Participation of IN2P3 physicists in the Hyper-Kamiokande experiment*

ILANCE, LLR, LPNHE, OMEGA (IN2P3-CNRS)

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Contents

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Executive summary

The dominance of matter over antimatter in the visible Universe is one of the most puzzling problems in our current understanding of the Universe. Indeed, there is no known reason that in an a priori symmetric Universe just after the Big Bang, there should be large structures like galaxies and stars made only of matter without being able to observe similar objects made entirely of antimatter. In order to explain this mystery, one of the most appealing possibilities is the so-called *leptogenesis* in which the asymmetry between matter and antimatter is originally produced in the leptonic sector via CP violating processes and is later transferred to the baryons.

Among the experimentally accessible sources of CP violation in the leptonic sector, the most convenient probe is through the phenomenon of neutrino and antineutrino oscillations described by the PMNS mixing matrix [1, 2]. This matrix is a 3×3 unitary matrix that, analogously to the CKM matrix in the quark sector, connects three neutrino mass states to the three neutrino flavor states and can be parametrized by three mixing angles (θ_{12}, θ_{23}, and θ_{13}) and at least 1 phase (δ_{CP}). If neutrinos are Majorana particles, there can be two additional phases, but without impact on the oscillation phenomenon.

It is already well established that all the three mixing angles are non-zero. Then, if also $\sin\delta_{\mathrm{CP}} \neq 0$, differences in the oscillation probabilities of neutrino and antineutrino correspond to a CP-violation phenomenon. Long baseline accelerator neutrino (LBL-ν) experiments searching for the differences in the $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ appearance probabilities are the most reliable option to investigate CP violation in the leptonic sector.

In such experiments, intense beams of ν_μ or $\bar{\nu}_\mu$ are created from the decays of hadrons (pions and kaons) produced in the collisions of protons in a long (usually graphite) target. The beam composition is first measured close to the target by the so-called near detectors, then again, after oscillation, a few hundreds of kilometers away, using a far detector which identifies the flavors of the detected neutrinos and antineutrinos via their charged-current (CC) interactions. One of the main challenges of future LBL-ν experiment is that, in order to measure CP-violation, an increase of statistics by a factor of ~ 100 is needed with respect to the currently running experiments. This increase can be achieved by a combination of higher intensity conventional neutrino beams and larger far detectors.

In this document we present the strategy proposed by the Hyper-Kamiokande (HK) experiment that is the next-generation LBL-ν experiment in Japan [3]. HK builds on a more than 40 years of successful neutrino program in Japan with accumulated experience on constructing and using large Water Cherenkov detectors in Kamioka (Kamiokande and Super-Kamiokande) and intense neutrino beams from KEK and J-PARC (K2K and T2K experiments).

The HK project was approved by the Japanese government in 2019 and it is planning to take its first data in 2027. It consists of a Water Cherenkov detector with a fiducial volume eight times larger than the existing Super-Kamiokande and will use the already operational J-PARC neutrino beam. J-PARC is currently able to provide ~500 kW beam power and is being upgraded to reach 1.3 MW during the T2K-II phase. Hence, one nominal year of operation of HK will allow to collect a statistics corresponding to more than 20 years of T2K, to provide a quick and powerful confirmation (or rejection) of the current hints for CP violation observed by T2K [4, 5]. For the CP asymmetry values of $\delta_{\mathrm{CP}} \sim -\pi/2$, which are currently favored by T2K, HK will measure CP violation with more than 5σ significance by 2029 (two years after the start of data-taking).

Moreover, the HK far detector will be a multi-purpose neutrino observatory that is not limited to the measurements of the PMNS parameters with both accelerator and atmospheric neutrinos. It has a very rich program in the few MeV to TeV energy range, covering solar physics, cosmology through the detection of Diffuse Supernova Neutrino Background (DSNB), search for proton decay, sterile neutrinos and *multi-messenger astrophysics* with the detection of galactic or extra-galactic core-collapse supernovae [6].

In this document, we present the strategy of the IN2P3 groups to contribute to the HK experiment. This strategy stands on two legs: first, use our long-standing contribution and expertise to the T2K experiment and the T2K oscillation analyses to have a strong impact on the HK program on neutrino oscillation physics. Second, directly contribute to the HK far detector construction. For the HK far detector, our original plan was to provide a large part of the photo-detectors electronics chain, including the digitizer, based on a chip developed by the OMEGA lab and IRFU, and the time generation and distribution system developed in close collaboration with SYRTE (Paris Observatory) and IRFU colleagues. In addition, we intend to strongly contribute to the computing efforts for the next 15 years in order to cover a large fraction of the needs of HK experiment.

Since our previous report in October 2021, a significant progress was achieved by the Hyper-Kamiokande collaboration. The construction of the 2-km access tunnel was completed as scheduled (the dome centre was reached on June 24 2022) and the cavern excavation was launched. The production of the 20-inch PMTs is progressing and reached more than 3500 units. Major upgrades of the J-PARC Main Ring and of the neutrino beamline were performed. The detector design was nearly finalized in accordance with available resources (funding, personnel, space, time, etc.).

The IN2P3 groups performed an intensive R&D program resulted in the detailed proposals of possible technical contributions submitted for the internal collaboration review. An impressive amount of high-quality work has been performed for both the digitizer and the timing system.

Unfortunately, the HKROC-based solution for the digitizer has not been selected as primary choice by the collaboration (decision announced on September 16). Though large physics advantages have been acknowledged, the HK management decided to use a conventional solution over a more innovative design. There are still possibilities to contribute to the project with the HKROC on e.g. the electronics of far and intermediate outer-detectors.

As to the timing system, the R&D is completed, and our proposal for the Hyper-Kamiokande detector, well within the collaboration requirements, has been submitted for the collaboration review. We are now preparing for the final production via purchase of the necessary components. A similar system could be deployed at the near and intermediate detectors without an additional R&D phase.

Finally, the work on the integration of the CC-IN2P3 computing resources into T2K and HK is continuing, along with the deployment of collaboration common tools at CC-IN2P3.

In summary, HK will be the leading neutrino oscillation experiment at the end of this decade and a major observatory for neutrinos from the cosmos. The French groups have accumulated a precious expertise in neutrino physics in Japan and intend to have a significant impact in both the HK detector and in the rich HK physics program.

1 Scientific context and positioning

Neutrino flavor oscillations were first discovered by the Super-Kamiokande (SK) experiment [7] in Japan by observing the zenith angle dependence of the atmospheric neutrino flux, and then in the SNO experiment [8] in Canada using the neutrino flux coming from the Sun. For these discoveries, the 2015 Nobel Prize in Physics was awarded to T. Kajita and A. B. McDonald. The neutrino oscillation phenomenon can be explained by assuming that the neutrinos have small but non-zero masses, leading to non-degenerate neutrino mass states and the possible presence of mass and flavor eigenstates mixing.

From these breakthroughs, a broad international program has been initiated to measure the parameters needed to describe the oscillation patterns within the PMNS (for Pontecorvo-Masaka-Nakagawa-Sakata [1, 2]) framework, i.e. three mixing angles θ_{12}, θ_{23} and θ_{13} and two mass-squared differences Δm^2_{21} and Δm^2_{31} along with a CP violation phase δ_{CP}.

As of today, the mixing angles and the mass differences have been measured by experiments using neutrinos of different origin, including natural sources (neutrinos from the Sun, from the Earth atmosphere) and artificial sources ((anti)neutrinos from nuclear reactors and from particle accelerators). The two still unknown parameters are δ_{CP}, and the sign of Δm^2_{31} (a.k.a. neutrino "mass ordering"). Both of these parameters are accessible with long-baseline experiments, by producing intense ν_μ and $\overline{\nu}_\mu$ beams and looking at differences in the appearance probability of ν_e and $\overline{\nu}_e$.

Long baseline neutrino oscillation (LBL-ν) experiments at accelerators are therefore unique experimental techniques because of their capabilities to precisely determine various oscillations parameters such as θ_{23}, Δm^2_{31}, θ_{13}, the CP violation phase, δ_{CP}, and the mass ordering.

Currently, two LBL-ν experiments are taking data: NOνA (for NuMI Off-axis ν_e Appearance) in the Unites States and T2K (Tokai-To-Kamioka) in Japan. These two experiments have taken data for about a decade and will continue providing the most precise measurements of the neutrino oscillation parameters for the next few years, until the next generation experiments (DUNE and Hyper-Kamiokande) will start operation.

The T2K experiment is a LBL-ν experiment running across Japan since 2010. The LLR, LPNHE and ILANCE neutrino groups significantly contribute to T2K since its very beginning. A description of this experiment and, in particular, of the T2K-II phase has been provided in a dedicated document submitted to the IN2P3 Scientific Council in October 2021.

Recent results from T2K show hints, at the level of $\sim 2\sigma$, of a large CP violation in the leptonic sector [4, 5]. These hints will be scrutinized in the next years by T2K-II that, in the most favorable case, could observe CP violation at 3σ by 2027.

1.1 Hyper-Kamiokande experiment

In order to reach a 5σ discovery of CP violation in the leptonic sector, a new generation of LBL-ν experiments is needed, namely the DUNE and Hyper-Kamiokande experiments. The DUNE experiment (see e.g. [9] and references therein) will use an on-axis beam with a 1300 km long baseline and plans to deploy, using a staged approach, four liquid argon Time Projection Chambers (TPCs) of 40 kt in total as far detectors.

Hyper-Kamiokande [3], the next generation Water Cherenkov detector that was approved by Japanese government in 2019, will become operational in 2027 and naturally follows the T2K experiment. Hyper-Kamiokande will use the same neutrino beam and the near detectors as T2K. It will greatly benefit from the beam and near-detector upgrades currently being performed for the T2K-II phase, as well as all the expertise and methods developed for the last ~15 years within the collaboration. Also the detection and analysis techniques employed for the far detector will be the same as the ones used for (Super-)Kamiokande.

One key element that is being upgraded is the proton Main Ring (MR) of the J-PARC accelerator used to produce the neutrino beam that, by the beginning of Hyper-Kamiokande is expected to provide a 1.3 MW beam power (to be compared with the 515 kW currently available for T2K), see Fig. 1.

The T2K Near Detector complex and in particular the on-going upgrades (described in the T2K document submitted to the Scientific Council in October 2021) will also be a key part of the Hyper-Kamiokande experiment that will hence profit from the existing, well-known, and extremely powerful

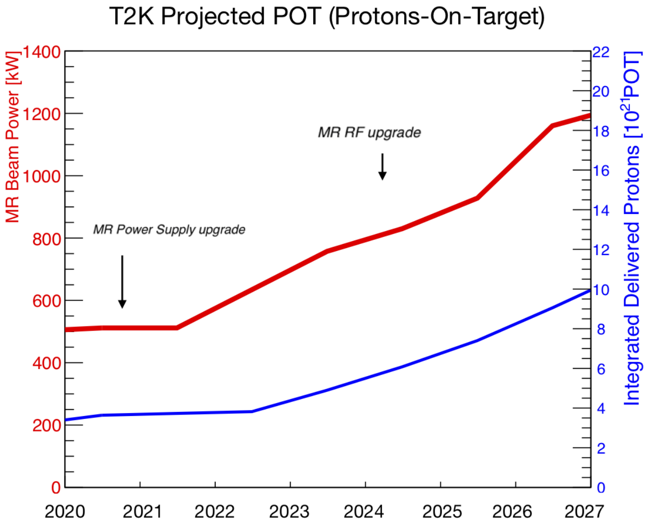

Figure 1: Expected beam power at the J-PARC Main Ring (red curve) before the start of Hyper-Kamiokande. The blue line represents the expected number of protons-on-target that will be collected by T2K-II.

magnetized near detector to characterize the neutrino beam and neutrino interactions before the oscillations. Expected performances of the upgraded ND280 for the T2K and Hyper-Kamiokande era can be found in [10].

The main component of the Hyper-Kamiokande program is the construction of a new large-scale water Cherenkov neutrino detector in the Kamioka mines, see Fig. 2. The chosen site is 8 km south of the current Super-Kamiokande detector, with the same baseline, energy and off-axis angle for neutrinos from the J-PARC accelerator. The cavern has a rock overburden of 650 m, corresponding to 1,750 meters of water equivalent. As depicted in Fig. 3, this new far detector called Hyper-Kamiokande will be a cylinder with a diameter of 68 m and an height of 71 m and will host 260 kt of pure water. The fiducial volume will be 8 times larger than the existing Super-Kamiokande detector and will be instrumented with up to 30,000 detection units, including at least 20,000 already funded 20-inch photomultiplier tubes (PMTs) from Hamamatsu (R12860HQE). Compared to Super-Kamiokande PMTs, these newly-developed PMTs have a detection efficiency two times higher, a reduced dark rate (4.2 kHz) and a factor of two better timing resolution (2.6 ns full width at half maximum). This setup will be complemented with about one thousand of so-called multi-PMTs based on a concept similar to KM3NET's and currently under development. The detector photo-coverage will depend on the final number of PMTs but will be at least 20%. An outer detector, surrounding the inner detector, will be equipped with 8,000 3-inch PMTs which will be used to detect charged particles entering the detector fiducial volume from outside.

Contrary to the Super-Kamiokande design, the frontend electronics collecting signals from the PMTs will be located under water. This novel design allows to reduce the length of the analog cables between the digitizers and the PMTs, therefore enhancing the physics output from the signal while reducing the overall weight of the structure. However, it requires the electronics to be installed in some water-tight boxes located under-water, which implies a high reliability of both the boxes and the electronics. In the current design, there will be 24 photosensors connected to a water-tight box. All the system signals required to monitor and control the electronics, including digitization, low- and high-voltage, clock and counter, must then be distributed to each box.

Hyper-Kamiokande will be the most massive and sensitive underground observatory for neutrinos in the Universe in the MeV-multiGeV energy range. After 10 years of data taking, this far detector should register about 4,200 ν_e CC events (equally split in ν_e and $\overline{\nu}_e$) and about 23,000 ν_μ CC events from J-PARC, thus increasing statistics by a factor of 40 compared to what has been achieved by T2K so far.

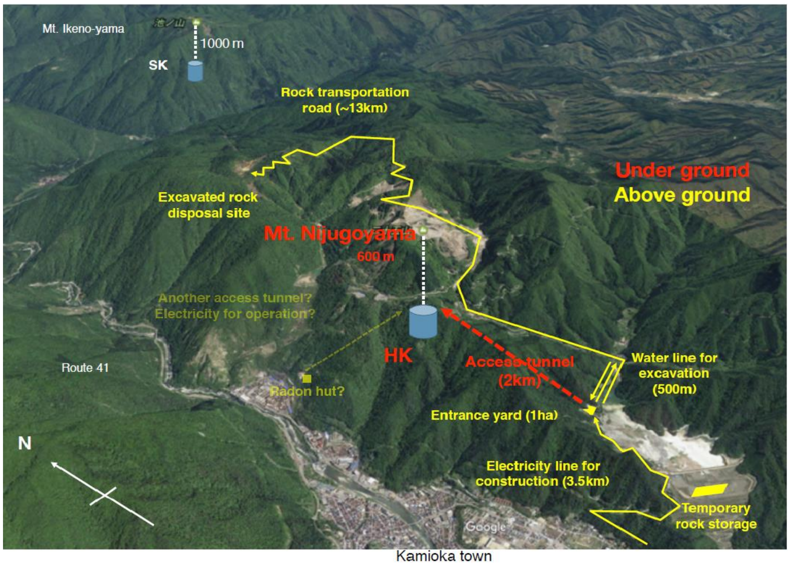

Figure 2: Layout of the area around the Hyper-Kamiokande far detector.

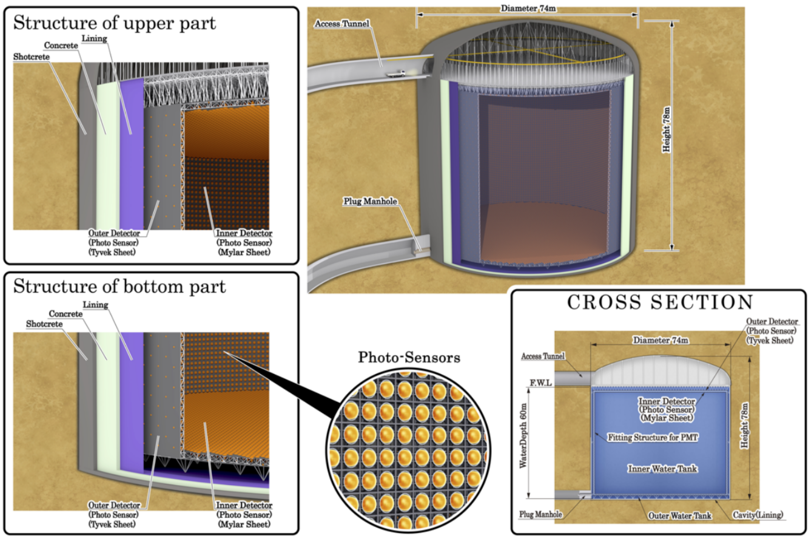

Figure 3: Schematic view of the Hyper-Kamiokande far detector.

1.2 Hyper-Kamiokande physics program

Thanks to this very large statistics and the constraints on the systematic parameters (cross-sections and flux) obtained with the near detectors, a combined oscillation analysis using disappearance and appearance samples will provide a world-leading sensitivity to the δ_{CP} phase.

In Fig. 4 we report some highlights of the Hyper-Kamiokande sensitivity to CP violation. For the most favorable value of δ_{CP}, close to $-\pi/2$, Hyper-Kamiokande will reach 5σ sensitivity by 2029. For other values of δ_{CP}, assuming a mild reduction of systematics with respect to that currently achieved in T2K, Hyper-Kamiokande will have more than 5σ (3σ) sensitivity for 50% (70%) of the possible values of δ_{CP} after 5 years of operation. After 10 years, Hyper-Kamiokande will measure δ_{CP} with a precision ranging between 7 and 20 degrees, depending on the value of δ_{CP}.

Finally, it should be noted that Hyper-Kamiokande will have a relatively short baseline of 295 km making the sensitivity to the mass ordering limited. As shown in Fig. 4, this limitation will be compensated by a huge sample of atmospheric neutrinos, which has large sensitivity to mass hierarchy (see Super-Kamiokande document submitted to the Scientific Council in October 2021). Even in the case in which the mass ordering will not be known by 2027, the combination of beam and atmospheric neutrinos

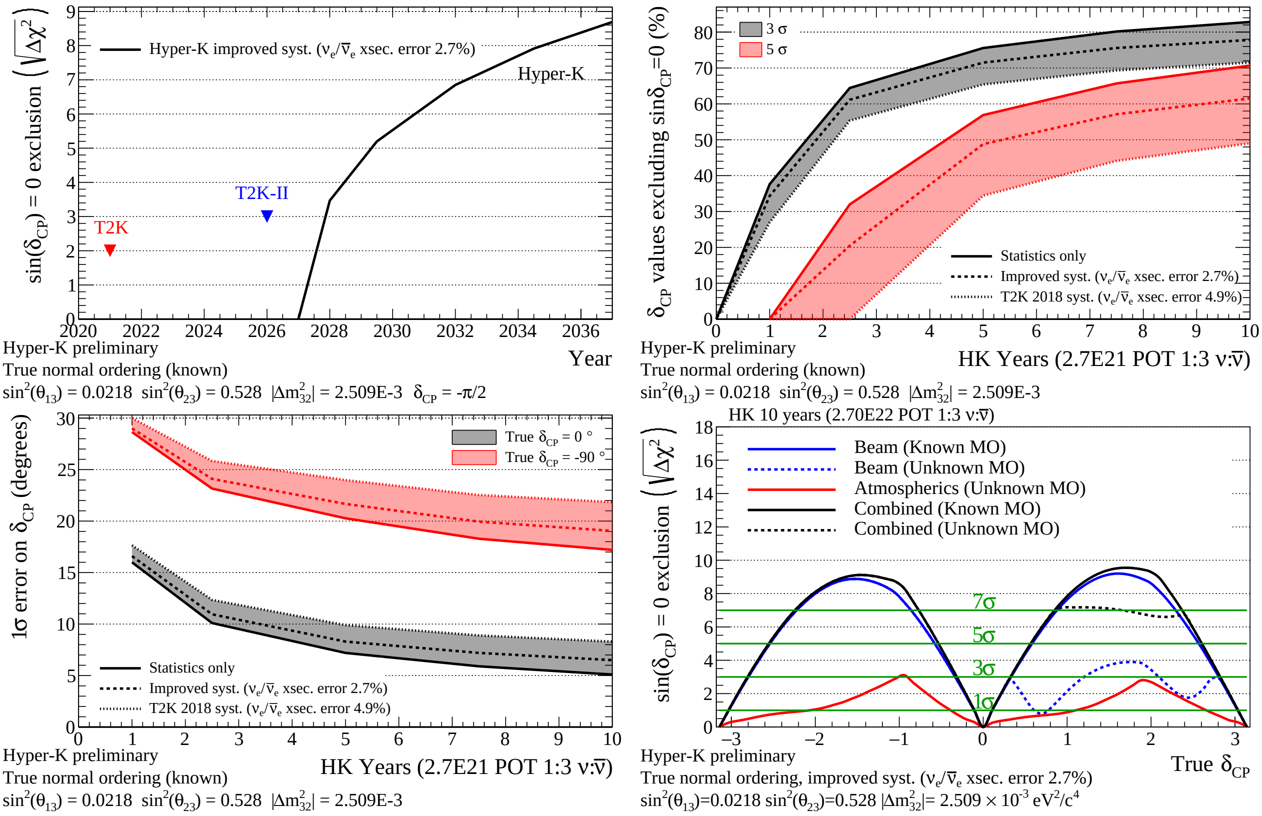

Figure 4: Top Left: Sensitivities of T2K, T2K-II and Hyper-Kamiokande to exclude CP conservation for $\delta_{\rm CP} = -\pi/2$. Top right: Percentage of true $\delta_{\rm CP}$ values for which $\sin(\delta_{\rm CP}) = 0$ can be excluded, as a function of HK-years. The shaded areas show the span of possible values, for various systematic errors assumptions. Bottom left: 1σ resolution of $\delta_{\rm CP}$, as a function of HK-years. Bottom right: Sensitivity to exclude $\sin(\delta_{\rm CP}) = 0$, as a function of true $\delta_{\rm CP}$ value, for 10 HK-years and true normal mass ordering.

will allow to break the degeneracies between CP and matter effects and measure the two parameters separately with Hyper-Kamiokande alone, as shown in the bottom right plot of Fig 4.

The rich Hyper-Kamiokande physics program goes well beyond the measurements of neutrino oscillation parameters and neutrino cross-sections. For example, thanks to its gigantic mass of purified water, the Hyper-Kamiokande far detector has an excellent sensitivity to test models predicting the proton decay, such as $p \to \pi^0 + e^+$. After 20 years of data-taking (similar to Super-Kamiokande overall operation period), Hyper-Kamiokande should be able to put a limit on the proton lifetime at 10^{35} years, which is 10 times better than the current limit from Super-Kamiokande [11].

In addition, Hyper-Kamiokande will detect thousands of electron antineutrinos (via inverse beta-decay) and electron neutrinos (via elastic scattering) from SN bursts in the galactic center. Using the elastic scattering events, it will be possible to reconstruct the direction towards a SN at a distance of 10 kpc with an accuracy of about 1 degree. Even for distances of 4 Mpc, we will observe few tenths of neutrinos in Hyper-Kamiokande and, at such distances, one SN is expected every three years. The events observed in Hyper-Kamiokande will allow to provide detailed information about the time profile and the energy spectrum to further inspect SN explosion mechanism.

2 Project schedule

The Hyper-Kamiokande experiment was approved by Japanese government in 2019. The beginning of the operation is expected in 2027.

The total Hyper-Kamiokande budget approved by the Japanese government is of 50.2 B¥(∼ 400 M€) and will allow to build the far detector equipped with 20,000 PMTs and to perform the necessary upgrades of the J-PARC beamline and of the near detector suite, including the construction of a new

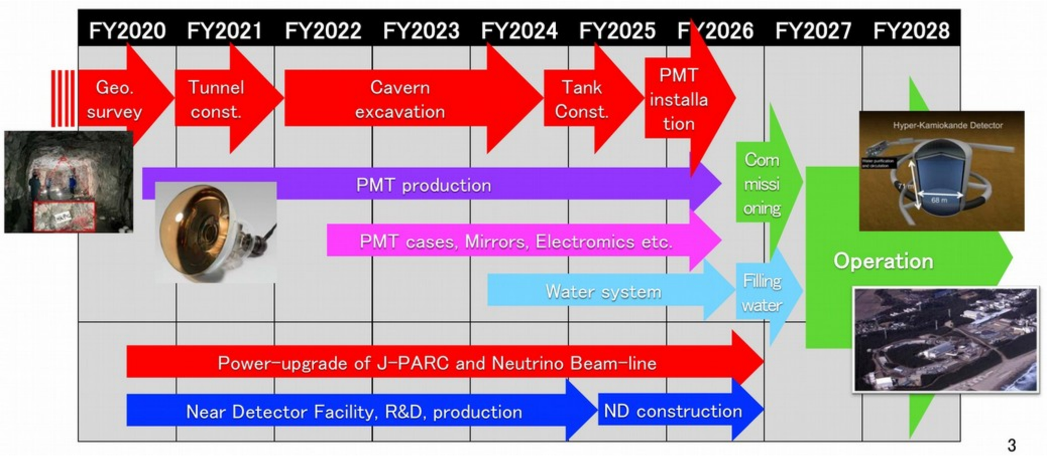

Figure 5: Construction schedule of the Hyper-Kamiokande experiment.

pit for an Intermediate Water Cherenkov Detector (IWCD) at ∼1 km distance from the neutrino target.

The Hyper-Kamiokande collaboration is currently composed of 450 researchers from 20 countries and is steadily growing since the official approval of the Hyper-Kamiokande experiment. International contributions to the project are mostly defined and will be mainly concentrated on the Near Detectors (both ND280 and IWCD), the HK outer detector, the multi-PMTs for the inner detector, the PMT electronics, and the computing.

These contributions are expected to add ∼ 20% to the total Hyper-Kamiokande budget. Figure 5 shows the overall official construction schedule of the Hyper-Kamiokande experiment.

2.1 Far detector

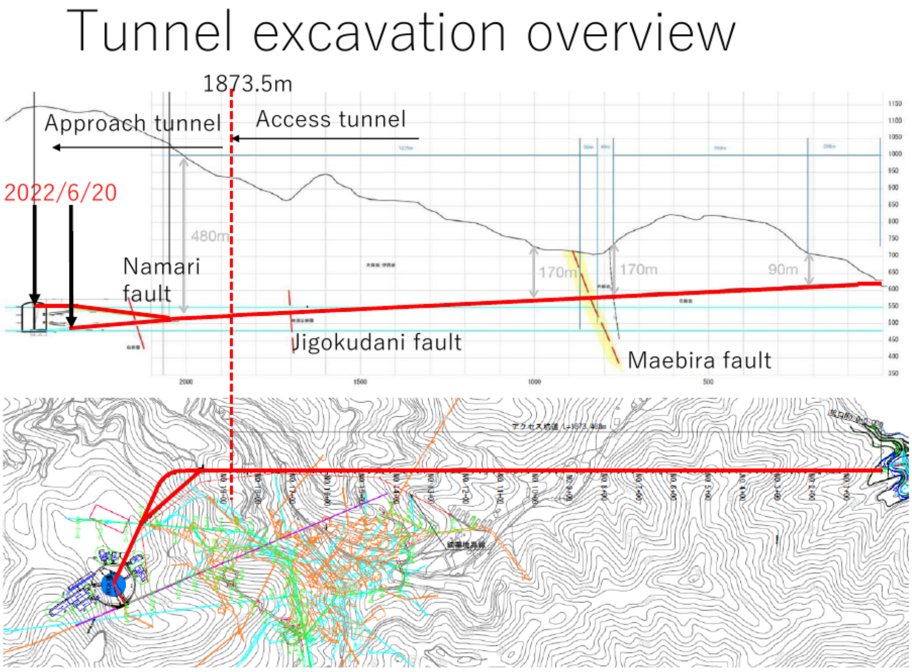

Figure 6: Progress on the HK tunnel excavation as of June 2022.

The construction of the Hyper-Kamiokande far detector was officially launched in 2020. After the successful completion of the geographical surveys, the construction of the 2- km long access tunnel was started in 2021 and was completed in June 2022, as scheduled (the dome centre was reached on June,24), see Fig. 6. The next steps will then be the excavation of the cavern (∼ 2.5 years) and the construction of the water tank (∼1 year).

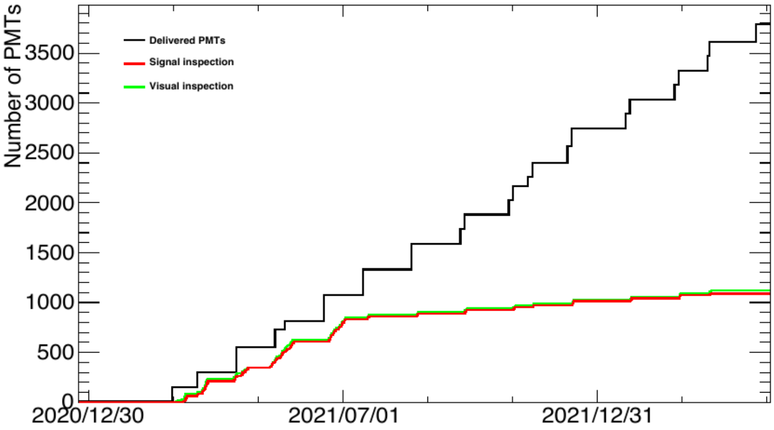

Figure 7: Progress on the 20" PMT production and tests. At the beginning the signal and visual inspection was performed for almost all the delivered PMTs. Since July 2021 the inspection rate was changed to ∼10%.

Concerning the large PMTs, a contract with Hamamatsu has been signed and the production has started with more than 3700 20" Box&Line PMTs already delivered to the collaboration, see Fig. 7. The production will continue (the planned capacity is to produce 400 PMTs per month) until 2026 in order to deliver the total required number of 20" PMTs.

The other photo-detection modules considered by the collaboration are the so-called multi-PMTs (mPMTs). These units, similar to the ones being deployed by the KM3NET collaboration, will host 19 3" PMTs. The main advantage of the mPMTs is their higher granularity which improves the vertex resolution and the particle identification in the whole detector, and even more on the edge of the detector, allowing to increase the fiducial volume and to reduce background contamination. Among other advantages, the mPMTs will bring important improvements on the detector calibration which is crucial for high-precision physics *e.g.* final δ_{CP} measurements. Several countries (Italy, Canada, Poland) are actively pursuing the developments of this technology. The total number of mPMTs will depend on the available funds and the mass production capabilities but we expect to add about 1300 mPMTs. The mPMTs are also the baseline option to instrument the IWCD, which will be described in the next section.

The PMTs will be installed in Hyper-Kamiokande in the first half of 2026 prior to the beginning of the water filling. Since the electronics for the Hyper-Kamiokande PMTs will be under water, it has to be ready for the installation in 2026. Different R&D projects have been performed for the digitizer and the clock distribution system.

Concerning the **digitizer**, three options have been submitted for an internal collaboration review:

- A solution based on the QTC chip developed by Japanese collaborators and currently used in the SK readout electronics;
- A solution based on discrete components proposed by Italian collaborators;
- The solution proposed by the French teams based on a new chip (HKROC) produced by the OMEGA lab and IRFU.

For the **clock synchronization system**, French groups from IN2P3 and CEA are collaborating with INFN and we propose to provide the full synchronization chain, from the generation of the time base through atomic clocks and Global Navigation Satellite System (GNSS), in charge of LPNHE, to the time distribution system, in charge of LPNHE and CEA-Saclay, to the end-point of the clock distribution system on the digitizer board, in charge of INFN. The goal is to synchronize all the PMTs at the level of 100 ps.

A mass production of the components should start in 2023 in order to be ready for installation in 2026.

2.2 Near site

As explained in the previous section, one of the main strengths of Hyper-Kamiokande is the existence of the neutrino beamline and of the near detector complex at J-PARC (both with a deep operation experience).

An intense beam is mandatory to collect enough statistics at the far detector for the discovery of CP violation while the near detector has the role of reducing the flux and cross-section systematics uncertainties in order to cope with the huge statistics collected at the far detector.

The beamline and the 280-m near-detector complex had been both built for T2K and are being upgraded for T2K-II. The neutrino beamline is operated by KEK and will be employed for Hyper-Kamiokande.

ND280 instead was mostly built by non-Japanese collaborators of T2K and discussions between the two collaborations are on-going in order to define how the transition from T2K to Hyper-Kamiokande collaboration will occur. This discussion is facilitated by the fact that most of the groups (including French groups) that constructed and operated ND280 for T2K are also part of the Hyper-Kamiokande collaboration.

Currently, the T2K Near Detector complex at 280 m hosts three detectors: INGRID, WAGASCI/Baby-MIND, and the off-axis ND280 that is being upgraded for T2K-II.

INGRID is an on-axis detector and it is used to monitor the beam profile and direction on a day-by-day basis.

WAGASCI/Baby-MIND is a newly built Near Detector, installed in 2017 at ~ 1.5 degrees off-axis. WAGASCI consists of a grid of plastic scintillators filled with water, while Baby-MIND is a magnetized calorimeter installed downstream and used to measure the charge of the leptons produced by neutrino and antineutrino interactions in WAGASCI.

The off-axis ND280 consists of a set of detectors installed inside the UA1 magnet. The detectors are located at the same off-axis angle of Super-Kamiokande and Hyper-Kamiokande and it is used to constrain flux and cross-section systematics in the T2K oscillation analysis by using the outgoing muon kinematics. With the upgrade currently on-going for T2K we expect to improve the reconstruction of the muons and to reduce the threshold to reconstruct the hadronic part of the neutrino interaction.

The upgraded ND280 and INGRID are expected to be the near detectors configuration of HK at the beginning of Hyper-Kamiokande data-taking, possibly accompanied by IWCD which will be discussed below.

INGRID will keep its role of monitoring neutrino beam direction and position. ND280 will continue to play its role of measuring the neutrino flux before the oscillation and constraining the neutrino-nucleus interaction uncertainties. ND280 will be at the same off-axis angle as Hyper-Kamiokande and will be the only magnetized detector in HK. It will have the crucial role to control the $\nu/\ \overline{\nu}$ systematic uncertainties which are fundamental for $\delta_{\rm CP}$ measurements.

ND280 will also provide the important advantage of anchoring the understanding of systematic uncertainties in an upgraded beam to a well-known detector, already under operation since years. This role, which highly enhance the credibility of the fast discovery of CP-violation in HK also poses the challenge of keeping in operation the ND280 detector (notably the not-upgraded parts) in the next ~5-10 years. **The contribution of the IN2P3 group to ND280 upgrade and to its maintenance and operation, is therefore a fundamental contribution to Hyper-Kamiokande.**

For small values of $\delta_{\rm CP}$ or to perform a precise measurement of the angle, the level of understanding of systematics attainable with the ND280 Upgrade might not be sufficient. In particular, it is expected that the target mass of ND280 will be large enough to make precise measurements of ν_μ but it will be not sufficient to measure $\nu_e/\overline{\nu}_e$ cross-section at the level of 2% needed to reach the ultimate Hyper-Kamiokande sensitivity.

The Hyper-Kamiokande collaboration is considering two options to further boost the potential of the near site: the IWCD and a possible further upgrade of ND280.

A possible new intermediate detector – IWCD – will be located 750 m downstream the neutrino target. In its default configuration, IWCD will move spanning off-axis angles from 1 to 4 degrees and, thanks to its large mass of ~ 1 kt will be able to collect a large sample of ν_e CC interactions. IWCD will be equipped with ~ 500 mPMTs and will measure neutrino cross-section on oxygen using the same detection technique and target material as Hyper-Kamiokande. It will therefore allow to highly reduce

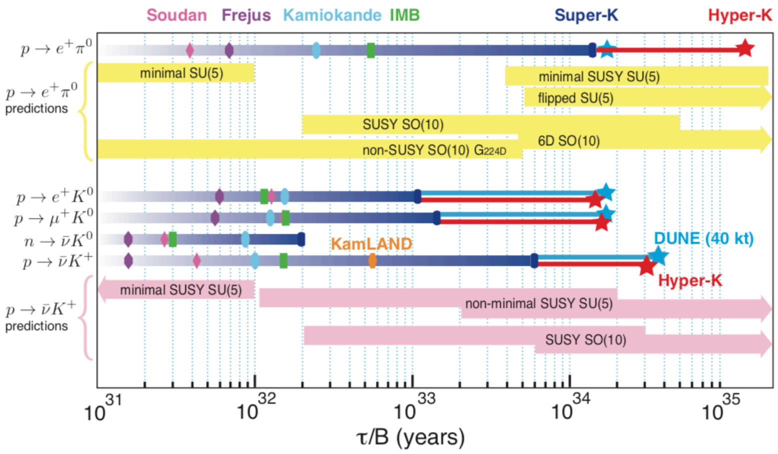

Figure 8: A comparison of historical experimental limits on the rate of nucleon decay for several key modes to indicative ranges of theoretical prediction. Included in the figure are projected limits for Hyper-Kamiokande and DUNE based on 10 years of exposure.

systematic uncertainties not only from neutrino cross-section models, but also, from detector model, which will be very similar between Hyper-Kamiokande and IWCD. IWCD is highly complementary with ND280 regarding physics and schedule. First, because although IWCD impressive new possibilities, its limitations *i.e.* to only be sensitive to the outgoing charged leptons (hadrons are typically below the Cherenkov threshold at the Hyper-Kamiokande energies) and not being able to measure the lepton charge, emphasize the importance of ND280. Second, because the ND280-upgrade is going to port T2K model of uncertainty into HK era with steady increased precision from 2023 (e.g. we fully characterize the upgraded beam before HK start), while IWCD will become operational on a longer timescale.

Further upgrades of ND280 are also being considered by some groups in Hyper-Kamiokande. For example, if the T2K-II data will prove that the newly built Super Fine Grained Detector (Super-FGD) is capable of distinguishing ν_e from ν_μ with high efficiency as predicted by our preliminary simulations, replacing part of the existing ND280 tracker system (FGDs and vertical TPCs) with a ∼10 tons detector with 3D-printed cubes will be an attractive option to collect a large number of ν_e CC interactions in ND280 [12]. The possibility of adding a water target in ND280, possibly employing scintillating water, is also being considered.

3 Highlights of the Hyper-Kamiokande physics program

Hyper-Kamiokande is the third generation Water Cherenkov detector that will be built in Kamioka, after KamiokaNDE and Super-Kamiokande. With respect to its predecessors, Hyper-Kamiokande will have a larger target mass with a fiducial volume 8 times larger than Super-Kamiokande.

On top of the long-baseline neutrino oscillation physics program, Hyper-Kamiokande will naturally follow Super-Kamiokande as the most sensitive observatory for rare events such as proton-decay, neutrinos emitted in SN explosions, and will perform precise measurements of solar and atmospheric neutrinos.

3.1 Proton decay with Hyper-Kamiokande

Grand Unified Theories (GUT) predict proton and bound nucleon decays, both of which are processes that violate baryon number. Such processes have been searched for a long time and Super-Kamiokande has set the strongest limit on proton decay with a half-life larger than 2.4×10^{34} years [11]. The huge size of Hyper-Kamiokande will quickly make it the most sensitive experiment in the search for the proton decay, surpassing the Super-Kamiokande sensitivity after two years of data taking.

The two favorite modes from two dominant classes of GUT models are the $p \to e^+\pi^0$ and $p \to \bar{\nu}K^+$, but the experiment will have world-leading sensitivity to several other channels, as shown in Fig. 8.

The $p \to e^+\pi^0$ decay has a very clean event topology in Water Cherenkov detectors, with no

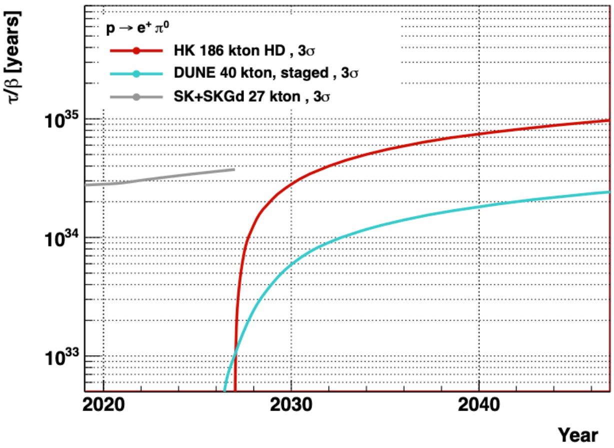

Figure 9: Comparison of the 3σ $p \to e^+\pi^0$ discovery potential as a function of year Hyper-K (red solid) as well as that of the 40 kt liquid argon detector DUNE (cyan solid) following [13]. Super-K's discovery potential in 2026 assuming 23 years of data is also shown.

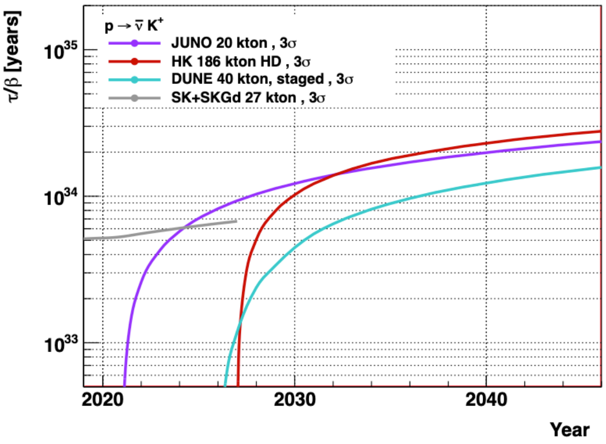

Figure 10: Comparison of the 3σ $p \to \bar{\nu}K^+$ discovery potential as a function of year for the Hyper-K as well as that of the 40 kt DUNE detector (cyan solid) based on [13] and the 20 kt JUNO detector based on [14].The expected discovery potential for Super-K by 2026 assuming 23 years of data is also shown.

undetected particles in the final state. As a result, it is possible to fully reconstruct the proton's mass from its decay products. The primary background to this and all nucleon decay searches is interactions of atmospheric neutrinos with processes such as $\nu_e + n \to e^- + \pi^0 + p$, where the proton is below the Cherenkov threshold. Figure 9 shows the 3σ discovery potential for observing a $p \to e^+\pi^0$ signal based on these estimates. Projections from other experiments, including DUNE and Super-K, are shown for comparison. A proton decay signal can be observed at 3σ if the proton lifetime is less than 10^{35} years with a 20 year exposure, surpassing other experiments by nearly an order of magnitude. If the proton lifetime is near the current Super-K limit of $\sim 7 \times 10^{34}$ years, Hyper-Kamiokande would expect to see a signal at 3σ significance in its first three years of running.

The other main decay mode, predicted by supersymmetric GUT models, is the $p \to \bar{\nu}K^+$. Unlike the search for $e^+\pi^0$ events it is not possible to fully reconstruct the initial proton kinematics because of the undetectable antineutrino in the final state. Furthermore, the kaon is emitted with momentum of 340 MeV/c, which is well below its Cherenkov threshold in water. Searching for this decay mode in Hyper-K is performed via identification of a monochromatic kaon with the appropriate momentum by reconstructing its decay products, that can be either a 236 MeV/c muon from the $K^+ \to \nu + \mu^+$ decay at rest (64% branching fraction) or the π^0 from the $K^+ \to \pi^+\pi^0$ decay. Figure 10 shows the 3σ discovery potential as a function of running time for the $p \to \bar{\nu}K^+$ search (in both Figs. 9 and 10 it is assumed that DUNE could start taking data before HK).

3.2 Hyper-Kamiokande as an astrophysical neutrino observatory

Right from the start of their history, the gigantic Water Cherenkov detectors have been particularly successful in detecting neutrinos from astrophysical sources. Back in 1987, Kamiokande detected a few neutrinos issued by the famous 1987A Supernova, while in 1998 Super-Kamiokande observed for the first time oscillations of neutrinos produced in the atmosphere and in the Sun. Super-Kamiokande has recently been filled with Gadolinium in order to improve its capability of detecting neutrons with the goal of observing neutrinos from the diffuse SN background (DSNB).

3.2.1 Neutrinos from Supernovae

Hyper-Kamiokande, thanks to its large mass, will detect thousands of $\overline{\nu}_e$ (via inverse β-decay) and ν_e (via elastic scattering) from SN bursts in the galactic center (see Fig. 11). Thanks to the elastic scattering events it will be possible to reconstruct the direction towards a Supernova at a distance of

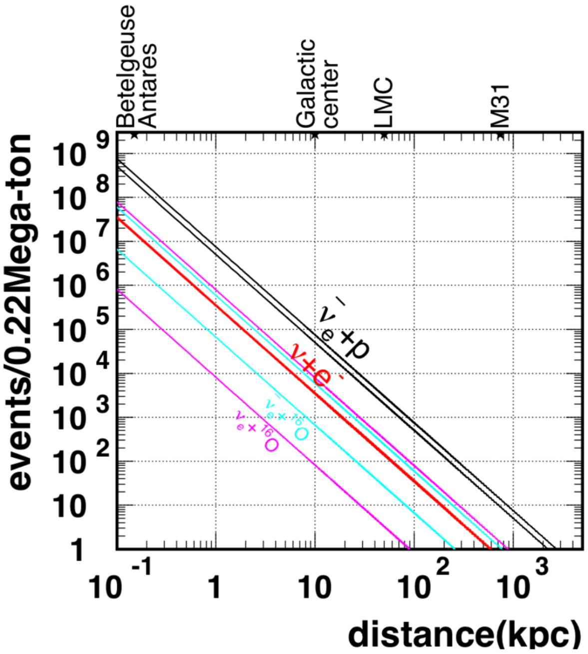

Figure 11: Expected number of supernova burst events for each interaction as a function of the distance to a supernova. Figure taken from [15].

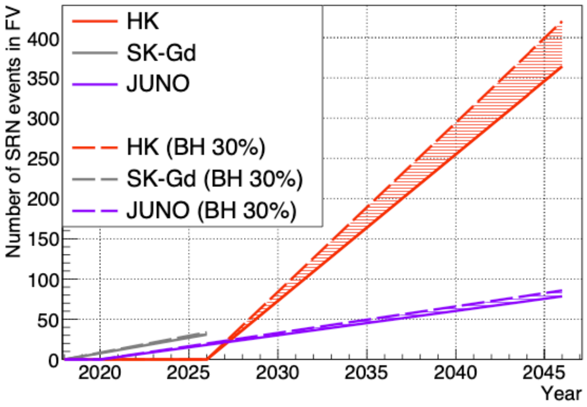

Figure 12: Expected number of inverse beta decay reactions due to supernova relic neutrinos in several experiments as a function of year. The neutrino temperature is assumed to be 6 MeV. Solid line corresponds to the case, in which all the core-collapse supernovae emit neutrinos with the particular energy. Dashed line corresponds to the case, in which 30% of the supernovae form black holes and emit higher energy neutrinos corresponding to the neutrino temperature of 8 MeV.

10 kpc with an accuracy of about 1 degree. The events observed in Hyper-Kamiokande will allow to provide detailed information about the time profile and the energy spectrum for inspecting Supernova explosion mechanism [6]. Such mechanisms are still largely unknown due to the fact that no neutrinos from Supernova explosions have been observed since the 1987A Supernova explosion.

With Hyper-Kamiokande it will be possible to detect neutrinos also from extra-galactic Supernova explosions. If Hyper-K can see signals out to 4 Mpc, then we could expect a supernova about every three years [16].

Hyper-Kamiokande will also be able to detect the Supernova relic neutrinos (SRN) that are neutrinos produced by all Supernova explosions since the beginning of the Universe. Such neutrinos fill the present Universe and have a flux of few tens/cm^2/sec. The observation of SRN would allow to understand how heavy elements have been synthesized in stellar formation and it is the main goal of the SK-Gd project [15].

Even if the first observation of SRN is performed at Super-Kamiokande, a mega-ton exposure in Hyper-Kamiokande will allow to collect a large statistics of SRN in the energy range between 16 and 30 MeV, the region where both spallation and atmospheric backgrounds are negligible. The number of expected events detected in Super-Kamiokande, JUNO and Hyper-Kamiokande as a function of time is shown in Fig. 12. Due to its unmatched statistics, Hyper-Kamiokande will be the first experiment to put stringent constraints on the SRN energy spectrum. **The spectrum is of first importance, as it provides information on the proportion of supernovae forming a neutron star or a black hole, as well as on the age of the supernovae.** In a nutshell, Hyper-Kamiokande will open a new era in understanding of the supernovae mechanism as well as in the cosmological constraints coming from SRN neutrinos. **A collaboration has been started between the LLR experimentalists and C. Volpe (APC) in order to explore the various exciting possibilities that Hyper-Kamiokande will open in this domain, and to prepare the corresponding analysis tools.**

3.2.2 Atmospheric Neutrinos

Hyper-Kamiokande will also collect a large sample of atmospheric neutrinos, see Fig. 13. Such measurements will complement the long-baseline program and joint analyses between beam and atmospheric neutrinos are planned in order to improve the sensitivity to the mass ordering. The sensitivity on the latter is mainly driven by the $\nu_\mu \to \nu_e$ and $\overline{\nu}_\mu \to \overline{\nu}_e$ oscillation comparison, as illustrated in Fig. 14.

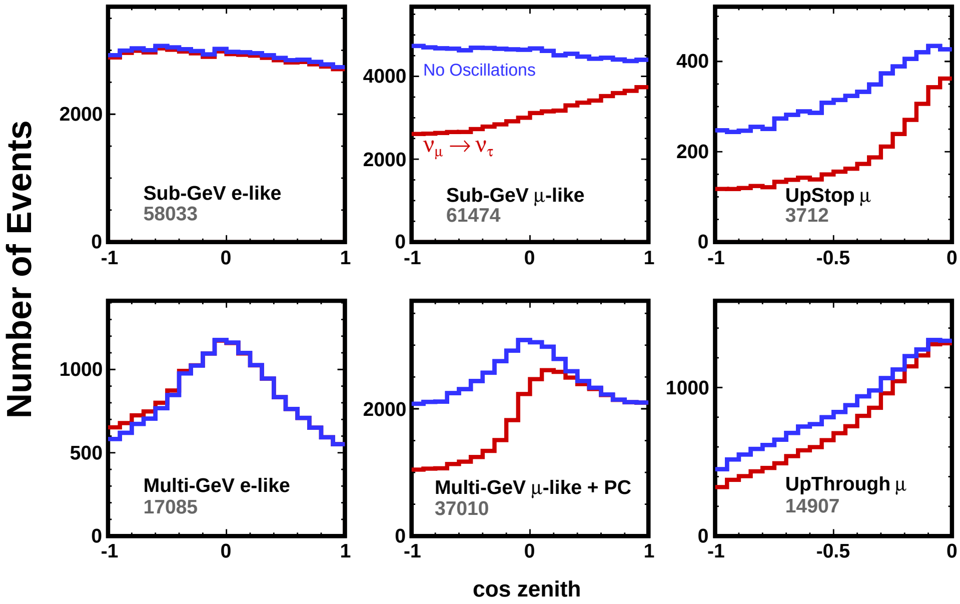

Figure 13: Expected zenith angle distributions for a subset of the atmospheric neutrino analysis samples after a 1.9 Mton·year exposure. Effect of neutrino oscillations is illustrated. Numbers in each panel represent the size of the corresponding event sample.

Note that atmospheric neutrino samples will be also crucial and complementary to the long-baseline neutrinos in order to test the robustness of the PMNS framework and probe scenarios beyond.

Several experiments, running and planned, are trying to determine the mass ordering so we expect that it will be determined before the beginning of Hyper-Kamiokande operation. In case it will not, the combination of atmospheric and beam neutrinos will allow to determine the ordering with the sensitivity shown in Fig. 15. Such combination will also improve the sensitivity to the octant of $\sin^2\theta_{23}$.

The interested reader may have a look at the dedicated document concerning atmospheric neutrinos at Super-Kamiokande submitted to the IN2P3 Scientific Council in October 2021.

3.2.3 Solar Neutrinos

As in the case of Super-Kamiokande, Hyper-Kamiokande will detect solar neutrinos from the ^{8}B with an energy threshold of a few MeV. The main output of the Hyper-Kamiokande solar neutrino program will be the observation of the spectrum upturn and of the day-night flux asymmetry.

3.3 Long-baseline neutrino oscillation physics

As explained in Section 1, the main goal of Hyper-Kamiokande will be the discovery of CP violation in the leptonic sector. This measurement relies on the high-statistics measurement of $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ oscillation probabilities and on a superb knowledge of neutrino flux and spectra.

In this respect Hyper-Kamiokande will have the advantage of profiting, from day 1, of a well-understood neutrino beam and near detector complex, informed by more than 15 years of running from T2K. This will allow to make fast and precise measurements of CP violation with HK right from the beginning.

The expected sensitivity of Hyper-Kamiokande to $\delta_{\rm CP}$ is shown in Fig. 4. Of course, a discovery of CP violation is only possible if CP is indeed violated in the leptonic sector. In case of large CP violation, with $\delta_{\rm CP} \sim -\pi/2$ corresponding to T2K's current best value, the state of the art at the beginning of Hyper-Kamiokande could be that early hints of CP violation had been observed by T2K and NOνA. In this scenario Hyper-Kamiokande will be able to confirm possible hints at the 3σ level in a few months and discover CP violation with 5σ significance after two years of running, in ~2029.

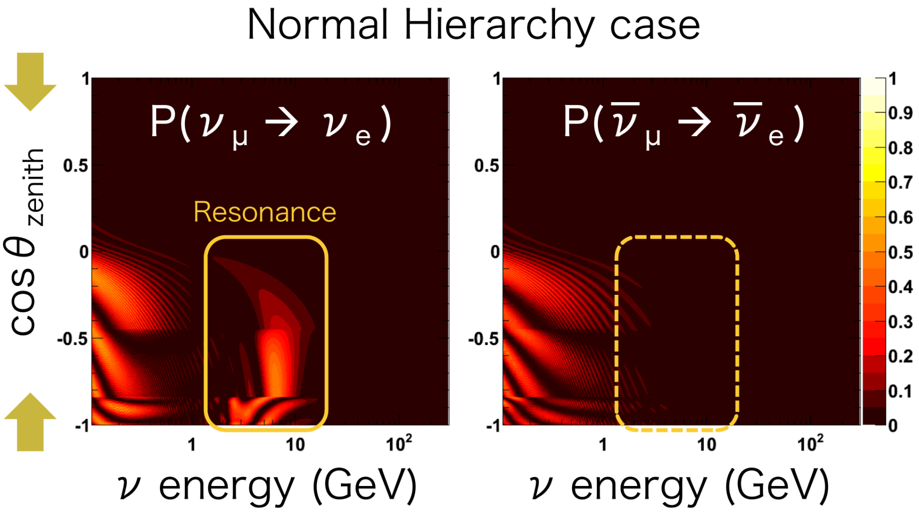

Figure 14: Oscillation probability as a function of the neutrino zenith angle and energy in case of normal ordering. Left: $\nu_\mu \rightarrow \nu_e$ oscillation. Right: $\overline{\nu}_\mu \rightarrow \overline{\nu}_e$ oscillation. In case of normal ordering, one observes a clear enhancement.

In case of smaller values of δ_{CP}, Hyper-Kamiokande will be able to observe CP violation at 3σ (5σ) for 50% (70%) of the values of δ_{CP} after 5 years of running and will be limited by the systematics after ~ 10 years of running, see Fig. 4.

The other future LBL experiment that is planned to come online in the late 2020s is DUNE. The DUNE collaboration has recently released its low-exposure sensitivity [17].

We believe that Hyper-Kamiokande will have several advantages with respect to DUNE, especially in the short-term:

- according to the current plans, Hyper-Kamiokande is expected to start data taking in 2027 while DUNE will start in 2029;
- Hyper-Kamiokande will use the well-known Water Cherenkov technology and will profit from a powerful Near Detector and a well-understood neutrino flux that will simplify early analyses;
- Hyper-Kamiokande will have the full target mass of 180 kt from the beginning while DUNE will reach the design target mass of 40 kt after a few years of running.

As an example, as stated above, Hyper-Kamiokande will observe CP violation at 3σ after a few months and at 5σ in two years for $\delta_{\text{CP}} \sim -\pi/2$, while DUNE will need an exposure of $100\ \text{kt} \cdot \text{MW} \cdot \text{yr}$ and $330\ \text{kt} \cdot \text{MW} \cdot \text{yr}$, respectively. Assuming the staged scenario proposed by DUNE [1] such exposures will be reached after 2 years and 7 years respectively.

For larger exposures, the complementarities between DUNE and Hyper-Kamiokande will be important. For example, looking at the precision on δ_{CP}, both experiments have similar precision even with a very different baseline, neutrino energy and detector technology. A combination or at least a cross-check and mutual validation will allow to help to disentangle oscillation parameters consequences from systematics effects and to improve the precision of the ultimate measurement of δ_{CP}.

4 Technical contributions to Hyper-Kamiokande far detector

The technical contributions envisioned by the French groups are described below. In addition to the ND280 detector upgrade and dedicated hadron production measurements with the NA61/SHINE spectrometer for improved flux predictions (reported to the IN2P3 Scientific Council in October 2021), they consist in contributions to the electronics of the Hyper-Kamiokande far detector and the computing effort. The estimated costs are summarized in Table 1.

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[1] 20 kt and 1.2 MW beam the year 0, increased to 30 kt in year 1, to 40 kt in year 3 and to 2.4 MW beam in year 6

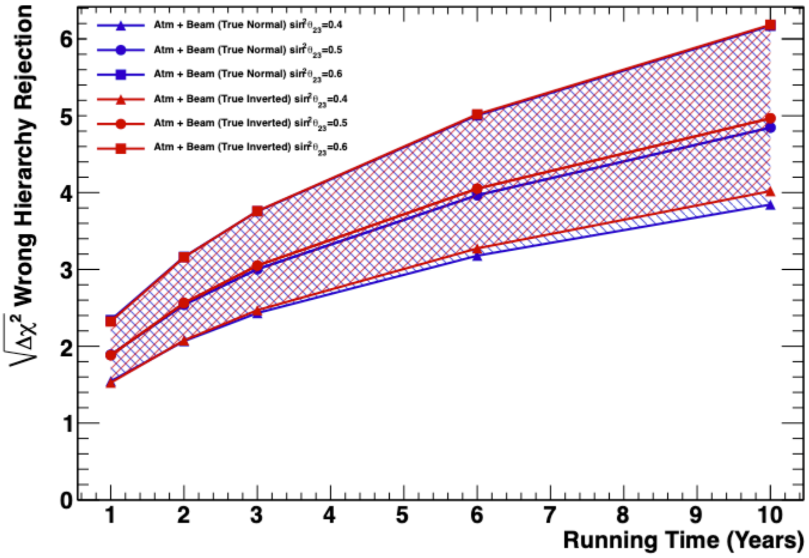

Figure 15: Neutrino mass hierarchy sensitivity as a function of the true value of $\sin^2\theta_{23}$. The blue (red) band denotes the normal (inverted) hierarchy and the uncertainty from δ_{CP} is shown by the width of the band.

4.1 Overview of the French contribution

The Hyper-Kamiokande teams have developed long-term contribution and collaboration in the T2K experiment. Among other items, they contributed to the design and construction of the INGRID, ND280 and WAGASCI detectors, with a leading role in both mechanical and digitization electronics aspects. On top of these hardware contributions, the long-standing support of the IN2P3 teams and funding agency to the T2K effort have allowed them to lead the key physics working groups and analysis software of the experiment, such as the oscillation analysis or the near-detector physics groups. **The strategy of the IN2P3 teams for Hyper-Kamiokande is to build a very strong contribution which will rely on both hardware and analysis & computing strengths. These items will be presented in Sec. 4.2 and 4.3 respectively.**

4.2 Far detector electronics

The whole Hyper-Kamiokande front-end electronics will be located in water-tight boxes under water, and attached to the PMT structure. **In order to maximize the visibility of the IN2P3 contribution, the LLR, LPNHE and OMEGA laboratories (in close collaboration with CEA) initially proposed to develop the core of the Hyper-Kamiokande electronics chain.** Fig. 16 shows the overall arrangement of the under-water electronics. The intended French contributions to the electronics can be summarized in two main categories: the digitization and data encoding of the PMT charge

Item	Cost (M€)	Partially covered with external fundings	Funding approval	Construction period	Requested fundings (M€)
ND280 Upgrade	6	T2K Collaboration	2019	2019 – 2022	0.6 (obtained)
Far detector timing	0.6	ANR - INFN - CEA	2022	2023 – 2026	0.4
Communication cables	2	European countries	2022	2023 – 2026	0.2-0.4
Chip and Front-end	2.5	CEA - INFN	2022	2023 – 2026	1-2.5
Computing (CC-IN2P3)	3.8	CEA	2021	2021 – 2037	3.8
	Note that costs for computing are spread over a much longer period of time (15 years).				
Total	14.9	-	-	-	∼6-7.7

Table 1: Summary of the cost estimates of the various items for Hyper-Kamiokande. Note that it includes only the production costs (the R&D costs has been already funded). See section 5 for more details about the other investments.

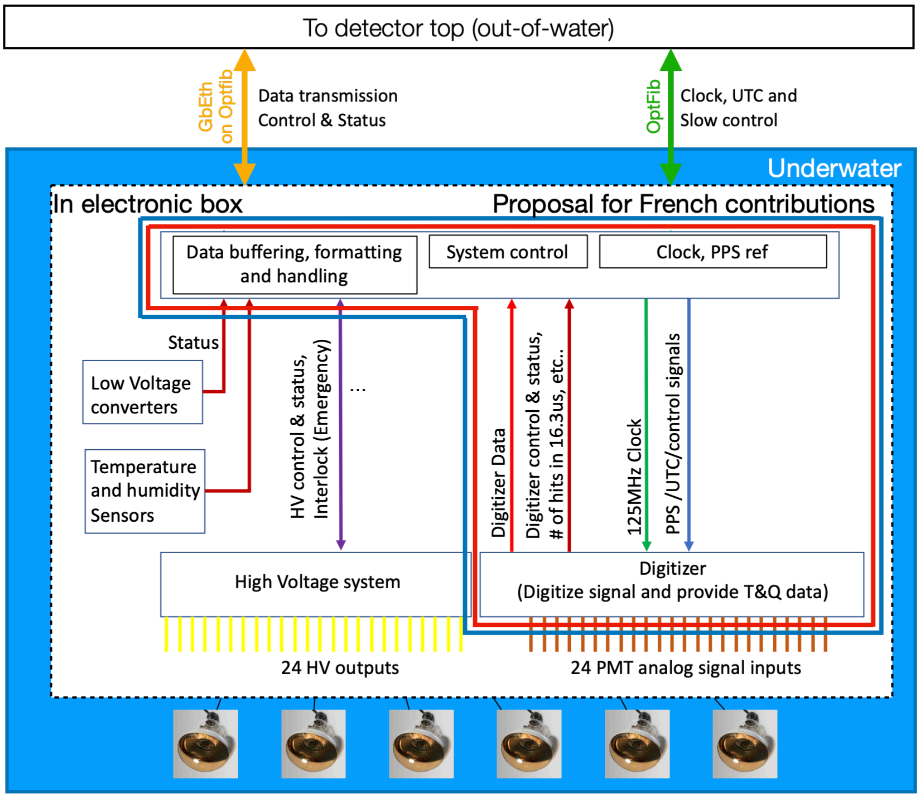

Figure 16: A front end electronics scheme with the main functional blocks. The intended French contributions are surrounded with a tricolor box.

(section 4.2.1) and the time generation, distribution and electronics synchronization (section 4.2.2). This project aims to tackle two major challenges:

- extract the full Hyper-Kamiokande potential, from a few MeV to a Multi-GeV energy range, without compromising the charge or time resolution, and
- have a very high reliability as its maintenance is likely to happen only once every 5-10 years.

The French proposal has in view to fulfill these goals, while aiming also to:

- maximize its synergy with other projects and previous developments in electronics at CEA, LLR, LPNHE and OMEGA laboratories,
- maximize the synergies between our 4 laboratories.
- maximize the visibility of the French contribution.

In the next sections, we describe the current status and next steps for each of these elements.

4.2.1 Digitization

Digitization requirements. We proposed to develop a digitization front-end board based on a new ASIC developed for the Hyper-K experiment: the HKROC. **Not only this chip has been developed for Hyper-Kamiokande, but it has been also designed to equip future PMT-based experiments in the coming decade, by proposing a major upgrade compared to the current-generation CATIROC.** HKROC combines the latest cutting-edge technology to adapt to Hyper-Kamiokande requirements and the advantages of an ASIC-solution: lower risk of failures, long-time durability, compactness, low power consumption. The Hyper-Kamiokande experiment requirements can be summarized briefly in:

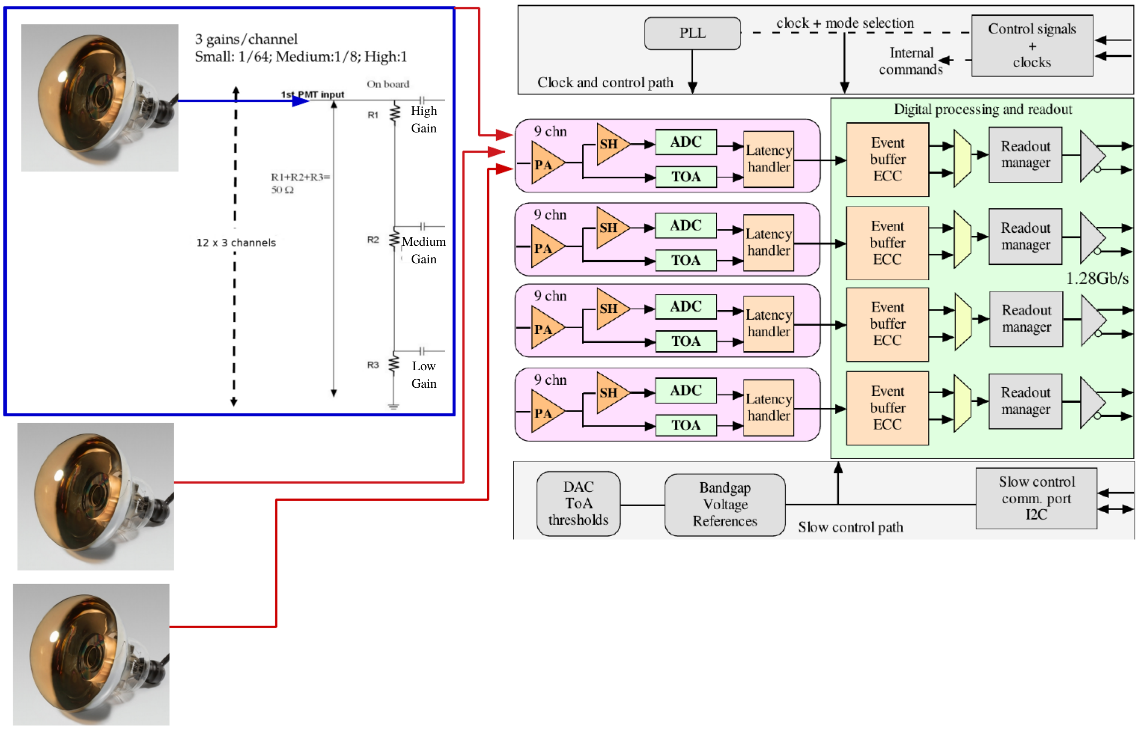

Figure 17: Schematic of the HKROC chip.

- a large dynamic range (0-2500 pC) to cover the full extend of Hyper-Kamiokande MeV to multi-GeV physics. For comparison, this dynamic range is ten times larger than the CATIROC chip. The charge linearity in this range should be within ±1%.
- a time resolution < 300 ps to be negligible compared to the internal PMT time resolution (1.1 ns).
- a deadtime < 1 μs. It allows to detect neutrinos coming from a close Supernova (such as Betelgeuse) with minimal loss of information, while also maximizing the detection efficiency of decay electrons, or reflected and scattered light. For comparison, the deadtime of the CATIROC is above 3 μs from pure readout limitations.

Characteristics of the HKROC digitizer and board. The HKROC chip has been developed by the OMEGA and CEA groups based on the existing HGCROC chip, which has been developed, tested and validated recently to equip the future CMS High-Granularity Calorimeter. The host board is developed by the LLR, based on the long experience of joint chip/board development with OMEGA on the HGCROC, the SPIROC (WAGASCI) and the CITIROC (Super-FGD).
The HKROC chip is etched in TSMC CMOS 130 nm, which allows to minimize the readout deadtime, reduce the electronic noise and cross-talk between channels compared to the AMS 350 nm in which the CATIROC chip has been etched. The schematic of the chip is shown in Fig. 17.

Each PMT is read-out by three "electronic channels", coupled to a different resistance in order to provide high-, medium- and low-gain channels. With its 36 electronic channels, the HKROC ASIC hence allows to read-out 12 PMTs. For each electronic channel, the PMT output charge is amplified by a low-noise pre-amplifier which has a tunable gain, and passed through a shaper which stretch the signal time with tunable shaping time (15 ns to 25 ns) and correct for variations in the signal shape with the input charge.
Each electronics channel has an independent trigger which is fired when the signal is crossing an adjustable threshold value. When one channel is fired, all the channels attached to the same high-speed link are digitized (*i.e.* 3 PMT signals in the current chip version). For each trigger, the hit timing is provided by the combination of a coarse and fine time-stamp. The coarse time-stamp is common for all channels and is provided by the FPGA through a 40 MHz clock. The fine time-stamp is provided for each channel independently using a 10 bits TDC developed by the CEA group. The combination of the

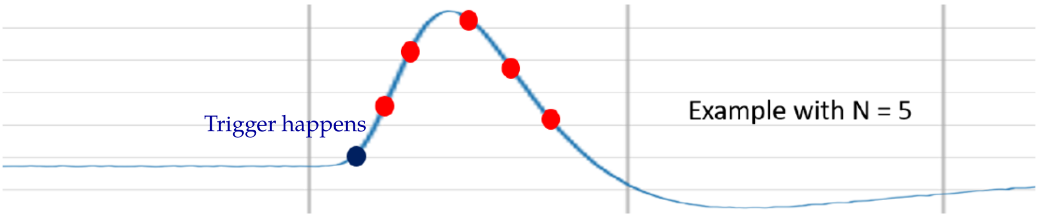

Figure 18: Schematic showing the PMT waveform (blue) and the N=5 points digitized by the ADC (red) after a trigger happens (dark blue).

two allows to reach a timing resolution better than 200 ps.
The charge is digitized at 40 MHz using a 10 bits successive-Approximation ADC developed by the AGH-Krakow group. The ADC clock is asynchronous with the trigger time. The signal charge is not integrated; instead, the waveform is digitized by N sampling points separated by 25 ns, as illustrated in Fig. 18. N could be set by slow control to be 1, 3, 5 or 7. Finally, both charge and timing attached to the same serial link are read-out at 1.28 Gb/s and sent to a downstream FPGA.

The HKROC digitizer board is currently being developed by the LLR, based on similar boards used for the HGCROC readout. All HKROC digitizer boards will be driven by the same clock system running at 125 MHz and synchronized by a beacon allowing the time-stamping of the events. These signals come from the master clock and control board. The board uses the 125 MHz clock to generate a 40 MHz clock which is distributed to the chip to determine the ADC frequency. Each board will be equipped by 2 HKROC chips in order to read-out 24 PMT outputs. The front-end configures the whole chip though an I^2C slave port, defining the channel trigger threshold, tuning the pre-amplifier gain etc. The digitized data from each HKROC are readout by 4 serial links to the Xilinx FPGA in order to cope with the large HK data rate. The FPGA selects only the triggered channel, reconstructs its charge based on the digitized waveform, and sends the charge and timing to the DAQ.

The first version of the HKROC ASIC (v1) has been received for tests at OMEGA, LLR and CEA at the end of January 2022. A massive and intense test campaign has been successfully undertaken in parallel at the 3 laboratories in order to finalize all measurements for the April dead-line that was set by the collaboration. For this purpose, the ASIC has been mounted on a test board using a flip-chip process. Fig. 19 shows one of these test boards. From bottom to top, the HKROC ASIC is placed on a mezzanine board using a flip-chip process and mounted on a mother board. The mother board is finally connected to a test board Xilinx Kintex UltraScale FPGA KCU which handles the communication with the ASIC, provides the differential clocks (320 MHz) from the distributed 125 MHz clock and allows to send slow control parameters and read out the digital data coming out of the chip.

HKROC performances. Fig. 20 summarizes the complete list of the measured performances of the HKROC. As will be stressed in the following lines, the HKROC digitizer fulfills all of Hyper-Kamiokande requirements. In this document, a focus is especially done on 4 aspects: the time and charge digitization, the dead-time, and the ASIC durability.

In order to maximize the signal for low energy events, the detection threshold may be lowered in Hyper-Kamiokande down to 1/6 photo-electrons (p.e.), and the collaboration requires an accidental noise lower than 1 Hz while keeping a 100% efficiency for signal $> 1/4$ p.e. Fig. 21 presents the detection efficiency for various thresholds, and especially shows that signals of 1/4 p.e. are reconstructed with a 100% efficiency. Actually, the S-curve provided a theoretical threshold of 1/26 p.e. In parallel, the trigger response to noise-only has been measured and an accidental trigger rate < 0.1 Hz was found. In a nutshell, the HKROC is considerably less noisy than the Hyper-Kamiokande requirements. Moreover, the collaboration requires the timing resolution of the digitizer to be < 300 ps (< 200 ps) for signals having a charge ≤ 10 p.e. (> 10 p.e.). This condition is required not to degrade the PMT intrinsic time resolution of 1.1 ns at the 1 p.e. level. Fig. 21 shows that HKROC timing resolution largely surpass these requirements, reaching 150 ps at 1 p.e. and < 30 ps for charges higher than 10 p.e. Regarding the charge, the collaboration requires a 1% linearity in the 1-1250 p.e. range in order to ensure no degradation of the energy reconstruction in both low to high energy physics. Moreover, a resolution

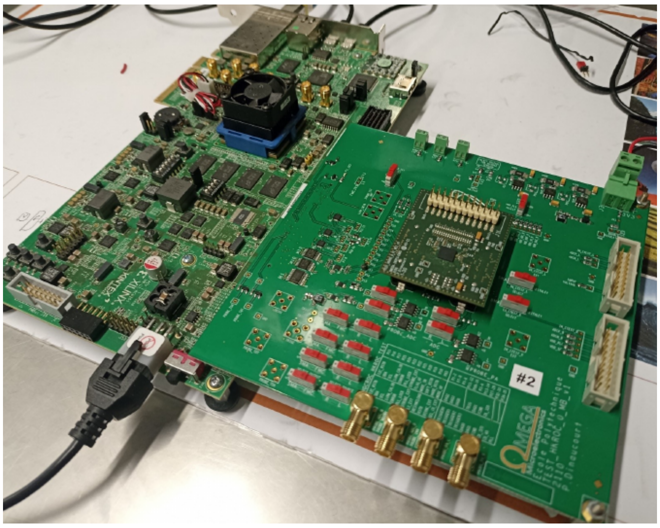

Figure 19: Test board used at OMEGA, LLR and IRFU to perform all the HKROC tests. The ASIC is mounted on a mezzanine board, itself mounted on a mother board connected to a KCU test board.

better than 0.1 p.e. is required for the events having a charge < 10 p.e., to avoid any degradation of the signal/noise separation. Fig. 22 shows the corresponding measurements for the HKROC which is found to completely match the requirements on both linearity and resolution.

Impacts on HK physics performances. The digitizer dead-time is another crucial aspect, which impacts both low and high energy physics. For very close supernova such as Betelgeuse, a rate of 1 MHz in each PMT is expected in Hyper-Kamiokande. At higher energy, most of the samples in both long-baseline and atmospheric neutrino physics relies on counting the number of decaying electrons from parent muons. The number of decay electron is especially (but far from being only) used as the most sensitive variable to separate neutrino from anti-neutrinos in atmospheric samples, which is the basis of the neutrino mass ordering sensitivity in Hyper-Kamiokande (see Fig. 14). Fig. 23 shows the distributions of the number of decay electrons in case of neutrinos or antineutrinos. These decay electrons are naturally emitted after their parent muons with a time difference average of 2.2 μs, and a significant fraction of their Cherenkov photons can hit the very same PMTs as their parent muons. In order to minimize the degradation of physics on these two aspects, Hyper-Kamiokande set a maximal dead-time of 1 μs. One understands that to minimize impact on physics here, a dead-time negligible with respect to the 1 μs and 2.2 μs time constants would have been preferable. The value of 1 μs was chosen mostly since this is the dead-time of current Super-K electronics, based on the philosophy that Hyper-Kamiokande electronics should do at least as good as the Super-K one. Fig. 24 shows the dead-time measurements. On the left plot, one observes a clear separation of the two peaks using the waveform even in the case of two peaks separated by 30 ns only. The dead-time naturally depends on the charge of the primary event, and has been measured with respect to the later on the right plot of Fig. 24. From low to high energy, as PMTs received dominantly 1 or few p.e., the dead-time in the vast majority of cases is only 30 ns for HKROC. It represents an improvement by a factor of 30 with respect to the requirements, and a factor of 15 compared to the other digitizers proposed for Hyper-Kamiokande. **Note that the dead-time could be even decreased below 30 ns down to 10 ns using more innovative waveform analysis techniques.** Such methods have been successfully applied to HKROC already, but are not presented here due to space limitation.

The impact on physics of this considerably smaller dead-time has been investigated. For supernovae, though the average hit rate for Betelgeuse is 1 μs, the hit distribution is actually completely random (Poisson). Therefore, HKROC low dead-time offers a fundamental advantage with respect to the other proposed solutions which have about 500 ns dead-time. A simple simulation shown in Fig. 23 highlights that **the HKROC digitizer has a supernovae hit efficiency of** 92.5%**, while a solution with 500 ns dead-time has an efficiency of only** 67%**.** This large improvement in the supernova hit efficiency leads to an increased precision of the measured supernova neutrino energy spectrum with respect to

Item measured	Performances
Trigger efficiency at 1/6 p.e.	$>$ 90% for 1/5 p.e signals 100% for $\geq$ 1/4 p.e signals
Trigger noise at 1/6 p.e.	$<$ 1 Hz (No trigger observed in 10 s)
TDC resolution	150 ps at 1 p.e, 70 ps at 5 p.e, 25 ps $>$ 10 p.e Validated with PMT
Charge linearity	$<$ 0.5% in high & medium gain channels $<$ 1% in low gain channel up to 1250 p.e Validated with PMT
Charge resolution	$<$ 0.1 p.e for signals up to 10 p.e $<$ 1% beyond 10 p.e signal Validated with PMT
Dead-time & pile-up	$\leq$ 30 ns for two signals of same amplitude $\leq$ 30 ns for a prompt $\leq$ 5 p.e and secondary of 1 p.e $<$ 1 μs for a prompt signal $\leq$ 850 p.e and secondary 1 p.e
Maximal hit-rate w/ 100% eff.	415 kHz in normal mode 950 kHz in SN-mode Potential extension beyond to be studied.
Cross-talk	Hit probability in neighbouring channel of a 1250 p.e signal is $<$ 0.1% *Note that cross-talk found at ASIC level, but cut by FPGA. Identified and will be removed in ASIC v2.*
Maximal hit-rate w/ 100% eff.	415 kHz in normal mode 950 kHz in SN-mode Can be extended even beyond for v2.
Temperature dependency	mean time ΔT = 17.5 ps/°C rms time $\Delta T \leq$ 1 ps/°C mean charge ΔQ = 0.1%/°C (no correction) charge variation has no dependency
Power consumption (W)	$\leq$ 6.6 W for 24 PMTs
Resistance to HV	Received 1,000 2000 V discharge from PMT-base Unprotected ASIC received 7×10^{10} 7V injections ($>$ 500 yrs of HK) without any impact on performances Validated protection circuit itself saturates signals $>$ 7 V to 7 V.
Failure rate / year	ASIC failure $\leq$ 0.03%

Figure 20: Summary of the measured performances of HKROC v1.

time, which is the key observable to constrain the supernova models. Moreover, this improved hit efficiency offers an enhanced resolution on the event reconstruction, which is the key to optimize the pointing accuracy for supernova.

Moving to high-energy neutrinos and decay electron, the impact of the very low HKROC dead-time has been evaluated using atmospheric neutrino and detector simulation. The detection efficiency of decay electron is limited to 68% in the current Super-K atmospheric events above 1 GeV, due to the electronics 1 μs dead-time. **We have shown that the HKROC would allow to increase this efficiency from 68% to 98% in Hyper-Kamiokande. It will bring major impact and improvements to both the neutrino mass ordering sensitivity, and long-baseline physics.**

On top of these aspects, this exceptionally low dead-time also allows to separate the direct Cherenkov light from the indirect light (scattered in water or reflected on the tank edges). This feature would be of key interest in high-precision physics, and the example of energy scale is presented in the next lines. Hyper-Kamiokande aims to improve its energy bias systematic from 2.4% (Super-K) to 0.5%. Among other goals, the main motivation for this effort is that energy bias will be the most limiting factor to δ_{CP} sensitivity, provided CP violation is close to maximal. Fig. 25 highlights that a 0.5% energy scale shift is basically equivalent to a 13° shift of δ_{CP}. The current energy bias systematic in Super-K is estimated using atmospheric neutrino samples, and is limited by the energy reconstruction systematics. **The**

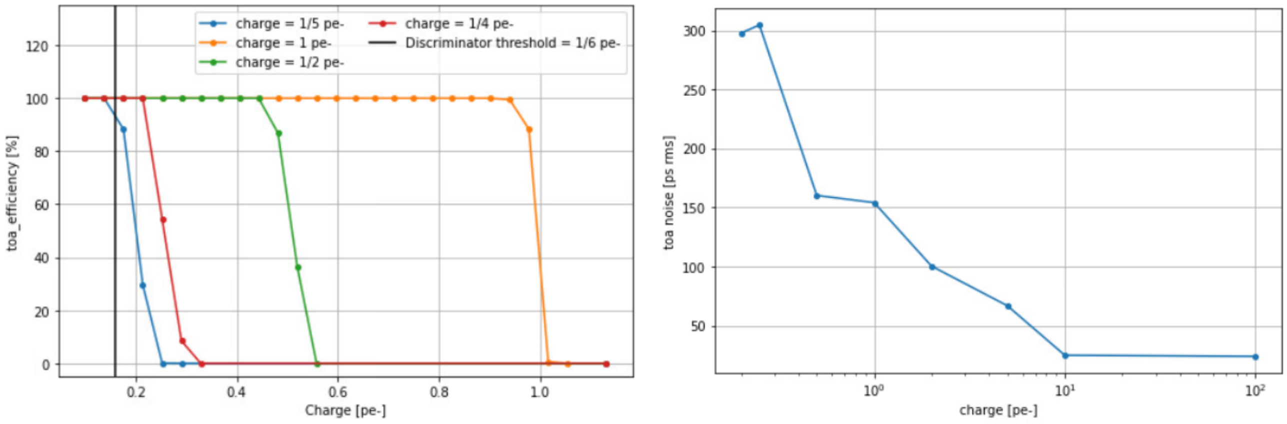

Figure 21: Left: Measurements of HKROC trigger efficiency for various thresholds and signal amplitudes. Right: Measurements of HKROC timing resolution.

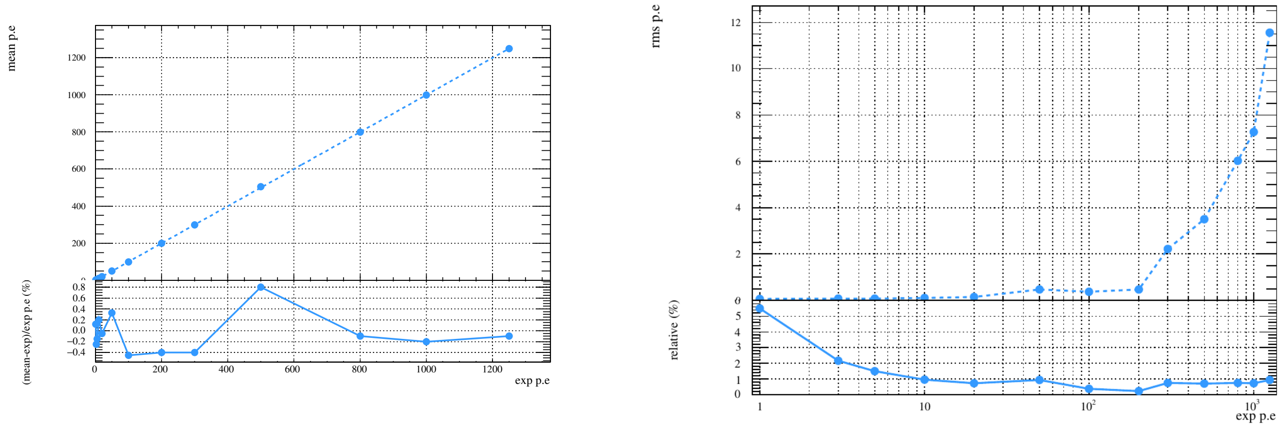

Figure 22: Left: Measurements of HKROC charge linearity. Right: Measurements of HKROC charge resolution.

ability to separate direct Cherenkov light from indirect (scattered, reflected) light is one of the key aspect that is limiting the current Super-K energy reconstruction systematics. The HKROC proposes a huge step forward that may be crucial to lower the final resolution of Hyper-Kamiokande on δ_{CP}.
For atmospheric events with energies larger than 1 GeV, about half of the PMTs receives both a direct and indirect photon right after. A dead-time of 500 ns (Hyper-Kamiokande solutions other than the HKROC) creates a loss of 45% of the indirect photons. For these PMTs hit by more than two photons, Fig. 25 shows that an important fraction of the indirect light photons hit the PMTs $>$ 30 ns after the direct photon. Quantitatively, 30% (65%) of the indirect photons hit a PMT $>$ 30 ns ($>$ 10 ns) after the primary hit. Note that the 10 ns case is also shown since the HKROC dead-time is likely to be brought down to this value using more sophisticated waveform analysis techniques, as explained before. Consequently, **the HKROC will help to retrieve from 30 to 65% of the scattered and reflected photons compared to the alternative solution for Hyper-K. It has a crucial impact on the energy scale bias and hence, on the ultimate Hyper-Kamiokande sensitivity to δ_{CP}.**

Finally, unlike Super-K, the Hyper-Kamiokande electronics will be located under-water in a water-tight vessel, with no possibility of easy maintenance. Consequently, the constraints on the digitizer durability as well as its behaviour with respect to temperature/humidity are of primary importance. The collaboration has set a challenging failure rate of 1% in ten years for the digitizers. On top of temperature test, we relied on an external company - Hensoldt Space Computing - in order to provide an estimate of the ASIC failure rate. Given the estimated conditions in the water-tight vessel, a failure rate $\leq$ 0.3% in 10 years has been estimated, which nicely fit the requirements for Hyper-Kamiokande.

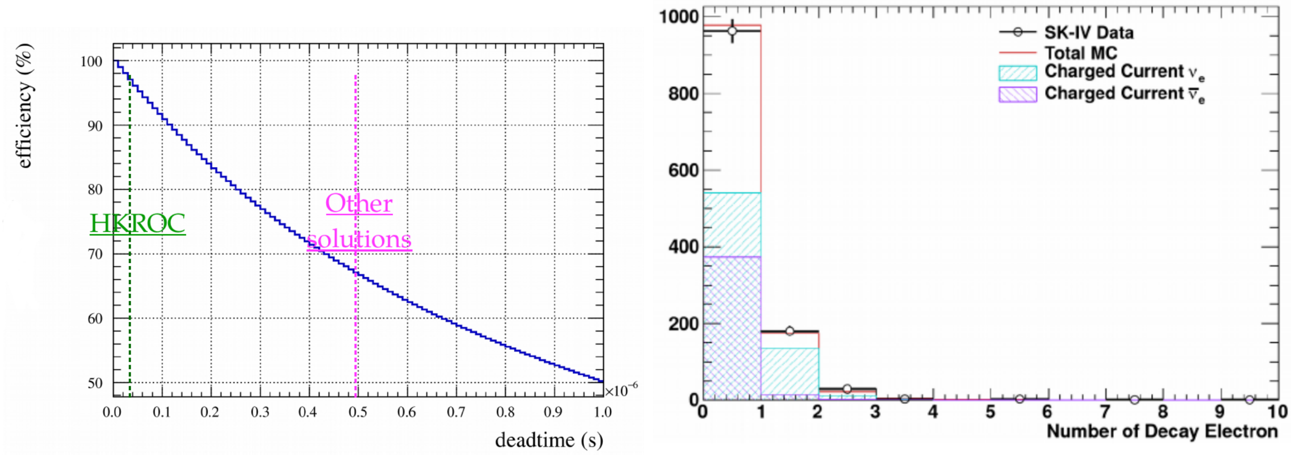

Figure 23: Left: Hit efficiency as a function of the dead-time of the digitizer for a supernovae such as Betelgeuse. Note that in case of supernovae, almost every PMT receives no more than 1 p.e. and the dead-time can therefore be taken as 30 ns for HKROC. Right: Number of decay electron in atmospheric neutrino samples in Super-K.

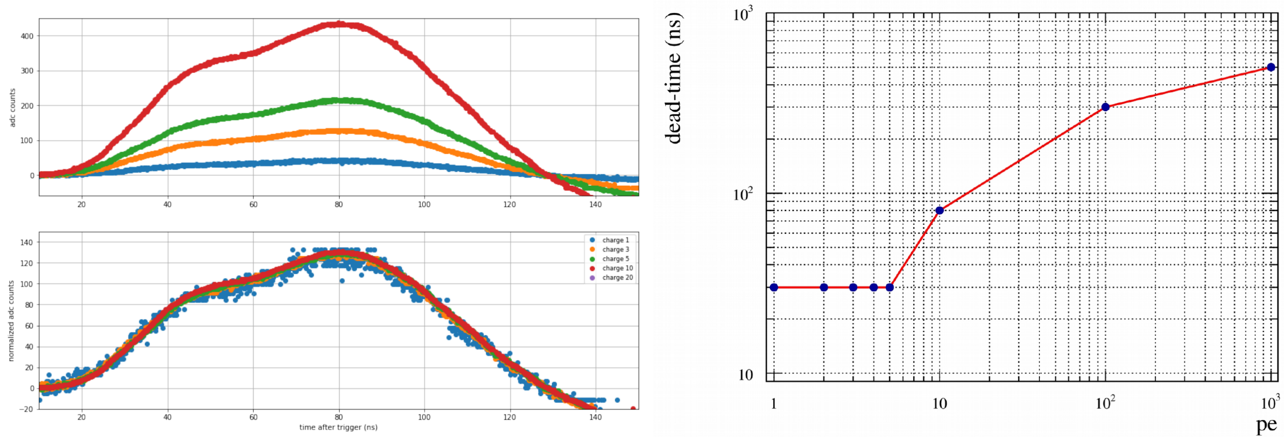

Figure 24: Left: Measurements of the HKROC waveform for two events separated by $\Delta T = 30$ ns. Measurements of the HKROC dead-time as a function of charge of the primary peak. The secondary peak charge is taken at 1 p.e., as it represents the most conservative case for dead-time.

In a nutshell, all of the HKROC performances satisfy the requirements from the collaboration in terms of physics, durability and power consumption. It should be noted that on the very first version of the chip, a very small cross-talk between channels exists, and has been evaluated to be 0.02%. This extremely tiny cross-talk is slightly above the requirements from Hyper-K, which requests $< 0.01\%$. In the first version of the ASIC, this cross-talk is suppressed at the FPGA-level, using the waveform shape analysis, which highlight the flexibility of a waveform-digitization electronics. Note that this cross-talk will be suppressed at the ASIC level in its second version. **Moreover, the HKROC ASIC has demonstrated performances considerably better than these requirements in timing resolution, dead-time, power consumption and lifetime.** Among these improved performances, the dead-time is of key importance. Though very premature and only centered on supernovae and mass ordering, initial studies has demonstrated the large and impressive benefits from HKROC exceptionally low dead-time in both low and high energy physics. Moreover, while the other digitizer solutions are charge integrators, the HKROC is a waveform digitizer. As such, it offers a more refined monitoring of the PMT signal which can be used to remove some specific noise (PMT glass accidental scintillation...) and to potentially identify unexpected non neutrino-physics effect in the tank (PMT degradation etc.).

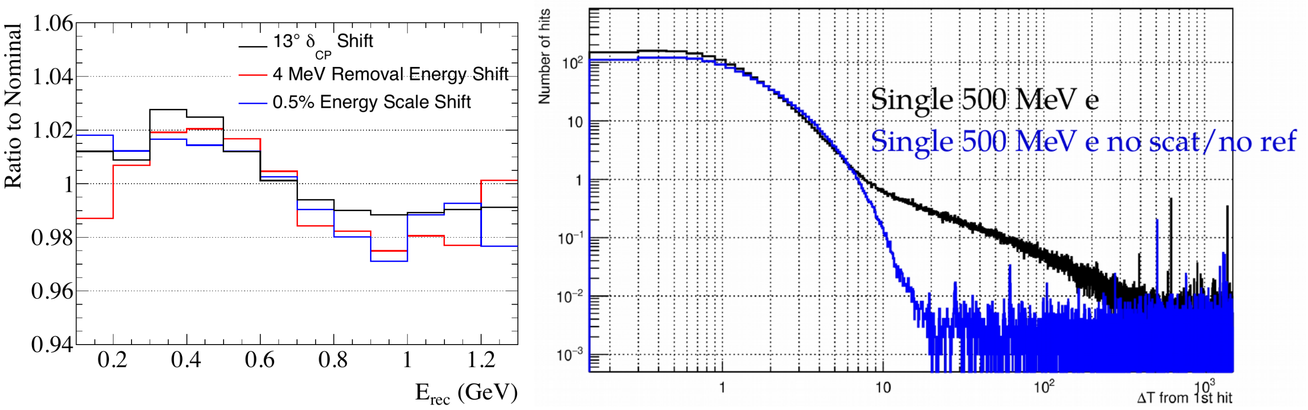

Figure 25: Left: Relative effect on the neutrino spectrum of a 13° shift of δ_{CP} (black) and a 0.5% shift of the neutrino energy scale at Hyper-Kamiokande (blue). Right: Time difference of photons hitting the same PMT in Hyper-Kamiokande for an atmospheric neutrino sample. Blue curve shows the case of direct Cherenkov light only, while the black curve takes into account both the direct Cherenkov light and the indirect scattered and reflected light.

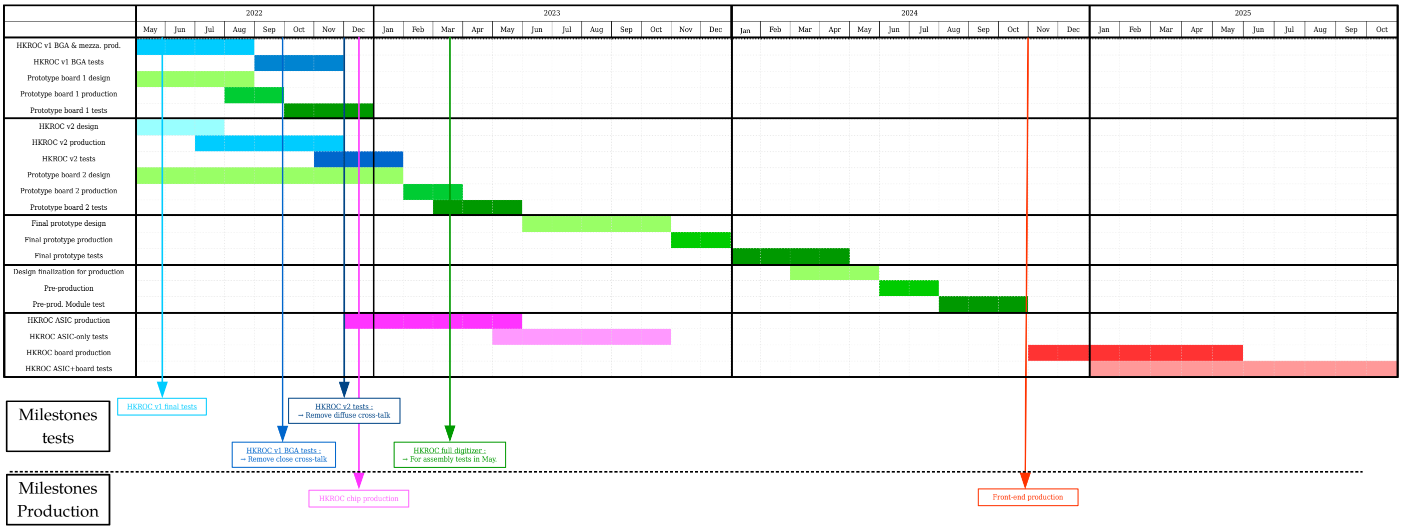

Figure 26: Schedule and milestones for the HKROC-based electronics R&D and production.

Status of the HK internal review and next steps. **Unfortunately, the HKROC digitizer has not been selected as primary option by the Hyper-K collaboration. Though large physics advantages have been acknowledged, the management has decided to use a more conventional solution (the discrete solution proposed by INFN) over an innovative design.** Though the HKROC digitizer schedule and feasibility has been considered by the collaboration to match Hyper-K schedule, the other digitizers are more advanced in their development, relying on decades of prototypes. Despite this decision (which happened on the 16th of September), at the time the present document is written, the future of the HKROC digitizer within the collaboration is still not completely set in stone and some potential use cannot be excluded (Hyper-K outer-detector, IWCD outer-detector, etc.). Consequently, in the remaining lines of this section, we will focus on our proposal concerning the HKROC project for IN2P3 (and not necessarily for Hyper-K), and will present a more detailed scheme for HK during the presentation.

The IN2P3 and IRFU HKROC teams are proposing to continue and complete the HKROC development. The timeline for the R&D and production are shown in Fig. 26. The HKROC teams propose to finalize the production of the HKROC ASIC v2, that will happen at the end of this year, as well as to produce a minimum of a few tens of digitizer board v2 (production in February 2023). This proposal is based on several strong motivations from the teams and their laboratories:

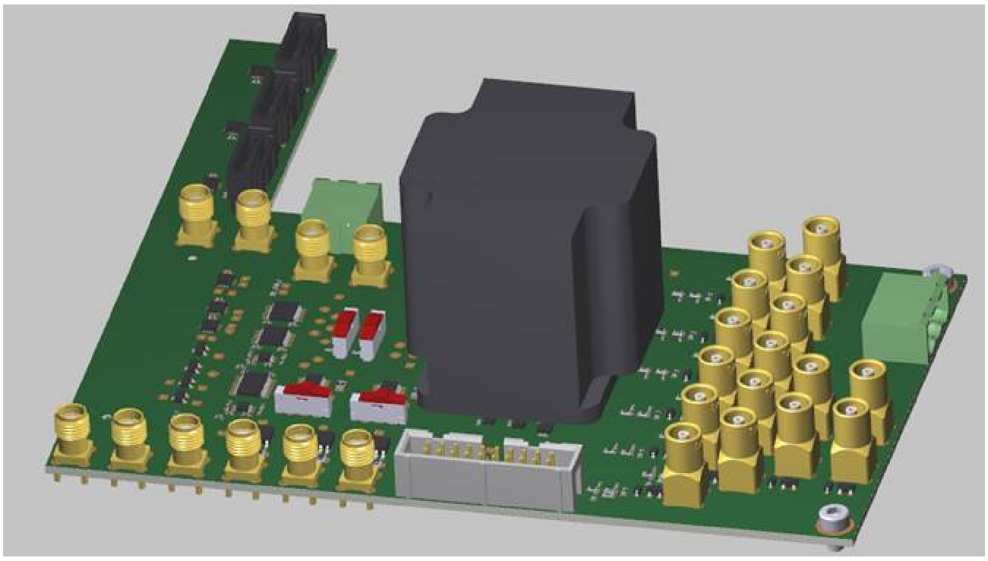

Figure 27: Schematic view of the HKROC digitizer v1 board.

- the complete HKROC digitizer has been developed to serve as a cutting-edge PMT-readout system for the next 10-15 years, and largely beyond Hyper-K. This digitizer will be proposed to current experiments such as IceCube-gen2. It should be noted that the lack of such up-to-date digitizer at IN2P3 and IRFU is the exact reason why the HKROC has required a significant R&D and has finally been ranked below the other solutions on Hyper-K, though its tremendous impact on physics, and finalizing the HKROC development is the best way to avoid such decision for future cutting-edge experiments at IN2P3.
- at the time the present document is written, the HKROC digitizer may still be used in Hyper-K (to read-out the outer-detector, to equip a part of the inner-detector or as an upgrade).
- the technology used in HKROC has already served as a base for the development of an ASIC reading other photo-sensors. The read-out board for such an ASIC as well as the FPGA reconstruction of the waveform will therefore serve as a generic basis for a serie of ASIC including not only PMT read-out, but also SiPM etc.

Considering these aspects, the HKROC team will receive the HKROC v2 ASIC in November this year. The HKROC will be thoroughly tested till January 2023, before a full production of 3,000 ASIC is launched. In parallel, the design of the digitizer board v1 has been finalized, and it will be received in November to test the HKROC. Fig. 27 shows a picture of the digitizer board v1. It includes almost every aspect of the final board, except for the FPGA (deported on a KCU board) and the calibration circuit. In parallel, the design of the second version of the board, including these two aspects, has already started. The board design will be frozen by the end of January 2023, and the board will be delivered for tests in March 2023. Note that this schedule allows for the HKROC digitizer to be completely ready for the May 2023 test of the Hyper-K collaboration, which consists in testing the whole electronics chain in a prototype of the HK water-tight vessel. It allows for the HKROC digitizer to maximize its potential use in Hyper-K (in outer-detector or in IWCD), while providing a prompt development for this electronics to be made available for other experiments as soon as possible. Note that several papers will be prepared from Spring 2023 to completely describe and highlight the unique features of HKROC digitizer board capabilities for PMT readout.

4.2.2 Synchronization of the PMTs signals with UTC

One of the main challenges in Hyper-Kamiokande is the synchronization among more than 20,000 PMTs and with the J-PARC accelerator in order to correctly reconstruct the Cherenkov ring(s) associated with an event based on the arrival time of the light emitted in water on the surrounding PMTs. To achieve this goal a reference time must be established and distributed to all the PMT front-end (FE) modules readout electronics.

The LPNHE group has started more than 3 years ago an R&D, in collaboration with the SYRTE experts and with CEA and INFN colleagues, with the aim to propose a timing system compliant with the requirements set by the Hyper-Kamiokande collaboration that are summarized in Table 2. The Hyper-Kamiokande experiment requires a time distribution jitter smaller than 100 ps RMS and the clock skew between front-end boards to be constant over any power-on and reset.

The time tag of each particle interaction needs to be in a format that allows its correlation with data collected by other experiments worldwide; for this reason the generated local time base has to be associated with the Coordinated Universal Time (UTC) with an accuracy better than 100 ns. This absolute time tagging will also be used to identify the events generated in the detector by the particles sent from the J-PARC accelerator. Along with the time synchronization some “critical information” like slow-control data have to be transmitted by this subsystem hence a 100 Mbps or greater bandwidth bidirectional data channel must be provided.

The first phase of the R&D carried out by LPNHE, CEA and INFN groups, allowed to define the system that is depicted in Fig. 28 and that can be subdivided into 3 main parts, as shown in the conceptual diagram reported in the top part of the picture which highlights its sub-constituents and their envisioned positions. The clock generation that will be located in an external lab, the time distribution boards will be in the electronics huts and the endpoint directly integrated on the digitizers underwater.

To guarantee the most stable and precise reference, the local time base originates in an atomic clock working in“free-running mode”, so without any steering by an external frequency. It generates a 5 MHz frequency that is sent to a time reference fan-out board. Here the 125 MHz reference clock is generated and sent to the distribution network along with a PPS (Pulse Per Second) “counted” using the 5 MHz time base. The 125 MHz frequency is distributed over different branches by means of two stages time distribution modules done with custom designed boards and delivered to all the leaves represented by the FE modules using the so-called Time Distribution Endpoints or TDE, integrated on the digitizers. In order to reach all the PMTs, $\sim$ 60 boards for the second distribution stage will be needed, each communicating with 16 front-ends. A 10 MHz clock is also generated and sent to a GNSS (Global Navigation Satellite System) along with the PPS. Here the time distance between the local PPS, the GNSS time and, in turn, a UTC prediction is measured and sent to the data acquisition computer infrastructure via Ethernet protocol where it is used to convert the event’s local time tag to UTC.

This scheme is detailed in a Technical Note that has been sent to the Hyper-Kamiokande collaboration in April 2022 and is currently under evaluation from the review committee. A summary of the results of the R&D, including several measurements with GNSS and different atomic clocks done on the Jussieu campus, the production of first prototype boards for the distribution system, and the precise characterization of the performances of the protocols chosen for the time distribution, will be presented in the rest of this section. **It should be noted that our group is the only one that proposed a complete solution for the time distribution system, going from the time generation to the endpoint, and we have good hope that our system will be approved via the ongoing review process.**

In the following paragraphs, more details about each item will be provided along with the results on their performances characterized during the R&D phase of the project.

Clock generation and UTC. The base clock represents the foundation of the cadence delivered to all the detector electronics elements; therefore it must be very stable and precise to guarantee, at

Time Synchronization Experimental Constraints	
Total Jitter	$\leq$ 100 ps
Board to Board skew	fixed over any reset and power cycle
Accuracy to UTC	$\leq$ 100 ns
Critical Slow-Control Data bandwidth	$\geq$ 100 Mbps

Table 2: Current experimental requirements for the time distribution and synchronization system.

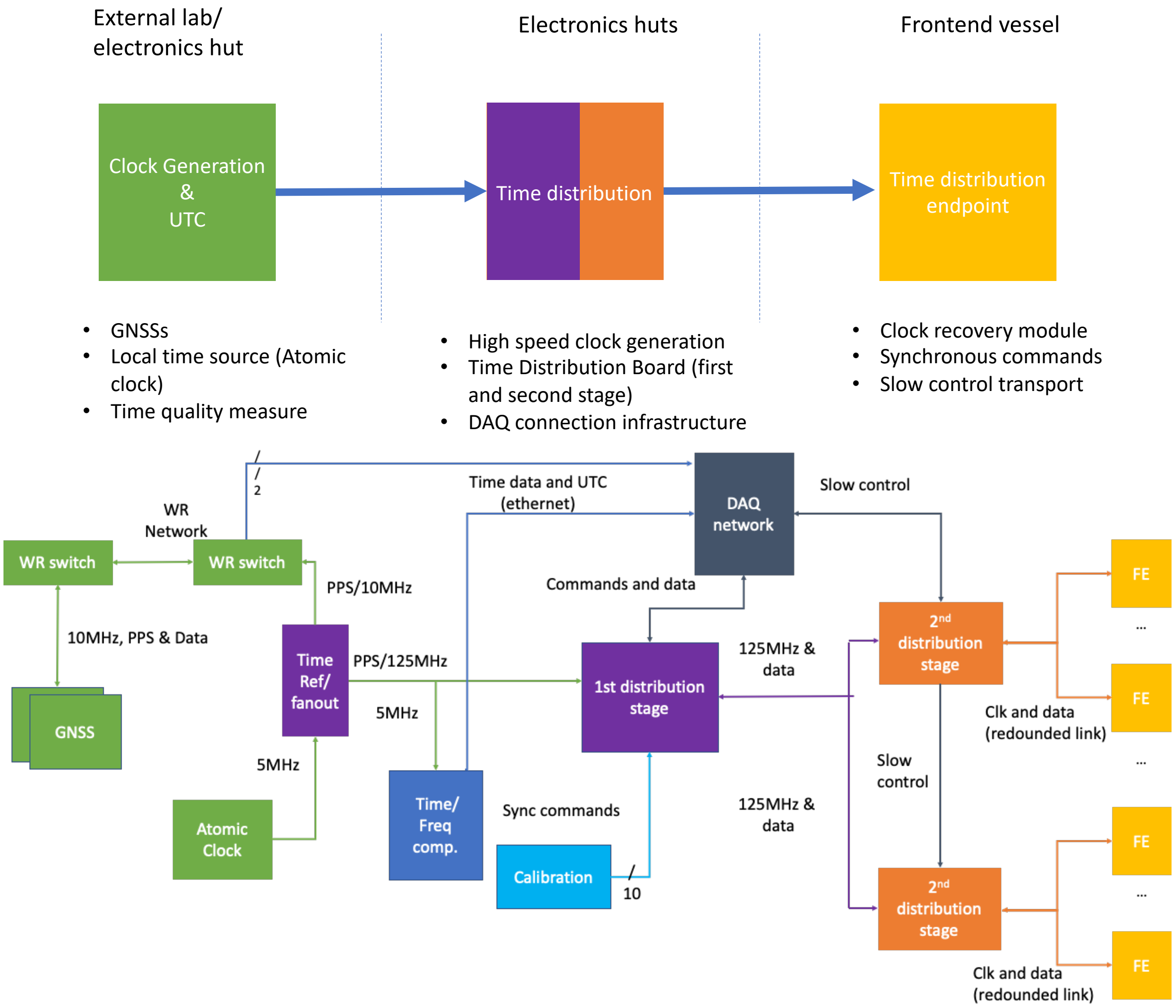

Figure 28: The top picture reports the block scheme that describes the 3 main time distribution subsystems. The bottom details the different parts. The green boxes compose the clock generation and UTC tagging. The purple elements constitute the first distribution stage, the orange ones are for the second distribution stage, while the yellow ones refer to the Time Distribution Endpoints, part of the front-end.

each end-point, a signal that still meets all the requirements in spite of the deterioration due to the distribution process. To achieve this goal, many elements must work together as shown in the block scheme of Fig. 29. As visible from it, the time origin is the atomic clock which delivers a stable 5 MHz clock cadence to the "time reference/fanout" element, physically embedded in the first distribution stage. Here the basic cadence is used to build all the needed clocks. A 125 MHz reference and the PPS are sent to the first distribution stage while a 10 MHz frequency and a PPS are broadcasted to the GNSS receivers via the White Rabbit (WR) protocol [18] which guarantees synchronicity and phase alignment over long distances[2]. The Navigation satellite systems use this two periodic signals to measure the time distance between the Hyper-Kamiokande local time and the GNSS time giving a projection to the UTC. This information travels over the Ethernet link established by the WR network to the data acquisition system which converts the local time tag, recorded by the front-end, to UTC. A second identical chain is proposed to enhance the total system reliability. The time reference/fanout entity serves also as a reference point for calibration and to check the time distance between the main and spare clock generation blocks.

The cadence generator technology that guarantees the best performance is the atomic clock, but, currently, on the market there is a vast range of instruments with different noise levels, stability char-

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[2] The phase of these frequencies must be all aligned with the PPS phase.

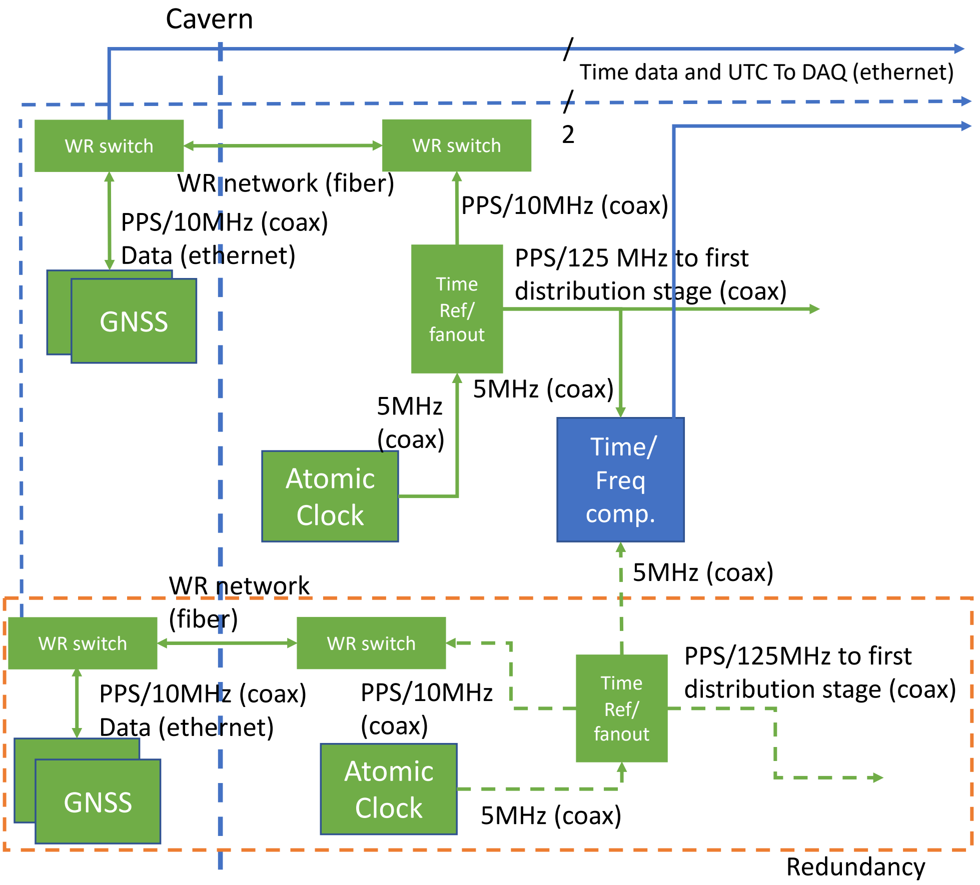


Figure 29: Detailed scheme of the clock generation section. The green boxes represent the clock and time generation instruments, the dashed orange box contains the hot spare clock generation chain while the blue box represents the subsystem used to monitor the time distance between the main and spare system.

acteristics and prices. At the present time we are evaluating 2 candidate instruments: the rubidium clock FS725 from Stanford Research (SRS) [19] and the Passive Hydrogen Maser (PHM) (microwave amplification by stimulated emission of radiation), model T4Science pHMaser 1008 [20]. Both output a PPS, a 5 MHz and a 10 MHz and the first has also a PPS input used as a reference for its internal PLL. Their characteristics have been verified in an extensive test campaign conducted in collaboration with the colleagues from the SYRTE laboratory, part of the Observatoire de Paris (OP) [21], one of the institutes that concur to the UTC definition. A comparison have been performed against a much more precise time reference available at LPNHE: a copy of the UTC implementation built at SYRTE (called UTC(OP)) and broadcasted via a White Rabbit link. This cadence is the most precise available, therefore it has been used as a benchmark.

A detailed comparison involving Allan Standard Deviation (ASD) [22] can be found in Figure 30. The time at which the curves reach the minimum indicates the time at which long-term frequency drifts become dominant over the short-time fluctuations. As evident from the plot, the most stable time generator is the PHM clock (green curve) with a stability of 10^{-14} at 10^4 seconds. Unfortunately, this instrument is also the most expensive of the two. The red curve shows the stability of the time reconstructed with the GNSS receiver, in this case the Galileo Standard Time (GST) compared to the UTC(OP). It is not very stable at short intervals but it improves constantly over longer periods. The Rubidium clock has almost the opposite behaviour with a fairly good stability at small time intervals (10^{-11} at 10^1 seconds) but with an evident drift starting at about 10^3 seconds when in free-running mode as shown by the blue curve. Analysing these results it is clear that the best performance can be achieved using a combination of the atomic clock for short range and the GNSS time for long one. To define the best method of combining these outputs, also the so-called steered mode feature available on

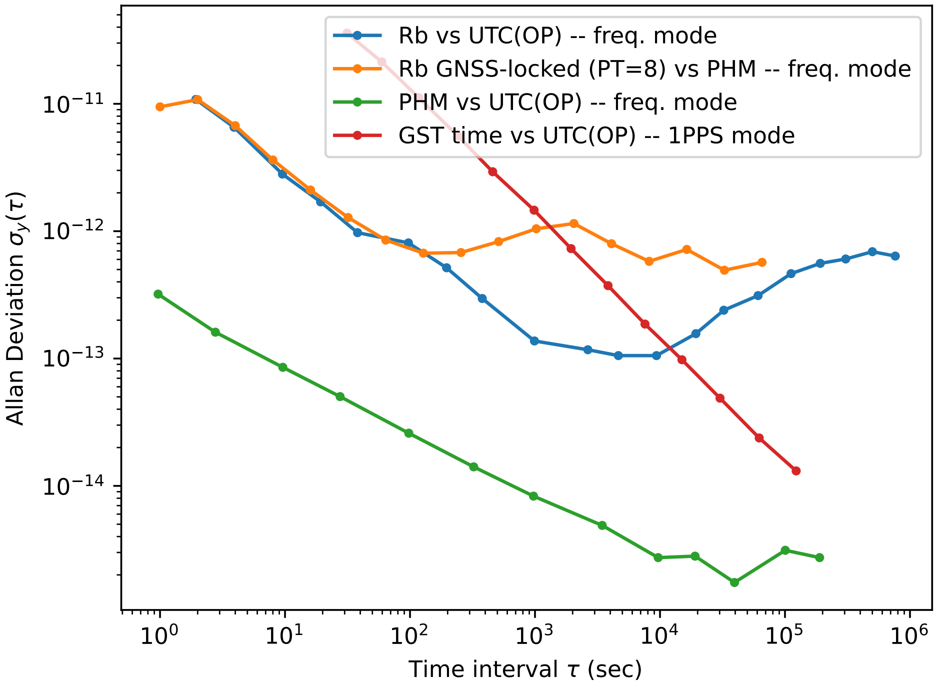


Figure 30: Measured performances of the Rb (blue) and PHM (green) clocks in terms of Allan deviation. The stability of the Galileo Time (GST) measured using the Septentrio PolaRx5 with respect to the UTC(OP) timescale is represented by the red curve. The orange curve corresponds to the stability of the Rb clock locked on the 1PPS output of the Septentrio receiver.

the Rb clock FS725 has been tested. As mentioned before, this instrument can accept a PPS input used as reference clock of an internal PLL that periodically corrects the output drifts. The results obtained with this method are plotted as the orange curve. As visible from it, the correction starts at around 10^2 seconds (the first minimum of the curve) and happens periodically. Moreover the user does not have any control on this correction process making the uncertainties evaluation harder.

Considering the far detector's need to synchronize all the front-ends in a very tight manner, we plan to use the atomic clocks in the so-called “free-running” mode, so without steering the clock PLL using a PPS coming from a GNSS receiver. Instead, the 5 MHz from the atomic clock is sent to the entity that generates the FE reference clock. The same entity also counts the number of cycles to reach one second and generates a local PPS. It then becomes the time distribution reference point as represented in Figure 29. It serves also as fan-out providing a very stable 10 MHz frequency and the PPS to the GNSS receivers to align the phase of their outputs overriding the instruments internal oscillators. This logical entity will be integrated in the first distribution stage board for practical reasons. The GNSS receivers measure the time distance between the PPS input and UTC. This information is then sent to the DAQ via Ethernet links and is used to convert the local time tag to UTC. It is also worth mentioning that any atomic clock drift, no matter its value, will affect all the detector's FEs equally then it will be invisible on the relative time tagging.

The conversion values to transform the local time tag into UTC will be calculated periodically by the GNSS receivers and sent to the data acquisition system via Ethernet to the data acquisition system. To compute the conversion factor we are planning to use a time transfer method based on the information included in the CGGTTS file produced by the GNSS receivers. According to the CGGTTS (Common Generic GNSS Time Transfer Standard) [23], each satellite receiver calculates the time distance between the local PPS and the GNSS system time periodically.

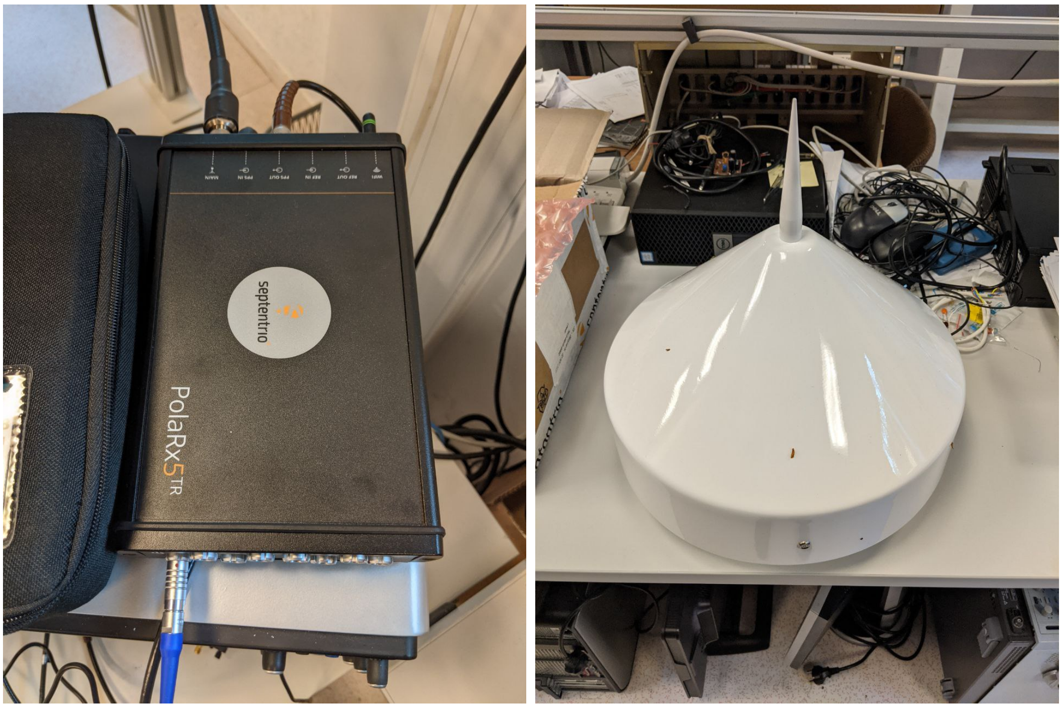


Figure 31: The Septentrio PolaRx5 GNSS receiver and the associated antenna.

Global Navigation Satellite System (GNSS). As already mentioned, the GNSS will be used to correlate the local time base with the universal coordinated time by means of the information included in its data stream. To guarantee an accuracy at the level of 100 ns or better, many parameters must be taken under control and corrected, if needed. Some of them are related to the satellites, like e.g. the position of each transmitter at any given time. This implies that each satellite's orbit must be known with a precision that sometimes goes beyond the one included in the data stream. Some other elements are relative to the receiver and concern the electromagnetic signal that reaches the antenna, the interference and the reflection to which it is subjected. To improve the first kind of uncertainty, correction algorithms will be implemented on the received data by means of a computer infrastructure that elaborates information coming from the UTC consortium. This consortium is composed from many laboratories spread around the world working together on the UTC definition. As part of their duty, they publish a weekly report that includes parameters needed to reconstruct the universal time at the "state of the art" precision. The uncertainty related to the local equipment can be mitigated performing an accurate calibration of the receiver, the associated antenna and the connection cable against a cadence generated by a so-called group 1 laboratory, like SYRTE, able to guarantee a resolution below 5 ns.

After an extensive R&D study, the Septentrio PolaRx5 multi-frequency multi-constellation timing/reference receiver associated with a multi-frequency B3E6 choke ring antenna [24, 25] have been selected. A calibration procedure has been conducted on the first purchased set and the results are reported in Tables 3, 4 and 5.

To achieve the best performances and use multiple devices together, each GNSS receiver will be supplied with a 10 MHz and a PPS input cadences generated from the atomic clock. The 10 MHz frequency will be used to override the internal receiver's oscillator, as it provides a more stable and precise clock for the internal logic. The PPS input will be used at start-up to synchronize multiple receivers outputs in order to use them together and switch from one to the other in case of malfunctions.

Institute	Equipment status	Measure MJD	Receiver type	BIPM code	RINEX name
OP	Traveling	NC-NC	Septentrio PolaRx5TR	LPN1	LPN1
OP	Group 1 reference	59508 – 59514	Septentrio PolaRx5TR	OP73	OP73

Table 3: GNSS calibration equipment description.

To achieve the best performance and enhance reliability, 2 GNSS receivers connected to the same antenna and sharing the same PPS input, will be installed and data from both instruments will be sent to the data acquisition system via Ethernet. This information will be used to constantly monitor the equipment and guarantee that at least 1 receiver will be operational at any time. To be more specific the DAQ will receive the CGGTTS files from both devices and will analyse them. In case of normal behaviour, they will provide the same time distance between the local PPS and the GNSS time, while, in case of malfunctions, one of them will have a different offset.

To avoid single point of failure, the entire chain of atomic clock, GNSS receivers, time distribution reference point and the first distribution stage will be duplicated in a hot spare configuration. This means that the second chain will be always active and its 5 MHz time base will be constantly compared with the main one. In addition, a third (if possible, more stable) clock should be installed and compared with the other two clocks in order to detect sudden jumps of one of the Rb clocks.

Time distribution system. The proposed time distribution system consists of two stages and the time endpoint, as shown in Fig. 28, that we present in the next paragraphs.

First Distribution Stage. The main function of the First Distribution Stage (FDS) is to distribute with minimal skew and jitter a reference clock at the desired selected frequency to the Second Distribution Stage (SDS) which then fans out the reference clock to all front-ends, underwater. The variations of clock skew at any end-point must be less than 100 ps during operation and after system restart. The master reference clock is provided to the FDS by an atomic clock at 5 MHz. It is scaled up in frequency to the desired value, 125 MHz in the current plan, by an appropriate clock synthesizer. In addition to the reference clock, the FDS must generate the required synchronization information for the front-ends: a periodic TDC reset signal with an associated coarse timestamp counter, and a 1PPS signal accompanied by a date code. The latency of synchronous signal distribution is required to be accurate to one period of the reference clock (i.e. 8 ns at 125 MHz). The FDS also has to provide a 10 MHz reference clock and a 1PPS signal for use on the GNSS receiver side. The FDS requires a certain number of user inputs for the fanout of external synchronous and asynchronous signals: a veto signal for the data acquisition, an emergency stop for high voltage sources, and possibly other ancillary signals. If this does not add too much complexity, the FDS may monitor the slow variations of delay of all, or a subset, of its transmission links, but it is not required to compensate for these variations. The FDS is housed in an electronic hut, outside of the water tank. Although reliability is a concern, this equipment remains accessible for replacement in case of failure. All the features described above will be integrated on a single electronics board and the needed connections to all the second distribution elements will be implemented using optical transceivers and splitter. Another copy of this circuit will be part of the hot spare chain so the total number of boards produced will be 3 including 1 spare.

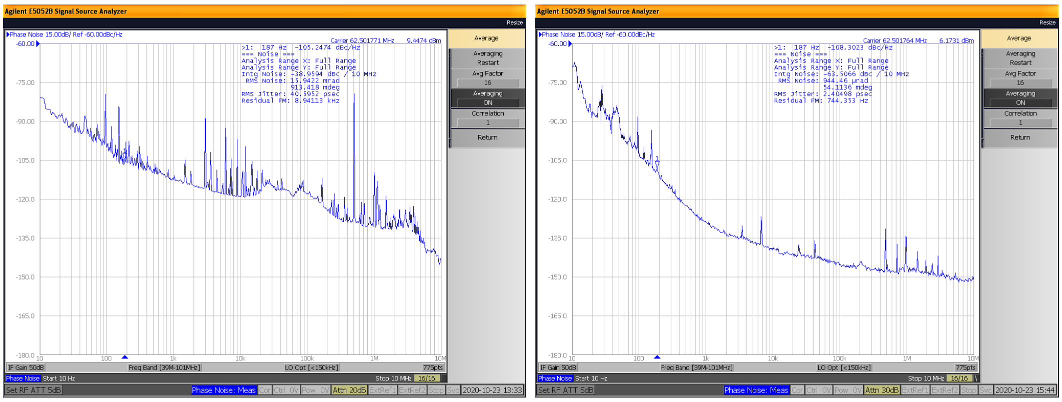
Second Distribution Stage. The second distribution stage receives the reference clock, the TDC reset, the global coarse counter, the PPS and the synchronous commands from the first stage and pass them to the front-ends. To accomplish this task it establishes a bi-directional, synchronous and phase deterministic link to each node over an optical fiber pair used also to exchange critical slow control

Receiver	Reference	Measure's MJD	REFDLY	CABDLY	P1 DLY	TDEV	P2 DLY	TDEV
OP73	Ref	59508 – 59514	85.2	129.6	29.500	NC	26.30	NC
LPN1	OP73	59508 – 59514	88.3	127.1	25.832	0.024	22.871	0.022

Table 4: GPS calibration table. All values are in ns.

Receiver	Reference	Measure's MJD	REFDLY	CABDLY	E1 DLY	TDEV	E5a DLY	TDEV
OP73	Ref	59508 – 59514	85.2	129.6	31.700	NC	31.300	NC
LPN1	OP73	59508 – 59514	88.3	127.1	28.242	0.040	25.431	0.034

Table 5: Galileo calibration table. All values are in ns.



```
>1:  187 Hz  -105.2474 dBc/Hz
=== Noise ===
Analysis Range X: Full Range
Analysis Range Y: Full Range
Intg Noise: -38.9594 dBc / 10 MHz
 RMS Noise: 15.9422 mrad
            913.418 mdeg
RMS Jitter: 40.5952 psec
Residual FM: 8.94113 kHz
```

```
>1:  187 Hz  -108.3023 dBc/Hz
=== Noise ===
Analysis Range X: Full Range
Analysis Range Y: Full Range
Intg Noise: -63.5066 dBc / 10 MHz
 RMS Noise: 944.46 µrad
            54.1136 mdeg
RMS Jitter: 2.40498 psec
Residual FM: 744.353 Hz
```

Figure 32: Frequency domain jitter measurements performed on the clock reconstructed by the custom board. On the left the clock before the jitter cleaner PLL and on the right as measured after the filter.

information between the data acquisition system and the front-ends. This module, hence, also has Ethernet connections to the DAQ network via optical fibers. All the links are handled by the FPGA's Multi-Gigabit Transceivers (MGT). The time synchronization system topology envisions 16 front-end's connections per second distribution element, so, considering a total of one thousand front-ends, the number of required SDS board is about 60.

The synchronous link's characteristics enumerated above represent the most critical aspect of the second distribution layer and an extensive R&D campaign has been carried out in the last two years to select the most suited technology for the Hyper-Kamiokande experiment.

Many solutions have been evaluated and the selected one is based on the Clock and Data Recovery (CDR) scheme: the process of extracting time information (clock) and data from a single serial stream. The CDR is implemented by means of a specific serializer-deserializer (ser-des) couple to be used on both sides of the link. The simplicity, reliability and the convenience of this technique has fueled its use in many different fields so that all the modern FPGAs have CDR compliant ser-des already embedded in the silicon. This represents a further advantage for the experiment because it allows sending slow control data and distribute the system clock using one single fiber. It does not require any dedicated chip-set beside the FPGA already used to perform all the digital operations needed for the data collection and communication with the DAQ. Reducing the components on the electronics boards has advantages on many critical aspects of the HK's design like the in-water electronics footprint, its power dissipation and the number of links and connectors between the design entities.

A test campaign has been conducted to evaluate the proposed clock and data recovery concept. The experimental tests are based on evaluation boards and prototypes used as platforms to develop the firmware and the methods that will be used in the final release. The first phase has been devoted to the data bandwidth compliance verification with the 1 Gbps Ethernet protocol; then, the attention has been focused on the jitter performances measurement for the embedded clock which represents the most important element at this stage of the R&D. An extensive measurement campaign has been carried out and the cadence characteristics have been evaluated in time and frequency domains. In the time domain the jitter has been measured by means of an oscilloscope (Lecroy Wavepro 760Zi 6 GHz 40Gsps) while in the frequency domain a phase noise analyser Keysight E5052B has been used.

The jitter on the received clock is 40.6 ps as readable from the text in the upper left part of Fig. 32 left. The custom board used to receive and reconstruct the clock is equipped also with a so-called jitter cleaner component, a Phase-Locked Loop (PLL) SI5345 capable to filter the jitter and produce a cleaner clock. A measurement of the jitter has been performed also on the clock treated by this filter and the results are shown in the right plot of Figure 32. **The excellent filtering capability of the PLL is evident since the measured jitter is now 2.4 ps well below the experimental requirements.**

The phase stability has been also tested using an oscilloscope in infinite persistence mode triggered on the transmitted clock. The receiver board has then been reset multiple times and the RX clock has been reconstructed always with the same phase distance to the TX clock every time the link has been re-established. The achieved results has allowed the design of the first prototype board sent to

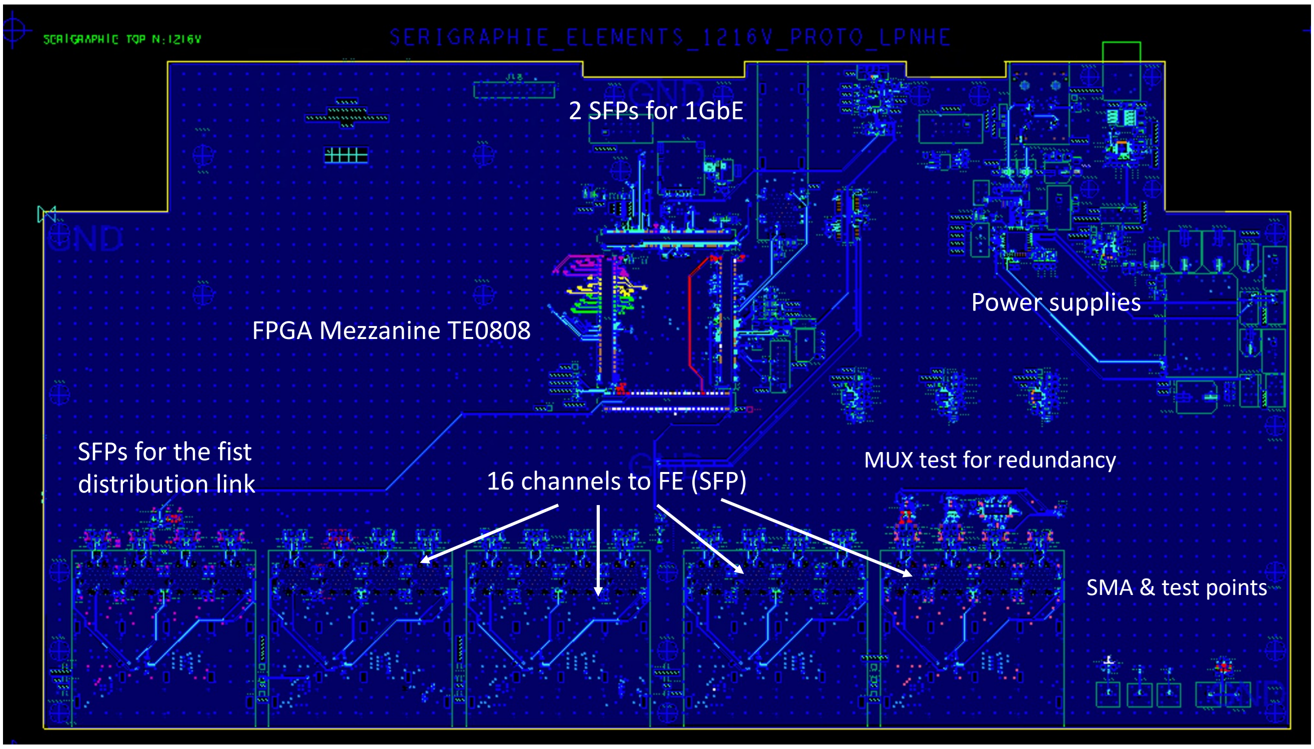


Figure 33: Layout of the first prototype of the time distribution module.

fabrication in September 2022. A layout of the board is shown in Fig. 33. Once constructed the board will be tested and characterized giving crucial feedback to finalize the design and start the production.

Time Distribution Endpoint. The TDE is the entity integrated in the front-end electronics that receives the data stream from the Time Distribution Module, reconstructs the clock embedded, cleans it by means of a PLL and provides it to all the logic elements that need it. A FE general block scheme that reports all the logic elements is depicted in Fig. 28.

From a hardware point of view the TDE needs an optical transceiver to establish the connection over the optical fiber, an FPGA with the corresponding ser-des to extract the clock, and a PLL to eventually clean the jitter. Even though the exact number of sensors to be read and its routing schemes are not completely defined, the TDE will be equipped with enough ports to handle environmental sensors and convey the information on the data transmission link.

Opportunities on near and intermediate detectors. The time generation system currently installed at the near detector relies on the steering of a Rb clock by a PPS originating from a GNSS receiver. As discussed above, such system is less precise with respect to the "free-running" clock system proposed to the far detector therefore discussions are now ongoing to evaluate the possibility of building the same clock generation scheme described in this document on both far and near sites. **This scheme would not only improve the overall performance of the long-baseline analysis but also simplify the time synchronization between the accelerator and the far detector.** A similar scheme could be applied also to the time synchronization of the Intermediate Water Cherenkov Detector assuming that appropriate funds would be allocated.

Expected work share between French labs. Over the last couple of years a strong collaboration between the LPNHE and IRFU groups has been established for the development of the time distribution system for HK. A hardware developed by IRFU engineers for the first distribution stage prototype has been used as a starting point for the the second distribution stage board. Once fully tested the corresponding prototypes will be employed also in the vertical slice test of HK electronics (see Fig. 34 for more details about the expected schedule).

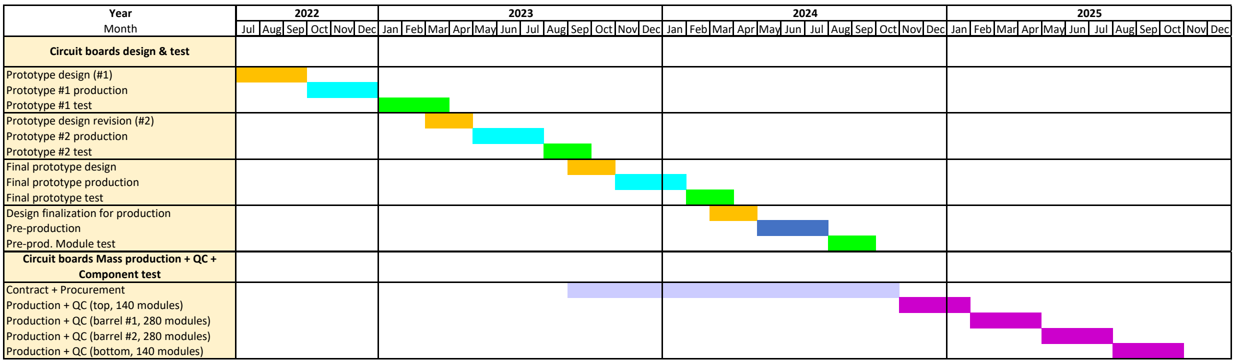


Figure 34: Expected schedule for the design, tests, approval and construction of the time synchronization system for the Hyper-Kamiokande far detector.

4.3 Computing

As computing is an important element for the success of modern experiments and CC-IN2P3 is playing a key-role for LHC and many other experiments, a French contribution to the T2K and Hyper-Kamiokande computing effort seems natural and desirable.

During the construction and exploitation of the detector suite, several simulations will produce generated events that will need storage. Starting from 2027, data files will also be produced by these detectors. Because of the size of the detector and the number of PMTs, the Hyper-Kamiokande far detector will produce a significant fraction of data that will need to be stored and processed. It does not seem feasible to store and process all the produced data using one single site (e.g. at the Kamioka site as it is the case for Super-Kamiokande).

For these reasons, we propose to use the computing resources of the CC-IN2P3 as part of T2K and Hyper-Kamiokande experiments computing schemes. Such a plan was initiated with the IN2P3 directorate and a more detailed proposal [26] was submitted in November 2020.

T2K and Hyper-Kamiokande Computing Model. Similarly to LHC, ND280 has used since 2010 a tiered system composed of three layers or *Tiers*. A T0 site is at KEK where the data are stored on HPSS/disk combo storage system. The raw data are transferred to RAL and Triumf as T1 sites. An additional T1 site is highly desired by the collaboration. Data reconstruction and MC generation are run on T1 and T2 sites and then copied on at least one T1 site and one or more T2 sites. A set of python scripts and DIRAC utilities is used for data transfer and registration.

It is also proposed to use a tiered computing model for Hyper-Kamiokande. Data collected by the detectors in Japan are stored in the two T0 sites (Kamioka and KEK) and copied to T1 sites. Data calibration and reconstruction along with Monte Carlo simulations will be performed at T1 and T2 sites. Data and workload management between sites is done using the DIRAC (Distributed Infrastructure with Remote Agent Control) framework [27]. T2 sites should have enough computing and storage resources to process and store part of these data or produce simulated and reconstructed events.

In this scheme, we propose to include CC-IN2P3 as a T1 site, that will therefore store part of data produced by T2K and Hyper-Kamiokande. More precisely, it will:

- host data and contribute to the simulation and analysis productions of the T2K experiment until the end of its data taking campaign in 2026,
- contribute to the simulation effort (data storage and computing) for the Hyper-Kamiokande construction era (until 2027),
- and host data and contribute to the simulation and analysis productions of the Hyper-Kamiokande starting from 2027 and for at least 10 years.

Part of this plan, e.g. the storage of the T2K data over the duration of the T2K-II era (2022-2027) was already discussed and agreed with the IN2P3 directorate, and the replication of data into the centralized place that is CC-IN2P3 has begun.

Tables 6 and 7 present the expected resources needed during the construction and data taking phases. The amount of produced data (raw, processed and MC) will be about 35 PB at the end of the 10-years data taking period.

In general, T1 sites are not expected to have more than one copy of each file as this would result in doubling our storage space request. Rather, it is expected that at least two T1 sites will host single copy of each data and simulation file.

CC-IN2P3 has many advantages over some of the other T1 sites already involved in T2K. At the moment, the UK computing efforts come as an overhead of the LHC experiments, therefore without good long-term planning; in addition, it is distributed over many small sites, each of them having their own specificity, making an integration into the Grid system rather difficult. The second T1 site for T2K is in Canada, but has been retiring over the last couple of years, sometimes leaving only one copy available for some of the files. **Having CC-IN2P3 as a full T1 site hosting all the data of T2K and Hyper-Kamiokande would be central to the success of the computing efforts in these experiments.**

The estimations made here bear uncertainties related to the fact that they are based on SK experience. In particular, SK stores all the raw data on disk and produce reconstructed events offline; however, the online trigger system of HK will allow us not to store any raw data, but reconstructed events directly. The uncertainty is therefore on the actual size of the reconstructed events, which depends on the far detector front-end electronics yet to be constructed. **Since the request is stretching over 15 years and that the data-taking period has not started yet, it is expected that we will need to reevaluate these estimates every couple of years.** Generally, the uncertainty on these estimations should be less than 50%. Given the current energy crisis, the operations cost are likely to increase, but these should stay reasonable compared with the equipment cost like tape purchase.

Of course, the computing needs would increase over time as the productions (reconstruction and analyses over real and simulated data) will be made assuming an increasing number of POT. An estimation of the needs increase for a T1 site (like CC-IN2P3) is represented in Fig. 35; this assumes that such site would contain only one copy of each file and share the computing burden with another T1 site. Compared with other high-energy physics experiments such as Belle-II or DUNE, the overall computing resources are rather reasonable: Hyper-Kamiokande far detector would produce about 5 TB per day, so about 2 PB per year, while experiments like Belle-II and DUNE will produce about 100 PB and 30 PB each year, respectively [28, 29].

Detector	MC Storage (TB)	MC (HS06 CPU.h)
INGRID	7	0.13M
ND280	1,757	107M
IWCD	508	4,666M
Far detector	2,726	606M
Total	4,991	537M

Table 6: Expected computing resources for the Hyper-Kamiokande experiment during the construction phase, considering only one copy of each file. 1 HS06 CPU.h is a typical CPU time unit corresponding to about one CPU running for 10 hours. Projections August 2022.

Detector	Data and MC Storage (TB)	MC (HS06 CPU.h)
INGRID	226	0.51M
ND280	6,891	384M
IWCD	1,460	6700M
Far detector	27,3630	2,004M
Total	35,715	9,138M

Table 7: Expected computing resources for the Hyper-Kamiokande experiment during the data taking phase, considering only one copy of each file. 1 HS06 CPU.h is a typical CPU time unit corresponding to about one CPU running for 10 hours. Projections August 2022.

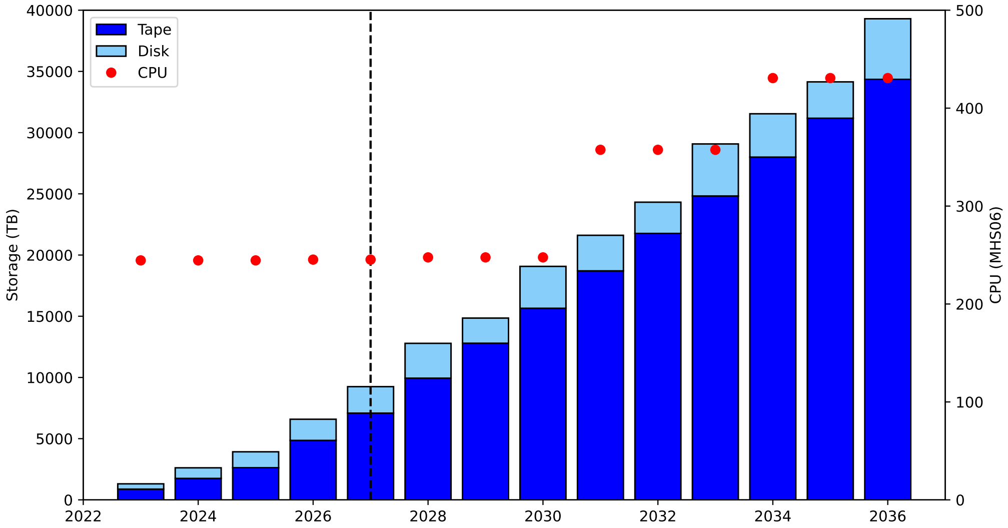


Figure 35: Time profile of the requested storage and computing resources.

At this moment, the computing costs are not included as contributions to the construction of the far detector. **Let us point out that there is a clear desire from the collaboration point-of-view, and especially from the non-Japanese contributors, to include the cost of the computing before and during data taking as part of the construction costs of the Hyper-Kamiokande experiment.** This should be discussed and agreed upon by the Hyper-Kamiokande Financial Forum.

Reconstruction and physics contributions. LLR and LPNHE have led the physics of LBL-ν for several years now, especially when it concerns the far detector, in the development of the Hyper-Kamiokande simulation, of new reconstruction algorithm for low-energy events in SK and Hyper-Kamiokande, and also in convenership of the highly-visible T2K oscillation analyses. This leadership has been acquired mainly in the current T2K and Super-K experiments, thanks to many years of software and analyses developments, but has yet to reach the same scale in Hyper-Kamiokande. Consequently, the physicists in these labs intend to boost their involvements in the Hyper-Kamiokande groups associated with these items, and especially, to develop then future high-energy reconstruction for Hyper-Kamiokande. The IN2P3 teams has had a key role to adapt the current high-energy reconstruction algorithm from Super-K to Hyper-Kamiokande. Since the later is based on a 15-years-old method, some investigation has started to replace this algorithm by modern methods before the start of Hyper-Kamiokande. We propose to participate and lead the development of this future algorithm. Not only it will build on our expertize in the current Super-K algorithm, but will offer a maximal visibility to IN2P3 in all high-energy physics, from CP violation search to atmospheric neutrinos and probing Grand Unified Theories. Note that this general software and oscillation analysis effort requires a significant increase of the IN2P3 manpower in the Hyper-Kamiokande experiment.

Hosting collaboration database infrastructure. Another French contribution to HK involving CC-IN2P3 is hosting of the database containing all the information related to the collaboration management, experimental conditions and operations. For instance, this database will contain information related to collaboration Single Sign-On authentication, shifts schedule, publications details, detector calibrations and documentation. Based on the work already made for the KM3NET collaboration and also hosted at CC-IN2P3 and after a R&D phase led by Italian collaborators, the infrastructure was deployed on IN2P3 servers and the database is now accessed using a web interface hosted on a virtual machine at CC-IN2P3. Recently, a milestone for such integration was reached with the synchronization of the collaboration database and the CC-IN2P3 mailing list system, appending all the HK mailing list with a "IN2P3.FR".

In addition, the databases related to the currently-running ND280 detector have been migrated from Triumf computing centers in Canada to CC-IN2P3. Several virtual machines were deployed at CC for allowing e.g. replication, updates and readout of ND280 slow-control and calibration databases. This transition will ensure the long-term support of the ND280 DBs needed over the duration of Hyper-Kamiokande.

5 Experiment resources

In this section the human, financial and organizational resources already acquired by the HK-France community are presented.

5.1 Human resources

Table 8 summarizes the permanent staff involved in the Hyper-Kamiokande experiment in the IN2P3 laboratories. The physicists involved in this experiment will bring their expertise acquired over the past 15 years in the Japanese neutrino program. LPNHE, LLR, OMEGA and IRFU have been collaborating on the T2K experiment on which the four labs are providing major hardware, software, and intellectual contributions. The groups have continuously held a central place in the construction, operation and analysis of the INGRID, ND280 and WAGASCI near detectors, the Super-Kamiokande far detector and the T2K oscillation analysis. In particular, the four groups are strongly collaborating on the construction of the upgraded ND280. The LLR and OMEGA laboratory have developed the WAGASCI and super-FGD front-end electronics, and the LPNHE and IRFU have collaborated on the development and production of the front-end and back-end readout electronics that will equip the High-Angle TPCs in

Name	Position	Laboratory	Employer
Maria Cristina Volpe	DR	APC	CNRS
Michel Gonin	DR	ILANCE	CNRS & University of Tokyo
Amine Afiri	IR	LLR	CNRS
Margherita Buizza-Avanzini	CR	LLR	CNRS
Olivier Drapier	DR	LLR	CNRS
Franck Gastaldi	IR	LLR	CNRS
Marc Louzir	AI	LLR	CNRS
Thomas Mueller	CR	LLR	CNRS
Jerome Nanni	IR	LLR	CNRS
Pascal Paganini	DR	LLR	CNRS
Benjamin Quilain	CR	LLR	CNRS
Alain Blondel	DR	LPNHE	CNRS
Jacques Dumarchez	DR	LPNHE	CNRS
Claudio Giganti	CR	LPNHE	CNRS
Mathieu Guigue	MCF	LPNHE	Sorbonne University
Marco Martini	Prof	LPNHE	IPSA
Boris Popov	DR	LPNHE	CNRS
Stefano Russo	IC	LPNHE	CNRS
Vincent Voisin	IR	LPNHE	CNRS
Marco Zito	DR	LPNHE	CNRS
Stephane Callier	IR	OMEGA	CNRS
Pierrick Dinaucourt	AI	OMEGA	CNRS
Selma Conforti	IR	OMEGA	CNRS
Frederic Dulucq	IR	OMEGA	CNRS
Ludovic Raux	IR	OMEGA	CNRS
Christophe de la Taille	IR	OMEGA	CNRS

Table 8: List of the permanent staff involved in the Hyper-Kamiokande experiment.

the upgraded ND280. Such collaboration continues in the development and integration of the detector responses and performances in the T2K official simulation, reconstruction and analysis tools.

Physicists from these laboratories, while continuing to contribute to the world leading results produced by T2K, T2K-II, and Super-Kamiokande, will gradually increase their contributions to the Hyper-Kamiokande experiment. This transition is expected to occur at different times depending on the responsibility of each person in the different experiments but we anticipate that, by the beginning of Hyper-Kamiokande data-taking the whole neutrino groups of LLR and LPNHE will be entirely committed to Hyper-Kamiokande.

As of today, physicists from French laboratories have already important responsibilities in Hyper-Kamiokande, being conveners of the long-baseline group, of the Near Detector group, and of the electronics sub-working group in charge of the time synchronization system.

5.2 Financial resources

The involvement of IN2P3 laboratories in the R&D for the Hyper-Kamiokande experiment is supported partially by the budget allocated to each group by the IN2P3 directorate. Let us emphasize that a significant financial support (of about 200 k€) was awarded by the IN2P3 directorate to the Hyper-Kamiokande R&D during the year 2022. Also internal investments made by the CEA directorate allow contributions from the IRFU.

For the final production of the time distribution system (with an estimated cost of about 0.6 M€) the following share is being discussed: the IN2P3 will cover about 2/3 of the total amount, while the IRFU will contribute about 1/3. The end-point of the clock distribution system (with a cost estimate of ∼60 k€) will be covered by our INFN colleagues.

Moreover, other sources of fundings are being received and are helping to develop the French contributions during the R&D and production phase. In particular, the Ecole Polytechnique has invested 400 k€ into the development of the HKROC chip for the under-water front-end electronics. Initial investments in the time generation system R&D were supported by an "Emergence" grant from Sorbonne Université (77 k€). In addition, an ANR "BERTHA" (ANR-21-CE31-0008; 297 k€) was awarded to the LPNHE-Neutrino group for the period 2022-2026. This funding will cover some of the person-power needed for the R&D of the time generation and clock distributions systems for the Hyper-Kamiokande far detector and contributions to the Water Cherenkov Test Experiment that will be done at CERN.

5.3 Organizational support

Organizational infrastructures are also contributing to the development of the French contributions to the Hyper-Kamiokande experiment. For example, a joint laboratory between the University of Tokyo and CNRS named "ILANCE" (International Laboratory for Astrophysics, Neutrino and Cosmology Experiments) was recently established. The primary mission of this International Research Laboratory (IRL) is to develop strong collaborations between Japan and France on the Hyper-Kamiokande experiment, by facilitating researchers travel to Japan and the organization of joint workshops, see e.g. [30]. We also receive support from the France–Japan Particle Physics Laboratory (FJPPL) which brings together Japanese and French researchers.

Finally, monthly meetings are organized among all the French groups involved in the Hyper-Kamiokande experiment in order to coordinate the national efforts.

6 Strength, weaknesses, and risks managements

In this document we also present our analysis of the strengths, weaknesses, risks and opportunities for our proposed contributions to Hyper-Kamiokande.

Strengths

- Hyper-Kamiokande will use the very well-known Water Cherenkov technology. Water Cherenkov detectors have proven to be exceptional detectors to study rare events in the MeV–TeV energy range thanks to the possibility of combining huge target masses and high signal-detection efficiency that allows to distinguish ν_e CC from ν_μ CC interactions (for LBL or atmospheric neutrinos) or to search for proton decays.

- Hyper-Kamiokande will use the neutrino beam and the near detector complex built for T2K, thus saving large amount of money for the long-baseline program. In addition, the combination of well-understood (anti)neutrino beams (characterized using NA61/SHINE hadron production measurements) and near detectors will allow a significant reduction of systematics uncertainties from the first day of the experiment. French groups have, since many years, leading roles in the operation of T2K Near Detector and in the corresponding reduction of systematics uncertainties.
- Construction budget for Hyper-Kamiokande was allocated by Japanese government in 2019 with a budget profile that allows to start the experiment in 2027. Given previous track records with similar projects in Japan, there is no doubts that budget will be allocated as expected.
- The French groups already have leading role and expertise in physics and software working groups in major areas of the T2K experiment (analysis coordinator, oscillation analysis, cross-section, near-to-far reduction of systematic uncertainties...). This would ensure a leading-role in the HK experiment as well, provided a continuous support of IN2P3.

Weaknesses

- The groups from LLR and LPNHE are relatively small and physicists are already committed to the operation of T2K-II and Super-Kamiokande. This weakness is partially mitigated by the large overlap in terms of physics case, technologies and tools between the two collaborations (for example, the Near Detectors or the use of reconstruction techniques in water), but, given the ambitious physics program, the groups would certainly benefit of additional researchers that could be hired in the coming years.
- Hyper-Kamiokande is an IN2P3 R&D project since one year, but not an official physics master project yet. This has undermined our visibility, especially in physics and analysis area, and our access to convenerships in the first phase of the experiment.

Opportunities

- Hyper-Kamiokande has the great potential to be the first experiment to measure CP violation in the leptonic sector. No experiments before Hyper-Kamiokande have the sensitivity to measure CP violation at more than 3σ and, once online, Hyper-Kamiokande will acquire statistics much faster than DUNE.
- The huge target mass of Hyper-Kamiokande will make it the most sensitive observatory for rare events in the MeV–TeV energy region. It will have, for example, the best sensitivity to proton decay and detection of SN neutrinos.
- IN2P3 groups can build on their long standing expertise in the T2K and SK experiments to propose strong and highly-visible contributions to Hyper-Kamiokande. Beyond the solutions proposed in this document, there are still many possibilities to contribute to the project *e.g.* the electronics of the Outer-detector, the second upgrade of the ND280 detector, the Intermediate Water Cherenkov Detector, the analysis and reconstruction software, etc.
- To fully benefit from the more precise time synchronization scheme we are proposing for the far detector, a similar system could be deployed at the near and intermediate detector sites. In addition, without any additional R&D phase, the required budget would be smaller than for the far detector.

Risks

- The approval from the CS-IN2P3 and support from IN2P3 is needed to capitalize on the R&D on the digitizer to make a strong contribution to the HK detector in addition to the timing system and computing. The French contribution to the HK detector is still being worked out after the recent electronics review and it might include a significant contribution to the outer detector digitizer.
- Since the HKROC digitizer was not selected as the primary option for the Hyper-Kamiokande inner detector, there is still an uncertainty about the outcomes of this contribution in the Hyper-Kamiokande experiment at the time this document is written.

7 Conclusions and requests to IN2P3

The Hyper-Kamiokande experiment is a next-generation LBL-ν experiment in Japan with a very rich physics program. In addition to providing world-leading constraints on CP violation in the leptonic sector and exquisite measurements of the neutrino oscillation parameters, it will be a multi-purpose rare events observatory for multi-messenger astrophysics and proton decay search with high discovery potential.

French physicists with a great expertise in this physics, thanks to their involvements in the T2K and SK experiments, are proposing several hardware contributions to the far detector construction and computing efforts. These contributions exploit the great expertise and the tight collaboration established between the French groups.

With this document we ask the IN2P3 Scientific Council to evaluate the physics case of the Hyper-Kamiokande project and the feasibility of the contributions to the experiment proposed by the IN2P3 groups. An approval of the IN2P3 Scientific Council, followed by the recognition of HK as one of the IN2P3 master projects, will reinforce our proposed contributions and allow IN2P3 groups to take important roles and responsibilities in the construction and operation of HK, followed by exciting physics analysis and results. Moreover, it will allow other IN2P3 groups to join and contribute to this important project which will certainly be the world-leading experiment in many different areas of modern physics for the next 20 years.

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