Front-end Design and Characterization for the $\nu$-Angra Nuclear Reactor Monitoring Detector

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ABSTRACT: The Neutrinos Angra ($\nu$-Angra) Experiment aims to construct an antineutrinos detection device capable of monitoring the Angra dos Reis nuclear reactor activity. Nuclear reactors are intense sources of antineutrinos, and the thermal power released in the fission process is directly related to the flow rate of these particles. The antineutrinos energy spectrum also provides valuable information on the nuclear source isotopic composition. The proposed detector will be equipped with photomultipliers tubes (PMT) which will be readout by a custom Amplifier-Shaper-Discriminator circuit designed to condition its output signals to the acquisition modules to be digitized and processed by an FPGA. The readout circuit should be sensitive to single photoelectron signals, process fast signals, with a full-width-half-amplitude of about 5 ns, have a narrow enough output pulse width to detect both particles coming out from the inverse beta decay ($\bar{\nu}_e + p \rightarrow n + e^+$), and its output amplitude should be linear to the number of photoelectrons generated inside the PMT, used for energy estimation. In this work, some of the main PMT characteristics are measured and a new readout circuit is proposed, described and characterized.

KEYWORDS: Front-end electronics for detector readout; Analogue electronic circuits

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1 Introduction

The $\bar{\nu}_e$-Angra Project [1, 2] aims to develop both a compact detector and new techniques to measure the flux of antineutrinos ($\bar{\nu}_e$) generated by nuclear reactions [3]. The detector was designed to operate at the surface aside one of the Angra dos Reis nuclear power plant reactors, located in the state of Rio de Janeiro, Brazil [4]. The main purposes of this project is to monitor the reactor instantaneous power dissipation and reveal the fissile composition of its nuclear fuel [5, 6].

In the past years, neutrino’s detectors have been more commonly installed underground, such as Goesgen [7], Bugey [8], Chooz [9], KamLAND [10] and Palo Verde [11], in order to be less sensitive to background sources like cosmic rays. The $\nu$-Angra Project proposes the development of a detector capable of operating at the surface, nearby the nuclear power plant reactor. Therefore, one of the challenges of this project is to build a readout system with proper time and amplitude resolution in order to allow identification and energy measurement of the $\bar{\nu}_e$ events immerse in a huge amount of background noise.

The $\bar{\nu}_e$ signature is given by the interaction characteristics of its secondary particles ($n + e^+$): the positron generates a prompt signal and the neutron capture gives rise to a second signal, which happens few microseconds after the prompt signal. Therefore, a time-shifted coincidence can be used to identify the $\bar{\nu}_e$ interaction events. Energy is another important quantity for the $\bar{\nu}_e$ identification since the energy spectrum of the positron and the neutron particles coming from the...
inverse beta decay is confined to a small energy region when compared to the energy spectrum left by the background events [2]. Additionally, a veto system must be provided to mitigate the misidentification occurrences due to cosmic ray events.

Front-end custom solutions are commonly proposed by particle physics experiments due to their particularities. This paper presents the design and characteristics of a front-end circuit developed for the $\nu$-Angra detector to condition fast signals produced by its sensors (photomultipliers), envisaging to provide to the data acquisition system an unipolar pulse shape with a time duration of few tens of nanoseconds in which the energy could be estimated directly from its peak amplitude. To detect and to estimate the energy of $\bar{\nu}_e$ events, the circuit should be capable of processing low-amplitude signals in order to be sensitive to single photoelectron (SPE) signals and have a fast recovery from saturation condition since high-amplitude signals will also be present due to cosmic rays crossing particles. The Collaboration intends to use the same front-end circuit to dress the entire detector and, therefore, different gain configurations may be needed. Additionally, new measurements related to the PMT signal characteristics under different gain configurations have been performed for the Hamamatsu R5912 PMT model [12, 13].

This paper is organized as follows. In section 2, an overview of the $\nu$-Angra detector and its readout electronics is presented. The front-end circuit is described in section 3. In section 4, the measurement system is presented; the PMT output signal characteristics under gain variation are measured; and the front-end main features are characterized. Conclusions are offered in section 5.

2 The Neutrinos Angra Detector

2.1 Detector Description

The $\nu$-Angra detector will be installed on the outer side of the concrete dome of the Angra II nuclear reactor. The adopted detector design is an assembly of mainly three subsystems: i) the inner detector (also called target detector), equipped with 32 PMTs; ii) the outer detector which is an additional layer surrounding the inner detector lateral walls, equipped with 4 PMTs; iii) two active caps positioned above and below the inner and outer detectors, each one equipped with 4 PMTs. While the inner detector is responsible for detecting the particles coming out from the inverse beta decay, the subsystems ii and iii are used to protect the inner detector from cosmic rays and low energy external background as natural radioactivity. All of them are filled with water [14], making the Cherenkov Radiation the main process to be measured by a total of 44 PMTs, all units of the same model (Hamamatsu R5912).

The 1 ton inner detector filling material will have a Gadolinium concentration. The Gadolinium addition enhances the neutron signal due to the higher energy of the deexcitation gammas ($\sum = 8$ MeV) and reduces the average time for neutron capture to a few microseconds. The target mass provides a neutrino interaction rate of about five thousands events per day considering a distance of 30 m to the reactor core and 4 GW of reactor power and the energy spectrum of the related positron and neutron events goes from 0 to about 250 photoelectrons (PEs) [1, 2]. A sketch of the inner and the outer detectors can be seen in figure 1. The inner detector has 16 PMTs positioned at the bottom wall and 16 PMTs at the top wall. The outer detector has 4 PMTs positioned at the top corners.
2.2 Electronics Overview

An overall scheme of the readout system is shown in figure 2. The 44 applied PMT devices are emerged into water and powered by a high-voltage (HV) system configured to set their gain to a value around $10^7$ electrons per photoelectron. Each detector channel is individually readout by a front-end circuit (Amplifier, Shaper and Discriminator), which provides both analog and logic outputs. The logic signals, formed by pulses generated by a discriminator circuit in which time width is proportional to the event energy, are sent to the first level trigger system (L1TS) where an initial decision about saving or not the ongoing events is made. The analog signals are delivered to the NDAQ modules [15] to be digitized and stored in buffers while awaiting for the L1TS decision signal; if the event is approved, the NDAQ data is sent to the next trigger’s level, where a more careful and time consuming decision is made. The PMT R5912 and NDAQ Analog-to-Digital Converter (A/D) main specifications are shown in tables 1a and 1b, respectively.

![Figure 2. Overall scheme of the readout system.](image)

Previous studies [1, 2] have shown that filtering events with energy below 200 PEs, summed over the 32 target PMTs, preserves more than 99% of the neutrinos events. Due to the anisotropic characteristics of the Cherenkov process, 15% of those 200 PEs may be generated by a single PMT and, therefore, the readout electronics should be designed to process signals produced by up to 30 PEs. Events producing a larger number of PEs in the target detector shall be discarded.
Table 1. PMT and A/D conversion main specifications.

| Spectral Response | 300 to 650 nm | (a) PMT R5912. |
|-------------------|---------------|----------------|
| Quantum Efficiency at 390 nm | 22% | |
| Dark Count (after 15 hours in the dark) | 4 kHz | |
| Anode Pulse Rise Time | 3.8 ns | |
| Typical pulse widths (FWHM) | 5 ns | |
| Sampling rate | 125 MHz | (b) NDAQ A/D conversion. |
| Dynamic Range | -1 to 1 Volts | |
| Number of bits | 10 bits | |

2.3 Front-End Requirements

The $\nu$-Angra front-end circuit should perform the following operations: reception of fast electrical signals coming from the PMT devices; signal amplification; pulse shaping; and signal detection. Hence, the front-end should provide conditioned analog signals to the NDAQ module for digitization and discriminant logical signals to the L1TS for events selection.

The detector electronics will be installed in a rack, two meters distant from the detector. The front-end modules will be sited in a crate nearby the NDAQ and the L1TS modules. The PMT signals are sent from the detector up to the front-end modules by means of 50 $\Omega$ coaxial cables with ten meters in length. A total of 44 PMT signals should be processed by the front-end modules, 32 from the inner detector, 4 from the outer detector and 8 from the two active caps. Taking into account the PMT specifications (table 1a), the NDAQ specifications (table 1b) and the $\bar{\nu}_e$ signature, the front-end circuit requirements are summarized below:

- sensitivity to SPE signals in the target detector;
- output pulse duration less than 1 $\mu$s;
- maximum bandwidth of 60 MHz;
- maximum voltage swing of 2 V.
- linear operation up to 30 PEs for the PMTs in the inner detector;
- peak amplitude of the front-end output signals should vary linearly with the PMT signal charge for fast energy estimation (concerning the second trigger level);
- front-end logic pulses duration should be proportional to the PMT signal charge for fast energy estimation;

3 The Front-end Circuit

Following the NDAQ boards configuration, each front-end module will receive eight PMT signals. Therefore, a total of six front-end modules will be required to instrument the detector. A block diagram representing a front-end channel can be seen in figure 3. The amplifier-shaper circuit interfaces the PMT in its input and the NDAQ in its output. The discriminator circuit basically
performs a voltage comparison between the analog pulse coming out from the front-end amplifier-shaper circuit and a threshold level, providing a logical signal for the L1TS. Offset and threshold control circuits have been foreseen in order to allow remote adjustment of the DC level of the front-end analog signal and of the threshold signal provided to the discriminator circuit.

3.1 Amplifier-Shaper Circuit

The amplifier-shaper circuit is based on a cascade arrangement of low order filters/amplifiers due to the simplicity in the design and to avoid fluctuations in the pulse shape as a consequence of the tolerance in the components values for higher order filters. This approach is commonly used in the shaping stage of front-end circuits applied to particle detectors [16]. The amplifier-shaper circuit simplified schematic is shown in figure 4.1 The circuit can be divided into 4 stages. The output of each stage is indicated by S1 (first stage), S2 (second stage), S3 (third stage) and output (fourth stage).

The first stage is responsible for the PMT signal reception and preprocessing, matching the cable impedance (50 Ω), limiting the signal bandwidth and providing signal amplification. An operational amplifier2 with high input impedance and a high gain-bandwidth product was used in this stage. Additionally, a limiter circuit based on high speed diodes3 is applied at the amplifier input

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1 Decoupling capacitors have been omitted.
2 OPA657 1.6 GHz FET-Input OpAmp by Texas Instruments.
3 BAL74 from NXP Semiconductors.
for protection. The second stage is a second order passive bandpass filter using a CRRC circuit, introducing a upper cutoff frequency of \(\approx 7\) MHz. The third and fourth stages are amplifiers followed by lowpass filters envisaging to adjust the circuit gain, the pulse duration and the circuit bandwidth to about 4 MHz. These last stages are implemented using wideband operational amplifiers and lowpass filters based on first order RC circuits. Additionally, two amplitude limiters are applied at the first and third stages outputs in order to guarantee a fast recovery from saturation caused by high-amplitude input signals. They are implemented using schottky barrier diodes working together with a negative output linear regulator.

The pulse shape and amplification at the output of each stage can be seen in figure 5. A SPICE simulation was carried out using a Gaussian shaped input signal of normalized amplitude (solid gray curve with peak amplitude equal to \(-1\)). The first stage provides a voltage gain around 12 and a fast response to the input signal. At the second stage output, the pulse duration is increased and its amplitude is significantly reduced. At the output of the third stage, an additional increase on the pulse duration and rise time is achieved and the signal is amplified in order to have a peak amplitude close to the same level of the first stage output. The fourth stage basically adjusts the pulse amplitude and introduces a phase inversion.

![Figure 5. Amplifier-shaper circuit simulation. Input and output signals for all the circuit stages.](image)

3.2 Offset/Threshold and Discrimination Circuits

The front-end circuit should also provide a logic output to the trigger system each time a detector signal is produced. To perform this task, a fast voltage comparator is used. The amplifier-shaper circuit output is used as input for the comparator and the voltage comparison level (threshold) is delivered by a low-power 16-bit DAC accessible via \(I^2C\) protocol through an amplification stage. The offset at the output of the amplifier-shaper circuit can also be adjusted using the same scheme based on the 16-bit DAC.

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*OPA842 by Texas Instruments.*

*BAT60 by STMicroelectronics.*

*TPS72301 by Texas Instruments.*

*AD8561 by Analog Devices.*

*AD5665R by Analog Devices.*

*AD820 by Analog Devices.*
3.3 Front-end Module

As already mentioned, each front-end module processes eight PMT signals and interfaces with one NDAQ module, sited in a crate two meters apart from the detector. A total of six modules are required in order to instrument the detector. The front-end module is a six layers printed circuit board, measuring $230 \times 180$ mm. Figure 6 shows a front-end module picture.

![Figure 6. Photography of a front-end module.](image)

4 Results

In this section, the applied measurement setup and its configuration are briefly described (section 4.1). Subsequently, the results regarding the PMT output signal characteristics under high voltage variation (section 4.2) and the characterization of the main front-end features (section 4.3) are presented and discussed.

4.1 Measurement Setup

To study the characteristics of the PMT and the front-end devices to be used in the detector, a measurement system was built with the following components: a dark chamber, a signal generator,\(^{10}\) a high voltage power supply,\(^{11}\) an oscilloscope,\(^{12}\) a PMT\(^{13}\) and a green LED. A scheme of this system can be seen in figure 7. For the PMT output signal measurements, the front-end shown in the scheme is bypassed, and the PMT output is directly connected to the oscilloscope. Two sampling rates have been used: 5GS/s and 250MS/s for the PMT (section 4.2) and the front-end (section 4.3) measurements, respectively.

\(^{10}\)Agilent 33250A.
\(^{11}\)Hamamatsu C9525.
\(^{12}\)Tektronix TDS 5034B.
\(^{13}\)Hamamatsu R5912.
The SPE response was used to measure the fundamental PMT and front-end characteristics. A LED was used to produce SPE signals at the PMT output stage. To calibrate the system, short pulses were injected in the LED circuit so that the probability to generate only one photoelectron in the PMT photocathode would be much higher than the probability to generate two or more photoelectrons. This condition can be achieved, following the Poisson distribution [17, 18], by setting the signal generator so that the majority of LED input pulses are not able to convert any photoelectron. Measurements configuring a signal generator to inject 8 ns pulses with peak amplitude values varying from 900mV to 975mV into the LED circuit was carried out. For the 900 mV value, it was estimated that the contamination with events with more than one photoelectron was 0.33% +0.03%. Those values were adopted as the system SPE calibration standard in this work. The resulting charge distributions for the four input voltages are shown in figure 8: charge was computed taking into account the 50 Ω oscilloscope input impedance.

The SPE charge was estimated to be equal to 1.48 ± 0.11 pC, which corresponds to a PMT gain of $0.92 \cdot 10^7 \pm 0.07 \cdot 10^7$ electrons per photoelectron.

4.2 PMT Gain Variation Effects

The $\nu$-Angra Collaboration will use the PMTs power supply values as recommended by the manufacturer. Nevertheless, adjusting the PMT gain during the experiment might be necessary. In this section the PMT device is tested under high-voltage variation, mainly to understand the behavior of the PMT signal waveform and its Signal-to-Noise Ratio (SNR) since it could affect the front-end output signal characteristics and, consequently, the trigger performance. To accomplish this task,
the PMT was supplied with five different voltages, 1300 V, 1400 V, 1510 V, 1600 V and 1700 V and, for each one of them, the same procedure to generate SPE signals as described in section 4.1 was executed. The PMT generated signals were acquired by the referred oscilloscope which was configured to work with an input impedance of 50 Ω. One hundred thousand measurements were carried out for each one of the proposed HV values. The charge evolution can be seen in figure 9. The dashed line represents an approximation by an log-linear function $\log_{10}(y) = Ax + B$ where $A = 2.04 \cdot 10^{-3} \pm 0.07 \cdot 10^{-3}$ and $B = -14.94 \pm 0.11$. At 1300 V and 1700 V the following charge values are measured: 0.506 ± 0.042 pC and 3.31 ± 0.34 pC, respectively.

**Figure 9.** High-voltage versus charge for the PMT output signal. The charge value relative to a PMT gain of $10^7$ is represented by the horizontal gray line.

As it can be noticed in figure 10, the normalized waveform is slightly dependent of the supply voltage; its full-width half-maximum (FWHM) varies from approximately 4.64 ns to 3.89 ns for 1300 V and 1700 V respectively.

**Figure 10.** (a) PMT’s output waveforms for different supply voltages. (b) High-voltage versus FWHM for the PMT SPE mean signal.

The log-linearity between the PMT supply voltage and its output signal peak amplitude, for the SPE response, can be observed in figure 11a. Figure 11b shows how the SNR varies with respect to the supply voltage for the SPE response signal. The SNR is computed according to Equation $\text{SNR} = 20 \cdot \log_{10} \left( \frac{\mu_s}{\sigma_n} \right)$, where $\mu_s$ is the mean peak amplitude value of the SPE signal and $\sigma_n$ is the noise standard deviation. It is possible to verify that the SNR can be considerably improved by increasing the PMT gain.
Figure 11. (a) High-voltage versus peak amplitude for the PMT output signal. (b) High-voltage versus SNR for the SPE response signal.

4.3 Front-end Characterization

The next measurements use the SPE generation technique as described in section 4.1. The PMT is supplied with the HV nominal value of 1510 Volts. Three different attenuation factors (AF) were used at the front-end input, corresponding to an amplitude attenuation of 0 dB (AF = 1), −6.0 dB (AF = 2) and −9.5 dB (AF = 3). One hundred thousand measurements were carried out for each one of them. From now on, a measurement is defined by an acquisition window lasting 2 µs with 500 acquired samples (250 MS/s sampling rate). The resulting mean waveforms are shown in figure 12.

Figure 12. Front-end output average waveforms in response to PMT SPE events.

The front-end mean peak amplitudes and SNR values for the SPE response signal are shown in table 2 for the three AFs. As expected, the higher is the attenuation factor, the worse is the SNR. A SNR enhancement has been observed for an AF of 1, whereas for the other AFs, the SNR has been reduced when compared to the PMT output stage.

Table 2. Front-end mean peak amplitude and SNR for the SPE response.

| AF  | Mean Peak Amp. (mV) | SNR (dB)  |
|-----|---------------------|-----------|
| 1   | 71.5 ± 0.9          | 31.5 ± 0.3|
| 2   | 35.8 ± 0.4          | 29.7 ± 0.3|
| 3   | 23.7 ± 0.2          | 27.1 ± 0.3|
In order to verify the front-end circuit linearity, a signal generator was used to emulate the PMT signal. It was configured to produce pulses with a FWHM of 8 ns and 5 ns for the falling and the rising edges. The generator output was connected to the front-end input and its trigger signal was sent to the oscilloscope trigger input. The front-end output was connected to one of the oscilloscope channels. The generator pulse peak amplitude was varied and, for each peak amplitude, two thousand acquisitions were performed. Figure 13 shows the relation between the input charge, computed over a 50 $\Omega$ impedance, and the peak amplitude of the front-end output signal for the three AFs. The lines alongside the measurement points represent the linear fit curves obtained for each one of the AFs. It can be noticed that at an output peak amplitude of approximately 1.4 V, the saturation effect becomes apparent. Table 3 shows the linear fit parameters $(Ax + B)$ for the three AFs.

![Figure 13. Output peak amplitude versus input charge.](image)

| AF | A (V/pC) | B (V) |
|----|----------|-------|
| 1  | $45.90 \cdot 10^{-3} \pm 0.09 \cdot 10^{-3}$ | $-3.34 \cdot 10^{-3} \pm 0.09 \cdot 10^{-3}$ |
| 2  | $25.3 \cdot 10^{-3} \pm 0.2 \cdot 10^{-3}$ | $-1 \cdot 10^{-3} \pm 3 \cdot 10^{-3}$ |
| 3  | $16.7 \cdot 10^{-3} \pm 0.2 \cdot 10^{-3}$ | $-3 \cdot 10^{-3} \pm 4 \cdot 10^{-3}$ |

This measurement can also be used to compute the excursion capability of the device in number of PEs for each of the three AFs. Considering a PMT gain of $10^7$ electrons per photoelectron, for AF = 1, the front-end is capable of processing approximately 18 PEs before entering into the saturation region; for AF = 2 and AF = 3 this value goes to 36 and 53 PEs, respectively. Those results indicate that the front-end output waveform is stable up to its saturation region and that it is possible to estimate the input charge from its output signal, by means of its peak amplitude.

To assess the channels uniformity, 24 channels were selected and configured with an AF = 1. Figure 14 shows the linear fit parameters $(Ax + B)$ obtained for each channel.

The noise characterization of the front-end channels may be important for defining the trigger system strategy and the energy estimation algorithm [19]. Figure 15 shows the channels' noise amplitude distributions. It shows that the noise is Gaussian with a standard deviation of $0.93 \pm 0.01$ mV.
Figure 14. Output peak versus input charge fit parameters \((Ax + B)\) for 24 front-end channels.

Figure 15. Noise amplitude distributions for different front-end channels.

Figure 16. (a) Noise autocorrelation measurement. (b) Noise power spectrum.

Finally, the dependency between discriminator pulse width and input charge has been evaluated considering different threshold values. This dependency will be used by the Level-1 Trigger System to discard events with energy above 200 PEs. As mentioned before, the experiment will be interested in estimating energies up to 30 PEs per PMT (approximately 50 pC). Figure 17 shows the resulting curves for \(AF = 1\). The acquired data have been fitted to the function \(f(x) = Ax^B + C\) and the estimated parameters are shown in table 4.
Figure 17. Discriminator pulse width versus input charge for AF = 1.

Table 4. Fit parameters ($A x^B + C$) from figure 17.

| Threshold | A       | B       | C       |
|-----------|---------|---------|---------|
| 10 mV     | -580 ± 169 | -0.064 ± 0.023 | 674 ± 173 |
| 15 mV     | -735 ± 200 | -0.051 ± 0.016 | 813 ± 202 |
| 20 mV     | -563 ± 125 | -0.071 ± 0.020 | 629 ± 128 |

5 Conclusion

This work presented a new circuit developed for the $\nu$-Angra Experiment to readout fast and low-amplitude PMT signals. Additionally, a measurement system has been proposed and configured, and the PMT model R5912 by Hamamatsu was tested considering its SPE response. Since high-voltage adjustments might be used to fine tune the PMTs gains during the experiment, it was shown that its output signal waveform and its SNR for the SPE response is stable throughout gain variation; it was considered gain values around $10^7$, more specifically from $0.3 \cdot 10^7$ (1300 V) to $2.1 \cdot 10^7$ (1700 V) electrons per photoelectron. Considering the front-end system, the circuit specifications, topology and characteristics were described and measured. It was tested for three different global gains in order to make it available to be used in different sectors of the detector. The circuit output signal presents an unipolar shape having a duration of approximately 80 ns at full-width half-maximum, being linear to the input charge up to an output voltage of 1.4 V. The PMT signal was properly conditioned to be read by the $\nu$-Angra acquisition system maintaining practically the same SNR as provided by the PMT; when no attenuation is used, the SNR is improved from 30.2 dB (PMT output) to 31.5 dB (front-end output) for the SPE response signal. The electronics noise standard deviation is less than 1 mV and the front-end circuit channels present adequate uniformity. The front-end circuit as described herein is currently being used in the detector characterization measurements and by the end of 2016 it will be operating alongside the Angra dos Reis nuclear reactor.

Acknowledgments

This work is supported by the following research agencies: FAPEMIG, CNPq and CAPES.
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