The Hyper-K Underwater Electronics Assembly project

-

Letter of Intent

ETH Zurich, Institute for Particle physics and Astrophysics, Zurich, Switzerland

L. Botao, T. Dieminger, M. Franks, A. Gendotti, U. Kose, A. Rubbia, D. Sgalaberna, X. Zhao, J. Wüthrich

Kamioka Observatory, Institute for Cosmic Ray Research (ICRR), U. of Tokyo, Japan

C. Bronner, Y. Hayato, K. Hiraide, K. Ieki, Y. Kataoka, Y. Noguchi, M. Shiozawa, Y. Takemoto

INFN Sezione di Bari, Bari, Italy

E. Radicioni

INFN Sezione di Napoli and Università Federico II di Napoli, Napoli, Italy

A. Boiano, G. De Rosa, A. Di Nitto, A. Langella, L. Lavitola, G. Ricciardi, G. Tortone

INFN Sezione di Padova and Università di Padova, Padova, Italy

G. Bortolato, G. Collazuol, D. D'Ago, M. Feltre, S. Levorato, A. Longhin, M. Mattiazzi, M. Pari, F. Pupilli

INFN Sezione di Pisa and Università di Pisa, Pisa, Italy

G. Lamanna, L. Morescalchi, J. Pinzino, M. Sozzi

INFN Sezione di Roma and Università di Roma La Sapienza, Roma, Italy

F. Ameli, L. Ludovici, M. Rescigno

CERN-SPSC-2023-021 / SPSC-I-260
16/08/2023

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France

S. Bolognesi, D. Calvet, T. Daret, S. Emery, E.M. Gonzalez, S. Hassani, S. Joshi, G. Vasseur

Jagiellonian University, Krakow, Poland

K. Ziętara

King's College of London, London, United Kingdom

F. Di Lodovico, S. Hayashida, K. Hayrapetyan, J. Migenda

Laboratoire de Physique Nucléaire et de Hautes Energies (LPNHE), Sorbonne Université, IN2P3-CNRS, Paris, France

J. Dumarchez, G. Diaz Lopez, C. Giganti, M. Guigue, B. Popov, S. Russo, W. Saenz-Arevalo, M. Zito

Laboratoire Leprince-Ringuet (LLR), Ecole Polytechnique, IN2P3-CNRS, Palaiseau, France

L. Bernardi, O. Drapier, M. Buizza-Avanzini, F. Magniette, T. Mueller, P. Paganini, B. Quilain

Lancaster University, Lancaster, United Kingdom

T. Dealtry, L. Kormos, H.M. O'Keeffe

Nicolaus Copernicus Astronomical Centre of the Polish Academy of Sciences, Poland

M. Suchenek, M. Ziembicki

Università di Salerno and INFN Gruppo Collegato di Salerno, Fisciano, Italy

C. Bozza, L. Fusco

Universitat Politècnica de València, Valencia, Spain

F. Ballester Merelo, R. Esteve Bosch, A. Gómez Gambín, V. Herrero Bosch, F.J. Mora Mas, J.F. Toledo Alarcón

University of Geneva, Geneva, Switzerland

F. Sánchez

University of Glasgow, Glasgow, United Kingdom

V.G.C. Lam, R.P. Litchfield, L.N. Machado, V. Mikola, S. Naik, D. Riley, F.J.P. Soler

University of Silesia, Katowice, Poland

A. Bubak, J. Holeczek, J. Kisiel

University of Tokyo, Tokyo, Japan

M. Yokoyama

University of Warwick, Warwick, United Kingdom

M. O'Flaherty, B. Richards

Warsaw University of Technology, Warsaw, Poland

A. Buchowicz, K. Dygnarowicz, G. Galiński, R. Kurjata, J. Marzec, W. Obrębski, G. Pastuszak, A. Rychter, K. Zaremba

Yerevan Institute for Theoretical Physics and Modeling, Yerevan, Armenia

A. Ioannisian

August 16, 2023

Contacts: `davide.sgalaberna@cern.ch`, `marcin.ziembicki@pw.edu.pl`

Contents

1 Executive summary

Starting in 2027, the Hyper-Kamiokande experiment in Japan will search for leptonic CP violation in long-baseline accelerator neutrino oscillations with a realistic potential of discovery within 3 to 10 years from the start of the data taking depending on the value of the CP violating phase, to be measured with a resolution better than 23°. The neutrino mass ordering will be determined with a significance better than four standard deviations by combining data from accelerator and atmospheric neutrinos. Beyond the physics of neutrino oscillations, Hyper-Kamiokande will achieve unprecedented sensitivities to the detection of proton decays and supernova burst and relic neutrinos and will look for other types of astrophysical neutrinos, indirect evidence of dark matter and sterile neutrinos.

A key contribution is given by European institutes, in particular to the far detector underwater electronics system, that will allow to operate about 23,600 PMTs of the Hyper-Kamiokande water Cherenkov far detector, of which 20,000 20-inch PMTs of the inner detector and 3,600 3-inch PMTs of the outer detector. About 900 electronics units will be installed underwater. Each one comprises two boards for the PMT signal digitization, a data processing board, a high-voltage and a low-voltage module, all contained inside a stainless steel water tight vessel.

In this Letter of Intent, we propose the SPSC to host at CERN under the program of the Neutrino Platform a new project focused on the assembly, testing and shipment to Japan of the 900 underwater electronics units. Such project is a common effort lead by the European institutes involved in Hyper-Kamiokande, that would have easy access to the experimental facilities at CERN. After a preparatory phase, the project will become fully operational at the beginning of 2025 for a duration of about 1.5 years. Space for the storage of the sub-system components, assembled units and for the test and assembly activities will be needed as well as technical expertise (mechanical engineer and technicians) and support for the shipment to Japan. The project will be fully funded by the Hyper-Kamiokande collaboration, including the technical personnel. CERN and the Neutrino Platform have been identified as the ideal framework to carry out such project. Full support has been expressed by the leaders of the Neutrino Platform.

2 Introduction and Physics Case

Neutrino oscillations were discovered at the Super-Kamiokande (Super-K) experiment in Japan in 1998 with atmospheric neutrinos [1]. **The existence of neutrino oscillations implies that at least two out of three neutrinos have non-vanishing masses**, which is evidence of physics beyond the Standard Model of particles. A few years later, the first hint of this phenomenon with solar neutrinos was found by combining the Super-K and the Sudbury Neutrino Observatory (SNO) experiment data [2], and confirmed by the SNO experiment [3]. Then, neutrino oscillations have been measured at KamLAND with reactor anti-neutrinos [4] and, finally, at K2K, the first neutrino accelerator experiment in Japan [5].

The field steadily advanced in the last twenty-five years, getting very close to the completion of the 3-flavor neutrino oscillation framework, described by the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) mixing matrix [6], lastly with the measurement of a non-zero θ_{13} angle by T2K [7, 8, 9] and Daya-Bay [10], as well as the precise measurement of the neutrino eigenstate mass squared difference, Δm^2_{32} and Δm^2_{21}. There remain only two undefined parameters: the neutrino mass ordering (MO), i.e. the sign of the neutrino mass splitting Δm^2_{32}, that could be measured with a precision better than three standard deviations by different experiments, including NOvA [11], currently running, and JUNO [12], under construction, and, in the future, with a significance better than five standard deviations by the DUNE experiment [13]; the leptonic CP violating phase (δ_{CP}) that, if different from 0 and 180°, would make the appearance oscillation probability different for neutrinos ($\nu_\mu \to \nu_e$) and antineutrinos ($\bar{\nu}_\mu \to \bar{\nu}_e$), hence, the laws of physics different between particles and antiparticles. While the determination of the MO is a very important input for the understanding of the nature of the neutrino mass, either Dirac or Majorana [6], CP violation is a necessary ingredient for the understanding of the large imbalance between matter and antimatter in the Universe. The precise measurement of δ_{CP} becomes even more important if one considers that the CP asymmetry in the quark sector is too small to generate such imbalance. Moreover, the fact that the measured value of neutrino mixing angle θ_{13} is relatively large has opened the door to the possible existence of a large leptonic CP asymmetry, that may have initiated a process, called leptogenesis [14], potentially responsible for the matter-antimatter imbalance generated after the Big Bang.

At the forefront in the field is the neutrino physics program in Japan, currently active with the Super-Kamiokande (Super-K) and Tokai-to-Kamioka (T2K) experiments. Solar, atmospheric and supernova neutrino studies are conducted with Super-K as well as proton decay searches. Recently, Super-K was upgraded by loading water with gadolinium (Gd) to improve the sensitivity to the supernova relic neutrinos. At T2K, searches for CP violation in neutrino oscillations are performed by relying on the precise measurement of the $\nu_\mu \to \nu_e$ and $\bar{\nu}_\mu \to \bar{\nu}_e$ transitions, to find the evidence for a difference in the respective oscillation probabilities. It consists of measuring the number of ν_e ($\bar{\nu}_e$) interactions as a function of the neutrino energy where the maximum of the oscillation probability occurs, far away from where neutrinos are produced, and comparing it with the one predicted before neutrinos have oscillated. T2K deploys a "near detector" (ND), a few hundred meters away from the neutrino production point, and Super-Kamiokande as "far detector" (FD), 295 km away. Whilst the ND allows constraining the systematic uncertainties related to the neutrino cross-section and flux, the role of the FD is to collect a large amount of neutrino interactions to measure the oscillation probability with low statistical uncertainties. T2K has recently reported the first indication of CP violation in the neutrino sector [15, 16] and is currently leading the field, with a projected sensitivity to CP violation up to three standard deviations by 2027.

The staged Japanese program ensures high quality physics results in the short term with the upgraded T2K (beam and ND) and the upgraded Super-K (Super-K Gd) and, in the medium/long term, with the upcoming Hyper-Kamiokande (Hyper-K) experiment [17, 18]. Hyper-K will adopt the same concept as a combination of T2K and Super-K. The higher intensity neutrino beam (up to 1.3 MW) and the 258 kton far detector, with a eight times larger fiducial mass than Super-K, will provide a **realistic potential of discovering the leptonic CP violation (CPV) in a few to ten years after the start of the accelerator neutrino data taking** and measuring $\delta_{\rm CP}$ with a resolution of $7-23°$ depending on its value. Moreover, by combining data from accelerator and atmospheric neutrinos, **the MO can be determined with a significance better than four standard deviations**.

Beyond accelerator physics, Hyper-K will have the world-leading sensitivity for several of the proton decay modes, which may bring to the experimental proof of the Grand-Unified Theory (GUT).

On the global level, Hyper-K has been approved by the Japan's Ministry of Education, Culture, Sports, Science and Technology (MEXT) in 2020. The CERN European Strategy for Particle Physics 2020 (ESPP) has classified the long baseline neutrino program as one of the major scientific objectives. For instance, the CERN Neutrino Platform is involved in the neutrino Japanese program in the T2K experiment with the upgrade of its magnetised near detector (ND280). The project NP07 was approved by the CERN SPSC to provide technical support, logistic and direct contributions important for the realisation of the novel plastic scintillator based neutrino active target (SuperFGD) and the two time projection chambers (TPC) [19]. The NP07 project is ongoing and close to be completed.

In this Letter of Intent (LoI), the Hyper-K collaboration proposes to the SPSC a new project to be hosted at CERN under the Neutrino Platform program. The goal is the realisation of the Hyper-K FD to start collecting accelerator neutrino data in 2027 Japanese Fiscal Year (JFY). In particular, the project will focus on the validation, testing, assembly and shipment to the experimental site in Japan of about 900 underwater electronics units that will allow the operation of approximately 23,600 photomultiplier tubes (PMTs).

2.1 The Hyper-Kamiokande experiment

In order to definitively discover CPV, Hyper-K will use the same 295 km baseline as T2K but will have a larger FD fiducial mass and a higher neutrino beam intensity.

A major upgrade of the J-PARC proton accelerator, just completed, will allow to constantly increase the neutrino beam intensity year after year, reaching 1.2 MW in 2027 and a maximum power of 1.3 MW in 2028, higher by more than a factor two with respect to before the upgrade.

The higher beam intensity will be accompanied by a new water-Cherenkov far detector of 258 kton, whose fiducial mass will be more than eight times larger than the Super-K one, making it the largest water pool under the ground ever built in the world. The FD is a 68 m diameter and 71 m high cylindrical-shape water tank detector filled with 258,000 metric tons of ultrapure water, currently in preparation at the Kamioka facility in Japan. The Cherenkov light is read out by photomultiplier tubes (PMT). The detector is divided into two optically-separated parts: the "Inner Detector" (ID) instrumented with about 20,000 20-inch PMTs, as the main active volume which provides the time of the reconstructed neutrino interaction vertex, the energy loss by charged particles, and their momentum. It will be surrounded by the Cherenkov "Outer Detector" (OD), the external shell of the water tank instrumented with 3,600 outward looking 3-inch PMTs, and act as a veto against incoming particles, like cosmic rays.

The ID will have a more performing photodetection system compared to Super-K. It will comprise two types of photosensors: 20-inch diameter PMTs and multi-PMTs. About 20,000 20-inch PMTs, with the same size as the Super-K one but a two times higher photodetection efficiency (PDE), will cover about 20% of detector surface. The 1.5 ns time resolution, a factor two better than the one of the Super-K PMT, and a comparable dark count rate (4 kHz) will provide an improved reconstruction of the neutrino interaction event from the detected Cherenkov radiation [20]. In the ID there will be also 800 multi-PMTs, which are composite sensors composed of nineteen 3-inch PMTs. Compared to the 20-inch PMTs, they will profit from a finer granularity, hence a more precise reconstruction of the particle direction as well as an even lower time resolution (1.3 ns). Being complementary to the 20-inch PMT, the multi-PMT will also allow to reduce the detector systematic uncertainties. The OD will surround the ID and will consist of approximately 3,600 3-inch diameter PMTs coupled with wavelength shifting plates to increase the total light yield. A simulation of a muon and an electron in the Hyper-K FD is shown in Fig. 1.

Despite the much bigger volume and mass, the reconstruction performance for high energy events at Hyper-K exceeds that of Super-K. This can be understood as a combination of higher light collection by the photosensors and better timing resolution from the larger number of photosensors. Compared to Super-K, the momentum resolution for electrons improves by 30% to 50% and for muons by 50%. The muon and electron classification is comparable between Hyper-K and Super-K. The direction and the position resolution is comparable to that of Super-K while significant improvements are seen in the particle identification of

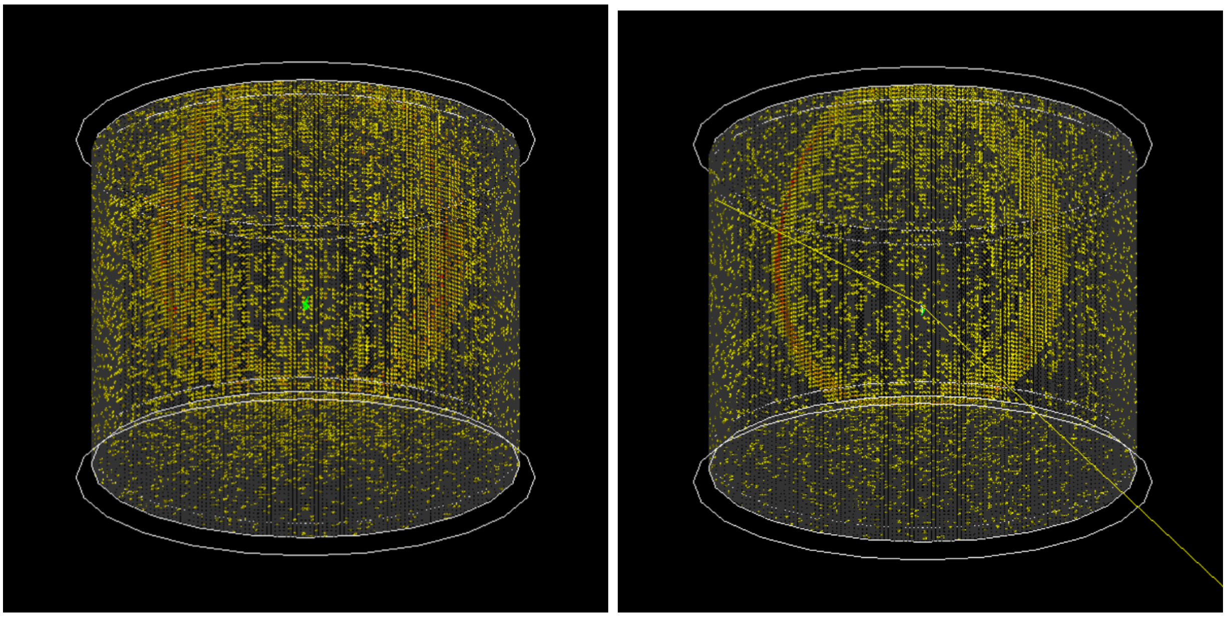

Figure 1: Simulated Cherenkov light detected from a 1 GeV electron (left) and muon (right) propagating in the Hyper-K far detector and detected by the ID PMTs.

neutral pion events, a critical background that could lead to the misidentification of these events as ν_e or $\bar{\nu}_e$.

Hyper-K will use the upgraded neutrino beam facility at J-PARC, currently serving T2K, and the ND complex at 280 m [1] from the beam target, which includes the magnetised ND (ND280), the neutrino beam monitor (INGRID) and the water-based WAGASCI detector system, ready in day 1. Moreover, an Intermediate Water Cherenkov Detector (IWCD), positioned at about 900 m from the neutrino production target will be built. It will span the neutrino beam at different off-axis angles using the "PRISM" technique [21].

The Water Cherenkov Test Experiment (WCTE) has been approved by the CERN SPSC and will take place in 2024 [22] with a prototype that will adopt the same water Cherenkov detection technology as IWCD. With a large overlap with the Hyper-K collaboration, its goal is to provide a platform to develop the percent level calibration techniques with particle fluxes of known type and kinematic properties as well as to probe important physics processes for the understanding of final state signatures, such as the production of high energy delta rays that produce Cherenkov light, the scattering and absorption of pions in the detector, and the secondary production of neutrons in the detector.

As shown in Fig. 2, the Hyper-K experiment will be able to achieve an unprecedented sensitivity to CPV. Both the high-intensity beam and the massive FD will allow to drastically increase the number of neutrino interactions compared to T2K and **precisely measure the CP violating phase (δ_{CP}) and will be able to exclude the hypothesis of CP conservation** ($\sin\delta_{CP} = 0$) for $\sim 60\%$ of possible true values of δ_{CP} at five standard deviations and $\sim 80\%$ at three standard deviations after 5 years of data taking. **After less than three years of data taking it will be possible to discover CPV if $\delta_{\mathbf{CP}} = -\pi/2$**. Instead, in

[1]The details of the handover of the ND complex at 280m from T2K to Hyper-K are currently under discussion.

the case of $\delta_{\rm CP} = -\pi/4$, such discovery will be achieved with three more years of data, as shown in Fig. 3. Overall, $\delta_{\rm CP}$ will be measured with a resolution better than 23° for any possible true value.

It is worth noting that, mostly thanks to the increased detection rate of the atmospheric neutrinos, also the MO can be determined with a significance between four and six standard deviations (depending on the true value of $\sin^2\theta_{23}$) by combining neutrino accelerator and atmospheric data, as shown in Fig. 3. After six years of data taking a significance of four standard deviations could be already achieved. Moreover, Hyper-K will improve the resolution of the atmospheric parameters, $\sin^2\theta_{23}$ and $|\Delta m^2_{32}|$, of the neutrino oscillation probability, respectively with a resolution as good as 0.015, depending on the actual value of the angle, and 1×10^{-5} eV^2.

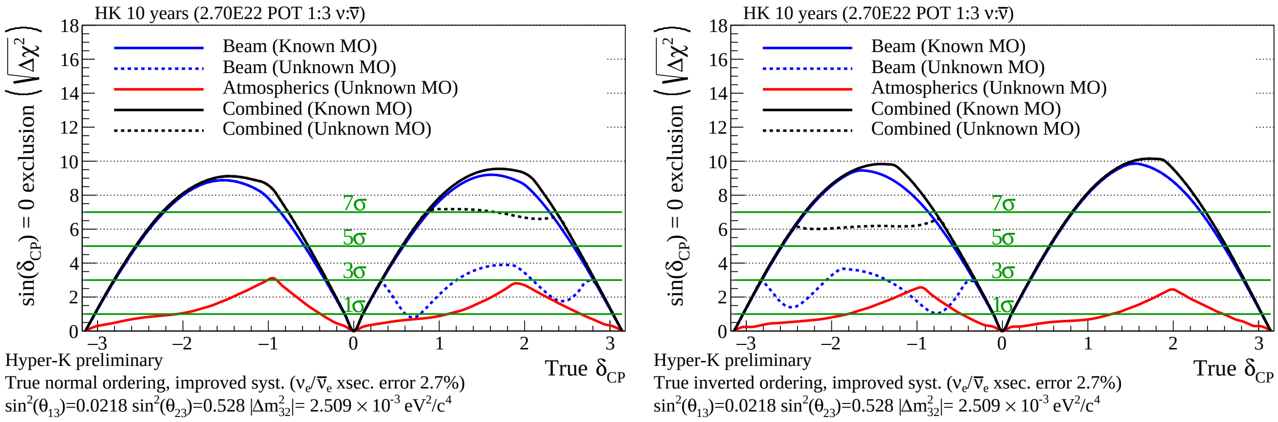

Figure 2: Left: Hyper-K sensitivity to exclude CP conservation as a function of the true value of δ_{CP} for 10 years data taking and true normal (left) and inverted (right) MO. The sensitivity is shown for neutrino accelerator (blue), atmospheric (red) and combined (black) data with both a known (solid line) and unknown (dashed line) MO. In case of unknown MO, the atmospheric sample allows to resolve the degeneracy between δ_{CP} and MO and achieve the 5 standard deviation sensitivity for the full range of δ_{CP}.

Hyper-K has a rich physics program beside its long baseline measurements [18]. Proton decay is a major physics target at Hyper-K, with the projected sensitivities surpassing limits from Super-K by approximately one order of magnitude for many decay modes. Hyper-K's increased fiducial mass and improved detection capabilities (as discussed above) will enable it to reach these limits both by accumulating larger exposures while suppressing atmospheric neutrino backgrounds.

If the proton decays into a positron and a neutral pion, as predicted by many GUT models, this process will be observed with more than 3σ significance if the proton lifetime is 10^{35} years or less. For GUTs incorporating SUSY, the favored decay into a neutrino and a positive kaon can be observed at the same level if the proton lifetime is 3×10^{34} years for the decay mode to a neutrino and a Kaon. It should be noted that various models predict many other possible decay modes. Hyper-K will have unprecedented sensitivity to these as well, enabling the discovery of multiple decay channels and possible determination of the underlying GUT symmetry.

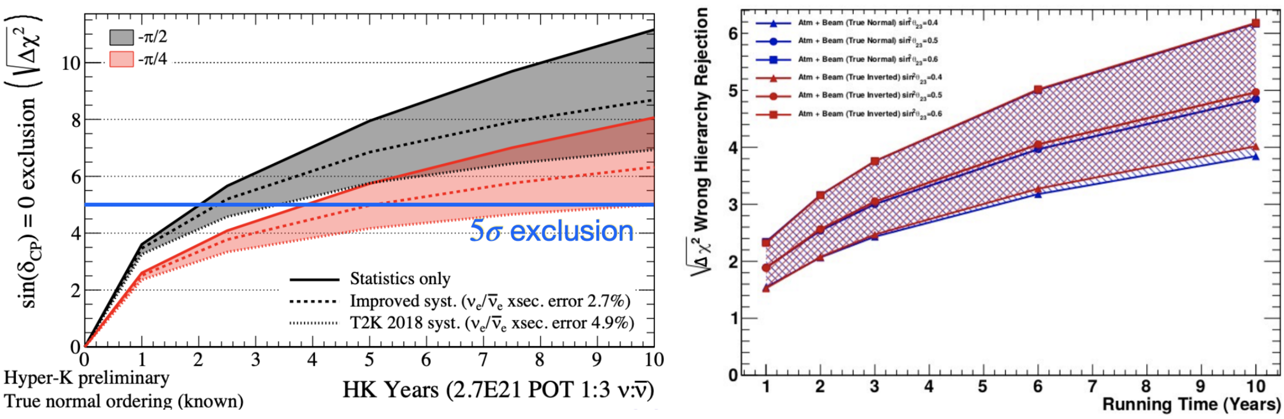

Figure 3: Left: Hyper-K sensitivity to exclude CP conservation for the case of true normal ordering as a function of running time assuming two different true values of $\delta_{\rm CP} = -\pi/2$, $-\pi/4$ and different systematic uncertainty scenarios (T2K uncertainty in 2018, improved, only statistical) given known MO. Right: Hyper-K sensitivity to MO as a function of running time for different true values of $\sin^2\theta_{23}$ and for the case of both true normal (blue) and inverted (red) ordering [23]. It is obtained by combining accelerator and atmospheric neutrino data.

Further, Hyper-K has the potential to achieve new discoveries with observations of astrophysical neutrinos, such as solar and supernova neutrinos, and will play an important role in multi-messenger astronomy at lower energies relative to the IceCube experiment. For example, Hyper-K's measurement of solar neutrino oscillations will probe matter effects in the Sun, confirming the upturn in the electron neutrino survival probability at a few MeV predicted by the standard PMNS oscillation scenario or identifying a spectral distortion consistent with exotic scenarios such as non-standard interactions. Due to its size, Hyper-K will have unprecedented sensitivity to a galactic supernova neutrino burst and expects to record about 75,000 inverse beta decay events and 3,500 neutrino-electron elastic scattering events for a core-collapse supernova at a distance of 10 kpc. With such high statistics the time variation of the neutrino event rate and energy spectrum can be determined precisely, allowing for powerful model discrimination [24]. Similarly, the elastic scattering measurement will allow Hyper-K to measure the direction to the supernova with an accuracy close to one degree. Observation of the as-yet unmeasured diffuse supernova neutrino background (supernova relic neutrinos) at more than 4σ is also expected. As the flux of this diffuse supernova neutrino background depends on the frequency of supernova bursts in the early universe, Hyper-K's observation will provide valuable information to constrain related processes and their corresponding models. Finally, Hyper-K's size and detection sensitivity will enable it to study other astrophysical neutrinos, dark matter annihilation in the sun, Earth, and galactic center, as well as to search for other types of exotic particles.

The ambitious physics program of Hyper-K is supported by a well-defined roadmap and the realistic scenario for a potential discovery of leptonic CP violation within the next years. The Hyper-K experiment will start collecting physics data in JFY 2027. The overall project schedule is shown in Fig. 4. **The cavern excavation has started and the access tunnel has been completed in February 2022. The excavation of the dome has also started and its diameter has already exceeded the Super-K one, as shown in Fig. 5.** It will be completed by JFY 2024, when the tank construction and, later, the detector installation will start. In parallel, the PMT production has started and their installation will be completed by JFY 2026, together with the related electronics and mechanical equipment. The water filling step and the detector commissioning will take place over JFY 2026, before the start of the operation. **The Hyper-K experiment will start collecting data for physics oscillation measurements in JFY 2027 with the full configuration, i.e. both the ND and the FD fully operative, with the potential of CPV discovery a few years after the start of data taking.** As of 2023, the Hyper-K collaboration includes 21 countries, 101 institutes and about 560 people from all around the world.

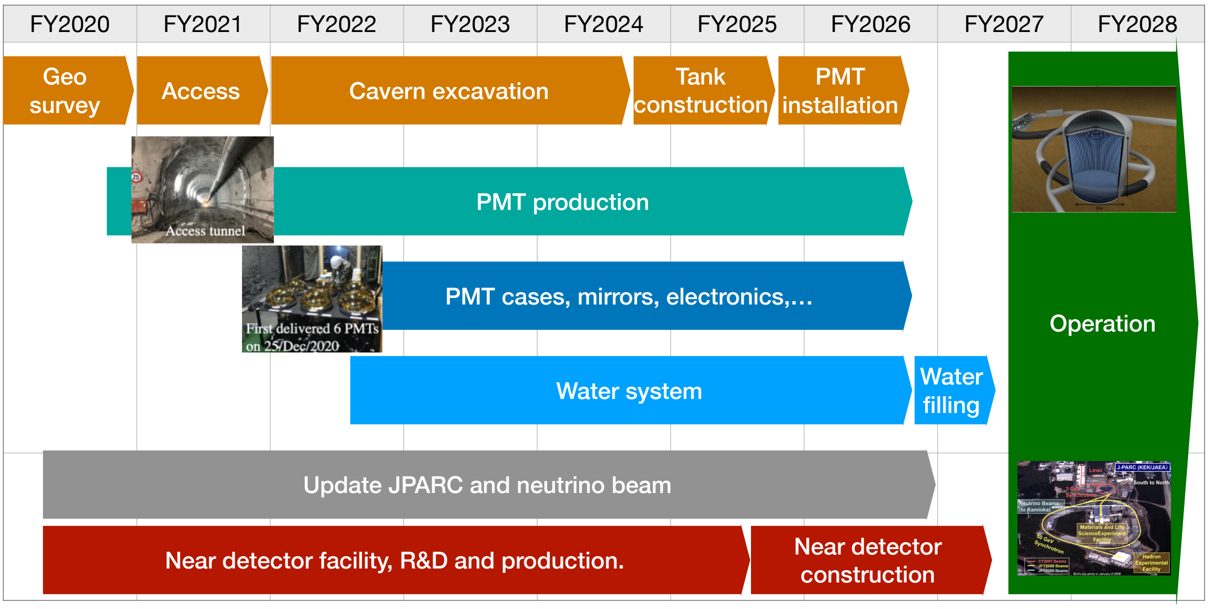

Figure 4: Hyper-K overall schedule in JFY towards the operation in 2027 [25].

3 The PMTs and the underwater electronics units

The integration of the PMTs inside the Hyper-K FD is shown in Fig. 6. The PMTs will detect the Cherenkov light produced by the charged particles propagating in the ultra-pure water inside the tank. The PMTs will be fixed to a mechanical frame and will surround the full water volume.

Three types of PMTs, which differ in size and granularity, will be used in Hyper-K: 20-inch Hamamatsu PMTs for the ID, 3-inch Hamamatsu PMTs for the multi-PMTs (mPMTs) of the ID, and 3-inch Hamamatsu or NNVT PMTs, but both satisfying the same criteria, for the OD. The 20-inch and the 3-inch PMTs are shown in Fig. 7 while the characteristics of both PMTs are shown in Tab. 1. For simplicity only the 3-inch

Figure 5: The status of the cavern excavation as of June 2023 is shown, the access tunnel (left) and top part of the dome (right) that will host the Hyper-K water tank.

Hamamatsu PMT for the OD is shown. Compared to the Super-K one, the Hyper-K 20-inch PMTs will profit of a better timing resolution for vertex reconstruction (1.5 ns), a charge resolution (30.8%), and a photodetection efficiency (PDE) all higher by a factor two. About 20,000 20-inch PMTs will provide a photocoverage of the ID of about 20%, lower by a factor two compared to Super-K, whilst maintaining an overall better performance. 3,600 3-inch PMTs will be used for the OD. In order to enhance the overall light yield, they will be mounted on wavelength shifting plates that, thanks to high-reflectivity Tyvek, will maximize the amount of light at the PMTs.

	Hamamatsu R12860-HQE	**Hamamatsu R14374**
Photocathode diameter	20 inches	3 inches
Sensitive wavelength range	300–650 nm	300–650 nm
Peak sensitive wavelength	420 nm	420 nm
Gain	10^7 at $\sim$ 2000V	5×10^6
Dark pulse rate	6 kHz at 10^7 gain	$<$ 1.5 kHz
Operational temperature	5–35 °C	-10 to 50 °C
HV resistance	5.9 MΩ	10.7 MΩ
HV range	0-2600 V	0-1500 V

Table 1: Characteristics of the Hyper-K PMTs.

The multi-PMTs are a particular configuration that replaces a single big PMT with different smaller ones. These multi-PMTs show different features in the output charge signal, hence the design and configuration of the readout electronics and related components are quite different from those of 20-inch and 3-inch PMTs. As a consequence, the multi-PMT electronics system uses a different scheme for the signal digitization and

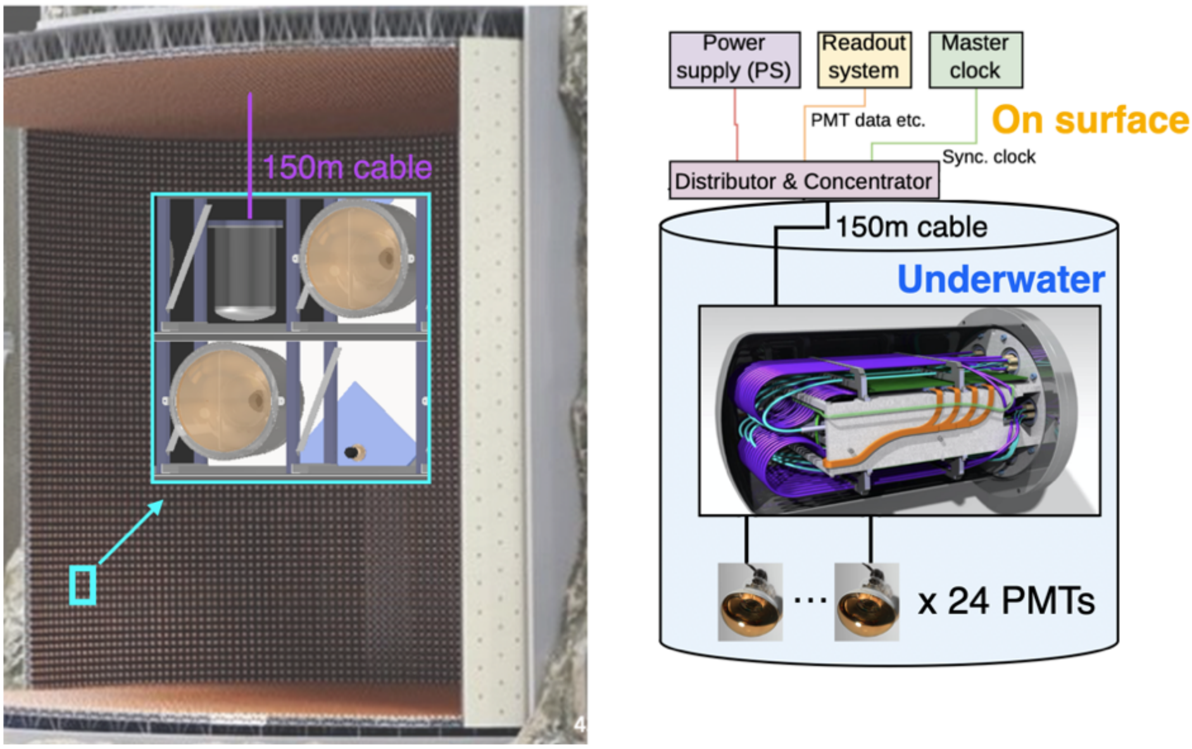

Figure 6: Left: inner view of the Hyper-K ID. A zoomed view on two 20-inch PMTs installed on the mechanical frame together with an underwater unit is shown. Right: CAD design of the underwater electronics unit and block diagram of the FD electronics from PMTs to the DAQ system.

the data transfer to the DAQ system, thus it does not use the electronics units to be assembled at CERN. The mPMTs assembly is not part of this LoI and it will be realized in dedicated infrastructures set up by the institutes involved in the mPMTs project.

Overall, around 900 underwater electronics units (including spares) will operate the ID and OD PMTs. There will be two variants of these units, one handling only the 20-inch PMTs (so called "pure-ID" type) and the other handling both 20-inch PMTs and 3-inch PMTs (the "hybrid ID+OD" type).

In the pure-ID type, twenty-four different 20-inch PMTs are connected via $\sim$ 20 meter long cables to the corresponding electronics unit, also placed underwater. A single underwater electronics unit provides high voltage to the PMT bases, independently digitizes the analogue signal of each PMT and sends it to the out-of-water Data Acquisition System via optical cables of lengths up to $\sim$ 150 meters. This configuration will allow to have a short distance between the front-end electronics and PMTs. The main advantages are the lower signal attenuation and suppression of electromagnetic interference pickup. Moreover, thanks to reduced cable length (thus lower weight), the PMT and electronics support structure would be simpler, thus allowing for cost savings. On the other hand, this implies that the front-end electronics, Low Voltage (LV) and High Voltage (HV) power supplies will not be accessible during the filling of the detector tank, which takes about 6 months, as well as during the operation, once the FD tank will be filled with water. Hence, long-term reliability of these components is essential for collecting high-quality data. The requirement is that the number of dead acquisition channels after ten years of detector running will not exceed the 10% of the total number of channels. Since the unit is underwater and exposed to high pressure, all the components will be placed inside a stainless steel water-tight vessel. In total, about 560 pure-ID underwater electronics units will operate the 20-inch PMTs of the ID.

The hybrid ID+OD unit is very similar to the pure-ID one described above but will operate twenty 20-inch PMTs as well as twelve 3-inch PMTs. A few additional circuit boards as well as small differences in the design related to the PMT signal digitizer board and their integration in the mechanical vessel are needed. More details can be found respectively in Sec. 3.1.1 and Sec. 3.1.6. In total about 320 hybrid units will operate a fraction of the ID 20-inch PMTs and all the OD 3-inch PMTs.

This Letter of Intent proposes to assemble at CERN the underwater electronics units that belong to the 20-inch ID and 3-inch OD PMTs.

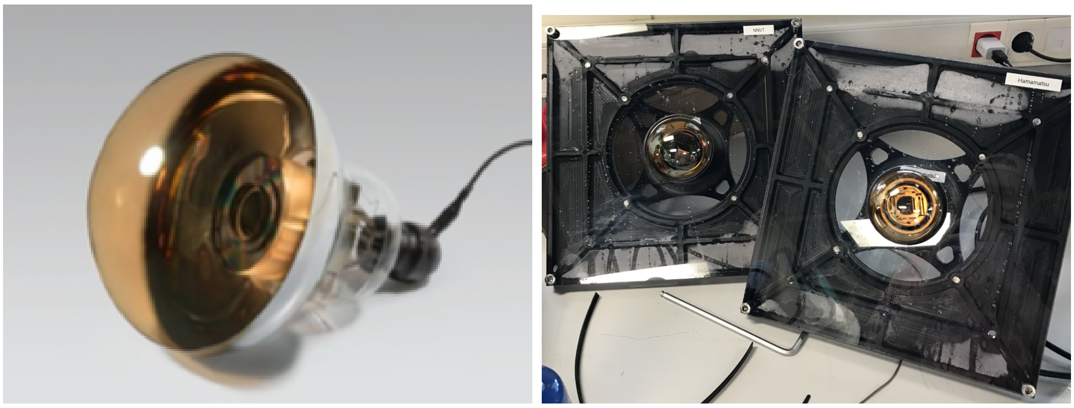

Figure 7: Left: 20-inch PMT of the ID. Right: 3-inch PMT of the OD right after tests in water.

3.1 The electronics underwater unit

The underwater electronics unit contains those components that stay underwater near the PMTs to provide them the High Voltage (HV), the Low Voltage (LV), and digitize their signals to provide time and charge estimates, that are subsequently transmitted to the on-surface data acquisition system via O(100 m) optical cable.

The CAD design of an underwater unit is shown in Fig. 6. Its block diagram is shown in Fig. 8. It comprises the two PMT signal digitizer boards, the HV power supply, the LV power supply and regulator, the slow monitor and control, the synchronization system. All the components are embedded inside a stainless steel water-tight vessel. Each vessel serves twenty-four 20-inch PMTs or twenty 20-inch PMTs plus twelve 3-inch PMTs. The PMT cables enter the underwater unit through six feedthroughs (PMT FTs). Each feedthrough for 20-inch PMT hosts four PMT cables, each of which conceals two coaxial cables, one for signal and the other for HV. The feedthrough for 3-inch PMT hosts 12 coaxial cables, each of which carries both HV and signal.

A central "communication" feedthrough (COM FT) hosts two copper cables with a length up to about 150 m that brings from on-surface the +48 V / ∼2A power and return to the LV power supply board inside the vessel, which then provides power to the other underwater components, and twelve optical fibers to send the PMT digitized signals to the on-surface DAQ system and the reference clock along with intertwined data transmission for timing-sensitive (deterministic) control signals.

Three 12 V outputs with various currents (from 1 to 2 A) are provided to the two digitizers and one data processing board (DPB). A 48 V output is sent to the 24-channel HV power supply board. Then the HV is supplied to the 24 ID PMTs, up to 2.6 kV voltage output at 0.5 mA with voltage setting resolution $< 0.2\%$. The same HV board is used to feed the OD PMTs, which operate in the range of 900 V to 1500 V.

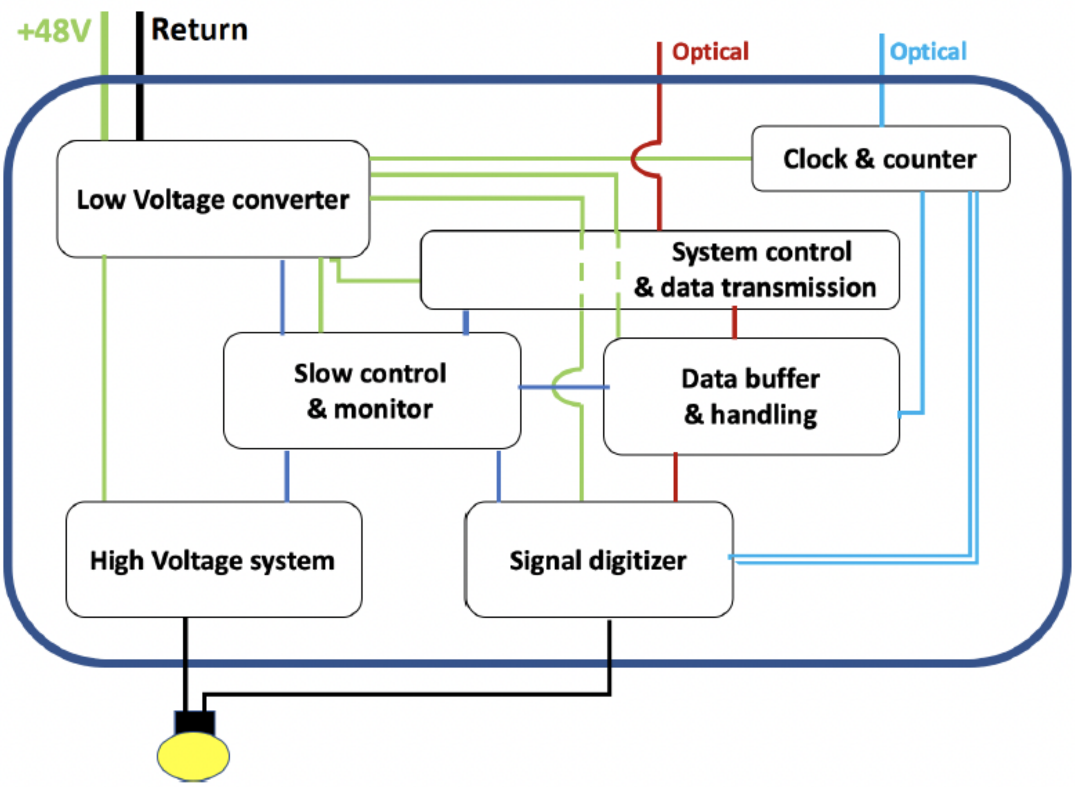

Figure 8: Block diagram of the underwater unit electronics.

This LoI is focused on the test and the assembly of the underwater units for the ID and OD parts of the FD. In the next sections a more detailed description of each unit syb-system component is given.

3.1.1 The digitizer

The signal digitizer block accepts PMT analog input signals and outputs the digitized timing and charge values. This implies that each channel of the digitizer must be equipped with a discriminator or has an equivalent mechanism. In order to have a sufficiently high efficiency to record 1 photoelectron (pe) level signal, the threshold level is required to be set at $\sim 1/6$ pe. Since the expected number of pe could exceed 1,000, the electronics is required to have at least a dynamic range up to 1,250 pe and a linearity of the measured charge better than 1 % from 1 pe to 1,250 pe. Furthermore, the charge resolution is required to be better than 0.5 pe (RMS) for signals below 25 pe. Accuracy of the timing is critical in reconstructing the vertex. The least significant bit (LSB) of the timing is required to be smaller than 0.5 ns and to have a resolution better than 0.3 ns for 1 pe and 0.2 ns above 5 pe. All the channels have to be synchronized and the relative difference has to be stable within 0.1 ns.

The basic idea is the implementation of the analog front-end using discrete integrated circuits (IC). The block diagram of the circuit of a single digitization channel is shown in Fig. 9. The circuit is divided into 3 sections: the *input receiver*, the *timing* path implemented by a fast discriminator which provides a fast signal that marks the beginning of the hit, and the *integration* path, which converts the charge of the hit to a voltage level, that is then sampled by an ADC.

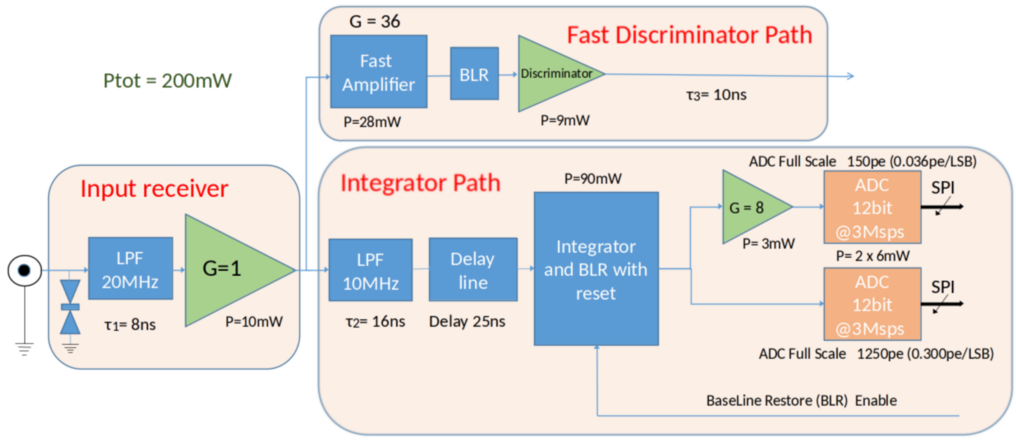

Figure 9: Front End circuit block diagram. The three main blocks are highlighted: the input receiver, the timing path, and the integration path.

The input signal is AC coupled to the circuit by a capacitor which allows to adapt the baseline to the requirements of the power supply of the circuit. A buffer is used to achieve wideband impedance matching and to feed both the fast discriminator path and the integrator path without affecting the input signal itself. To protect the input circuit from Electro-Static-Discharges (ESD) and over-voltages, there are 4 precautions: firstly, there is a *Gas Discharge Tube* to protect the receiver from HV spark coming from the PMT; then there is a *Transient Voltage Suppressor* (TVS) and a clamping diode. Last, but not least, the 100 Ohm series resistors help limiting the input current fed to the clamping diode and the TVS.

The discriminator path consists of an amplifier with such a high gain (G ∼36) that the amplifier itself is promptly saturated and its response is fast and repetitive. Such amplification is obtained with a BJT transistor followed by an operational amplifier. The threshold can be set by a suitable DAC not shown in the block diagram. A traditional baseline restorer circuit prevents baseline shifts resulting from AC coupling, PMT pulse overshoots and signal rate variations. A time walk effect is observed in the discriminator output, especially for low amplitude signals, with an approximate inverse dependence on hit amplitude. Such effect will be minimized using the information of the measured charge, after a careful calibration of the circuit.

The integrator is the other fundamental block in the acquisition chain, since the charge resolution depends on it. To stabilize the integrator baseline value, a feedback system will constraint the voltage value on the input of the circuit at a predetermined value, that in our case was set at 200 mV. During the integration phase, which is triggered by the discriminator in the timing path, the feedback loop is opened by the *BLR_Enable* logic signal shown in Fig. 9. The *BLR_Enable* signal, which enables the integration of the input signal, is generated by the FPGA using combinatorial logic, in order to reduce as much as possible the time to open the BLR feedback loop. To compensate this delay, which sums up to ∼15 ns, a delay line of 25 ns is included in the integrator block.

After a programmable amount of time, the FPGA generates the *convert* signal for the ADC to freeze the integrated value and start the acquisition. After issuing the conversion signal, the FPGA logic can reset the integrator, closing again the feedback loop on the Baseline Restore circuit.

Due to the huge dynamic range and the very high resolution required on the charge digitization, two gain paths with two ADCs are used. The gain ratio of the two signal paths is about 8; for each event signals from both low- and high-gain paths are acquired and stored; later on it is possible to choose in the FPGA logic the most suitable value between the two. Each ADC has a maximum sampling frequency of 3 MHz and a resolution of 12 bit, with a power dissipation of 6.5 mW.

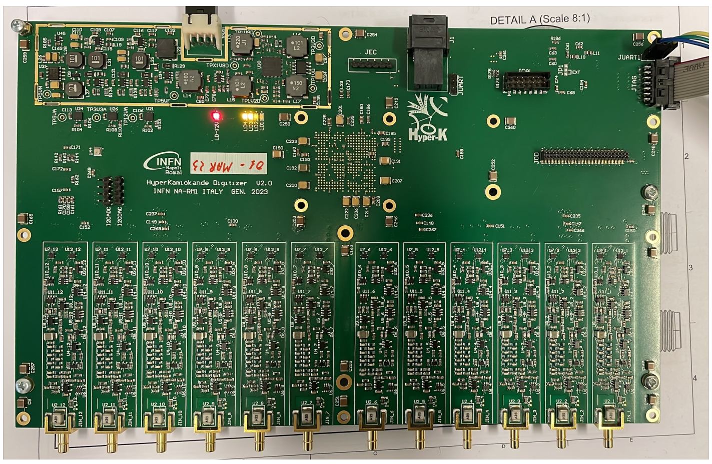

Figure 10: Picture of ID digitizer first prototype board.

The digitizer board is shown in Fig. 10: there are the 12 input channels to take data from PMTs, the power section, the FPGA to drive all the logic signals, the *MiniSAS* connector to exchange data and control signals with the DPB board (see 3.1.2 paragraph). The board features a bunch of sensors to monitor the state of the board itself and also of the environment (temperature, and pressure, just to name a few); there is a calibration circuit to check performance consistency, and a connector dedicated to OD board connection.

As described above, there will be a mixture of electronics underwater pure ID units and hybrid ID+OD units. For the latter, there is a dedicated OD PMT digitizer and HV splitter board to process the OD signals. This board digitizes the OD PMT signal and sends the digital data to the ID digitizer board. One important difference between the OD PMTs and the ID PMTs is that there will be a single cable attached to the OD PMTs (compared to one HV and one signal cable attached to the ID PMTs). This design choice was carried out to simplify the OD design and to reduce cost. This necessitates the use of a HV splitter input stage to the OD boards to ensure that the high voltage and the PMT signal are decoupled in the board. Otherwise, the signals are processed in a very similar way, with an input receiver stage, fast amplifier and discriminator path, and an integrator path connected to the ADC. The design of the ID and OD circuits is very similar, but the OD design can be further simplified due to the relaxed requirements of the OD boards. The input receiver has an input bandwidth of 80 MHz (due to the faster 3-inch signals), and only one gain (as opposed to two gains) before the ADC, due to the reduced dynamic range requirement of the OD PMTs (from 0.25 pe to 100 pe).

The design of the OD board is at an advanced stage, nearly ready for prototyping. A schematic of the 6-channel OD board can be found in Fig. 11. The HV splitter portion of the OD board is seen on the bottom part of the OD splitter/digitizer board. The board will have two HV connectors and six connectors to the PMT. A single HV channel powers three PMT channels. The six individual digitizer channels can be seen on the upper part of the board. A 50-pin connector will connect to the main digitizer board that will drive its operation.

3.1.2 The Data Processing Board

The Data Processing Block (DPB) implements three functionalities in the front-end electronics block diagram (Fig. 8):

- data processing and network interface (data buffer and handling, system control and data transmission), which requires a large buffer to handle supernova events, preventing network congestion in the DAQ, a processor running Linux to implement ZMQ protocol for the DAQ and redundant optical transceivers for DAQ;
- synchronization (clock + counter), which requires a clock synthesizer and feedback loop as well as

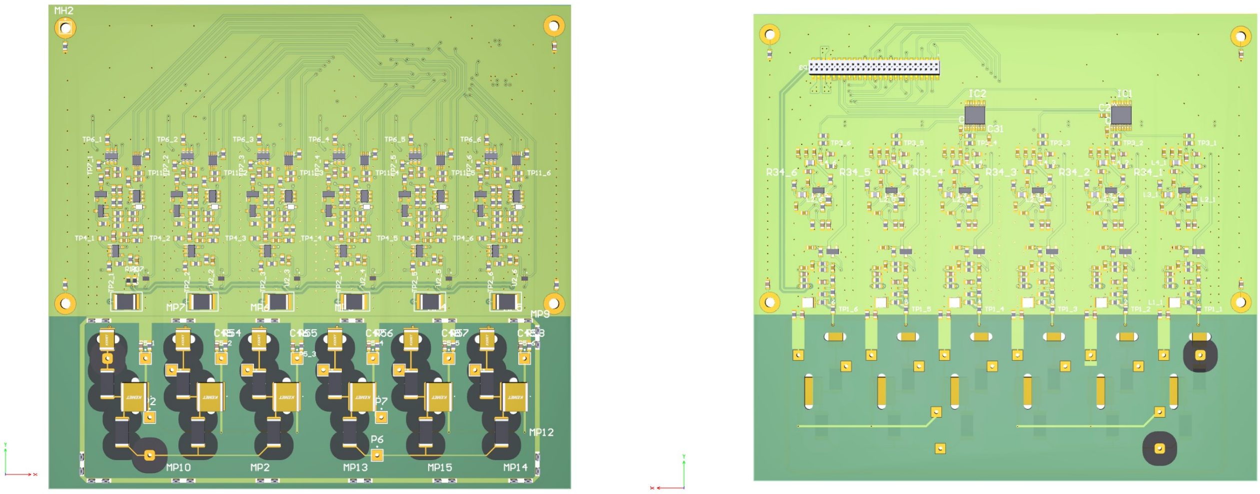

Figure 11: Schematic of OD Digitizer. Top view (left) and bottom view (right).

fanout to send copies to other units; redundant optical transceivers for the timing & sync system;

- slow control and monitor, which requires RS-485 interfaces for HV and LV modules, serial port and JTAG to interface digitizers.

The requirements listed above have been met in the DPB prototype with a combination of a SoM (System-on-Module) and a baseboard that adds communication interfaces and other features missing in the SoM. The SoM is a Mercury+ XU8 from Enclustra company. The SoM includes a Xilinx Zynq Ultrascale+ with dual ARM Cortex-A53 running Linux, ECC DDR4 memory, QSPI and eMMC boot memories (Fig. 12), as well as a number of high-speed serial interfaces.

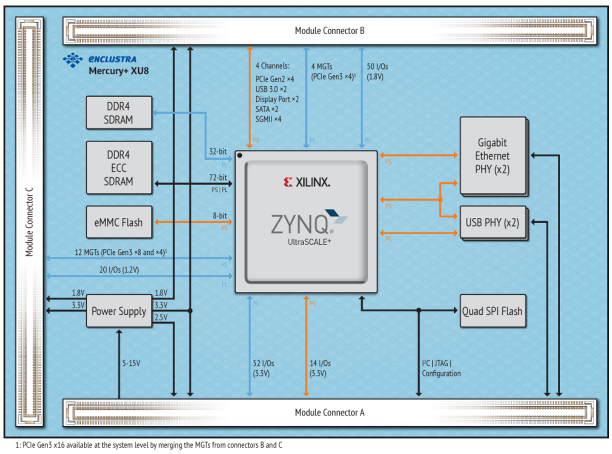

Figure 12: Block diagram of the SoM module for the DPB.

The DPB2 prototype will equip a ME-XU8-4CG-1E-D11E-R2.2 SoM with 4 GB ECC DDR4 memory, though 8 GB are intended for the final production units. The module equips a XCZU4CG-1FBVB900E Zynq Ultrascale+ SoC. The baseboard has been jointly designed with Enclustra, in order to reduce risks and speed-up development. Fig. 13 shows the top and bottom board views, indicating the main I/O and components.

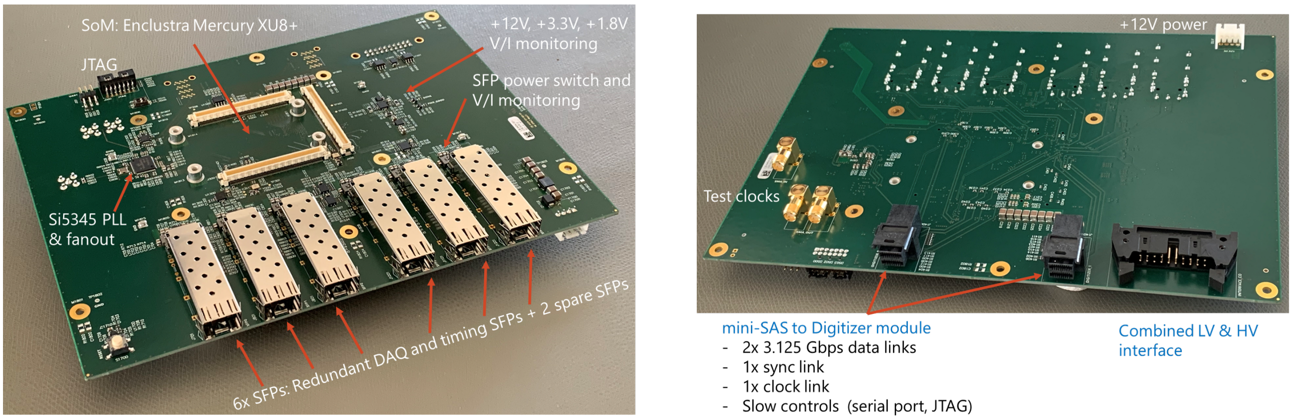

Figure 13: DPB hardware overview: top (left) and bottom (right) side.

3.1.3 The Low Voltage modules

Each underwater vessel will serve twenty-four ID PMTs through six PMT FTs. Each FT hosts four HV cables (modified RG-174/U cable) and four signal cables (RG-58). An external power supply is located out of the water tank and connected to the underwater unit through COM FT via two copper cables with lengths up to about 150 m each in the range of +40 to +55 V. It will provide ∼2 A of power and "Return" for the electronics through a low voltage power supply board inside the vessel. The long cable can pick up voltage and current noise from various disturbances, such as electrostatic discharges, high frequency electrical fast transients, surge transients, over-voltage, etc. In order to avoid any damage to the front-end electronics, protection circuits, and noise filters are implemented.

As seen in Figure 14, the LV board includes redundant isolated DC-DC converter, providing isolation between the input and the output and referenced to its local ground on the LV board. The local ground is then connected to the output section with optional mounting points allowing its connections to the vessel ground.

Since the LV board will have to function for years without being replaced, its long-term reliability is essential. For this reason, redundant components are included for the critical elements, such as the DC-DC converter, the micro-controller, the step-down as well as the environmental sensors as depicted in the LV block diagram.

The LV boards provide three 12 V outputs with various currents, up to 2 A, for two digitizers and one data processing board. As shown in Fig. 14, one of the 48 V power line voltages coming out of the EMI filter and 48V-to-48V DC-DC converter is used as an input for the HV board, i.e. 48 V with current around 1.5 A. Such configuration will allow to improve the reliability of the whole system. Tab. 2 summarizes the power requirements on the LV board. Since the LV power supply board is placed underwater inside the watertight vessel and provides the power to the rest of the electronic payload, its overall reliability must be ensured, and its failure rate must be kept below 1% per board for 10 years of operation. We consider the board failed if any of the following conditions are met: failure of the input filter; complete failure of the redundant isolated DC-DC converter; complete failure of redundant CPU; complete failure of slow control link; complete failure of the 12 V output to the data processing board. In case of a failure of the 12 V output to one of the digitizers, we assume half of the board is malfunctioning.

The LV board will be remotely controlled and monitored using the RS485 communication interface. It allows switching ON/OFF each channel independently and remotely, except the always-ON auxiliary output channel used by the data processing board. In addition, with existing environmental sensors on the board, it will provide information on the temperature, humidity, pressure, and water leak inside the vessel. The LV board also provides monitoring input voltage and currents for each channel. Last but not least, the power efficiency of the LV board must be higher than 84% above 60% of full load (100 W delivered at full load), in order to minimize the heat deposition in the vessel.

Unit Component	**Supply Voltage**	**Power**	**Current**
Input to Low Voltage module			
Low Voltage	+48 V	100 W	< 2.5 A
Input to electronics components from Low Voltage module			
High Voltage	+48 V	~ 45 W	1.5 A
Digitizer board #1	+12 V	~ 7.5 W	< 1 A
Digitizer board #2	+12 V	~ 7.5 W	< 1 A
Data processing board	+12 V	~ 25 W	1.25 A

Table 2: Input to LV modules and corresponding outputs to the other underwater electronics components.

3.1.4 The High Voltage modules

In Hyper-K, PMTs will operate at around 900 V to 1500 V for the OD and 1400 V to 2600 V for the ID using precisely controlled high voltage power supplies and with very low ripple requirements. The maximum current is 500 μA. It is important that the high voltage applied to the PMT is stable since it affects the stability of the PMT gain. A variation of the high voltage induces a gain variation, deteriorating the measurement of the energy deposited by particles.

The HV board will supply 24 voltage outputs via six 4-channel connectors compatible with RG-174/U cables, regulated between 20 V and 2600 V with a maximum current of 500 μA and independently settable

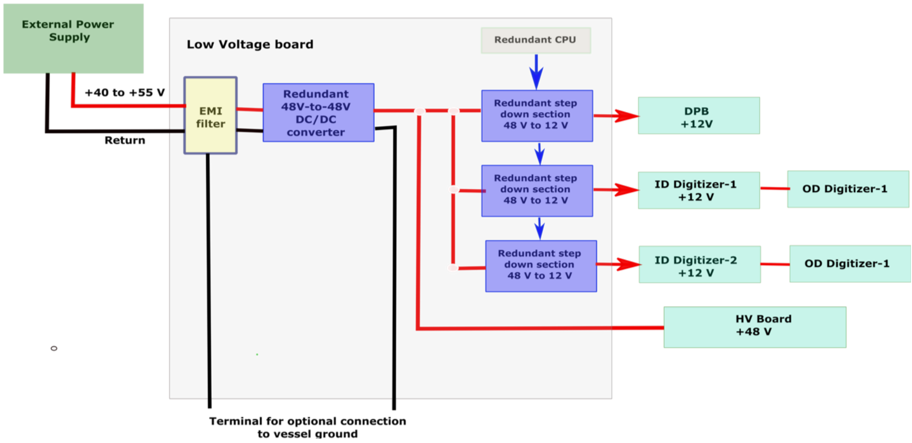

Figure 14: Low Voltage power supply board block diagram.

with a precision of ±1% in the range of 900 V to 2600 V. The applied high voltage must be stable, with a spread better than ±0.2% per year for long term operation, ensuring a ripple smaller than 100 mV peak to peak from 10 Hz to 10 kHz and 10 mV peak to peak from 10 kHz to 20 MHz. All output channels are software configurable ramp-up and ramp-down voltage rates from a minimum of 1 V/s to a maximum of 500 V/s with a step of 10 V.

The HV board can be remotely controlled and monitored via RS485 communication interface, allowing to set, monitor and adjust each individual channel. To maximize the ability to operate of the detector in case of problems, the HV board allows to control individual channels; it is required that one or more channels can be operated normally while some other channels are inhibited, i.e. switched off. The precision of voltage and current monitoring is better than ±1% and ±2% respectively, in the range of 900 V to 2600 V. The HV board will be equipped with overvoltage, undervoltage and overcurrent protections. Occurrence of any of these fault conditions will cause the channel to be switched off. The status of each channel is monitored, including its temperature.

The electronics unit in Hyper-K will be placed inside a watertight vessel submerged in water, without access for about 10 years. Therefore, long-term reliability and redundancy are crucial also for HV boards. The average HV channel failure rate must be less than 1% for 10 years of operation. Fig. 15 shows the HV block diagram with possible redundant components.

The allowed power consumption and heat dissipation of the electronic units is limited by the cooling capability inside the underwater vessel. The heat dissipation on the HV board is limited to less than 24 W. In other words, the board efficiency must be better than 50% at a voltage of 2500 V and a load of 5.9 MΩ. The HV board must be hosted in a metallic case, behaving as EMI shield. To ensure the stability of the electrical performance and its reliability, and to have the temperature inside the pressure vessel stay within the maximum allowable temperature, the HV board must be designed in such a way that the heat dissipation is channeled through the "bottom" face of the metallic case. This face will be the "fixing side" of the mechanical support inside the underwater vessel, which acts as a thermal contact for heat dissipation.

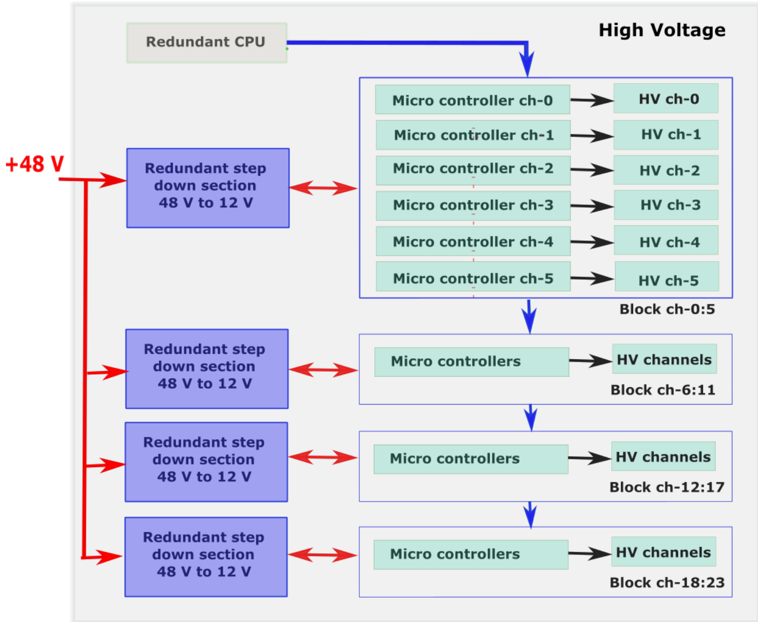

Figure 15: High Voltage power supply board block diagram.

3.1.5 The time synchronization

A crucial piece of information to reconstruct the Cherenkov ring(s) associated with an event in the Hyper-Kamiokande experiment is the arrival time of the light emitted in water on the detector's PMTs. To achieve this goal a reference time must be established and distributed to all the PMT front-end (FE) module readout electronics.

The time synchronization precision is directly related to the event's reconstruction accuracy; therefore, great care must be devoted to this task to control all sources of errors and inaccuracies. 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 full block scheme of the proposed system is depicted in Fig. 16.

To guarantee the most stable and precise reference, the local time base originates in an atomic clock

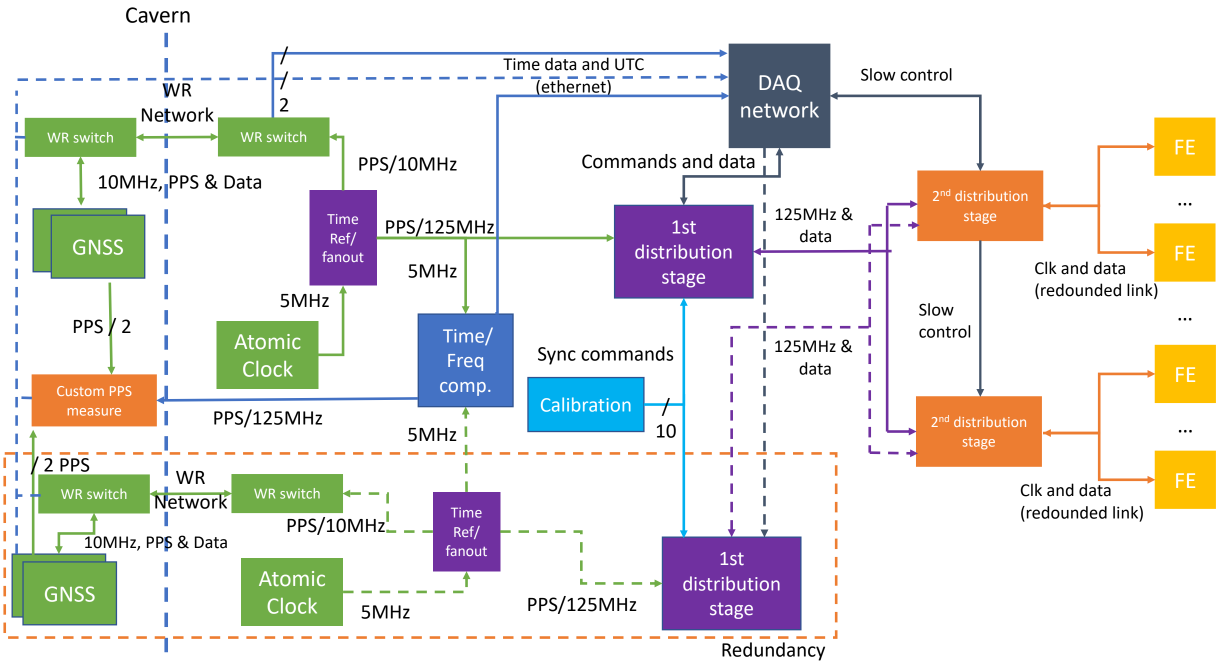

Figure 16: The proposed time distribution block scheme. The green boxes are part of the clock generation and UTC tagging. The purple elements constitute the first distribution stage, the orange ones are for the second distribution stage, while the yellow ones refer to the time distribution endpoint, part of the front-end.

working in free-running mode. 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 time distribution modules and delivered to all the leaves represented by the FE modules using the so-called Time Distribution Endpoints or TDE embedded on the DPB. 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 it. The PPS signals from the GNSS receivers will be also compared directly to the locally generated one using a custom board. This feature will be used to double check the performances of the satellites receivers.

3.1.6 The water-tight vessel

The water-tight vessels and the electronics stand are the mechanical parts where the different electronics components are assembled and hosted underwater in a safe environment. The importance of the vessels is that it must remain water tight under a pressure up to about 7 bars in ultra-pure water. Even if, initially, the Hyper-K FD will not contain Gadolinium (Gd), like currently Super-K does to enhance the neutron capture, the collaboration decided to still keep the option of adding Gd doping in the future. For such reason, the design complies also with the case of Gd doped water. The material for the vessel is passivated Stainless Steel 304, which has been used in Super-K and its compatibility with ultra-pure and Gd-loaded water is firmly established. The electronics stand is a relatively simple aluminum support fixed at the flange inside the vessel. Its purpose is to host the electronics components (two digitizer boards, DPB, HV and LV modules) and transfer the heat to the water outside the vessel. Each underwater vessel that will host the components for the ID-related PMTs will have six feedthroughs, which will include the high voltage and signal cables for four PMTs each, giving a total of twenty-four PMTs that will be supplied by each vessel. Each feedthrough hosts four composite cables and is composed of a 90 mm long polyethylene mold that is attached to each of the six pass-through holes of the cover flange using a silicon gasket. A very similar design is also adopted for the hybrid configuration, which will support 20 ID and 12 OD PMTs. The CAD model of the underwater vessels are shown in Fig. 17.

Nominal water pressure	7 bar
Pressure and tightness test	10 bar
Total heat cooling through flange or vessel	75 W
Max Total weight	60 kg
Envelope volume	400 mm × 400 mm × 550 mm

Table 3: Requirements on the water-tight vessel.

In Tab. 3 the requirements on the vessel design are listed. Pressure and tightness test was successfully performed at the Paul Scherrer Institute (PSI) and officially protocolled. The vessel stayed water tight for the entire test and absolutely no mechanical deformation was observed.

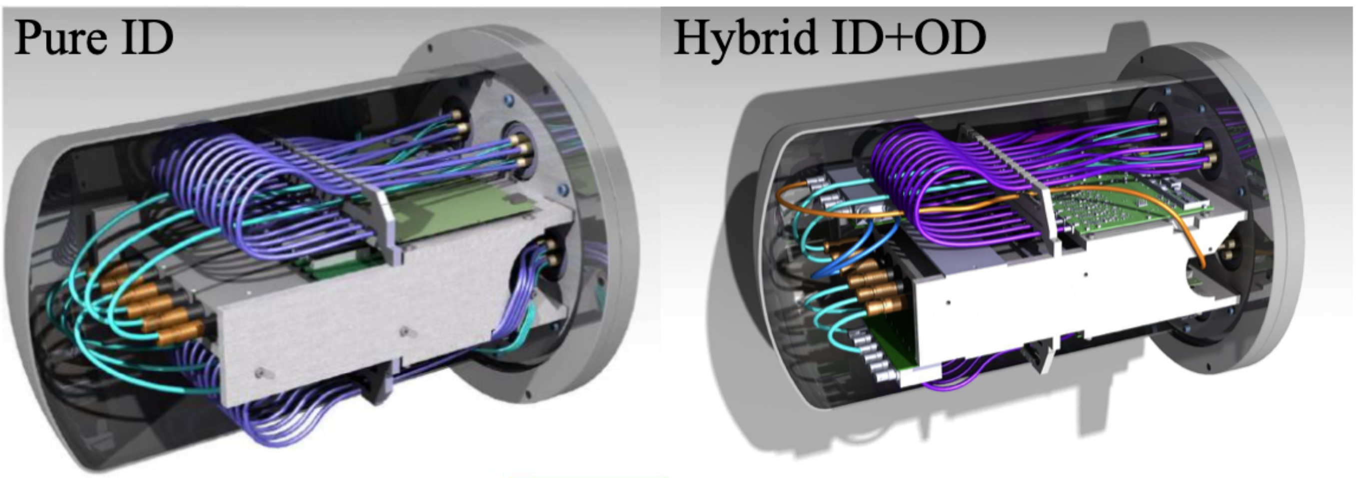

Figure 17: 3D model of the pure ID (left) and hybrid ID+OD (right) underwater vessels.

The total number of vessels and electronics stand is 560 for pure ID units and 320 for hybrid ID+OD units. The vessel final design is the result of many iterations and optimizations. A compromise was sought in the geometry in order to use parts available on the market and, consequently, minimize the overall production costs by avoiding, where possible, custom made parts. The exact same strategy applies for the design of the electronics stand whose choice of material, geometry and manufacturing process are the result of an optimisation path seeking the best balance between cost and design. Everything is also optimized from the point of view of the assembly by simplifying, where possible, the assembly procedure whilst always prioritizing the safety of the equipment inside the vessel. The 2D drawings of the designed vessel and electronics stand as well as the results of the Finite Element Analysis (FEA) studies are shown in Fig. 18.

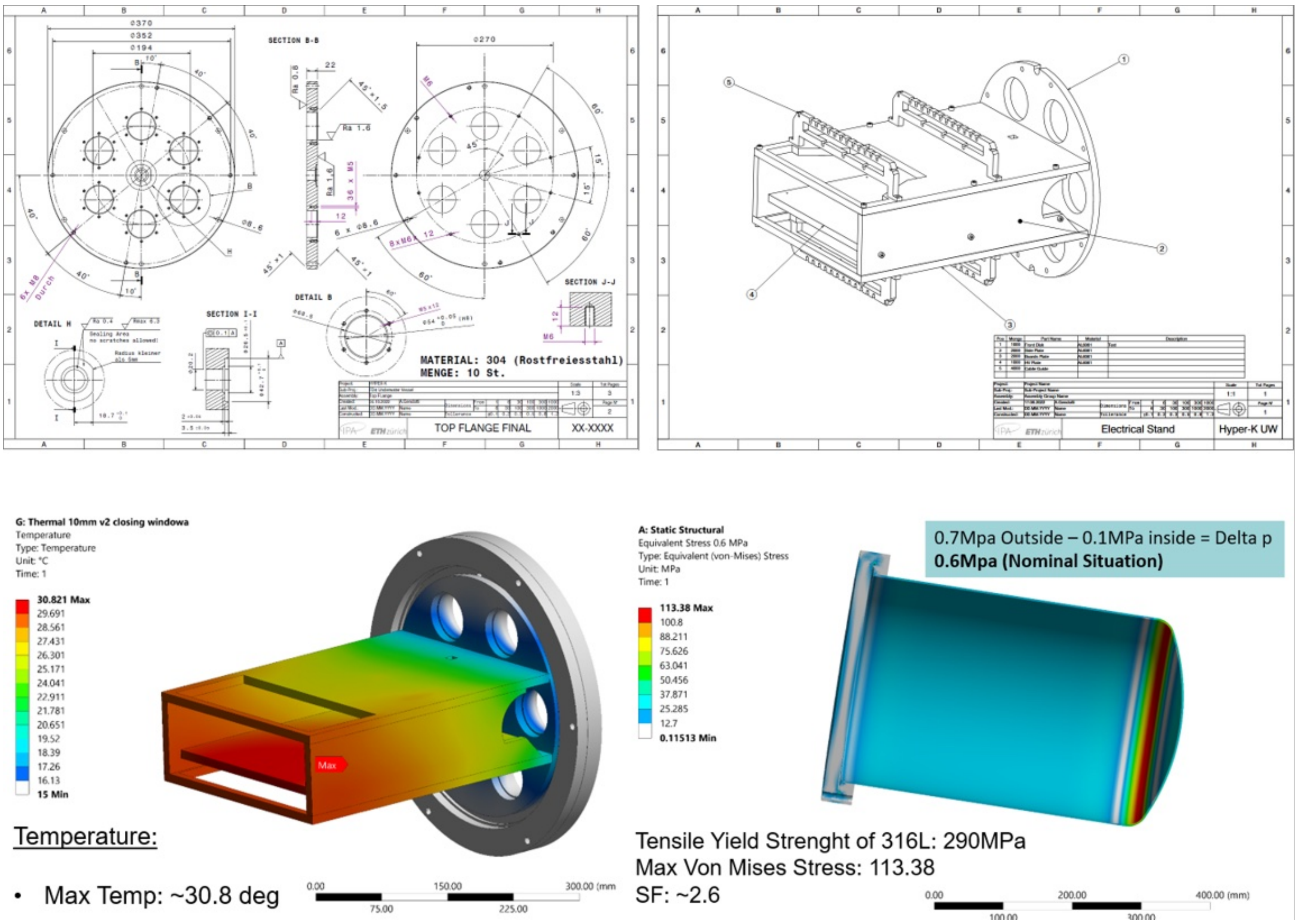

Figure 18: Top: manufacturing drawings of the Pure ID vessel design. Bottom: FEA results of the pressure applied to the vessel (bottom left) as well as of the thermal behaviour inside the vessel (bottom right).

As it will be shown in Fig. 24, the prototype has already been assembled with the goal of verifying, implementing and optimizing the design and the assembly procedure. A thermal test in water has been successfully performed and confirmed the results of the preliminary thermal FEA. Final pressure tests have been performed by exposing the vessel to a pressure up to 17.7 bars (about 2.5× the nominal pressure). The vessel did not show any leak and no visual deformation was found.

At the top flange there is a total of seven water-tight feedthroughs (FT): six of them are placed on a circular pattern and allow the HV and signal cables to exit the vessel and connect to the PMTs. These are called PMT FTs. The remaining one is called communication FT (COM FT) and is located in the center of the flange and lets the cables to connect the communication module and the power supply inside the vessel with the modules outside the water.

The hybrid vessel has two additional 6-channel OD splitter/digitizer boards connected to the main ID board by a 50 conductor ribbon cable. Two HV channels are connected to the OD splitter/digitizer boards, with each HV channel powering three 3-inch PMTs. Six PMT channels will also be connected to each of the OD splitter/digitizer boards. The connections to the OD PMTs is carried out through a 12-cable (RG-58) FT. This will be one of the six FTs through the electronics vessel. The other five FTs will carry the remaining 20 ID channels. The RG-58 cable on the water side of the FT will be connected to the 3-inch PMTs.

3.1.7 DAQ and Slow Control

The Hyper-K DAQ systems will be built using the ToolDAQ framework [26]. ToolDAQ is a modular, highly scalable and fault tolerant DAQ framework, which will be installed on each of the commercial computing server nodes that form the DAQ system. The server nodes will be connected via commercial network switches, to permit transfer of data and allow communication between elements of the system. Multiple connections are used alongside dynamic service discovery to reduce the impact of hardware failure by re-routing data in the event of faults. In addition, further resilience is achieved by using layers of network and networking and messaging protocols within ToolDAQ.

Fig. 19 is a simplified diagram of the DAQ system, and shows the network layers that connect each of the nodes and the front-end electronics. There are two physically separate networks. The front-end network connects the Front End Electronics (FEEs) to the Readout Buffer Units via network switches. The back-end network, connects the Readout Buffer Units (RBUs), Trigger Processing Units (TPUs), Event Builder Units (EBUs), Brokers and other systems (e.g. archiving, monitoring and control machines). The back-end network has a significant role in the processing of hit data stored in the RBUs and saving it to disk via the TPUs, EBUs and Brokers.

Raw data from the Front-End Electronics (FEEs) is transferred via a network switch to the RBUs, where it is buffered, catalogued and stored on the RBU disk and in memory for as long as possible. The flow of data from the RBUs to the TPUs and EBUs is managed by a single broker. Two brokers are used to provide redundancy in the system, one will always act as the primary with the other as an active backup, which would be automatically used in the event of any hardware issue. Whilst the broker manages the flow of data within the DAQ systems by assigning jobs/tasks to the Trigger Processing Units (TPUs) and Event Builder

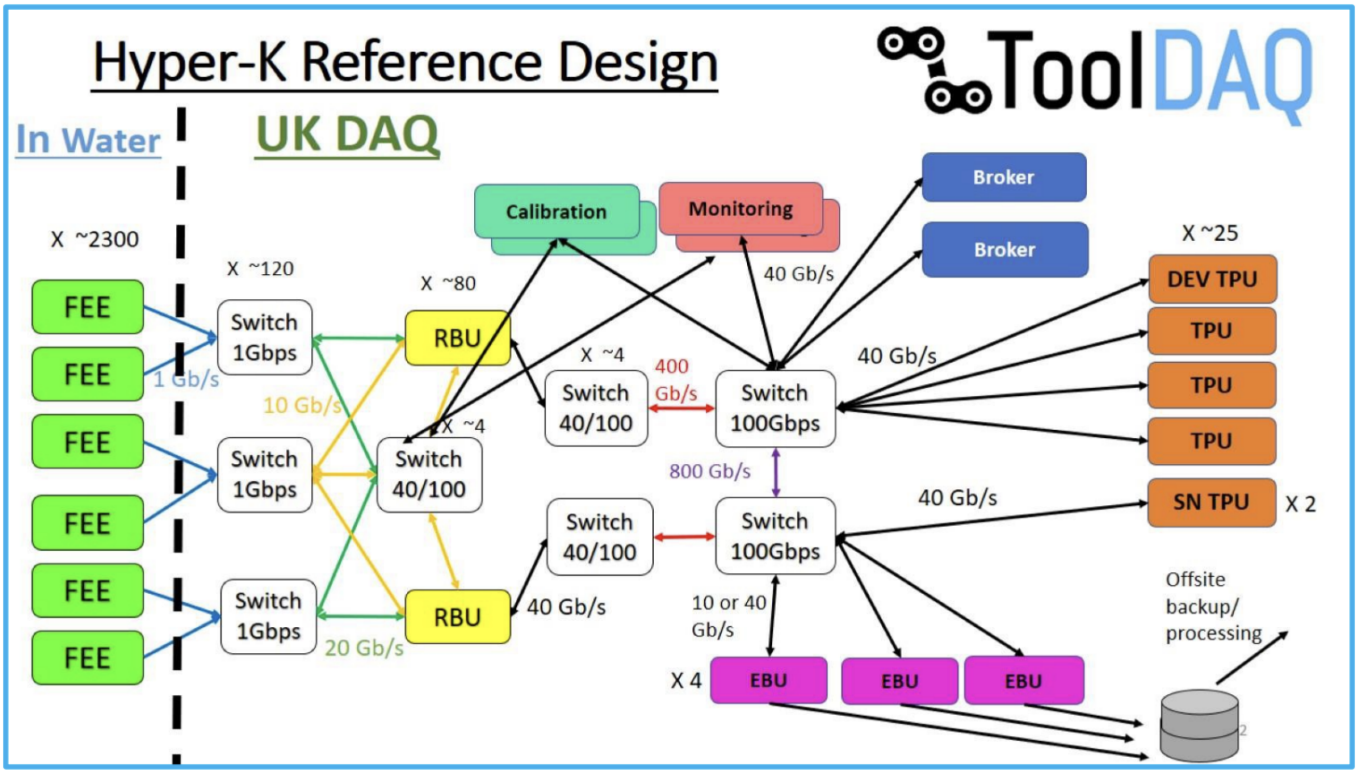

Figure 19: Diagram of the reference design for the Hyper-Kamiokande DAQ systems.

Units (EBUs), it does not participate in the actual transfer of data. The broker issues instructions to the TPU and EBU nodes requesting them to analyse or save data respectively and crucially, it maintains records of the results and job/task assignments. Once allocated a task, The TPU and EBU nodes request the data for their assigned jobs independently from the RBUs.

Incoming data is split into slices of ~ 100 ms and ~ 1 ms pieces are handed to the TPUs, where a series of trigger algorithms are applied. Decisions from the triggers are returned to the Broker, where if at least one trigger is passed, data is handed to the EBUs where it is prepared for permanent storage. Once a predetermined file size is reached, the data is archived off site, where it can be accessed for later processing and analysis.

For the proposed electronics tests and assembly at CERN, a small-scale version of the Hyper-K DAQ systems will be used. This will provide an ideal opportunity to test the performance and stability of the DAQ systems and the full readout of the Hyper-K data chain. In addition, a small-scale version of the monitoring and slow control system would be deployed for the assembly and testing work.

3.2 Ongoing activities at CERN

Currently two main activities are ongoing at CERN: the electronics vertical slice test (VST) and the 10-units test.

The VST will prove the functioning of the full electronics chain, testing all the sub-components together to read a 20-inch PMTs, and verify the integration procedure.

The 10-unit test will verify the electronics performance in the "real" conditions. This test will be particularly useful to check the long-term temperature stability and the cross-talk effects when the electronics boards are mounted and cabled on the mechanical stand.

The schedule of the ongoing tests is shown in Fig. 31 together with the overall assembly project one.

3.2.1 Vertical Slice Tests

The vertical slice test (VST) is a precious tool because it provides feedbacks to validate the final electronics design. The main goals are:

- the validation of the subsystems' compatibility, i.e. to verify that the various component interfaces are correctly set;
- performance tests, i.e. study the whole system performance and compare it to the one obtained when testing every single component independently and to the one obtained when the whole system is enclosed in the vessel;
- optimize the integration and assembly procedure;
- the definition of the integration test protocol and mechanical tools;
- Electro-Magnetic Interference (EMI) immunity test, to define the vessel grounding scheme;
- vessel thermal profile test, i.e. study the temperature reached by the various components and the definition of the cooling system plate.

The test will require all the elements to read and control the PMTs including the one to be installed out of the water such as the set of boards in the front-end vessel, the time distribution system, the data acquisition system, and the external power supplies that will provide the main power to the LV/HV modules. To make it more realistic and to prepare the integration phase, also mechanical supports, water-tight connectors, and feed-troughs will be used.

To fully simulate the analog signals to be converted, pattern generators and real PMTs will be used. The last will also serve to test the HV module together with dummy loads.

The VST will be carried out using a sort of continuous integration procedure, on which the various electronic components will be constantly updated following their development.

This effort has started in May 2023 when the current prototypes of the data processing board, the digitizers, and the second time distribution layer have been connected together for the first time. In the time prior to the boards design finalization, the bench will be used to check the interfaces and verify that all the sub-systems comply with the specifications. Also firmware and software development will be carried out. In parallel to the electronics design, verifications will be conducted on the mechanical part giving important feedback to the mechanical design and helping to finalize the integration procedure.

Once the whole system is considered stable enough, four front-end units will be fully integrated in vessels and tested in water using the 10-units test facility (see Sec. 3.2.2). This will represent a further step to test the hardware in conditions that are as close as possible to the real one.

The criteria that have been established to evaluate the stability of the system are the following:

- DPB
  - the DPB can exchange data with the DAQ;
  - the DPB firmware and software can be updated over the data communication channel and the fallback mechanism works in case of corrupted firmware;
  - slow control data can be acquired properly.
- Digitizer:
  - the digitizer can transfer data at nominal speed;
  - charge and time resolutions are within specs;
  - the firmware can be updated remotely and the fallback mechanism works properly.
- The LV/HV are delivered properly and the slow control is correctly exposed to the DPB.
- The grounding scheme has been fully tested and the electromagnetic interferences are under control, including tests with long cables and PMTs (either bases only or full photodetectors).
- The thermal profile of the system is stable and no hot spots are present on the boards.
- The time distribution system can transfer clock and synchronous data to the DPB.
- The overall system performances do not change when the vessel is closed (to be verified with quick tests due to possible thermal issues).

While the 4 units will be tested in water, the VST system in air will be kept operational to have a reference and to help understanding any possible misbehavior on the fully integrated systems.

3.2.2 10-unit tests

As discussed in Sec. 3.1, the front-end electronics together with LV and HV power supply boards will be placed inside the stainless steel pressurized vessel and then submerged into the water. The electronics will not be accessible during the experiment lifetime. Therefore it is very crucial to have long-term reliability of the system. A 10-unit test aims to identify possible failure modes of the complete system, whether related to mechanical, thermal or electrical interference, or due to the setup itself, as well as to study possible ground configurations. The test platform is also considered to develop and tune the slow control and the DAQ system of the experiment.

The 10-unit test is composed of six dummy underwater units for testing the long-term stability and reliability of LV and HV boards and four fully-assembled underwater units with full electronics to study the integration of electronics, grounding as well as noise emissions. The dummy units include LV, HV prototypes, dummy digitizers and DPB, and dummy feedthroughs. Dummy boards are designed by taking into account the size of the digitizer and DPB boards, their fixing holes, the type of connectors, and the position of the active components, such as FPGAs, ADC, SFPs, etc. Heat resistors placed on dummy boards are used to simulate the heat dissipation of active components. The heat transferred inside the vessel will be checked to study how the electronics stand can convey the heat to the water outside the vessel as well as how the performance of the HV and LV modules are affected. Currently, a 40-pin flat cable is used as COM FT providing 48V to the LV board and communicating with LV, HV, and dummy boards. Two dummy PMT FTs are used to provide a 6 MΩ dummy load for the HV board in order to simulate the PMTs. Moreover, dummy feedthroughs are also used to test the water tightness of the vessel. Fig. 20 shows one of the assembled dummy units. As shown in Fig. 21, six units have been installed at CERN in Building 182 in the WA105 $3 \times 1 \times 1$ m^3 cryostat tank filled with water, to reproduce the conditions as close as possible to the Hyper-K FD.

The four remaining units will have all the components (HV, LV, DPB and Digitizer prototypes) and will be placed underwater with the available PMT FTs and COM FT and added to the six as-yet running units. The work was carried out with the help of CERN electrical technicians, in particular in the preparation of cables, setting up the main power system, and providing technical support when needed.

The plan is to run the test for about one year to check the long-term reliability of the system.

3.3 The design and production schedule of the electronics underwater units

A simplified version of the Hyper-K FD electronics project schedule is shown in Fig. 22. The digitizer board design will be finalised by the end of 2023 and, after the final checks and validations are performed, the mass production will start in the second half of 2024. Both the HV and LV module mass production will start around Fall 2023 and beginning of 2024, to be completed in the beginning of 2025. The same applies to the mass production of the underwater vessels and related components.

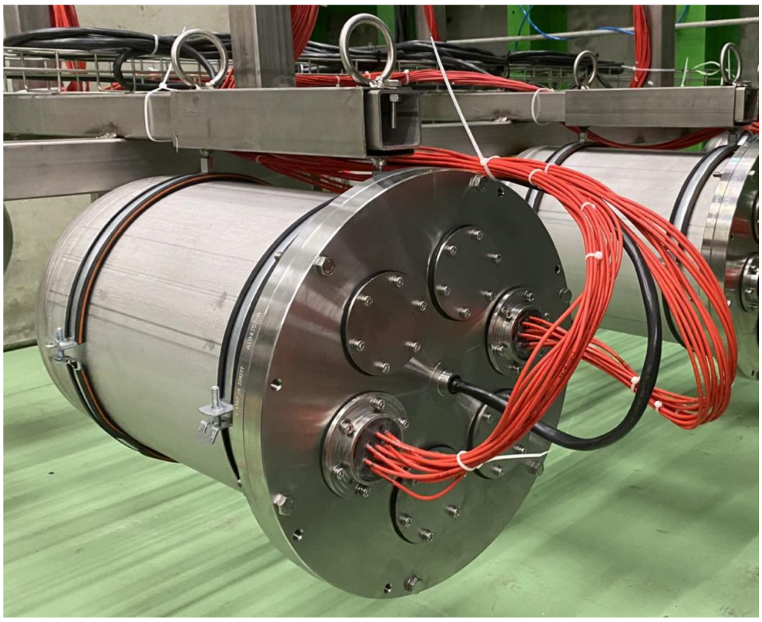

Figure 20: Fully assembled dummy unit. The black cable is used as dummy COM-FT and the red cables indicate the dummy PMT FTs.

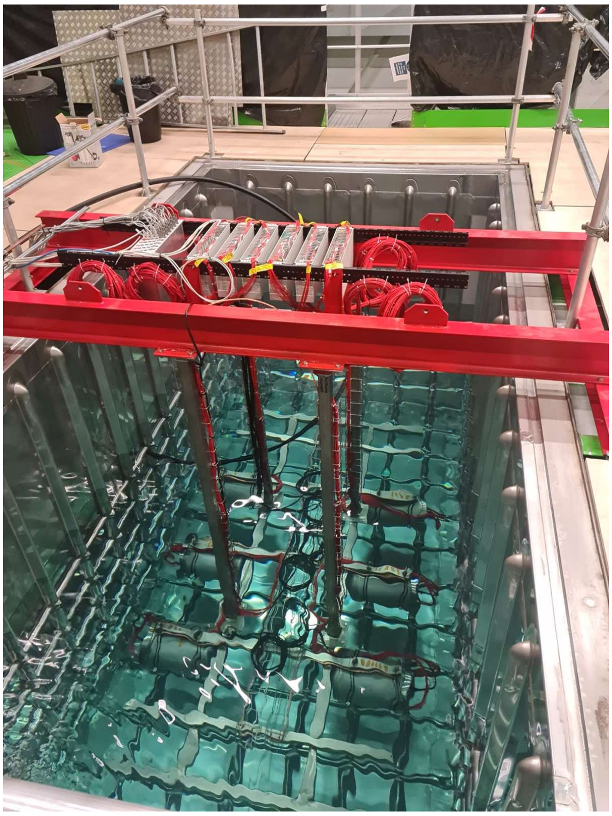

Figure 21: The 10-units set-up: the six dummy underwater units are immersed in water in the WA105 cryostat tank.

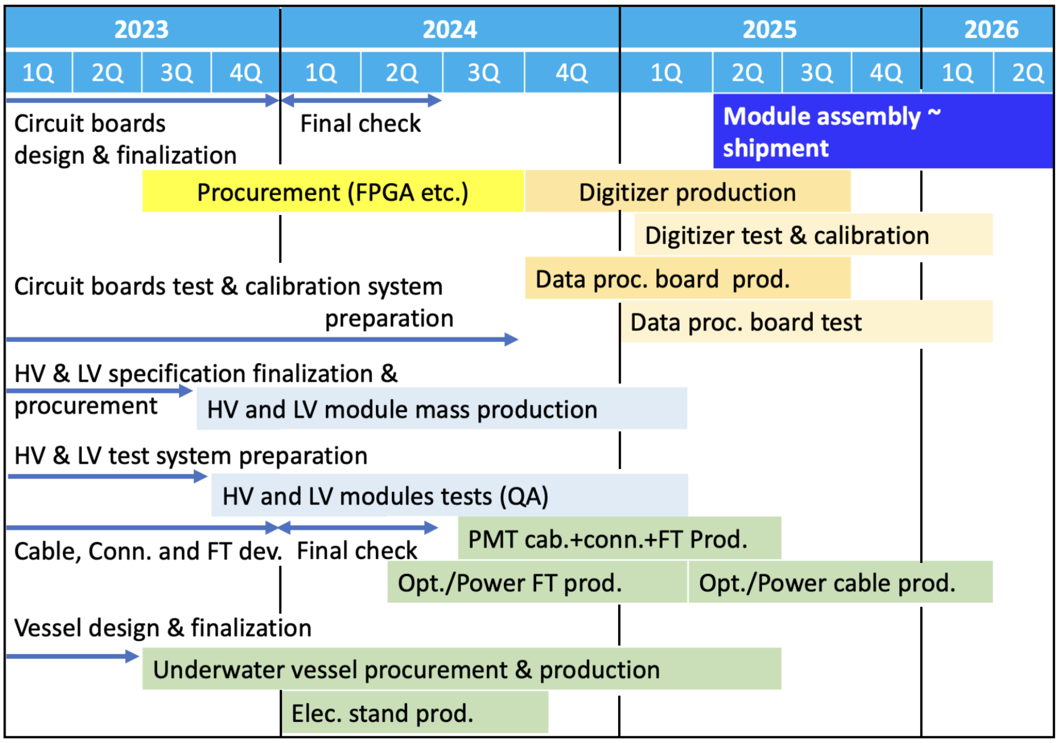

Figure 22: Hyper-K FD electronics schedule.

4 The Hyper-K Assembly project at CERN

The goal of the project is to assemble all the 900 underwater electronics units, ensuring their functioning and the shipment to the Hyper-K experimental site, where they will be installed inside the FD tank in 2026. More in detail, the collaboration will

- supervise the mass production of the underwater electronics unit components and coordinate the shipment to the assembly site at CERN where they will be temporarily stored;
- assemble all the underwater units;
- ensure the functioning of the underwater units;
- ship all the underwater units to the Hyper-K experimental site in Kamioka.

The various activities will be shared by all the institutes involved in the project, that will also participate to daily shifts to be organized in order to keep the Hyper-K target schedule.

The institutes involved in the underwater unit design and production will provide the support and the expertise during the tests and the assembly. The collaboration organization is shown in Fig. 23. Spokepersons and the technical and safety coordinators have been appointed. A contact person have been defined for each underwater unit sub-component as well as for the test bench that will be used to test the functioning of all the units (see Sec. 4.1.2).

In Tab. 4 the list of institutes involved and their commitment to the project is shown.

The Hyper-K Underwater Electronics Assembly project will necessitate of space, support for the logistic and shipment, facilities and technical expertise. Moreover, the collaboration consists of mostly European institutes. Hence, we propose CERN SPSC to host the project under the program of the CERN Neutrino Platform.

Fruitful discussions with the leaders of the CERN Neutrino Platform are currently ongoing. The CERN Neutrino Platform expressed full support to host the project under its program.

4.1 Planned activities

In this section a detailed description of the activities at CERN is given. They will consist of

- supervising the mass production of the underwater unit components;
- coordinating the shipment to the assembly site at CERN where they will be temporarily stored;
- testing the functioning of the components before the assembly;
- calibrating the digitizer;

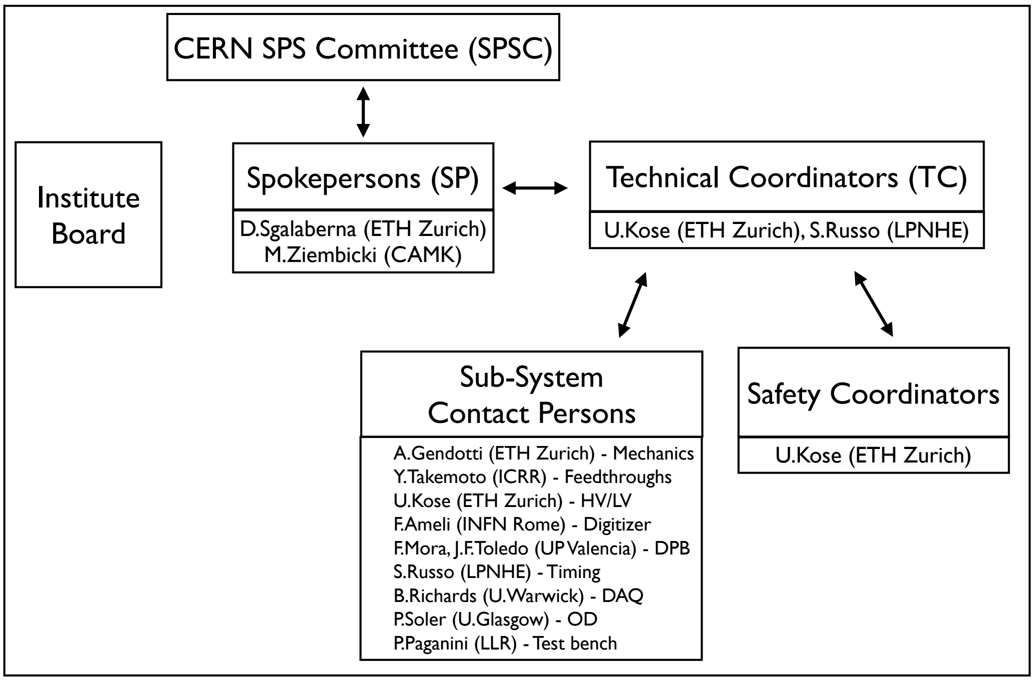

Figure 23: Organigram of the assembly project.

- assembling all the underwater units;
- testing the functioning of the assembled units in and out of water;
- performing vessel pressure tests;
- long-term tests for the system reliability;
- shipping all the units to the Hyper-K experimental site in Kamioka.

The following sections describe in detail the assembly and test activities.

4.1.1 Assembly of the underwater unit

The steps necessary for the underwater unit assembly have been studied and tested with a prototype to understand the potential weaknesses of the design and to optimise the assembly procedure. The main steps are shown in Fig. 24 with the following numbering: (1) assemble the DPB board on the support plate; (2) mount the HV and LV modules on the support plate and assemble the side aluminum walls; (3) assemble the HV, LV, DPB on the electronics stand, sandwiching the HV plate between the LV and DPB ones, mount the two digitiser boards and route the internal cables; (4) mount the front disk on the electronics stand; (5) mount the top flange on the electronics stand, mount the feedthroughs on the lid and insert it with the cables.

	Item	Institutes
Unit sub-components	High Voltage Low Voltage Vessels and related	ETH Zurich, U.Geneva, U.Glasgow
	Digitizer ID	INFN and U. of Naples, Padua, Pisa, Rome
	Digitizer OD	U.Glasgow
	Data Processing board ID	U.Politècnica Valencia, WUT Warsaw CAMK Warsaw, AGH Krakow, UJ Krakow
	Clock distributor	IN2P3 LPNHE, Irfu CEA Saclay, INFN and U.Rome
	Power supply (AC to DC)	ICRR Tokyo
	DAQ and Slow Control	U.Warwick, King's College of London, Lancaster University
	Feedthroughs, power and fibre cables, PMT connectors	U.Glasgow, ICRR Tokyo, U.Tokyo
Assembly related	Test bench	IN2P3 LLR
	Pressurized tank	ETH Zurich
	Assembly activities	All institutes

Table 4: List of institutes involved in the Hyper-K FD underwater electronics and related activity commitment.

This step is the most delicate in the assembly process because mistakes could result in the penetration of water inside the vessel. Thus, qualified technicians will be required; (6) connect the power cable at the front side; (7) connect the HV, optical and signal cables to the respective boards; (8) check the cable routing and add the side aluminum plates to complete the electronics stand; (9) insert the electronics stand inside the aluminum vessel and close it.

A stand is needed to support the mechanical vessel during the assembly and mount the boards inside and route the cables in an easy way. An initial design is shown in Fig. 25. First the top flange of the vessel is installed on the frame which will have wheels to facilitate its transport from the storage area to the assembly room. Supports are needed for the ~ 3 m long cables that connect the electronics to the PMT cables. Moreover, it shall provide the possibility to rotate the vessel by 180°. The support stand has to be designed, purchased and produced. A minimum of four support stands is foreseen.

A total of eight technicians full time are planned, two working together on the same vessel, for a total of four assembly stands. Such approach will allow to keep the necessary pace during the assembly to meet the time schedule requirements, described more in detail in Sec. 4.3.1.

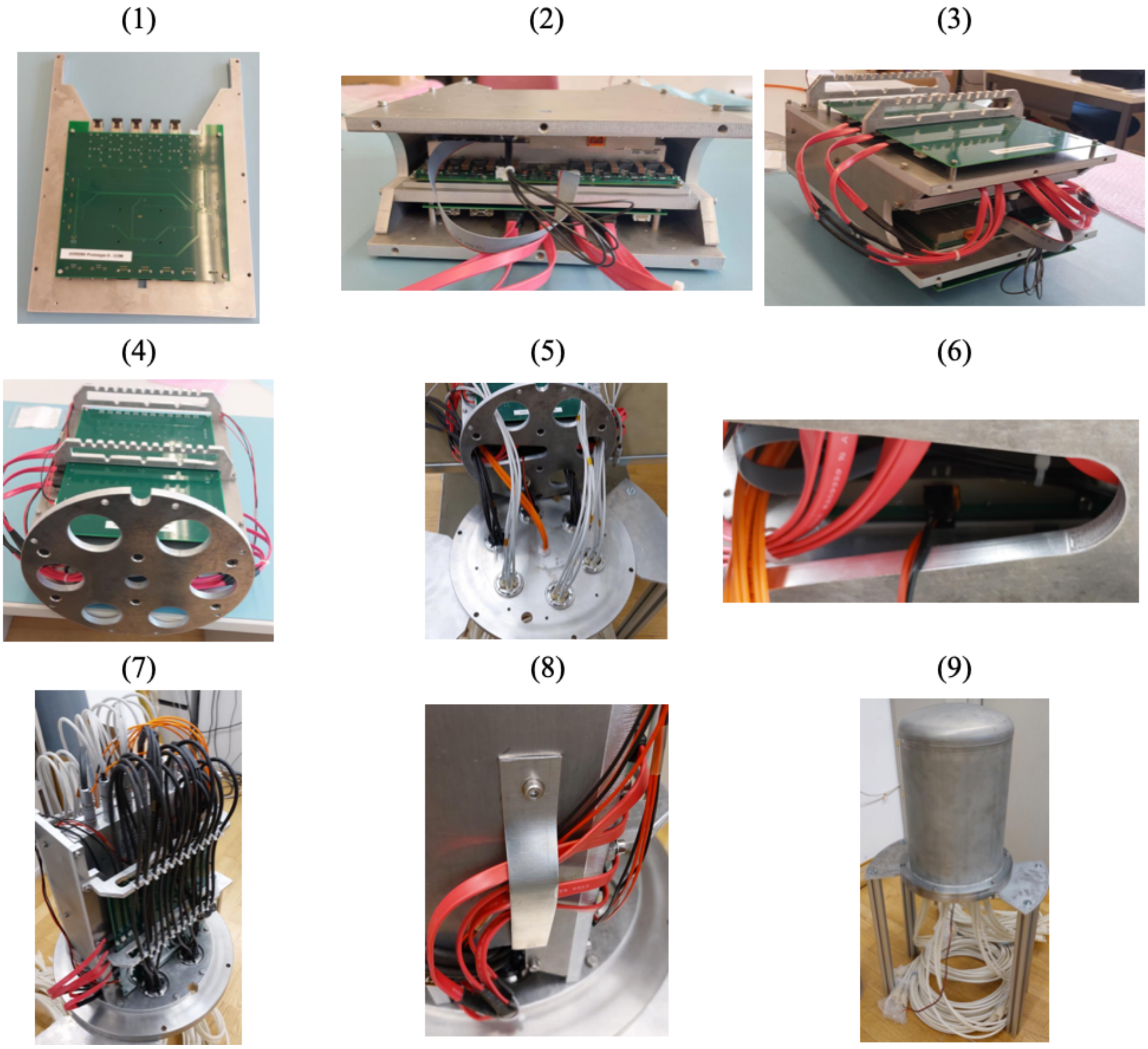

Figure 24: Summary of the steps necessary for the assembly of an underwater electronics unit.

4.1.2 Electronics tests

During the whole integration process, tests will be performed to verify the various steps of the assembly procedure. The full test set can be divided into pre-assembly and during-assembly.

Pre-assembly Before starting the integration, the digitizer board will be carefully characterized injecting precisely controlled analog signals and analyzing the conversion results. This procedure will be carried out at different temperatures and by swiping all the converter dynamic range. This work represents a fundamental step that will facilitate the data analysis once the full detector will be operational.

During-assembly The assembly process will be controlled with a series of tests that will verify the various steps of the procedure and, to make the verification process effective and efficient, an automated test bench will be developed. It will be composed of a subset of the DAQ and time distribution system, dummy loads

Figure 25: Conceptual design of the support stand for the fixation of the mechanical vessel and the installation of the boards and cables inside (left), photo of the simple support used for testing the assembly steps (middle) and conceptual model of the pressurized tank (right).

to simulate the PMT connection to the high voltage system, a Tektronix pulse generator (a wide range of arbitrary function generator is available, AFG31252 for example) with an amplifier and signal switching boards with fan-out, provided by the Korean Hyper-K group including Kyungpook National University, Center for Precision Neutrino Research, Chonnam National University, and Seoul National University, to inject well known signals from a single source into the digitizers and a power supply to provide current to the front end module under test. A block scheme of the test stand is reported in Fig. 26.

The relation of the timing of the analog signal and the reference clock is independently recorded. This feature will allow not only to verify the conversion process but also to check that the main clock is correctly distributed to the boards. The converted data will be acquired using the data acquisition system and automatically analyzed. The results will be compared to a benchmark to provide a pass/fail result. The entire procedure will be carried out by means of a set of software scripts to reduce human interventions and possible errors.

Testing the electronics assembled on the stand together with the flange and the water-tight connectors and feed-troughs will allow to check the entire system and the various interfaces. A test report, that will contain the board serial numbers as well as the test result, will be produced and stored in a database.

4.1.3 Pressurized tests

Once the assembly of an underwater electronics unit is completed, a custom-made setup will be used to fully test both its mechanics and the electronics performance in the same conditions (pressure and temperature) as inside the Hyper-K FD tank filled with water. Such test shall be performed under pressure, also to validate

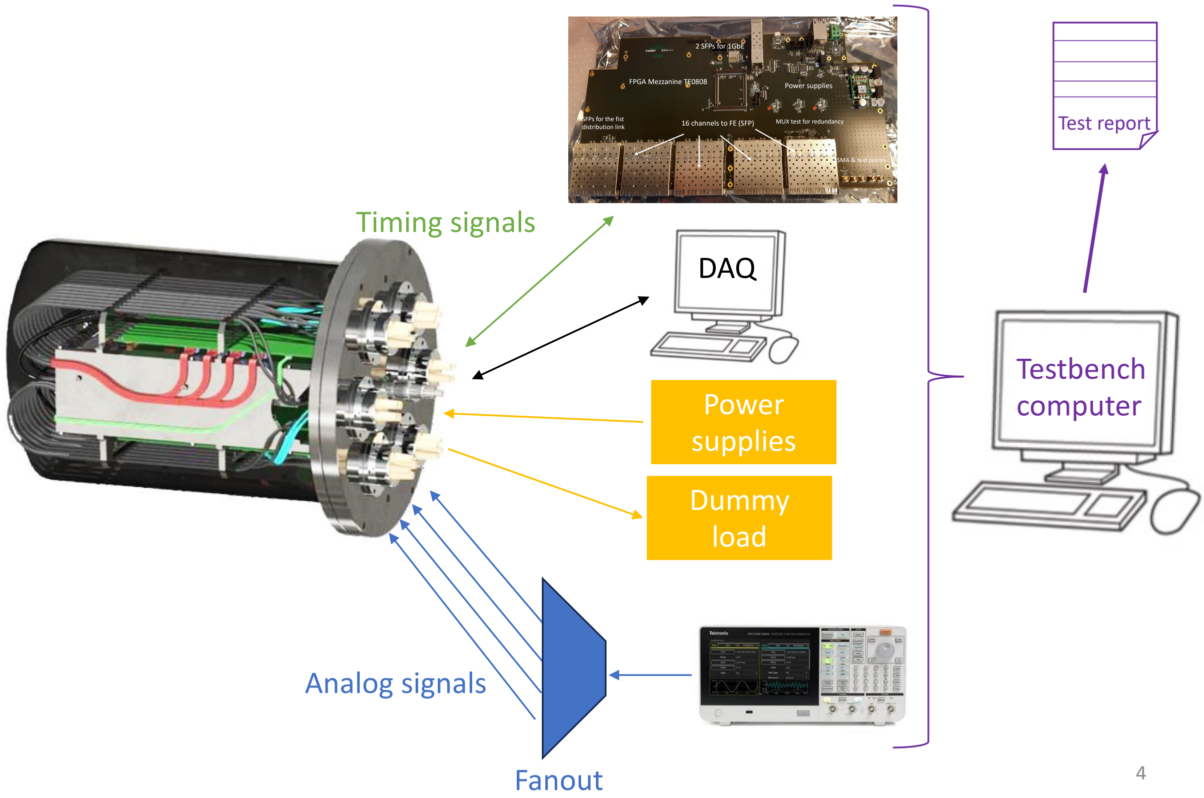

Figure 26: A block scheme of the electronics test stand that will be used during the installation process. In the center the front end board mounted on the stand and the flange with the connectors. On the right side of the picture the equipment to perform the test are presented.

the water-tightness at the pressure to which it will be exposed in the FD tank.

The conceptual model of the pressurized tank is shown in Fig. 25. Such test has yet to be fully studied. The pressurized tank has to be engineered, designed, studied with finite-element analysis (FEA) and, eventually, approved by the CERN Occupational Health and Safety and Environmental Protection Unit (HSE), before being purchased. A mechanical engineer will be necessary for this task. The design shall be optimized also for an easy opening and closure of the underwater vessel and shall ensure an easy and safe routing of the PMT cables from the vessel feedthroughs to outside the pressurised tank setup.

4.1.4 Long-term tests

As discussed in Sec. 3.2.2, the current 10-unit test will last until the end of 2024 verifying that all components of the underwater vessels can run reliably under extreme conditions. Additional tests are planned to be performed until Summer 2026. We are planning the delivery of the electronic boards in batches. A sub-sample of the unit components will be taken from each delivery batch and will be used to assemble 10 additional underwater electronics units. A 100 to 150 m long COM FT cable with two wire cables and optical fibers will allow testing voltage drop on the cable as well as to identify the presence of noise picked up from the environment. The cables coming out of the PMT FTs will be connected to 20 m long PMT cables, ensuring a watertight connection, and then soldered into 6 MΩ dummy load to simulate the PMT.

The test would be carried out by using the same infrastructure as that of the ongoing 10-unit test, i.e. the WA-105 cryostat tank in building 182 at CERN, as shown in Fig. 21. A test stand, analogous to the one used for testing the units during the assembly, will be used to control and monitor the whole system (Sec. 4.1.2).

4.2 Assembly project definition

The collaboration has identified the main project items, which include: the space for the storage of the 900 unit components, for the test and the assembly activities as well as for the shipment of the assembled units (see Sec. 4.2.1); the long-term tests, described in Sec. 4.1.4, to be carried out in the WA-105 cryostat in building 182 (see Sec. 4.2.2); qualified personnel (see Sec. 4.2.3), such as one mechanical engineer for the design of the test and assembly tools and equipment (see Sec. 4.1.1 and Sec. 4.1.3). Moreover, technicians will be needed to take on the more delicate tasks during the underwater unit assembly steps.

4.2.1 Space for storage and activities

The activities for the underwater unit can be divided in three macro areas: the storage area, to host the components just delivered from the supplier to the assembly site; the assembly and testing area; the shipping area. The estimated total amount of space needed, as shown in Fig. 27, is about about 850 m^2, of which 300 m^2 are for the tests and the assembly. For logistic reasons a close collocation of the various areas would be preferable. **Such first estimate is currently under study. Further optimisations, like increasing the pipelining of the underwater components, are ongoing in coordination with the CERN Neutrino Platform.**

Storage area

A big fraction of the area will be taken by the mechanical vessels, that could be stored outside still in the pallets used for the shipment. One pallet will contain 6 units, for a total approximate surface of 120 cm × 80 cm. As it would be worth avoiding the stacking of different pallets, it may be not trivial to further reduce the size of this area. Optimisation could rely on a higher delivery rate with smaller batches. For the electronics stands, boxes containing 10 units, for a total volume of 80 cm × 60 cm × 50 cm are estimated. They shall be stored inside and with the possibility of stacking boxes. Overall, about 150 units per month are expected. Concerning the PMT FTs, boxes containing 4 units, for a total volume of about 55 cm × 45 cm × 25 cm, can be stored inside. Both the LV and the HV boards, will be delivered in batches of 5 units contained in a box of about 60cm × 40cm × 50cm. They shall be stored inside with the possibility

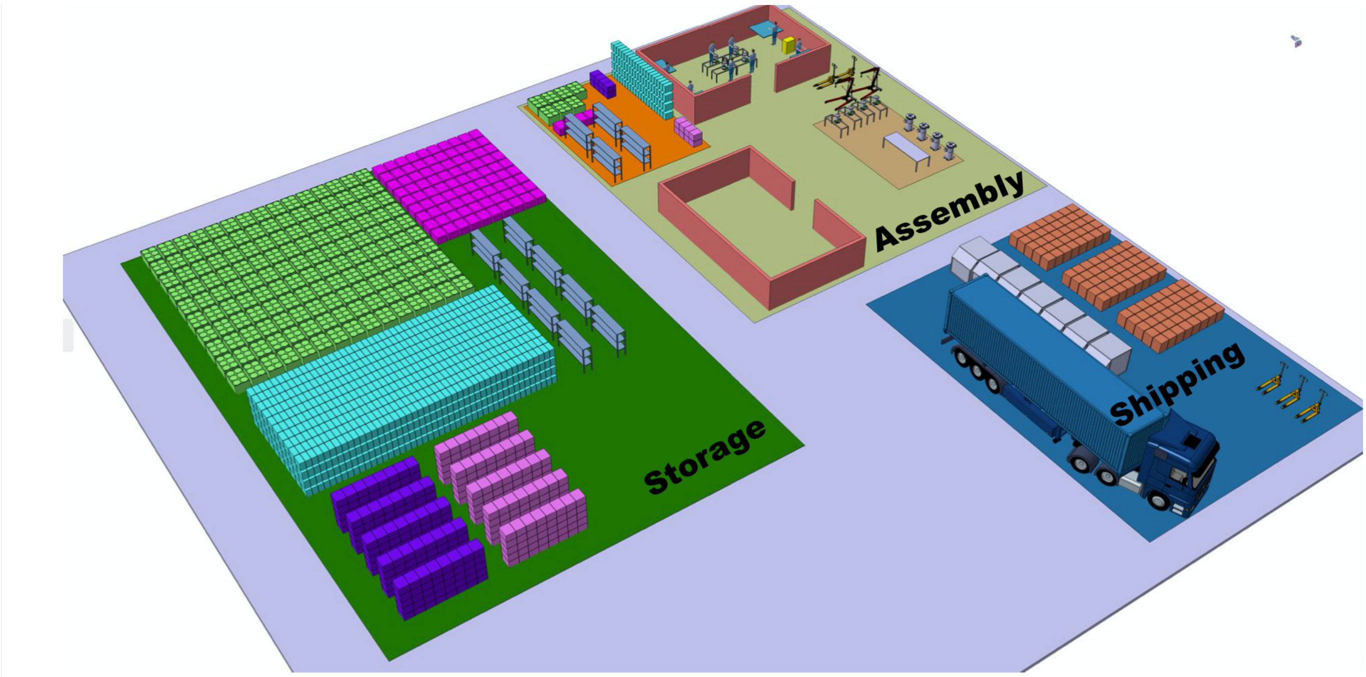

Figure 27: Estimated needed spaces for the various project activities: storage, assembly and tests, shipping.

of stacking up to 5 boxes in order to reduce the full area. Given the very similar dimension between the LV and HV modules, two areas of the same extension will be needed. The remaining components, i.e. COM FTs, digitizer boards, DPB boards, bolts and nuts, will need relatively small boxes and will take a small fraction of the total space, also because they can be stored in dedicated shelves.

The total area shall also facilitate the possibility of moving components from different places, also using movable cranes and a pallet transporter. Overall, a total area of approximately 250 m^2 has been estimated. It accounts for about 30% of the full capacity needed for all the 900 units, in order to provide enough buffer space in case the assembly has to stop but the delivery of the components from the supplier companies shall continue. The estimated storage area can be found in Fig. 28.

Assembly and Test area

This area shall be compatible with the planned daily routine needed for the assembly and the test of the underwater units. The assembly area will be divided into four main areas, for a total of approximately 300 m^2. It includes a weekly storage area to contain up to approximately 40 vessels. Further optimisation could be achieved if, for example, only daily vessel storage is planned. The assembly area will have to include at least 4 assembly stations where 8 people will work simultaneously. Depending on the space available, a tent for environment protection may be used. An area will be dedicated to the integrated electronics and pressurized tests, while another area might be needed if additional tests will have to be included or, for example, if offices will be needed.

In each assembly station the following daily routine is foreseen:

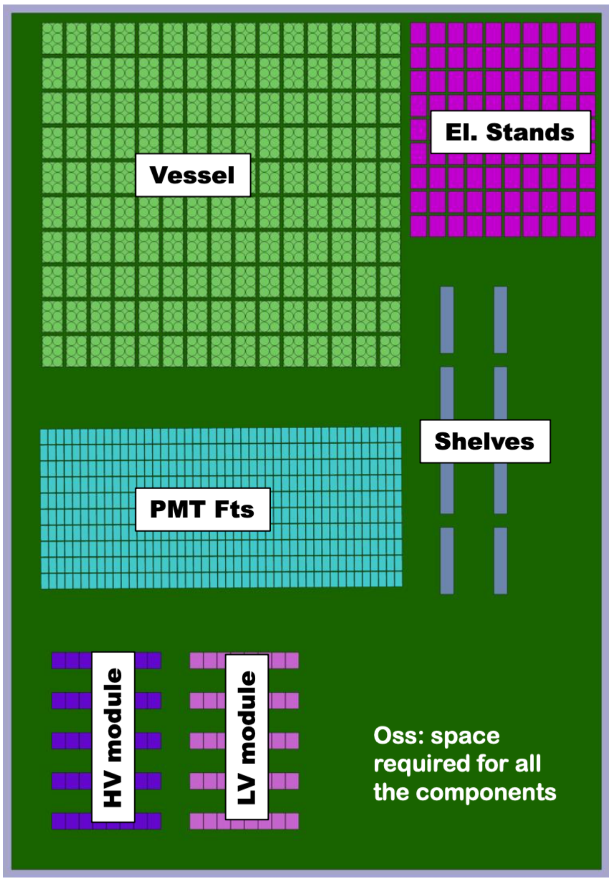

Figure 28: Estimated space needed for the storage of the underwater unit components.

- prepare the weekly/daily storage;
- prepare the assembly stations;
- start the assembly of the underwater unit with the electronics stand and the top flange;
- perform the first integrated system tests;
- close the vessel once the electronics units are installed inside;
- perform the final integrated system test in pressurized water to fake the conditions to which the underwater unit will be subjected once in the Hyper-K FD tank;
- place the assembled and validated underwater unit in the shipping box;
- eventually, the shipping box will be moved to the shipping area.

The estimated assembly and test area is shown in Fig. 29.

Shipping area

The shipping area will allow to store the boxes containing the underwater units ready to be shipped to

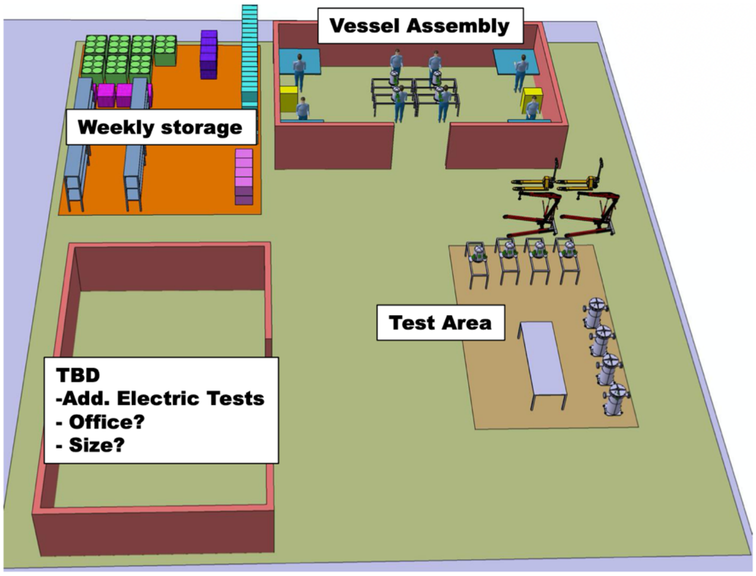

Figure 29: Estimated area of the area dedicated to the assembly and the test of the underwater units.

Japan. Preliminary estimates account for a weekly quantity of 20 to 40 boxes to be stored in this area. We are considering stacking of multiple boxes in order to reduce the size of the area.

A loading area shall include the space for the containers ready for shipment, the access for trucks to pick up the containers, and free space for workers to load and prepare the boxes.

Eventually, a buffer area is needed to prevent from piling up with multiple boxes and from filling the loading area, in case the shipping has to stop while the assembly activities continue. Ideally, the shipping/loading area should be relatively close to the assembly area to facilitate the movement of the boxes with the assembled units from one site to the other.

A total area of approximately 300 m^2 is currently considered. A sketch of the estimated area can be found in Fig. 30.

4.2.2 WA105 facility for long-term tests

As described in Sec. 4.1.4, we plan to perform long-term tests with some fully-assembled underwater units. The test would be carried out by using the same infrastructure as that of the ongoing 10-unit test, i.e. the WA-105 cryostat in building 182 at CERN, as shown in Fig. 21.

4.2.3 Person power and technical personnel

Several of the project tasks can be carried out by the members of the Hyper-K collaboration:

- testing the electronics with the available test benches or moving components from one site to the other. Standard tasks will be taken by "shifters", i.e. members of the Hyper-K collaboration with no particular roles in the project or technical qualifications;

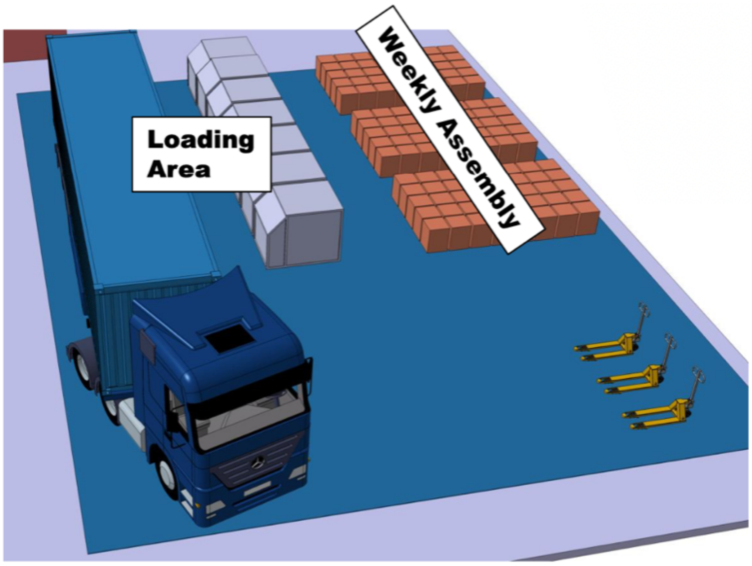

Figure 30: Estimated area dedicated to the storage of the assembled underwater units and the shipment to the Hyper-K site in Japan.

- supervise the logistic, i.e. check the arrival of the equipment, the workflow, and keep the contact with CERN staff (shipment and safety). This role will be taken by the project technical coordinators present on site;
- supervise each sub-system of the underwater unit. This task will be taken by the contact persons listed in Fig. 23;
- overall supervision of the project. It will be ensured by the spokepersons, with the support of the technical coordinators.

However, the project will also necessitate dedicated person power to carry out particular tasks:

- 8 qualified technicians to take care of the main assembly work of the underwater units (8 hours per day, 5 days per week for 45 weeks, for a total of 14'400 hours). The goal is to complete the assembly of at least 4 vessels per day. Tasks like the installation of the feedthrough assemblies in the vessel are critical and delicate, hence they cannot be taken by the shifters. The technicians would be hired from the CERN Field Support Units (FSU) and will be budgeted within the Hyper-K funding scheme;
- External company for the preparation of the boxes for transportation. The work will have to be carried out on-site (e.g. filling the shipping containers). The outside of the vessel should be sufficiently clean to not degrade the FD water quality, for instance by placing it in a vinyl bag, like the one used for 20-inch PMT (still, before the installation in the FD the vessels and the cables will be cleaned);
- support from CERN staff for shipping, i.e. for usage of crane, forklift, etc. 3 persons, 2 days per week for 45 weeks for a total of about 2'160 hours are considered a reasonable preliminary estimate;

- A mechanical engineer in charge of the design and the production of the custom-made equipment (approximately 1 month of full-time work), that would be hired from the CERN FSU and budgeted within the Hyper-K funding scheme.

4.2.4 Computing

In addition to the items described above, it will be useful to have dedicated computing resources to store the data collected during the electronics tests. About 100 TB should be sufficient for the entire dataset.

4.3 Project milestones, time schedule and costs

4.3.1 Project schedule

The inputs to the project organization described in the previous section are based on realistic assumptions and, at the same time, fulfill the requirements of the overall Hyper-K schedule.

The schedule of the assembly project is shown in Fig. 31. The mass production of the sub-system components will start in the second half of 2023 and will end in Fall 2025. The production will be done in different batches that will be immediately shipped to CERN once ready. The batch sizes and delivery rate is currently under definition in order to optimise the space that can be provided for the project.

The currently ongoing activities at CERN, i.e. the vertical slice tests (VST) and the 10-units tests, have started recently. While they both will provide important results in Fall 2023, they will run for up to 1 year in order to check the stability of the system, both in and out of water, and validate the ageing of the underwater unit components.

The preparation for the project has started and the number of activities will increase, in particular starting from 2024 when the project plan will have to be finalised and the engineering work for the assembly stand, pressurised tank, electronics test bench will be ongoing.

The overall project will take about 2 years. It will mostly take place in 2025, starting from system tests, i.e. the calibration of the digitizer boards, followed by the actual assembly of the vessels. The shipment of the 900 underwater unit components will be done in different batches. The last batch is expected to arrive at the Hyper-K site in Kamioka by the end of August 2026.

4.3.2 Project costs

A preliminary cost estimate of the overall project includes a complete set of tools and commercial equipment for the assembly activities. The main items are related to the cleaning of screws and metallic parts before the assembly. Chemical products will be required and proper storage will have to be ensured. Also ultrasonic bath can be used. Shelves, tables, cupboard, etc. will be needed for the storage of small components as well as movable cranes and pallet transporters to facilitate the transport of the vessels.

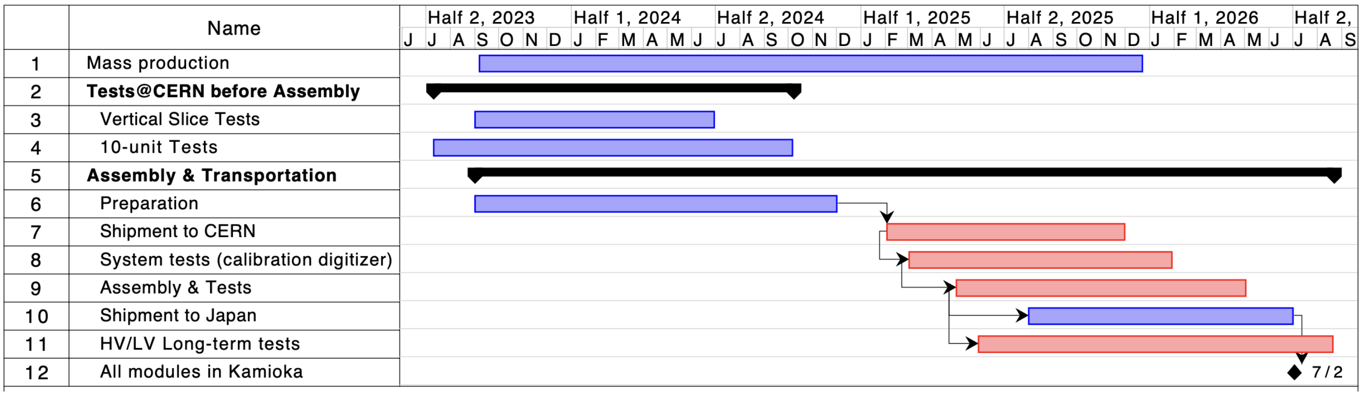

Figure 31: Simplified Gantt chart of the Hyper-K Assembly project.

Four pressurised tanks (one for each assembly stand) plus spares for testing the integrated underwater unit in pressurised water will have to be produced, after the custom design has been completed and validated. Four supports stands, one for each assembly station, (plus spares) for vessel assembly have to be procured.

Electronics test benches for the calibration of the digitizer boards and the tests of the underwater units will be needed as well.

The cost of the person power has been estimated. It does not include the cost for "shifters", which will be accounted for independently by each institute. Instead, one mechanical engineer (part-time), technicians for the underwater unit assembly (both from CERN FSU) and personnel for the shipment (CERN Staff) are taken into account. A more detailed description of the person power can be found in Sec. 4.2.3.

Finally, a preliminary estimate of the shipment cost has been done accounting for the procurement of the shipment boxes, the in-loco packaging at CERN by the shipment company, the actual shipment from CERN to Kamioka in Japan.

A preliminary total cost of about 2,400 kCHF has been estimated. It includes a 30% cost contingency. Cost optimisation is ongoing and updates are expected by the time of the submission of the final proposal to the SPSC. **The Hyper-K collaboration will cover the full cost of the project, including the additional qualified personnel. No funding is requested to CERN.**

5 Conclusions and Outlook

The Hyper-K long-baseline neutrino experiment will search for leptonic CP violation in long-baseline neutrino flavor oscillations with a realistic potential of discovery within 3 to 10 years after the start of the data taking. It will measure the CP violating phase with a resolution better than 23° depending on its value and define the neutrino mass ordering with a significance better than four standard deviations by combining data from accelerator and atmospheric neutrinos. Beside the accelerator neutrino physics, Hyper-K will achieve unprecedented sensitivities to the detection of proton decays as well as supernova and astrophysical neutrinos.

The Hyper-K experiment has now entered its construction phase and will start collecting accelerator and atmospheric neutrino data in 2027. An essential contribution is given by European institutes, in particular to the far detector underwater electronics system, that will allow to operate the about 23,600 PMTs, of which 20,000 20-inch PMTs of the inner detector and 3,600 3-inch PMTs of the outer detector. Each of about 900 underwater electronics units comprises a module that provides the high voltage to the PMTs, two boards that digitize the analogue signal received from the PMTs, a data signal processing board, and a low voltage module that provides power to all the modules within the vessel. The digitized signal is sent to the on-surface DAQ system via up to 150 m long electro-optical cables used for both data and power. All the components are contained in a stainless steel vessel that will be installed underwater in the far detector tank and exposed to pressures up to 7 bars. The PMT signal, power and optical cables reach the sub-system modules inside the vessel through water-tight feedthroughs.

With this Letter of Intent we propose to base the test and the assembly of the 900 underwater electronics units at the CERN Neutrino Platform. We need to collect the sub-system components, calibrate the digitizer boards, assemble the underwater electronics units, test them in water under pressure and ship them to the far detector site in Kamioka. Such project is a common effort lead by the European institutes involved in Hyper-Kamiokande, that would have easy access to the experimental facilities at CERN. We will need space to store the sub-system components upon their arrival at CERN, assemble and test them and store the assembled vessels before the shipment to Japan. Technical expertise (mechanical engineer and technicians) and support for the shipment will be needed. CERN with its Neutrino Platform has been identified as the ideal framework to carry out such project. After a preparatory phase, the test and the assembly activities will start in early 2025 and will last for about 1.5 years. The WA105 cryostat tank, being used for the 10-units test, would be needed to perform additional long-term tests with sub-system components from different batches for the whole duration of the project. The project will be fully funded by the Hyper-K collaboration, including the technical personnel. A preliminary project cost estimate is also provided in this Letter of Intent.

Full support has been expressed by the leaders of the Neutrino Platform to host the project under its program. Currently, discussions are ongoing in order to optimise the implementation of the project, like the space required.

6 Acknowledgements

We thank Francesco Lanni and Filippo Resnati, respectively the head and the technical coordinator of the CERN Neutrino Platform, for the very fruitful discussions and their support to the project.

References

[1] Y. Fukuda et al. Evidence for oscillation of atmospheric neutrinos. *Phys. Rev. Lett.*, 81:1562–1567, 1998.

[2] Q. R. Ahmad et al. Measurement of the rate of $\nu_e + d \to p + p + e^-$ interactions produced by ^{8}B solar neutrinos at the Sudbury Neutrino Observatory. *Phys. Rev. Lett.*, 87:071301, 2001.

[3] Q.R. Ahmad et al. Direct evidence for neutrino flavor transformation from neutral current interactions in the Sudbury Neutrino Observatory. *Phys. Rev. Lett.*, 89:011301, 2002.

[4] K. Eguchi et al. First results from KamLAND: Evidence for reactor anti-neutrino disappearance. *Phys. Rev. Lett.*, 90:021802, 2003.

[5] M.H. Ahn et al. Measurement of Neutrino Oscillation by the K2K Experiment. *Phys. Rev. D*, 74:072003, 2006.

[6] M. Tanabashi et al. Review of Particle Physics. *Phys. Rev. D*, 98(3):030001, 2018.

[7] K. Abe et al. Indication of Electron Neutrino Appearance from an Accelerator-produced Off-axis Muon Neutrino Beam. *Phys. Rev. Lett.*, 107:041801, 2011.

[8] Y.Ajima et al. Tokai-to-Kamioka (T2K) Long Baseline Neutrino Oscillation Experiment Proposal. http://j-parc.jp/researcher/Hadron/en/pac_0606/pdf/p11-Nishikawa.pdf.

[9] K. Abe et al. The T2K Experiment. *Nucl. Instrum. Meth. A*, 659:106–135, 2011.

[10] F.P. An et al. Observation of electron-antineutrino disappearance at Daya Bay. *Phys. Rev. Lett.*, 108:171803, 2012.

[11] M. A. Acero et al. Improved measurement of neutrino oscillation parameters by the NOvA experiment. *Phys. Rev. D*, 106(3):032004, 2022.

[12] Fengpeng An et al. Neutrino Physics with JUNO. *J. Phys. G*, 43(3):030401, 2016.

[13] B. Abi et al. Long-baseline neutrino oscillation physics potential of the DUNE experiment. 6 2020.

[14] S. Pascoli, S.T. Petcov, and Antonio Riotto. Connecting low energy leptonic CP-violation to leptogenesis. *Phys. Rev. D*, 75:083511, 2007.

[15] K. Abe et al. Constraint on the matter–antimatter symmetry-violating phase in neutrino oscillations. *Nature*, 580(7803):339–344, 2020. [Erratum: Nature 583, E16 (2020)].

[16] K. Abe et al. Improved constraints on neutrino mixing from the T2K experiment with $\mathbf{3.13 \times 10^{21}}$ protons on target. *Phys. Rev. D*, 103(11):112008, 2021.

[17] K. Abe et al. The Hyper-Kamiokande Experiment - Snowmass LOI. In *2021 Snowmass Summer Study*, 9 2020.

[18] K. Abe et al. Hyper-Kamiokande Design Report. 5 2018.

[19] K. Abe et al. T2K ND280 Upgrade - Technical Design Report. 1 2019.

[20] C. Bronner, Y. Nishimura, J. Xia, and T. Tashiro. Development and performance of the 20" PMT for Hyper-Kamiokande. *J. Phys. Conf. Ser.*, 1468(1):012237, 2020.

[21] S. Bhadra et al. Letter of Intent to Construct a nuPRISM Detector in the J-PARC Neutrino Beamline. 12 2014.

[22] M. Barbi et al. Proposal for A Water Cherenkov Test Beam Experiment for Hyper-Kamiokande and Future Large-scale Water-based Detectors. Technical report, CERN, Geneva, 2020.

[23] Megan Friend. Long-Baseline Neutrino Oscillation Physics Sensitivities of the Hyper-Kamiokande Experiment (NuFact 2022). https://indico.fnal.gov/event/53004/contributions/244613/. (NuFact 2022).

[24] K. Abe et al. Supernova Model Discrimination with Hyper-Kamiokande. *Astrophys. J.*, 916(1):15, 2021.

[25] Michael Smy. Hyper-Kamiokande (NuFact 2022). https://indico.fnal.gov/event/53004/contributions/242342/. (NuFact 2022).

[26] Benjamin Richards. ToolDAQ framework v2.1.1. https://doi.org/10.5281/zenodo.1482767, November 2018.