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Characterization of the JUNO Large-PMT readout electronics

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Summary. — The Jiangmen Underground Neutrino Observatory (JUNO) is a neutrino medium baseline experiment under construction in South China, expecting to begin data taking in 2022. JUNO is a liquid-scintillator-based detector with an active target mass of 20 kt; it aims to detect and study electron antineutrinos from reactors to improve the knowledge in the field of neutrino oscillations. The scintillation light emitted by the interaction of an antineutrino in the detector is detected by a system of 17612 20-inch Large-PMTs and 25600 3-inch small-PMTs. The signal from the Large-PMTs is processed by the JUNO Large-PMT readout electronics, which consists of several hardware components and is partly placed underwater. Given the ambitious physics goals of JUNO, the electronic system has to meet specific requirements, and a thorough characterization is required. After describing the readout electronics, tests and results performed with an integration test facility at Laboratori Nazioni di Legnaro, Italy, and at Y-40 The Deep Joy, Montegrotto Terme (PD) Italy, are here presented and discussed.

1. – The JUNO experiment

The Jiangmen Underground Neutrino Observatory [1] (JUNO) is a neutrino medium baseline experiment under construction in the Guangdong Province, in Southern China. JUNO will detect electron antineutrinos produced mainly by two Nuclear Power Plants located at about 53 km from the experimental site and aims to determine the neutrino mass ordering with a significance of 3 σ within six years of data taking.

JUNO consists of 20 kton of liquid scintillator (LS) contained in an acrylic vessel with a 17.7 m radius, supported by a stainless steel latticed structure. A system of 17612 20-inch PMTs (Large-PMTs) and 25600 3-inch PMTs (small-PMTs) is employed to detect the scintillation light produced by the interaction of a reactor antineutrino with a proton of the LS. The LS target is surrounded by a 30-kton pure water Pool, which is instrumented with 2400 20-inch PMTs, shields the inner part of the detector from environmental radioactivity, and works as a muon veto, together with the Top Tracker on top of the whole structure.

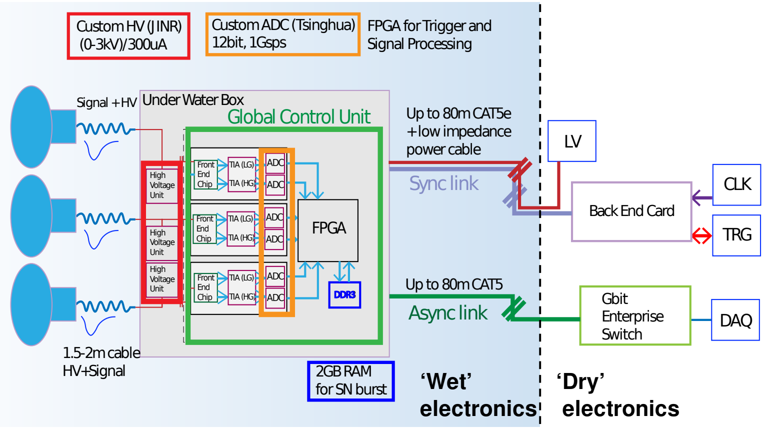

Fig. 1. – Scheme of the Large-PMT readout electronics, with a focus on the components of the Under Water Box and the Global Control Unit (GCU). Picture taken from [1].

In order to achieve the physics goals, several requirements have to be met; among them, an unprecedented energy resolution of 3% at 1 MeV is required. The JUNO Large-PMT electronic system, which reads and processes the signals coming from the Large-PMTs, also plays a fundamental role.

2. – Large-PMT readout electronics

A scheme of the Large-PMT readout electronics is presented in fig. 1 [1]. Three Large-PMTs are connected through coaxial cables to one Under Water Box, which consists of three High Voltage Units and a Global Control Unit (GCU), and is placed underwater near the PMTs. Inside the GCU, the analog signal coming from a PMT is processed through a front-end chip, which sends the signal into both a low gain and a high gain Trans Impedance Amplifier (TIA). Then, the signal is digitized from a flash ADC and sent to the FPGA, a Kintex 7, with the main tasks of generating a local trigger, reconstructing the charge, tagging events with a timestamp, temporarily storing the waveforms in the local memory, and transferring them to DAQ upon request.

The flash ADC is characterized by a sampling frequency of 1 GSps and a wide dynamic range spanning from 1 pe (for low energy neutrino events) to 1000 pe (*e.g.*, for muon events); both characteristics are fundamental in the reconstruction of events in the JUNO detector [1].

Each GCU is also equipped with a 2 GB DDR3 RAM to be used in case of a very high increase in the trigger rate, for example, for a neutrino burst from a nearby supernova.

The GCU is connected to the back-end electronics through a CAT6 cable, with a fixed and known latency, and which constitutes the *synchronous link*. The back-end electronics consists of a Back-End Card (BEC), which distributes the clock to 48 GCUs and is responsible for the trigger distribution between the GCUs and the trigger electronics (which will not be described here).

48 GCUs are also connected via an ethernet CAT5 cable, which constitutes the *asynchronous link*, to a Gbit Enterprise Switch, which is connected to the DAQ system.

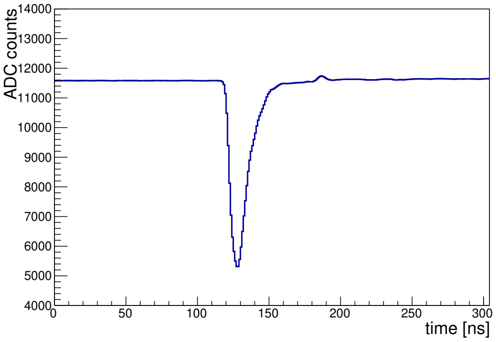

Fig. 2. – Digitized waveform from one channel of a GCU at Laboratori Nazionali di Legnaro, from a run with cosmic rays. The length of the waveform (*trigger window*) is fixed at 304 ns. One ADC count corresponds to 75 μV.

The data acquisition is done through the IPbus protocol [2], which also allows for the use of a detector slow control system. Three different data streams are foreseen: standard waveform acquisition; T/Q acquisition, where only the reconstructed charge and the timestamp are acquired, mainly for the multimessenger part of the JUNO physics program; and the DDR3 stream.

Since the Under Water Boxes will be placed under water a few meters from the Large-PMTs, after installation and detector filling, it will not be possible to access the electronics for repair or replacement. For this reason, the electronics needs to be highly reliable over time, with a required loss rate $< 0.5\%$ in 6 years [1].

3. – Tests with an integration test facility at Laboratori Nazionali di Legnaro

In order to properly and thoroughly characterize the electronic chain, in the last years, a small-scale integration test facility has been assembled at Laboratori Nazionali di Legnaro, Italy [4]. A brief description of the setup, the kinds of measurement that can be performed, and some results are here presented.

3·1. *The integration test facility.* – The setup consists of a small cylindrical vessel containing 17 l of JUNO's LS, instrumented with 48 Philips XP2020 PMTs. Three PMTs are connected to one GCU. The GCUs are connected to one BEC through the synchronous link and one switch through the asynchronous link.

The integration of the electronics with a small vessel with liquid scintillator and PMTs allows us to take data with different signal sources. It is indeed possible to take data using external gamma calibration sources, a laser, or cosmic muons with the help of three plastic scintillator bars used as an external trigger. Each channel is also equipped with an internal test pulse generator, which can be used to test the electronic chain without connecting a PMT, as will be the case for the large-scale integration tests.

3·2. *Waveform analysis.* – After data acquisition, the binary data files are processed with a dedicated software to obtain raw data in the form of `ROOT` `TTree` [5] objects, ready for analysis. For example, fig. 2 shows one digitized waveform from a data taking with cosmic muons. The signal window, which corresponds to the number of samples, has

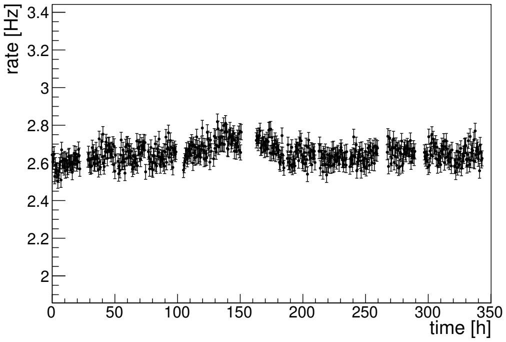

Fig. 3. – Results of the rate stability test for channel 0 of GCU 3. Each point corresponds to the rate observed in a 30-minute interval by evaluating the time difference between two consecutive events.

been fixed at 304 ns for this data taking, but it is one of the configuration parameters and can be changed during acquisition via the IPbus protocol.

Data quality monitoring can be performed by looking at different quantities to check if the electronic is working correctly. For example, it can be checked if each event has a valid timestamp, and if the measured waveform length equals the input configuration parameter. The baseline value, the baseline noise, signal amplitude, and integrated charge are also evaluated for each waveform. It is possible to study the evolution of these quantities with time for every channel, or compare them among different channels, to highlight possible malfunctioning and test the reliability over time.

3˙3. *Rate stability test.* – We also performed a rate stability test with cosmic muons, using the coincidence of three plastic scintillator bars as an external trigger connected to the BEC. We took several one-day-long runs for several days in the same month for a total of almost 350 consecutive hours of data taking. Each data set has been divided into time intervals of 30 minutes, and for each time interval, the rate has been evaluated. The rate values for all intervals are shown in fig. 3 for one channel; the same behavior is obtained for the other channels, as expected since we are using an external trigger. The observed cosmic muon rate is quite stable over almost 350 hours, with a mean value of about 2.65 Hz. Furthermore, during the whole test, all GCUs remained synchronized.

4. – Test at Y-40 The Deep Joy

In May 2021, we had the opportunity to perform a test at Y-40 The Deep Joy, in Montegrotto Terme (PD), Italy, which is the second deepest pool in the world, with a maximum depth of about 40 m. After welding one UWB, we submerged the box in the pool at maximum depth for almost 35 consecutive hours and successfully acquired data using the internal test pulse generator.

In the test, we were interested in the value of the FPGA's temperature, also for testing the slow control system. Figure 4 shows the evolution of temperature with time: right after switching on the GCU, the temperature is around 42 °C; after an hour and a half, the temperature stabilizes at about 55 °C, 23 °C above the water temperature.

During the test, it was also possible to acquire data by using the internal test pulse

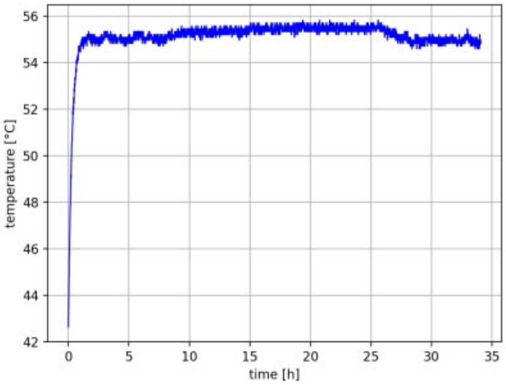

Fig. 4. – Temperature as a function of time of the GCU tested in an underwater environment at Y-40 The Deep Joy, Montegrotto Terme, PD, Italy.

generator, which can be controlled through the IPbus protocol. By analyzing the acquired waveforms, we monitored some of the properties and found out that the baseline value slightly depends on the temperature.

5. – Conclusion

The tests performed so far with the integration test facility show that the Large-PMT electronics system is reliable and meets the specifications needed for the analysis. The test at Y-40 The Deep Joy was a milestone in the testing of the electronics. It allowed us to test the electronic hardware and firmware in an environment similar to the one in the JUNO experiment, and it also allowed us to test the internal test pulse generator for the first time.

In preparation for an upcoming large-scale integration test, further tests are being done and others foreseen.

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