Large Water Cherenkov Detectors - Technical Issues -

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Abstract
We address technical issues and challenges to construct a one-megaton scale water Cherenkov detector for neutrino detection. Studies presented here are mostly based on preliminary work for Hyper Kamiokande project.

1 Large Water Cherenkov Detectors

A large water Cherenkov detector with a total mass of about one megaton has been envisioned as a far detector for a next generation long baseline neutrino oscillation experiment as well as a fully active detector for a nucleon decay experiment. There are currently at least three independent proposals to construct such a detector: Hyper Kamiokande in Japan, Water Cherenkov detector(s) at DUSEL in US and MEMPHYS in Europe.

The current design of Hyper Kamiokande, shown in Fig. 1, calls for two identical large caverns, each containing a cylindrical detector of 43 m in diameter and 250 m in length. Each detector holds the amount of water corresponding to a fiducial volume of 540k ton and is instrumented with 50,000 20-inch Super-Kamiokande type phototubes. The total photo cathode coverage is 20% of the water surface. Its site is in Tochibora mine in Kamioka town in Japan and has overburden of 680 m..

Deep Underground Science and Engineering Laboratory (DUSEL) at Homestake in USA is a multi-disciplinary lab to address the underground needs of all the major scientific fields. There is a proposal to build three water Cherenkov detectors, each having a fiducial volume of 100k ton, at the site 4850 feets below the ground as shown in Fig. 2. It has 1455 m worth overburden. US neutrino physicists are pursuing to build these detectors as far detectors for a long baseline neutrino experiment using neutrinos produced at Fermilab.

A European project, MEMPHYS (MEgaton Mass PHYSics), is to build three large cylindrical (65 m diameter × 65 m high) water Cherenkov detectors (Fig. 3). The total fiducial mass of three detectors amounts to 440k ton. Each detector will be instrumented with 81,000 12-inch phototubes, providing 30% photocathode coverage of the water surface. It is envisioned to site in Frejus tunnel and the site has 4800 m water equivalent overburden.

2 Large Cavern Engineering

The issues related to excavating large caverns are specific to the candidate site that houses the proposed large Water detectors. For example, Finite Element Analysis has been done for Hyper Kamiokande site. Because the cavern is so large (48 m wide × 54 m high × 250 m long) cavern displacement and stability are of critical concern. The study showed that North-South cavern direction results in the smaller displacement ($\sim$ 55mm) of the cavern wall than East-West. Required are further site evaluation including global geological mapping (rock composition and position of faults), and in-situ rock mass properties (3D initial stress, Modulus of deformability and Young's modulus). Exploratory drilling is scheduled prior to finalizing the caver design.

R&D issues on excavation method include development of speedy and cost-effective method, design of main haulage tunnels, and disposal (or reuse) of excavated waste rocks. These are strongly coupled with environmental assessment and have a significant impact on the construction schedule.

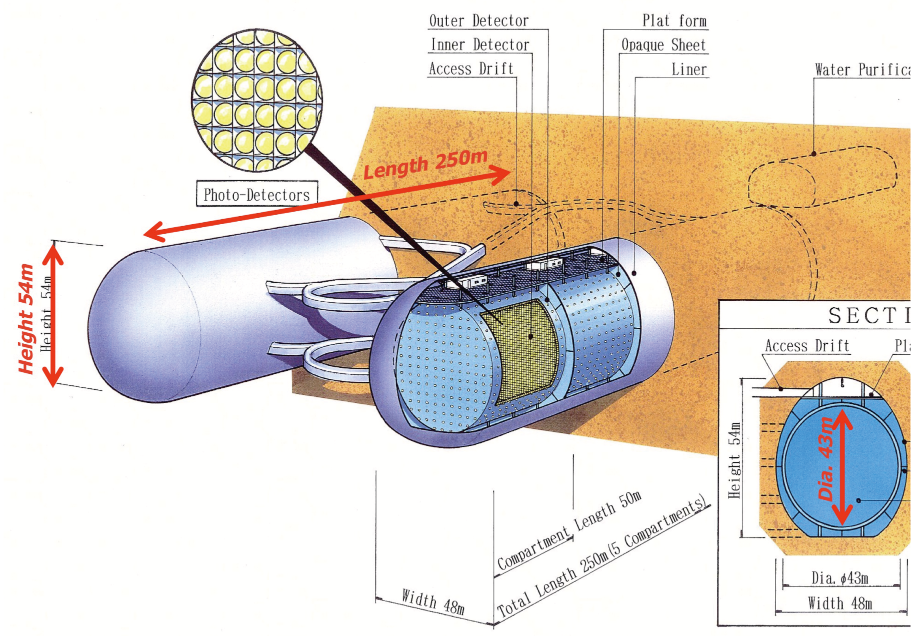


Fig. 1: Hyper Kamiokande, a megaton water Cherenkov detector, is proposed as a successor to Super Kamiokande, to be located at Tochibora, a few kilometers from the Kamioka site.

3 Tank and Water

Different types of tank wall (i.e. liner) material have been considered. They include self supporting steel can, segmented concrete blocks, self supporting concrete vessel, self formed concrete from top or bottom, and no liner (i.e. water barrier over shotcrete). Hyper Kamiokande plans to use plastic (high density polyethylene) liner, which is commonly used for public dump/landfill sites to protect environment from being polluted.

The choice of liner material imposes severe constraint on the performance of a water purification system. Water in Super Kamiokande, which has stainless steel liner, must be continuously purified. It was also the case for IMB (plastic liner) and SNO (acrylic liner).

The current baseline design of Hyper Kamiokande has 5 segmentation walls in a water tank. These walls define 5 sensitive compartments within a tank and also serve as a support structure of phototubes.

4 Photosensors and Electronics

These items are cost drivers as well as a schedule driver. A study for DUSEL shows that the total project cost breaks down to 30% for cavern construction and 70% for instrumentation. The instrumentation cost is driven by the price of photosensors and the associated electronics. The baseline design of Hyper Kamiokande deploys 100,000 20-inch Super-Kamiokande type phototubes to cover 20% of water surface with photocathode. The total cost of phototubes plus protective covers amounts to $\sim$\$350M and that of associated electronics $\sim$\$30M.

The cost reduction has been considered; 1) simply to reduce the photocathode coverage from 40% (of Super Kamiokande) to 20%, 2) to develop phototubes with higher quantum efficiency allowing fewer phototubes for the same photon collection, and finally 3) to develop a new photosensor whose price is lower than a phototube.

Other issues related to instrumentation are optimization of the aperture of phototubes (20 inch or smaller), optimization of the readout electronics in general, and design of protective covers or improving

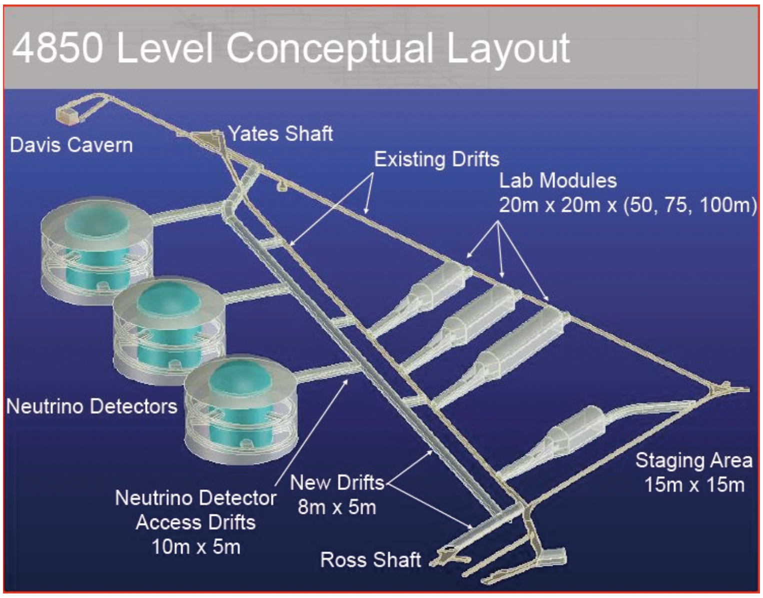


Fig. 2: Three 100k ton fiducial water Cherenkov detectors proposed for the Deep Underground Science and Engineering Lab (DUSEL) at Homestake

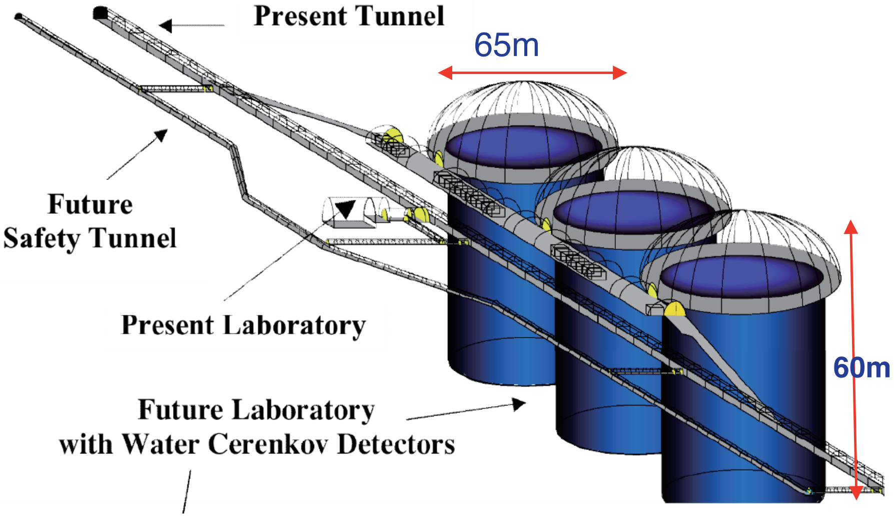


Fig. 3: MEMPHYS (MEgaton Mass PHYSics), proposed for the Frejus site, consists of three large cylindrical (65m diameter × 65m high) water Cherenkov detectors.

pressure-resistance of phototubes.

4.1 Photocathode coverage

Photocathode coverage is one the most critical parameters when designing a large water Cherenkov detector. There exist a few experimental proofs to show a reduced coverage of 20% will just do the job as well as the coverage of 40%. Super-Kamiokande collaboration reported a preliminary study on search for proton decay through $p \rightarrow \bar{\nu} K^+$ using data from SK-II data taking period and compared with the published result from SK-I data. SK-II data represents the photocathode coverage of 20% while the original SK-I data 40%. In this analysis it is a key to identify a faint π^+ signal from $K^+ \rightarrow \pi^0\pi^+$. In SK-I data a typical number of photoelectrons from π^+ is about 60 and the analysis then required a π^+ signal have a number of photoelectrons between 40 and 100, while the corresponding number for SK-II data is from 20 to 50. Figure 4 shows the forward-backward display of $p \rightarrow \bar{\nu}K^+ \rightarrow \bar{\nu}\pi^0\pi^+$ simulation event for SK-I (the photocathode coverage of 40%). In the end, Super-Kamiokande collaboration finds the overall detection efficiency of $p \rightarrow \bar{\nu}K^+ \rightarrow \bar{\nu}\pi^0\pi^+$ for SK-II ($\epsilon \sim 4.8\%$) is about 80% of that for SK-I ($\epsilon \sim 6.2\%$) and the amount of background is comparable.

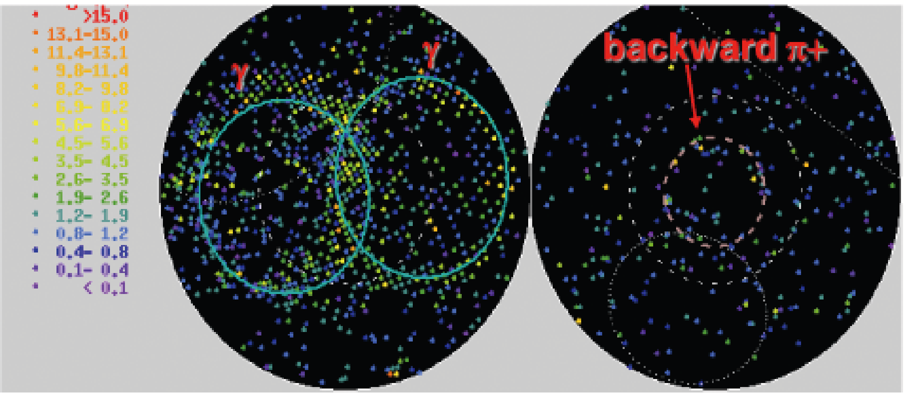


Fig. 4: Forward-backward display of $p \rightarrow \bar{\nu}K^+ \rightarrow \bar{\nu}\pi^0\pi^+$ simulation event for SK-I whose photocathode coverage is 40%.

Another example is Super-Kamiokande results of $p \rightarrow e^+\pi^0$ and $p \rightarrow \mu^+\pi^0$ search [1]. They have found almost identical detection efficiencies for SK-I and SK-II data, $\epsilon \sim 44\%$ for $p \rightarrow e^+\pi^0$ and $\epsilon \sim 35\%$ for $p \rightarrow \mu^+\pi^0$.

In addition, under study is whether the sensitivity to CP violation in a long baseline neutrino oscillation experiment degrades or not due to the reduced photocathode coverage.

4.2 High quantum efficiency phototubes

Hamamatsu Photonics (HPK) recently announced a new phototube whose quantum efficiency (QE) exceeds 42% at wavelength of 350 nanometers [2]. The QE of this device is about 1.7 times higher than that of the currently popular phototube as shown in Fig. 5. The increase in Q.E. compensates the loss of the photocathode coverage.

4.3 A new photosensor

A large aperture Hybrid Avalanche Photodetector (HAPD) has been developed. Figure 6 illustrates the structure of HAPD. HAPD accelerates photoelectrons by a high voltage (ranging from 10 to 20 kV) applied between a photocathode and an avalanche diode (AD) to bombard them into AD. Each photoelectron generates secondary electrons ($\sim$ 5000 electrons at 20 kV) and they, in turn, go through avalanche multiplication of $\sim 30 - 50$. This two-stage multiplication results in a total gain of $\sim 10^5$ for each photoelectron. HAPD has several advantages over a phototube with dynodes. The large first gain (i.e. bombardment gain) reduces an output pulse height fluctuation. HAPD is, therefore, expected to have better pulse height resolution than a phototube. HAPD does not have dynodes that introduce variation in transit time of secondary electrons. HAPD is expected to have smaller transit time spread (TTS). Power consumption of HAPD is also less because there is no dynode current. Because HAPD has fewer components than a phototube (AD vs dynodes), it is also expected to be less expensive.

A 13-inch HAPD shown in Fig. 7 has been developed by HPK, the University of Tokyo and

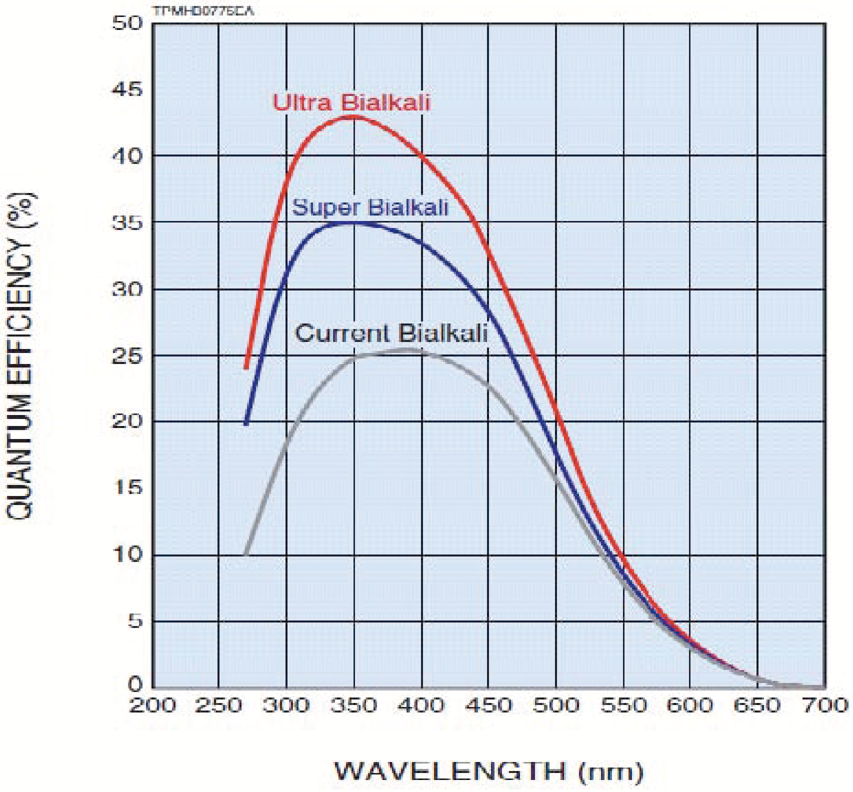


Fig. 5: Quantum Efficiency (QE) of ultra and super bialkali photocathodes. QE of ultra bialkali reaches 43% at 380nm, a factor of ~ 1.7 improvement over the conventional one.

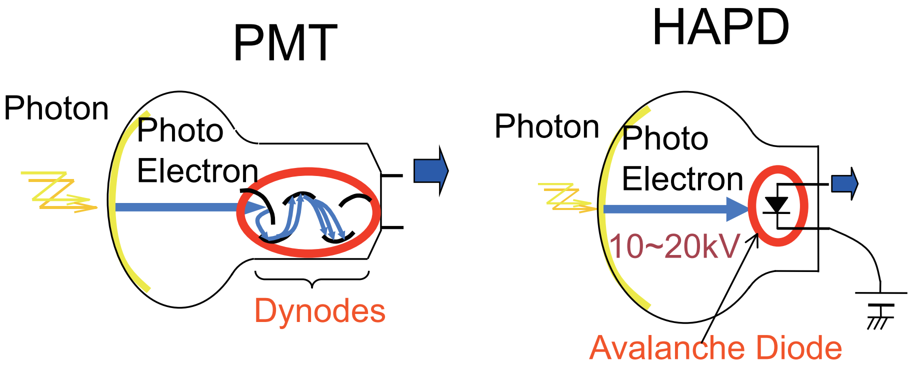


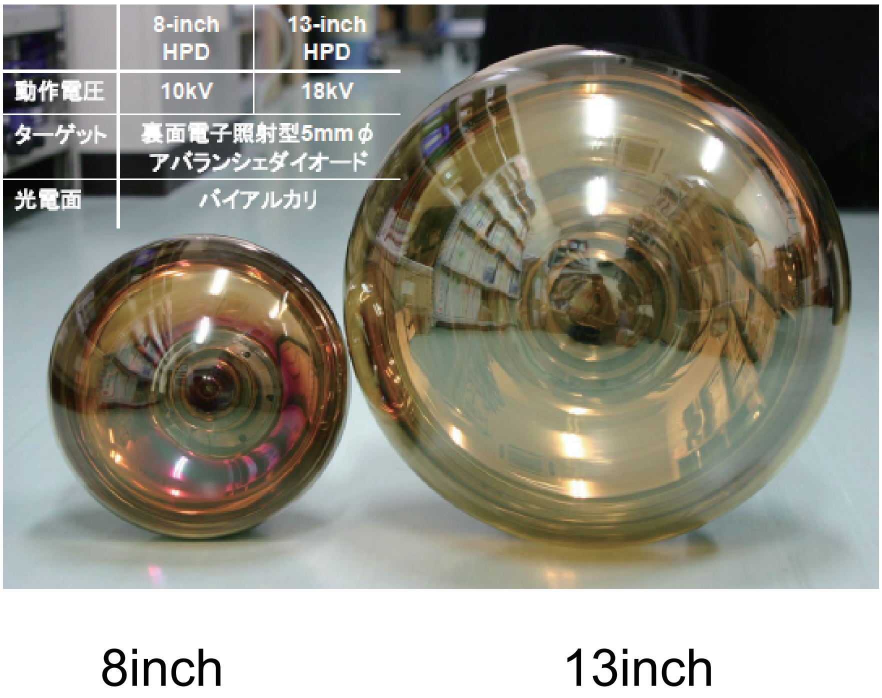
Fig. 6: Schematic presentaion of operation principles of phototubes (PMTs) and Hybrid Avalanche Photodetectors (HAPDs).

KEK [3]. A compact digital readout electronics based on waveform sampling has also been developed. Table 1 summarizes its performance compared with that of phototubes. Large aperture (13 and 8-inch) HAPDs are expected to be commercially available from HPK by 2013.

In Europe a project called PMm^2 [4] has been launched to develop large photomultipliers and innovative electronics for the next-generation neutrino experiments. The very large surface of photodetection is segmented in macro pixels made of 16 hemispherical (12-inch) photomultiplier tubes connected to an autonomous front-end which works on a triggerless data acquisition mode. The expected data transmis-

Table 1: Summary of HAPD performance compared with that of phototubes. All devices are HPK products.

	13-inch HAPD	**13-inch PMT** (R8055)	**20-inch PMT** (SK type)
single photon time resolution (TTS)	190 ps	1400 ps	2300 ps
single photon pulse height resolution	24%	70%	150%
Quantum efficiency	20%	20%	20%
Electron collection efficiency	97%	70%	70%
Power consumption	$<<$ 700 mW	$\sim$ 700 mW	$\sim$ 700 mW
Total gain	10^5	10^7	10^7



	8-inch HPD	13-inch HPD
動作電圧	10kV	18kV
ターゲット	裏面電子照射型5mm φ アバランシェダイオード	
光電面	バイアルカリ	

Fig. 7: Large aperture HAPDs soon to be commercially available.

sion rate is 5 Mb/s per cable, which can be achieved with existing techniques. Figure 8 illustrates the architecture.This architecture allows reducing considerably the cost and facilitating the industrialization.

5 Conclusion

We have presented a snapshot of on-going R&D of large water Cherenkov detectors for neutrino physics. Although there are still many technical issues ahead of us, we conclude that it is certainly feasible to construct such a large detector or detectors based on the experience gained by its predecessors such as Super Kamiokande. The instrumentation of photosensors is the major cost driver and the efforts to reduce its cost is underway. The construction of such a large water Cherenkov detector is estimated to take 7 to 10 years. It is generally agreed among those who have worked on a large water Cherenkov detector that it is not necessary to take the intermediate steps before we embark on a full-scale construction.

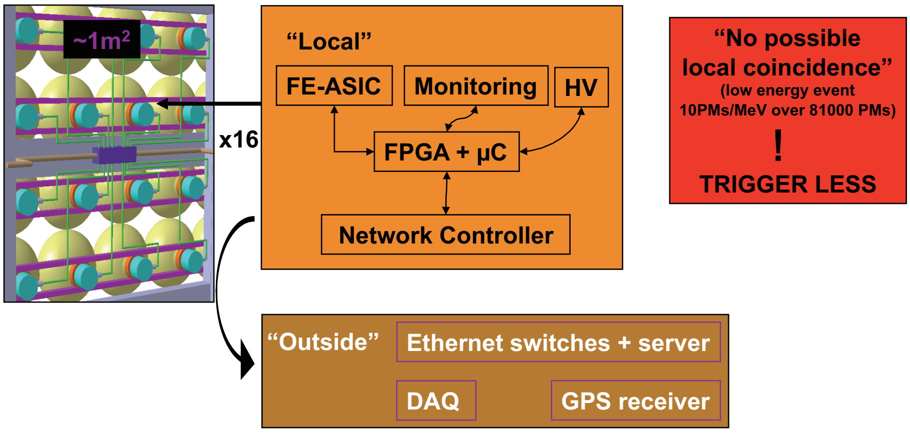


Fig. 8: The signal readout architecture developed by PMm^2 project for large water Cherenkov detectors.

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