Hyper-K Photodetector Development

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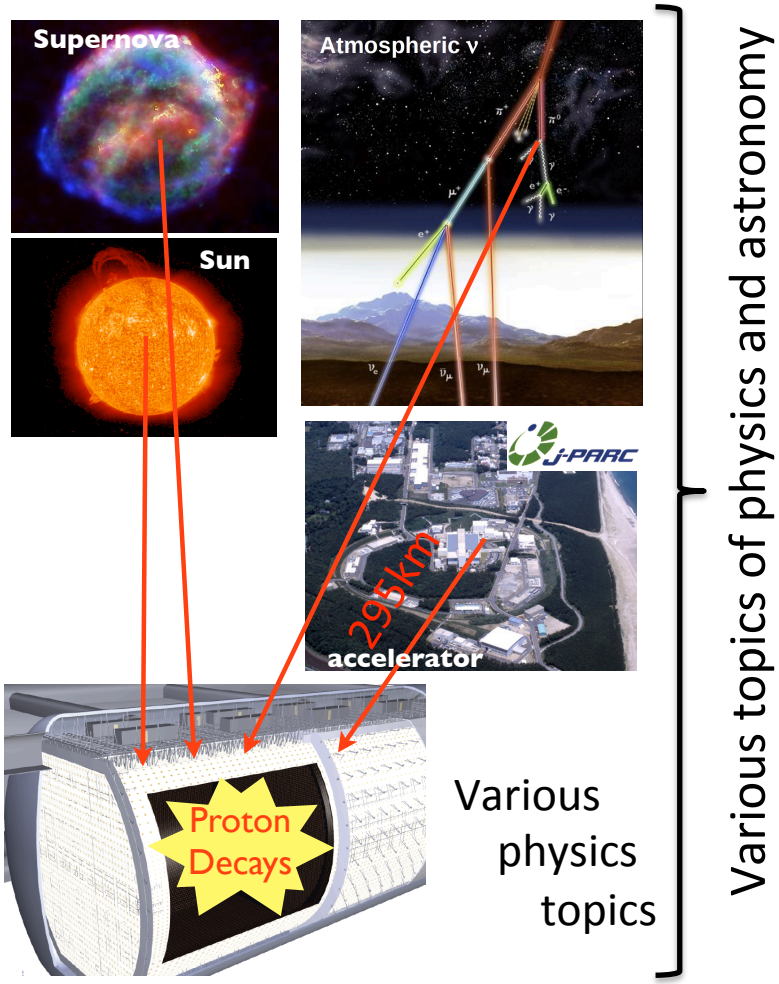
Hyper - Kamiokande

- Neutrino oscillation
  - Atmospheric, solar, accelerator ν
  - ν mixing parameters
    - Leptonic CP, etc.
- Nucleon decay
- Astronomy
  - Supernova, etc.
- Neutrino geophysics
- Dark matter



Photodetectors for Hyper-K

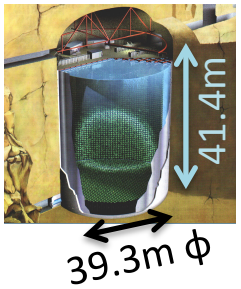
Super-Kamiokande (since 1995)

0.0225 (0.05) Mton
Fiducial (Total)

x 25(20)

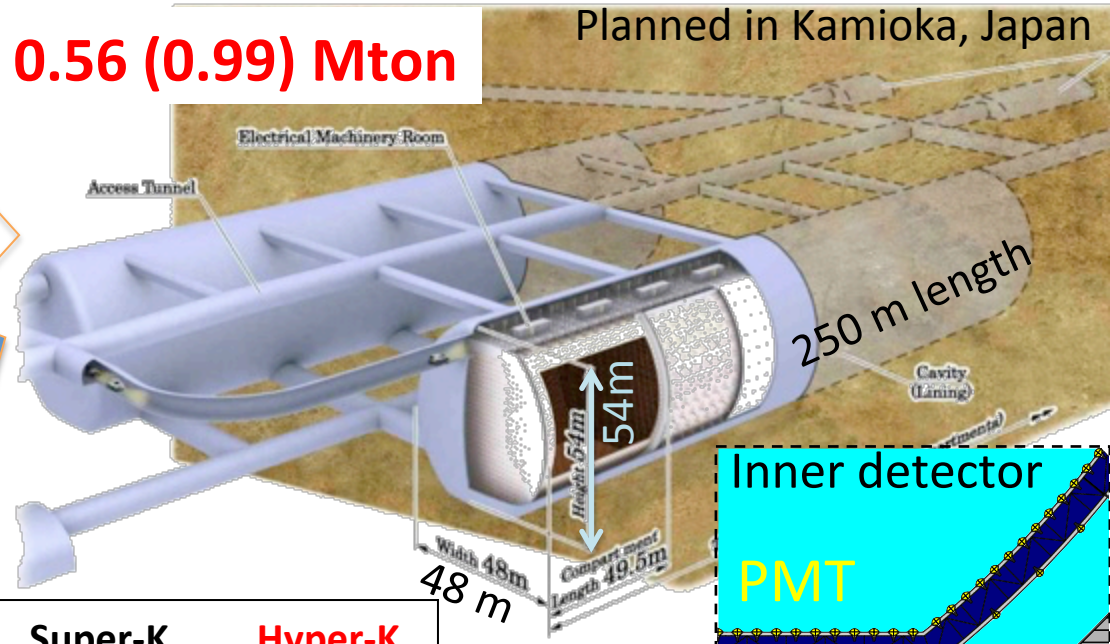
Hyper-Kamiokande Large water Cherenkov detector
Planned in Kamioka, Japan

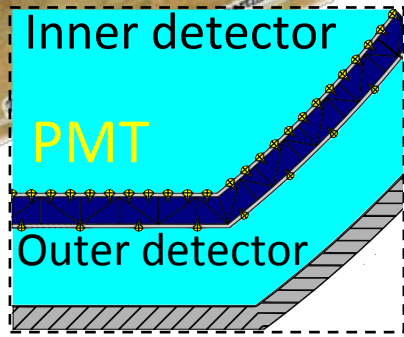
0.56 (0.99) Mton



Based on established technologies

+ Improvement with new technologies





Photosensors

Photo-sensor	Super-K	Hyper-K
Inner detector (for ν detection)	11,129 (50cmΦ)	**99,000 (50cmΦ)**
Outer detector (for cosmic-ray veto)	1,885 (20cmΦ)	**25,000 (20cmΦ)**
Photo-coverage	40%	20%
Sensor efficiency (Quantum × Collection Eff.)	15% (22%×67%)	**29% (30%×95%)**

Develop high performance photodetector with low cost worked over tens years

Expected in new photo-sensor R&D

New Photodetectors

By Hamamatsu Photonics K.K.

- New 50 cm Φ photodetectors developed for HK.

† still in R&D

Model	R3600 (Used for 2-30 yrs)	R12860	R12850
Amplification	Venetian blind dynode	Box and line dynode	20mmΦ Avalanche diode
Q.E.	~22%	~30%	~30%
C.E. Φ46 (Φ50)	67% (61%)	95% (85%)†	93% (76%) w/ 5ch AD†
T.T.S. (FWHM)	5.5 ns	2.7 ns	0.75ns (w/o Preamp.)
Bias voltage	2 kV bias	2 kV bias	8 kV bias + AD bias (<1kV)
Proof test	1.8 yrs for HQE	0.8 yrs now from Sep.2014	> 0.5 yrs expected

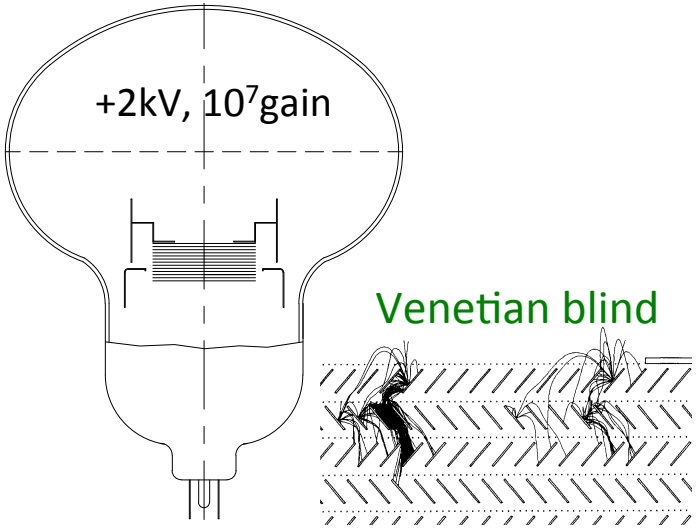
High-QE Box&Line PMT

50cmΦ

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

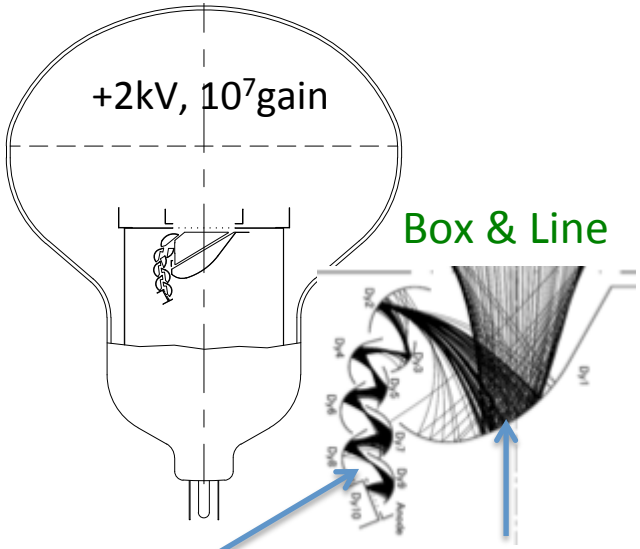
Photomultiplier tube (PMT)

Venetian blind dynde
(Super-K)



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

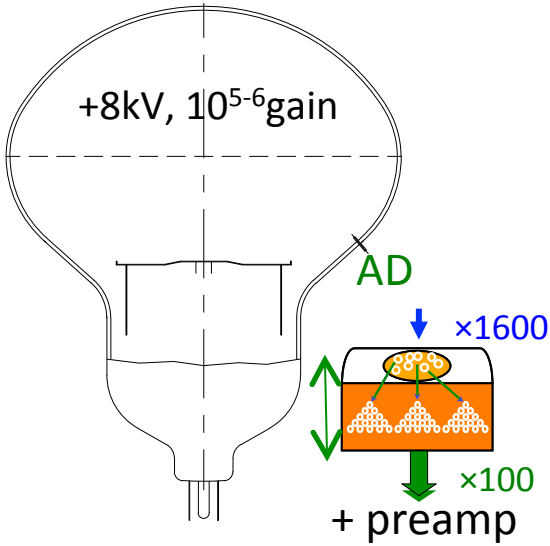
New **Box & Line dynode**
(KamLAND 43cm Φ, etc.)



High collection efficiency
Uniform drift path (& high 1st dynode gain)
→ High charge&time resolution
Uniformity improved to achieve large aperture

Hybrid photodetector (HPD)

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



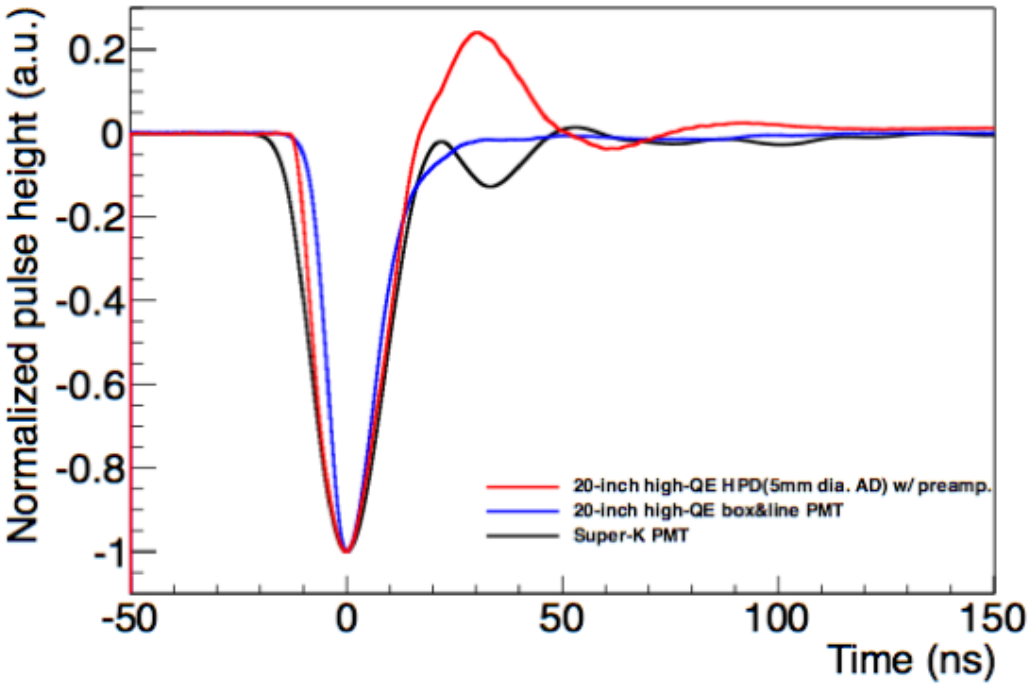
Symmetric and fast response, high S/N, low cost

Reliability

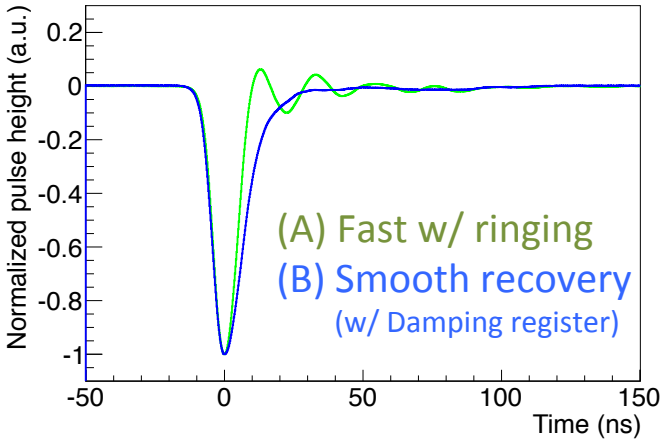
No experience using in water for a long time
→ Proof test planned in Kamioka

Low cost, High performance

Response



Box&Line PMT
w/ different bleeder circuit



Similar time resolution is confirmed.

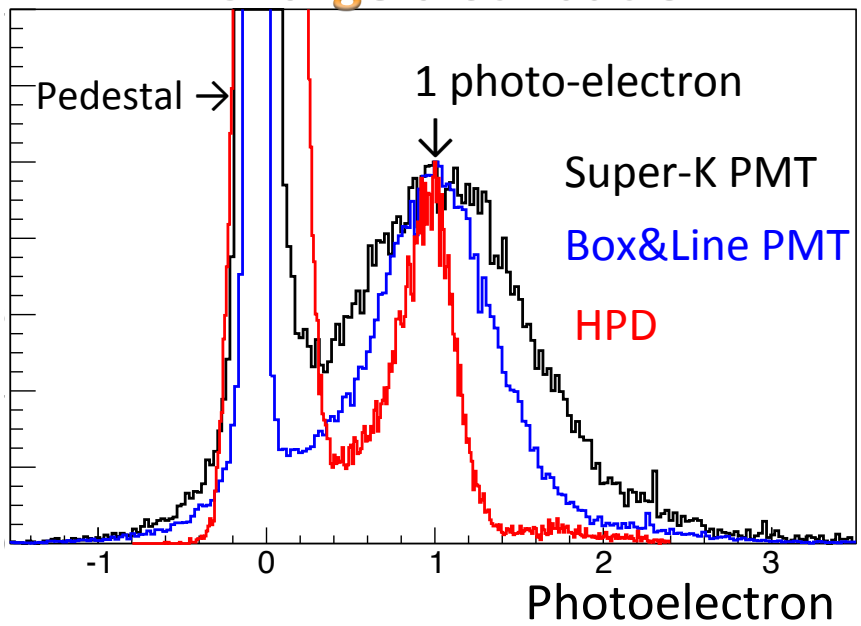
→ (B) for proof test

10% - 90%	HPD	B&L PMT (A)	B&L PMT (B)	SK PMT
Rise time [ns]	7.4 (1.7)	6.2	6.7	10.6
Fall time [ns]	11.5 (2.7)	6.3	15.2	13.1
FWHM [ns]	17.1	16.7	13.0	18.5

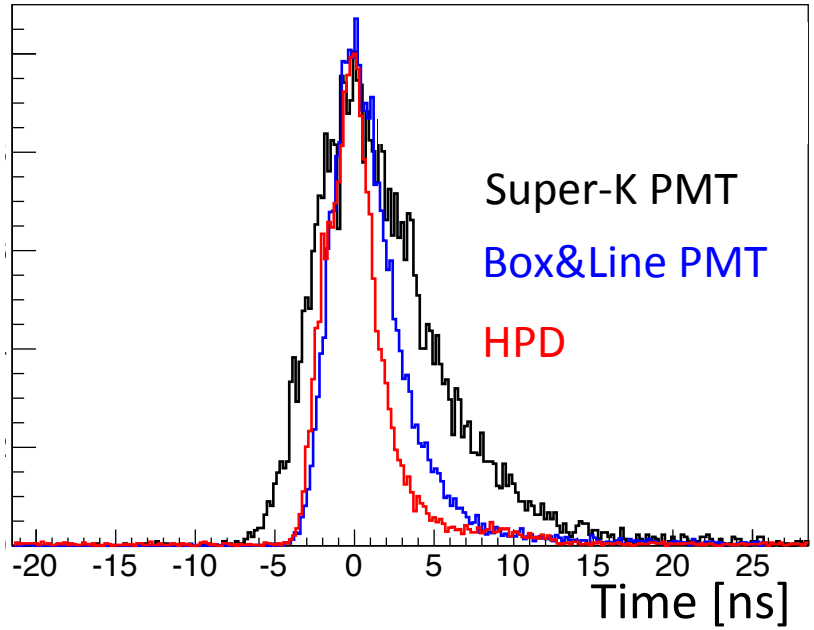
(intrinsic waveform of 20ch HPD w/o amp.)

Resolution at single photoelectron

Charge distribution



Time distribution



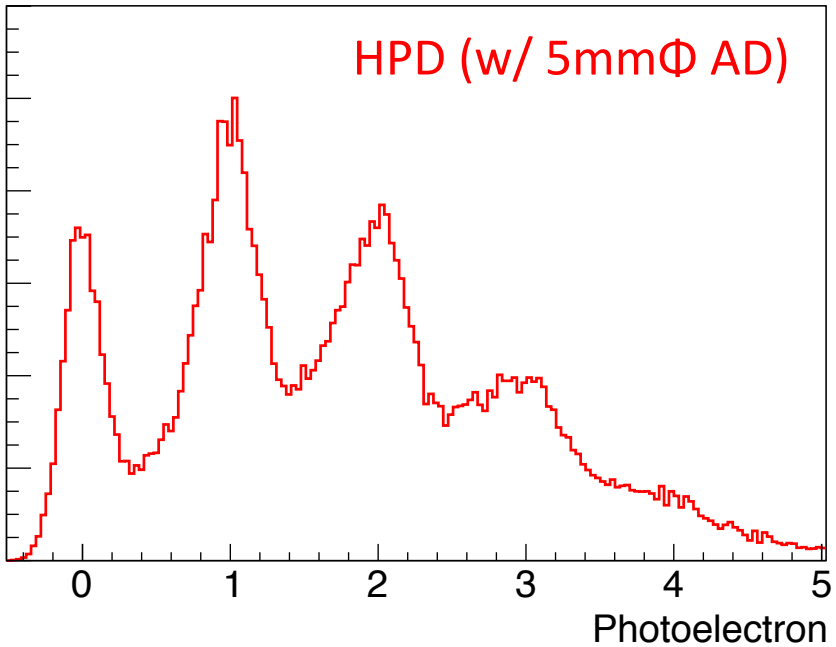
Single p.e. resolution	Charge σ / peak	Time σ (left)	FWHM
Super-K PMT	**53%**	**2.1 ns**	**7.3 ns**
Box&Line PMT	**35%**	**1.1 ns**	**4.1 ns**
HPD (w/5mmΦ AD†)	**16%**	**1.4 ns**	**3.4 ns**
(20cmΦ HPD)	(12%)	(1.1 ns)	(3.3 ns)

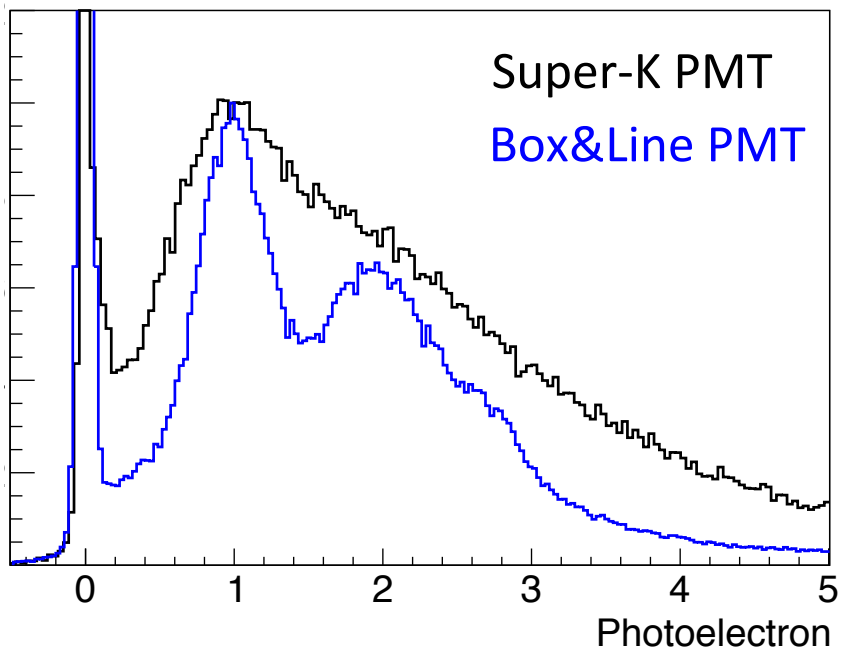
† 20mmΦ Avalanche Diode in final design with full efficiency

Limited by preamplifier (intrinsic resolution is better, less than 1ns)

Single p.e. charge and time resolutions are better for both new photodetectors.

Detection of multi-photoelectron





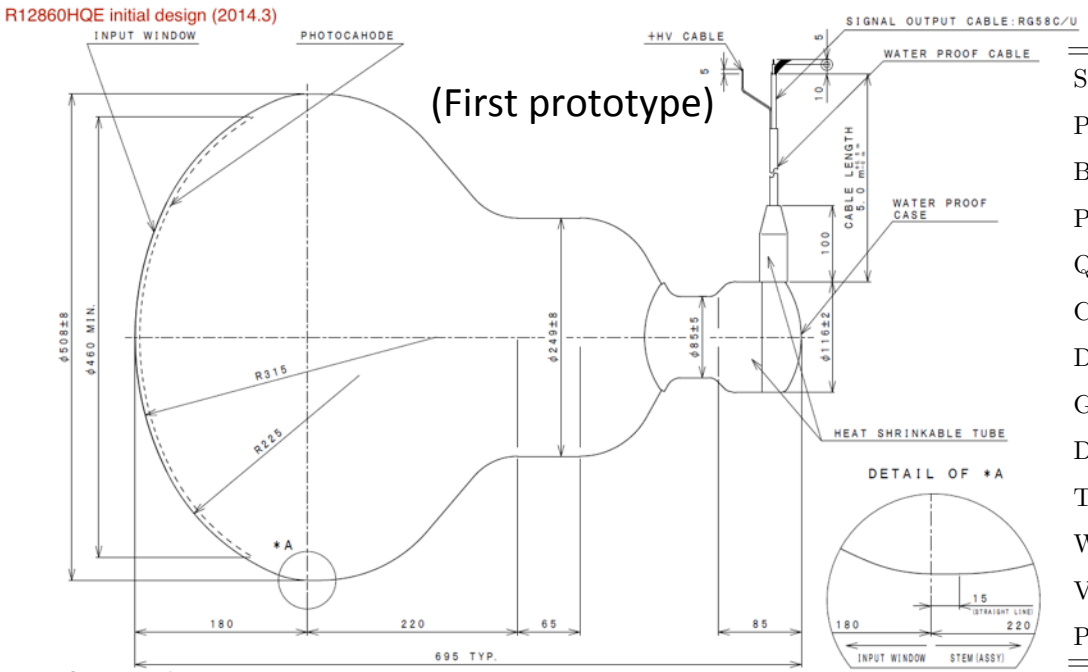
Multi photoelectron peaks were confirmed clearly in both new 50cm photodetectors.

Photodetector R&D list

Tried so far

- Super-K PMT (R3600 Hamamatsu)
- High-QE Super-K PMT (R3600HQE)
  - For first trial of high-QE application on 50 cm Φ
- High-QE Box&Line PMT (R12860HQE)
  - Initial prototype (tested in water)
  - Low noise ver. (Dark rate and after pulse were reduced.)
  - Improved ver. with high pressure and geomagnetism resistance
- High-QE HPD
  - 20 cm HPD (R12112)
  - 50 cm HPD with 5 mmΦ avalanche diode
  - 50 cm HPD with 20 mmΦ avalanche diode

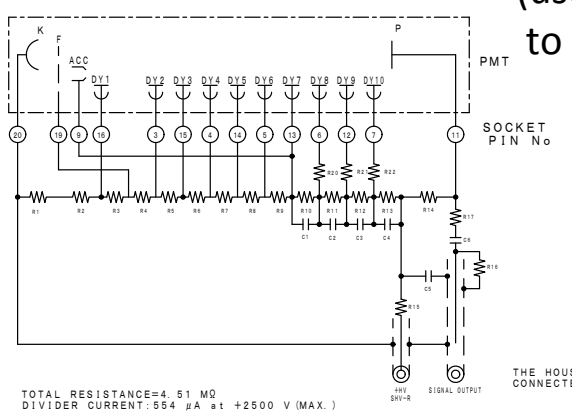
High-QE Box&Line PMT



Shape	Hemispherical
Photocathode area	50 cm diameter (20 inches)
Bulb material	Borosilicate glass ($\sim$ 3 mm)
Photocathode material	Bialkali (Sb-K-Cs)
Quantum efficiency	30 % at $\lambda = 390$ nm
Collection efficiency	95 % at 10^7 gain
Dynodes	10 stage box and line type
Gain	10^7 at $\sim$ 2000 V
Dark pulse rate	$\sim$ 8 kHz at 10^7 gain (13 Celsius degrees)
Transit time spread	2.7 nsec (FWHM) for single photoelectron signals
Weight	7.5 kg (without cable)
Volume	61 cm^3
Pressure tolerance	9 kg/cm^2 water proof

Bleeder circuit

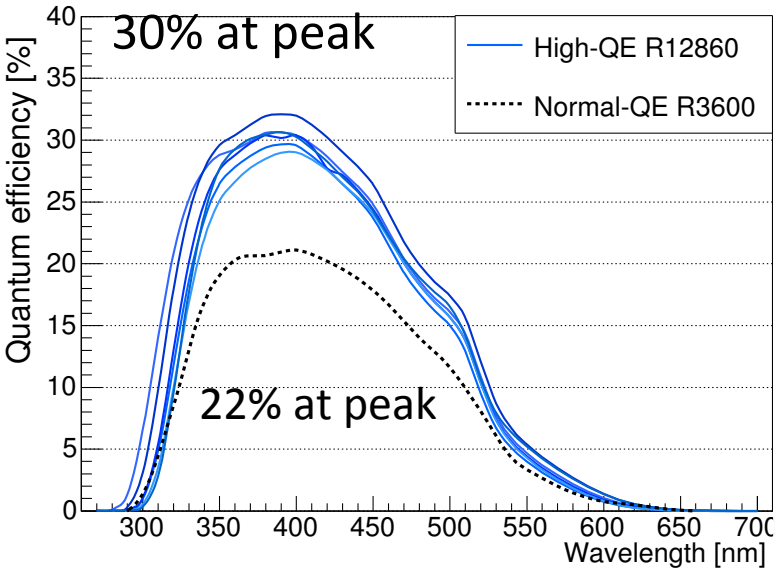
(used in evaluation, to be optimized)



- Similar outward form and material to Super-K PMT, compatible with PMT fixing band, comparable HV-gain characteristics

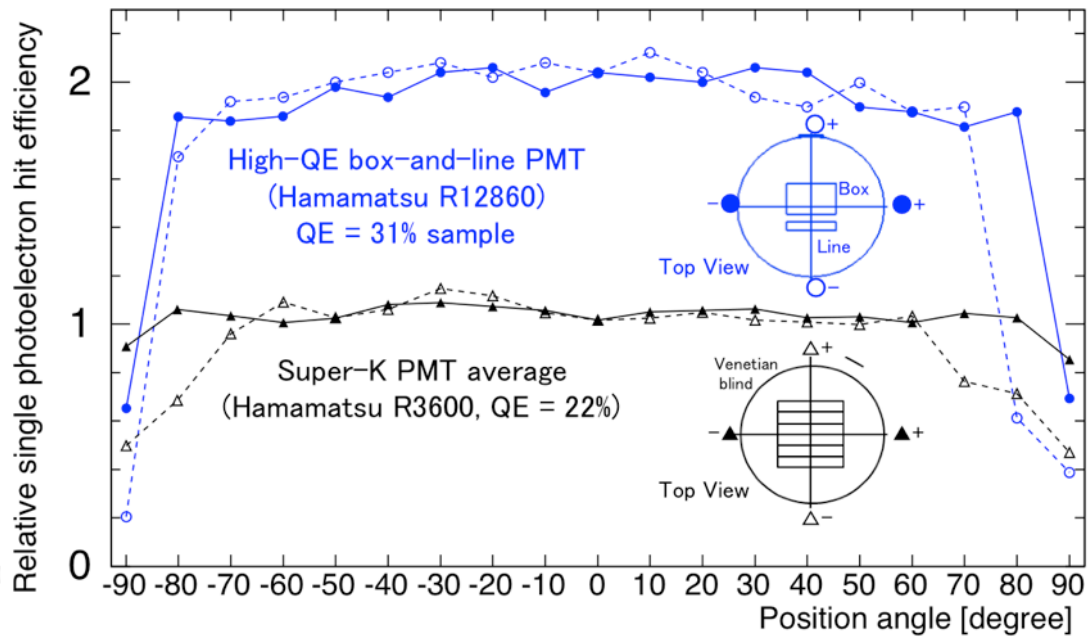
QE and CE

High QE of Box&Line PMT



Total detection efficiency

QE x CE measured by hit counting efficiency



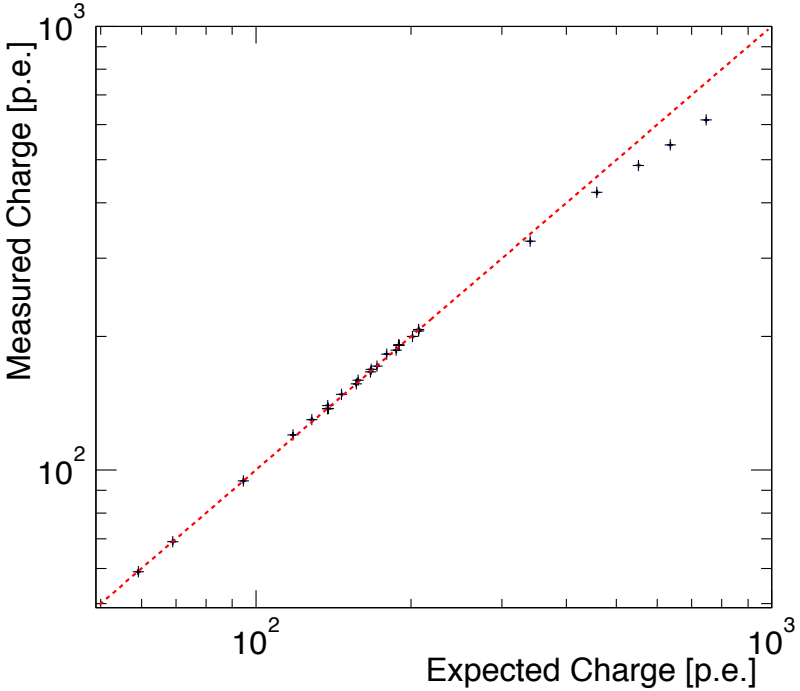
- High QE and CE were confirmed in measurements.
  - QE 22% → 30%
  - CE 67% → 95% (Calculated in Φ46cm)

(Super-K PMT → Box&Line PMT)

In total, double from Super-K PMT

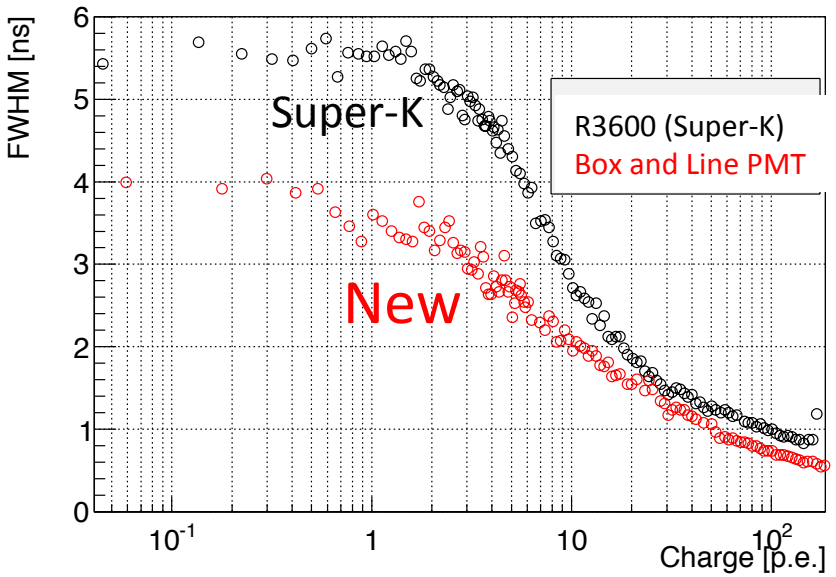
Response in wide dynamic range

Output linearity



Up to 340 PE within 5% linearity,
still not fully saturated
in several hundreds PEs

Time resolution at FWHM

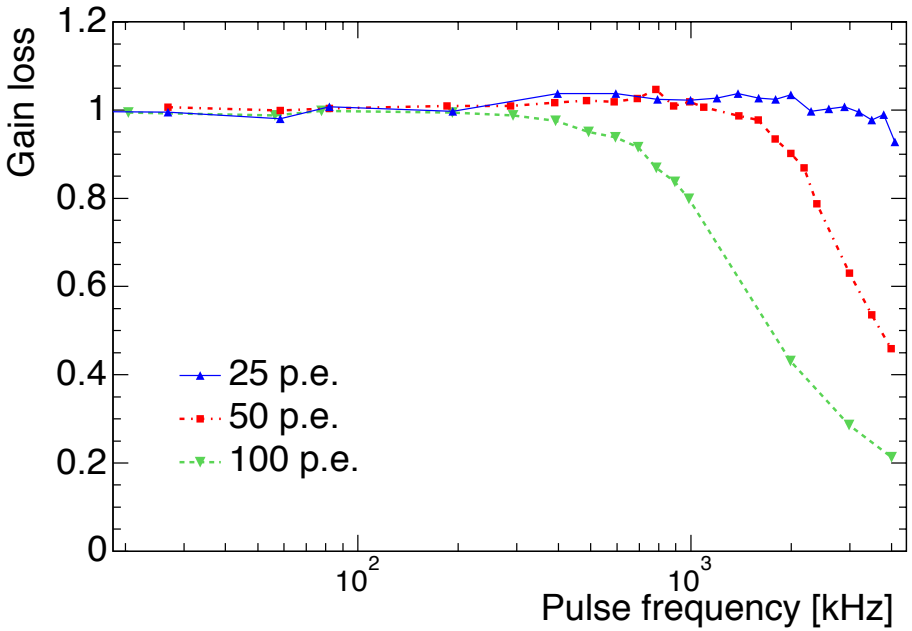


High time resolution in all region

Detailed evaluation

Super Nova < O(100)kHz

High rate resistance

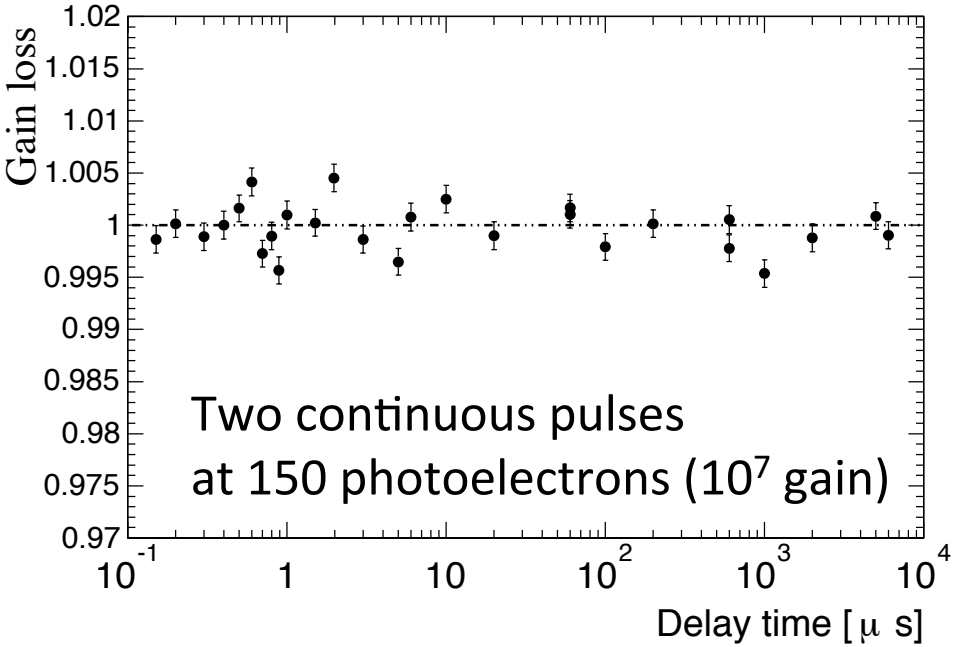


For single photoelectron,
up to 87 MHz within 5%.

Decay electron tagging from μ, etc.

Gain recovery after primary pulse

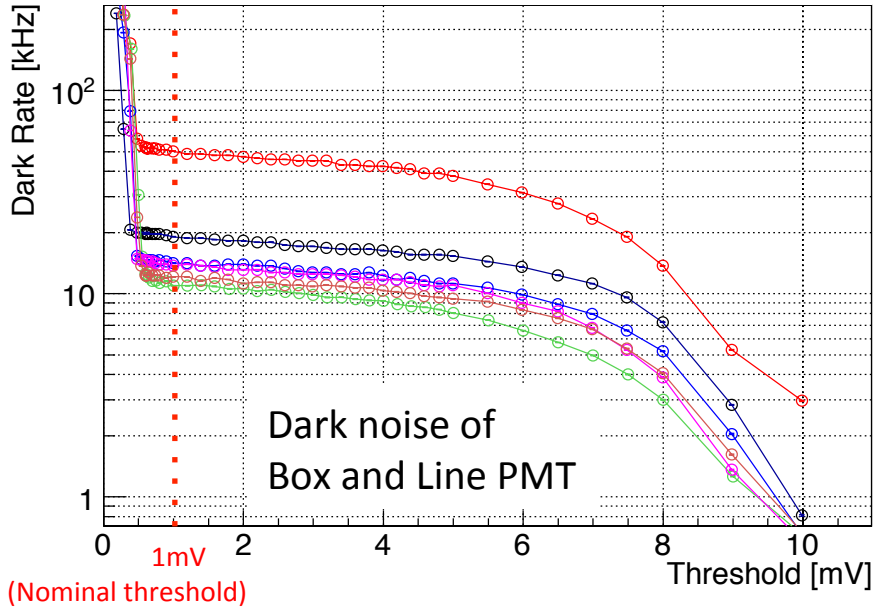
Monitored stability of later pulse



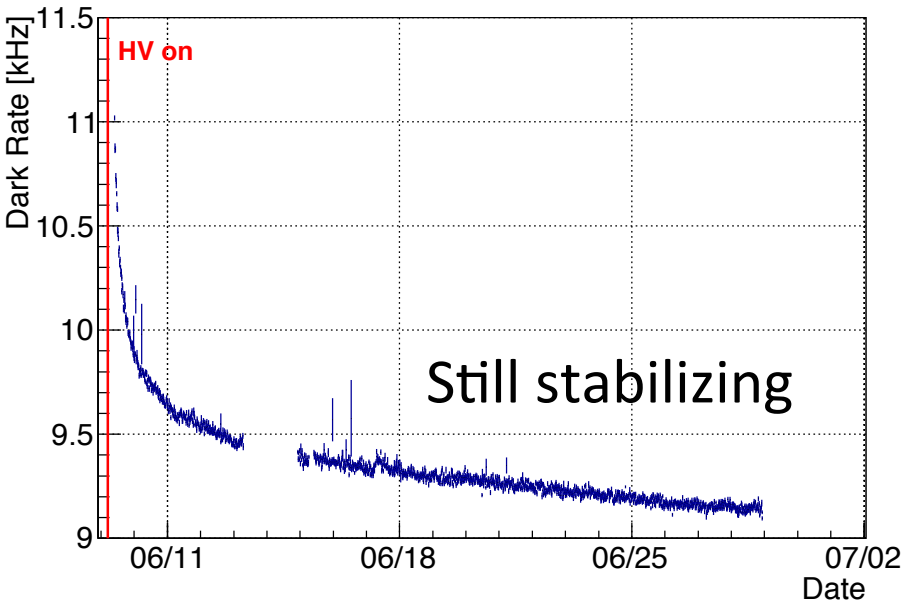
Constant within 0.5%

Dark rate

Dark rate as a function of thresholds



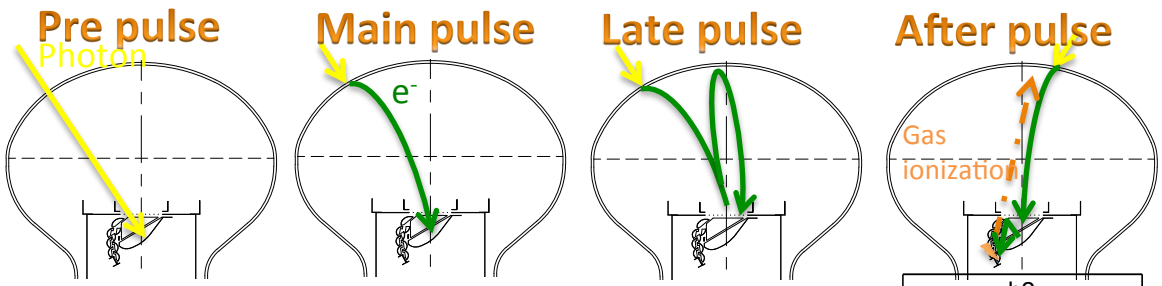
Stabilization of dark rate
(Threshold: 2mV, 14°C)

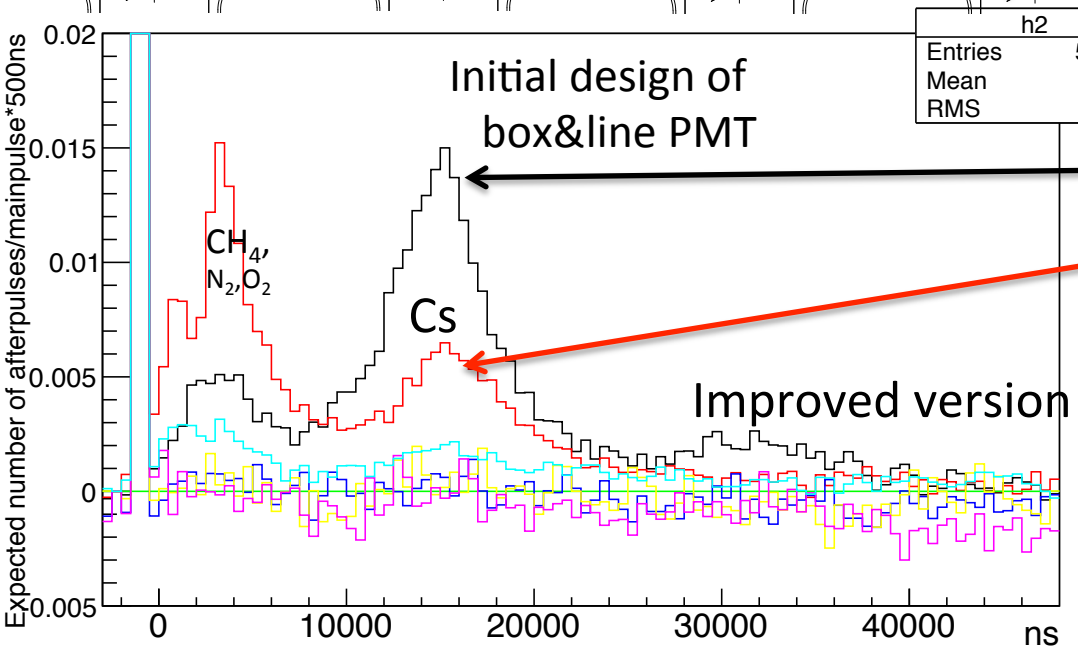


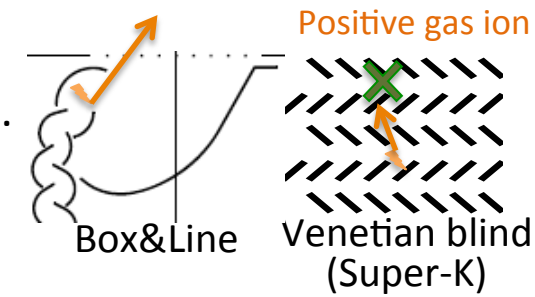
- Dark rate is comparable with high-QE Super-K PMT, but higher than PMTs in Super-K (about 4.2 kHz).

After pulse

- After pulse could be background of delayed e from μ decay, ..
- Box&line PMT tends to have much after pulse rate due to its structure, while it was suppressed by improvements in R&D.





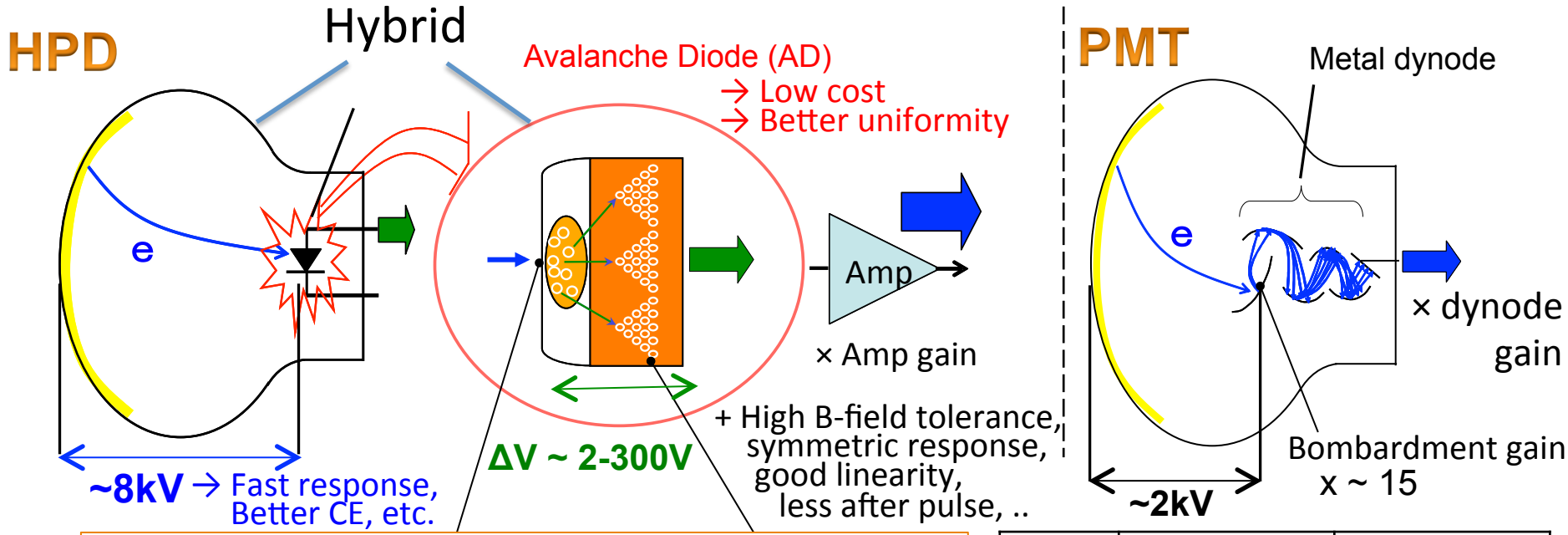


(expected number of after pulses) / main pulse

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

Amount of after pulse is now comparable level with Super-K PMT's.

Hybrid Photo-Detector



Bombardment gain **~1600**× Avalanche gain **50~200**

→ Good resolution

Typ.	HPD	PMT
HV	8kV	2kV
Gain	10^4 - 10^5	10^7
C.E.	95%	80%

High voltage around 8kV is required

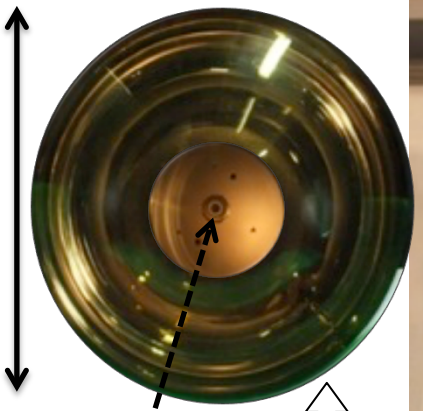
- to collect electrons in the small region of AD (5-20mm)
- to increase gain at electron-bombardment

- High performance and low cost
- Factors to be considered for viability in Hyper-Kamiokande:
  - Dark noise from AD + Amp., high 8kV bias, low gain, thermal dependence of AD, no prior experience using

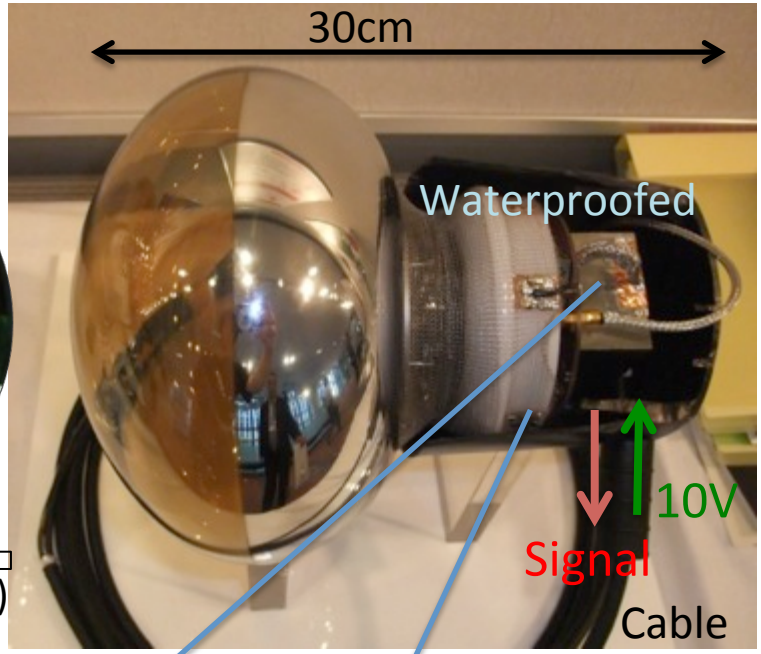
20 cm HPD

Size for outer detector

20cm photocathode



5mm ϕ avalanche diode (AD)

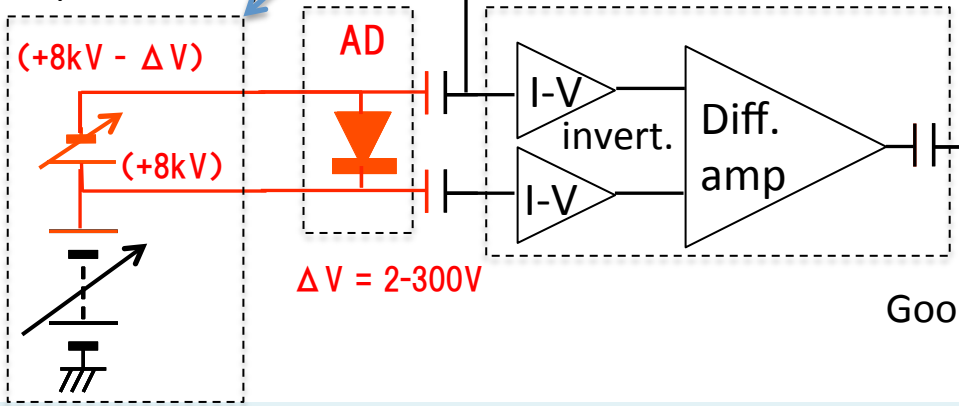


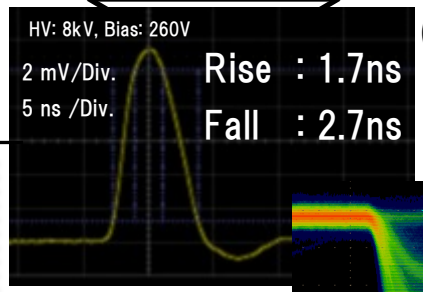
HAMAMATSU

Spectral response		300 - 650 (420 max.) nm
Photocathode		Bialkali
Window material		Borosilicate glass
Gain		4 - 9 ×10^4
Time	Rise	1.7 ns
	Fall	2.7 ns
	T.T.S.	0.62 ns (σ)
Dynamic range		100 pC (1.5×10^4 p.e.)

High voltage module
(2ch 10kV/500V Max)

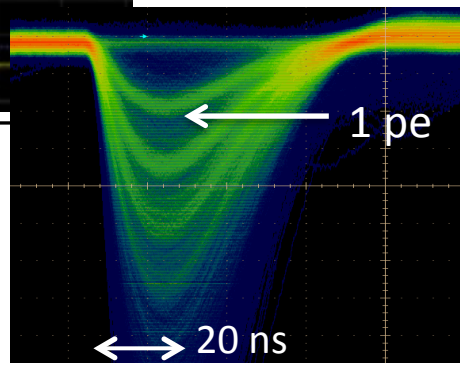
No HV line in water





Fast intrinsic response (w/o preamplifier)

Shaped in preamplifier

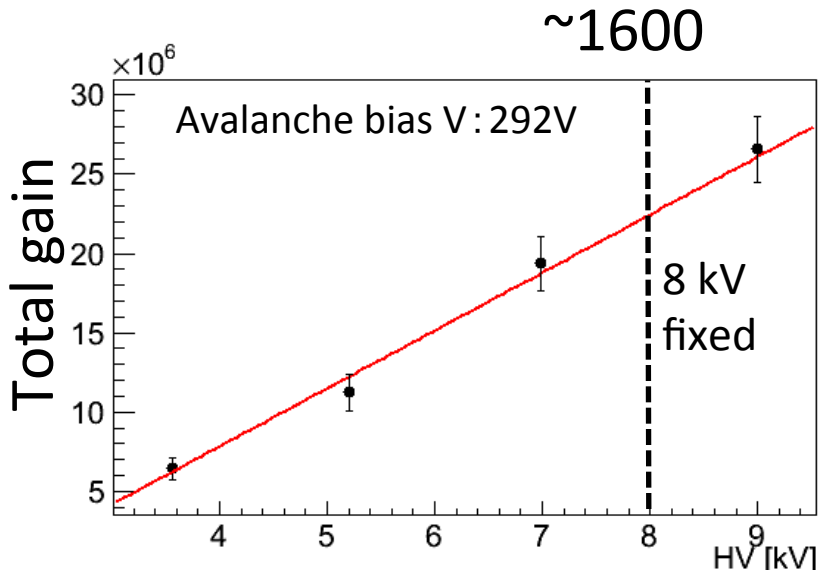


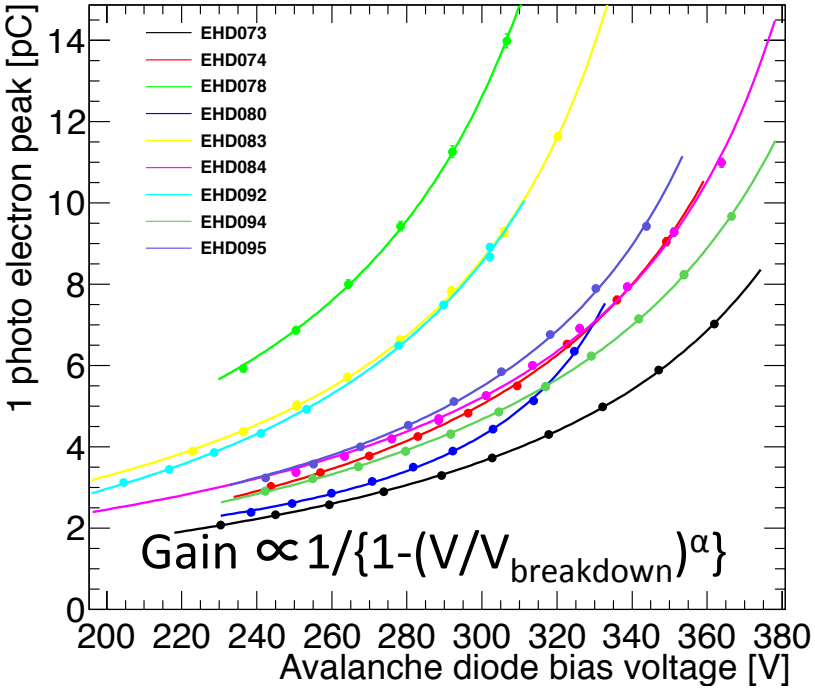
Good photoelectron separation

Gain of 20 cm HPD

- Gain was measured in several samples.
- Adjust HPD gain by AD bias voltage.

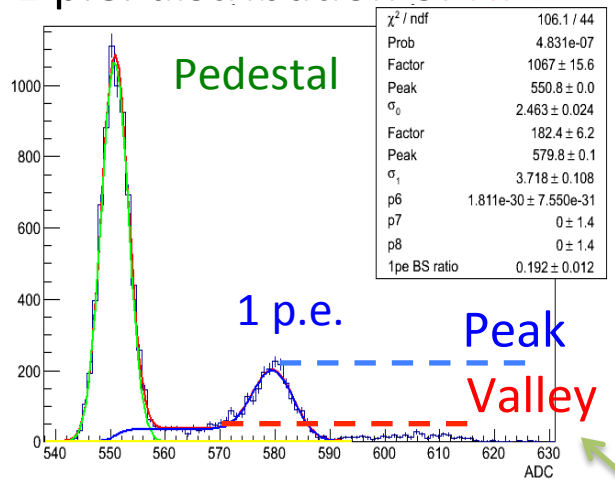
Total gain = Bombardment gain × Avalanche gain (× preamp gain)

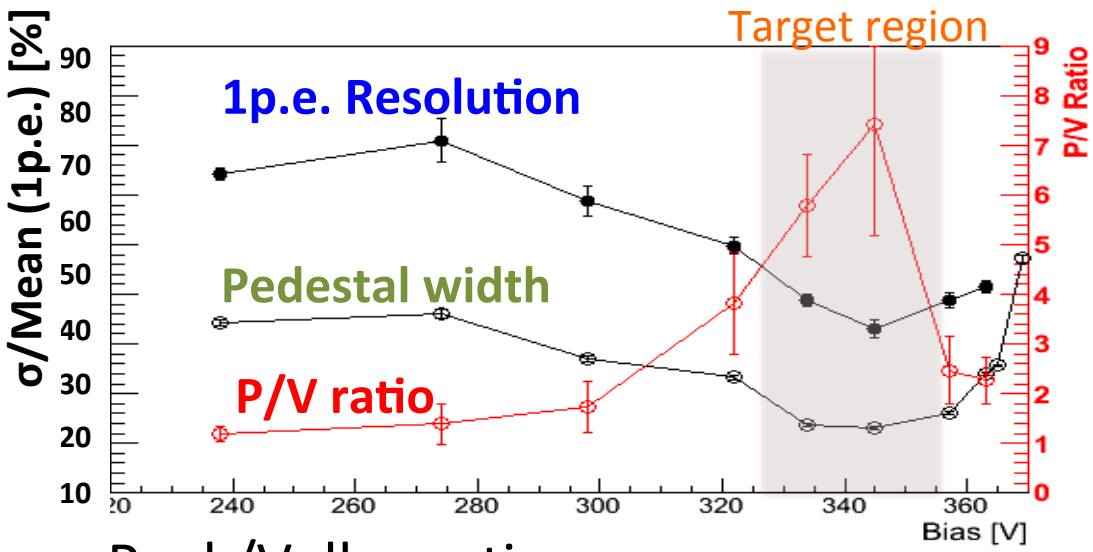




Performance of 20 cm HPD

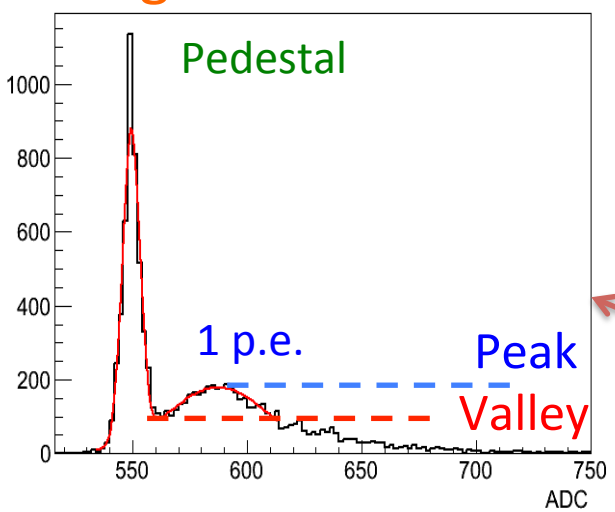
1 p.e. distribution of HPD

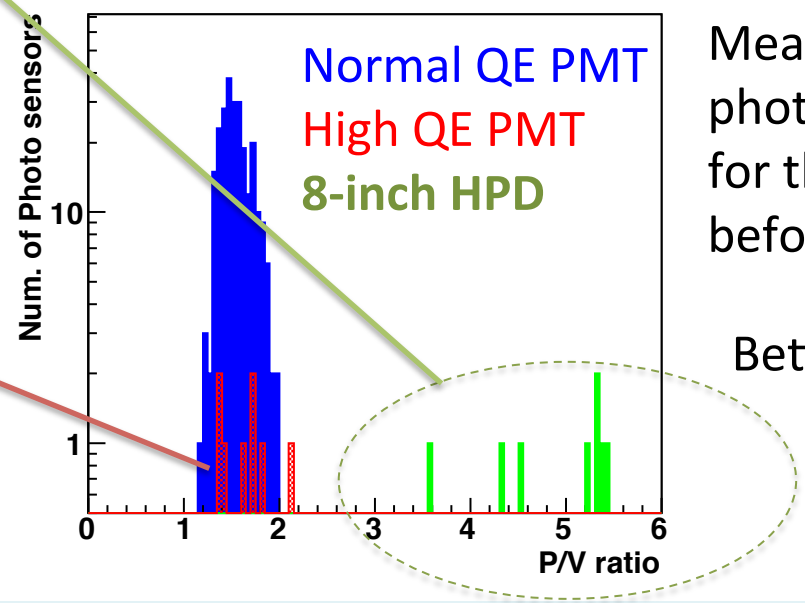




Peak/Valley ratio

High-QE PMT

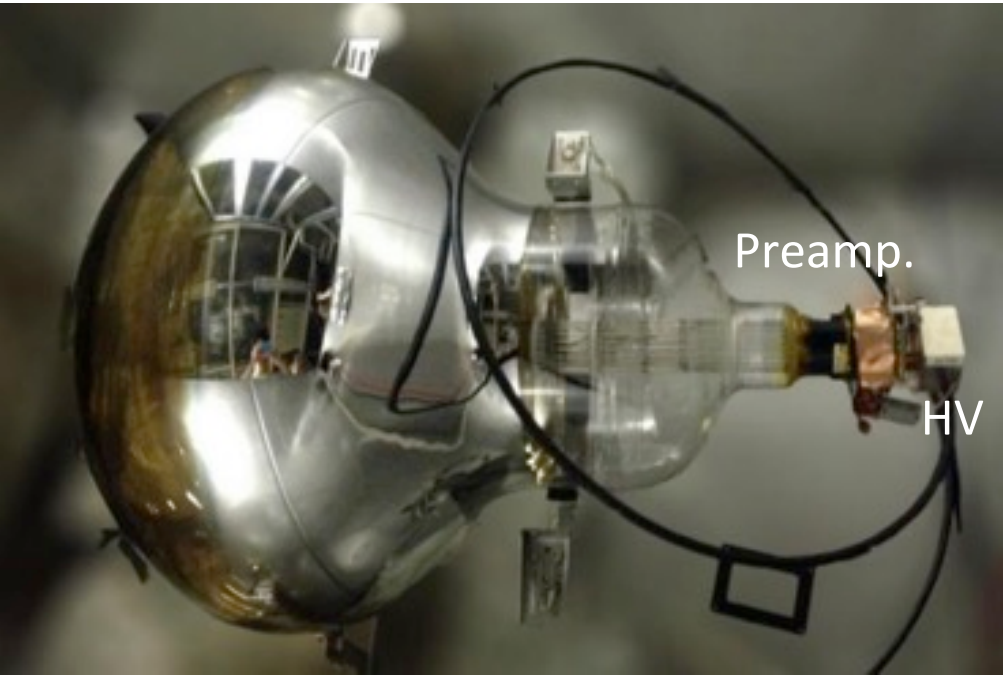


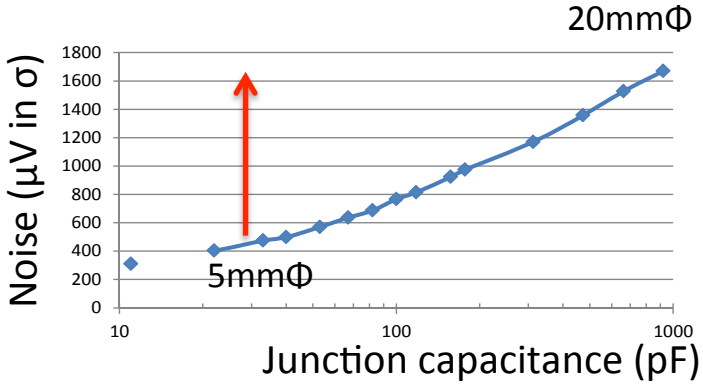


Measured all photodetectors for the proof test before installation.

Better separation for HPD

50 cm HPD

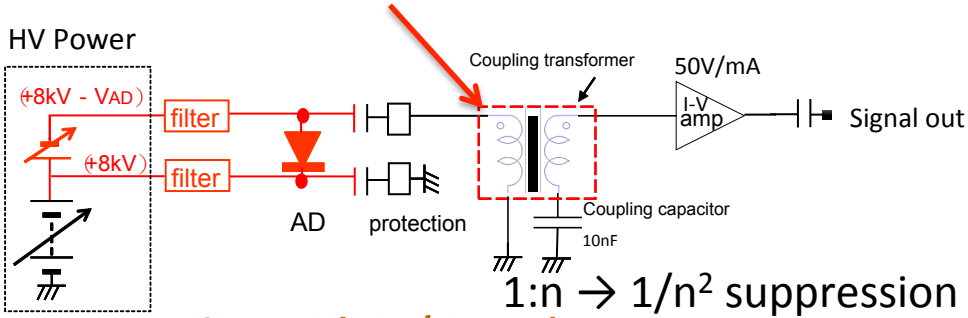




- At first, 5 mm Φ avalanche diode (AD) and electronics were employed for 50 cm HPD.
- To get a full efficiency (95% CE), 20 mm Φ AD and its preamplifier are required.
- Because a large junction capacitance tends to give large noise and slow response, preamplifier design is difficult.
- Preamplifier is still under development, and 50 cm HPD will be ready for test in water soon in 2015.

Preamplifier R&D

1. Transformer coupling

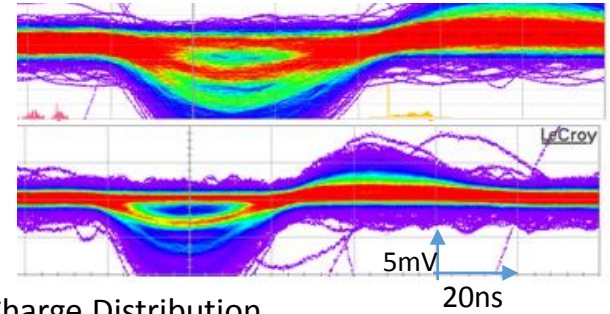


1:n → 1/n² suppression

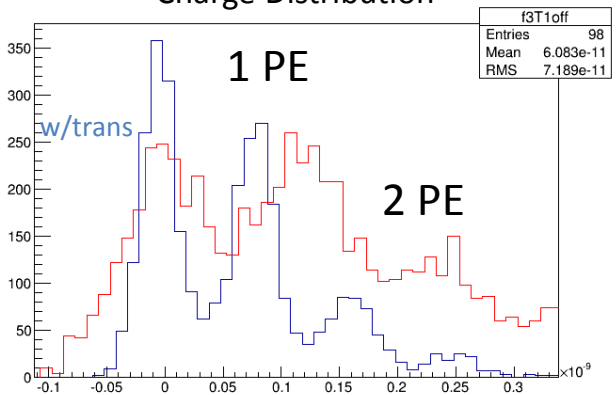
Demonstration at 11kV w/ 15mmΦ AD

w/o trans

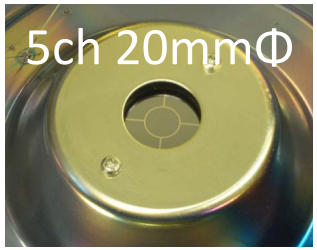
w/ trans

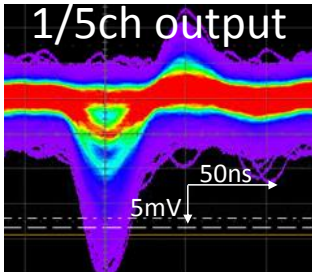


Charge Distribution

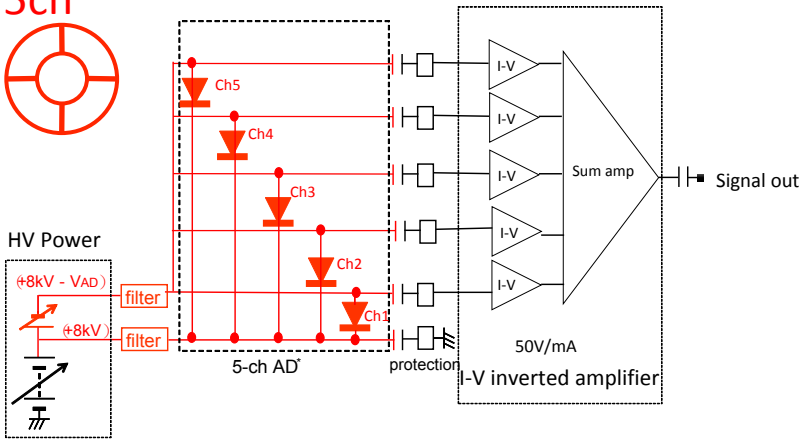


2. 5 segmented avalanche diode





5ch



- Based on combination of two, preamplifier for 20mm Φ AD is being developed and 50cm HPD will be ready within 2015.

Proof test

2012 | 2013 | 2014 | 2015 | 2016

20cmΦ HPD

8 HPDs

1st proof test (2013.8 -)

5 PMTs

High QE
for Super-K PMT

New PMT
w/ box&line dynode

3 PMTs

(2014.10 -)

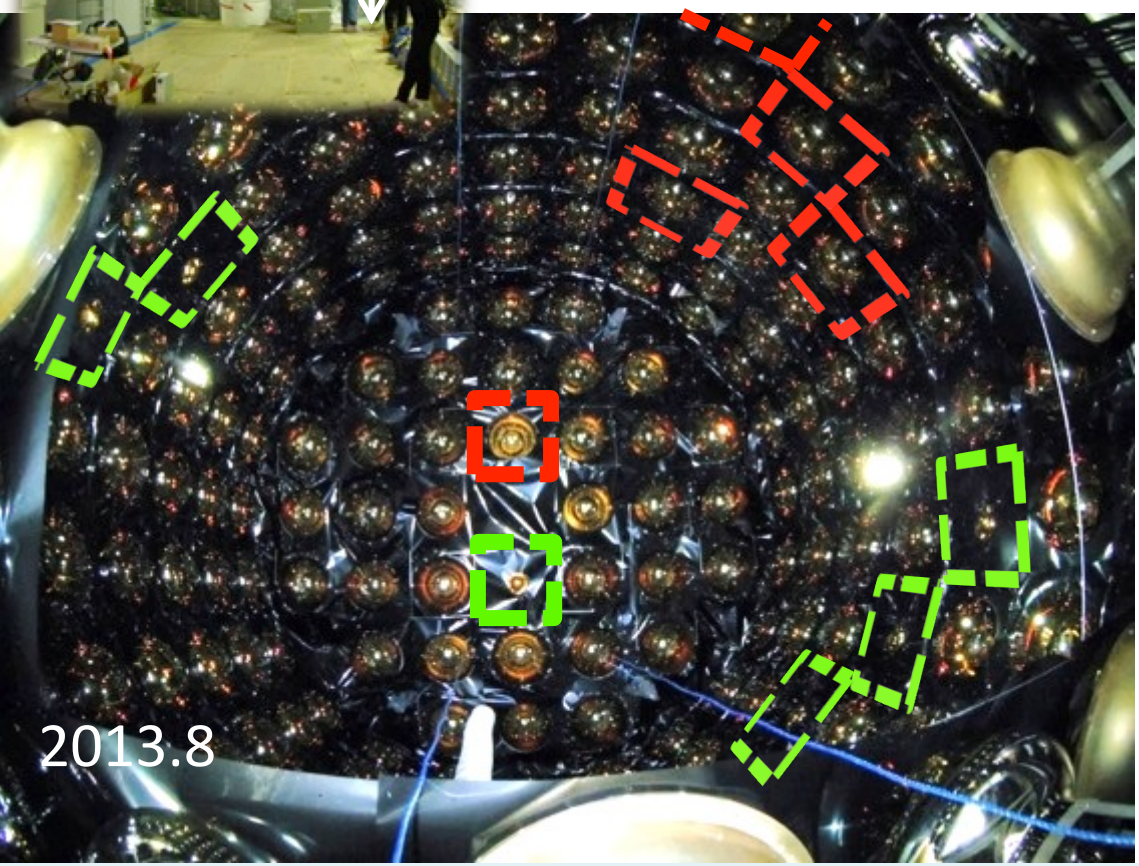
50cmΦ HPD

(Coming soon)

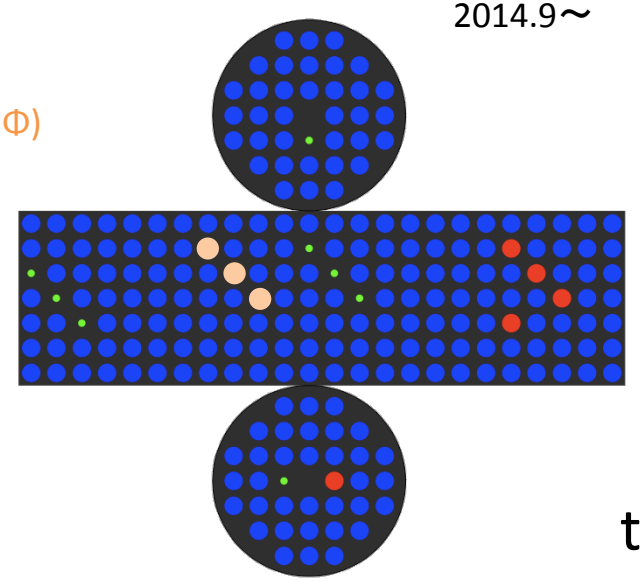
Proof test

Setup

5 High-QE Super-K PMT (50cmΦ)
+ 8 HPD (20cmΦ)
+ 3 High QE Box&Line PMT (50cm Φ)
+ 224 Super-K PMT

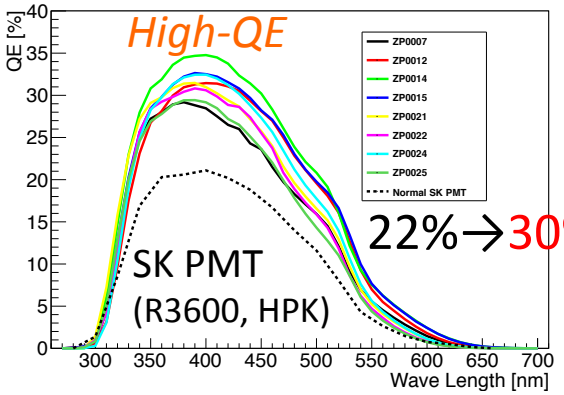


2014.9～



test

High-QE photocathode is applied on Super-K PMT

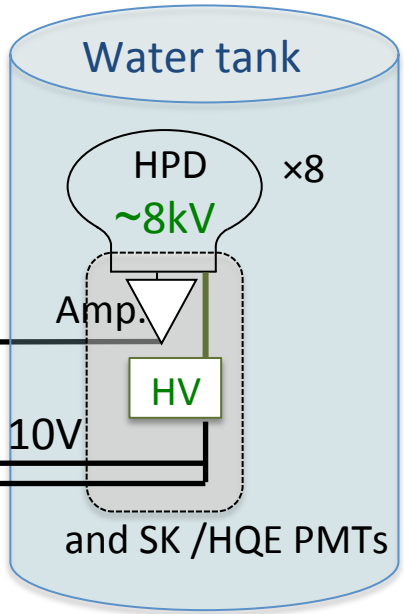


Continue long-run test for a few years

Electronics for proof test

- Trigger is issued by sum of hits with all photo detectors.
  - 1 hit = 1 HPD (PMT) with 1 p.e. or more signal
- In same DAQ system, electronics of HPD/HQE PMT is separated.
  - 1 p.e. level differs between PMT and HPD.
  - Photons/p.e. differs between normal and high QE.

NOT for Hyper-K case

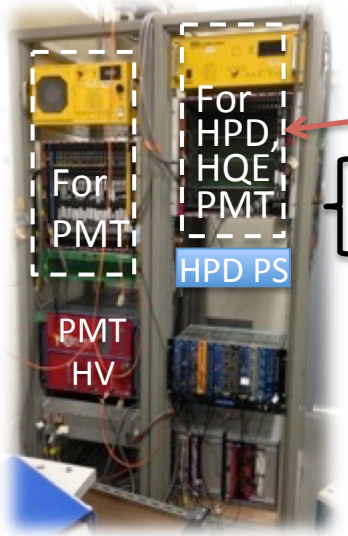


DAQ of charge + time

ATM (Analog Timing Module)

12ch x (2TAC+2QAC)→ADC

used in old SK



1 board for HPD (8/12ch)
1 for HQE PMT (5/12ch)
Trigger threshold is set **by each board (0-12mV)**
Set threshold separately (0.25p.e. in PMT case)
⬇
Calibrated HPD/HQE PMT.

*) ATM replaced with QBEE(current SK board) later

70m signal cable

Control Power Supply

10ch x 6 LV cables

2 Power supply lines (10V)
- For HV unit and Pre-amp. (<500mA) + GND

4 HV control lines (<1mA, 5V)
- HV control (0 - 4V out)
- AD bias control (0 - 4V out)
- Latch up monitor (+5V in)
- Enable switch (+5V out)

70m
Low voltage (10V)
+ control cable (5V)

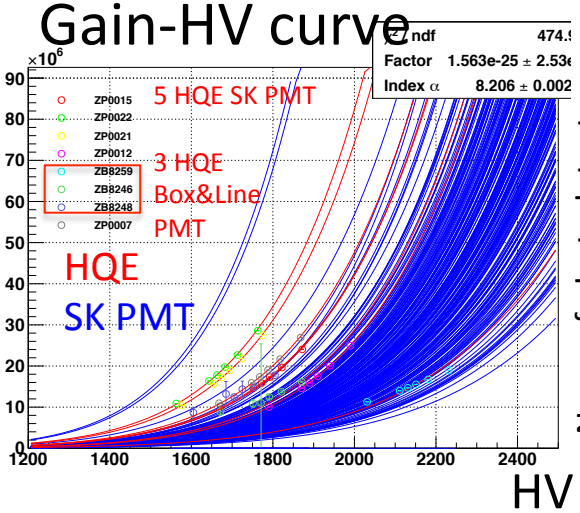
Calibration and Performance

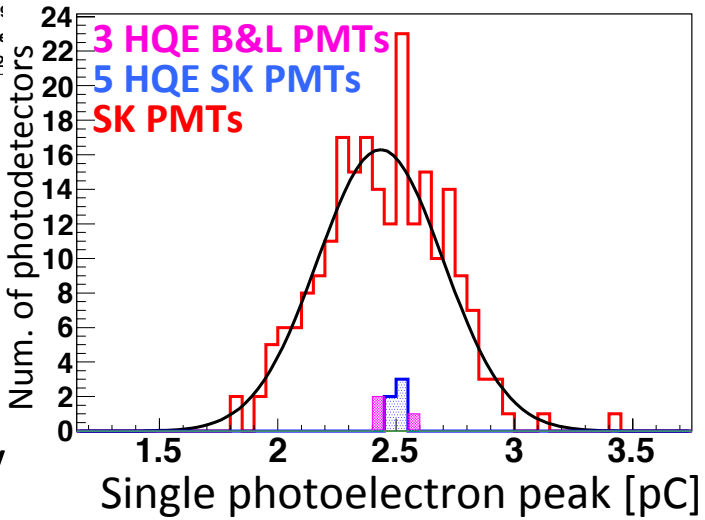
Diffused light at center of tank by LED or laser diode

Calibration

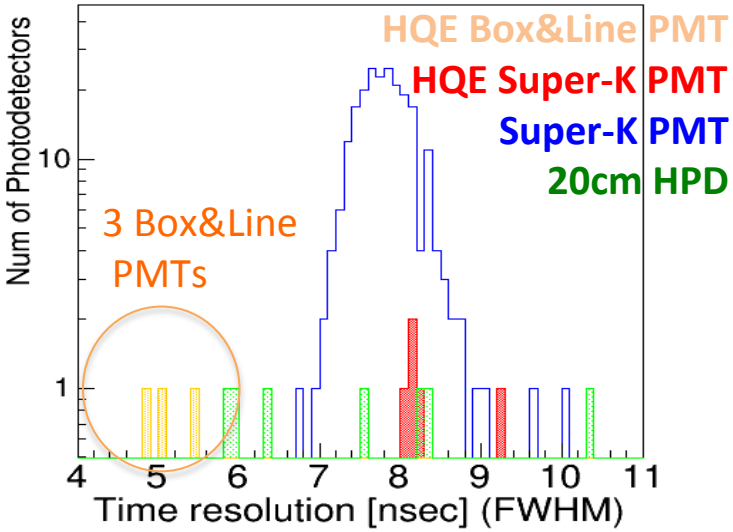
- HV of SK PMTs in EGADS determined by QE×CE×Gain.
- Gain of HQE SK, Box&Line PMTs adjusted by 1 p.e. peak to get same gain as SK PMT's.

Gain-HV curve

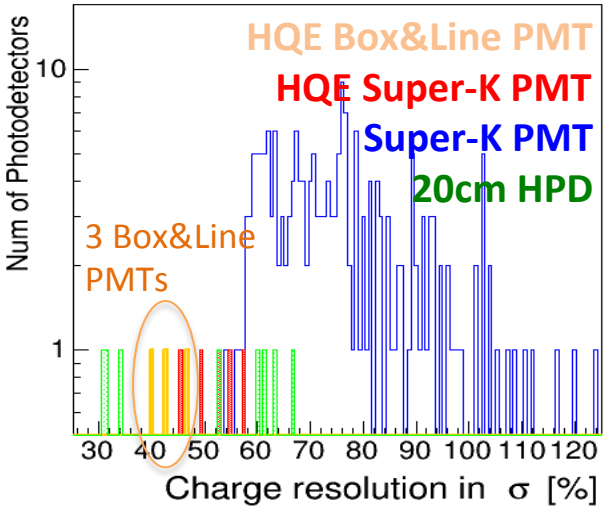




Time resolution at 1 p.e.

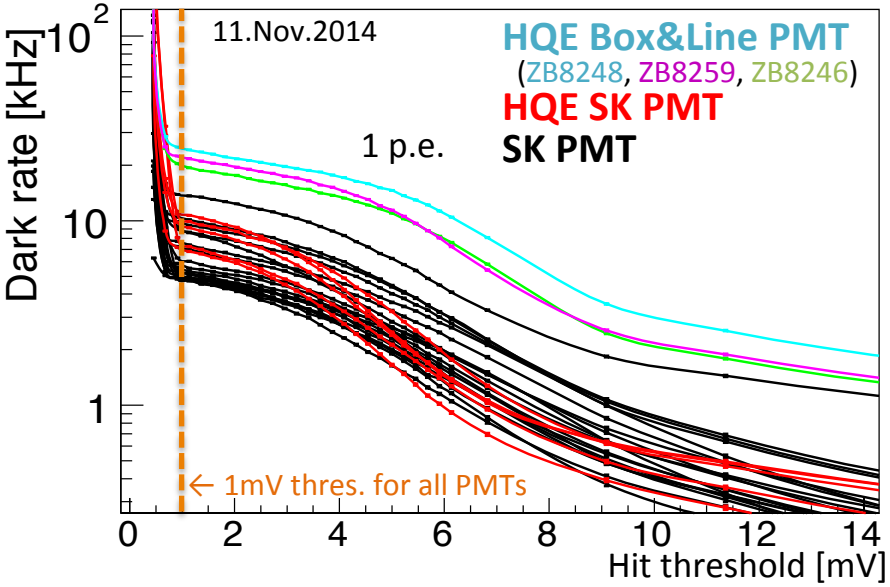


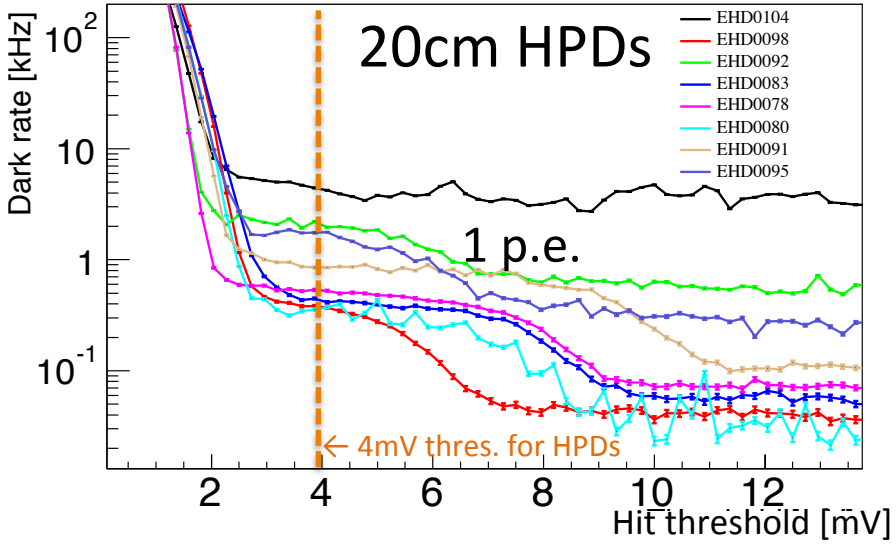
Charge resolution at 1 p.e.



Dark rate in water tank

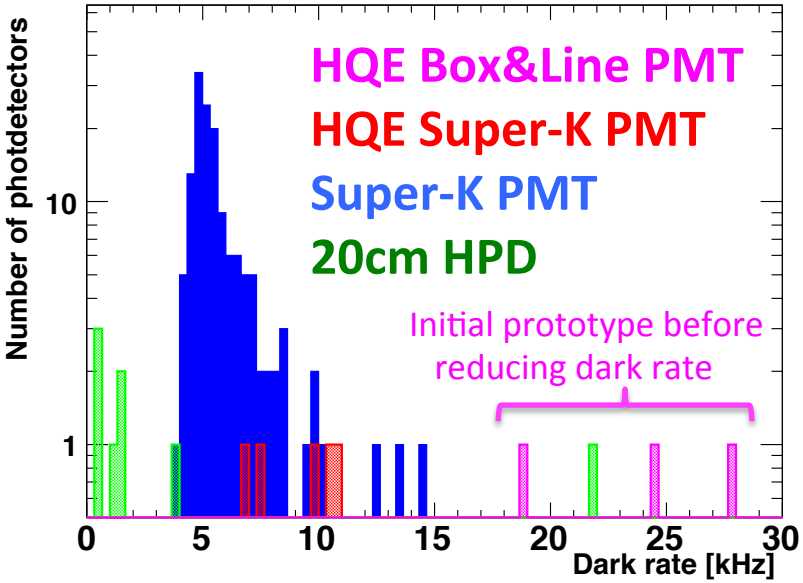
Dark rate measured in tank by thresholds





- Dark rate scanned by thresholds, where the rates are flat around 1 p.e. hit threshold defined as dotted lines.

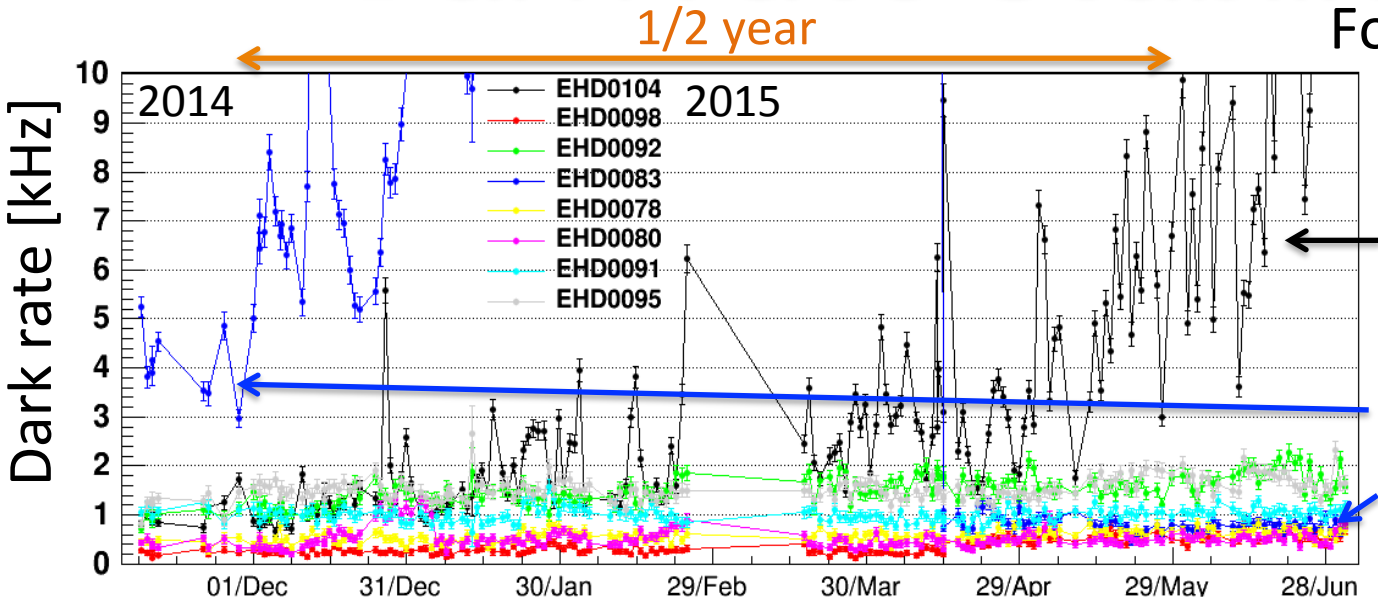
Dark rate in recent 8 months average



- HQE PMTs tend to get high rate because of high QE, while the 20 cm HPDs show 1 kHz or less due to small aperture.

Dark rate stability

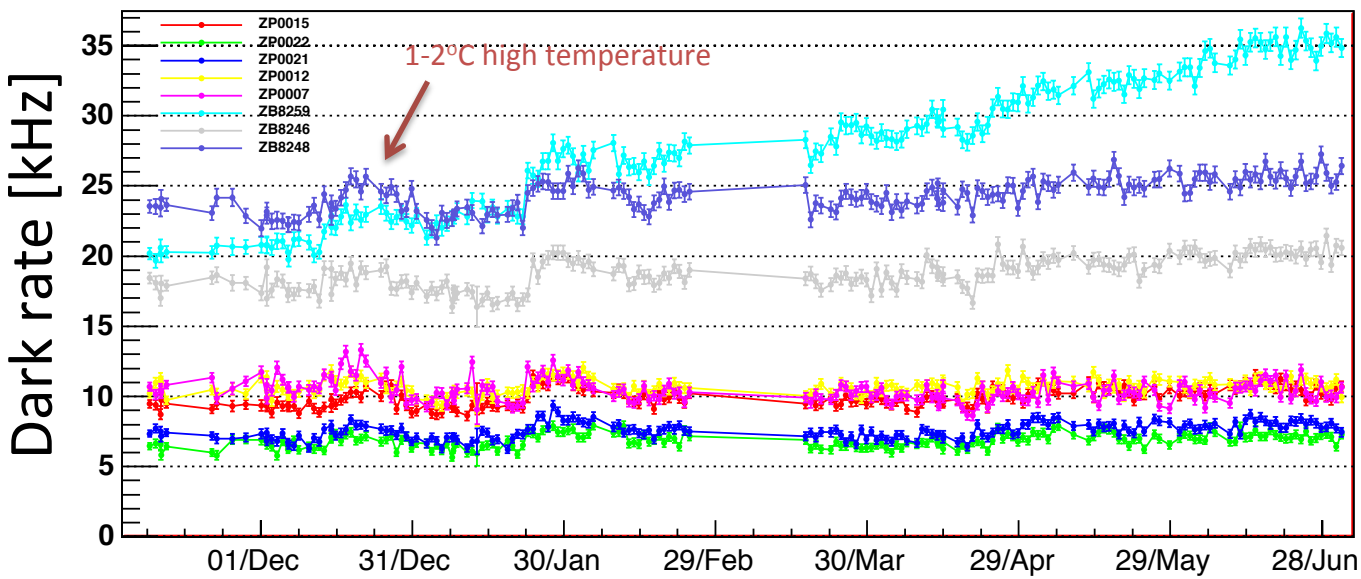
For recent 8 months



20cm HPD

Low gain and unstable

1 HPD got unstable rate, due to high AD bias V near to breakdown, and stable after bias lowered.



High QE PMT

3 HQE Box&Line PMTs

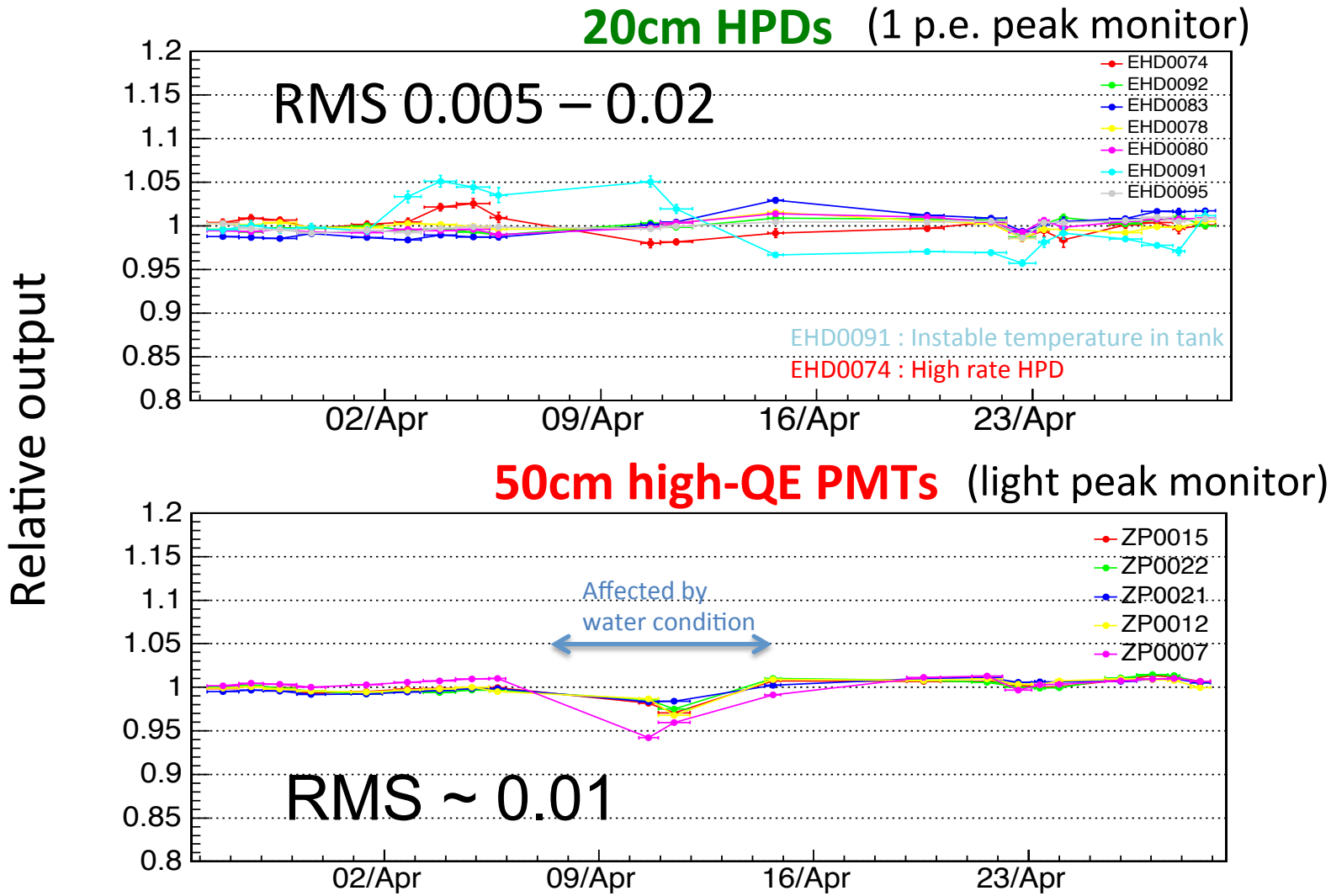
1 PMT getting high rate.

NOTE : Recent version got half reduction similar to HQE Super-K PMT's

HQE Super-K PMT

Almost stable ~8.4kHz

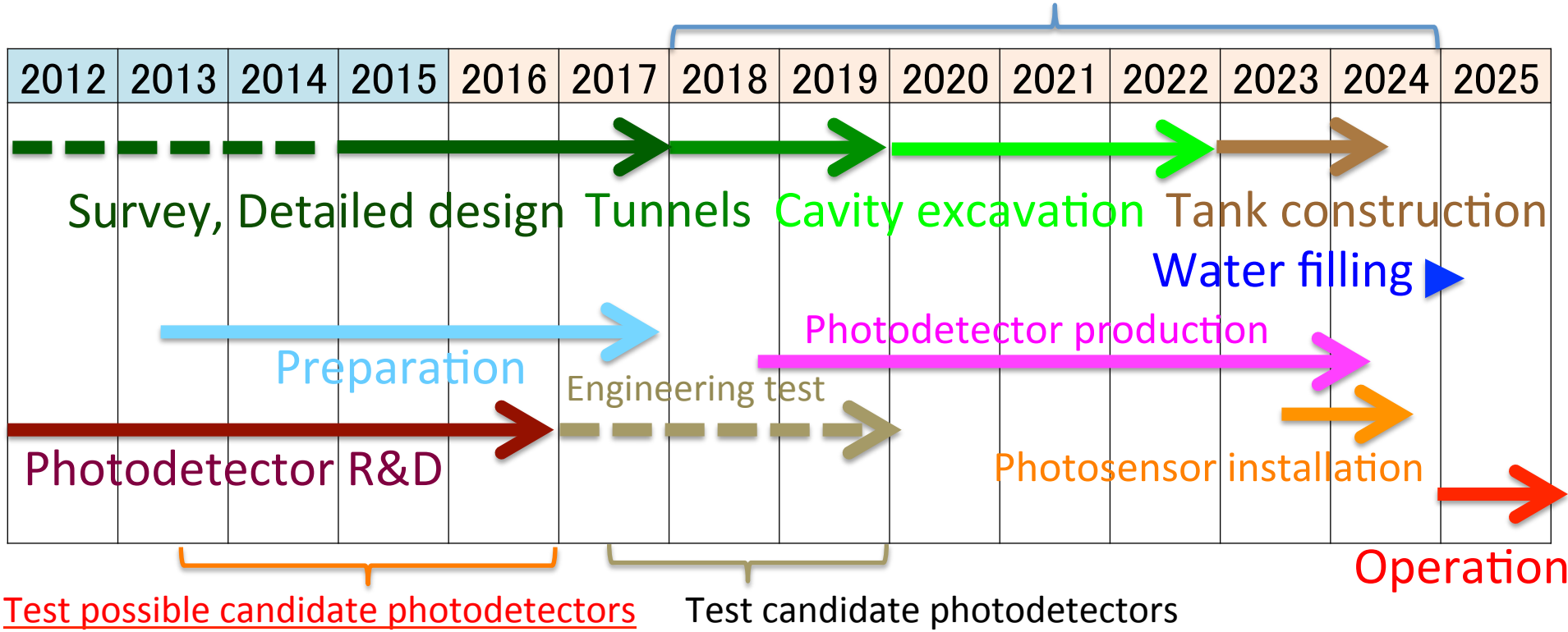
Gain Stability for 1 month



A good gain stability (1% RMS) is confirmed. Long-term stability will be concluded in the end later.

Notional Timeline

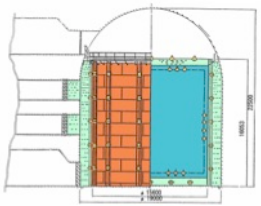
(Assuming budget approval, not determined yet) 7 years construction



- Determine photodetector for Hyper-K in 2016.
- Hyper-K starts from 2015 in earliest case

Summary

Kamiokande (1983-1996)



1k PMTs
/ 3 kton water
Hamamatsu R1449

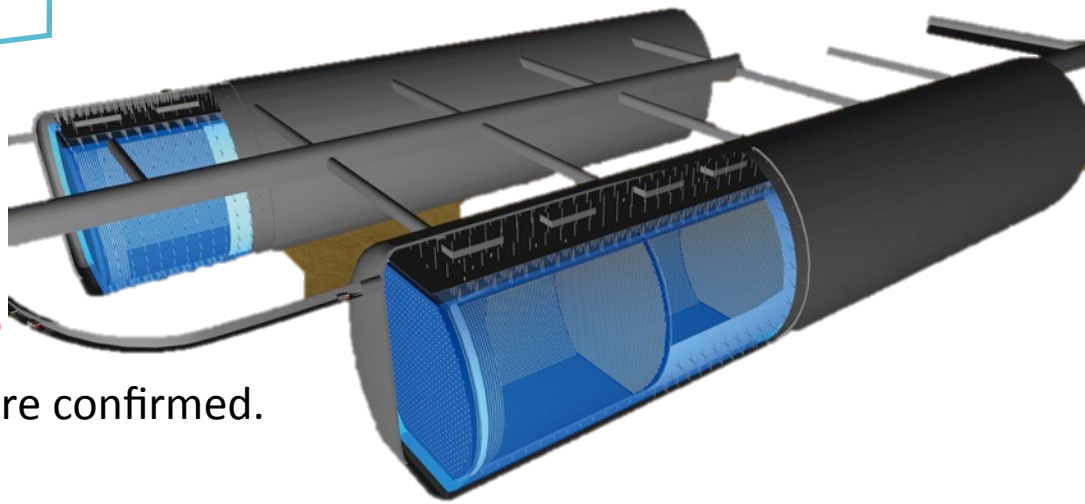
Super-Kamiokande
(1996-)

Hamamatsu R3600

11k PMTs
/ 50 kton water

Hyper-Kamiokande
(2025?-)

99k Photodetectors
/ 1 Mton water



Hamamatsu R12850HQE, R12860HQE, …?

Double efficiency and high resolution were confirmed.

Hyper-K performance would be improved by new photodetectors.