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# Characterization of the JUNO Large-PMT readout electronics

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**Abstract.** The Jiangmen Underground Neutrino Observatory (JUNO) is a neutrino medium baseline experiment under construction in Southern China, expecting to begin data taking in 2023. JUNO is a liquid-scintillator-based detector with an active target mass of 20 kt and 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 17 612 20-inch Large-PMTs and 25 600 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 a small-scale integration test facility at Laboratori Nazioni di Legnaro, 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 South 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 $\sigma$ within six years of data taking.

JUNO consists of 20 kton of liquid scintillator contained in an acrylic vessel with a 17.7 m radius, supported by a stainless steel latticed structure. A system of 17 612 20-inch PMTs (Large-PMTs) and 25 600 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 liquid scintillator. The liquid scintillator 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.

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

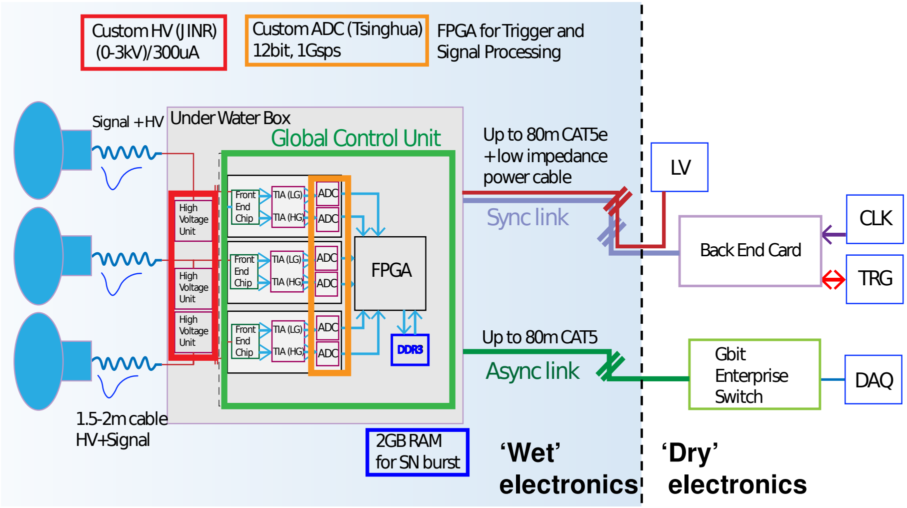


**Figure 1.** Scheme of the Large-PMT readout electronics, with a focus on the components of the Under Water Box and the Global Control Unit (GCU). Picture taken from [1].

## 2. Large-PMT readout electronics

A scheme of the Large-PMT readout electronics is presented in figure 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 from each TIA is digitized by a dedicated flash ADC (analog-to-digital converter) and finally sent to the FPGA (Field Programmable Gate Array), 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 ADCs are characterized by a sampling frequency of 1 GSps and the combination of two ADCs per channel provides 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, in case of 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, 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. 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

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required loss rate $< 0.5\,\%$ in 6 years [1].

## 3. Tests with an integration test facility at Laboratori Nazionali di Legnaro, Italy

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 [3]. A brief description of the setup, the kinds of measurement that can be performed, and some results are now presented.

### *3.1. The integration test facility*

The setup consists of a small cylindrical vessel containing 17 l of JUNO's liquid scintillator, 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 [3], a laser [4], or cosmic muons [3] 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 foreseen in China.

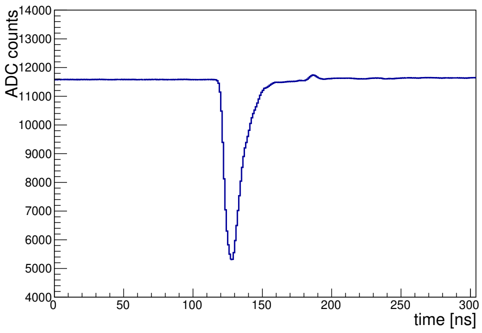


**Figure 2.** Digitized waveform from one channel of a GCU at Laboratori Nazionali di Legnaro, from a run with cosmic rays. The length of the waveform (*signal window*) is fixed at 304 ns. One ADC count corresponds to 75 µV.

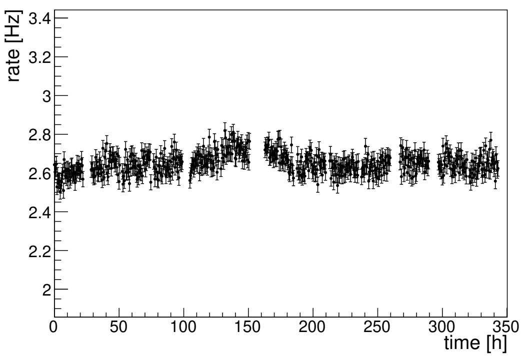


**Figure 3.** Results of the rate stability test for channel 0 of GCU 3. Each point corresponds to the rate observed in a 30-minute interval. The same behavior is observed for the other channels.

### *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, figure 2 shows one digitized waveform from a data taking with cosmic muons. The signal window, which corresponds to the number of samples of each waveform, has been fixed at 304 ns for this data taking, but it is one of the configuration parameters that 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 [6]. 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, 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 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 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 figure 3 for one channel; the same behavior is obtained for the other channels, as expected since all channels are connected to the same external trigger through the BEC. 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.

### *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 have found that the event loss starts at a rate of about 30 kHz, which corresponds to a bandwidth of about 460 Mb/s [7], knowing that each event has a fixed size in bits. Thus, we have verified that the Large-PMT electronics is capable of working at the JUNO rate, which is expected to be less than 1 kHz in standard data taking condition (*i.e.*, not in case of a supernova explosion, which the DDR3 RAM is dedicated to). Further details can be found in [7].

## 4. Conclusion

The tests performed so far [3, 4, 6, 7] with the integration test facility with 13 GCUs show that the Large-PMT electronics system is reliable and meets the specifications needed for JUNO physics analysis [4]. Further tests are being done [6] and are foreseen, in preparation for the upcoming large-scale integration test in China, where about 270 GCUs will be tested simultaneously.

## Acknowledgments

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## References

[1] Abusleme A *et al.* (JUNO collaboration) 2021 JUNO Physics and Detector *Preprint* 2104.02565
[2] Ghabrous Larrea C *et al.* 2015 *JINST* **10** no.02 C02019
[3] Callegari R 2020 *Characterization and tests of 39 channels of the JUNO large PMT electronics* Master's thesis `http://tesi.cab.unipd.it/65100/`
[4] Cerrone V 2021 *Characterization of the final readout electronics for the large PMTs of the JUNO experiment* Bachelor's thesis
[5] Brun R and Rademakers F 1997 ROOT - An Object Oriented Data Analysis Framework *Nucl. Inst. & Meth. in Phys. Res.* **A** 389 81-86
[6] Coppi A 2021 *Design and development of Data Quality Monitoring protocols for the integration tests of the JUNO large PMT electronics* Bachelor's thesis
[7] Triozzi R 2021 *Supernova neutrino detection in JUNO, a large liquid scintillator neutrino detector* Bachelor's thesis `http://tesi.cab.unipd.it/66298/`