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**Development and optimization of detector and
electronics system for Hyper-Kamiokande**

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Introduction

Neutrino physics plays a crucial role in the understanding of our universe. In the last centuries many important experiments focused their attention on neutrinos. Those are characterized by a very small mass (indeed they are massless for the Standard Model) and no electric charge. They interact only through weak interactions, making them even more difficult to detect.

In the last decades, one of the country that contributed with some of the most important results in this field is Japan, thanks to the Kamiokande and Super-Kamiokande (Super-K) experiment, both of them recognized with a Nobel Prize, both hosted by Japanese institutions.

Hyper-Kamiokande (Hyper-K) is the next generation of large-scale water Cherenkov detector in Japan. With a volume an order of magnitude bigger than its predecessor Super-Kamiokande, with an improved photosensors' system and beamline, Hyper-K aims to obtain exciting results in many fields such as the study of CP violation in the leptonic sector, the search for proton decay and the study of atmospheric neutrinos and neutrinos from astronomical origin.

For the Hyper-K far detector the collaboration decided to adopt a hybrid configuration that combines the 20" PMTs, already adopted in Super-K but improved with a better performance, with the multi-PMT (mPMT) modules, a novel technology first designed for the KM3NeT experiment. This detector consists of a number of 3" PMTs inside a vessel, each one with a different orientation. A big improvement in the event reconstruction is expected with this solution, especially thanks to an improved directional sensitivity, better timing and energy resolutions and an overall lower dark rate. The electronics systems for the two photosensor systems are the aim and the result of this work, in particular the development of the final version of the electronics for the mPMT system and the development of a novel proposal for the 20" PMTs digitizer system, that is also now in the final stages of the R&D. Also, a combination of the two electronics has been adopted as the main point for the development of the Front End for the Outer Detector 3" PMTs that will be mainly used as veto.

This work is organized as follows:

- A brief introduction to neutrino physics is given in the first chapter, with a description of the principal experimental results in the sector, in particular on the investigation of leptonic CP violation and to the study of neutrinos from supernovae.
- The second chapter is dedicated to an introduction to the Hyper-K exper-

iment, in particular with a description of the detector and its capability in the various different fields where it will be important. A brief introduction and description of a test experiment at CERN, called WCTE (Water Cherenkov Test Experiment) will also be provided, since we will see that this test will be the final test before mass production for the proposed new mPMT detector in Hyper-K.

- The third chapter describes the Hyper-K photosensors, both the 20" PMT and the mPMT. We discuss the main characteristics of the photosensors and the improvements to the physics capabilities in Hyper-K, in particular for the mPMT.
- In the forth chapter we will describe a general overview of the Electronics in the experiment and also a brief description of the Data Acquisition and timing system will follow.
- The fifth chapter describes the mPMT as a whole detector. We will focus mainly on the electronics system for the mPMT and its development, but also the mechanics and all the prototypes developed in the years will be described. We will see that now the detector is basically ready for the mass production of the experiment which will start in early 2025.
- The sixth chapter is dedicated to the development of the 20" PMT electronics system. The work is focused on the development of the digitizer, that acquires the PMT signals to produce digital signals for charge and time measurements. Also this system is now basically ready for mass production, with the planned schedule to start the electronics assembly by summer 2025.
- The seventh chapter is dedicated to the future application of the work developed in this work. In particular we will focus on the development of a mPMT detector for another experiment that is now in the R&D phase, the Southern Wide-field Gamma-ray Observatory (SWGO), that will be the largest gamma ray observatory ever built and will observe the southern sky of the planet.

This work has been realized in collaboration with the electronic workshop of the Naples INFN section. The systems developed in this work will be the core of the whole detection and acquisition system for the Hyper-K experiment, that hopefully will lead the neutrino physics for the next couple of decades. Part of this work is also of interest of another experiment, SWGO, which will also lead the gamma ray observation in the south hemisphere for the next decades.

Chapter 1

Neutrino Physics

Neutrinos were introduced by W. Pauli in a famous letter dated 4 December 1930. The idea was to introduce a neutral particle needed to explain the problem of the missing energy in the beta decay. Initially this particle has been called "neutron".

James Chadwick discovered another neutral nuclear particle in 1932 and named it a neutron also, leaving two kinds of particles with the same name. The word "neutrino" entered the scientific vocabulary through Enrico Fermi, who used it during a conference in Paris in July 1932 and at the Solvay Conference in October 1933, where Pauli also employed it. The name (the Italian equivalent of "little neutral one") was coined by Edoardo Amaldi during a conversation with Fermi at the Institute of Physics of via Panisperna in Rome, in order to distinguish this light neutral particle from Chadwick's heavy neutron.

The first detection of a neutrino came only in 1956, when C. Cowan and F. Reines observed neutrinos for the first time using the beta decays from the Savannah River nuclear reactor in South Carolina [1].

1.1 Neutrinos in standard model

The Standard Model (SM) is the most complete model to describe particles and their interactions, in particular, it describes the electroweak and the strong interactions. An overview is included in Fig. 1.1. The Standard Model is based on the idea that everything in the universe is made up of elementary *fermions* interacting through fields. The particles associated with the interaction fields are *bosons*.

Fermions are particles of spin $1/2$ that can be further divided into two families:

- *quarks*, the constituents of all the hadrons, which interact via strong and electroweak interactions;
- *leptons*, which interact only via electroweak interactions.

Bosons have integer spin and are the mediator of the strong and electroweak interactions. They correspond to the massless gluons g , the massive $W^\pm$ and Z_0 and the photon γ .

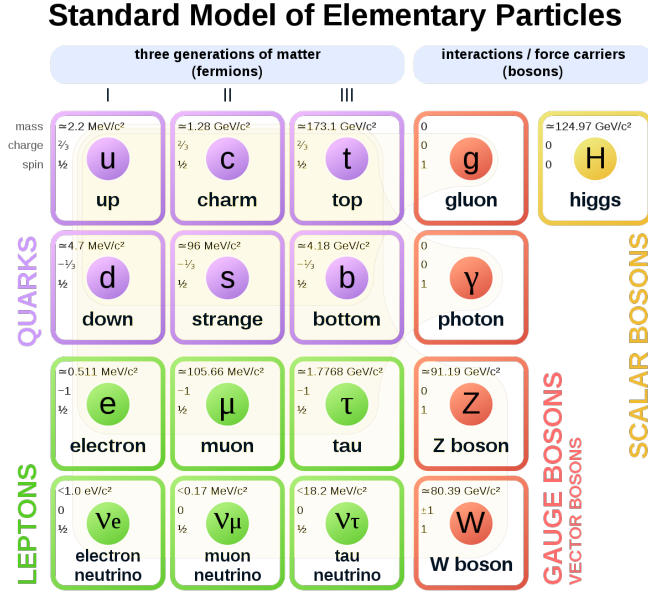


Figure 1.1: A graphical overview of the Standard Model particles and interaction mediators along with their properties. For each particle the mass, charge and spin are reported in the corresponding box.

The Higgs boson H is also part of the SM and both the fermions and the electroweak gauge bosons obtain their masses through the Higgs mechanism. The existence of this mass-giving field was confirmed only in 2012, when the Higgs boson particle was discovered at CERN thanks to the ATLAS [2] and CMS [3] experiments.

Neutrinos in the SM are leptons and exist in three flavors: the electron neutrino ν_e , the muon neutrino ν_μ and the tau neutrino ν_τ . Each flavor is identified by a leptonic family number. Neutrinos are considered massless in the SM.

Neutrinos in SM can interact with matter only via the weak interaction exchanging a $W^\pm$ boson (charged-current interaction, CC) or a Z_0 boson (neutral-current, NC). In a CC process a neutrino (antineutrino) in the initial state converts into a charged lepton in the final state. Due to the conservation of the leptonic number the flavor of the incoming neutrino gives the flavor of the outgoing lepton, while its charge depends on if the incoming neutrino is a neutrino or an antineutrino. A NC mediated process presents both an incoming and an outgoing neutrino (antineutrino). In Fig. 1.2 are reported the Feynman diagram of (anti)neutrino interaction vertex in the case of CC (left) and NC (right) interactions.

In the next sections a description of the framework of neutrino oscillation will follow, both from a theoretical and experimental point.

1.2 Neutrino Oscillation

The first idea of neutrino oscillation was introduced by Pontecorvo in 1957 [4][5]. At that time only the first neutrino family had been discovered and he proposed

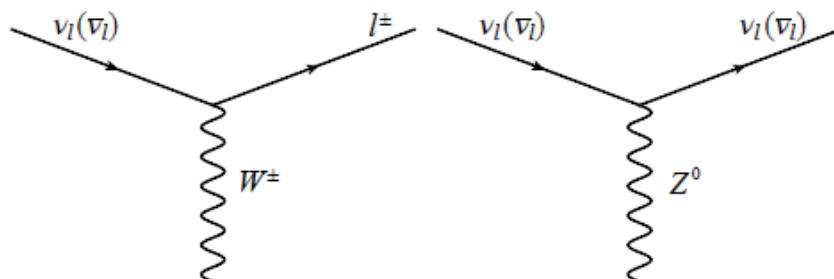


Figure 1.2: Feynman diagram of (anti)neutrino interaction vertex in the case of CC (left) and NC (right) interactions. In the first case the outgoing lepton is positive if the interaction involve antineutrino and it is negative in the other case. The exchanged W boson is negative in antineutrino interaction.

the possibility of having a neutrino/antineutrino oscillation of the type $\nu \leftrightarrow \bar{\nu}$ in analogy with $K_0 \leftrightarrow \bar{K}_0$. After the discovery of a second neutrino family, Z. Maki, M. Nagakawa and S. Sakata considered the possibility of having oscillations of neutrinos among the different types [6].

The evidence of oscillations accumulated from the observation of solar and atmospheric neutrinos over many years. The decisive role of the results of SNO (Sudbury Neutrino Observatory) [7] and Super-Kamiokande (Super-K) [8] as a proof of oscillations was recognized with the Nobel prize in 2015.

1.2.1 The Solar Neutrino Problem

The Sun is a very powerful source of electron neutrinos, thanks to the thermonuclear fusion reactions happening inside it. Solar neutrinos fluxes are predicted by the Solar Standard Model (SSM) developed by J. Bahcall [9]. Two main cycles occur in the Sun, the pp-chain and the CNO cycle, a schematic view is presented in Fig. 1.3.

Neutrinos interact weakly with matters, so they travel from Sun to Earth without any appreciable absorption by the Sun's outer layers. Since they are produced by many different reactions, they will have different energies, so we expect a spectra, that is the one predicted by the SSM, as shown in Fig. 1.4. In the same picture it is also possible to see the different threshold of the main solar neutrino experiments.

The Homestake experiment [11], in the late 1960's by R. Davis, was the first to measure solar neutrino flux. After several years of running, the experiment produced a results for the average capture rate of solar neutrinos of 2.56 ± 0.25 SNU, where 1 SNU corresponds to 10^{-36} neutrino interactions per target atom per second. The results were not in agreement with the prediction of the SSM of 8.1 ± 1.2 SNU, three times larger than the measured rate. This discrepancy became known as the **Solar Neutrino Problem**. By looking at Fig. 1.4, it's possible to see that Chlorine experiments can just observe part of the ${}^7\text{Be}$ line and higher energy components, so not the most of the neutrino flux that comes from the pp neutrinos with energies below 0.4 MeV.

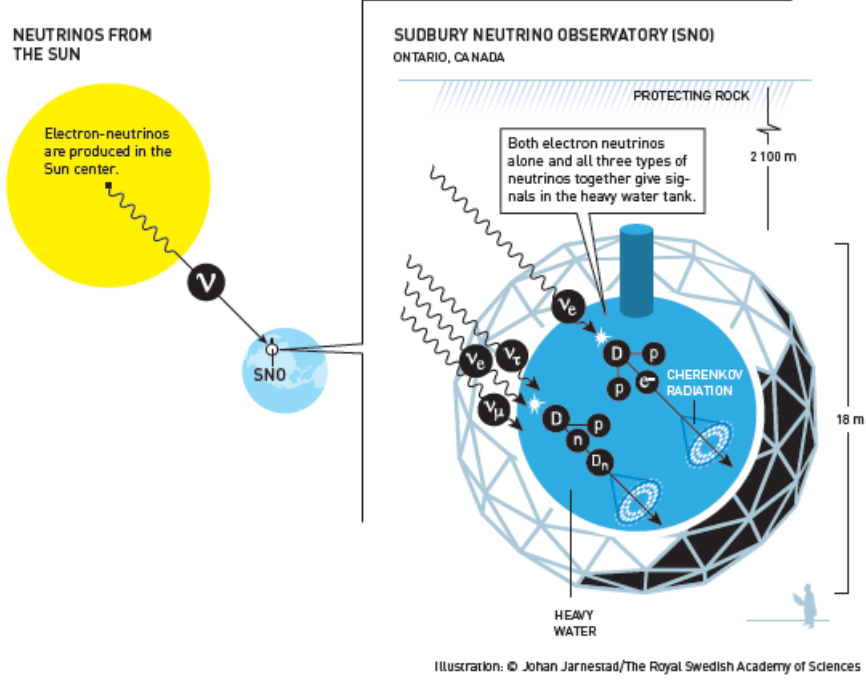


Figure 1.5: Schematic overview of the SNO experiment. Figure from [14].

A later measurements has been provided by Kamiokande Water Cherenkov experiment and later Super-K, through the elastic scattering channel $\nu_e + e^- \rightarrow \nu_e + e^-$. This channel is important, since it is possible to study the direction on the incoming neutrinos and in this way Super-K proved that the electron neutrinos indeed come from the sun.

A last important proof of the flux problem came from Gallium experiments, like SAGE, that ran with 57 ton of Gallium and observed a capture rate of $70.8 \pm 5.0 SNU$ [12] (the prediction was $129 \pm 9 SNU$, and GALLEX that observed a rate of $77.5 \pm 8 SNU$ [13]). These observations indicate that the deficit is energy dependent.

The final answer to the solar neutrino problem was found in 2002 by the SNO (Subdury Neutrino Observatory) experiment. This experiment was able to detect not only the CC and elastic scattering electron neutrinos interaction, but also NC interactions with the deuterium nuclei that involve any neutrino flavor (see Fig. 1.5). The results [15] was the following:

$$\begin{aligned}\phi_{ES} &= \phi(\nu_e) + 0.15(\phi(\nu_\mu) + \phi(\nu_\tau)) = 2.39 \pm 0.26 SNU \\ \phi_{CC} &= \phi(\nu_e) = 1.76 \pm 0.01 SNU \\ \phi_{NC} &= \phi(\nu_e) + \phi(\nu_\mu) + \phi(\nu_\tau) = 5.09 \pm 0.63 SNU\end{aligned}$$

The total flux of the three flavors was roughly 3 times larger than the flux of the only ν_e . Since the Sun produces only electron neutrinos, the only possible

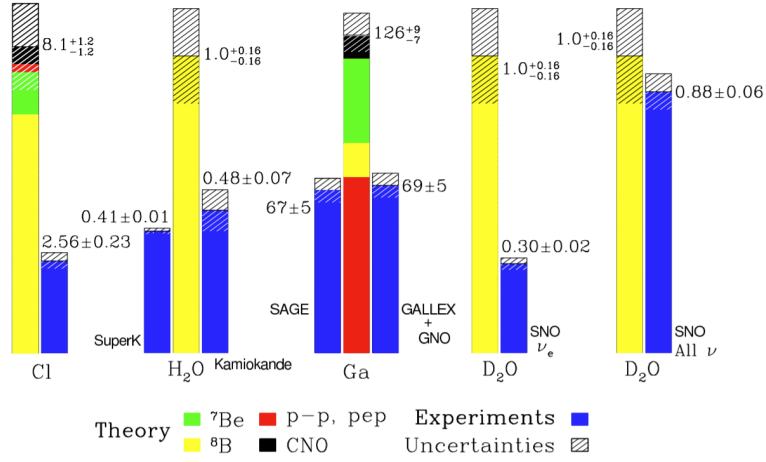


Figure 1.6: The state of the solar neutrino problem until SNO. Each group of bars represents a different type of experiment: starting from the left Chlorine, water, Gallium and D_2O experiments. The blue bars in each cluster represent the measurements of individual experiments, in SNUs. The middle bar shows the Standard Solar Model prediction. In all cases, the measurements are less than predicted. Figure taken from [16].

conclusion is that in the path from the Sun to the detector, neutrinos must change flavor, that's why previous experiments were seeing less electron neutrinos than expected. A summary of all the experiments' results is reported in Fig 1.6.

1.2.2 Atmospheric Neutrino Anomaly

Atmospheric neutrinos are typically produced when a cosmic ray crashes into Earth's atmosphere. These are mainly composed by protons (95%), alpha particles (5%) and heavier nuclei (<1%). When the primary cosmic rays hit nuclei in the atmosphere a cascade of hadrons is generated. The atmospheric neutrinos stem from the decay of these hadrons during flight. In general, the spectra of these neutrinos peaks at about 1 GeV and extends up to hundreds of GeV, as seen in Fig. 1.7.

The experimental data are reported in terms of μ -like and e -like events and the criterion used to reveal an anomaly is the ratio-of-ratios, also called *double ratio*,

$$R_{\mu/e} = \frac{(N_{\mu-like}/N_{e-like})_{data}}{(N_{\mu-like}/N_{e-like})_{MC}} \quad (1.1)$$

where $(N_{\mu-like}$ and N_{e-like} are the numbers of μ -like and e -like events respectively, while the numerator is the ratio obtained by the data and the denominator the one predicted by the Monte Carlo (MC) simulation. An anomaly is so defined as a double ratio different from unity. A summary of $R_{\mu/e}$ values obtained by different experiments are reported in table 1.1. It is possible to see that all the experiments, with the expectation of Frejus, measured a $R_{\mu/e}$ well below 1. This became known as the **Atmospheric Neutrino Anomaly**.

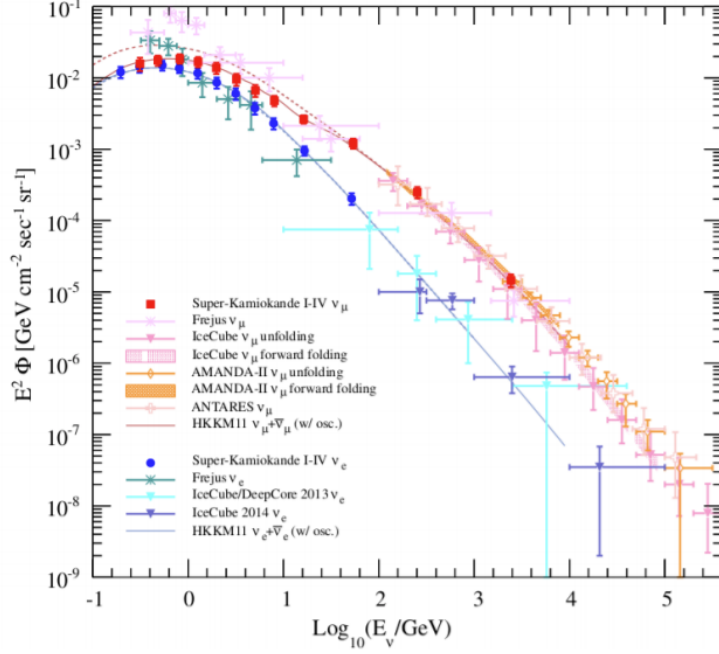


Figure 1.7: Present measurements of the atmospheric neutrino energy spectrum, compared with theoretical predictions. Figure from [17].

Experiment	Type of experiment	$R_{\mu/e}$
Super-Kamiokande [18]	Water Cherenkov	0.675 ± 0.085
Soudan2 [19]	Iron Tracking Calorimeter	0.6 ± 0.1
IMB [20]	Water Cherenkov	0.54 ± 0.12
Kamiokande [21]	Water Cherenkov	0.60 ± 0.07
Frejus [18]	Iron Tracking Calorimeter	1.0 ± 0.15

Table 1.1: Measurements of the double ratio for various atmospheric neutrino experiments

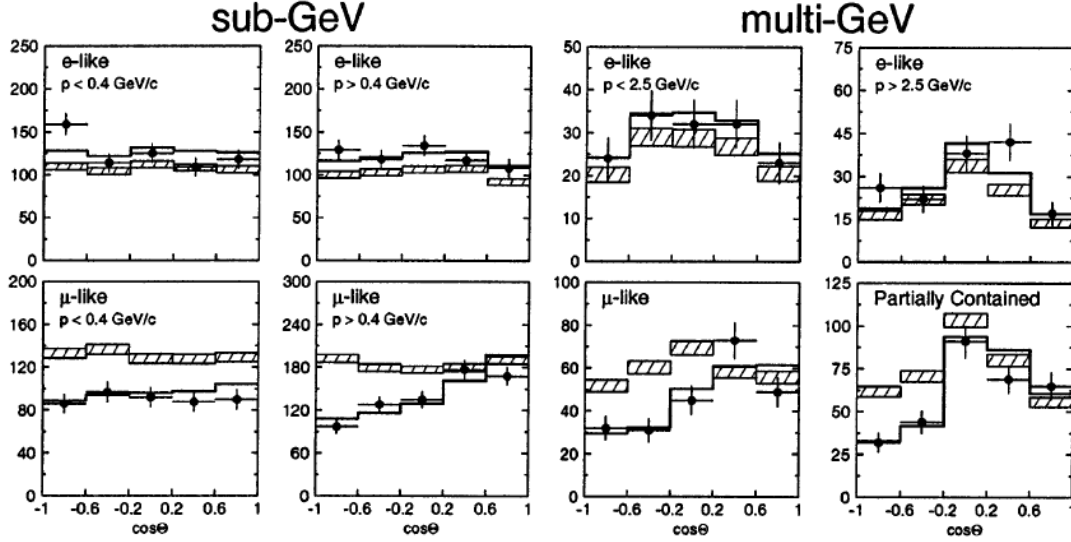


Figure 1.8: Zenith angle distribution of events for sub-GeV and multi-GeV data sets. Upward-going particles have $\cos\theta < 0$ and downward-going particles have $\cos\theta > 0$. The bold line is the best fit expectation considering $\nu_\mu \rightarrow \nu_\tau$ oscillation, while the hatched region shows the Monte Carlo prediction for no oscillations. Figure taken from [22].

Super-K was able to measure also the direction of the incoming neutrinos. In principle, one expects that the neutrinos' flux is isotropic, since they are produced everywhere in the atmosphere. In 1998 Super-K proved that neutrinos flux observed depends on the zenith angle distribution [22] (see Fig. 1.8). In the figure it is possible to see that there is an important deviation for muon-like events, while the electron-like events are in agreement with the expectation. At low energies, about half of ν_μ are missing over the full range of zenith angles. At high energy, the number of ν_μ coming down from above the detector seems to agree with expectation but half of the same ν_μ coming up from below the detector are missing. These results can be easily explained within the context of neutrinos' flavor oscillations.

1.2.3 Neutrino Oscillation in Vacuum

In the previous paragraphs it has been outlined many hints on neutrino oscillations, in the subsequent sections a more structured approach will follow to describe this phenomena.

It is possible to define the mass eigenstates as the stationary states of the free-particle Hamiltonian, satisfying the equation:

$$\hat{H}\psi = E\psi, \quad (1.2)$$

where $E = \sqrt{m^2 + p^2}$, considering neutrino massive and in the relativistic approximation.

The mass eigenstates are labelled ν_1 , ν_2 and ν_3 and they evolve as a plane wave as

$$|\nu_i(t)\rangle = |\nu_i(0)\rangle e^{-ip_i \cdot x} = |\nu_i(0)\rangle e^{ip_i \cdot \vec{x} - E_i t} \quad i = 1, 2, 3 \quad (1.3)$$

where $(E_i, \vec{p}_i)$ are the energy and the momentum of the mass eigenstates ν_i and the product $p_i \cdot x$ is the Lorentz-invariant phase.

The neutrino weak (or flavor) eigenstates, which by definition are the members of the weak isospin doublets that transform into each other through interaction with the W boson, are instead labelled ν_e , ν_μ , ν_τ and the fact that the mass eigenstates do not correspond to the flavor eigenstates is the cause of the neutrino oscillations.

The weak eigenstates ν_α are, in general, linear combinations of the mass eigenstates ν_i with $i = 1, 2, 3$:

$$|\nu_\alpha\rangle = \sum_{i=1}^{n=3} U_{\alpha i}^* |\nu_i\rangle \quad (1.4)$$

where U represents the *PMNS matrix* (*Pontecorvo-Maki-Nakagawa-Sakata matrix*), a mixing matrix analogue of the *CKM matrix* for quarks. The standard parametrization of the PMNS matrix employs 3 rotation matrices and 3 complex phases:

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \quad (1.5)$$

where:

$$\begin{aligned} U &= \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \cdot \\ &\cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\beta} & 0 \\ 0 & 0 & e^{i\gamma} \end{pmatrix} = \\ &= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \\ &\cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\beta} & 0 \\ 0 & 0 & e^{i\gamma} \end{pmatrix}, \quad c_{ij} = \cos \theta_{ij} \quad , \quad s_{ij} = \sin \theta_{ij} \quad (1.6) \end{aligned}$$

The mixing is a function of three *mixing angles* (θ_{12} , θ_{23} and θ_{13}). The phase factors *beta* and *gamma* are no-zero only if neutrinos are Majorana particles, and do not enter into oscillation phenomena regardless. The phase factor δ is no-zero only if neutrino oscillation violates the CP symmetry. If experiments show this 3×3 matrix to be not unitary, a sterile neutrino or some other new physics is required.

After travelling a distance L (or, equivalently for relativistic neutrinos, a time t), a neutrino originally produced with flavour α evolves as follows:

$$|\nu_i(t)\rangle = e^{-i(E_it - \vec{p}_i \cdot \vec{x})} |\nu_i(0)\rangle \quad (1.7)$$

In the ultra-relativistic limit ($|\vec{p}_i| = p_i \gg m_i$) one can approximate the energy as:

$$E_i = \sqrt{p_i^2 + m_i^2} \simeq p_i + \frac{m_i^2}{2p_i} \approx E + \frac{m_i^2}{2E} \quad (1.8)$$

assuming $p_i \simeq p_j \equiv p \simeq E$. Using $t \simeq L$ and also dropping the phase factors, the wave function becomes:

$$|\nu_i(t \simeq L)\rangle = e^{-im_i^2 \frac{L}{2E}} |\nu_i(0)\rangle \quad (1.9)$$

Considering this last relation, the probability that a neutrino originally of flavor α will later be observed as having flavor β is given by:

$$P_{\alpha \rightarrow \beta} = |\langle \nu_\beta | \nu_\alpha(t) \rangle|^2 = \left| \sum_i U_{\alpha i}^* U_{\beta i} e^{-im_i^2 \frac{L}{2E}} \right|^2 \quad (1.10)$$

or in more convenient form:

$$P_{\alpha \rightarrow \beta} = \delta_{\alpha\beta} - 4 \sum_{i>j} \Re \left(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^* \right) \sin^2 \left(\frac{\Delta m_{ij}^2 L}{4E} \right) \quad (1.11)$$

$$+ 2 \sum_{i>j} \Im \left(U_{\alpha i}^* U_{\beta i} U_{\alpha j} U_{\beta j}^* \right) \sin \left(\frac{\Delta m_{ij}^2 L}{2E} \right) \quad (1.12)$$

where $\Delta m_{ij}^2 \equiv m_i^2 - m_j^2$ with $i, j = 1, 2, 3$. Restoring c and $\hbar$ the *oscillation phase*, that is responsible for oscillation, is often written as:

$$\Phi_{ij} = 1.27 \Delta m_{ij}^2 [\text{eV}^2] \frac{L [\text{Km}]}{E [\text{GeV}]} \quad (1.13)$$

where $L = ct \simeq t$ is the distance between the source of ν_α and the detector (i.e.

the detection point of ν_β). The transition probability $P_{\alpha \rightarrow \beta}$ has an oscillatory behavior, with *oscillation length*:

$$L^{\text{osc}} = \frac{4\pi E}{\Delta m_{ij}^2}. \quad (1.14)$$

The transition amplitude is proportional to the elements present in the mixing matrix. Thus, in order to have oscillations, neutrinos must have different masses ($\Delta m_{ij}^2 \neq 0$) and they must mix ($U_{\alpha i} U_{\beta i} \neq 0$), since flavor oscillation is due to interference between different mass eigenstates.

In order to be sensitive to a given value of Δm_{ij}^2 , an experiment has to be set up with $E/L \simeq \Delta m_{ij}^2$ (where L is the source-detector distance). If $E/L \gg \Delta m_{ij}^2$ ($\Rightarrow L \ll L^{\text{osc}}$) the oscillation does not have time to give an appreciable effect because $\sin^2 x_{ij} \ll 1$. For $E/L \ll \Delta m_{ij}^2$ ($\Rightarrow L \gg L^{\text{osc}}$), the oscillating phase goes through many cycles before detection and, since in general neutrino beams are not monochromatic, the phase is averaged to $\langle \sin^2 \theta_{ij} \rangle = 1/2$ and the oscillation pattern is vanished.

For a two neutrino case, the mixing matrix depends on a single parameter θ and there is a single mass-squared difference Δm^2 .

$$U = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix} \Rightarrow P_{\alpha \rightarrow \beta} = \delta_{\alpha\beta} - (2\delta_{\alpha\beta} - 1) \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{4E} \right) \quad (1.15)$$

Neutrino mass hierarchy

The combined information on neutrino oscillations and the upper mass limit from tritium decays show that the heaviest active neutrino state is nine to eleven orders of magnitude lighter than the other fermions in the third family. The oscillations experiments measure only mass squared differences and the mixing parameters, so cannot give information about the absolute neutrino mass. The *hierarchy scale* among the eigenvalues m_i is still unknown. Regardless of the absolute mass scale of the lightest neutrino, there are two possible hierarchies for the neutrino masses, shown in Fig. 1.9. In the normal hierarchy $m_3 > m_2$ and in the inverted mass hierarchy $m_2 > m_3$, with $m_1 \simeq m_2$.

CP symmetry violation in neutrino oscillation

Neutrino oscillations depend on a phase δ_{CP} of the PMNS matrix (Eq. 1.6), making so possible the observation of the CP violation in the neutrino oscillation.

The magnitude of the CP violation in neutrino oscillation can be characterized by the difference of the probabilities between neutrino and antineutrino appearance channels: $\Delta P_{\alpha\beta} = P(\nu_\alpha \rightarrow \nu_\beta) - P(\bar{\nu}_\alpha \rightarrow \bar{\nu}_\beta)$, that corresponds to twice the imaginary part of the neutrino oscillation probability (Eq. 1.11) [23]. It is

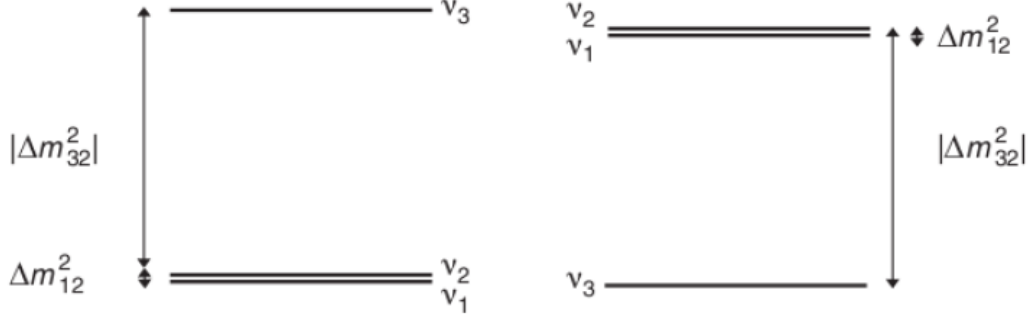


Figure 1.9: The two possible neutrino mass hierarchies, normal where $m_3 > m_2$ and inverted where $m_2 > m_3$, with $m_1 \simeq m_2$ -

possible to rewrite the magnitude of the CP violation as:

$$\Delta P_{\alpha\beta} = \pm 16J \sin \frac{\Delta m_{21}^2 L}{4E} \sin \frac{\Delta m_{31}^2 L}{4E} \sin \frac{\Delta m_{32}^2 L}{4E}, \quad J = \text{Im}[U_{\alpha 1} U_{\beta 1}^* U_{\alpha 2}^* U_{\beta 2}] \quad (1.16)$$

with a positive (negative) sign for (anti-)cyclic permutation of the flavor indices. The quantity J is a measure of CP violation of the PMNS matrix and is called **Jarlskog invariant**. Using the standard parametrization of the PMNS matrix it's possible to write:

$$J = \frac{1}{8} \cos \theta_{13} \sin 2\theta_{12} \sin 2\theta_{13} \sin 2\theta_{23} \sin 2\delta_{CP}. \quad (1.17)$$

Therefore, a necessary condition for CP violation in neutrino oscillation is that all three mixing angles are nonzero and the phase δ_{CP} is different from 0 and π . Another important condition came from Eq.1.16, implying that Δm_{21}^2 , Δm_{31}^2 and Δm_{32}^2 must be non vanishing, so all neutrino masses should be different.

The CP-violating term in neutrino oscillation is universal, so it does not depend on the oscillation channel (up to a sign) [23]. The effect of CP violation can be observed only in experiments that are sensitive to the subdominant oscillations governed by Δm_{21}^2 , since the CP violation effect is proportional to $\sin(\Delta m_{21}^2 L/4E)$. This is why experiments searching for CP violation involve long baselines (several hundreds of km), intense neutrino beams and enormous detectors [23].

1.2.4 Neutrino Oscillation in matter

The probabilities shown in the previous section are modified if neutrinos can interact with matter. In particular, travelling in the ordinary matter, ν_e can have both NC and CC interactions because of the presence of electrons, while for ν_μ and ν_τ only NC reactions are possible, see Fig. 1.10. The modification of the oscillation probability is known as the Mikheyev-Smirnov-Wolfenstein (MSW) effect [24]. The main consequence of the MSW effect is that the oscillation probabilities for neutrinos and antineutrinos can be different, even if neutrino interactions with

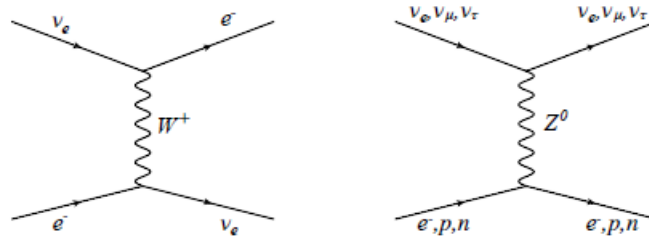


Figure 1.10: Feynman diagrams of the CC (left) and NC (right) elastic scattering processes in matter: as shown on the left there is the possibility of also having CC interaction with neutrino and electron in the final state. This is of coarse not allowed for ν_μ and ν_τ

matter do not violate CP. MSW had a fundamental role in solving the Solar Neutrino Problem. Vacuum oscillations, in fact, cannot fully explain the deficit since neutrinos travel through the matter in the Sun [25].

1.3 Neutrino Oscillation Experiments

The main goal of last decades neutrino experiments have been the determination of the parameters of the PMNS matrix. Each experiment focuses on a subset of parameters to be measured and thus developes the best approach to do that.

Generally, neutrino oscillation experiments can be divided in two families:

- **Appearance experiments:** they measure the transition between different neutrino flavors. The main problem of this type of experiment is to understand well the background which could mimic the appearance signature.
- **Disappearance experiments:** in this case they measure the survival probability of a neutrino flavor by counting the number of interactions in the detector and comparing it with the expectation. The ratio of these spectra should show the oscillation pattern.

We already saw in 1.2.3 that an experiment designed to be sensitive to a specific Δm^2 must choose the correct L/E ratio value, since it is:

$$\frac{\Delta m^2 L}{E} \sim 1 \quad (1.18)$$

Based on that, a different classification for neutrinos experiments can be done, depending on the average of the L/E .

Solar neutrino experiments

The solar neutrino experiments are sensitive to small Δm^2 values, since the Sun-Earth distance is around 1.5×10^{11} and the energy of detectable neutrinos is in

the range 4.2 – 15 MeV, giving a ratio and a sensitivity of:

$$\frac{L}{E} \sim 10^{12} \frac{m}{MeV}, \quad \Delta m^2 \sim 10^{-12} eV^2. \quad (1.19)$$

Atmospheric neutrino experiments

For atmospheric neutrinos we have a two different direction, an upwards direction ($L \sim 1.3 \times 10^4$ km) and a downward direction ($L \sim 1 \times 10^1$ km). Neutrinos' energy range goes from about 500 MeV to more than 100 GeV and they are mainly produced by the decay of pions and kaons in the atmosphere produced by primary cosmic rays in the upper layers of the atmosphere. Based on that, the Δm^2 sensitivity and typical L/E value are

$$\frac{L}{E} \sim 10^4 \frac{m}{MeV}, \quad \Delta m^2 \sim 10^{-4} eV^2. \quad (1.20)$$

Reactor neutrino experiments

Reactor experiments use a large isotropic flux of electron antineutrinos produced by β^- decays of the fission products. They can be divided in ShortBaseLine (SBL) and LongBaseLine (LBL) experiments according to the distance between the reactor and the detector.

The SBL experiments have a typical neutrino energy around few MeV and $L \sim km$, thus the Δm^2 sensitivity and typical L/E value are

$$\frac{L}{E} \sim 10^3 \frac{m}{MeV}, \quad \Delta m^2 \sim 10^{-3} eV^2. \quad (1.21)$$

For the LBL experiments the only difference is the distance $L \sim 100km$, thus it is

$$\frac{L}{E} \sim 10^5 \frac{m}{MeV}, \quad \Delta m^2 \sim 10^{-5} eV^2. \quad (1.22)$$

Accelerator neutrino experiments

Neutrinos beam can also be produced thanks to a proton beam that, by hitting a target, produces pions, kaons, and muons which subsequently decay producing neutrinos. They can be divided as well in SBL and LBL. The SBL have a neutrino energy between tens of MeV and hundred of GeV and a typical L between 10 m and 1 km, thus it is

$$\frac{L}{E} \sim 10^{-2} \frac{m}{MeV}, \quad \Delta m^2 \sim 10^{-2} eV^2. \quad (1.23)$$

$$\frac{L}{E} \sim 1 \frac{m}{MeV}, \quad \Delta m^2 \sim 1 eV^2. \quad (1.24)$$

$$\frac{L}{E} \sim 10^3 \frac{m}{MeV}, \quad \Delta m^2 \sim 1 eV^2. \quad (1.25)$$

Type of experiment	L	E	Δm^2 sensitivity
Solar	$\sim 10^{11} \text{ km}$	$0.2 - 15 \text{ MeV}$	$\sim 10^{-12} \text{ eV}^2$
Atmospheric	$\sim 20 - 10^4 \text{ km}$	$0.5 - 10^2 \text{ GeV}$	$\sim 10^{-4} \text{ eV}^2$
Reactor SBL	$\sim 10 \text{ m}$	$\sim 1 \text{ MeV}$	$\sim 0.1 \text{ eV}^2$
Reactor LBL	$\sim 1 \text{ km}$	$\sim 1 \text{ MeV}$	$\sim 10^{-3} \text{ eV}^2$
Accelerator SBL	$\sim 10^{-2} - 1 \text{ km}$	$10^{-2} - 10^2 \text{ GeV}$	$\sim 1 - 10^2 \text{ eV}^2$
Accelerator LBL	$\sim 10^3 \text{ km}$	$\gtrsim 1 \text{ GeV}$	$\gtrsim 10^{-3} \text{ eV}^2$

Table 1.2: Characteristic values of L , E and Δm^2 for various neutrino sources and experiments.

In LBL the energy are around or greater than 1 GeV and the distance is in the order of 10^2 km, thus it is

$$\frac{L}{E} \lesssim 10^3 \frac{m}{\text{MeV}}, \quad \Delta m^2 \gtrsim 10^{-3} \text{ eV}^2. \quad (1.26)$$

A summary of all the type of experiments along with their typical source-detector distance, energy and sensitivity is reported in Tab. 1.2.

A new generation of accelerator and reactor experiments is opening an era of high-precision neutrino measurements to tackle questions such as CP violation, mass hierarchy and the possibility of a fourth “sterile” neutrino.

1.3.1 Reactor Neutrino Experiments

Nuclear reactors provide a huge source of electron antineutrinos produced by the β^- decay of the fission products. Each fission event produces, in average, about 200 MeV and about six electron antineutrinos.

The total rate of antineutrino production of a typical nuclear power plant is enormous ($\sim 10^{21}$ per second). The counterpart of this is that the flux is isotropic, thus it decreases rapidly with the distance. This problem is partially compensated by a relatively short oscillation length due to the the low-energy of the produced electron antineutrinos (few MeV). Such a low energy prevent the formation in the detector of muons or taus and implies that only $\bar{\nu}_e$ disappearance can be investigated in reactor experiments. Reactor electron antineutrinos are detected through the inverse β -decay (IBD):

$$\bar{\nu}_e + p \longrightarrow n + e^+ \quad (1.27)$$

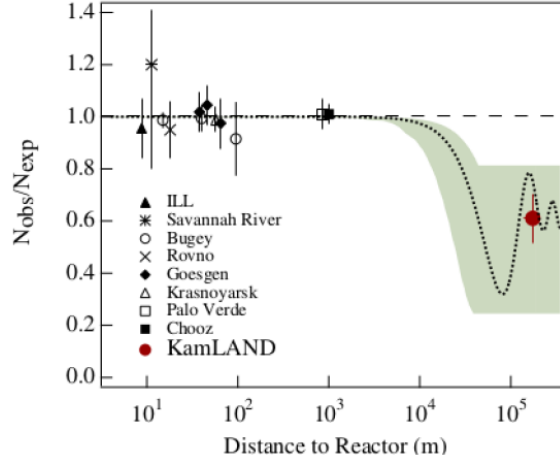


Figure 1.11: Ratio of measured $\bar{\nu}_e$ over expected versus the distance of different reactor antineutrino experiments. The solid red dot is the KamLAND point plotted at a flux-weighted average distance (the dot size is indicative of the spread in reactor distances). The shaded region indicates the range of flux predictions corresponding to the 95% C.L. Large Mixing Angle (LMA) region found in a global analysis of the solar neutrino data. The dotted curve corresponds to $\sin^2 2\theta = 0.883$ and $\Delta m^2 = 5.5 \times 10^{-5} eV^2$ and is representative of recent best-fit LMA predictions while the dashed curve shows the case of small mixing angles (or no oscillation). Figure taken from [26].

Antineutrino events are distinguished from the background by the coincidence of the prompt positron signal with the delayed signal produced by the nuclear capture of the neutron.

The Kamioka Liquid Anti-Neutrino Detector (KamLAND) [26] is a 1 kton ultra-pure liquid scintillator detector located at the old KamiokaNDE site in Japan, and detects $\bar{\nu}_e$ coming from 16 reactors with an average distance of 160 km and the sensitivity for Δm^2 is down to $\sim 10^{-5} eV^2$. The first KamLAND results was published in 2002 and are shown in Fig. 1.11. It is possible to see that the ratio of observed to expected number of events was:

$$\frac{N_{obs} - N_{BG}}{N_{NoOsc}} = 0.611 \pm 0.085(stat.) \pm 0.041(syst.) \quad (1.28)$$

where N_{obs} is the actual number of events observed by KamLAND, N_{BG} is the number of background events expected and N_{NoOsc} is the number of events expected if no oscillations occur. The probability to be consistent with no disappearance hypothesis was less than 0.05%, showing clear evidence of the event deficit expected from neutrino oscillations.

KamLAND collaboration reported updated results in 2011 [27] along with a combined analysis with solar neutrino data. The data set benefits of an increased exposure and of a lower background due to a radiopurity upgrade.

The Jiangmen Underground Neutrino Observatory (JUNO) is a multipurpose neutrino experiment designed to determine neutrino mass hierarchy and precisely measure oscillation parameters by detecting reactor neutrinos from the Yangjiang

and Taishan Nuclear Power Plants, observe supernova neutrinos, study the atmospheric, solar neutrinos and geo-neutrinos, and perform exotic searches, with a 20 kton liquid scintillator detector of unprecedented 3% energy resolution (at 1 MeV) at 700-meter deep underground.

1.3.2 Accelerator Neutrino Experiments

Another way to study neutrino oscillations, is given by accelerator neutrino experiments. The neutrino beam can be produced using three different strategy:

Pion Decay In Flight (DIF) where the beam is produced by the decay of pions and kaons produced in turn by a proton beam hitting a target.

Muon Decay at Rest (DAR) where the beam is characterized by a low energy and it is made of muon neutrinos coming from the muon decay.

Beam Dump where the beam have an energy of the order of 10^2 GeV and is produced by a proton beam with very high energy which impinges a target producing charmed heavy hadrons that rapidly decay in electrons and muons and again in electron and muon neutrinos. In this case there can be contamination of ν_τ from the decay of D_s .

The experiments have the possibility to create both neutrinos and antineutrinos, using magnets to select positive or negative pions given by the interaction of protons on the target. As already said, accelerator neutrino experiments can be classified in terms of the distance source-detector: SBL experiments with $L \sim 10m - 1km$ and LBL with $L \sim 10^2km - 10^3km$.

SBL experiments will not be described in this dissertation, but it is important to mention a results from the LSND [28] experiments, which found a signal in the $\bar{\nu}_\mu \longrightarrow \bar{\nu}_e$ and a weaker signal in $\nu_\mu \longrightarrow \nu_e$ that could require an extension of the three-neutrino mixing scheme.

The LBL accelerator neutrino experiments measure the oscillation parameters Δm_{23}^2 , θ_{23} , also measured by atmospheric neutrino experiment, θ_{13} , measured by reactor experiment as well, and the CP violation phase δ_{CP} . Usually, the neutrino beam is measured in a near detector to calibrate the beam and then again in a far detector, after the oscillation. The past and present LBL experiments are: K2K and T2K in Japan, MINOS and NO ν A in USA and OPERA in Italy.

The K2K (KEK to Kamioka) was the first LBL accelerator-based experiment and it had as goal the confirmation of atmospheric ν_μ disappearance observed at Super-K. A muon neutrino beam with an average energy of about 1.3 GeV was directed toward Super-K, located 250 km far from the neutrino production point, serving as far detector. The spectrum and profile of the neutrino beam were measured by a near detector located 300 m from the production target. The K2K experiment started data-taking in 1999 and was completed in 2004. It observed 112 Flavor-Changing (FC) events in the fiducial volume of Super-K, compared with an expectation of $158.1_{-8.6}^{+9.2}$ events without oscillation. This discrepancy of

about 4.3σ indicated the muon neutrino disappearance, excluding other interpretations of the atmospheric neutrino anomaly [29]. K2K also investigated the $\nu_\mu \rightarrow \nu_e$ oscillation reporting no events above the expected background [30].

In the MINOS [31] experiment (Main Injector Neutrino Oscillations) the beam was produced by the NuMI facility (Neutrinos at the Main Injector) using protons accelerated by the Fermilab Main Injector. The far detector was a 5.4 kton (total mass) iron-scintillator tracking calorimeter with a distance to the source of 735 km. It is also equipped with a near detector which is a 0.98 kton iron-scintillator tracking calorimeter. MINOS started the neutrino-beam run in 2005 searching for ν_μ disappearance and ν_e appearance. The collaboration reported also the measurements of oscillation parameters from ν_μ and $\bar{\nu}_\mu$ disappearance using beam and atmospheric data.

OPERA (Oscillation Project with Emulsion-tRacking Apparatus) was a combination of the *Emulsion Cloud Chambers* and magnetized spectrometers [32]. It had its neutrino source at CERN and a target detector mass of 1290 tons at Gran Sasso with the baseline distance of 730 km. The CNGS (CERN Neutrinos to Gran Sasso) neutrino beam with $E_\nu = 17 \text{ GeV}$ was produced by high-energy protons from the CERN SPS. The experiment reported discovery of ν_τ appearance with a 5σ significance observing 10 ν_τ candidate and confirming the atmospheric ν_μ oscillation into ν_τ [33].

T2K (Tokai to Kamioka) is, with NO ν A, a running LBL oscillation experiment. More details on T2K will follow in the next section, here it is just important to mention here that T2K was the first experiment to find an indication of electron neutrino appearance from an accelerator-produced off-axis neutrino beam [34].

NO ν A (NuMI Off-Axis ν_e Appearance) started taking data in 2013. It has as goals the measurement of θ_{13} , study CP violation and the neutrino mass hierarchy. The beam is produced by the NuMI (Neutrinos at the Main Injector) facility and it has an average energy of 2 GeV . The far detector is located 810 km from the target and 14.6 mrad off-axis. It use also a near detector which is located 1 km from the target and 14.6 mrad off-axis. The collaboration reported results on ν_μ disappearance and ν_e appearance [35].

The two next generation LBL experiments are the Deep Underground Neutrino Experiment (DUNE) [36] in the US and the Hyper-K experiment [37] in Japan.

DUNE will use four Liquid Argon time projection chambers, of 10 kton each, as target of neutrino interactions. The neutrino beam will be produced at Fermilab, and will be sent 1,300 km away, to the Sanford Underground Research Facility (SURF) in South Dakota.

This experiment will allow a clean measurement of the mass ordering and of δ_{CP} .

Hyper-K detector and its physics capability will be described in the next chapter.

Experiment	Dominant	Important
Solar Experiments	θ_{12}	$\Delta m_{21}^2, \theta_{13}$
Reactor LBL (KamLAND)	Δm_{21}^2	θ_{12}, θ_{13}
Reactor MBL (Daya-Bay, Reno, D-Chooz)	θ_{13}	$ \Delta m_{3\ell}^2 $
Atmospheric Experiments	θ_{23}	$ \Delta m_{3\ell}^2 , \theta_{13}, \delta_{\text{CP}}$
Accelerator LBL ν_{μ} Disapp (Minos, NOvA, T2K)	$ \Delta m_{3\ell}^2 , \theta_{23}$	
Accelerator LBL ν_{μ} App (Minos, NOvA, T2K)	δ_{CP}	$\theta_{13}, \theta_{23}, \text{sign}(\Delta m_{3\ell}^2)$

Table 1.3: Experiments contributing to the present determination of the oscillation parameters. Figure taken from [38].

1.3.3 Current Knowledge of Neutrino Oscillation Parameters

Within the standard three-neutrino framework, the absolute neutrino masses and their ordering are currently unknown. Anyway a global fit of current data coming from oscillation experiments can provide interesting constraints for such parameters. In Tab. 1.3 a lists of the typologies of neutrino oscillation experiments is reported along with their contribution to the determination of oscillation parameters. In Tab. 1.4 are reported the last best-fit values and parameter ranges in normal (NO), inverted (IO) and any ordering. A more detailed description of this global analysis can be found in [39].

1.4 Astrophysical neutrinos

Astrophysical neutrinos are particles generated somewhere in our universe. Astrophysical neutrinos are particularly prized as information carriers because their tiny interaction rate allows them to pass through clouds of gas and dust that would otherwise hide distant astrophysical objects. Since there are a large number of experiments where in principle we can learn on neutrino properties, we can afford to use cosmic neutrinos to acquire informations on their astrophysical sources, and talk therefore of neutrino astronomy. Of particular interest are high energy neutrinos and there are many experiments focused on their detection. Among them stands a one of a kind experiment, the IceCube experiment located at the South Pole. Since 2013, it has reported detections of more than 100 cosmic neutrinos in the energy range $10^{14} \sim 10^{16}$ eV, an achievement that has marked the beginning of galactic and extragalactic neutrino astronomy [40]. Other important results come from other experiments, like ANTARES [41] and NEMO [42], now superseded by KM3NeT [43].

1.4.1 Neutrinos from supernovae

The observation of the burst of neutrinos from supernova SN1987A in the Large Magellanic Cloud just outside our Milky Way galaxy confirmed the basic picture of core-collapse supernovae [44]. A total of about two dozen events were recorded. Future experiments awaits the next supernovae burst, with one of most promising candidate is Betelgeuse, which is expected to become a supernovae in the next fu-

parameter	best fit $\pm 1\sigma$	2σ range	3σ range
$\Delta m_{21}^2 [10^{-5} \text{eV}^2]$	$7.50^{+0.22}_{-0.20}$	7.12–7.93	6.94–8.14
$ \Delta m_{31}^2 [10^{-3} \text{eV}^2]$ (NO)	$2.55^{+0.02}_{-0.03}$	2.49–2.60	2.47–2.63
$ \Delta m_{31}^2 [10^{-3} \text{eV}^2]$ (IO)	$2.45^{+0.02}_{-0.03}$	2.39–2.50	2.37–2.53
$\sin^2 \theta_{12}/10^{-1}$	3.18 ± 0.16	2.86–3.52	2.71–3.69
$\theta_{12}/^\circ$	34.3 ± 1.0	32.3–36.4	31.4–37.4
$\sin^2 \theta_{23}/10^{-1}$ (NO)	5.74 ± 0.14	5.41–5.99	4.34–6.10
$\theta_{23}/^\circ$ (NO)	49.26 ± 0.79	47.37–50.71	41.20–51.33
$\sin^2 \theta_{23}/10^{-1}$ (IO)	$5.78^{+0.10}_{-0.17}$	5.41–5.98	4.33–6.08
$\theta_{23}/^\circ$ (IO)	$49.46^{+0.60}_{-0.97}$	47.35–50.67	41.16–51.25
$\sin^2 \theta_{13}/10^{-2}$ (NO)	$2.200^{+0.069}_{-0.062}$	2.069–2.337	2.000–2.405
$\theta_{13}/^\circ$ (NO)	$8.53^{+0.13}_{-0.12}$	8.27–8.79	8.13–8.92
$\sin^2 \theta_{13}/10^{-2}$ (IO)	$2.225^{+0.064}_{-0.070}$	2.086–2.356	2.018–2.424
$\theta_{13}/^\circ$ (IO)	$8.58^{+0.12}_{-0.14}$	8.30–8.83	8.17–8.96
δ/π (NO)	$1.08^{+0.13}_{-0.12}$	0.84–1.42	0.71–1.99
$\delta/^\circ$ (NO)	194^{+24}_{-22}	152–255	128–359
δ/π (IO)	$1.58^{+0.15}_{-0.16}$	1.26–1.85	1.11–1.96
$\delta/^\circ$ (IO)	284^{+26}_{-28}	226–332	200–353

Table 1.4: Neutrino oscillation parameters summary determined from the global analysis. The ranges for inverted ordering refer to the local minimum for this neutrino mass ordering. Table from [39].

ture. We will see that according to different models a copious amount of neutrinos will be detected.

First of all, let's discuss on why a star becomes a supernovae and why neutrinos are emitted. White dwarfs represent the final evolutionary stage of middle size stars, with mass between approximately 0.8 and $8 M_\odot$. Normally stars start fusing H into He and this nuclear reaction is exothermic and the energy released in this process can be used to resist the inward gravitational pressure. This process can be replicated with heavier elements, requiring of coarse higher temperatures and so an higher density of the star. In the cores of medium-sized stars, hydrogen and helium undergo fusion to form carbon and oxygen, but further fusion is not possible due to insufficient temperatures. As the star nears the end of its nuclear fuel supply, it begins to lose mass, ejecting its outer layers and leaving behind a dense carbon-oxygen core known as a white dwarf. This white dwarf typically has about half the mass of the Sun, but is only slightly larger than Earth, making it one of the densest forms of matter, second only to neutron stars. Stars like those can just cool down for the rest of its life, but there is a possible different scenario in case of binary systems [45].

In a binary system one star can start to attract matter from the second star

of the system due to its very strong gravity. The white dwarf gradually becomes more massive—this process is known as accretion. During this phase the mass of the white dwarf increases up to $1.4 M_{\odot}$, the so called Chandrasekhar limit. Eventually, the increased pressure on the core is sufficient to reignite and produce a chain of runaway fusion reactions that creates more energy than that which holds the star together gravitationally, causing the star to explode, and form a SN. This is the so-called thermonuclear (or thermal runaway) mechanism. The explosion does not leave any compact remnant nor produce significant neutrino emission through fusion processes.

These supernovae, known as thermonuclear supernovae, are classified as type Ia [46]. Type Ia supernovae can occur in any type of galaxy, without a preference for star-forming regions, which aligns with their origin from an older or intermediate-age stellar population.

In contrast, other types of supernovae, such as type II, Ib, and Ic, occur exclusively in star-forming regions, where young, massive stars are present. These supernovae are thought to result from a different process: the gravitational collapse of the star's core.

It arises in the final stage of single stars with high mass, at least about $8 M_{\odot}$. In the stellar core, nuclear fusion initially burns hydrogen nuclei into helium nuclei. A massive star can reach the high temperatures requested in the subsequent burning stages, that can produce carbon (C), oxygen (O), neon (Ne), silicon (Si) and iron (Fe). After helium fusion, the star's evolution speeds up significantly due to energy loss from neutrinos. Additionally, electron-positron annihilation occasionally produces a neutrino-antineutrino pair, which easily escapes from the star, prompting the fusion process to accelerate in order to compensate for the energy loss. While hydrogen and helium fusion take millions of years, the final stage—silicon burning—lasts only about two weeks. By the end of the fusion processes, a massive star is made up of concentric shells representing the remnants of its previous fusion stages (hydrogen, helium, carbon, neon, oxygen, and silicon). During this time, an inert iron core forms as the fuel from lighter elements is exhausted. With the mass increasing the star becomes unstable with respect to gravity, and can undergo to a dramatic gravitational collapse within less than a second. The inner core becomes incredibly dense and rigid, eventually rebounding and creating a powerful shock wave. This marks the beginning of a series of events that ultimately lead to a supernova explosion. During the explosion, parts of the star's heavy-element core and its outer layers are expelled into interstellar space. The collapse of the core continues until it either forms a black hole or is halted by neutron degeneracy pressure, resulting in the central core becoming a neutron star.

The optical SN outburst can be seen only a few hours after the onset, thus one has to rely on the observations of neutrinos generated in the core collapse and of gravitational waves which are emitted when the collapse does not proceed perfectly symmetrically because of rotation, violent turbulent mass motions, and anisotropic neutrino emission. Moreover, neutrinos dominate the energetics of core-collapse supernovae. Only about one percent of the gravitational binding

energy released in the formation process of the compact remnant ends up as kinetic energy of the expanding ejecta, whereas the remaining is radiated away in neutrinos.

In the core-collapse supernova (CCSN), the process of SN explosion can be broadly described as a sequence of phases: the infall, the neutronization burst, the accretion phase and the cooling phase. During those phases, neutrinos are emitted, in particular:

- in the neutronization, in which a fusion reaction between electrons and protons produces neutrons and electron neutrinos. This process produces a peak in the ν_e luminosity curve as a function of time that lasts for about 25 ms. During neutronization, electron neutrinos are trapped behind the shock wave formed by the collapse and are only released when the matter density becomes sufficiently low.
- in the accretion, in which the matter from the collapsing star is attracted to the newly formed neutron star. Electron neutrinos and antineutrinos are produced in large numbers by charged-current processes in the mantle, while thermal neutrinos and antineutrinos of all flavours are produced in the core.
- cooling, which occurs after the SN explosion. The proto-neutron star releases all types of neutrinos and antineutrinos for about 10 s. The luminosities of all kinds of neutrinos and antineutrinos become similar (within about 10%) and decline with time in parallel.

The probability of having a core collapse supernovae in the Milky Way is relatively low [47]. But the cumulative flux of neutrinos and antineutrinos, emitted by all core-collapse supernovae in the causally-reachable universe, is called the diffuse supernova neutrino background (DSNB) [48]. It will appear isotropic and time independent in feasible observations. Given the large number of SNe per year, we expect a nonzero rate of the DSNB, even when the large distance of the SN reduces the probability of detecting a single neutrino to practically zero.

1.5 The neutrino oscillation program in Japan

The technique of ring imaging water Cherenkov detection, has been successfully employed by several neutrino and nucleon decay experiments over the last few decades. In Japan, the Kamiokande detector (1983-1996, 3 kiloton) and Super-Kamiokande (in operation since 1996, 50 kiloton) have achieved several important scientific results, notably detection of extraterrestrial neutrinos from the Sun and Supernova 1987a and discovery of neutrino flavor mixing and neutrino mass.

T2K is a currently-operating experiment which uses Super-K to measure neutrinos produced in the J-PARC beam line.

The magnitude of the charge-parity (CP) violation in neutrino oscillation has been characterized in T2K by the difference of neutrino oscillation probabilities between neutrino and anti-neutrino channels. The current data coming from T2K

have determined a 3σ confidence interval for δ_{CP} value [49]. Published in Nature (see Fig. 1.12), the results are a major step forward in the study of the difference between matter and antimatter. In case of normal mass ordering it is $[-3.41;-0.03]$ while in case of inverted mass ordering it is $[-2.54;-0.32]$.

This exciting result pushed to the upgrade of the neutrino oscillation program in Japan, thus the project of Hyper-K, that, with an improved detection system, based on newer detectors and a completely new electronics and more statistic, can hopefully lead to a 5σ confidence interval for δ_{CP} . Hyper-K will use much of the existing infrastructure used by T2K, particularly the beam line and the near detectors. Hyper-K will also benefit from any improved data analysis techniques developed for T2K. Several important T2K upgrades and improvements are planned for the coming years, and this will have a direct impact on improved Hyper-K performance.

1.5.1 T2K

T2K (Tokai-to-Kamioka) is a long baseline neutrino oscillation experiment located in Japan. It started its first operation in March 2010 and its aims is to measure the parameters of the PMNS matrix and to look for the first indication of CP violation in the leptonic sector. It uses a (anti)neutrino beam produced by the complex of J-PARC (Japan Proton Accelerator Research Complex), in Tokai. Neutrinos are detected first in a near detector complex at 280 *m* then from the far detector Super-Kamiokande 295 *km* far away. A scheme of neutrinos' journey is reported in Fig. 1.13.

In 2011 T2K observed for the first time a non-zero value for θ_{13} with a significance of about 3σ [50], then the evidence with a significance of 7.3σ with only $\sim 8.2\%$ of the total data [51], which correspond to an exposure of 7.8×10^{21} proton on target (POT), and the world best measurement of $\sin^2 \theta_{23}$ [52]. The measurement of non-zero values for all three mixing angles opened the possibility to measure the CP violation in the leptonic sector, obtaining a big achievement in this way through a 3σ measurement of the CP violation phase δ_{CP} [49].

The neutrino beam

Neutrinos are produced via the decay of pions and kaons generated from the collision of a high-intensity proton beam on a graphite target. The proton beam for T2K experiment is provided by the J-PARC complex.

The beam of the T2K experiment is sent to the near detector and to the far detector that are aligned at an angle of 2.5° respect to the beam as shown in Fig. 1.14.

T2K was the first experiment using an off-axis neutrino beam, a technique that allows the production of an almost monochromatic neutrino beam. This allowed to energy maximize the oscillation probability, as shown in Fig. 1.15, where the the energy peak is compared with the disappearance and appearance probability for the T2K baseline. In addition to this advantage, the method also cuts the



Figure 1.12: Nature cover for the publication of the T2K article on the Constraint on the matter-antimatter symmetry-violating phase in neutrino oscillations

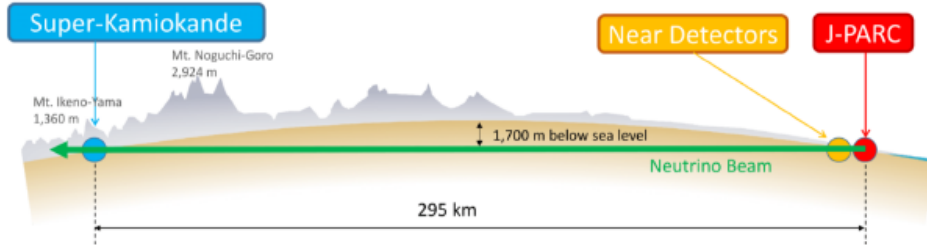


Figure 1.13: A schematic of a neutrino journey from the neutrino beamline at J-PARC, through the near detectors which are used to determine the properties of the neutrino beam before the oscillation, to Super-Kamiokande located 295 *km* west of the beam source, 1000 *m* deep underground.

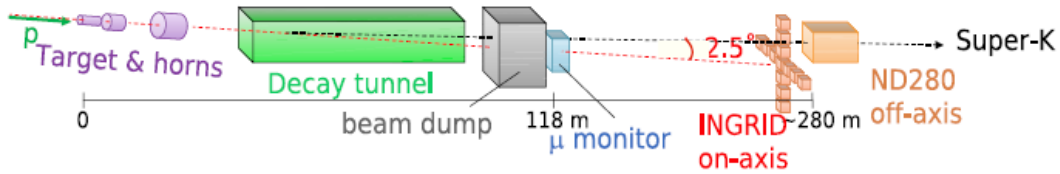


Figure 1.14: Schematic representation of the off-axis configuration.

high energy tail present in the neutrino beam to remove the background to the oscillation signal.

Another advantage of the off-axis beam is that it reduces the ν_e contamination in the beam. This contamination, is one of two main backgrounds to the ν_e appearance signal. It comes from decays of muons and kaons (the so-called Ke3 decay, that has a branching ratio of 5%) in the decay tunnel. Since these are both 3 body decays, while the off-axis strategy enhances the number of neutrinos coming from a two body decay, an off-axis neutrino spectrum will be less affected by the ν_e contamination.

The near detector complex

The near detector complex is located at a distance of 280 *m* from the target. The near detectors are used to measure the properties of the un-oscillated beam and to predict the neutrino interactions at the far detector. The complex consists of two detectors: the on-axis detector INGRID (Interactive Neutrino GRID) and the off-axis detector ND280.

The on-axis detector

The on-axis neutrino detector is used to monitor the neutrino beam observing particles produced by neutrino interactions. Being on-axis INGRID is sensitive to a large portion of the neutrino spectrum.

INGRID [54] consists of 14 identical units, arranged to form a cross of two identical groups along the horizontal and vertical axis and two separate modules located at off-axis locations outside the main cross, as shown in Fig. 1.16. The purpose

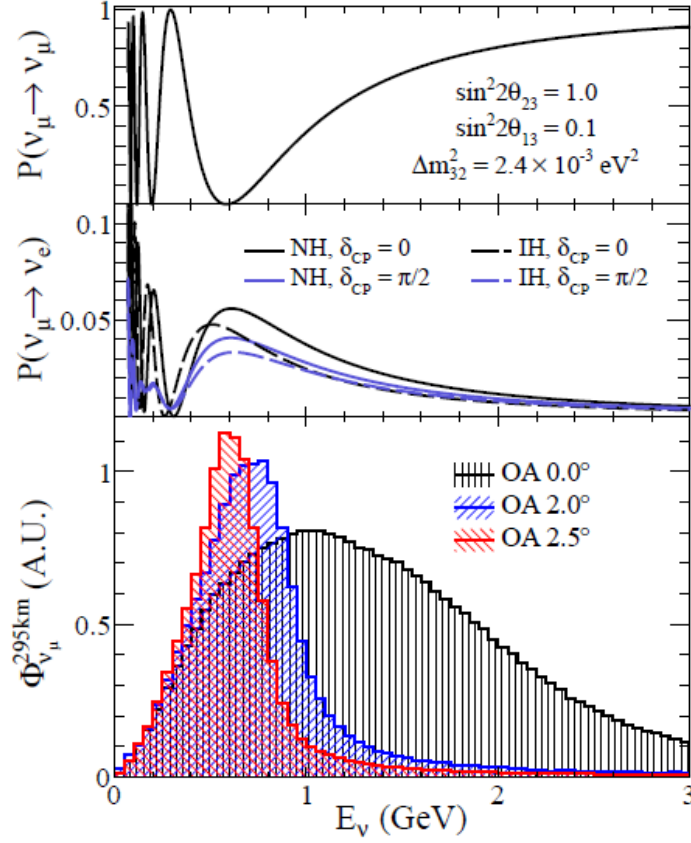


Figure 1.15: Muon neutrino disappearance (top figure) and electron neutrino appearance (middle figure) probability at 295 km compared to the neutrino fluxes for different off-axis angles. The neutrino beam at Super-K has a peak energy at about 0.6 GeV maximizing the effect of the neutrino oscillations at 295 km.

of the two off-axis modules is to check the axial symmetry of the neutrino beam. The 16 INGRID modules consist of a sandwich structure of 9 iron plates and 11 tracking scintillator planes. Each of this latter consists of 24 scintillator bars, in the horizontal direction glued to 24 perpendicular bars. A surrounding scintillator plane is used as a veto to reject interactions outside the module. The total iron mass of the neutrino target is 7.1 tons per module. The dimensions of the scintillator bars used for the tracking planes are $1.0 \text{ cm} \times 5.0 \text{ cm} \times 120.3 \text{ cm}$. The modules cover a beam area of 5 m^2 and the neutrino beam direction is measured with an accuracy better than 0.4 mrad.

The Proton Module is an extra module different from the other that has been added in order to detect the proton produced with the muon in neutrino interactions with good efficiency. It consists of scintillator planes surrounded by veto planes. A different size scintillator bar was used to improve tracking capabilities. It is placed in the center of the INGRID cross between the standard vertical and horizontal central modules.

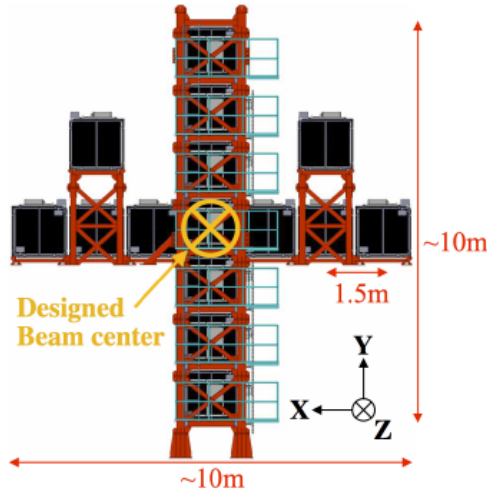


Figure 1.16: INGRID on-axis detector. Figure taken from [53].

The off-axis detector, ND280

ND280 [55] serves to measure the flux, energy spectrum and beam contaminations in the direction of the far detector, along with measuring rates for exclusive neutrino reactions, in order to characterize signals and backgrounds in the far detector. It must satisfy several requirements:

- It must provide information to determine the ν_μ (or $\bar{\nu}_\mu$) flux at Super-K.
- The content of the beam must be measured as a function of neutrino energy. The intrinsic beam background creates a significant non-removable background for the oscillation analysis.
- Precise measurements of ν_μ , $\bar{\nu}_\mu$ and ν_e cross-sections.

The off-axis detector (see Fig. 1.17) consists of: the π^0 detector (PØD), three Time Projection Chambers (TPC), two Fine Grained Detectors (FGDs), placed inside of a metal frame container, called the *basket*; an Electromagnetic Calorimeter (ECal) that surrounds the basket; and the refurbished UA1/NOMAD magnet instrumented with scintillator to perform as a muon range detector (SMRD). The basket has dimensions of $6.5 \times 2.6 \times 2.5 \text{ m}^3$ (length $\times$ width $\times$ height). The region covered by the TPCs and FGDs is called *tracker volume*.

1.5.2 The far detector: Super-Kamiokande

The Super-K water Cherenkov detector is located 295 km far of the beam source where it is used to sample the beam's flavor composition and look for $\nu_\mu \rightarrow \nu_e$ oscillations. It is built 1 km deep (2,700 meters water equivalent) in the Kamioka mine. Super-K has been running since 1996 and operation time was divided in four running periods: SK-I, SK-II, SK-III, and SK-IV during which it has produced data for a number of well-known results that include world-leading limits on the

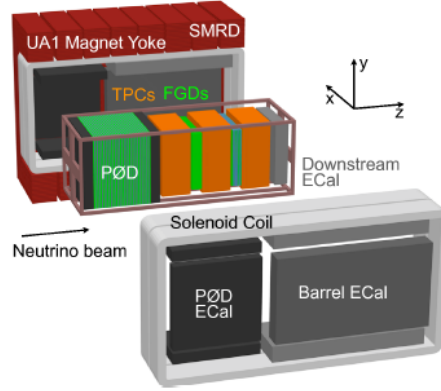


Figure 1.17: A schematic view of the ND280 off-axis detector.

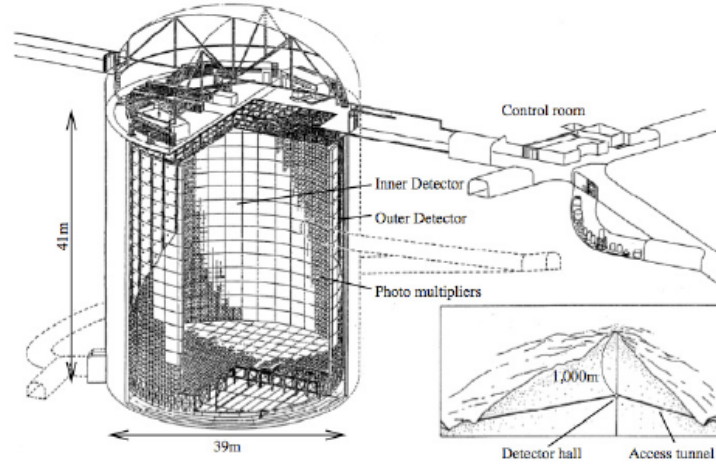


Figure 1.18: Diagram of the Super-Kamiokande Detector. It is mainly comprised of two segments, the inner and outer detectors. The boundary between the two segments is defined by a cylindrical scaffold used to mount photomultiplier tubes and optically separate the segments. Figure taken from [53].

proton lifetime and the measurement of flavor oscillations in atmospheric, solar and accelerator-produced neutrinos. A schematic view of detector is shown in Fig.1.18. It is a cylindrical tank whose dimensions are 41 *m* in height and 39 *m* in diameter and is filled with 50 kton of pure water. On the detector walls roughly 13,000 photomultiplier tubes (PMTs) detect neutrino interactions. The geometry of the Super-K detector consists of two major volumes, an inner and an outer detector which are separated by a cylindrical stainless steel structure. The inner detector (ID) is a cylindrical space 33.8 *m* in diameter and 36.2 *m* in height which currently houses along its inner walls 11129 inward-facing 50 cm diameter PMTs, representing 40% of surface coverage. The outer detector (OD) is a cylindrical space about 2 *m* thick radially and on the axis at both ends. The OD contains along its inner walls 1885 outward-facing 20 cm diameter PMTs and is used as an anti-counter to identify entering/exiting particles to/from the ID. The ID and OD boundaries are defined by a cylindrical structure about 50 *cm* wide. This

structure consists of a stainless steel scaffold covered by plastic sheets which serve to optically separate the ID and OD. The wall facing into the ID is lined with a black sheet of plastic meant to absorb light and minimize the number of photons which either scatter off of the ID wall back into the ID volume, or pass through from the ID to the OD.

The primary strategy to measure the flavor composition of the T2K neutrino beam at SK, and thereby observe the oscillation of ν_μ to ν_e is to count CCQE (Charge Current Quasi-Elastic) interactions for muon and electron neutrinos, both of which produce leptons of their respective flavor. Relativistic charged particles, produced in these neutrino interactions, travel through the detector with a speed faster than the velocity of light in water. The polarized water molecules rapidly turn back to their ground state and emit Cherenkov light, which is detected by the ID PMTs. For both ν_μ and ν_e events the starting position of the leptons is required to be fully contained in the fiducial volume, which is defined to be more than 2 m away from the ID wall for a total fiducial mass of 22.5 kton. The pulse height and timing information of the PMTs are fitted to reconstruct the vertex, direction, energy, and particle identification of the Cherenkov rings. A typical vertex, angular and energy resolution for 1 GeV muons is 30 cm, 3° and 3%, respectively. The typical ring shape, which is obtained from fully contained charged particles with an energy above the Cherenkov threshold, allows to infer the vertex position and the momentum of the charged particles. An example of reconstructed event is shown in Fig. 1.19

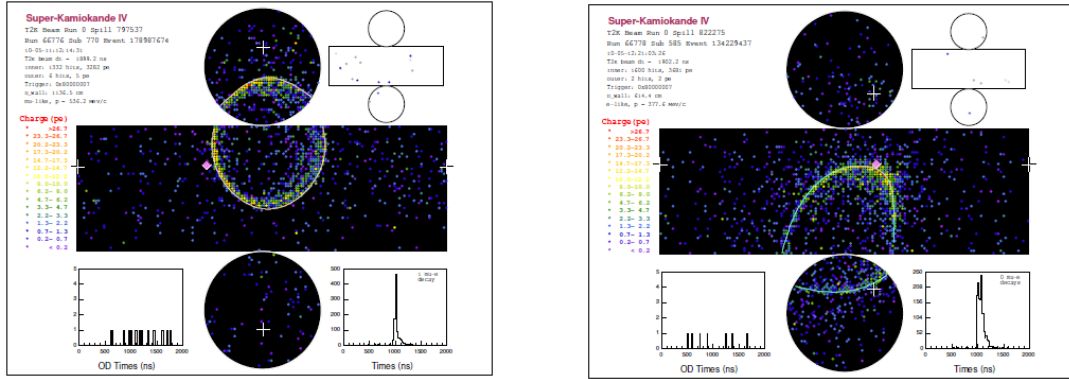


Figure 1.19: Example of reconstructed T2K events in Super-Kamiokande for (a) a muon-like ring and (b) an electron-like ring. Each colored point represents a PMT, with the color corresponding to the amount of charge, and the reconstructed cone is shown as a white line. The second figure in the upper right corner shows the same hit map for the OD. The white crosses indicate the location of the reconstructed vertex.

A very good discrimination between fuzzy electron like Cherenkov rings and sharp edged rings from muons enables to separate ν_e from ν_μ interactions. The fuzzy electron like ring is due to the multiple scattering, which is more likely to occur for electrons than for muons because of the electron smaller mass, and to electromagnetic showers almost always induced at these energies. The electrons and muons are further separated by detecting decay electrons from the μ decays.

A typical detection efficiency of decay electrons from stopping cosmic muons is roughly 80%. A 4π coverage around the interaction vertex provides an efficient π^0 detection.

Super-Kamiokande Gadolinium (SK-Gd)

In June 2015, the Super-Kamiokande Collaboration approved the SK-Gd project. This project is an upgrade of the detector's capabilities, achieved by dissolving 0.2% gadolinium sulfate into Super-K's water in order to enhance detection efficiency of neutrons from neutrino interactions. One of the main motivations of SK-Gd is to discover supernova relic neutrinos (SRN), the diffuse flux of neutrinos emitted by all supernovae since the beginning of the universe. SRN primarily interact in Super-K via inverse beta decay (IBD). Therefore, following the prompt detection of a positron, the accompanying IBD neutron can be identified in SK-Gd by a delayed gamma cascade, the result of the neutron's capture on gadolinium. As a result of this positive identification of true IBD events, a much improved separation between signal and background can be achieved. As Super-K will be the first example of gadolinium loading in a large-scale water Cherenkov detector, this will be a template for any future possibility of loading gadolinium into Hyper-K. In addition to determining the physics performance of gadolinium-loaded water, Hyper-K will also benefit from the extensive research done to optimize the water purification system, as well as the tests for material compatibility that was required to upgrade the Super-K detector.

Chapter 2

Hyper-K experiment

Hyper-K is the next generation of large water Cherenkov neutrino detector with a fiducial volume which will be approximately 10 times larger than its precursor Super-K for increased statistics, with improved photosensors for better efficiency, with higher intensity neutrino beam and updated/new near detectors for accelerator neutrino study.

Hyper-K is a multipurpose experiment for the observation of atmospheric, solar and accelerator neutrino oscillations, for neutrino astrophysics, proton decay and physics beyond the Standard Model. In particular, it will observe neutrino produced at JPARC accelerator complex, about 300 km far, to investigate leptonic CP violation.

The Hyper-K experiment will use the J-PARC accelerator complex, which will provide a power proton beam with a beam energy of 30 GeV from the J-PARC Main Ring synchrotron. The proton beam is extracted to the neutrino beam line, which will be upgraded by Hyper-K from the current beam line used by T2K to allow operation up to 1.3 MW beam power. The neutrino beam line is broken into the primary beam line, which transports the proton beam from the main ring to the target hall, and focuses the proton beam spot on the target, and the secondary beam line, which includes the production target, magnetic horns decay volume and beam dump. Both the primary and secondary beam lines include beam monitors, of both the primary proton beam and the secondary muon beam. To achieve operation at 1.3 MW beam power, upgrades to both the primary and secondary beam lines will be needed. These will include new high intensity beam monitors, remote maintenance systems in the final focus section of the primary beam line, upgrades to the target station beam window, to the target and horn cooling, and to the radioactive cooling water disposal system.

After the neutrino beam is produced, the neutrino fluxes and interaction cross sections must be measured with near and intermediate detectors. Hyper-K plans a suite of near and intermediate detectors to address all systematic effects that are critical for the Hyper-K physics program. As in T2K, Hyper-K will use the INGRID on-axis detector to measure the neutrino beam direction with better than 0.3 mrad precision and to monitor the neutrino interaction rate. It is expected that minimal upgrades to INGRID is needed to keep it operational during Hyper-K. Also located at the 280 m site is the magnetized ND280 detector, which can

be used to study neutrino interaction final states, including reconstruction of the hadronic recoil system. ND280 already underwent a very important upgrade in the last years [55] and another upgrade is in the design phase for the next year, called ND280++ [56]. ND280 also measures the charge of final state lepton, providing a measurement of the wrong-sign component of the beam. Upgrades of ND280 to improve the angular acceptance and the reconstruction of the hadronic recoil system are being carried out by T2K.

2.1 The Intermediate Water Cherenkov Detector (IWCD)

An Intermediate Water Cherenkov Detector [57] with off-axis spanning and Gd loading capabilities, placed at around 1 km from the J-PARC beam line, will be installed to measure the intrinsic ν_e and $\bar{\nu}_e$ backgrounds, the cross section ratios, the neutrino interactions final state and neutron multiplicities as a function of neutrino energy. These measurements will be used to predict the expected event rates in Hyper-K and to measure the properties of neutrino interactions to reduce systematic errors related to neutrino cross section uncertainty. This is one of the major contribution to systematic in the analysis, as also reported in [49]. The detector provides an identical nuclear target to Hyper-K with no need for subtraction analyses. It also naturally provides 4π angular coverage, although the momentum coverage is limited by the detector size. The detector size is large enough to contain neutrons, and with Gd loading, the detector can be used to study the neutron multiplicities in neutrino and antineutrino interactions.

The design for the IWCD includes the capability to make measurements at different off-axis angles by moving the instrumented detector vertically, (see Fig. 2.2). This capability will allow the detector to probe the relationship between neutrino energy and final state particle multiplicities and kinematics. Ideally, mono-energetic neutrino beams would allow the final state charged lepton kinematic distributions to be measured for each energy, including all of the nuclear effects contributing to the event distributions. Narrow energy beams can be modelled with the off-axis spanning detector by using measurements at different off-axis angles to subtract of the contributions from low energy and high energy tails in the neutrino spectra. The conceptual design of the IWCD is shown in Fig. 2.1. The vertical shaft will be filled with water to a few meters above the position of the instrumented detector region to allow for shielding. The instrumented detector is placed in a water-tight stainless steel tank to allow for primary containment when the detector is loaded with Gd. The detector diameter is 10 m. An outer detector region of 1 m gives an inner detector diameter of 8 m. With a such inner detector diameter the detector has high efficiency to contain muons up to 1 GeV/c. The 8 m diameter also allows for the containment of most neutrons produced in neutrino interactions at the center of the tank. The energy range of interest for the near detector physics measurements spans from ~ 8 MeV for the neutron capture events on Gadolinium, up to ~ 2 GeV for the higher energy contained muons from

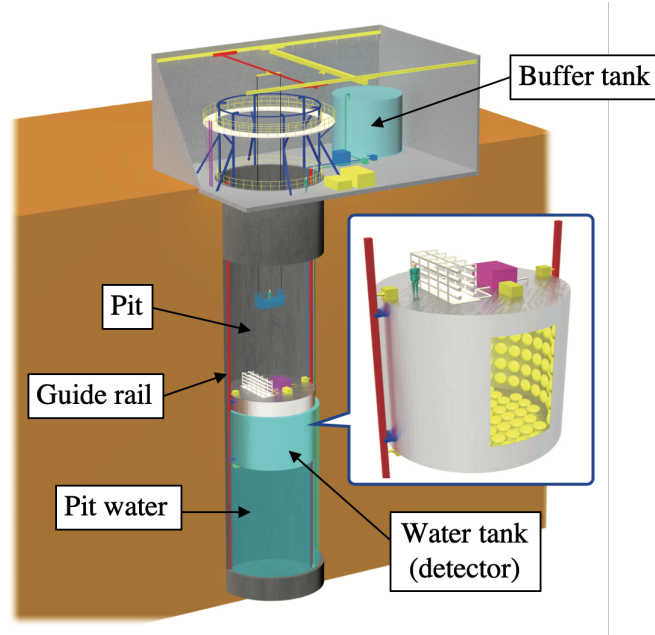


Figure 2.1: Conceptual design of IWCD facility.

beam interactions, which peak at ~ 0.6 GeV, requiring calibration over a large dynamic range. The IWCD baseline design is equipped with multi-PMT module (mPMT) as photodetection system. A detailed description of the mPMT module will be given in Chapter 3.

2.2 The Water Cherenkov Test Experiment at CERN (WCTE)

Before building IWCD a detailed study of the performances of such detector should be performed. For this reason in 2020 a proposal to build a kiloton scale experiment at CERN has been submitted. The experiment is called WCTE, Water Cherenkov Test Experiment [58].

WCTE will use the PS beam line to generate then a secondary beam to focus on those goals:

- Operate and understand the performances of new detectors, such as the mPMTs;
- study the performance of a less than 1 kton scale water Cherenkov with known particle fluxes;
- Develop and test calibration systems necessary for accurate modelling of such detectors;
- Measure important physics process like pion scattering and absorption or secondary neutron production in hadron scattering.

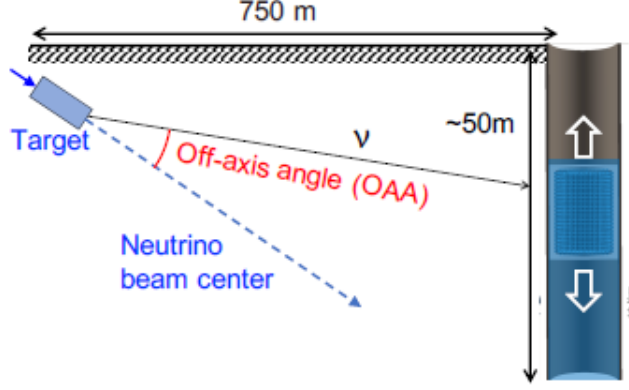


Figure 2.2: Experimental setup of intermediate water Cherenkov detector with concept for measurements at different off-axis angles.

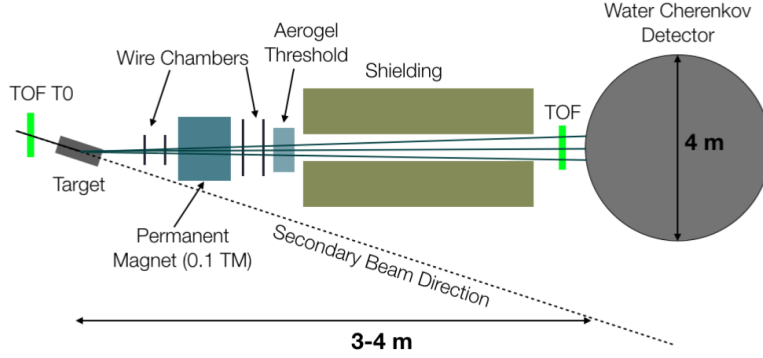


Figure 2.3: WCTE overview diagram

The schematic view of the WCTE experiment is shown in Fig. 2.3. The water tank has a diameter of 4.1 m and a height of 4 m. The WCTE will have two phases of operation. The first phase will use standard ultra-pure water and the deployment of mPMT photosensors and calibration systems that will be used in the IWCD. In addition, WCTE will also serve as a final testbench for all the subsystem to be used in Hyper-K, such as the timing system and the concentrator board for the mPMTs, that we will see in detail in the next sections.

The second phase of the experiment will include loading with $Gd_2(SO_4)_3$ to investigate neutron production and detection capabilities. Super-K and Hyper-K will use measured neutron multiplicities in neutrino interactions to make statistical separation of neutrinos and antineutrinos or exclusive final states in neutrino interactions. To properly model the neutron production and detection, it is necessary to model the production of secondary neutrons as particles traverse and interact in the detector medium. During this phase, the production of neutrons from particles propagating through the detector will be measured.

WCTE detector will be exposed to a charged particle beam which includes $e^\pm, \mu^\pm, \pi^\pm$ and p , with the desired momenta between 140 MeV/c and 1200 MeV/c.

and 71m in diameter with a total water mass of 258 kt. This volume is segmented into an inner detector (ID) of 64.8m diameter and 65.8m height (217 kt), used to measure neutrino interactions and proton decays, and an outer detector (OD) region used to veto incoming muons. The fiducial volume is 186 kt. Between the ID and the OD regions there is a "dead space" of 0.6m thickness occupied by the ID and OD photosensors, their support structure, and the front-end readout electronics.

2.3.1 Inner Detector design

The Inner Detector (ID) basic unit is a 70 cm square cell on the outer surface of the inner detector region with photosensors pointing inwards to detect the Cherenkov photons. There are 40,000 of these unit cells. Each cell can either house a single 50 cm (20") diameter photosensor with a cover, or an array of 8 cm (3") photomultipliers, known as a multi-PMT module (mPMT). If all the cells are instrumented with the 50 cm B&L PMTs, we would have the maximum photosensor coverage with 40% photosensitive area. A few percent of the cells will be needed for placing front-end electronics modules for the PMTs. We will discuss in detail the ID photosensors in the following chapter.

2.3.2 Outer Detector design

The Outer Detector (OD) acts as a veto shield surrounding the ID region. Neutrino interactions inside the ID volume are characterised by a lack of incoming particles, and it is important to veto events where there is activity in the outer part of the detector, induced from cosmic ray muons or neutrino interactions in the surrounding rock. There is also a contribution from spallation interactions in the rock by cosmic muons. The hard component of the cosmic muon flux, which penetrates deep inside the Earth, is shown in Fig. 2.5. Muons that enter the outer detector create a large number of Cherenkov photons which can be identified by the outer photosensors. A very efficient veto against incoming muons is essential for the physics program, particularly for atmospheric neutrinos and proton decay searches. Another function of the OD is to provide a passive shield against low energy backgrounds coming from gammas or neutrons due to natural radioactivity in the surrounding rock. The radiation length of water is 36 cm, and the typical capture distance for neutrons is roughly 2 m, after thermalisation in the water. From Super-K we know that this is sufficient to contain most, but not all the low energy backgrounds.

To veto activity in the OD it has to be optically separated from the ID, with photons detected by a separate array of photosensors. The current design has an OD thickness of 1 m (barrel) and 2 m (endcap), and a dead region of 60 cm between the OD and ID photosensors, determined by the size of the ID covers. The inner and outer walls of the OD are covered with reflecting materials to increase the photon collection efficiency.

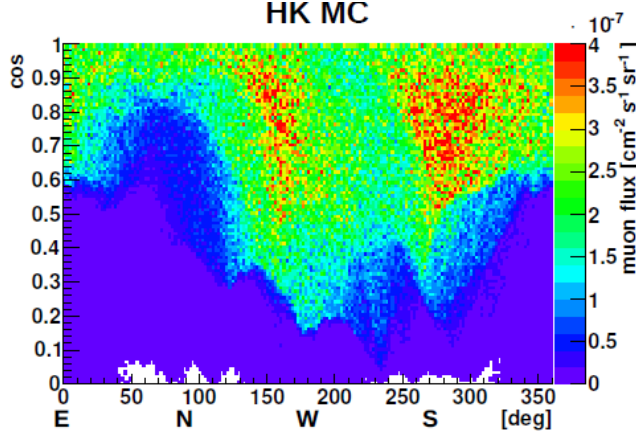


Figure 2.5: Hyper-K cosmic muons flux simulated at Toichibora mine.

2.4 Physics performance

The discovery of neutrino oscillations in 1998 was a milestone in particle physics because it revealed the finite mass and flavour mixing of neutrinos. This was a breakthrough to new physics beyond the Standard Model. The extremely light neutrino masses with respect to the other fermions indicates the existence of different mechanisms than a nominal Higgs coupling. The large mixing angles, in contrast with those in the quark sector, provide insight into the underlying symmetry mechanisms. Since the discovery, significant progress has been made by world-wide neutrino experiments to measure the neutrino oscillation parameters, and now three flavor mixing is well established. This opened the door to measure the CP violation phase in the neutrino sector and, among the current and future projects, Hyper-K has a good opportunity to make the discovery of CP violation in its long baseline project with an upgraded J-PARC neutrino beam. Theoretical studies suggest that CP violation in the neutrino sector may hold clues to understanding the origin of the matter-antimatter asymmetry in the present universe through the process known as leptogenesis [59]. New physics beyond the standard three flavor oscillations will be further tested by the precision measurement of the oscillation parameters in Hyper-K. If Hyper-K finds that θ_{23} is close to 45° (maximal mixing) and δ_{CP} is close $\pm 90^\circ$, or more clearly if unitarity is violated in neutrino mixing, then these results could be taken as a hint of new physics at an ultra-high energy scale. In addition, atmospheric neutrino observation has sensitivity to determine the mass ordering due to the matter effects in the Earth. While, the current precision in Super-K is limited by the statistics, significant improvement is expected by Hyper-K with higher statistics atmospheric neutrino data.

Verification of the grand unified theories (GUT) and baryon number violating processes are also major subjects of Hyper-K. No signal for proton decay was observed so far in Super-K, which is dominating the current searches, and the limits are set at around 10^{34} years for major decay modes [60]. Hyper-K will extend the searches by an order of magnitude beyond the current limit where some

major GUT models predict the lifetime. It should be noted that the atmospheric neutrino background will be strongly suppressed by the improved performance of the detector which results in the improvement of the sensitivity. Moreover, the unprecedented high statistics neutrino data within its huge fiducial mass, Hyper-K has the potential to make discoveries by the observation of astrophysical neutrinos, such as solar neutrinos, supernova neutrinos and the neutrinos from annihilation of dark matter. Verification of the matter effects in solar neutrino oscillation is one important subject to test new physics beyond the standard neutrino oscillation model. Neutrino data from supernova bursts within the galaxy (or nearby) will provide precious information to test various theoretical models of the supernova burst and understand the mechanism. In addition, the observation of supernova relic neutrinos is expected in Hyper-K. This flux depends on the frequency of supernova bursts in the early universe, so its observation by Hyper-K may advance the study of the evolution of the universe.

2.4.1 Accelerator Neutrinos

Hyper-K will perform a precise study of CP asymmetry in the lepton sector by using the J-PARC neutrino beam. A direct comparison of the oscillation probabilities for neutrinos and anti-neutrinos is required for a direct and model-independent measurement of leptonic CP asymmetry. This measurement is significant since the existence of leptonic CP violation may be a necessary condition to explain the matter-antimatter asymmetry in the Universe.

It will also be possible to check the consistency of the PMNS mixing framework by comparing the accelerator ($\nu_\mu \rightarrow \nu_e$ appearance of GeV neutrino over 295 km) and reactor ($\bar{\nu}_e$ disappearance of MeV neutrino over ~ 1 km) θ_{13} measurements, which may have different contributions from new physics.

The Hyper-K long-baseline program will also be able to make precise measurements of the oscillation parameters $|\Delta m_{23}^2|$ and $\sin^2\theta_{23}$ based on disappearance analysis.

The $\nu_\mu \rightarrow \nu_e$ oscillation channel is the most sensitive to the oscillation parameters $\sin^2\theta_{13}$ and δ_{CP} . Fig. 2.6 shows the $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation probabilities as a function of the true neutrino energy for a baseline of 295 km for various true values of δ_{CP} and the mass hierarchy.

The current measured value of θ_{23} is compatible with maximal mixing, thus $\theta_{23} = \pi/4$, while NOvA collaboration reported a possible hint of non maximal mixing [62]. It is of great interest to determine if $\sin^2\theta_{23}$ is maximal or not, and if not, whether θ_{23} is less or greater than $\pi/4$, as it could constrain models of neutrino mass generation and quark-lepton unification.

Because the mass squared difference measurements by Hyper-K and reactor experiments give independent information, the comparison can be used to check the consistency of the PMNS mixing matrix framework. In order to have sensitivity to the mass hierarchy, the uncertainties of both measurements must be $<1\%$. Future medium baseline reactor experiments, JUNO and RENO-50, plan to measure Δm_{ee}^2 with precision better than 1%, and a precision measurement of Δm^2 by Hyper-K will also be required.

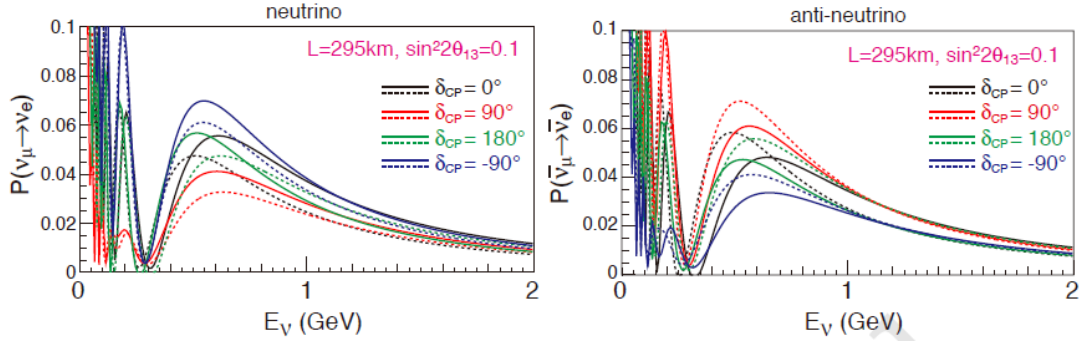


Figure 2.6: Oscillation probabilities as a function of the neutrino energy for $\nu_\mu \rightarrow \nu_e$ (left) and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ (right) transitions with baseline $L=295$ km and $\sin^2\theta_{23} = 0.1$. Black, red, green, and blue lines correspond different values of δ_{CP} as reported in figure. Solid (dashed) line represents the case for a normal (inverted) mass hierarchy. Figure from [61].

2.4.2 Atmospheric Neutrinos

Cosmic ray interactions with air nuclei provide a continuous flux of both electron and muon neutrinos (and their antiparticles) through the decays of mesons emerging from those interactions. In addition to being produced isotropically about the Earth, and therefore yielding neutrinos of pathlengths ranging from $O(10)$ to more than 10,000 km, the neutrino spectrum spans many orders of magnitude. Unlike the neutrino beam measurement, there is no a priori knowledge of the direction and energy of these neutrinos, so they must be inferred by reconstruction of the particles produced in their interactions. Despite these limitations the large size of Hyper-K, coupled with its precise reconstruction capabilities, makes its atmospheric neutrino sample a useful probe of many types of oscillation physics. Hyper-K will make combined beam and atmospheric neutrino oscillation measurements to a yield increased sensitivity.

2.4.3 Proton Decay

Though baryon number is explicitly conserved in the Standard Model, its violation is thought to have a critical role in the evolution of the early universe. One of the hallmarks of Grand Unified Theories (GUT) is the predictions of proton and bound nucleon decays, both of which are processes that violate baryon number.

Accordingly, the search for proton decay at Hyper-K is an important part of its physics program, not only for the purpose of studies these theories but for understanding the development of the early universe. One of the main research channel is $p \rightarrow e^+ + \pi^0$. Proton decay into a positron and a neutral pion is two body process which creates a back-to-back topology of three electromagnetic showers within Hyper-K: two showers from the pion decay appear opposite than the positron one.

Fig. 2.7 shows the one-sided 3σ discovery potential for observing a $p \rightarrow e^+ \pi^0$ signal based on these estimates. Projections from other experiments including

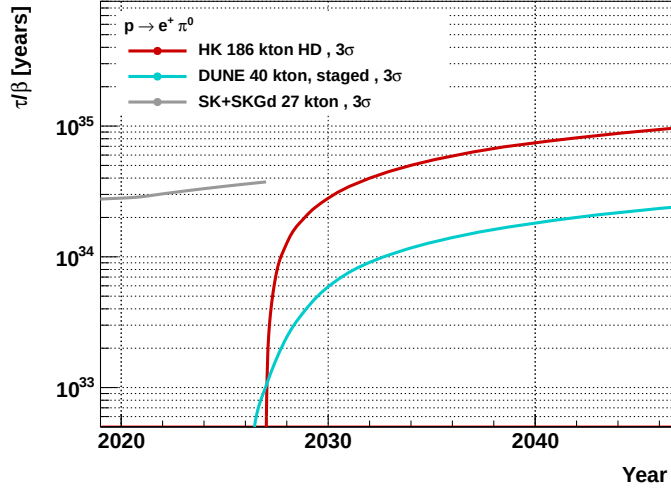


Figure 2.7: Comparison of the $3\sigma p \rightarrow e^+\pi^0$ discovery potential as a function of year Hyper-K (red solid) assuming a fiducial volume of 186 kton as well as that of the 40 kton liquid argon detector DUNE (cyan solid). Super-K’s discovery potential up to 2027 is also shown. Figure from [61].

DUNE and Super-K as well as the expectation for Hyper-K are shown for comparison. In Hyper-K a proton decay signal can be observed at 3σ if the proton lifetime is less than 10^{35} years with a 20 year exposure. If no signal is observed, Hyper-K is expected to produce limits as shown in Fig. 2.8. After a 15 year exposure, the lifetime limit on this decay mode will exceed 10^{35} years. It should be noted that Hyper-K leads other experiments by nearly an order of magnitude in both metrics.

2.4.4 Solar Neutrinos

The neutrino oscillation parameters between mass eigenstate ν_1 and ν_2 are determined based on the solar neutrino data and the reactor anti-neutrino data in KamLAND assuming CPT invariance. The constraint on Δm_{21}^2 comes mainly from the Super-K data observing the zenith angle and energy dependent neutrino fluxes. Hyper-K, with its unprecedented statistics, will measure the short-period flux variations, realizing a real-time monitor of the Sun’s core temperature. Hyper-K could also achieve the first measurement of hep solar neutrinos, providing new information on solar physics, to clarify fusion conditions in the core region of the Sun.

2.4.5 Supernovae Neutrinos

The observation of supernova neutrinos from SN1987A proved that the basic scenario of the supernova explosion was correct. However, more than three decades later the detailed mechanism of explosions is still unknown. Among current or

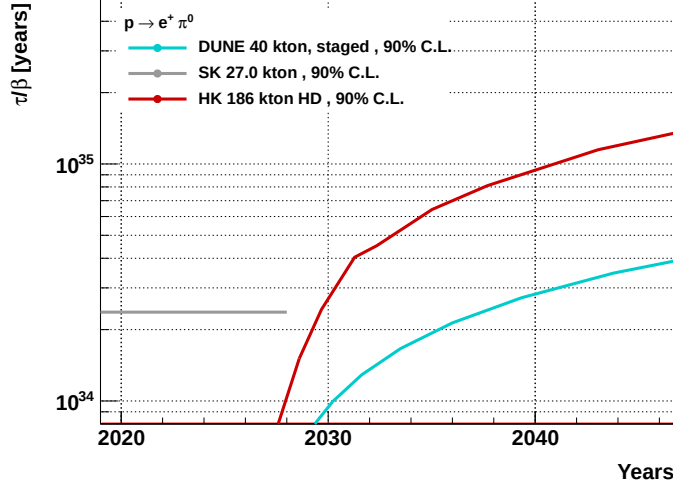


Figure 2.8: Hyper-K’s sensitivity to the $p \rightarrow e^+\pi^0$ decay mode at 90% C.L. as a function of run time appears in red in comparison with Dune. Super-K’s current limit is shown by a gray horizontal line. Figure from [61].

Neutrino source	Single Tank (220 kt Full Volume)	2 Tanks (440 kt Full Volume)	Ref.
$\bar{\nu}_e + p$	50,000 - 75,000 events	100,000 - 150,000 events	[63]
$\nu + e^-$	3,400 - 3,600 events	6,800 - 7,200 events	[64]
$\nu_e + {}^{16}\text{O CC}$	80 - 7,900 events	160 - 11,000 events	[65]
$\bar{\nu}_e + {}^{16}\text{O CC}$	660 - 5,900 events	1,300 - 12,000 events	[66]
$\nu + e^-$ (Neutronization)	9 - 55 events	17 - 110 events	[64]
Total	54,000 - 90,000 events	109,000 - 180,000 events	

Table 2.1: Expected number of neutrino events from Galactic supernova (10 kpc) in Hyper-K with the detection threshold of 3 MeV. References for each neutrino cross-section are also shown.

planned experiments, Hyper-K has several advantages: the high statistics of neutrino events owes to the large volume, the low detection threshold of 3 MeV, and the event-by-event directional sensitivity. It will allow the comprehensive study of supernova neutrinos. The expected number of supernova neutrino events in Hyper-K is summarized in Table 2.1. This high statistics data will provide key information of the supernova explosion mechanism and neutrino oscillations.

Expected observation in Hyper-K

Expected time profiles for various interactions in Hyper-K for a supernova at a distance of 10 kpc are shown in Fig.2.9. The burst time period is about 10 s and the peak event rate of inverse beta decay events reaches about 50 kHz at 10 kpc. The DAQ and its buffering system of Hyper-K is being designed to accept the broad range of rates, for a galactic supernova closer than 10 kpc.

Hyper-K can observe in total 54,000 to 90,000 events, for a 10 kpc supernova, depending on the neutrino oscillation scenario (no oscillation, normal hierarchy,

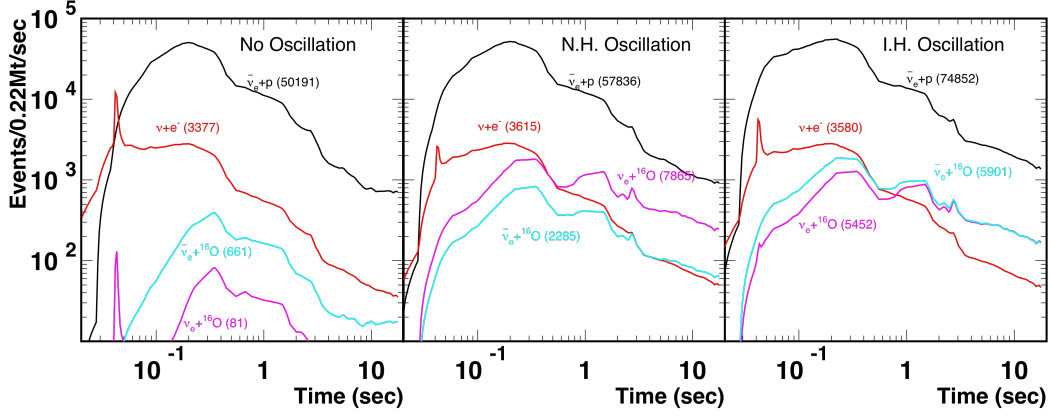


Figure 2.9: Expected time profile of a supernova for various interactions, inverse beta decay ($\bar{\nu}_e + p \rightarrow e^+ + n$), νe -scattering ($\nu + e^- \rightarrow \nu + e^-$), $\nu_e + {}^{16}\text{O}$ CC ($\nu_e + {}^{16}\text{O} \rightarrow e^- + {}^{16}\text{F}^{(*)}$), and $\bar{\nu}_e + {}^{16}\text{O}$ CC ($\bar{\nu}_e + {}^{16}\text{O} \rightarrow e^+ + {}^{16}\text{N}^{(*)}$), at 10 kpc. Left, center, and right figures show profiles for no oscillation, normal hierarchy, and inverted hierarchy, respectively. The numbers in parentheses are integrated number of events over the burst. The fluxes and energy spectra are from the Livermore simulation [67].

Table 2.2: Expected total number of neutrino events from supernovae at 10 kpc (galactic center) and 200 pc (Betelgeuse) in Hyper-K. Table from [68].

time window	10 kpc (galactic center)	200 pc (Betelgeuse)
0–1 sec	24,000 - 30,000 events	60,000,000 - 75,000,000 events
0–10 sec	47,000 - 72,000 events	117,500,000 - 180,000,000 events

and inverted hierarchy). The expected total number of neutrino events from supernovae at 10 kpc (galactic center) and 200 pc (Betelgeuse) for each time window after the onset of the burst are shown in Table 2.2, which gives estimates of the temporal trigger rate.

Chapter 3

Hyper-K Photosensors

The Hyper-K experiment will use as baseline Hamamatsu R12860-HQE 20" PMT, referred to as B&L PMT, since based on a box-and-line dynode structure. An innovative system of small photomultipliers assembled in a resistant pressure vessel with power supply and all the necessary electronics, as implemented in the KM3NeT experiment [69], the so called multi-PMT module (mPMT), will be used to improve the Hyper-K physics capability.

Fig. 3.1 shows the event display of Hyper-K in the hybrid configuration with 20k B&L PMTs and 10k mPMT modules. Muon with the momentum of 200 MeV was generated at a distance of 2.4 m far from the ID wall.

3.1 20" PMT

For Hyper-K a 20" R12860-HQE PMT called B&L 20" PMT (Fig. 3.2) has been developed in collaboration with Hamamatsu, improving the R3600 PMT used for Super-K (SK PMT), with a faster time response, better charge resolution, and higher detection efficiency and with a more uniform response over the detection area.

The two main differences with respect to the R3600 PMTs are the change of the dynode configuration from "Venetian blind" to "box and line" one and the higher quantum efficiency, with a peak of 30%, compared to the 22% of the SK PMTs.

The change to a box and line dynode provides a more uniform drift path for the electrons, improving the timing resolution, and reduces the probability that an electron misses the first dynode. The main characteristics of the new PMT are reported in tab. 3.1. For single photo-electron events, the Transit Time Spread (TTS) is improved from 6.73 ns to 2.59 ns (FWHM), and the charge resolution from 60.1% to 30.8%.

During the summer of 2018, Super-K was opened for refurbishment to prepare for the SK-Gd project, with gadolinium dissolved in the water to provide additional ability to detect neutrons. During the refurbishment work, 136 R12860 B&L PMTs have been installed in Super-K replacing not properly working R3600 PMTs.

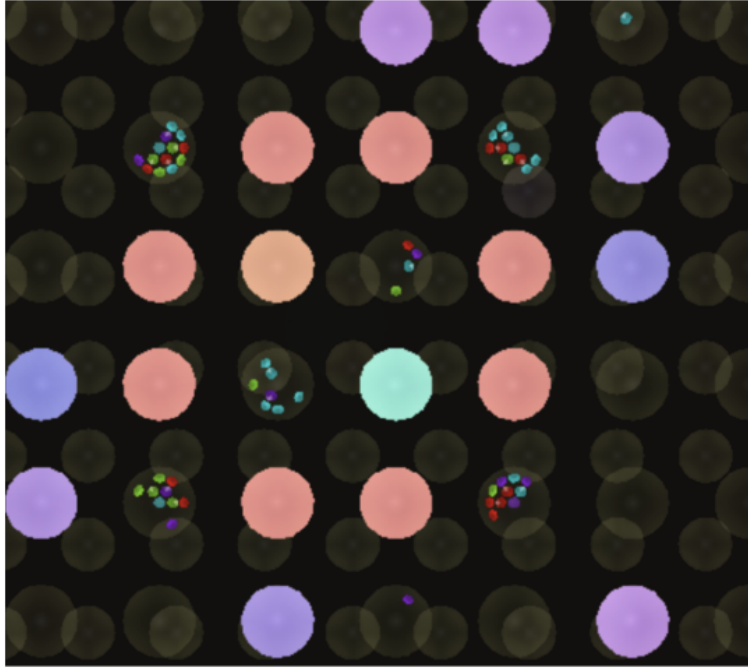


Figure 3.1: Event display of hybrid configuration Hyper-K detector with 20k B&L PMT and 10k mPMT uniformly arranged on ID wall.

Their performances in the detector were measured during the initial calibration campaign at the restart of data taking, and they confirmed the improved performances compared to the R3600 PMTs. The charge resolution of the installed R12860 PMTs was measured to be $27 \pm 3.8\%$, and their timing resolution to be 3.53 ns FWHM. This timing resolution is larger than the one measured in the pre-calibration setup, but this is due to the limitation of the Super-K electronics which was not designed for PMTs with such a low timing resolution. An acquisition of the single photo-electron spectra shows the clear difference from the previous generation Super-K PMTs (see Fig. 3.4 for the charge and Fig. 3.3 for the timing resolution).

In the R12860 PMTs, The typical waveform at 1×10^7 gain has 5.2 ns rise time (from 10% to 90% pulse height), 9.4 ns fall time and 11.2 ns pulse width at half maximum. A normalized template is showed in Fig. 3.5. A long positive overshoot is expected after the main pulse because of the capacitor coupling. The baseline voltage level can be shifted by increasing the pulse current. The typical signal height is around -6 mV per single photo-electron, that is 1.5 times higher than the Super-K R3600 PMT of -4 mV. The maximum pulse height will be 6–9 V, varied by individual difference and bias voltage.

In Fig. 3.6 the bleeder circuit at the HV base is shown.

Protective acrylic covers are used to prevent a chain implosion in the case of a PMT breaks and implodes in the detector. Such protective covers are already used in Super-K, but they were found to produce noise due to radio impurities, and were not designed to function at the high pressure expected at the bottom of Hyper-K. The covers are validated through implosion tests, in which the PMT

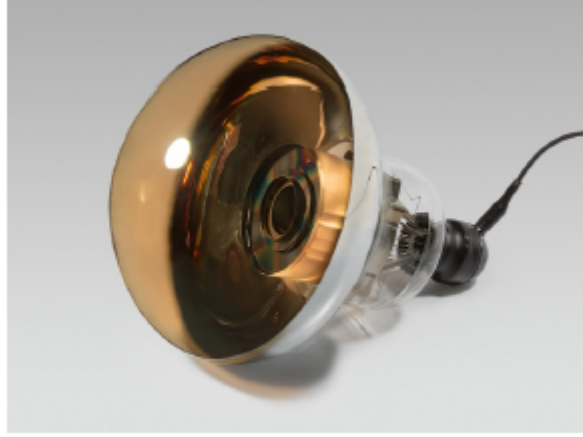


Figure 3.2: Picture of the HQE 50 cm B&L R12860 PMT.

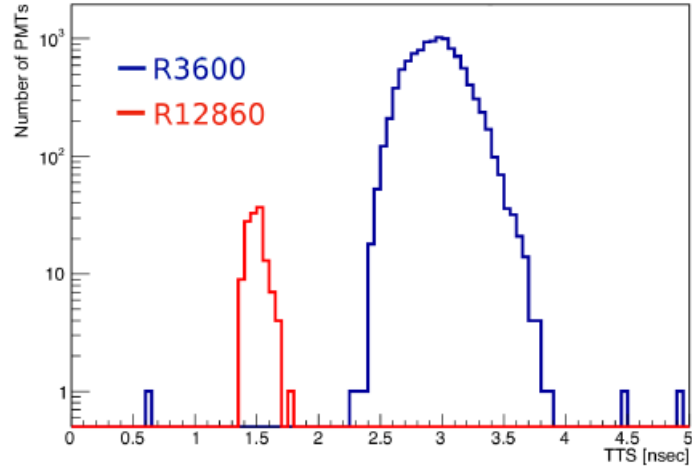


Figure 3.3: TTS distribution measured during the calibration run in Super-K in 2018.

Shape	Hemispherical
Photocathode area	50.8 cm diameter (20 inches)
Bulb material	Borosilicate glass (~ 3 mm)
Photocathode material	Bialkali (Sb-K-Cs)
Sensitive wavelength range	300 – 650 nm
Peak sensitive wavelength	$\lambda = 420$ nm
Dynodes	10 stage box (for the first dynode) and line (from the second to tenth dynodes) type
Gain	10^7 at ~ 2000 V
Dark pulse rate	6 kHz at 10^7 gain (13°C , after stabilization, update in Jul)
Bleeder current	$339\ \mu\text{A}$ at 2000 V (Total resistivity : $5.9\ \text{M}\Omega$)
Mean cathode current	$15\ \mu\text{A}$ at 2000 V
Capacitance between electrodes (bulb only)	
Between cathode and last dynode	about 18 pF
Between cathode and all dynodes	about 32 pF
Operational temperature	$5 - 35^\circ\text{C}$
Storage temperature	$-5 - 45^\circ\text{C}$
Weight	8.8 kg (without cable)
Volume	$61,000\ \text{cm}^3$
Pressure tolerance	1.25 MPa water proof

Table 3.1: B&L PMT characteristics provided by Hamamatsu.

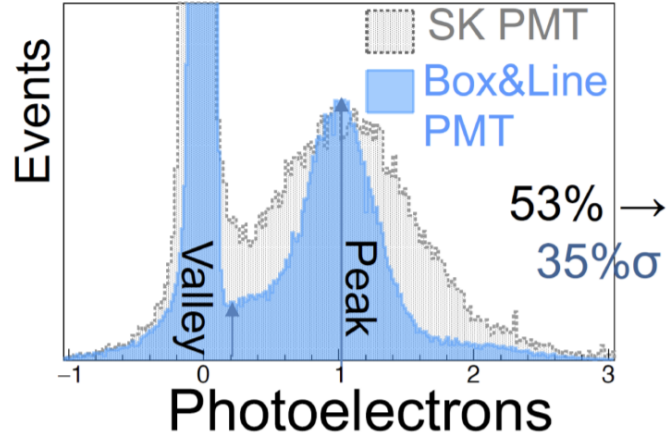


Figure 3.4: The single photon distribution of the 50 cm B&L PMT compared with the Super-K R3600 PMT one. Single photon and noise regions are clearly separated and high single photon efficiency is expected if we set the discriminator threshold lower than 0.25 p.e.

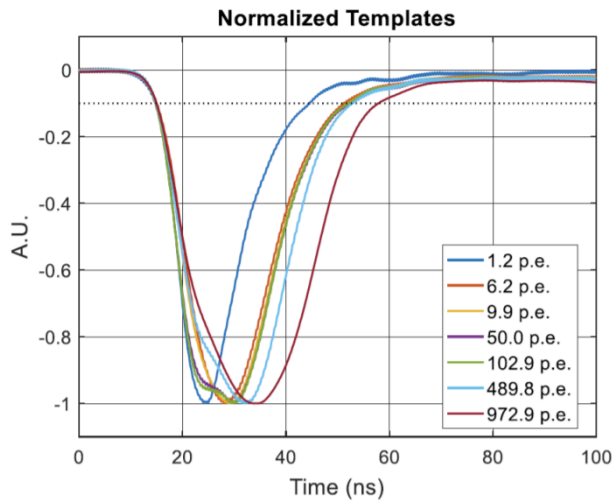


Figure 3.5: Pulse width measured with the B&L 20" PMT prototype. Maximum pulse height of each measurement is normalized to -1

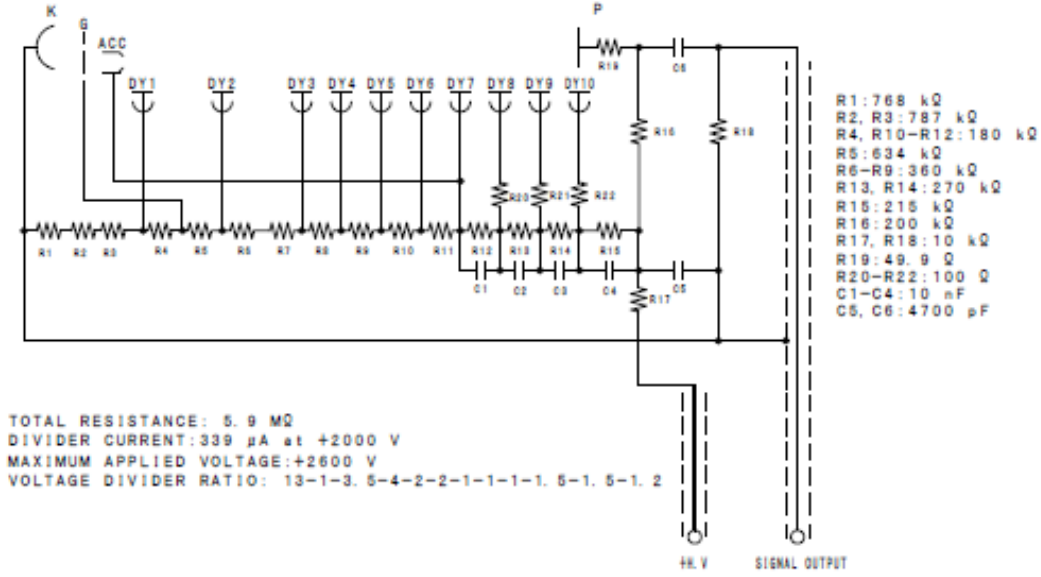


Figure 3.6: Bleeder circuit for the B&L PMT. This circuit is important for the definition of the input protection circuit of the FEB.

inside the cover is made to implode, triggering a shock wave.

3.2 3" PMTs

Several manufacturers like Hamamatsu Photonics K.K., ET Enterprises Ltd., MELZ FEU Ltd. and HZC Photonics Ltd. have developed similar 3" PMTs that can be used in the mPMT module. These PMTs have been characterised for compliance testing with the Hyper-K requirements by different institutes.

Most efforts have focused on the Hamamatsu R14374 and the HZC XP82B20. In the last years, HZC produced an improved version of its 3" PMT, XP72B2F, that has been under study by the Hyper-K Collaboration. Time resolution and charge resolution of both PMTs are showed in Fig. 3.7 and 3.8. While the charge resolution is similar to both PMTs, the time resolution of the Hamamatsu PMT is significantly better than the HZC PMT's one. Detailed measurements of the dark rate have been realized because this is one of the crucial parameters to improve the performances of Hyper-K.

A comparison between the Hamamatsu R14374 and the HZC XP82B20 and XP72B2F PMTs is shown in Fig. 3.9. At 13 $^{\circ}$ C, namely the operation temperature in Hyper-K, the XP72B2F PMT from HZC and Hamamatsu-R14374 have similar dark rates. However, the temperature dependency of the dark rate appears to be larger for HZC-XP72B2F than for the Hamamatsu-R14374, increasing respectively to 600 Hz and 300 Hz at 20 $^{\circ}$ C.

In 2023 the collaboration approved the specification documents for the tender of the 3" PMTs to be used and the contract is now assigned to Hamamatsu to

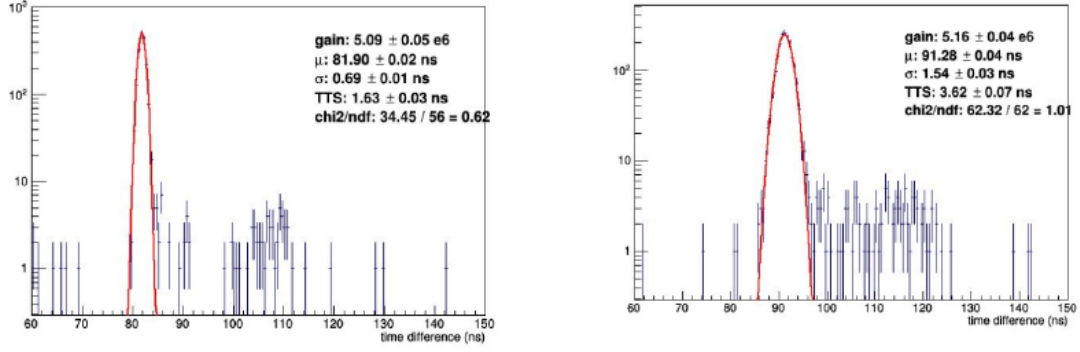


Figure 3.7: TTS of the Hamamatsu R14374 (left) and the HZC XP82B20 (right) with a gain of 5×10^6 .

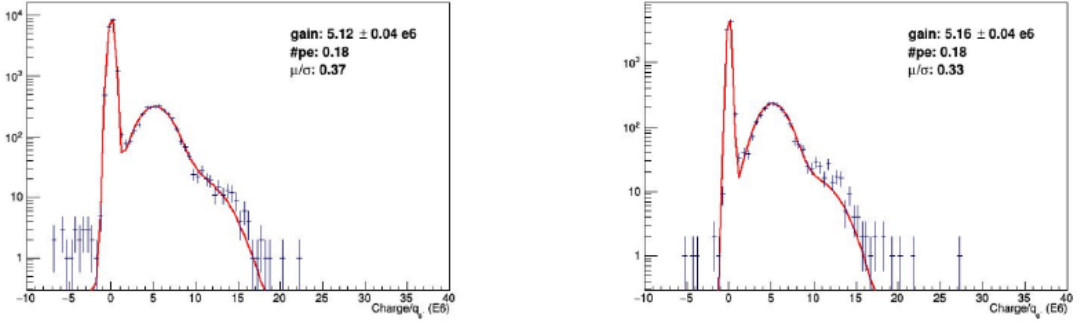


Figure 3.8: Charge resolution of the Hamamatsu R14374 (left) and the HZC XP82B20 (right) with a gain of 5×10^6 .

provide the R14374 for the mPMT production. 3" waterproof PMTs will be used in the OD. Specifications are being defined.

3.3 The mPMT concept

The mPMT is a photodetector system proposed for the first time for the KM3NeT experiment [69]. The hardware functionality and physics capability of the mPMT concept have been demonstrated in-situ with the deployment and operation of KM3NeT mPMTs in the Mediterranean sea.

The first design of the mPMT for Hyper-K was based on a spherical shape as the detectors in the KM3NeT experiment, with an hemisphere looking at the Inner Detector (ID) and the other one at the Outer Detector (OD). Based on this technical design a first prototype has been realized at INFN in Naples to test the HV and read-out electronics of the mPMT. This prototype has been fully tested and characterized using the Memphyno setup at APC in Paris [71].

The final design of the mPMT has only 19 PMTs facing out the fiducial volume and an hemispherical shape. This "ID-sided" design makes production and installation easier and reduces the cost of each module, preserving the improvements in reconstruction capability.

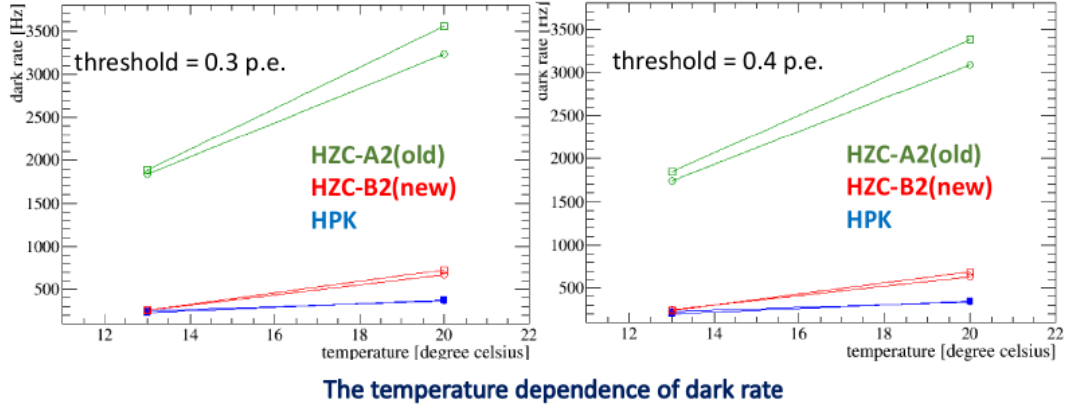


Figure 3.9: Dark rate of Hamamatsu R14374 (blue), HZC XP82B20/old (green) and HZC XP72B2F/new (red) operated at a gain of 1×10^7 in negative HV mode. The squares represents the first set of measurement, and the circles the second one to test reproducibility. Figure from [70].

The mPMT is designed to occupy the same footprint as the 20" PMT in order to simplify the integration in the Hyper-K frame.

Currently, the design for the mPMT includes the following components:

- mPMT vessel
- mPMT photosensors
- PMT Reflector Rings + cups
- PMT Support Structure
- Optical gel
- Ethernet cable, penetrator/feedthrough and under-water RJ-45 connector
- mPMT Electronics: PMT HV supply, Front End board and Main Board

An image of the mPMT with all its components is shown in Fig. 3.10. In the next paragraphs a description of these components will be given. We will focus in particular on the electronics that has been developed during this work.

3.4 mPMT for physics and calibration

3.4.1 Calibration with mPMTs

To reach Hyper-K physics goal the collaboration aims to suppress the uncertainty between data and MC using cosmic muons and electrons from muon decays (also called Michel electrons) well below 1%.

As the mPMT is an independent photon detection device from B&L PMT system, possible biases in the one of the photo-sensor systems can be investigated

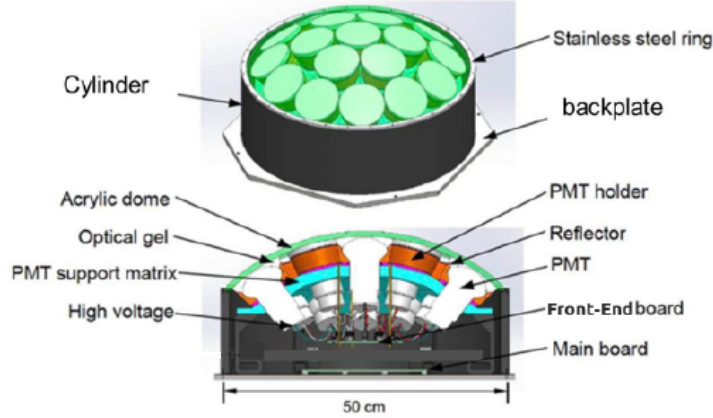


Figure 3.10: The mPMT photodetection system.

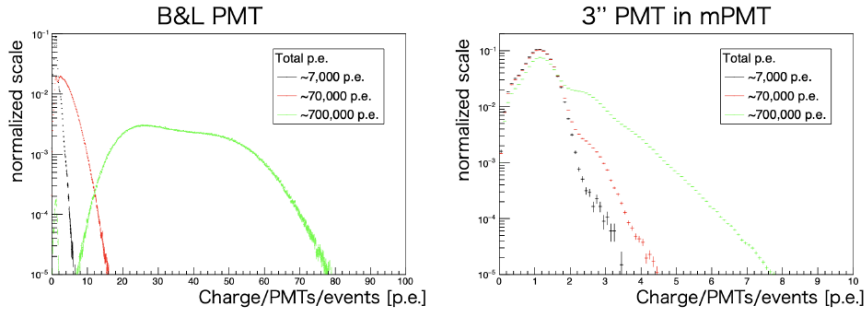


Figure 3.11: Number of p.e. observed by one PMT (20" PMT or 3" PMT in mPMT module) for events with different total p.e.. Number of p.e. observed by B&L PMT increases with the total p.e. while 3" PMT observes typically one p.e. even for relatively large number of total p.e.. $O(10^4)$ p.e. are expected for 1 GeV electron with 20k B&L PMTs, which corresponds to black histograms in the plots. Figure from [70].

by the comparison between the two. Due to the large difference of the photocatode dimension, the two photo-sensor systems measure different number of p.e. from the same light source as shown in Fig. 3.11. Therefore, non-linear bias, if it exists, appears differently to B&L and mPMTs. Fig. 3.12 indicates the 0.5% non-linear bias causes a shift in the ratio of the measurements by B&L PMTs and mPMTs, and, hence, can be detected in the calibration phase using light source with different light intensities.

3.4.2 Physics Capabilities with the mPMT

In the previous section the improvements in terms of performances with mPMT modules were shown. The addition of mPMT modules will led to the following physics capabilities for Hyper-K:

- A possible extension of the fiducial volume, which is beneficial for all physics studies including CP violation measurements. Moreover an enhance effi-

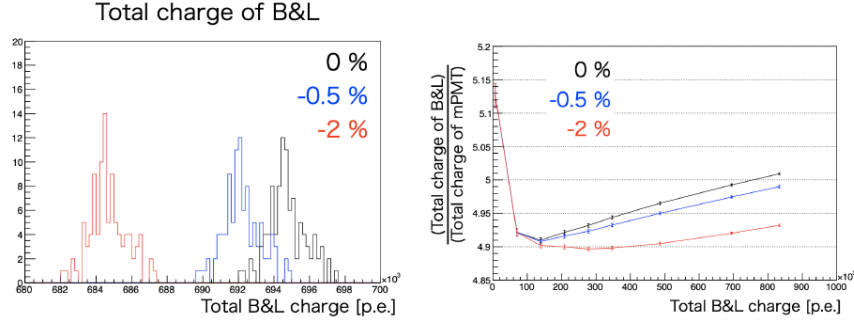


Figure 3.12: Left: total number of p.e. observed by 20k B&L PMT. Right: ratio of total p.e. observed by 20k B&L PMT with respect to the one by 10k mPMT. In both plots, different non-linear responses of B&L PMT are assumed: no bias (black) and 0.5% (bue) and 2% (red) non-linearity above 10 p.e. Figure from [70].

ciency and purity of neutral current selection to study exotic models (mainly due to the improvement of π^0 identification) is expected.

- Various exciting physics studies are expected by Hyper-K concerning atmospheric neutrino observation with unprecedented statistics.
- In the proton decay search no neutron at primary event is expected. While more than one neutrons are often produced in background events due to atmospheric neutrino interactions (typically DIS interactions). Improvements on neutron tagging and reconstruction of multi-ring events lead to suppress the background events for proton decay. In addition, extension of fiducial volume will directly enhance the sensitivity.
- Physics of solar and supernova neutrinos is sensitive to the photosensor configurations due to the low energy range of O(1) to O(10) MeV where the separation of the background and performance of event reconstruction rely on the photocoverage and dark rate. Thus a dark rate of 100 Hz for PMTs in the mPMTs can make a huge difference at this energy scale. The average energy of O(10) MeV supernova burst neutrinos can be measured well with any of the photosensor configurations.

Chapter 4

Hyper-K DAQ and electronics

In this chapter we will describe the general core of Hyper-K DAQ, trigger and electronics, analyzing the overall architecture and in particular describing the DAQ and the general timing system.

4.1 The underwater electronics

In Super-K all the electronics was out of water and 5 main electronics huts were placed on top of the tank. In Hyper-K all the front-end and the associated electronics will instead be placed underwater in watertight vessels and only the DAQ and part of the timing system will be placed on top of the tank.

In this section the electronics vessel that will collect signals from the 20" PMTs and from the 3" PMTs for the OD is discussed.

Having all the electronics underwater allows to have a short distance between the front-end electronics and PMTs. There are two main advantages with this configuration, one is the lower attenuation on the signal, thus having the possibility to lower the threshold and the second is to have a reduced weight in cables, that means a simpler and lighter structure for the detector, saving money. There is, however, a drawback since the electronics will not be accessible during the filling of the experiment and during the operation, hence long-term reliability of all the electronics systems is essential. 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.

In order to read out and power 20000 20" PMTs around 900 electronics vessels will be placed in the detector. There will be two types of vessel, a pure-ID type and an Hybrid ID+OD type.

In the pure-ID type, 24 different 20" PMTs are connected via ~ 20 m long cables to the corresponding electronics vessel. 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 ~ 150 m.

In total, about 560 pure-ID underwater electronics units will operate the 20" PMTs of the ID.

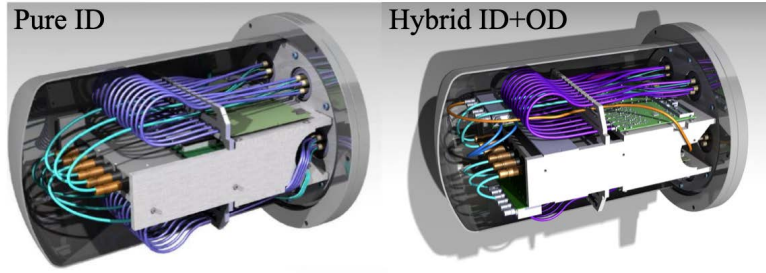


Figure 4.1: CAD Rendering of the two possible underwater electronics vessel.

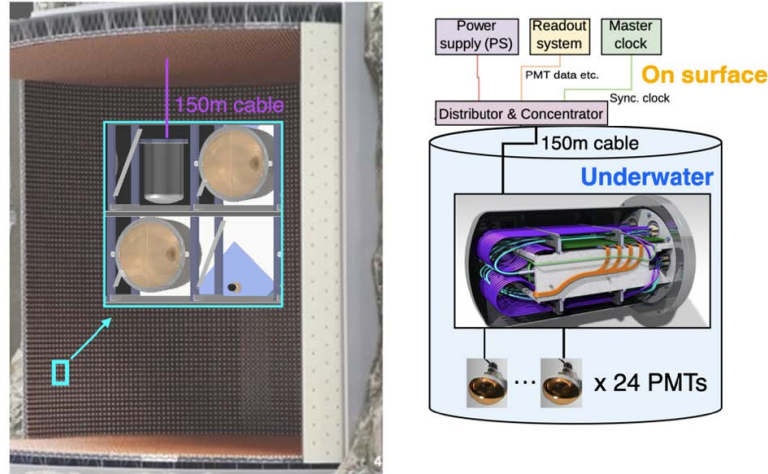


Figure 4.2: On the left a representation of the ID with a detail of the vessel and the 20" PMT positioned in the support structure. On the right a CAD rendering of the vessel with an overview of the connections to the surface and to the PMTs.

The hybrid ID+OD unit will instead operate twenty 20" PMTs and also 12 3" PMTs for the OD. There will be the addition of few boards to digitalise the OD channels. Details will be given in the next chapters. In total about 320 hybrid units will operate a fraction of the ID 20" PMTs and all the OD 3" PMTs.

A CAD drawing of the underwater vessel is shown in Fig. 4.1.

The underwater vessel will contain all the electronics needed to power and acquire signals, in particular it will include a module to give the High Voltage (HV) to the PMTs, a Low Voltage (LV) module to power all the boards and one or more digitizer board to acquire time and charge and send them to the DAQ on the surface via optical fiber. In Fig. 4.2 an overview of the electronics system in Hyper-K is shown, while in Fig. 4.3 a general block diagram of the underwater electronics is provided.

In order to better introduce the front-end electronics in the next chapters, it is necessary to give now more details on some of the other systems in the vessel; in particular, we will describe the following:

- The HV module
- The LV module

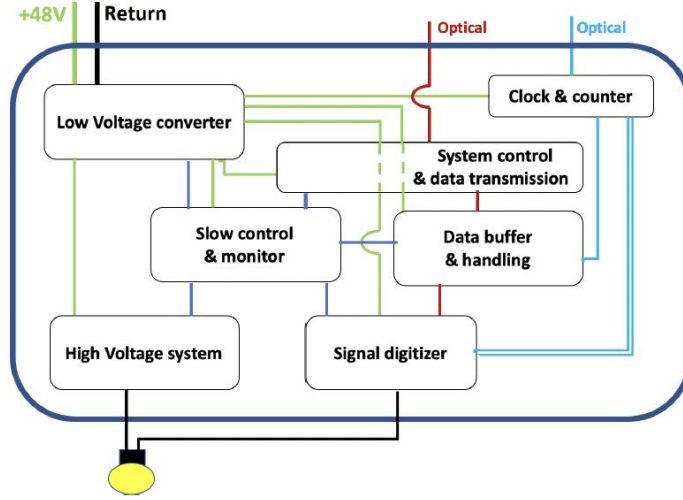


Figure 4.3: Block diagram of the underwater electronics system.

- The Data Processing Module (DPB)

As the main developers of the Front-End for the 20" PMTs we helped the collaboration in the definition of the requirements and interfaces for all the parts of the electronics vessel.

4.1.1 The HV Module

In Hyper-K, the PMTs will operate with a voltage ranging from approximately 900 V to 1500 V for the OD and 1400 V to 2600 V for the ID. The maximum current allowed by requirement is 500 μA . Stability of the high voltage applied to the PMT is crucial, as fluctuations can affect the stability of the PMT gain. Any change in high voltage leads to gain variation, compromising the accuracy of particle energy measurements.

The HV board is a custom one designed by CAEN [72] (see Fig. 4.5) to offer 24 voltage outputs through six 4-channel connectors compatible with RG-174/U cables, adjustable from 20 V to 2600 V with a maximum current of 500 μA and independently configurable with a precision of $\pm 1\%$ within the required range of 900 V to 2600 V. To ensure long-term stability, the high voltage must remain consistent within a spread of $\pm 0.2\%$ annually, with a ripple less than 100 mV peak-to-peak from 10 Hz to 10 kHz and 10 mV peak-to-peak from 10 kHz to 20 MHz.

The HV board can be controlled and monitored remotely through an RS485 communication interface, for setting, monitoring, and adjusting of individual channels. To enhance the detector's operational capability the HV board can control each channel individually, enabling some channels to continue operating normally while others are turned off. Voltage and current monitoring accuracy is within $\pm 1\%$ and $\pm 2\%$ respectively, across the 900 V to 2600 V range. The HV board

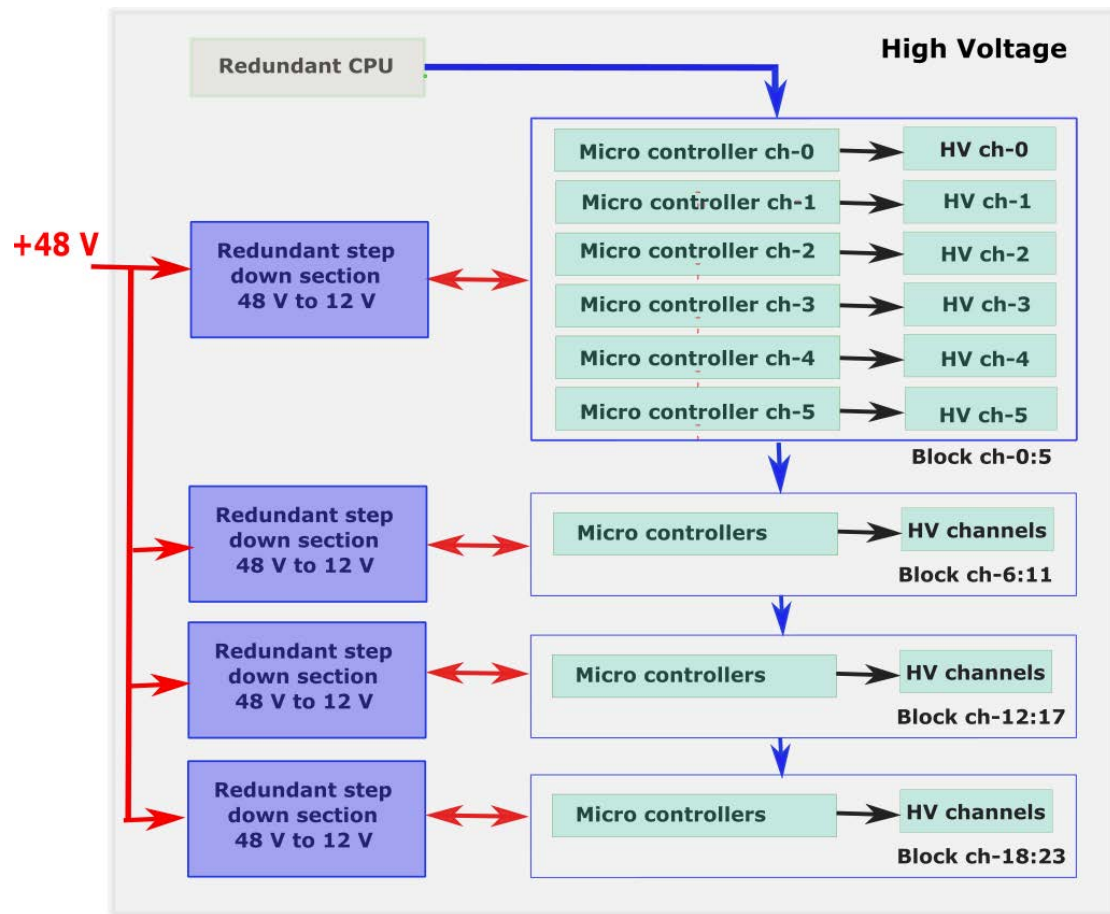


Figure 4.4: HV board diagram.

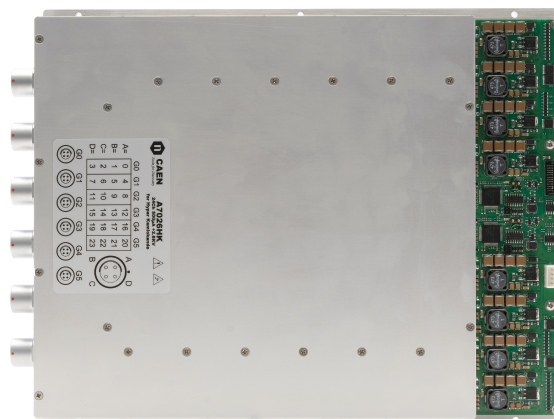


Figure 4.5: Top view of the HV board designed by CAEN. The board is almost fully shielded and coated to prevent Electromagnetic interference problems and discharges.

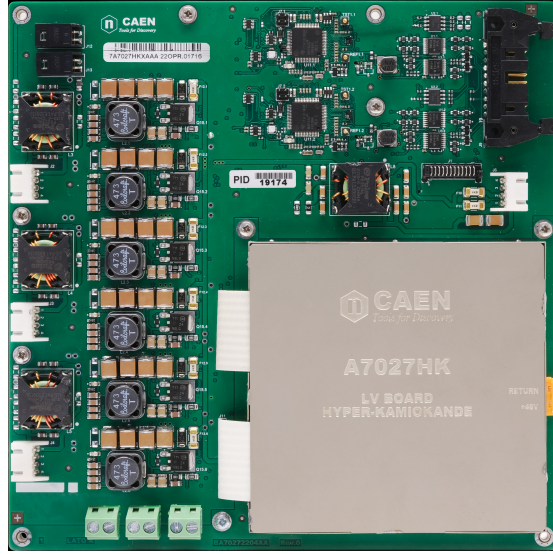


Figure 4.6: LV board produced by CAEN on custom specification by Hyper-K.

is also equipped with protections against overvoltage, undervoltage, and over-current. If such faults occur, the affected channel will be automatically turned off. Monitoring includes the status and temperature of each channel. Fig. 4.4 illustrates the HV block diagram along with potential redundant components.

The limit in power consumption and heat generation of the electronic units are constrained by the vessel's cooling capabilities. Specifically, the heat dissipation on the HV board should not exceed 24 W. Accordingly, the board must achieve over 50% efficiency at 2500 V and a 5.9 M Ω load, that is the load of each PMT. The HV board is required to be enclosed within a metallic case that serves as an EMI (Electro Magnetic Interference) shield. To maintain stable electrical performance, ensure reliability, and keep the internal pressure vessel temperature within safe limits, the HV board must be constructed to direct heat dissipation through the "bottom" surface of the metallic case. This surface serves as the "attachment side" for mechanical support inside the underwater vessel, facilitating thermal contact for heat transfer.

4.1.2 The LV Module

Each underwater vessel will be powered by an external power supply at 48 V. This will be provided via a couple of copper cables from the top of the tank to the vessel via a composite power and fiber cable. The 48 V will be received by a Low Voltage board which aim is to filter the incoming 48 V, decouple from the external ground and generate the 12 V needed by the other boards in the vessel. Only the HV board will be directly powered at 48 V. Also the LV board is designed by CAEN, see Fig. 4.6 for the final board overview.

The LV board incorporates a backup isolated DC-DC converter, ensuring isolation between the input and output, with its own local ground on the LV board. This local ground is subsequently linked to the output section, featuring optional

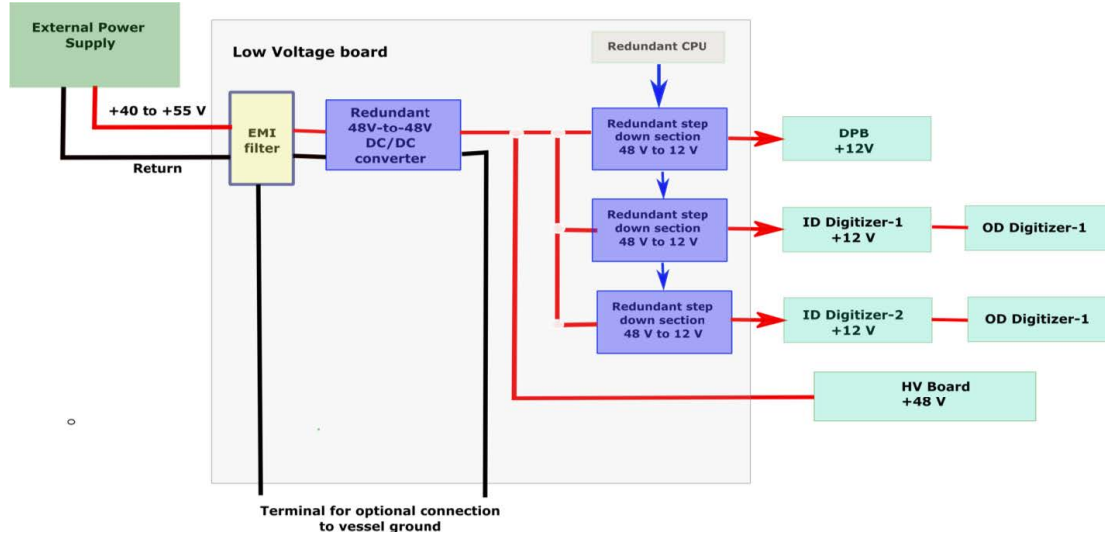


Figure 4.7: LV board diagram.

mounting points for connecting to the vessel ground. Given the requirement for the LV board to operate for many years without replacement, its long-term reliability is crucial. Consequently, redundant components are incorporated for key elements such as the DC-DC converter, microcontroller, step-down, and environmental sensors, as illustrated in the LV block diagram. The LV boards deliver three 12 V outputs with varying currents of up to 2 A, intended for two digitizers and one data processing board. As depicted in Fig. 4.7, one of the 48 V power line voltages from the EMI filter and 48V-to-48V DC-DC converter serves as an input for the HV board, providing 48 V with a current of approximately 1.5 A.

Implementing such system configuration is expected to enhance the overall reliability of the entire setup. As the LV power supply board is situated underwater within the watertight vessel and is responsible for powering the rest of the electronic components, its high reliability is crucial.

The RS485 communication interface will be employed for remote control and monitoring of the LV board, enabling independent remote switching of each channel, with the exception of the always-on auxiliary output channel used by the data processing board that we will describe in the next section. Additionally, onboard environmental sensors will provide readings of temperature, humidity, pressure, and water leakage inside the vessel.

Finally, the power efficiency of the LV board should exceed 84% when operating at above 60% of full load (100 W delivered at full load) to reduce heat generation within the vessel.

4.1.3 The DPB

The Data Processing Board (DPB) is the interface between the DAQ and the Front End. It embeds three main functionalities:

- data processing and network interface (data buffer and handling, system

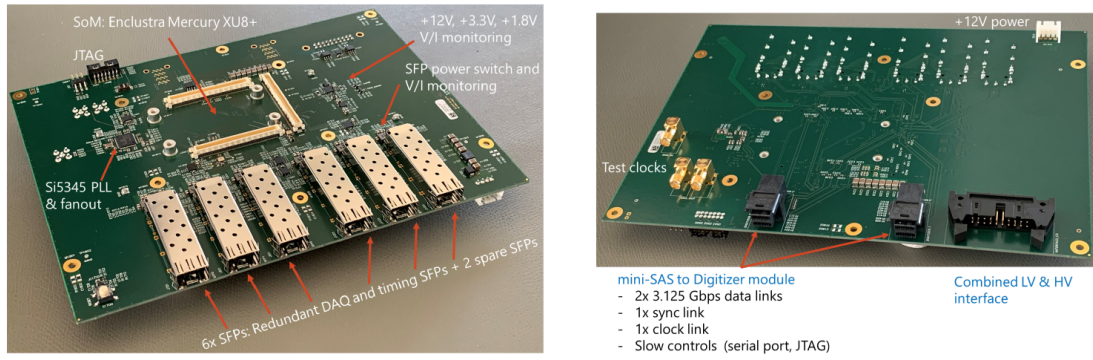


Figure 4.8: DPB first prototype board; the top view on the left and the bottom view on the right. The SoM will be mounted on the Top side where the three white connectors are placed.

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 the required DAQ protocol and redundant optical transceivers for data transmission;

- synchronization (clock + counter), which requires a clock synthesizer and feedback loop as well as 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.

In order to speed up the development of this board and also to reduce the risk in the development phase a specialized company in board design, Enclustra [73], has been contracted to design and produce this board. The board will be based on a commercial board (a SoM, system on module) embedding the CPU and the FPGA and a custom basemodule for the connectors and some of the other circuits. The SoM will include the main hardware of the board, in particular the SoC (system on Chip), which is a Xilinx Zynq Ultrascale+. The baseboard for the SoC will instead include the SFP for the fiber connection, the clock and synchronization circuit and all the other peripherals for monitoring and connection to the other boards in the vessel. In Fig. 4.8 a first revision of the DPB baseboard is presented, together with a description of the main blocks of the board.

The collaboration decision of having a dedicated board to be the interface between the front-end and the DAQ guided the design of the front-end system, letting us, as designer, to build a front-end much simpler than one with all those functionalities integrated. There is indeed a drawback in this decision, since with this architecture more boards and thus more systems will be underwater, risking to reduce the overall reliability of the experiment.

and reaches all terminal nodes, represented by the FE modules, via the Time Distribution Endpoints (TDE) embedded in the DPB. Additionally, a 10 MHz clock is produced and transmitted to a GNSS along with the PPS signal. The time offsets between the local PPS, GNSS time, and subsequently, a UTC prediction are determined and sent to the data acquisition computer infrastructure using the Ethernet protocol for converting the local event time tags accordingly. The PPS signals from the GNSS receivers are also directly compared with the locally generated signals utilizing a custom board, providing a validation mechanism for the satellite receivers' performance.

4.3 DAQ and triggering

Hyper-K will be basically a triggerless experiment, meaning that all the channels will collect and send to the DAQ every hit, without any selection. Even if thousands of channels have to be managed, the interesting events happen at a low rate. Each underwater vessel will be connected to the top of the tank via an Ethernet link at 1 Gbps. This implies that the DAQ will be strongly dependant on Ethernet communication and on standard servers that will have to manage the data collection, initial calibration, event building and triggering. Hyper-K DAQ will be based on ToolDAQ [75], a custom DAQ framework developed to be very flexible and easy to implement. The system was developed to employ standard software design paradigms to structure and organize DAQ modularly, ensuring scalability. This scalability was crucial as the design aimed to support a range of applications from simple hardware test stands to very big physics experiment, like Hyper-K. The modular nature of this code played a vital role, allowing components to be developed in test environments and then deployed across multiple experiments, facilitating the reuse of common elements. Additionally, when designing the software, great emphasis was placed on fault tolerance, error correction, and dynamic data routing, given that the targeted experiments might operate for many years, or even decades, handling critical data where the loss of a single event could result in significant consequences.

The main idea behind ToolDAQ is to use a pipeline model of execution which is referred to as a ToolChain and each step of this chain is a Tool. The communication between each tool, in case of different systems, is strongly based on ZMQ (ZeroMQ) [76] that is a very reliable network protocol for data transfer.

An overview of the hardware implementation of the DAQ in Hyper-K is represented in Fig. 4.10

Underwater vessels, in particular the DPB boards, are connected to commercial Gigabit switch on the surface, here more switches collect those data packet and send them to the RBU (Readout Buffer Unit), where all the raw data are collected, sorted in time and calibrated by applying any possible online factors already defined. The new data are then sent in chunk of 10 ms time to the TPU (Trigger Processing Unit), with the goal of finding possible time slices with interesting events.

In case of high rates from the Frontend the RBU should be capable of buffering

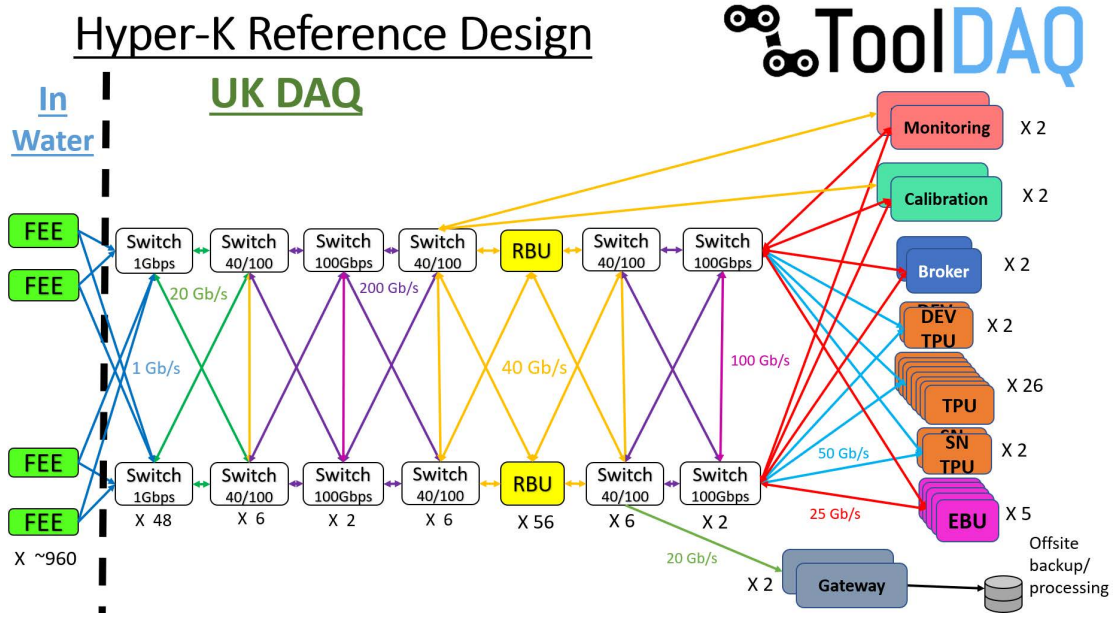


Figure 4.10: An overview of the network structure representing the DAQ hardware for Hyper-K.

the data from many hours, giving time to the TPU or other systems to look for triggers in the data, so the RBU machines will have more fast memory on board. Only the triggered events will be instead written to disk for permanent storage and they will also be backup offsite.

The data format has not yet fixed, custom binary format is expected from the frontend where bandwidth is limited. A general decision on the usage of a custom binary format also for the offline has been made, but details on which data and how to store them is still under discussion.

4.3.1 Triggering

The physics programme of the Hyper-Kamiokande experiment spans many orders of magnitude in energy. As such, it is essential that the detector is able to accurately record information from events with energies of a few MeV to many GeV. A series of trigger algorithms will be implemented in software and run in parallel on each time slice of incoming data. The output(s) of the trigger(s) will be used to determine whether a specific time slice should be written to disk and stored for analysis. To this end, a set of specialist trigger algorithms are being designed for use in Hyper-K.

Prior to the application of trigger algorithms, the raw data undergoes a set of algorithms at the preprocessing stage using a flexible number of CPU cores. Hits in a given readout window are sorted by time-stamp, and calibration as well as a mask for potential non-operative PMTs are applied.

A very simple and logic trigger is the NHits trigger. A cut on the number of hits in a given time slice is applied, and if that number is above a set threshold a

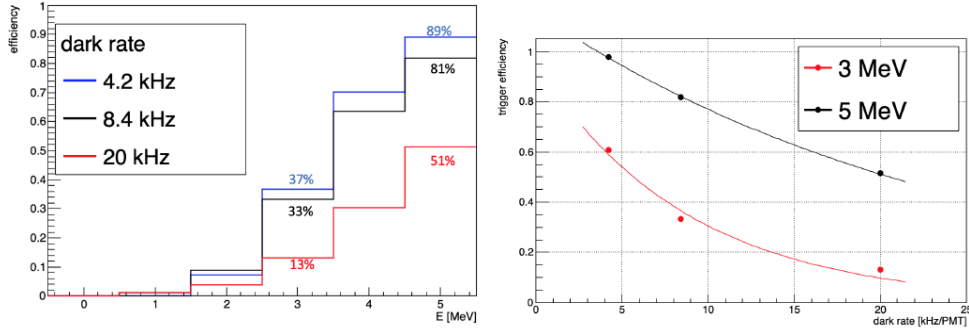


Figure 4.11: Trigger efficiency for the NHits trigger at different dark noise levels, as a function of energy (left) or dark noise per PMT (right; the continuous lines are a simple exponential fit).

positive trigger is returned. Tuning and optimisation of this threshold, as well as the length of the time slice are necessary to achieve good performance. The NHits trigger is applied on sub-windows for a given readout window. A temporal overlap between sub-windows is chosen to avoid losing events with hits split between consecutive sub-windows. The step size at which the sub-window slides across the readout window impacts the performance. An example of the performances of this trigger is provided in Fig. 4.11. With a conservative dark noise of 8.4 kHz/PMT, the NHits trigger efficiency is above 99% at 8 MeV.

The 20" PMT dark rate is nominally 4.2 kHz and the current production units are indeed showing values with this mean value. Simulations have been done also considering a higher dark rate of 8.4 kHz/PMT and even 20 kHz. So, the data that we must consider to analyze the trigger efficiency are the one at 4.2 kHz when available.

In order to enhance the acceptance of low-energy events ($\lesssim 10$ MeV), primarily due to solar ν that interact with atomic electrons in the Hyper-K water, a more sophisticated trigger operates as follows. About 2000 fixed points, laid out on a grid in the ID, are tested as vertex candidates for the detected PMT hits; for each of these points, one subtracts from the hit time the time-of-flight separating the two, thus turning the detection time into the time of emission of light from that vertex; so if a large number of hits are all consistent with coming from the same vertex at the same time the event is triggered.

This trigger is able to identify physics events down to ~ 3 MeV (see Fig. 4.12) while rejecting dark noise (which has no spatial or time coherence); as a by-product, it also provides at trigger level a guess for the vertex position (with a resolution dictated by the grid spacing, about 5 m), which, together with the position of the center of all hits, defines a reconstructed line of motion of the electron (with enough statistics, for example in the case of a supernova explosion, this can in principle be used to point back to the source direction outside of the detector).

Another advantage is that events with a reconstructed vertex near the detector wall can be recognised as radioactivity and separated from events with a vertex in the middle of the tank - in other words a fiducial volume cut is possible in real

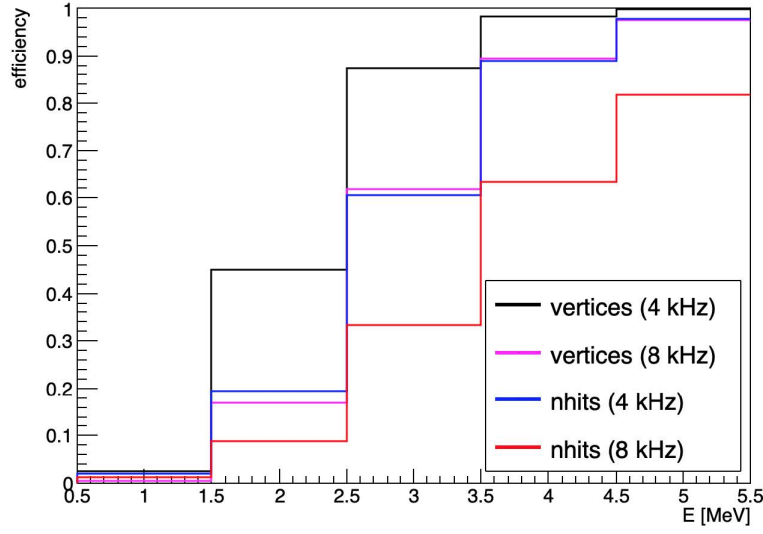


Figure 4.12: Trigger efficiency as a function of electron kinetic energy, for both the NHits trigger and the test vertices trigger, and for two levels of dark noise (4.2 or 8.4 kHz per PMT).

time.

When a superluminal charge moves in the Hyper-K water, it will project a cone of light onto a section of the detector wall; we therefore expect to measure a collection of hits all appearing in the same region of space and in a small interval of time, as opposed to dark noise (which has a flat time distribution and is equally spread on all PMTs). A cluster trigger has thus been designed to look for clusters of PMT hits in space and time. As it is illustrated in Fig. 4.13, each PMT hit is tried as the center of a spherical cluster and all other hits within a given radius and a given time interval are associated with the same cluster; if one (or more) populated cluster is found, the event is classified as signal and triggered.

Because only a small space-time interval is analysed, rather than the entire detector as in the NHits trigger, the cluster trigger is less affected by dark noise and allows to further reduce the energy threshold, or equivalently to increase the trigger efficiency at low energies (2–3 MeV); this can be seen in Fig. 4.14, where the performances of test vertices trigger and cluster trigger are compared; it is also shown that a logical combination (OR) of the two triggers allows to further improve the trigger efficiency.

The decision on which trigger will be used on day 1 of the experiment will be done when the real hardware will be available and after also a careful study on possible alternatives, also using dedicated neural network triggers.

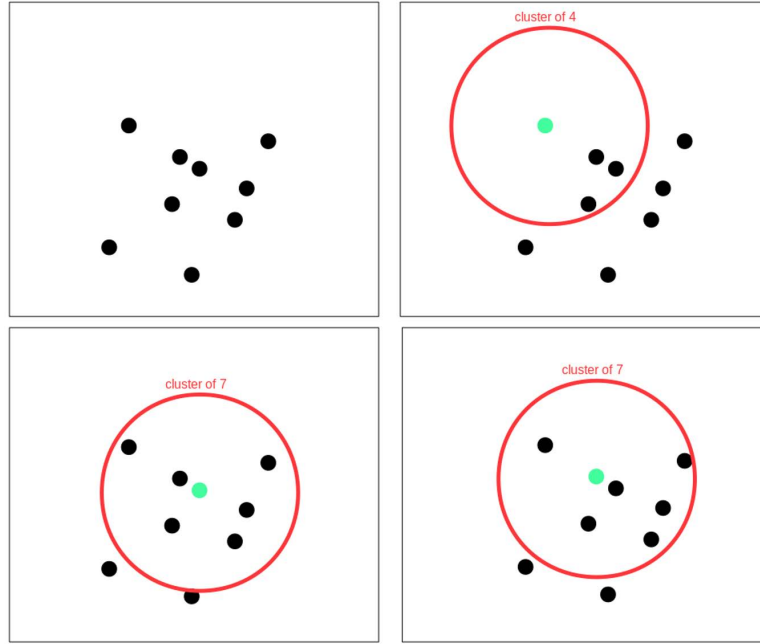


Figure 4.13: A cartoon illustrating how clusters are looked for in a collection of PMT hits (black dots).

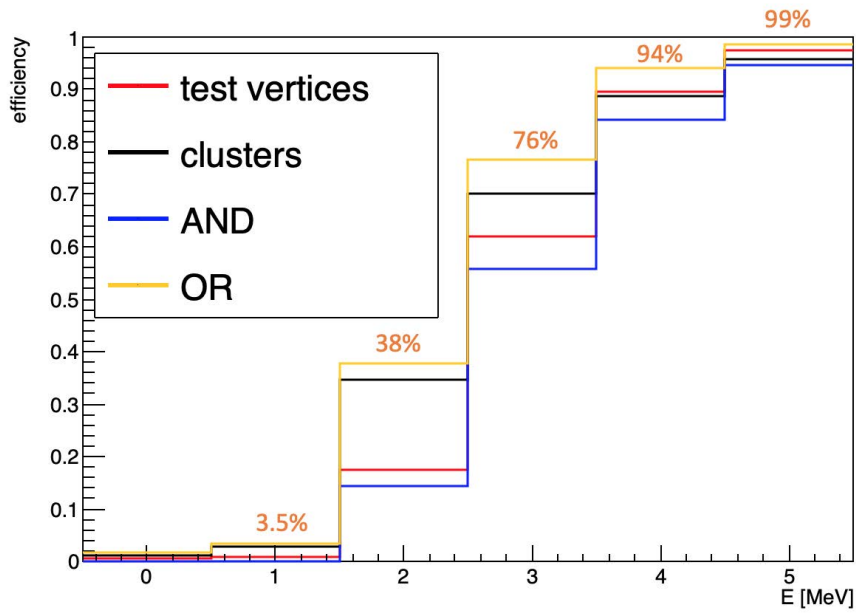


Figure 4.14: Trigger efficiency for low-energy events when using the test vertices trigger, the cluster trigger or a logical combination of the two; 8.4 kHz dark rate per PMT is assumed.

Chapter 5

mPMT detector

We already introduced the mPMT detector in the previous chapters, now we will go in to the details on how it has been designed and how it will be built, focusing on the electronics components of the system.

5.1 The mPMT system

The mPMT mechanical design has been adapted to fix the mPMT to the photo-sensors support in the FD Hyper-K tank. The mPMTs will be submerged under ultra pure water up to a depth corresponding to 0.7 MPa of pressure for at least 20 years.

The mPMT pressure vessel consists of an acrylic dome, which acts as a window for the PMTs to view the detector volume; a cylindrical section that houses the PMT support structure and electronics. The acrylic dome fits into a circular ledge cut into the cylinder wall. The ledge has an O-ring seal between the acrylic and the cylinder to keep the detector watertight, and a clamping ring that applies 4 bar of pressure to the dome, keeping the acrylic in place. The vessel is closed by a stainless steel backplate that will act also as cooling system for the internal electronics components.

The mPMT mechanical parts can be summarized as:

1. mPMT Vessel:
 - acrylic dome
 - cylinder
 - backplate and closure system
2. PMT support structure
3. PMT reflector ring
4. Optical gel

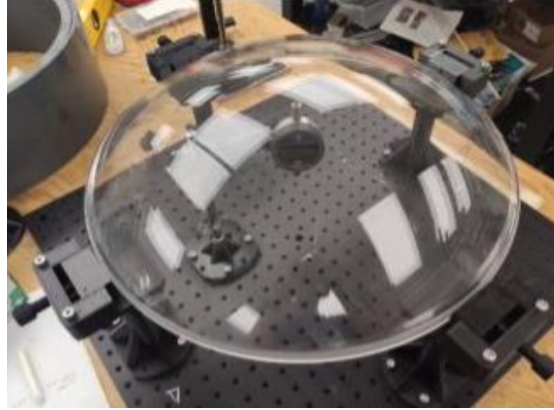


Figure 5.1: Acrylic cover for the mPMT together with a QC jig for mass production

To reduce the background in low energy neutrino search, all the materials in the mPMTs have to be characterized by low radioactive contamination and Rn emanation. Thus all the mPMT components have been chosen to match these requirements.

An overview on the technical design of each system will follow in this section. Later in the chapter we will carefully describe the electronics and finally we will look to prototypes of the mPMT detector and their operation.

5.1.1 mPMT vessel

Acrylic dome

Acrylic was chosen for the dome because it is more robust, cheaper, lower in radioactivity, and easier to fabricate than most other optical window materials. Transmittance, water absorption and radioactivity contamination were measured to identify the best material for the mPMT window. The mechanical design of the acrylic cover was realized at TRIUMF, and further optimization studies for the closure system for the mPMT have been realized at INFN. The acrylic cover is realized starting from a 15-mm thick acrylic sheet based on simulation to withstand the pressure in the tank.

The thermoforming (or vacuum forming) process has been identified as the best solution for manufacturing to avoid potential surface contamination due to contact with mold during the forming process and to have reasonable control over the dome thickness during manufacturing. A machining step is then carried out to create the surfaces (step) for the following assembly, remove processing burrs, and achieve the final dimensional/geometrical tolerances of the part. Successive annealing is performed to reduce the residual stresses caused by thermoforming and machining. The surfaces of the final component are polished to remove residuals and discontinuities and improve the cover surface's clarity.

An example of the realized cover is shown in Fig. 5.1, with also a jig for Quality Control (QC) of dimensions during mass production.

Before selecting the final materials to build the dome a lot of optical mea-

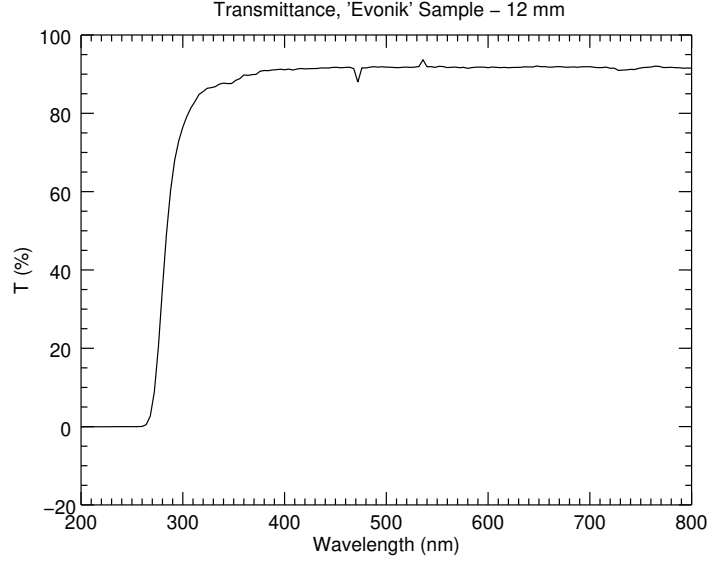


Figure 5.2: Acrylic transmittance measurement for a final 12 mm thick sample of the production acrylic. The thickness is not 15 mm, since in the thermoforming phase the nominal thickness will be around 12 mm.

measurements have been done to evaluate the best option. After a review process it has been established that the Plexiglas GS-UVT by Roehm satisfies the Hyper-K requirements. The transmittance measured for this material is reported in Fig. 5.2.

Backplate and Clamping Ring

The cylinder that contains the PMTs will be placed on the backplate and the acrylic dome will be fixed to the cylinder through a clamping ring.

AISI-304 stainless steel has been selected for both the backplate and the clamping ring due to its resistance to water pressure and to corrosion in pure water. Though AISI-316 quality fits with humid environments and is a little more suitable with respect to AISI-304 stainless steel, the cost of AISI-304 is cheaper and this aspect is to take into account in mass productions. This is the same material chosen for the already described electronics vessel.

All the metal parts should be finished by acid cleaning, and packed in a clean bag until those are brought to the assembly site. Passivation of the metal is also expected, since it forms a very thin, transparent passive layer of chromium trioxide (Cr_2O_3) on the stainless-steel surface that will protect from corrosion and rust.

The backplate will also be used as a cooling system to avoid a possible overheating of the electronics components. The electronics main board and cooling system will be fixed on the backplate by screws.

A feedthrough is located on the backplate and it is meant for the communication cables and power supply (from outside water to communication module inside the vessel). Penetrator hole position has been designed to have the cable

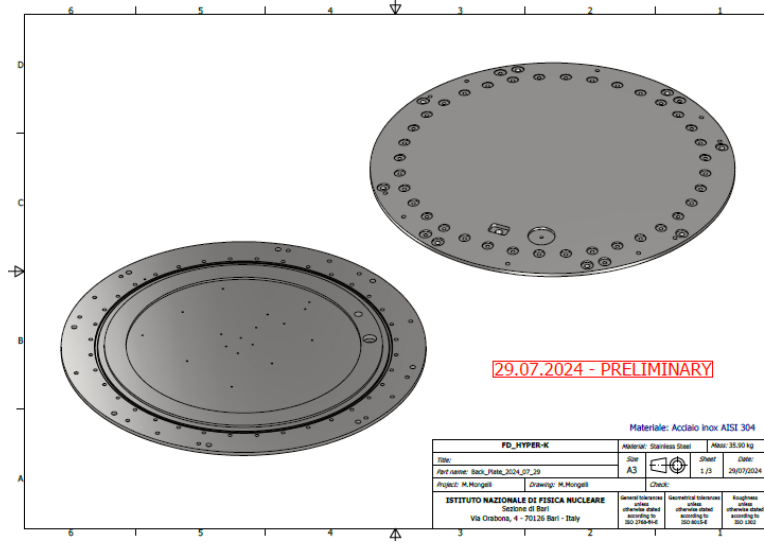


Figure 5.3: Drawing of the backplate for the mPMT.

closer to the electronics Main Board and its shape to help in the cable assembly. The design of the backplate is reported in Fig. 5.3.

The clamping ring (see Figure 5.4) will fix the acrylic cover on the cylinder with screws. Spring washers are used to always keep the bolts in tension.

The clamping ring has been designed to be mounted with clearance on the acrylic dome and then fixed via a threaded connection on the cylinder. The pressure that is generated between the lip of the acrylic dome and the clamping ring during tightening should force the O-Ring inside the specific groove, thus guaranteeing its maximum effectiveness. To make this happen, also managing the dimensional tolerances, the conditions must be verified under which the acrylic lip always protrudes beyond the cylinder. This condition guarantees that, when the screws that fix the clamping ring on the cylinder are fully tightened, this releases the clamping pressure completely on the acrylic lip rather than on the cylinder itself. Furthermore, it is important to consider that, due to the deformation of the acrylic cover due to external pressure, it is highly probable that the clamping ring (steel) and the cover (acrylic) come into contact, thus risking damage to the latter.

Tolerances has been defined to consider these effects and limit risks.

The last version of design in Figure 5.4 has been optimized for cost reduction, with a shorter edge, while preserving the performances of the closure system.

Cylinder

As regarding the cylinder, the main considerations are the strength required to withstand the Hyper-K water pressure and the contribution to the module mass.

The technical design of the cylinder has been realized at INFN considering the optimization of the closure system and the requirement for resistance at the FD pressure.

Several materials have been considered for the FD mPMT cylinder:

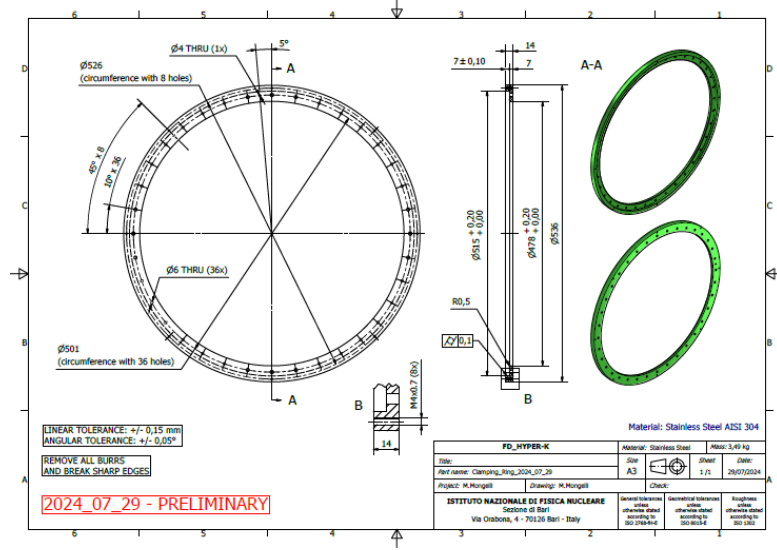


Figure 5.4: Technical design for the clamping ring.

- High Density Polyethylene (HDPE): a plastic very flexible, weatherproof, easy to process by most methods, low cost, good chemical resistance. Prototypes realized with a HDPE cylinder show deformations that makes difficult to match with other components. This is related to the production process and cannot be improved. This option has been discarded.
- Acetal copolymer (POM-C): The material has excellent dimensional accuracy properties, good mechanical strength, rigidity, and hardness, as well as low moisture absorption and has low water absorption (0.05/0.1%). This option is considered for the production of cyliders for the mPMTs.

In Figure 5.5 the technical design is shown. The design has been optimized to reduce risks in the closure system and surface planarity and linear tolerances have been defined according with the water tightness requirement.

5.1.2 PMTs support structure

The support structure is necessary to hold the PMTs steady inside the vessel. Studies on the efficiency of the mPMTs demonstrated that the efficiency depends on the orientation of the first dynode, thus we need to maintain a fixed orientation during the construction and the installation of the mPMTs. The PMT support has numbered holes, so each PMT has a specific position. These orientations will be the same in each support and will be preserved by the cylinder and the backplate too and during the installation in the tank frame.

The PMT support has been engineered by a specialised company in 3D printing (3DNA, <https://www.3dnasrl.it/en/>) to create a design optimised for the mass production phase. Printing of a such huge support is too expensive and time consuming to be done in one piece, thus the support will be printed in parts and then glued together with a patented technique proposed by the company.

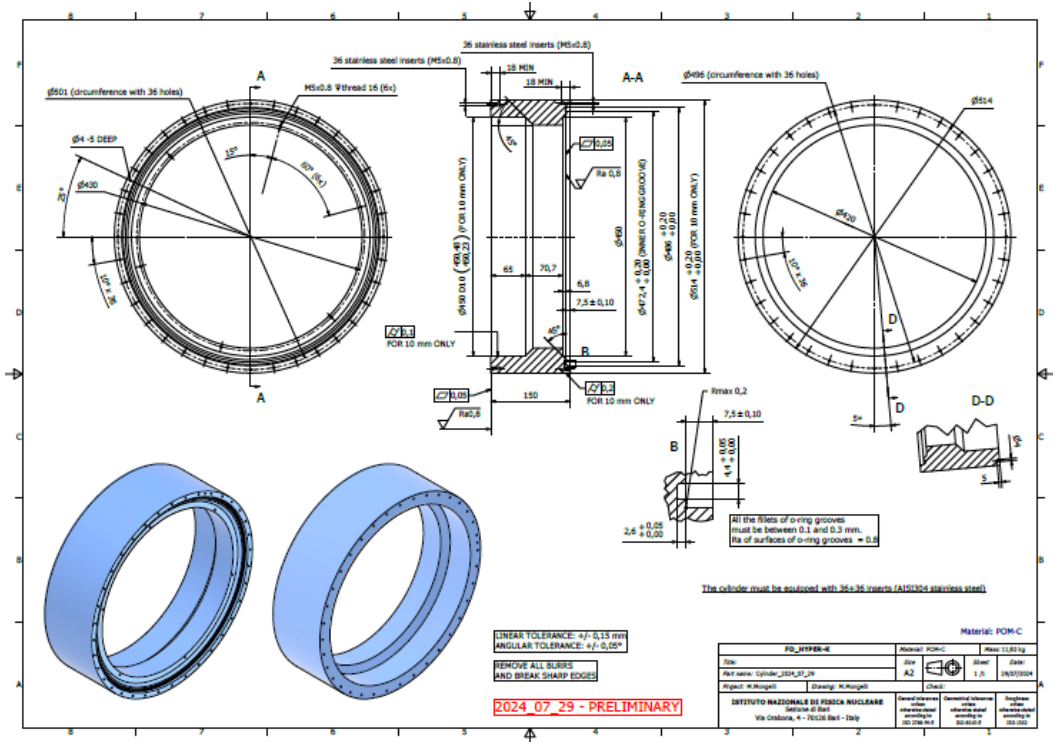


Figure 5.5: Technical design of the cylinder in POM-C.

In the proposed solution, the PMT support matrix is composed with 4 parts and the PMT cups are screwable from the bottom surface (see Figure 5.6). The lodging for reflector ring has some pins to fix it (see Figure 5.8).

The PMT cups are designed to host a dedicated gasket that prevents the PMTs to fall from the hole and also the optical gel to pour on the inside of the structure. The design has been optimized to guarantee a fixed distance between PMT and reflector ring to be filled by optical gel.

Holes and small tubes are added to allow the pouring of the optical gel and venting of air bubbles (see Figure 5.8).



Figure 5.6: 3DNA-PMTSupport.

Figure 5.7 shows details of numbered holes of the PMT support structure.

The powder-based 3D printing process Multi Jet Fusion (MJF) has been chosen due to its high component quality, high throughput, and low unit costs. This



Figure 5.7: Details of the PMT support structure.



Figure 5.8: Details of the PMT support structure for the pouring of the optical gel and venting of air bubbles.

manufacturing technology is particularly suitable for functional parts and details in the drawings can be realized with high precision. PA12 material and 3D printer HP 5200 has been chosen for mass production. Test for compatibility with optical gel of PA12 material has been done.

5.1.3 PMT reflector ring

A substantial difference between the 20-inch B&L PMT and the mPMT is the effective area. The total photocathode area of a mPMT module is, in fact, $\sim 3800 \text{ cm}^2$ to be compared with $\sim 7800 \text{ cm}^2$ of the B&L PMT. A way to improve the effective area of the mPMT is to use a reflecting metallic layer around each PMT that enlarges the collection-light area and reflects the light onto the photocathode. Fig. 5.9 shows the PMT with reflector ring.

This can lead to an increase of the light collection efficiency by 20%. The reflectors are produced from a flat aluminium sheet cut into sectors of an annulus

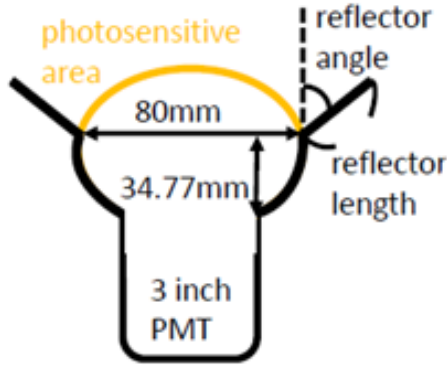


Figure 5.9: PMT and reflector ring

with an inner diameter that matches the diameter of the PMT bulb at its widest point and polished like a mirror.

5.1.4 Optical gel

The photomultiplier will be optically coupled to the acrylic cover using a transparent silicon rubber.

The main requirements for the optical gel were:

- high transparency;
- a refractive index close to the ones of the acrylic cover and pure water;
- a good rigidity to hold the mPMT components, with sufficiently elastic properties to absorb shocks and to accommodate for the deformation of the acrylic cover under pressure;
- stability of the optical and mechanical characteristics over more than 20 years.

The refractive index has to be close to those of the acrylic cover (1.49) and the window of the photomultiplier (1.50-1.54). We have tested a number of different gels, including Wacker 601, 604 and 612, Momentive RTV 615 and Shin-Etsu prototype gels. Different kinds of the optical gels by ShinEtsu (X-32-3547 and X-32-3539), in a phenyl and a methyl group have been studied in Kashiwa ICRR. The type in the phenyl group turned into a white colour, while type of the methyl group was kept transparent. These results are in agreement with the expected as the phenyl group gel is known to change the colour to white when absorbing water. The methyl group can also keep the same transparency for a long time.

The results of the tests and also the huge experience in KM3Net suggested to use the same material and ratio as the latter, so we decided for the Silgel 612 with a ratio of 3:2.

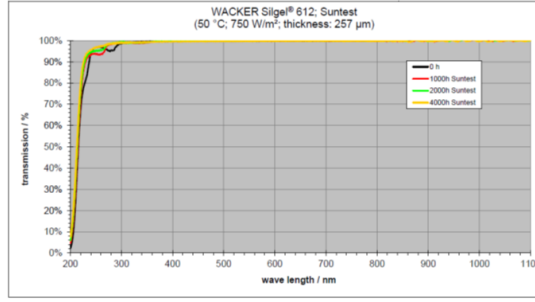


Figure 5.10: Gel measurement by the company of the sample and of the same sample after UV exposure

The transmittance of the gel has been measured and also data from the producer company have been obtained, in particular the company also provided data for the gel exposed to light showing how much degradation we should expect in the module, as reported in Fig. 5.10.

5.2 Electronics

The Hyper-K mPMT electronics to be used for the far detector shall conform to the following performance requirements:

- **Timing resolution:** it should be better than 3" PMT TTS, namely less than 1.5 ns for 1 p.e. This requirement implies that the timing resolution from electronics for 1 p.e. should be below 500 ps; a better timing resolution of about 200 ps is required for large p.e. pulses.
- **Charge resolution:** The charge resolution must be at least the same as the Super-K electronics digitizer, called QBEE. Based on that, the requirement 0.1% FWHM in the range ~ 0.05 p.e. up to 25 p.e..
- **Dynamic range:** The dynamic range must be at least the same as the 20" PMTs, thus 1250 p.e.. Based on that, the collaboration choose a value of 100 p.e. per channel.
- **Power Consumption:** Driven by water circulation requirements and its temperature stability, it should be less than 4 W per mPMT module, otherwise the transparency of the water could be compromised.
- **Reliability:** At least 20 years of working time without any maintenance. This imply a study of the Failures in Time (FIT) of the components and an accurate study of the thermal dissipation, since the expected lifetime of a chip is strictly related to the operating temperature.

To match these requirements, a Charge and Timing digitization board, based on discrete components, has been designed and fully tested in Naples with the

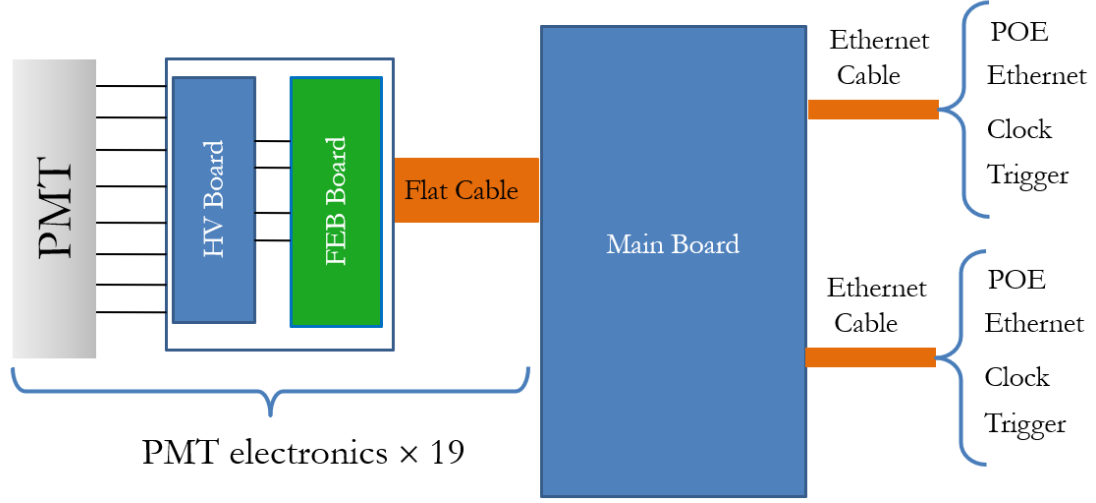


Figure 5.11: Block diagram of mPMT electronics systems, composed by the HV boards and the FEBs connected to the 19 PMTs and the Main Board.

collaboration of Hyper-K group and INFN Electronic workshop. On the electronic point of view, the circuit can be divided in three blocks: directly connected to the PMT there is the High Voltage (HV) Board, then, connected to it, there is the Front End Board (FEB) while the last is the Main Board to which the FEBs of all the 19 PMTs are connected by cables (Fig. 5.11).

The mPMT cannot be integrated directly in the Hyper-K experiment, we described the electronics underwater vessel for the 20" PMTs in previous chapter and for the mPMTs a similar vessel will be used to collect 8 mPMT and send the data to the top of the tank with a fiber. In this vessel only one board will be hosted, the mPMT concentrator card, or MCC. This vessel is thus called the MCC vessel.

A sketch of the full mPMT chain is reported in Fig. 5.12. One could notice that in the diagram 12 mPMT are connected to each MCC, but it was impossible to fit a big enough FPGA in the MCC board for 12 mPMTs, so the final number will be 8.

5.3 HV board

Each photomultiplier needs an appropriate high voltage supply to provide a proper voltage gradient between each dynode. The solution designed to provide the voltage distribution is strongly related to the selected PMT. In our case, the selected PMTs have 10 dynodes and thus it needs 11 different power supply with a maximum difference between anode and cathode of 1500 V (Fig.5.14). The easiest way to give the power supply is to use a high voltage supply and a resistive voltage divider. Even though this is a very easy solution and the most common used, it is not ideal in HK because of the total power consumption requirement. Another way to generate the 11 voltages for the PMT is to generate a relatively

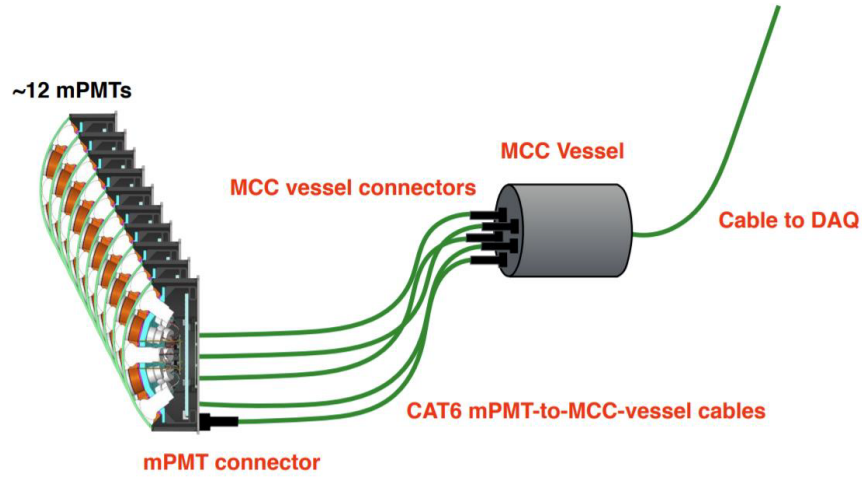


Figure 5.12: mPMT Concentrator Card connected to 8 mPMTs and then MCC vessel connected to the DAQ on top of the tank.

low voltage of about 150 V and then multiply it with a Cockcroft-Walton circuit up to 1500 V. This technique is circuitally more complicated than the resistive divider, but produces stable voltages (multiples of the initial voltage) with a low power consumption.

To produce a signal, the anode of the PMT has to be at a higher voltage respect to the cathode, so it exists two choices are possible: it is possible to put the cathode to ground potential and so set the anode to a positive high voltage, otherwise it is possible to put the anode to ground potential and the cathode to a negative high voltage. Both choices have advantages and disadvantages. With the positive voltage supply, the dark current stabilize quickly. In this configuration, the cathode of the PMT is connected to ground so there is no possibility to generate discharges in the glass envelope. But positive voltage supply is not optimal to be provided by a voltage multiplier, since the available current drops as the voltage increase. Furthermore, because of the anode voltage, it's also necessary to have a decoupling capacitance with a very high insulation voltage. Finally, by taking the signal from the powered anode, the noise on this supply voltage will be added to the signal. On the other hand, in negative high voltage polarity, the photocatode is not properly insulated from its surroundings and insulation breakdown may occur between the envelope and earth; this could generate an high and unstable dark count. The negative HV has the advantage that the signal is taken by the anode, thus it does not require the high voltage decoupling capacitance. Current measurements show that both options generate the same dark rate in the mPMT if the PMT is coated with an high resistive protecting coating.

To satisfy the constrains on the mPMT module the HK group at INFN decided to realize a board based on the Cockcroft-Walton voltage multiplier to provide the 11 different voltages for the cathode and the 10 dynodes. The HV board is equipped with an embedded current and voltage monitor to check the power supply value, and thus the PMT gain, and the absorbed current to detect the state of the PMT. The PMT gain is related to the cathode voltage accordingly

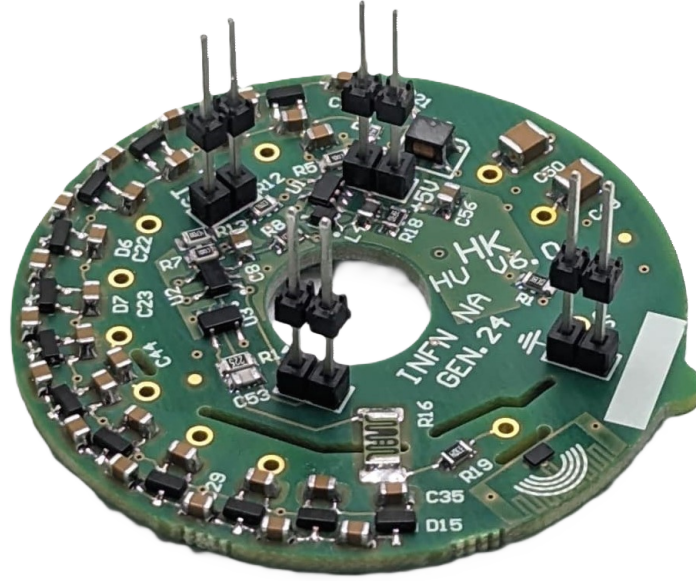


Figure 5.13: Picture of the HV board realized.

VOLTAGE DISTRIBUTION RATIO AND SUPPLY VOLTAGE

Electrodes	K	Dy1	Dy2	Dy3	Dy4	Dy5	Dy6	Dy7	Dy8	Dy9	Dy10	P
Ratio	3	1	1	1	1	1	1	1	1	1	1	1

Supply voltage: 1250 V, K: Cathode, Dy: Dynode, P: Anode

Figure 5.14: 3" PMT dynodes circuit and supply voltage

the relation between the measured charge and the collected light. The current is monitored to check an eventual overcurrent to turn off the PMT and prevent damage.

The HV board also embed a RFID chip with a unique serial number hardware encoded to keep track of the different board during mass production.

The High Voltage (HV) board has a single power supply of 5 V and it is controlled by one analogue input that set the high voltage and one digital input that controls the state ON/OFF of the board. Two analogue output are provided to measure the voltage and the current absorbed by the board and finally 11 output voltages are generated to supply the PMT. The HV board includes only the circuit that generates the supply voltage and it does not include the logic to control it, since the logic is embedded in the Front End board with a Micro-Controller Unit (MCU), as discussed in the following.

The HV board can be divided in three main block, as seen in Fig. 5.15:

- The switching flyback supply;
- The voltage multiplier
- The I/V measurement circuit.

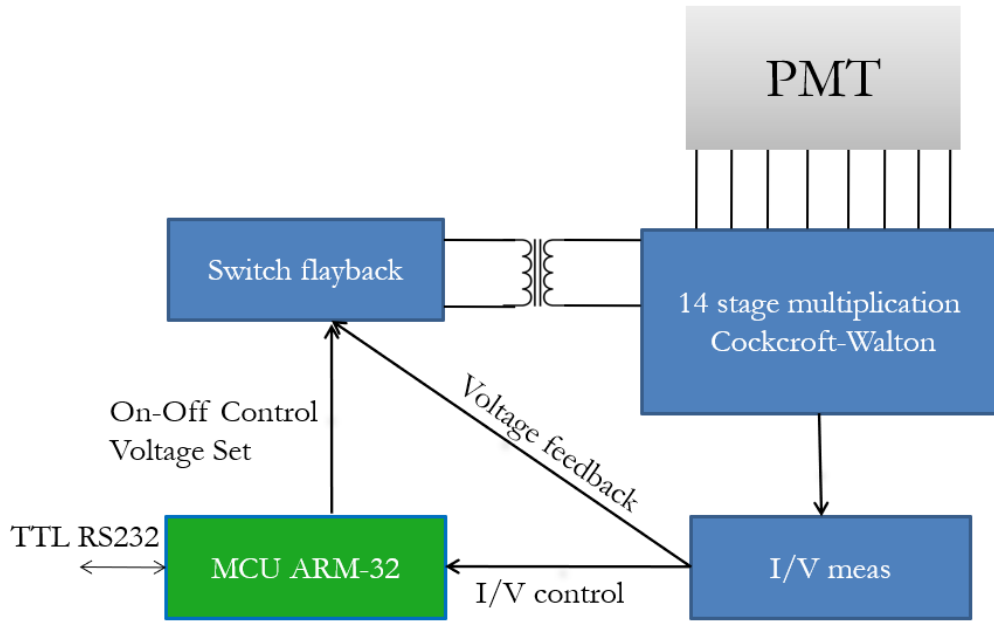


Figure 5.15: Block diagram of the HV circuit, in blue the components on the High Voltage board and in green the component out of the board.

The core of the HV board is the Cockcroft–Walton (CW) multiplier, namely an electric circuit that generates a high DC voltage (1500 V in our design) from a low-voltage AC. With this circuit is possible to generate positive or negative voltage changing the diodes direction. Both solutions has been realized and tested. The basic cell of the circuit is composed by two diodes and two capacitors as shown in the Fig.5.16.

When the input voltage is positive the current flows through the diode D1, charging the capacitance C1 to a voltage of $-V$; at the same time the diode D2 is blocked. When the input voltage is negative D1 is blocked and the input voltage is added to the capacitor voltage to produce a voltage of $-2 \cdot V$. The current flows through D2 charging the capacitance C2 to a voltage double with respect to the

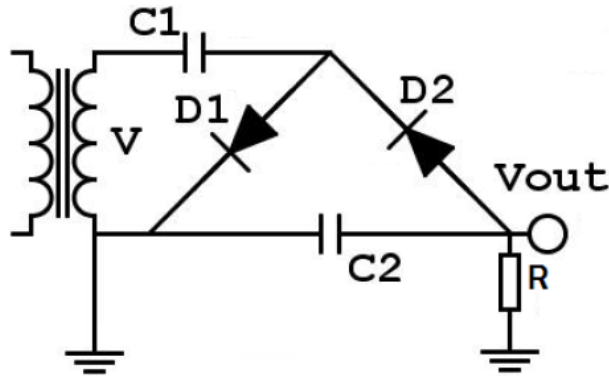


Figure 5.16: A single stage Cockcroft-Walton voltage multiplier.

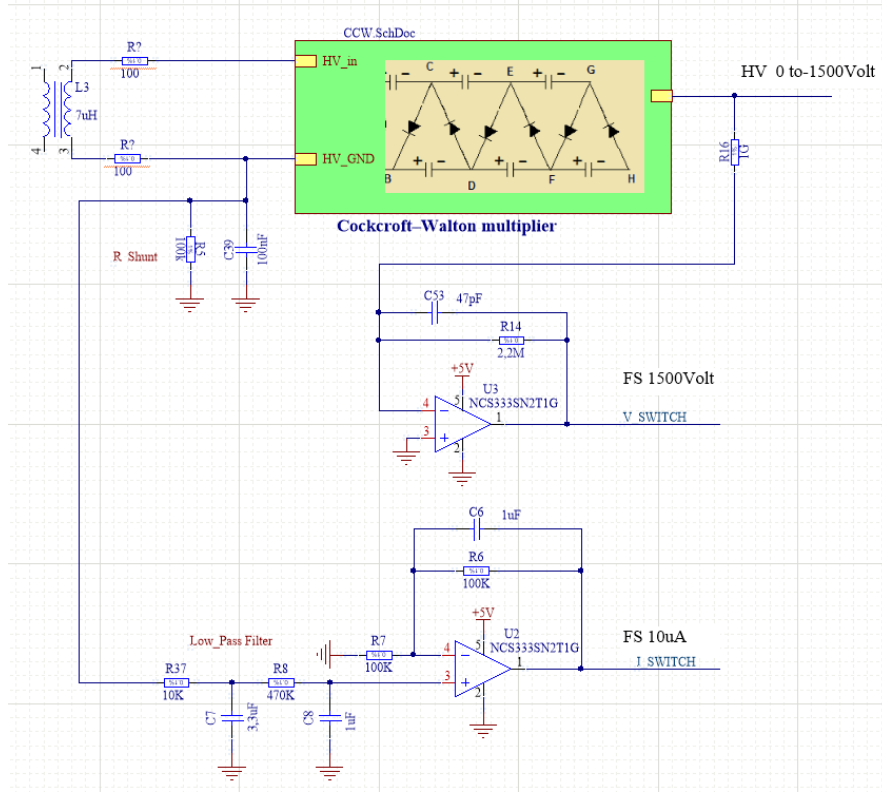


Figure 5.17: Schematic of the I/V measurement circuit

input, minus the voltage drop on the diodes.

When the input voltage turns positive again, the capacitance $C2$ discharge on the load R with a time constant $\tau = R \cdot C2$ until the input voltage becomes negative. Because of this process the output voltage is not constant but has a voltage variation called ripple. If $\tau \gg T$, where T is the input voltage period, than the ripple is small.

Using more blocks it is possible to generate a voltage that is much higher than the first one and if the capacitors are the same in all the stages, the ripple grows cubically[77]:

$$\Delta V_{n-out} = \frac{I}{fC} \frac{n(4n^2 + 3n - 1)}{6}, \quad (5.1)$$

where n is the number of stages, $f = 1/T$, C is the capacitance and ΔV_{n-out} is the ripple. This equation limits the number of stages that can be used.

To supply the dynode system in Fig. 5.14, the ideal solution seems to be a 13 stages voltage multiplier, in order to use no resistors. With this solution the input of the voltage multiplier is 115 V to generate 1500 V. A board with a single 5V power supply and a switching flyback supply has been realized to provide the maximum 115 V for the voltage multiplier.

A I/V measurement circuit has been realized to monitor the stability of the HV and ensures that the PMT is operating in safe conditions. A schematic is provided in Fig. 5.17.

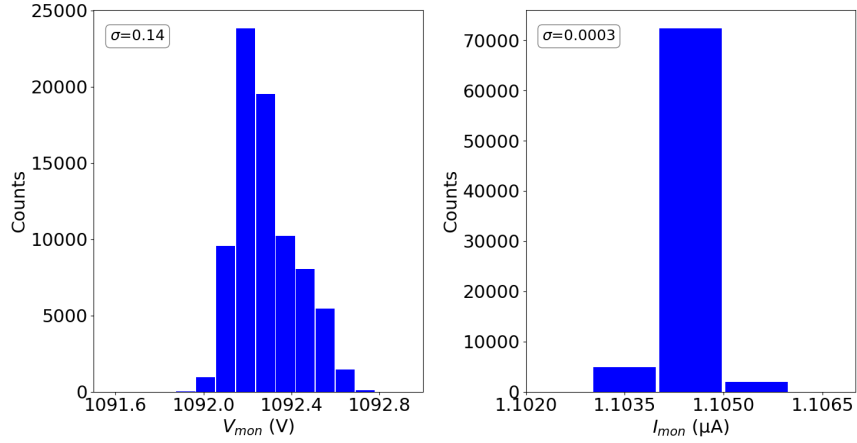


Figure 5.18: I and V monitoring for 24h, with $V_{set} = 1092 V$.

These outputs are then monitored by an ADC embedded in the MCU of the Front End board, as discussed in the next section.

The first test has been the validation of the design in terms of HV stability and noise. In particular the HV is highly stable, with a variation of $< 200 mV$, in agreement with the requirements (see Fig. 5.18).

The noise induced by the flyback transformers has an amplitude of 0.4 mV and a total collected charge of ~ 0.4 pC is obtained, lower than the nominal 0.25 PE threshold of the digitizer, that corresponds to 0.5 pC (see Fig. 5.19). These results have been obtained by carefully separating the ground of the flyback from the one of the signal as much as possible in the PCB design.

The power consumption is the major issue to be faced to, with very strict requirements. The goal was to keep the power consumption of the single HV board under 10 mW, thus having a overall power consumption for the HV boards inside the mPMTs below 200 mW. The Fig. 5.20 shows that the power consumption at 1500 V is of the order of 3.2 mW, that is an astonishing result. This led to a total power consumption for the HV boards of ~ 60 mW in the mPMT.

In Fig. 5.21 the HV linearity is shown, while in Fig. 5.22 the HV stability as a function of temperature is shown.

The last important test was the integration with a real PMT and the first data collection to ensure a good performance in the real application. The plot in Fig. 5.23 shows the charge spectra of a 3" PMT at different HV values.

With the completion of the described tests, the HV board design has been basically frozen. After that, a Quality Assurance (QA) validation and the development of the necessary test infrastructure for mass production have started. In the next sections, we will describe all the mass production and reliability study done on the system.

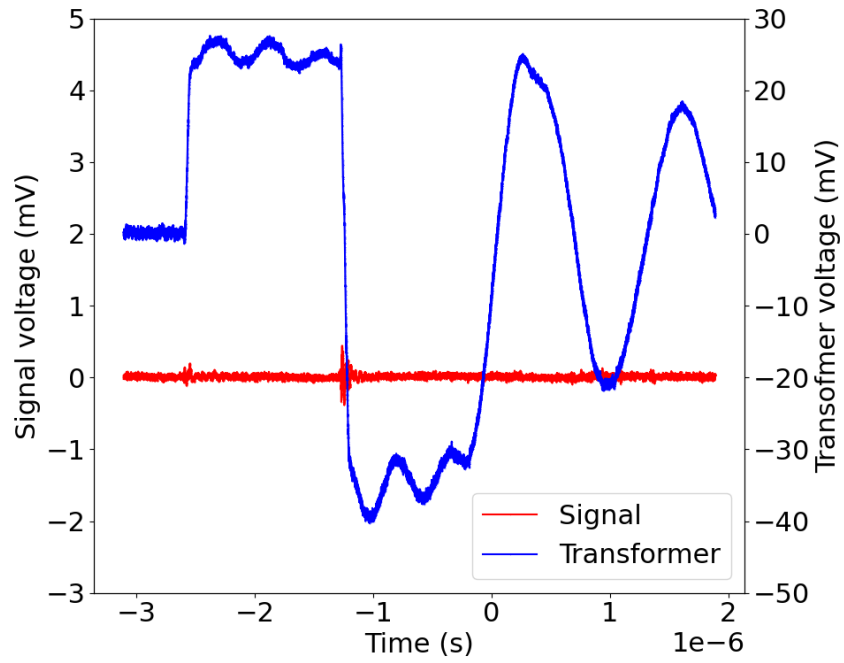


Figure 5.19: Flyback waveform (blue) and related induced signal (red) in the last prototype HV board.

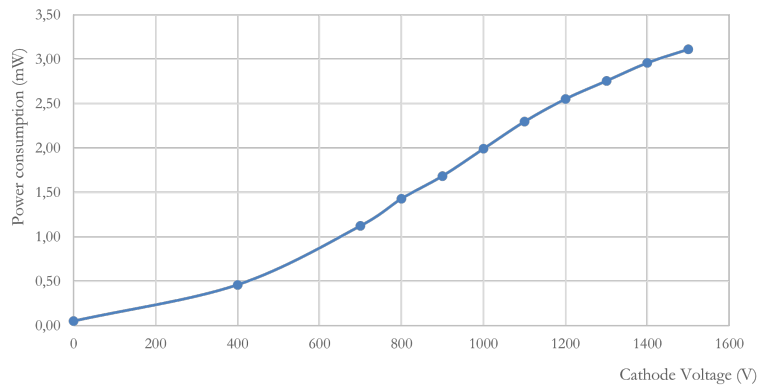


Figure 5.20: HV board power consumption at different HV output values

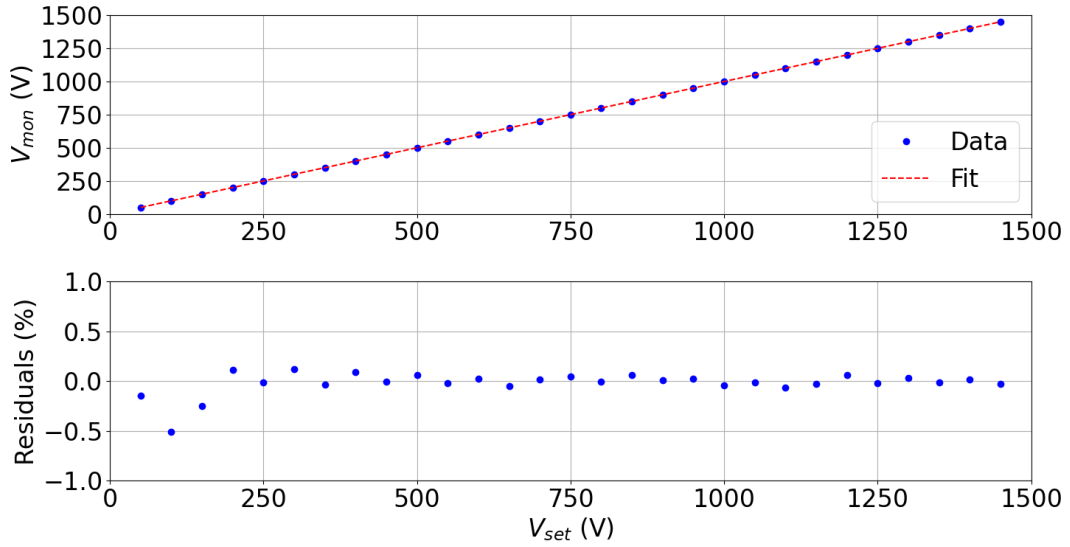


Figure 5.21: HV linearity from 50 to 1450 V.

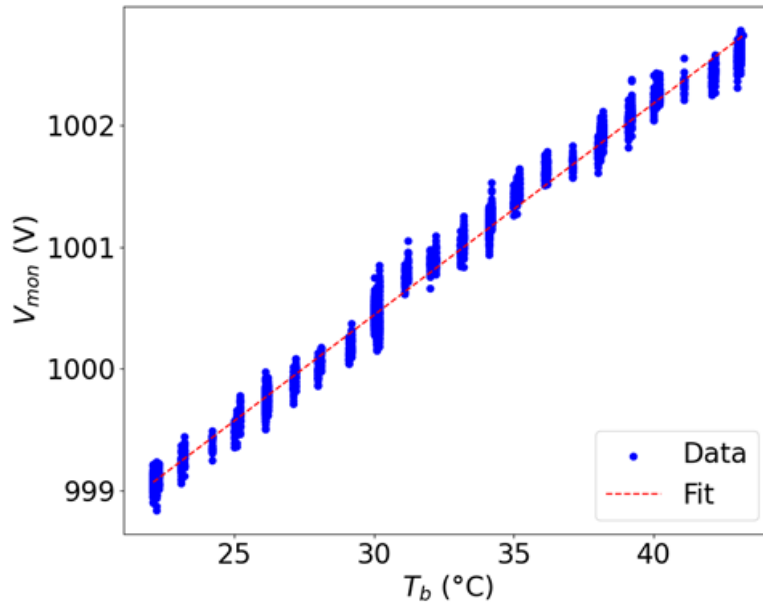


Figure 5.22: HV stability in temperature (1000 V set). The board temperature T_b is measured using the FEB onboard temperature sensor embedded in the microcontroller.

5.4 Front End Board

The readout system of the mPMT can be divided in two part. The first is the Front-End board which collects the signal from the PMT and performs the time and charge measurement. It is described in this section. The second is the Main Board that collects all the information from the single channel electronics and generates digital stream of data. This will be described in the following sections.

The Front End Board (FEB) is the interface between the PMTs and the ac-

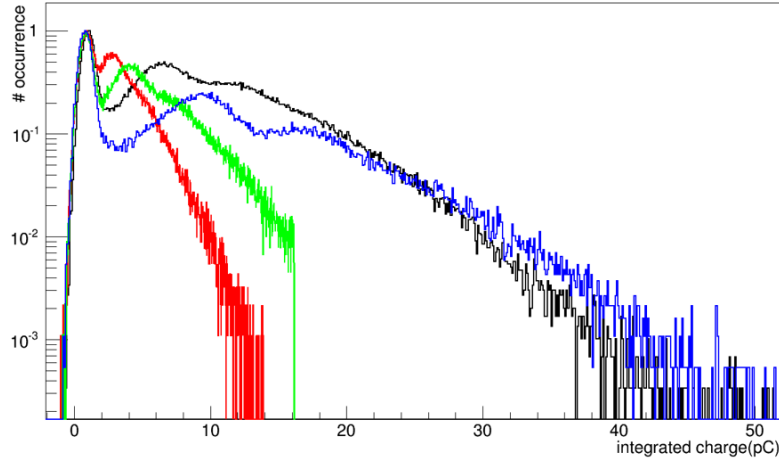


Figure 5.23: 3" PMT charge plot for different HV values. Red curve is at 1200 V, green curve at 1300 V, black curve at 1400 V and the blue one is at 1500 V.

quisition system. To minimize the effect of the electronic noise on the charge and time measurement the FEB has been designed to be very close to the PMT. A MCU controls the parameters of both HV and FEB.

The FEB needs two supply voltages, 5 V and 3.3 V, and it is controlled by a two UART lines on which a Modbus protocol is implemented. The FEB also includes a SPI to transmit the charge information from the ADC to the Main Board and a trigger signal as a differential pair.

It is possible to divide the circuit in two part as shown in the block diagram (see Fig. 5.24): the time measurement circuit and the charge measurement circuit. The charge measurement circuit is based on a Sample and Hold (S/H) ADC that stores the charge value if the input of the ADC receives an acquisition signal. A typical sample and hold circuit stores electric charge in a capacitor and uses one switching device and normally a buffer. This solution avoids a peak detector circuit, thus, reducing the power consumption. Both the charge measurement circuit and the time measurement circuit are based on discrete component to fulfill the restrictive requirement on the power consumption.

5.4.1 The Time measurement circuit

A very fast circuit with a very low jitter is needed to generate a logic signal when the PMT generates a signal with a good resolution. This circuit is also used to hold the ADC and start the conversion.

The time measurement circuit is composed by two blocks:

- **A fast amplifier at high gain.** The choosen configuration is called Complementary Feedback Pair (CFP) or "Sziklai-pair" from his inventor [78] [79]; this configuration is similar to the Darlington pair configuration and the closed loop gain is the usual $1 + R_{F1}/R_{F2}$, as showed in Fig. 5.26 from [79]. A schematic of the realized circuit is shown in Fig. 5.27.
- **A discriminator to generate the logic signal.** The discriminator is a

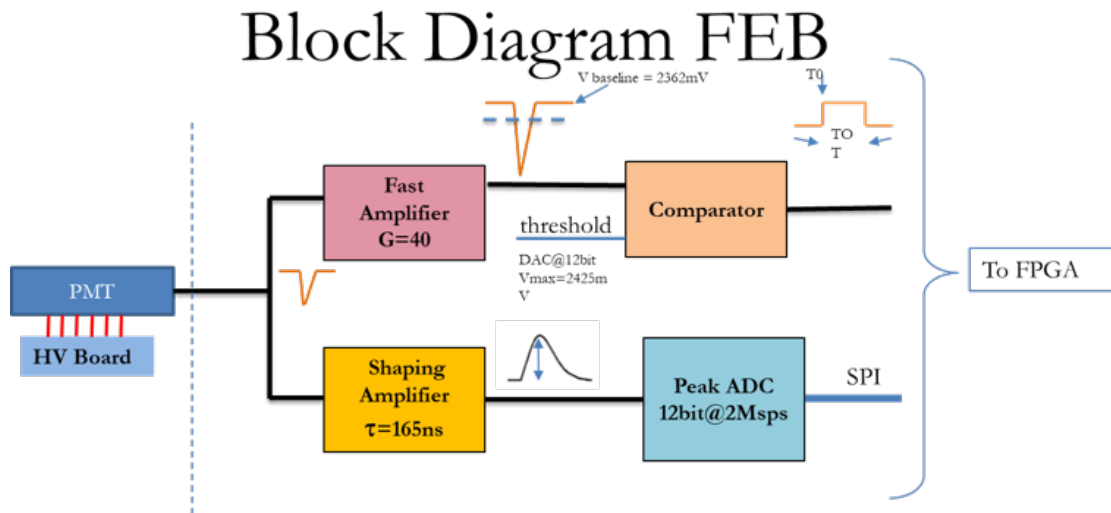


Figure 5.24: Block diagram of the Front-End Board. In the upper part the time measurement circuit and in the lower part the charge measurement circuit.

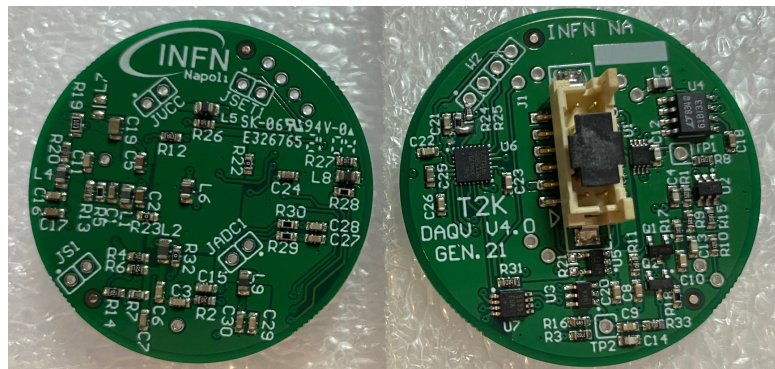


Figure 5.25: Picture of the FEB realized

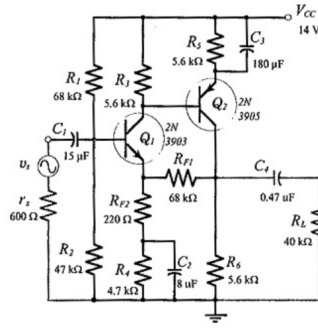
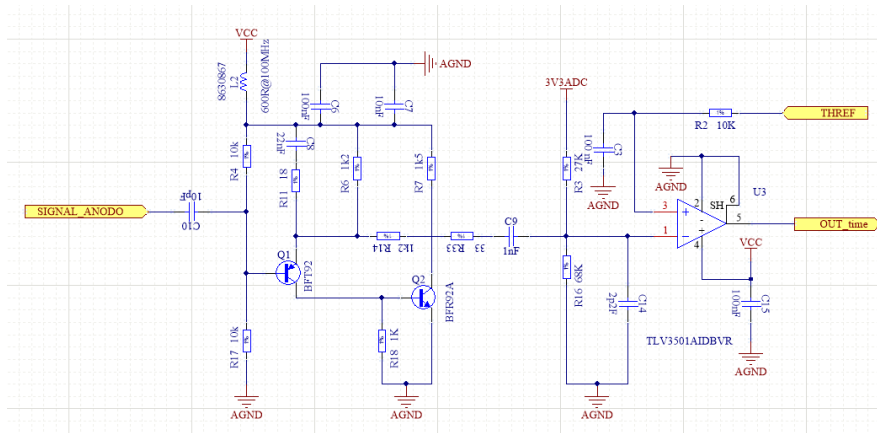


Figure 13-17
Complementary, direct-coupled
amplifier using series-voltage
negative feedback. The amplifier
closed-loop voltage gain is,
 $A_{cl} = (R_{f1} + R_{f2})/R_{f2}$

Figure 5.26: Complementary, direct-coupled amplifier using series-voltage negative feedback. The amplifier closed-loop gain is $A = 1 + R_{F1}/R_{F2}$. The circuit is also called Sziklai pair. Figure from [79].



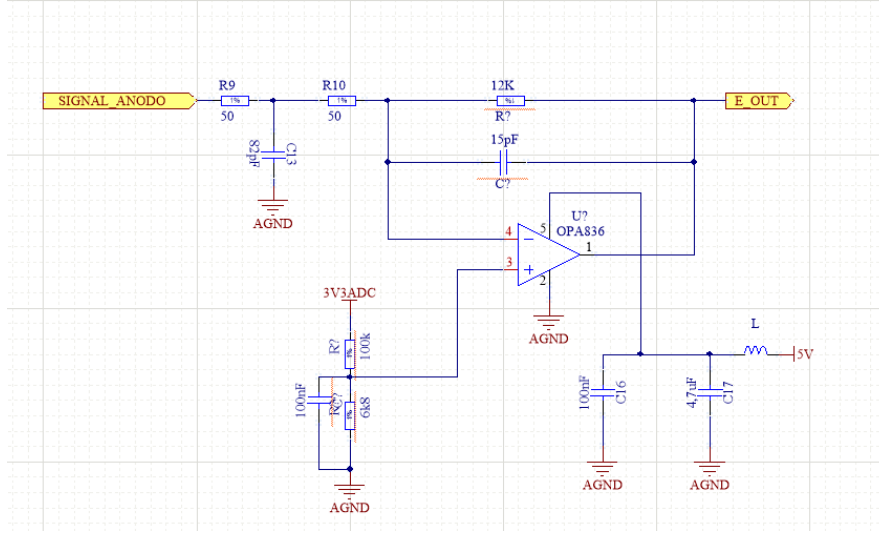


Figure 5.28: Integrator Schematic of the FEB.

S/H of the ADC and to rapidly restore the baseline level within $1 \mu s$. The ADC is the last step in the charge measurement chain. The hold signal is generated by the FPGA starting from the time measurement logic signal with a programmable delay so that it is centered on the maximum of the shaped signal .

Many FEBs have been realized and tested to validate the correct functionality of the overall system.

The measured power consumption is 40.5 mW, giving a total power consumption for the mPMT of $\sim 760mW$.

Charge and time resolution and linearity have been measured with a pulser to verify the specifications. The charge spectra acquired with a pulser is shown in Fig. 5.29. The charge resolution is obtained using the relation:

$$\Delta E = \frac{2\sigma\sqrt{2\ln 2}}{\mu} \quad (5.2)$$

This led to a charge resolution of 0.1%, fulfilling the requirement.

The linearity has been tested firsts without and then with a passive attenuator to keep the noise as low as possible and to measure both the upper part of the dynamica range and the lower part (see Fig. 5.30 and Fig. 5.31). A linearity below 1% over the whole dynamic range has been observed.

The last measurement was the time resolution. This measurement is more difficult because it is necessary to generate a synchronization signal to be used as reference. A trigger for the pulser signal is generated and the time difference between the trigger and the discriminator output is measured with a very fast scope. A FWHM of 100 ps has been obtained, well below the requirements.

5.4.3 The MCU firmware

Each channel needs a very low power embedded MCU to control and monitor the PMT and to set the discriminator threshold. We select the very low power

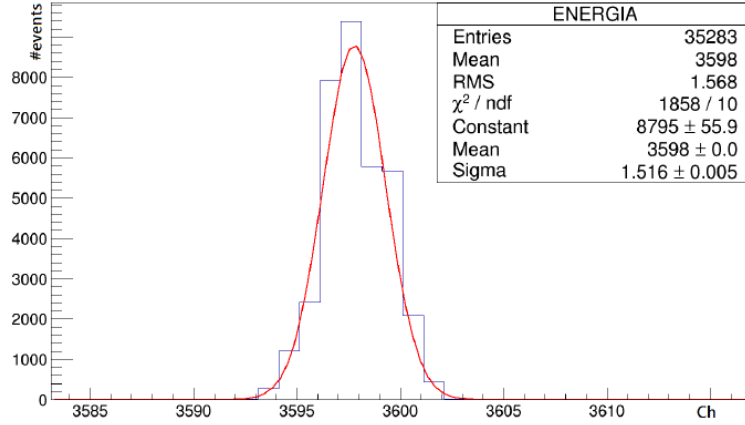


Figure 5.29: Charge spectra acquired with a pulser. The horizontal axis shows the ADC channel.

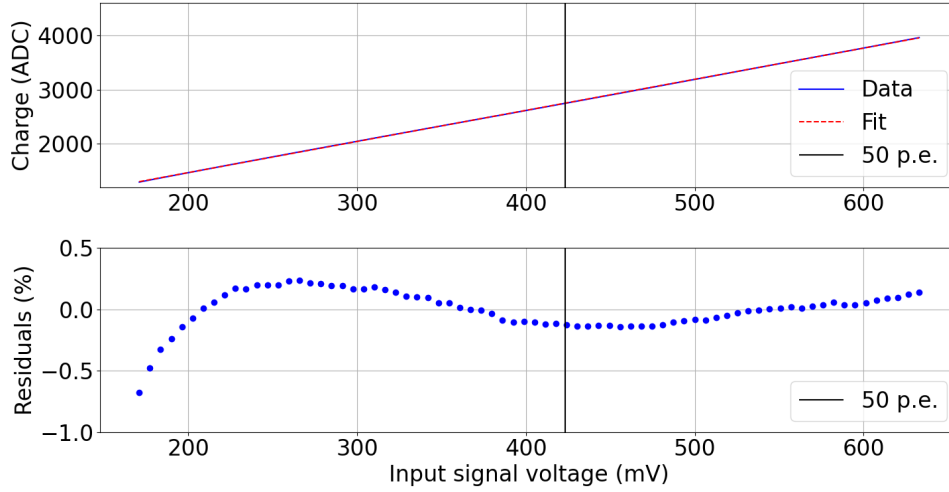


Figure 5.30: Linearity plot for the Front End Board tested with an arbitrary waveform generator (AWG). The signal used for this measure is trapezoidal with a fall time of 7 ns and a rise time of 15 ns and a width of 40 ns. The amplitude of the signal was changed each measure (x axes).

component STM32 MCU of the family L0.

The MCU concentrates in a single UART communication the seven wires needed to completely set and control the FEB and the HV board. Another advantage of the UART is that it is possible to merge the 19 single channel UART in a single couple of cables. The 12 ADC embedded in the MCU is used to acquire and digitalize the analog values from the HV board for the I/V monitoring without using a separate component and thus saving power.

The MCU firmware has been designed to use FreeRTOS, a Real Time Operating System really light. Two main tasks run on the OS, one related to the communication protocol, that is Modbus, and the other task is the ADC one, to check the HV status. The functionality of the OS can be summarized in a Finite

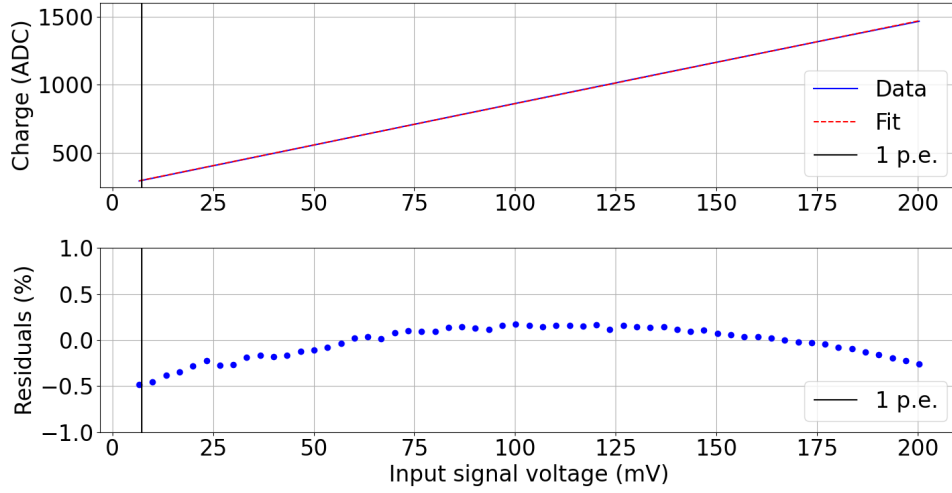


Figure 5.31: Linearity plot for the Front End Board tested with an arbitrary waveform generator (AWG) and a passive attenuator of 10 dB. The signal used for this measure is trapezoidal with a fall time of 7 ns and a rise time of 15 ns and a width of 40 ns. The amplitude of the signal was changed each measure (x axes). The attenuator allowed us to measure down to the single p.e. with low noise.

State Machine, as shown in Fig. 5.32. This state machine is designed to monitor the value of the HV and the anode current from the PMT and according to some parameters to decide if the board is safe or not. All the parameters can be controlled by Modbus on the Main Board.

The last utility in the MCU is the storage of information like the serial number of the PMT, of the HV board and the FEB board itself. These numbers can be read anytime, but they can be write only using a password, since the memory allocations are write protected and specific precalibration parameters will be recorded in the database and used in the reconstruction analysis.

5.4.4 Integration with the HV Board

An important step in the testing has been the integration of the HV with the FE board. In particular, it was important to check if the switching noise could deteriorate the performances of the FE or of the PMT. To easiest way to check is to perform a pedestal measurement with and without the HV applied to the board. In Fig. 5.33 it is possible to see that the pedestal width is basically unaffected by the HV.

Another possible test is the threshold scan (see Fig.5.34), where one change the threshold applied on the FE and monitors for each threshold the rate of the triggers. This is a direct measurement of the noise on the fast amplifier, that in the case of a board without the PMT of other signal source, is of coarse from the induced noise of the HV. The rate is limited to ~ 60 kHz by the firmware. The important value in this case is at which threshold the intrinsic noise level gives less than 1 Hz triggers. In this case over 25 mV (less than 1 mV if we consider

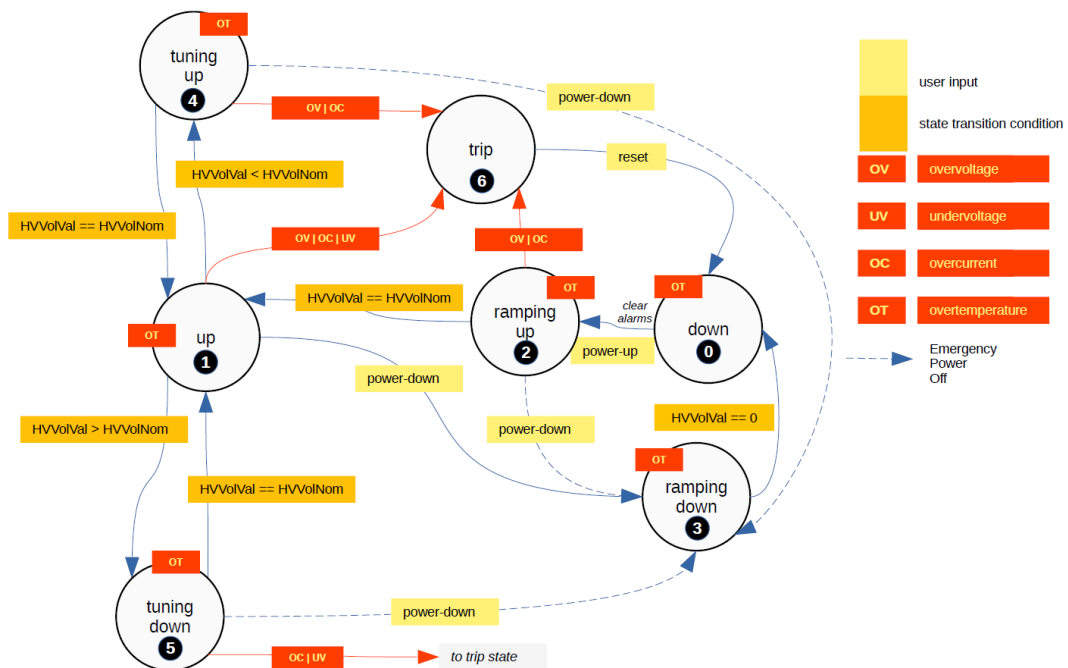


Figure 5.32: Finite state machine that controls the HV board inside the MCU.

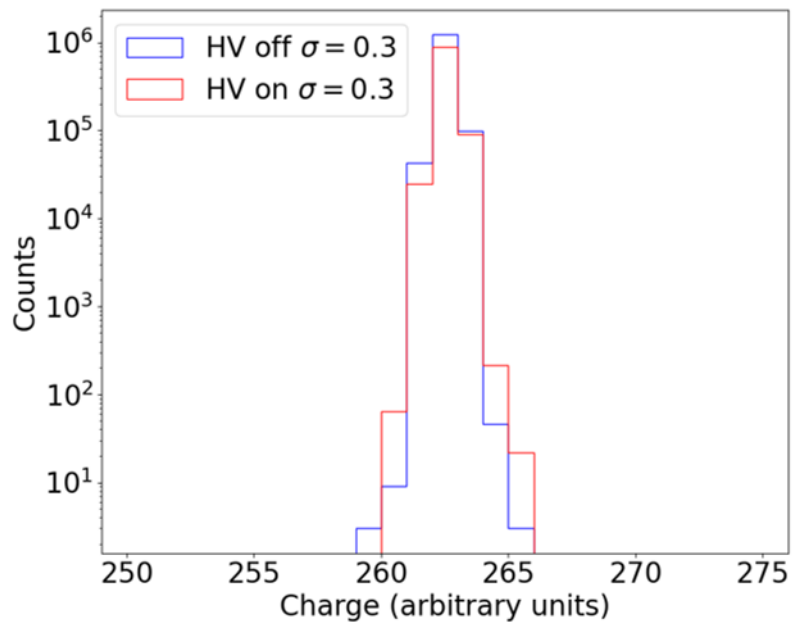


Figure 5.33: Pedestal charge distribution with HV on and off.

the fast amplifier gain) there is basically no noise, so the noise does not affect the performances of the FE.

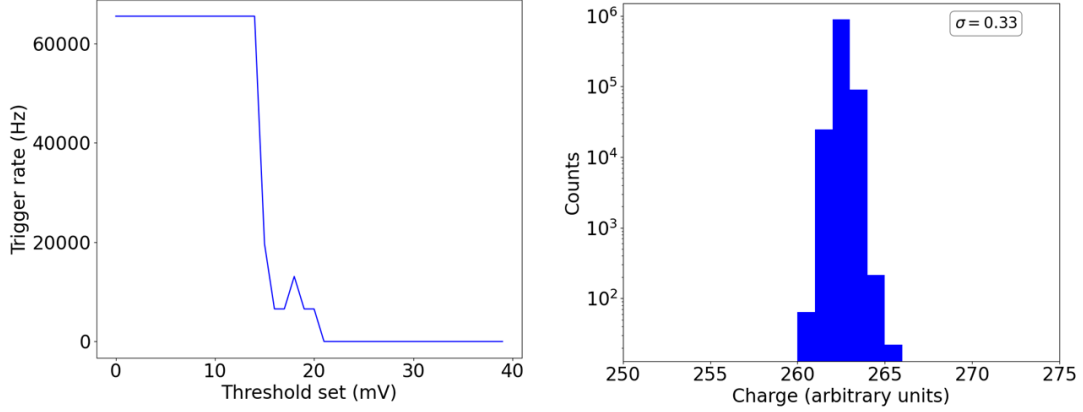


Figure 5.34: Results of noise tests for the HV board. On the left a threshold scan made with a HV of 1100V. On the right the distribution of the pedestal charge with the usual 0.3 LSB of sigma.

5.5 Internal cables

An important component of the mPMT is the cable that connects the 19 FEB to the Main Board. This cannot be a simple cable since it will transfer power, UART, SPI and also a differential signal for the trigger. After a first prototype based on a flat cable, we found as best option a flexible Printed-Circuit-Board (PCB), also known as Kapton cables.

The flexible PCB gives us the advantage to use different impedance profile, as needed for the specific interface. In addition, the flexible PCB let us to directly solder the connectors onto it, making easy the assembly in the mass production phase. The connectors must also be safe to ensure a stable connection of the channels for 20 years, so we choose a Hirose connectors with a locking system [80]. The first prototype of the cable is shown in Fig. 5.35. During this work hundreds of those cables have been realized and tested, none of them was not working, thus validating the design.



Figure 5.35: First prototype of the flexible PCB cable realized to connect the 19 FEBs to the Main Board of the mPMT.

5.6 The Main Board

The Main Board is the interface between the single channel boards and the global acquisition system of the experiment. The Main Board provides the power to the mPMT, manages the data acquisition from the channels to the acquisition servers and also manages the synchronization to the global time of the experiment.

The power supply is composed by three different parts: the Power over Ethernet (PoE) module, the DC-DC converters and switches to turn the individual channels on and off.

The data processing is composed by two stage. A FPGA acquires and processes the data and generates an output of 12 Byte/event that is transferred on the Ethernet with the ARM chip embedded in the Xilinx Sistem on Chip (SoC).

Because of the power consumption of the FEBs and HV boards, we can use about 3 W for the Main Board to satisfy the requirement of 4 W total power consumption. In the following sections, each component of the Main Board will be described.

When designing the Main Board we were focused on two main goals, a low power consumption but powerful acquisition system and an high reliable acquisition system.

To success in both goals we considered some new devices and also an hardware redundancy for the most critical components.

The elements we needed were:

- High efficiency Power supply
- Safe options for the board boot
- Arm chip for the Linux OS
- A tiny but with more than 200 IOs FPGA for the data acquisition
- The possibility to control individually each channel

Fig. 5.36 describes the schematic block of the Main Board. In particular we identified as the most critical component of the board the DDR chips that act as volatile memory for the processing unit. DDR stands for Double Data Rate or DDR SDRAM (Double Data Rate Synchronous Dynamic Random Access Memory). Their expected lifetime is small compared to the rest of the components and, so, a natural choice was to double the DDR chips; the second critical component was the Ethernet PHY chip that is the interface between the CPU and the physical layer of the Ethernet protocol. That chip is in communication with the outside and, thus, it could be damaged by any interference coming from the cables.

The easiest way to overcome the difficulties of creating a redundant system for DDR and Ethernet PHY was to double also the processing core, the CPU itself.

The first idea was to use two small ARM processors and a single Xilinx Artix 7 FPGA, a powerful enough FPGA for our design. Simulations on the power

consumption of different CPUs, indicate that the best solution could be the usage of a different Xilinx technology that embeds on a System on Chip (SoC) both a FPGA and an ARM CPU. This technology is called ZYNQ SoC.

There is also another reason that pushed to choose a ZYNQ SoC and was the reliability of the data transmission system. In the case of a single FPGA and two external CPU we had to include a chip that transforms the parallel data transmission from the FPGA in something readable from a CPU, like a USB data transmission protocol. The standard solution is to adopt chips called FTDI, really powerful and quite easy to use, but that are a bit tricky to setup in terms of hardware interface, in particular for the clock of the parallel data. Moreover, the FTDI system is composed by many components that can fail anytime. To have a more reliable system, a ZYNQ SoC has been chosen to manage the data stream internally without any other external component.

At this point, the only way to use a second CPU was to include an external ARM chip and the FTDI system already described; this is acceptable in terms of reliability since we will keep this overall system off during the normal operation of the board to extend the system lifetime. As external CPU we choose a SAMA5D27 from Microchip [81], since it is available in a System in Package (SiP) chip than includes on the same package the CPU and the DDR memory and this makes the design of the board easier and increased also the reliability.

The ZYNQ chip used is the XC7Z14s-2CLG484E. Looking at Xilinx specification [82] this chip includes a single core ARM Cortex-A9 (called PS, processing system) and an equivalent Artix7 FPGA (called PL, processing logic) in a $19 \times 19 mm^2$ package with 200 IOs for the FPGA and 128 IOs for the ARM CPU.

The boot process is also another critical point of the system, since a failure in the boot image can cause a halt on the overall system. A QSPI memory hosts the basic boot files for the ZYNQ, like the First Stage BootLoader (FSBL). The FSBL is designed for a specific hardware and it must be saved on a QSPI memory. All the files needed to boot the operating system are then uploaded through Ethernet using a remote boot server. A dedicated machine will be used in the experiment.

A double Ethernet connection allow to fully exploit the two CPUs, realizing a double link with the external of the mPMT. This means also double clock and trigger from the outside. To increase reliability on the connection, we choose to not use the classic and standard RJ45 since it is very easy to unplug them accidentally, in particular during transportation or due to vibration. As a better choice, we decided to use a very cheap and plastic connector with 16 pins and a very strong locking mechanism. Of coarse, this come to the cost of adding the magnetic for the Ethernet communication on the board, adding two more components to an already quite complex design.

The main component of the designed board are described in the following.

5.6.1 Power supply

The Main Board includes two PoE+ power supply for reliability reason. PoE+ is a novel standard for the power transmission over Ethernet lines that is based on a 48 V supply on all the 4 pairs of the Ethernet cable to support higher currents

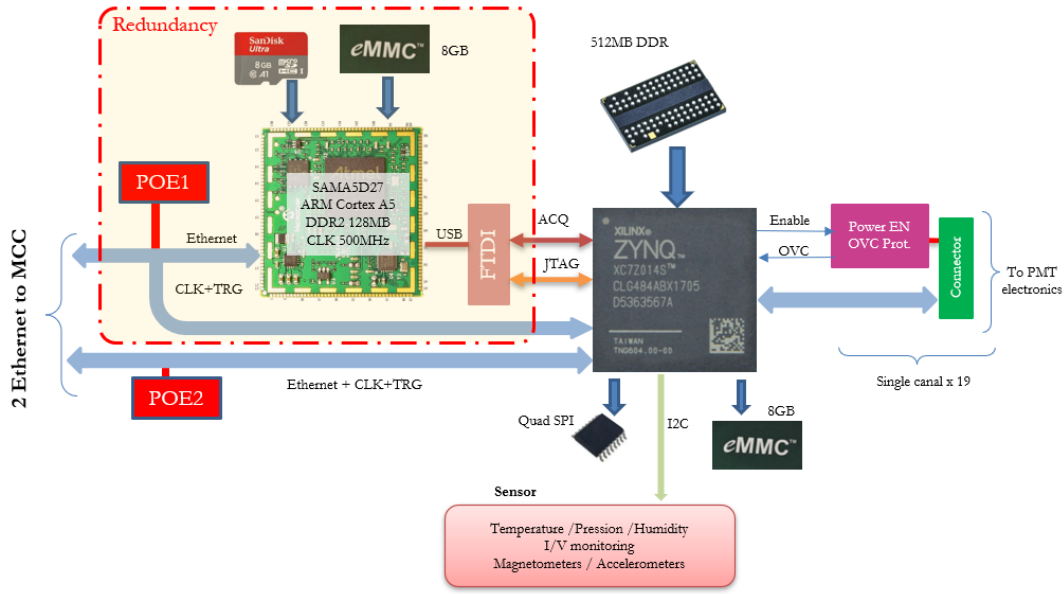


Figure 5.36: Main Board block diagram. The redundancy block is reported and also the double clock and power lines from the concentrator board.

from the devices. The POE+ allows to reduce the energy loss on the cable because of the reduced resistivity using 4 pairs instead of just 2 as in the standard POE.

With a DC-DC converter the 48 V input is transformed in a 5 V supply. The PoE+ DC-DC converter has been carefully designed at INFN to maximize the efficiency and thus, a *Quasi-Resonant DC-DC with a Mosfet rectifier* [83] has been realized (Fig. 5.37). A snapshot of a few cycles is shown in Fig. 5.38. The first resonance at the top of the signal is due to the leakage inductance of the flyback transformer. This leakage inductance is one of the main cause of efficiency loss in the DC-DC converters. The next resonance shown in the plot is the one generated by the primary coil of the transformers and the capacitance in the circuit. This second resonance is the designed one and it is the responsible for the power generation. The commutation of the Mosfet can happen only on the negative cycle of the resonance and this allowed to reduce the switching losses of the Mosfet and to improve the efficiency. The last part of each cycle, the flat one in the figure, is when the Mosfet is in conduction and a current flows in to the circuit.

As already said, the DC-DC converter is doubled and then an ideal diode act as a logic OR to keep the system alive even in case of a single power supply failure.

From the the 5 V supply we generate also the 3.3 V used for the FEBs and the CPU, the 2.5 V, 1.8 V, 1.35 V and the 1 V output used by the ZYNQ SoC. The voltage supplies for the ZYNQ are generated by a Power Management Integrated Circuit (PMIC), see Fig. 5.39. In the total power consumption one of the most important contribution is the efficiency of the DC-DC converter. To measure the efficiency a 48 V power supply is used and its supplied current is measured and also the current on the 5 V output is measured.

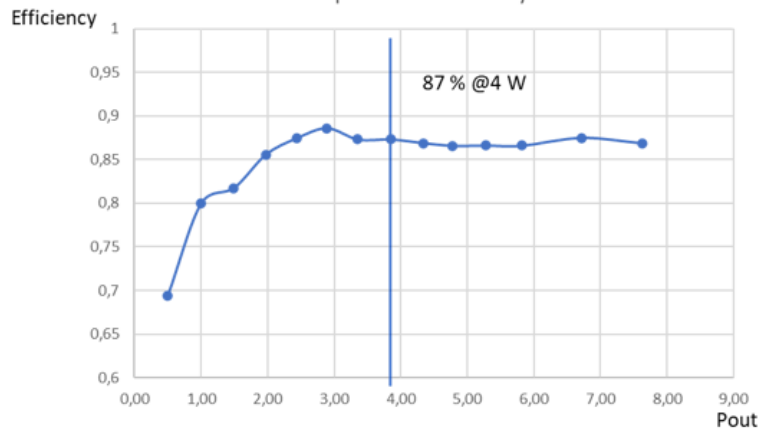


Figure 5.40: Efficiency plot of the DC-DC converter. An astonishing result of 87% efficiency at 4 W is marked in the plot.

The results are reported in Fig. 5.40. We obtained a really good efficiency of 87% at the nominal value of 4 W. For power values so small, this solution is a very good result.

5.6.2 The Board Prototype

A prototype has been designed using the professional software *Altium Designer* [84]. The ZYNQ SoC and the DDR memory use a really high speed parallel interface to transmit data making the design of this block really challenging. The first step in the design is the board schematic drawing. This phase is critical to understand the constraint in the DDR connection to the SoC, in terms of impedances, length tracks equalization and layer stack. Once the schematic was ready, also another difficult part started, the routing of the PCB. This part was also challenging since the traces had to be kept in the electrical specification for our DDR chip, constraining our number of layers choice to be really high, with a 10 layers custom designed PCB. Not only the number of the layers was really high but each of them has been designed to give an accurate impedance value for the traces. In particular we needed the values of 40Ω single ended, 80Ω differential, 50Ω single ended, 90Ω differential, 100Ω differential. The layer stack of the Main Board is reported in Fig. 5.41.

An unusual choice in our design has been to interrupt the alternation of signal-ground layer in the core of the board, to have two near layers instead of one for the fastest signal to be routed. This was in particular needed in the case of parallel data communication protocol where all the bits' trace must have the same length in order to arrive to the other endpoint of the communication at the same time.

The obtained board has been realized (Fig. 5.42) and tested. Also, a fully working firmware and Operating system for the CPU have been developed. A shield that covers the two DC-DC converters to reduce EMI interference on the PMTs has been also realized.

After this first prototype many possible improvements were found and so we

#	Name	Material	Type	Weight	Thickness	Dk	Copper Orient...
	Top Overlay		Overlay				
	Top Solder	Solder Resist	Solder Mask		0.01016mm	3.5	
1	Top Layer		Signal	1oz	0.0356mm		Above
	Dielectric1	Core-011	Core		0.1016mm	4.4	
2	GND2		Plane	1oz	0.0356mm		Below
	Dielectric6	PP-017	Prepreg		0.12954mm	4.3	
3	Mid-Layer 1		Signal	1/2oz	0.017mm		Above
	Dielectric2	Core-028	Core		0.254mm	4.3	
4	Mid-Layer 2		Signal	1/2oz	0.017mm		Below
	Dielectric3	PP-017	Prepreg		0.12954mm	4.3	
5	POWER1		Plane	1oz	0.0356mm		Above
	Dielectric7	Core-016	Core		0.127mm	4.3	
6	POWER2		Plane	1oz	0.0356mm		Below
	Dielectric8	PP-017	Prepreg		0.12954mm	4.3	
7	Mid-Layer3		Signal	1/2oz	0.017mm		Above
	Dielectric4	Core-028	Core		0.254mm	4.3	
8	Mid-Layer 4		Signal	1/2oz	0.017mm		Below
	Dielectric5	PP-017	Prepreg		0.12954mm	4.3	
9	GND7		Plane	1oz	0.0356mm		Above
	Dielectric9	Core-011	Core		0.1016mm	4.4	
10	Bottom Layer		Signal	1oz	0.0356mm		Below
	Bottom Solder	Solder Resist	Solder Mask		0.01016mm	3.5	
	Bottom Overlay		Overlay				

Figure 5.41: Layer Stack of the Main Board PCB in the Altium Designer software.

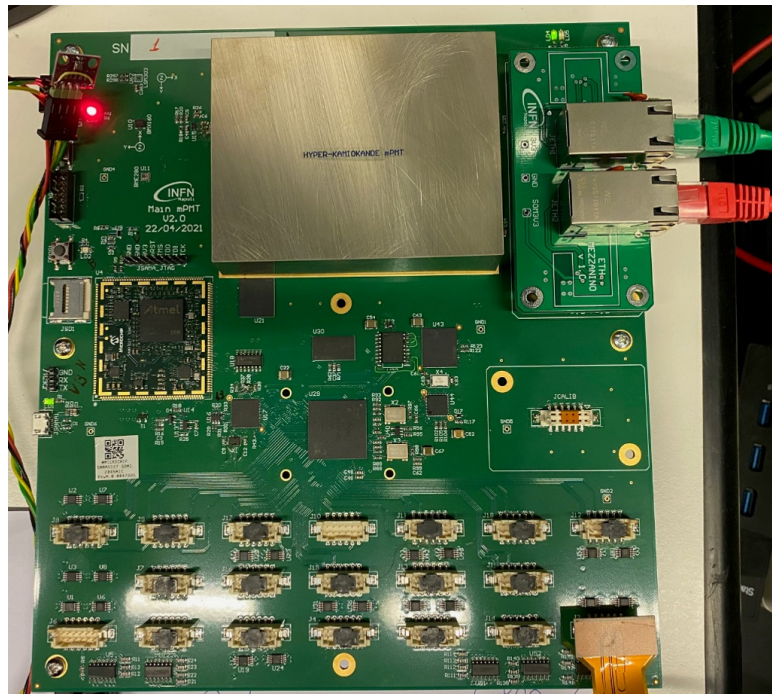


Figure 5.42: First mPMT Main Board prototype produced and tested.

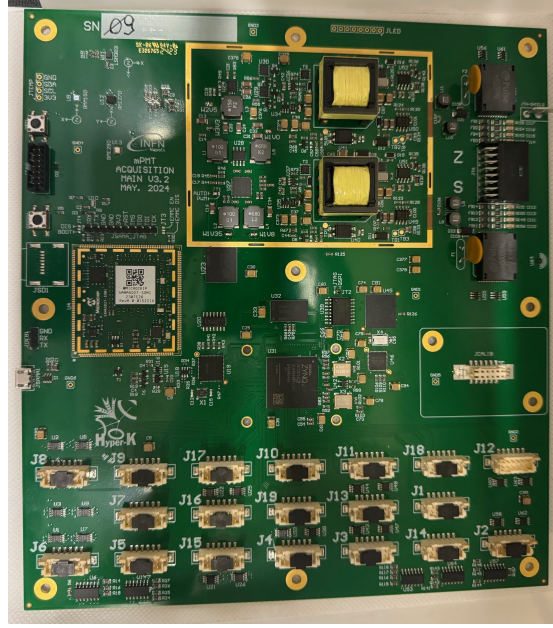


Figure 5.43: mPMT main board final revision. 15 Boards have been produced and tested to verify that the system is stable.

decided to iterate the design for at least two new generations of the board. In particular, in the first revision the major modification was the change and definition of the connector, as already described. Thus let the group to also define the cable specification for the experiment, letting the chosen company to realize the first prototype.

In the last revision we tried to realize what we think will be the mass production board. Basically we removed all the LED from the board, we reduced the number of unique part numbers to save money in production and we also removed the useless components, like the SD card slot, used only for initial debugs.

A picture of the final board revision is visible in Fig. 5.43.

5.6.3 Acquisition firmware and data processing

The firmware of the Main Board has been designed with a Xilinx software called Vivado[85] in a hardware descriptive language called VHDL. For a such custom designed board, the first thing to do is the definition of a custom Board File that let us to create a project for the specific board, once defined power supply, interfaces, speed, clocks and so on. An example of Vivado interface showing the INFN board is shown in Fig. 5.44.

The PMT signal is acquired by the FEB that generates a logical signal for the time stamp and a 12 bits data for the charge information. The Main Board produces the time stamp and the hold signal for the ADC. The charge data are acquired from the ADC through the SPI communication protocol. Once obtained the time stamp and the charge information, an event packet is generated and transferred out of the mPMT to the DAQ system, external to the mPMT. The



Figure 5.44: Custom Board file defined in Vivado to create the Firmware project

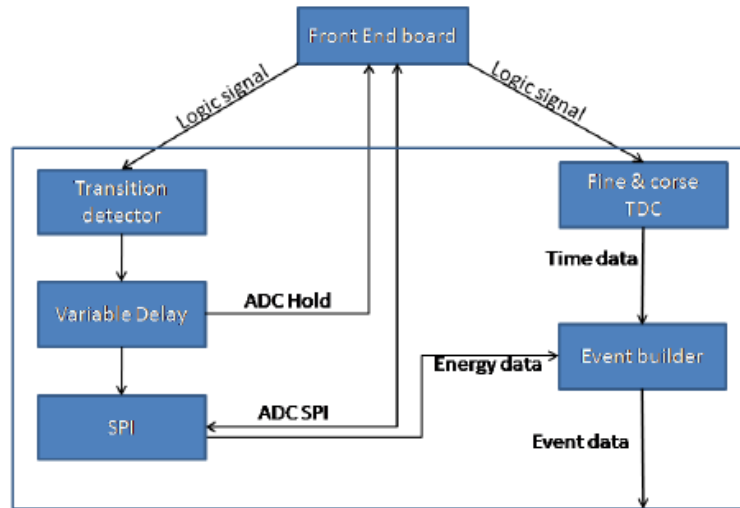


Figure 5.45: Block diagram of the Main Board FPGA firmware and his connection with the FEB boards

event is described in the following. The FPGA was a natural choice to generate the 19 time stamp because we need to process parallelly all the channels and because of the time resolution requirement. With a 5 ns clock (200 MHz) we sample the logic signal provided by the FEB to generate the so called "coarse time", then it is possible to improve the time resolution performance with the multi-phase Time to Digital Converter (TDC) technique.

In Fig. 5.45 a schematic block diagram of the Firmware is presented.

The overall FPGA is controlled by an AXI memory mapped interface from the ZYNQ PS, while in the case of usage of the emergency hardware (SAMA5D27) a UART has been designed and then a custom memory mapped protocol has been implemented to communicate with the FPGA registers. Thanks to this Run Control system we can read and/or write registers that control the acquisition system. At the moment the registers control:

- Start the ADC single channel calibration
- Turn on and off each channel in terms of power
- Disable each channel in terms of acquisition controlling the hold signal of the ADC

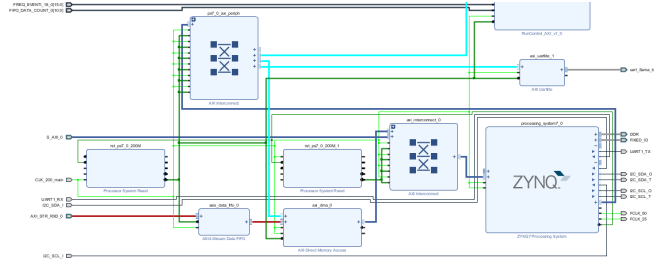


Figure 5.46: IP diagram utilized to integrate the PL and the PS side of the ZYNQ and to define the necessary configuration for the ARM CPU core.

- Set the time between the discriminator transition and the ADC hold signal for each channel
- Set the recovery time of the TDC
- Acquire the frequency event of each channel
- Monitor the overcurrent state of each channel
- Monitor the clock stability and the timing link stability (we will talk about that in detail later)
- Control if and which board is in Boot Mode in case of a MCU firmware update

The data stream is indeed managed by a AXI DMA protocol to send the data directly in the DDR memory without using the CPU. In the case we need to use the SAMA5D27, a FTDI system with a FIFO synchronous communication protocol has been implemented. As seen in Fig. 5.45 an event builder collects the 19 single channels events and generates the stream for the DMA. The data format choosen for the implementation is described in Fig. 5.48. Each packet contains also a CRC for packet integrity check. It is the bitwise XOR of the words that compose the event.

The diagram of the Xilinx IP blocks used to integrate the PL and the PS side of the ZYNQ is reported in Fig. 5.46. An overall representation of the implemented hardware inside the SoC is shown in Fig. 5.47.

5.6.4 Clock and synchronization system

Clock distribution is one of the most critical component for the experiment since the clock must be distributed to all the acquisition systems with a very low jitter. In addition, a synchronization mechanism must be implemented to synchronize the mPMT with the global GPS time used in the other neutrino experiments. We already described the global timing system that will be used by the experiment.

For what concern the mPMT, we had to design a system that could use the copper cable in the Ethernet cable to transmit the clock and the synchronization signal. The global timing distribution system will be based on optical fibers, thus,

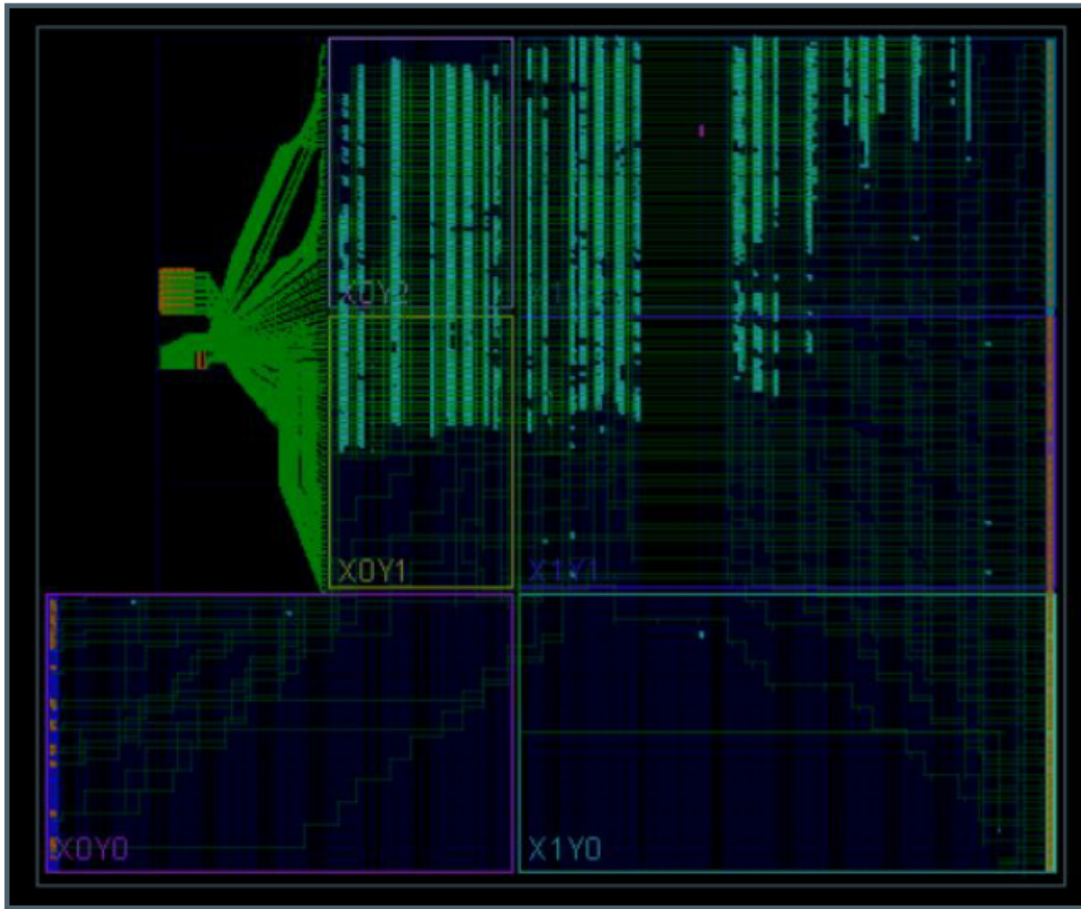


Figure 5.47: Vivado implemented design on the ZYNQ, the upper left corner is the ARM CPU, the remaining part of the chip is dedicated to the FPGA itself.

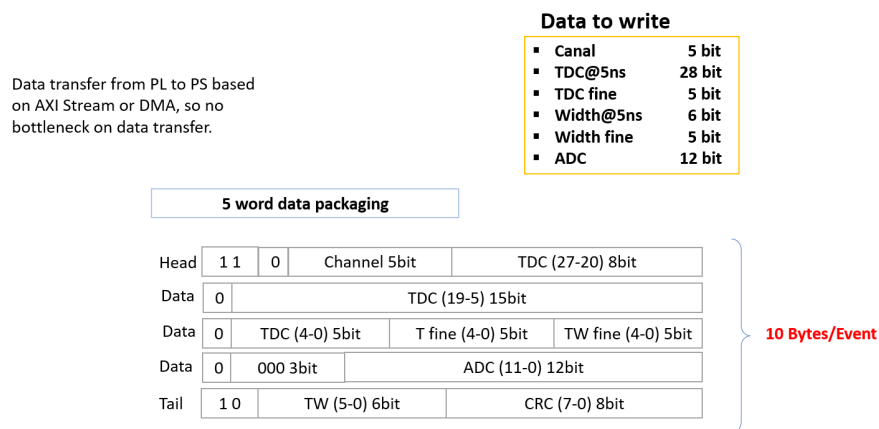


Figure 5.48: Data format and data to be stored in the mPMT for each event.

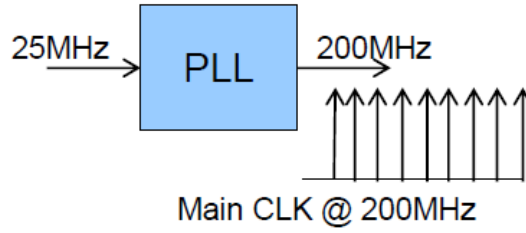


Figure 5.49: Main Board Clock generation schematic. The 25 MHz is automatically checked with a rate-meter and the system can choose which clock is the correct one to be used according to the frequency.

a concentrator card, called MCC, external to the mPMT, will transform the light signal in an electronic signal to be transmitted over copper cables. A complete redesign of the protocol is then needed since we can not use the same protocol as in fibers.

This MCC board is under design by the Cracow group in Hyper-K and it will be basically a custom board embedding a Ethernet switch to collect 8 mPMTs and send the data on fiber. It will also act as a translator layer for the timing as already explained.

The Ethernet connectivity requires only 2 of the 4 pairs at the speed of 100 Mb/s, so we have two spare pairs in the cable. Since we designed the board with a redundant CPU we have indeed two Ethernet cable that go outside the mPMT, leaving 4 pairs to manage the clock and the synchronization system.

The main idea of the timing system is the distribution of a 25 MHz differential clock on one of the pairs and for redundancy also on another pair of the other Ethernet cable. The other two pairs will be used for a possible implementation of a trigger or for a loopback of the clock to evaluate the quality of the clock and the cable length. This leaves us only one degree of freedom to include a synchronization signal in the cable: the duty cycle of the main 25 MHz clock to encode a Pulse Per Second (PPS) signal, one of the most common used synchronization signal in the Timing systems and naturally provided by the GPS system.

The rising edge of the clock is used by the FPGA PLL to generate the internal clocks, so it must be unaltered. Based on that, we choose to modify the falling edge of the clock. The 25 MHz generates a 200 MHz clock into the FPGA (Fig. 5.49) and this 200 MHz clock is used to sample the 25 MHz clock and look for the PPS, also called "Tag0". In normal condition, on a 50% duty cycle clock, a 200 MHz clock will measure 4 times the presence of a high clock and 4 times a low clock. While in case of a PPS encoding we will measure in the FPGA the combination of length 2-6-6-2. This means that we changed the duty cycle of two sequential clock periods. This allows to reduce the Bit Error Rate of the tag detector, since we have a double condition and not a simple one. Furthermore, using two clock periods let us to have a null mean on the Clock signal and this is particularly useful for the AC-coupled signals like the clock ones, avoiding any shift on the mean value of the signal.

Using the same technique we added another tag on the clock, called TagRes,

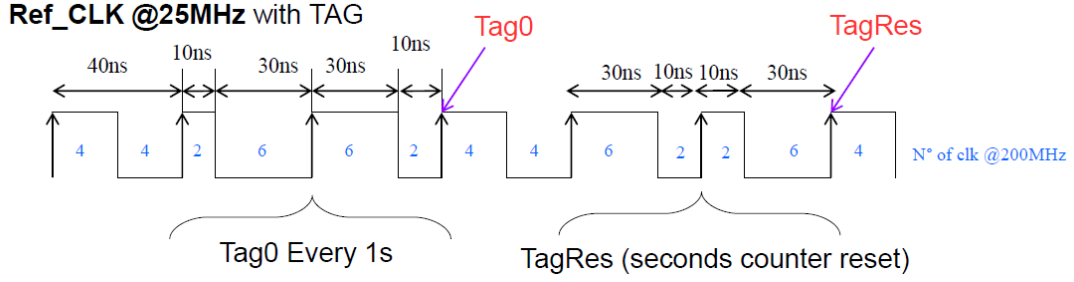


Figure 5.50: PPS or Tag0 and TagRes detection system. The blue numbers stand for the number of 200 MHz clock edges in each period of the 25 MHz.

to reset the counter for the elapsed seconds in the FPGA; this is really useful at the start of each run to synchronize all the subsystems to the same value of elapsed seconds.

In Fig. 5.50 a schematic view of this protocol implementation is presented.

The MCC will have basically the work to generate the modulated 25 MHz clock embedding also the PPS from the 125 MHz clock received on the timing link. This is a simple firmware to be developed and also the two frequencies are multiple of each other, making the design even more direct. The implementation that we choose is very flexible, basically the frequency of the clock can be changed to accomodate different decision in the collaboration. For example the 20" PMTs electronics will use a periodic time tag that is not directly a multiple of the elapsed seconds counter, making difficult for the two different systems to be aligned. We are thinking to switch also our base clock to the one used in the 20" PMTs digitizer, making the link more uniform. For the mPMT this will imply a change in clock frequency to 15.625 MHz with a time tag every 1.07374 s to reset our TDC counters. This work will be carried out in the next months, but it is mainly a firmware change, so nothing will change in the hardware and the mass production can go on without any delay.

Jitter evaluation

The jitter can be influenced by many factors, from the cable to the path used in the FPGA to route the clock. To make jitter measurement we had to design also a simple clock distribution system for our system since the definitive one from the collaboration is not ready, in particular the MCC board is not yet ready. This system can add the clock on the correct twisted pair of the Ethernet cable and it can also encode the two Tag defined in the timing protocol. The system can manage up to 7 boards, providing also Ethernet connectivity and power using a standard POE+ Ethernet switch. The system is shown in Fig. 5.51.

The first test we did was a measurement of clock jitter using a standard CAT5 Ethernet cable, characterized by unshielded twisted pairs. The histogram of the measured jitter is reported in Fig. 5.52. The result was not good, since the shape is not even a gaussian.

To solve this problem we did the same test using a CAT6 S/STP that is

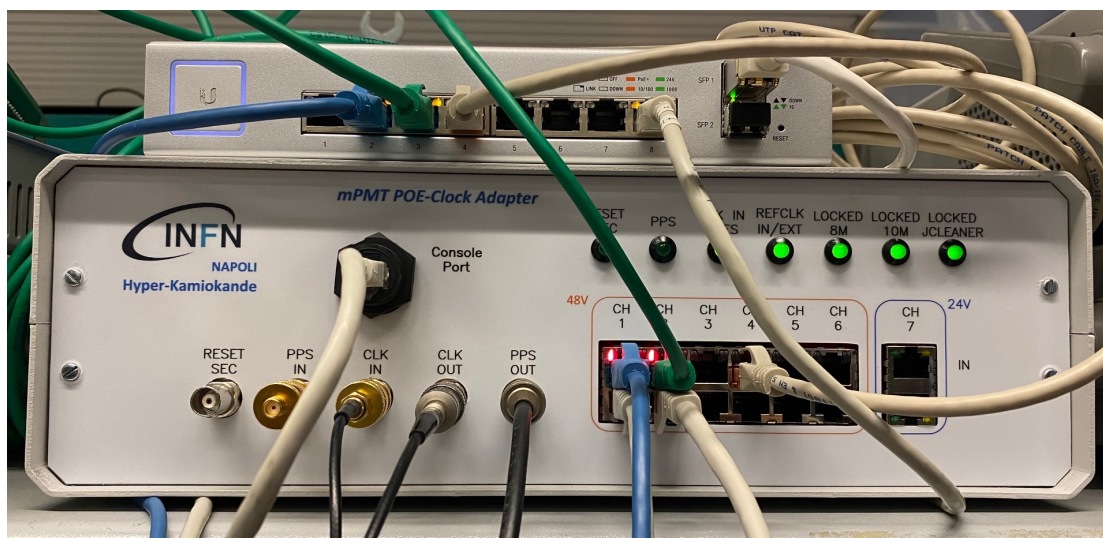


Figure 5.51: POE-Clock adapter designed at INFN to make jitter tests and to distribute clock in the R&D phase.

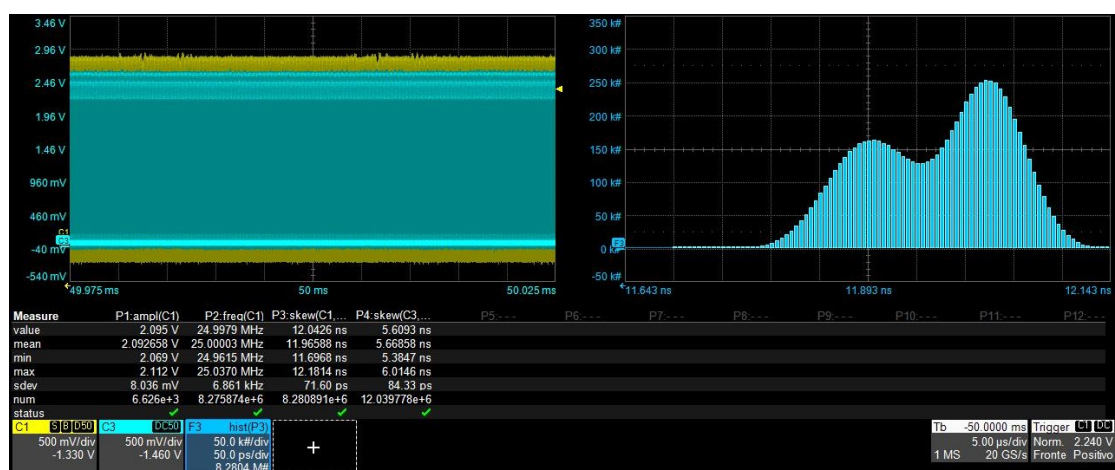


Figure 5.52: Jitter measurement using a standard unshielded twisted pairs Ethernet cable.

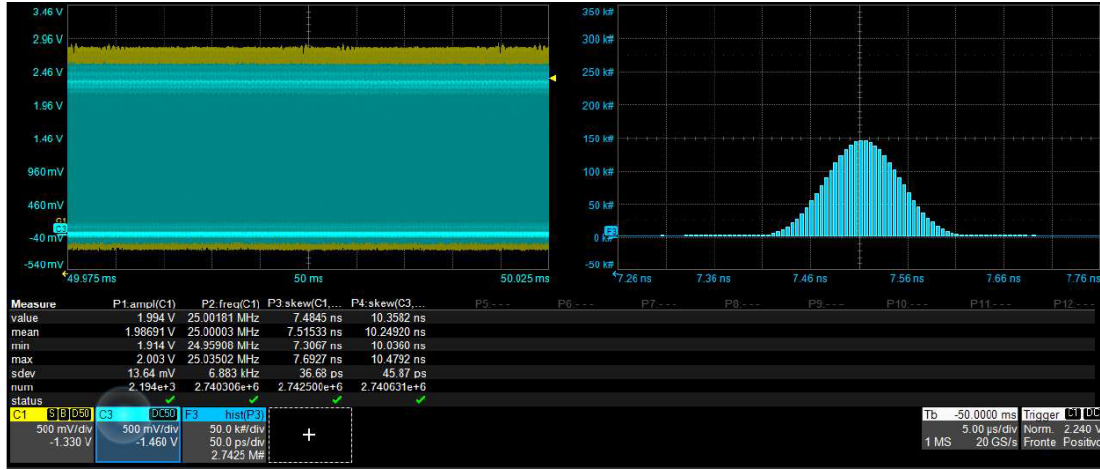


Figure 5.53: Jitter test using a CAT6 S/STP Ethernet cable.

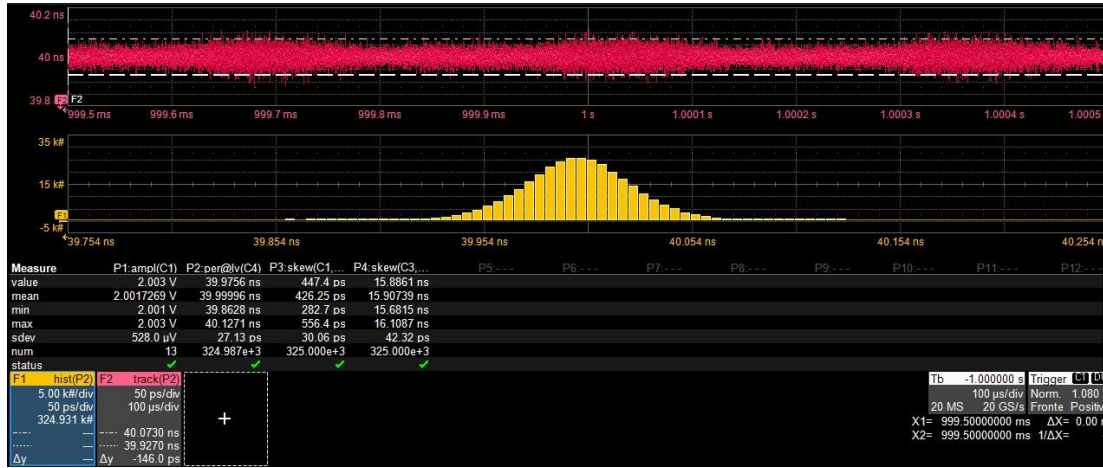


Figure 5.54: Jitter measurement on the input clock of the FPGA.

composed of shielded twisted pairs and the whole cable is then shielded. With this cable we obtained a good result of 36 ps for the σ , as reported in Fig. 5.53.

Once defined the correct cable to keep the jitter low, the next step is to check how the Main Board transforms the clock in the PLL. The input buffers of the FPGA should not increase the jitter due to any coupling with other signals. To control if this is true, we used an output pin of the FPGA to send the clock to the oscilloscope and then we measured the Jitter, obtaining a $\sigma = 27.1ps$, as reported in Fig. 5.54. In this case we measured the clock without any PLL instance in the FPGA.

After that we used the same output pin to measure the clock after the full chain: the multiplexer and the PLL. In the definition of the PLL we instantiated also a Jitter Cleaner, so we expect this clock to be better than the input one. The test result is reported in Fig. 5.55 and shows a $\sigma = 14.5ps$. Indeed, it is lower than the input jitter, as expected.

Finally, we tried the test that is the most similar to the real world application, that is the jitter measurement between two identical Main Boards that receives

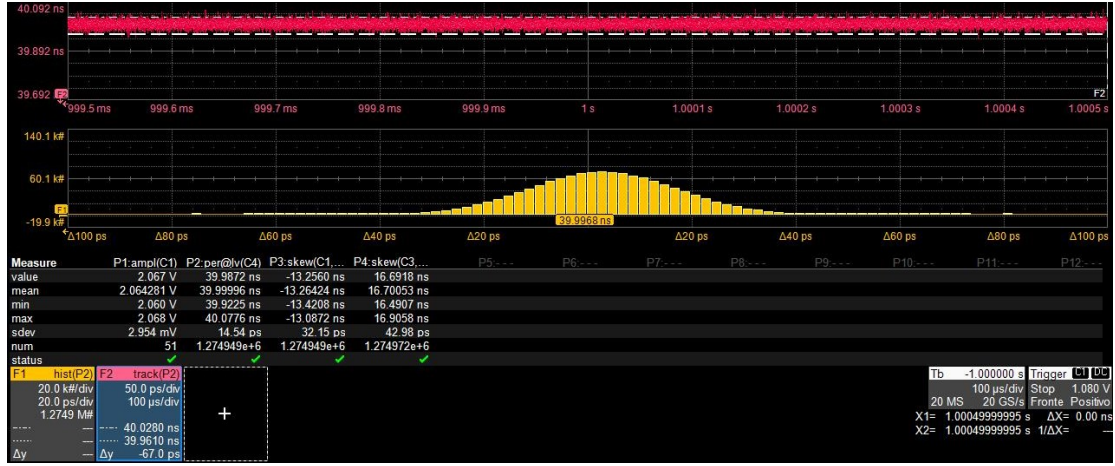


Figure 5.55: Jitter test after the full clock chain, including the Jitter Cleaner.

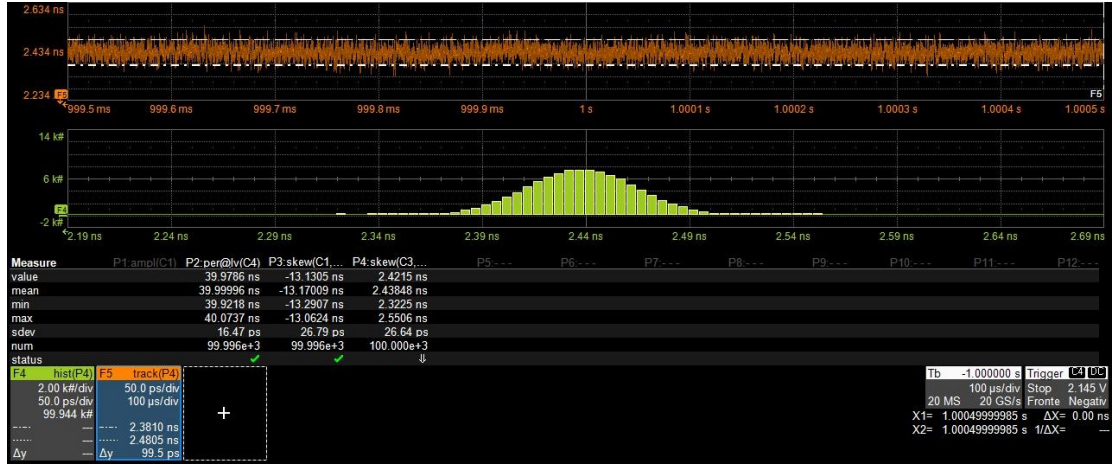


Figure 5.56: Jitter measurement between two identical Main Boards with an external common reference clock.

the reference clock from the clock distribution system. The result is $\sigma = 26.6ps$ within the requirement, see Fig. 5.56.

5.6.5 Time to Digital Conversion, TDC

The data acquisition is composed by two parts: the TDC and the ADC control, The data acquisition block is individual for each channel so in the FPGA is replicated 19 times. The TDC is divided in two part called coarse and the fine. The coarse one has a 5 ns time resolution realized with the 200 MHz clock generated from the 25 MHz, while the fine one provides the 300 ps resolution by a multiphase TDC.

The FEB discriminator transition is transferred to a very fast delay line realized with the hardware carry line. For each FPGA slice it is possible to digitalise the signal with a flip flop as shown in Fig.5.57. In our design there are 18 flip flops to generate the fine part of the time stamp.

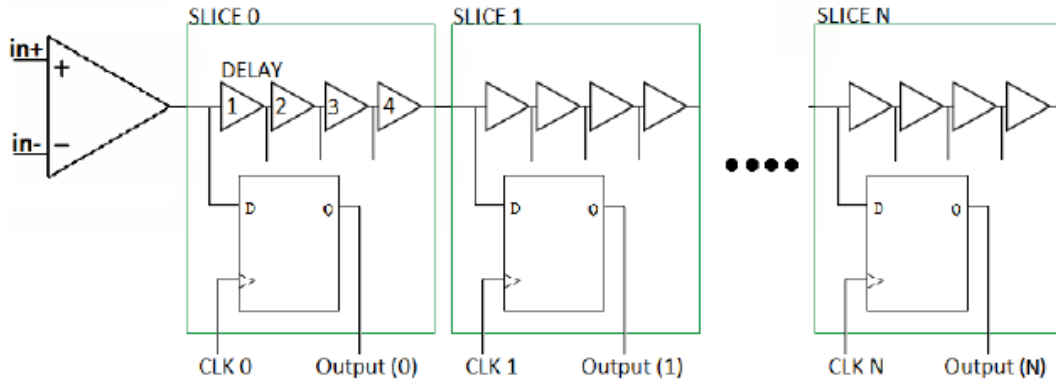


Figure 5.57: Block diagram of the delay line to determinate the TDC fine part.

The first 14 flip flops are clocked at 200 MHz with seven different phases. The first seven flip flops of the carry line uses the rising edge while the last seven uses the falling edge of the clock signal. The ideal time difference between the edge of the clocks is 357 ps. The last four flip flops of the chain are used as overflow.

The carry line is the fastest connection in the FPGA and it is usually used for fast TDC implementation, although it also need few picoseconds to cover the distance between the flip flop of the slices. This time can be calibrated to improve the TDC resolution.

The signal flows through the carry line with a delay of 80 ps for each slice. We consider as 0 the time of the rising edge of the 0 ° clock phase used in the TDC. The flip flops should sample the signal at the time $357 \text{ ps} \times N$, where N is the step of the carry line. The signal arrives to the step N with a delay of $80 \text{ ps} \times N$. Thus, the time in which the conversion takes place is $277 \text{ ps} \times N$.

With a time resolution of 277 ps we need 18 flip flop to cover the 5 ns between two rising edge of the phase 0 clock. The fine part of the TDC is thus coded in 5 bits with a number form 1 to 18.

When the discriminator has a high to low transition a second time stamp composed by coarse and fine is generated to measure the event duration, also called Time over Threshold (ToT). The measurement of the ToT can be useful to improve the dynamic range. Indeed, as shown in Fig. 5.58, a Charge vs. ToT matrix can be realized and a trend can be extrapolated also for signals bigger that our dynamic range, since the range of the time measurement is not limited. Another advantage is that the electronics noise generates signals of a width that is different from the one of the PMT signal, thus the ToT measurements could increase the signal to noise ratio in event reconstruction phase.

With the possible modification in the mPMT timing scheme also the TDC will need minor modifications, in particular the base frequency is going to be 250 MHz, with a reduction in the number of phase to 6. Considering the same Carry line architecture the final number of phases is expected to be 15, meaning a TDC LSB of 266 ps, even slightly better than the original one.

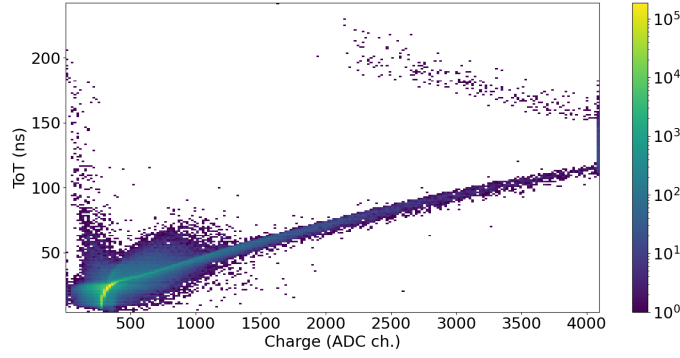


Figure 5.58: ToT measurement, a clear trend is visible. This trend could increase the signal to noise ratio and could also extend the dynamic of the mPMT.

5.6.6 Electronics cooling system

A passive cooling system will be used to dissipate heat and keep a low temperature of the electronic components. This is important as each 8 to 10 degrees rise in temperature typically decreases the lifetime of electronic components by a factor of two. The backplate closing the mPMT vessel will be also used to dump the heat and to avoid a possible overheating of the electronics components. This will be obtained by placing a pad between the Main Board and the backplate that conducts thermally but non electrically. To increase the thermal dissipation capability of the system a passive heatsink will be placed on the most critical component, as the ZYNQ SoC and the DDR. This heatsink will transfer the heat to the backplate through metal columns. The thermal dissipation system is shown in Fig. 5.59.

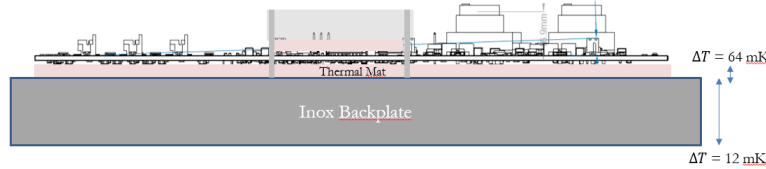


Figure 5.59: Thermal dissipation system of mPMT.

We performed tests in air to check the performance of this approach and we obtained good results. We built an aluminium backplate to simulate the thermal capacity of the backplate and the small heatsink to be put on top of the SoC. In Fig. 5.61 and Fig. 5.60 a detail of the system in testing. We measured the ambient temperature and with two sensors we measured the temperature of the Main Board (near the DC/DC region) and the ZYNQ temperature.

The ambient temperature was 25 degree, stable since the lab is air-conditioned.

We tried firstly with only the backplate simulator and we obtained a temperature of 27 degree for the PCB and 32 degree for the ZYNQ SoC. Without any dissipation system the temperature of the ZYNQ was 37 degree.

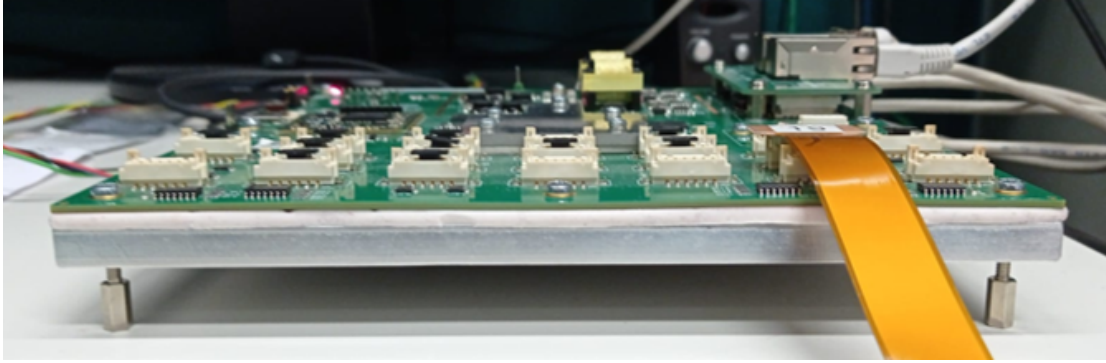


Figure 5.60: Thermal dissipation system of mPMT for testing. Side view.



Figure 5.61: Thermal dissipation system of mPMT for testing. Top view.

Adding the top heatsink on the FPGA we get 26 degree on the PCB and 31 degree on the ZYNQ.

With a water temperature of 15 degree in HK we expect to reach a stable temperature of 20-30 degree for the FPGA. The normal CPU load expected during the data taking is below 30% but more precise numbers will be available after the final DAQ integration.

In the 5.62 it is possible to see the main hotspots on the Main Board, the board was fully working with DAQ running, so the heat generated is representative of the real load. The main hotspots are the FPGA and the additional CPU. They will be cooled with a thermal mat connected to the backplate.

After tests in air we placed a fully instrumented mPMT in water in a dedicated pool in Caserta, in a KM3Net facility. We monitored there the temperature for few days and the results are shown in fig. 5.63.

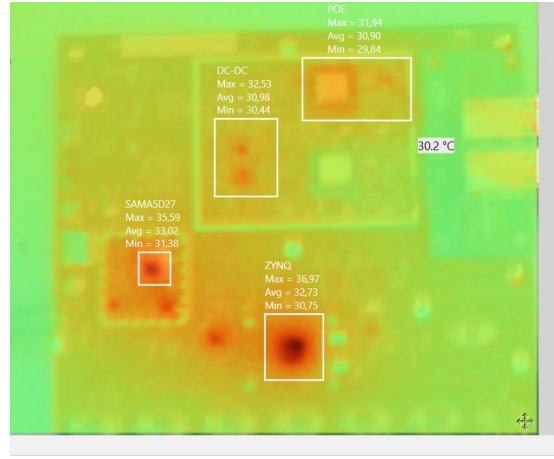


Figure 5.62: Main Board Thermal picture.

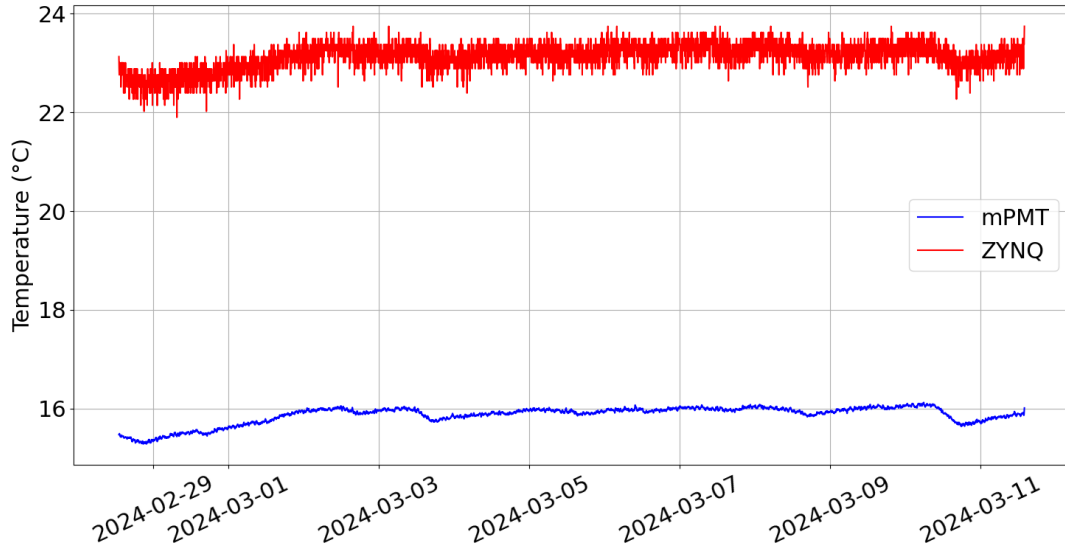


Figure 5.63: Temperature trend in Caserta pool for the mPMT

5.6.7 Temperature/Humidity/Pressure sensors online monitoring

The mPMT is a complex system and to check the stability of the acquisition system it is possible to monitor a set of environmental parameters. The Main Board design includes an I2C communication line for temperature, humidity and pressure sensors. This information will be read periodically by the DAQ software and it will be transmitted to the external DAQ. Another important parameter is the orientation of the mPMT and the magnitude of magnetic field in the proximity of the mPMT. To monitor these parameters also a IMU (Inertial Measurement Unit) and a magnetometer are included in the Slow Control sensors system.

5.7 Ethernet Cable

The mPMT needs only one Ethernet cable to be operated, due to the redundancy in the Main Board indeed the cables are two. One should design a custom cable that can work underwater for many years and can carry two Ethernet connection inside. We already saw that the cable must also be very well shielded to reduce the injection of noise in the clock line, so we should also use shielded twisted pairs instead of normal twisted pairs.

The mPMT cable must also be realized in a material compatible with ultra pure water and with Gadolinium, without being too expensive.

The list of the requirements are reported in the following.

Materials:

- Compatible with Steel AISI 304, ultrapure water and Gadolinium
- Low nuclear contamination. The total radioactive contamination of the cable per 1 meter in length is as follows:
 1. less than 10 mBq for U-series
 2. less than 30 mBq for Th-series
 3. less than 30 mBq for Potassium 40 (40K)

Pressure:

- Depth of 60 m maximum
- Safe pressure of 13 bar
- The cable connection to the waterproof assembly outlet should resist 0.95 MPa pressure in water.

Reliability:

- 20 years working without maintenance

Electrical Specification:

- Approved and tested for Ethernet Connectivity (100 Ohm impedance, as standard Ethernet cable)
- 16 conductors in 8 twisted pairs (each Ethernet needs 8 pairs, we need 2 Ethernet connections for redundancy)
- Shielding
 1. each pair must have a shield, an external general shield is positive but not sufficient to prevent noise
 2. Penetrator, nut and bolt must be in AISI 304 for the mass production and the final configuration

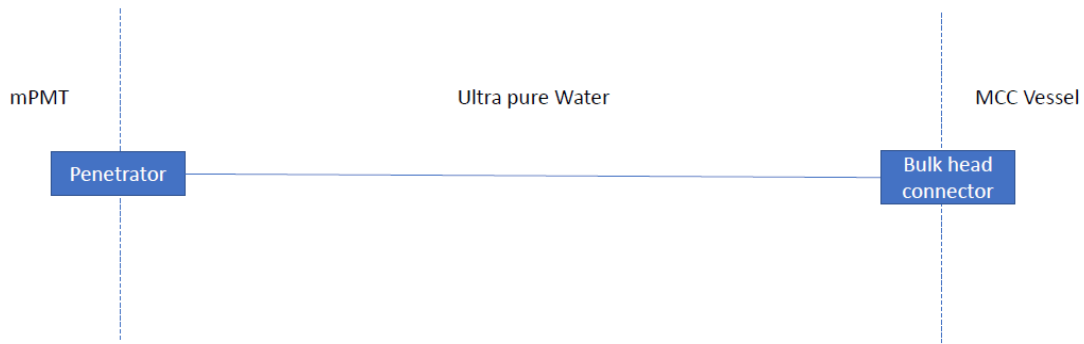


Figure 5.64: Scheme of connection of a mPMT to its MCC vessel. A penetrator is planned on the mPMT side, while a bulkhead connector is planned on the MCC side.

The cable has to basically behave as a standard CAT6, with pairs of 26 AWG. A 48V standard POE+ and a power of 4W (thus low current) need to be considered. Number of pins is related to the need to have 8 twisted pairs, thus at least 16 pins are required. More pin can be considered for ground and shielding, depending on the cost.

The first prototypes used a custom cable realized by [86]. The company only provided a cable and at that point no solution on how to integrate the cable in a full system.

To realize a full system we opted for the following scheme of connection, the cable is connected to the mPMT thanks to a penetrator in the backplate so the mPMT is a monolithic piece together with its own cable. The cable length is 25 m, based on the necessity to route the cable in the Hyper-K tank. The other end of the cable should be plugged in an underwater bulkhead connector mounted on the MCC underwater vessel. The diagram of the proposed connection is represented in Fig. 5.64.

Realizing such system by ourself was almost impossible, so we created a strong collaboration with MacArtney company [87] who offered to design and customize a cable based on the latter requirements.

The final technical drawing is reported in Fig. 5.65.

During the years many prototypes of this cable have been ordered and tested, in particular to verify the noise performances on the clock line and to check also how much noise the mPMT could introduce in the 20" PMT cables or in the OD PMT cables.

To test the injection of noise on the clock line we injected a pulse generated with a pulse generator on one of the pairs and we monitored the other pairs on an oscilloscope. What we expect is basically a flat line on the monitored pairs, with the exception of the discontinuity points like the connector.

In Fig. 5.66 it is possible to see how good a standard home CAT6 Ethernet cable performed in this test. On the other hand in Fig. 5.67 it is possible to see how noisy was the second prototype received from MacArtney. The results of this test suggested that was essential to include the shielding on each pair, but this was already a requirement for us. Also, from the randomness of the noise it is



Figure 5.66: Standard CAT6 pulse test on the cable. The monitored lines on CH2, CH3 and CH4 shown no injection of the pulse.

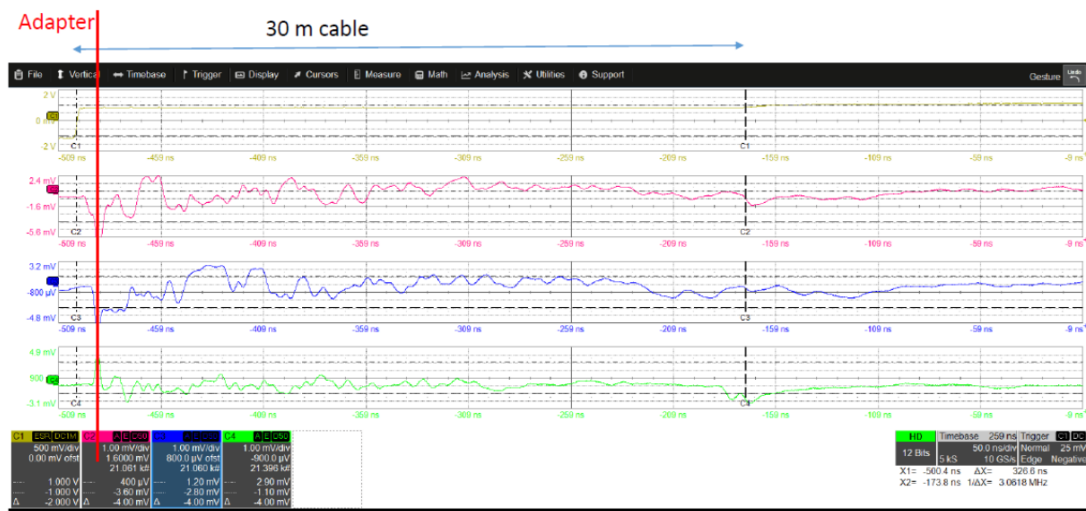


Figure 5.67: Second prototype pulse test. The monitored lines on CH2, CH3 and CH4 shows a very strong capacitive coupling between the pairs.

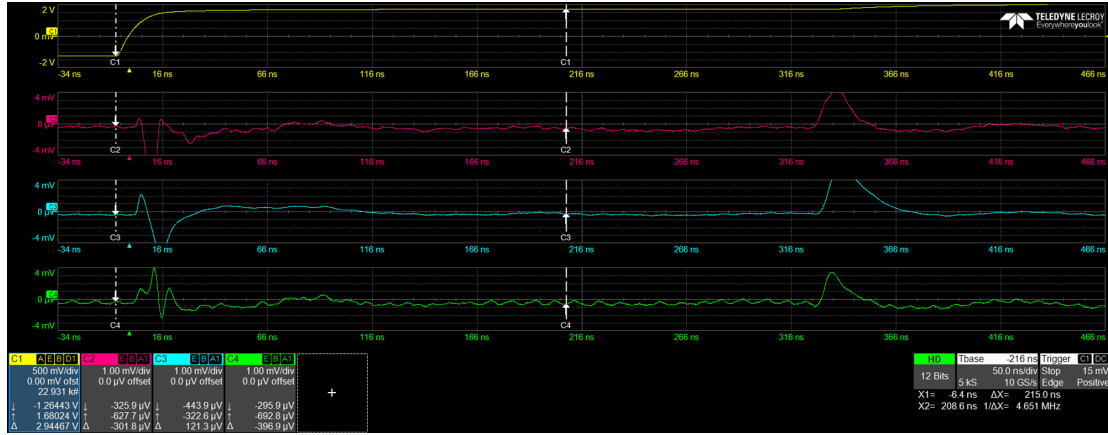


Figure 5.68: Final prototype pulse test on the cable. The monitored lines on CH2, CH3 and CH4 shows much less noise and distortion. This design is good enough to be used in the mPMT.

and loaded in a central Hyper-K database for future needs. The HV and FE tested are based on a bed on nails to inject or evaluate signals where needed. This type of system is quite complex to design and also time consuming so a specialized company helped in this project.

The cable testers, on the other hand, for both the MacArtney cable and for the flexible internal cable, were designed by our group and are based on simple board powered by small microcontrollers. Those testers will not save any data on the database since their main goal is just to verify if every pin is connected and in the right place.

A summary of all the testers realized is visible in Fig. 5.69. In total we will provide 4 unit of each tester to the company to make the work parallel and thus more efficient.

5.9 Reliability and long term tests

In this section we will describe the major tests done to ensure an high reliable electronics to the mPMTs. In particular we will describe the MTTF (Mean Time To Failure) calculation and the HALT testing.

5.9.1 MTTF calculation report

MTTF calculation has been realized for each board and for the complete mPMT electronics system.

Reliability prediction was performed based on the failure rates of the Siemens SN29500 using the tool Medini Analyze R2022. Each component has been categorized according to SN29500, the base failure rate has been associated to it and, where required by SN29500, stress parameters have been associated too (for example, for a capacitor the ratio between operating voltage and rated voltage has been considered). Moreover, the ambient temperatures considered for the compo-

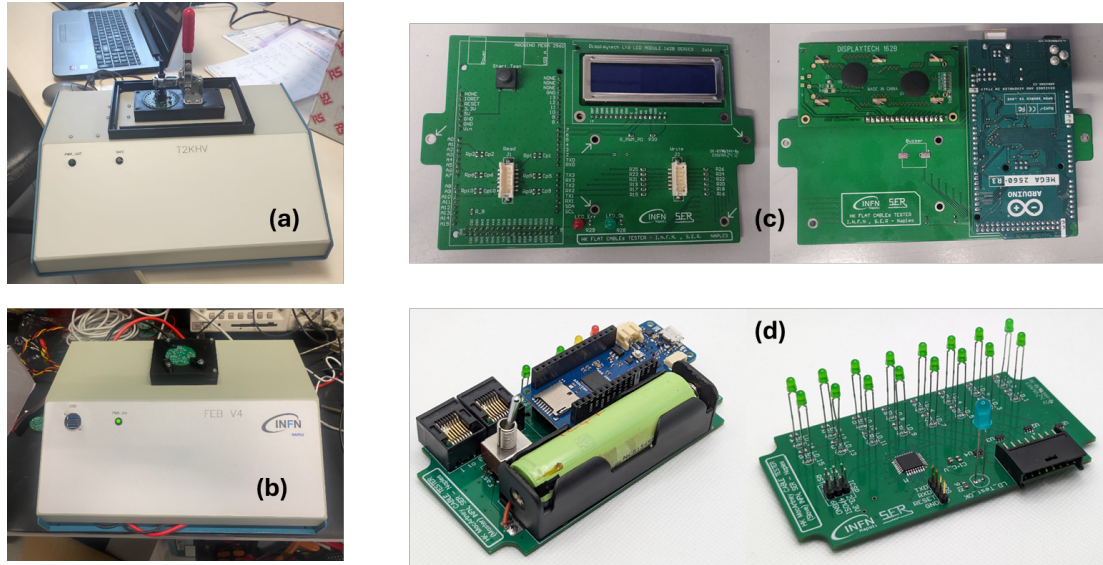


Figure 5.69: Test systems for the mPMT electronics and cables. In order: the FEBs testing station (a), the HVBs testing station (b), the Kapton cables testing board (c) (front and back) and the MacArtney cable testing boards (d).

nents are 15°C and 30°C , since the boards are cooled at a reference temperature of 15°C and the safety threshold is set at 30°C . A stress consisting of a self-induced temperature rise of 10°C was considered for each component.

The Reliability Block Diagram is represented in Fig. 5.70 with a fault tree description. The top event represents the system failure, which can be generated by the underlying events. The "HV-FEB (k out of 19) - Failure" event represents the number of failed channels compared to the total number (19); a channel fails when of one of the two HV and FEB fails.

We know from Xilinx that the FIT of the ZYNQ that we want to use is 11 while we do not have precise numbers from ST for the MCU, so we have to use the one calculated using the standard. The HV board dissipates only 3 mW so it is almost impossible to measure any difference from the ambient temperature, while the FE board dissipates 40 mW and the temperature of the MCU is stable at 30 degrees with 25 degrees of ambient temperature. The values reported from the MTTF calculation will be for sure better in real life, so tests like the HALT can be important to have more experience on long term operation of those boards.

The MTTF of the separate boards is shown in Fig. 5.71, while the MTTF of the whole system is shown in Fig. 5.72.

5.9.2 HALT (Highly Accelerated Lifetime Test) for the mPMT electronics

To test the reliability of the components, a HALT has been performed on 19 coupled HV and FE boards. The components have been stressed at high temperatures for a month, and during this time the performance of the boards were

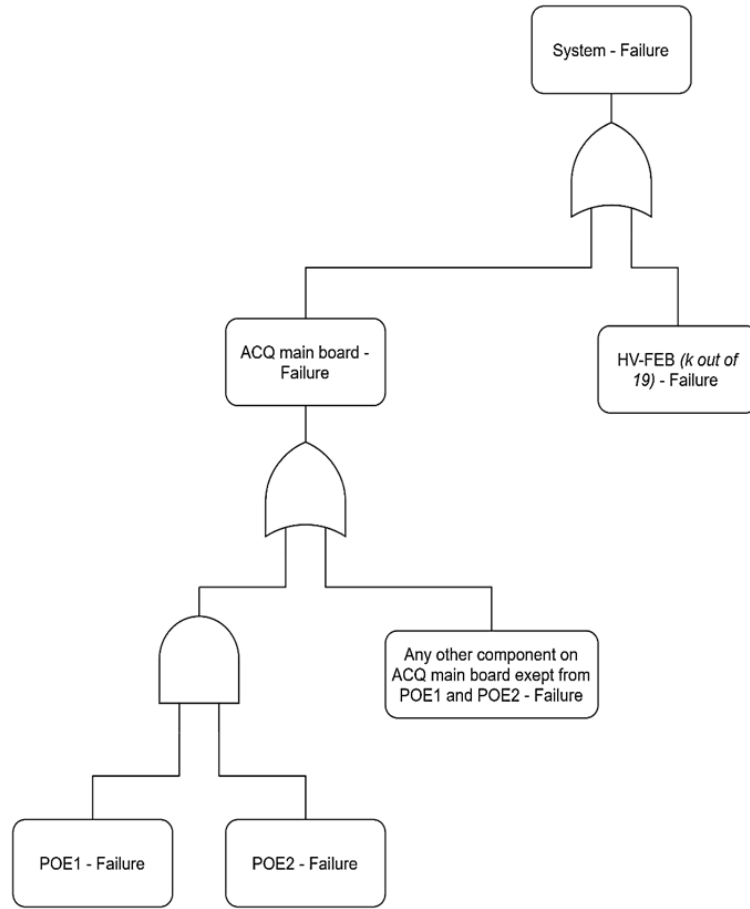


Figure 5.70: Reliability Block Diagram.

Board	Tamb [°C]	MTTF [h]	MTTF [years]
ACQ main board	15	1,04E+06	119,06
ACQ main board	30	6,14E+05	70,06
HV	15	1,73E+06	196,92
HV	30	8,66E+05	98,80
FEB	15	5,73E+06	653,54
FEB	30	3,81E+06	435,39

Figure 5.71: MTTF of the separate boards at 15°C and 30°C.

tested performing HV sweeps (from 950V to 1200V) and threshold scans at 1100V.

Nineteen sets of FEB and HVB have been under test at 70°C, while the normal use temperature in Hyper-K is $\sim 16^\circ\text{C}$. This translates to the Arrhenius acceleration factor of ~ 83.17 (calculation made assuming a mean activation energy of 0.7 eV [88]). The results of these tests after ~ 10 years of simulated time are in Figure 5.73.

All the channels were still working after one month and no major change was seen in the performance of the boards. Statistically this HALT can assure a reliability of 1% of failures per PMT per year for 10 years at $\sim 90\%$ confidence level [89]. The test will continue in the next months to finally have failures on at least one channel, letting us to fix a more precise value on the reliability.

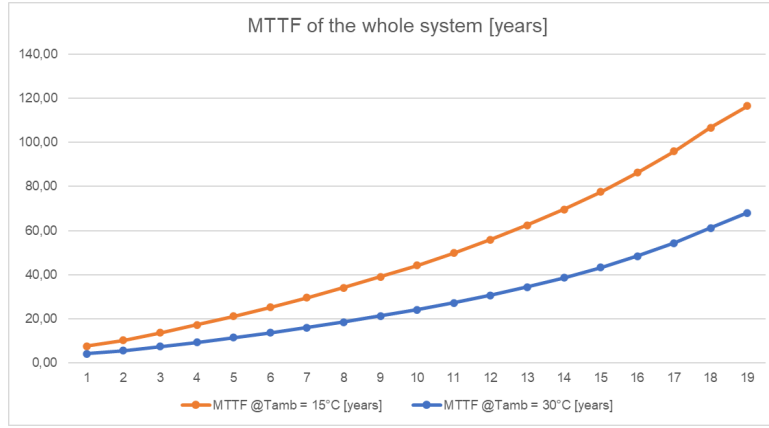


Figure 5.72: MTTF of the whole system at 15°C and 30°C.

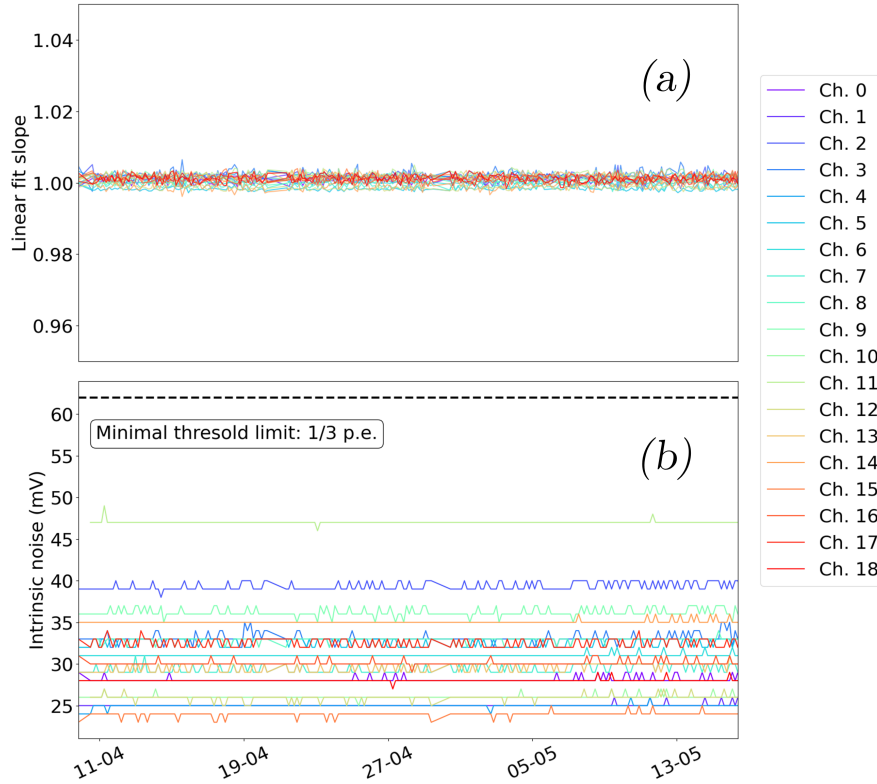


Figure 5.73: Monitoring during the HALT. Linearity of the HV supplied (a). Noise measured (b) with the dotted black line indicating the 1/3p.e. equivalent threshold used for pulse finding.

5.10 mPMT prototypes

During the last years many mPMTs were build to ensure that everything was ready for mass production. The electronic chain can be validated even in air or in a dark box, but the integration within a fully enclosed mPMT was also important.

Another fundamental aspect was the validation of the whole mPMT detector, the ability to build a mPMT, the ability to operate in realistic condition and with



Figure 5.74: Picture of the first mPMT prototype assembled.



Figure 5.75: First fully operating mPMT assembled for Hyper-K.

the final components that will be used in the real experiment.

A quick presentation of the mPMTs build in the last years will now follow.

A first mechanical prototype for the mPMT has been assembled in June 2021 just to verify our ability to perform the gelling procedure and to build something new. The assembly was indeed a success and the prototype has been used for pressure test and also for implosion test in Japan. Another mPMT mechanical prototype has been constructed to check the assembly procedure with new mechanical drawings of many parts (see Fig. 5.74).

This prototype allowed the successful validation of the INFN assembly procedure and gelling and the study of the long-term gel contact with the acrylic dome.

After those first two prototypes it was time for the first fully instrumented mPMT in late 2022, early 2023. It is clearly visible from Fig. 5.75 that the cylinder in this prototype is white due to the lack of black POM-C all around the world.

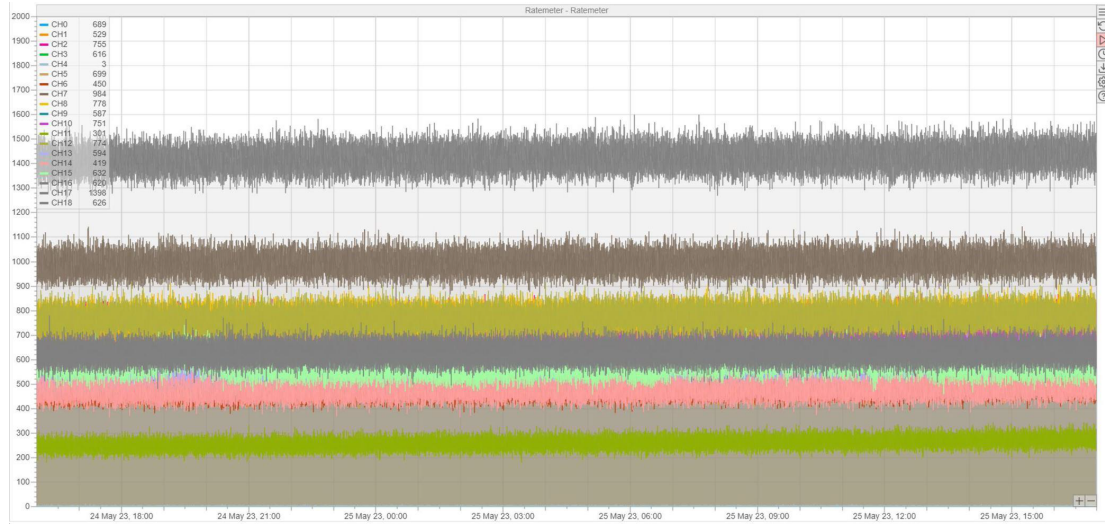


Figure 5.76: Few hours acquisition of the first prototype dark rate. Every channel is stable as expected and all the rates are in the limit given by the collaboration.

Having the first working mPMT it was finally possible to perform some testing on the whole module. In particular it was possible to monitor the dark rate for a long amount of time to check the stability of the full system (see Fig. 5.76) and also to measure temperature and humidity inside the vessel for a longer period. This first prototype is now being tested by canadian colleagues in the university of Carleton, where they are performing a long term test in water.

We already described WCTE experiment in the previous chapters and we also described it also as a test bench for the future detectors to be used in IWCD and Hyper-K. For Hyper-K we decided to test our ability to build 5 mPMTs in one week and to operate them in a real experiment, in this case WCTE. In late 2023 we were ready with all the components and we built the 5 mPMT for WCTE in 4 days. Now, in the late 2024 4 of them have successfully installed in WCTE. The data taking is not yet started, so no results are yet ready from them, but it was a very impressive result for the whole mPMT project. An example of the final mPMT assembled is visible in Fig. 5.78.

In Fig. 5.79 it is possible to see the mPMTs installed on the bottom of the WCTE tank. The decision to install all the 4 mPMTs in the bottom was conditioned by the weight of the modules, since the mPMT for Hyper-K are much heavier than the ones for IWCD.

For the construction of these prototypes, we had to produce 100 electronics channels, complete of HV, FE and flexible cables and 5 Main Boards and we experienced for the first time the use of the HV automatic testbench and the integration with the Hyper-K database.

Temperature/Humidity/Pressure sensors online monitoring

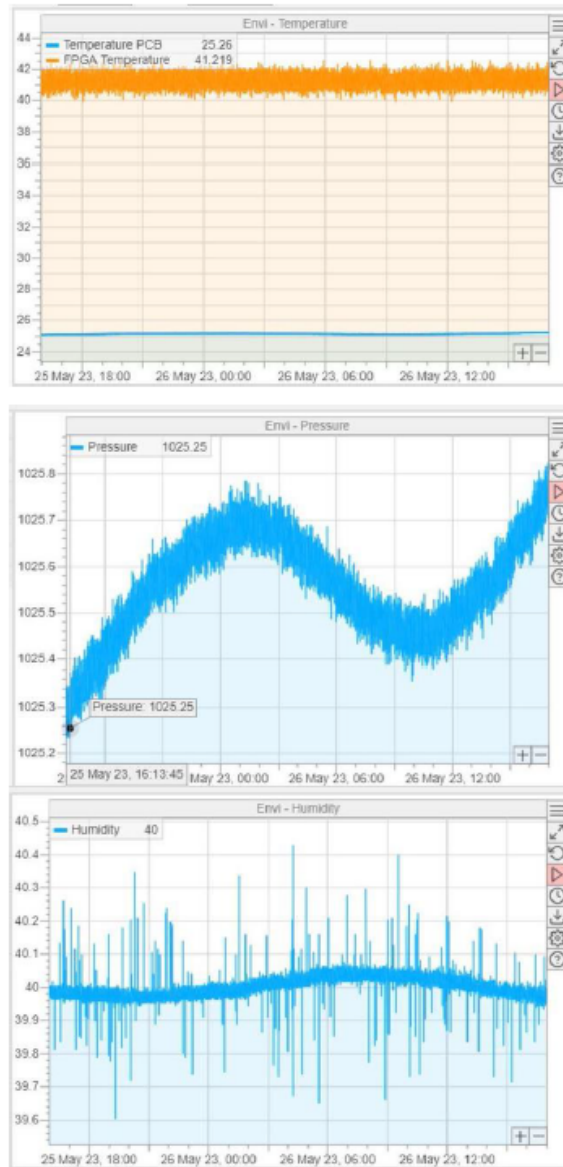


Figure 5.77: Few hours acquisition of the environmental parameters of the first mPMT. Temperature is the one expected in air and the pressure is basically following the atmospheric pressure.

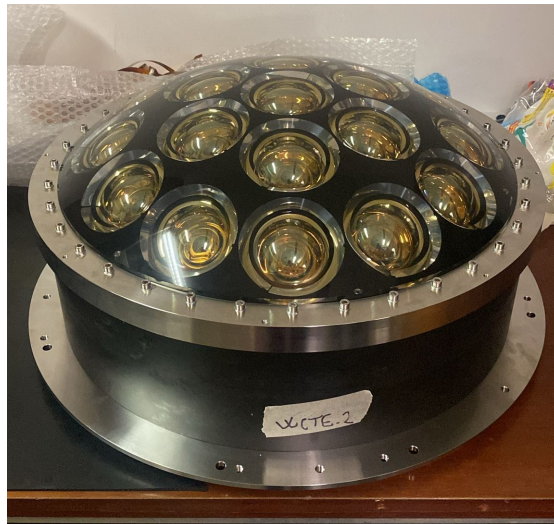


Figure 5.78: One of the WCTE mPMT build in Naples.



Figure 5.79: Overview of the bottom of the WCTE tank with the 4 mPMTs installed. They are clearly different by the IWCD ones, in particular is it possible to see the different backplate and clamping ring, much bigger in the Hyper-K ones.

Chapter 6

20" PMT electronics

In this chapter the electronics to be used for the 20" PMT in Hyper-K is described. We will also quickly present a modification to the mPMT and 20" PMTs front-end that will be used for the OD.

The electronics that we will described is based on a proposal started by INFN in 2020, with the idea of using the experience gained in the mPMT electronics to develop also a front-end for the big PMTs. At that time, in the collaboration, it was not defined what to do with the electronics, it was yet unclear if the system should be in water or out of water, but there were basic requirement for every possible system developed.

In this context we decided to propose an analog front-end using discrete integrated circuits (IC). We will focus our attention only on the analog part of the system. The project is realized in collaboration with INFN Rome and INFN Pisa and also with the Japanese colleagues that realized the front-end system for Super-K.

In particular our group developed and took care of the analog part of the circuit, while Rome and Pisa was developing the firmware to control the system. In parallel, the Japanese colleagues took the responsibility to validate the system with their huge experience in Super-K.

This proposal was not the only one considered by the experiment. There were other two systems, one was an updated version of the Super-K electronics, based on a very old ASIC but still with good performances, and the other proposal was the development of a complete new ASIC, custom designed on the Hyper-K requirement by the french groups. After an internal performance review our proposal has been selected as the one to be used in the experiment. We will go now in the detail of how it works, starting with a focus on the requirements.

6.1 Digitizer requirement

As already described in section 3.1 the out of water electronics used in Super-K was not able to acquire the new PMT signal with the best resolution. Hyper-K is trying to improve the reconstruction of the events compared to Super-K and one of the first proposed improvement is to move the electronics systems in water.

This will reduce the noise on the signal, improving the quality of the data. In this way the performance of the new B&L PMTs can be really exploited.

Each PMT will be connected through a composite signal + HV cable to a pressure vessel containing the complete acquisition system for 24 PMTs. Thus, a 24 channels digitizer was our original idea for the design. In the final vessel configuration the digitizer will be based on a 12 channel board, so the digitizers will be installed in each vessel. The DPB will then collect the data from the digitizer and send to the acquisition system through a composite power + optical fibers cable.

In Fig. 6.1 a list of specifications is presented.

The PMT is not internally terminated and so the input stage must adapt the impedance to the $50\ \Omega$ of the coaxial cable. The accepted reflected signal is $< 0.1\%$ due to dynamic range of more than 1000 P.E..

Each PMT must have a dedicated trigger line, because we don't know when and where the event will occur. The noise must be kept very low. The final request on the threshold by the PMT group in Hyper-K is to trigger at $1/6$ of P.E..

The maximum signal rate has been predicted to be 1 MHz in case of a Supernova explosion in our galaxy and, since this is an interesting event, the maximum rate for the digitized must be more than 1 MHz, giving a processing time of less than $1\ \mu s$.

The dynamic range is really high, 1250 PE or 2500 pC, implying an input signal amplitude of $\sim 10V$ ($\sim 6\ mV$ for 1 P.E. signal). This dynamic must be acquired with a resolution of 0.05 P.E. for small signals and the linearity must be kept in the 1% on the whole dynamic.

We have to sample also the arrival time of the signal with a resolution of $\sim 300ps$ for the smallest signals.

The last two requirements are the power consumption of 1 W at last per channel, so 12 W for the single digitizer board and, since the system will be not accessible for more than 10 years, an high reliability and stability.

6.2 Discrete component Front End Board

To fulfill all the requirements a Front End Board based on Discrete components has been proposed and a single channel prototype has been realized and tested as a pathfinder. We will also describe the final 12 channel board and its performances at the end of the general description.

The idea is really similar to the mPMT FEB, since also in this case we have two main blocks: the charge measurement circuit and the timing measurement circuit. The main difference is that the PMT is not attached directly to the FEB but through a cable and the PMT is also not terminated. This means that an input circuit is needed to reduce reflections and to protect the following systems from HV discharges. The second important difference is the dynamic range of the PMT, that is wider by a factor of more than 10 compared to the 3" PMTs. A

Item	Requirements
Trigger	self triggering for each channel
PMT impedance	$50\ \Omega$
PMT signal cable impedance	$50 \pm 5\ \Omega$
Pulse height of the reflected signal (Nominal impedance cable and PMT) (includes attenuation of the cable)	$<0.1\%$ (-60 dB)
Discriminator threshold	$<0.25\ \text{p.e.}$ (well below 1 p.e.)
Noise level	$<1\text{Hz}$ when the discriminator threshold is set to 0.25 p.e.
Channel dead time	$<1\ \mu\text{s}$
Maximum hit rate (Note 1)	$>1\ \text{MHz}$ for each channel
Charge dynamic range	0.1 to 1250 p.e. (0.2 to 2500 pC)
Charge resolution	RMS 0.05 p.e. for signals below 10 p.e. better than 0.5 % above 10 p.e.
Charge linearity	$\leq 1\%$ from 0.1 p.e. to 1250 p.e.
Timing LSB	$<0.5\ \text{ns}$
Timing resolution	RMS $<0.3\ \text{ns}$ at 1 p.e. RMS $<0.2\ \text{ns}$ for signals above 5 p.e.

Figure 6.1: Basic requirements for the performance of the signal digitizer.

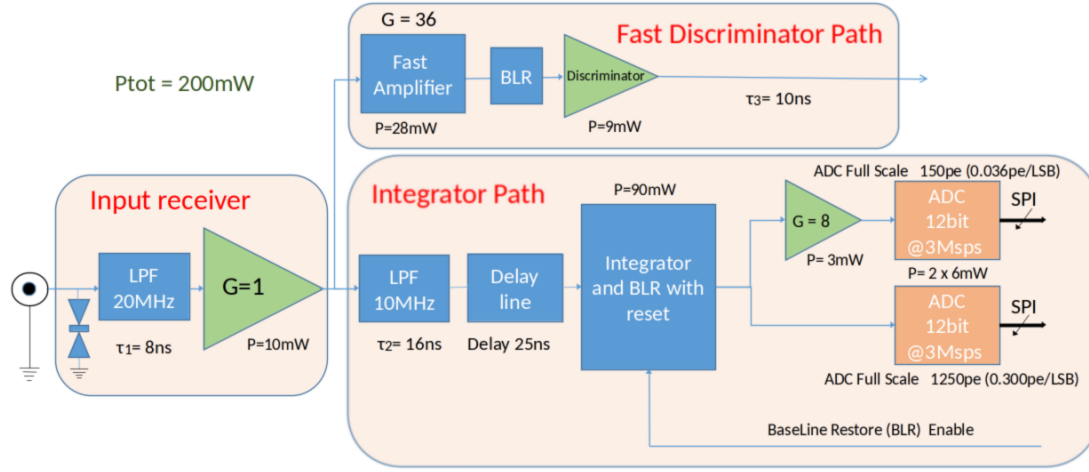


Figure 6.2: Block diagram of the Discrete FE. The main blocks are highlighted: the input receiver, the fast discriminator path and the integrator path.

Block diagram of the Discrete FE is presented in Fig. 6.2. Each block will be described in detail in the following.

The timing diagram in Fig. 6.3 describes the acquisition process of the FEB; the PMT signal arrives at the input stage which has the task of filtering it, adapting the impedance and protecting the electronics from possible discharges in the PMT. The signal is then divided between two path. The first path is a fast amplifier and a discriminator to generate a trigger signal. The other path is composed by an integrator and 2 ADCs to get the charge information. The logic in the FPGA generates the integrator hold and the conversion signals for the ADCs. This logic is controlled by the trigger signal generated in the fast discriminator path.

The PMT signal is filtered at 20 MHz and then it generates a logic signal for the FPGA, we will refer to this signal a trigger. In the meantime the PMT signal is filtered again at 10 MHz and delayed by 25 ns through a passive delay line; after that the signal is integrated, producing a stable and flat signal that can be acquired by the ADC. The FPGA controls the integrator reset and the time to start the sampling of the event. The complete acquisition duration is the sum of the time needed to complete an ADC acquisition and the integration time. In our design this time is limited to $\sim 500\text{ns}$. The integration time will be decided by the collaboration after more studies on the PMTs response, so the final dead time will basically be $330\text{ ns} + \text{Integration time}$.

We initially realized two prototypes of the FEB, with two different fast amplifier, as described in the following. The second prototype is shown in Fig. 6.4.

6.2.1 Protection circuit and input receiver

The first block of the single channel FE is the input receiver. Each input stage on a FE system is usually composed by a buffer and a filter to maximize the signal

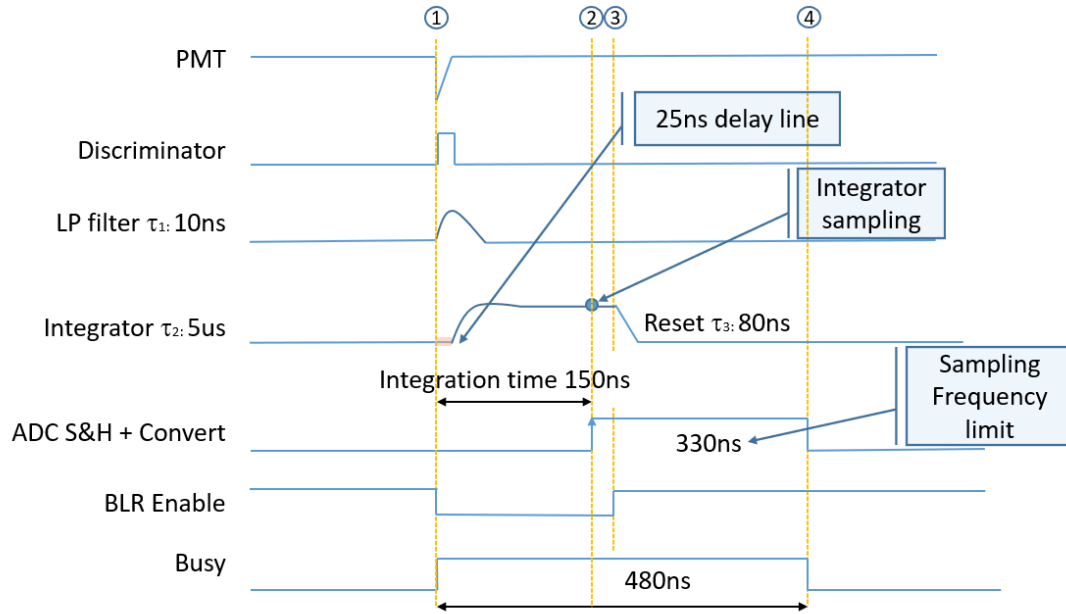


Figure 6.3: FE timing diagram



Figure 6.4: Picture of the second prototypes realized to test the functionality of our design for the FE. Top and bottom view of the board are presented.

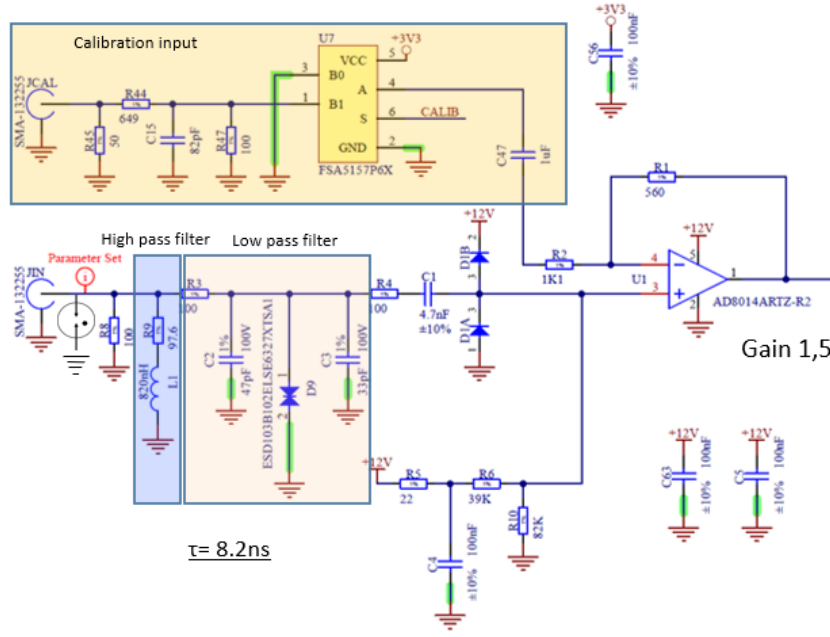


Figure 6.5: Schematic of the input receiver.

to noise ratio and to match the $50\ \Omega$ impedance of the cable. In the case of a PMT also a protection circuit is needed since the signal can be higher than the tolerated ones by the ICs on the FE.

Finally, a calibration input is also requested by the collaboration, so each channel can be calibrated separately before the run.

Input Receiver

The collaborations provided B&L sample waveforms to design the circuit. The main waveforms characteristics are the rise time and the width of the signal, since these parameters affect the design of the input receiver. For the B&L PMT the rise time is $< 10\text{ns}$ and the signal width is $< 50\text{ns}$.

To buffer this signal on the input we need a very fast buffer, that usually has a very high power consumption, followed by a Low Pass Filter (LPF) to reduce the signal height for the following stages and to eliminate any high frequency noises. To reduce the power consumption and also to make the circuit more stable we put the LPF as the first stage of the chain and we choose a frequency of 20 MHz; thus, the buffer could be much slower, saving more than 100 mW of power only on the first stage.

The filter is not a simple RC filter, since we also need to match the cable impedance and this matching is required in the entire frequency range of the signal, not only in the High Frequency range. To do so we designed an input crossover filter at 20 MHz, composed by a high pass filter and a low pass filter, each one designed with a cross frequency of 20 MHz. The input receiver schematic is reported in Fig. 6.5 and the simulation of the crossover filter is presented in Fig. 6.6.

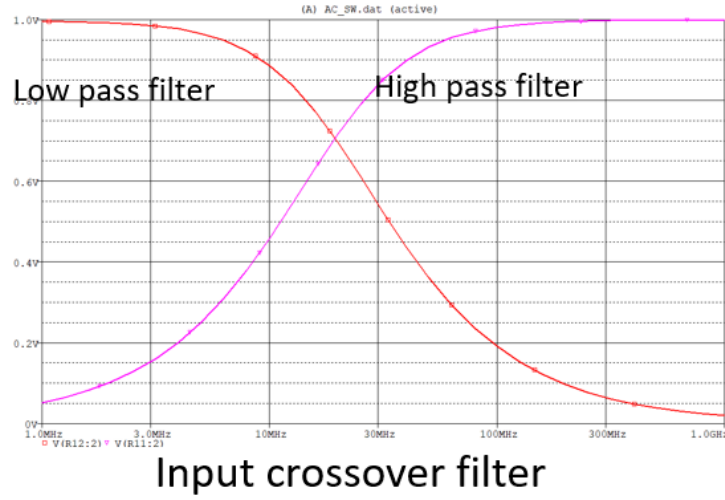


Figure 6.6: Simulation of the input crossover filter at 20 MHz.

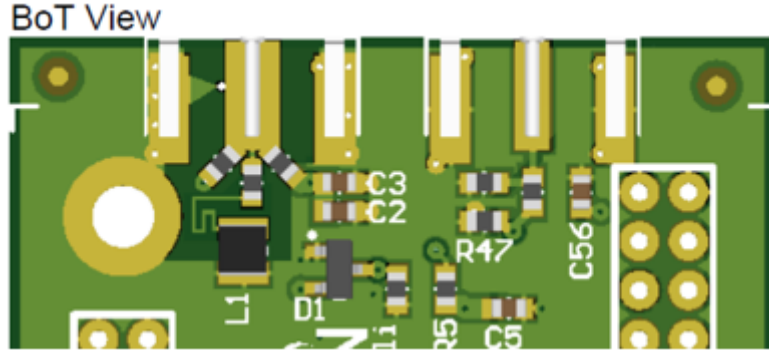


Figure 6.7: Detail of the PCB realization of the input receiver filter. The triangular shape of the filter helps to reduce the parasitic effect on the board.

The low pass filter matches the impedance at low frequencies, while the high pass filter matches the impedance at the high frequencies. To have a good matching also at the crossing frequency the filter must be carefully realized. As shown in the schematic in Fig. 6.5 the high pass is highlighted in blue and it consists of a RL filter and the resistors are two $100\ \Omega$ resistors, giving an equivalent resistor of $50\ \Omega$. The Low pass is highlighted in orange and it is composed by a RC filter, also here the resistors are two $100\ \Omega$, giving $50\ \Omega$ of equivalent resistor. The filter response is reported in Fig. 6.6 and shows a crossing at the desired frequency of 20 MHz.

The PCB design is another important aspect of the impedance matching. We designed a PCB with $50\ \Omega$ traces and we tried also to keep the parasitic capacitance effect as low as possible. In Fig. 6.7 is presented a detail of the PCB realization. The filter has been realized in a triangular shape to keep the traces' differences as low as possible. Finally, to obtain the exact inductance value, a small inductance has been realized on the PCB with a trace.

The input impedance has been tested with a VNA by Rohde&Schwarz (100 kHz-

20 GHz). The VNA has been firstly calibrated with a calibration kit. Then S11 parameter of S11 has been measured. The result is in fig. 6.8.

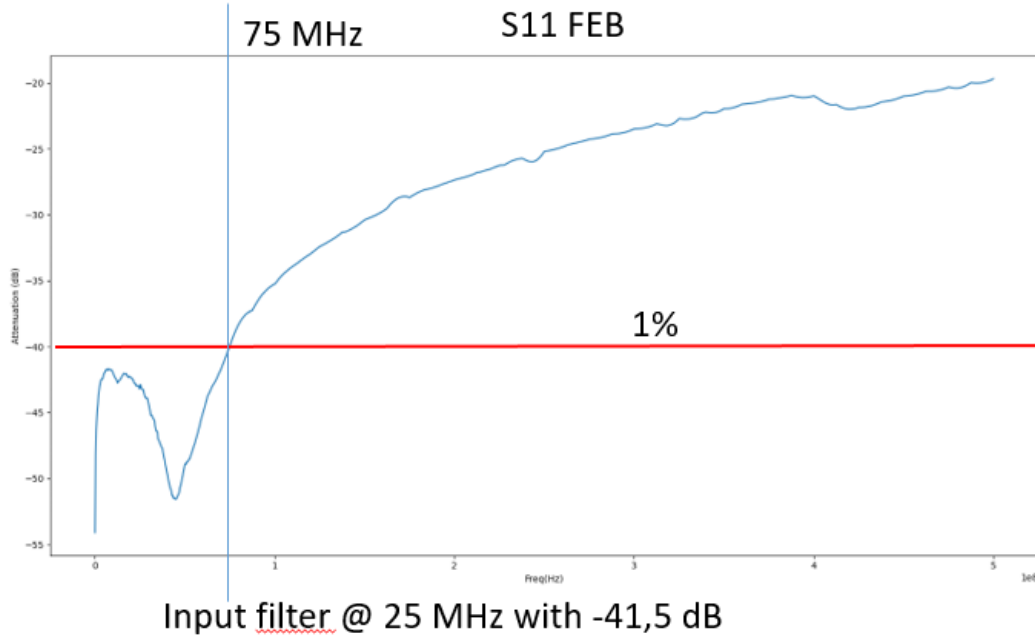


Figure 6.8: S11 parameter plot of the FE input connected directly to the VNA. The threshold is 40 db, which correspond to 1% signal reflection.

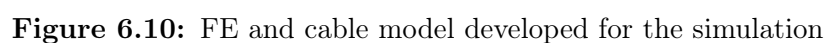
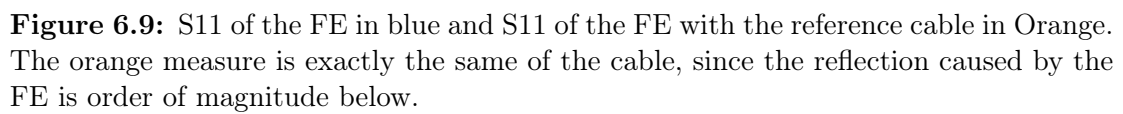
The 20" PMT is attached to a long 20 m Hamamatsu cable and this cable is also attached to a short 2 m Axon cable that is connected to the electronics vessel to facilitate the installation. This note is important to understand the following data.

Before connecting the reference cable (Hamamatsu + Axon cables) we also measured S11 of the cable itself and finally we measured S11 with both cables and FE. Since the FE can be considered as an ideal 50 Ohm for the cables, S11 of the last two measures shows the same result (fig. 6.9).

Then, we developed a model that matches the behaviour of the FE and the reference cables in Cadence Orcad. We used an RG58 cable with custom delay parameter and impedance parameter, while for the input receiver we used directly the FE schematic, see fig. 6.10.

To understand the simulations we first measured the reflection pulses to the oscilloscope (a Lecroy HDO9404). We used a waveform with a similar shape to the one from the PMT, but without any additional noise, to better identify the noise origin. We measured that with both cables attached. The main reflection is due to the mismatch between Axon and Hamamatsu cable (that in this case is a positive reflected pulse). In fig. 6.11 we see a zoom of the reflected pulse, both for the cable mismatch and for the FE mismatch, that leads to a 2.5% reflected signal. In case we match the FE to the Axon cable (48 Ohm) we reduce the reflected signal to 2%, as reported in fig. 6.12.

Finally, adapting both the FE and the mismatch between the cables (5 Ω



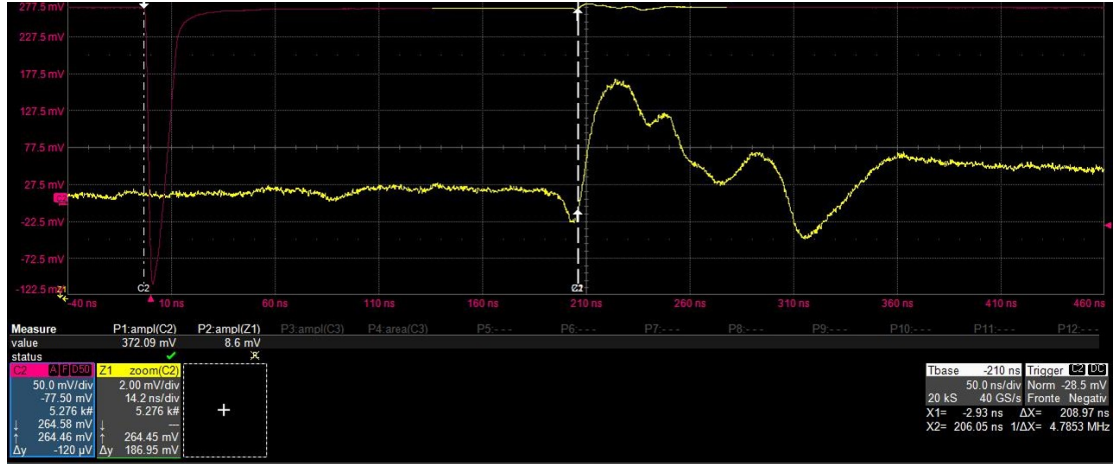


Figure 6.11: Acquisition of the signal at the input of the FE. In yellow the zoom of the same signal in the time window of the expected reflection. The positive reflection is due to the mismatch between the cables while the negative one is due to the mismatch between Axon cable and the FE.

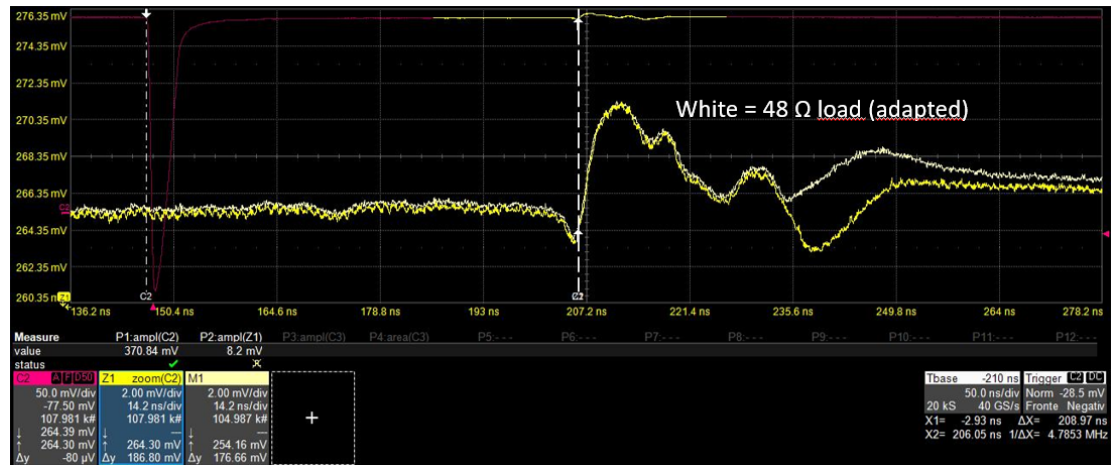


Figure 6.12: Acquisition of the signal at FE input with input receiver matched to the Axon cable in white. In yellow the signal without the matching of the cable at 48 Ω .

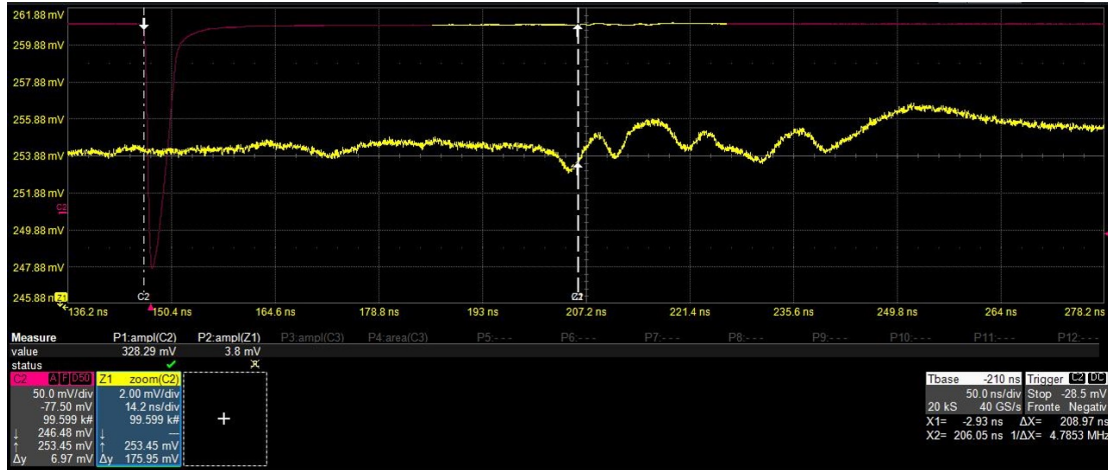


Figure 6.13: Acquisition of the signal at FE input after adaptation of both the FE and the mismatch between cables.

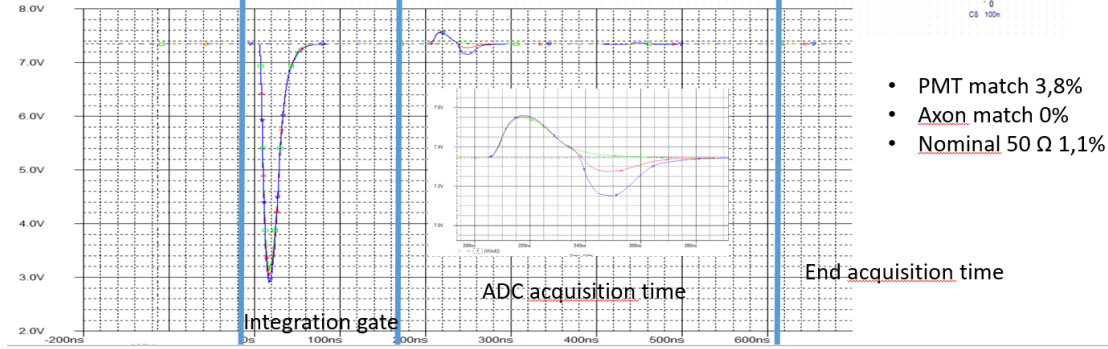


Figure 6.14: Simulation of the input receiver and the reference cables. The positive reflected pulse in the zoom window is due to the cables mismatch while the negative ones are due to the mismatch between Axon and input receiver of the FE. In red we have the ideal 50 Ω matching of the FE, in green the best matching with 48 Ω input resistor and in blue the matching of the PMT cable by Hamamatsu. The last one is not useful since there will be for sure the Axon cable in the experiment.

series resistor between the two cables) we reduced the reflected signal to $\sim 1\%$, see fig. 6.13. This results show that adapting on the FE is less important than matching the cables. However, thanks to these measurements we could develop the simulation that reproduce these results.

In fig. 6.14 the results are shown. In particular this simulation can reproduce the results obtained with the previous measurement at the oscilloscope. The zoom in the figure shows that the reflected pulse is 1.1% with a nominal 50 Ω input resistor (in red in the figure), while adapting the resistor to the PMT cable we obtain a 3.8% mismatch. Finally, adapting the FE to the Axon cable we have an almost perfect match. In all the simulation the positive reflected pulse, due to the mismatch between the two cables, is still present.

We reproduced also the matching between the two cables in the simulation, adding 5 Ohm series resistor between the cables and in fig. 6.15 we see that no

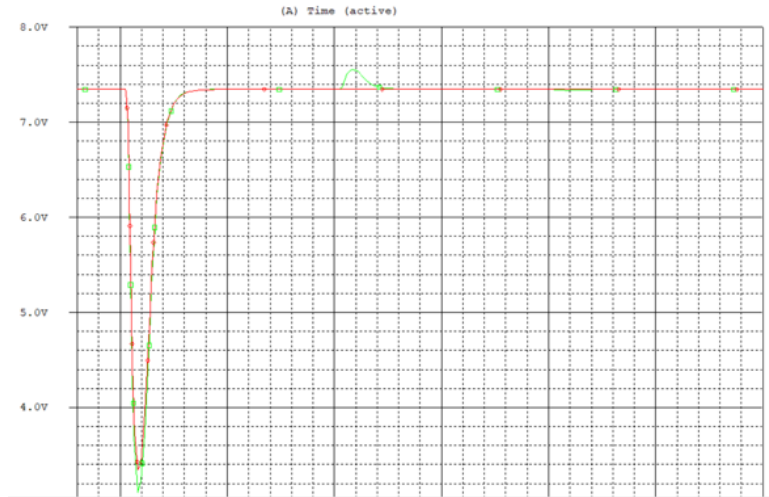


Figure 6.15: Simulation results including also a series matching resistor between the two cables. In this case $5\ \Omega$, corresponding to the measured difference between the two cables. In red the matched signal and in green the reflection.

more reflection is observed on the digitizer. It has to be said that this method comes with the cost of a small signal attenuation, but that can be calibrated, in this case we measured a 5% signal attenuation.

The final simulation has been the application of a Monte Carlo to study the effect of the component tolerance. We used the current tolerance of the components used on the FE and we made 5000 runs, the maximum allowed by Orcad for a single run.

We made both an AC simulation to measure the behaviour at different frequencies and a time simulation to analyze the waveform on the FE. The first simulation has been the AC one. We see that even with component tolerance variation the input impedance is quite stable (fig. 6.16). To understand better the amount of variation we acquired the data and we made the histogram for the input impedance at various frequencies, for 1, 10 and 25 MHz.

Finally, we performed the time simulation with the monte carlo and we report the results in fig. 6.20 and the zoom of the results in fig. 6.21.

Another advantage of using a Filter before the buffer is the reduction of the dynamic in terms of signal amplitude. This let us to supply the circuit with a 10 V supply instead of the ideal 12 V, lowering the power consumption of the single FE channel. This is possible because the input filter has an attenuation of 33% with respect to the input signal, reducing the maximum pulse height from 12 V to less than 9 V.

Protection Circuit

The FE circuit must be protected against sparks and large signals, thus, a Protection Circuit must be designed. The basic protection is a clamping diode, that limits the voltage on the following components to a fixed value, in our case this block is composed by a BAV99 diode clipped to a 12 V power supply, giving a

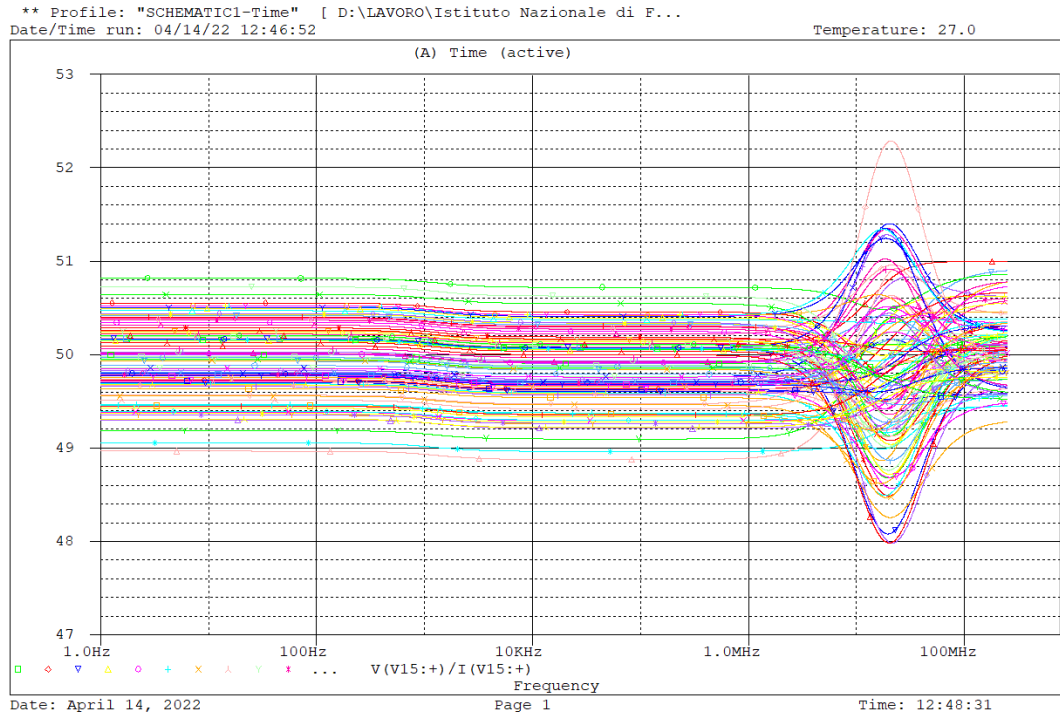


Figure 6.16: AC sweep of the Monte Carlo simulation. The plot shows the input impedance in the interesting range of frequency for many runs of the Monte Carlo simulation. The different peaks around 30 MHz are related to the low pass filter on the FE input.

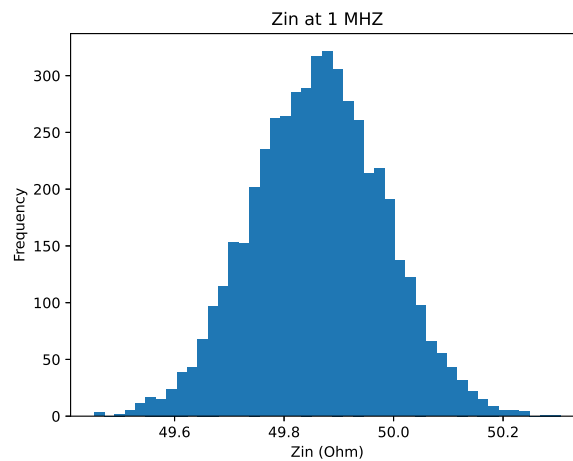


Figure 6.17: Input impedance at 1 Mhz from the Monte Carlo simulation

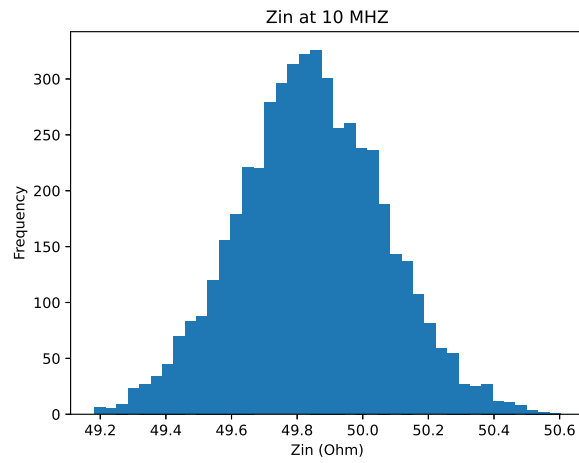


Figure 6.18: Input impedance at 10 MHz from the monte carlo simulation.

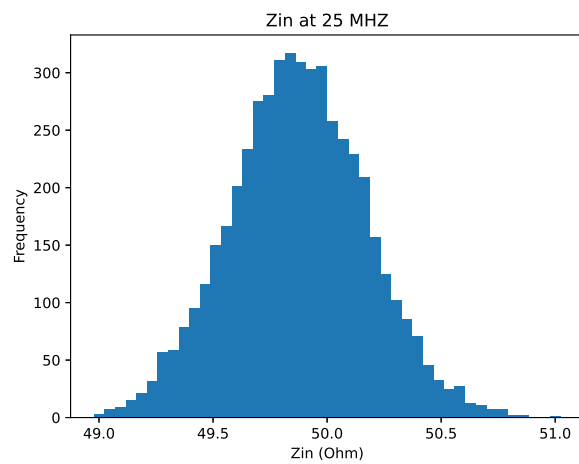


Figure 6.19: Input impedance at 25 MHz from the monte carlo simulation.

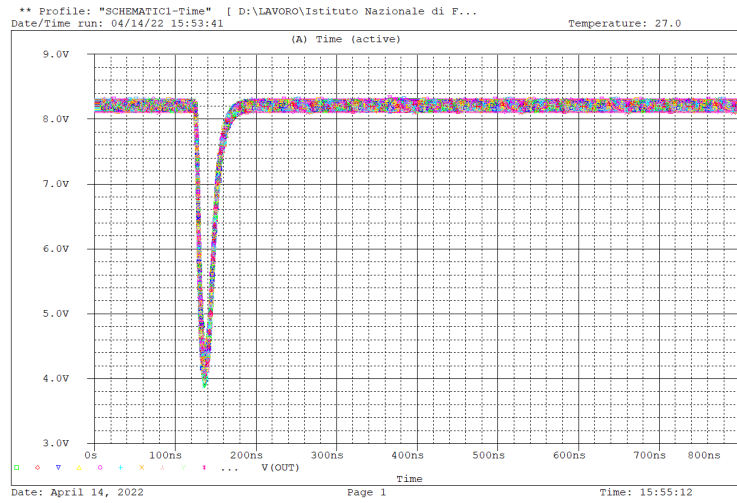


Figure 6.20: Waveform captured at the input of the FE in the simulation. The reflections are small and hidden by the parameter variation.

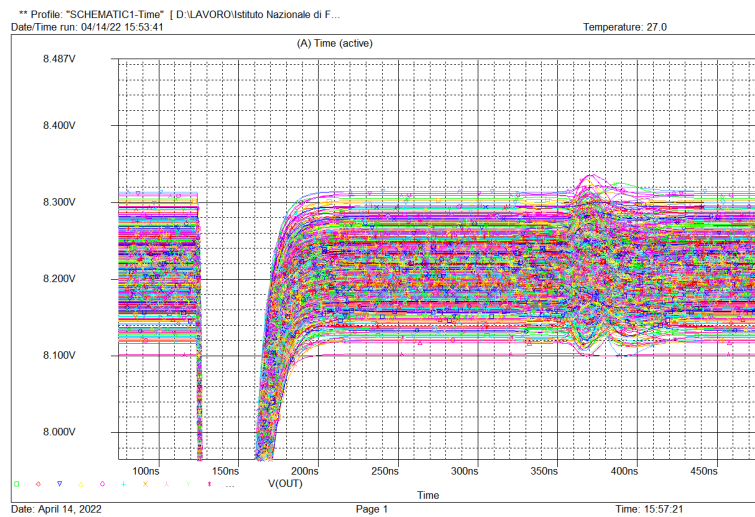


Figure 6.21: Zoom of the waveform captured at the input of the FE in the simulation. It is visible a structure due to the reflections at +200 ns but all the reflections are quite small.

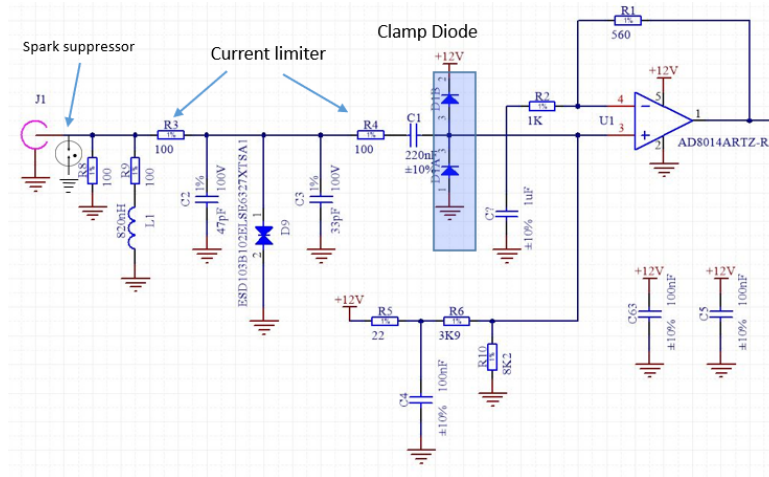


Figure 6.22: Protection circuit schematic. It is possible to see the Clamping diode, the current limiter resistors and the TVS diode (the component with a double triangular shape). There is also the Gas Discharge Tube added after the first tests.

voltage limit of 12 V. The diode does not protect against high current pulses, as HV discharges from the phototube. To solve this problem it is possible to use a resistor as current limiter. In this case the resistor must be high voltage compliant. The easy solution is the usage of a so called TVS diode, that stands for Transient Voltage Suppressor. We realized this circuit in the first prototype and the schematic is provided in Fig. 6.22.

To test the circuit we simulated a spark from the PMT; referring to Fig. 6.23, in case of a real spark that would occur between R19 and the signal output we would have 2000 V on the FE input. The spark simulator is shown in Fig. 6.24 on the top.

The first test was not a success, as shown on Fig. 6.24 on the bottom, since the resistors blew up, in particular due to the sublimation of the resistive surface layer which they are built of. The main reason is the voltage rating of the resistors. A possible solution would be increase the voltage rating for the resistors. The best solution is the addition of a Gas Discharge Tube on the input, these devices are used in industry to protect RF receivers/transmitters and therefore have a very low parasitic capacitance. This last test was successful and in Fig.6.25 it is possible to see that the signal was not affected by the many sparks provided to the circuit, more that 1000.

The signal after the protection circuit and the input receiver is then provided to the next two main sections of the FE, the Fast discriminator and the Integrator.

6.2.2 Fast discriminator

The fast discriminator is necessary to generate a logic signal that will be sent to a FPGA to start the acquisition and to generate the time stamp with a TDC.

The fast discriminator is internally composed by three blocks: the fast amplifier, the BaseLine Restorer and the discriminator.

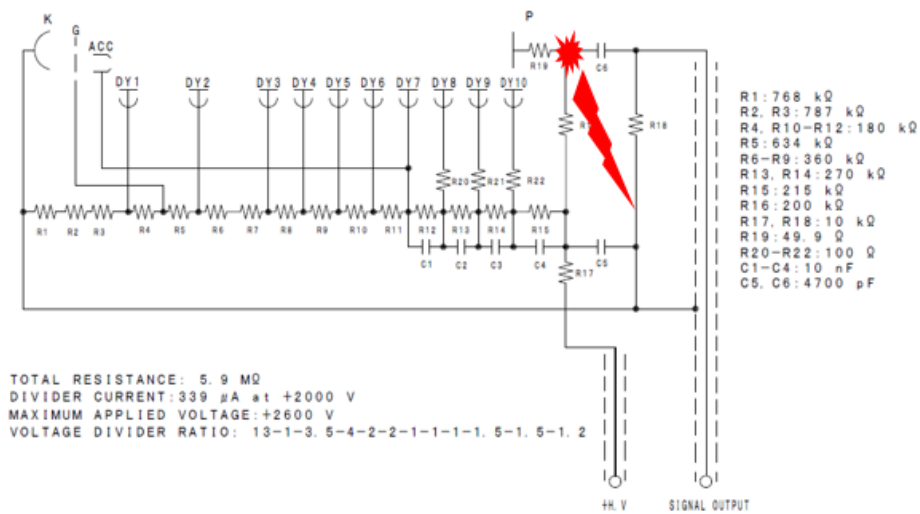
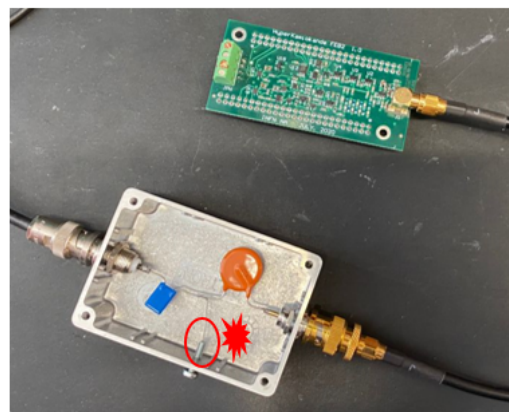


Figure 6.23: PMT bleeder circuit with the highlight of the spark we simulated to test the protection circuit.

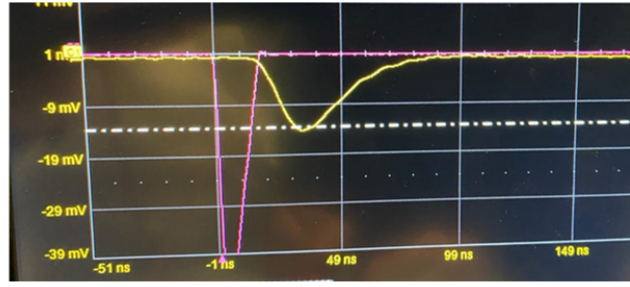


2kV spark generator



Test without gas discharge tube

Figure 6.24: Spark simulator on the top to test the protection circuit and test results on the bottom without using the Gas Discharge Tube.



Test result (cursor level was
before 1000 sparks)

Figure 6.25: Results of the spark test on the FE. The cursor level was the voltage level before the test and the yellow waveform is at the same exact value even after the test, validating the result.

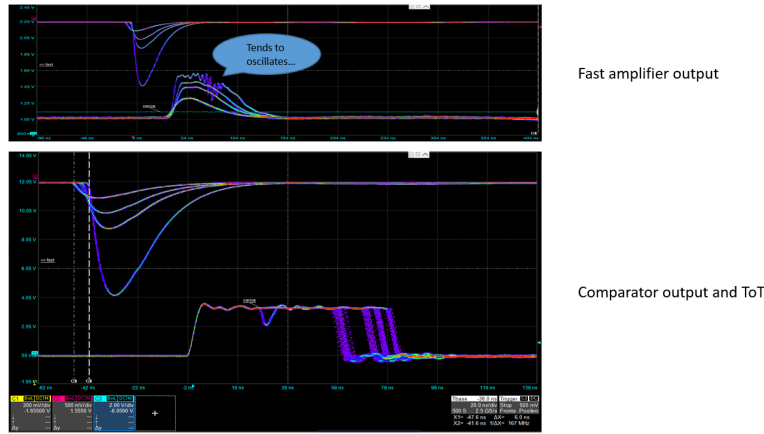


Figure 6.26: Waveforms for the input signal (negative one) and for the output signal (positive one) taken on the oscilloscope of the first fast amplifier developed. The signals correspond to 1,2,3,7 PE and they show an oscillation for big signals that generates a wrong trigger signal on the discriminator.

The fast amplifier is an high gain amplifier, with $G \sim 40$. We developed two configurations, one based on three operational amplifiers and one based on BJT transistor and an operational amplifier. The first prototype, realized using the operational amplifiers, tends to oscillate when in saturation. This is a big problem since it could generate a trigger during the acquisition window of the previous event. A detail of the signals is shown in Fig. 6.26.

To overcome this problem the BJT solution has been designed. It showed better performance in saturation. The schematic of the circuit is presented in Fig. 6.27. A BJT transistor followed by an operational amplifier has been used; also in Fig. 6.28 the signals of the new prototype are shown and the saturation problem is not present any more.

The next section of the circuit is the BaseLine Restorer (BLR). This component is essential since the signal is AC coupled from the receiver and, thus, the baseline

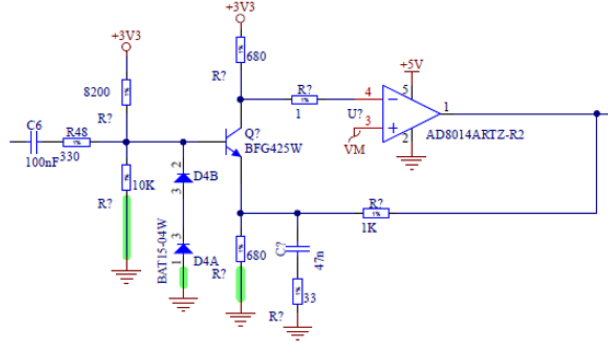


Figure 6.27: Schematic of the BJT fast amplifier developed to solve the oscillation problem of the first prototype.

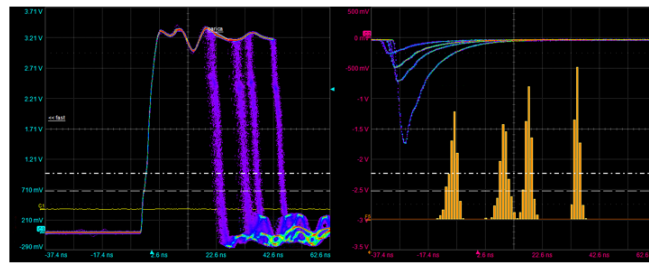


Figure 6.28: BJT fast amplifier signals on the oscilloscope. It is possible to see that the same 1,2,3,7 PE signal does not generate a wrong trigger anymore. The histograms on the right clearly show the ToT of the discriminator signal and the 4 gaussians distribution are well defined, meaning also a good baseline for the time resolution.

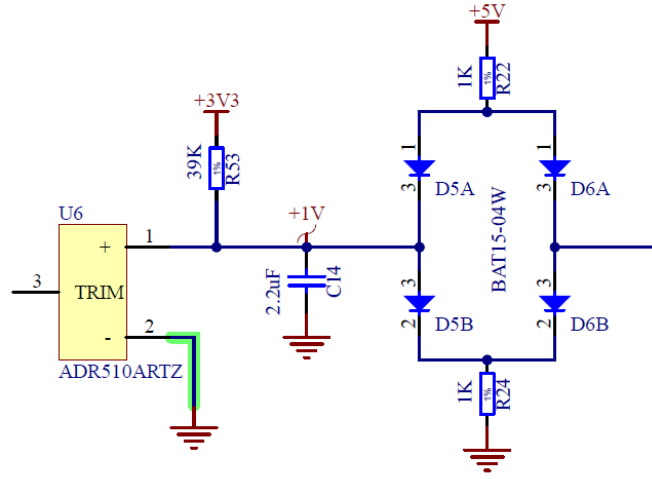


Figure 6.29: BLR schematic circuit. The four diodes are supplied with two symmetric current generators and the voltage level is fixed with a voltage regulator at 1 V.

could depend on the signal rate. We developed a classical BLR composed by four diodes and two current generators, realized with two resistors to reduce the power consumption. An offset voltage of about 1 V has been introduced to avoid using negative voltages for the discriminator. The schematic is in Fig. 6.29.

The signal after the BLR is fed into the discriminator that generates the logic signal for the FPGA; the threshold is programmable through a DAC controlled by a SPI.

6.2.3 Integrator

The integrator is the fundamental block in the acquisition chain, since the charge resolution depends in particular on it. The design of this block has been really difficult and required hours of simulations to be realized. For the simulation we used the professional software *Cadence Orcad*[90]. These simulations were useful to identify the best trade off between stability, noise and power consumption.

The main problem of an ideal integrator scheme, based on operational amplifier, is the reset and the stability. The ideal circuit is always in integration and this is not possible with pulse signals like the ones from PMTs. Also, we need a very stable baseline to keep homogeneity in the acquired values also at different signal rate.

The easiest way to stabilize the baseline value is to include a reaction system in the circuit, this will constraint the voltage value on the input of the circuit at a predetermined value, which in our case was set at 200 mV. The problem with this solution is that the system would also keep the voltage to the fixed value during the acquisition of a PMT signal. The solution is to open the reaction just before the integration of a signal, using the logic signal called *BLR_Enable* reported in the simulation in Fig. 6.30. The diagram of the circuit is reported in Fig. 6.31. The *BLR_Enable* signal is controlled by the FPGA and the time needed for the

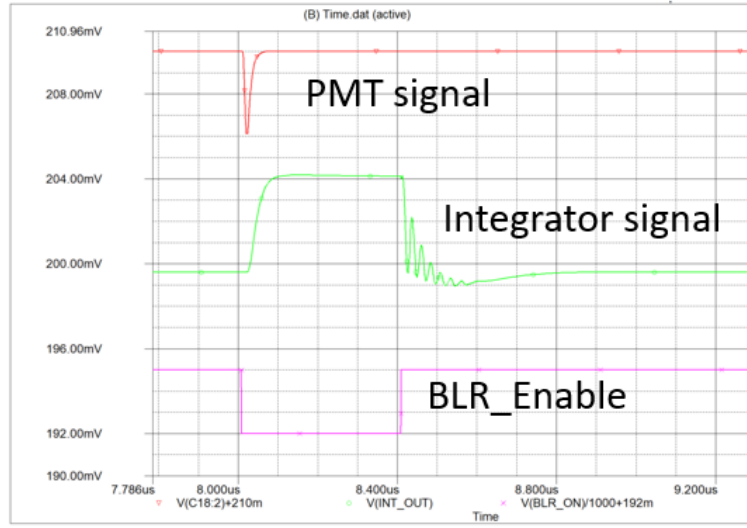


Figure 6.30: Integrator signal simulation in Orcad. Only one logic signal is needed to control the system. The *BLR_Enable* signal acts as a switch for the reaction and also resets the integrator output. The time for the reset is programmable and can go from 100 ns up to 600 ns.

signal to be read and managed by the FPGA is $\sim 15\text{ns}$; that is the reason of the delay line of 25 ns in the integrator block of the FEB. The logic signal generated in the fast amplifier block triggers the FPGA that can generate the signals for the integrator and the ADC in time to not lose the signal due to the closed reaction.

The *BLR_Enable* signal is generated in the FPGA using a combinatorial logic, in order to reduce as much as possible the time to open the reaction loop. After that, the FPGA generates the hold signal for the ADC to start the acquisition. After a programmable delay, the FPGA logic starts also the integrator reset, closing the reaction. Since the ADC stores the acquired value internally during the acquisition there is no need to wait the complete acquisition of the ADC before resetting the integrator.

The Frequency response of the integrator has been also studied. We designed the system with a very tight bandwidth (Fig. 6.32), with a low cutoff of 1 MHz and an high cutoff of 4 MHz. This helps in minimizing the low frequency shift and also the high frequency noise that can enter in the circuit.

The integrator signal is acquired by two different ADCs, one preceded by a unitary gain buffer and one by a buffer with a gain of 8. This choice was a consequence of the huge dynamic range of the B&L PMT, to be acquired with a very high resolution. For small signals the resolution must be even better, since a photon counting is still possible. The buffer at $G=8$ acquires the small signals with the highest resolution, while the other buffer covers the entire dynamic range with a lower resolution. It is important to say that for each event both gains are acquired and stored, only in software it is possible to choose the most suitable value between the two.

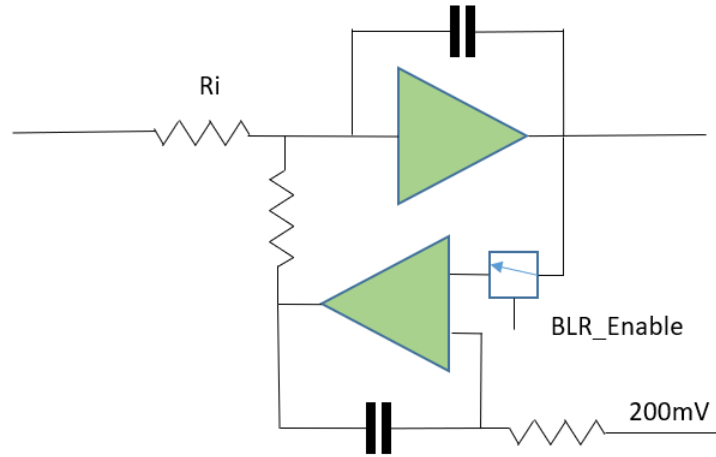


Figure 6.31: Integrator circuit ideal diagram. The circuit is composed by two operational amplifiers in a closed loop configuration. This acts as a fast BLR when the reaction is closed and as an integrator when the reaction is opened by the signal *BLR_Enable*.

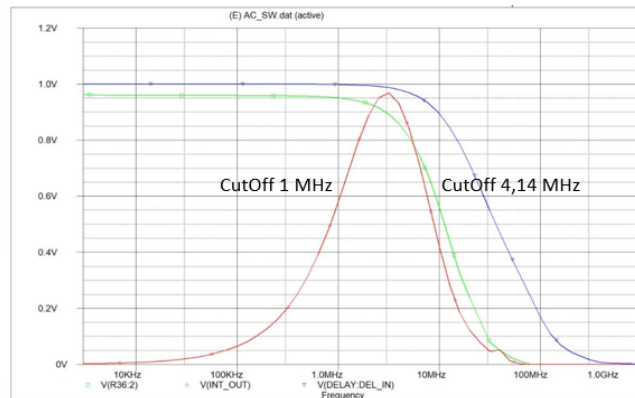


Figure 6.32: The red line is the Integrator frequency response, while the blue line is the response of the 20 MHz filter and the green one the response of the 10 MHz filter.

6.2.4 Acquisition system

The FEB is quite simple and it requires only few IOs of a FPGA. The latter receives the trigger and generates the control signal for the integrator; also two SPI sharing the Clock and Hold signal are needed, giving a total of 6 IOs for each channel.

A very simple FPGA firmware controls the single channel FEB. The code is mainly composed by two blocks. The first one controls the integrator and acquires the charge, the second one acquires the time of the event using a Multiphase TDC. Based on the design of the fast amplifier, even in this digitizer it is possible to measure the ToT of the event.

The first step of the acquisition is the generation of the *BLR_Enable* signal when a trigger is generated in the fast discriminator path. This operation is combinatorial and can occur only if the last event has been acquired. It is possible to add a programmable time window from the last trigger in which the FPGA does not accept any further trigger, it acts as an hardware Death Time.

The trigger generates also the Enable to a *Ring Oscillator* that generates a clock at a specific programmable frequency, in our case $\sim 400MHz$. We opted for a ring oscillator because a standard clock can detect the trigger only on his edges and this mean an uncertainty of one clock cycle in the trigger detection and, thus, in the time measurement. The clock generated from the the ring oscillator controls the exact moment of the acquisition with the hold signal of the ADC and also the reset of the integrator. The ring oscillator is stopped when the acquisition is complete and another acquisition can then start. The FPGA controls also the threshold of the trigger setting an external DAC.

6.3 Measurements and results on the first prototypes

A demo board has been designed and realized to test the system. It is based on an Artix7 Evaluation Board and on a ESP32 microcontroller board to control the system also in WiFi. The system is shown in Fig. 6.33

The system embeds the basic firmware described in the previous section and also a the ESP32 can control the FPGA parameters using a custom UART (Universal Asynchronous Receiver-Transmitter) protocol.

We fully characterize the FEB using this evaluation system. The first tests has been made with a pulser that emulates the PMT signal.

The first important measurement is the charge resolution. We generated PMT equivalent signals of 1,2,3 and 7 PE amplitude and we acquired the data at the nominal threshold of 0.25 PE. We calibrated the 1 PE signal as 1.46 pC using an oscilloscope, while the waveforms have been generated using a Detector Emulator developed by CAEN. In the plot the pedestal measurement is also visible (Fig. 6.34). The pedestal measurement is the zero value of the integrator, namely the value acquired when there is no signal on the input, this signal is obtained in the FPGA with a programmable frequency. Fig. 6.34 shows the results of this

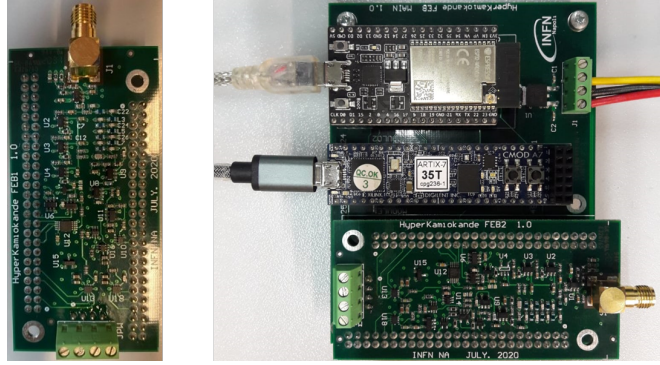


Figure 6.33: Demo board designed and realized to test the system. It is based on a Artix7 Evaluation Board and on a ESP32 microcontroller board to control the system also in WiFi.

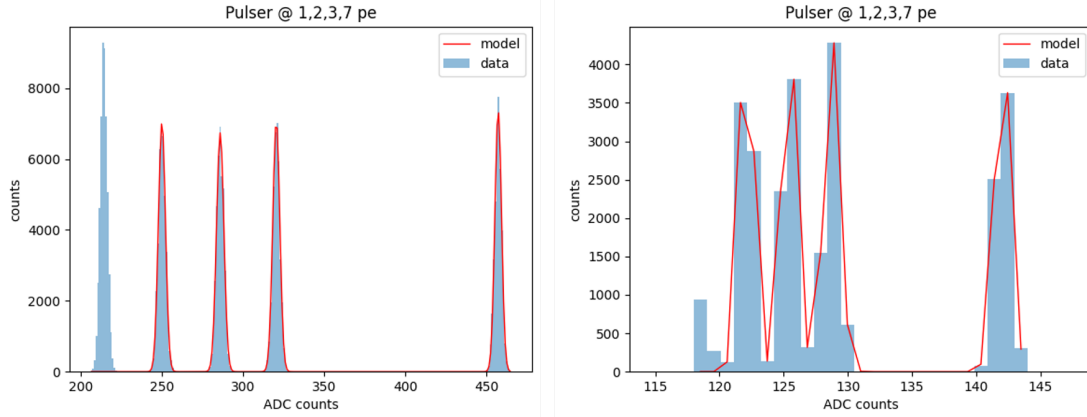


Figure 6.34: Plot of the charge acquired on the two gain channels using a Pulser at 1,2,3 and 7 PE. The red curves are the Gaussian distribution fit for the charge resolution measurement. With a 1 PE charge of 1.46 pC, the resolution is 5.5% @ 1 p.e. on the high gain channel and 2.35 % @ 7 p.e. on the low gain channel.

first test and the obtained resolution is a $\sigma = 0.083$ counts at 1 PE, meaning a resolution of 5.5%. On the low gain range, the maximum signal was the 7 PE one, for which we obtained a resolution of 2.35% with a $\sigma = 0.24$ counts.

The next important test is the linearity, since the PMT response is linear up to more than 1000 PE. The digitizer must have at least the same linearity. The requirement was a maximum deviation from linearity, namely the residual, of 1%. Fig. 6.35 shows the linearity trend and the residual for the two gains. In both gains the residuals are well below 1%, validating the linearity of the system.

The linearity test validates the integrator block. The next important tests are the time resolution and the stability of the acquired charge value at different acquisition rate. To test the time resolution the frequency of the acquired signal has been measured at different amplitude. To measure the frequency we used the reconstructed time of the TDC. A constant data rate was expected due to the pulser stability and, thus, the width of the distribution is almost the resolution of the time provided by the TDC. A factor of $1/\sqrt{2}$ must be taken into account

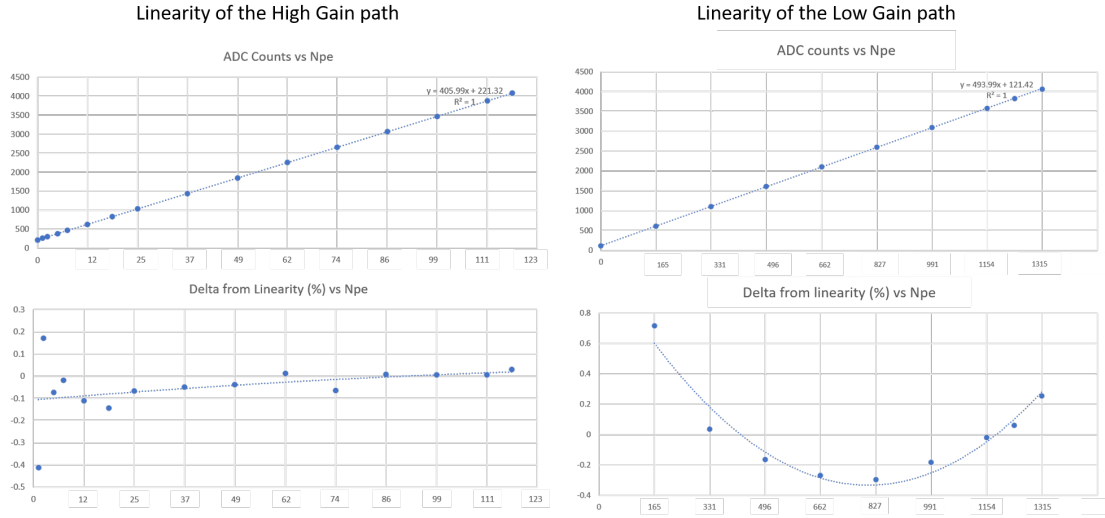


Figure 6.35: Linearity plot of the FEB prototype. On the left the linearity trend and the residual for the High gain path and on the right the linearity trend and the residual for the low gain path. For both paths the residuals are well below the 1% deviation on the whole dynamic range.

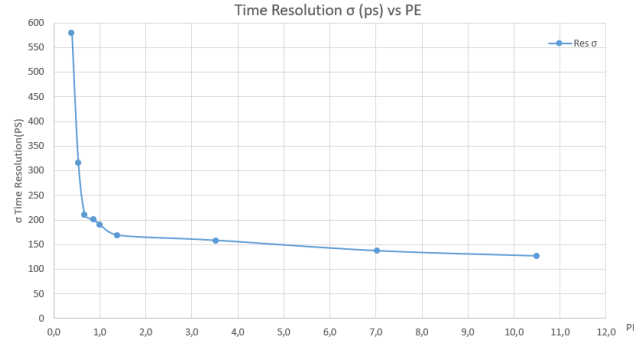


Figure 6.36: Time Resolution

since the frequency has been calculated as the difference between two times. We obtained the plot in Fig. 6.36; the resolution at 1 PE is $\sim 200ps$, decreasing to $\sim 100ps$ for bigger signals. This fulfills the requirement. The rate stability is another important aspect, since the rate in Hyper-K will be uneven, in particular in case of Supernovae, where the expected rate is ~ 1 MHz. We acquired the same 1 PE signal at 1 KHz and at 1 MHz, and both the charge value and its resolution are exactly the same, as reported in Fig. 6.37.

The rate stability completes the validation test of the single channel FEB. The next step was the first test with a real PMT. We collaborated with the Rome INFN group to make the test. We tested a B&L PMT using the FEB discussed in this chapter. We acquired charge and ToT at different HV values also to calibrate the photosensor itself. The results in Fig. 6.38 and 6.39 are in line with the ones obtained by other groups with other B&L PMTs, validating both the PMT and the FEB design.

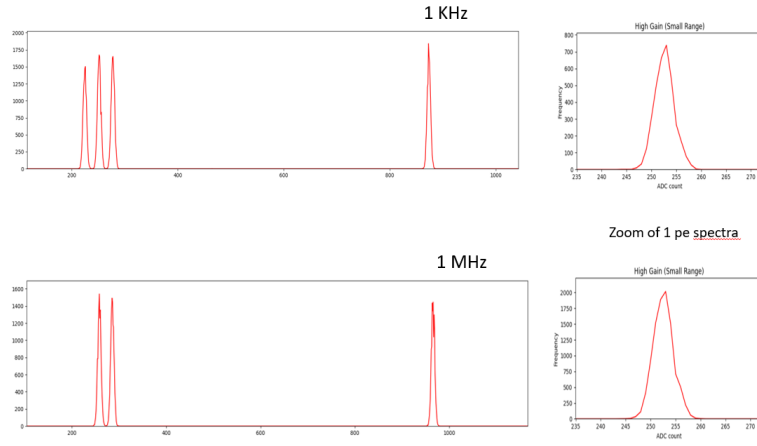


Figure 6.37: Rate Stability

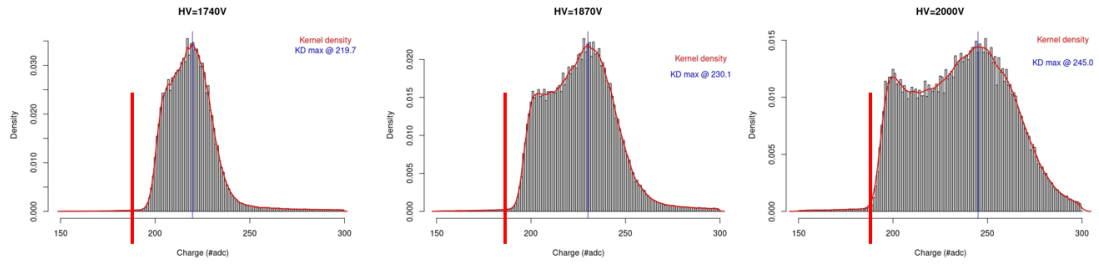


Figure 6.38: Charge plot different HV

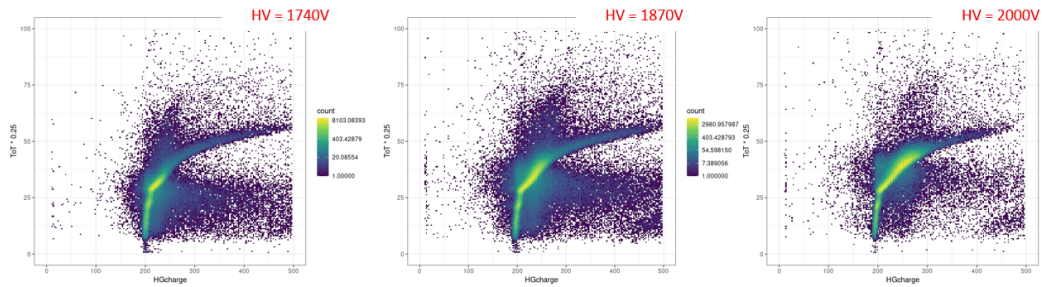


Figure 6.39: ToT different HV

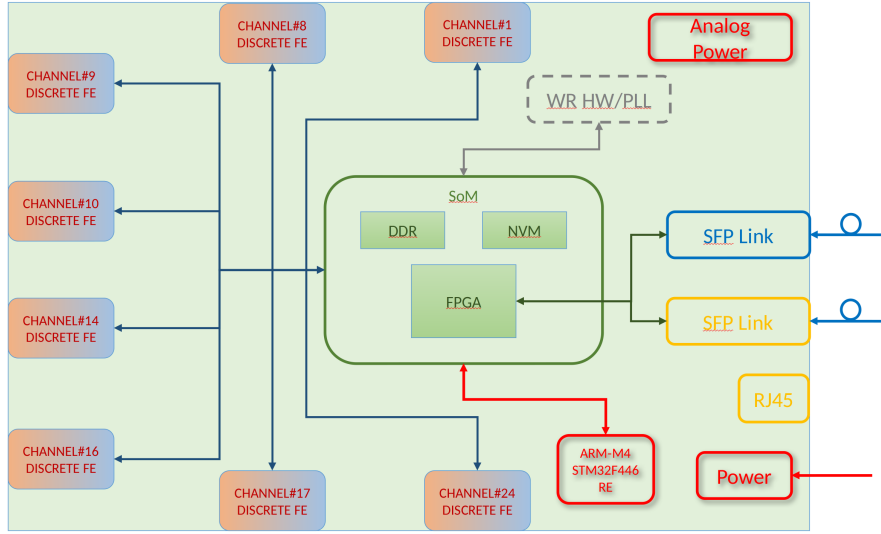


Figure 6.40: 24 channels board diagram.

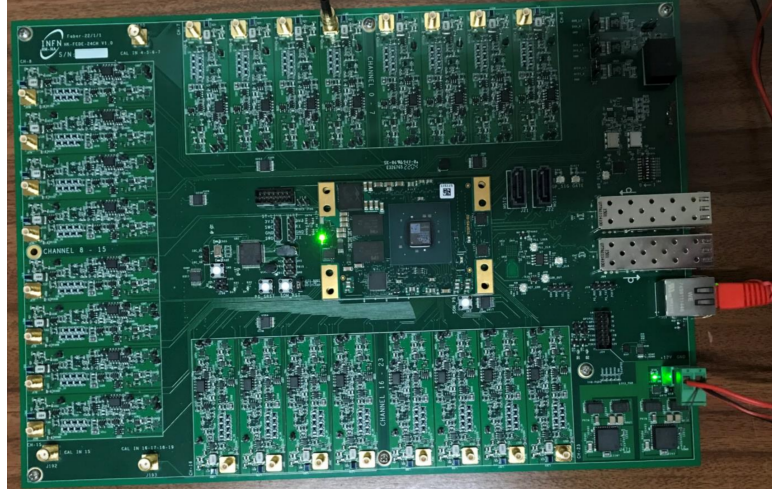


Figure 6.41: 24 channels board realized in collaboration to INFN Rome.

After this initial phase of testing and validation of the proposal, the design was finally selected by the collaboration and we could move to the design of a final complete board. Based on the status of the systems after the selection process we choose to still design a board with 24 channels and embedding also the functionalities of the DPB. The diagram of the board is presented in Fig. 6.40.

In Fig. 6.41 the 24 channel board realized in collaboration to INFN Rome is shown.

6.4 The Digitizer board

After the first test with the 24 channels it was becoming clear that the final layout of the vessel will include two digitizers, each with 12 ID channels. Based on this idea, we started the design of this final board, that is, the one that will be installed

in the real experiment after few production iterations.

In particular it was necessary to design a board that could fit the electronics stand in the vessel, to the width was limited to 25 cm. Also, the LV board will provide 12 V directly to the digitizer so a new power supply section should be designed to derive the necessary voltages from the 12 V one.

Since the DPB board already provides the necessary CPU for the vessel, it was useless and more complex to include a CPU also in the digitizer board, so we decided to include a simple FPGA that will send the data to the DPB with a 2.5 Gbit/s serial link. This link can be also doubled for redundancy.

Another point was the necessity of having a calibration system for the digitizer in the vessel. This calibration board will be designed by the Japanese colleagues, but will be plugged as a mezzanine to the digitizer. For this reason a connector with the necessary IO will be included.

We discussed that the OD channels will be connected in some special hybrid vessels.

Our idea has been to split the ID and OD front end, but to have the logic to control OD channels in the ID digitizer, meaning that the OD front-end will be composed only by the analog section and will be connected to the ID digitizer via a cable or as a mezzanine.

Based on all this assumption we designed the final digitizer board. The rendering of the board with the detail on the different blocks is reported in Fig. 6.42.

This board has been successfully produced and tested. A picture of the realized board is in Fig. 6.43.

A very basic code has been used for initial testing, while the colleagues at INFN Rome and Pisa developed the final one. A sketch of the firmware is presented in Fig. 6.44 with just the main blocks needed to acquire data from the ID channels.

As already anticipated the final validation of the board is done in Japan by our colleagues, since they have the necessary equipment to perform all the necessary test and also since they want to test the digitizer in real operation, for example connecting the board to some of the operating Super-K PMTs to see if our board is able to operate in real condition. In the following there will be some of the test done in Japan to validate the system and also a first example of the real performances of the board when connected to the Super-K PMTs.

The first tests have been realized with a function generator to test as usual the intrinsic performance of the digitizer. The results are reported in Fig. 6.45 where the charge resolution is shown and in Fig. 6.46 where the time resolution is shown.

After those first tests a setup with PMTs connected and two digitizers connected in a fully integrated electronic vessel has been prepared in the Super-K mine, in a small laboratory dedicated to PMT testing. The performances has been thus evaluated in a controlled environment, also using a LED source to inject light in the PMTs.

The first important result is the threshold scan, where it is possible to see that all the channel noise is under the requirement of 1 mV (see Fig. 6.47).

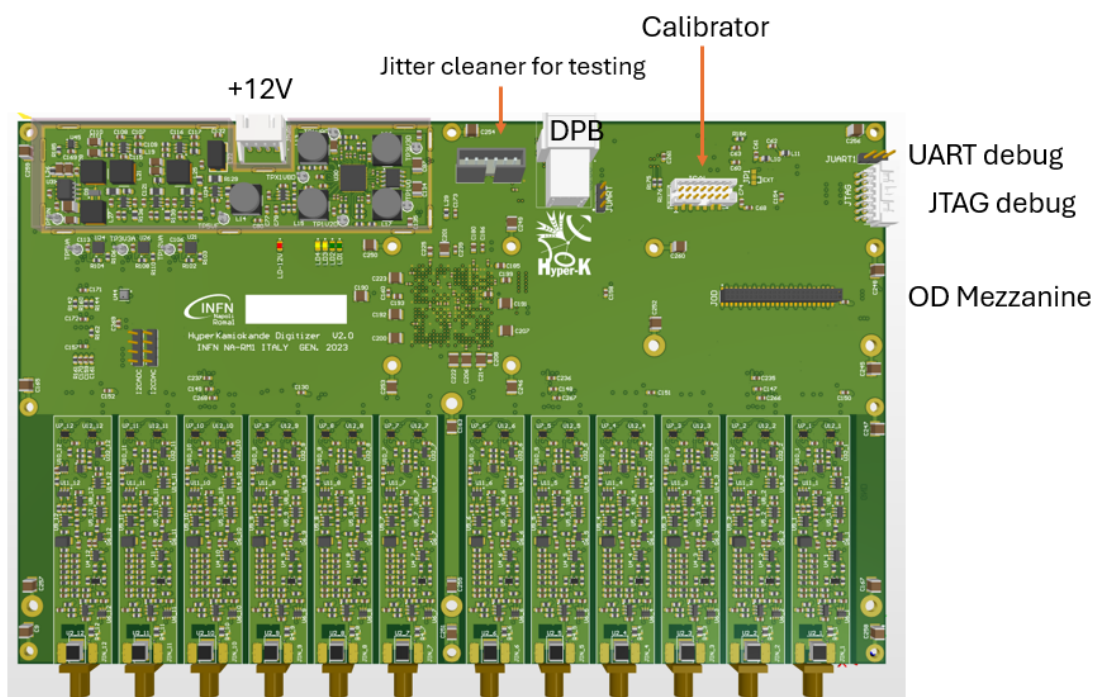


Figure 6.42: Digitizer board rendering. On the bottom part of the picture there are the 12 channels. The FPGA is not visible but it is in the center on the bottom of the board to facilitate also the cooling. The calibrator, OD and the connector for the DPB communication are also highlighted. The power supply section is on the top left and in the experiment will be covered with a metal shield to reduce EMI interference.

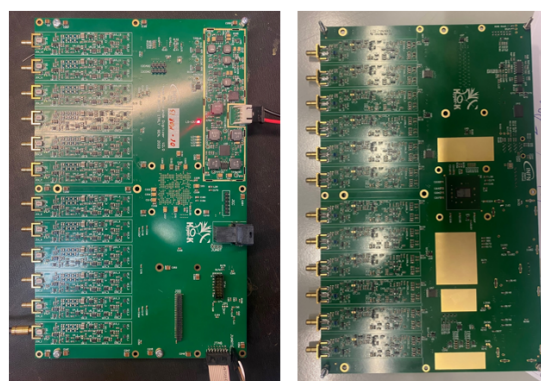


Figure 6.43: Digitizer board prototype.

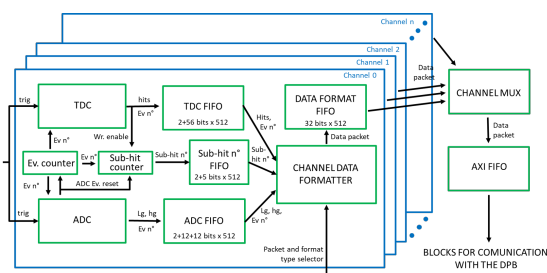


Figure 6.44: Firmware blocks for the digitizer.

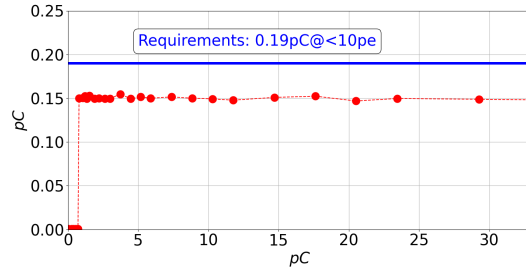


Figure 6.45: Charge resolution of the latest digitizer board prototype

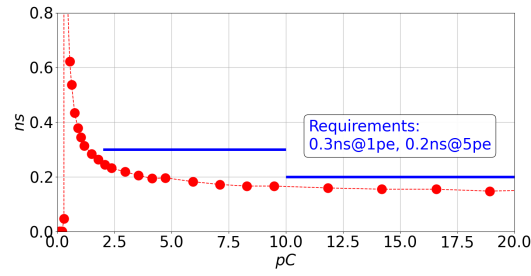


Figure 6.46: Charge resolution of the latest digitizer board prototype.

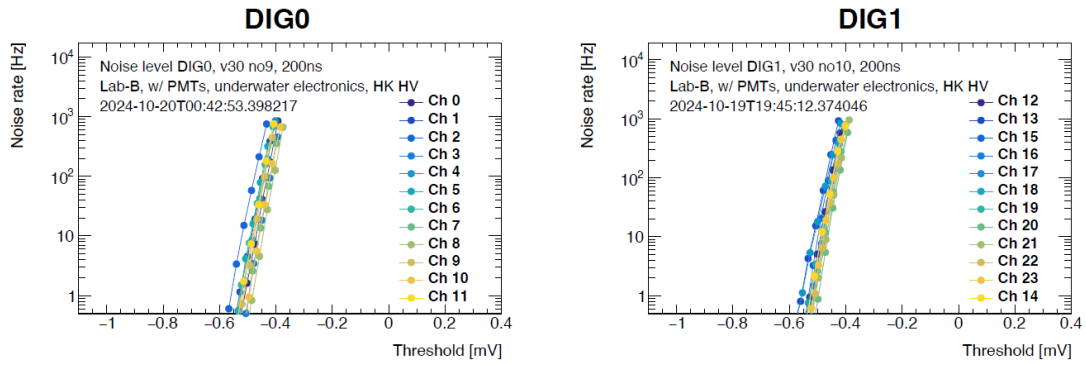


Figure 6.47: Threshold scan of two digitizer board in a fully assembled vessel in the Super-K mine.

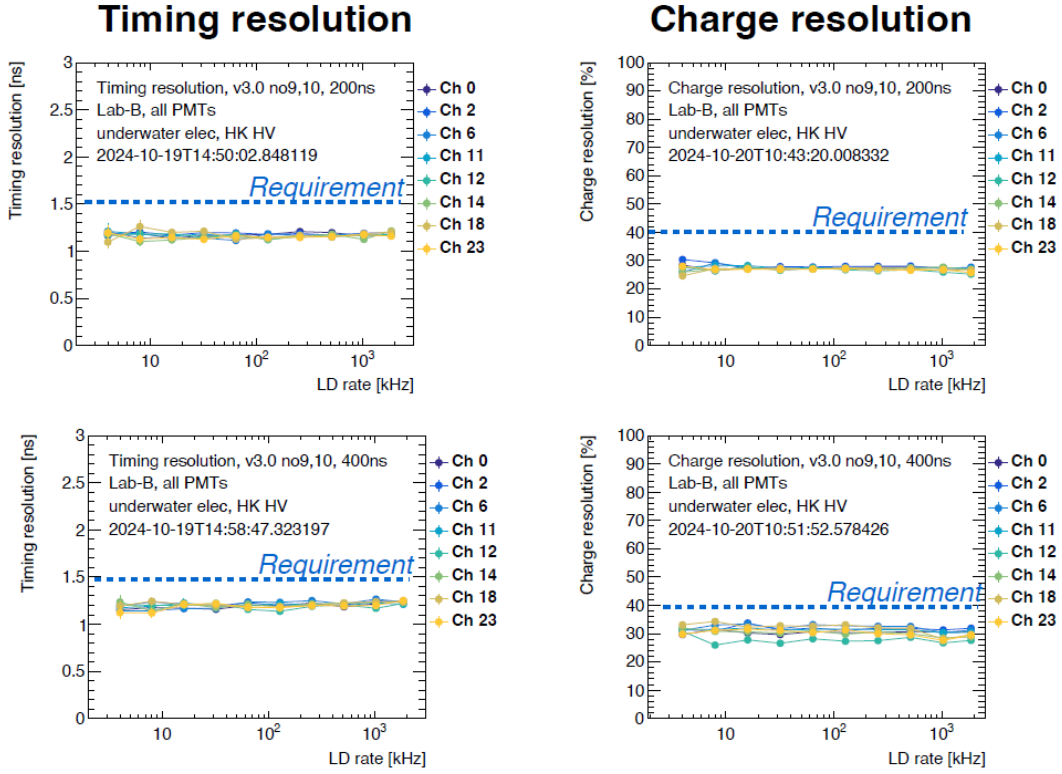


Figure 6.48: Timing and Charge resolution measured with a digitizer connected to real Hyper-K PMTs and flashed with LED light pulses.

Charge and time resolution with the PMTs connected have been verified, as presented in Fig. 6.48.

Linearity has also been measured and confirmed to be better than 1%, as reported in Fig. 6.49.

The final test has been the installation of the Hyper-K electronics vessel in Super-K. This has been done without opening the Super-K tank since all the electronics in that case is out of the water on top of the tank. Results are presented in [91], here we just report the first neutrino event acquired with the new Hyper-K electronics in Super-K (see Fig. 6.50).

6.5 The OD Front-end

For the OD a modified version of the ID design has been proposed. We combined our experience with the 3" PMTs for the mPMT and the design of the digitizer. Thus, for OD, our solution is to use the input circuit of the discrete solution, with the necessary protection circuit, and then feed the signal in a circuit equivalent to the FD mPMT FE, as explained in fig.6.51. The requirement of the OD let us to relax the performance of the digitizer in terms of charge dynamic, while keeping excellent time resolution and good charge resolution.

To validate this idea we literally combined the 20" PMT FE and the mPMT one in one circuit and we acquired some data to check mainly the resolution. The

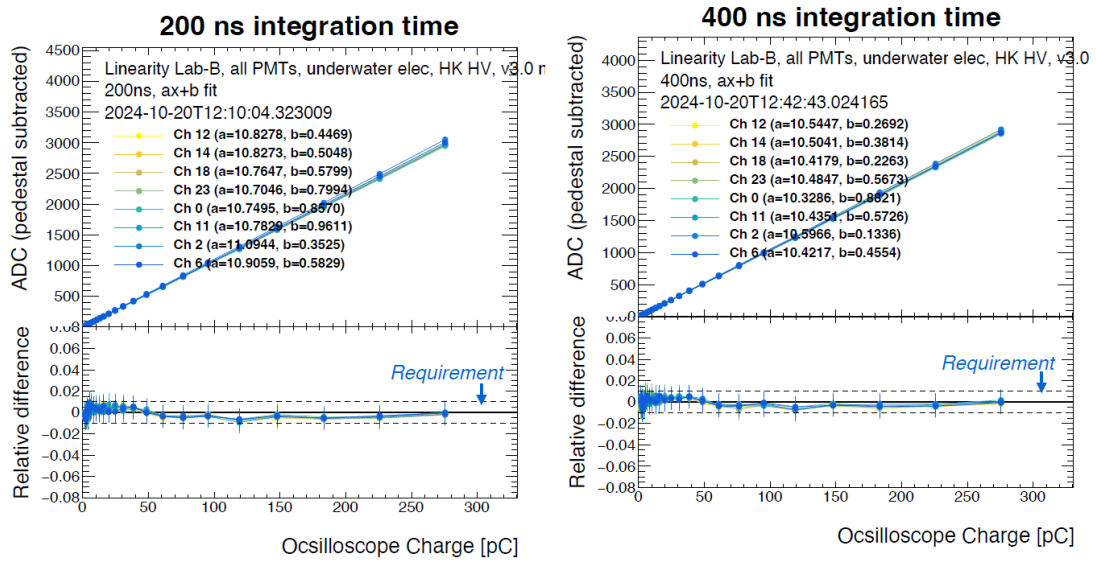


Figure 6.49: Linearity measurement of the digitizer done in Japan using LED light pulses.

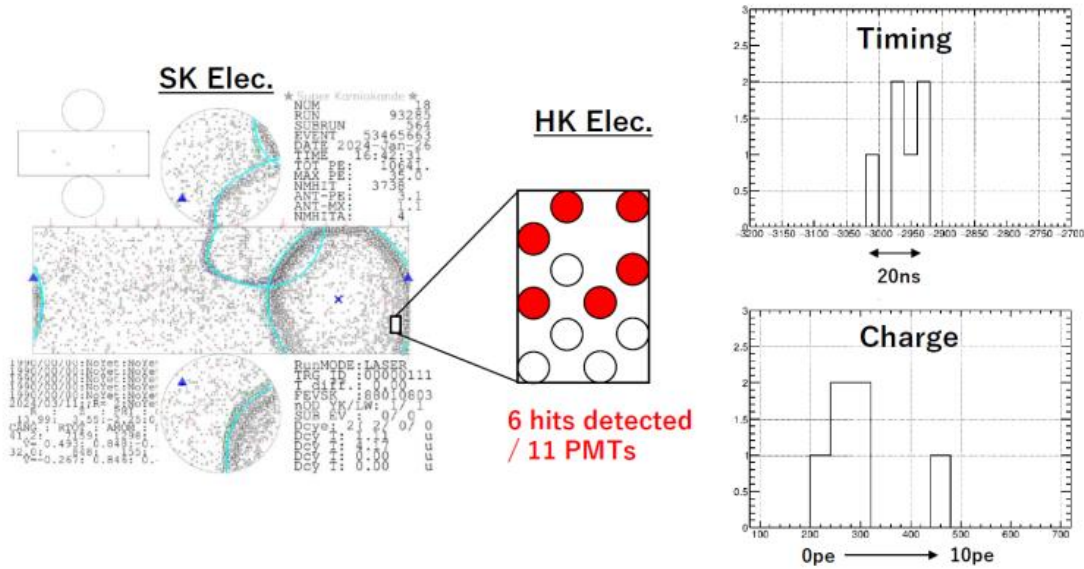


Figure 6.50: Observation of neutrino event by Hyper-K electronics.

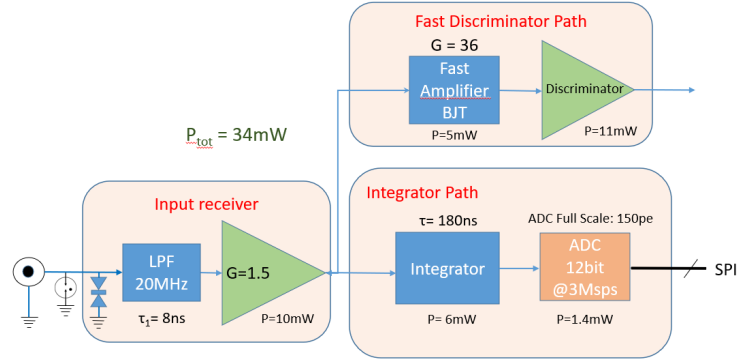


Figure 6.51: Concept of the single channel FE of the OD PMTs

detail of the test system is in fig. 6.52 and a picture of the test system is in picture 6.53.

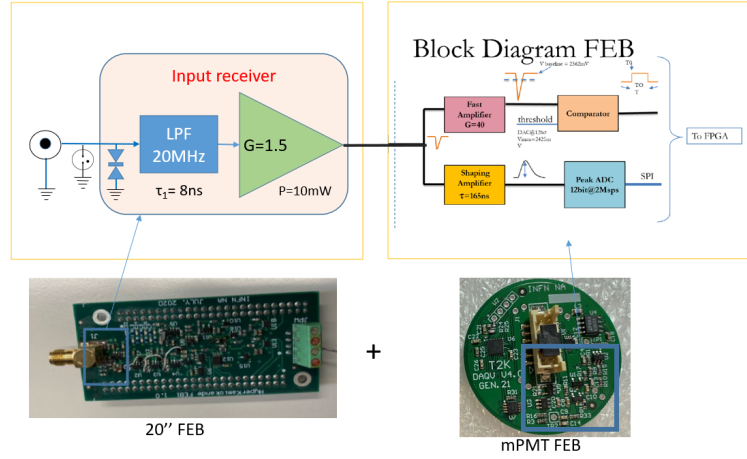


Figure 6.52: Diagram of the test system used to validate our OD implementation.

The timing resolution is comparable to the one obtained with both the mPMT and the ID FE, since it mainly depends on the TDC implementation that is embedded in the FPGA. The charge resolution is below 5% at 1 photoelectron. The dynamic range can be adapted to the need of the OD changing the input gain.

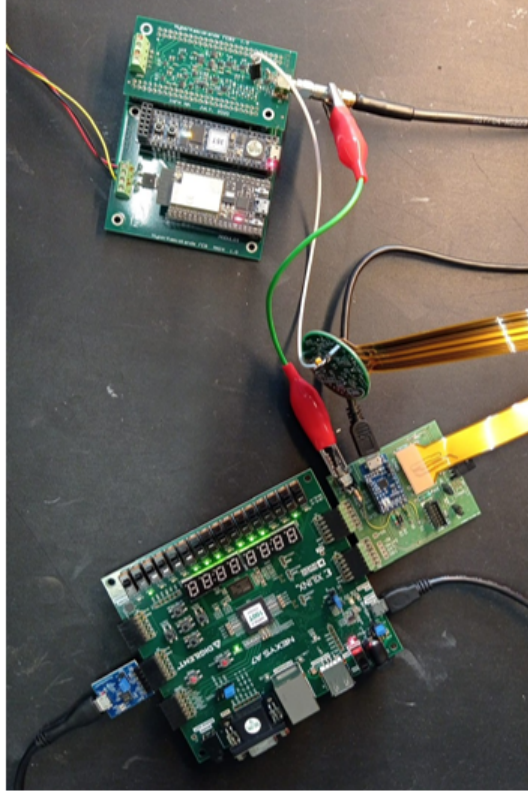


Figure 6.53: Picture of the test system used to validate our OD implementation.

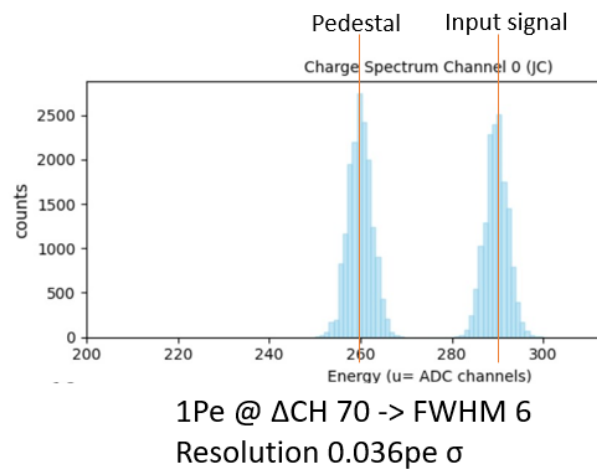


Figure 6.54: Histogram of the test done to validate our OD implementation. The charge resolution is below 5%. at 1 p.e..

Chapter 7

Future applications

The mPMT is gaining more and more attention in the astroparticle experiments and the work carried out in the last years by our group and KM3NeT group lead to the interest of another experiment in building a mPMT.

One of the possible future experiment is SWGO, that stands for Southern Wide-field Gamma-ray Observatory and that is now in the finalization of its initial R&D phase, so it is moving to the final design phase, with the detector option consolidation. mPMTs are also the baseline for the upgrade of IceCube and many other experiments are looking to this new detector to improve physics performances of detectors.

Based on the experience and the huge work already described in this work, the Naples SWGO group decided to propose in SWGO a mPMT. Here we will briefly describe what is SWGO, why a mPMT is a good choice also in this experiment and we will briefly describe the design. In particular the electronics system is deeply inspired to the work presented in this work for the HyperK mPMT.

7.1 SWGO

The detection of electromagnetic radiation can occur through satellite experiments or via ground-based detectors. The advantage of the first type of methodology lies in the fact that the detection is direct, without interference issues related to interaction with the Earth's atmosphere. The latter, in fact, is opaque in wide regions of the electromagnetic spectrum, which therefore can only be studied through satellite experiments.

The low flux of high-energy γ -rays, the weight and size limitations that satellites must adhere to because of the payloads requirements, and the necessity for redundant electronics to avoid potential malfunctions due to radiation, seriously challenge the technological implementation capabilities for satellite experiments. It is in this context that ground-based detectors come into play. Two different types are implemented: the Imaging Air Cherenkov Telescopes (IACT) and the Extensive Air Shower (EAS) Arrays. These have a much larger effective collection area, making it possible to observe events with energy levels where the γ -ray flux is so low that it would take satellite experiments decades to reach adequate

sensitivity.

When using a ground-based detector, one must account for the interaction of γ -rays with the Earth's atmosphere. When this occurs, high-energy particles are produced. These particles, interacting with nuclei in the atmosphere, generate additional secondary particles, creating a particle cascade known as **Extensive Air Shower**. Experiments that exploits this phenomenon essentially treat the atmosphere as a calorimeter and deduce the properties of the incident particle by studying the energy and distribution of the secondary particles produced.

Current air shower experiments like HAWC [92] and LHAASO [93] have demonstrated the potential of air shower detectors to discover new sources of energy above the TeV range. Their wide field of view and near 100% duty cycle, place these experiments perfectly within the multimessenger astronomy framework. The idea is to have facilities in both hemispheres that continuously survey the gamma-ray sky in the space and time domain. Wide-field-of-view observatories can not only provide prompt alerts of transient events to the astrophysics community, but they also retain information about gamma-ray emissions covering large regions of the sky. However, the lack of a wide field-of-view detector array in the southern hemisphere, which would complement northern instruments and IACTs in investigating the VHE sky, has led to the proposal for a next-generation detector.

SWG0 will provide wide-field coverage of a large portion of the southern sky, effectively complementing current and future instruments in the global multimessenger effort to understand extreme astrophysical phenomena throughout the universe.

The SWGO experiment will be a wide field-of-view, high duty cycle, ground-based water Cherenkov detector array that will survey the gamma-ray sky ranging between 100 GeV and the PeV scale. Its site will be in South America to provide access to some regions of the sky that are extremely interesting but not visible from experiments located in the northern hemisphere, see Fig. 7.1.

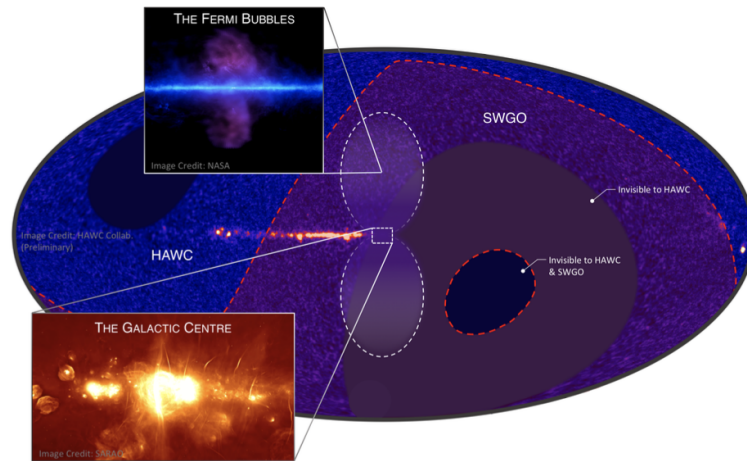


Figure 7.1: Sky coverage of SWGO in Galactic coordinates overlaid on HAWC significance map.

SWG0 will be built in Pampa la Bola, in Chile, inside the Atacama Astro-



Figure 7.2: SWGO multiPMT prototype realized to do basic testing and characterization in lab.

nomical Park at an altitude of $\sim 4700m$.

SWGO will be based on the water Cherenkov detection technique, with thousands of tanks deployed on the field to build a km^2 detector. The final configuration of the array and of each tank is not yet defined, but there will be for sure a denser central array to study to lower energies and a sparser bigger array to study more the high energy events.

7.1.1 mPMT in SWGO

Given the expertise gained by the INFN Naples section in developing mPMT modules, particularly the availability of proven knowledge in the fields of electronics and mechanics, a mPMT module has been proposed as the detection unit within the Cherenkov tanks of the SWGO experiment.

The detector will be composed of a watertight vessel made of an acrylic dome and a stainless steel backplate. Each tank in SWGO will be maximum 5 m deep, thus the multiPMT should not sustain any big load like in HyperK or KM3NeT, making the mechanical design much easier and cheaper.

Regarding the active detector, the choice is to use the same photosensor, the Hamamatsu R14374, given the huge experience of the previous experiments. In order to match the minimal performances expected from the collaboration the group decided to propose a multiPMT with 7 3" PMT looking in the water. This guarantees the same photocathode area and the same light collection of a 8" PMT, that is the baseline detector for the SWGO experiment.

The first prototype of this new detector has been built in mid 2024 and it is visible in Fig. 7.2. More prototypes will be built and tested, in particular during 2025 some prototypes will be used to build a pathfinder experiment in Pampa la Bola in Chile to do initial study on the selected site for the experiment and to verify that everything works at high altitude.

7.1.2 The electronics chain

The electronics chain for SWGO multiPMT has been derived from the one described in this work for Hyper-K mPMT, and it has been appropriately modified and optimized to meet the requirements set by the SWGO collaboration.

The proposed electronic chain for the multiPMT consists of three interconnected blocks:

- The High Voltage Board (HV);
- The Front-End Board (FEB);
- The MainBoard.

Each PMT is thus equipped with its own HV and FEB, while the MainBoard is unique for each module and is connected to all the FEBs of the PMTs in that unit, see Figure 7.3.

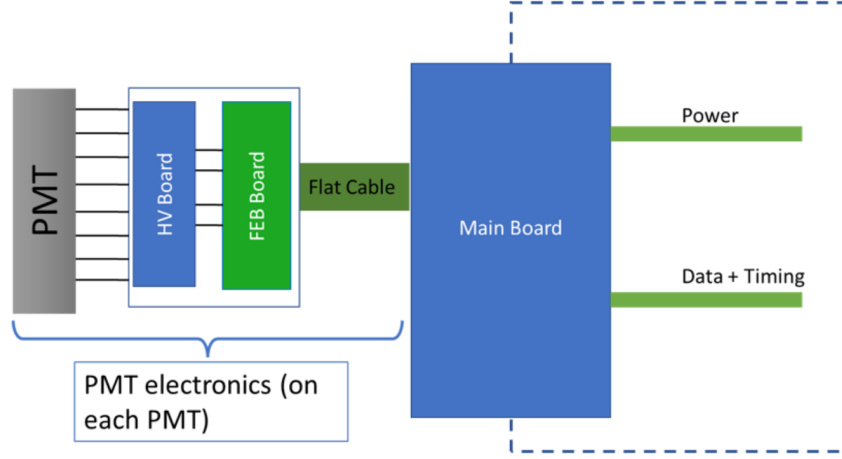


Figure 7.3: Schematic representation of the electronic readout chain proposed for the multiPMT in SWGO

The HV Board

The HV board is very similar to the one designed for Hyper-K, the main difference is that in SWGO it was necessary to extend the linearity of the 3" PMTs from Hamamatsu. Studies done in the SWGO Naples group demonstrated that linearity can be increased to ~ 1000 photoelectrons if the voltage divider is modified in a tapered voltage divider. The one suggested by Hamamatsu is :

$$3 : 1 : 1 : 1 : 1 : 1 : 1 : 1 : 1 : 1 : 1, \quad (7.1)$$

while the one used for SWGO is

$$3 : 1 : 1 : 1 : 1 : 1 : 1 : 1 : 1 : 1 : 2 : 2. \quad (7.2)$$

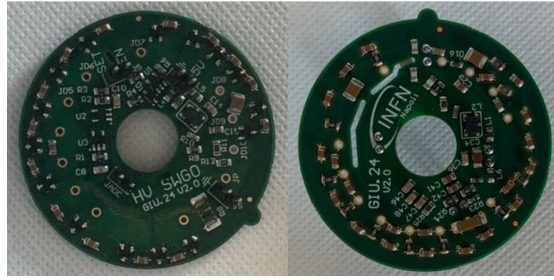


Figure 7.4: The HV board realised for the SWGO multiPMT.

This modification of coarse implied a full redesign of the PCB, that for this board is the most critical part of the design, as already described previously, so more prototypes will be build to better check uniformity and long term functionality of the system. At the current stage the board is being used for the first prototypes with good results. We will see some of the test at the end of the description of the electronics.

The FE board

Given the extended linearity of the PMT a major modification of the Front End was needed. In particular the FE designed for Hyper-K was very limited in dynamic range, while here the requirement is to have more than 300 photoelectrons per PMT of dynamic range. This extended dynamic range should also be associated with a good linearity.

To reduce power consumption in the Hyper-K FE the Slow shaper filter for the integration has been optimized to work only for signal up to 100 pe with good linearity and resolution.

The gain of PMT in SWGO will be half the one in Hyper-K, requiring a FE with a better resolution to be able to exploit the performances of the detector.

To do so, two major modifications have been done in the FE:

- The ADC has been upgraded with a 14 bit version and its reference voltage has been moved to 5 V, instead of 2.5 V, to have more resolution and also to spread the dynamic range on a bigger span of input signals.
- The slow shaper has been completely redesigned, in particular using a 5 pole shaping circuit described in the follow.

Another upgrade has been the addition to the FE of a signal analog output, since it is not yet clear in the collaboration if the waveform of the signal is needed for exotic analysis, so we preferred to include more flexibility in the design. The possibility to acquire those waveform is included in an upgrade of the main board also, but this will come in the next section.

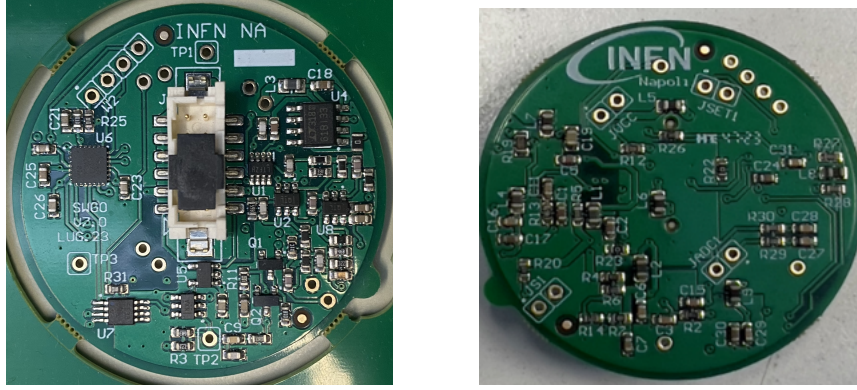


Figure 7.5: The FE board realised for the SWGO multiPMT.

The Main Board

The MainBoard is the heart of every multiPMT unit. It provides the power to the multiPMT, manages the data acquisition from the channels and the synchronisation to the global time of the experiment.

For SWGO this board has been basically designed from scratch, since the interfaces to be used in the experiment are not clear yet. We decided to keep as a baseline the interfaces already used and described for Hyper-K, so the POE power supply, the Ethernet communication on copper and the timing distribution on copper with the clock duty cycle modulation.

In addition to that, due to the size of the experiment, it is possible that the communication will be based on fiber instead of copper, which is limited by standard to 100 m of cable lenght.

To do so the Main Board is equipped with SFP connection to test the Ethernet connectivity and the clock distribution can also be based on fiber. To include the communication on fiber it was necessary to change also the FPGA, since it must include some special hardware necessary to serialize the data on the fiber, which not included in the one used for Hyper-K. To do this change and to save time in the development we decided to use a SoM, that is a small board which includes the FPGA, or SoC in this case, and all the necessary circuits for the boot of the SoC system.

Another upgrade in the system is the addition of the possibility to use White Rabbit for the clock system. White rabbit is an open source and open hardware project realized by the CERN comunity to build a timing system with very good performances, we are talking of jitter in the order of $1 - 5ps$ or even less. This system is quite expensive, since it requires special fibers and SFP modules but it is also very very performant. A decision of if White Rabbit will be the timing system in SWGO will follow so it was necessary to include the circuit needed for it in the Main Board design. The firmware to then implement White Rabbit is quite complex and it will be developed in the next month in the SWGO group.

As previously described the FE also includes the analog output for all the channels, so it was necessary to include in the Main Board the possibility to add a flash ADC to digitilise the waveforms. This has been realized with a very high

reliability and high density connector on the Main Board, where all the analog signals and a set of signals from the main SoC are routed. In particular a multi-Gigabit link has been routed to this connector and also a JTAG line. This will enable to possibility to develop a Flash ADC mezzanine to be plugged in this new custom Main Board.

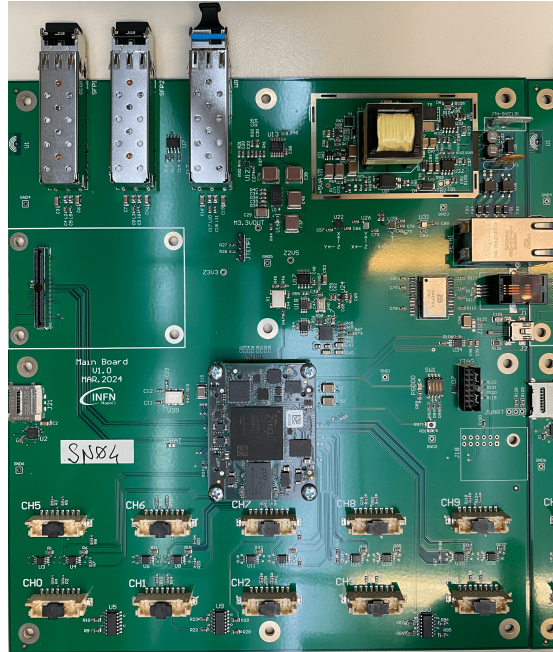


Figure 7.6: SWGO MainBoard.

Conclusion

Hyper-K aims to obtain exciting results in many fields such as the study of CP violation in the leptonic sector, the search for proton decay and the study of atmospheric neutrinos and neutrinos from astronomical origin. One of the major improvement to the previous generation Super-K is the development of novel photosensors and, thus, a redesign of the electronics system.

The goal of this work was the development of the final version of the mPMT electronics and the INFN proposal for a completely new Front End system for the B&L PMTs by Hamamatsu that in the end will be the real acquisition system for Hyper-K.

Before discussing the core of the work an overview on the Hyper-K experiment, in terms of physics capabilities, DAQ, triggers and Electronics subsystems has been provided.

After this introduction we discussed in detail the mPMT development. The mPMT is a complex detector, with a very strong mechanical structure needed to withstand the 7 bar of maximum pressure at the bottom of the tank. Studies of the selection of the material have been presented and an overview of the full system has been provided. The mPMT electronics can be considered as three different circuits, performing three different tasks. The HV board and the FEB has been optimized and now are in the pre-production phase, basically ready for mass production which will start in early 2025. An improved Main Board has been designed, realized and tested, meaning that now every part of the system is ready for the experiment. All this system has been designed with the power consumption goal of 4 W maximum and we obtained a good result of 3.5 W, in particular due to the design and the development of an High efficiency POE+DC/DC power supply, that reported an efficiency of 87% at 4 W.

The second part of the work was the design of a proposal for a new FE system for the 20" B&L PMT developed by Hamamatsu. We developed a low power and low noise circuit based on Discrete Components. To fulfil the requirements a complex circuit has been designed, in particular a protection circuit and an input receiver is the first block implemented; this block showed very good performance, especially the protection circuit has been developed and tested and it can stands to more than 1000 HV discharges from the PMT. The following blocks are the fast discriminator and the integrator, which finally gives us a charge resolution of 5% at 1 PE, a $< 1\%$ linearity and a time resolution of 100 ps thanks to a TDC embedded in the FPGA. The acquisition rate of the system is higher than 1 MHz, without altering the quality of the reconstructed charge value. After a numbers

of internal and external reviews this proposal has been selected as the one to be used in the experiment. For this a new board equipped with 12 channels has been realized and presented. The board has been deeply tested, both at INFN and at international laboratories. One of the most important test has been the integration of this new board in the Super-K data taking, which shown to the collaboration the real physics capabilities of the system. The board is also now in the pre-production phase, with the aim of starting the 2000 boards production by mid 2025.

We finally described the opportunity to use the systems developed in this work, in particular the mPMT electronics, in SWGO, the future biggest gamma ray observatory on the planet, that in the last years proposed to use a multiPMT detector equipped with a modified version of the electronics developed for the mPMT in Hyper-K.

To conclude, the systems developed in this work will be the core of the next decades Hyper-K neutrino experiment. Possibly, also, the system developed for the mPMT will be further adapted and used in another leading experiments, such SWGO.

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