The JUNO LNF group

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1 The JUNO experiment

Despite the great progress accomplished in the last decades, a number of fundamental questions concerning the nature of neutrino and their interactions remains. These elusive particles are among the least understood in the Standard Model. The fascinating and well-established phenomenon of neutrino oscillation has clearly shown that neutrino do have masses but as its sensitive only to the differences in the squared masses, the absolute mass of neutrinos has not yet been determined. Likewise it is not known how masses are ordered, i.e. if the mass of the neutrino mass eigenstate m3 is heavier or lighter than the m1 m2 pair. The two possible options are known as normal or inverted mass hierarchy (MH).

The neutrino MH is then among the most important issues in the future neutrino oscillation program, and its also crucial for the neutrino-less double-beta experiments looking at Majorana neutrinos. The Jiangmen Underground Neutrino Observatory (JUNO) is an experiment designed to determine the neutrino mass hierarchy at the 3-4 σ significance level as a primary physics goal, by detecting reactor anti-neutrinos from two power plants at 53 km distance. The measurement of the anti-neutrino spectrum will also lead to the precise determination of three out of the six oscillation parameters to an accuracy of better than 1 %.

Mass hierarchy can be determined in JUNO exploiting an interference effect between the 3-flavour oscillations in the disappearance of electron anti-neutrino emitted from nuclear power reactors at the medium baseline. The interference manifests itself in a rapid oscillation pattern superimposed on the solar oscillation. The oscillation amplitude and the frequency of the pattern depend on the mass hierarchy. The determination of the neutrino mass spectrum hierarchy, however, will require an unprecedented level of detector performance and collected statistics, as well as the control of several systematics at (sub)percent level.

The JUNO experiment will also be able to observe neutrinos from terrestrial and extra-terrestrial sources, i.e. supernova neutrinos, diffuse supernova background, atmospheric neutrinos

and neutrinos from the annihilation of dark matter particles in our galaxy. JUNO can then be defined as a multipurpose experiment able to explore the neutrino nature as well as to perform neutrino astronomy and astrophysics.

The detector, whose concept is shown in figure 1, will be placed in a 700 m deep underground laboratory, presently under excavation, located at Jiangmen (Guangdong province) in South China, 53 km away from the Taishan and Yangjiang reactor complexes. The central detector consists of a 20-kiloton of Linear Alkyl-Benzene (LAB) liquid scintillator contained inside a 12 cm thick and 35.4 m wide acrylic ball, supported by a Stainless-Steel Struss (SSS) of 40 m diameter, and instrumented by 17561 20-inch PMTs covering more than 75 % of the SSS area. In addition, up to 25600 3-inch PMTs will fill the gaps among the large PMTs in order to improve the energy and vertex resolutions. To achieve the primary goal of the MH determination, an unprecedented energy resolution of 3 % at 1 MeV is a critical parameter which requires the total photocathode coverage bigger than 75%, a large PMT quantum efficiency (35%) and the LS attenuation length bigger than 20 m at 430 nm. The central detector is immersed in a 44 m-high, 43.5-wide ultrapure water Cherenkov pool, instrumented by about 2000 20-inch PMTs that will tag events coming from outside the neutrino target. It will also act as a passive shielding for gammas and neutrons induced by cosmic rays in the surrounding rock. A muon tracker, composed of three layers of plastic scintillator strips, will be installed on top of the detector in order to tag cosmic muons and validate the muon track reconstruction.

The civil engineering works are proceeding: the digging of shafts and tunnels, as well as of the experimental hall have been completed during 2018. 15000 20-inch PMTs are being produced by NNVT, while 5000 (with better time performances needed for position measurements) have been shipped from Hamamatsu. Up to now, 8000 PMTs from NNVT and all those from Hamamatsu have been already delivered in the test facility located in ZhongShan; their testing is progressing. The 25600 3-inch PMTs are being produced by HZC Photonics. The read-out electronics for the PMTs of the central detector is under finalization, as well as the installation procedures. According to the present schedule, the detector installation will start in January 2020 and the data taking during 2021.

2   Activities of the LNF group

The LNF group is responsible for the design and the construction of the Top Tracker electronics, in cooperation with the IPHC Strasbourg and the JINR Dubna groups. The JUNO Top Tracker will be used to select a golden sample of cosmic events in order to estimate the cosmogenic background for anti-neutrino detection and to monitor the performances of the central detector. The 62 walls constituting the OPERA Target Tracker [3] will be used and disposed into three layers on top of JUNO experiment. Each wall is made by 256+256 crossed scintillator strips, 2.6 cm wide and 6.7 m long; the light, collected by wavelength shifting fibers glued on the strips, is read-out on both fiber ends by 64 channel H7546 Multi-anode PhotoMulTipliers (MaPMT). Each wall contains therefore 16 MaPMTs.
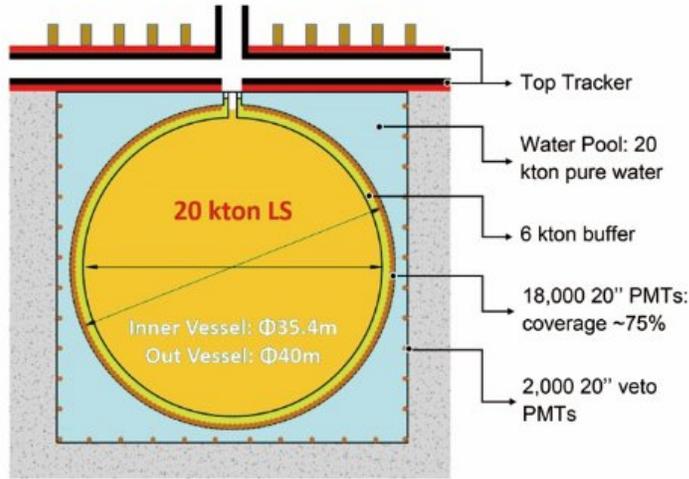
Figure 1: *JUNO detector concept.*

2.1 Description of the Top Tracker acquisition system

Due to the environment (rock) radioactivity, counting rates of up to 50 kHz/MaPMT are expected, therefore the electronics of the OPERA experiment needs to be replaced because of the increased rate. A scheme of the acquisition of one wall is shown in figure 2. Like in OPERA, each MaPMT is served by two electronic boards, the Front-End (FE) board and the Read-Out (RO) board. The 16 RO boards are connected to the Concentrator board, located in the middle of the wall, to equalize the cable length.

The FE board contains a 64 channel MAROC3 chip [4], performing the discrimination of the 64 analog signals at 1/3 photo-electron (pe), the OR of the discriminated signals and the charge measurement by an internal Wilkinson ADC; a multiplexed analog output permits also to acquire the charge with an external ADC. The 64 digital outputs are multiplexed in an 8 channel output connection by a FPGA.

The RO board contains a Cyclone5 GX FPGA. It configures the MAROC3 chip in the FE board and in presence of a signal in the MAROC, delivers the OR to the Concentrator board and starts the acquisition of the digital pattern and further of the charges of the fired strips through a track-and-hold technique. Two options are possible, to use the internal MAROC3 Wilkinson ADC or to multiplex in output analogic signals (OutQ) proportional to the charge and convert them using a 12 bit FADC located in the RO board. In absence of a coincidence between the x and y strips, performed in the Concentrator, a reset of the started MAROC3 acquisition is performed. The RO board also hosts an HV module (the MaPMT works at 800 V with currents up to 500 μA) and a test pulse unit for calibration purposes: the latter is recoverable from the OPERA experiments, while a special HV module has been designed by CAEN, A7511, matching JUNO Top Tracker specifications.

The Concentrator board perform the coincidence between the 16 MaPMT OR signals coming
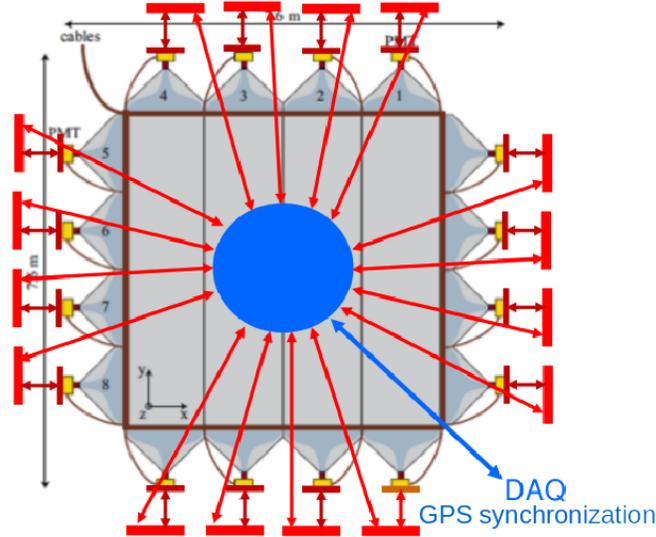
Figure 2: *Scheme of the acquisition system of one Top Tracker wall.*

from x and y strips of the wall; a rate of about 10 kHz/wall is expected, assuming a 100 ns shaping for the discriminated signals, dominated by random coincidences. In presence of a coincidence, an FPGA based TDC perform the measurement of the time difference between the coincidence inputs and the shaped trigger signal. In addition the digital patterns and the charges are collected from the 16 RO boards, and a global UTC timestamp is given to the trigger signal, in order to reconstruct tracks in the Top Tracker and to synchronize its acquired data with the Water Cerenkov VETO and the Liquid Scintillator Central Detector. In addition the Concentrator collects also slow control data and sets different data taking modes: normal, calibration (LED pulsers are used to measure pedestals and single pe charge), debugging (counting rates are measured for each strip, to find eventual light leaks). A maximum data flow of few Mbit/sec is expected from each Concentrator. A data reduction is foreseen, either based on a software algorithm running on a dedicated machine, or performed with a second level trigger board.

A picture of the first prototypes of the FE card and of the RO board, installed inside a Top Tracker module, is shown in figure 3. The two prototypes have been successfully tested since 2017. The second prototype of the concentrator is expected in Spring of this year, together with the final prototypes of the RO and FE boards.

2.2 ROB prototype tests

To finalize the design of the two boards, tests of the FE card together with the RO Board have been performed both at Strasbourg university and at Frascati laboratories since 2017. At LNF a charge is injected in the PMT connector of the FE Card sending a squared signal on a 10 pF capacitor. The injected charge is estimated as the product of the square signal amplitude times

Figure 3: *Picture of the FE card and RO board prototypes installed inside a Top Tracker module.*
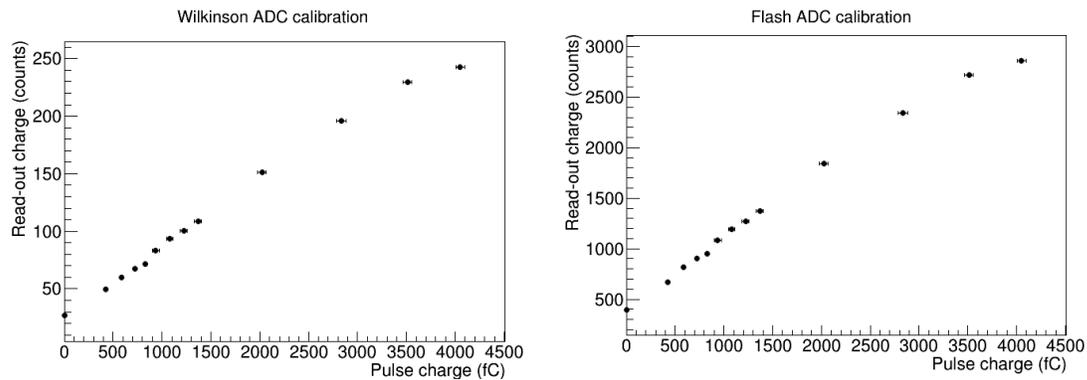

Figure 4: *Calibration curves of the Wilkinson (left) and of the Flash ADC (right).*

the capacitance.

The preamplifiers of the MAROC3 have been set with gain equal to one, while the shapings both of the digital and of the analogic sectors of the chip have been chosen according to OPERA experience: in particular we want a rise time in the track-and-hold chain as short as possible. The Hold signal issued by the ROB has been optimized in order to maximize the charge read out by the internal Wilkinson ADC. Its delay can be either set by means of a PLL loop in the FPGA, with a total jitter of 2.6 ns, or with a monostable as input to a discriminator with a programmable threshold. With the first solution a charge resolution about 1%, dominated by the time jitter of the hold signal, has been obtained both with the internal Wilkinson and the Flash ADC of the RO board. The calibration curves obtained with the second solution are instead shown in figure 4; the response saturation about 3.5 pC (for unitary gain in the preamplifier) is characteristic of the MAROC3 analogic chain. A resolution on the charge measurement better than 0.3% is obtained, using either of the ADCs, with a linearity at the level of few %.

The functionality of the HV control and of the test pulse have also been verified in the RO board prototype. The first prototype of HV module produced by CAEN, has been successfully

tested on the board, measuring a ripple as low as 5 mVptp, The board design will be frozen during Spring 2019, after the tests with the concentrator prototype.

3 Publications

1. The JUNO Collaboration, Conceptual Design Report, ArXiv:1508.07166.

2. The JUNO Collaboration, J. Phys. G: Nucl. Part. Phys. 43 (2016) 030401.

3. M. Grassi et al., JINST vol.13 (2017) P02008.

4. P. Lombardi et al., NIM A925 (2019) 6-17.

References

1. The JUNO Collaboration, Conceptual Design Report, ArXiv:1508.07166.

2. The JUNO Collaboration, J. Phys. G: Nucl. Part. Phys. 43 (2016) 030401.

3. T. Adam *et al.*, Nucl. Instrum. Meth. A577 (2007) 523.

4. http://omega.in2p3.fr/index.php/products/maroc-front-end-chip.html.