Expression of Interest from IN2P3 physicists to participate in the Hyper-Kamiokande experiment in Japan

LLR and LPNHE neutrino groups

Prepared in consultation with the IN2P3 – June 2019

1 Executive Summary

In this document we express strong support to the Hyper-Kamiokande experiment, currently under construction in Japan, and review possible IN2P3 contributions to the project.

2 Hyper-Kamiokande experiment in Japan

2.1 Physics case

Two next-generation long baseline neutrino oscillation experiments are planned to start taking data in the second half of 2020s [1]: **DUNE** in the US and **Hyper-Kamiokande** (Hyper-K or HK) in Japan. The two experiments have the common goals of measuring the δ_{CP} phase and the mass ordering but using different experimental techniques (LAr vs Water Cherenkov), different neutrino energies ($E_\nu \sim$2 GeV for DUNE and $E_\nu \sim$600 MeV for HK), and different baselines (1300 km for DUNE and 295 km for HK), hence being highly complementary.

Both experiments expect to discover CP violation at more than 5σ (3σ) for 50% (75%) of the values of δ_{CP}. An independent comparison of experiments' sensitivities can be found in a recent study [2].

While we believe that the successful construction and exploitation of both experiments is mandatory for the neutrino community, it is clear to the members of the LPNHE and LLR neutrino groups that the Hyper-Kamiokande project is the most attractive option in order to pursue their scientific activities.

The already proven water Cherenkov technology represents a realistic approach. The larger size of HK makes it the most sensitive experiment to rare events such as proton decay or neutrinos from supernova explosion. Finally, our past, on-going and future contributions to the T2K and T2K-II projects are important investments and make it rather natural to continue with HK.

The advantage of such staged and incremental proposal, is that, while getting full experience with a precision neutrino oscillation experiment like T2K and T2K-II, they allow us to work on beam design studies, detector R&D's and physics potential at each stage.

Hyper-Kamiokande [3] is a proposed next-generation general purpose neutrino detector whose broad physics program covers many areas of particle and astroparticle physics. Based on the proven technology of (Super-)Kamiokande, its much larger detector volume and additional improvements in key points, like photosensors and near/intermediate detectors, make HK a straightforward yet powerful extension of the very successful Japan-based neutrino program.

HK consists of an underground water Cherenkov detector that will be located about 8 km south of Super-Kamiokande in the Tochibora mine with an overburden of 1750 m.w.e. The detector will be cylindrical (60 m high and 74 m in diameter) and will have a fiducial (total) mass of 187 (260) kton, making it more than 8 (5) times as large as its predecessor. HK will use 40,000 photomultiplier tubes (PMTs), thus reaching the same 40 % photocoverage as SK, and benefit from newly designed high-efficiency PMTs.

Construction is expected to take about eight years, with start of operations planned for 2026. The option to add a second detector soon afterwards is actively being explored.

While the second detector could be located in Japan at the same site as the first one, the alternative possibility of building the second tank in Korea was explored in a recently published white paper [4]. In addition to sensitivity improvements for the long baseline experiment, the Korean candidate sites offer a higher overburden (and thus lower spallation backgrounds) than the Japanese HK site, which would increase sensitivity to low energy rare events like for instance supernova relic neutrinos.

A new 50 cm PMT model, the Hamamatsu R12860-HQE, was developed for HK. It is based on Hamamatsu R3600 PMT used in SK, but includes a box-and-line dynode and several other improvements. As a result, this new model offers better timing resolution and twice the detection efficiency due to improvements in both quantum efficiency and collection efficiency. Work to reduce the dark noise rate and to design new PMT covers for pressure resistance is currently ongoing.

Possible contributions of LLR and LPNHE physicists to the HK project are briefly described in the next section. These ongoing discussions also involve our colleagues from CEA (Saclay) in order to define common French hardware contributions. Let us stress that our already on-going significant involvement in the ND280 upgrade can be considered as a hardware contribution to the future HK project.

2.2 Possible Contributions for 20-inch PMT electronics

2.2.1 Introduction

The front-end electronics modules for the detectors are required to digitize all signals from photo-sensors that are above a certain threshold, i.e. the acquisition needs to be self-triggered. The digitized information is then either recorded or discarded, depending on the decision of the detector wide trigger system.

The photo-sensor for the inner detector of HK is newly developed. In the baseline option, around 20,000 20-inch PMT R12860-HQE are used. The R12860-HQE PMT has better timing and charge resolution compared to the same diameter PMT (R3600), which has been used in SK. The dark noise rate is required not to exceed 4 kHz, which is a similar requirement to the R3600PMT. Based on this information, we have estimated the total data rate and concluded that it is possible to design the data acquisition system, which is similar to the concept of the SK-IV DAQ.

If we locate the front-end electronics modules on the top of the detector, it is necessary to run the cables from the PMT to the roof and the detector structure has to support the weight of the cables, which is expected to be 800 tons. Thus, it would be possible to simplify the detector structure if we can reduce the weight of the cables. Also, the maximum length of the cable is $\sim$30% longer than in the SK case. This not only reduces the signal amplitude, but also degrades the quality of the signal – the leading edge is smoothed out due to higher attenuation of the cable in the high frequency region. Therefore, we plan to place the modules with the front-end electronics and power supplies for the photo-sensors in the water, close to the photo-sensors.

2.2.2 Current design

The current baseline design of the front-end module is prepared considering all these requirements.

There are 4 main function blocks in the front-end board. The signal digitization block, the photo-sensor power supply block, the slow control block and the communication block. In the current baseline design, one module accepts signals from 24 photo-sensors, digitizes them and sends out the data.

The signal digitization block accepts the signals from the photo-sensors and converts them to the digital timing and charge data. One possible way to satisfy the requirements is to employ charge-to-time conversion (QTC) chips. The QTC chip receives the signal from the photo-sensor and produces a digital signal, whose width is linearly dependent on the amount of the input charge. The leading edge of the output digital signal corresponds to the time when the input signal exceeded the pre-defined threshold to produce the output digital signal. The output signal from the QTC is read out by a TDC. The QTC chips (CLC101) used in the front-end module of SK-IV, called the QBEE, are a good reference and satisfy all the requirements.

Even though the current baseline design is to use the QTC-TDC approach, we are also investigating the possibility of adopting Flash-ADC (FADC) type digitization. In this case, the FADC chip would run all the time and digitize the input signal. Afterwards, FPGA-based on-the-fly digital signal processing would be utilized to find the PMT pulse and determine its charge and time of arrival. An advantage of this approach is that it is completely dead-time free – we would be able to detect photons both from prompt muons and from decay electrons, even if this occurs only 100 ns after the initial interaction. We may also be able to distinguish photons from direct and reflected light. The disadvantage is potentially larger power consumption and higher cost.

2.2.3 Contributions from IN2P3

Our foreseen contributions could be the parts related to the communication block. We do have in our electronic group experts regarding these parts. The main components are trimming synchronization, data handling and communication.

Synchronization of the timing of each TDC or FADC is crucial for precise measurement of the timing of photon arrival. In Hyper-Kamiokande, timing resolution of the photo-sensor is expected to be largely improved. Therefore, we have to be careful with the synchronization of the modules – the design should minimize the clock jitter, so that the timing resolution of the whole system is as good as possible. We are planning to distribute the common system clock and the reference counter to all the modules.

Regarding the communication block, in order to reduce the amount of cables, we are planning to connect the modules in a mesh topology, with each module connected to its neighbours. Only the top modules would be connected to the readout computers. Each module will have several communication ports, so that a single point of failure would be avoided. In case of failure of one of the modules, the data would simply be re-routed to one of the neighbours, thus ensuring that communication path will be secured.

The communication module is expected to have the following functionalities:

- receive the commands from the DAQ system and control the digitizer,
- return the status of the request from the DAQ system,
- receive the data from digitizer, keep them in the local DRAM buffer, and transmit to the DAQ system,
- receive the commands from the slow control/monitor system and control or monitor the slow control
- return the status of the request from the slow control/monitor system.

2.2.4 Schedule

Current plan from the finalization of the design to the completion of the production and tests is shown in Tab. 1.

Spring 2020	Final design review of the system
Autumn 2020	Start the design of the system based on the design review
Autumn 2021	Start bidding procedure
Autumn 2022	Start mass production
Autumn 2023	Start final system test
Autumn 2024	Complete mass production
Autumn 2025	Complete system test and get ready for install

Table 1: Schedule for design and production of Front–end modules for 20-inch PMT electronics

2.3 Possible contributions for multi–PMTs

In addition to this baseline design, R&D on alternative photosensor options like hybrid photo-detectors, LAPPDs and multi-PMT modules is actively being carried on by several countries (mostly Canada, Italy, UK) with the goal of providing half of the photo–cathode coverage for Hyper-Kamiokande.

In particular the multi–PMTs option, based on design developed for KM3NeT is particularly appealing.

In this context there is the attractive possibility of using the existing Memphyno water tank [5] at APC for performing underwater tests of the multi-PMT modules developed in Europe, Canada and Japan. There is also a possibility of contributing to the development of electronics for the multi–PMTs readout based on a chip designed by the Omega laboratory.

The use of the Write Rabbit technology [6] to perform synchronization between different PMT modules is currently under investigation.

2.4 Possible contributions via hadron production measurements

The importance of dedicated hadron production measurements with the **NA61/SHINE** spectrometer at the CERN SPS for future advances in accelerator neutrino physics is now widely recognized within the community, see e.g. documents prepared for the update of European Strategy for Particle Physics [7, 8].

The IN2P3 physicists have already played a leading role in obtaining recent NA61/SHINE results with both thin carbon [9] and T2K replica targets [10]. There measurements are currently being used to reduce the (anti)neutrino flux uncertainties in T2K and T2K-II down to about 5%.

Similar measurements are planned for the new target to be used for the HK experiment.

3 Possible IN2P3 contributions to Hyper-K

Here is a list of activities in which IN2P3 physicists are interested and which could represent the IN2P3 contribution to the Hyper-Kamiokande project.

3.1 Multi-PMTs

Multi-PMTs prototypes, initially based on the design of the domes for KM3NeT, are being built and are considered as the baseline solution for the Hyper-K intermediate detector (E61) and to complement the photocathode coverage of Hyper-K.

In this context we will contribute to the underwater tests of the m-PMTs prototypes using the existing **Memphyno** water tank at APC and we will work on the simulation and reconstruction code to better define the impact of the m-PMTs on the Hyper-K physics case.

In addition, a **test beam experiment** to be carried on at CERN with a tank instrumented with ~ 100 m-PMTs is being proposed by a part of the Hyper-K collaboration. The IN2P3 physicists will contribute to these efforts.

3.2 Time Synchronization

In the Hyper-K detector about 40000 PMTs will have to be synchronized at the ns level. A possible solution is to use the White Rabbit technology, already exploited in KM3NeT, and thus developing synergies with other IN2P3 groups.

At IN2P3 we plan to contribute to the development of such synchronization system that will be tested on small scale with the test beam experiment and will eventually be extended to the full Hyper-K detector.

3.3 Software and Computing

The very-performant IN2P3 Computing Centre at Lyon will allow us to play a leading role in the Hyper-K software and computing group.

As physicists we plan to develop new reconstruction tools for Water Cherenkov detectors based on Machine Learning techniques while on the computing side we can contribute to the Hyper-K needs by providing storage elements and working on the distributed computing for which DIRAC is planned to be used.

This will also allow us to exploit synergies with Belle-II groups in the context of the already funded Jennifer-II European project.

4 Summary

Given a highly-recognized importance of the Hyper-Kamiokande project and a significant interest from IN2P3 physicists with already identified contributions, the IN2P3 is ready to invest *(put your preferred number here)* M€ in order to support participation of IN2P3 physicists.

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