The Intermediate Water Cherenkov Detector for the Hyper-Kamiokande experiment

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The Hyper-Kamiokande Experiment

Hyper-Kamiokande (Hyper-K) is a world-leading neutrino experiment building on the success of Super-Kamiokande.

Broad & ambitious physics programmes covering many neutrino sources as well as proton decay measurements.

Water Cherenkov detector technology provides huge target mass with excellent particle ID and reconstruction capabilities.

- **Water Cherenkov Test-beam Experiment (WCTE) at CERN**
- **J-PARC ν beam**
- **Near detectors**
- **Intermediate Water Cherenkov Detector (IWCD)**
- **Super-Kamiokande**
- **Hyper-Kamiokande**
  - Talk by M. Malek
  - Tuesday 14:40

- **Poster by L. Anthony**

**Distances:**
- 280 m
- ~ 1 km
- ~ 295 km
Long-Baseline Neutrinos

Neutrino beam produced at 295 km baseline from Hyper-K

Near and intermediate detectors measure unoscillated flux and cross sections

Oscillations observed through $\nu_\mu$ disappearance and $\nu_e$ appearance, for both neutrinos and antineutrinos

Difference between $\nu_e \rightarrow \nu_\mu$ and $\bar{\nu}_e \rightarrow \bar{\nu}_\mu$ provides sensitivity to CP violation and $\delta_{CP}$ measurement

Intermediate Water Cherenkov Detector (IWCD)

Proton beam

Off-axis angle

Beam target

Average pion decay point

Near detectors

Intermediate Water Cherenkov Detector (IWCD)

280 m ~ 1 km ~ 295 km

J-PARC $\nu$ beam

Hyper-Kamiokande

$\sin^2 \theta_{23} = 0.5$

$\Delta m^2_{32} = 2.5 \times 10^{-3} \text{ eV}^2$

$\sin^2 \theta_{12} = 0.083$

$\nu_e \rightarrow \nu_\mu$

$\bar{\nu}_e \rightarrow \bar{\nu}_\mu$

$\nu_\mu \rightarrow \nu_e$: NH, $\delta_{CP} = \pi/2$

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$: IH, $\delta_{CP} = -\pi/2$

$\nu_\mu \rightarrow \nu_e$: NH, $\delta_{CP} = \alpha/2$

$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$: IH, $\delta_{CP} = -\alpha/2$
Systematic Uncertainties

1.3 MW beam (2.5x T2K) and 260 kton fiducial mass far detector (8x Super-K) gives 20x event rate

Systematic uncertainties must be reduced to exploit Hyper-K’s increased statistical power

<table>
<thead>
<tr>
<th>Current T2K uncertainty for CPV</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Super-K detector</td>
<td>1.5</td>
</tr>
<tr>
<td>Super-K FSI + SI + PN</td>
<td>1.6</td>
</tr>
<tr>
<td>Flux and cross section (near detector constrained)</td>
<td>2.7</td>
</tr>
<tr>
<td>Flux and cross section (near detector unconstrained)</td>
<td>1.2</td>
</tr>
<tr>
<td>Nucleon removal energy</td>
<td>3.6</td>
</tr>
<tr>
<td>$\nu_e / \bar{\nu}_e$ cross section ratio</td>
<td>3.0</td>
</tr>
<tr>
<td>NC$\gamma$ + other interactions</td>
<td>1.5</td>
</tr>
<tr>
<td>Total</td>
<td>6.0</td>
</tr>
</tbody>
</table>

Total systematic error at Hyper-K should be reduced to less than 3 %
The Intermediate Water Cherenkov Detector

- Measure flux and cross sections of mostly unoscillated beam to reduce systematics at far detector
- Located ~ 1 km from $\nu$ beam source
- Moves vertically in ~50 m tall pit
  - Spans range of angles off axis from $\nu$ beam for different $\nu$ energy spectra
- 6 m tall x 8 m diameter surrounded with ~ 500 multi-PMT modules
- Gadolinium doped water provides enhanced neutron detection
- Small detector with high event rate introduces challenges for hardware, calibration and event reconstruction
Spanning Off-Axis Angles

- $\nu$ energy spectrum depends on angle off-axis to the neutrino beam
- Far detector @ 2.5° for peak at ~600 MeV, but oscillated $\nu_e$ spectrum is different to unoscillated spectrum at near detectors
- Moving IWCD varies angle, allowing measurements at different energies
- Linear combinations allows mimicking far-detector spectrum or monochromatic beams
1% contamination of $\nu_\mu / \bar{\nu}_\mu$ beam with $\nu_e / \bar{\nu}_e$ allows measurement of $\nu_e / \bar{\nu}_e$ cross-sections

- Larger off-axis angle positions have more $\nu_e$ contamination

- CP-violation search depends on double-ratio
  \[
  \frac{\sigma(\nu_e)/\sigma(\nu_\mu)}{\sigma(\bar{\nu}_e)/\sigma(\bar{\nu}_\mu)}
  \]
  - Existing T2K systematic errors on $\sigma(\nu_e)$ and $\sigma(\bar{\nu}_e)$ come from theoretical uncertainties
  - IWCD can measure these cross-sections directly

- Large background from entering $\gamma$ removed using outer-detector (OD) as active shield

See also poster by C. Naseby
Moving detector

- Moving detector vertically to span off-axis angles is challenging
- Air-filled regions used to make detector buoyant in water
- Water is filled below the detector, raising it to the desired level
- Rail system guides detector as it moves
- Parts of water system, readout electronics and calibration system located on top of the moving tank
Multi-PMT modules

- IWCD is much smaller detector compared to far detector
- Improved photosensor resolutions and increase granularity required for equivalent event reconstruction performance
- 19 x 8 cm PMTs integrated into water-tight mPMT module
  - High voltage and readout electronics inside mPMT
  - Scintillator panel for OD veto
- 8cm PMTs compared to far detector’s 50cm PMTs
  - Better position resolution
  - 1.6 ns (FWHM) timing resolution
  - Additional directionality information
- Also under investigation: Combining 50 cm PMTs + multi-PMT modules in far detector
mPMT Assembly

mPMT components designed for mass production

- Assembly starts from stainless steel backplate
- Components added inside PCV cylinder
- 3D support matrix holds PMTs in place
- Optical gel added to PMTs before assembly
  - Provides good optical contact with transparent dome
- Acrylic dome lowered into place with jig
- Attached with stainless steel ring
mPMT Electronics and HV

- IWCD close to beam source
  - High event rate can cause pile-up of multiple neutrino interactions
  - Full PMT waveform can allow better identification and reconstruction of pile-up events

- 20-channel 125 MSPS FADC electronics board developed
  - Full waveform can be read-out
  - On-board waveform processing in FPGA to reduce readout size

- Cockroft-Walton HV base for each PMT
  - Reduced power consumption compared to resistive base
Calibration

- Calibration is critical for precision measurements at IWCD
  - Precise calibration needed at each vertical position

- Calibration source deployment system with full 3D movement to place source at any location in tank
  - Arm rotates around axis
  - Cart moves radially along arm
  - Source hangs from vertically from cable

- Photogrammetry position calibration system
  - Small shifts in detector components possible after moving
  - Cameras placed inside detector volume
  - Calibration LEDs mounted in mPMTs
  - Stereoscopic reconstruction measures geometry to precision of a few mm
Machine Learning

- Machine learning methods being developed to exploit all information from mPMTs
- Improved reconstruction and PID performance over likelihood-based reconstruction
  - Statistical separation of $e^-$ and $\gamma$ not previously possible
  - Better handle on entering $\gamma$ and NC$\gamma$ backgrounds
- Identification and reconstruction of multi-vertex and multi-ring events from beam pile-up

Reconstructed energy resolution

$e^-$ efficiency with 99.9% $\mu$ rejection

$e^-$ efficiency with 80% $\gamma$ rejection
Summary

- Hyper-Kamiokande is currently under construction with first data taking planned for 2027.
- IWCD will provide critical measurements to control systematic uncertainties in Hyper-K’s search for CP violation.
- Vertically moving detector spans off-axis angles to measure cross sections at varying energy spectra.
- New multi-PMT photosensor hardware and calibration systems enable precision measurements in small water Cherenkov detector.
- Machine learning reconstruction techniques will maximise potential of IWCD.
- IWCD is now moving towards design completion and construction phase!