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The Top Tracker of the JUNO Experiment

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The Jiangmen Underground Neutrino Observatory (JUNO) is a large liquid scintillator neutrino experiment under construction in South China; the main goal of JUNO is the direct measurement of the neutrino mass ordering using reactor antineutrinos. The main role of the Top Tracker of the JUNO Experiment is to identify and perform precision reconstruction of cosmic muons passing through the JUNO detector. This will allow the study of the contribution of the cosmogenic isotope background to the detector signal and thus decrease the related systematic error. The Top Tracker will cover about 60% of the surface area above the Water Cherenkov detector and the Central Detector and will be able to precisely track about 30% of the muons crossing the JUNO detector. A sample of well-reconstructed muon tracks provided by the Top Tracker will be used to calibrate the muon track reconstruction algorithms that use only the Central Detector information. The Top Tracker is a 3-layer array of plastic scintillator strips, re-purposed from the OPERA Target Tracker. The Top Tracker will use state-of-the-art electronics that are capable of coping with the high levels of event rate dominated by the radioactive background from the surroundings. This paper will present the Top Tracker and report its performance based on the electronics tests, calibration, and detector simulation results.

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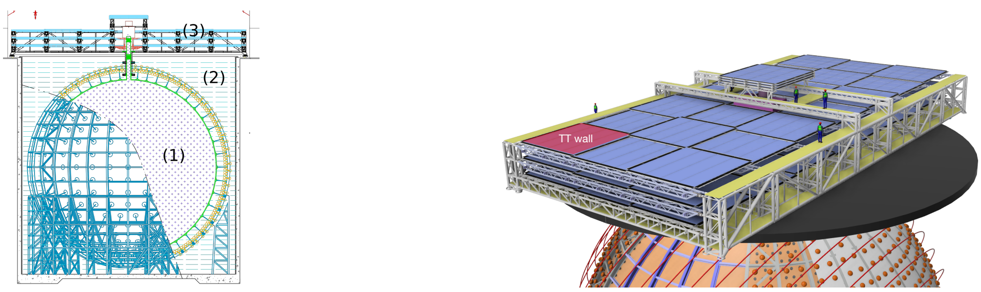
1. Introduction

The Jiangmen Underground Neutrino Observatory (JUNO) is a 20-kton liquid scintillator (LS) detector under construction in Jiangmen province, China [1]. Its large fiducial volume coupled with an excellent energy resolution offers interesting prospects to probe many compelling topics in neutrino physics as well as astroparticle physics. JUNO carries the potential to determine the neutrino mass ordering (NMO) with 3-4σ significance with 6 years of data, as well as to measure some of the neutrino oscillation parameters with sub-percent precision already after a few months of data taking. The JUNO experimental site is situated about 53 km from two nuclear power plants (NPP). The distance is optimized to achieve the best sensitivity for the NMO determination via the detection of electron antineutrinos ($\bar{\nu}_e$) emitted by the NPPs.

A schematic of the JUNO detector is shown in Fig. 1. The LS will be placed in the Central detector (CD) and it will be the neutrino target. The CD will be equipped with 17612 20-inch and 25600 2-inch photomultiplier tubes to achieve an optical coverage of 78%. JUNO will detect $\bar{\nu}_e$ via the inverse beta-decay (IBD) interaction, where a $\bar{\nu}_e$ interacts with a proton in the CD via charged current weak interaction, producing an e^{+}+n pair. However, cosmic muons that cross through the JUNO detector can generate cosmogenic isotopes, most notably ^{9}Li and ^{8}He, that decay to produce e^{-}+n pairs that mimic the IBD signature. The CD is immersed in a cylindrical pool of ultra-pure water which acts as a Water Cherenkov Detector (WCD) that picks up Cherenkov radiation produced by muons crossing the water pool. The WCD and the Top Tracker (TT) [2] constitute the muon veto system, to track and veto almost all the muons passing through the CD. To suppress the muon-induced cosmogenic background, JUNO will deploy a cylindrical veto cut around well-reconstructed muon tracks passing through the CD for a sufficiently long time.

2. The Top Tracker Detector

The main role of the TT is to track and perform precision reconstruction of cosmic muons passing through the TT. It covers about 60% of the surface area above the WCD, and can precisely track about 30% of the total muon flux at the CD. The TT will provide a well-reconstructed muon sample that can be used to calibrate the CD-only muon reconstruction. The TT is a modular 3-layer array of plastic scintillator strips, coming from the de-commissioned OPERA Target Tracker [3].



(a) (b)

Figure 1: Schematic view of (a) the JUNO detector and its sub-detectors (1) Central Detector, (2) Water Cherenkov Detector, and (3) the Top Tracker. (b) Schematic view of the Top Tracker detector.

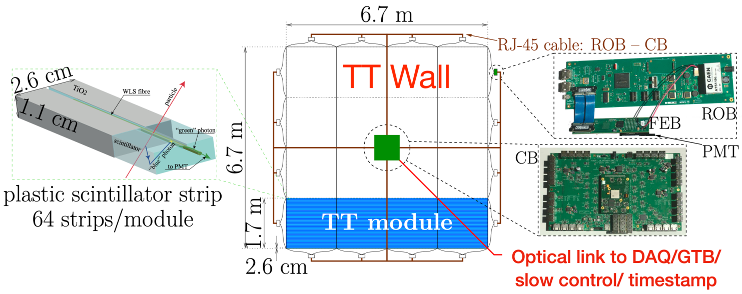


Figure 2: The TT electronics chain and the electronics board arrangement on a single TT wall.

The TT consists of 62 square walls arranged in a 3×7 configuration on 3 layers, as illustrated in Fig. 1(b). Each wall consists of 8 TT modules, with 64 plastic scintillator strips each, which are laid in 2 sub-layers as shown in Fig. 2, to obtain 2-D track information of the passing muons. The scintillation light is collected using optical fibers embedded in the scintillator strips, which are coupled to 64-channel multi-anode Photomultipliers (MA-PMT) situated at either end of the TT modules, instrumented with electronics developed for JUNO, which will be detailed under Section 2.1. At the JUNO site, the expected muon rate crossing the entire TT is around 4 Hz. In contrast, the expected event rate following the MA-PMT trigger over the full TT detector is dominated by the radioactivity of the surrounding rock, which amounts to about 8 MHz. Dedicated electronics that are capable of efficient event selection, data readout, and timestamping have been designed to cope with such high rates, as shown in Fig. 2.

2.1 Top Tracker electronics

The Front-End Boards (FEB) act as a fast-triggering electronics interface directly plugged to the MA-PMTs. The MAROC3 [4] ASIC in the FEBs performs the digitization of MA-PMT data, allows to tune the gain equalization factors of each of the MA-PMT channels individually, as well as to detect charge levels as low as 1/3 of a photoelectron (PE) while keeping noise levels low. Then the FEBs transmit the digitized data to the Readout Boards (ROB) that facilitate the PMT interfacing, control of the MAROC3, high voltage supply, and TT calibration. The TT requires 992 FEBs/ROBs. 1160 FEBs (including spares) have been tested and validated to be used in the TT, and, 1020 ROBs are currently in production. The Concentrator Board (CB) aggregates information from the 16 electronic readouts (i.e. 16 MA-PMTs/FEBs/ROBs) of a TT wall. It provides a timestamp for the MA-PMT triggers with nanosecond-level precision. Then the CB selects PMT triggers from both the x and y sub-layers of the TT wall that appear within the same time window (x-y trigger), and sends the valid events to the DAQ. 62 CBs are required, and 80 CBs are currently in production. The Global Trigger Board (GTB), coupled to all the CBs in the TT via optical links, performs a second-level trigger on the data selected by the CBs. It selects x-y triggers aligned across the 3 TT layers. This 2-level selection of aligned x-y coincident events allows a significant suppression of the background due to the radioactivity of the surrounding rock.

2.2 Top Tracker muon reconstruction

The TT reconstruction aims to recover the directionality information of muons crossing the TT. Each valid x-y trigger is translated into a 3D coordinate by invoking the corresponding x and y

(a) (b) (c)

Figure 3: (a) Charge measured vs. charge injected at different gain equalization factors. (b) The Top Tracker Prototype. (c) Time difference between x-y coincident pairs measured by the Top Tracker Prototype.

sub-layer information. Then, each group of more than 3 points at different vertical positions is fit with a 3D line via a χ^2 minimization, to reconstruct muon candidates. The current reconstruction algorithm is capable of suppressing the residual background rate due to radioactivity to a level such that the event rate is found comparable to the expected rate of muons in the TT. It can reconstruct almost all the muons with a median resolution of 0.2°, which translates to a median distance of about 20cm between the simulated and the reconstructed tracks at the bottom of the WCD.

3. Electronics validation and performance analysis using muons

Fig. 3(a) shows the charge collection vs. charge injection response at different gain equalization factors for a particular FEB. It indicates that the FEBs have stable pedestal and electronic saturation levels at different gain equalization factors. Upon a detailed analysis of all the FEBs using an automatic test bench, they were found to perform very consistently with each other. To test and calibrate the TT electronics using muons, a TT prototype (TTP) (Fig. 3(b)) has been constructed at Strasbourg, France. It is made with the same material as the TT itself and has 4 x-y layers. The detection area of a TTP layer corresponds to 1/16th of that of a TT wall. Preliminary results showing the distribution of time difference between x-y coincident pairs observed by the TTP are shown in Fig. 3(c). It demonstrates that the TT electronics can perform x-y coincidence tagging within a resolution of about 3 ns.

References

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