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Front-End Board for large area SiPM detector

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ABSTRACT. Silicon PhotoMultipliers (SiPMs) are widely employed for several applications, such as High Energy Physics experiments, as well as other research and industrial fields. SiPMs operating at low temperature, in particular, are the most interesting application for the new large particle detectors for neutrinos and dark matter experiments. In this work we present a low-noise, high-speed front-end electronics (Front-End Boards, FEBs) for large area SiPMs to be employed in the JUNO-TAO experiment for rare event searching. The FEBs are able to manage the signals coming from a 25 cm² SiPM tile, showing single photoelectron resolution better than 13% and dynamic range up to 250 photoelectrons. A careful approach to the front-end electronics design has shown to be critical in order to fully keep the exceptional performances of the SiPMs in terms of single photon detection, dynamic range, and fast timing properties. The sub-nanosecond timing properties make them suitable to work with the typical mixtures of liquid scintillators currently being used in particle and astroparticle physics experiments. The JUNO-TAO detector will achieve an energy resolution better than 2% at 1 MeV by the use of state-of-the-art SiPMs operating at -50°C . A dedicated readout system has been developed in order to collect and digitize the $\sim 8,000$ channels needed to ensure the requested performances. A complete test report about the performance of the pre-production FEBs batch will be presented, showing the solution taken to ensure a high stability and reproducibility of the results.

KEYWORDS: Front-end electronics for detector readout; Large detector systems for particle and astroparticle physics; Neutrino detectors; Photon detectors for UV, visible and IR photons (solid-state)

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1 JUNO-TAO Experiment

The Taishan Antineutrino Observatory (TAO) [1] is a satellite experiment of the Jiangmen Underground Neutrino Observatory (JUNO) [2], located in southern China, expected to start collecting data in 2024. TAO consists of a spherical ton-level liquid scintillator detector at about 40 m from the reactor core 1 of the Taishan Nuclear Power Plant (4.6 GW) in Guangdong Province, 53 km far away from the JUNO site.

By means of about 4,000 Silicon PhotoMultipliers (SiPMs, with Photon Detection Efficiency > 50%) tiles of 50×50 mm² covering the 10 m² sphere surface, the reactor antineutrino spectrum will be measured with an unprecedented sub-percent energy resolution ($\leq 2\%$ at 1 MeV). By means of the Inverse Beta Decay (IBD), TAO will allow a neutrino detection rate of about 2,000 events per day. The Central Detector operates at -50°C to lower the dark/thermal noise of the SiPMs by 3 orders of magnitude.

The main purposes of the TAO experiment are to provide a model-independent reference reactor antineutrino spectrum for the JUNO Neutrino Mass-Hierarchy (NMH) measurement [3], to monitor the reactor thermal power status, and to perform a new benchmark measurement to test and improve nuclear databases, by comparing the measurement with the predictions of the summation method.

1.1 TAO Central Detector

The schematic drawing of the overall TAO detector is shown in figure 1. The Central Detector consists of 2.8 ton Gadolinium-doped Liquid Scintillator (Gd-LS) contained in a spherical acrylic vessel of 1.8 m in inner diameter, which is submerged in a liquid buffer of non-scintillating Linear AlkylBenzene (LAB). The scintillation photons will be collected by the SiPM tiles assembled on the inner surface of a spherical Copper Shell of 1.88 m inner diameter, with an almost full coverage of about 95%, installed in a cylindrical Stainless Steel (SS) tank insulated with 20 cm thick PolyUrethane (PU).

In order to avoid an extremely high dark count rate, the whole tank will be cooled down to -50°C by means of a cryostat (with 4.5 kW cooling power) equipped with custom flanges allowing power supply and signal cables entry for the readout electronics.

Moreover, since TAO will operate at ground level with limited shielding from cosmic muons and environmental radiation, the Central Detector is surrounded by an active muon veto system composed by a water tank equipped with PhotoMultiplier Tubes (PMTs) and plastic scintillator detectors on the top; outer passive shielding is also inserted on the top and bottom of the detector to help reducing the cosmogenic and ambient backgrounds. Finally, a calibration system has been designed, including an Automated Calibration Unit (ACU) and a Cable Loop System (CLS) in order to deploy different LED light sources and radioactive sources, to map the response of the whole detector.

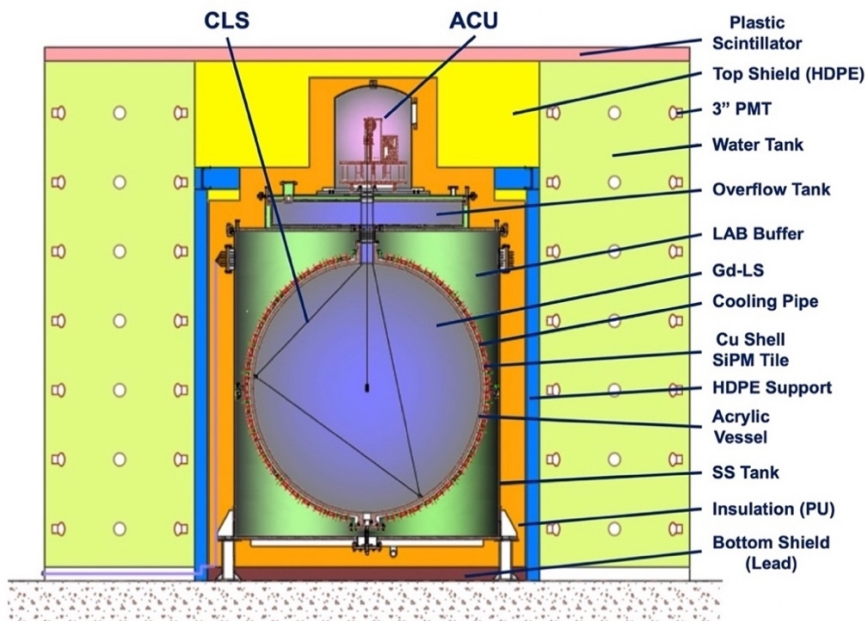


Figure 1. Schematic drawing of the JUNO-TAO detector, comprising of the Central Detector installed inside the SS tank, the cryogenic system, outer shieldings and the muon veto system. Reproduced with permission from [1].

2 TAO Readout Electronics

Given the large surface of the sphere containing the liquid scintillator ($\sim 10 \text{ m}^2$), the Silicon PhotoMultipliers employed for the Central Detector have been assembled by Hamamatsu Photonics K.K. in about 4,000 large arrays (tiles) of 8×4 independent elements of $12 \times 6 \text{ mm}^2$ each (S16088: overall area $\sim 50 \times 50 \text{ mm}^2$) [4]. Moreover, to reduce the number of readout channels, the outputs of different SiPM elements are merged into a single analog output by means of dedicated front-end electronics. The high capacitance of the SiPMs is a significant challenge in combining several SiPM elements as a single device without degrading the single photon and timing resolution [5].

The proposed readout electronics proved to work smoothly at low temperatures and to have a low power consumption, in order to avoid excessive heat dissipation in the cryogenic environment, still guaranteeing the experiment requirements in terms of energy resolution, noise, timing and dynamics.

In the electronics readout scheme, shown in figure 2, the tiles are connected to the Front-End Boards (FEBs), which split them in 2 independent channels (each one consisting of 16 SiPM elements with serial/parallel connections). The $\sim 8,000$ overall differential signals are subsequently sampled and read by means of custom ADC boards, managed by FPGA-based Front-End Controllers (FECs), that digitize the signal coming from each channel and perform signal pre-processing. Each FEC will work as a White Rabbit (WR) node to ensure the synchronous acquisition from the whole detector [6]. In order to allow the passage of the cables in and out of the cryogenic tank, there are dedicated flanges for the output signals and the power supply for the FEBs.

The raw data, in terms of charge and time information (Q&T), will be collected through optical fiber connections by the Data Acquisition (DAQ) system, that will filter and record occurring events, rejecting dark count events. The FECs and the Trigger-DAQ system are hosted on μ TCA crates outside the cryostat.

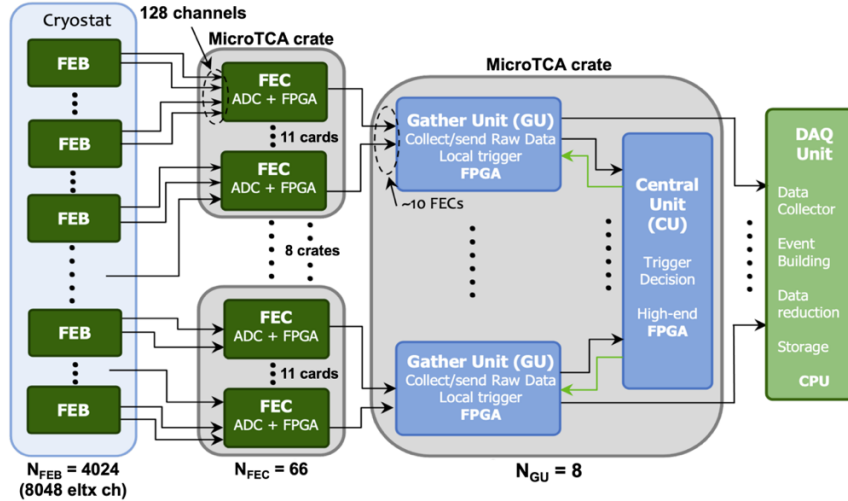


Figure 2. Overall block design of the TAO readout electronics, mainly divided in Front-End Board interfaces, FPGA-based Front-End Controllers with ADC devices and Data Acquisition System.

2.1 Front-End Board

The Front-End Board consist of a 2-stage amplifier: a TransImpedance Amplifier (TIA: Analog Devices LTC6269 500 MHz Ultra-Low Bias Current FET Input OpAmp) and a differential driver (Analog Devices LTC6405 Low Noise, Rail-to-Rail Input Differential Amplifier/Driver) [7], with a combined overall gain of about 16kV/A ($8.2\text{ kV/A} \times 1.95\text{ V/V}$).

The 32 SiPMs on the tile are split in 4 TIAs with 8 elements each, corresponding to the series of 4 SiPMs parallel-connected. The voltage signals coming from 2 TIAs (half-tile) are then combined and routed to one of the differential drivers, employed in order to output the signals as analog differential pairs, thus allowing the use of $\sim 14\text{ m}$ twisted-pair cables preventing additional noise. Figure 3 shows the simplified block scheme and the pictures of the front and rear side of the FEB, made with an Aramid PCB substrate. The board dimensions are $50 \times 30\text{ mm}^2$, so it can be perfectly arranged with the $50 \times 50\text{ mm}^2$ SiPM tile.

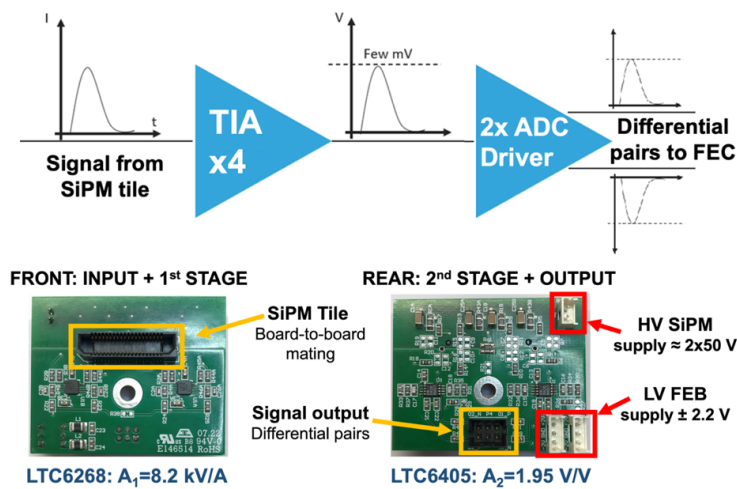


Figure 3. Block scheme about how the SiPM current pulse signal is managed by the FEB, and pictures of the front and rear side of the board (with input and output connectors highlighted).

2.2 ADC Board Prototype

Outside of the cryostat, the differential signals from the FEBs are digitized and collected by the ADC boards, managed by the Front-End Controllers. The FEC is based on a Xilinx Kintex 7 UltraScale FPGA and can control up to eight 16-channel ADCs, for a total of 128 channels. All the ADCs will work in free running mode and the collected data will be analyzed and pre-processed on the FPGA itself searching for the pulses related to the collected photoelectrons.

The design of the custom ADC board has been defined with 32 differential input channels and an FMC connector for the power supply and the connection with the FEC. The board is based on the AD9083 16-channel, 250 MS/s, 125 MHz bandwidth by Analog Devices Inc. with $2 V_{PP}$ differential input voltage [8]. As it is shown in figure 4, there are 2 AD9083 on the PCB, thus a single board can read data from 16 SiPM tiles, with a maximum sampling rate of 250 MHz with 12-bit resolution (or 16 bits at 125 MHz). Each FEC can control up to 4 ADC boards, by means of the FMC connectors.

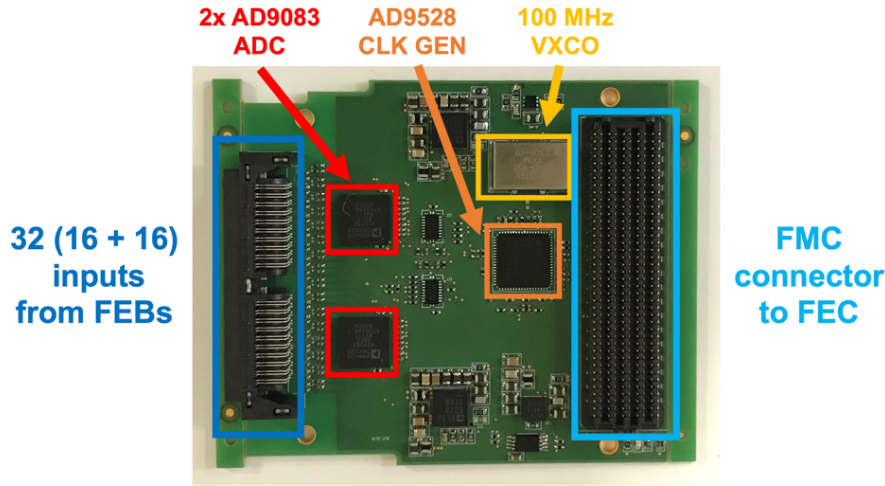


Figure 4. Picture of the front side of the ADC board prototype with 32 differential inputs, 2 AD9083 devices and an FMC connector for the power supply and output signals.

3 Characterization

The experimental setup employed for testing the performance of the front-end electronics at -50°C is based on a climate chamber where the SiPM tiles coupled with the FEBs are hosted, a very low-intensity UV laser source with a wavelength of 407 nm employed to mimic the scintillation light, two power supplies for biasing the integrated circuits on the board (Low-Voltage = $\pm 2.2\text{ V}$) or the SiPMs (High-Voltage $\approx 100\text{ V}$), and a Teledyne LeCroy WavePro digital oscilloscope for the data acquisition and analysis.

Four figures of merit have been defined in the TAO experiment, with specific requirements in order to accomplish the desired resolution of the detector: Crosstalk ($\text{XTLK} < 20\%$) and Dark Count Rate ($\text{DCR} < 100\text{ Hz/mm}^2$), both evaluable only in dark condition, Signal-to-Noise Ratio ($\text{SNR}: \frac{\mu_1 - \mu_0}{\sigma_0} \geq 10$) and Single Photoelectron Resolution ($\text{RES}: \frac{\sigma_1}{\mu_1} \times 100 \leq 15\%$), where μ_k and σ_k are, respectively, the mean value and the width of a gaussian fit over the k -th peak of the signal

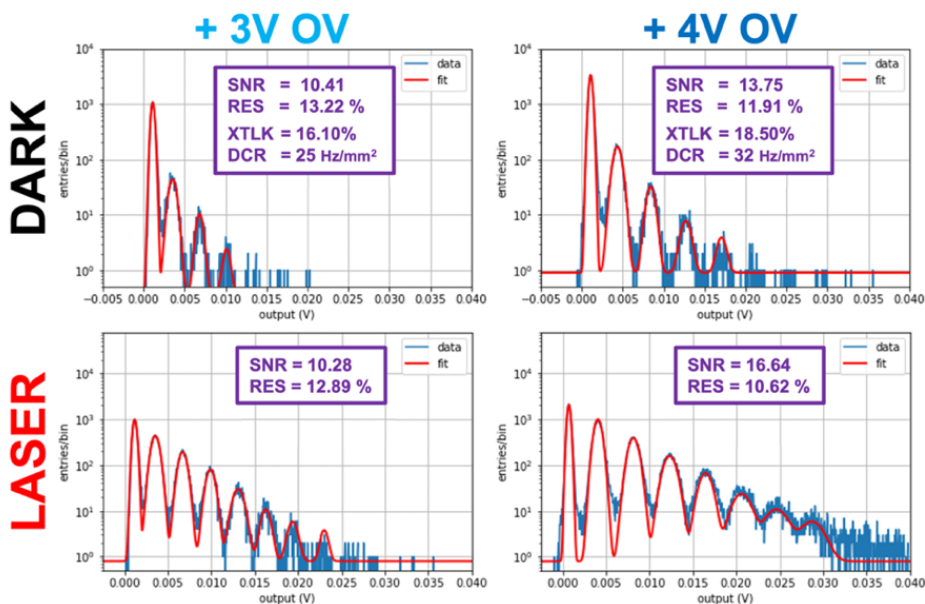


Figure 5. Results of the characterization on the pre-production FEBs batch. The signal amplitude distributions, for 2 different overvoltages in dark condition and with a very low-intensity UV laser source, are shown together with the computed values of the figures of merit.

amplitude distribution. Moreover, a Dynamic Range of 250 photoelectrons (p.e.: $\mu_k - \mu_{k-1}$) for each SiPM tile, compatible with the 0–2 V ADC input range, is mandatory [1].

A first batch of 100 pre-production FEBs has been manufactured, optimizing the values of the SMD passive components on the board. Moreover, by acting on the bias over the SiPM breakdown voltage (OverVoltage: $V_{OV} = V_{BIAS} - V_{BR}$), it is possible to adjust the dynamic range and the values of these figures of merit. Figure 5 reports the results of the characterization, for 2 different overvoltages in dark condition and with the UV laser source, demonstrating the fulfillment of the detector requirements. Since the single p.e. is about 8 mV for +3 V and 10.5 mV for +4 V overvoltages, considering the 0–2 V ADC input range, a dynamic range greater than 125 p.e. for a single channel (half-tile) and more than 250 p.e. for the entire tile is achieved. Finally, the shaping time is about 500 ns, whereas the recovery time is below 1 μ s. Several samples have been stressed with thermal cycles showing no failures.

4 Conclusion

The JUNO-TAO experiment is a spherical ton-level liquid scintillator detector that will be built near the Taishan power plant in southern China, and covering its inner area with Silicon PhotoMultipliers it will be possible to measure the reactor antineutrino energy spectrum with an unprecedented high resolution ($\leq 2\%$ at 1 MeV). Here, we reported the design of the readout front-end electronics for the Hamamatsu Silicon PM tiles at -50°C , consisting of an analog discrete Front-End Board and a digital board that contains the ADCs and an FPGA providing ADC control and signal pre-processing, demonstrating the fulfillment of the TAO requirements. The mass production of the electronics boards is ongoing, and the detector will be online in 2024. It will be a promising tool to significantly contribute to applied antineutrino physics, and the study and monitoring of nuclear reactors.

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