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Characterization of JUNO Large-PMT electronics in a complete small scale test setup

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The Jiangmen Underground Neutrino Observatory (JUNO) is a neutrino medium baseline experiment under construction in southern China. The experiment has been proposed with the main goals of determining the neutrino mass ordering and measuring the oscillation parameters with sub-percent precision. To reach these goals, JUNO is located about 53 km from two nuclear power plants and will detect electron antineutrinos from reactors through inverse beta decay. Furthermore, an unprecedented energy resolution of 3 % at 1 MeV is required. The JUNO detector consists of 20 kt of liquid scintillator (LS) contained in a 17.7 m radius acrylic vessel, which is instrumented with a system of 17 612 20-inch Large-PMTs and 25 600 3-inch Small-PMTs, with a total photo-coverage greater than 75 %. Additionally, 2400 Large-PMTs are installed in the instrumented Water Pool detector.

The signal from the Large-PMTs is processed by the JUNO electronics system, which can be divided into two main parts: the front-end electronics, placed underwater, consisting of a Global Control Unit (GCU); and the back-end electronics, outside water, consisting of DAQ and trigger. Each GCU reads three Large-PMTs and has the main tasks of performing the analog-to-digital conversion of the signals, generating a local trigger to be sent to the global trigger, reconstructing the charge, tagging events with a timestamp, and temporarily storing data in the local FPGA memory before transferring it to DAQ upon a global trigger request. The poster will mainly focus on the description of the underwater electronics for the Large-PMTs. Results from tests on a small setup with 13 GCUs at Laboratori Nazionali di Legnaro, Italy, will also be presented.

41st International Conference on High Energy physics - ICHEP2022
6-13 July, 2022
Bologna, Italy

[*] Speaker

PoS(ICHEP2022)1112

1. The JUNO experiment

The Jiangmen Underground Neutrino Observatory (JUNO) [1] is a next-generation neutrino experiment under construction in South China. The experiment has been proposed with the main goal of determining the neutrino mass ordering (NMO) at 3 σ significance in 6 years and providing a measurement of three oscillation parameters with sub-percent precision.
Its central detector (CD) is a 20 kton liquid scintillator (LS): particle interactions in the LS generate scintillation photons, which are then converted into photoelectrons (PEs) by 17612 20-inch Photomultiplier Tubes (PMTs) (*Large-PMTs*) and 25600 3-inch PMTs (*Small-PMTs*).
The initial design of the Large-PMTs electronics and the following R&D program [2] have been driven by the main requirements of reconstructing the deposited energy in the LS with an unprecedented energy resolution of 3% at 1 MeV [3] and a good linearity response (non-linearity $\leq$ 1 %) over a wide dynamic range: from 1 PE up to thousands of PEs.

2. Large-PMT readout electronics

A scheme of the JUNO Large-PMT electronics is given in Figure 1; the design is an optimization of previous developments [2].

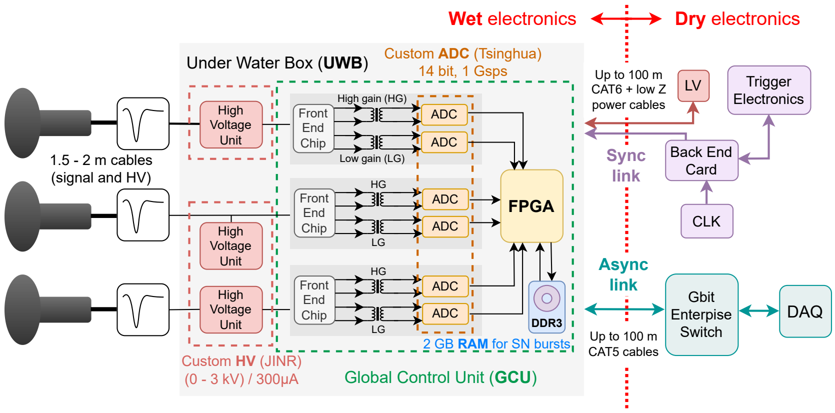

Figure 1: JUNO large PMT electronics Read-Out electronics scheme.

The full electronics chain is composed of two parts: the *front-end* (FE), or *wet*, located very close to the PMT output, inside the JUNO Water Pool; and the *dry* electronics, installed in the electronics rooms of the JUNO underground laboratories, which consists of the *back-end* (BE), or trigger, electronics and the data acquisition (DAQ) system. The FE electronics will be installed underwater on the JUNO Steel Truss structure, inside a stainless steel, water-tight box, the so-called Under Water Box (UWbox). Three PMT output signals are fed to one UWbox, where they are processed by one Global Control Unit (GCU), a motherboard incorporating the FE and Readout electronics components. On the other hand, the main active element of the BE electronics is the Back End Card (BEC) with the Trigger and Time Interface Mezzanine (TTIM). In-depth details on the JUNO Large-PMT electronics components can be found in [2].

3. Tests in complete small scale test setup at Laboratori Nazionali di Legnaro

To validate the full electronics performances, a medium-sized setup with 48 independent channels has been built and operated at the Legnaro National Laboratories (LNL) of the Italian National Institute of Nuclear Physics (INFN) [4]. A brief description of the setup, the types of measurement that can be performed, and some results are now presented.

3.1 The integration test facility

The apparatus is composed of a cylindrical acrylic vessel, made of transparent Plexiglas, filled with about 17 liters of JUNO liquid scintillator (LS). The LS vessel is instrumented with 48 Philips XP2020 2-inch PMTs. The setup is equipped with ancillary systems (e.g., plastic scintillators to trigger on cosmic muons) that can be exploited to induce signal pulses on the PMTs.

3.2 Waveform reconstruction

After data acquisition, the raw data files are processed with a dedicated software that stores them in a ROOT `TTree` object. For example, Figure 2 (left) shows one digitized waveform from a data taking with cosmic muons. Data quality monitoring can be performed by examining different quantities, e.g. the baseline value and noise, the signal amplitude, and the integrated charge. It is then possible to investigate the evolution of these quantities throughout time to highlight possible malfunctioning and test the system's reliability over time.

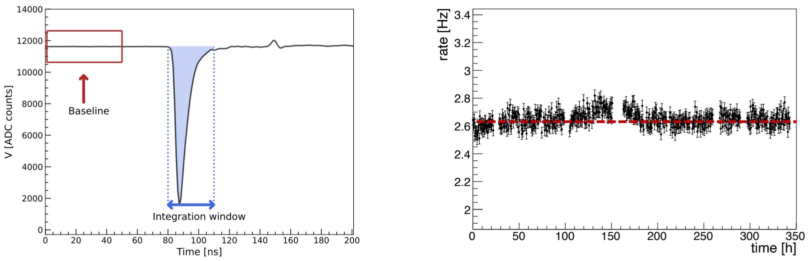

Figure 2: *Left*: Digitized waveform from one GCU channel. *Right*: Results of the rate stability test for one channel. Each point corresponds to the rate observed in a 30-minute interval.

3.3 Cosmic rays rate stability test

We performed a rate stability test with cosmic muons, using the coincidence of three plastic scintillator bars as an external trigger for the BEC. We took one day-long runs for a total of almost 350 consecutive hours of data taking. Data-sets were divided into 30 minutes samples and the acquisition rate was evaluated for each one of them (see right panel of Figure 2). The observed cosmic muon rate remained relatively stable over nearly 350 hours, with a mean value of ~ 2.65 Hz.

3.4 Bandwidth test

By means of the external trigger, a bandwidth test has been performed to check the maximum amount of data that can be transferred by one GCU to the DAQ server without losing a significant fraction of events. We found that the event loss starts at a rate of ~ 30 kHz, which corresponds to a bandwidth of ~ 460 Mb/s (Figure 3 left). Thus, we have verified that the Large-PMT electronics is

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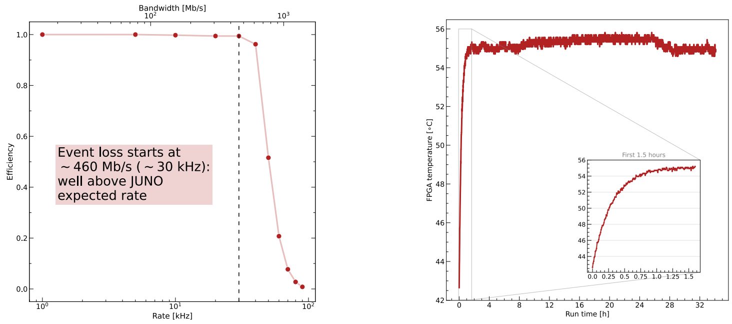

Figure 3: *Left*: Results of the rate test from 3 channels of 1 GCU. The external pulser is set at fixed rated in the range 1-100 kHz. The packet size is fixed at 5.12 kb. *Right*: FPGA temperature over time during tests at Y-40. After a fast increase, the temperature stabilizes at about 55°C, 23°C above the water temperature.

capable of working at the JUNO rate, which is expected to be less than 1 kHz in standard data taking conditions (i.e., not in case of a supernova explosion, to which the DDR3 RAM is dedicated).

3.5 Test at Y-40 The Deep Joy

A further electronics and mechanical verification has been performed thanks to a collaboration with the *Y-40 The Deep Joy* pool in Montegrotto Terme (PD), Italy, the deepest thermal water pool in the world, with its 42.15 meters in depth. The box stayed underwater at the bottom of the pool for roughly 30 hours. During this time, the FPGA temperature was monitored, as well as the baseline average value and standard deviation. The board was set in auto-trigger mode, where calibration pulses were triggered remotely via IPBus. Figure 3 (right) shows the evolution of temperature with time: the FPGA recorded temperature complies with the reliability standards. Furthermore, by analyzing the obtained waveforms, we can conclude that the acquired data is consistent with the proper operation of the system.

4. Conclusions

Several tests were performed in the integration test facility to assess the performances of the JUNO Large-PMTs electronics: they show that the electronics system is reliable and meets the required specifications. Furthermore, the UWBox was tested ~ 40 m underwater, in order to verify the behavior of both the hardware and firmware in a JUNO-like environment.

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