A Muon Telescope as Demonstrator of the JUNO Top Tracker Detector

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A four-layer muon telescope has been built, employing the equipment and electronics developed for the Top Tracker (TT) detector of the Jiangmen Underground Neutrino Observatory (JUNO). It will serve as a demonstrator of the hardware capabilities in terms of detection efficiency, processing power and system reliability. The entire readout, trigger and acquisition systems have been conceived and built around versatile modular electronics embedding the latest generation of system on chips. A detailed description of the telescope will be given along with the status of the TT electronics and their preliminary validation tests.
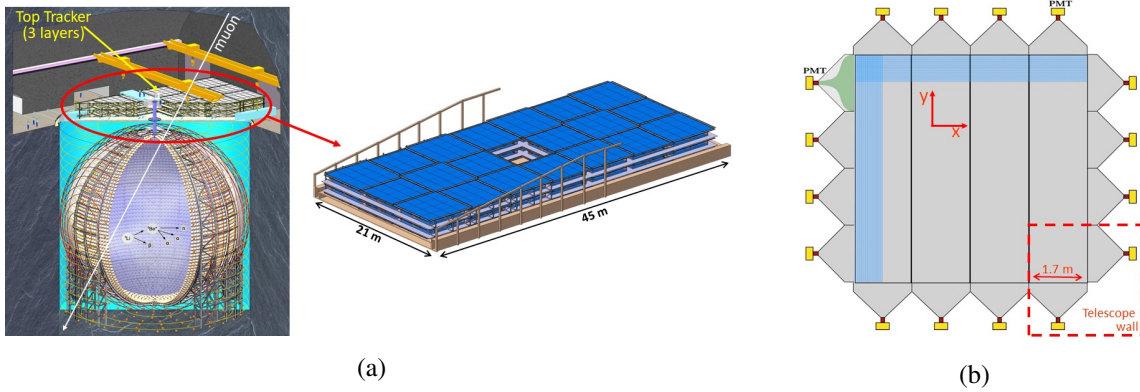
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Figure 1: (a) Schematic view of the JUNO detector with a zoom on the Top Tracker sub-detector. (b) Schematic view of a Top Tracker wall.

1. Introduction

The Jiangmen Underground Neutrino Observatory (JUNO) is a 20 kton multi-purpose underground liquid scintillator detector proposed with the primary goal of determining the neutrino mass ordering with a sensitivity better than 3σ [1]. The excellent energy resolution and the large fiducial volume foreseen for the JUNO detector offer the opportunity for addressing many important topics in neutrino and astro-particle physics.

The JUNO experiment is located in the south of China, in the Guangdong province. The experimental site is at 53 km from two nuclear power plants consisting of ten reactor cores delivering a total thermal power of 35.8 GW$_{th}$ once all reactors are built. This distance was choosen for an optimal performance to measure the neutrino mass ordering. The JUNO detector consists of a central detector (CD), a Water Cherenkov Detector (WCD) and a muon tracker called Top Tracker (TT) [2]. Fig. 1a shows a schematic view of the full detector. The CD is submerged in a water pool to be shielded from external background: natural radioactivity and fast neutrons from the surrounding rocks and air. The water pool, equipped with Photomultiplier Tubes (PMTs) in order to detect the Cherenkov light produced by cosmic muons, acts also as a Water Cherenkov Detector (WCD) veto. On top of the water pool, there is another muon veto detector, the TT, to accurately measure muon tracks. Section 2 will describe in detail this sub-detector.

A small demonstrator of the TT has been built. It will be referred in the following as muon telescope since it can track atmospheric muons and in general perform muon tomography. The detection system of this muon telescope is composed of the same elementary blocks as the TT but arranged in a different configuration. Equipping this muon telescope with the same readout and trigger electronics that will be deployed in the TT detector allows us to validate the whole readout chain of the future JUNO external veto system.

2. Top Tracker Detector

Studying neutrino properties with the JUNO experiment requires dealing with important background signals caused by atmospheric muons traversing the main detector. To reduce the atmospheric muon rate, the experiment will be located ∼700 m underground, but the surrounding rock
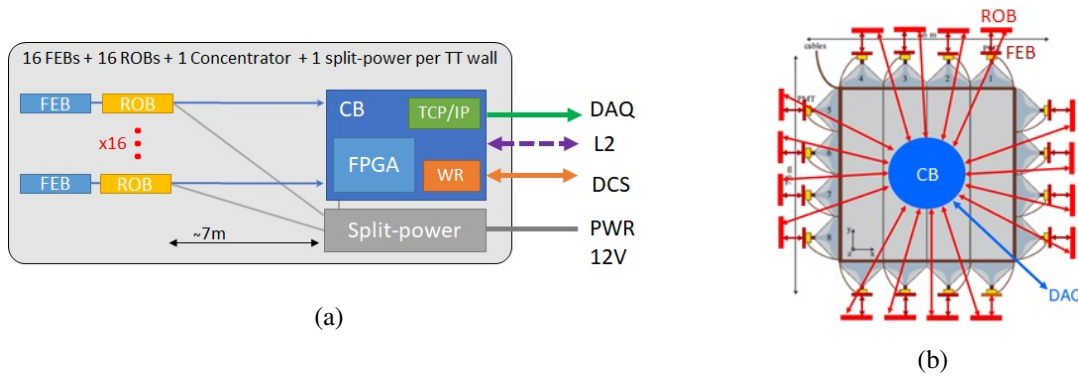
(a)

(b)

Figure 2: (a) Readout and trigger electronics chain of the Top Tracker subdetector. (b) Boards arrangement on a Top Tracker wall.

is not sufficient to perfectly shield the detector. To account for the remaining muon-induced background, JUNO will be equipped with the TT and the WCD. The TT is made of crossing planes of plastic scintillator strips, which have a high muon detection efficiency to identify and reconstruct muon tracks. The TT covers more than 60% of the water pool top area and it can detect ~1/3 of muons crossing the CD. It consists of 63 square walls with a sensitive area of 6.8×6.8 m^2. The walls are arranged in a 3×7 grid on 3 layers. Each wall is composed of eight modules placed in two planes that are perpendicular to each other (see Fig. 1b). One module contains 64 scintillator strips equipped with wavelength shifting fibers, which are readout at both ends by two 64-channel multianode photomultiplier tubes (PMTs). In total the TT will comprise more than 64,000 channels.

2.1 Top Tracker Electronics

Fig. 2 shows the electronics chain of the TT and the board arrangement on a single wall. The 64-channel PMT (Hamamatsu H8804) collects the light of each strip layer and feeds directly the Front-End Board electronics (FEB, Fig. 3a). The heart of the FEB is a multipurpose ASIC called MAROC3, developed by Omega Microelectronics [3]. It is a 64-channel preamplifier followed by a fast shaper and a discriminator, allowing for fast triggering, in parallel with a slow shaper plus two Track&Hold circuits for providing charge information multiplexed into a single analog output. A digital version of the latter is also available thanks to an internal Wilkinson ADC (8/10/12 bits). The goal in designing the FEB card was to keep the noise level as low as possible in order to achieve the detection of the charge corresponding to 1/3 of a photo electron. The mass production of FEB (1200 boards plus spares) has already started and an automated test bench with charge injection is going to be setup in order to characterize the production.

All the infrastructure needed by the PMT and MAROC3 is provided by a Read Out Board (ROB) that configures, controls and reads out the MAROC3. The high voltage required by the PMT and the control of the calibration LEDs are also generated by the ROB. A 100 pins micro-coaxial cable serves as interconnection between FEB and ROB, while a couple of standard Ethernet cables are used to connect the ROB to the trigger and DAQ electronics. For the TT demonstrator described in the next Section a special version of ROB has been developed (Fig. 3b). Such ROB has its

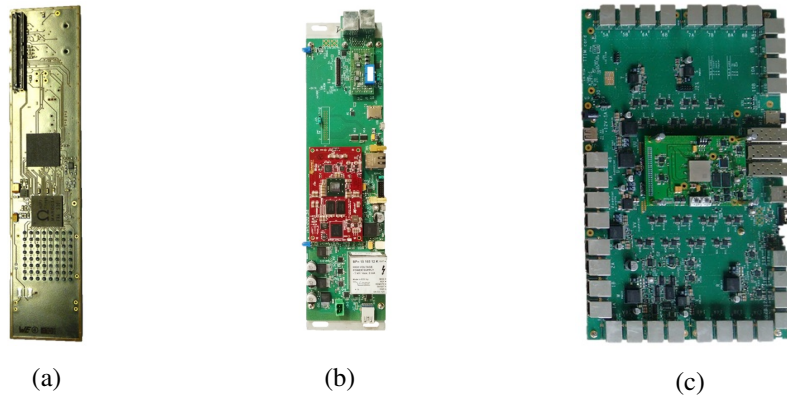(a)   (b)   (c)

Figure 3: (a) Front End Board (FEB). (b) Read Out Board (ROB). (c) Concentrator Board (CB)

own readout system based on GbE for spy monitor purposes. It is a carrier board based around a commercial mezzanine module called PicoZed [4] which embeds a Zynq7000 SoC and 1GB DDR3 memory. This board is used only on the telescope because for the final experiment another version of ROB will be produced by INFN-Frascati where all the functionalities will be embedded on a single card to optimize the power consumption. A flash ADC will also be exploited to reduce the intrinsic dead time of the MAROC3 Wilkinson ADC.

A third board called Concentrator (CB, Fig. 3c) aggregates all the data coming from the ROBs of a TT wall (Fig. 2) and sends them to the DAQ through a GbE optical link. The CB provides a timestamp for ROB data with nanosecond resolution before applying the first level (L1) trigger functionality. As a minimal configuration a simple coincidence algorithm has been implemented in order to reject the events that do not appear in the same time window in both the X and Y planes of the same detector layer. Finally, the CB sends valid events to the DAQ. The CB has been implemented as a motherboard that accommodates a daughter card hosting the processing unit. All the connectivity with the ROBs, DAQ, the slow control system, as well as the L2 trigger electronics (present only in JUNO and aiming to accept only the aligned walls) is provided by the motherboard while the daughter is an embedded high-performance system on module. It hosts a Xilinx SoC of the latest generation (Zynq Ultrascale+) along with a 2 GB DDR4 RAM.

Each PMT trigger rate is estimated to be around 50 kHz due to background decays. This means that FEB and ROB should sustain that rate while CB should implement the L1 algorithm to reduce the total trigger rate of a factor $\sim$10 (depending on the L1 algorithm). The trigger system was designed to identify muon hits on-the-fly, and reset PMTs signal digitization triggered by radioactive decays in order to reduce the dead time caused by charge readout ($\sim$14 μs using MAROC3 internal ADC at 8 bits, or $\sim$7 μs using the external flash ADC). Since each strip is readout from both sides the L1 trigger is designed to implement algorithms that ask for a coincidence in a temporal window of up to four hits.

3. Muon Telescope

As a demonstrator of the TT, four tiles of two-layer scintillator strips crossed in a XY lattice are used for precise muon tracking. The detection surface of one telescope wall corresponds to
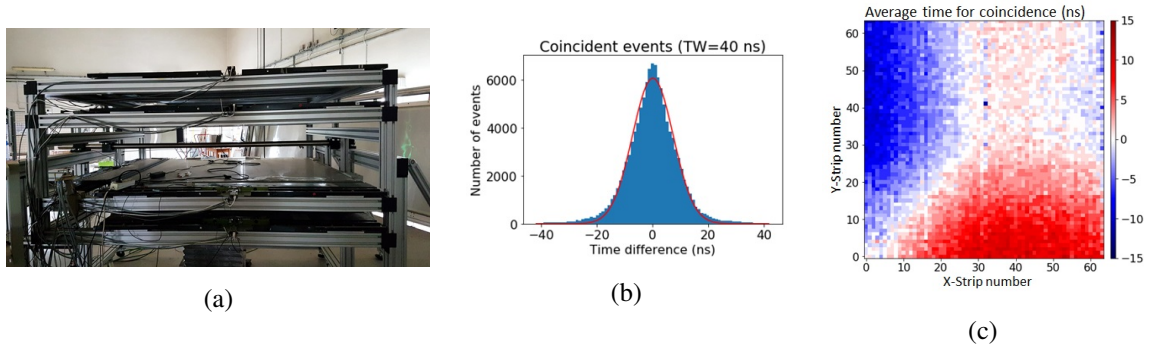
Figure 4: (a) The muon telescope. (b) Distribution of XY coincident events. (c) Average time for XY coincident events

1/16 of one TT wall (see Fig. 1b). They are mounted on a mechanical structure that allows 360° rotation on a single axis (Fig. 4a). In this demonstrator the strips are readout only from one side. This limits the L1 trigger to accept XY coincidence made by two hits. The full telescope system is equipped with 8 FEB, 8 ROB and one CB. In the telescope setup, both ROB and CB timestamps the trigger signal generated by MAROC3 and readout trigger and charge data in order to have a double check for identifying possible hardware and firmware failures. Since the ROB is also in charge of the generation of the HOLD signal for the Track&Hold circuit of the MAROC3 it needs to react fast to the trigger signal. For sampling the trigger signal the onboard SoC uses four 240 MHz clocks shifted by 90°. In this configuration a low latency is achieved during signal sampling while allowing a nanosecond resolution in the timestamping. A measure of linearity was done on the Time to Digital Converter (TDC) that timestamps the trigger signal from MAROC3 leading to a very good Differential NonLinearity $DNL_{MAX} = 0.078\,LSB$ and $DNL_{rms} = 0.041\,LSB$.

Preliminary results on coincidence events on two XY planes are showed in the plots of Fig. 4b and 4c. The gaussian time distribution of coincidences (Fig. 4b) has a σ=7.6 ns that is a value compatible with the different time needed by the light to cross the length of the optical fiber within a strip. The average time for coincidence (Fig. 4c) shows that the distribution is centered at zero when the length of the fibers of two strips are the same, and non zero otherwise with the shorter length cable seeing the signal earlier.

4. Conclusions

JUNO is a multipurpose neutrino observatory with a rich program in neutrino physics and astrophysics. In this paper we have presented the three main boards that have been developed for building the readout and trigger system of the TT veto sub-detector. Electronics mass production for the front-end part has already started. The full electronics is at present functional and operational on a demonstrator that serves as test bench for L1 algorithms validation and firmware improvements. Finally it will also help determine if further hardware developments for a L2 trigger are needed.

Acknowledgments

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