Signal processing and electronic noise in LZ

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ABSTRACT: The electronics of the LUX-ZEPLIN (LZ) experiment, the 10-tonne dark matter detector to be installed at the Sanford Underground Research Facility (SURF), consists of low-noise dual-gain amplifiers and a 100-MHz, 14-bit data acquisition system for the TPC PMTs. Pre-prototypes of the analog amplifiers and the 32-channel digitizers were tested extensively with simulated pulses that are similar to the prompt scintillation light and the electroluminescence signals expected in LZ. These studies are used to characterize the noise and to measure the linearity of the system. By increasing the amplitude of the test signals, the effect of saturating the amplifier and the digitizers was studied. The RMS ADC noise of the digitizer channels was measured to be $1.19 \pm 0.01$ ADCC. When a high-energy channel of the amplifier is connected to the digitizer, the measured noise remained virtually unchanged, while the noise added by a low-energy channel was estimated to be $0.38 \pm 0.02$ ADCC ($46 \pm 2 \mu V$). A test facility is under construction to study saturation, mitigate noise and measure the performance of the LZ electronics and data acquisition chain.

KEYWORDS: Digital signal processing (DSP); Front-end electronics for detector readout; Data acquisition concepts

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1 Introduction

The LUX-ZEPLIN (LZ) experiment is a second-generation dark-matter detector to be installed in the Davis Cavern at the Sanford Underground Research Facility (SURF) [1]. LZ contains 10 tonnes of liquid xenon with a 7-tonne active volume in a two-phase time projection chamber (TPC). The detector will be housed in the same water tank that is currently used for the Large Underground Xenon (LUX) dark-matter detector to shield it from environmental radiation [2]. To further reduce the background level in the detector, the TPC is surrounded by a gadolinium-loaded liquid scintillator active veto. The scintillator and a portion of the water tank are viewed by 120 PMTs. Another 180 PMTs, mounted inside the cryovessel, monitor the thin layer of xenon between the cryostat and walls of the TPC.

Figure 1. (Left) Overview of LZ installed in the Davis Cavern. (Right) Close-up of the mezzanine level showing the breakout boxes and the cable conduits. The electronics racks on the upper level are also indicated.
The TPC employs 488 Hamamatsu R11410 3-inch-diameter PMTs [1], distributed in two arrays, one on the top with 247 PMTs in a hexagonal configuration with two circular outer rows and one on the bottom with 241 PMTs distributed in a hexagonal configuration. The high voltage (HV) and signal cables for these PMTs are routed to a mezzanine level where two breakout boxes are installed, as shown in figure 1. The design of the electronics signal chain for these PMTs is motivated by requiring a 90% detection efficiency for a single photoelectron and to provide a dynamic range that allows the use of 236 keV Xenon activation line for calibration. In this paper we describe tests carried out on pre-prototype components of this electronics chain and discuss a setup that is being assembled to test the full electronics and data acquisition chain.

2 Preliminary tests of the LZ TPC electronics chain

The HVs for TPC PMTs are provided by Weiner MPOD EDS 20130x_504 modules [3]. Kerpen cables with 48-cores feed HV to the flanges on the breakout box from the electronics rack, each of which provide HV for 32 PMTs [4]. Gore 3007 cables are used to supply HV from the breakout box to the base of the PMTs and also to transport the signals from the PMT base to the breakout box [5]. These cables have been chosen for their low heat load and low signal attenuation. The area attenuation was measured with 45 and 90 feet of these cables with 2-ns risetime pulses and found to be 18% and 28%, respectively. The amplitude attenuation was found to be 56% and 80%, respectively.

To provide the required efficiency at low energies to detect single photoelectron and appropriate dynamic range for higher energy signals corresponding to calibration sources, custom dual-gain amplifiers are used. These amplifier cards are located in cages on the breakout boxes with each cage containing four amplifier cards with eight input channels each. The high-energy (HE) output of the pre-prototype amplifier card has a full-width at tenth maximum (FWTM) shaping time of 30 ns and an area gain of 0.5, while the low-energy (LE) output has a FWTM shaping time of 60 ns and an area gain of 20. The total front end LZ detector electronics noise requirement for the amplifiers and digitizer is $<0.5 \text{ mV (rms)}$.

The output signals from the amplifiers are routed to electronic racks located directly above the breakout boxes on the upper level of the experimental hall, using LMR-100-FR cables [6]. These cables have a low signal area attenuation and, as required by SURF, are low smoke and zero halogen (LSZH) cables.

The output signals of the amplifier are digitized using DDC-32 digitizers built by Skutek Instrumentation [7]. These digitizers were built to have a low inherent electronic noise to provide high efficiency for single photoelectron detection. The digitizers have 32 input channels, 2 V dynamic range, 14 bit resolution and a sampling frequency of 100 MHz. The RMS noise of the DDC-32 is $1.19 \pm 0.02 \text{ ADCC}$, increasing to $1.22 \pm 0.02 \text{ ADCC}$ when a HE output channel of the amplifier is connected to it and $1.58 \pm 0.02 \text{ ADCC}$ in the case of the LE channel. The HE channel adds almost no noise to the inherent noise of the digitizer and the LE channel of the amplifier adds $1.04 \pm 0.02 \text{ ADCC}$ of noise in quadrature.

The amplifier and digitizer chain was further studied to determine if the RMS noise was dominated by noise at a particular frequency. For each of the three combinations (DDC-32, HE+DDC-32 and LE+DDC-32), a thousand waveforms of 8,192 samples each were collected. The
Figure 2. Averaged noise spectrum for the pre-prototype amplifier and digitizer chain. The trace of the noise spectrum for the DDC-32 is shown in black. The noise spectra for a combination of the DDC-32 and the LE and HE channels is shown in light and dark grey, respectively.

magnitude squared of the Fourier transforms were averaged together and these spectra are shown in figure 2. All three spectra fall as $1/\sqrt{\text{Hz}}$ and there are no dominant noise contributing frequencies. As was expected, the HE channel adds almost no noise to the noise of the digitizer. The LE channel adds noise uniformly over a broad range of frequencies.

Figure 3. Gain linearity plots generated with the pre-prototype amplifier. The pre-prototype amplifiers have an area gain factor of 0.5 for the HE channel (left) and an area gain factor of 20 for the LE channel (right).

The response of the pre-prototype amplifier and digitizer were tested for area linearity with two types of pulses: a fast pulse with 10%–90% rise times in the range 10–50 ns and fall times two and a half times the rise time and with a slower pulse of Gaussian shape with rise times in the range of 150–1500 ns. The input pulse amplitude to the amplifier was varied between 0.020 V and 0.50 V. For the results shown in figure 3, a fast pulse with a rise time of 20 ns was used. The deviation from linearity of these points and standard deviation of the population before saturations is < 1%. For all tested pulses, the measured area gains match specifications. For slower pulses the saturation points moved to larger input areas, thereby giving us a pulse width dependent dynamic range for LZ [8].
3 Full electronics test facility

To test all the components of the LZ data acquisition system, an electronics chain test facility is being created at the University of Rochester. This facility will include all the LZ components from PMT to disk, as shown in figure 4. The LZ data acquisition system is designed to meet the need of digitizing 788 PMTs located within the TPC, the skin of the cryostat and the liquid scintillator external to the cryostat. This system is designed to handle a rate of 150 Hz of calibration events in the TPC.

The test facility will include two full signal and data-acquisitions chains. The purpose of the test facility is to provide a development system to extensively test and measure the performance of hardware, software, and firmware, before deployment in LZ. This setup will include two Hamamatsu R11410 PMTs in a small vacuum vessel, which includes a feed through for an LED signal. The same signal and HV flanges to be used on the breakout boxes are used on the vessel. Only one feed-through connector on the HV flange will be populated to bias the two PMTs. The signal flange is mounted with an amplifier cage and two amplifier cards. These extra channels from the amplifier will be digitized to measure crosstalk and develop methods to mitigate common mode noise.

The signals from the amplifiers will be digitized with two DDC-32s. Only when a valid event is identified from the external trigger in the DAQ Master is data off-loaded from the DDC-32 to disk on the Data Collector via the Data Extractor [9]. Field Programmable Gate Array (FPGA) firmware is being developed for real time data sparsification and pulse only digitization [10]. Further firmware is being developed to off-load the data from the DDC-32s to the Data Extractor using a

![Figure 4. Schematic overview of the setup for the electronics chain test.](image)
custom serializer/deserializer protocol over a HDMI connection. This entire digital chain will be monitored and controlled by the Data Acquisition Master computer.

The Event Builder reads data from the disks on the Data Collectors and builds full event files. Software is being developed to convert the raw data on the Data Collectors into full event files on the Event Builder in real-time. Run Control will initiate the start and stop of the data acquisition, as well as monitor its status and the status of the Event Builder. Run Control will also be responsible for communicating the run parameters to the Data Acquisition Master Computer and the Event Builder.

The use of an LED will allow a range of components in the chain to be tested. Small, well-timed pulses will be generated in the LED to study relative timing difference between channels, while large pulses will be used to study saturation in the PMTs, the amplifiers, and the digitizers. Using a high pulse rate provides the opportunity to stress test the data throughput and benchmark the performance of the acquisition system. Currently, the vacuum vessel is being assembled and firmware and software are being deployed.

4 Summary

Testing has been completed on pre-prototypes of the amplifier and digitizer and they have met noise and area linearity requirements. The process of constructing an electronics test facility to mimic the setup of LZ TPC PMTs has begun. Using this setup we will study the effects of saturation as well as possible time difference between channels at the PMT, amplifier, and digitizer and develop techniques to mitigate noise. This setup will also be used to optimize the performance of the data acquisition and event building hardware and software.

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