**The JUNO LNF group**

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in collaboration with

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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 it is 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 $m_3$ is heavier or lighter than the $m_1$ - $m_2$ 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 it is 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 3 $\sigma$ 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 (geo-neutrinos) and extra-terrestrial sources (solar, atmospheric and supernova neutrinos). 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 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 17612 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 a 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.

During September 2021 the excavation of the water pool has been completed; the external campus at Kaiping is active since January 2021. The Liquid Scintillator facilities in the external campus have been completed and the installation of those in the underground site is ready to start. The photomultipliers of the different Read-Out systems have been already procured and tested. The other detector systems are in the material procurement phase and the installation of the detector is expected to finish during 2023.

## 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/)

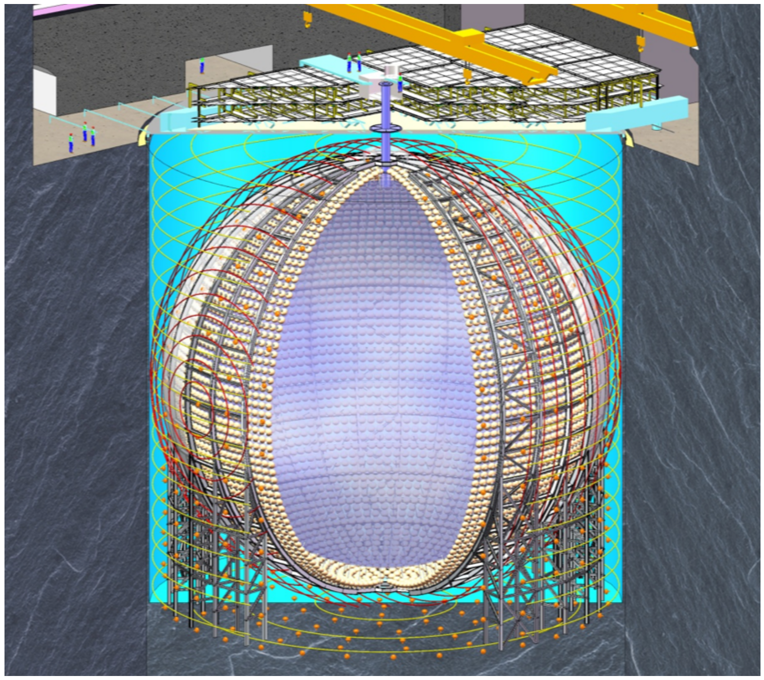

Figure 1: *JUNO detector sketch.*

### 2.1 Top Tracker electronics status

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 an 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

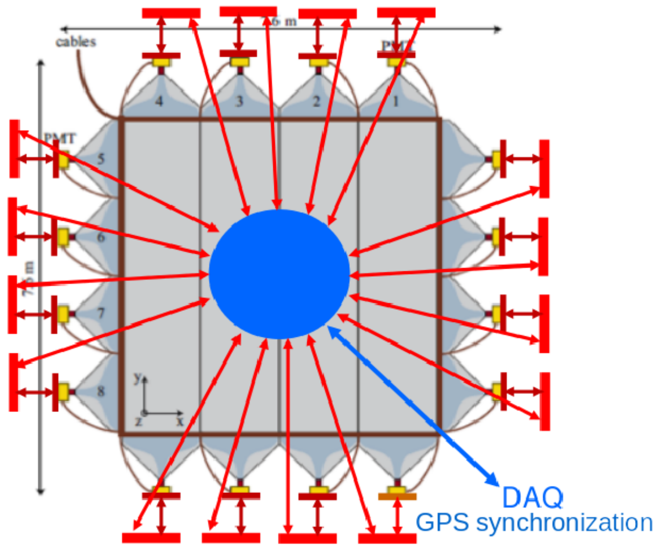


Figure 2: *Scheme of the acquisition system of one Top Tracker wall.*

$\mu$A) 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 50 kHz/wall is expected. In presence of a coincidence, an FPGA based TDC performs 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 FE cards have been produced and shipped to the detector site, where the Top Tracker modules, recovered from OPERA, are presently located. During March 2021 the RO Board project passed the Final Design Review of the collaboration. The extensive test campaign performed by the LNF Group has been described in the internal note [5] and in the 2020 LNF activity report. The hardware of the RO board has been finally validated during November 2021 at Strasbourg University both in a test bench and in a prototype detector set-up, shown in figure 4; the same set-ups are also used to test the concentrator prototypes. The


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

production of the RO boards, realized by CAEN, started in December 2021 and is expected to finish at the end of September 2022.

## 3 List of Conference Talks by LNF Authors in Year 2021

1. A. Paoloni on behalf of JUNO collaboration, "Status of JUNO experiment", NUFACT 2021: the 22nd International Workshop on Neutrinos from Accelerators Cagliari, Italia, 6-11 Settembre 2021.
2. A. Paoloni, "JUNO experiment and the neutrino mass hierarchy measurement", GSSI astroparticle physics colloquia, 24 novembre 2021.
3. A. Paoloni, "Reactor neutrino experiments: status and perspectives", XXIII Roma3 Topical Seminar on Subnuclear Physics: "Where we stand and where we go with neutrino physics", 13 Dicembre 2021.

## 4 Publications

### 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.
5. A. Paoloni *et al.*, "Validation tests on the pre-production of the JUNO Top Tracker Read-Out Board.", JUNO-doc-6823 (February 2021).
6. M. Bellato *et al.*, "Embedded readout electronics R&D for the large PMTs in the JUNO experiment", NIM A985 (2021) 164600.

Figure 4: *RO board final prototypes tests at Strasbourg. Test bench simulation of one wall (16 FE+RO boards coupled to one concentrator) at left and detector prototype for track reconstruction at right.*


7. The JUNO collaboration, "Feasibility and physics potential of detecting 8B solar neutrinos at JUNO", CPC Vol.45 No. 1 (2021).

8. A. Abusleme *et al.*, "Optimization of the JUNO liquid scintillator composition using a Daya Bay antineutrino detector", NIM A988 (2021) 164823.

9. The JUNO collaboration, "Calibration strategy of the JUNO experiment", JHEP3 (2021) 4.

10. The JUNO collaboration, "Radioactivity control strategy for the JUNO detector", JHEP11 (2021) 102.

11. The JUNO collaboration, "JUNO sensitivity to low energy atmospheric neutrino spectra", Eur. Phys. J. C 81 (2021) 887.

12. The JUNO collaboration, "The Design and Sensitivity of JUNO's scintillator radio purity pre-detector OSIRIS", Eur. Phys. J. C 81 (2021) 973.