Detector Physics with MicroBooNE

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Abstract. The MicroBooNE detector is a liquid argon time projection chamber (LArTPC), designed for the short-baseline neutrino physics program in the Booster neutrino beamline at Fermilab. Because of their exceptional calorimetric and tracking capabilities, LArTPCs are employed in many current and future neutrino experiments. MicroBooNE, as an operating physics experiment, plays a crucial role in characterising the performance of this technology. We present an overview of the ongoing detector physics studies in MicroBooNE, including a brief introduction to the detector sub-systems and a procedure for calibrating calorimetry in LArTPC. The latter involves studies of signal processing, charge uniformity, ionised electron lifetime and charge recombination. Through the laser system in MicroBooNE, we demonstrate that profound knowledge of the electric field is essential to conduct a neutrino experiment with LArTPCs.

1 Introduction

MicroBooNE is one of three neutrino experiments in the short baseline neutrino program at Fermilab [1] which employ liquid argon time projection chamber (LAr TPC) as the main detection technology. The MicroBooNE detector is located 470 m downstream of the Booster Neutrino Beam (BNB), which is subjected to a similar beam flux profile as received in MiniBooNE [2]. The primary goal of MicroBooNE is to understand the electron-neutrino-like low energy excess observed in MiniBooNE. To reach this goal, a profound understanding of LAr TPCs is necessary. This proceeding presents studies which characterise the MicroBooNE detector response.

2 The MicroBooNE Detector System

MicroBooNE [3] is composed of a LAr TPC with an 85 t active mass, a light detection system, a cosmic ray tagger system and a ultraviolet (UV) laser system. The detector operates on the surface and is exposed to a high rate of cosmic rays (∼3 kHz). This offers us a rich calibration source and is also a challenge for the reconstruction and selection of neutrino events.

The TPC has dimensions of (x, y, z) = (2.56 m, 2.32 m, 10.36 m). Where x is the horizontal axis with the anode at x = 0 and the cathode at x = 2.56 m; y is the vertical axis; and z is the axis along the BNB axis. When charged particles travel through the TPC volume, they deposit energy by ionising LAr. 70kV of high voltage is applied on the cathode, which creates a nearly uniform electric-field (E-field) of 273 V cm$^{-1}$. Ionised electrons drift to the anode following the E-field with a speed of ∼1.098 mm µs$^{-1}$. The TPC has three wire read-out planes: one collection plane is oriented vertically and the two induction planes are ± 60° to the vertical. 3D trajectories of the particles can be reconstructed by matching the wire read-out signals in time. The collected charge signals provide calorimetric information which is vital for particle...
identification. MicroBooNE has mm-scale spatial resolution and $4\pi$ angular coverage. The proton detection threshold is about 300 MeV/c in momentum.

LAr TPCs also benefit from the fact that LAr is transparent to its own scintillation light ($O(10^4$ photons/MeV)). 128 nm UV photons are released isotropically through the de-excitation of LAr excimers. The MicroBooNE light detection system is composed of thirty-two photomultiplier tubes (PMTs) that are behind the anode. Each 8-inch PMT is covered by a tetraphenyl butadiene (TPB) coated acrylic plate. The TPB shifts the wavelength of LAr scintillation light to 430 nm (in the PMT sensitive region).

Given the BNB profile, a large fraction of beam-triggered events contain only cosmic activity. Requiring PMT activity in time with beam trigger can suppress empty beam-triggered events by 95%. Moreover, in MicroBooNE, we construct a prediction for the light signal which corresponds to the observed charge deposition in the TPC, and compare the prediction with the observed light signal in the PMT. This further reduces the cosmic background in the neutrino event selection, as used in the first MicroBooNE cross-section measurement [4].

The MicroBooNE cosmic ray tagger (CRT) [5] is made of panels composed of scintillating strips with wavelength shifting fibres and silicon photomultipliers (SiPMs). The CRT panels cover the top and bottom, and the anode and cathode sides of the TPC. For MicroBooNE, the CRT is essential for further suppressing the cosmic background. With the CRT, we are able to measure precisely the time (~ns) and position of particles which pass through it. It helps to select cosmic particles as a calibration source and also plays an important role in the studies of cosmic flux and trigger efficiency.

Another crucial part of MicroBooNE is the UV laser system [6], which is composed of two similar sub-systems, located upstream and downstream of the TPC. For the first time in LAr TPCs, the UV laser system installed in MicroBooNE is steerable and can be remotely controlled. Via multi-photon ionisation, UV laser (266 nm) can generate reproducible, long and straight tracks. We were the first to demonstrate that TPC tracks induced by a UV laser can be longer than 10 m. The true laser track position can be inferred independently of the TPC readout, using the mirror positions and reference locations in the TPC infrastructure. The UV laser system therefore enables a TPC-independent measurement of the E-field.

3 Calorimetry: Charge $dQ/dx$ and Energy $dE/dx$

In MicroBooNE, we can identify particles using topological and calorimetric information. Electrons and photons often leave patterns in LAr TPCs which can be reconstructed as showers, while muons, protons, pions and kaons are often reconstructed as tracks. There are two differences between photon-induced showers and electron-induced showers: (1) photons leave a conversion distance before they are visible in LAr TPCs (2) the $dE/dx$ at the beginning of a photon-induced shower is double that of an electron-induced shower. When particles travel through LAr, they lose energy ($dE/dx$) which is characteristic for different types of particles. To distinguish muons, protons and other particles which leave track-like topologies, we compare their $dE/dx$ profiles, especially the Bragg peak, to the theoretic calorimetric profile of a specific particle. Particle identification in LAr TPCs therefore requires precise calorimetric information.

Although we are interested in the energy deposition, what we observe is the charge ($dQ/dx$) induced at the readout planes. However, there are processes such as recombination, charge diffusion and charge attenuation which can alter the observed $dQ/dx$. As a result, it is essential to calibrate the charge-response as a function of deposited energy to fulfil the MicroBooNE calorimetry requirements.

Furthermore, the read-out system and signal processing may also induce distortions. MicroBooNE has produced a simulation of dynamic-induced current in a LAr TPC for the first time, which improves the data-Monte Carlo (MC) agreement, and is necessary for understanding the charge response. The novel 2D (time and wire) deconvolution used in the signal processing significantly improves our ability to identify charge signals in different read-out planes.
The necessary steps to produce a calibrated dE/dx value from the observed dQ/dx are as follows. Gain factors are applied to each read-out plane, but there may be slight differences in the charge-response of wires (read-out channels) within a plane. We perform a charge uniformity study in a 10 × 10 cm² (y, z) grid [7], using charge deposited close to the anode, which is largely immune to the diffusion and impurity effects. The charge uniformity correction factor is defined as

\[ C(y, z) = \frac{(dQ/dx)_{\text{reco}}}{(dQ/dx)_{\text{true}}}, \]

which is applied on the dQ/dx from the readout.

The next step is to correct the charge attenuation and diffusion. Currently, in MicroBooNE, we treat charge diffusion as a systematic, and do not correct it with calibration. Charge attenuation is caused by electro-negative impurities, such as oxygen and water. In MicroBooNE, the LAr has high purity most of the time, so the charge attenuation is negligible. For the data taken with low purity LAr, the charge signal attenuates exponentially with respect to the drift time. We characterise the electron lifetime \( \tau \) using tracks that pierce the anode and the cathode, by

\[ \frac{(dQ/dx)_{\text{anode}}}{(dQ/dx)_{\text{cathode}}} = \exp(-t_{\text{drift}}/\tau). \]

We can then calibrate the charge attenuation by

\[ dQ/dx = (dQ/dx)_{\text{anode}} \exp(t_{\text{drift}}/\tau). \]

Charge recombination is a local effect close to where the ionised electrons are produced. In MicroBooNE, we used the modified box model [8] \( \mathcal{R}_{\text{box}}(E, dE/dx) = \frac{1}{\beta} \ln(\alpha + \beta' dE'/dx) \) and \( \beta' = \beta' \rho_e \) to account for the recombination. MicroBooNE measures the parameters of the model using neutrino-induced protons [7]. The value of \( dE'/dx \) used for the parameter extraction is an approximate estimate of \( dE/dx \) calculated from an independent range-based method. The recombination rate depends on the particle energy loss and the local E-field. Finally, we use \( dE/dx = (dQ/dx)/(\mathcal{R}_{\text{box}} W_{\text{ion}}) \) to retrieve the energy deposition of the particles, where \( W_{\text{ion}} \) is the work function in LAr.

4 E-field Measurement Using UV Laser

Precise control of the E-field is essential for large LAr TPCs, such as MicroBooNE. It regulates how many electrons are released and how they drift to the read-out planes.

To characterise the E-field, we utilize the UV laser system introduced in Section 2. We select 266 nm photons from the primary commercial laser head and direct them into the LAr. Through multi-photon ionisation, the UV laser can leave a track in the TPC. A steerable mirror in the LAr controls the direction of the UV laser in the TPC, and with the TPC infrastructure as additional reference, the position of the true laser track can be reconstructed independently of the TPC readout. Ionised electrons are released along the true track, which drift following the E-field. We characterise the E-field, which is distorted due to the space charge in MicroBooNE. The reconstructed position is obtained assuming a uniform E-field.

To measure the E-field in the TPC, we first establish the spatial displacement between the true and reconstructed positions. The perpendicular projections of the reconstructed track points on to the true tracks give good estimations of the displacement vectors. We iterate the process utilizing two track samples originating from the two separate laser sub-systems, which helps to largely reduce the track angle dependency. We also apply the condition that there should be no spatial distortion at the anode. Figure 1 shows the x, y, z components of the distortion from the true position on a regular grid. The scale of the distortion can be up to \( \sim 15 \text{ cm} \).

![Figure 1. Calculated distortion map from laser data at a central slice in Z. [6]](image-url)
Figure 2 is a schematic of the E-field calculation. The grey dots are the reconstructed points, and those aligned in the drift direction would be read out in the same position (orange dot). The red arrows are their displacement vectors, and the green dots are the corresponding true positions. The black arrows are along the field line. Through the known relationship of drift speed as a function of E-field, we can trace the local E-field. The E-field distortion is up to $\sim 10\%$ of the nominal E-field ($\sim 30$ V cm$^{-1}$) in MicroBooNE.

**Figure 2.** Schematic of electric field calculation. The grey dots are the true positions on a regular grid and the green dots are their corresponding reconstructed positions. The black arrows are along the field line. $\Delta x$ is the interval between the neighbouring reconstructed positions on a regular grid and $R_n$ is the distance in between two neighbouring true points. $\Delta t$ is the time corresponding to both $\Delta X$ and $R_n^T$. [6]

5 Conclusion

The MicroBooNE experiment utilises a LAr TPC with an integrated light detection system, CRT and UV laser system for calibration and physics analysis. Detailed studies of the MicroBooNE detector performance have been carried out for the upcoming low energy excess study and to inform future LAr TPC experiments. In this proceeding, a consistent and inclusive calibration procedure for calorimetric information in LAr TPCs was outlined, including the first data-driven spatial displacement and E-field calibration maps.

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