Proto-DUNE NP04 Horizontal Drift Shift control and Purity Monitor using Bi-207

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Abstract

The Deep Underground Neutrino Experiment (DUNE) is a flagship neutrino physics experiment aimed at probing the fundamental properties of neutrinos, some of the universe's most elusive particles. As part of the DUNE validation process, ProtoDUNE, a prototype detector hosted at CERN is employed to test and optimize the Liquid Argon Time Projection Chamber (LArTPC) technology, which is essential for the full-scale DUNE detector. This report focuses on the beam run of the NP04 horizontal drift detector in ProtoDUNE, a 1:25 scale prototype with full-scale components of the DUNE Far Detector 1, a single-phase LArTPC with horizontal drift. This study examines my responsibilities in the control room and the analysis of Bismuth-207 (Bi-207) as a potential tool for monitoring the purity of liquid argon (LAr) at DUNE. We present a comprehensive analysis of the detector's shift control, LAr purity assessment, and future work to fully utilize Bi-207 for purity monitoring.

Keywords: ProtoDUNE, NP04-Horizontal Drift, LArTPC, LAr Purity, Bi-207, NP04-HD shift control

1 Introduction

The Deep Underground Neutrino Experiment (DUNE) represents a significant advancement in neutrino physics[1]. It aims to uncover fundamental insights into the behavior of neutrinos, some of the most enigmatic particles in the universe. Central to this effort is developing and testing LArTPCs, critical for tracking neutrino interactions with unprecedented precision. ProtoDUNE, a large-scale prototype located at CERN, is a crucial testbed for the technologies deployed in the full-scale DUNE experiment[2].

The NP04 horizontal drift detector, a 1:25 scale prototype of the DUNE Far Detector-1 Single Phase Liquid Argon Time Projection Chamber (FD1-HD), plays a pivotal role in validating the performance of the LArTPC design[3]. Central to its operation is monitoring LAr purity, which directly impacts the drift of ionization electrons through the detector. Ensuring and maintaining high LAr purity is vital for achieving the desired signal clarity and detector sensitivity levels.

This report focuses on my work as a summer student at CERN. My work was primarily divided into hardware and analysis. For the hardware component, I worked on the mechanical mock-up testing of a vertical drift field cage module for the DUNE far detector, where we constructed four different field cage modules. For the analysis work, I primarily focused on shift control for NP04-Horizontal Drift and the analysis of the potential use of Bismuth-207 for the purity monitor of LAr. The ability to precisely control the detector environment and assess the purity of LAr is essential for ensuring the optimal performance of the LArTPC technology, which will be scaled up for the entire DUNE experiment.Through this research, we aim to further our understanding of these systems and provide insights for future detector upgrades and operational efficiency.

2 ProtoDUNE Experiment

The ProtoDUNE experiment, hosted at CERN, is a critical prototype for the DUNE Experiment. Its primary purpose is to test and validate the technologies and designs intended to construct the

DUNE Far Detector at the Sanford Underground Research Facility (SURF). Proto-DUNE plays a pivotal role in mitigating technical risks and refining detector performance for the DUNE project by providing a large-scale testbed[2].

Figure 1: Horizontal and Vertical drift Proto-DUNE detector hosted at EHN1, CERN

ProtoDUNE-SP (Single Phase), designated as NP04, is a significant step toward building the first DUNE Far Detector module, which will have a total LAr mass of 17 kt. With its 1 kt fiducial mass, ProtoDUNE-SP is one of the largest Liquid Argon Time Projection Chambers (LArTPCs) ever constructed. LArTPCs offer superior neutrino detection capabilities due to their excellent spatial resolution and efficient background rejection[4, 5].

During my summer research, I worked with the High Voltage (HV) group, which is responsible for maintaining the stable high voltage inside the cryostat, which is essential for detecting and measuring neutrino interactions. A high voltage of approximately 300kV is applied across the drift volume to generate the required electric field strength of 500V/cm [3]. This electric field enables the free electrons, produced during the neutrino's interaction, to drift toward the anode planes. Aluminum profile modules establish a uniform electric field within the LAr, ensuring efficient collection of ionization electrons and optimal detector performance.

3 Mock-Up of Vertical Drift Field Cage for the DUNE Far-Detector

As part of the development efforts for the DUNE Far Detector's vertical drift configuration, we conducted mock-up testing to evaluate the assembly procedures and mechanical integrity of the field cage modules. These modules are crucial for establishing the uniform electric field required to drift ionization electrons in the LArTPC[3]. The mock-up focused on emulating the corner modules, which present unique assembly challenges due to their geometry.

Figure 2: Field cage construction for Mock-Up at B. 185, CERN.

The testing involved a total of 219 thin aluminum profiles and 56 thick aluminum profiles, including both straight and bent variations of both long and end walls. As a part of our exercise, we also calculated the stretching and compression of thin and thick profiles while bending. For example, a 5.1mm contraction of the thick profiles was observed, and a expansion of 2mm was observed in the thin profile. So, the thick and thin profiles were cut to 3126.2mm and 3119mm, respectively, to account for the compression and stretching.

Assembly procedures were meticulously documented to optimize efficiency and ensure repeatability in constructing the field cage modules. The process began with a thorough visual inspection and cleaning of the aluminum profiles to eliminate contaminants that might affect performance or assembly integrity. Precise bending was performed using specialized machinery, accounting for material stretching and compression to achieve the geometries required for straight and bent profiles. Quality control checks were implemented at each stage to verify dimensional accuracy and adherence to specifications. End caps were attached securely to the profiles, ensuring proper alignment and mechanical stability.

Timing measurements were recorded for each step to enhance the assembly process, from the initial quality inspection to the final construction of the field cage modules. This data was critical for identifying bottlenecks and areas for improvement, allowing for adjustments that increased efficiency and reduced assembly time. Overall, the mock-up testing validated the design and assembly methods for the vertical drift field cage modules. By systematically documenting and analyzing each phase of the procedure, we established a reliable and repeatable assembly workflow that can be scaled for the production of the full-scale DUNE Far Detector. This meticulous approach ensured the mechanical integrity of the modules and contributed to the overall success of the future implementation of the DUNE detector.

4 NP04 ProtoDUNE Horizontal Drift Shift Control

The NP04-Horizontal Drift is part of the ProtoDUNE experiment and serves as one of the prototypes for the DUNE Far Detector. The main goals of the NP04 beam run were to validate the detector design, assess the performance of critical systems, and collect data for hadron cross-section measurements on argon. These measurements are essential for providing accurate inputs to the DUNE Physics[3].

The NP04 beam run took place between June 24th and September 16th, 2024. During this period, the detector was exposed to various particle beams, ranging from protons to pions, with energies between 0.3 and 7 GeV/c. The objective was to study detector performance across a range of beam conditions and to collect sufficient data for cross-section measurements of pions, protons, and kaons. Particular emphasis was placed on increasing statistics for low-energy interactions, which are critical for neutrino physics[6].

Figure 3: Control Room at B. EHN1, CERN.

Throughout the beam run, the NP04 detector operated under the supervision of the control room team, which monitored critical subsystems such as the high-voltage system, LAr purity, and the data acquisition system. Maintaining stable detector conditions during high-intensity beam periods was a key challenge, but the system proved highly resilient. The shift control operations ensured that the detector's performance remained within the required specifications for data acquisition.

During the beam run, my primary role focused on shift control operations, explicitly monitoring the incoming beam and verifying the quality of the collected data. My responsibilities included ensuring the smooth and continuous operation of the detector and starting new data acquisition runs when necessary. I adjusted beam quality and properties according to expert instructions to optimize conditions for data collection. Additionally, I was tasked with verifying the integrity and quality of the incoming data, promptly addressing any anomalies, and contacting subsystem experts in case of emergencies or unexpected issues.

These duties were integral to the successful operation of the NP04 detector during the beam run. By maintaining optimal detector conditions and ensuring high-quality data acquisition, we contributed significantly to the overall objectives of the ProtoDUNE experiment. The experience underscored the importance of diligent monitoring and swift responsiveness to any issues arising during the operation of such a complex detector system.

5 Bi-207 for Purity Monitoring of LAr

The performance of LArTPCs used ProtoDUNE and future DUNE expderiment critically depends on purity of LAr, as impurities such as oxygen and water can capture ionization electrons produced by neutrino interactions, significantly reducing signal strength and degrading spatial resolution. Given the extensive drift distances of up to 6 meters in DUNE's detectors, achieving and sustaining LAr purity at parts per trillion (ppt) is essential to ensure that electrons can traverse the full drift length without significant attenuation, thereby preserving the accuracy and sensitivity of neutrino detection.

Continuous monitoring of LAr purity is vital for the DUNE, not only during stable operations but also throughout the prolonged filling period of the cryostat, which can span up to a year. Traditional purity monitoring methods employ a small, double-gridded Time Projection Chamber (TPC) equipped with a xenon flash lamp that emits ultraviolet (UV) light to generate photoelectrons at the cathode[3]. These electrons drift towards the anode, and the electron attenuation between creation and collection provides a measure of the electron lifetime (τ) in the LAr. However, this xenon lamp-based system presents significant drawbacks: the intense UV light requires large, fragile optical fibers within the cryostat, increasing mechanical complexity and the risk of component failure. Additionally, high-energy UV flashes can blind the main detector's photon detection system (PDS), necessitating temporary shutdowns during purity measurements. These interruptions hinder continuous data collection and complicate the operational schedule.

To address these challenges, a noble purity monitoring system utilizing Bismuth-207was developed and established in the current NP04-Horizontal Drift detector[7]. Bismuth-207 (^{207}Bi) is a stable isotope of bismuth with a mass of 207 and a half-life of approximately 32.9 years, which undergoes electron capture decay emitting monochromatic electron with energies 1MeV[8].These electrons provide a consistent and localized source for purity measurements. Due to its favorable decay properties, ^{207}Bi could serves us as an effective internal electron source for monitoring the purity of LAr[9]. Bi-207 undergoes beta decay (β^+) emitting positron(e$^-$), gamma rays(γ) and electron neutrino(ν_e). The nuclear reaction is:

$$^{207}_{83}\mathrm{Bi} \longrightarrow {}^{207}_{82}\mathrm{Pb} + \beta^+ + \nu_e \tag{1}$$

The resulting Pb-207 nucleus is in an excited state. It de-excites by either emitting gamma rays or ejecting an internal conversion electron through a process where the nucleus transfers its excess energy to an orbital electron, causing its ejection from the atom. The emitted gamma rays interact with the surrounding liquid argon (LAr) via the photoelectric effect and Compton scattering, resulting in the ionization of argon atoms and the generation of free electrons. These free electrons, along with the internal conversion electrons directly emitted from the decay, drift toward the anode under the influence of the electric field within the LArTPC. The presence of impurities in the LAr captures these drifting electrons, causing signal attenuation. By measuring the degree of attenuation, the electron lifetime can be determined, providing a direct assessment of the argon's purity.

5.1 Preparation of data for analysis

The data used in this analysis were collected from the NP04-Horizontal Drift (NP04-HD) detector at ProtoDUNE. Each event recorded by the detector provides detailed information, including Analog-to-Digital Converter (ADC) counts and corresponding timestamps for every readout channel. These data are essential for reconstructing the energy deposits and timing of interactions within the detector. For our purposes, we are specifically interested in the low-energy deposition signals from the Bi-207 source, which are expected to fall within the range of 100 to 2000 ADC counts. In this analysis, we consider the charge deposition, measured in ADC counts, as directly proportional to the energy deposited, without applying any conversion factors.

The data collected from NP04-HD, are stored in the grid, which need to be downloaded locally using rucio. The raw data file was not suited for analysis, so for the purpose of data management it needed to be converted into a Pickle file, which can be loaded much faster in Python. Each channel has its own baseline, so they needed to be subtracted. For our purpose we subracted our data from running median baseline with window size of 100. Figure 4 shows the example of baseline subtraction. Since the bismuth produces the monochromatic free electron at 1MeV energy range, we can confidently threshold the data at 100ADC counts with very less to no signal loss, as shown in Fig 5.

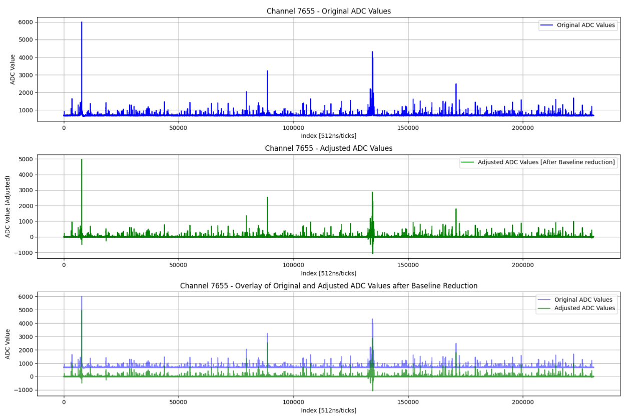


Figure 4: Baseline Reduction at Channel 7655

Figure 5: Thresholding at 100ADC value

The data preparation process involved the following steps:

1. **Baseline Establishment:** For each channel, a baseline was established using a running median with a window size of 200.
2. **Thresholding:** Channels were thresholded at 100 ADC counts to filter out signal noise effectively.
3. **Cosmic Muon Rejection:** Events were discarded if adjacent channels exhibited higher activity, thereby removing potential cosmic muon-induced signals.
4. **ADC Integration:** For each identified peak, the start, end, and maximum activity were determined. The total charge deposition was calculated within four standard deviations from the mean.
5. **Spectrum Generation:** The processed data were used to generate the energy spectrum for ^{207}Bi

5.2 Cosmic Muon Rejection and Signal Isolation

Cosmic ray muons constitute one of the main background sources in measurements involving Bi-207 decay. However, we can effectively distinguish and eliminate signals originating from cosmic rays or beam backgrounds by analyzing the activity in adjacent channels. Electrons emitted from Bi-207 decay are typically localized to one or two channels. In contrast, cosmic muon, being highly energetic, can traverse multiple channel, depositing energy along their path. Therefore, if we observe elevated activity above 50 ADC counts simultaneously in three or more neighboring channels, it is highly indicative of a cosmic muon or beam-induced event. By examining the activity in adjacent channels and identifying such patterns, we can confidently exclude these cosmic or beam-induced signals from our analysis. Figure 6 illustrates the result of thresholding based on activity across adjacent channel.

Once the cosmic muon events were removed, we focused on accurately quantifying the charge deposition from the remaining events, presumed to be primarily from Bi-207 decay. However, we recognized that sometimes the signal energy could be shared among neighboring channels due to factors like electronic cross-talk or slight spreading of the electron cloud. To avoid double-counting the same physical event, we implemented a procedure to associate the signal with a single channel based on the highest amplitude.

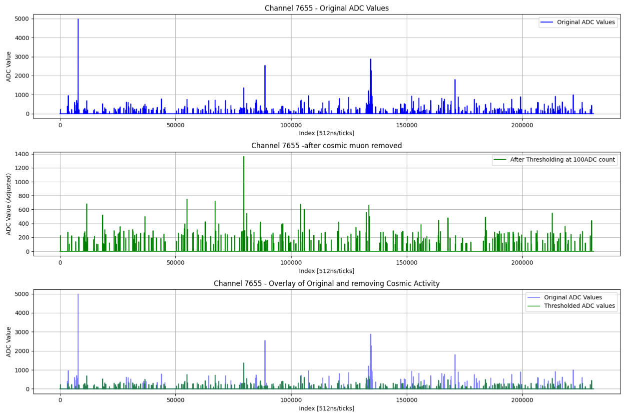


Figure 6: Cosmic Events removed based on comparing ADCs in adjacent channel

For each event, we identified the channel with the maximum ADC value and attributed the entire event's charge deposition to that channel. This approach ensures that each physical decay event is counted only once, preventing overestimation of the Bi-207 activity. We then summed the total charge deposition for these events, which allowed us to construct the energy spectrum of the Bi-207 source in the NP04 detector.

5.3 Identification of Bi-207 Source Channel

With the cosmic muon events removed and the charge deposition accurately assigned, we proceeded to identify the specific channels where the Bi-207 source is active. Based on the detector configuration and the beam run conditions, we expected the Bi-207 activity to be located in Anode Plane Assembly 2 (APA2), specifically between channels 7600 and 7680. These channels correspond to the physical location where the Bi-207 source was installed. This can be clearly observed with isolated signal in given channel [7600-7680] in fig 7.

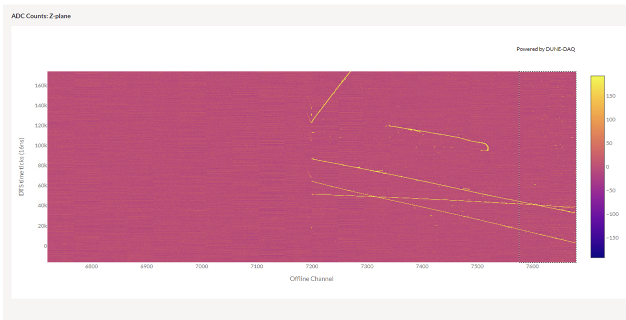
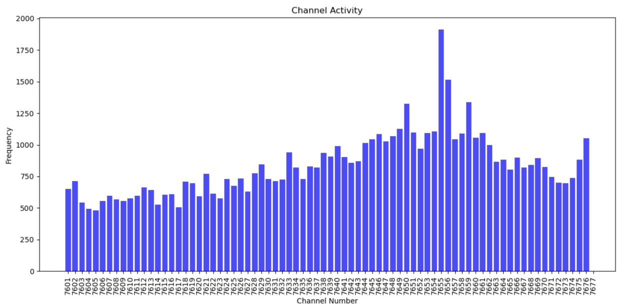
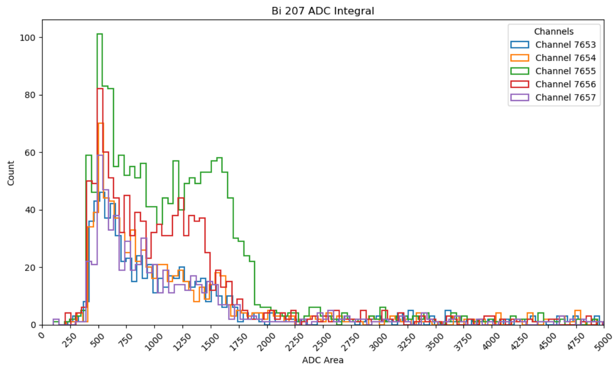


Figure 7: Visible Bi-207 activity in channel 7600-7680 in APA2

To verify this, we analyzed the event rates and charge deposition across all channels within this range. Figure 8a shows the activity across channels 7600 to 7680, where a noticeable increase in low-energy, isolated signals is observed around channel 7655. This pattern aligns with our expectations for Bi-207 decay events.



(a) Activity across all 80 channels with potential bismuth activity.



(b) ADC count adjacent channels for 7653±1,7654±1, 7655±1, 7656±1, 7657±1.

Figure 8: Channel activity and ADC count across Bi-207 channels.

Further analysis involved comparing the ADC counts of channel 7655 with its neighbors 7653±1,7654±1, 7655±1, 7656±1, 7657±1. Figure 7(b) presents the ADC count distributions for these channels. Channel 7655 exhibits a higher frequency of events within the expected energy range for Bi-207 decay, while adjacent channels show significantly fewer events. This confirms that channel 7655 is the primary channel detecting the Bi-207 activity. By narrowing our focus to channel 7655 and its immediate surroundings, we effectively isolated the Bi-207 signals from other background activities.

5.4 Bismuth Signal Analysis

The objective of this analysis is to evaluate the feasibility of using Bismuth-207 (Bi-207) as an internal source for continuous monitoring of LAr purity in the detector. After applying rigorous data cleaning procedures—which removed approximately 98.579% of the data—we analyzed the total charge deposition attributable to the Bi-207 signal.

The total charge deposited by the Bi-207 decays was assessed by integrating the Analog-to-Digital Converter (ADC) values over each event. This integration yields the total ADC area for a given event, corresponding to the total energy deposition expected from the conversion electrons emitted during the decay of Bi-207. For my purpose, I tested with 5952 readout ticks, providing me with a trigger window of 3.0ms per trigger record, and a total of 234 trigger records were analyzed. To estimate the total expected number of Bi-207 events within the analyzed time interval, we performed the following calculation:

$$\begin{aligned}\text{Trigger Window} &= \frac{\text{Trigger Window}}{\text{Trigger Records}} \times \text{No. Trigger Records} \\ &= 3.0\text{ms} \times 234\text{trigger records} \\ &= 702ms \end{aligned} \tag{2}$$

$$\begin{aligned} &= \text{Rate} \times \text{Trigger Window} \times \text{Half Source}, \\ &= 3\,\text{kBq} \times 3.0\,\text{ms} \times 234\,\text{trigger records} \times 0.5 \\ &= (3000\,\text{s}^{-1}) \times (0.702\,\text{s}) \times 0.5 \\ &= 2106\,\text{decays} \times 0.5 \\ &\approx \mathbf{1053\ decays}. \end{aligned} \tag{3}$$

where:

- **Activity of Bi-207**: The radioactivity of the Bi-207 source is 3 kilobecquerels (kBq), corresponding to 3000 decays per second.
- **Trigger window duration**: The time window during which the detector is sensitive to capturing events is ≈ 702 milliseconds (ms), or ≈ 0.702 seconds (s).
- **Geometrical efficiency factor**: The factor of 0.5 accounts for the isotropic emission of electrons from the Bi-207 source. Since electrons are emitted uniformly in all directions, only approximately half are directed toward the collection plane and can be detected.

This calculation provides a simplified approximation of the expected number of Bi-207 decays, assuming uniform conditions and an ideal detector response. In reality, several factors may influence the observed count, including detector inefficiencies, scattering effects, and signal losses due to variations in the electric field. These factors could cause deviations from the calculated decay count of 1053. However, for our purpose, this approximation is sufficient as we analyze data over a longer period, which should help average out such deviations.

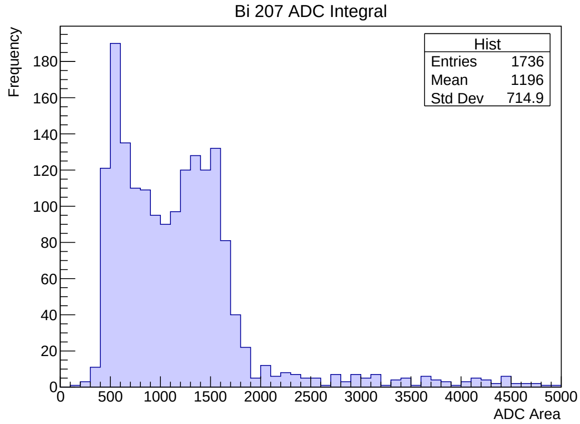


Figure 9: ADC integral of channel 7655

Statistics	**Count**
Data (702 μs)	1,386,816
After Threshold (reduced to 1.421%)	19,709
After cosmic removal	1,736
Mean	1,196.17
Standard Deviation (std)	715.14

Table 1: Data Processing Summary for Ch. 7655

The observed number of potential Bi-207 events in channel 7655 was approximately 1,736, which is higher than the expected 1,070 events calculated based on the decay rate and geometrical considerations. This excess is likely due to background contributions from radioactive isotopes like Ar-39 (^{39}Ar), which emits beta particles that can mimic the signals from Bi-207 decays or other smaller source. While this discrepancy highlights the need for further refinement in background suppression techniques, the ability to detect a significant number of Bi-207 events demonstrates the feasibility of this method. Also, as we increase our data sample, we expect the small noise from the external source to be suppressed.

In conclusion, our analysis demonstrates that utilizing Bismuth-207 as an internal electron source is a promising method for monitoring the purity of LAr in the NP04-Horizontal Drift detector. By integrating the ADC values over each event and applying stringent data cleaning procedures—including baseline subtraction, thresholding, and cosmic muon rejection—we effectively isolated signals attributable to Bi-207 decays. This approach offers several advantages over traditional purity monitoring methods. It provides continuous and localized measurements without the need for external UV light sources or intrusive equipment that could disrupt detector operations. Consequently, the use of Bi-207 has the potential to improve operational efficiency and reduce downtime, making it a valuable technique for large-scale LArTPC experiments.

6 Conclusion and Future Work

In conclusion, this report has detailed the shift control operations and procedure for Bi-207 analysis for purity monitoring in the NP04 horizontal drift detector at ProtoDUNE. our analysis demonstrates that Bi-207 is a promising tool for LAr purity monitoring in the NP04 horizontal drift detector. I plan to continue working on the Bi-207 analysis. Future work will focus on scaling this method for continuous monitoring during extended detector operations, potentially improving the efficiency and reliability of purity measurements in the DUNE experiment. This involves analyzing the purity of LAr during the full duration of the run and comparing it with the purity data obtained from the xenon laser purity monitor. The goal is to demonstrate that we can confidently monitor the purity of LAr using a simple bismuth source without incurring downtime, which is crucial for the operation of future LArTPC detectors.

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