Photodetectors for Hyper-Kamiokande

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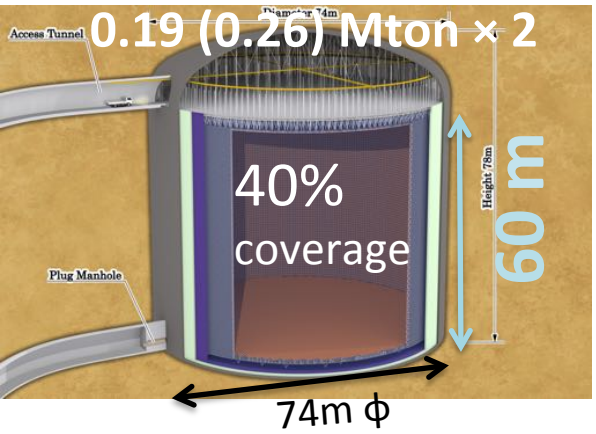
7th Open Meeting for the Hyper-Kamiokande @ QMUL, London UK

2016. Jul. 11 (Mon)

Photodetectors for Hyper-K

- *Photodetectors are essential to determine HK performance & design.*

Hyper-Kamiokande (HK) + **New high-QE 50 cm Box&Line PMT**



0.19 (0.26) Mton × 2

×2 tanks (staging)

×2 high efficiency
and half time&charge resolutions

×2 high pressure bearing

Compared to Super-K PMT (original baseline)

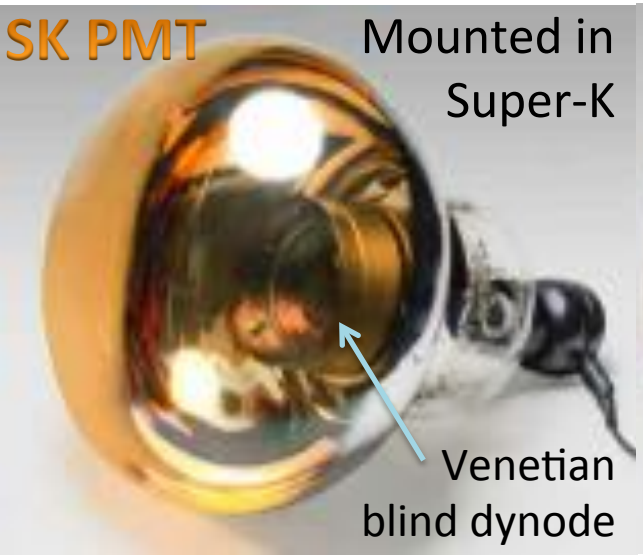
Optimal design with deep 60 m tank is enabled by much photon statistics and less background

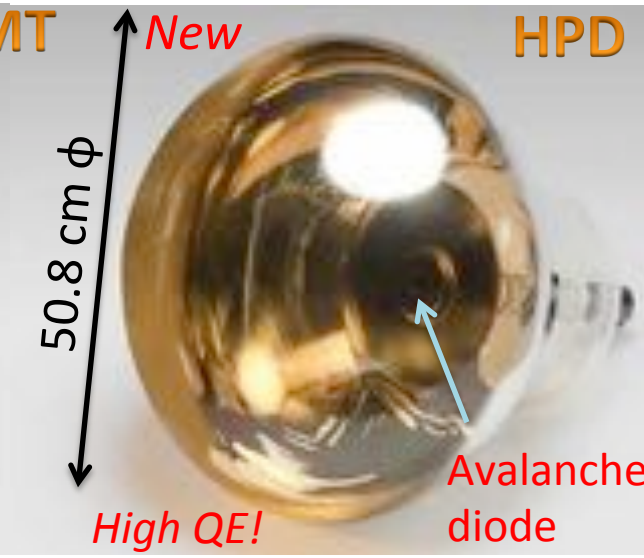
50 cm photodetectors for ID : 40,000 × 2
20 cm photodetectors for OD : 6,700 × 2

66,000 for 2 tanks in previous
(6 years for production)

- Staging construction allows more R&D time to improve photodetector.
- More improvements on HK are still expected by photodetector R&D.
- Oversea contribution is necessary for construction with full coverage.

New 50 cm Photodetectors





Model	R3600 (Established)	R12860HQE	R12850HQE
Amplification	Venetian blind dynode	Box and line dynode	20mmΦ Avalanche diode
Q.E.	~22% (or ~30% in HQE)	~30%	~30%
C.E. Φ46 (Φ50)	67% (61%)	95% (85%)	93% (76%) w/ 5ch AD† still in R&D
1PE Time	5.5 ns (FWHM)	2.7 ns (FWHM)	0.75ns (w/o Preamp., FWHM)
1PE Charge	50% σ	30% σ	15% σ (expect)
Bias voltage	2 kV bias	2 kV bias	8 kV bias + AD bias (<1kV)
	Impossible for 60 m water	Positive improvement and conservative, completed.	Challenging but excellent performance, low cost expected, being ready.

History of Photodetector R&D

50 cm PMT

Venetian blind

First 50 cm PMT
Hamamatsu R1449
for Kamiokande
→ IEEE milestone

began developing in 1979

Improved CE
R3600
for Super-K

R&D started since 2011 for Hyper-K
improved during R&D

High-QE
R3600-HQE

50 cm Box&Line PMT (Current baseline)

Box&Line

R7250 for KamLAND
(42 cm active area)
Good resolution, worse CE and afterpulse

R12860-HQE

- Dark rate & after pulse were reduced with dynode optimization.
- Bulb shape improved for high pressure
- Waterproof housing was reinforced.

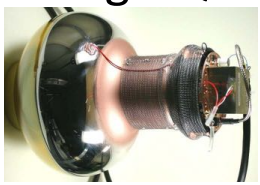
HPD

20 cm HPD

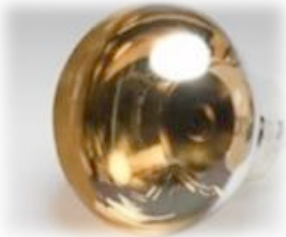
R12112

First waterproof

R12112-HQE
High QE



R12850-HQE



Elec. R&D is hard, performance is now limited by preamp.

- Segmented avalanche diode (AD) to 2 or 5 channels
- Half capacitance of AD

50 cm HPD (Alternatives)

Possible short ver. of 50 cm HPD concept (in future)

Suitable for high pressure sphere vessel

(Similarity to 1st 20cm HPD)

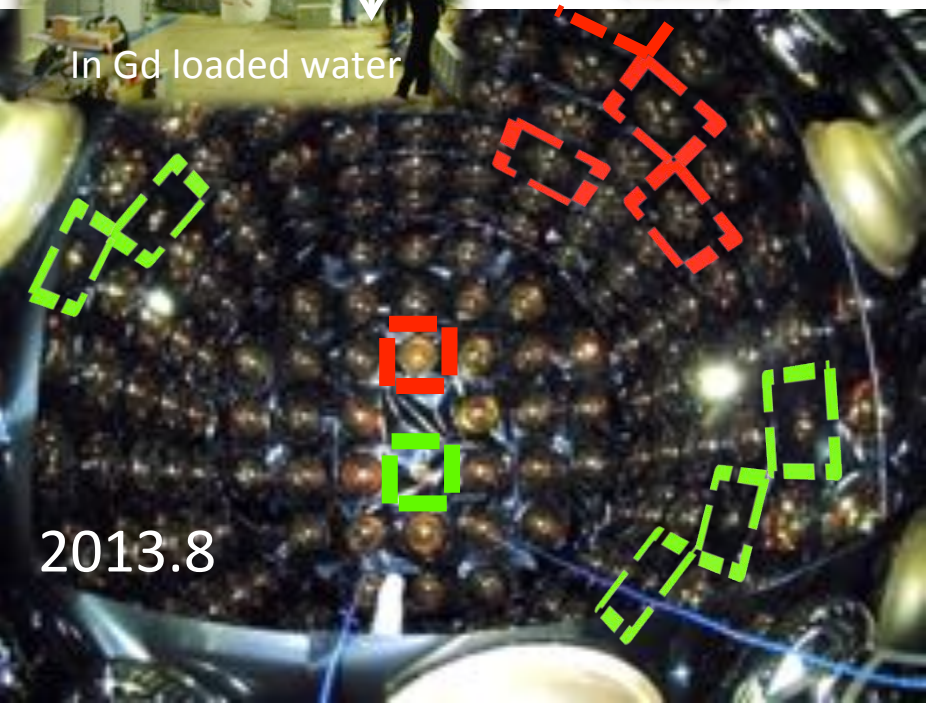
Proof Test in Water

2013 → 2014 → 2015 → 2016

+ 5 HQE Super-K PMT
+ 8 HPD (20cmΦ)

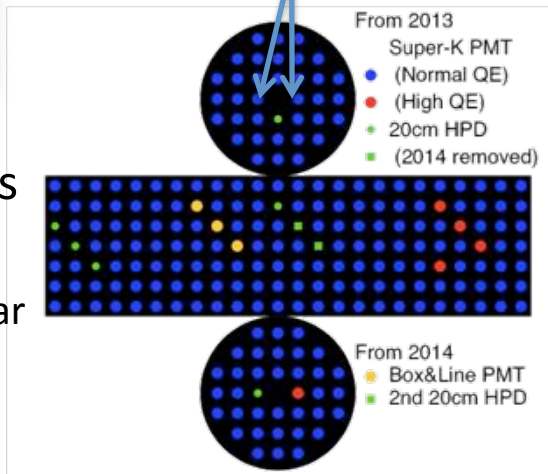
+ 2 HPD (replaced)
+ 3 HQE Box&Line PMT (50cm Φ)

(+ 2 50 cm HQE HPDs)



In total,
240 photodetectors

Monitoring stability of performance over a year



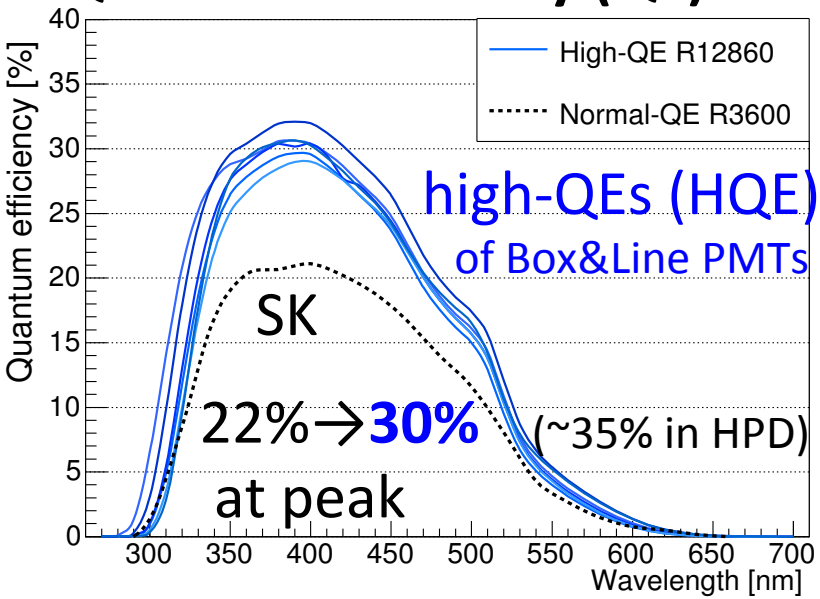
To be known :

Stability in acceptable level with calibration,
Performance as water Cherenkov detector,
Validation with finding unexpected failures,..

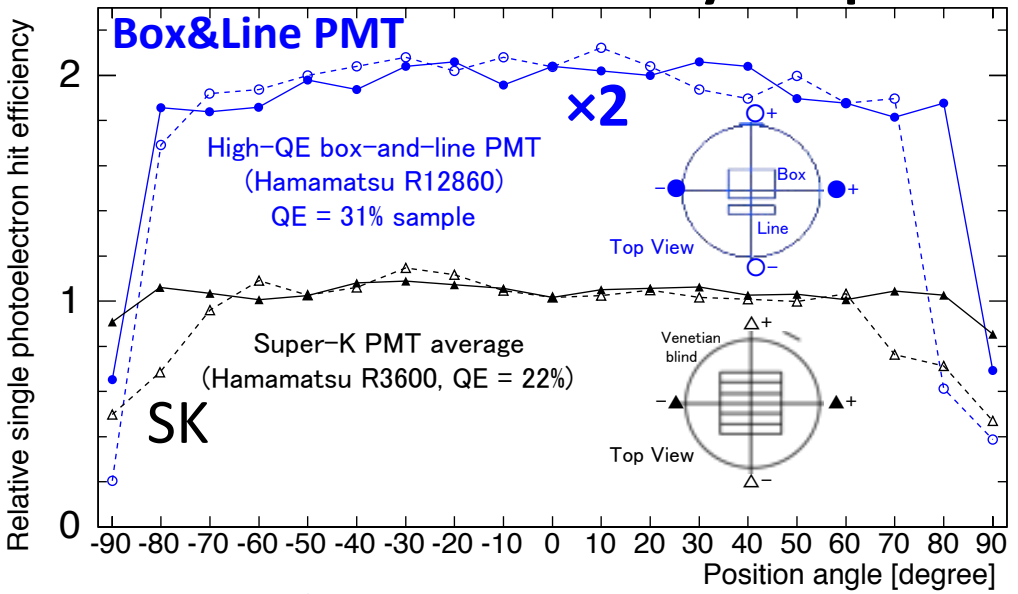
After new techniques are validated, next Hyper-K prototype test using about hundred photodetectors is planned in one or two years for start.

High Detection Efficiency

Quantum Efficiency (QE)



Total Detection Efficiency of 1pe



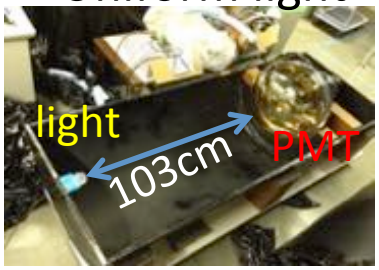
Measured at Hamamatsu by point source injection↑

We confirmed relative detection efficiency among various photodetectors by comparing 1 PE counting.

An HPD also indicates high efficiency (x1.8)

a little low due to higher threshold (not 1/4 but 1/2 p.e.), dead region of 2ch and edge drop of CE → To be improved

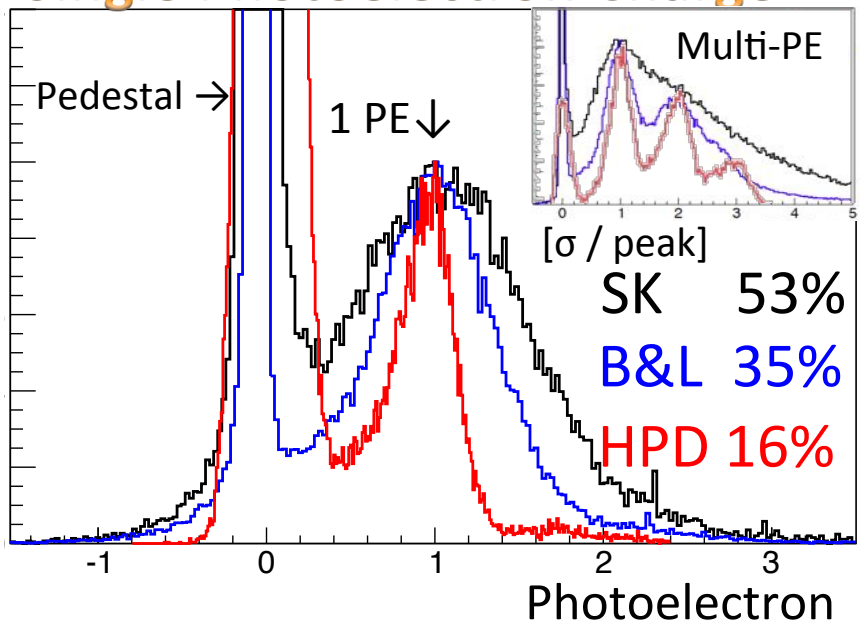
Uniform light



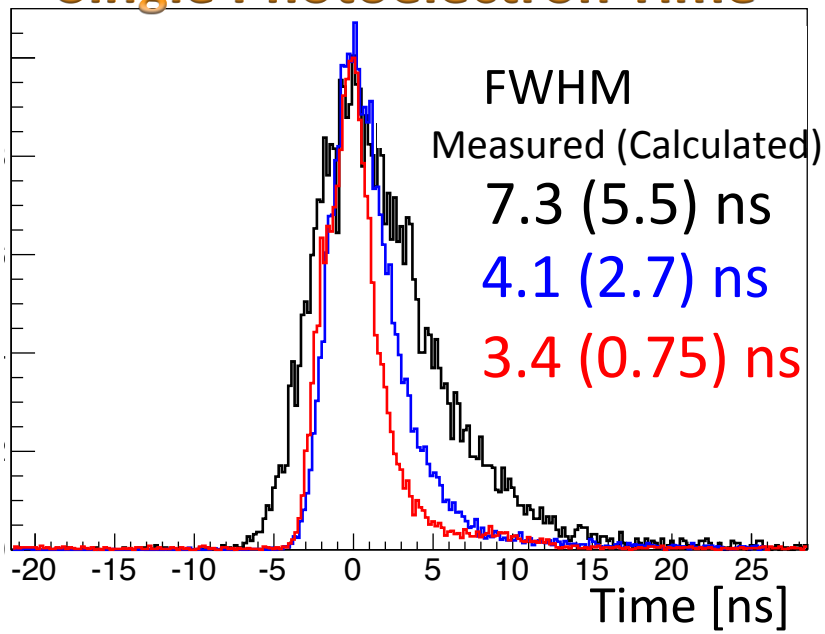
4 high-QE (HQE) samples	QE [%]	Relative total eff
SK PMT	N/A	1
HQE SK PMT	34.8	1.59
HQE BL PMT 1	30.7	**1.96**
HQE BL PMT 2	29.2	**1.85**
2ch HQE HPD	35.8	**1.76**

Single Photon Detection

Single Photoelectron Charge



Single Photoelectron Time



50 cm sensors	Charge σ / peak	Time σ (left)	Time FWHM
Super-K PMT	**53%**	**2.1 ns**	**7.3 ns**
Box&Line PMT	**35%**	**1.1 ns**	**4.1 ns**
HPD (5mmΦ AD)	**16%**	**1.4 ns**	**3.4 ns**
HPD (20mmΦ AD) *new!*	(10%)	(1.6 ns)	(3.8 ns)

AD = Avalanche Diode
5 mmΦ with low CE
is plotted here.

Recent R&D with full CE
using 20 mm Φ AD
indicates the best value.

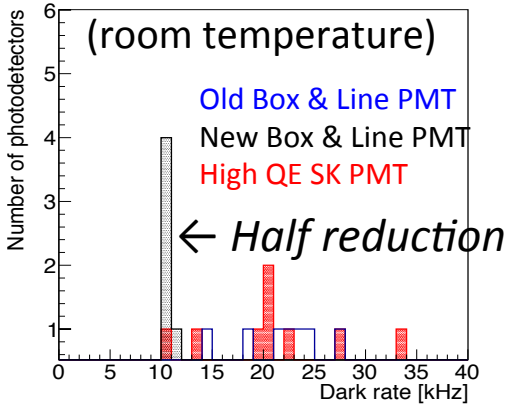
← Current record

HPD performance was still limited by preamplifier. (intrinsic resolution is less than 1 ns at FWHM)

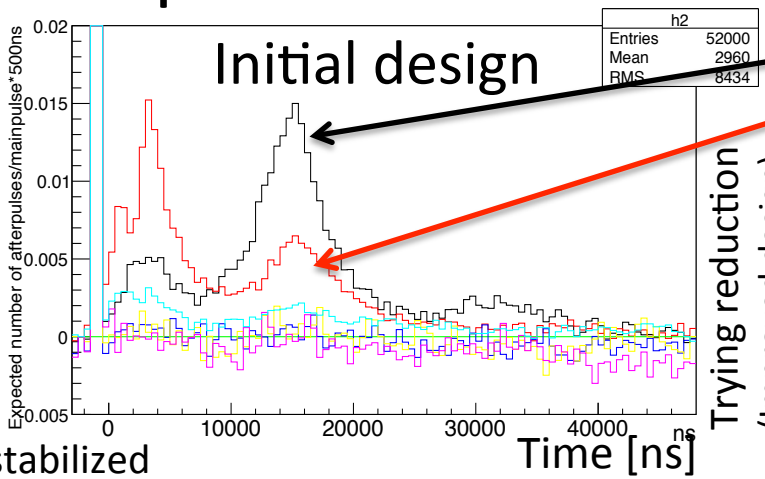
High-QE Box&Line PMT for HK

- Noise reduction from initial version

Dark rate in air



After pulse time



(Expected number of after pulses) / main pulse

PMT serial (HV)	Ratio
ZB8210(1770V)	0.31
EA0037(2050V)	0.26
EA0045(1650V)	0.02
EA0046(1800V)	-0.01
EA0047(1705V)	-0.01
EA0052(1700V)	-0.04
EA0053(1725V)	0.09

To be confirmed in water after stabilized

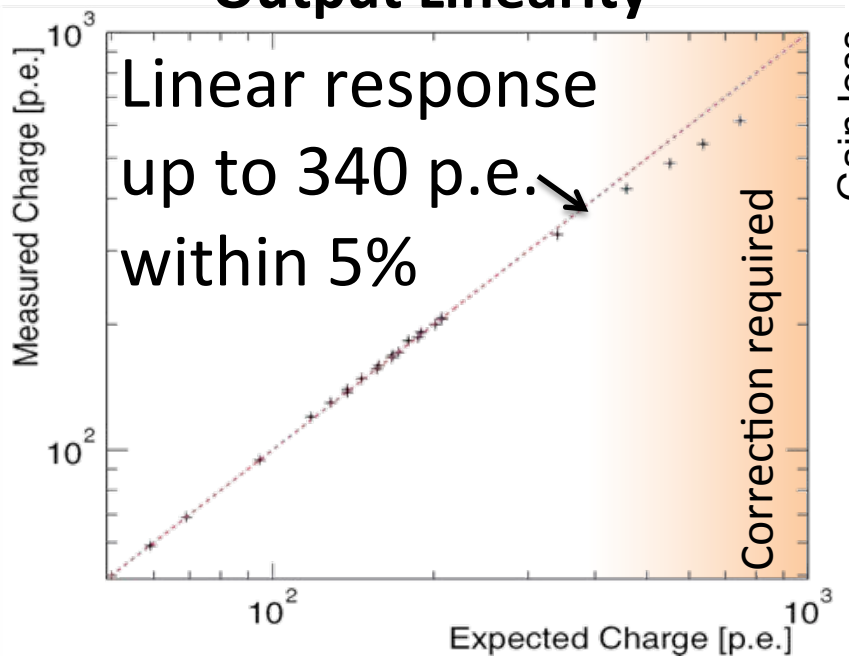
Reached in a few percentages

  - Still trying to reach much lower level.
- All related performance was measured in detail and confirmed to be sufficient for Hyper-K.
- Mechanical strength was confirmed in tests.
  - Cover design was also validated with implosion test.
- Box&Line PMT design is ready for Hyper-K.

Performance in wide range

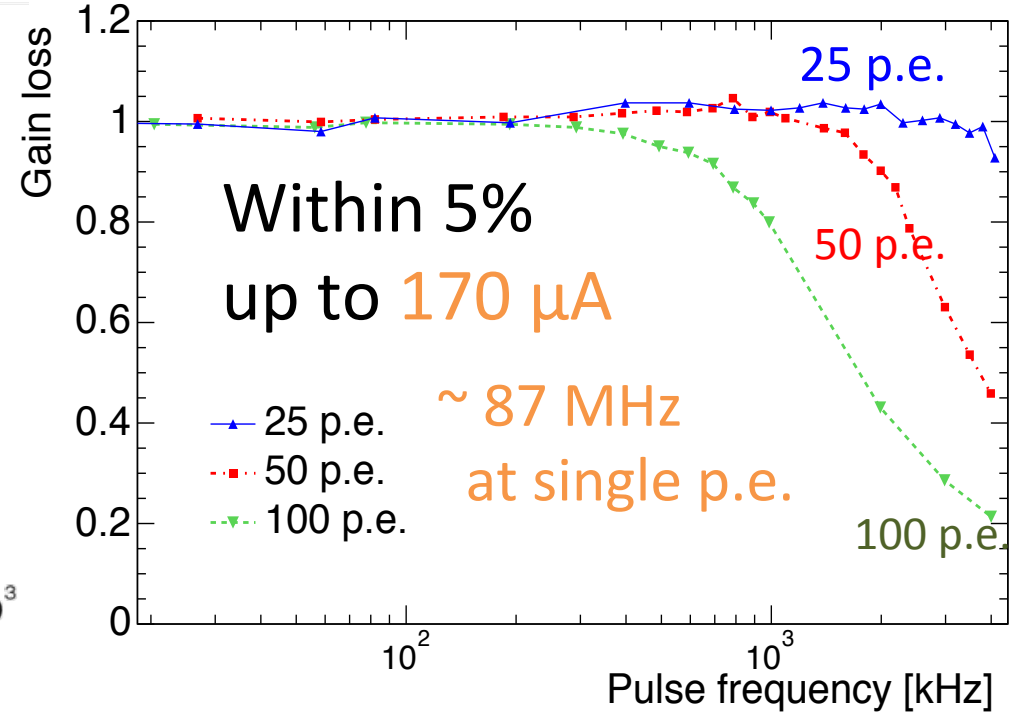
High-QE Box&Line PMT

Output Linearity



No saturation in expected range by HK

High Rate Tolerance



Sufficient for supernova detection (10MHz at max.)
(Okay for HPD also)

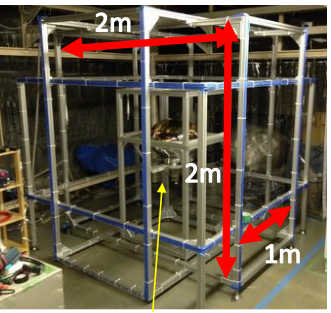
- Sufficient capability of detection in various range.

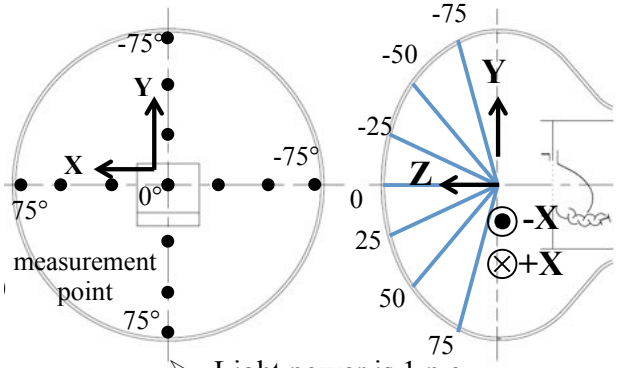
Performance in HK environment

Uniformity of relative collection efficiency

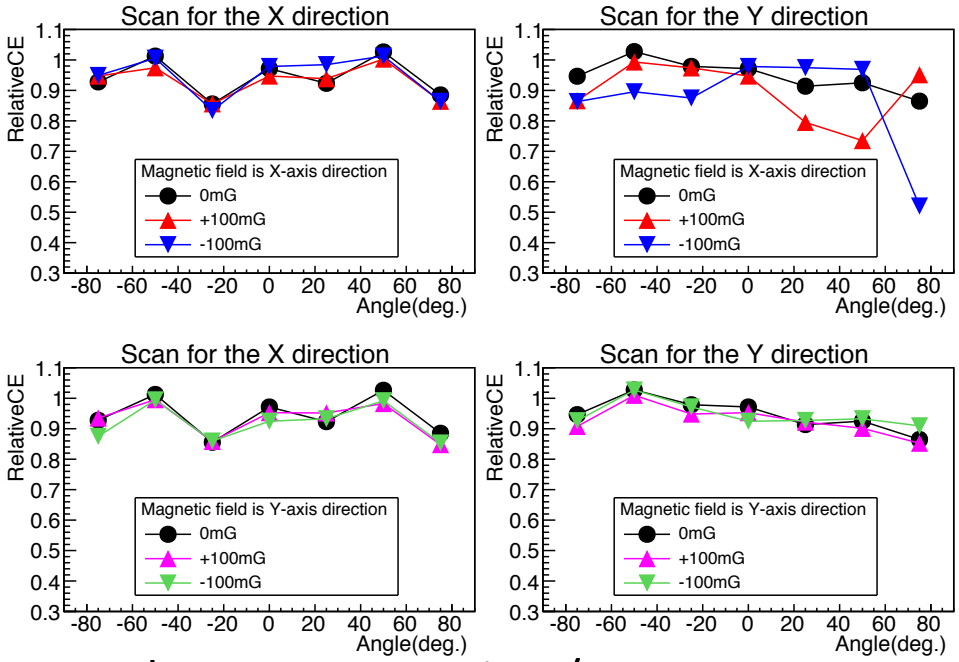
in expected range of residual geomagnetism

measured in the coil



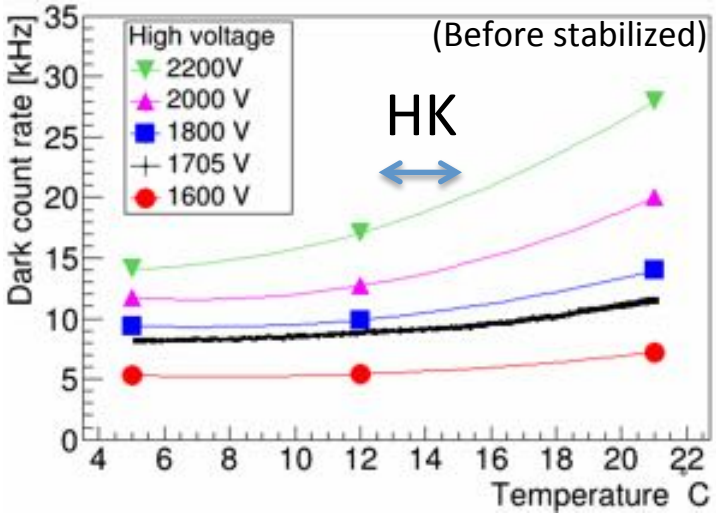


- Light power is 1 p.e.
- HV is 2000V



Almost constant in +/- 100mG range

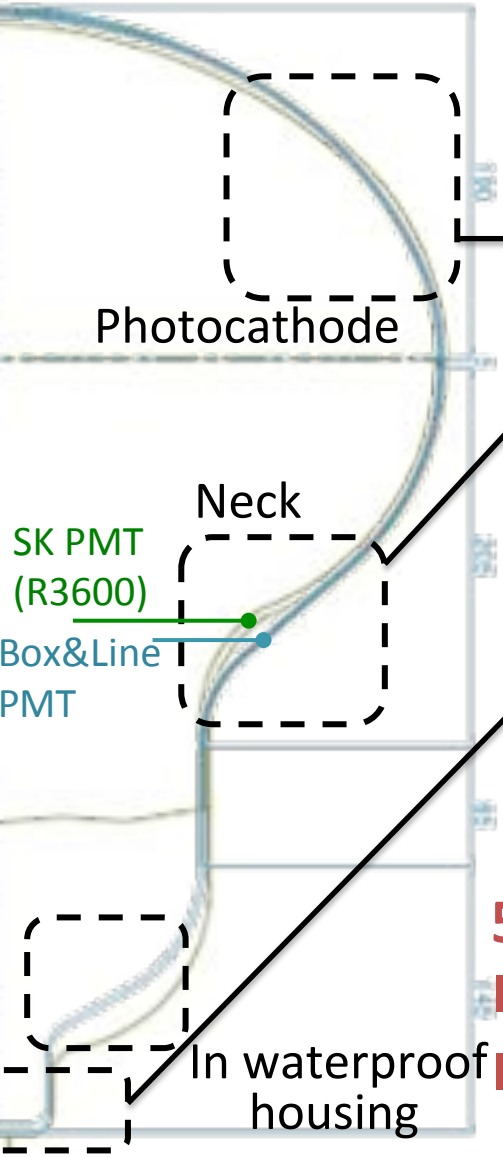
Dark rate by temperature and HV



Response by position such as CE, transit time and gain was confirmed to be uniform as expected.

- Capable of using in HK tank

Improvements on Mechanical Strength



The bulb shape is 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 by automated tool.
- Tough waterproof housing

Hard & round design to protect the weakest point

Soft PE (polyethylene)

Hard PPS (Poly Phenylene Sulfide Resin)

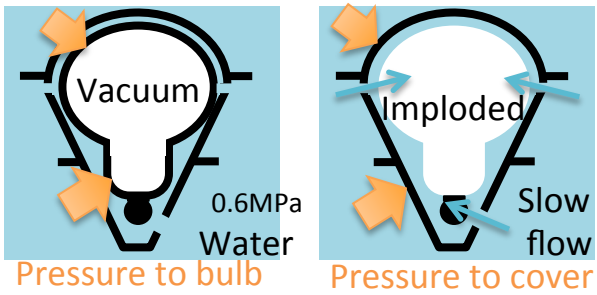
50 Box&Line PMTs were tested up to 1.25 MPa (125m).

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

50 cm Photodetector Cover

Cover was newly designed for a use in HK 60 m water depth.

Cover should be enough tough to avoid shock wave to outside by implosion



Cover pressurized

OK for 100 m water load

SK cover
(FRP + acrylic)

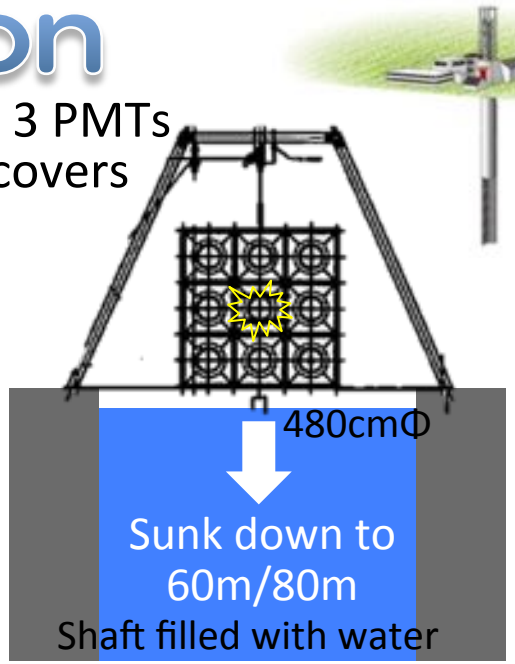
Initial prototype
(for implosion test)

Stainless steel (3mm)

- Test of cover with PMT with implosion was done in Mar.2016

Cover validation

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



Procedure

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

Reproduction of implosion

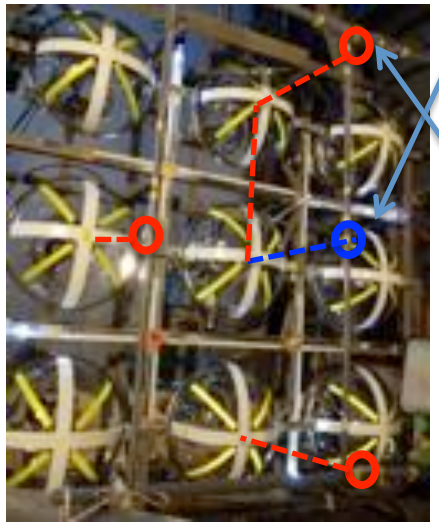
- Single implosion test (Only center PMT w/o cover) → OK
- Chain implosion of 9 PMTs w/o cover → OK

Test of shock wave prevention cover

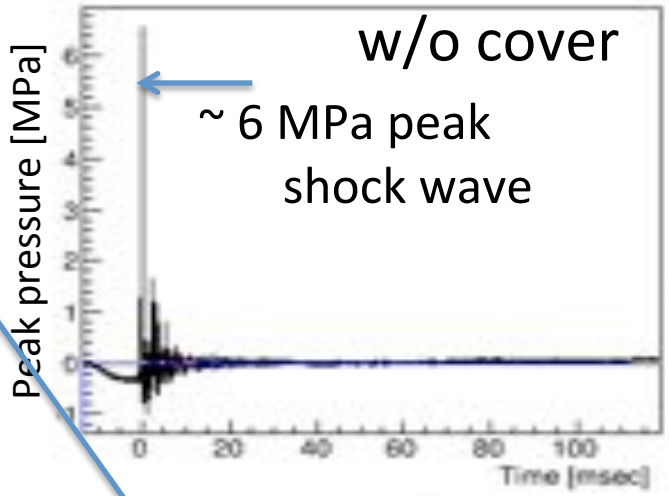
- 60m depth with (15mm Acrylic + 3mm stainless steel cover) x 3
  - 1st Cover only with center PMT → OK
  - 2nd & 3rd Cover with center PMT + surrounding 8 PMTs w/o cover → OK
- Same set of 3 tests in 80m water → OK for all

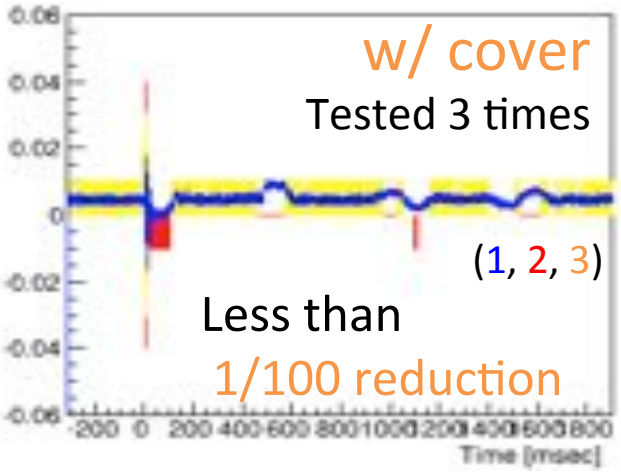
Validation of Cover

Pressure gauge

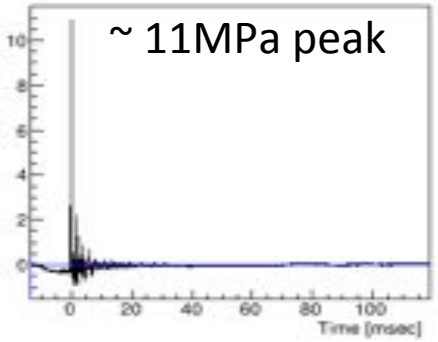


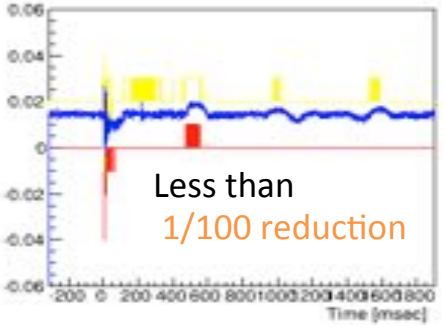
Front of imploded PMT (Pressure monitor at 70 cm front)





Upper side





- One of cover design was established, also for 80 m.
- Light and cheap design is desired.
  - Next test with improved design is planned. (made of resin material, etc.)
  - Innovative design w/ optimum shape and/or material is welcome!

Test of Single Ch HPD in Water

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

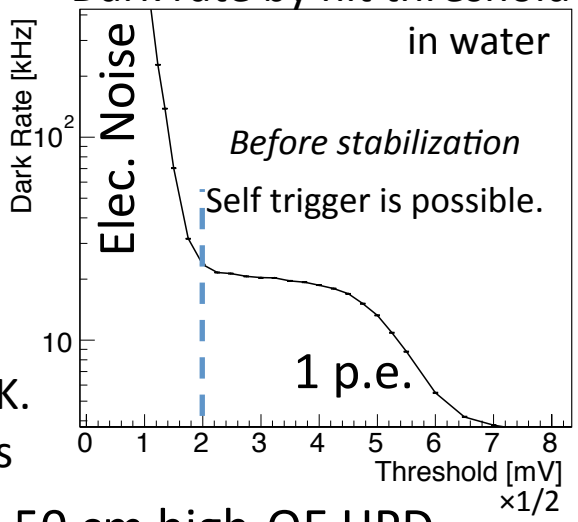
(20 cm HPD already in tank)

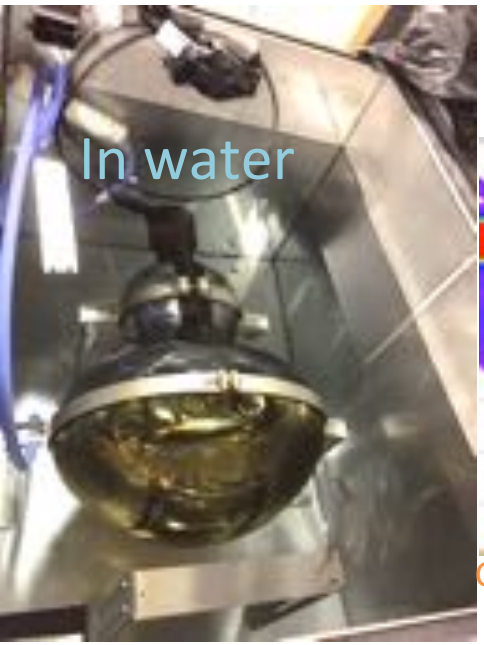
Preamp & HV power supply (10V->8kV) are equipped.

Waterproof design based on SK PMT will be improved for HK.

>1.4 MPa tolerance in 3 samples

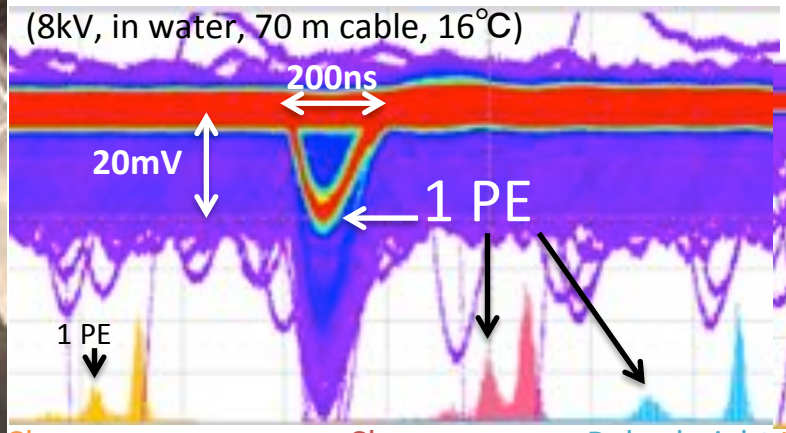
Dark rate by hit threshold in water



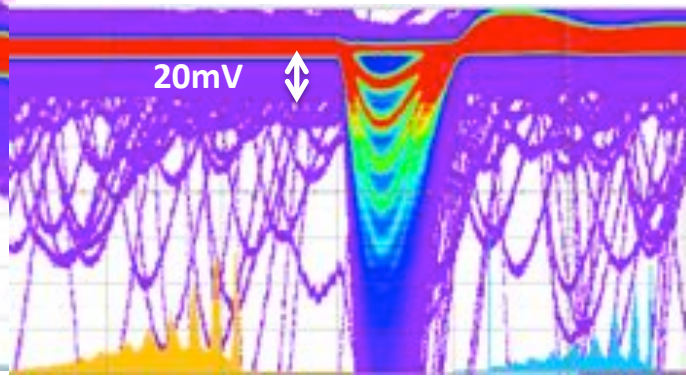


Measured in water using single channel 50 cm high-QE HPD + 70m cable extension

Clear 1 photo-electron (PE) signal



Precise multi-PE counting

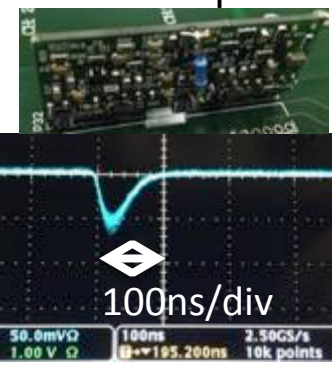


Under safety test for 1st proof test in the 200-ton tank

R&D for 50 cm HPD

- 1st waterproof HPD is ready for proof test.
  - Timing performance could be improved with fast amp R&D.
  - Design for cost reduction (including electronics) is desired.
- Many R&Ds required.
  - Electronics is essential to achieve the best performance.

Preamp

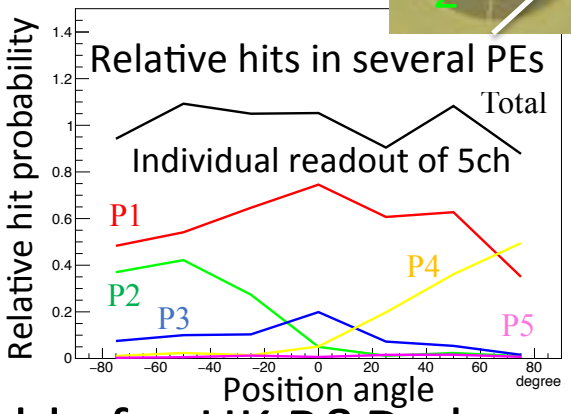


Test w/ Italy group

Built-in 8kV power supply
By 3 manufacturers

8kV & signal connector
in 100m water

Possibility of
position sensitivity



Built-in
digitizer

and many tests..

- AD and 50 cm HPD could be available for HK R&D abroad in a year.
- Welcome to join in HPD R&D

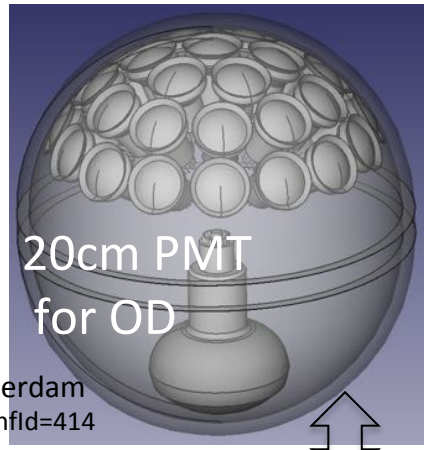
Multi-PMT for Hyper-K

- Multi-channel optical module
  - Explore possibility of cost reduction, better high-pressure resistance, directional sensitivity, …
  - Implemented in simulation ongoing to study HK performance

(Concept design)

Based on KM3NET optical module

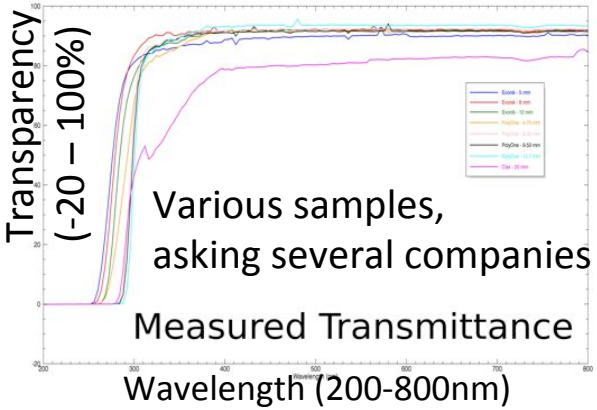
7.7cm PMTx33



MoU for sharing knowledge

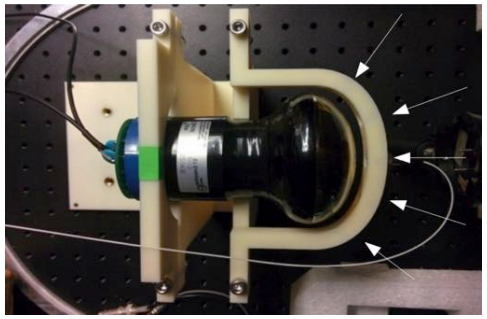
Workshop from 14 to 15 July at Nikhef, Amsterdam
https://indico.nikhef.nl/conferenceDisplay.py?confId=414

Acrylic for vessel



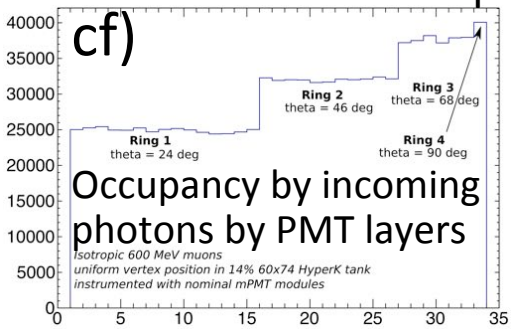
Optical and mechanical characteristics being measured

PMT Test



Measuring response by position, dark rate, … with R12199-02(Hamamatsu), 9320KB (ETEL), …

Simulation



Occupancy by incoming photons by PMT layers

For optimization and physics sensitivity study

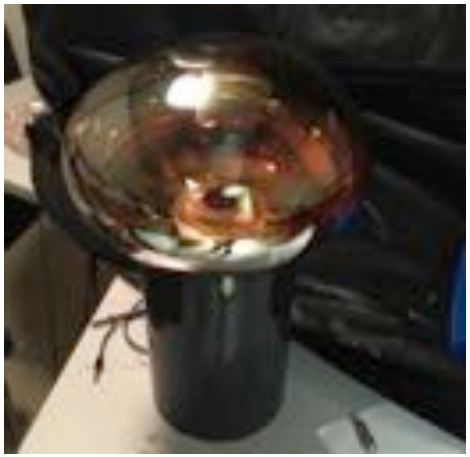
Top cf)

Many common R&D items with short bulb HPD

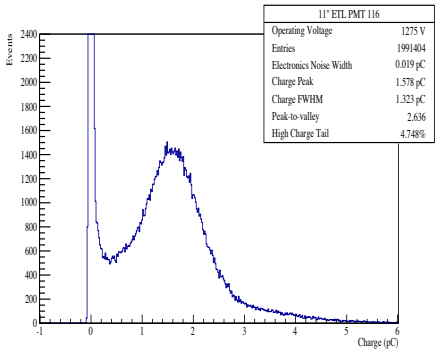
Active international works!

Photodetector for HK OD

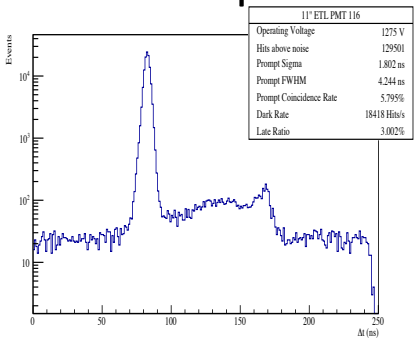
- 20 cm PMT + wavelength shifting plate (Same as in SK)
  - Several ideas on improvement are being considered.
- Test of high-QE 20cm PMT (Hamamatsu R5912-100)
  - Uniformity measurement at TRIUMF, Canada
  - Preparing setup for various tests in Padova, Italy
- New HQE 11”(28cm) PMTs from ET Enterprises
  - Competition with Hamamatsu small PMTs (8-12 inches)



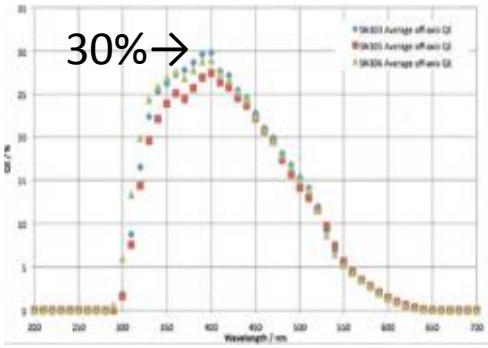
1PE charge



1PE time peak and late pulse



High-QE spectra



- Better photon enhancement is to be considered.

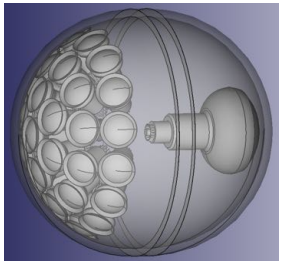
Photodetector Working Group

- 55 worldwide members
  Active R&D but need more

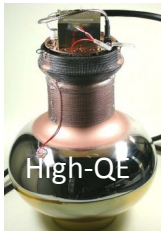
New photo-sensor development

50cm photosensors (HAMAMATSU)

Multi-PMT



20cm HPD

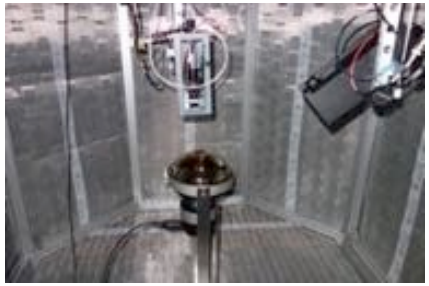


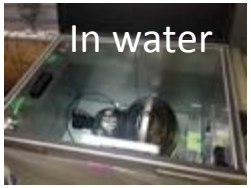
28cm PMT (ETEL/ADIT, US)

Safety design & test

Characterization

Response property measured at TRIUMF





HPD and mPMT development are required in short period.
Any interest and contribution are welcome.
Many items such as cover, preamp. of HPD, outer sensor are essential.

Summary

- High-QE Box&Line PMT : Current baseline
  - Allow optimal tank design with 60 m water depth
  - Established for use in 60 m / 80 m water with cover
- Photodetector is essential to determine Hyper-K design and physics reach
  - Further improvements are expected.
    - HPD for low cost, low noise and high resolutions
    - Study for possible improvements by multi-PMT in HK
  - International contribution is necessary to get full photo-coverage as proposed and to improve Hyper-K as much as possible.
    - mPMT, HPD, Cover, OD sensor, test in water, safety validation, etc.

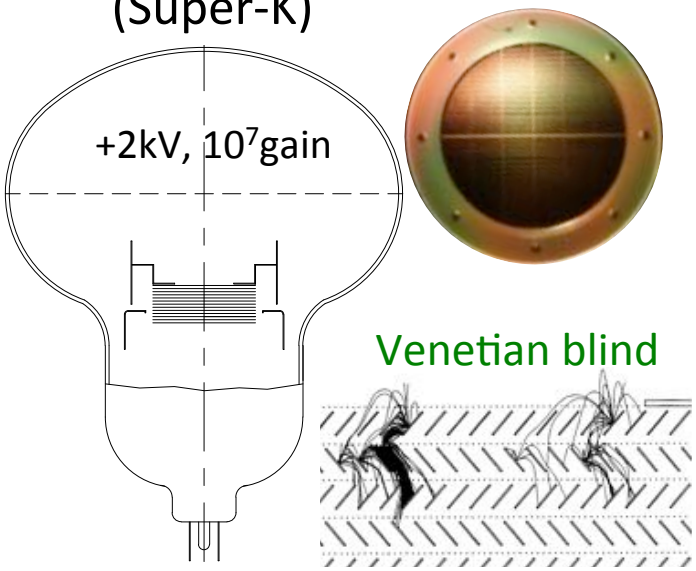
Principle of amplification

50cmΦ

All is possible for high QE option, 22%→30%

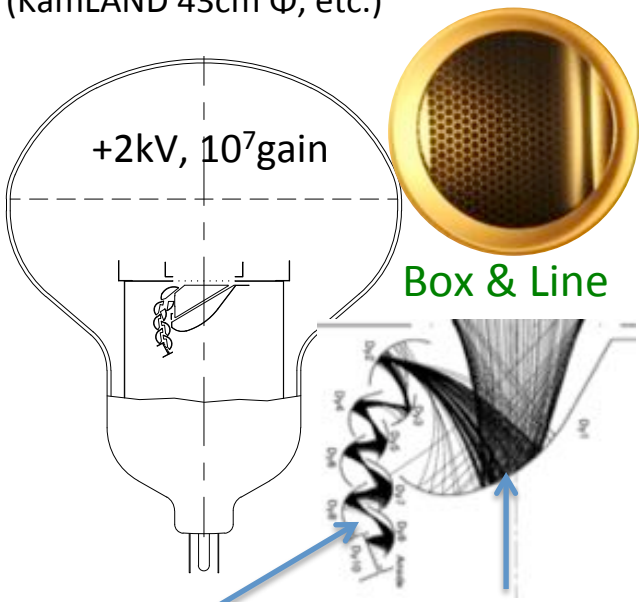
Photomultiplier tube (PMT)

Venetian blind dynode
(Super-K)



- Photoelectron might miss 1st dynode → less collection eff.
- Ambiguity of drift path resulted in losing uniform charge and time response.

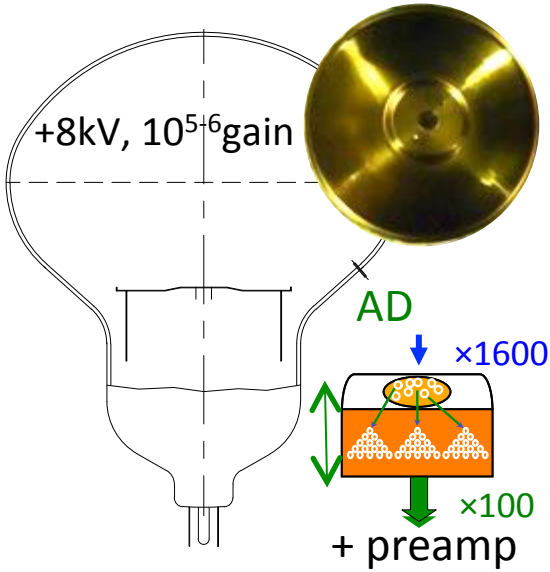
New **Box & Line dynode**
(KamLAND 43cm Φ, etc.)



High collection efficiency
Uniform drift path
→ High charge&time resolution

Hybrid photodetector (HPD)

New **Avalanche diode (AD)**
(Not yet used with large aperture)



Symmetric and fast response, high S/N, low cost

Uniformity improved to achieve large aperture

No experience using in water for a long time
→ Proof test in a 200 ton water tank

Reliability

Low cost, High performance