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# Status of JUNO experiment

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JUNO is an experiment conceived primarily to study neutrino oscillations. It is composed by 20 kton of high purity liquid scintillator, read-out by a dual system: the large PMT system (LPMT), 17612 20-inch photomultipliers, and the small PMTs (SPMT), 25600 3-inch photomultipliers. The experiment is also endowed with a Water Cherenkonv Veto and a Top Tracker, made by scintillator strips, to control the background due to cosmic rays.
The design of the experiment has been performed in order to reach an unprecedented energy resolution of 3% at 1 MeV, needed to infer the neutrino mass hierarchy from the spectrum measurement of the electron anti-neutrinos produced by two nuclear power plants and observed at a baseline of about 50 km.
The large mass, together with the performances of its detectors, will allow JUNO to precisely measure at sub-percent level several oscillation parameters ($\theta_{12}$, $\Delta m^2_{21}$, $\Delta m^2_{31}$). JUNO will be also an excellent observatory for solar, atmospheric, SuperNova and geo-neutrinos. Other exotic researches, such as the proton decay, will also be made.
To improve the neutrino mass hierarchy measurement, recently the collaboration approved the construction of a reference detector, TAO (Taishan Anti-neutrino Observatory), at a short baseline (30 m) from one of the rector cores. The TAO detector will also be based on the liquid scintillator technology, with the light read-out by SiPM (Silicon Photomultipliers) in order to improve the energy resolution.

In this presentation the experiment design will be presented and the installation status reported.

In addition the physics reach of the experiment will also be discussed.

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## 1. Introduction

Reactors are a pure and intense source of $\overline{\nu}_e$ with energy lower than 10 MeV. They have been used during 1956 to assess the existence of the neutrino [1] and more recently to precisely measure the oscillation parameters $\Delta m^2_{21}$ [2] and $\theta_{13}$ [3]. The re-evaluation of the neutrino flux from reactors led to the so-called Reactor Anti-neutrino Anomaly (RAA) [4], which triggered a new generation of small scale and short baseline experiments devoted to sterile neutrino research [5] as well as investigations about models of fissile isotopes $\beta$-decay chains.

As pointed out in [6], reactors neutrinos can also be used to measure the mass hierarchy exploiting the interference between the "solar" and "atmospheric" oscillation amplitudes. With respect to other methods, e.g. $\nu_\mu$-disappearance and $\nu_\mu \rightarrow \nu_e$ long baseline experiments, the advantage is that the $\overline{\nu}_e$-disappearance probability is independent of $\theta_{23}$ and $\delta_{CP}$, the less known oscillation parameters. An unprecedented detector energy resolution is however required.

Typical reactor $\overline{\nu}_e$ detectors employ Liquid Scintillator (LS) as target and sensitive medium. Anti-neutrinos interact through Inverse Beta Decay (IBD): $\overline{\nu}_e + p \rightarrow e^+ + n$. IBD events are characterized by a prompt energy deposition, given by the positron ionization energy loss and annihilation ($E_{prompt} \simeq E_{\overline{\nu}_e}$ - 0.8 MeV), followed, after thermalization in times of several hundreds of $\mu$s, by the neutron capture on protons with the release of a 2.2 MeV $\gamma$. In case of small size, ton-scale detectors, the liquid scintillator is usually doped with gadolinium, for a faster thermalization (in times of tens of $\mu$s) and a neutron capture with the emission of $\gamma$s for a total of 8 MeV. The delayed coincidence technique is at the base of IBD events selection; isotopes produced by cosmic ray interactions on $^{12}$C, such as $^9$Li and $^8$Be, can mimic the signal because of their $\beta$ decays with the emission of a neutron. Their rejection is based on veto-ing detector volumes around reconstructed cosmic ray tracks.

JUNO (JiangMen Underground Neutrino Observatory) in the GuangDong province of P. R. China has been designed primarily for such a measurement. It is located at an average distance of 52.5 km from the eight cores of two nuclear power plants (Yangjiang and Taishan) for a total thermal power of 26.6 GW. Its description is shown in section 2, its physics reach outlined in section 3 and the installation status reported in section 4. A summary of the contribution is given in section 5.

## 2. JUNO detector description

JUNO [7] [8] has been designed to measure primarily the neutrino mass hierarchy, collecting about $10^5$ IBD events in six years of data taking with 20 kt mass of liquid scintillator. The ambitious goal of 3% energy resolution at 1 MeV energy requires good liquid scintillator transparency over tens of m distances and a photocoverage greater than 75%, obtained by means of 20" photomultipliers (LPMTs) with Photon Detection Efficiency (PDE) greater than 27%. The expected light yield is 1345 photo-electrons/MeV [8]. An energy scale uncertainty lower than 1% is obtained by means of a dedicated calibration system [9] and stereo-calorimetry with smaller PMTs (SPMTs). Another important feature is the radio-activity control of the detector components, whose strategy is described in [10]. A sketch of the detector can be found in figure 1.

The liquid scintillator used in the experiment is composed by Linear Alkyl Benzene (LAB), PPO (2.5 g/l) and bis-MSB (3 mg/l) [11]. In order to measure the neutrino mass hierarchy,

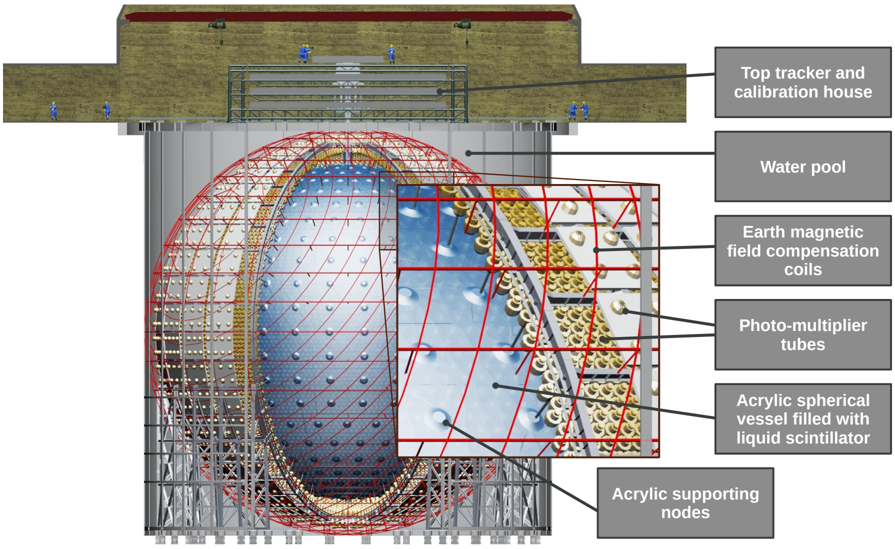


**Figure 1:** JUNO detector sketch.

contaminations lower than $10^{-15}$ g/g for $^{238}$U/$^{232}$Th, $10^{-16}$ g/g for $^{40}$K and $10^{-22}$ g/g for $^{210}$Pb are needed. To measure the flux of low energy solar neutrinos ($^{7}$Be and pep) purity levels two orders of magnitude better are required. A sketch of the LAB purification system is shown in figure 2. The purification is performed in multiple steps: in the external laboratory LAB passes through an $Al_2O_3$ filtration column (for improvement of optical properties) and a distillation tower (to remove heavy elements and improve the transparency); it is then mixed with the PPO and the bis-MSB. Underground the liquid scintillator undergoes water extraction (for removal of U/Th/K radioisotopes) and steam or nitrogen stripping (for removal of gaseous impurities like Ar,Kr,Rn). To measure the purity exploiting fast coincidences in the U/Th chains, a specific detector, called OSIRIS, using 17 t of liquid scintillator will be also installed in the underground laboratory [12].

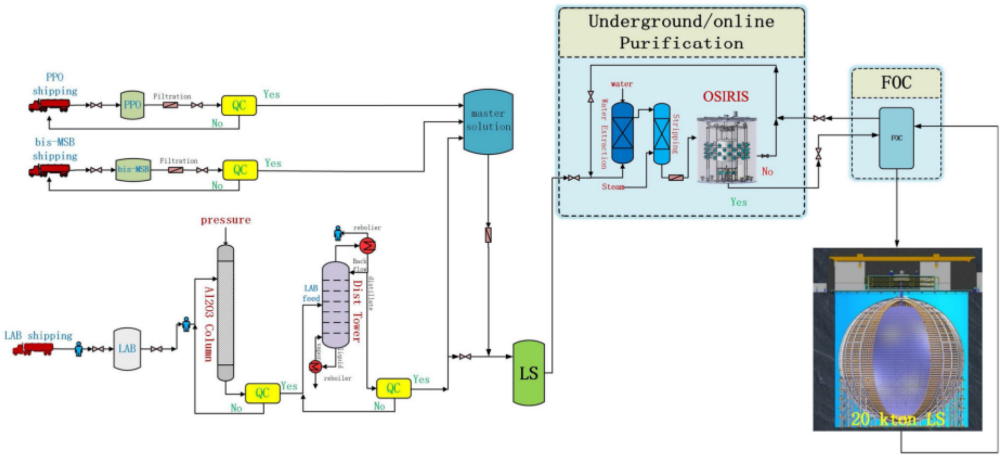


**Figure 2:** Liquid scintillator purification scheme.

The scintillator is enclosed inside an acrylic vessel, made by bulk polymerization of 265 panels, 12 cm thick, for a total weight of about 600 t. The acrylic transparency is required to be greater than 96% with high radiopurity (U/Th/K contamination lower than 1 ppt). The sphere is held by the Stainless Steel Structure (SSS) by means of supporting bars. The SSS and the acrylic vessel, filled with the LS, constitute the Central Detector (CD), which is immersed in a water pool. Sketches of the acrylic sphere and of the SSS are shown in figure 3.

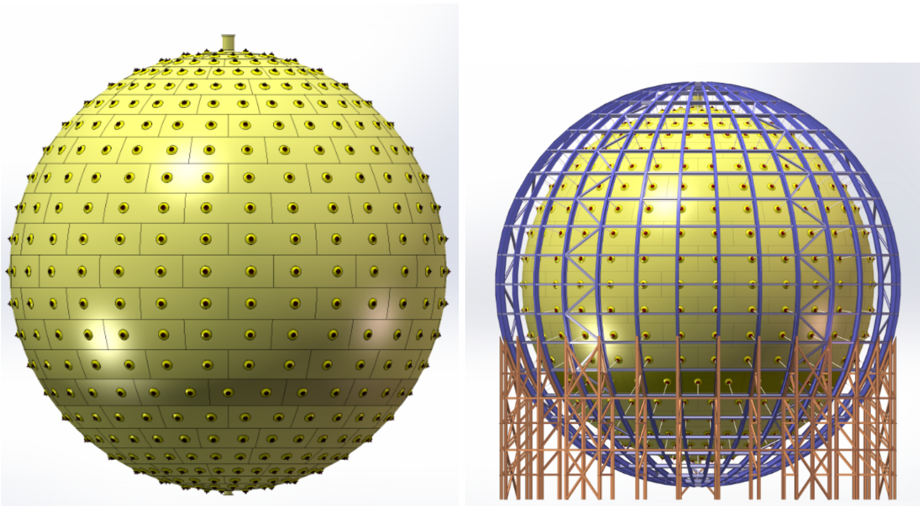

**Figure 3:** Acrylic vessel (left) and Central Detector structure (right).

The SSS holds also the PMT read-out systems. The light produced inside the LS is collected by means of more than 17612 20" PMTs, 5000 of which are R12860 dynode PMTs by Hamamatsu and the rest are produced by North Night Vision Technology (NNVT) comapny and based on Micro-Channel Plate (MCP) electron multiplication. Additional 2400 20" MCP PMTs are faced towards the water pool and used for collecting Cherenkov light. The PMTs are water-proof potted with the voltage divider and have anti-implosion protection.

Each PMT is powered by one DC-DC converter and its signal is digitized at 12 bit by a custom ADC with 1 Gs/s sampling frequency. The converters and the ADCs of three PMTs are placed inside under-water boxes, containing also a dedicated 2 GB RAM memory for SuperNova events and driven by a FPGA based Global Control Unit. The trigger system (with a fixed latency of 2 $\mu$s) and the white rabbit for synchronization are located outside of the water pool, inside the electronics rooms. A scheme of the read-out is shown in figure 4.

All the produced LPMTs have been qualified in a dedicated facility located in ZhongShan by measuring their operating voltage, dark count rate, Transit Time Spread (TTS) and PDE [13]. In figure 5 the distributions of the measured PDE and TTS are shown. MCP PMTs have a slightly higher PDE (increased after the first delivery batches) with respect to Hamamatsu dynode PMTs at a price of a worse TTS. The average PDE greater than 27% matches the requirements. MCP PMTs because of their higher PDE are more suited for energy measurement, while the dynode ones are crucial for tracking and vertex reconstruction, their disposition optimized by means of a dedicated MonteCarlo simulation.

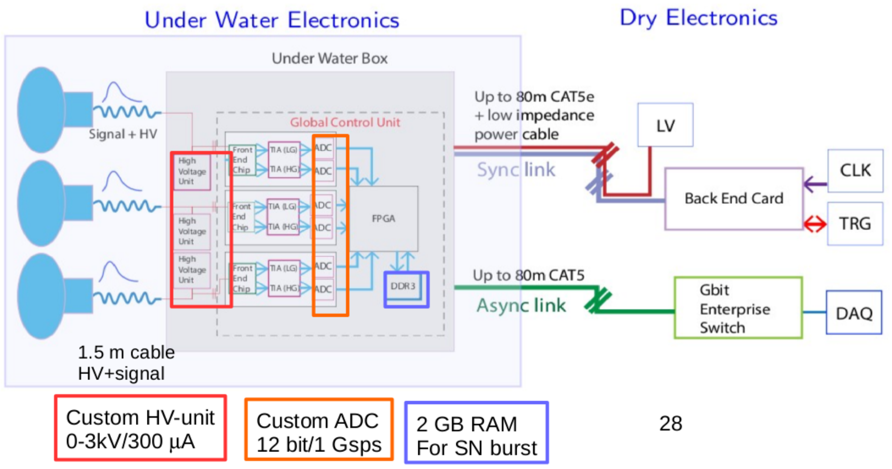


**Figure 4:** LPMT read-out system scheme.

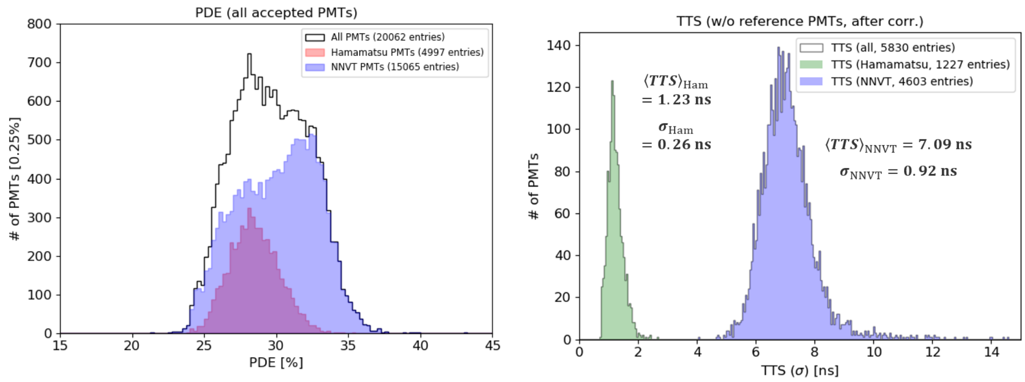


**Figure 5:** PDE measured over the whole LPMT production (left plot) and TTS measured on a sub-sample (right plot).

The total photocoverage of the LPMT system is 75% and reaches 78% with the SPMTs.

A scheme of the SPMT system is shown in figure 6. It is conceived similarly to the LPMT one, with 128 PMTs connected to an under-water box. The 25600 PMTs have been produced tested by HZC company [14]. The Front-End electronics is based on the use of the CatiROC chip by weeroc [15]. The SPMT system is used as a complementary photo-detection system to improve the control of systematics and increase the dynamic range in photon-counting mode.

A systematic error lower than 1% is obtained by means of the SPMTs and of the calibration system, whose sketch is shown in figure 7. It is composed by four different subsystems employing $\gamma$, $\beta$ and neutron sources:

- Automatic Calibration Unit (ACU): deploying sources in one dimension along the vertical axis.
- Cable Loop System (CLS): deploying sources in a 2D plane inside the acrylic vessel.

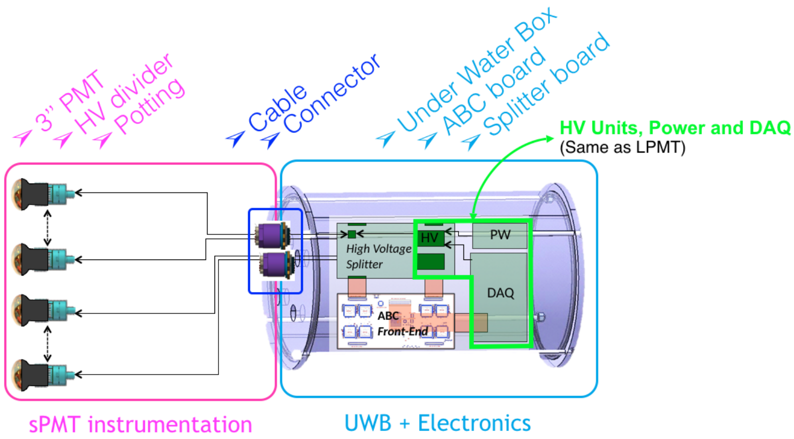


**Figure 6:** SPMT system overview.

- Guide Tube (GT): running in a 2D plane in the inner surface of the vessel.
- Remotely Operated Vehicle (ROV): transporting sources in any position internal to the vessel.

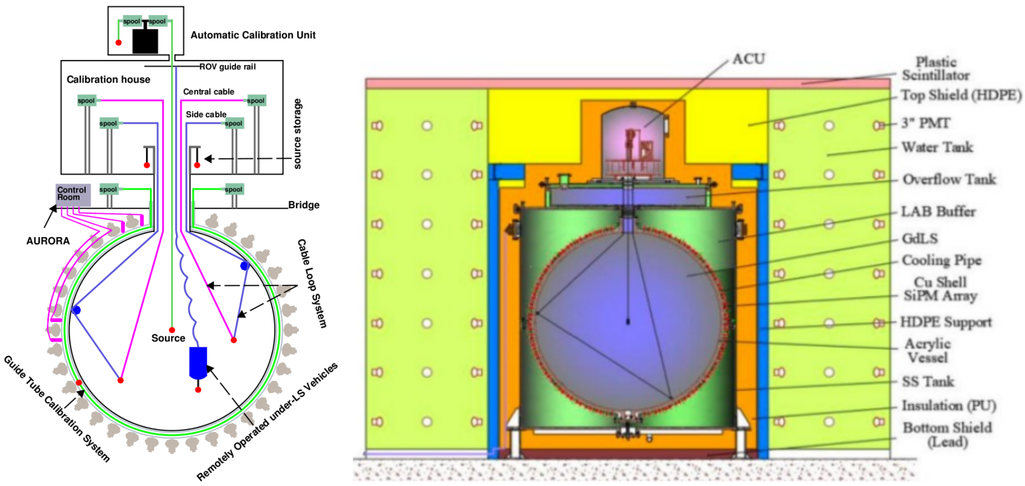


**Figure 7:** JUNO calibration system (left plot). TAO detector sketch (right plot).

The non-linearity of the liquid scintillator response is tackled with the use of different sources, the non-linearity of the Front-End electronics with intensity tunable sources and the detector non-uniformity by positioning sources in different detector places.

The CD is surrounded by 35 kt of ultra-pure water, acting as a shielding against neutrons, produced by cosmic rays interaction in the surrounding rock, as well as a Cherenkov veto for cosmic rays (a tagging efficiency greater than 99% is required against cosmogenic backgrounds). The Cherenkov light is collected by means of 2400 PMTs, installed on the SSS and instrumented similarly to those for LS light read-out. The water is refilled and kept at 21 $^{o}$C degree (with 1 degree tolerance) to avoid mechanical stresses to the Central Detector and to cool read-out electronics.

In the SSS and in the water pool walls, Helmotz coils are placed in order to compensate the Earth magnetic field to avoid PMT performance deterioration [16].

The water pool is covered by a Top Tracker of area 21×40 $m^2$ made by three layers of plastic scintillator strips, 2.6 cm wide and 6.86 m long, recovered from OPERA experiment [17]. The light from the strips is collected by means of WLS fibers and read-out by means of 992 H7546 Multi anode PMTs by Hamamatsu. OPERA electronics, not suited because of the increased environment background, will be refurbished by a new read-out system based on MAROC3 chip by weeroc.

The collaboration will also build, at a distance of 30 m from one of the cores, a reference detector, called TAO (Taishan Anti-neutrino Observatory) [18], in order to provide a a model-independent reference spectrum for JUNO and to investigate about anti-neutrino production models in reactors. A sketch of TAO detector is shown in figure 7. The experiment is composed by 2.6 t of liquid scintillator enclosed in an acrylic vessel, surrounded by a water Cherenkov veto and a top plastic scintillator tagger. For an improved energy reconstruction with respect to JUNO, the light read-out will be based on a full coverage of SiPM tiles (with PDE ~ 50%). To cope with the thermal noise of semi-conductor devices, the liquid scintillator and the read-out electronics will be operated at -50 $^oC$. The light yield of TAO detector will be about 4500 photo-electron/MeV, corresponding to an energy resolution better than 2% at 1 MeV.

## 3. JUNO physics reach

The JUNO experiment has been designed to reach at least 3 $\sigma$ significance in the determination of the neutrino mass hierarchy [19]. The 20 kt liquid scintillator detector, by means of suitable cuts, will detect, on the basis of a preliminary estimation, about 47.1 IBD/day with 3.6 background event/day, dominated by cosmogenic production of $^9$Li and $^8$Be in the LS. According to [20] a 5 $\sigma$ determination is possible in combination with $\nu_\mu$-disappearance data from PINGU, ORCA or No$\nu$a and T2K in a time ranging from 2 to 7 years. Profiting of the large mass, JUNO will also determine $\Delta m^2_{31}$, $\Delta m^2_{21}$ and $\sin^2(2\theta_{21})$ with sub-percent precision.

The experiment will also measure solar neutrinos from the $^8$B branch [21], performing an independent measurement of the solar neutrino oscillation parameters. Solar neutrinos from $^7$Be and pep branches will also be measurable, depending on the reached purification level of the scintillator (see section 2).

JUNO will also be a neutrino observatory from other natural sources (geo-neutrinos, supernova and atmospheric neutrinos [22]) as well as for other exotic phenomena, like, for instance, the proton decay (in particular through the channel $p \to K^+\overline{\nu}$).

## 4. Installation status

The external campus at Kaiping is active since January 2021. At the present time, the Liquid Scintillator hall, the liquid nitrogen towers, the 5 kt LAB tank and the $Al_2O_3$ filtration plant have been built and the first scintillator batches delivered.

During September 2021 the excavation of the water pool has been completed; the installation of the other liquid scintillator facilities and of OSIRIS detector, delivered on site, is ready to start.

The photomultipliers 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 at the end of 2022.

## 5. Conclusions

Reactor neutrino experiments played a key role in neutrino oscillation physics by measuring $\Delta m^2_{21}$ and $\theta_{13}$. In the near future electron anti-neutrino disappearance will also be used to determine the neutrino mass hierarchy.

JUNO will be the largest reactor anti-neutrino detector ever built (20 kton of liquid scintillator) with an unprecedented energy resolution (3% at E=1 MeV). Located at about 50 km from two nuclear power plants with a total power of 26.6 GWth, the experiment has been designed to reach in six years of data taking a 3 $\sigma$ sensitivity on the neutrino mass hierarchy. At the same time, it will also measure other oscillation parameters with sub-% precision ($\theta_{12}$, $\Delta m^2_{21}$ and $\Delta m^2_{31}$) as well as neutrinos form natural sources.

The external laboratory is already active, while the underground site excavation is finished. The installation of the liquid scintillator purification system has begun, while the production and assembly of the other detector components is going on. The detector completion is foreseen before the end of 2022.

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