Hyper-K Photodetectors

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Hyper-Kamiokande

Hyper-Kamiokande Detector
60 m(H) x 74m(D)
Total volume 260 kt
Fiducial volume 190 kt ~10x Super-K

E61 – Intermediate detector for Hyper-Kamiokande Project
Movable Water Cherenkov detector
Inner diameter 8 m
Inner detector height 6-8 m

Inner-detector: 40000 20” PMTs
Outer-detector: 6700 8” PMTs
ID: 50 cm Photo-Detectors

First 20-inch (50 cm) Photomultiplier Tube (PMT)
- **Hamamatsu R1449**
  - (Venetian blind dynode)
  - For Kamiokande
  - (1983-1996)
  - 1k PMTs / 3 kton water

- **R3600**
  - (Venetian blind dynode, improved)
  - For Super-Kamiokande
  - (1996- )
  - 11k PMTs / 50 kton water
  - Supernova $\nu$ observation!
  - $\nu$ oscillation discovery!

- **R7250**
  - (Box&Line dynode)
  - with 50 cm bulb of R3600
  - For KamLAND

- **50 cm MCP PMT**
  - By NNVC, IHEP
  - Recently developed in China

For other experiments

- **50 cm Box&Line PMT**
  - **R12860-HOE**
    - (Box&Line dynode)
    - Developed
    - Photo-detector in Hyper-K baseline design

- **50 cm Hybrid Photo-Detector (HPD)**
  - **R12850-HOE**
    - (Avalanche diode)
    - Under development
    - Possible further improvement of Hyper-K

For other experiments
**ID: Alternative option**

to increase the yield of the effective area of the optical system introducing intrinsic directional sensitivity

**Multi-PMT Digital Optical Module**

Firstly proposed by KM3Net Collaboration
multi-PMT in Hyper-K and E61

- The E61 baseline design is equipped with multi-PMT modules (mPMT) as photodetector system
- Hybrid configuration considered for Hyper-K: 20” + mPMT
Hybrid configuration for Hyper-K

Baseline configuration:
- 40k of 20” PMTs

Hybrid configuration:
- 20k of 20” PMTs
- 5k mPMTs

About 15,000 PMTs for Outer Veto Detector

× 2 tanks
Large PMT vs mPMT?

Intermediary goal: determine capabilities of standalone mPMTs → Hyper-K with 40% coverage of mPMTs: compare with 20”

e-generated at the tank center

Zoom-in

Increased granularity enhanced event reconstruction, in particular for multi-ring events

Complete simulation and reconstruction chain has been developed and validated
Performance Studies for mPMTs in HK

Variation of resolutions with $\nu$ energy

- Vertex and angular resolution better for low energy with reduced dark rate in mPMTs
- At high energy: muon/electron separation improved near the wall; vertex resolution improved
- Improvements strongest near edges of FV
- Introduce $(\theta, \phi)$ dependent efficiency functions for individual PMTs in mPMT

Mixed geometry next step

If operate 100Hz: improved vertex resolution and lower down the Energy threshold from 5 to 3 MeV

→ Access to low energy neutrino physics!
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 Hyper-K project in which charge measurement is important.

- Assembling procedure:
  mPMT production time
Prototype module design and testing

Two prototypes under construction and test

@INFN:
same design as KM3Net: vessel 17inch;
spherical shape;
goal:
test the acrylic vessel and new electronics

@TRIUMF:
new design and mechanics optimized for HK/E61
goal:
HK/E61 design: test mechanics and assembling procedure

Canada, Italy, Japan, Poland groups collaborating on development of parts for the multi-PMT module
Several acrylics tested: PLEXIGLAS® GS UV Transmitting by Evonik choosen for the construction of mPMT for Hyper-K and E61

Checked compatibility between optical gel and acrylic and measuread the transparency of acrylic+optical gel.
Acrylic vessel - 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

The Evonik acrylic is very clean, no radioactivity contamination
Acrylic vessel - Mechanical tests

The diagram shows the stress-strain curve for acrylic vessels under various mechanical tests. The curve is divided into different regions:

- **Elastic** region: Stress increases linearly with strain, indicating a reversible deformation.
- **Yielding** region: Stress plateaus as the material starts to deform permanently.
- **Strain softening** region: Stress decreases as further deformation occurs.
- **Strain hardening** region: Stress increases again, indicating a densification of the material.

The graph includes data from multiple tests indicated by different line styles and colors, labeled as `Test_01` to `Test_06`.
Acrylic vessel - Hydrostatic Pressure test

15mm and 20mm-thick vessels tested
Arduino pressure sensors for monitoring

Constrain: resist up to 1.26 MPa
Pressure test results: vessel resisted to 18 bar.
No damage at the 15mm-thick vessel!
The 20mm-thick vessel was inserted into a 400-bar tank for a crash test
Implosion at 86 bar

Acrylic: PLEXIGLAS® GS, UV transmitting by Evonik
mPMT Electronics Performance Requirements

Performance Requirements
– Timing resolution: better than 3” PMT TTS
  • ~300-500ps timing resolution from electronics for 1PE.
  • Better timing resolution (100-200ps) for large PE pulses.
– Charge resolution ~0.05PE up to 25PE.

Power consumption:
– For Hyper-K <3-4W per mPMT
Driven by water circulation requirements
– For E61 ~5-10W per mPMT
• Not as strongly constrained as Hyper-K

Moderately low cost: ideally ~$50 per channel for digitization part.
Electronics Design for mPMTs
Currently working on two different designs for the mPMT digitization

**Design A:**
Q/T digitization based on discrete components (INFN Naples)
Simple, low power, low cost

**Design B:**
FADC digitization, with on-board signal processing (TRIUMF, WUT)
Fully active during spill.
Noise suppression in FPGA.
Can export raw ADC information.
Trade off between bandwidth and power consumption

*Figure 2: conceptual block diagram for the mPMT E61 Main Board (EMB).*
**mPMT prototype: HV**

Cockcroft-Walton (CW) voltage multiplier, as in KM3Net

Voltage & current monitoring: stable HV

Power consumption:
- 12.5 mW/ch
- ID: 19 ch → 237.5 mW

Switching noise 500μV (~1pC)
Design A: mPMT digitization

Sample&Hold + ADC based on discrete components

- System integrated with the HV board
- Same MCU for both boards and only one connection

Single Board Computer-Linux:
- Slow control (HV and Threshold set, I/V)
- Data acquisition and transmission
- Power consumption and temperature

FPGA:
- TDC/ADC control
- Time stamp
Design A: FEB

Energy resolution: FWHM/ch 0.1%

Time resolution: 100ps
Design A: main board

Block Diagram

Total Power consumption:
- ID: 19 ch → ~ 4.1 W
Evolution in Hyper-K and E61 design

**KM3Net (31 PMTs)**

**Spherical → Cylindrical**

- 19(ID) + 7(OD)

**2-Sided mPMT Design (26 PMTs)**

**Single-sided mPMT module:**

- Lighter, less dead space, simple feedthrough at back of module
- mPMT full module weight ~ 80 kg → Single-sided mPMT module weight as 20” PMT
- only one OD photosensors system for the whole Hyper-K
ID-mPMT

Single-sided mPMT module:
- 19 3 inch PMTs system observing the inner detector
- Lighter, less dead space
- only one OD photosensors system for the whole Hyper-K

Weight: ~44kg
Volume: ~46L
Length: ~300mm
Outer-detector

• Design based on Super-K Outer-detector
  – ~ 6700 20 cms (8”) PMTs facing outward
  – → 1% coverage
  – OD Water thickness: 1m barrel / 2m top and bottom

• The outer-detector is a veto for background particles
  – Classify Fully Contained (FC), Partially Contained (PC), and Upward-going muons

  – Shield from gamma particles
OD: Alternatives Designs

- Alternative design with 10k 3” PMTs

1% OD coverage with 2x8” PMTs in 3x4 cells

0.28% OD coverage with 4x3” PMTs in 3x4 cells

Smaller tubes give better redundancy, spatial and angular resolution
Candidates PMTs

8” Hamamatsu R5912
8” ETEnterprise 9354KB
3” ETEnterprise 9302KFLB

+ WLS plates

• 2 more PMTs from Hamamatsu incoming:
  – 3.5” R14689
  – 3” R14374

+ Cost saving
+ Deadzone
Dark rates comparison

3” ETEL 9302KFLB

8” ETEL 9354KB

- Datasheet @20deg:
  - 400 Hz at 950V

- Datasheet @20deg:
  - 4000 Hz at 1300V

Dark rates don’t scale to photocoverage!

More data will be taken with more statistics
Photons traps

- WLS plates are made of plastic, with $n_{WLS} = 1.58$
- They are at the interface with water, $n_{water} = 1.33$
  - When photon exit the plastic they bend towards it!

Candidates WLS Plates: Eljen EJ-286

- Max absorption in UV (Cerenkov photons)
- Max emission at 420 nm
- Material defines critical angle
Test Setup

- 3" PMT (9320KFLB) and Wavelength Shifter Plate (WLS – EJ286)
- UV LED @ 375 nm
- Neutral Density filter @ 2.0
- A pulser provides signal to the UV LED with rate: ~ 10 kHz
- A fibre is used to guide the LED signal to the PMT.
- Plan: Take data in different points of the WLS plate to estimate the efficiency
Simulation studies

- Study photocollection for 3” and 8” PMTs:
  - Muons particle gun coming towards the side of HK
    - “sand muons”
  - Cosmic muons generator
    - Muons selected in a 10m sphere around centre of tank
    - Energy and momenta are randomly generated accorded to Super-K flux extrapolated at Hyper-K
    - Vertex generated outside Hyper-K

Mean PE collected per event

<table>
<thead>
<tr>
<th>OD Design</th>
<th>13.3k 3”</th>
<th>15k 3”</th>
<th>20k 3”</th>
<th>6.8k 8”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cosmos</td>
<td>238</td>
<td>314</td>
<td>414</td>
<td>1254</td>
</tr>
<tr>
<td>Sand Muons</td>
<td>46</td>
<td>69</td>
<td>118</td>
<td>203</td>
</tr>
<tr>
<td>Thru-going</td>
<td>14</td>
<td>25</td>
<td>44</td>
<td>51</td>
</tr>
</tbody>
</table>

Every 3” configurations collects enough light to detect events
Conclusions

mPMTs offer several benefits compared to large area PMTs
- Directionality, Improved granularity and timing resolution, lower dark noise, less magnetic field sensitivity, pressure tolerance

Reconstruction studies show improvement with respect to large area PMTs for the E61 and Hyper-K detectors
- Optimisation of the design for physics underway
- Studying impact of 5000 mPMTs on Hyper-K physics

R&D plan:
- Construction and test of the mPMT module prototyope
- Further tests on materials to be used
- Optimization of the PMT read-out system

Hyper-K OD:
- compare 3” and 8” configurations to define the future OD
Thank you!
Milestones in JENNIFER2

Main limits of KM3NeT solution for HK project:

- **Vessel:**
  Glass spheres as used in KM3Net are characterized by high $^{40}\text{K}$ and other radioactive contamination.

- **PMT Read-Out and HV:**
  Time over threshold (ToT) strategy is exploited in KM3Net; in HK charge measurement is important.

Comparative studies on commercial acrylics:
- Optical propertied
- Radioactive contamination
- Mechanical tests
- Pressure tests

HV: Cockcroft-Walton (CW) voltage multiplier
PMT Read-out: Sample&Hold+ADC based on discrete components

Construction and test of the mPMT module prototype.