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 excavation of the underground laboratory has been accomplished by the end of 2020. All the PMTs for the central detector have been delivered and the testing almost finished. The read-out electronics for the PMTs of the central detector is under finalization, as well as the installation procedures. The detector installation will start in July 2021 and finish before the end of 2022.

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.

The LNF group is also involved in the implementation and testing of the computing system for the simulation and analysis of the experiment data. The file management system is based on "RUCIO". This software is developed at CERN (https://rucio.cern.ch/) and used by the LHC experiments. It is being tested and integrated with the "DIRAC" middleware which allows the distributed computing in the GRID environment. DIRAC is developed in a consortium of universities and research centers (http://diracgrid.org/)

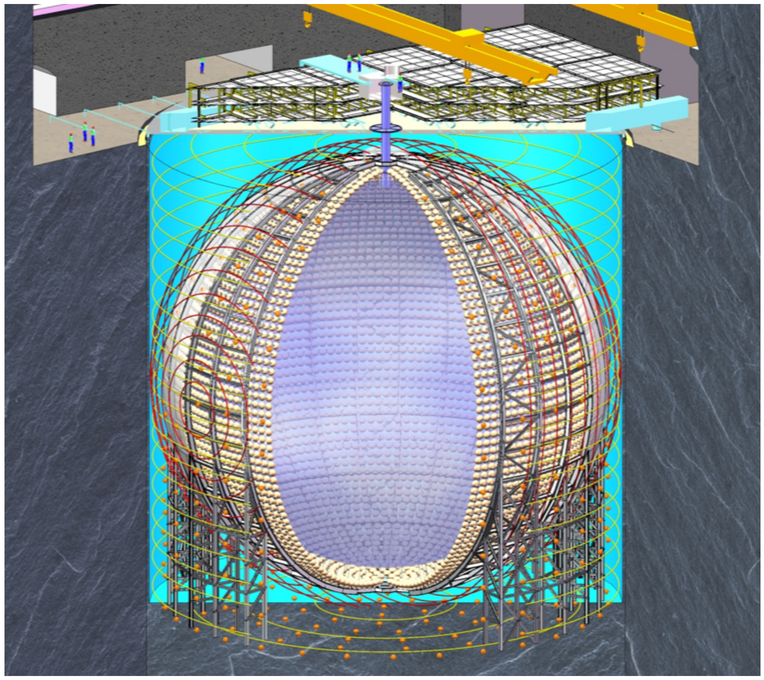

Figure 1: *JUNO detector sketch.*

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

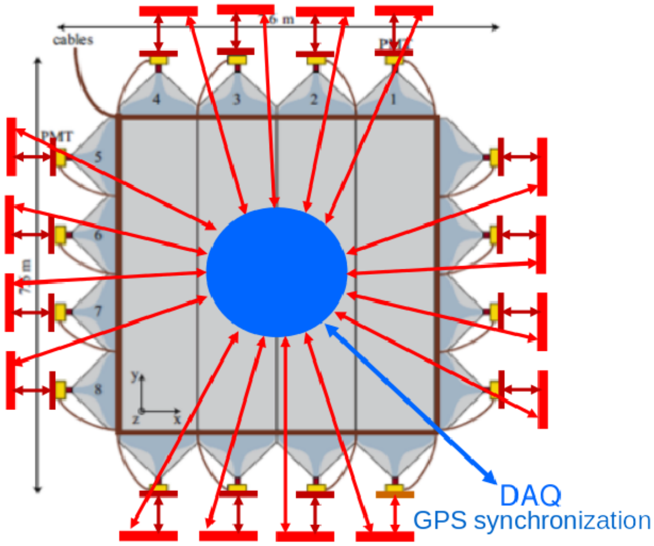

Figure 2: *Scheme of the acquisition system of one Top Tracker wall.*

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 performs the coincidence between the 16 MaPMT OR signals coming 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 second level trigger board is under development for data flow reduction.

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 production of the FE cards has started during the end of 2019, while tests are ongoing on the second prototype of the Concentrator and on the final prototypes of the RO boards, also produced during the last months of 2019. The Final Design Review of the RO boards is foreseen in February 2021 and the final production during the second half of 2021.

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

2.2 Final ROB prototype tests

Due to the COVID pandemics, the tests on the full acquisition chain have been delayed to the first months of 2021. In the meanwhile we have performed tests on the RO board prototypes both on bench (MAROC3 configuration studies) and on a detector prototype (calibration runs).

The charge acquisition in the MAROC3 chip is based on a track-and-hold technique, in which the analog chain shapes the signal from the MaPMT and converts its value in presence of an Hold signal (issued by the RO board in presence of fired channels in the digital chain of the chip). The analog chain is composed by an RC buffer circuit and a shaper, shown in figure 4. For JUNO Top Tracker we have chosen to minimize as much as possible the shaping and the recovery time of the slow shaper.

According to preliminary measurements, in order to minimize both the peaking time and the baseline recovery time, three configuration have been investigated:

- $C_{buf} = 0.5$ pF and $C_{buf} = 0.3$ pF, defined as the standard setting;
- $C_{buf} = 0.5$ pF and $C_{buf} = 0.6$ pF, with a slightly slower shaping time;
- $C_{buf} = 0.0$ pF and $C_{buf} = 0.9$ pF, with a better sensitivity.

In our tests the Hold is emitted ad a variable delay with respect to the MAROC3 test input signal. The results are shown in figure 5 for a charge of 1.2 pC.

For each configuration, first of all, we have found the "Hold" delay that maximizes the response (peaking time), then we have used that value to measure the input charge in a range from 0 to 7 pC. A linear fit is carried out up to 3.5 pC; the inverse of the slope is taken as an estimate of the sensibility and the average of its residuals as the linearity deviation. The RMS of the charge distributions gives the precision. The baseline recovery time is defined as the time required for the baseline to reach 99% of its value prior to the arrival of the input signal (pedestal); the recovery time measurements reported here have been performed for an input charge of 1 pC. The results are summarized on table 1.

The first configuration (C_{feed}=0.3 pF) has the minimum recovery time but the peaking time do not match the "Hold" signal timing of the present version of the RO board (ranging from 48 to

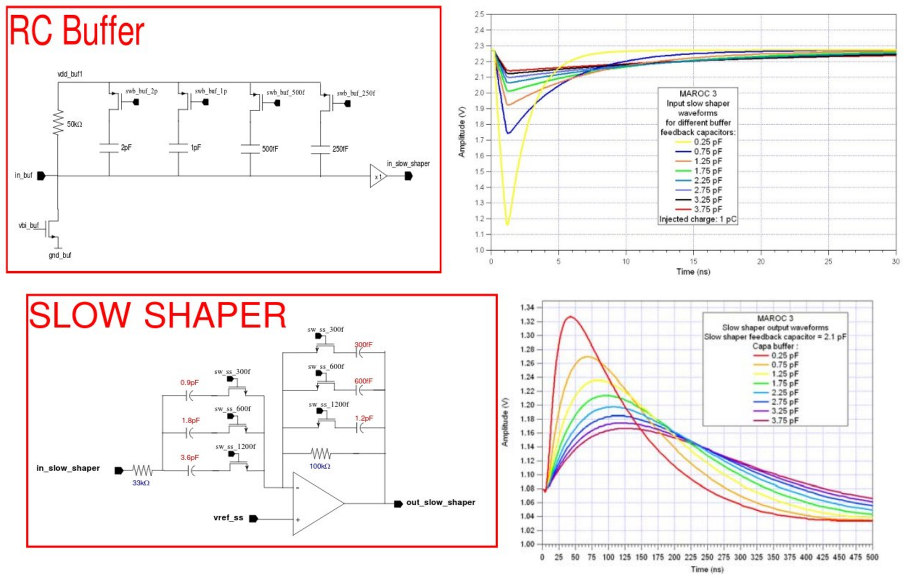

Figure 4: *RC buffer (top left) and simulated signals for different parameters choice (top right). Slow shaper (bottom left) and simulated signals for different parameters choice (bottom right). The figures are taken from MAROC3 datasheet.*

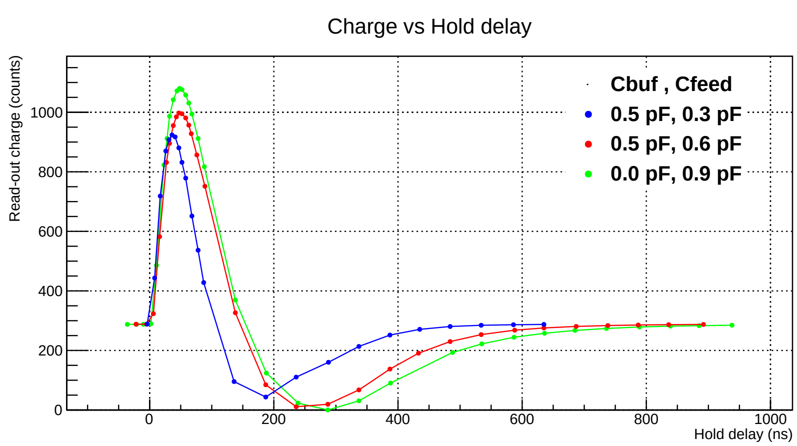

Figure 5: *Flash ADC output as a function of the Hold delay with respect to the input signal for the considered MAROC3 slow shaper settings. The measurements have been performed with 1.2 pC input charge.*

Table 1: MAROC3 slow shaper setting results.

C_{buf},C_{feed}	peak time	recovery time	sensibility	precision	linearity
0.5 pF, 0.3 pF	36 ns	550 ns	2.35 fC/count	$< 1\%$	0.7 %
0.5 pF, 0.6 pF	47 ns	800 ns	2.03 fC/count	$< 1\%$	1 %
0.0 pF, 0.9 pF	48 ns	950 ns	1.78 fC/count	$< 1\%$	2 %

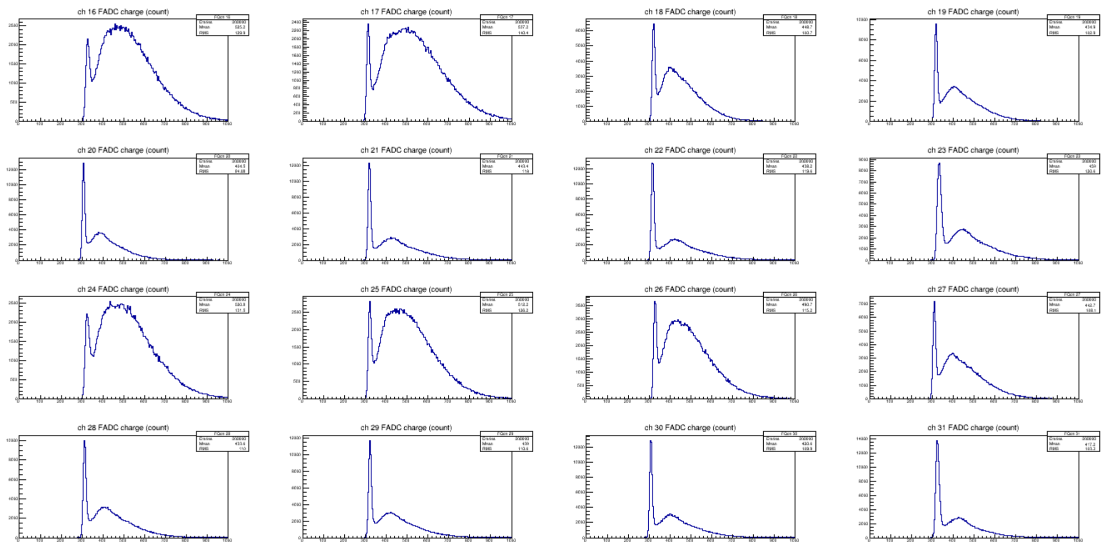

Figure 6: *Example of a SPE calibration run performed at an operating voltage of -750 V using the FADC.*

62 ns). The other configurations are within the range but, because of the better sensitivity, have a worse linearity. For the lowest C_{buf} the response deviates visibly from the linearity around 3 pC (that is 20 photoelectrons for a MaPMT gain of 10^6). Using C_{buf}=0.5 pF and C_{feed}=0.6 pF looks like a reasonable compromise, but the recovery time is 250 ns worse than with the standard setting. Using the standard setting with an un-optimized Hold delay of 48 ns gives performances similar to those reported in table 1 at the peak time.

Data acquisition tests have also been performed on the detector prototype used for the HV tests. Single photoelectron (SPE) calibrations have been performed using either the Wilkinson or the Flash ADC at a MaPMT voltage ranging from -1000 V to -750 V. In the calibration runs, the Hold delay is set with respect to the LED driver pulse and its delay is adjustable in order to emulate the standard acquisition in terms of delay with respect to the MaPMT output signals. For these runs the MAROC3 pre-amplifier gain is set to 1 for all the 64 channels. In figure 6 examples of the SPE spectra obtained for a set of 16 channels, using the FADC, are shown: pedestal and SPE peaks are clearly visible and well separated.

During the first months of 2021, the communication tests with the final Controller prototype are being performed, in order to start the production of 1000 ROBs by CAEN before the second half of 2021.

3 JUNO internal notes with contributions by LNF group

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4 Publications

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2. The JUNO Collaboration, J. Phys. G: Nucl. Part. Phys. 43 (2016) 030401.
3. M. Grassi et al., JINST vol.13 (2017) P02008.
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