Optimization and Analysis of ICEBERG LArTPC Run Configuration for Data Collection

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Abstract

This paper presents the findings from the ICEBERG project at Fermilab, focusing on the development and optimization of Liquid Argon Time Projection Chamber (LArTPC) detectors for the DUNE project. Various parameters, including Vref, gain, and peak time, were systematically varied to ensure accurate data collection and diagnostics. The analysis revealed optimal settings that enhance the detector's performance, paving the way for improved neutrino detection and research.

1. Background

The Deep Underground Neutrino Experiment (DUNE) is an international collaboration aimed at advancing the understanding of neutrino properties and exploring fundamental questions about the universe. DUNE's experimental setup involves two neutrino detectors positioned within the most intense neutrino beam ever created. One detector is located at the Fermi National Accelerator Laboratory in Batavia, Illinois, close to the neutrino beam source. The second, much larger detector, is situated over a kilometer underground at the Sanford Underground Research Laboratory in Lead, South Dakota. This arrangement allows for comprehensive data collection on neutrino interactions and behavior, contributing to groundbreaking discoveries in particle physics.

The DUNE far detector uses a Liquid Argon Time Projection Chamber (LArTPC) to capture and reconstruct three-dimensional images of neutrino interactions. When a neutrino collides with an argon atom, it produces a reaction, which ionizes surrounding argon atoms as it moves through the liquid. This ionization generates free electrons, which then drift towards an array of wires by way of a strong electric field. As these electrons reach the wires, they create detectable pulses of current. By analyzing these pulses, researchers can reconstruct the neutrino's path and interaction details with extreme precision, providing valuable insights into neutrino properties and their role in the universe.

2. Motivation

The ICEBERG project at Fermilab is dedicated to advancing the development and testing of LArTPC detectors. The ICEBERG LArTPC setup includes a substantial volume of liquid argon and features three planes of wires—two induction planes and one collection plane—totaling 1280 wire channel outputs. The detailed setup and systematic testing aim to ensure optimal performance and reliability for future large-scale neutrino experiments.

A critical aspect of this development is understanding the behavior of the detector under various conditions to ensure accurate data collection and diagnostics. Specifically, the project aims to analyze the relationship between Digital-to-Analog Converter (DAC) and Analog-to-Digital Converter (ADC) values to identify linear and saturation regions (see Figure 1 below). This involves determining the optimal settings for reference voltage (Vref), gain, peak times, and baseline values to avoid ADC saturation and maintain a wide dynamic range for precise signal detection.

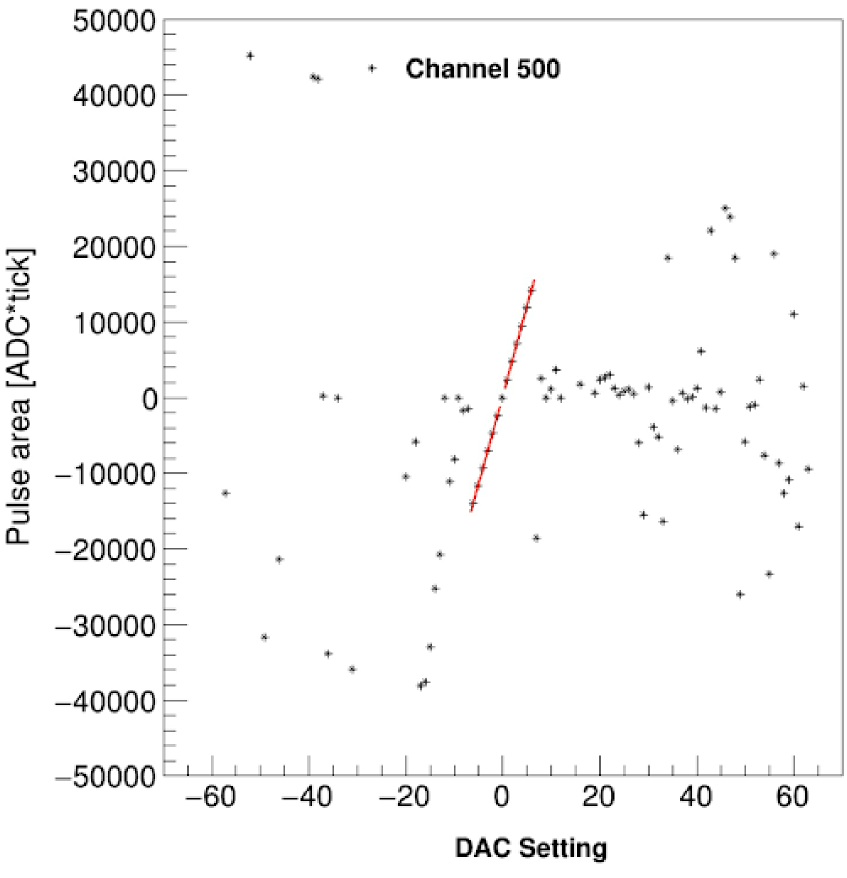

Figure 1: Run Analysis on DAC Setting vs. Pulse Integral Values

To achieve these goals, a pulser was used to create charge injection runs to mimic known charge deposition amounts on the LArTPC wires. This approach allows for controlled testing and calibration of the detector's electronics. By systematically varying parameters such as Vref, gain, and peak time, and analyzing the resulting data, the project seeks to optimize the LArTPC setup for enhanced performance in detecting and studying neutrino interactions in future experiments.

3. Procedure

The data collection process involved conducting multiple runs under varying conditions to assess the detector's performance across different parameters.To examine the influence of the reference voltage on the ADC output, Vref levels were varied between 1.5V, 1.78V, and 1.9V. This variation aimed to identify the optimal Vref that maintains signal integrity and avoids saturation zones, yielding a higher dynamic ADC range. For gain values, different settings were applied to modify the signal amplification. The gain values tested included 7.8 mV/fC, 14 mV/fC, and 25 mV/fC. These variations helped identify the gain setting that provides a clear and precise signal without causing the ADC peak to reach the maximum of the Vref range too quickly for larger DAC values.

The peak times, defined as the time taken for the signal to reach its maximum value, were adjusted to 1 µs, 2 µs, and 3 µs. This testing was performed to understand how timing affects the ADC response and to optimize signal detection. Lastly, runs were conducted with different baseline values, measured in millivolts, representing the initial charge level before signal detection. The baseline value for the collection and induction planes was set to a steady 900/200 mV throughout each of the trials, after the initial calibration runs.

For each set of runs, a specific Vref value configuration was set, and then data from each run was recorded against 64 evenly spaced DAC values. Each set of runs consisted of the following run schedule:

1. 13 calibration runs
2. 192 runs with a gain of 7.8 mV/fC and the peak time varying from 1-3 µs every 64 runs
3. 192 runs with a gain of 14 mV/fC and the peak time varying from 1-3 µs every 64 runs
4. 99 runs with a gain of 25 mV/fC and the peak time varying from 1-3 µs every 33 runs

This allowed the systematic measurement of ADC outputs for each of the specified DAC values for every possible base configuration of the electronics.

4. Analysis

The data analysis on the runsets was completed offline using the CERN ROOT software framework, focusing on determining a linear region in the plotted relation between the ADC peak values and different DAC values for various run configurations. The procedure involved collecting values and generating ADC min and max plots for each specific run to evaluate the performance of the detector under various conditions. These plots (like Figure 2 below) illustrate the ADC min and max values for a specific run, along with statistical properties such as the mean and standard deviation of the different planes of wires.

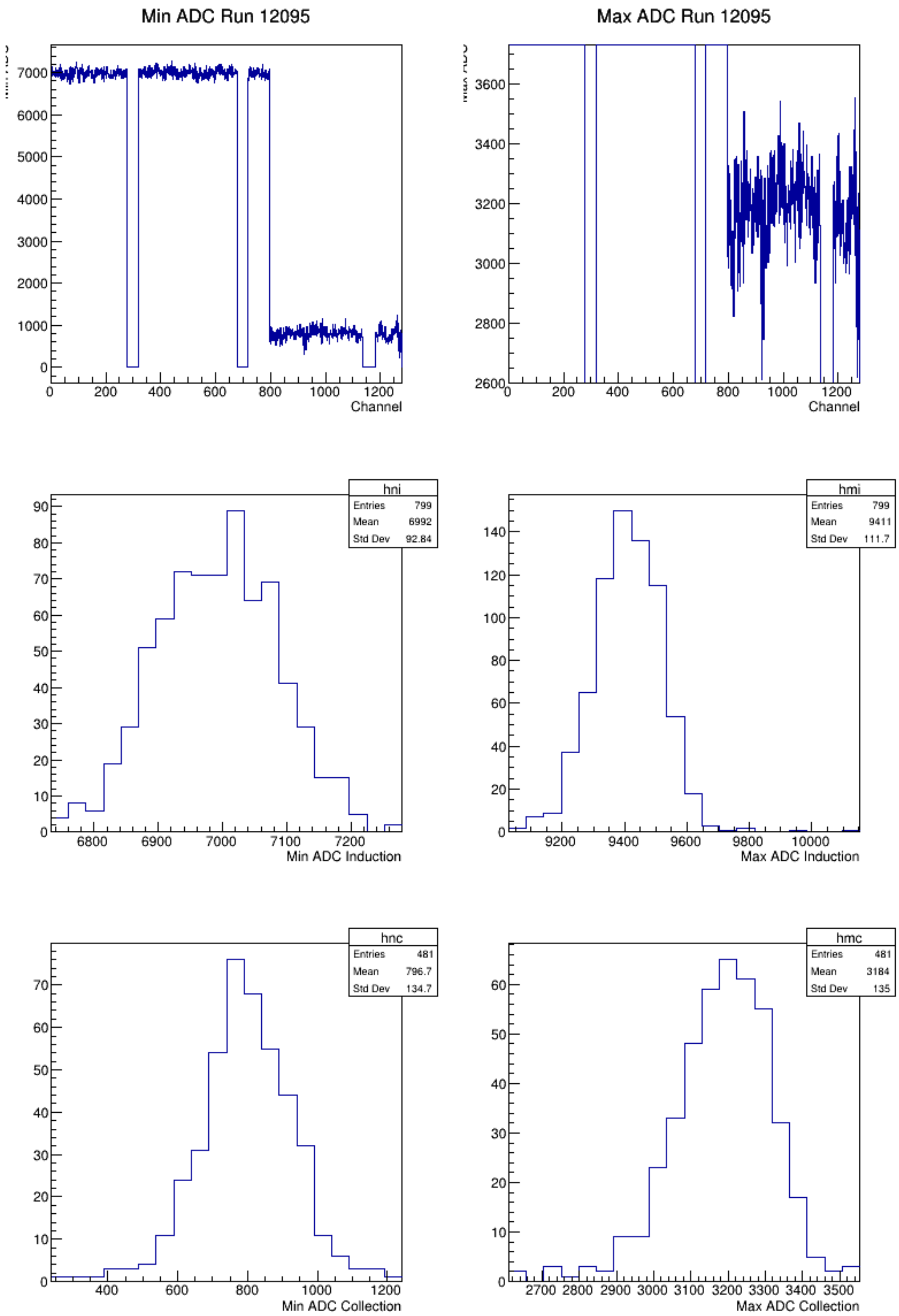

Figure 2: ADC Values by Channel and Mean/Std of Induction/Collection Planes

5. Results

The research results indicated significant findings regarding the optimal settings for the ICEBERG LArTPC detector to ensure precise signal detection and avoid rapid saturation of the ADC. Initially, it was observed that a reference voltage of 1.5V led to rapid saturation and a limited linear region, as shown in Figure 3. This resulted in a narrow range of DAC values over which the ADC response remained proportional to the input, thus limiting the detector's effectiveness. In contrast, Vref values ranging from 1.8V to 1.9V provided an extended linear region. This wider range allowed for a more proportional ADC response across a broader spectrum of DAC values, enhancing the detector's ability to accurately measure signals without quickly reaching saturation.

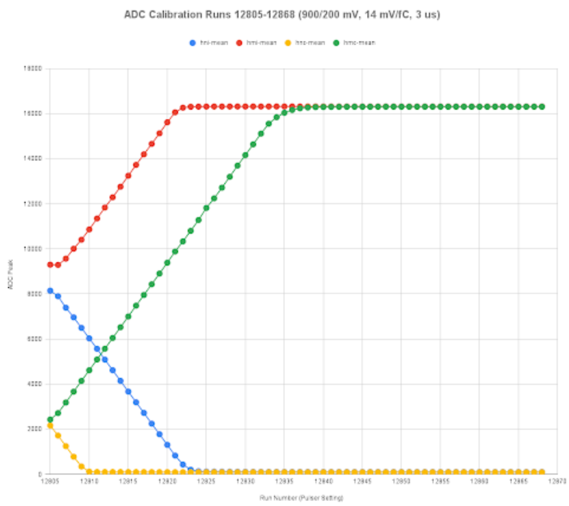

Figure 3: DAC vs. ADC Peaks for Vref Range = 1.5 V

In terms of gain settings, the study revealed that a gain of 25 mV/fC caused the ADC to max out quickly, within approximately 10 DAC values (Figure 4). This high gain setting resulted in the ADC reaching its maximum output too swiftly, thus constraining the dynamic range and reducing the accuracy of the measurements. On the other hand, a gain setting of 7.8 mV/fC was found to be preferable compared to 14 mV/fC. The 7.8 mV/fC setting provided a higher dynamic ADC range, allowing for a more gradual increase in the ADC response with increasing DAC values and thereby preventing rapid saturation. Although the 14 mV/fC setting was better than 25 mV/fC, it was still less optimal than 7.8 mV/fC in maintaining a broad dynamic range.

Interestingly, variations in peak time, which included testing at 1 µs, 2 µs, and 3 µs, demonstrated negligible impact on the overall performance of the detector (Figure 5). This finding suggests that within the tested range, peak time adjustments do not significantly influence the ADC's response or the overall signal detection capabilities of the LArTPC.

Based on these comprehensive measurements and analyses, the DUNE-CE Consortium

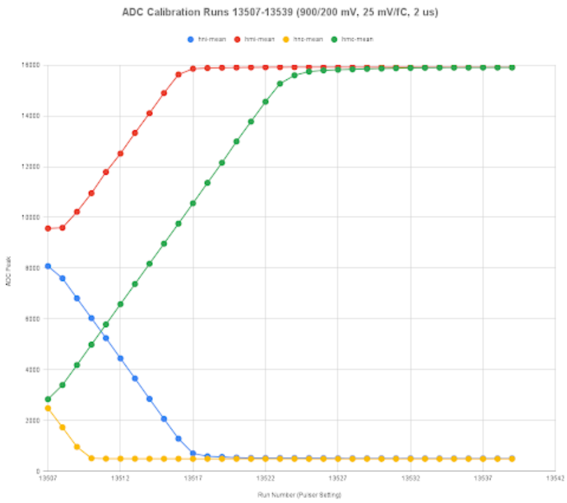

Figure 4: DAC vs. ADC Peaks for Gain = 25 mV/fC

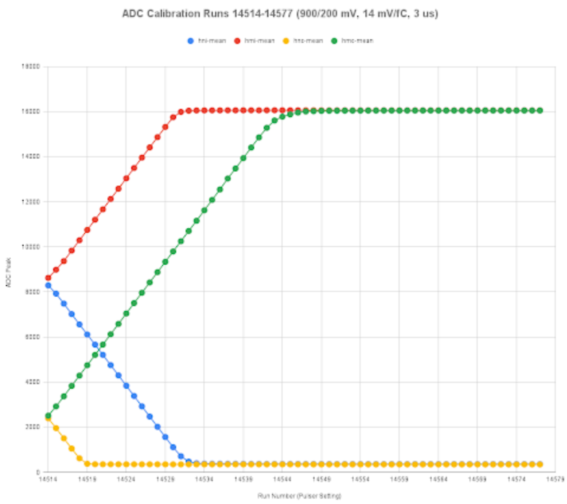

Figure 5: DAC vs. ADC Peaks for Peak Time = 3 µs

made a strategic decision to switch the gain setting for the upcoming ProtoDUNE-II-HD run at CERN from 14 mV/fC to 7.8 mV/fC. This adjustment is expected to enhance the detector's performance by providing a wider dynamic range and more accurate signal detection. Additionally, the baseline of the collection plane was adjusted to approximately 225 mV, effectively positioning the collection plane pedestal around 2000 ADC counts. This baseline adjustment aims to stabilize the initial charge level before signal detection, ensuring that the signals detected are more accurately measured against a consistent reference point. These optimizations are crucial for improving the accuracy and reliability of the LArTPC detectors in future large-scale neutrino experiments.

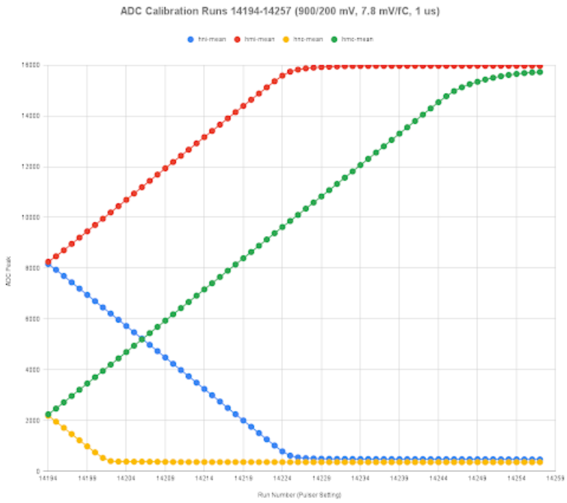

Figure 6: Ideal DAC vs. ADC Peaks Configuration

6. Future Work

Optimizing these detector parameters directly impacts the quality of data collected in neutrino experiments. Ensuring a wide linear range and avoiding saturation allows researchers to accurately measure the energy and interaction patterns of neutrinos, leading to more precise scientific insights. The adjustments made based on this study will enhance the performance of the ProtoDUNE-II-HD detector, thereby contributing significantly to the success of the DUNE project.

Future research will focus on further refining the detector settings and exploring additional parameters that could influence performance. Long-term tests under varying environmental conditions will be conducted to ensure the stability and reliability of the optimized settings. Additionally, real-world data from neutrino interactions will be analyzed to validate the effectiveness of the adjustments made in this study. Furthermore, future work will explore the integration of advanced signal processing techniques to enhance data accuracy and reduce noise. Collaborations with other research groups and institutions involved in neutrino experiments will be pursued to share findings and collectively advance the field. These efforts will not only solidify the improvements made but also pave the way for innovative approaches in neutrino detection and analysis.

7. Conclusion

This study underscores the importance of optimizing Vref and gain settings for LArTPC detectors to enhance their performance in neutrino research. The findings provide a strong foundation for improving data accuracy and detector reliability, essential for the success of large-scale neutrino experiments like the DUNE project. By ensuring a broad linear range and preventing premature saturation, the optimized settings enable more precise measurements of neutrino interactions. The continued refinement and validation of these settings through future research will further advance the capabilities of LArTPC detectors, contributing to significant scientific breakthroughs in understanding the fundamental properties of neutrinos and the universe.

8. Acknowledgments

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