PROCEEDINGS OF SCIENCE

The JUNO detector: design concept and status

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The JUNO central detector will contain a 35.4 m diameter acrylic vessel filled with 20-kt of linear alkyl benzene based scintillator, and submerged in a water pool equipped with photomultipliers to act as Cherenkov detector. The scintillation light will be read-out by 17612 20" photomultipliers and 25600 3" photomultipliers, reaching a geometric coverage of about 78%. On top of the main detector, a plastic scintillator tracker will complete the JUNO veto system for cosmic muons. JUNO's ambitious design primarily aims to the determination of the neutrino mass ordering at high statistical significance ($3-4\,\sigma$ in about 6 years of data taking), by measuring the oscillation pattern of electron antineutrinos generated by two nuclear power plants, on a $\sim$ 53 km baseline from the experimental site. JUNO will target an unprecedented 3% energy resolution at 1 MeV scale, thus it will be a unique facility for particle and astroparticle physics. Besides its main goal, JUNO indeed aspires to the sub-percent determination of the neutrino oscillation parameters ($\sin^2\theta_{12}$, Δm^2_{21}, and Δm^2_{31}) as well as to the measurement of atmospheric neutrinos, to solar neutrino precision spectroscopy, and to the detection of low-energy neutrinos coming from supernovae and geo-neutrinos. In this contribution, the JUNO detector design and the status of the experiment construction are presented.

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[1] On behalf of the JUNO collaboration.
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1. Introduction

The Jiangmen Underground Neutrino Observatory (JUNO) [1] is a large liquid scintillator neutrino experiment which is currently in construction in the Jiangmen underground facility, near the city of Kaiping, in Southern China. This location is really peculiar since it is at about 53 km from both the nuclear power plants of Yangjiang (6 reactors, 2.9 $\mathrm{GW_{th}}$ each) and Taishan (2 reactors, 4.6 $\mathrm{GW_{th}}$ each), and since there is no other nuclear power plant within a 200 km radius.

The experimental site construction started in 2014 and it now includes an assembly hall, a vertical and a slope tunnel, an underground experiment hall, and some other facilities.

Due to the very small neutrino interaction rate, the shielding against cosmic rays and the experiment extreme radiopurity are mandatory. To suppress the muon induced backgrounds, the JUNO detector is located below an average rock overburden of about 650 m, resulting in a shielding capacity against cosmic rays of about 1800 m.w.e.: in JUNO we expect a muon flux [1] of $\Phi(\mu) \approx 0.004\ \mu\ \mathrm{m^{-2}\,s^{-1}} \rightarrow \approx 10^5\ \mu\ \mathrm{m^{-2}\,y^{-1}}$, with an average muon energy of 207 GeV.

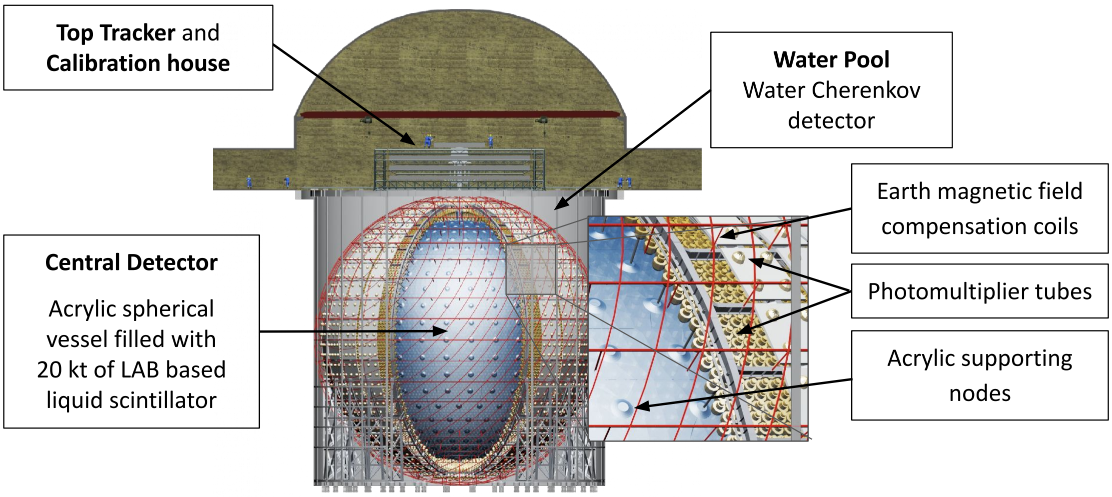

Figure 1: Schematic view of the structure of the JUNO apparatus.

2. The JUNO detector structure

In order to fulfil its very rich physics program, JUNO has to target the highest radiopurity from its very beginning. The detector structure (Fig.1) will exploit the principle of graded-shielding: the more moving towards the center of the detector, the radiopurer the detector will be. Starting from the external, there is the Top Tracker with the calibration house (Sec. 2.1) and the Water Pool (Sec.2.2), which will act as gamma and neutron shield as well as water-Cherenkov detector. Then there will be the Central detector Support Structure (Sec. 2.3) on which photomultipliers (PMTs, Sec. 3) will be installed in a specific geometric pattern that will guarantee the maximum geometric coverage. Finally, the acrylic spherical vessel which will contain the core of the JUNO experiment: 20-kt of organic linear alkyl benzene (LAB) based liquid scintillator (Sec. 4).

2.1 The Top Tracker and the Calibration house

The top tracker's goals are to provide a precise muon tracking and to study the cosmogenic background. The JUNO top tracker will cover about 60% of the water pool top surface and, thus, will be able to monitor about one-third of all atmospheric muons passing through the central detector. The detector medium of the top tracker will consist of three layers of plastic scintillator panels (dimensions: $\approx 40\,\mathrm{m} \times 20\,\mathrm{m} \times 3\,\mathrm{m}$), which were inherited from the OPERA experiment target tracker [2]. Currently, all plastic scintillator modules are already in China and we are finishing up the electronics installation.

JUNO will profit from an advanced calibration system [3] to test and study the energy scale, the detector response non-uniformity and the energy non-linearity. These crucial items will be achieved thanks to three different scan systems: the 1D automatic calibration unit, the 2D cable loop system and guide tube calibration system, and the 3D remotely operated vehicle. Several radioactive sources (γ, e^+, n) with energy covering from 0.5 to about 8-10 MeV will be used in order to fully map the JUNO energy region of interest.

2.2 The Water Pool

The JUNO water pool will contain the central detector, and about 35 kt of ultra pure water, aiming to protect the central detector itself from natural radioactivity in surrounding rocks. Being equipped with 2400 20"-PMTs, the water pool will also serve as water Cherenkov detector to tag cosmic muons Cherenkov light, with an efficiency of more than 99.5% [4]. The water pool was constructed according to strict requirements of low radon radioactivity, stable temperature so to prevent any convective motion of the water, and an attenuation length of 35 m.

Figure 2: The JUNO stainless steel support structure in the water pool.

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2.3 The Central Detector: support structure and acrylic vessel

Inside the water pool there is a steel support structure (Fig.2) of about 40 m diameter which will support PMTs and bear the JUNO acrylic vessel. The support structure, whose weight is around 600 t, was assembled in Spring 2022.

The acrylic sphere encloses the scintillator. It is a 35.4 m diameter sphere, with a weight of about 600 t, designed and selected for its high radiopurity and optimal optical features. The acrylic sphere structure is modular: 265 plates are currently being prepared, polished, cleaned, and pre-assembled at their production factory.

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3. The JUNO Photomultipliers tubes

The JUNO experiment will use a huge number of photomultipliers: besides 2400 20”-PMTs in the water pool, 17612 20”-PMTs [5] and 25600 3”-PMTs [6] will be installed in the central detector as per the scheme of Fig.3. Their photon detection efficiency was evaluated to be ∼30% and ∼25% for the 20” and the 3” PMTs, respectively. The PMTs assembly precision will be tight ($<$ 1mm) and final clearance between photomultipliers will be an impressive 3mm: this will guarantee JUNO a PMT geometric coverage of about 78% (75.2% and 2.7%, for the 20” and the 3” PMTs, respectively), the largest ever achieved so far.

JUNO will profit of an optimal light level for a PMT-based detector: indeed, the expected light-yield value is 1345 p.e./MeV [3]. Moreover, some recent studies have shown that, thanks to refinements to the optical model and improvements on the central detector geometries, the JUNO light-yield could further increase to an unprecedented 1665 p.e./MeV.

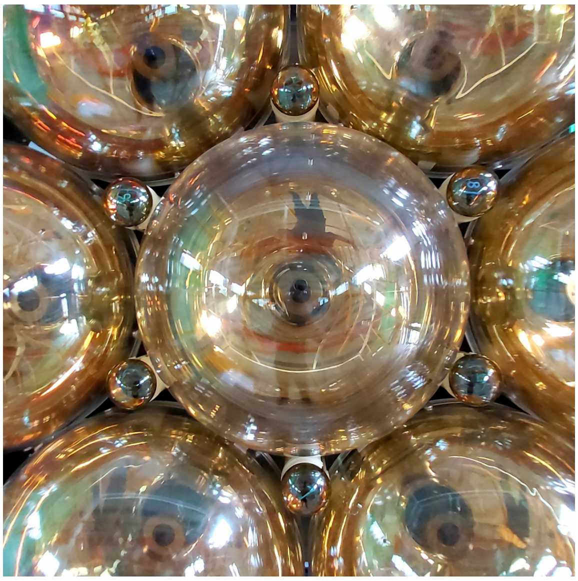

Figure 3: Installation pattern for the JUNO photomultipliers tubes.

All PMTs have already been produced, tested and instrumented with waterproof potting. The related electronics [7] will be specially custom-made and it will be installed close to the PMTS, i.e. underwater, to improve and maximize the signal-to-noise ratio.

4. The JUNO Scintillator

The chosen liquid scintillator [8] for the JUNO experiment is an organic mixture of linear alkyl benzene as solvent, plus a fluor (PPO, 2.5 g/L), and a wavelength shifter (bis-MSB, 3 mg/L) as solutes. The strict background constraints to perform reactor and solar physics ($10^{-15} - 10^{-17}$ g/g in ^{238}U and ^{232}Th, respectively) call for the JUNO scintillator to be extremely radiopure. Moreover, the scintillator will have to show a high light yield ($\sim 10^4$ photon/MeV) and an attenuation length of more than 20 m at the characteristic light emission ($\lambda_{\text{avg}} = 430$ nn).

Prior to its insertion into the JUNO acrylic sphere, the 20-kt liquid scintillator will be purified onsite with Alumina (Al_2O_3) filtration to remove particulates, distillation and water extraction to remove radioactive impurities, and gas stripping to remove Radon and Oxigen. Before and during the filling, part of the scintillator (about 15%) will be analyzed in a dedicated facility named OSIRIS [9] in order to test and verify the radiopurity constraints.

5. Conclusions

The JUNO history started back in 2014 when the collaboration was established, and has progressed a lot so far. Despite the unavoidable delays due to the pandemics, the construction of the detector is expected to be completed by 2023. Its key features will be the large mass of ultra-radiopure liquid scintillator, the low background levels thanks to a clever background suppression strategy, and the very careful installation procedures. Moreover, JUNO will profit from the scintillator high light yield and transparency, from the largest ever PMTS geometric coverage, and from the comprehensive calibration program to precisely address the detector response function and its energy scale.

These factors allow JUNO to target the very high energy resolution ($\lesssim 3\%$, at 1 MeV) needed to accomplish all the goals of its impressive scientific program.

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