JUNO Detector Design & Status

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Abstract. The Jiangmen Underground Neutrino Observatory (JUNO) is a next-generation liquid-scintillator reactor neutrino experiment under construction in Southern China. It is a multi-purpose experiment with a wide range of applications in neutrino physics, ranging from a neutrino mass ordering (NMO) determination, the detection of solar, geo-, atmospheric neutrinos, and Supernova neutrinos, to the measurement on particular oscillation parameters with sub-percentage precision. The JUNO central detector (CD) is designed to reach an energy resolution of 3% at 1MeV. The detector is being installed in a recently excavated experimental hall, 50 m wide and located under 700 m of granite overburden (1800 m.w.e.). The CD contains a 35.4-meter diameter acrylic vessel filled with 20-kt of LAB-based liquid scintillator, making it the largest liquid-scintillator detector of its kind in the world. The scintillation light will be read-out by 17612 20" photomultiplier tubes (PMTs) and 25600 3" PMTs, reaching a photocathode coverage higher than 75%. A water pool filled with ultrapure water equipped with 2,400 PMTs surrounds the CD; on top of the water pool, a 3-layer plastic scintillator tracker completes the JUNO veto system for cosmic muons detection. JUNO construction will be completed in 2022. This talk presents the detector design and status of the experiment.

1. Introduction

The Jiangmen Underground Neutrino Observatory (JUNO), a 20-kton multi-purpose underground liquid scintillator detector, was proposed to determine the neutrino mass ordering (NMO) as a primary physics goal [1, 2]. Besides the neutrino mass ordering, the large fiducial volume and the excellent energy resolution of JUNO offer exciting opportunities for addressing many important topics in neutrino and astro-particle physics.

The JUNO experiment is located in Jinji town, 43 km to the southwest of Kaiping city, a county-level city in the prefecture-level city Jiangmen in Guangdong province, China. As shown in Fig. 1, the experimental site is at equal distances of ~53 km from the Yangjiang nuclear power plant (NPP) and the Taishan NPP, optimized to have the best sensitivity for determining the mass ordering. Yangjiang NPP has six reactor cores of 2.9 GWth each (thermal power). Taishan NPP has two 4.6 GWth cores. The total thermal power of the Yangjiang and Taishan NPPs is 26.6 GWth. The JUNO detector will be located in a cylindrical pit in an underground cavern. The vertical overburden for the detector center is 700 m (1800 m.w.e). The experimental hall will have two accesses: a 564 m deep vertical shaft and a 1266 m long tunnel with a slope of 42.5%. The surrounding rock is granite. The muon rate and average energy in the JUNO detector are 0.004 Hz/m2 and 207 GeV estimated by simulation, taking the surveyed mountain profile into account.

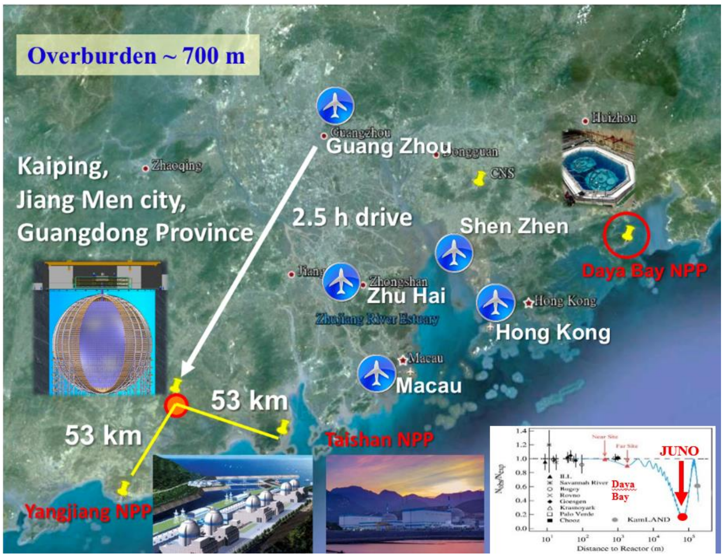

Fig.1 The location of the JUNO experiment

2. Signal and backgrounds

JUNO determines the NMO using the neutrino oscillation interference pattern at a medium baseline (53 km). Precise measurement of the oscillated antineutrino spectrum is a key for JUNO. This requires a 20-kton liquid scintillator detector with an unprecedented effective energy resolution of 3%/√E(MeV) [3]. JUNO detects the reactor antineutrino signal via inverse beta decay (IBD) reaction. The reactor antineutrino interacts with a proton, creating a positron (e+) and a neutron. The positron quickly deposits its energy and annihilates into two 0.511-MeV-rays, which gives a prompt signal. The neutron thermalizes and is subsequently captured on hydrogen or carbon nuclei, forming a delayed signal. The spatial and temporal coincidence of the prompt-delayed signal pair in such a short time significantly reduces backgrounds. Accidental coincidence background, 8He/9Li, fast neutrons and (α ,n) reactions are the major backgrounds for the reactor antineutrino detection in JUNO. A fiducial volume and muon veto cut can significantly reduce the Muon related, accidental and the (α ,n) backgrounds. Energy selection, time coincidence, and vertex correlation of the prompt and delayed signals are used in the antineutrino selection to further suppress the accidental background. To reject the cosmogenic backgrounds such as ^{8}He/^{9}Li and fast neutrons, muon veto cuts need to be optimized to maximize the detector live time and minimize the dead volume losses. A set of preliminary selection criteria is studied in [2]. Tab. 1 summarizes the efficiencies of the selection cuts and the corresponding reductions for various backgrounds. JUNO will observe ~60 IBD events per day, with an about 6% background contamination.

Table 1: The efficiencies of antineutrino selection cuts, signal and backgrounds rates

Selection	IBD efficiency	IBD	Geo-νs	Accidental	^{9}Li/^{8}He	Fast n	(α, n)
-	-	83	1.5	-	84	-	-
Fiducial volume	91.8%	76	1.4	410	77	0.1	0.05
Energy cut	97.8%	73	1.3		71		
Time cut	99.1%						
Vertex cut	98.7%			1.1			
Muon veto	83%	60	1.1	0.9	1.6		
Combined	73%	60	3.75				

Compared to the assumptions in the Yellow Book [2], several important changes have occurred to the experimental inputs now [4]. The location of the JUNO experimental hall was shifted by about 60 m to adapt to the underground geological conditions. The cosmic muon flux in the new experimental hall increases by 30% due to a reduction of the vertical overburden by 58 m. Recent efforts in optimization of the antineutrino selection show a possibility to minimize the dead time after the muon veto. The live time fraction increases from 83% to 93%, partially compensating for the statistics loss due to less reactor power. The changes on the baselines and the overburden have negative but negligible impacts on the

NMO sensitivity. All 20-inch PMTs have been procured and tested. The average photon detection efficiency for PMTs in the Central Detector is 29.1%, comparing to the designed value 27% used in [2]. Combined analysis of the TAO and JUNO data shows that a moderate improvement could be achieved compared to the simple assumption of 1% bin-to-bin uncertainty, while the model dependence of the input spectrum can be removed.

3. JUNO detector system

The JUNO detector consists of the Central Detector (CD), a water Cherenkov detector and the Top Tracker (TT). A schematic view of the JUNO detector is shown in Fig. 2. The CD is a liquid scintillator (LS) detector with a designed effective energy resolution of $3\%/\sqrt{E(\mathrm{MeV})}$. It contains 20-kton LS in a spherical acrylic vessel, which is submerged in a water pool. The acrylic vessel is supported by a stainless steel (SS) structure via connecting bars. The CD photomultiplier Tubes (PMTs) are installed on the inner surface. A total of 17,612 20-inch and 25,600 3-inch inward-facing PMTs are installed to detect the scintillation light. The photocathode coverage is 75% for the 20-inch PMTs and 2.7% for the 3-inch PMTs. The water pool is instrumented with 2,400 outward-facing 20-inch PMTs to detect the Cherenkov light from cosmic muons, acting as a veto detector. The muon detection efficiency is expected to be 99.8%. Compensation coils are mounted on the SS structure to suppress the Earth's magnetic field and minimize its impact on the photoelectron collection efficiency of the PMTs. The CD and the water Cherenkov detector are optically separated. On top of the water pool, a muon tracker will be installed to measure the muon tracks. Plastic scintillator strips decommissioned from the Target Tracker of the OPERA [5] experiment will be reused as the JUNO Top Tracker (TT). The TT covers more than 25% of the area of the top surface of the water pool. A chimney for calibration operations connects the CD to the outside from the top. The calibration instruments are stored in the Calibration House, above which a special radioactivity shielding and a muon detector are designed.

The JUNO LS has a similar recipe as the Daya Bay LS [6] but without gadolinium loading. Linear alkyl-benzene (LAB), a straight alkyl chain of 10-13 carbons attached to a benzene ring, is used as the detection medium due to its excellent transparency, high flash point, low chemical reactivity, and good light yield. The LS will be purified before filling to improve its radio purity and transparency, which is crucial for such a gigantic detector. A pilot plant test shows that the LS attenuation length can reach > 20 m. Combined with the PMT detection efficiency and other detector parameters, a yield of 1345 photoelectrons per MeV is obtained in simulations. The targeted LS radio purity of JUNO is 10^{-17} g/g for U/Th/K.

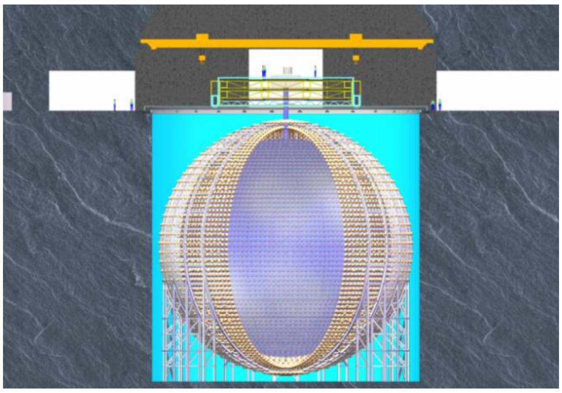

Fig.2 Side view of JUNO detector system

4. Progresses

The ambitious goal of the JUNO detector, to determine the neutrino mass ordering, requires an excellent energy resolution of 3% at 1 MeV. The 20-kton liquid scintillator detector is one of the most challenging parts of JUNO, especially in mechanics, given its huge size. The LS will be contained in a spherical acrylic vessel with an inner diameter of 35.4 m and a thickness of 120 mm. The acrylic vessel will be supported by a spherical stainless steel shell structure with an inner diameter of 40.1 m via 590 connecting bars. The shell structure sits on a bearing consisting of 30 pairs of supporting legs, made of stainless steel truss structures and rooted on the concrete floor of the water pool. The shell structure and its bearing is called the main structure. The main structure also provides support for the front-end electronics, cables, and the anti-geomagnetic field coil. The whole structure must be stable and reliable for 30 years of the designed JUNO lifetime. All the productions of the components, pre-testing, and pre-assembly of the acrylic vessel and the main structure are going smoothly as showing in Fig. 3. And the proposed installation procedure also tested on the lifting, platform assembly and moving, and pre-integration test as showing in Fig.4.

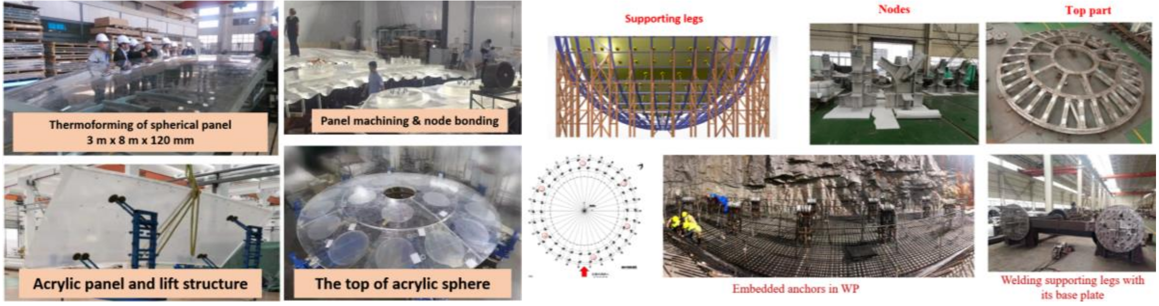

Fig 3: Left: The acrylic panels prototyping, production, transportation test, and pre-assembly. Right: the supporting legs, roots on the water pool floor, connecting bars, and production of the Main Structure.

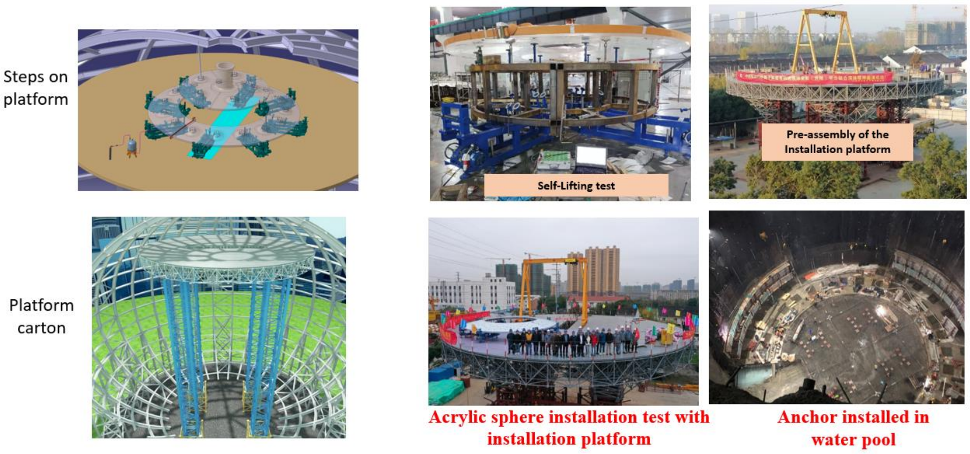

Fig 4: Installation carton, platform, and pre-testing

From the perspective of PMTs, the key ingredients to reach the design energy resolution are a large photodetector area coverage, high photon detection efficiency, low dark noise, and stable operation of the whole PMT system. Requirements for the PMTs were formulated in the production contracts with NNVT and Hamamatsu companies to produce 15,000 MCP PMTs and 5,000 dynodes PMTs, respectively. Based on that, procedures and devices were developed to test the PMTs after they were received from the producers, and extensive tests were carried out to ensure the PMTs' performance and quality. After then, the PMTs were instrumented with high voltage dividers, waterproof sealing, and protection covers to eventually work in water for the JUNO experiment. All PMTs have been tested. The average photon detection efficiency (PDE) is 29.1% for the 20-inch PMTs and > 24% for the 3-inch PMTs. The waterproof potting of 20-inch PMT is finished in Sep 2021, and the protection cover manufacturing is going well.

A satellite experiment of JUNO, Taishan Antineutrino Observatory (TAO) [7], aims for precisely measuring reactor antineutrino spectrum, provide a model-independent reference spectrum for JUNO's NMO determination, reactor monitoring and safeguard, and search for new physics. A 1:1 prototype is under construction and it will be tested without full SiPM; TAO is expected to start operation in 2022. The R&D is going smoothly.

The civil construction at Kaiping JUNO experimental site is almost finished, with the water pool excavation completed, and doing the pre-installation of the water pool as shown on Fig 5 and Fig 6.

Fig 5: The latest (July) status of JUNO onsite surface building

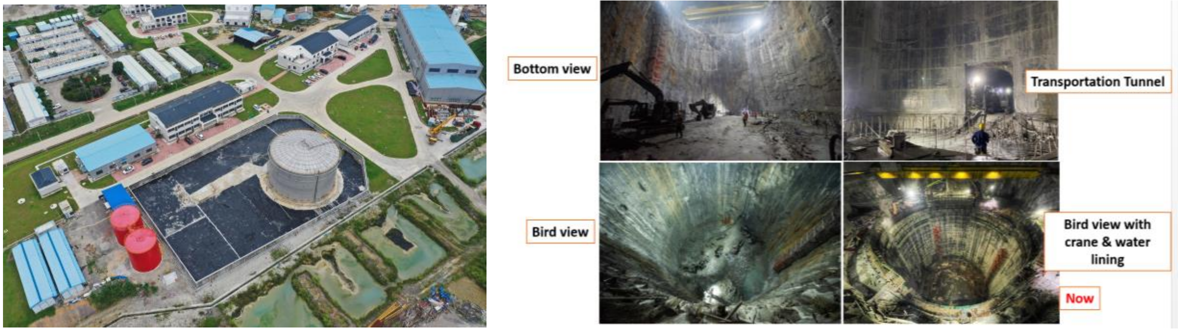

Fig 6: Left, the LS storage tank; Right, the water pool water lining in progress.

5. Summary

JUNO has extensively program in particle physics & astrophysics, including to probe the neutrino oscillation mechanism at unprecedented precision. The water pool civil construction is completed, and the waterproof lining is in progress. The production, assembly and installation of the detector components all are going on well too. The detector construction is planned to be completed by the end of 2022.

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