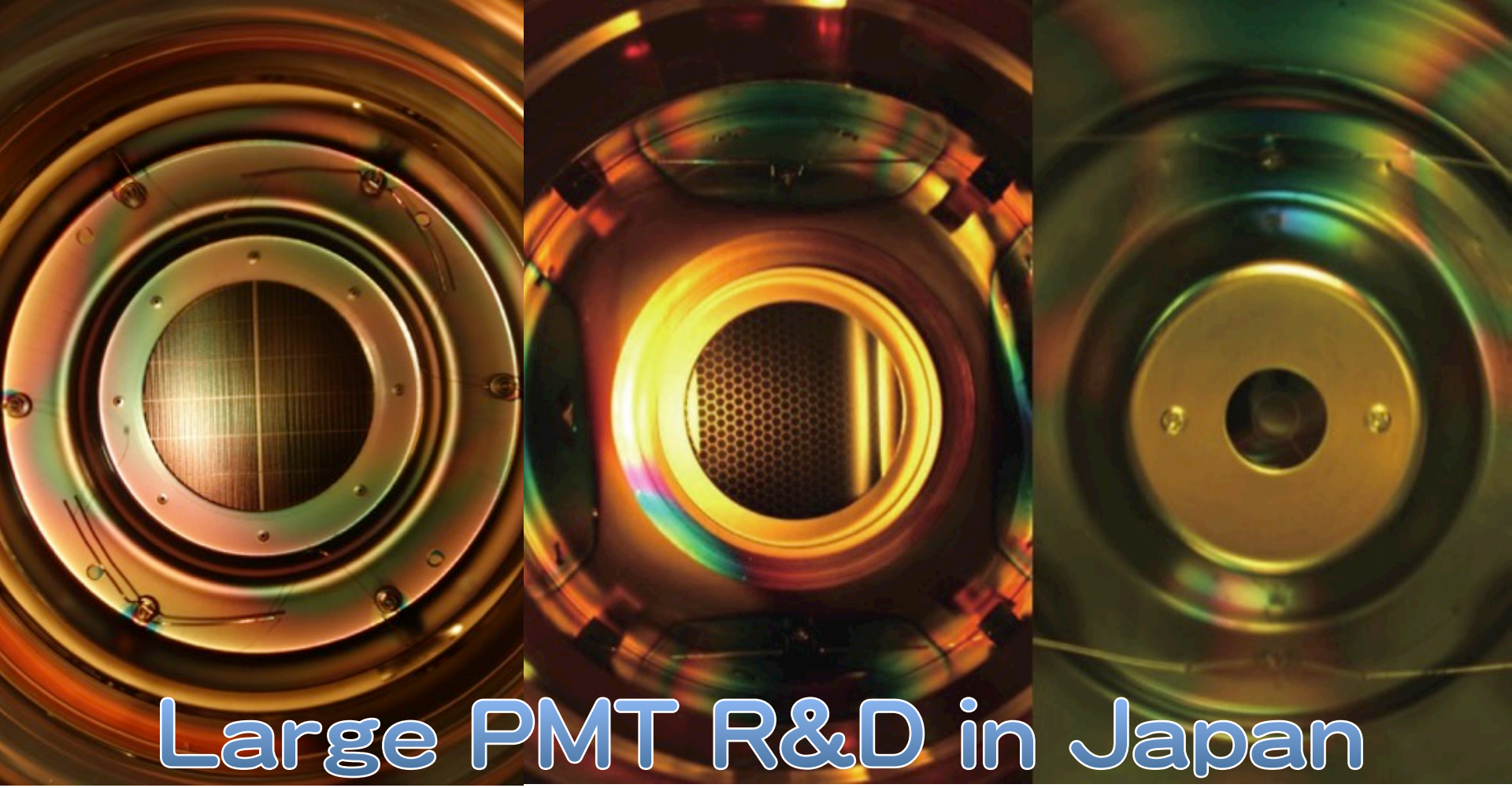

Large PMT R&D in Japan

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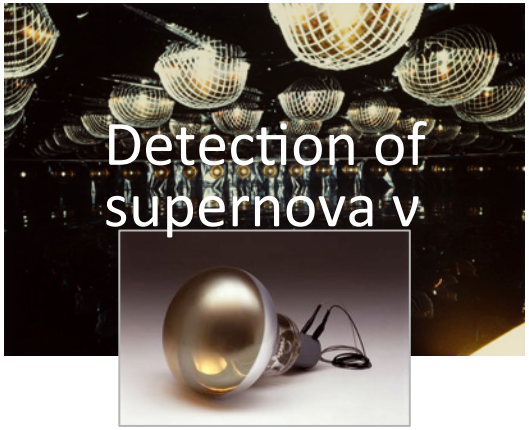
NNN16 @ IHEP, China
- International Workshop on Next Generation Nucleon Decay and Neutrino Detectors -
5/Nov/2016

Large PMT applications in Japan

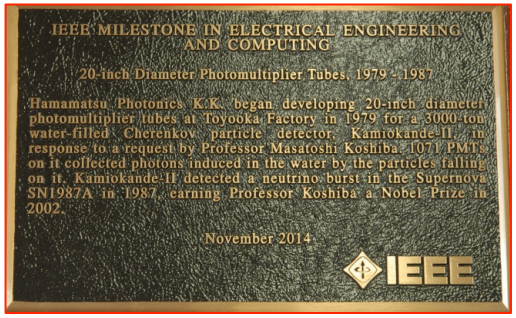
By Hamamatsu Photonics K.K.

Kamiokande
1983-1995

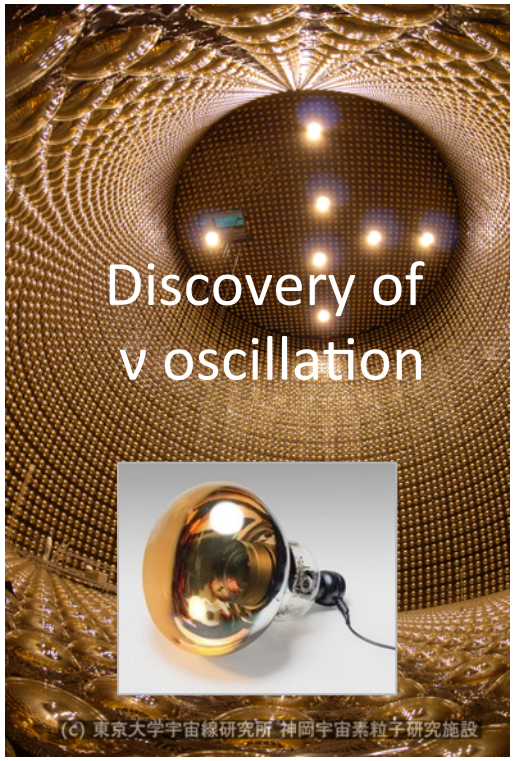


R1449 20″ PMT

Certified as an
IEEE milestone
(October 2014)

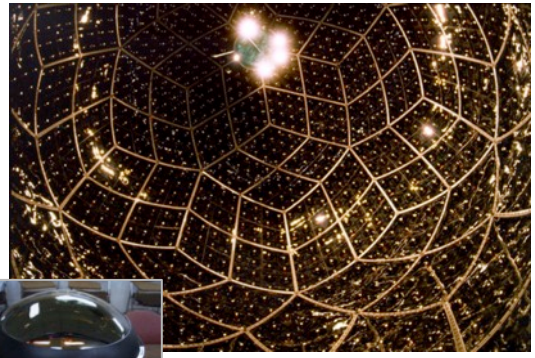


Super-Kamiokande
1996-



R3600 20″ PMT

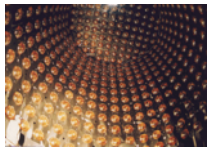
KamLAND(-Zen)
2002-



R7250 17″ PMT

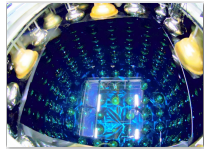
CANDLES
20″+13″ PMT

K2K 1kt



XMASS

EGADS



and for near future plan of Hyper-Kamiokande
with improved photodetectors

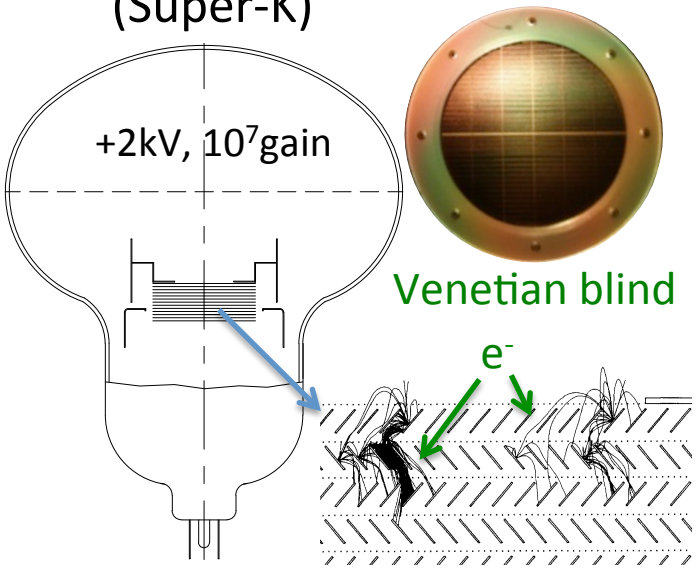
20" Photodetector R&D for Hyper-Kamiokande

Super-K PMT

Hamamatsu R3600

Venetian blind dynode

(Super-K)

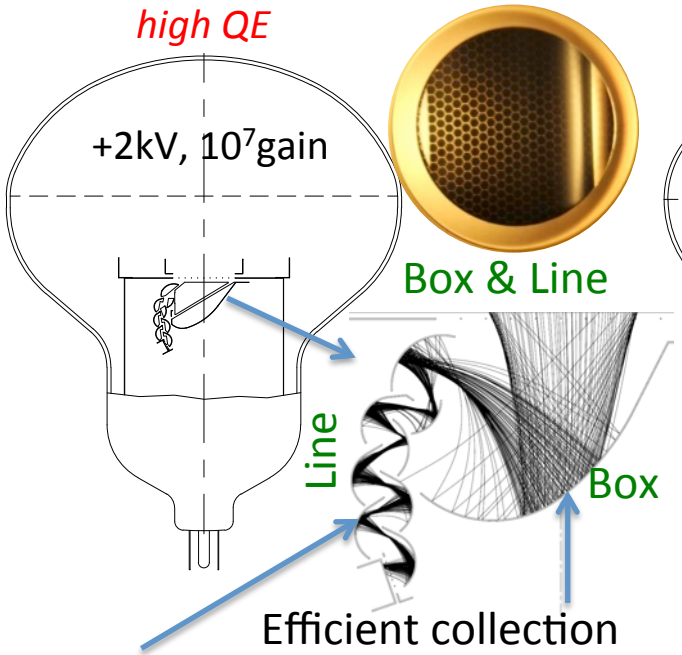


- Electron might miss dynodes
  → less collection efficiency
- Ambiguity of drift path limits charge and time response.

Box&Line PMT

New Hamamatsu R12860

Box & Line dynode

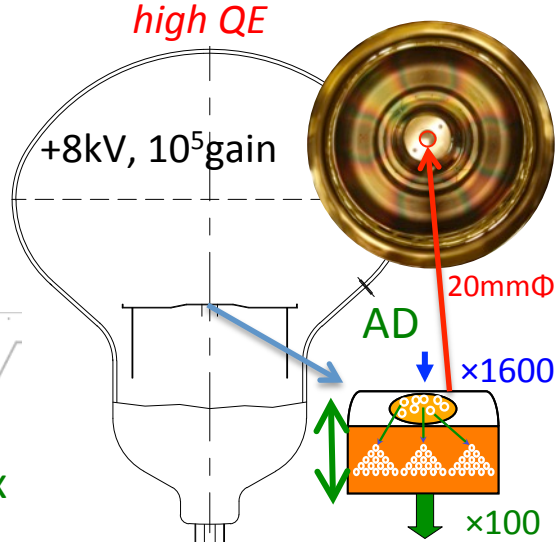


Uniform drift path
→ High charge&time resolutions
→ Performance was improved with safety design
→ Now Hyper-K baseline sensor

Hybrid PhotoDetector (HPD)

New Hamamatsu R12850

Avalanche diode (AD)



+ preamp

High resolutions, simple structure

Developed with sufficient performance (Superior to PMTs)

R&D and test ongoing for practical use

Hyper-Kamiokande

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

High-QE 50 cm Box&Line PMT

×2 high detection efficiency

×1/2 time&charge resolutions

×2 high pressure bearing for 60 m height

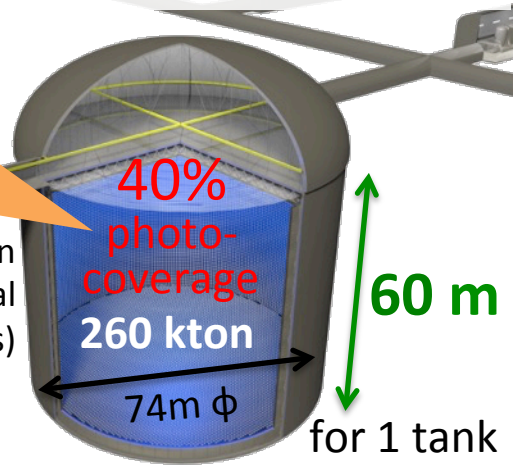
Water Cherenkov detector in Kamioka, Japan

→ **Hyper-Kamiokande (HK)**

×40,000

×2 tanks

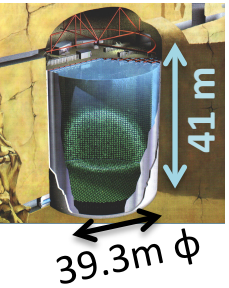
(190 kton Fiducial Mass)



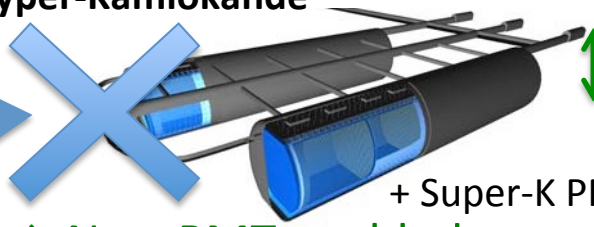
for 1 tank

And 6,700 of 20 cm (8") PMTs for Outer Veto Detector

Super-Kamiokande



Hyper-Kamiokande



+ Super-K PMT

→ New PMT enabled an optimization of Hyper-K design with keeping physics sensitivities

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

Requirements

→ Wide dynamic range ~O(10^3)PEs

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

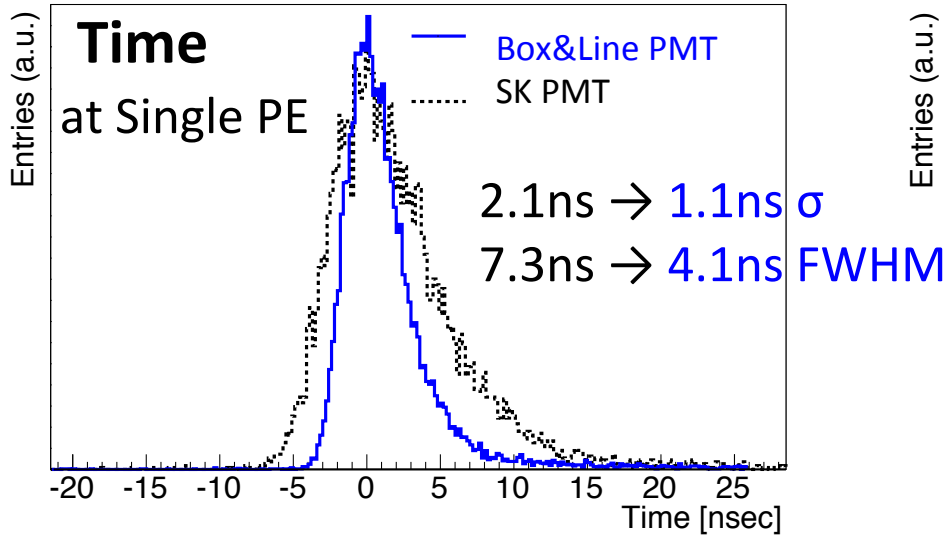
→ ~nsec time resolution, low background

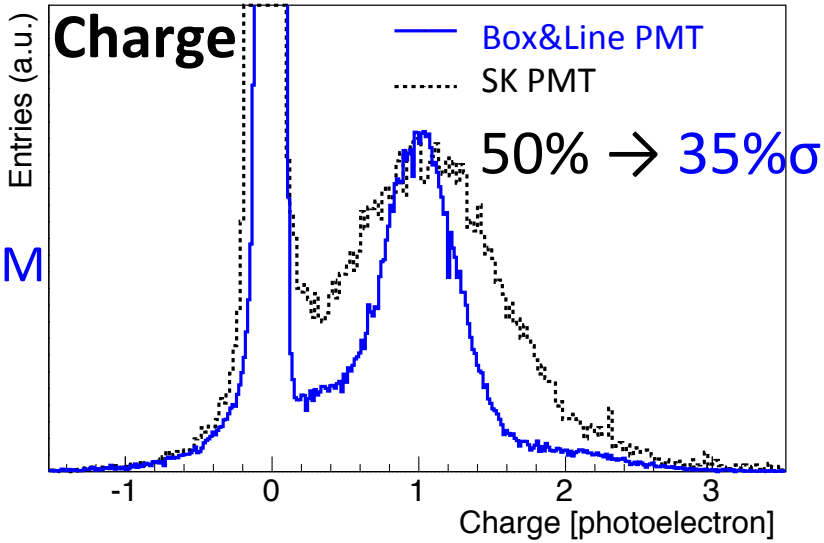
→ Clear photon counting,

→ High rate tolerance O(10)MHz at a few PEs

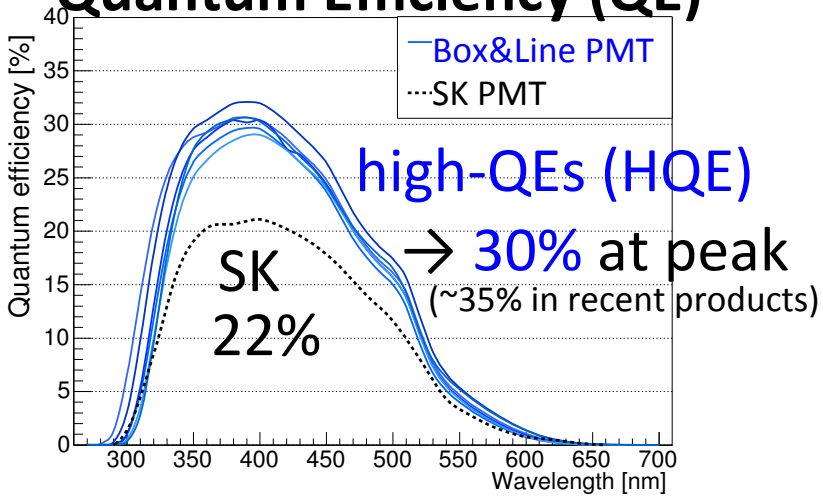
Box&Line PMT Performance

Confirmed sufficient performance in Hyper-K (Reported in NNN14,15)

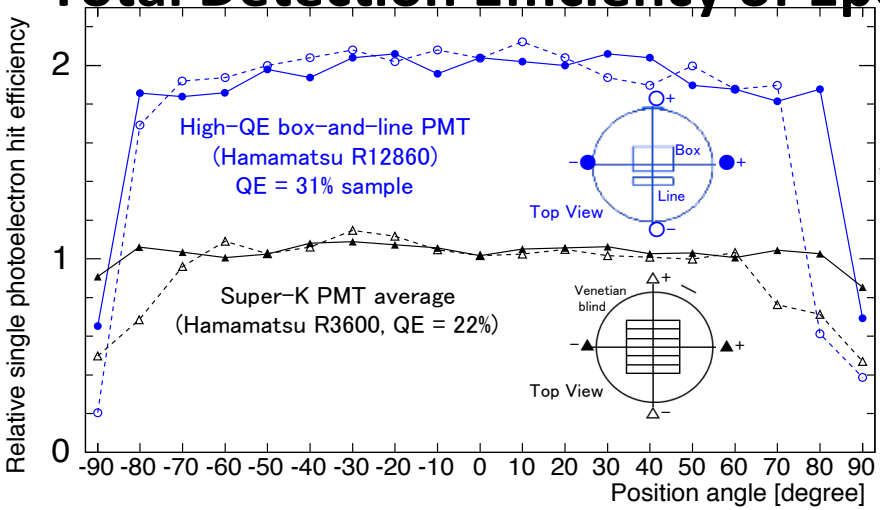




Quantum Efficiency (QE)



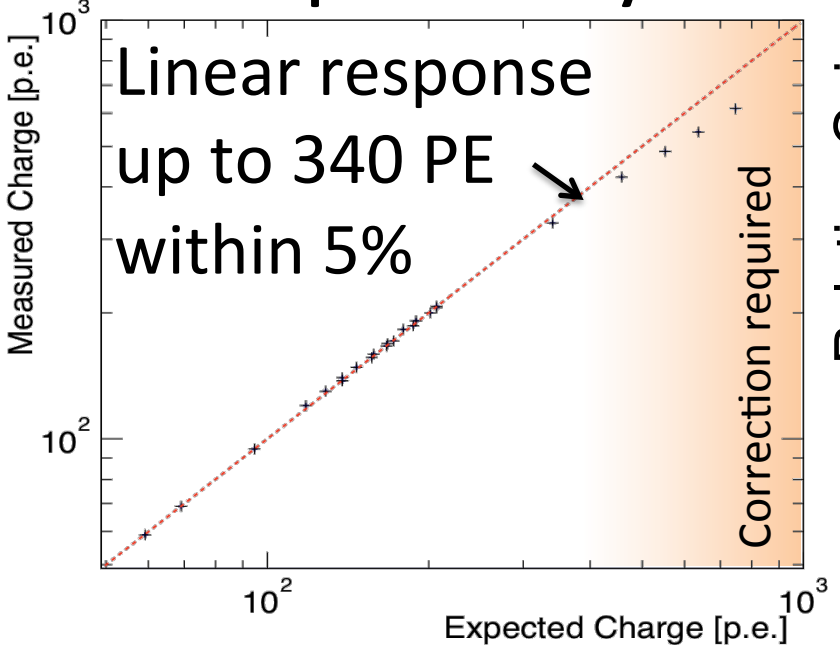
Total Detection Efficiency of 1pe



×2

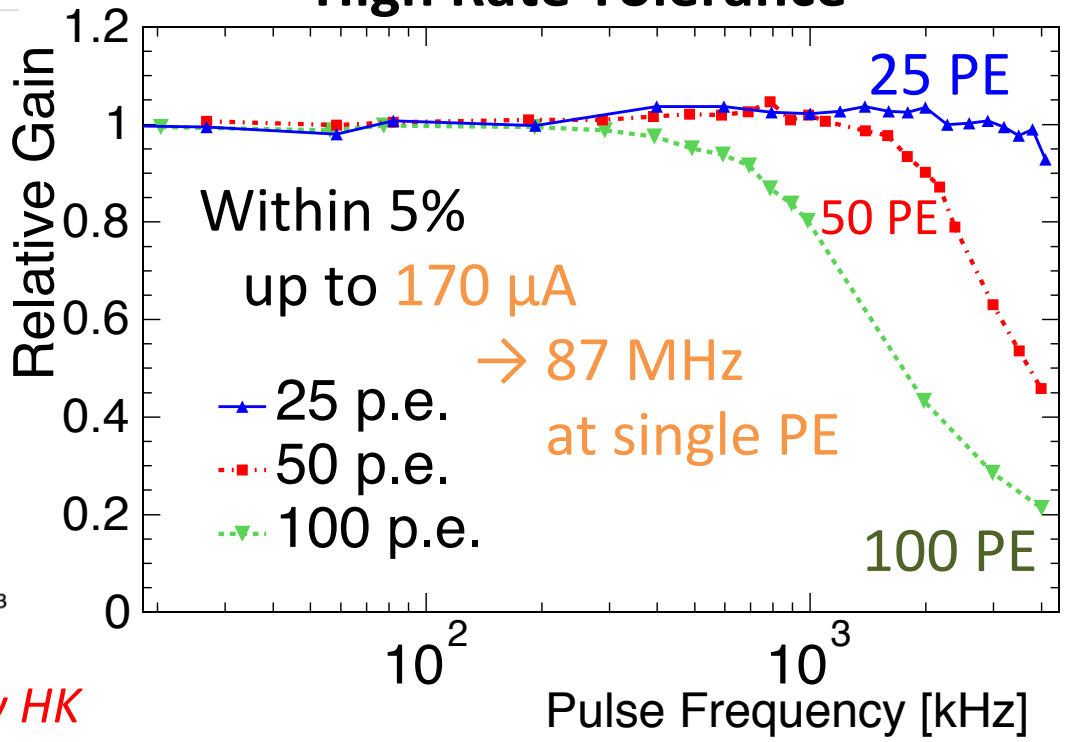
Response in wide range

Output Linearity



→ *No saturation in expected range by HK*

High Rate Tolerance

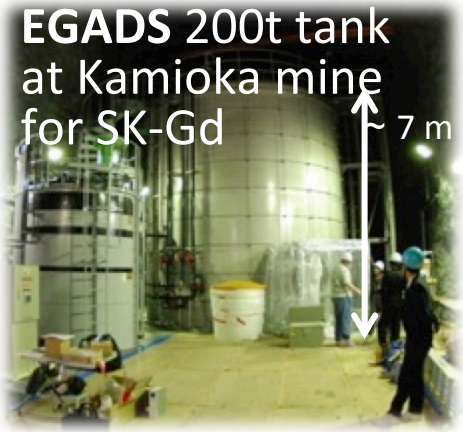


→ *Sufficient for supernova detection*
(10MHz at max in low PE)

Proof test in water

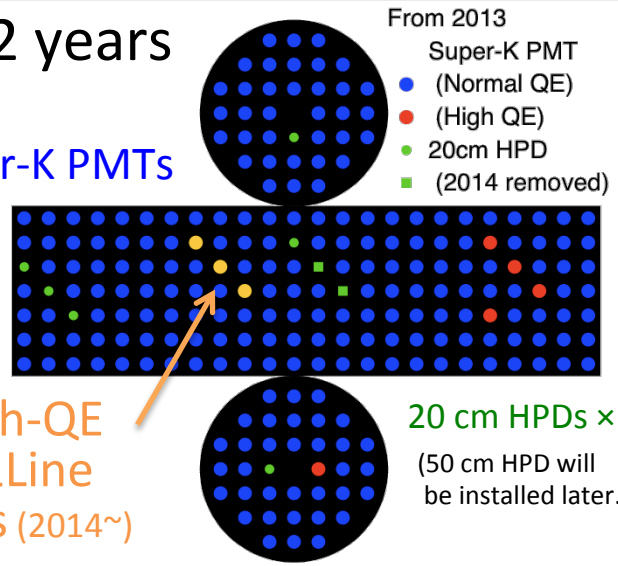
Operated in water Cherenkov detector for 2 years

EGADS 200t tank at Kamioka mine for SK-Gd



Imitating Super-K

224 Super-K PMTs



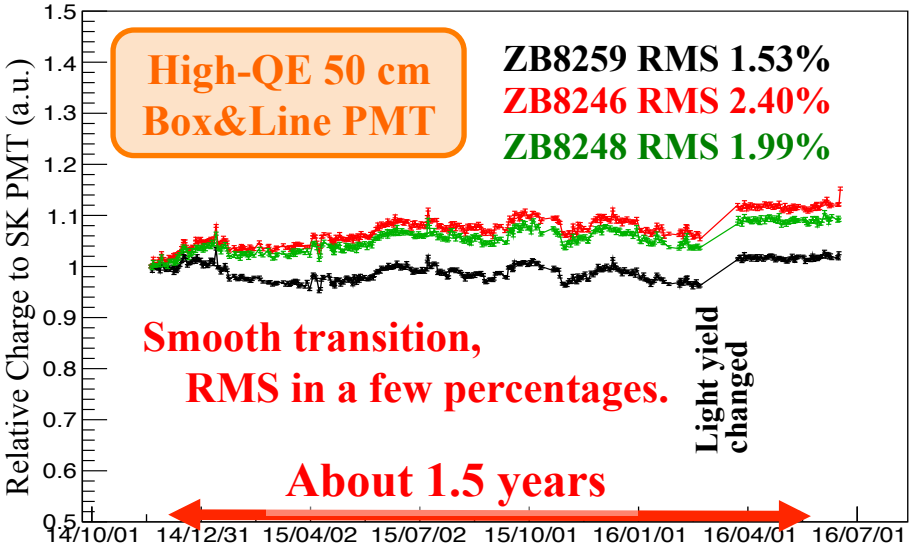
3 High-QE Box&Line PMTs (2014~)

20 cm HPDs × 8

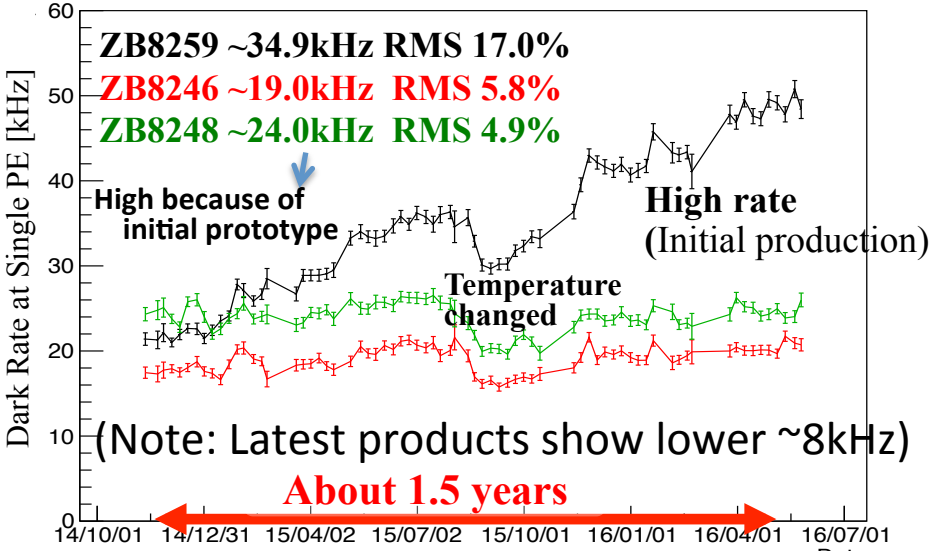
(50 cm HPD will be installed later.)

Monitoring stability of performance over a year

Gain stability monitor



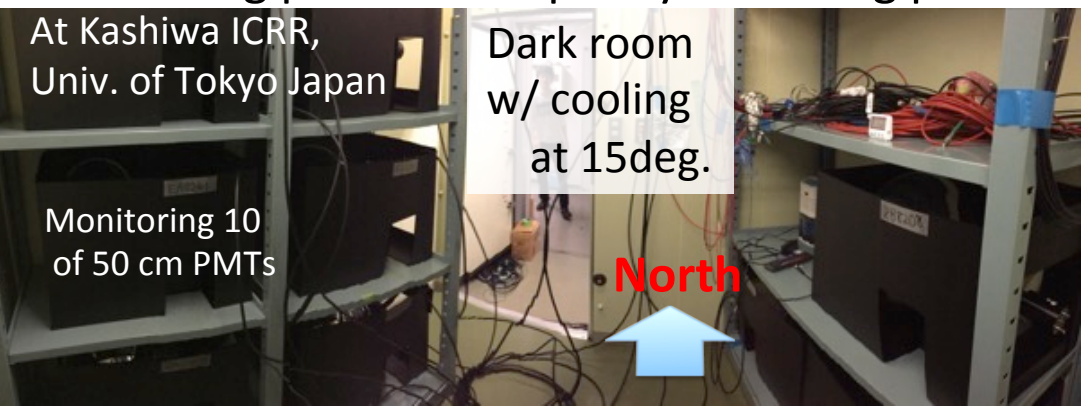
Dark rate stability monitor

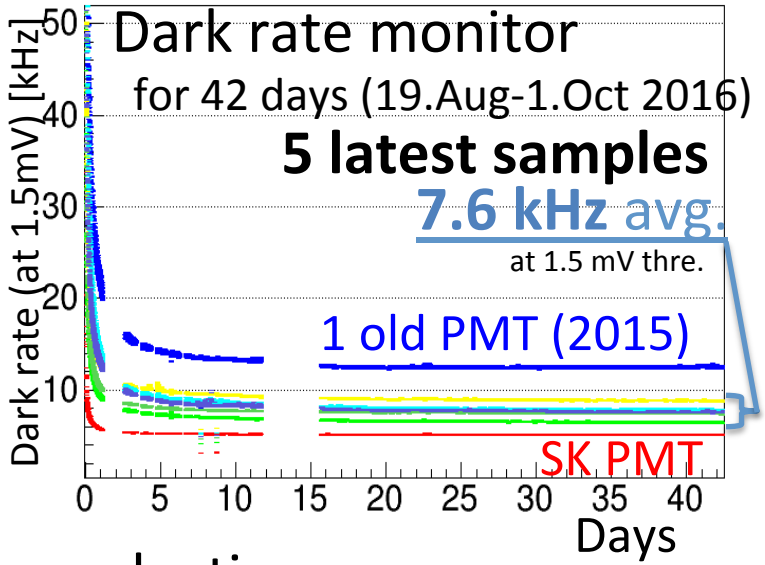


Dark rate in recent products

- Still trying to reduce dark rate (20 kHz→10 kHz→8 kHz→...)

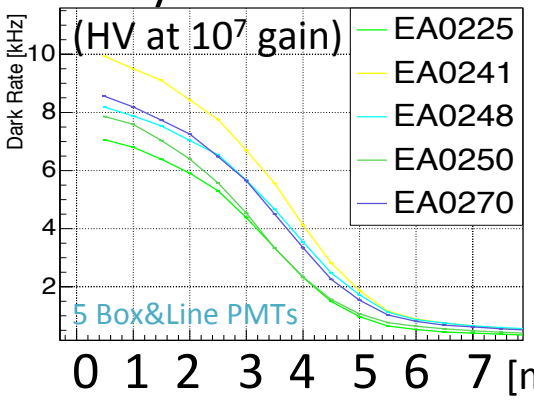
  Checking production quality for a long period



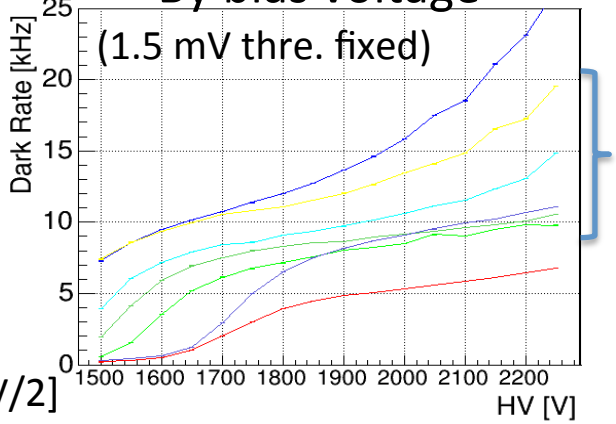


Dark rate was characterized by parameters to consider a good quality control in mass production.

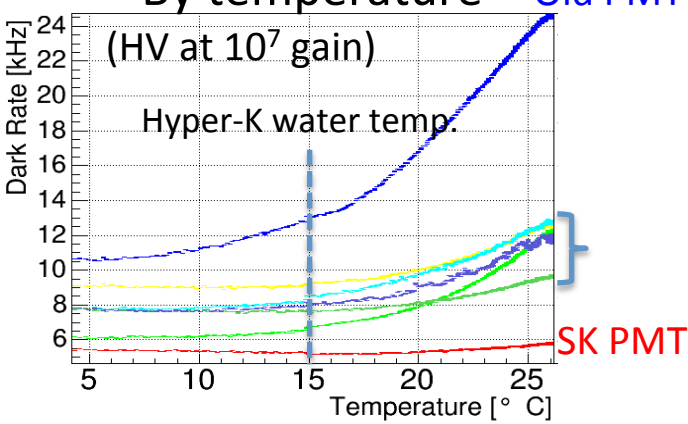
By hit threshold



By bias voltage

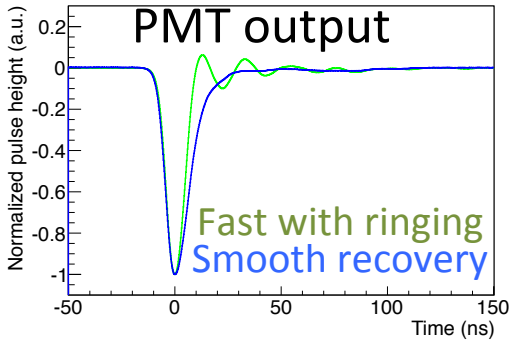


By temperature



What was improved during R&D?

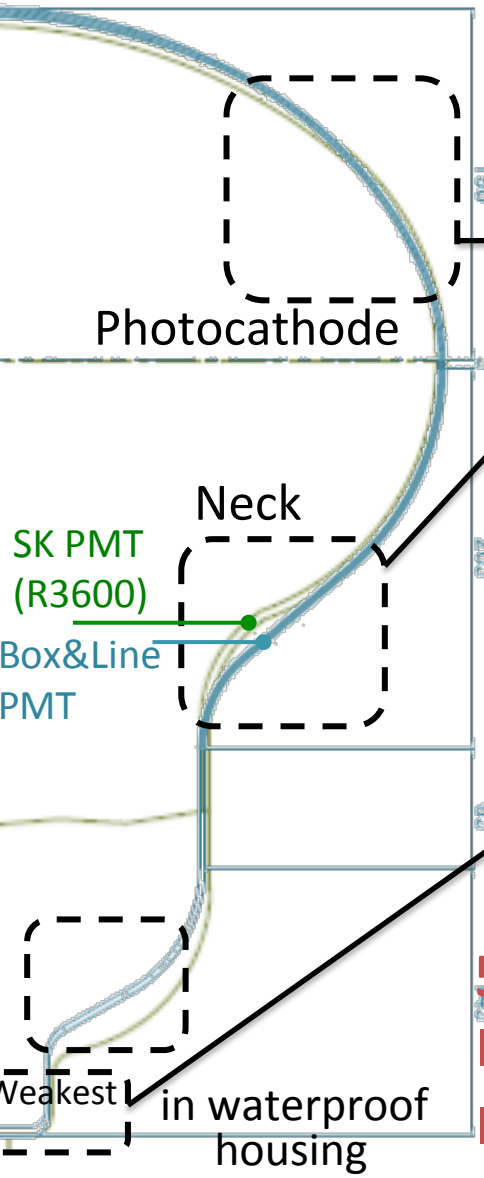
- Pulse shape
  - Bleeder circuit was optimized with minimizing ringing (in 2014)



FWHM 10.4ns ↔ 12.9ns
Height 1.3 : 1

- Response uniformity in whole acceptance
  - Improved by changing bulb design (in 2015)
  - Confirmed within +/- 100mG, 1600 - 2200V (in 2015)
- After pulse : Less than 5% recently reduced from initial 30% of hit probability from single photo-electron pulse.
  - By changing dynode shape, evacuation process, voltage ratio, etc. (in 2015)
- Dark count rate : Reduced from 20% to 8%, and still trying to reduce it.
- Quantum efficiency : Achieving 35% typ. from 30%
- Mechanical strength : Improved by design, established PMT cover

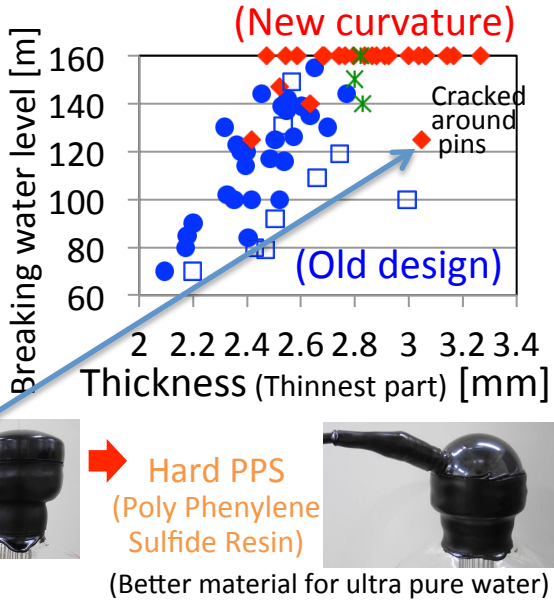
Design and Confirmation



The bulb shape was designed to get lower tensile stress, and improved for deep water level.

- Smoother curvature
  - Photocathode part < 1/16 stress of SK PMT's
  - Neck part (weakest in SK PMT) < 1/8 stress of SK PMT's
- Thicker glass (about ×1.3)
  - Because of correlation confirmed with breaking level by test
  - New criteria on quality control was established with measuring thickness at various points.
- Tough waterproof housing

Hard & round design to protect the weakest point



Soft PE (polyethylene)

Hard PPS (Poly Phenylene Sulfide Resin)

(Better material for ultra pure water)

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

- **No damage at all 50 samples.**
- **×1.9 safety factor for 60m. (1.5 for 80m, 1.5 = SK screening)**

Safety measures

1. Design and confirmation of the PMT glass bulb
   - To minimize the single PMT implosion

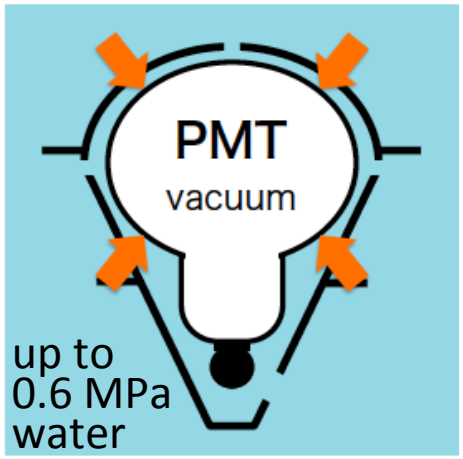
2. Screening by the individual inspection in all products
   - Pre-selection by glass thickness, inspection of bulb glass quality, etc.
   - Quick pressure test before the installation

3. Shockwave prevention by the cover
   - In the very unlikely event of a single-PMT implosion, the cover significantly reduces the shockwave released outside
   - Eliminate the catastrophic chain reaction of PMT implosions completely

Concept of PMT cover

- Cover should protect outside PMTs of the cover without broken.

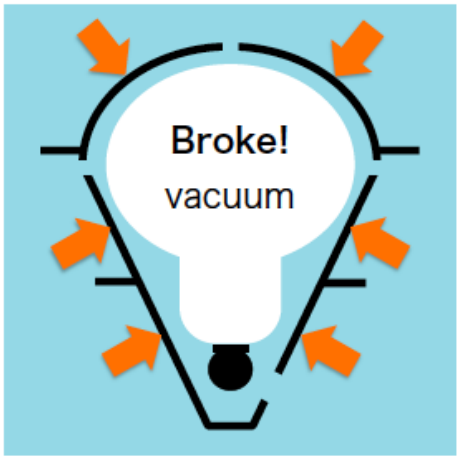
Usual case



Cover has small holes

PMT always exposed to the water pressure

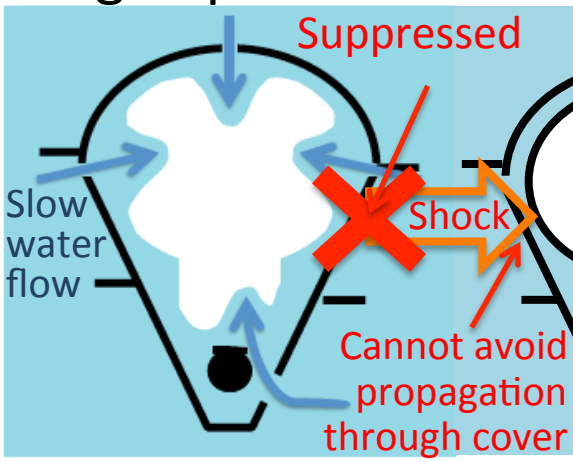
Bulb cracked



Unexpected implosion!

→ Cover pressurized, but strong enough to keep its shape

During implosion inside



Water flows in slowly

Large pressure shock-wave doesn't arise outside the cover

<u>Confirmation by 3 steps</u>

PMT pressurized test

(and screening during construction because of individual difference of glass quality)

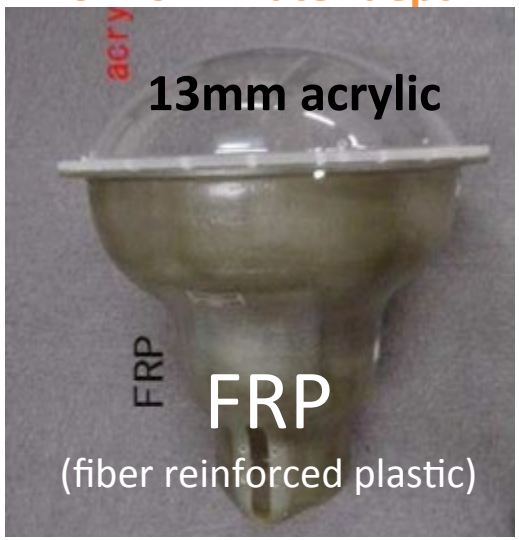
Hydrostatic pressure test of cover

PMT implosion test with cover

All tests were done this year.

Cover design

Super-K cover
for 40 m water depth



PMT fixed to SK tank

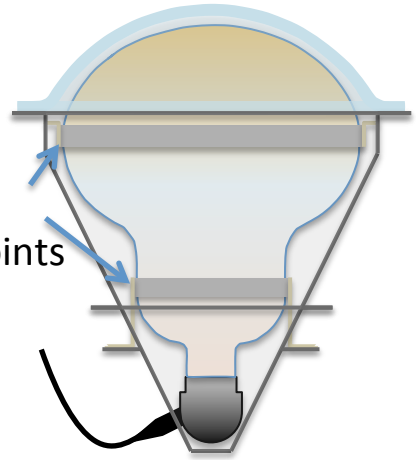
Initial prototype
for 60 m water depth

t = 11mm @ center
15mm @ flange

SK acrylic cover
t = 9mm @ center
13mm @ flange

Acrylic front : 6 kg
Stainless back : 23 kg

cf.
PMT : 8 kg
PMT buoyancy : -60 kg



- Establish at least one design for 60 m water tank
  - Optimized later

Hydrostatic pressure test

Cover pressurized test

A set of the cover packed in a plastic bag was pressurized from outside.

Tested two samples to 1.1MPa (=100 m water depth) and there were no damages.

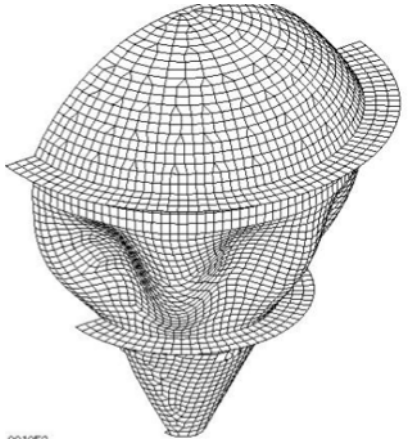
→ OK for 100 m water load

Confirmation of consistency with analysis

Tested more to validate the calculation.

Damaged as expected around 1.2-1.5 MPa, but not completely collapsed.
(This part can be reinforced in improved design.)

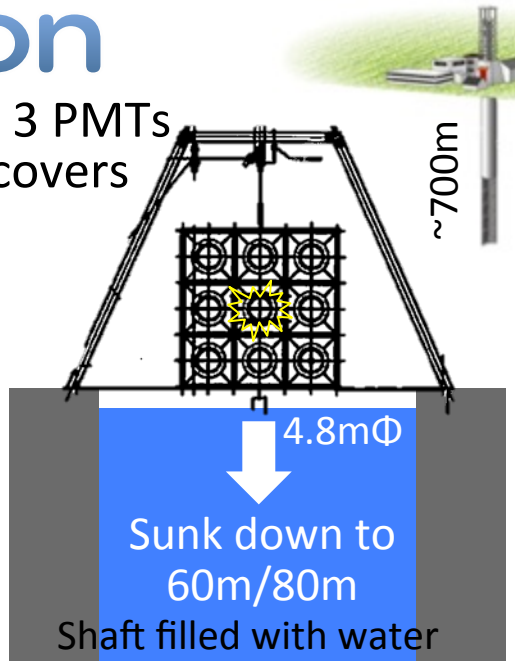
Buckling analysis



Cover validation

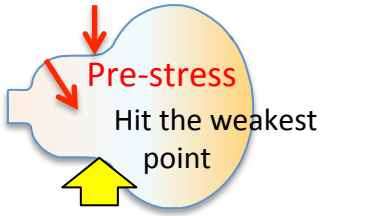
1st demonstration test was performed in Feb-Mar 2016.

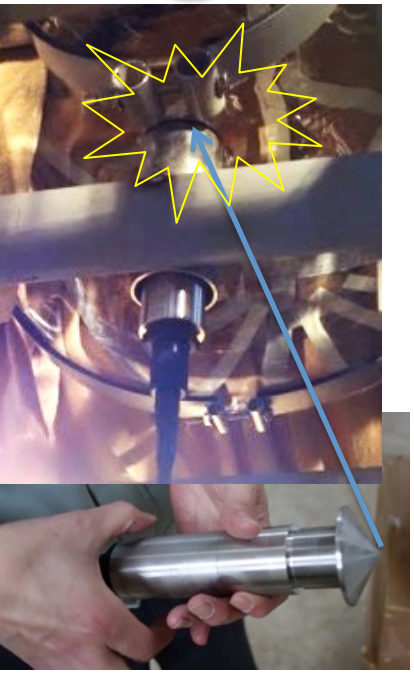
3 x 3 PMTs + covers



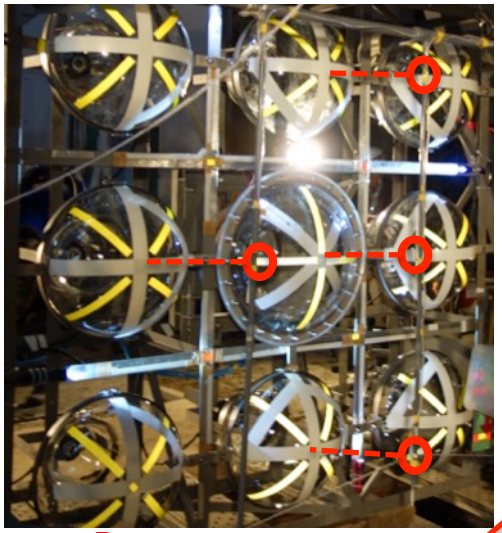
Procedure

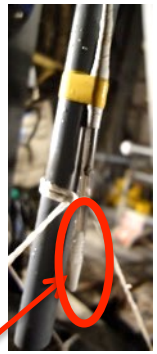
1. Center PMT is imploded by tool.
2. Confirm no damage of central PMT cover and surrounding PMTs with monitoring



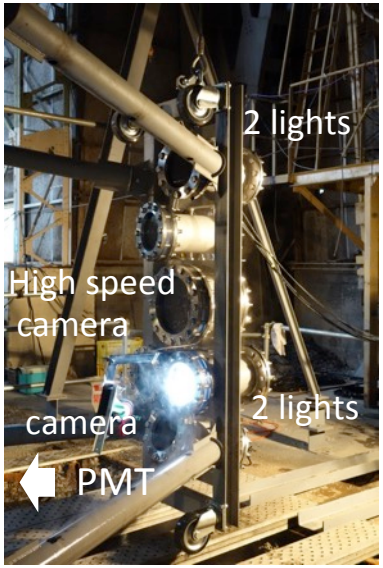


Shock wave monitor in water





Pressure gauge



Strain gauges

1st test in Feb-Mar 2016

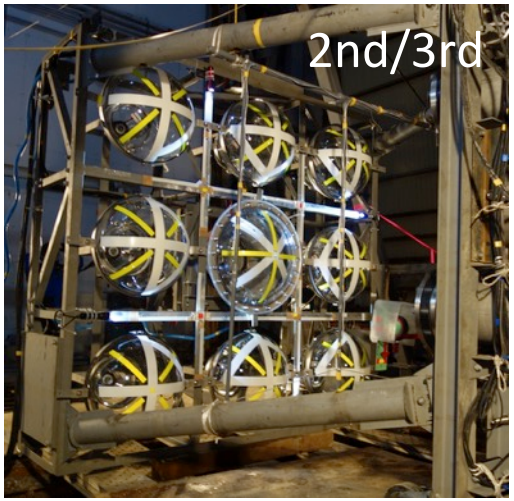
Procedure of implosion test

Reproduction of shock wave from implosion (w/o covers)

- Single implosion test (Only center PMT w/o cover) → OK
- Chain implosion of 9 PMTs w/o cover → OK

Test of shock wave prevention cover (w/ cover at center PMT)

- 60m depth with (15mm Acrylic + 3mm stainless steel cover) x 3
  - 1st Center PMT with cover → OK
  - 2nd & 3rd Center PMT with cover + surrounding 8 PMTs w/o cover → OK



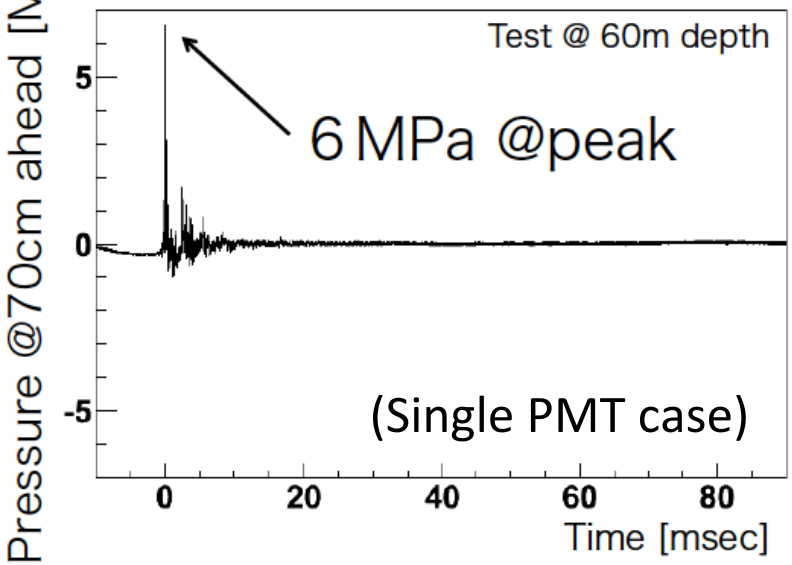
Confirmed that
1. reproduction of implosion
2. No damage on cover
3. Surrounding PMTs are safe

→ Cover was established.

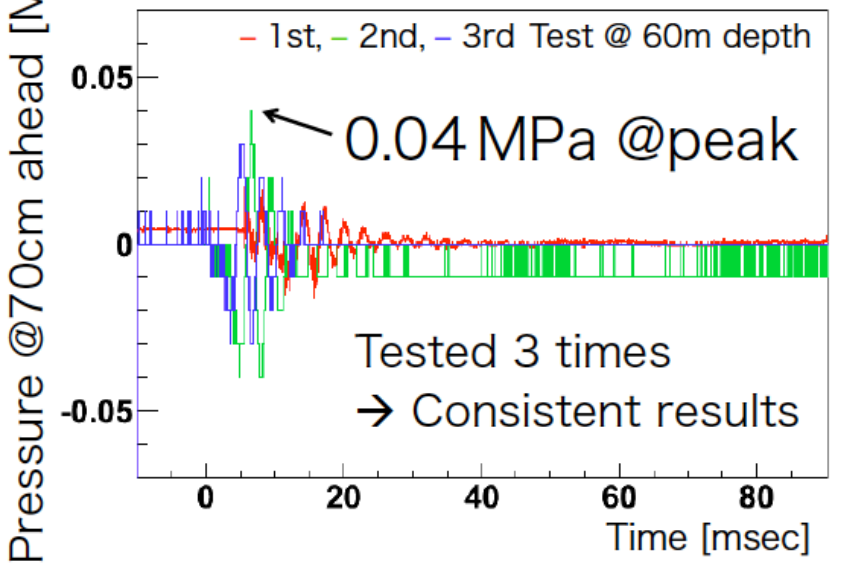
- Same set of 3 tests in 80m water → OK for all

Reduction of pressure pulse

Bare PMT implosion



Covered PMT implosion



- Large shockwave by successful implosion
- All neighboring PMTs broke in a chain

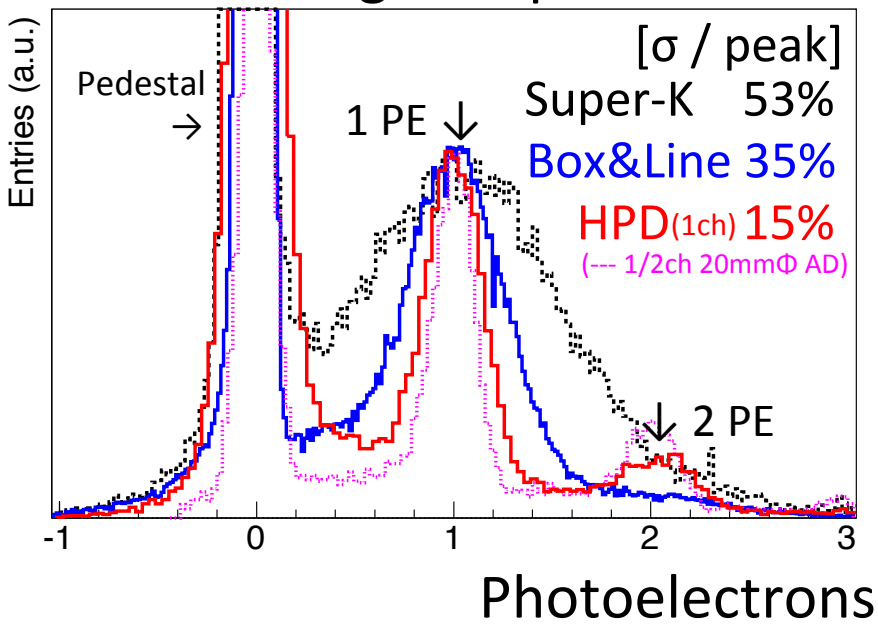
In both the 60m/80m tests

- Cover was not crushed.
- Pressure pulse outside was very weak.
  - Less than 1/100
- Neighboring bare PMTs all survived

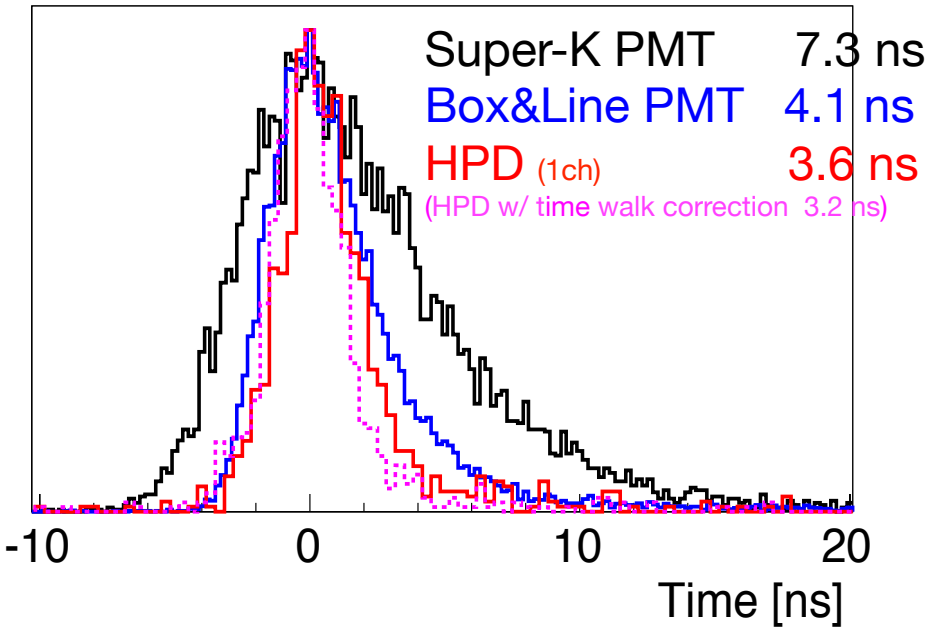
R&D of Hybrid Photo-Detector

- A large junction capacitance (800 pF) of 20 mmΦ avalanche diode (AD) is a difficulty to read a single PE.
- AD with reduced capacitance to 400 pF and fast low-noise preamplifier were successfully developed.

Single PE peak

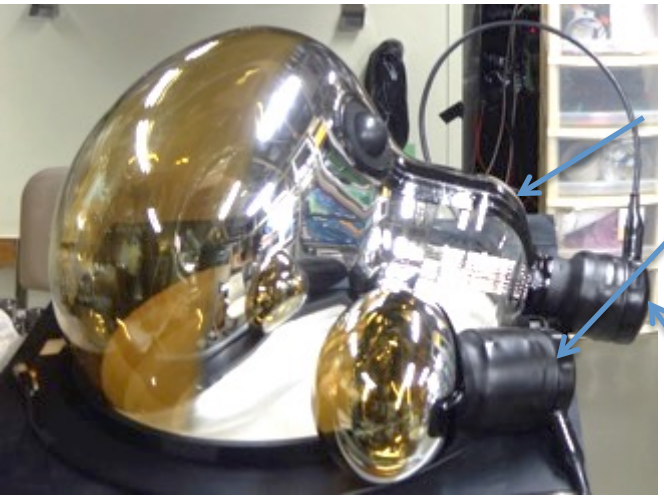


Single PE transit time spread FWHM



- Detection efficiency : ×1.8 higher than SK PMT, similar to Box&Line PMT, confirmed in measurement.
- Low after pulse less than 2%, much lower than Box&Line PMT

HPD test in water



Prototype of waterproof 50 cm high-QE HPD for proof test

(20 cm HPD already in tank)

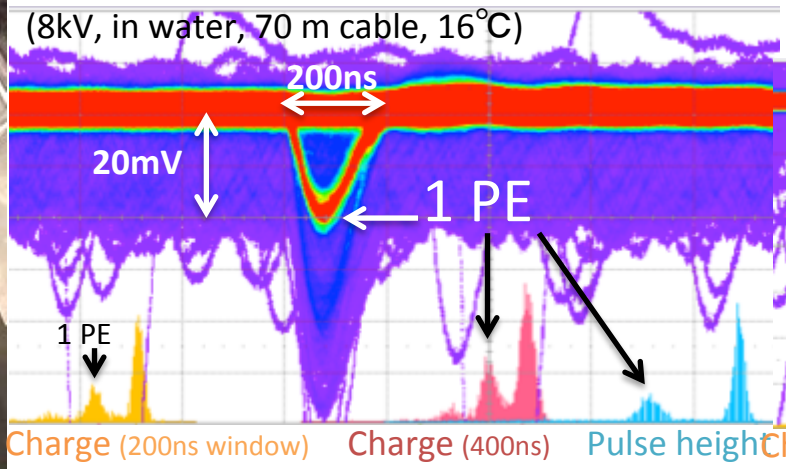
>1.4 MPa tolerance in 3 tested samples

Same waterproof design as Super-K PMT (will be improved for HK)

Measured in water for 20 days without any problem

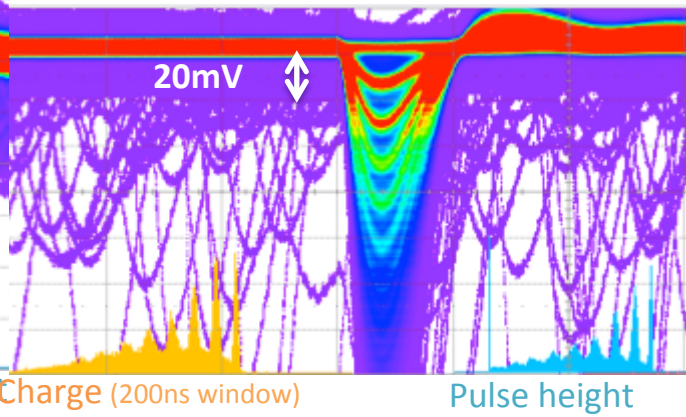
Clear 1 photo-electron (PE) signal

(8kV, in water, 70 m cable, 16℃)



+ 70m cable extension

Precise multi-PE counting



Aiming at proof test in the 200-ton tank

Activities in KamLAND-Zen

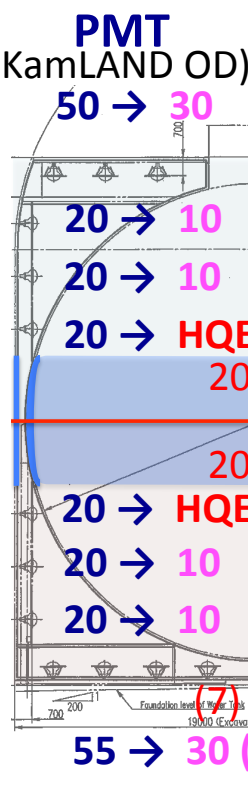
In Tohoku University

OD PMT replacement in KamLAND

47 of 50 cm "High-QE" Super-K PMTs were installed.

(Replaced Kamiokande R1449 PMT used so far)

5 High-QE Super-K PMTs are also under test
in EGADS 200 ton tank for HK since 2013.



Studies on light collection for KamLAND2-Zen

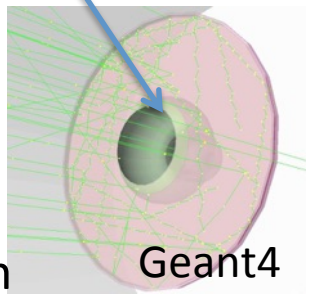
Winston cone for 20" PMT made of PET+Al
→ x1.8 enhancement
Study with simulation and measurement
Test of stability, background, etc.

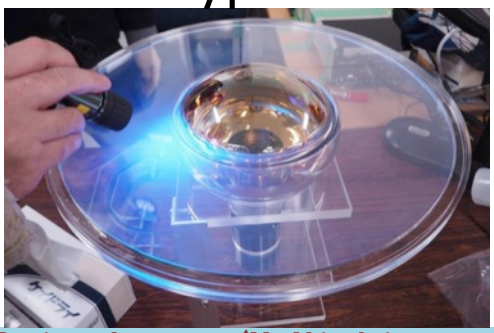
Wavelength shifting plate

8" R5912 PMT Prototype Polystyrene w/ POPOP for test

w/acrylic plate
and mirror in edge
for reflection

470mmΦ × D10mm





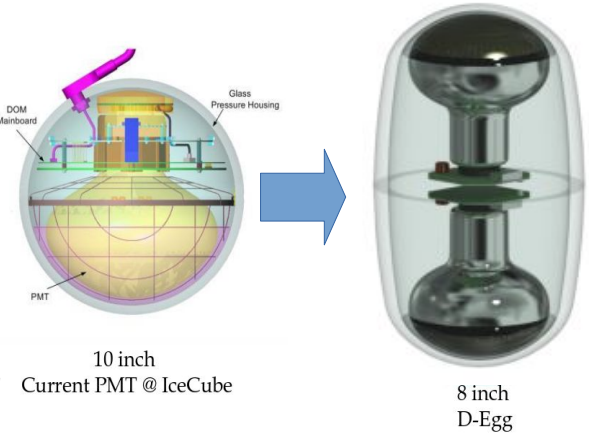
About 1.5 factor
in both measurement
and simulation

20 cm (8") PMT for IceCube-Gen2

D-Egg design for IceCube-Gen2

High-QE 20 cm R5912-100

(Also High-QE 20 cm HPD was measured)

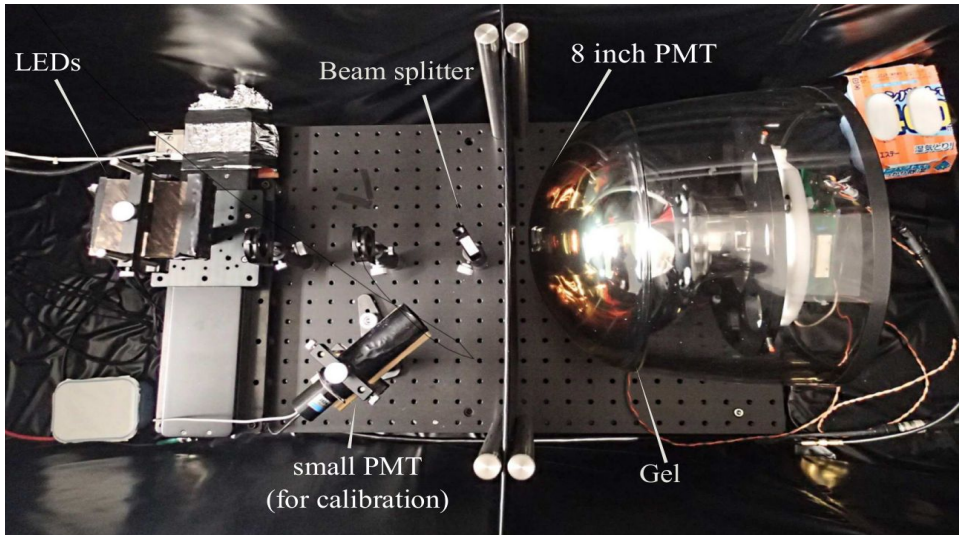


10 inch
Current PMT @ IceCube

8 inch
D-Egg

with better optical properties of glass and gel

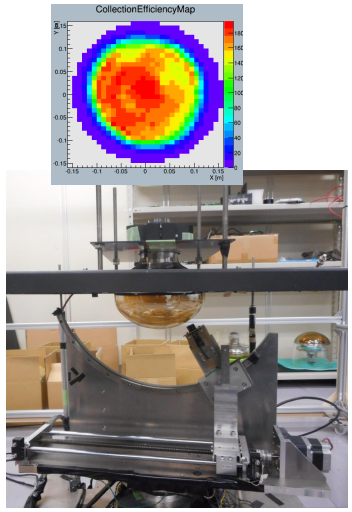
In Chiba University



Measured with new glass+optical gel+magnetic shield

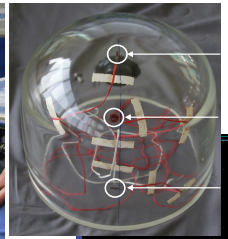
Cathode uniformity measurement

2mx2mx2m
Helmholtz coil

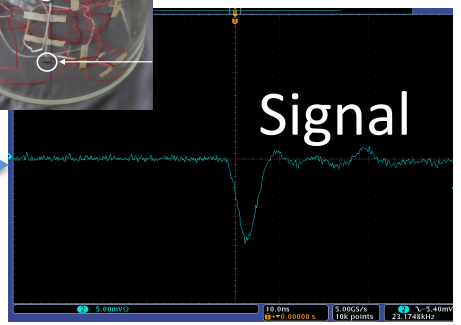


3rd test in high pressure at JAMSTEC, Kanagawa JP

(Japan Agency for Marine-Earth Science and Technology)



3 strain gauges
up to 70 MPa



Conclusion

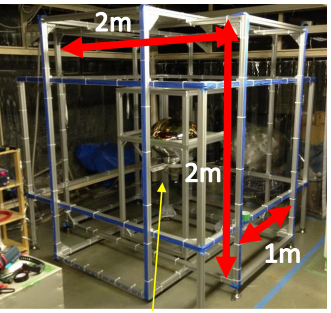
- Box&Line PMT was established for Hyper-K.
  - Bulb and cover can be used for 60 m water height.
    - Optimization of cover for light weight and low cost design ongoing
  - Planning demonstration test using ~100 PMTs
    - With good production quality

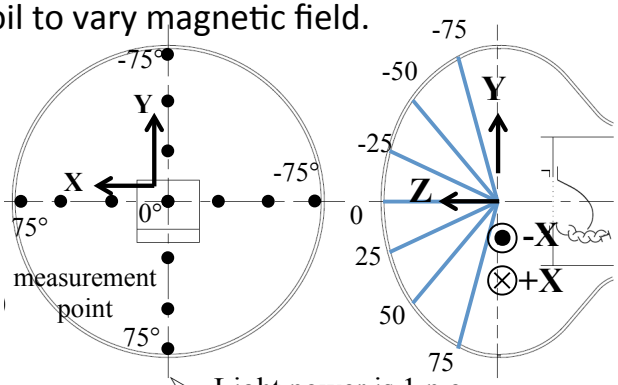
- HPD realized the better resolutions than 50 cm PMTs.
  - High efficiency, comparable with Box&Line PMT
  - Considering a possibility for Hyper-K by end of 2017
    - R&D for practical use is required (proof test, etc.)

Response Uniformity of Box&Line PMT

Presented in NNN15

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

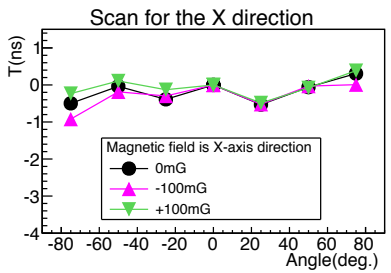


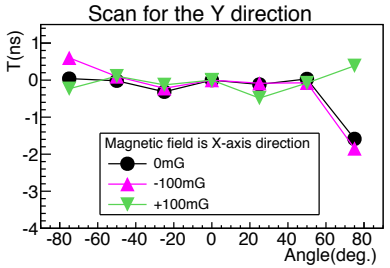


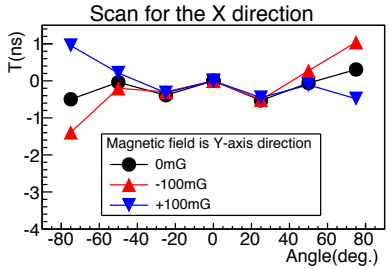
- Light power is 1 p.e.
- HV is 2000V

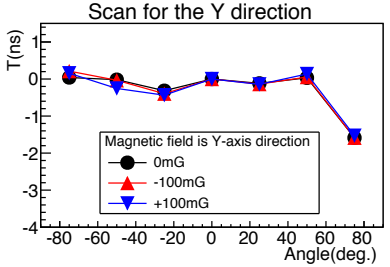
±100 mG is maximal residual range in HK.

Uniformity of relative transit time

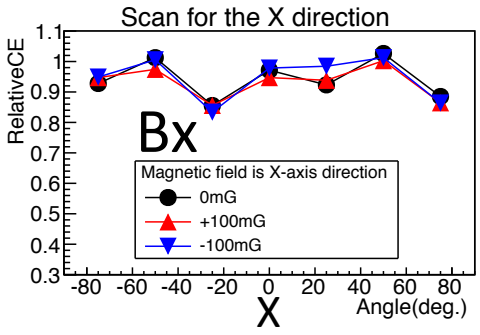


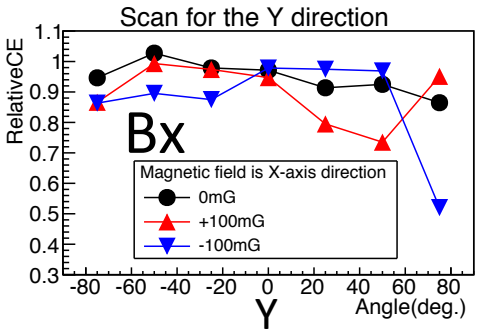


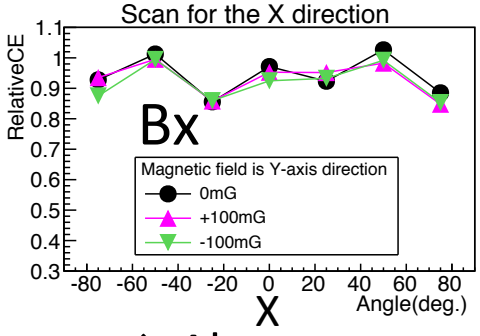


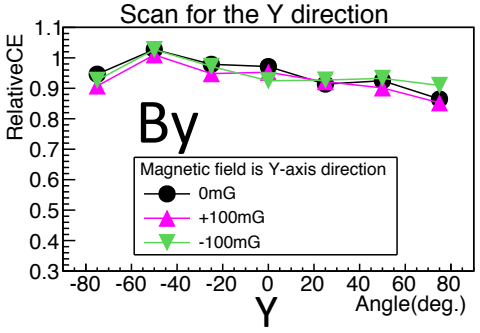


Uniformity of relative collection efficiency



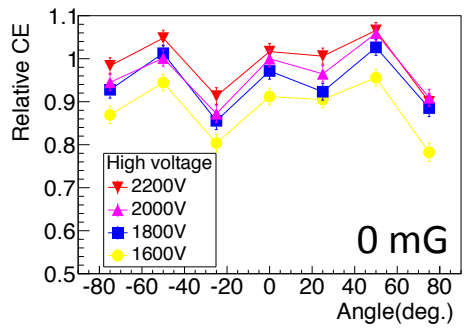


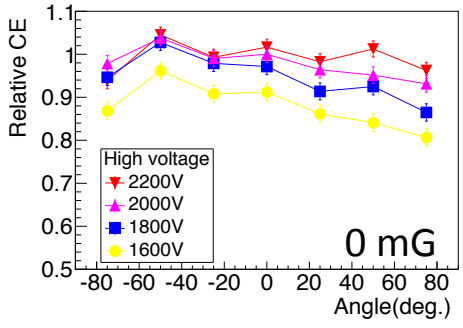




→ Almost constant in ± 100 mG range

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

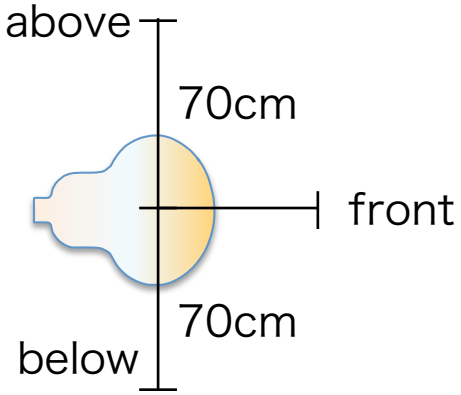


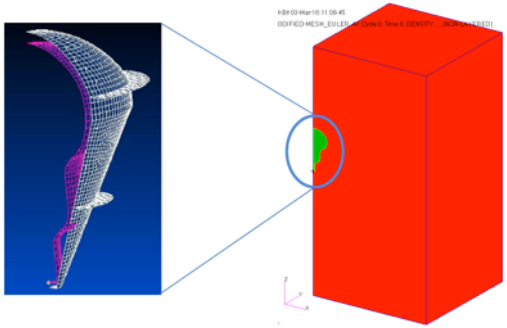


Comparison to implosion simulation

- Measured peak pressures agree with expectation by a dynamic behavior simulation in the first order.

unit : MPa	no cover		with cover	
	data (above/bottom)	calc	data (front)	calc
60m	11.0/6.0	9.3	0.03	0.2
80m	18.2/6.3	9.7	0.03	0.1





- Roughly consistent even in simple model without considering non-uniform acrylic thickness, glass collapse, effect of gravity/ buoyance, water flow through holes, …

Simulation can be utilized for cover design.

- More optimization for further improvement is being tried.
  - Light weight with thin thickness, another material such as a full resin cover, reinforcing, PMT supporting structure, …
  - Design based on simulation, and validation test finally