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

Sara Bolognesi[1], Margherita Buizza Avanzini[2], Olivier Drapier[2], Jacques Dumarchez[3], Sandrine Emery[1], Frank Gastaldi[2], Claudio Giganti[3], Michel Gonin[2], Mathieu Guigue[3], Samira Hassani[1], Jean-Michel Lévy[3], Edoardo Mazzucato[1], Thomas Mueller[2], Pascal Paganini[2], Boris Popov[3], Stefano Russo[3], Georges Vasseur[1] and Marco Zito[1]

[1]IRFU/DPhP Neutrino group, CEA, Saclay
[2]LLR Neutrino group, CNRS/IN2P3
[3]LPNHE Neutrino group, CNRS/IN2P3

Prepared in consultation with the IN2P3 and IRFU – June 2019

Executive Summary

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

Contents

1 Hyper-Kamiokande experiment in Japan

Hyper-Kamiokande (Hyper-K or HK) is the next generation long-baseline neutrino oscillation experiment planned to start taking data in the second half of 2020s. The main physics goal of the experiment is the discovery of CP violation in the leptonic sector. The experiment will be built in Japan and will exploit same experimental technique (Water Cherenkov detector), neutrino energy (E_ν ~600 MeV) and baseline (295 km) of the existing T2K experiment to which IN2P3 and IRFU/DPhP physicists are participating since more than 15 years.

Hyper-Kamiokande will exploit the already well proven water Cherenkov technology that lead to two Nobel prizes in physics for the previous detectors of the Kamiokande saga but, thanks to its large size, has a sensitivity to measure CP violation at more than 5σ (3σ) for 50% (75%) of the values of

δ_{CP} and will be a fundamental experiment to bring the neutrino oscillation physics into the era of high precision measurements.

Besides the measurements of neutrino oscillations, the large size of HK makes it the most sensitive experiment to rare events such as proton decay or neutrinos from supernovae explosions.

The participation of the members of the LPNHE, LLR and IRFU/DPhP neutrino groups to the Hyper-Kamiokande project is a natural continuation of the T2K activities, which will allow the most prominent physics output, notably a timely discovery of CP violation.

The engagement of the groups in Hyper-Kamiokande is built upon the human and financial investments made along the years in T2K and T2K-II, which allowed the French groups to acquire a deep expertise and a primary role in the collaboration, thus ensuring a large return in terms of visibility and responsibility even in the very competitive environment of such large international collaborations.

2 The Hyper-Kamiokande detector

Hyper-Kamiokande [3] is a 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 on 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 pressure-proof PMT covers is currently ongoing.

Possible contributions of IRFU/DPhP, LLR, and LPNHE physicists to the HK project are briefly described in the next section. Let us stress that our already on-going significant involvement in the ND280 upgrade for T2K-II can be considered as a hardware contribution to the HK project.

3 Possible contributions from French groups to HK

In this section we will list a list of contributions to the HK experiment envisaged by the different groups. Some of them (NA61/SHINE or ND280 upgrade) are based on the work done by the three groups in T2K and T2K-II.

The possible contributions to the HK far detector are written taking into account existing expertise in the different technical services of the laboratories and/or the presence of infrastructure (such as Memphyno at APC) that can be exploited for HK. Possible synergies with other activities on PMTs in France (Km3Net or JUNO) have also been considered and will be exploited in the coming months.

3.1 Hadron production measurements with NA61/SHINE

The importance of dedicated hadron production measurements with the **NA61/SHINE** spectrometer at the CERN SPS for 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 [5, 6].

The IN2P3 physicists have played a leading role in obtaining NA61/SHINE results with both a thin carbon target [7] and a T2K replica target [8]. 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.

3.2 Constraints of flux and neutrino cross-section systematic uncertainties with ND280

The biggest challenge for the Hyper-Kamiokande experiment will be the control of systematic uncertainties at the unprecedented level of about 2%. The most complex and large systematic uncertainties are due to flux and neutrino-nucleus cross-section, as shown, for instance, in Ref. []. The Hyper-Kamiokande strategy is based on the successfull experience of T2K, where the near detector (ND280) has a crucial role to constrain such systematic uncertainties. The French group had a primary role in the construction, maintenance and data exploitation of ND280 and we have today a leading role in the upgrade of such detector in preparation of the higher statistics expected after JPARC beam upgrade.

ND280 is a magnetized detector with outstanding tracking performances. It allows a precise measurement of the wrong sign background (measurement of neutrino background in the antineutrino beam and viceversa), which is compulsory for the discovery of CP-violation. The upgrade of ND280 includes a new concept of 3D finely-segmented scintillator detector (superFGD) capable of exclusive measurements of the hadronic final states in neutrino-nucleus interactions. The superFGD enables the reconstruction of the neutrino energy with a calorimetric approach, also in presence of neutrons, thus validating the neutrino energy reconstruction based only on muon kinematics which is a large source of systematic uncertainty in the Hyper-Kamiokande water Cherenkov detector.

ND280 is a modular detector which can be further upgraded, on the basis of the results observed at larger statistics, in order to match the challenges which the Hyper-Kamiokande experiment will certainly face in the run to the ultimate precision in neutrino oscillation measurements.

3.3 Hyper-Kamiokande Far Detector

3.3.1 20-inch PMTs and their electronics

The front-end electronics modules for the detectors are required to digitize all signals from photo-sensors above a certain threshold, i.e. the acquisition must 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 with 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 a DAQ system design similar to that of SK-IV is feasible.

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 their weight, which is expected to be about 800 tons. It would be possible to simplify the detector structure if we can reduce this weight. 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.

The current baseline design of the front-end module takes all these requirements into account.

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 digitizes both the timing and the charge. 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 exceeds a pre-defined threshold to produce the output digital signal. This output 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.

3.3.2 Multi–PMTs option for HK

In addition to this baseline design, R&D on alternative photosensor options like hybrid photo-detectors, LAPPDs and multi-PMT (mPMT) 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.

This option is particularly appealing for French groups that could profit of the existing expertise from KM3NET and from the developments of the small PMTs for JUNO. In 2019 we plan to organize a workshop in order to exploit these possible synergies.

In addition there is the attractive possibility of using the existing Memphyno water tank [9] at APC for performing underwater tests of the mPMT modules developed in Europe, Canada and Japan and further characterize the in-situ response of the mPMTs. Such tests are expected to begin with the first mPMT prototype from Italy before summer 2019 and will be continued with a second prototype that is expected to be ready in the fall of 2019.

There is also a possibility of contributing to the development of electronics for the mPMTs readout based on a chip designed by the Omega laboratory.

In addition, a **test beam experiment** to be carried out at CERN with a tank instrumented with ~ 100 mPMTs is being proposed by a part of the Hyper-K collaboration. This design corresponds to a scaled-down version of the Intermediate Cherenkov Water Detector (E61), proposed in the Hyper-K design to better control the cross-sections related uncertainties. This experiment aims at:

- test the technological choices for E61 and Hyper-K far detector in terms of modules synchronization, DAQ and storage;
- characterize the mPMTs response with respect to a calibrated source of charged particles, allowing to further contraint the simulations.

The performances of an hybrid design for HK with a combination of large PMTs and multi-PMTs are being studies by the collaboration. Preliminary study show that if the dark noise can be keep at the level of 100 Hz, better vertex reconstruction for events close to the wall and a lower energy threshold can be obtained. The better vertex reconstruction will allow to increase the Fiducial Volume while the lower energy threshold will improve perfomances for low energy events, in particular increasing the sensitivity of HK to the up-turn of the ^{8}B spectrum of solar neutrinos, probing the MSW-LMA prediction in the transition region between vacuum and matter-dominated neutrino oscillations.

3.3.3 Clock distribution and time synchronization for small and large PMTs

Our foreseen contributions could be related to the communication block and in particular to the time synchronization and clock distribution to the PMTs (20k large PMTs and few thousands mPMTs).

We do have in our electronic group experts regarding these parts. The main components of the communication block are timing 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, at the level of 1 ns. 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.

The use of the White Rabbit technology [10] to perform synchronization between different PMT modules is currently under investigation within the collaboration and would represent an attractive option for French groups but different methods based on the SK or on the Belle-II experience could also be exploited.

The chosen time synchronization system could be tested on a small scale on the test beam experiment at CERN.

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.

To our mind, an advantage of this task is that it is independent on the chosen technology for the PMTs and could be useful for both large and small PMTs assembled together in the mPMTs.

3.4 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 the highly-recognized importance of the Hyper-Kamiokande project, its exceptional physics case and the significant interest from IN2P3 and IRFU/DPhP physicists with already identified possible contributions, we hope to receive a support from IN2P3 and IRFU at the level of the project scientific interest.

References

[1] J. Cao, A. de Gouvea, et al.*Roadmap for the international, accelerator-based neutrino programme*, arXiv:1704.08181 (2017).

[2] K. Chakraborty, K. N. Deepthi, et S. Goswami, *Spotlighting the sensitivities of T2HK,T2HKK and DUNE*, arXiv:1711.11107 (2017).

[3] Hyper-Kamiokande, *Hyper-Kamiokande Design Report*, (2016).

[4] K. Abe, K. Abe, et al., *Physics potentials with the second Hyper-Kamiokande detector in Korea*, Prog. Theor. Exp. Phys. **2018** (6), 063C01, arXiv:1611.06118 (2018).

[5] A. Dell'Acqua, A. Aduszkiewicz, et al., *Future Opportunities in Accelerator-based Neutrino Physics*, arXiv:1812.06739 (2018).

[6] A. K. Topaksu, E. Blucher, et al., *Research and Development for Near Detector Systems Towards Long Term Evolution of Ultra-precise Long-baseline Neutrino Experiments*, arXiv:1901.04346 (2019).

[7] N. Abgrall, A. Aduszkiewicz, et al., *Measurements of $\pi^{\pm}$, $K^{\pm}$, K^0_S, Λ and proton production in proton-carbon interactions at 31 GeV/c with the NA61/SHINE spectrometer at the CERN SPS*, Eur. Phys. J. C **76** (2), 84, arXiv:1510.02703 (2015).

[8] N. Abgrall, A. Aduszkiewicz, et al., *Measurements of $\pi^{\pm}$, $K^{\pm}$ and proton yields from the surface of the T2K replica target for incoming 31 GeV/c protons with the NA61/SHINE spectrometer at the CERN SPS*, Eur. Phys. J. C **79** (2), 100, arXiv:1808.04927 (2018).

[9] A. Tonazzo, *The LAGUNA-LBNO Project*, Nucl. Part. Phys. Proc. **265-266**, 192 (2015).

[10] M. Lipinski, T. Wlostowski, et al. (2011), in *2011 IEEE Int. Symp. Precis. Clock Synchronization Meas. Control Commun.* (IEEE) pp. 25–30.