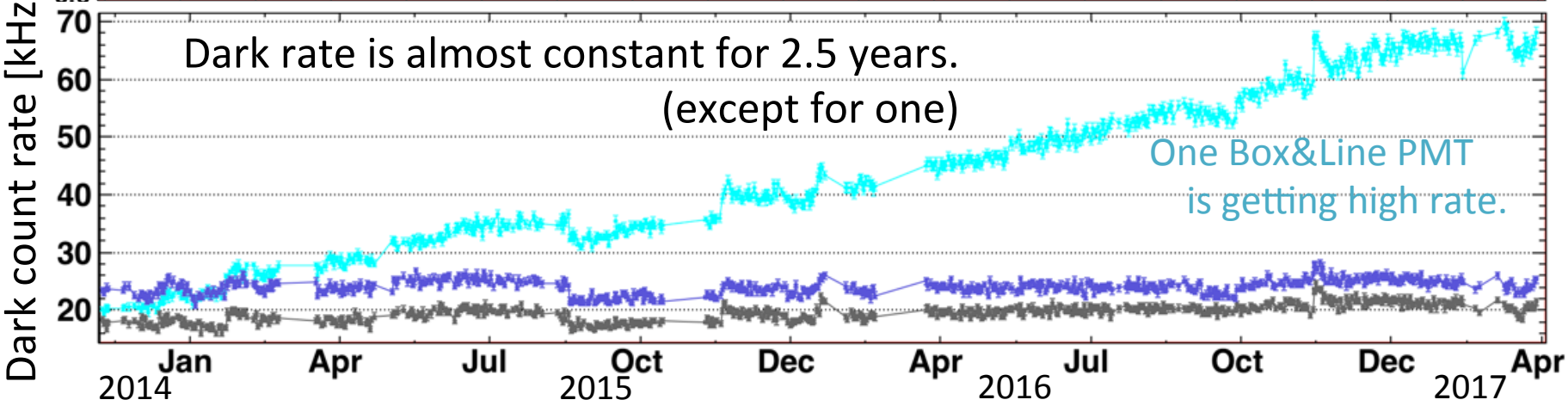




3 High-QE Box&Line PMTs



Smooth shift of gain was monitored (Similar tendency to Super-K PMT)



Dark rate is almost constant for 2.5 years.
(except for one)

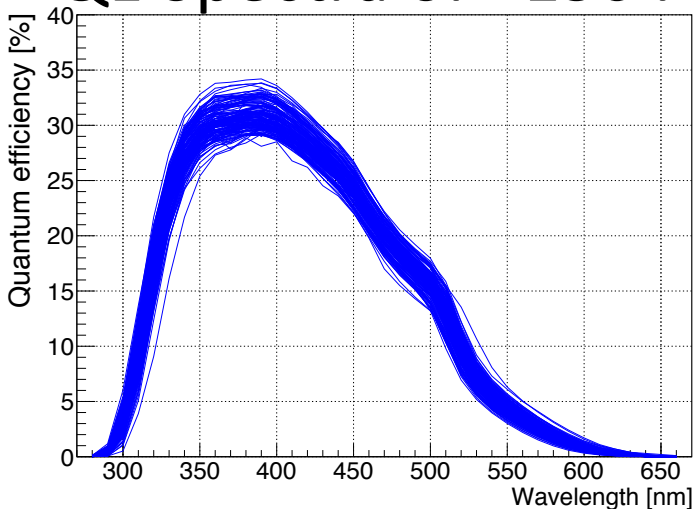
One Box&Line PMT
is getting high rate.

- Dark rate & after pulse were largely reduced in the latest version after the 3 PMTs.
- Stable detection for .

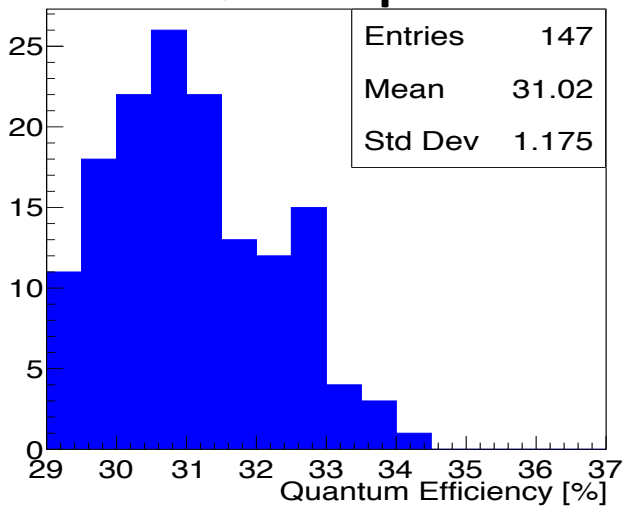
Production of ~150 PMTs

~150 Box&Line PMTs were manufactured.

QE Spectra of ~150 PMTs

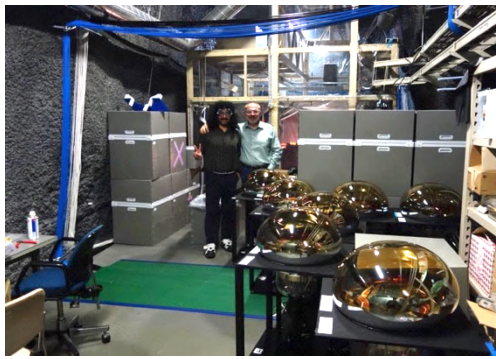


QE at peak



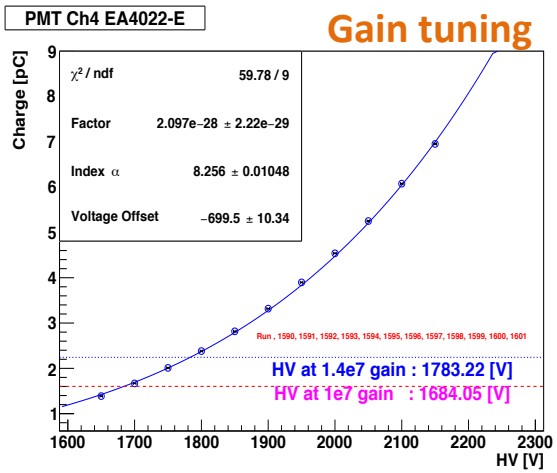
- All PMTs were screened at high pressure water up to 0.95 MPa.
  - No damage found in the bulb.
- Transferred to Kamioka, Japan and performance was evaluated.
  - 6 PMTs / day
  - No rejected PMTs over 30kHz in short stabilization ~1/2 – a few days

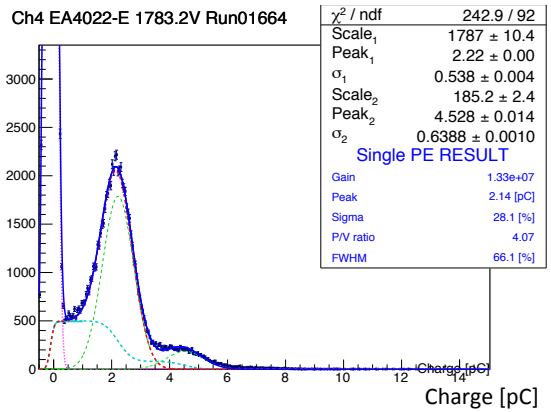
Mar-Jun 2018, in dark room

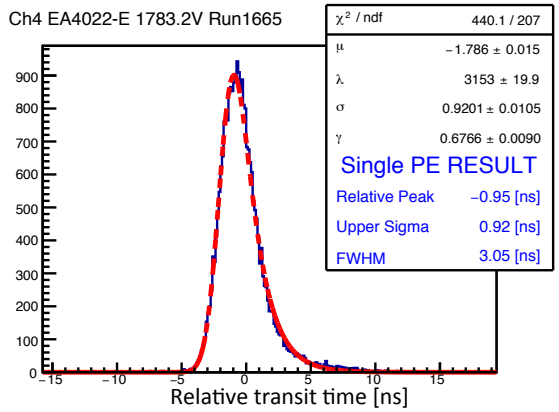


Quality of ~150 PMTs

Example of evaluation

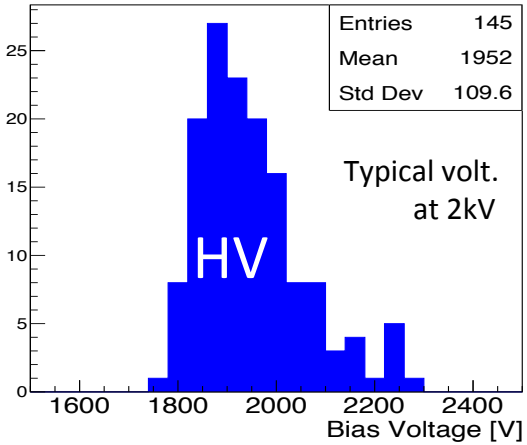






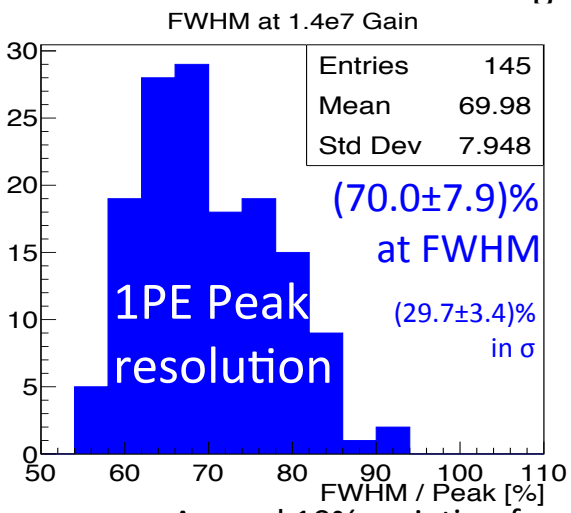
Individual difference of performance

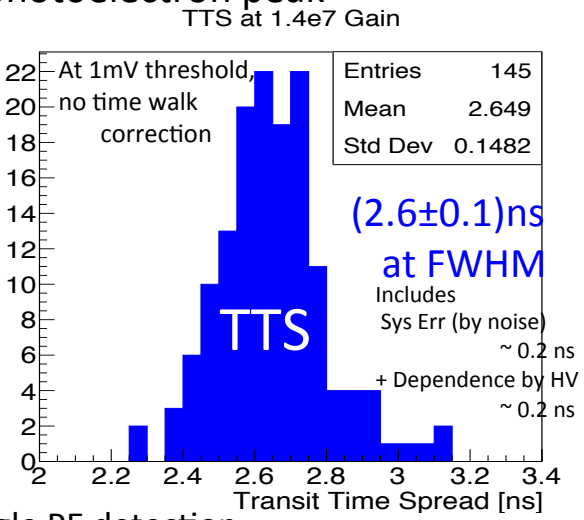
HV calibrated to 1.4×10^7 gain



Within reasonable operation range

Resolutions at single photoelectron peak



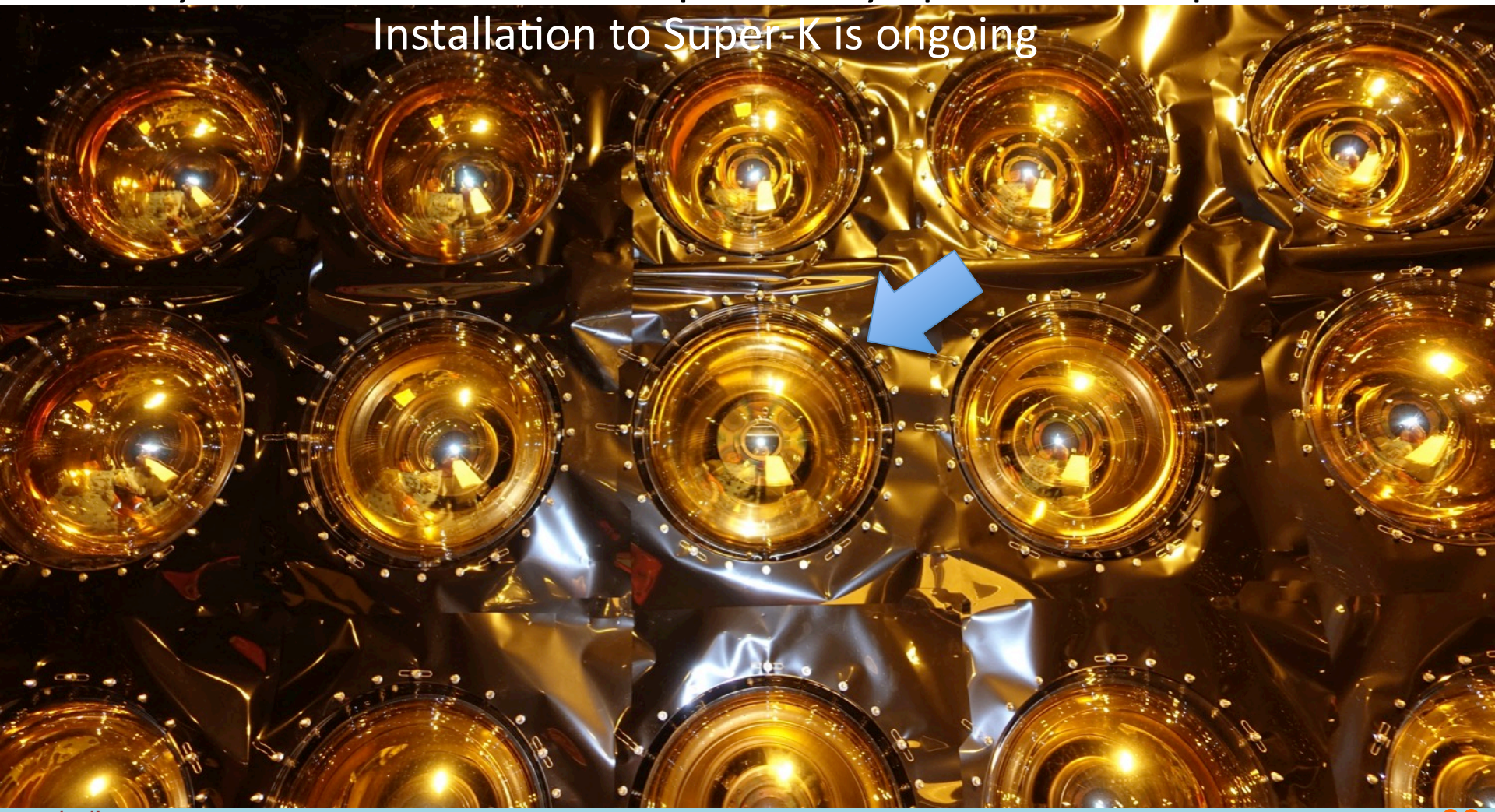


Around 10% variation for single PE detection

Ready for mass production with a good quality control.

Installation to Super-Kamiokande

- Super-K is now being refurbished for the next Super-K Gd project.
- Many Box&Line PMTs will be practically operated in Super-K soon.



Clean Hyper-K Covers for Super-K

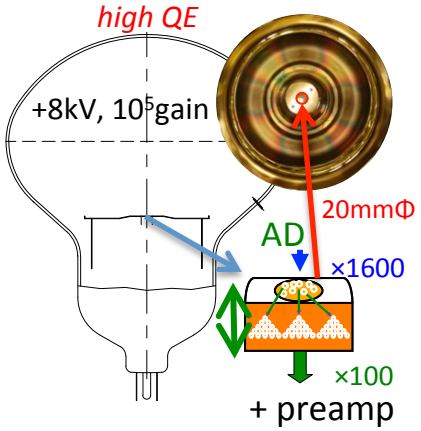
- 10 Hyper-K covers, made of clean materials with low backgrounds, are installed in SK top/bottom.

View of Super-K top from back side

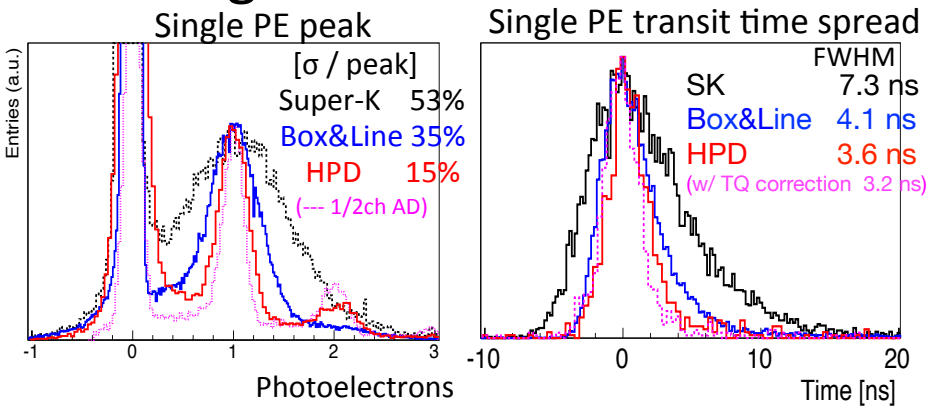
Fixing structure to the tank is modified for Super-K.

Other 50-cm Photodetector Candidates

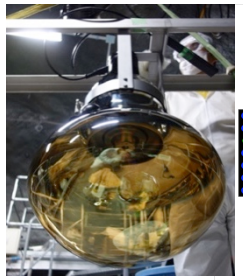
- HPD (Hybrid Photo-Detector)

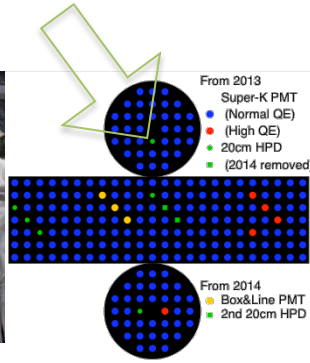


Highest 1PE resolutions

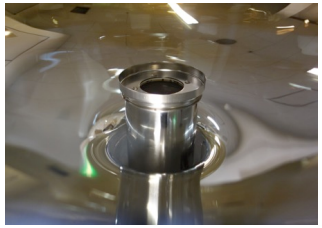


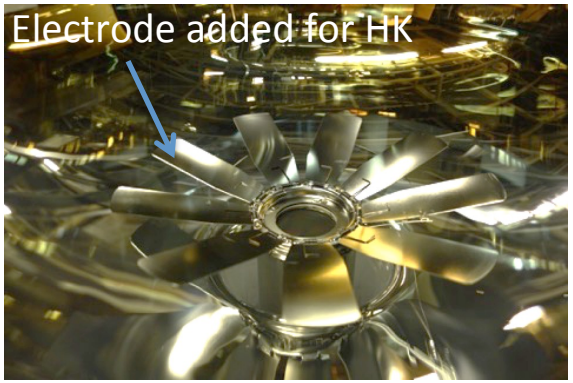
1 20” HPD was installed in 200-ton water tank.



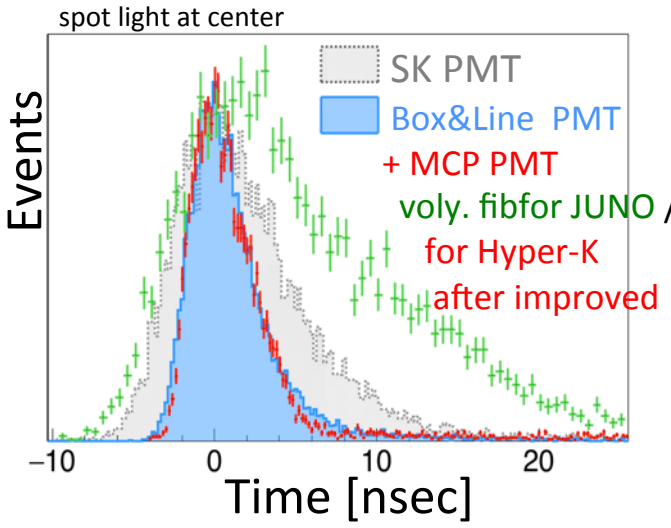


- MCP PMT
  - Originally for JUNO
    - Using micro channel plate
  - Confirmed comparable performance with the Box&Line PMT.





TTS largely improved.



Summary

- High-QE Box&Line PMT was developed for Hyper-K.
  - Full photo-detection system was established.
    - In addition, electronics for HK in another talk
  - Good prospect for high quality in mass production
  - Being operational in Super-K

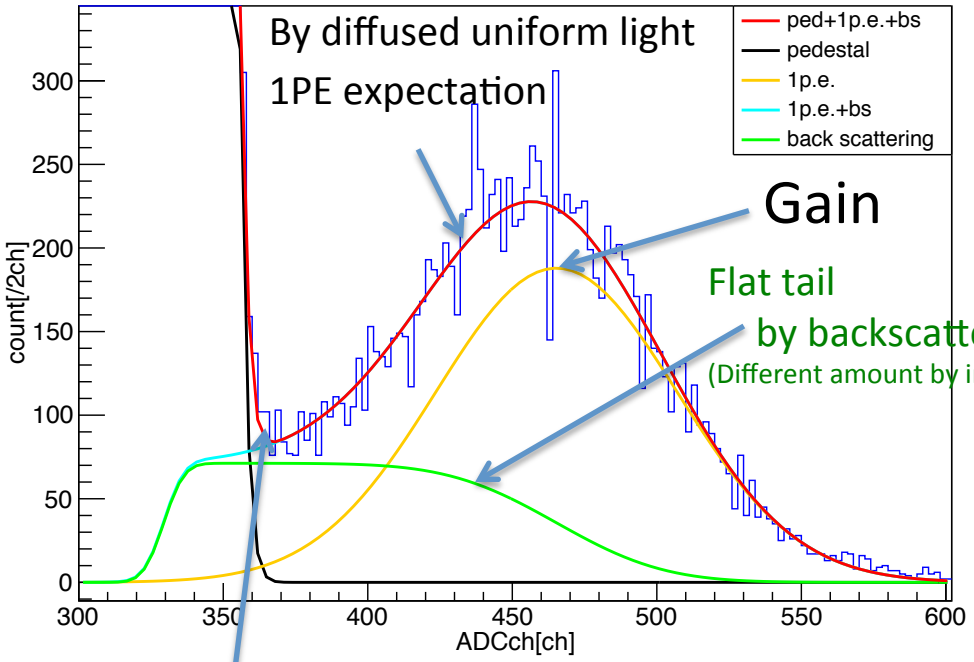
- Other options are also promising for Hyper-K.
  - HPD for the highest resolutions, etc.
  - MCP PMT for low radioactive glass, etc.
  - Multi-PMT for high granularity, etc.

] Details in other talks

Single Photoelectron Distribution

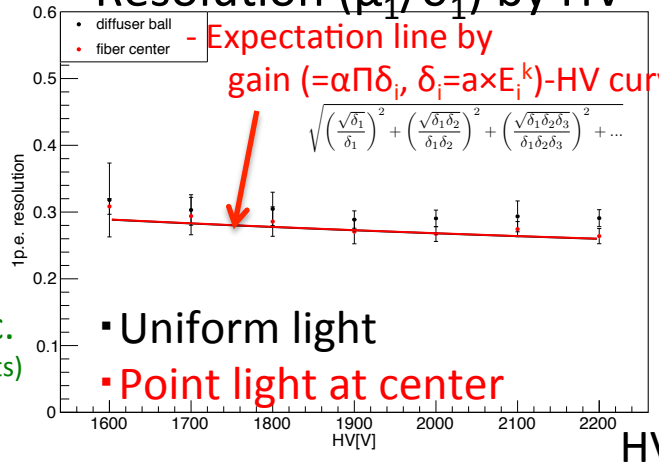
Pedestal - Gaussian + Flat inelastic backscattering distribution

$$N_0 \exp\left(-\frac{(x-\mu_0)^2}{2\sigma_0^2}\right) + N_1 \exp\left(-\frac{(x-\mu_1)^2}{2\sigma_1^2}\right) + N_2\left(erf\left(\frac{x-\mu_0}{\sigma_0}\right) - erf\left(\frac{x-\mu_1}{\sigma_1}\right)\right)$$



Tail by few contamination at special points around edge can be ignored for overall SPE modeling function in case of the Box&Line PMT.

Resolution (μ_1/σ_1) by HV

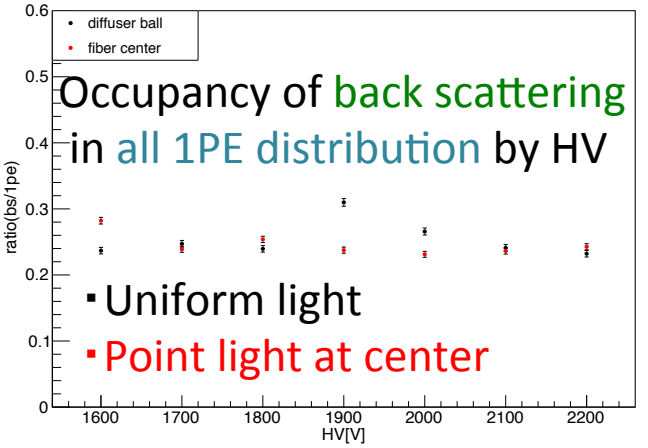


- Expectation line by gain ($=\alpha\Pi\delta_i$, $\delta_i = a \times E_i^k$)-HV curve fitting

$$\sqrt{\left(\frac{\sqrt{\delta_1}}{\delta_1}\right)^2 + \left(\frac{\sqrt{\delta_1\delta_2}}{\delta_1\delta_2}\right)^2 + \left(\frac{\sqrt{\delta_1\delta_2\delta_3}}{\delta_1\delta_2\delta_3}\right)^2 + \ldots}$$

- Uniform light
- Point light at center

HV[V]



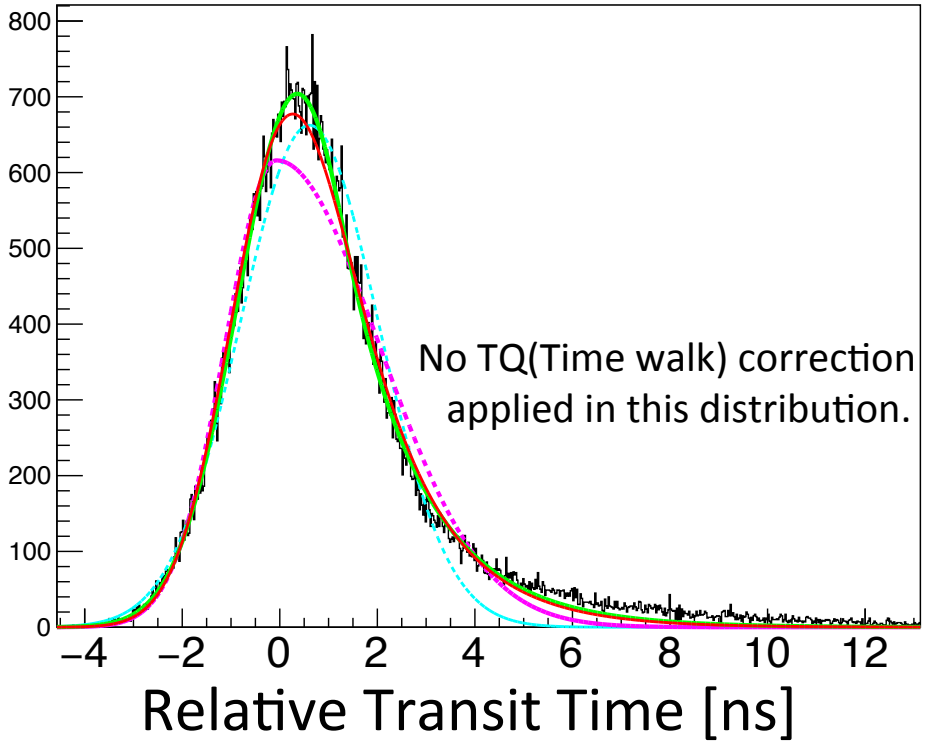
Occupancy of back scattering in all 1PE distribution by HV

- Uniform light
- Point light at center

HV[V]

Transit Time Spread

Example of fitting 1PE transit time



Func model	FWHM	Chi2/NDF
Gaussian	3.34[ns]	10963.3/1180
AsymGaus	3.72[ns]	10963.3/1180
Exp+Gaus	3.02[ns]	10963.3/1180

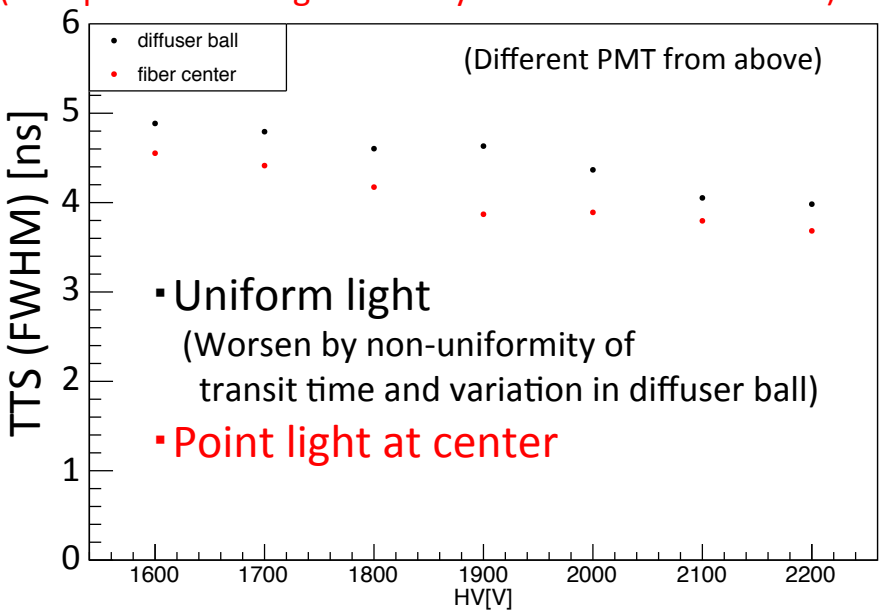
Connect Gaussian with exponential smoothly

ExpModG 3.25[ns] 1283.3/734

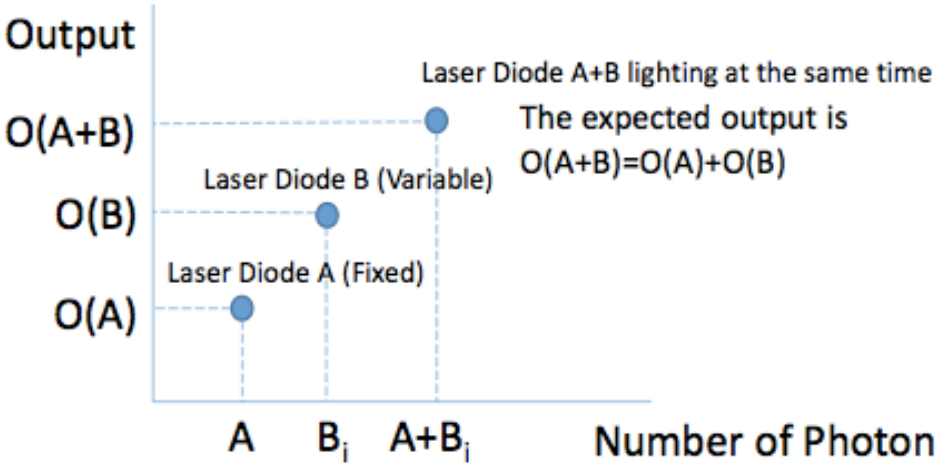
$$f(x) = \frac{\lambda}{2} e^{\frac{\lambda}{2}(2\mu+\lambda\sigma^2-2x)} \mathrm{erfc}\left(\frac{\mu+\lambda\sigma^2-\mathrm{x}}{\sqrt{2}\sigma}\right)$$

Best modeling for Box&Line PMT in HK simulation
(Late pulse tail in high intensity is not considered here.)

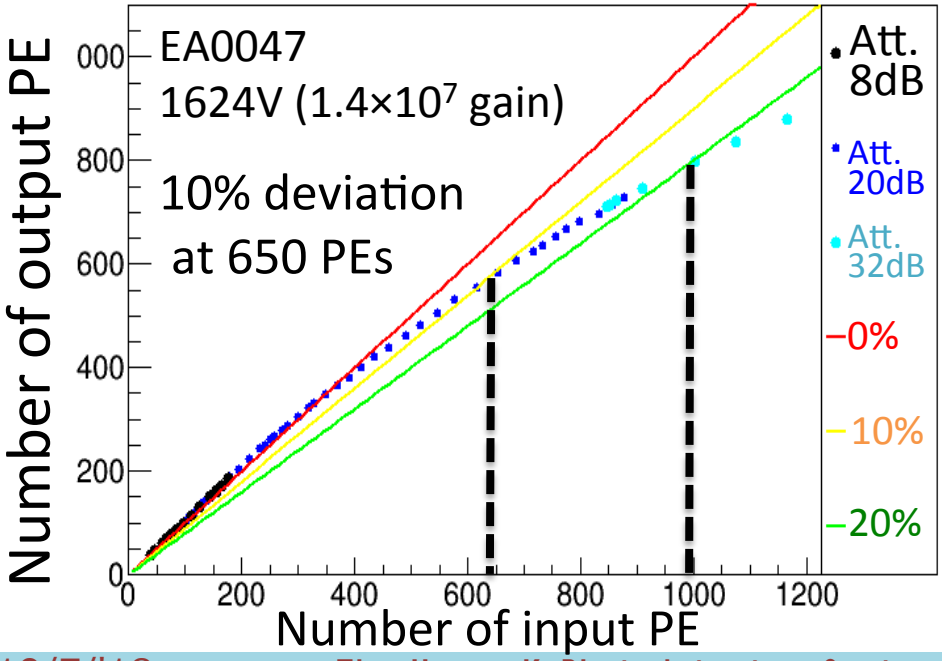
- Timing is defined at fixed hit threshold (~-1mV).
  - Time walk should be corrected later.



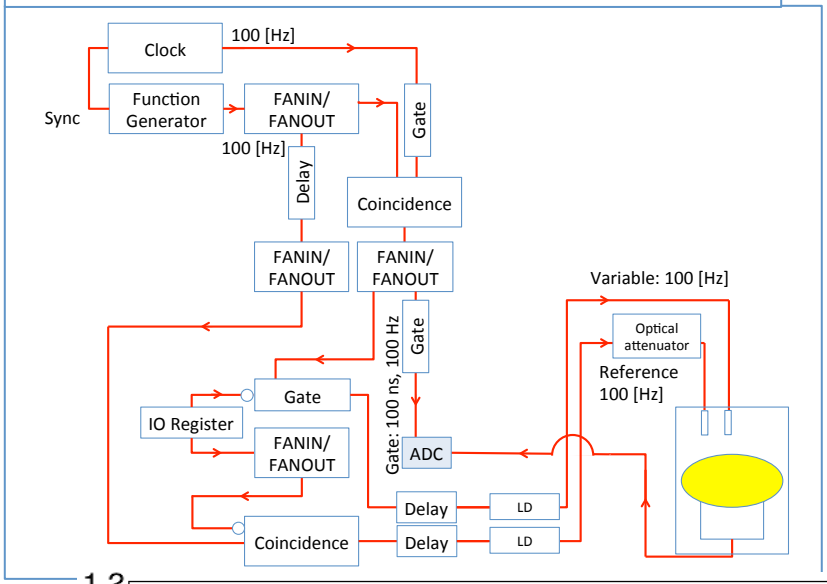
Dynamic Range

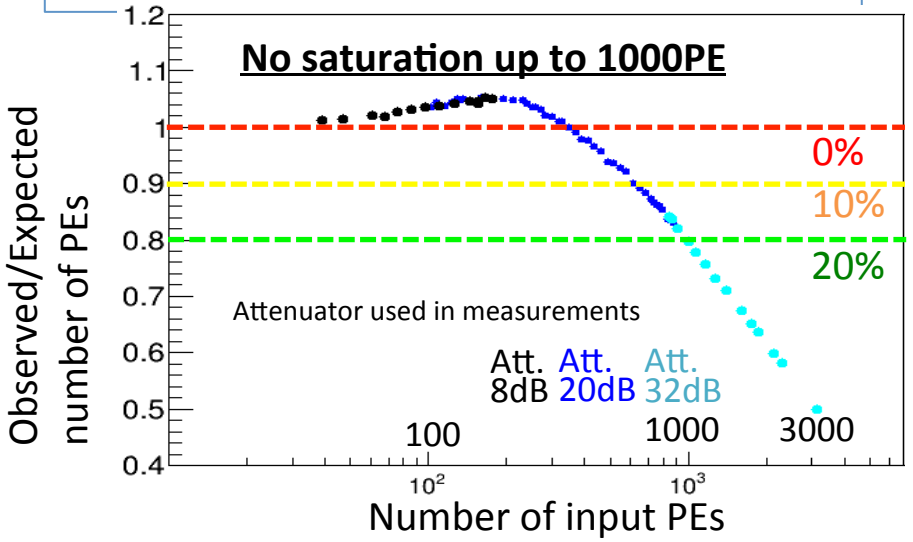


Output linearity



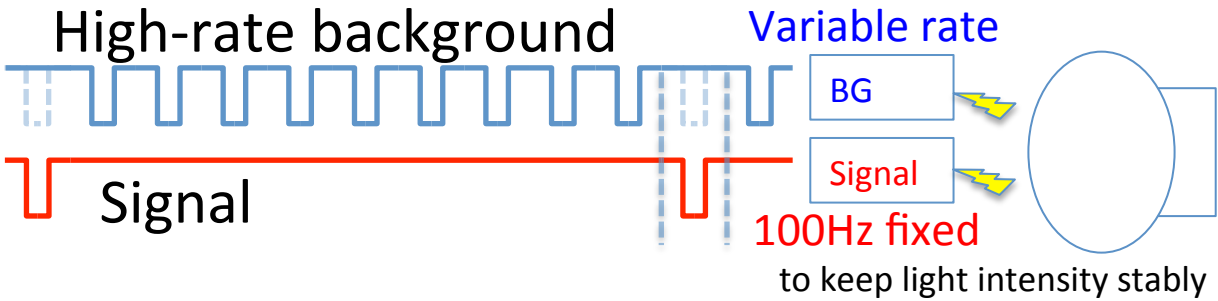
Circuit for Linearity measurement

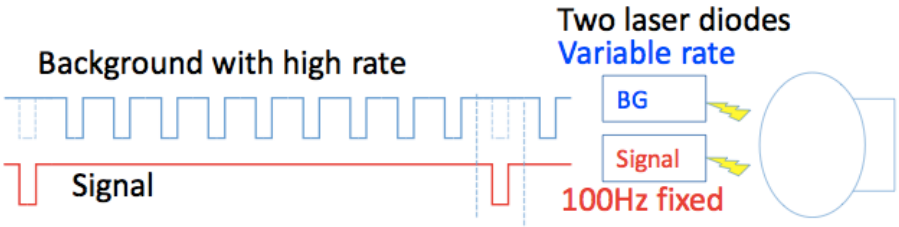




Rate Tolerance Measurement

Measured change of signal pulse in different background configuration.



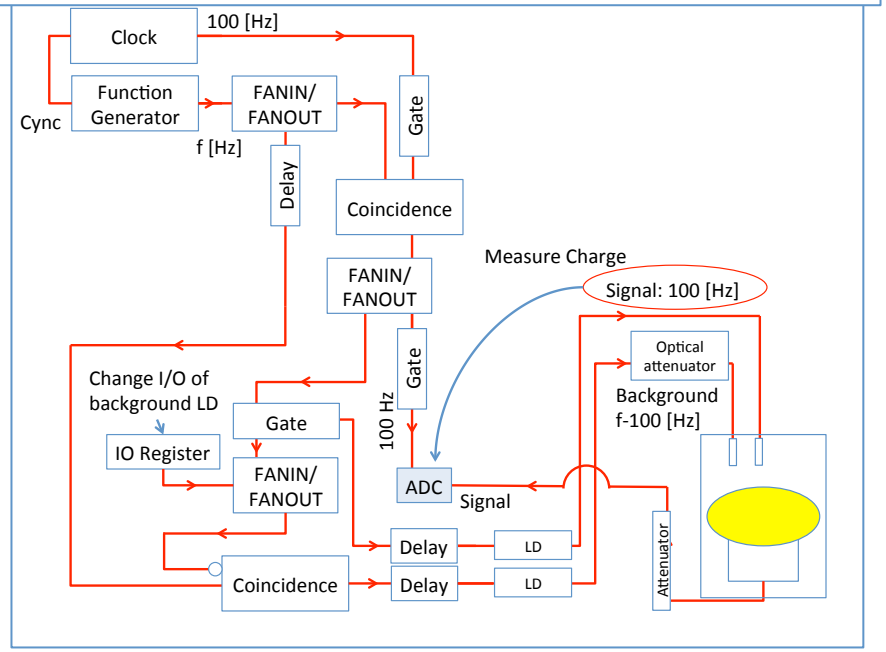


In order to evaluate rate tolerance, two laser diodes (LDs) were put.

- One for signal with 100 Hz
- One for background with a variable rate

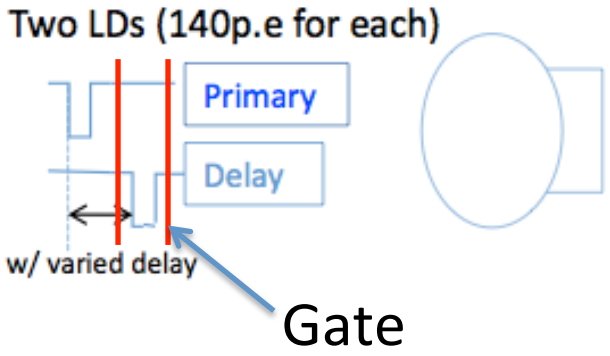
And measure change of signal pulse in different background configuration.

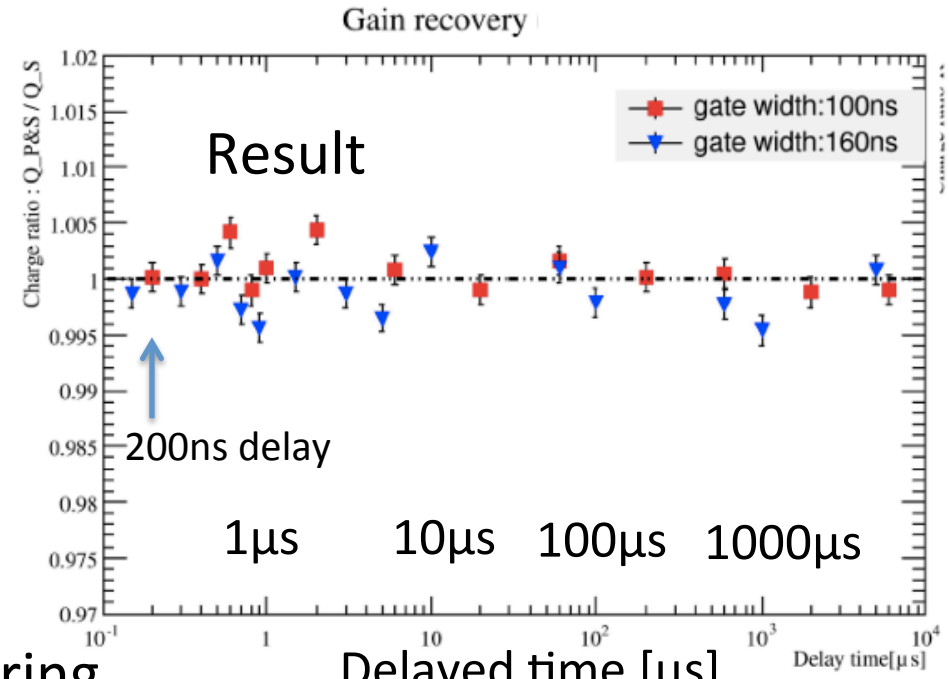
Circuit for rate tolerance measurement



Recovery Time

- Confirm gain stability of delayed signal



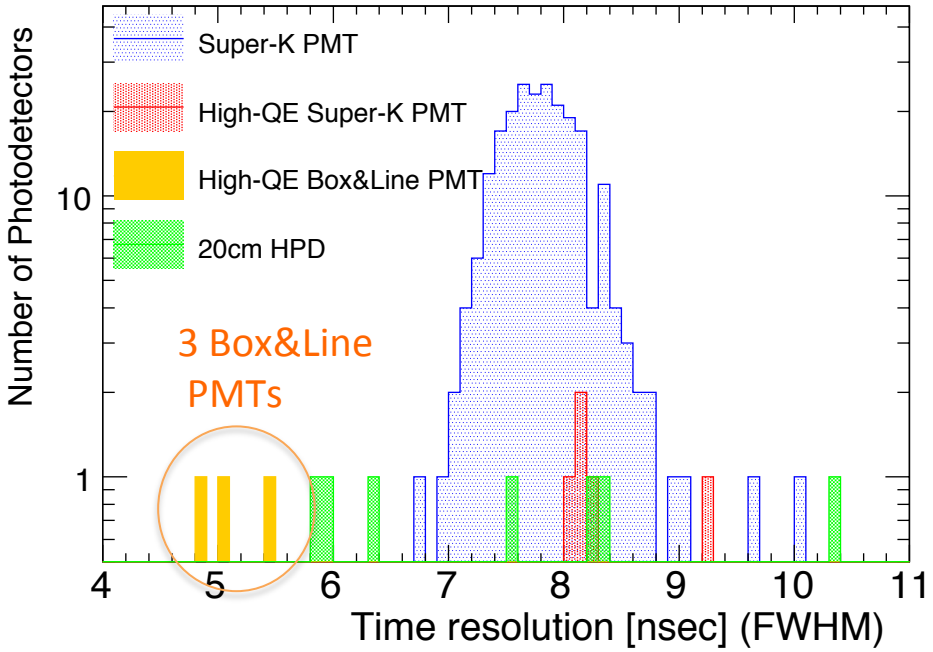


Stability was evaluated by comparing
"delayed signal w/ primary" with "delayed signal w/o primary".

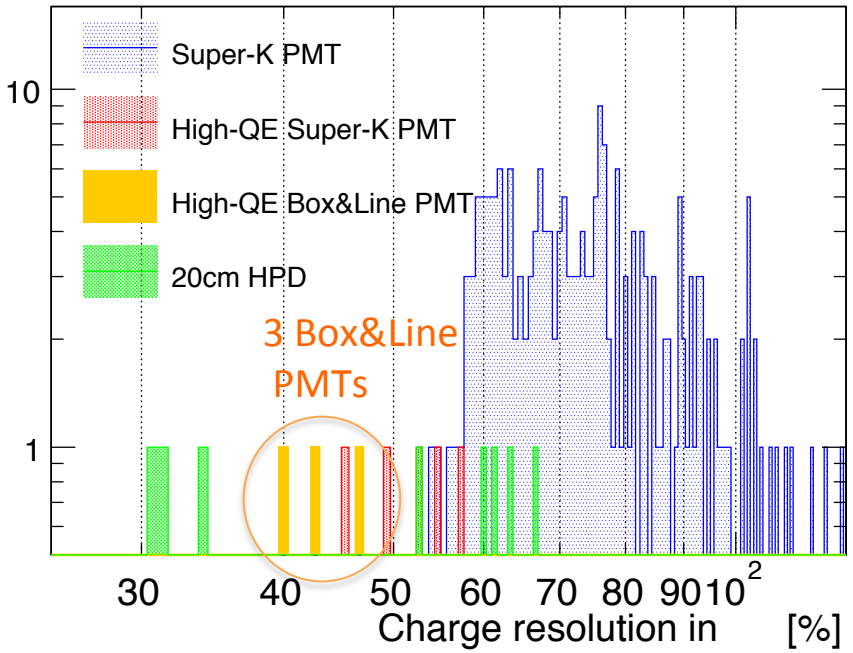
Stable because of high intensity (140PE)
(need to be checked in low intensity)

Performance in 200-ton Tank

Time resolution at 1 p.e.



Charge resolution at 1 p.e.



New Box&Line PMTs show better performance than Super-K 20” PMTs.

Sources to worse TTS:

Diffuser ball : 2.2 ns, Fiber : ~1 ns, Electronics : 0.5 ns

(HPD performance is limited by preamp noise.)

Hydrostatic Test

Glass thickness measurement

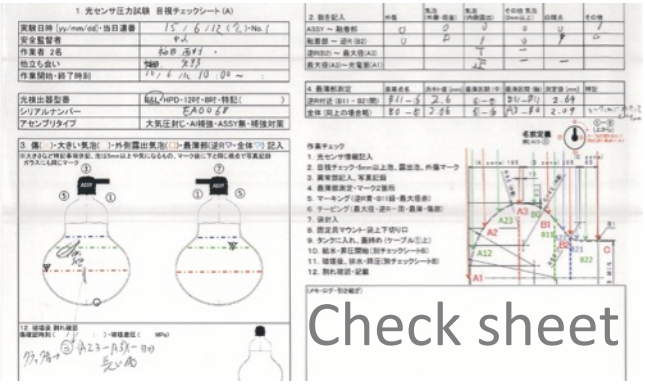
Glass thickness was measured at 97 points at Hamamatsu.
Find thinnest point scanned by ultrasonic thickness gauge at Kamioka.


Measurement with ultrasonic thickness gauge at Kamioka

Installation to pressure vessel

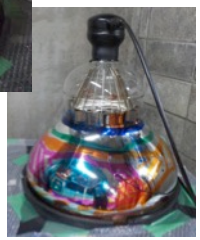
Visual inspection

Check glass quality by eye such as scratch, bubble, foreign matter


Check sheet

Marking

Coloring by position, taping to trace crack


Coloring by thickness

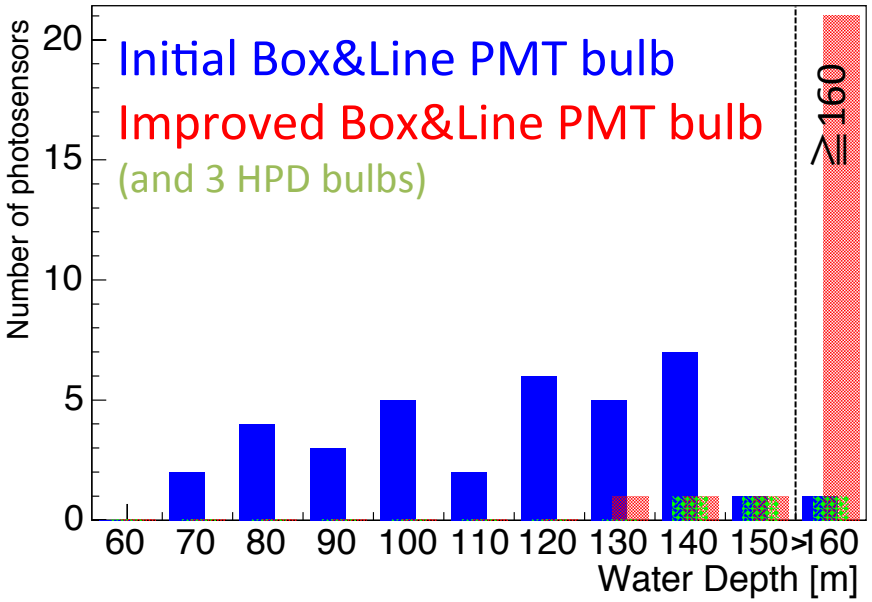
Investigation

After broken, check with protective clothing

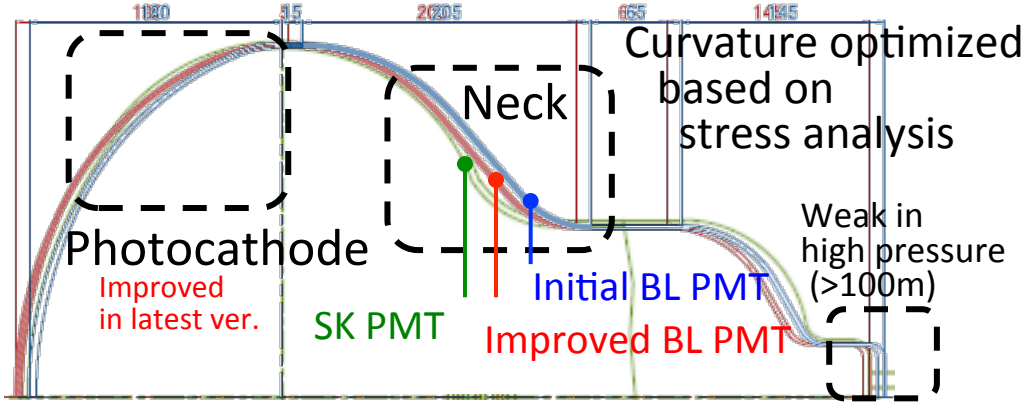

Neck

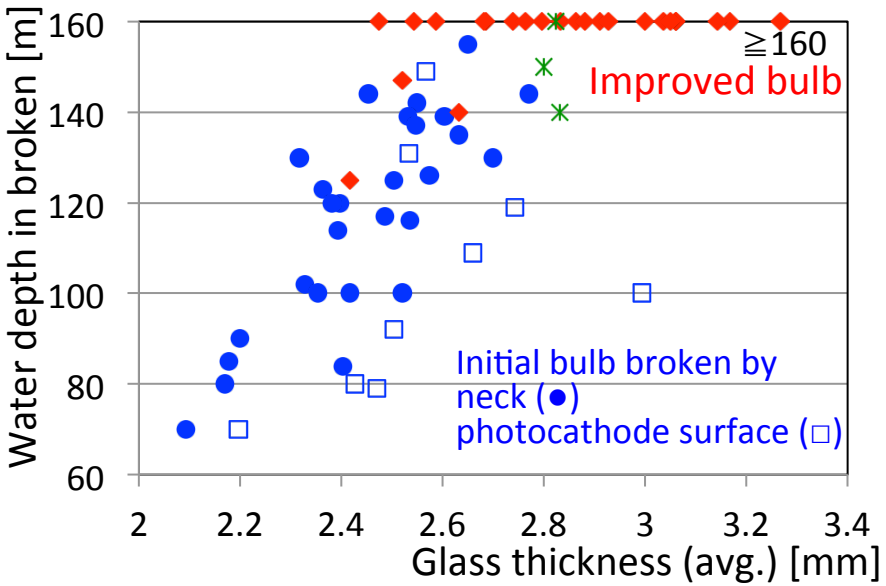

Crack on photocathode

Broken Pressure vs Thickness



SK PMT is imploded by a crack around neck in high pressure, as well as initial Box&Line PMT.





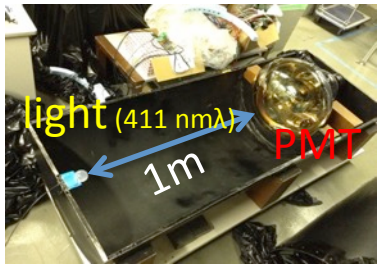
- Sometimes there was crack on photocathode surface in Box&Line PMT.
- Confirmed correlation between breaking pressure level and glass thickness.
- Pressure resistance was improved by thin thickness and optimized photocathode curvature, where less stress (Less than 10% indicated by stress analysis) is achieved.

Detection efficiency of BL PMT

A. Relative efficiency by diffused light pulse counting

HV set to 2000V, measured for 100kHz x 5min, counted 1pe hit at 1mV thr.

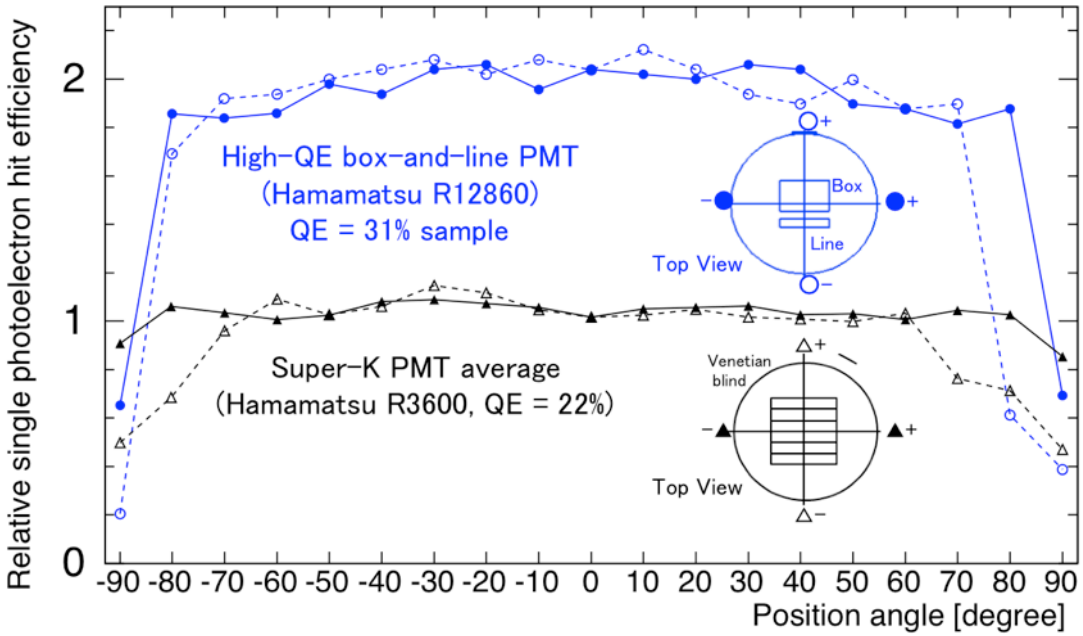
4 samples	QE	1pe count	Dark count	Relative eff
Normal SK PMT	N/A (22% typ)	176441	28964	**1**
HQE SK PMT	34.8	389775	155142	**1.59**
HQE BLPMT 1	30.7	658179	368883	**1.96**
HQE BLPMT 2	29.2	393792	121394	**1.85**



CE improvement
in simulation
67%(61%)→95%(85%)
in Φ46cm (50cm) area

B. Scanned by point source

Relative hit counting of 1 pe
on each injection point at 2 axes



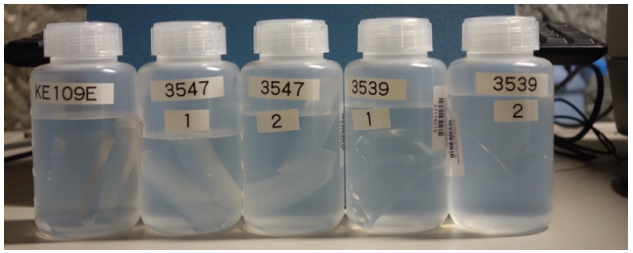
Detection efficiency is doubled
in HQE Box&Line PMT
compared with Super-K PMT.

Material Test

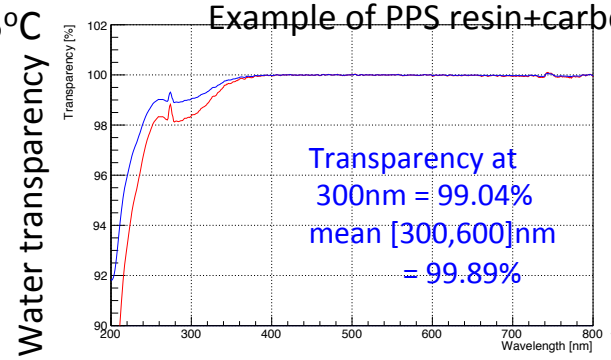
- Requirement of material to be immersed in water.
- Test in ultra pure water/Gd loaded water (0.2%w $Gd_2(SO_4)_3$)

- Soak test for 3 months (circulation to replace all SK water in tank)

Examples in 250ml/500mL water bottles, stored at 15°C for 3months



Example of PPS resin+carbon fiber



Raw data
Converted to Hyper-K

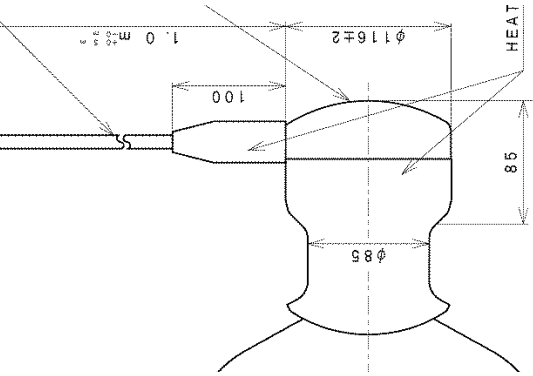
No problem in this case

- Total organic carbon to avoid bacteria in water
  - < 10.0 mg/m^2 day/mPMT, test in a week for fast test, 3 months to complete
- Metal ions to water for 7 days
  - Zn < 10 mg/m^2
  - Cu < 14mg/m^2
  - Si < 10mg/m^2

Waterproof ASSY

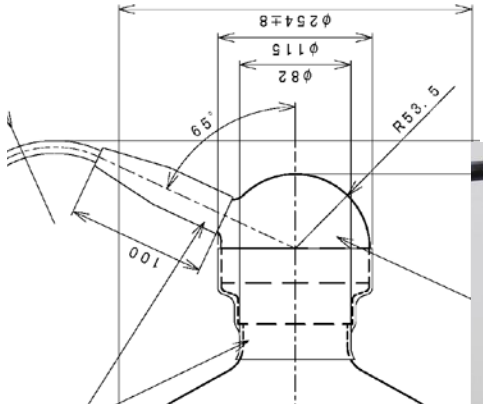
- Changed shape and adopted hard material to reduce stress around stem pins covered with cap.

Super-K PMT



PE
(polyethylene)

New housing

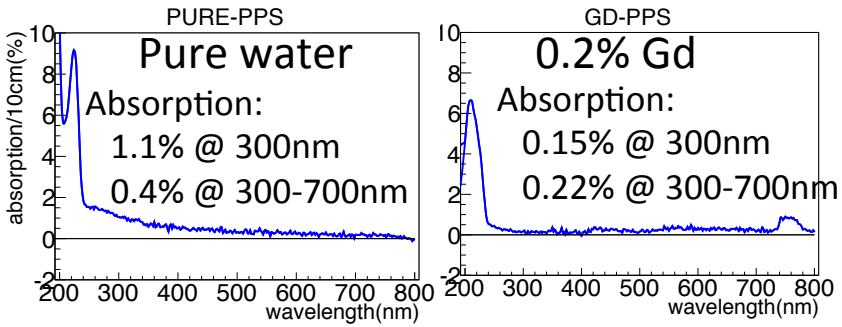


PPS
(Poly Phenylene Sulfide Resin)

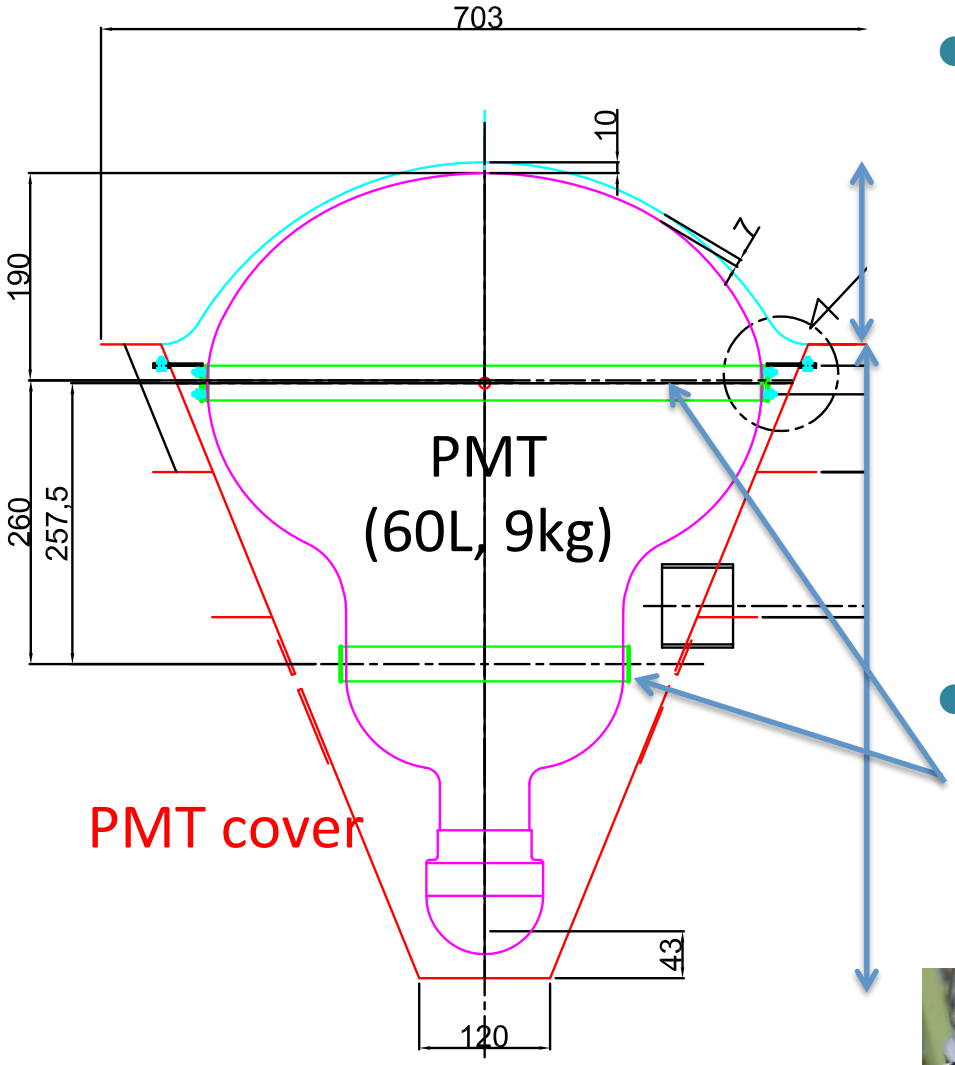
(Similar shape for both 20cm and 50cm)

- PPS material was tested in pure and Gd loaded water

PPS is known to be proper for pure water.
No problem for material soak test in pure/Gd water for 50 days.



Gel for 20-inch PMT



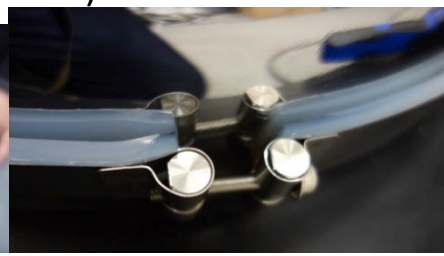
- To hold PMT in water
  - Several possible options for easy handling and safe assembly

1. Between UV transparent acrylic and PMT glass (~20L) using optical gel in water

2. Between PMT cover and PMT (~60L or less) using cheap commercial gel
To minimize space by optimizing cover shape, or spot to fix PMT in water

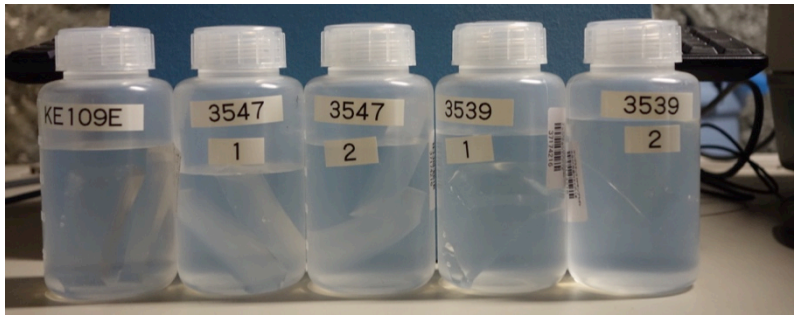
3. Instead of rubber used in PMT band to fix (Rubber can worsen water quality)

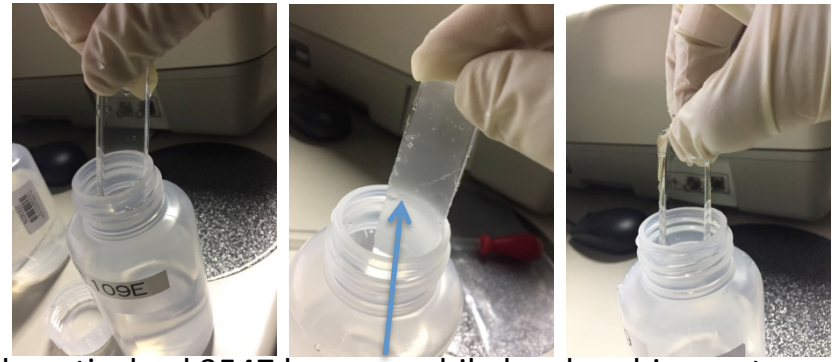
Prototype to use gel for PMT fixing band
(Same hardness as rubber)



Gel Measurement

- Soak test in water is required to keep UV transparent ultra pure water
  - 250ml ulta pure water for 1+2 months (measured 2 times), at 15°C



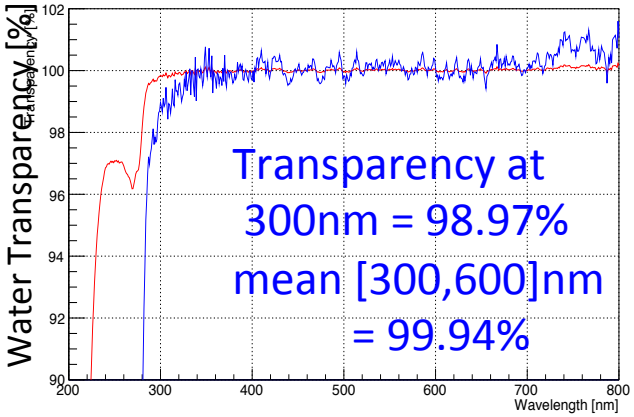


Only optical gel 3547 became while by absorbing water
(general property of phenyl group, others are in methyl group)

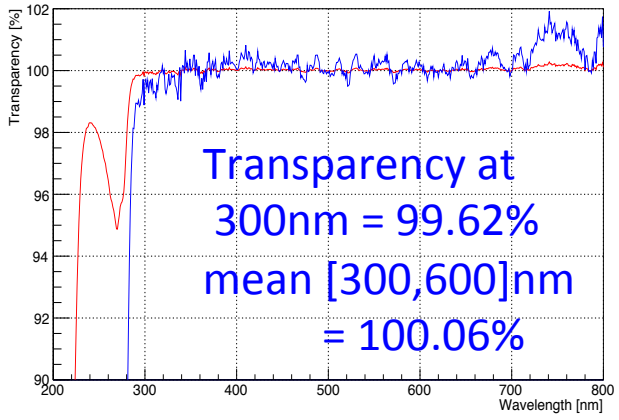
Raw data,

Scale to Hyper-K (surface area/water volume)

Optical Gel 3539



Optical Gel 3541



- Very clean for ultra pure water.
- Also commercial gel (KE109E) is stable,
another gel is under test.
- Very clean
in RI measurement.
- Degradation of mechanical characteristics by water absorption is to be measured.

Requirement of HK Photosensor

Requirements	Value		Conditions
Detection efficiency	16%	Typ.	Quantum Efficiency × Collection Efficiency
Timing resolution	2.2 nsec	σ, Typ.	Single Photoelectron (PE)
Charge resolution	50%	σ, Typ.	Single PE
Signal window	200 nsec	Max.	More than 95% of a total signal area
Dynamic range	2 photons/cm^2	Max.	Per detection area on wall
Gain	$10^7 \sim 10^8$	Typ.	
Afterpulse rate	15%	Max.	For single PE, relative to the primary pulse
Rate tolerance	10 MHz	Max.	Single PE pulse, within 10% change of gain
Magnetic field tolerance	100 mG	Typ.	Within 10% degradation
Life time	20 years	Typ.	Less than 10% dead rate
Pressure rating	0.8 MPa	Min.	Static, load in water

- Important factors : High detection efficiency, sub-nanosec timing resolution, single photon counting, low dark count rate

Specification

Shape	Hemispherical
Photocathode area	50 cm diameter (20 inches)
Bulb material	Borosilicate glass (~ 3 mm)
Photocathode material	Bialkali (Sb-K-Cs)
Quantum efficiency	30 % typical at $\lambda = 390$ nm
Collection efficiency	95 % at 10^7 gain
Dynodes	10 stage box-and-line type
Gain	10^7 at ~ 2000 V
Dark pulse rate	~ 8 kHz at 10^7 gain (13 Celsius degrees, after stabilization for a long period)
Weight	9 kg (without cable)
Volume	61,000 cm^3
Pressure tolerance	1.25 MPa water proof