The Hyper-Kamiokande detector: R&D studies of a new generation of Photosensors

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On behalf of the Hyper-Kamiokande Proto-Collaboration
50 cm Photo-Detectors

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

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

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

For Kamiokande

(1983-1996)

Supernova ν observation!

1k PMTs
/ 3 kton water

R3600 (Venetian blind dynode, improved)

For Super-Kamiokande (Super-K, SK)

(1996-)

ν oscillation discovery!

11k PMTs
/ 50 kton water

For Hyper-Kamiokande (Hyper-K, HK)

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

Developed → Photo-detector in Hyper-K baseline design

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

Under development → Possible further improvement of Hyper-K

Two types of new 50 cm photo-detectors have been developed since 2011 with much improvement for Hyper-Kamiokande.

For other experiments

42 cm (17”) Box&Line PMT
R7250 (Box&Line dynode) with 50 cm bulb of R3600

For KamLAND

50 cm MCP PMT
By NNVC, IHEP (Micro-Channel Plate)

For JUNO

Recently developed in China

03/01/2017

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**Hyper - Kamiokande**

New high-QE 50 cm Box&Line PMT

- ×2 high pressure bearing for 60 m height
- ×2 high detection efficiency
  and half time&charge resolutions
compared to Super-K PMT (up to ~40m depth)

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

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

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

- Requirements
  - Wide dynamic range
  - High time&charge resolutions, high detection efficiency, ..
  - ~nsec time resolution, low background
  - Clear photon counting,
  - High rate tolerance

- Water Cherenkov detector in Kamioka, Japan

- Hyper-Kamiokande (HK)

- ×40,000
  - 40% photo-coverage
  - 260 kton
  - 74m φ

- 60 m

- 190 kton Fiducial Mass

- ×2 tanks

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

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

50 cm Φ

**Photomultiplier tube (PMT)**

- Venetian blind dynode (Super-K)
  - +2kV, 10^7 gain
  - New
- Venetian blind
- Electron might miss dynodes → less collection efficiency
- Ambiguity of drift path limits charge and time response.

**Hybrid photodetector (HPD)**

- Box & Line dynode
  - +2kV, 10^7 gain
  - Uniform drift path
  - High collection efficiency (CE)
  - High charge & time resolutions
- Box & Line
- High QE
- Simple inside
- Low cost, high resolutions

**Avalanche diode (AD)**

- +8kV, 10^5 gain
- High QE
- AD
- 20mmΦ
- ×1600
- + preamp
- Low cost, high performance

- Performance evaluation
- Validation for a long operation in water are required.
**Design of New Photo-Detectors**

**Box & Line PMT**

Mechanical strength was improved by new bulb design.

- Smoother curvature
- Thicker glass
- Tough waterproof housing

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**HPD**

Built-in HV power and preamplifier

Operated by low voltage lines (<10V)

External HV Option → Confirmed with 100 m HV extension

8 kV & signal connector

R&D, up to 100 m water

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**High pressure water test**

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

- No damage at all samples.
- ×1.9 safety factor for 60m.

→ Established in HK 60m water depth.

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**AD Segmented Option** (400 pF/20 mmΦ)

→ 2 or 5 channels to avoid large capacitance

For amp noise reduction and fast response

5ch AD + Sum amp etc.

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**High pressure water test**

3 HPD bulbs were tested, and there is no damage up to 1.25 MPa as well.
**Detection Efficiency**

**High Quantum Efficiency (QE)**

- **Super-K**
  - 22% at peak
  - 30% at peak (2016 yr)
- **Box&Line PMTs**
  - 30%
- **HPD**
  - 36%

**Collection Efficiency (CE)**

- **Super-K**
  - 67% (61%)
- **Box&Line PMT**
  - 95% (85%)
- **HPD**
  - (1ch 20mmΦAD) 97% (80%)

**Total Detection Efficiency of 1 PE**

- Measured at Hamamatsu by point source injection
- **Box&Line PMT**
  - ×2
- **Super-K**
  - (Hamamatsu R12860) QE = 31% sample
  - (Hamamatsu R3600, QE = 22%)
- **Super-K PMT average**

**Confirmation in relative hit counting**

- Relative comparison of single PE counting compared with SK PMT by a uniform light injection
- **Box&Line PMT**
  - 1.91 of SK PMT
- **HPD**
  - (2ch 20mmΦAD) 1.76 of SK PMT

Detection efficiency was doubled in both new photo-detectors.

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**Gain**

**Box & Line PMT**

10^7 gain at 2000 V typical, by 10 stages of dynode

Gain-HV curve is similar to that of Super-K PMTs

**HPD**

Total gain = Bombardment gain × Avalanche gain × preamp gain

Bombardment gain

~1600 at 8 kV

8 kV nominal

Gain-HV curve is similar to that of Super-K PMTs

Gain is adjusted by AD bias voltage
- Recovery shape is determined by electronics design such as coupling constants.
- Both new photo-detectors show faster response.
  - HPD requires a preamplifier to detect single photoelectron.
Clear photon counting and narrow transit time spread in both new photo-detectors

- Allow precise event reconstruction, background reduction, ...
- HPD performance is still limited by a preamplifier and to be improved.
4. Temperature dependence of dark rate

The dark rate of the Box&Line PMT is currently around ten kilohertz. Figure 11 illustrates the temperature dependency of dark rate. As higher HVs are applied, the dark rate is found to increase, with the temperature dependences varying with the HV as well. The dark rate was found to decrease approximately 30% from room temperature (22°C) to the water temperature (13°C) at 2,000 V, with an approximately 20% reduction seen at 1,800 V.

Figure 11: Temperature dependency of dark rate, 1705 V date is detail measurement tp continuously varied the temperature, which is typical HV gain.

5. Afterpulse

An “afterpulse” occasionally accompanies a primary pulse signal. When the primary pulse is amplified in the dynode, residual gases are ionized via interactions with electrons. Subsequently, the residual gas ions backtrack and ultimately emit electrons on the photocathode. These afterpulses are usually generated within approximately 50 µs after a primary pulse generation. They can be a result of the Hyper-K’s inherent physics, which are coincident signal events associated with decay electrons via muon decay. Virtually all PMTs face difficulties associated with the afterpulse events. However, afterpulses with Box&Line dynodes can be particularly serious because of their large first dynode structures; thus, improvement in this regard was achieved by optimizing the dynode structure itself, as well as enhancing the manufacturing process, dividing voltage rates, and so on. Afterpulse measurements were accordingly performed to confirm such sought-after reduced levels.

5.1 Results

Figure 12 shows the result of the expected ratio of the afterpulse per 500 ns to the primary pulse, as a function of timing. Moreover, Table 1 shows the summary of afterpulse ratios for several Box&Line PMT models. The original (“old”) Box&Line PMT has a large afterpulse rate, which is

- Box&Line dynode tends to bring a large afterpulse rate by its structure.
  - Reduction from 30% to 5% level was accomplished.
- HPD shows a low afterpulse rate.
  - Comparable with Super-K PMT, less than a few percentages.
Dynamic range of HPD is currently limited by a rated voltage of amplifier.

(Intrinsic HPD response is limited by AD (=APD), which is sufficiently high in principle.)
EGADS 200t tank at Kamioka mine for SK-Gd

**Monitoring stability of performance over a year**

**Gain stability monitor**
- ZB8259 RMS 1.53%
- ZB8246 RMS 2.40%
- ZB8248 RMS 1.99%

**Dark rate stability monitor**
- ZB8259 ~34.9kHz RMS 17.0%
- ZB8246 ~19.0kHz RMS 5.8%
- ZB8248 ~24.0kHz RMS 4.9%

Smooth transition,
RMS in a few percentages.

**About 1.5 years**

**High-QE 50 cm Box&Line PMT**

About 1.5 years

224 Super-K PMTs

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

20 cm HPDs × 8
(50 cm HPD will be installed later.)

Imitating Super-K

Light yield changed

Temperature changed

Less than half in the latest type

High rate (Initial production)

(Note: Latest products show lower ~8kHz)
Accidental implosion of bulb in tank might cause a chain implosion by a shock pulse.

**Usual case**
- Bulb is pressurized.

**Implosion**
- Cover is pressurized.
- Should be enough tough not to generate shock wave outside.

**Super-K cover**
- For 40 m water depth
  - 13mm acrylic

**Initial prototype**
- For 60 m water depth
  - 15 mm acrylic
  - Stainless steel (3 mm)

**Cover pressurized test**
  - OK for 100 m water load
  - FRP (fiber reinforced plastic)
  - Air
  - Water
  - Cover in a plastic bag

- Optimization and reduction of cost and weight are under consideration.

03/01/2017
Validation of Cover at Implosion Test

1st demonstration test in Feb-Mar 2016.

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

● No damage for all tests
  ○ 3 times w/cover (2 with surrounding PMTs)
  ○ OK for 60 m (HK), and for 80 m also.

Shock wave monitor (At 70 cm front)

Pressure gauge

< ±0.04 MPa

Tested 3 times

Less than 1/100 reduction

Cover was established for HK!
Multi-PMT Option for Hyper-K

- Multi-channel optical module
- (Almost) uniform coverage
- Directionality
- Several manufacturers;

Photodetectors and electronics arranged inside a pressure resistant vessel

Based on KM3NET optical module

(Concept design) 3-inch PMT x 33

Preparing prototype this year.
mPMT Prototype

Main limits of Km3Net solution for HK project:

- **Vessel:**
  Km3Net experience demonstrated that glass spheres are characterized by high $^{40}$K and other radioactive contamination.

- **PMT Read-Out:**
  In Km3Net the time over threshold (ToT) strategy is exploited; this is not a good solution for HyperK project in which charge measurement is important.
Several acrylics tested: EVONIK UV transmitting PLEXIGLAS® GS chosen for the construction of the prototype.

Checked compatibility between optical gel and acrylic and measured the transparency of acrylic+optical gel.
The acrylic vessel will have a **diameter of 17”** (432 mm, like in Km3Net), with 3 different thicknesses, **starting from 15, 18 and 20 mm.**

**Vessel Production:**
Pre-production tests at Evonik concluded on the 7th Feb.: test vessels passed.

Evonik will send to us their pre-production vessels, before to send our requested spherical vessels

Our three vessels in production phase.
These vessels will undergo a pressure test (at Italian Navy high pressure facility)
- Box&Line PMT is almost ready.
  - Finalizing manufacture process.
- HPD is being ready.
  - Proof test is planed.
Conclusion

- 50 cm high-QE Box&Line PMT was developed.
  - Hyper-K baseline design to be used in 60 m water height
  - Established.
    - High performance (x2 detection efficiency and half resolutions)
    - Long operation in water over a year

- 50 cm high-QE HPD is under development.
  - Much improved resolutions
  - Preparing for a test in the water tank.

- mPMT R&D is under development.
  - PMT modules are under test and prototype will be ready by June 2017.
Backup slides
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

**2000V typical and varied volt. from 1600 to 2200V**
20 cmΦ (8-inch) HPD

Size for outer detector

20cm photocathode

5mm φ avalanche diode (AD)

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

No HV line in water

Waterproofed

Signal

30cm

10V

Cable

Spectral response 300 - 650 (420 max.) nm

Photocathode Bialkali

Window material Borosilicate glass

Gain $4 - 9 \times 10^4$

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.)

Preamplifier

(+8kV - ΔV)

(+8kV)

ΔV = 2-300V

No HV line in water

Fast intrinsic response
(w/o preamplifier)

Shaped in preamplifier

Good photoelectron separation

ΔV = 2-300V

I-V invert.

I-V

Diff. amp

2 mV/Div.

5 ns /Div.

Rise : 1.7ns

Fall : 2.7ns

20 ns

1 pe
The first prototype will be realized with the following parameters:

- 17” diameter of the vessel (the same as in Km3Net)
- 2 hemisphere:
  - ID hemisphere: 19 PMTs
  - OD hemisphere: 4/7 PMTs

Acrylic: EVONIK UV transmitting PLEXIGLAS® GS

3” PMTs:
Hamamatsu R12199-02 (as in Km3Net)

PMT Read-out:
read-out chip CITIROC by OMEGA

Cooling system: design under study at INFN Bari
mPMT Prototype: Timeline

- **Aug**: Acrylic study and vessel pre-production
- **Sep**: Vessel production and pressure test
- **Oct**: PMT Read-out: preliminary test
- **Nov**: PMT Read-out: final test
- **Dec**: PMT support
- **Jan**: PMT test
- **Feb**: Ready for mPMT integration by the end of June 2017
• For the first prototype, we decided to use the same PMTs as in Km3Net but a better solution is preferred in HK
• Needed comparative studies of commercial 3” PMTs and other options exist...

• An investigation for a mass production is fundamental. Possible solution: PMT from several manufacturing and, in this case, PMT calibration needed
PMT test:
As in Km3Net, we can realize a PMT test facility to test more and more PMTs.