New Large-Aperture Photodetectors by Hamamatsu

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ICRR Institute for Cosmic Ray Research University of Tokyo RCCN, University of Tokyo

on behalf of the Hyper-Kamiokande Japanese photodetector group

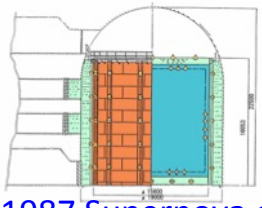
Water detector satellite meeting at Stony Brook, NNN15 satellite

27/Oct/2015

History of Hamamatsu large aperture photodetector(PD)s

Photodetectors by Hamamatsu, related with Kamiokande series

Kamiokande (1983-1996)



1k PDs
/ 3 kton water

1987 Supernova observation
by Hamamatsu R1449

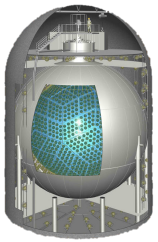
1st 20" PMT becomes IEEE milestone

Super-Kamiokande (1996-)

11k PDs
/ 50 kton water

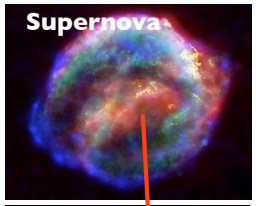
1998 Discovery of ν osc.
by Hamamatsu R3600

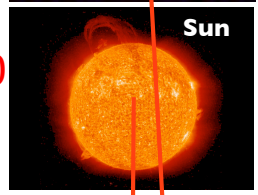
KamLAND

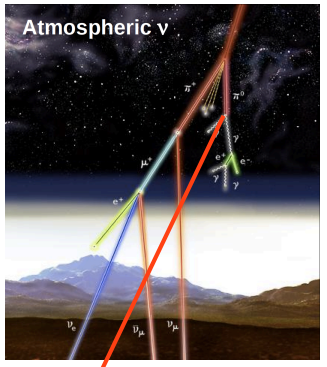


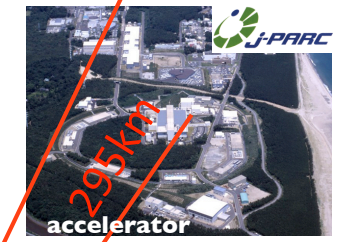
Hamamatsu R7250
(17" Box&Line PMT)

Hyper-Kamiokande (2025?-)

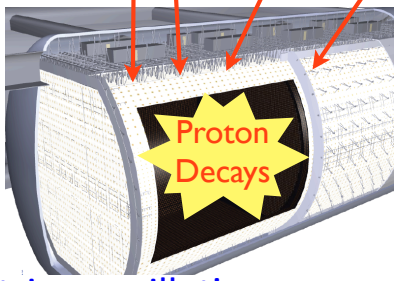








99k PDs
/ 1 Mton water
Hamamatsu ?



Various physics topics

- Neutrino oscillation
  - Atmospheric, solar, accelerator ν
- Nucleon decay
- Astronomy, Neutrino geophysics, Dark matter

Various topics of physics and astronomy

Test of new photodetectors & Hyper-K prototype

Developing and testing new photodetectors

240 PDs
/ 200ton

Hamamatsu R3600HQE,
HPD (R12112, R12850HQE),
Box&Line PMT (R12860HQE)

50 cm photodetectors

By Hamamatsu Photonics K.K.

- New 50 cm Φ photodetectors developed for HK.

Model	R3600 (Used for 2-30 yrs)	R12860	R12850 † still in R&D
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

C.E. = Collection efficiency of 1 photoelectron, T.T.S. = Transit Time Spread, by calculation

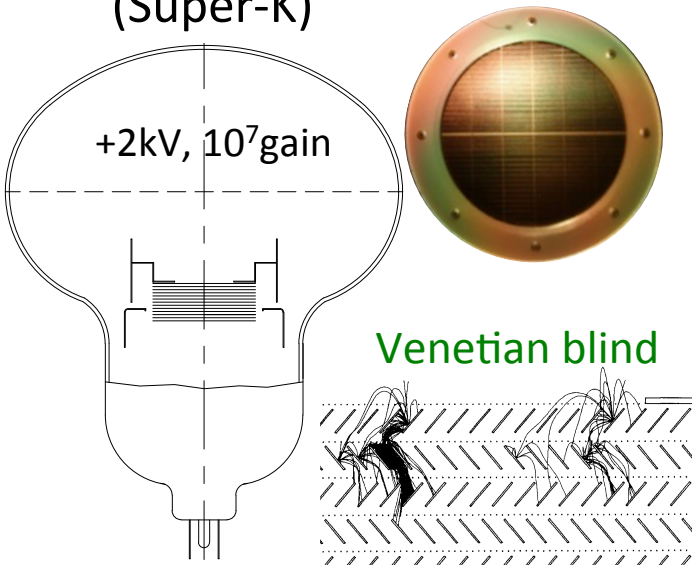
Principle of amplification

50cmΦ

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

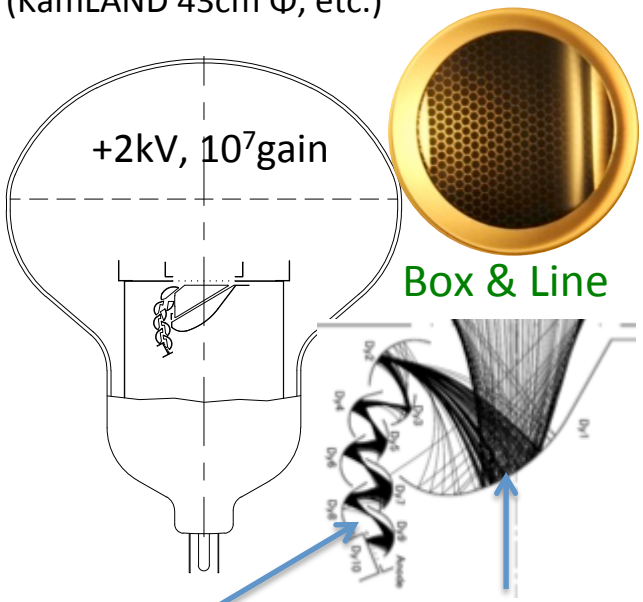
Photomultiplier tube (PMT)

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.

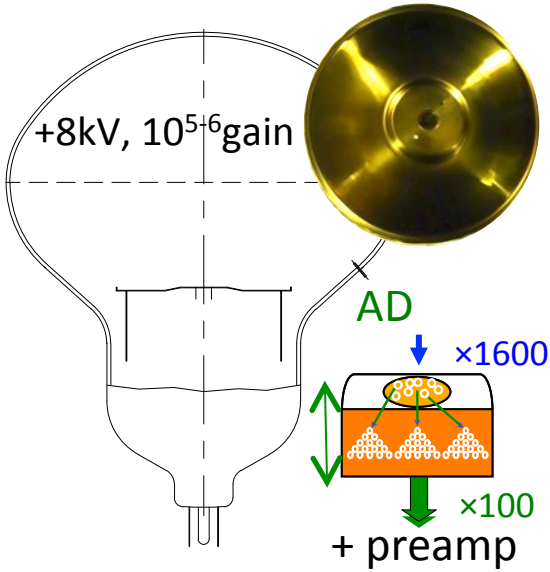
New **Box & Line dynode**
(KamLAND 43cm Φ, etc.)



High collection efficiency
Uniform drift path
→ High 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 planned in Kamioka

Reliability

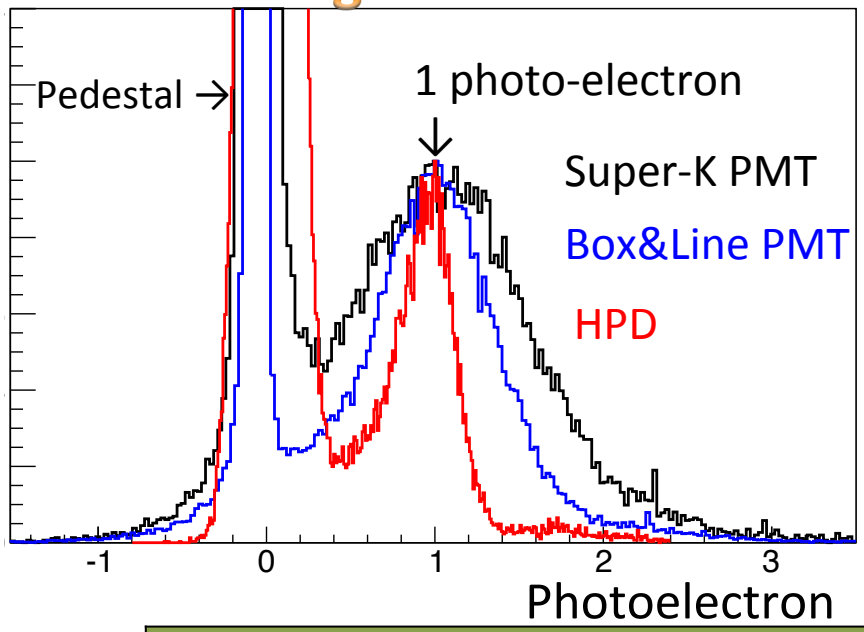
Low cost, High performance

Single Photo-detection performance

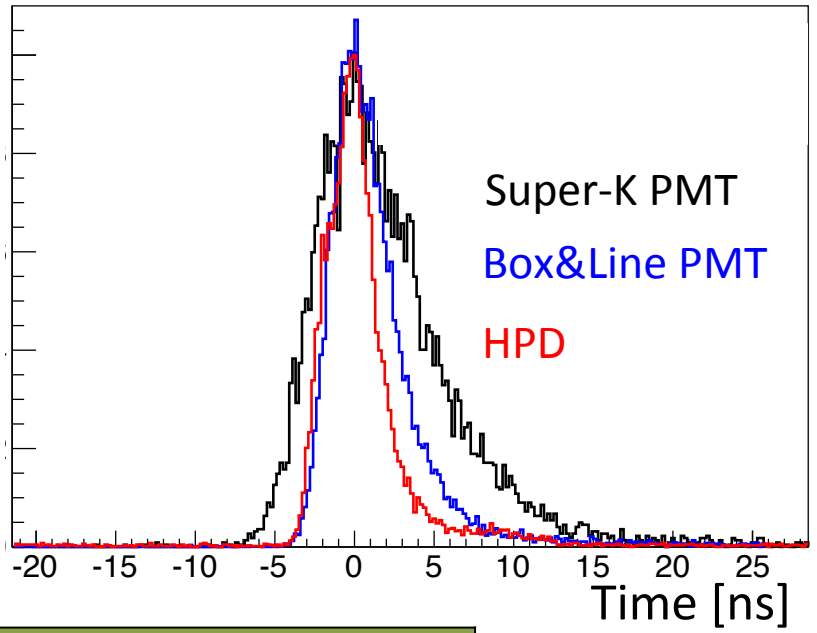
(Presented in NNN14)

Evaluated three 50 cm photodetectors

Charge distribution



Time distribution



Single p.e. resolution	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 (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.

List of photodetectors

- Super-K PMT (R3600 Hamamatsu) *Many at Kamioka!*
- High-QE Super-K PMT (R3600HQE)
  - For first trial of high-QE application on 50 cm Φ diameter.
    - 5 of 8 are being tested in water.
- High-QE Box&Line PMT (R12860HQE)
  - Initial prototype (3 are tested in water, ~20 kHz)
  - Low noise ver. (Dark rate and after pulse were reduced, 6 samples were measured.)
  - Improved ver. with high pressure and geomagnetism resistance, coming soon.
- HPD (20 cm R12112 and 50 cm R12850)
  - 20 cm HPD (8+2 of R12112 are tested in water, and two R12112HQE at Kamioka)
  - 50 cm HPD with 5 mmΦ avalanche diode
  - 50 cm HPD with 20 mmΦ avalanche diode (1,2,5ch)

A few samples for preamplifier R&D

Many R&D items

- Design and calculation
  - Electron track, waterproof, simulation in full acceptance

By Hamamatsu with discussion

- Measurement and setup
  - Efficiency (CE, QE, hit inefficiency, window transparency)
  - Detection performance (Gain, charge and time, dynamic range of voltage and frequency)
  - Environmental dependence (HV, magnetic field, temperature, in water)
  - Background (dark rate, flasher, radio isotope, after pulse)

By ICRR, Japan, ..

- Electronics and accessories
  - Bleeder circuit / preamplifier
  - HV power supply, cable and connector
  - Cover, supporter band, reflection sheet, light collector
- Mechanical strength
  - Pressure resistance of glass bulb
  - Protective cover and implosion test
- Implementation of performance in software

By ICRR, Japan, but would appreciate any help.

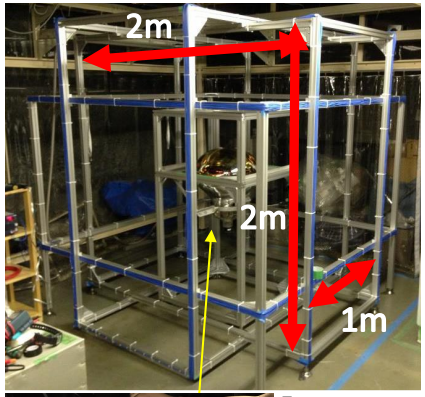
Many R&Ds are still ongoing.

Test facilities in ICRR, Japan

Performance evaluation (Kamioka)

VME ADC(CAEN V265, Lecroy 1182), TDC (CAEN V1290 multi-hit), Scaler (REPIC), HV (iseg), FADC (AVM16 WIENER, DRS4 at PSI up to 5GHz sampling), TKO ATM and QBEE (SK electronics)

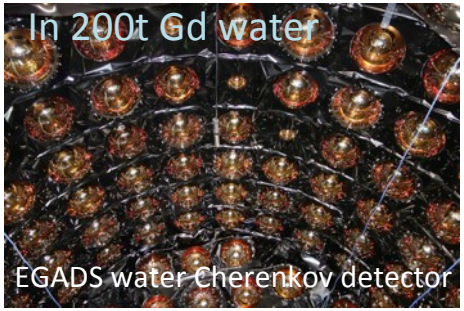
3-D Helmholtz coil (Kamioka)



For response uniformity measurement

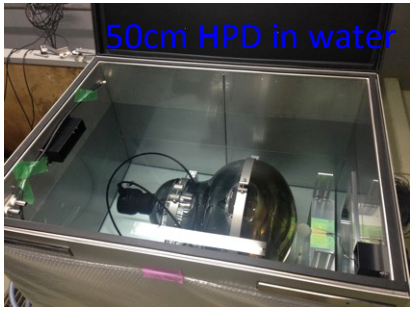
High pressure water vessel (Kamioka)

Proof test (Kamioka)



Thermal control room (ICRR, Kashiwa)

Dark water box (ICRR, Kashiwa)

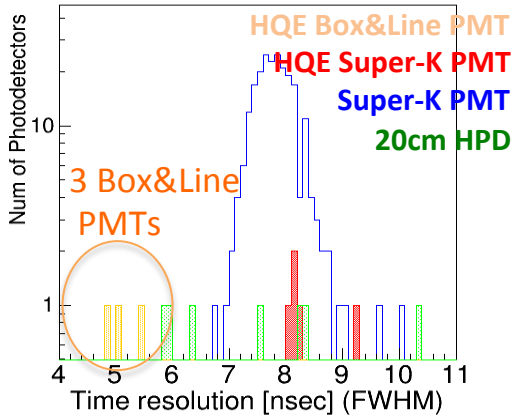


- Still preparing several setups: large high pressure vessel for PD cover, automated uniformity scanner (to check design and production quality, with multi-ch LED pulser), PD holder, setup for reflection sheet/right collection study, …

Examples of measured performance

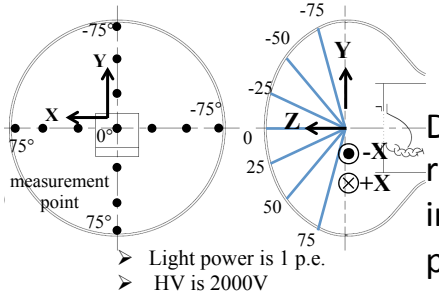
Using the facilities

Time resolution at 1 PE in 200t water tank

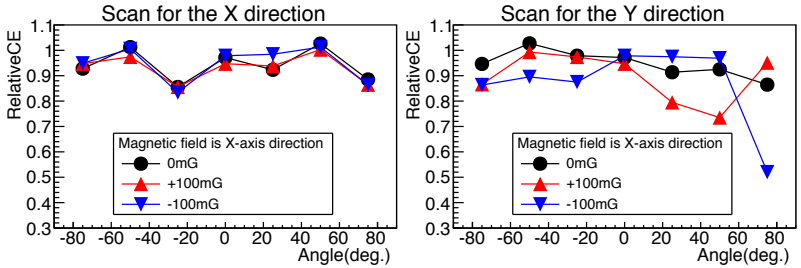


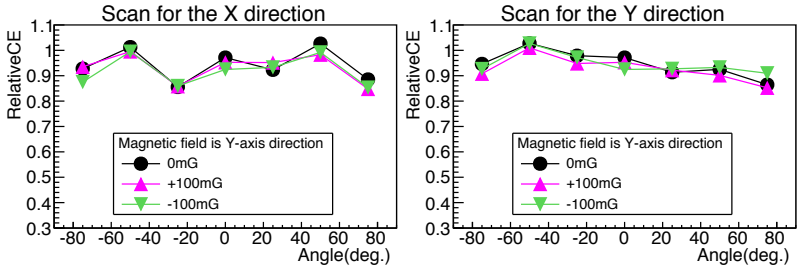
Uniformity of relative collection efficiency

measured in the coil

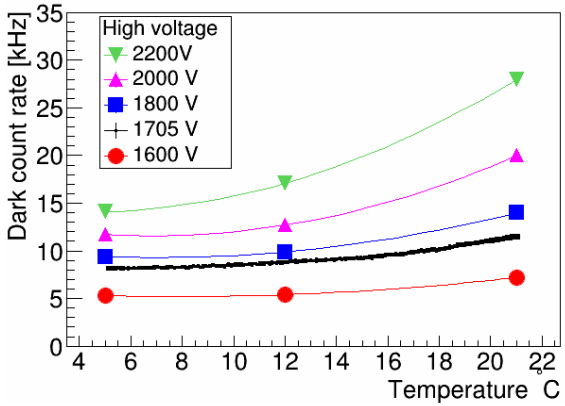


Details will be reported by D.Fukuda in NNN15 poster presentation.





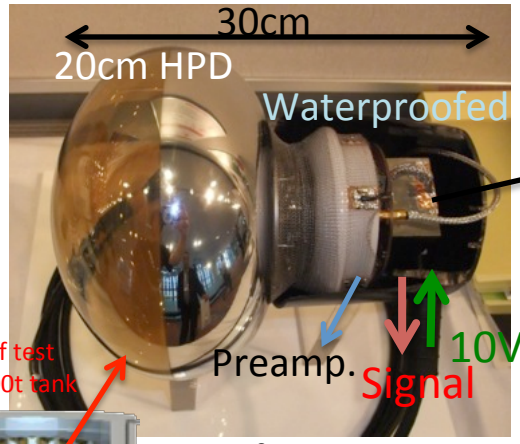
Dark rate as a function of temperature

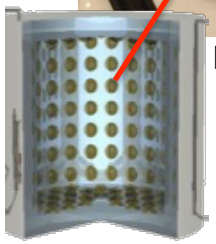


- Further improvement on HQE Box&Line PMT recently
  - low dark rate (20→10 kHz) and after pulse (0.3 → 0.05 for 1 primary pulse)
  - and next with reinforced bulb shape

R&D of built-in HV power supplies

Built-in HV was adopted for 20cm HPD in proof test.





In proof test, one HV module got over current, thus improved version was developed.

Control Power Supply

10ch x 6 LV cables

2 Power supply lines (10V)

- For HV unit and Pre-amp.

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)

Built-in HV prototype for 50cm Box&Line PMT

There are built-in HV application for PMT in other experiments.

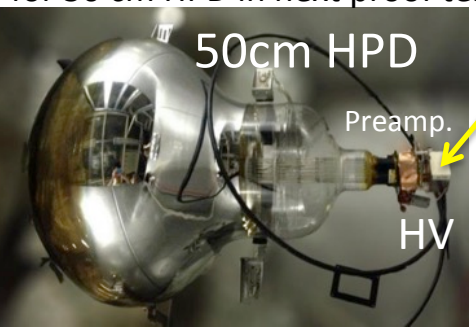
Alternative to consider possibility of cost saving and stabilization (if possible)

8kV power supplies for HPD
(By 3 manufacturers)

Works instead of bleeder circuit attached on PMT

(+12V power, up to 2500V out)

Best product will be selected for 50 cm HPD in next proof test.

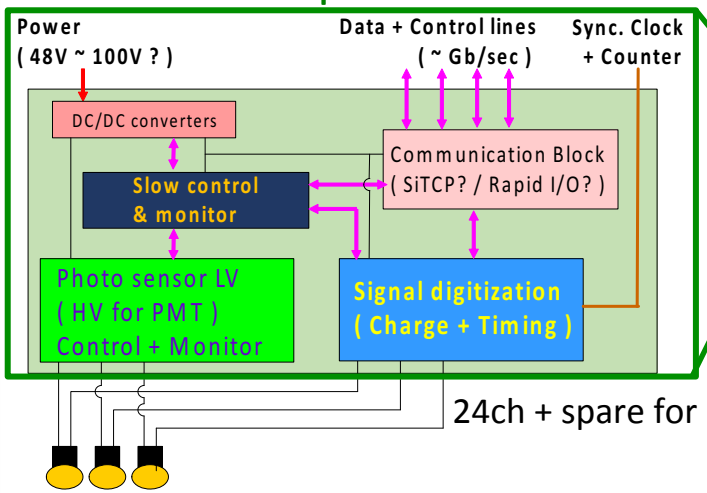


Long life over 20 years and few failure rate are necessary(, but hard). Dedicated study is required to prove it.

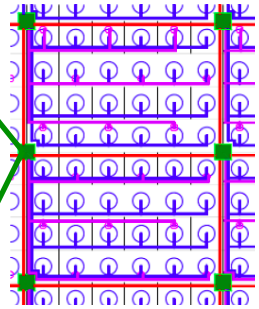
R&D of external HPD HV power

External HV is still primary option for both HPD and PMT.

HV from waterproof electronics



Part of inner tank wall



24ch + spare for redundancy for ID sensors

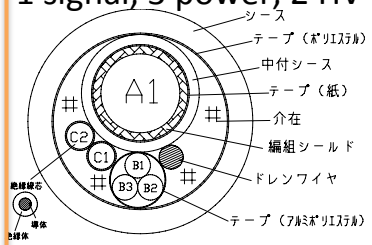
Need external HV R&D including cable and connector.

Requirements of multi-ch HV for HPD

Size	within 40cm x 25cm x 5cm height
Number of output channels	24 ch + Spare (2-3)
HV rating	High volt. (HV) 0.25 – 10 kV / Low volt. (LV) -80 - -1000 V
Maximal HV/LV current	25/1 uA
Polarity of output HV	Positive referred to GROUND
Polarity of output LV	Negative to the output HV, refer to HV
Power	12-24V DC
Power consumption	< 50 W (&Protection for power cut)
Exhaust heat	Radiator to chassis (No heat sink&Fan)
Ripple	< 10 mV pp
High volt. precision, linearity	< 1%, < 5 ppm/V at 6 kV
Voltage stability	< 80 ppm/℃
Individual difference of I/O	Within 1%
Line regulation	< 0.2% at 20% fluctuation of Vin
Control	Not decided (Analog, Ethernet, ..)
Type of control	Enable, LV, HV, Max current for each
Type of monitor	Current, HV, LV, temperature
Spare	Remotely replaced with dead ch
Ramp up speed	3500 V/sec
Rating life	Over 15 years

HPD cable and connector R&D

1 signal, 3 power, 2 HV



HPD cable complex including 8kV lines

Connector mock-up used in 100m water depth.

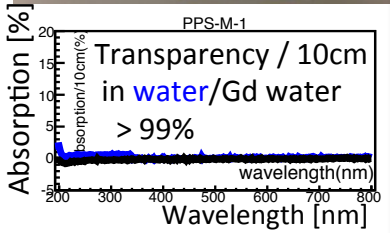
HV cable was also developed for HPD.

HPD two HV lines

Material selection

Soak test in pure /Gd loaded water for 3 months.

Most material got no trouble. PPS and FMK are good candidate.

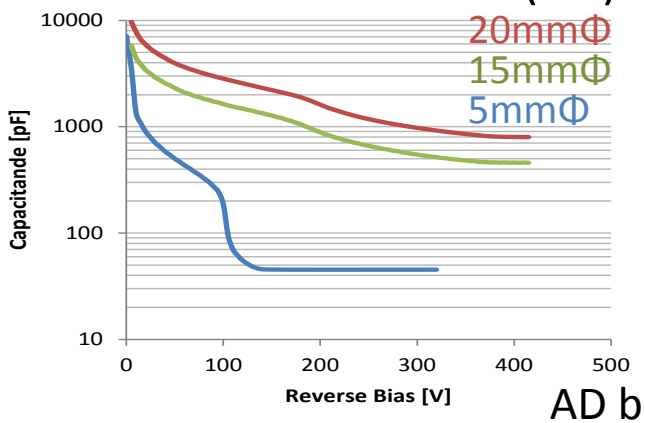


High potential test of cable and connector are going.

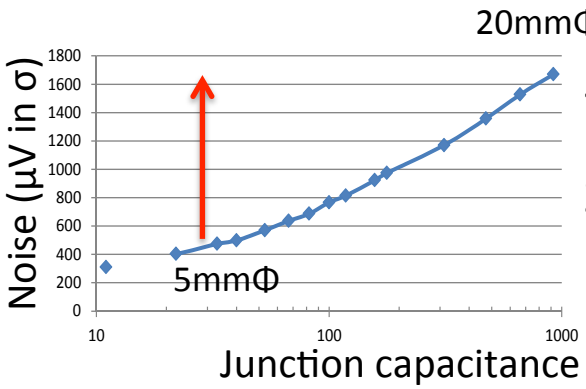
Prototype for test in water in half a year.

HPD preamplifier R&D

Junction capacitance of avalanche diode (AD)



Noise level by capacitance



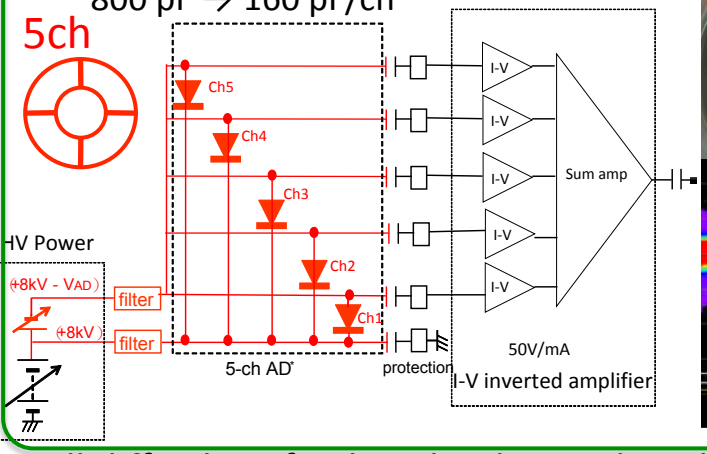
5mm Φ was used in 20 cm HPD and initial 50 cm HPD evaluation.
20mmΦ is required for 50cm HPD.
→ Amplifier design becomes difficult in 50cm HPD.

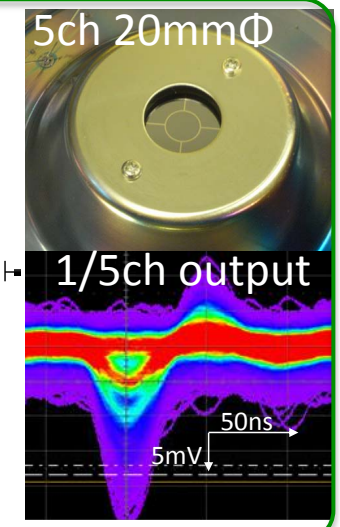
AD bias [V]

Two solutions were tried to suppress noise.

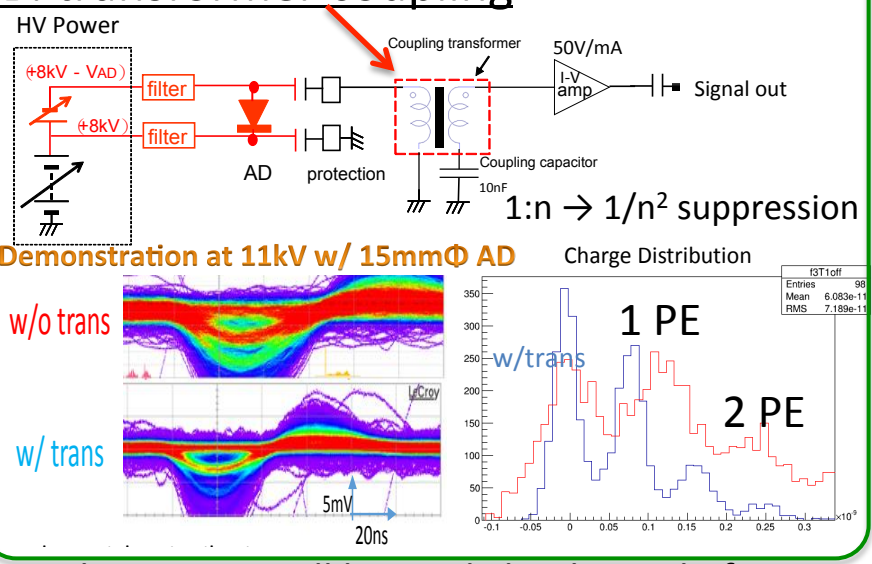
A. 5 segmented area

800 pF → 160 pF/ch



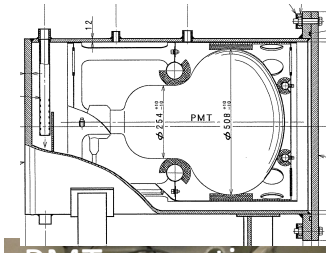


B. transformer coupling

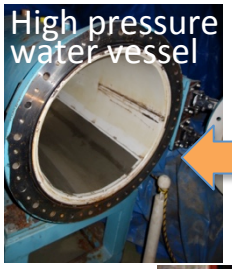


Still difficult to finalize the design, but the first version with combining two will be ready by the end of 2015.

High pressure test

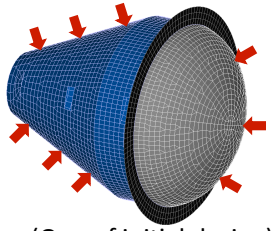


More safety design is required in HK (SK ~40 m → HK ~50m).
→ Test HQE Box&Line PMT and cover



- High pressure resistance
  - Test of initial design for the 35 PMTs
    - All above 70m water, weak PMTs have thin glass
  - Improved design showed no implosion at 1.5MPa
    - For ten PMTs for first samples, still continuing
      - Other two with thin glass imploded between 1.25-1.5 MPa.
- Cover design and chain implosion test
  - Cover to prevent shockwave from going outside without broken.
    - New design is being studied.→

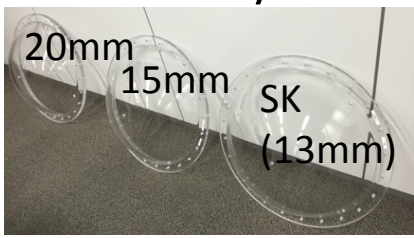
Stainless steel



(One of initial design)

\+

Thick acrylic

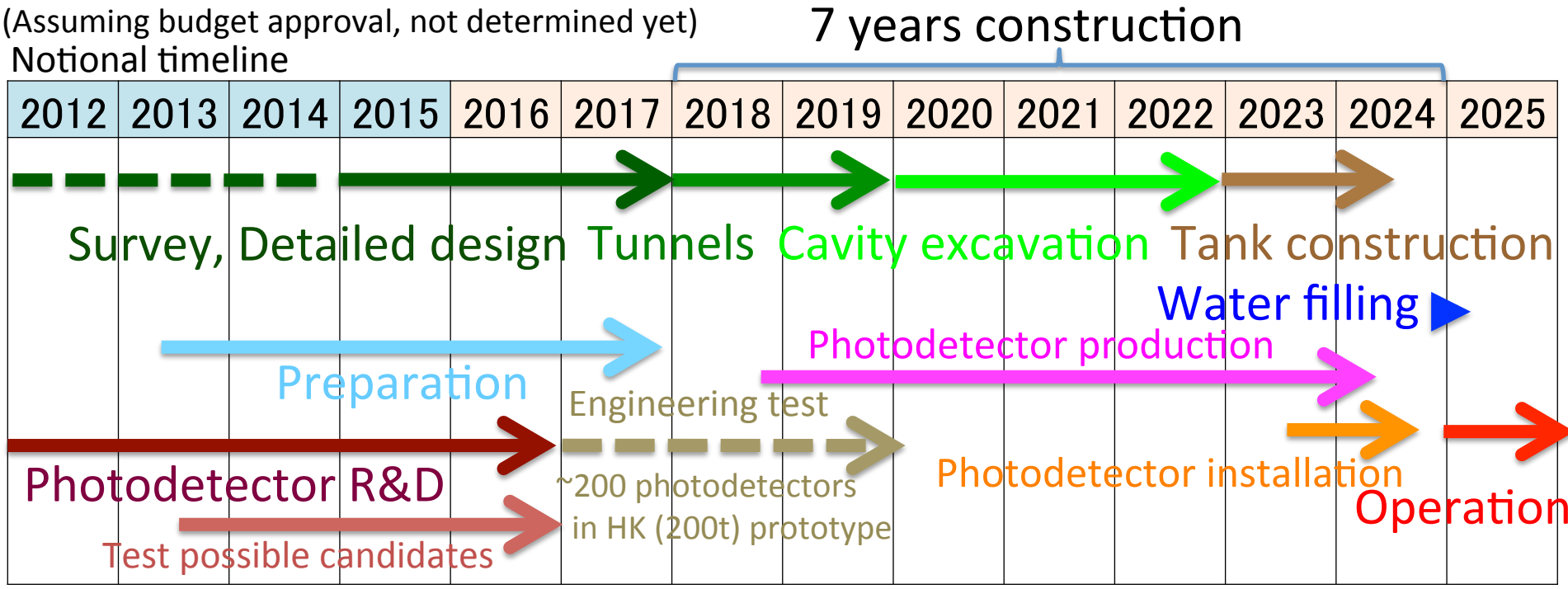


  - Chain implosion test will start in deep 60-80m water in early 2016.
    - Nine aligned PMTs with cover are monitored during imploded.

Flow of Hyper-K & photodetector R&D

(Assuming budget approval, not determined yet)

Notional timeline



Photodetector R&D and test

Determination of HK PD

Construction of HK prototype

2015 | 2016 | 2017 | 2018

HQE 20" HPD

Preparation & Test

20"HPD in water tank

Prepare

Construct

Production

~200PDs

Start

Most related R&D, design for PD

To be ready for HK prototype

Electronics and DAQ R&D

…

Ready in a coming few years for HK

Summary

- New 50 cm photodetectors showed high performance.
- Remaining R&D items
  - High-QE Box&Line PMT
    - Ready for HK after high pressure test and implosion test with cover.
  - High-QE HPD
    - Preamplifier design is necessary. Ready soon and tested in early 2016.

- 2nd HK Proto-Collaboration Meeting on 31/Jan – 2/Feb
  - http://indico.ipmu.jp/indico/conferenceDisplay.py?confId=79 (Under preparation, open soon)
    - Join HK proto-collaboration if you attend.
- Any cooperation would be appreciated.
  - Contact HK photodetector conveners (Y.Nishimura and S.Nakayama) freely.

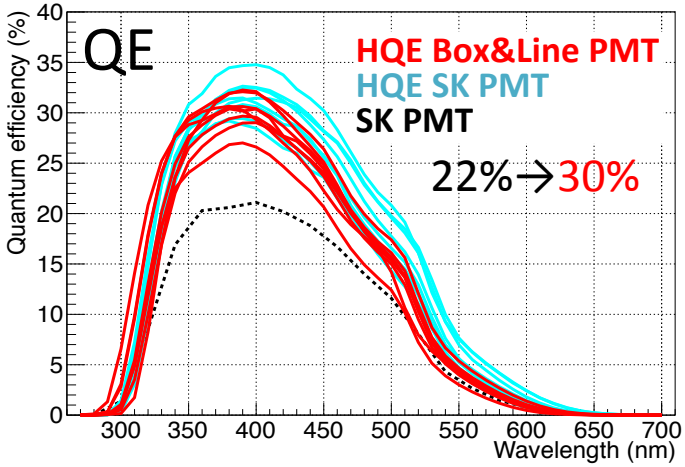
HPD preamplifier requirement

	Goal in 2015	HK ideal target
Charge gain	140	500
(IV gain)	(200V/mA)	(200V/mA)
Input charge / 1 PE	10fC	5fC
Output pulse height / 1 PE	12mV	8mV
Rise/Fall time (After amp, 10-90%)	12ns / 18ns	4ns / 4-20ns
Ringing (Pulse height ratio)	< 20 %	< 5 %
Recovery time (Baseline to be within 0.5mV)	< 150 ns	< 40 ns
Noise (Pk-Pk RMS)	0.3 mV	0.1mV
Noise (Pk-Pk Max、<1Hz)	2mV	1mV
Linearity range (10%)	-1.5V	-4V
Dynamic range	- 2V	- 6V
Life time (<1% failure)	> 2 years	> 15 years

Box&Line PMT

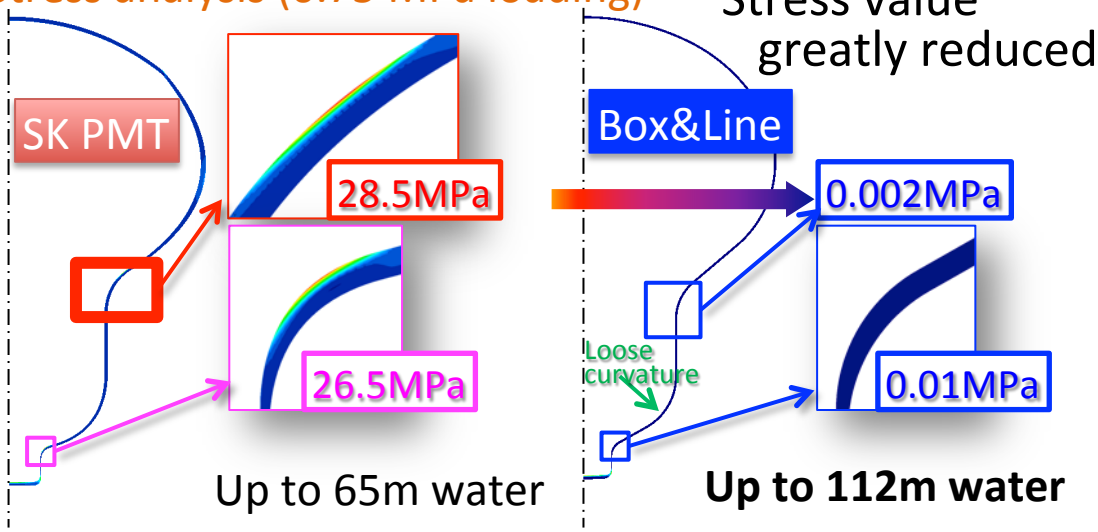
- High QE is applied for all Box&Line PMTs.

QE of Box&Line PMT is similar to that of high-QE Super-K PMT



- Safety design
  - Good high pressure tolerance

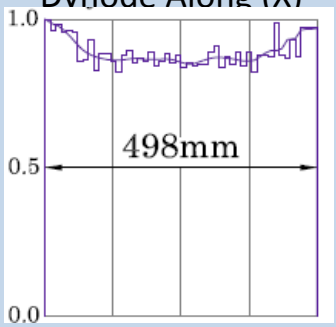
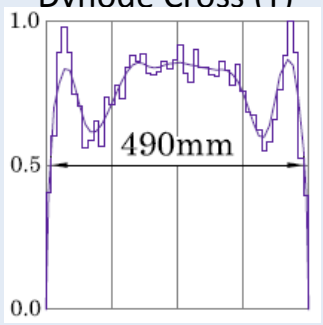
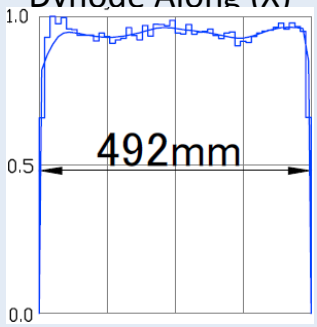
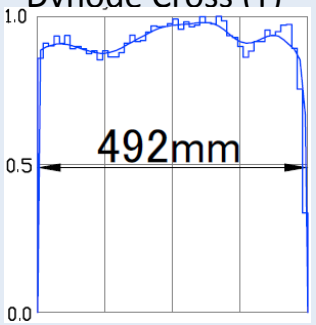
Stress analysis (0.75 MPa loading)



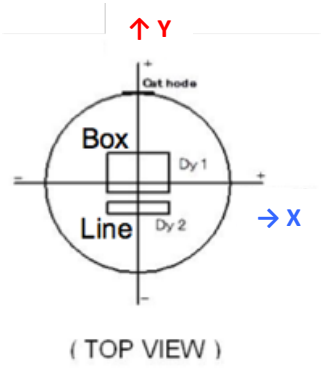
Also actually tested in 0.9MPa water for 1 day

- Same material outside and size except for curvature as SK PMT → No problem for use in Gd water

Uniformity of Box&Line PMT

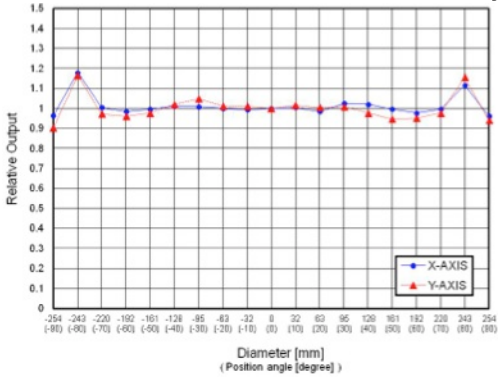
Simulation (Hamamatsu)	R3600 SK PMT		HQE Box&Line PMT	
Gain × CE uniformity	Dynode Along (X) 	Dynode Cross (Y) 	Dynode Along (X) 	Dynode Cross (Y) 
C.E.[%]	86.0		98.2	

Measurement (Hamamatsu)

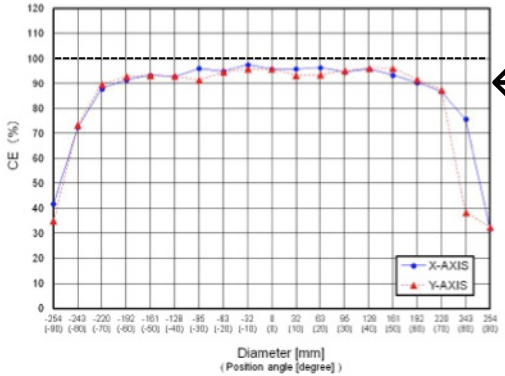


Uniform response & high efficiency confirmed in measurement

Relative QE uniformity



Collection efficiency



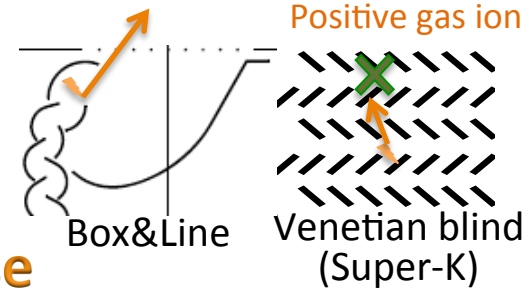
←90%

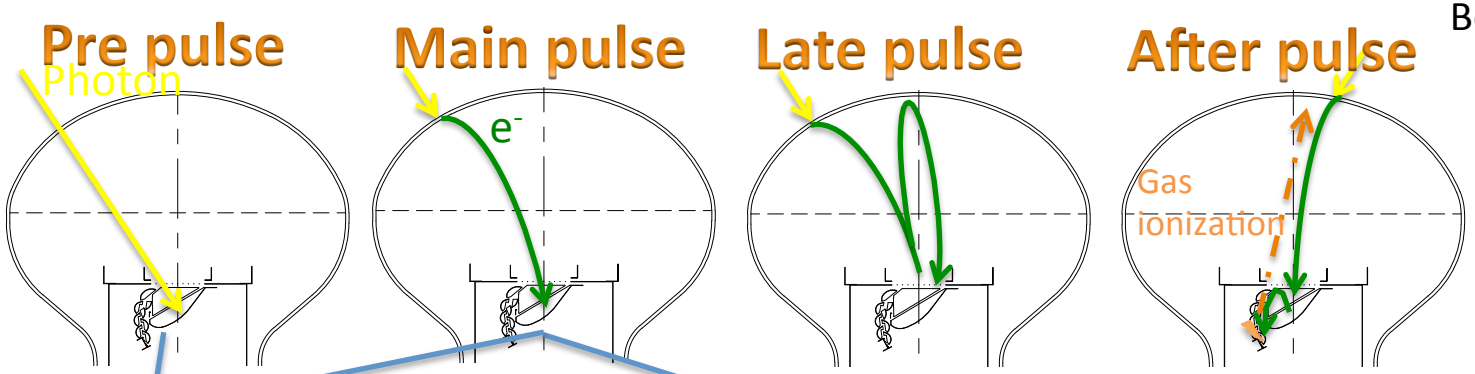
Diameter

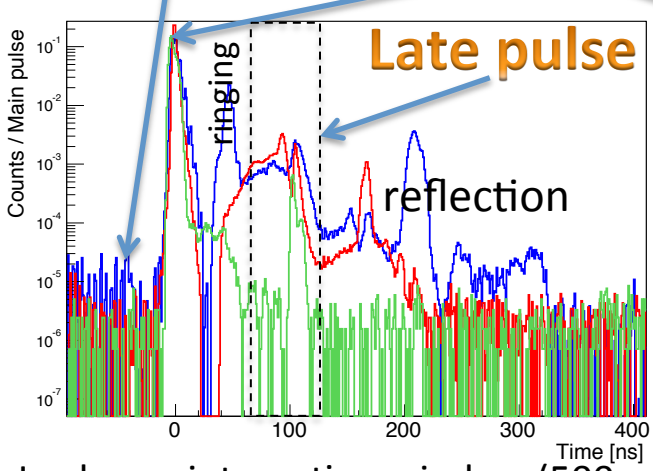
- Setup to measure resolution, transit time, … is under preparation.

After pulse

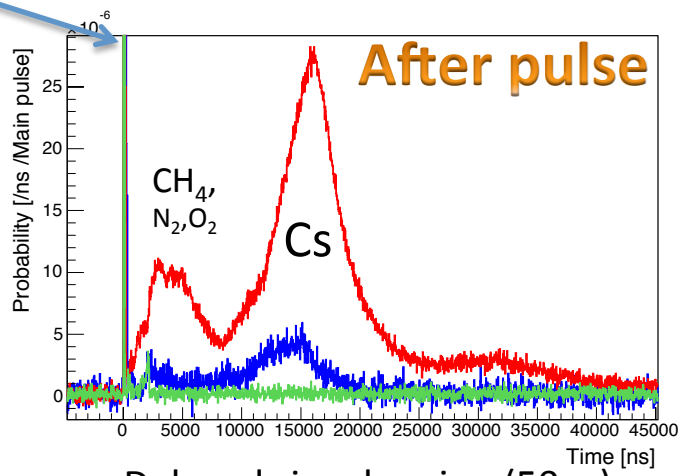
- Concern on Box&Line PMT about after pulse rate.
  - Intrinsically more than SK PMT in its design.







In charge integration window (500ns)



Delayed signal region (50μs)

50cm Φ PDs
- HQE Super-K PMT
- HQE Box&Line PMT
- HQE HPD (w/5mmΦAD)

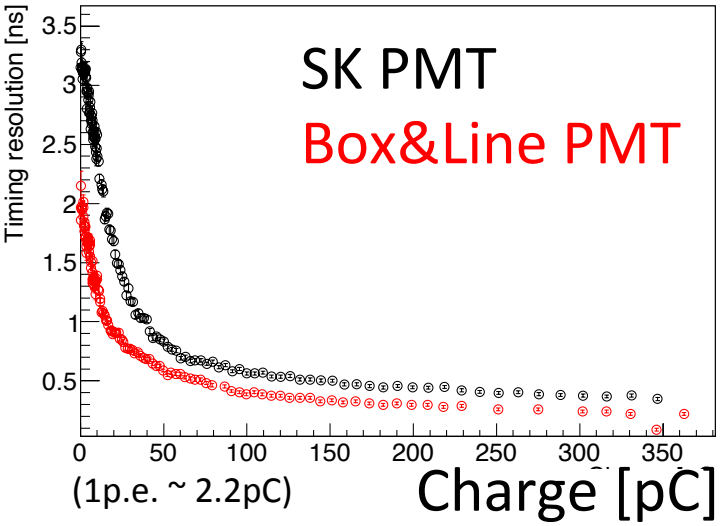
NOTE : HPD w/5mm Φ AD prototype has less collection efficiency, half than its design (20mmΦ). Need evaluation in final design.

(Before reduction of HQE Box&Line after pulse)

Performance in wide range

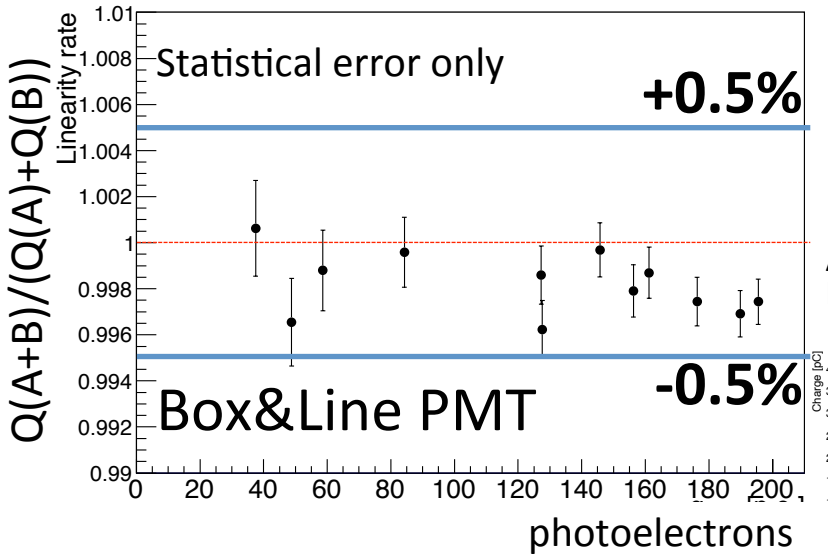
By large amount of photons

Better time resolution
was confirmed in wide range

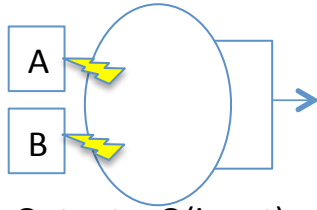


Gain stability in two continuous pulses

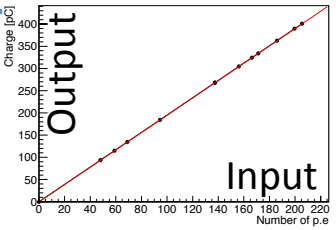
Good output linearity within +/- 0.5%



Using 2 laser diodes
with coincident or
individual pulse

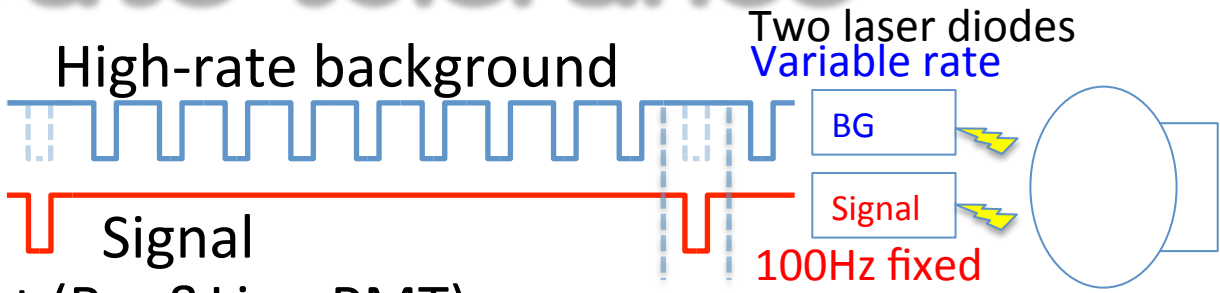


Output = Q(input)
A : Variable
B : Fixed (10pe)

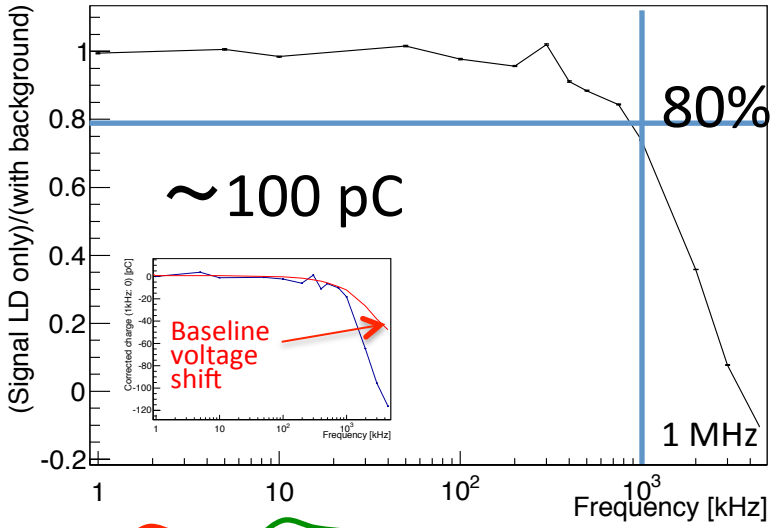


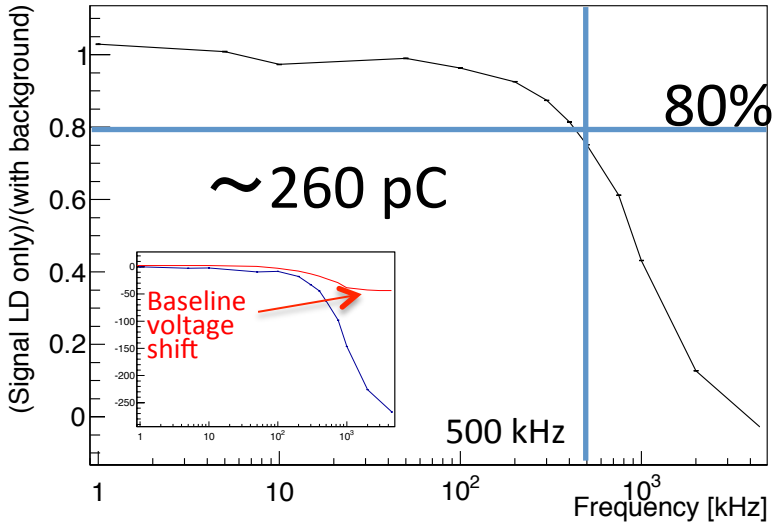
High rate tolerance

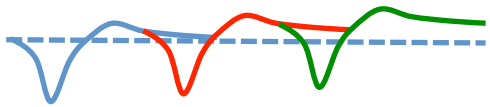
Measured change of signal pulse in different background configuration.



Gain drop in high rate input (Box&Line PMT)

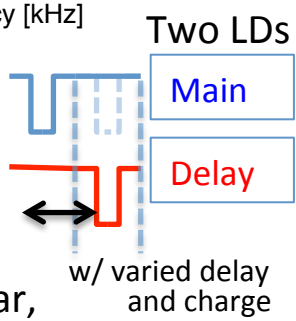






Baseline is shifted due to RC in bleeder circuit.
→ Comparable level with SK PMT.
Shift depends on integration time range and readout electronics.

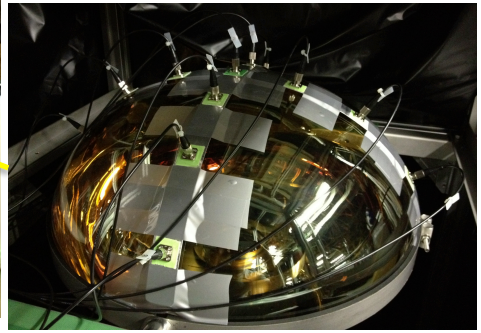
- Gain recovery was also measured with two continuous pulse.
  - Observed change of delay pulse charge = (Delay w/ main) / (Only delay pulse)
  - No significant change was observed so far, within 1.5%.



Magnetic field effect

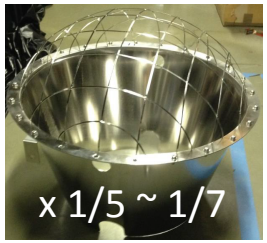
3D Helmholtz coil was constructed to compensate/control B-field.

X-Y scanning of single hit rate
(LD + optical fibers)



Also tested option using passive μ-metal shield

μ-metal shield
prototype



+

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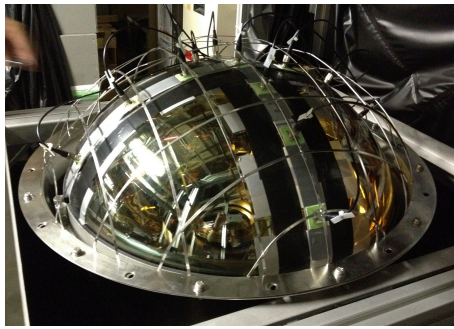
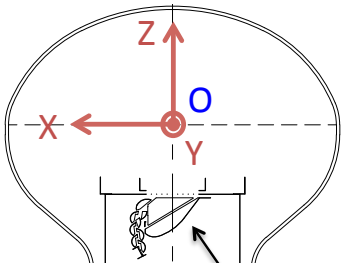


Just for consideration of possibility
with combination use of active and passive (in part of HK) shield

Result on efficiency scan in Box&Line PMT

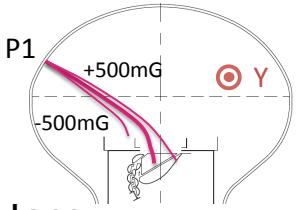


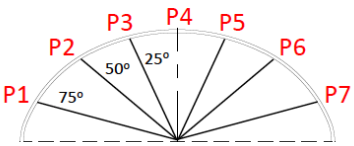
Box&Line dynode

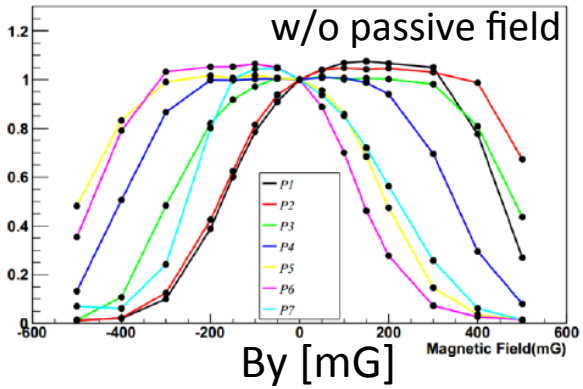
Examples with largest loss (By along X)

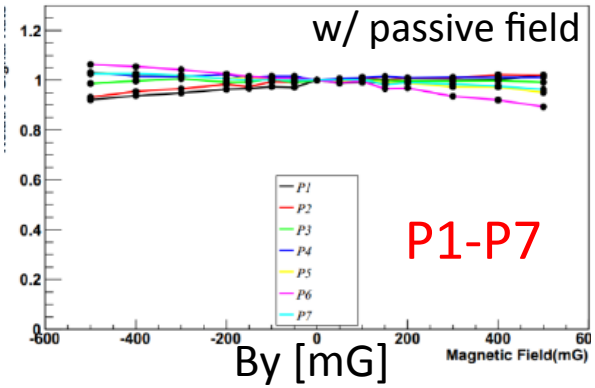
Relative hit counting loss by B

Worse in its design









Maximum efficiency loss

- Bx 100mG : 20% loss
- By 100mG : 30% loss
- Bz 100mG : 5% loss

Plan to measure effect on gain, transit time, resolution, … in all sensors

Proof test in EGADS

2012 | 2013 | 2014 | 2015 | 2016 | 2017

20cmΦ HPD

8 HPDs

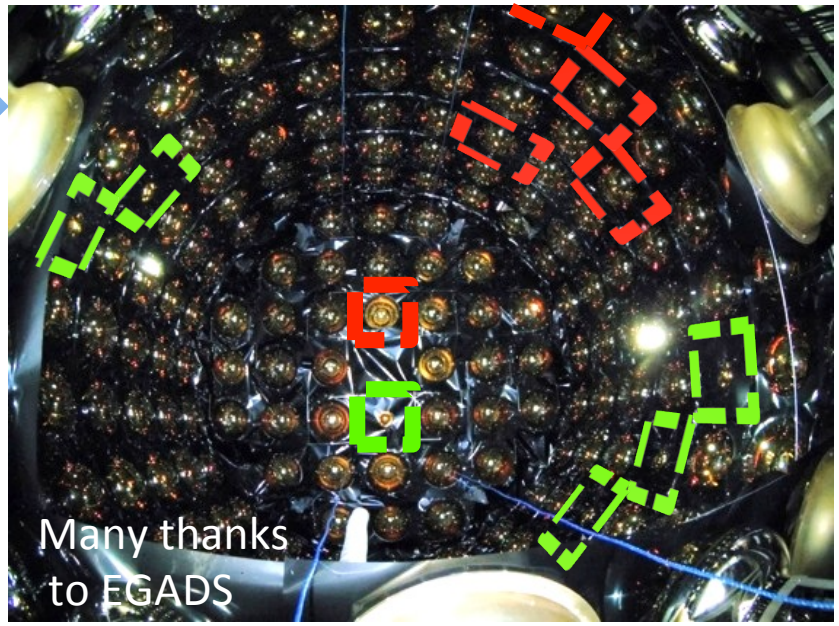
1st proof test (2013.8 -)

5 HQE PMTs

1st test with
5 HQE PMTs and
8 20cm HPDs
over half a year so far

High QE
for SK PMT

Proof test



New PMT
w/ box&line dynode

(2014.9 -)

Installed 3 HQE Box&Line PMTs in summer.
Started 2nd phase test

50cmΦ HPD

(Under preparation)

Determine HK photosensor in 2016