A Modular Readout System For A Small Liquid Argon TPC

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Abstract

A dual-FET preamplifier and a multi-channel waveform digitizer form the basis of a modular readout system for a small Liquid Argon Time Projection Chamber. Simulated signals typical of a minimum ionizing particle sampled on a 5 mm pitch can be reliably detected with a simulated detector capacitance of at least 600 pf.

Introduction

A Liquid Argon Time Projection Chamber (LArTPC) operates by drifting the ionization of charged particle tracks through the liquid Argon to a three plane stereoscopic set of wires in a manner pioneered by the ICARUS collaboration[1]. In a recent report[2], a program of R&D was proposed that would demonstrate a scalable multi-kiloton for neutrino oscillation experiments. A 5 mm wire pitch was selected as a compromise between frequent sampling for track pattern recognition, and a wider pitch yielding a lower capacitance for a larger signal and lower noise. A minimum ionizing particle sampled every 5 mm along its length generates a signal of ~25,000 electron. This signal is, however, reduced by the residual oxygen contamination in the Argon and other loss mechanisms. To account for these losses a charge collection efficiency of ~90% is assumed, reducing the signal to ~22,000 electrons.

An initial step is the construction of a ~30 liter LArTPC (mini-TPC) as a test-bed for front-end and data acquisition electronics. To bring this system up quickly we searched for an existing low-noise hybrid preamplifier capable of reliably identifying the 22,000 electron signal under the test conditions. Also needed was a unit to perform a 10-bit waveform digitization and store the digitized data for later readout. A sufficient number of preamplifier and waveform digitizer channels would be needed to readout the ~300 wires of this detector.

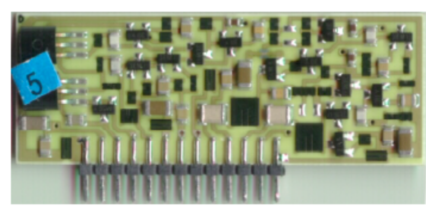

Fig. 1. LAr calorimeter preamplifier used by the D-zero experiment in Run II

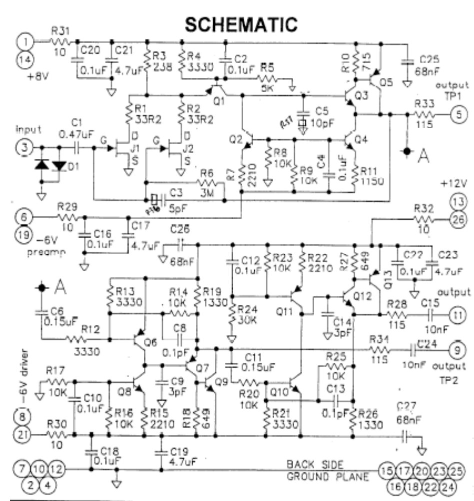

Fig. 2. Preamplifier circuit schematic

Preamplifier

The ICARUS collaboration has developed many techniques that are essential for successful operation of a LArTPC. In their current readout electronics, signals on the wires are received by preamplifiers with an FET based front end. For the (warm) electronics being considered, we believe that this configuration has a excellent performance which would be hard to improve upon. A low noise dual-FET hybrid preamplifier, as pictured in Figure 1, with a circuit schematic as shown in Figure 2, is used by the D-Zero experiment in Run II. Given the similarity in the front end design, we anticipated that the performance of this preamplifier would be similar to the ICARUS preamplifier. A sufficient number of preamplifier hybrids are available for the mini-TPC.

Waveform digitization

By another stroke of luck, another module developed by MSU for the D0 calorimeter trigger in Run II, the ADF-2, can digitize the preamplifier output waveform. The ADF-2 module, pictured in Figure 3, contains 32 channels of a modern and fast 10-bit ADC with FPGA data control and storage. A block diagram of the ADF2 digitization section is shown in Figure 4. Pedestal voltage adjustment and variety of other functions can be performed by the module.

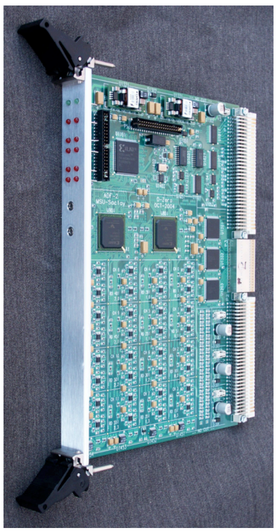

Fig. 3. ADF-2 module

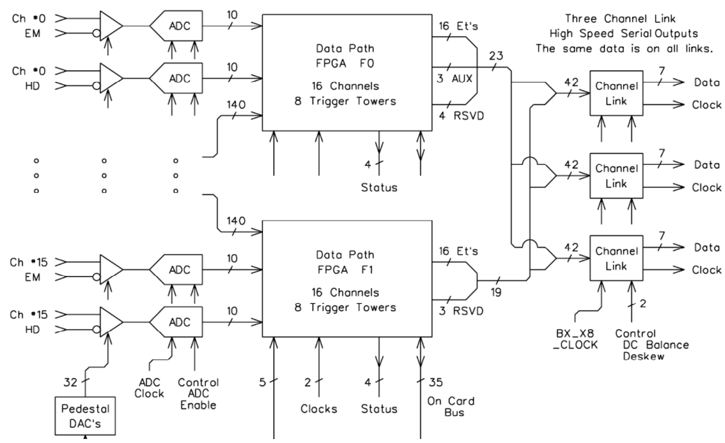

Fig. 4. ADF-2 signal processing block diagram

The module can be configured to sample a voltage at a time interval that is a multiple of 9.4 ns (e.g., 14 x 9.4 ns = 132 ns) with the 10-bit digitized data stored in the available FPGA circular buffer space. Since the signal rise time is expected to be about 1 μsec, we chose to sample the signals every 197 ns (21 x 9.4 ns), thus allowing 2048 samples to be stored in the FPGA for each channel.

Simulating the signal

We simulated the signals of a three plane LArTPC, two induction planes followed by a collection plane separated by 5 mm, and each with wires on a 5 mm pitch. For simplicity we simulated the signal generated by a minimum ionizing particle traveling perpendicular to a signal wire at a distance of 1 m from, and parallel to the wire planes. Assuming a drift field of 1500 V/cm, the ionization drifts toward the signal wires with a speed of ~1.5 mm/μsec. The ionization from a segment of track diffuses along the drift direction. For track ionization drifting only 1 m, the distribution is sufficiently narrow that nearly all the charge can be contained within a longitudinal distance of 5 mm.

The signal charge seen by a wire in the second induction plane is easiest to simulate. The first induction plane shields the signal wire from the cluster of electrons until they begin to pass through it where by the signal begins to rise. The signal peaks when the cluster is centered on the signal wire, and drops as the cluster moves toward and is absorbed by the collection plane. We simulate this signal with a 150 Khz sine function which has rise and fall times and width comparable to the signal generated by the cluster of electrons. It will be assumed that when centered on the wire the cluster produces an induced charge equal to the 22,000 electrons of a minimum ionizing track.

A number of factors can cause tracks to behave differently from the idealized one simulated here. The charge diffuses during the drift time, the signal is shared among wires, the tracks have slopes, ionization varies, there may be neighboring tracks, and and many others. With appropriate signal digitization and shaping functions, such as digital charge integration or differentiation, can be applied to optimize the signal to noise once pattern recognition has established the basic properties of each track.

Test setup

An HP arbitrary waveform generator is used to make the half cycles of 150 KHz with an amplitude of a few Volts. This signal goes through a coaxial choke as it enters a shielded preamp enclosure where it is attenuated. Connected to the preamp input is a series of high value resistors to make the test signal appear as a current source. Connected between the preamp input and ground is a silver mica capacitor to simulate the detector capacitance. Three different values of detector capacitance were used in this test: 0 pF, 330 pF, and 660 pF. Also contained in the preamp enclosure are the noise filters for the preamp power supplies. An additional stage of amplification follows the preamplifier to drive the cable leading out of the shielding box and to match the input properties of the ADC.

The frequency response is not flat at a number of points in the analog sections of the preamplifier and amplifier. The high frequency and low frequency roll off in gain that were used for these tests are "reasonable" but have not been optimized. Optimizing the response of the analog section as a function of frequency requires knowing: the real signal shape, the characteristics of the noise sources, and how the signal will be extracted from the raw ADC data. Nevertheless, the frequency spectrum of the noise seen in these tests will be presented.

The analog output signal cable from the preamp enclosure runs about 10 feet to a VME crate that holds the ADF-2 card. The response of the ADF-2 card is basically flat across the frequencies of interest in these tests. The ADCs on the ADF-2 card are "sampling converters", i.e., at a specified time they sample the analog input voltage and provide a digital output value proportional to this voltage. The VME crate is controlled by a PC through a commercial hardware interface from Bit-3. The software on the PC and the ADF-2 firmware are both derived from their corresponding elements in the D-Zero trigger control system.

Test results

The waveform presented to the ADF–2 module was digitized for 400 μsec with the time of the test pulse set at ~340 μsec after the start of the digitization. Typical “traces” were recorded for each of the three test capacitances. The first 300 μsec of each trace characterizes the noise while the region around 340 μsec displays the signal plus noise. The pedestal subtracted data for four traces are overlapped and plotted as shown in

Figure 5 for a 0-pf capacitance and in Figure 6 for a 600-pf simulated detector capacitance. Shown in the inset of each figure is an expanded region around the signal.

The signal to noise is usually characterized by the standard deviation of the noise compared to the signal amplitude. Since the noise is sensitive to the filtering which has not been optimized and other noise sources will be present in a real detector, we quote

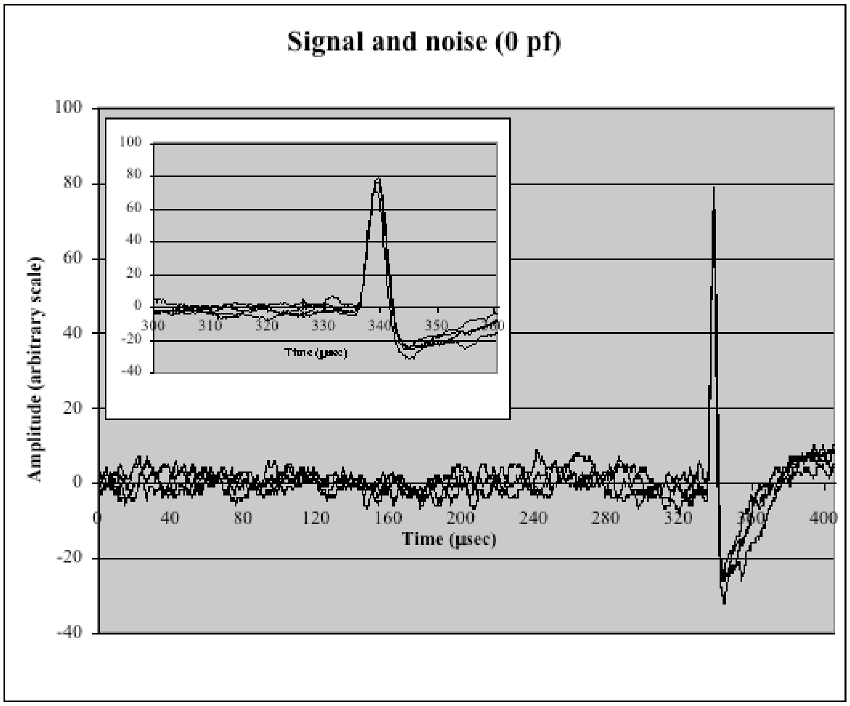

Fig. 5. Waveform for 0-pf detector capacitance

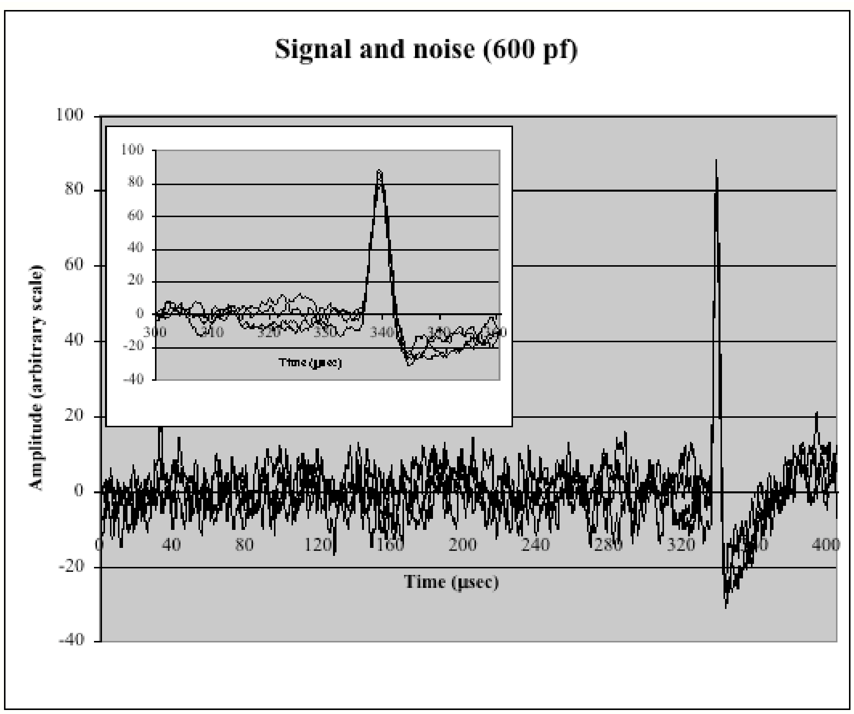

Fig. 6. Waveform for 600-pf detector capacitance

only the approximate signal to noise ratios of ~20/1 for the 0-pf capacitance data and ~10/1 for the 600-pf simulated detector capacitance.

To provide more information regarding the noise observed in these tests, we investigated the noise frequency spectrum for detector capacitances 0 pf and 600 pf, as shown in Figure 7. To normalize these spectra, a 150 kHz calibration signal was input to the preamplifier with an amplitude just barely visible above the noise. This amplitude relative to the amplitude of the signal for 22,000 electrons (10^0 on the vertical axis) determined the height of the curves at 150 kHz. Near this frequency the signal to noise for each capacitance and their ratio are roughly consistent with the standard deviation values quoted above. It is clear from this data that the low frequency filtering could have been a bit stronger.

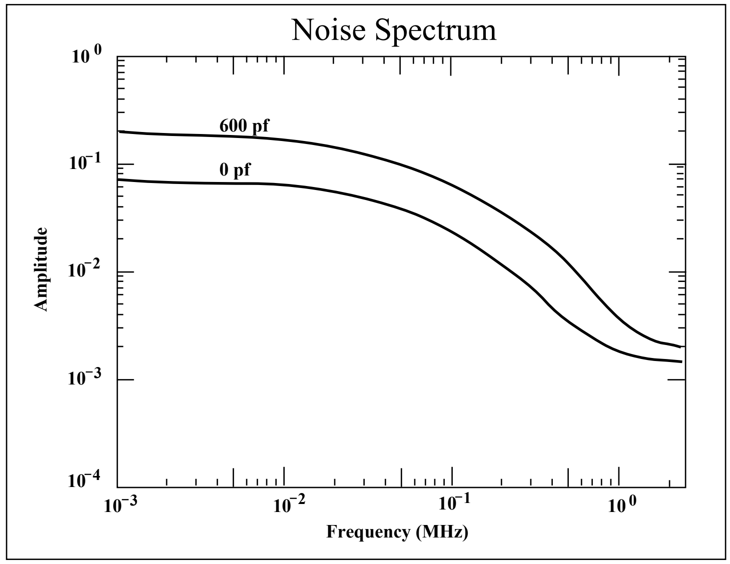

Fig. 7. Noise power for two detector capacitances.

Conclusions

The tested preamplifier is certainly adequate to successfully readout the small LArTPC that we are building due to its rather low capacitance. We note that the 600-pf capacitance is in the range one expects for the long wires of a large detector. The data therefore suggests that readout of a large detector will be possible utilizing techniques similar to the ones in this test. Also, it is encouraging that equipment designed for another experiment with a well established cost appears to have adequate performance for the large LArTPC detector we envision.

References

1. S. Amerio et al, "Design, construction and tests of the ICARUS T600 detector" Nucl. Inst. Meth., A527 (2004) 329-410

2. D. Finley et al, “A Large Liquid Argon Time Projection Chamber for Long-baseline, Off-Axis Neutrino Oscillation Physics with the NuMI Beam”, Submission to NuSAG committee, Sept. 21 2005, http://lartpc-docdb.fnal.gov/0000/000011/001/LArTPC.pdf