Mu2e Tracker Electronics - Construction of a Straw Tracker.

Alec Michael Lynch
Physics Department, University of California, Berkeley, Berkeley, CA, USA
Particle Physics Department, Fermilab, Batavia, Il, USA
FERMILAB-PUB-25-0549-STUDENT

(Mu2e Collaboration)

(Dated: August 6th 2025)

This manuscript has been authored by FermiForward Discovery Group, LLC under Contract No. 89243024CSC000002 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

Abstract

The Mu2e experiment, located at the Fermi National Accelerator Laboratory (FNAL), also known as Fermilab, in Batavia, Illinois, is an in-progress particle physics experiment aiming to detect Charged Lepton Flavor Violation (CLFV) via the $\mu^- Al \rightarrow e^- Al$ interaction, a Beyond the Standard Model (BSM) process. One of the sections of the Mu2e experiment is the Tracker, which aims to identify the signal and reject the background while the experiment is running. A total of 20,736 Calibration (CAL) and High-Voltage (HV) preamplifiers (preamps) are being installed within 36 planes that make up the Tracker. During this process, MHz oscillations were discovered on the CAL preamps, obscuring desired signal detection in the k̃Hz range. To solve this issue, copper clips are installed onto the CALs to remove the MHz oscillations. The installation of electronics into the Tracker will be discussed in depth.

I. INTRODUCTION: GOAL OF THE RESEARCH

A. CLFV Process

What lies beyond the Standard Model is one of the most pressing questions in physics at present. The reason for this is that the Standard Model is successful in explaining most theoretical and experimental results, but fails to explain all of them. Such a process is Charged Lepton Flavor Violation (CLFV), where one of the flavors of a lepton changes during an interaction. The search for CLFV is motivated by the discovery of neutrino oscillations, which were initially believed to be forbidden, meaning that lepton flavor numbers (L_e, L_μ, L_τ) would be conserved [1] during a particle interaction.

B. Mu2e Experiment

The M2e experiment, currently under construction, aims to observe the $\mu^- + N \rightarrow e^- + N$ process, which is the primary focus of the Mu2e experiment located at the Fermi National Accelerator Laboratory (FNAL). It uses an Aluminum target, examining the $\mu^- Al \rightarrow e^- Al$ process. The project aims to observe CLFV by measuring the ratio $R_{\mu e}$, which compares the rate of neutrinoless muon-electron conversions in a nucleus's field to the rate of ordinary muon capture on the nucleus [3].

$$R_{\mu e} = \frac{\mu^- + A\,(Z,N) \rightarrow e^- + A\,(Z,N)}{\mu^- + A\,(Z,N) \rightarrow \nu_\mu + A\,(Z-1,N)}$$

Mu2e intends to probe with a single-event sensitivity of $R_{\mu e} = 2.87 \times 10^{-17}$, which is four orders of magnitude smaller than the current limit $R_{\mu e} < 3.6 \times 10^{-20}$, established by the SINDRUM II experiment [3], with a 90% confidence level.

C. Tracker

Due to the sensitivity of this detector, a significant number of background interactions will be detected. Its detector, which is intended to detect the $\mu^- Al \rightarrow e^- Al$ process, also measures electrons with energies of 105 MeV/c[2], while accurately rejecting background data such as Decay in Orbit (DIO) electrons [3]. This is accomplished by using a pulsed beam sent through the tracker, which examines only tracks appearing between a window of t = 700 ms and t = 1695 ms [2]. All of this is accomplished while the Tracker lives within the superconducting solenoid, which is vacuumed out.

D. Electronics Process

This signal data is observed via straw tubes and read out by 20,736 preamplifiers (preamps) within 36 Tracker planes, or 18 Stations. Each station is comprised of two planes, and within each plane, there are six panels, each consisting of 96 preamplifiers designed to amplify the signal detected via the wires within the straws. In the panel, as shown in Fig. 1, two sections contain different preamps. The left side of the image holds calibration (CAL) preamps, and the right side holds High Voltage (HV) preamps. One of the purposes of the CAL preamp is to send pulses to the HV side to confirm proper communication between both sides.

II. PLANE AND PANEL PREPARATION

When a plane first arrives in Clean Room A, the first component that is confirmed to be added is the copper cooling ring. This is used to cool down the plane while the DRACs are being used.

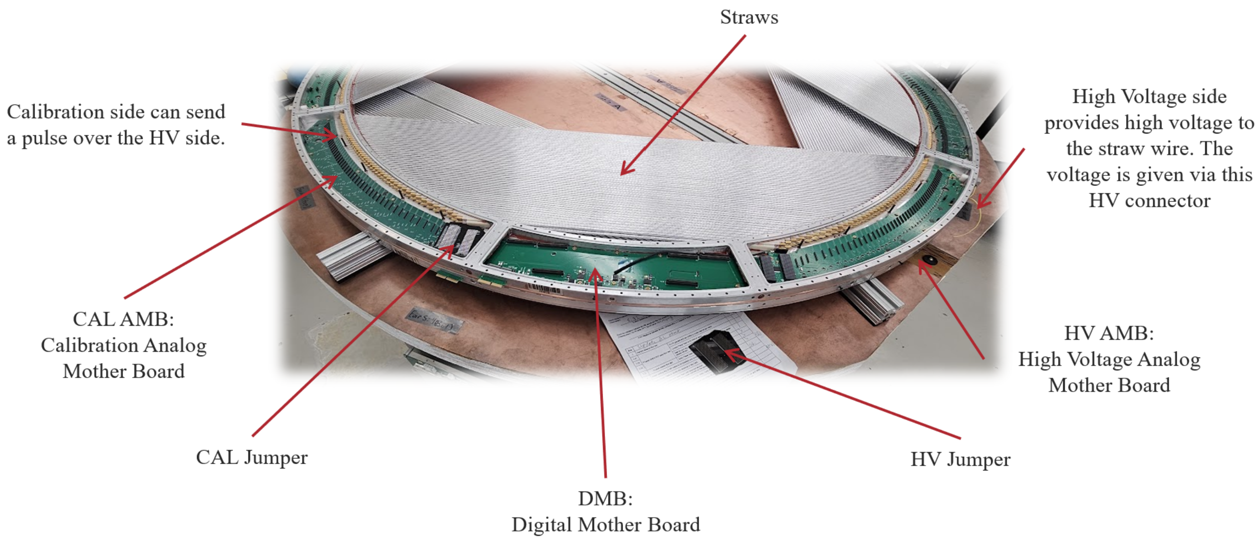

FIG. 1. Image of an empty panel. To the left is the CAL AMB, and to the right is the HV AMB.

A. Cooling ring and flow test

With the help of Vincent Fischer, the cooling ring is installed, and eventually, the center covers are removed from each of the three panels on the plane to access the gas tube. Before removing the side covers on each of the panels, the flow test needs to be performed. The way this is accomplished is by checking if there is at least 80% flow through the straws. ArCO2 is used for this step because it is a drier gas than air. Then, using a flow-meter, the panel is checked to see if there is 0.4 LPM coming from the wall; there should be a gas flow of 0.36 LPM or higher for this to pass. If it passes, plane preparation continues. If it fails, the gas is switched from ArCO2 to P5. P5 is a gas that is not flammable but is detectable through sniffers, and after letting the gas flow for approximately 30 minutes, the sniffer is used to detect the location of the gas. Once the leak is located, the plane team confirms what their next steps are to fix the leak.

B. Flow Sensors

With the test having been completed, Vincent Fischer is asked to install the flow sensors, as well as the DMB ph wire. This takes approximately one working day to cure, after which the depth of the flow sensor is measured. This is conducted to ensure the flow sensor is below the height of the frame and has sufficient space to allow gas to flow out of it.

C. LVHV Component Connection

When this is accomplished, the low- and high-voltage test components (power line, high-voltage supply (Droege), DC converter, Keys, USB cables, and copper strips are attached. The power line supplies the LV power, and the droege supplies the HV power.

D. AMB preparation and installation

To prepare for the installation of the Analog Mother Boards or AMBs, Mylar sheets are cut and placed inside the panels, which act as a separation barrier between the aluminum frame and the AMBs, to prevent shorts. Then copper washers are placed onto the screw holes. These act as spacers between AMB and the mylar sheet.

E. Solder Bridge Check

Before the installation of the AMBs, they are checked for solder bridges. These bridges cause shorts on the AMBs and cause the panel to fail during Low-voltage testing. Then begin the installation of the AMBs by placing them down onto the mylar sheet within either of the side sections of the panel. Next is lightly screwing the nuts onto the bolts on the AMB.

F. High-Voltage Preamp Installation

The jumper is initially lightly placed into the DMB and AMB jump connections. This is because the DMB is fixed in place, and the AMB is not, necessitating the AMB to be in line with the DMB. Once the screws not under the jumper are lightly tightened, they are then fully finger-tightened. Then the jumper is removed, and the screw underneath is finger-tightened as well. After which, the jumper is fully inserted into the board. This is repeated for the rest of the CAL and HV AMBs for each panel.

G. DMB Modification/AMB HV Soldering

The HV AMB voltage connector is connected to the AMB via solder so that high voltage can be supplied to the panel. Bryan Wells or another trained professional is asked to modify the resistors on the DMB and connect the high-voltage wire on the HV AMBs to the HV socket wire.

III. PREAMP INSTALLATION

Initial checks are needed before installation, such as checking the travelers. These are pieces of paper that record previous issues for the panel being worked on, and are checked for channels that are dead. Now that the plane has been prepared, preamp installation can begin.

The high-voltage preamps are installed first so that high-voltage continuity can be checked for the wires. During installation, quality checks need to be performed, mainly on the HV disconnect wire. The HV wire needs to be properly curved, similar to the Nike symbol, flush with the board, no wires sticking out of the solder, clean of flux, and the solder is smooth.

A. High Voltage Continuity Check

After the HV preamps are plugged into the AMB, the trip setting is changed to $100\mu A$ and the voltage is ramped up to $\sim$100V. Then the voltage is checked on the CAL side anode pins to see if there are any issues with the wire within the straw or if any of the sockets on the preamps are broken during installation.

B. Calibration Preamp Installation

Once the wires are checked and confirmed to be good, the CAL preamps are installed. However, some channels that had previous issues, such as missing wires, missing straws, anode-to-cathode shorts, or more, are marked down on our checklists. If there are channels that are missing, preamps with broken sockets from installation are used.

C. Low Voltage Tests

1. Setting Thresholds

This test confirms proper communication between the AMB and the front-end electronics, i.e., the preamps, DMB, and DRAC. By telling the system what voltage threshold to search for, it attempts to create a voltage difference of 35mV, for example, between the negative and positive pins on the preamp. If the script is unable to set the voltage, this is indicative of potential issues. These issues range from shorts on the board, an improperly seated preamp, and a solder bridge on the bottom of the header for the AMB.

2. Coincidence Rates

When all of the preamps have correctly set thresholds, the next Coincidence test can be run. This is done via the calibration preamps sending over around 4000 pulses to the HV side. This acts as a game of telephone where the CALs are attempting to verify if the HV preamps can receive signals. If any preamps do not show a rate that is coincident with the correct amount of pulses sent from the CAL, they are replaced with a fresh preamp.

With all preamps passing the threshold and coincident rate tests, the DRAC production test is run, where the plots of the calpulses are affirmed to not demonstrate instances of oscillations or disconnected channels.

D. High Voltage Tests

When the panels pass all of the LV tests, O-rings and plastic covers are attached to the panel so the Plastic Cover High Voltage test can be performed. The gas input socket is connected to the panel from the wall, and then turned on, where the gas flow is set to 0.5 LPM for each of the three panels on the plane. The flow meter on the table or wall should read out ~1.5 LPM. As with the flow test, 15-30 minutes is how long the gas should flow through the straws so that any air displaced within the volume. The voltage may be raised to 500V within this time, and once 15-30 minutes have passed, ramp the voltage up by 250V every 15 minutes until the maximum voltage is reached. On each droege, there are "different" max voltages, with the actual max voltage being 1450V. However, each droege has an offset so that the readout will be different for each HV supply.

While ramping up the voltage, there might be sparks that can be viewed via quick spikes in the current. This may be seen either on the Droege monitor or on the Droege current meter. If there are consistent sparks above 1000nA within five-minute intervals, the panel should be troubleshooted. This may be done by using previously recorded information from the travelers or by turning off the lights and visually searching for sparks. When all of the preamps have been fixed, make sure the panel is at maximum voltage and leave it on either overnight or half a workday. If there are no trips during this period, the panel has passed its plastic cover high-voltage test.

For the Aluminum cover, high voltage test, it essentially follows the same steps as plastic covers, albeit with aluminum covers installed. This test only needs to be run for one hour with no trips, as the panel has already acclimated to the voltage during its high-voltage test with its aluminum cover.

E. Disconnection and purging

If this plane is on its first half, it needs to be flipped, and the process written above needs to be repeated for this half. If the plane is in its second half, and all electronics are installed, the LV/HV components are disconnected, and the cooling ring is purged of water. Afterwards, it is sent to the plane for them to perform their long-term leak tests.

IV. CONCLUSION

In summary, from initially preparing the planes to performing the low- and high-voltage tests, there are numerous steps sensitive to minute details. In October of 2024, fifteen planes had their electronics installed, and currently, thirty-five of thirty-six planes have had their electronics installed. Each step and process for installing electronics is a result of the cumulative work from October 2024 to the present. It would be remiss not to acknowledge the massive effort from the people whose aid made the project possible, enabling it to have many planes with their electronics installed.

V. ACKNOWLEDGMENTS

This manuscript has been authored by Fermi Research Alliance, LLC under Contract No. DE-AC02-07CH11359 with the U.S. Department of Energy, Office of Science, Office of High Energy Physics.

This work was supported in part by the U.S. Department of Energy, Office of Science, Office of Workforce Development for Teachers and Scientists (WDTS) under the Science Undergraduate Laboratory Internships Program (SULI).

---

[1] R. E. Ray, *Mu2e Technical Design Report (TDR)*, Technical Design Report 15 (Fermi National Accelerator Laboratory, 2015) chapter 1.

[2] R. E. Ray, *Mu2e Technical Design Report (TDR)*, Technical Design Report 15 (Fermi National Accelerator Laboratory, 2015) chapter 8.

[3] R. E. Ray, *Mu2e Technical Design Report (TDR)*, Technical Design Report 15 (Fermi National Accelerator Laboratory, 2015).