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CATIROC, a Multichannel Front-End ASIC to Read Out the 3″ PMTs (SPMT) System of the JUNO Experiment

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Abstract. The ASIC CATIROC (Charge And Time Integrated Read Out Chip) is a complete read-out chip designed to read arrays of 16 photomultipliers (PMTs). It finds a valuable application in the content of the JUNO (Jiangmen Underground Neutrino Observatory) experiment [1], a liquid scintillator antineutrino detector with a double calorimetry system combining about 17k 20″ PMTs (Large PMTs system) and around 25k 3″ PMTs (Small PMTs system). A front-end electronics based on the ASIC CATIROC matches well within the 3″ PMTs system specifications as explained in this paper. CATIROC is a SoC (System on Chip) that processes analog signals up to the digitization to reduce the cost and cables number. The ASIC is composed of 16 independent channels that work in triggerless mode, auto-triggering on the single photo-electron (PE). It provides a charge measurement with a charge resolution of 15 fC and a timing information with a precision of 200 ps rms.

Keywords: Front-end electronics for photomultipliers read-out
Multichannel ASIC · Analog electronic circuits

1 Introduction

The Jiangmen Underground Neutrino Observatory (JUNO) is a multipurpose neutrino experiment designed to determine neutrino mass hierarchy with a 20-thousand-ton liquid scintillator spherical detector at about 700-m deep underground. The detection principle in JUNO is based on the observation of the light emitted in the Inverse Beta Decay in the liquid scintillator volume by array of large photomultipliers (LPMT). To reach the expected sensitivity of mass hierarchy, the energy resolution has to be better than 3% at 1 MeV. In order to achieve this target the LPMT will have to cover approximately 75% of the inner surface of the sphere, elevating the number of necessary LPMTs to 18,000. In order to improve the calorimetry control of the LPMT system 25,000 small 3-in. small photo-multipliers (SPMTs) will be installed between

the LPMTs [2]. The size of these PMTs is chosen to operate in photon-counting mode for all events inside the detector. The large number of SPMTs increases the density and the complexity of the detector system. A customized multichannel Application Specific Integrated Circuit (ASIC) with the integration of all the analog and digital components into a single chip will simplify the electronic system, decreasing the total power consumption and increasing the reliability.

2 CATIROC for the Small PMT System

The SPMTs are expected to detect about 50 PE per event at 1 meV spread over 25,000 PMTs, working thus in photon counting regime with a time resolution within a few ns, typical of the PMTs. For the installation, the SPMTs will be connected in groups of 128 to an autonomous front-end electronics located in underwater boxes near the SPMTs. This is possible thanks to the integration of 8 multichannel ASIC CATIROC in each readout board. The CATIROC processes the analog signals up to digitization and sends out only zero-suppressed digital data to the central processing and storage unit.

CATIROC has been designed in AMS SiGe 0.35 μm technology and integrates 16 identical channels to provide charge and time information [3].

In each channel a trigger path allows to auto-trigger on the single photo-electron thanks to a fast shaper (5 ns) followed by a low offset discriminator with threshold sets by an internal 10-bit DAC common to the 16 channels.

A charge path, made by a preamplifier, a slow shaper, a switched capacitor array and an internal 10-bit Wilkinson ADC, provides a charge measurement over a dynamic range from 160 fC (1PE, assuming a PMT gain of 10^6) up to 70 pC ($\sim$400PE).

The time measurement is obtained by two paths: a "time stamp" performed by a 26-bit counter at 40 MHz and a "fine time" obtained thanks to a TDC ramp per channel converted by another 10-bit Wilkinson ADC.

3 Measurements

CATIROC has been tested in the laboratory with a dedicated test board [3] and the measurements have been performed with a pulse generator to simulate a PMT input charge. Preliminary measurements with a 3″ PMT have been performed.

A first information is the detection efficiency of the single-PE signal. It is measured scanning the discriminator threshold at a given injected charge (up to 2 PE = 320 fC) and monitoring the discriminator response. Figure 1 (left) shows the trigger efficiency for given injected charges as a function of the threshold. The 50% trigger efficiency as a function of the input charge is shown in the same figure (right panel). These measurements show a trigger channel sensitivity of about 100 DACu/PE (i.e., a DAC resolution of 0.6 DACu/fC) and a noise (σ) of 3.5 DACu (5.6 fC) fitting the pedestal curve (black curve on Fig. 1, left). The minimum threshold can be calculated from the baseline mean value including 5σ noise (Fig. 1 right). Considering the noise measurement of 3.5 DACu, there is a very comfortable range to set the auto-triggering at a fraction of photo-electron (usually 1/4th to 1/3rd).

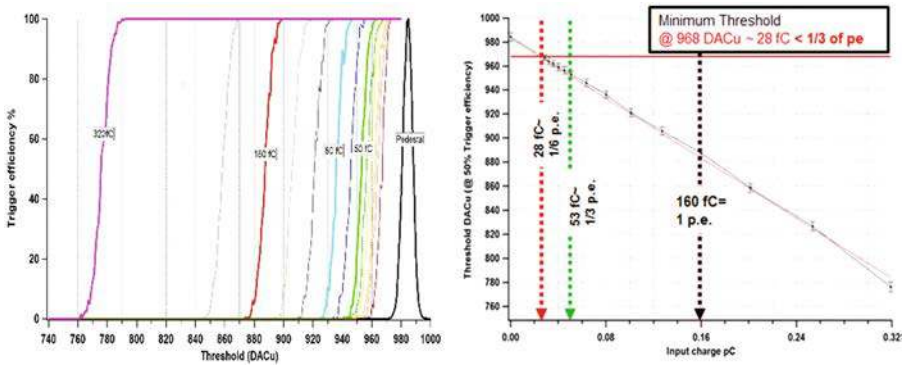


Fig. 1. Trigger efficiency at a given injected charge as a function of the threshold (left) and the 50% trigger efficiency as a function of the input charge up to 2 PE (right).

The SPMT system will collect typically single-PE up to a few PE's (so a good charge resolution for the single PE detection is mandatory). The charge distribution for various input signals (from 1 to 10 PE equivalent) are shown in Fig. 2 (left). The sensitivity is 16 ADCu/PE and the noise is nicely gaussian with a RMS of 1.5 ADCu (15 fC).

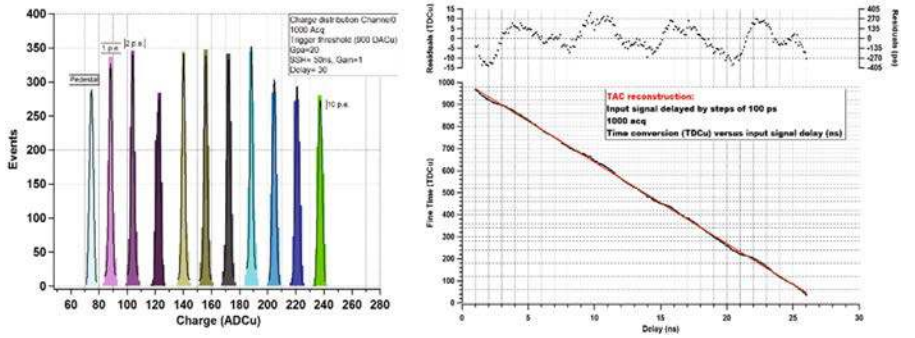


Fig. 2. Charge measurements with the full chain for different input charges (160 fC to 1.6 pC) (left). TDC ramp reconstruction for one channel by a pulse generator signal delayed by step of 100 ps (right).

Another crucial feature is the time resolution of the ASIC which is required to be smaller than 1 ns, such that the electronics resolution is negligible compared to that of the PMT's. The ASIC provides the signal "time of arrival" operating in self-triggered mode. The TDC ramp has been reconstructed and is displayed in Fig. 2 (right). A periodic pulse signal is injected in one channel and delayed by steps of 100 ps. The linear fit provides the slope which gives a LSB (or TDCu) of: LSB = 1/slope = 27 ps/TDCu. The residuals are within ± 15 TDCu, corresponding to ± 450 ps, with an

RMS value of 167 ps. The residuals exhibit a periodical shape due to a coupling of the 160 MHz clock, most likely through the substrate.

The performances of CATIROC are also evaluated (very preliminary test) with signal from the PMT planned to be used for the JUNO SPMT system (3″ HZC PMT). The ASIC test board is connected to the PMT placed in a light-tight box. The dedicated SPMT acquisition code developed for JUNO is used to collect the CATIROC output data (Fig. 3 left). An example of the signal spectrum measured by the ASIC for two channels is shown in Fig. 3 right, with a clear evidence of the single-photoelectron peak. The PMT high voltage is to yield $\sim$106 gain. This measurement indicates that the ASIC has the ability to detect a single photoelectron with a charge resolution of 30%. The two channel distribution are very similar. The wiggles observed in the curves is due to a digitization artefact caused by the ASIC clock coupling. Their impact on the determination of the single-PE position and resolution has been evaluated with Monte Carlo simulations and found to be negligible for JUNO. Further testing is ongoing for full characterization of the performance of the CATIROC with JUNO PMT's.

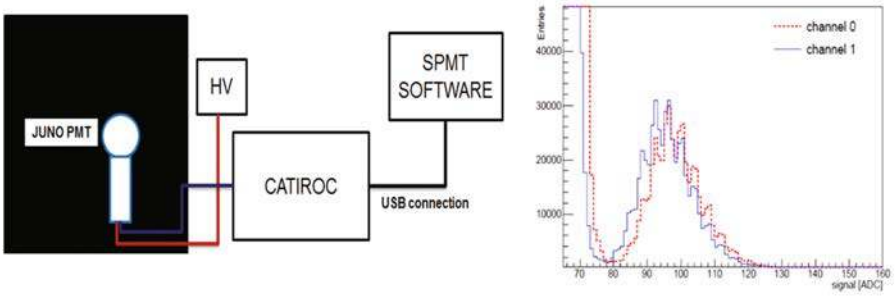


Fig. 3. Test bench for PMT measurements. The PMT is placed in a dark box, connected to an high voltage and to the CATIROC ASIC (left). Single photoelectron spectrum, in dark noise configuration, measured by the ASIC (right)

4 Conclusion

The JUNO experiment is the largest liquid scintillator antineutrino detector ever built, currently under construction in the south of China. A double calorimetry system will be used for the first time ever combining about 17k 20″ PMTs (Large PMTs system) and around 25k 3″ PMTs (Small PMTs system). The ASIC CATIROC has been tested and evaluated against the requirements of the JUNO SPMT system. The results show that CATIROC fulfils the JUNO requirements. Preliminary tests with a JUNO PMT have been performed to measure the single-PE with CATIROC. In the near future, CATIROC will be installed on the first prototype of the front-end board to study the performances in real conditions.

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