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

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Hyper-Kamiokande (Hyper-K) is the next generation large volume water Cherenkov detector currently under construction in Japan. The fiducial volume will be approximately 8 times larger than its precursor Super-Kamiokande. Its broad physics program includes nucleon decay, neutrinos from astrophysical sources and accelerator neutrinos, with the main focus to determine the leptonic CP violation. In order to detect the weak Cherenkov light generated by neutrino interactions or proton decay, a system of small photomultipliers as implemented in the KM3NeT experiment, the so called multi-PMT module (mPMT), is considered as an option to improve Hyper-K physics capability. A mPMT Optical Module based on a pressure vessel instrumented with multiple small diameter photosensors, read-out electronics and power, offers several advantages as increased granularity, reduced dark rate, weaker sensitivity to Earth's magnetic field, improved timing resolution and directional information with an almost isotropic field of view. In this contribution the development of a mPMT module for Hyper-K and the prospects for physics capabilities with a hybrid configuration of the photosensor system with 50cm PMTs and mPMTs is discussed.

Keywords: Water Cherenkov detectors, photosensors, neutrino detectors

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1. The Hyper-Kamiokande Experiment

Hyper-Kamiokande (Hyper-K) [1] is a next generation underground water Cherenkov detector for neutrino observation currently under construction in Japan employing the successful strategies as in Super-Kamiokande, K2K and T2K experiments. Hyper-K is a multipurpose experiment for the observation of atmospheric, solar and accelerator neutrino oscillations, for neutrino astrophysics, proton decay and physics beyond the Standard Model. In particular, it will observe neutrinos produced at JPARC accelerator complex, about 300 km far, to investigate CP violation in the leptonic sector of the Standard Model. A system of near detectors will monitor the neutrino beam for the accelerator neutrino investigation. An Intermediate Water Cherenkov Detector (IWCD) is proposed to be newly constructed at about 1 km distance from the neutrino production target to measure the properties of neutrino interactions to reduce systematic errors related to the neutrino cross section uncertainty. Hyper-K data taking is expected in April 2027.
The detector tank is 71 m in height and 68 m in diameter with a fiducial volume of 0.19 Mt. It is separated into an inner detector region observed by 40,000 large area photo-detectors (50 cm diameter), with a photocathode coverage of 40%, and an outer detector veto region. The inner detector (ID) will be instrumented with 50-cm Hamamatsu Photonics R12860-HQE PMT with a box-and-line dynode type, a high quantum efficiency photocathode, and with an improved design to resist the high pressure in the tank [2]. It is also considered to supplement it with MCP-PMT, originally developed for JUNO experiment [3], and the so called 'multi-PMT modules' (mPMT), each housing multiple 3″ photomultiplier tubes (PMT) and read-out electronics in a pressure vessel. The outer detector veto region will be instrumented with 13300 3" PMTs to reject background from external sources [4].

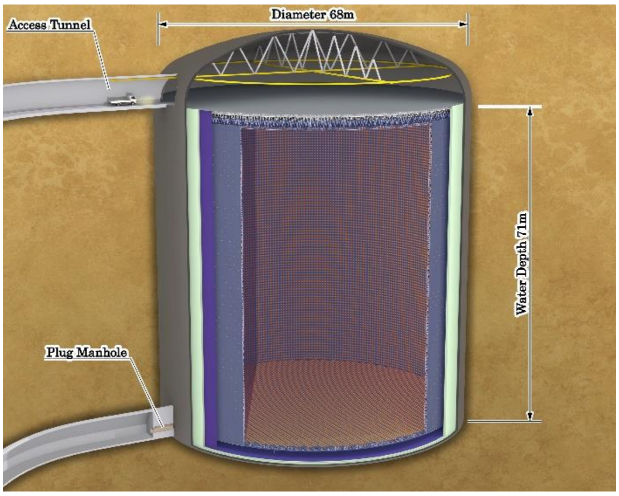

Figure 1: Artistic picture of the Hyper-Kamiokande detector

2. mPMT photodetector system in Hyper-K

A system of small photomultipliers as implemented in the KM3NeT experiment [5], the so called multi-PMT module (mPMT), is considered as an option to improve the Hyper-K physics capability. This alternative option involves a combination of 50-cm PMTs and mPMTs, with the mPMTs supplementing the 50-cm photosensors, in the observation of the ID Hyper-K far detector. The IWCD baseline design is instead equipped with mPMT as photodetection system.

In the mPMT, the photosensors and the read-out electronics are hosted within a pressure-resistant vessel, protecting the system from the external water pressure. The resulting segmentation of the sensitive area features several attractive advantages compared to the single PMT concept as superior photon counting, improved angular acceptance, extension of dynamic range. The intrinsic directional sensitivity and the increased granularity improve the event reconstruction capability, in particular for multi-ring and near-wall events.

Detailed simulation studies are ongoing to investigate the impact of the mPMT system in Hyper-K physics in both the high and low energy sectors. Preliminary results show improved vertex resolution as well as an increased PID separation using mPMTs compared to 20,000 50-cm PMTs only. The improvements with mPMTs are clear with the use of at least 3,000 mPMTs, increasing by adding more mPMTs (see Figure 2).

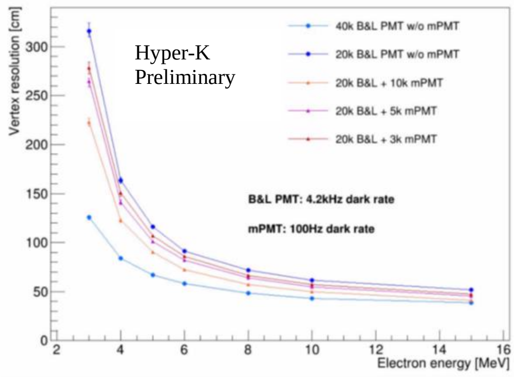

Figure 2: Vertex resolution as a function of electron energy for several configurations of the photodetector system in the far detector. Preliminary results

The baseline design of the Hyper-K mPMT is based on the use of 19 7.7 cm PMTs in a cylindrical vessel with a radius of about 26 cm with an acrylic cover and a cylindrical body, as illustrated in Figure 3.

Reflector cones are added to each 7.7 cm PMT to increase the effective photocathode area. The 7.7 cm PMTs are supported by a 3D printed structure and optically coupled by Silicon Gel to the 15mm thick acrylic cover. Signal and power cable are fed into the module via a feedthrough, which is placed in the back side of the mPMT module. The front-end electronics and HV supply are integrated within the pressure vessel.

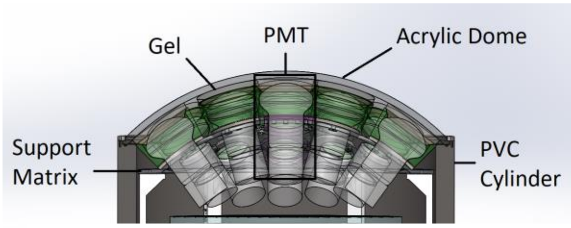

Figure 3: mPMT design for Hyper-K

A huge R&D activity is ongoing to optimize the mPMT photosensor system for Hyper-K, mainly to improve the mechanical design to resist at the high pressure in the far detector and for long term operation in water.

Several prototypes have been realized and are currently under test:

- a first prototype with a spherical shape as in KM3NeT, with a 43 cm acrylic vessel has been realized to test the acrylic vessel and the electronics to be used for the mPMT in the far detector. This prototype is currently in data taking at the MEMPHYNO setup at APC in Paris [6].
- new design and mechanics optimized for Hyper-K as well the assembly procedure have been tested with the mechanical prototype based on the Hyper-K mPMT design described in Figure 3.

More prototypes are currently under construction.

2.1. PMTs

mPMT performances are strictly related to the ones of the PMTs used. Two PMTs are currently considered for the multi-PMT module: R14374 by Hamamatsu Photonics (7.7 cm tube, 3'') and XP82B20 by HZC Photonics (9 cm tube, 3.5''). So far, testing concentrated on measuring charge resolution, transit time spread (TTS), dark rate and pulse shape parameters of the two sensors. In case of Hamamatsu R14374, the TTS was as low as 1.4 ns (FWHM at 1 PE), charge resolution was ≈37% (σ at 1 PE), while typical dark rate was about 200Hz-300Hz (at 0.3 PE), ranging from 100Hz to 500Hz. For HZC XP82B20, the results were: TTS of 3.7 ns, charge resolution of 35%. Dark rate has been improved in the new HZC PMTs ranging from 200Hz to

700Hz (at 0.3 PE). Tests of both PMTs were done at the gain of 5×10^6 and positive and negative high voltage.

PMT dark counts affect the mPMT reconstruction capability, especially at low energy. Several strategies are under study to improve dark counts, as adding a dielectric material (HA-coating) to insulate the PMT surface and reduce the probability for accidental discharges, adopting a conformal coating as in KM3NeT experiment [7], or reducing continuous pulses. R&D together with manufacturers to reduce radioactive material in the PMT glass is also ongoing. The best treatment of the PMT and the preferred HV polarity will be adopted for dark counts reduction.

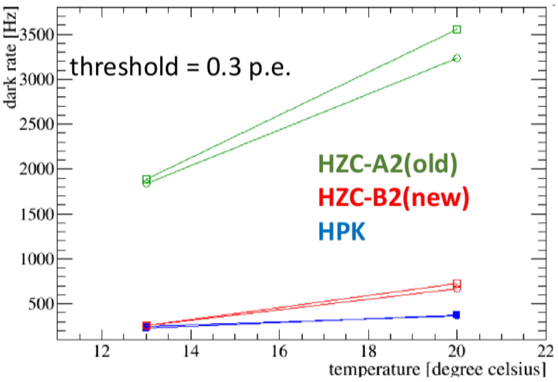

Figure 4: Measured dark rate as a function of themperature for Hamamatsu R14374 and HZC XP82B20 PMTs

2.2. mPMT electronics

To match the experimental constraints, we need to provide a system that has low power consumption (< 3-4 W for the Hyper-K far detector), good charge resolution and timing accuracy better than 300 ps for 1PE (200 ps for larger signals), so that the good timing performance of the small PMTs can be maintained.

To cope with power consumption constrains, an active power supply based on the Cockcroft-Walton voltage multiplier circuit is used to generate multiple voltages for the PMT. In order to choose the optimal PMT base design, two possible voltage multiplier circuits with positive and negative polarity were designed and tested. Negative HV board has been tested in the mPMT complete configuration. The system draws less than 1.5 mA of supply current at 3.3 V and can provide up to -1500 V cathode voltage.

A power consumption of ~3 mW per channel has been achieved, corresponding to a ~60 mW power consumption for the HV board for a full mPMT. The positive HV board is currently under test. The best solution to have a reduced dark rate will be adopted.

To match the experimental constraints, two different designs for the mPMT digitization are currently under development: one is a Q/T digitization based on discrete components with a very low power consumption to be used for the mPMTs in the Hyper-K far detector; the other is based on FADC digitization, with on-board signal processing to distinguish between different hits in different neutrino beam bunches in the IWCD.

In the Q/T digitization option, the single channel electronics is an integrated HV and FEB system, using the same MCU for both boards and only one connection. The output of the single channel is merged to the main board where we process the information. The acquired data are transmitted out of the mPMT with a single Ethernet cable, serving also for power supply, clock and trigger. The achieved timing resolution is ~300 ps, the charge resolution is 0.1% and good linearity of the circuit response to charge was observed. The system has very low power consumption, reaching 40.5 mW for the digitizer per-channel, with a total power consuption of ~4W per mPMT module.

In the FADC based design, the digitization relies on waveform sampling with time and charge estimation done in the FPGA controlling the ADC to preserve timing resolution and pulse separation, with no dead-time. The shaped signals travel as differential signals to the main board, where they would be further shaped and then digitized by a 125 Msps 12-bit FADC with a sampling period of 8 ns.

Summary

Hyper-Kamiokande experiment has been officially approved in Japan and is currently under construction. Operations will begin in 2027.
mPMTs are considered as an option in the Hyper-K far detector and used in the IWCD.
Preliminary studies show that adding mPMTs improves the Hyper-K physics capability.
Extensive R&D program related to the mPMT photosensor system for the Hyper-K experiment was summarized. All the described studies are ongoing, and more developments are foreseen in the near future.

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