The JUNO LNF group

M. Cordelli (Ass.), G. Felici, A. Mengucci (Tec.), A. Martini, A. Paoloni (Resp.),
M. Spinetti (ospite), M. Ventura (Tec.), L. Votano (Ass.)

in collaboration with

LNF-SEA: M. Gatta, G. Papalino

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 construction of the underground laboratory is expected to finish during 2020. 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, 12800 PMTs from NNVT and all those from Hamamatsu have been already delivered in the test facility located in ZhongShan; their testing is progressing. The production of the 26000 3-inch PMTs by HZC Photonics is finished. 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, before the start of Coronavirus spread, the detector installation will start in July 2020 and the data taking in the second half 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.

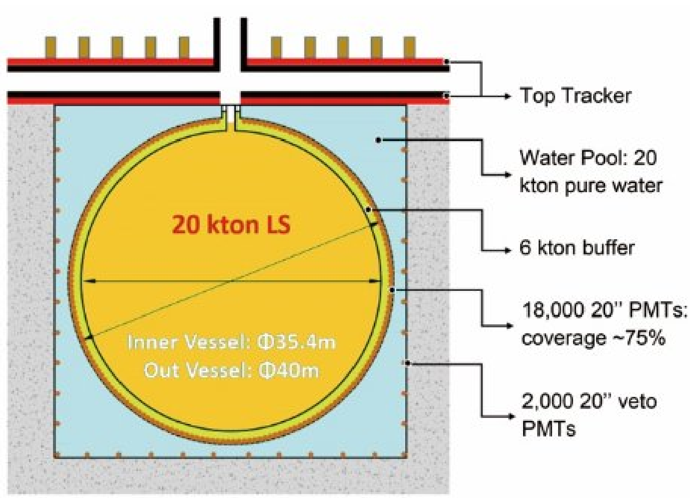

Figure 1: *JUNO detector concept.*

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

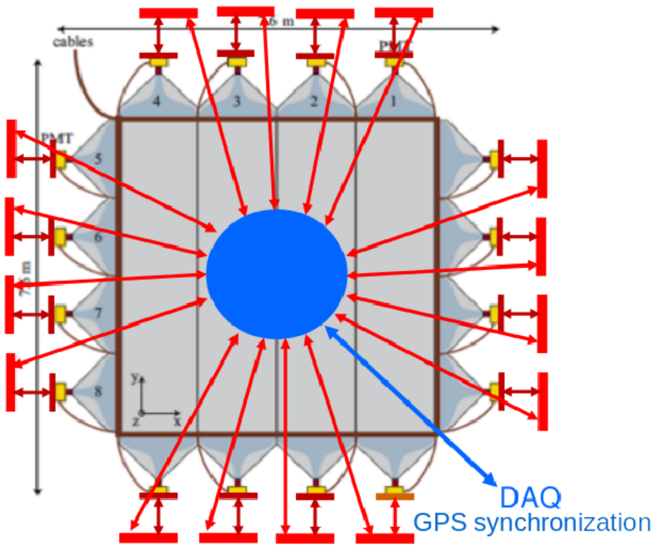

Figure 2: *Scheme of the acquisition system of one Top Tracker wall.*

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 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.

2.2 Final ROB prototype tests

The tests on the final RO Board prototypes have been performed at Frascati laboratories at the end of 2019, both on a test bench and on a detector prototype.

In the test bench, a charge is injected in the PMT connector of the FE Card sending a squared

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

signal on a 2.7 pF capacitor. The injected charge is estimated as the product of the square signal amplitude times 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 (of the order of 50 ns). 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. Better resolutions, shown in figure 4 have been obtained with the monostable solution, thanks to the improved time jitter of the Hold signal (lower than 1 ns).

The response of both ADCs shows a saturation at about 4 pC (for unitary gain in the preamplifier), characteristic of the MAROC3 analogic chain. Below 4 pC, the linearity is at the level of few %, as expected, with 2 fC/count and 17 fC/count using the Flash and the Wilkinson ADCs respectively.

On the test bench we have also verified that:

- the HV DC-DC converter block, A7511, produced by CAEN, has a ripple as low as 5 mVptp, within specifications.
- the communication with the Controller, emulated by a looping word as output of the ROB, doesn't interfere with the Front-End, in terms of noise rate and charge measurement spoiling.
- the operating current of the ROB (powering also the FEB and the MaPMT) is lower than 350 mA for a supply voltage of 12 V.

On a detector prototype, in standard running conditions of High Voltage and MAROC3 setting, we have evaluated the noise of the signal baseline to be at the level of 1 mV, by acquiring several waveforms with an oscilloscope.

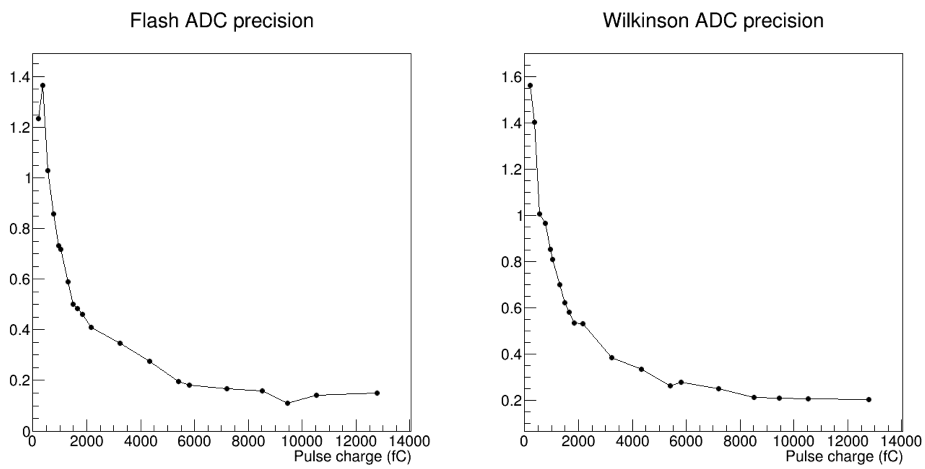

Figure 4: *Charge resolutions measured with the Flash (left) and the Wikinson ADC (right). The single photo-electron charge is 160 fC for a PMT gain of* 10^6.

During 2020, the communication tests with the final Controller prototype will be performed, in order to start the production of 1000 ROBs by CAEN before the end of the year.

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. M. Reguzzoni et al., Journal of geophysical research: solid Earth, 124 (2019) doi 10.1029/2018JB016681.
5. 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.