MicroBooNE TPC Calibrations

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Abstract

This paper presents a few of the studies performed to test the electronic equipment on the MicroBooNE detector at FermiLab. The aspects of the electronics that are being checked include the gain and linearity of the output data pulse, the cross talk between wires, and the effects of a change in the trigger time on the pulse. This analysis is done at every stage of the set up, thus the comparison of old and new data tests is pivotal to the calibrations analysis.

1 Introduction

1.1 Neutrino Physics

The neutrino was first experimentally seen in the mid 20th century by scientists looking at the beta-decay process. Neutrinos are leptons, of which there are three generations: electron neutrinos, muon neutrinos, and tau neutrinos. Each lepton also has a corresponding antiparticle.

![Figure 1: Standard Model-Elementary Particles](image)

Neutrinos were initially viewed as massless particles. However, when looking at neutrinos coming from the sun, physicists noted that they were only receiving a fraction of the electron neutrinos they expected given the theoretical output of the sun. It was later determined that neutrinos could oscillate between flavors (electron, muon, tau). If the particles could oscillate, then by the standard model, they must have a mass, as the oscillation is dependent upon the difference of the squared masses (\(\Delta m^2\)). Neutrinos exist in three mass eigenstates, which are not equivalent to the flavors.[1]

Neutrinos do not have a charge, and are thus were very difficult to detect in the lab as they pass through most matter. Neutrinos do interact through the weak force. A large volume of ionizing and scintillating material or fluid is often used to indirectly detect neutrinos by the electrons and muons they give off. Neutrinos travel extremely close to the speed of light, so when going through dense materials like liquid argon, they often ionize the liquid.

1.2 MicroBooNE Goals

The purpose of the MicroBooNE experiment is three-fold: to explore the low energy region of neutrino interactions, to further study neutrino cross sections, and to test the liquid argon detector technology.[2] MiniBooNE, the predecessor experiment to MicroBooNE, reported an inexplicable excess of \(\nu_e\) events in the low energy region seen in figure (2).

The MiniBooNE experiment sees neutrino interactions that agree with background predictions at higher energies, but the excess at lower energies warranted further exploration. MicroBooNE was then created to explore this low energy region of around 0.1-1 GeV. The MiniBooNE experiment, however, is
unable to distinguish between electrons and photons because it is a cherenkov radiation detector. MicroBooNE’s liquid argon time projection chamber (LArTPC) will be able to discern photons from electrons, allowing more accurate results. Looking at figure (2), the pion and kaon background events both produce photons. Because MicroBooNE can tell the difference and run in electron or photon only mode, these background sources are no longer a problem.

The MicroBooNE detector, also at Fermilab, is a 170 ton liquid argon cryostat. MicroBooNE is part of the Booster Neutrino Experiment (BooNE). The neutrino beam line goes down the axis of the cylinder. Liquid argon is extremely dense, providing a large cross section for neutrino interactions, and is much less expensive than other comparable liquid scintillators. A cathode plane on one side of the detector pushes the charged particles toward three planes of wires. Two are induction planes, which simply see the moving charge. The final plane is the collection plane of wires. All three planes are offset 60 degrees from each other. Beyond the wire planes is an array of photomultiplier tubes (PMTs) to detect photons that will not be absorbed by the wires. The wire planes combined with the PMTs allow excellent timing and reconstruction of the neutrino events occurring in the detector.

MicroBooNE also has a few non-beam related functions. The detector will see neutrinos from cosmic events like supernovas at almost twice the rate of most existing detectors. The detector will also see cosmic ray background of proton decays. This aspect of the detector will always be running, but will take data at a much lower rate than is used for actual beam studies.

1.3 Electronics

The MicroBooNE detector has a complex system of electronics to properly read out and analyze the data from neutrino interactions. A signal on the wire, or in the case of the calibrations runs, a signal generated on a capacitor parallel to the wire, is sent to an ASIC chip which shapes the pulse given a certain shaping time. From there the signal goes to an ADC chip, which digitizes the input pulse. An ADC converts a voltage pulse into a digital signal in binary, between 0-4095. The data from the ADC then goes to the FPGA where the data is processed and reduced, and then onto the data acquisition PCs (DAQ) where the data is stored and analysis is done. There are 16 channels for each ASIC and a total of 4 ASICs per FEM, of which there are 12 total. The wires and ASIC chips are in the cooled cryostat. The feedthrough then exits the cryostat, where the ADCs, FPGAs, and PCs are located.

To simulate the pulse on the wires, a trigger pulse is sent from a pulser to a function generator which then sends a signal to the capacitor in parallel to the actual wire. This gives the appearance of the wire receiving an actual pulse during data acquisition, and so is extremely useful for calibrations.
Figure 5: TPC Electronics setup, from technical manual[2]
2 Calibrations

The MicroBooNE experiment, only partly constructed, requires testing to determine that the electronics are working correctly before the detector can actually start taking data. Three aspects of the calibrations are covered in this section: the gain and linearity, cross talk, and peak timing tests. The calibrations are done by a variety of software. First, most of the data is processed in LArSoft. The calibrations module in LArSoft outputs data that then can be analyzed by LArLight files. Finally, simple ROOT macros are often required to fine tune the plots. LArSoft and LArLight are frameworks developed for liquid argon detectors using ROOT[2].

2.1 Run Formation

When calibrations are run, they are done in a specific format so as to be consistent, making it easy to run the same code for calibrations at different points of the experiment. The first run consists of 125 subruns, each of 100 events. the first 90 runs are at varying input voltage, gain, and shaping settings to test the gain and linearity. The next fifteen (90-105) subruns are cross talk tests. The final 20 are peaking time tests. Both will be explained later. A second run of longer events for noise tests is also run, but will not be dealt with in this paper.

2.2 Gain and Linearity Tests

The data from the FPGA is run through a LArSoft module to create trees of the run data. Each event has 8256 channels, and so has 8256 waveforms. From each individual waveform the maximum ADC count and baseline (or average over the entire waveform) is extracted. From this run data histograms of each channel for each event are drawn and fit to a line. The following equation (1) describes the gain, which comes in three parts: from the ASIC, from the internal system, and the ADC.

\[ C \ast V_{ASIC} = Q_{in} \ast G_{ASIC} \ast G_{int} \ast G_{ADC} \]  

The total gain, \(G_{ASIC} \ast G_{int} \ast G_{ADC} / C\) is then proportional to the slope of the plot, taking into account the fact that \(Q_{in} = C \ast V_{in}\) for the capacitor. For the gain test subruns, all of the channels in a feedthrough are pulsed at the same time.

For figure (6), each point plotted is a different event, where a different input voltage was put in. The point represents the input voltage and the maximum ADC count for that event. Then all the points for different input voltages are fit to a line.

Then the lines are compared for each gain and shaping setting. This shows if there are any easily discernible bad channels, and also allows the calibration for actual data. Because the input voltage is known, the rest of the parameters can be calculated. Then during actual data acquisition the output pulse is easily converted into a charge collected by the wires, which then is identified as a sort of particle.

The residuals for every feedthrough (64 channels) were overlaid in plots similar to figure (7). There is a slight pattern to the residuals, perhaps underlying a slight non-linearity in the gain.

A couple plots comparing the gain for different settings follow in figures 8 and 9. The two different levels are a product of the difference between the induction and collection channels. The induction channels have a baseline around 2000 ADCs whereas the collection channels have a baseline around 450 ADCs.

As the gain increases, the slope of the lines also increase, which is expected. The induction wires lines top off due to the saturation of the ASIC. Because of this effect, a lower gain setting is preferable. All together, the gain/linearity tests show that the detector is working as expected, and that we have one broken channel (FEM 9, channel 19). Now that the code for this linearity analysis is written, it can be used in the future when actual data is taken to convert input pulses from ADC counts to actual voltages or charges, from which we can tell the type of particle.
2.3 Cross Talk Analysis

In the cross talk subruns of the calibrations test data, only a few channels of the FEM are pulsed. The rest of the channels are then checked for noise. Because the wires are so close to each other, there is often an increase in noise from wires neighboring it. For the post-move calibrations tests, one channel per ASIC is pulsed (48 per FEM). This allows the analysis to highlight the effect of cross talk within an ASIC, when one channel is pulsed and the other fifteen are not. Next, the cross talk was calculated by:

\[
\text{Cross Talk} = \frac{\text{Max ADC-Baseline for unpulsed channel}}{\text{Max ADC-Baseline for pulsed channel}}
\]

This gives an estimate of the effect of the pulsed channels on the unpulsed channels in terms of the height of the peaks on the other channels. It is then useful to compare this plot to the cross talk seen in an event where no channels are pulsed.

As seen from the previous plots, there is definitely a significant amount of cross talk on the induction channels. Taking the average of 100 events where the same channels are pulsed, there is a clear trend of cross talk on an asic to asic basis.

The difference in alternating channels is due to the fact that half are of the U plane of wires, and the other half are V plane wires. It is possible that there are different noise levels on the different planes, which
Figure 10: The pulsed channels have a much higher maximum ADC value than the unpulsed channels.

Figure 11: The cross talk is around 1.5-2% for the unpulsed induction channels.

Figure 12: Empty event cross talk noise levels around 1%

Figure 14: Average of events 8901-9000
might explain that effect. It would be nice in the future to somehow control for the noise on different planes if that is in fact the cause of the deviation.

The noise for each channel was also calculated to give another estimation of the cross talk between channels.

\[
\text{RMS Noise} = \sqrt{\frac{\sum (ADC - \text{Baseline})^2}{N}}
\]  

(3)

Looking at the RMS noise during the pulse (on a non-pulsed channel) shows a definite increase.

![Figure 15: Distribution of RMS noise—Blue is empty event, others are cross talk events](image)

2.3.1 Comparison of Cross Talk Data

It is then useful to compare cross talk data for events in which we pulsed a different number of channels. In the pre-move test, one ASIC per FEM was pulsed, so 16 channels per 64 were pulsed. The post-move data (shown previously) had only 4 channels per 64 pulsed. As a comparison, the following figure is what the pre-move maximum ADC by channel looks like. Due to the fact that an entire ASIC was pulsed at once, this analysis looks instead at the overall cross talk, from ASIC to ASIC instead of within one ASIC.

![Figure 16: Pre-move cross talk event—16 channels pulsed on 4 ASICs](image)

Then looking at the cross talk there is a definite increase over the post-move data, which is what is expected given the increase in number of channels pulsed.

![Figure 17: The cross talk levels are significantly higher, around 2.5% on induction channels](image)

It is also helpful to compare the distribution of cross talk for both the pre- and post-move data. The pre-move data is clearly shifted slightly to the right.

From the first plot, pre-move, where 64 total channels were pulsed, there is a peak around the regular noise level at 1%, and then a distribution to the right, some sort of tail. It seems to be that the proximity of the wire to another wire that has been pulsed would definitely cause this tail, as wire closer to the pulsed wire would see higher noise. However, because
there is not yet a clear mapping of channel number to wire position available (to me at least) for the MicroBooNE experiment, this is unfortunately unable to be confirmed at the moment. Ultimately, it would be nice to have a definitive measure of cross talk for different effects, mostly within a particular ASIC so that the effect can be controlled for if it is significant. For the most part, however, the effect looks to be relatively small (around 1-2%) which may be small enough to ignore.

To further test the cross talk, in the future it would be extremely useful to, instead of pulsing 1 channel per ASIC, change to two per ASIC, then three, etc., to get a clear picture of the relationship between the number of channels pulsed and the cross talk seen. This is something that will probably be done in future calibration runs.

2.4 Peak Timing Tests

Another aspect of calibrations is the peak timing tests. In these runs, the trigger time is delayed in multiples of 50ns. Because the ADC is digitizes the signal at a 2 MHz rate, the difference in trigger times will affect the digitization of the pulse slightly. These calibration runs are designed to test how much the change in trigger time affects the data.

There are 20 subruns of data for the peak timing test–10 for a shaping time of 1µs and 10 for 3µs. For each subrun, the waveform for a single channel is average over all 100 events. Then the maximum ADC count and pulse area for each subrun are compared in the following plots.

Unfortunately from these plots there is no clear distribution visible. With further plots from all 768 channels instead of just the one, a distribution might be more visible. In any case, with the data available,
the trigger time seems to have little to no effect upon the pulse maximum or area, as the spread in average maximum ADC values is only around 5 ADCs and the difference in average pulse area is around 15 ADCs. This effect is thus at most around 1% of the pulse amplitude, and so probably negligible.

3 Silicon Photomultipliers

Most current detectors use Photomultiplier tubes. Silicon Photomultipliers (SiPMs) represent the next stage of development in this area. SiPMs provide a few benefits over conventional PMTs. SiPMs are quite small, coming in sizes of about 1-6 mm. SiPMs require much smaller bias voltage due to their small size. They still get a gain of around $10^6$, which is less than PMTs, often requiring the use of an amplifier with a SiPM\[6\]. SiPMs are also unaffected by magnetic fields, another useful aspect. To test the SiPM, it was placed in a dark box opposite an LED. A function generator sends a trigger to the LED, which fires, sending photons to the SiPM. The photons hit the SiPM, releasing photoelectrons that are accelerated by the electric field, creating new electron-hole pairs. These carriers in turn release more carriers. This is known as avalanche multiplication. This signal is then amplified again and viewed on an oscilloscope.
Figure 26: Linear fit of SiPM Bias Voltage vs Output. The equation for the line is \( Y = p_0 + p_1*V \)

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## 5 References


