A multi-PMT photodetector system for the Hyper-Kamiokande experiment

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On behalf of the Hyper-Kamiokande Proto-Collaboration

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Hyper-Kamiokande

New high-QE 50 cm Box&Line PMT

×2 high pressure bearing for 60 m depth

×2 high detection efficiency and half time&charge resolutions

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

About 7,000 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 photodetectors are essential for physics sensitivities.

→ 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)

Requirements

Planned 40,000 photosensors
Baseline option: 20” PMTs
Alternative option: 50% 20” MPTs and 50% mPMTs

(187 kton Fiducial Mass)

40% photo-coverage

258 kton

74m Ø

×2 high pressure bearing

60 m

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Multi-PMT Option for Hyper-K

Multi-channel optical module

- (Almost) uniform coverage by PMTs
- Directionality
- Several manufacturers

Photodetectors and electronics arranged inside a pressure resistant vessel

Based on KM3NeT optical module

(Almost) uniform coverage by PMTs

(Concept design) 3-inch PMT x 33

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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.
Large PMT vs mPMT?

### Table

<table>
<thead>
<tr>
<th>Detector</th>
<th>Directional sensitivity</th>
<th>TTS</th>
<th>QE</th>
<th>Dark rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>mPMT (3” PMT)</td>
<td>1/6 of solid angle</td>
<td>1.3 ns</td>
<td>27% (35% super-alkaline PhotoC.)</td>
<td>10 kHz</td>
</tr>
<tr>
<td>20” PMT</td>
<td>1/2 of solid angle</td>
<td>2.7 ns</td>
<td>30%</td>
<td>8 kHz</td>
</tr>
</tbody>
</table>

- **CC1π:**
  - Increase in acceptance for long baseline neutrinos
  - currently, large background from $\pi^0$ with 1γ missed
    - *missed 1γ may be tagged with finer granularity with mPMT.*
  - Exclusive multi-ring event reconstruction:
    - Important for mass hierarchy study
      - *Reduces the systematics from $\tau$ contributions.*
    - multi-ring efficiency can be improved by finer granularity

- **More physics justifications for mPMT.**
- **Many efforts how to manage mPMT tasks** *(photosensor, readout electronics, support structure, calibration, (DAQ, software))*
PMT R-12199 Hamamatsu
QE: 21% (@470nm); 26.9% (@390nm)  
TTS: 1.67 ns  
Dark Counts: 86% tested for KM3NeT < 2 kHz 

Gain: $5 \cdot 10^6$ 
Peak-to-valley ratio: 3.3 @ 1.1 kV 

Hamamatsu R14374 new 3-inch PMT 
- modified version of R12199 used by Km3net 
- QE=28% @400nm 
- TTS(FWHM) = 1.3nsec (4.5nsec for R12199) 
- Dark rate = 500-1000Hz
Pressure Vessel

The acrylic vessel of the first prototype will be a sphere with a **diameter of about 17”** (432 mm, like in Km3NeT) and a thickness of 18 mm.

A preliminary sketch for acrylic spherical vessel + cooling (seal) system

A seal will be used between the acrylic hemispheres and metal support.

**Inside:**
- Read-out system
- PMT support
- 3” PMTs

A mechanical closure guarantees:
- longer endurance
- Easier and better assembling
- Good cooling system by a metallic flange
Requirements (from SK)

<table>
<thead>
<tr>
<th>wavelength (nm)</th>
<th>minimum (%)</th>
<th>maximum (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>76.5</td>
<td>83.8</td>
</tr>
<tr>
<td>310</td>
<td>80.0</td>
<td>86.0</td>
</tr>
<tr>
<td>320</td>
<td>81.7</td>
<td>87.0</td>
</tr>
<tr>
<td>325</td>
<td>83.0</td>
<td>87.5</td>
</tr>
<tr>
<td>340</td>
<td>85.0</td>
<td>89.3</td>
</tr>
<tr>
<td>350</td>
<td>86.5</td>
<td>90.3</td>
</tr>
<tr>
<td>360</td>
<td>87.5</td>
<td>91.0</td>
</tr>
<tr>
<td>375</td>
<td>89.0</td>
<td>92.0</td>
</tr>
<tr>
<td>380</td>
<td>89.2</td>
<td>92.3</td>
</tr>
<tr>
<td>400</td>
<td>90.0</td>
<td>93.0</td>
</tr>
<tr>
<td>800</td>
<td>91.0</td>
<td>94.0</td>
</tr>
</tbody>
</table>

Table 1: Transparency of Super-Kamiokande acrylic
Several acrylcs tested: PLEXIGLAS® GS UV Transmitting by Evonik choosen for the construction of the first mPMT prototype for Hyper-K

Checked compatibility between optical gel and acrylic and measured the transparency of acrylic+optical gel.
Radioactivity

- Radioactivity measurements (at LNGS)
- Contamination results are here reported

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Activity</th>
<th>Contamination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ra-228</td>
<td>&lt; 0.11 mBq/kg</td>
<td>&lt; 0.027 ppb</td>
</tr>
<tr>
<td>Th-228</td>
<td>&lt; 93 µBq/kg</td>
<td>&lt; 0.023 ppb</td>
</tr>
<tr>
<td>Ra-226</td>
<td>&lt; 65 µBq/kg</td>
<td>&lt; 0.0052 ppb</td>
</tr>
<tr>
<td>Th-234</td>
<td>&lt; 4.6 mBq/kg</td>
<td>&lt; 0.38 ppb</td>
</tr>
<tr>
<td>Pa-234m</td>
<td>&lt; 2.5 mBq/kg</td>
<td>&lt; 0.20 ppb</td>
</tr>
<tr>
<td>U-235</td>
<td>(0.15 ± 0.07) mBq/kg</td>
<td>(3 ± 1)·10^{-1} ppb</td>
</tr>
<tr>
<td>K-40</td>
<td>&lt; 0.69 mBq/kg</td>
<td>&lt; 0.022 ppm</td>
</tr>
<tr>
<td>Cs-137</td>
<td>&lt; 25 µBq/kg</td>
<td>-</td>
</tr>
</tbody>
</table>

Evonik acrylic.
Weight: 13.4567 kg;
Live time: 22 days

Requirements:
- U-238 < 0.3 ppb
- Th-232 < 1 ppb
- K-40 < 0.3 ppm

This positive concentration of U-235 has been investigated in detail.

The Evonik acrylic is very clean, no radioactivity contamination
The diagram illustrates a stress-strain curve with distinct regions labeled:

- **Elastic** region:
  - Represents the linear portion of the curve where stress is directly proportional to strain.

- **Yielding** region:
  - Begins at the point of yield and shows the curve starting to deviate from linear behavior.

- **Strain softening** region:
  - Follows the yielding region and continues to show the curve deviating from linearity, with the stress decreasing at constant strain.

- **Strain hardening** region:
  - Begins after strain softening and shows the stress increasing at a constant strain rate.

The different colors and labels indicate various tests (Test_01 to Test_06), each representing different conditions or samples in the experiment.
Pressure Tests

Pressure Curve - 15mm-thick vessel
Resinex Company (Italy)

Pressure Curve - 20mm-thick vessel
Resinex Company (Italy)
mPMT electronics

PMT electronics × 26

Requirement: Total Power consumption <4W
HV Board Characteristics

HV circuit power consumption

<table>
<thead>
<tr>
<th>Electrodes</th>
<th>K</th>
<th>Dv1</th>
<th>Dv2</th>
<th>Dv3</th>
<th>Dv4</th>
<th>Dv6</th>
<th>Dv6</th>
<th>Dv7</th>
<th>Dv8</th>
<th>Dv9</th>
<th>Dv10</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ratio</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

K: Cathode, Dv: Diode, P: Anode

Total power dissipated for HV in mPMT module is about:
26 × 12.5 mW = 325 mW
17 × 12.5 mW = 213 mW
PMT Read-out

- System integrated with the HV board
- Same MCU for both boards and only one connection
- Very compact system thanks to the design of HV board

Ready and under test at INFN-Na
Conclusions

mPMT R&D is well advanced and a mPMT module prototype will be ready by fall 2018.
Backup Slides (mechanical)
Acquisition rate: 1 image/s

Illumination system

Punch

Specimen

Flat plate

Stochastic Pattern

Calibration Image Panel

Digital Cameras

Left

Right
Stress and Strain

\[ \text{Stress, } \sigma = \frac{\text{Force}}{\text{Cross-Sectional Area}} = \frac{F}{A_0} \]

\[ \text{Strain} = \frac{\text{Elongation}}{\text{Original Length}} = \frac{\Delta L}{L_0} \]
Stress and Strain 3D
• All shear stresses are zero $\tau_{r\phi} = \tau_{\phi r} = 0$ and $\tau_{\theta\phi} = \tau_{\phi\theta} = 0$
• The normal stress $\sigma_{rr}$ varies from zero on the inner free surface to the the pressure $p$.
• The normal stresses $\sigma_{\theta\theta}$ and $\sigma_{\phi\phi}$ are equal and constant over the entire vessel, equal to $\sigma$. 

Mechanical tests: simulation

Figure 3.4. Stress analysis of a spherical pressure vessel in spherical coordinates. Once again thickness is grossly exaggerated for visibility.
Mechanical tests: simulation

- **Wall Thickness.** The wall is assumed to be very thin compared to the other dimensions of the vessel. As a result, we may assume that stresses are uniform across the wall.
- **Symmetries.** In spherical vessels, the geometry and the loading are spherically symmetric. Therefore the stresses may be assumed to be independent from the two angular coordinates of the spherical coordinate system.
- **Uniform Internal Pressure.**
- **Ignoring End Effects.** This includes supports and cylinder end caps. The assumption is that disturbances of the basic stress state are confined to local regions and may be ignored.
Evolution of displacement
Backup slides (electronics)
A basic Cockcroft-Walton (CW) voltage multiplier circuit design developed by Km3Net Collaboration (See P. Timmer, E. Heine, H. Peek, *JINST* 5 (2010) C12049) used to generate multiple voltages to drive the dynodes of the photomultiplier tube.

10 different voltages from 5 volt supply

Similar HV circuit developed at INFN-Na