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

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In this document we express strong support to the Hyper-Kamiokande experiment and review possible contributions from the French groups to the project.

1 Motivations for our participation to the Hyper-Kamiokande experiment

Hyper-Kamiokande (Hyper-K or HK) is a 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 lepton sector.

The experiment has recently been approved by the Japanese government and will be built in Japan. It will exploit the same experimental technique (Water Cherenkov detector), neutrino energy ($E_\nu \sim$ 600 MeV) and baseline (295 km) as the existing T2K experiment to which IN2P3 and IRFU physicists have been participating for more than 15 years.

This well-proven technology has already led to two Nobel prizes in physics with the previous detectors of the Kamiokande saga. Thanks to its larger size, HK has a sensitivity to measure CP violation at more than 5σ (3σ) for 50% (75%) of the values of $\delta_{\rm CP}$ and will be a fundamental experiment to bring neutrino oscillation physics into the era of high precision measurements. Besides measurements of neutrino oscillations with accelerator, atmospheric and solar neutrinos, 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 French neutrino groups to the Hyper-Kamiokande project is built upon the human and financial investments made along the years in T2K, T2K-II, and SK. It 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.

HK constitutes a natural extension of the on-going activities that will allow most prominent physics outputs, notably a timely discovery of CP violation in the lepton sector and a search for rare events, such as proton decay, with unprecedented sensitivities.

Possible contributions of French groups to the HK project are briefly described in the next section and detailed in the Appendix. 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.

2 Summary of the possible contributions from French groups to HK

In this section we will present a list of possible contributions to the HK experiment by the French groups. Some of these contributions (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 discussed in the Appendix taking into account existing expertise in the different technical services of the laboratories and/or the presence of infrastructure (such as Memphyno water tank [1] at the APC laboratory in Paris) 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 further investigated.

2.1 Current manpower

The French groups have a very strong expertise being present in T2K since the beginning and having large contributions to the construction and maintenance of the near detectors and important responsabilities at analysis level. This vibrant community is distributed among IRFU, LLR and LPNHE laboratories. The approval of the HK experiment by the Japanese government (MEXT) can potentially allow the French groups to enlarge thanks to the synergies mentioned above.

2.2 Possible contributions to HK

Table 1 summarizes the possible contributions from the French groups to the experiment. The level of possible contributions is expected to be more precisely known in 2021. Following the approval of the project by the Japanese government, we will present the possible contributions to the funding agencies. Since the project is approved by the Japanese government, we could now increase and negociate our contributions with our funding agencies, considering an investment profile starting in 2020 or 2021.

2.3 Possible requests for funding from French researchers

Table 2 shows the possible timeline of the funding.

With the final approval of the HK experiment in Japan we can now start preparation of our funding requests to the French funding agencies. The first step would be to present our potential contributions to the IN2P3 and IRFU Scientific Councils in order to get their approval. This can be done in the first part of 2021. Then the funding requests would have to be approved by the IN2P3 and IRFU directorates. Given the current difficult situation due to COVID-19 our negotiations with the funding agencies are still on-going, thus the content of this EoI would have to stay fully confidential till the end of 2020.

Contribution	Item
Far detector	
20-inch PMTs electronics	R&D and production of front-end electronics modules (TR III.7.A,B,C)
Multi-PMTs	In-situ characterisation of multi-PMTs with Memphyno (TR III.6.A,B,D)
	Test beam experiment (Not listed in TR - support II.3 and III.6)
DAQ & overall electronics	R&D and construction of clock distribution and time synchronisation (TR III.7.D)
Additional contributions	
NA61/SHINE	new replica target measurements and data analysis (TR II.I.F)
ND280-upgrade	Electronics for superFGD (TR II.2.D)
	MicroMegas, Electronics, mechanical engineering and DAQ for HA-TPC (TR II.2.D)
Current INGRID, WAGASCI, ND280	Maintenance of existing detectors & electronics (TR II.2.A,B,C,E)
Physics, Software, Computing	Expertise in shared computing resources
	Storage and CPU (TR IV.3)
	Development of far detector simulation (TR IV.1.A,B)
	Development of low and high energy fitters for HK (TR IV.2.A,B,C)

Table 1: Intended contributions to the Hyper-K experiment.

Source	Item	Starting year
French funding agencies (IN2P3 & CEA)	ND280 upgrade	2019
	Computing resources	2019
	HK electronics	2021
JENNIFER-II European project	T2K upgrade	2019
	HK design	2019
	mPMT development	2019
	Computing and common tools	2019
TYL-FJPPL projects[1]	HK R&D	2019
Sorbonne Université[2]	mPMT tests	2019
Ecole Polytechnique[3]	chip and front-end board design	2020
IRL CNRS-UoT	HK manpower	2021

Table 2: Possible fundings timeline for the French laboratories.

A Details about the possible contributions

A.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 [2, 3].

The IN2P3 physicists have played a leading role in obtaining the NA61/SHINE results with both a thin carbon target [4] and a T2K replica target [5]. 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. Moreover, a preparatory work has now started to allow the NA61/SHINE spectrometer to be served with a lower-energy (below 10 GeV/c) beamline which is crucial for further reduction of uncertainties on both accelerator and atmospheric (anti-)neutrino fluxes in the HK era.

[1] about 10k euros per year
[2] 80k euros already funded
[3] 400k euros already funded

A.2 Constraints of flux and neutrino cross-section systematic uncertainties with INGRID, WAGASCI and 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. [6]. 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 **INGRID**, **WAGASCI** and **ND280**. A first important role will be the operation of all these detectors during the HK data-taking coupled to the development of new analyses required to bring the HK systematic uncertainties down to their required limits. Moreover, we have today a leading role in the upgrade of the ND280 detector currently in preparation for the higher statistics expected after the J-PARC 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 leptonic CP-violation. The upgrade of ND280, foreseen to be completed in 2022, includes a new concept of 3D finely-segmented scintillator detector (superFGD) capable of exclusive measurements of the hadronic final states in neutrino-nucleus interactions, coupled with two additional horizontal TPCs. 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 obtained with 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.

The role of ND280 to constrain the systematics for Hyper-Kamiokande physics results will be crucial as demonstrated in [**TDR˙Addendum**]. Moreover at the start of HK data taking, with a new beam, a new far detector and a new IWCD, ND280 will be a well understood and calibrated detector which will allow to gauge the analysis. The contribution to ND280 must be therefore understood as an integral part of the Hyper-Kamiokande collaboration and quantified accordingly from a financial point of view. In addition, an agreement between HK and T2K collaborations will have to be reached to bring the detector from T2K to HK.

In order to be fully functional for HK, ND280 will need to be steadily operated and maintained from today until the start of HK. This will be possible only if a sufficient amount of run time is allocated with a reasonable frequency. Moreover the collected POT must be sufficient for an interesting physics program around which to build a community which will transfer the ND280 know-how from T2K to HK era. In absence of such conditions, we cannot commit to the resurrection and maintenance of ND280 for HK.

The draft of the HyperK collaboration agreement [**HKagreement**] foresees that the ND280 detector is fully part of the HyperK project.

A.3 Hyper-Kamiokande Far Detector

A.3.1 20-inch PMTs and their electronics

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. R12860-HQE PMTs have better timing and charge resolutions compared with the same diameter PMTs (R3600), which have been used in SK. The dark noise rate is required not to exceed 4 kHz, which is a similar requirement to the R3600 PMTs. Based on this information, the total data rate is estimated demonstrating that a DAQ system design similar to that of SK-IV is feasible.

The front-end electronics modules for the detectors are required to digitize all signals from photosensors 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.

If the front-end electronics modules is located 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 ∼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 which are currently used in the front-end module of SK-IV, called the QBEE. 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.

We propose to develop and produce the Front-End electronics of HK, using an alternative to the QTC chip. This new chip is based on a new version of the current CATIROC chip developed by OMEGA laboratory, and used for the readout of JUNO 3" PMTs. This new chip is developed with several goals: extend its commercial availability compared to the QTC chip, reduce the deadtime and increase chip durability. The current QTC chip, as well as the current generation CATIROC, are printed in AMS 350 nm. This technology is close to reach its expiration date, which will limit the time for R&D of QTC or current CATIROC, as well as conflict with a potential future production of this chip for a later upgrade of the detector. We propose to develop a new chip in TSMC 130 nm. On top of its longer availability, this technology allows to reduce the time required for readout, decrease the electronic noise as well as the cross-talk between the channels of the same chip. Moreover, the new flip chip packaging will be used for this chip, allowing to improve the chip durability. It is especially crucial for HK which will run several decades with the electronics in water. The new chip will also rely on an improved analog part compared to the CATIROC, allowing to reduce the conversion deadtime. Such an almost deadtime free chip would have significant improvement on HK physics, among which:

- increase the number of detected events for galactic Supernovae, and therefore improve the constraints on the explosion mechanisms.
- reduce the experiment energy threshold through monitoring of the so-called "continuous dark-rate".
- detect very prompt decay electrons.
- distinguish photons from direct and reflected light, therefore improving the energy reconstruction and ring counting especially at very high energies.

The OMEGA group will be responsible of the chip R&D. In parallel, the LLR group proposes to develop and produce the Front-End board hosting the chip. The two laboratories are part of Ecole polytechnique which **fully supports this project and approved the funding of 400,000 euros** for the R&D of the chip and Front-End board. Moreover, the two laboratories also have the experience of several successful collaborations in various projects, among which the T2K WAGASCI and Super-FGD or the CMS-HGCAL detectors. We are anticipating also to provide the production of the chips and boards necessary to fully equip the HK inner detector photo-sensors.

A.3.2 Clock distribution and time synchronization for small and large PMTs

The time distribution system is one of the most crucial parts of the HK electronics since it is essential for the correct reconstruction of the particle tracks that cross the detector. A very stable and precise cadence needs to be created at the detector site and distributed to all the front-end modules where it is used to associate a time tag to the signals recorded from the PMTs. This time tagging has to be expressed in a form that will allow its correlation with data from other experiments therefore, the local time base needs to be accorded with the Universal Time Correlated (UTC) by means of GNSS (Global Navigation Satellite System) signals. This absolute time information will be also used to trigger the detector when the particles packets will be sent from the J-PARC accelerator. Along with the clock, a data channel to transport critical information like the FPGA remote updating stream and slow control data needs to be implemented.

The LPNHE group is performing, since one year and half, an aggressive R&D program to define the best architecture that not only satisfies the experimental requirements of 1 ns jitter and fixed latency but also be cost effective and ready on time for the start of the detector construction. The first part of this program, already concluded, has defined the following 2 technologies that are the most promising:

- The White Rabbit solution based on the CERN developed protocol [7] that guarantees a precise time distribution and board to board skew compensation.
- The so-called "custom" solution that guarantees the same jitter characteristics as the White Rabbit option but is based on a custom protocol which is more flexible and more easily adapted for the experimental's needs.

Both schemes have been accepted by the collaboration's electronics working group and, along with a third one proposed by our Japanese collaborators, are now the subject of the last R&D phase devoted to the detailed characterisation of each protocol in light of the final choice. The partnership with our Japanese colleagues is so effective and well established that, recently, we have decided to merge our efforts working as one single group of developers. This is a great sign that we are very well placed to put our electronics in the final detector.

Great effort has also been devoted to the atomic clock and GNSS architecture thanks to the strong partnership established with another CNRS laboratory SYRTE (Systeme de Reference Temps-Espace): the Paris Observatory's department leader in time and frequency metrology and responsible for the "France official time". With their help we have defined the most suitable architecture for the time base generation and UTC reference which consists of an atomic clock placed very close to the read-out electronics and a GNSS receiver installed outside the detector cavern. The two instruments exchange a low frequency (10 MHz) and a Pulse Per Second (PPS) signal over a synchronous and phase deterministic link implemented with the same methods mentioned above. The synergy between them guarantees great stability and very low jitter of the HK clock over the full detector's lifetime and an accord to the UTC at a precision of less then 100 ns.

Our fast progress puts ourself also in the position of supporting the front-end electronics developers in their R&D providing components, software and firmware IPs to implement the time distribution system starting on the first FE prototypes. This aspect represents a great opportunity to test the time distribution system in situ well ahead of the final deployment.

Our time synchronization apparatus could be also validated on a smaller scale with Memphyno setup and/or test beam experiment at CERN and could also be potentially used for the IWCD.

A.3.3 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. The multi-PMTs are also the baseline photosensor option for the Intermediate Water Cherenkov Detector (IWCD). This option is particularly appealing for French groups as they could profit from the existing KM3NeT expertise and from the developments of the small PMTs for JUNO.

In addition there is the attractive possibility of using the existing Memphyno water tank 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 have already been started with the first mPMT prototype from Italy and will continue in the coming years.

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 downscaled version of the Intermediate Water Cherenkov Detector (E61), proposed in the Hyper-K design to better control the cross-sections related uncertainties. This experiment aims at:

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

Our contribution to this test beam experiment will be a continuation of the work carried on the mPMTs studies with Memphyno.

The performances of a hybrid design for HK with a combination of large PMTs and multi-PMTs are being studied by the collaboration. Preliminary results show that if the dark noise can be kept 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.

A.4 Software and Computing

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

The French groups are already leading the development of new simulation and reconstruction tools for both low and high energy sectors. We plan to strengthen this contribution by:

- upgrading the simulation of the PMT front-end and clock-distribution systems in synergy with our progress on hardware,
- developing a new generation of reconstruction algorithms for Water Cherenkov detectors based on Machine Learning techniques,
- providing storage and computing resources from CC-IN2P3 to Hyper-K using DIRAC [8].

A proposal containing several options with several levels of contributions to the overall Hyper-K computing efforts is currently being discussed with CC-IN2P3 and IN2P3 directorate. This proposal was positively received by CC-IN2P3 directorate.

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

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