Work done at Kansas State University in support of the Muon-to-Electron Conversion Experiment (Mu2e)

by

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Abstract

The Muon-to-Electron Conversion Experiment (Mu2e) located at Fermi National Accelerator Laboratory (FNAL) is an exciting probe into the Intensity frontier of modern particle physics. It aims to study charged lepton flavor violation (CLFV), a rare process that has never yet been observed experimentally, with a single event sensitivity of 2.87×10^{-17} [1]. Because this target sensitivity is so high, extensive background elimination is required to achieve it. Cosmic rays are a significant contribution to the background. Therefore, the Cosmic Ray Veto system was developed for Mu2e. If cosmic ray muons capable of producing false CLFV signals in the detection apparatuses are detected in the veto system, the data from the time period during which this particle traverses the detector will be vetoed or deleted. The Cosmic Ray Veto system (CRV) aims to help eliminate cosmic ray background while minimizing detector dead time. The Mu2e team is comprised of hundreds of scientists from around the world, including a team located at Kansas State University (K-State). In this work, I will give a brief description of the experiment, explore the software and hardware central to its mission, and describe the work done at Kansas State to support this endeavor. I will also prompt future studies that can be completed at K-State to further the mission of the Mu2e team.

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Nomenclature

$CLFV$ Charged Lepton Flavor Violation

CRV Cosmic Ray Veto

$FHiCL$ Fermilab Hierarchical Configuration Language

$FNAL$ Fermi National Accelerator Laboratory

$K-State$ Kansas State University

$Mu2e$ Muon to Electron Conversion

Acknowledgments

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Dedication

This work is dedicated to my thesis coach and wonderful partner, Sydney Matheis. To Katelynn Hubenig, James Natoli, and Braden Allmond, thank you for helping me believe in myself and for keeping me afloat all these years. To Cassandra Myskiw for opening my eyes to my potential; and to all those who accepted and believed in me from the start. You have left an indelible imprint on my life and work, past, present, and future.

Chapter 1

Introduction

The muon-to-electron conversion experiment was developed to study a rare process called charged lepton flavor violation. This experiment uses the pre-existing proton beam line that is already in operation at Fermi National Laboratory in Batavia, IL. Once the experiment is in operation, the beamline will deliver 8 GeV Protons that will then decay into charged pions. These pions will travel down the transport solenoid, decaying into muons as they travel, and be guided to the detector chamber. Once in this chamber, they will strike an aluminum target wherein some muons will be slowed down enough to convert into an electron without emitting neutrinos. Figure 1.2 shows the layout of Mu2e.

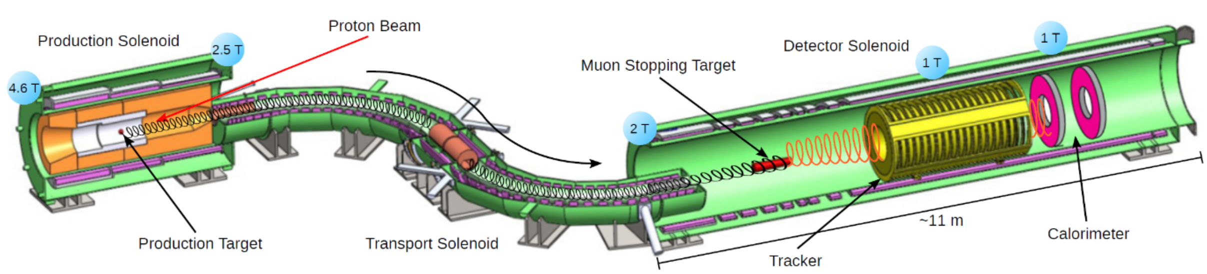

Figure 1.1: *The layout of the Mu2e Experiment from the Technical Design Report*

This process is an example of a charged lepton flavor violation and, if observed, will prove that charged lepton flavor need not be conserved in all cases, thereby expanding our idea of the standard model. This specific muonic decay is extremely rare. Because of that, the sensitivity of the Mu2e experiment is extremely high, about 2.87×10^{-17} [1]. There are several processes that could mimic the muon-to-electron conversion signal. These processes are known as background. To obtain this experiment's ideal sensitivity, the background must be very thoroughly inspected and eliminated. One source of background is electrons and muons that come from cosmic radiation permeating the experiment [1]. Since the Mu2e experiment is located above ground in order to utilize the existing infrastructure at Fermilab, cosmic radiation permeates the sensitive detecting elements that have been designed for the experiment.

Figure 1.2: *View of the Muon campus at Fermilab. Mu2e will be located in the white building pictured in the lower right of the photo.*

These cosmic rays can decay and present as a signal in the data collected by Mu2e. Every minute, about one cosmic ray muon passes through one square centimeter of Earth. There is expected to be about one that causes an event detected that mimics the signal [2]. In Mu2e, this source of background is mainly addressed with an active cosmic ray veto detector system. Cosmic ray signals detected in the veto system are used together with data taken in the detector solenoid to find matching events. These matching events are then taken out of the data that corresponds to the "livetime" of the detector run. Running Mu2e requires extensive resources, so we want to remove as little data as possible. At the same time, we want to collect as much data as possible when we have the experiment in progress. The removal of data adds to a metric called deadtime, which is something we want to minimize.

Chapter 2

The Cosmic Ray Veto

At Kansas State, we on the mu2e team focus our work primarily on the CRV. The CRV, a sensitive detector, encases the entire Mu2e detector solenoid and part of the Mu2e transport solenoid. Figure 2.1 shows this system housing the detector solenoid and parts of the transport solenoid. Around 500 extruded scintillator counters are bonded into 83 modules with

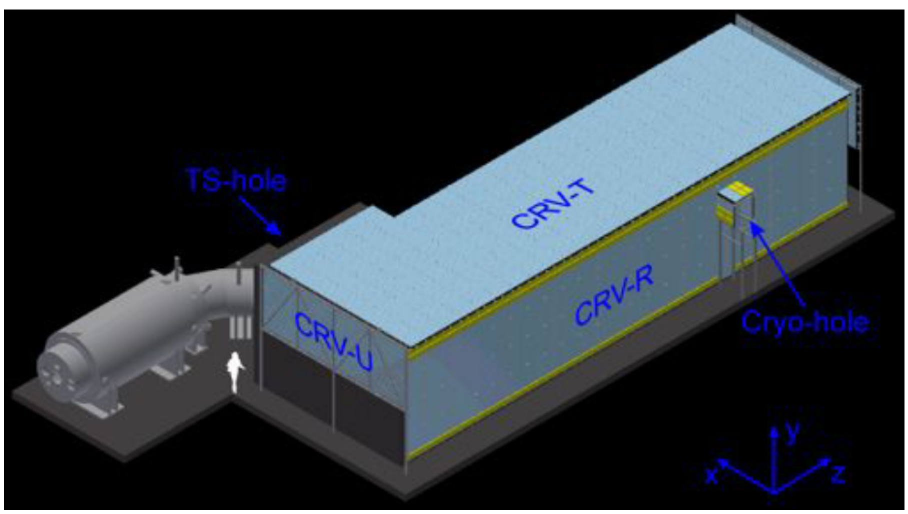

Figure 2.1: *The Cosmic Ray Veto encases the detector solenoid and part of the transport solenoid.*

4 counters separated by thin layers of aluminum per module [1]. Embedded within each counter are wave-length shifting fibers that connect to silicon photomultipliers or SiPMs. The SiPMs deliver information about particles that pass through the counters to a com-

puter system managed by front end circuit boards mounted on each sector of the CRV. Each scintillator, fiber, and SiPM combination is known as a counter. The counters are stacked upon each other at an offset of 42 mm on the top and side modules and 0mm for the upstream and downstream modules to minimize gaps between them [3].

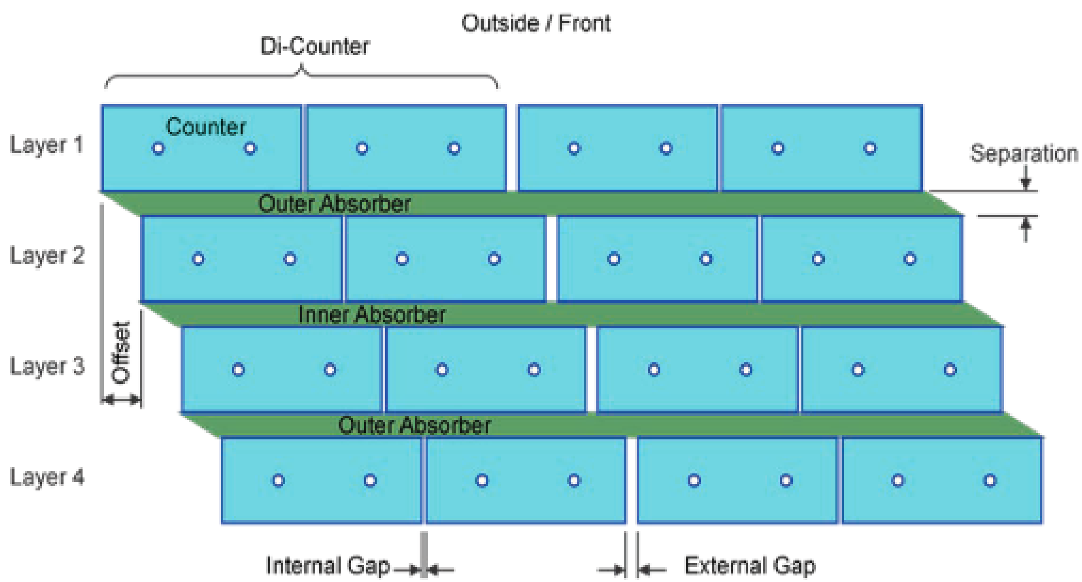

Figure 2.2: *A single module of the CRV.*

The front end circuit boards send the data from the counters to an algorithm that calculates crucial information about the hit. We can look at the time-synced data for all the counters in all of the modules that surround the detector and see any patterns. When the radiation interacts with the counters, this is known as a "hit" if three or four adjacent counters experience a hit, that sequence is then tagged as an event and any data gathered in the detector during that time will be vetoed. This is a very effective tool in preventing possible false signals, but it decreases the amount of time that the detector is live and collecting data. as mentioned briefly in the introduction, these periods of vetoed data are part of what is known as "dead time". This quantity should be minimized to ensure efficient use of resources. The target veto efficiency is 99.99% [4]. We need to find a perfect balance between eliminating enough background and minimizing detector dead time. Many efficiency studies have been carried out to look at everything from the spacing between the counters to the material used to construct the counters and a myriad of other things. Since this veto system and its sensitive mechanisms are constantly being bombarded by cosmic radiation, we also have to consider the aging of the equipment. As the equipment ages, it becomes less able to detect and transmit important data about the cosmics hitting the detector. There are several studies that determine how many counters we can lose to aging and ways to mitigate this.

Chapter 3

Before Beam Time

In 2016, the Technical Design Report for the Muon-to-Electron Conversion Experiment was presented to the funding organization–the United States Department of Energy–approved, and published. This work was the culmination of the work of scientists from the Fermi National Accelerator Laboratory and the Mu2e Collaboration [1]. Construction on the facilities began shortly after. As of today, the construction is ongoing. There have been delays due to the global COVID-19 pandemic which stalled the ability to construct the project as well as critically delayed the delivery of crucial circuitry and mechanical parts needed to construct components of the experiment. For example, a problem faced at K-State was that the front end boards reading out data from the SiPMs that are attached to each counter had to be completely redesigned due to the unavailability of a key processor. What are scientists doing in all of this time between design and run time? The majority of the work done to prepare for the first run of the experiment primarily deals with the construction of various parts of the experiment and simulation studies. These simulation studies serve the important job of preparing analysis algorithms for the job of processing future data. They are also invaluable to troubleshooting the experiment.

Chapter 4

Software

There are several specific algorithms and languages that we use for Mu2e. The Mu2e computing environment is very complex. There is a steep learning curve that comes along with most high energy physics experiments and Mu2e is no different. There is a very helpful public Wikipedia with several guides to help the young experimenter acclimate to the environment. However, they must be careful to use updated guides. Some algorithms change very quickly as scientists actively work to perfect different computational systems integral to the experiment. Mu2e makes use of the Fermilab Hierarchical Computing Language, a language developed for Fermilab to help manage the run-time configuration for several projects. Mu2e's primary data is stored in the "art" format. This is an event-processing framework that is widely used in particle physics experiments. Once the data is collected and stored, the next step is to retrieve the data in a manageable way. We extract the most paramount information from the data (such as momentum and hits-on-target) and group it into an "ntuple." These ntuples are often in the form of ROOT TTree. ROOT is a tool for large-volume scientific data processing that was developed at CERN. With these root files, we can quickly make histograms and analyze massive amounts of data in a friendly, relatively easy-to-learn manner. One such ntuple that has been helpful in completing work at K-State is a track-based system called TrkAna. This was developed by Andrew Edmonds, David

Brown, Sophie Middleton, and Ray Culbertson[1]. Once a data set is selected and retrieved from tape, the user can make a TrkAna tree by setting up the correct version of Muse and running an analysis FHiCL file on the data. Once this tree is made, the user can now use ROOT to easily make and review pertinent histograms. These ntuples make it efficient for scientists to work with the data taken during the experiment.

TrkAna is useful because you can also adjust the fcl parameters to fit your needs. There are several branches specifically developed for CRV data. These direct the tree maker to include CRV hits when creating the trees. To make use of this, the CRVExpert.fcl is used on the data set. Several workable ROOT leaves are produced as a result.

[1] The TrkAna TTree maker can be found on GitHub here.

Chapter 5

Work at K-State

The majority of Mu2e supporting work done at K-State revolves around the electrical integration of front-end circuitry components to the Cosmic Ray Veto. Quality Assurance (QA) and Quality Control (QC) of the related apparatuses are also priorities of the Mu2e team at Kansas State. To satisfy these quality checks, a testing station was set up in the K-State Experimental High Energy Physics Lab clean room. Figure 5.1 shows the testing setup.

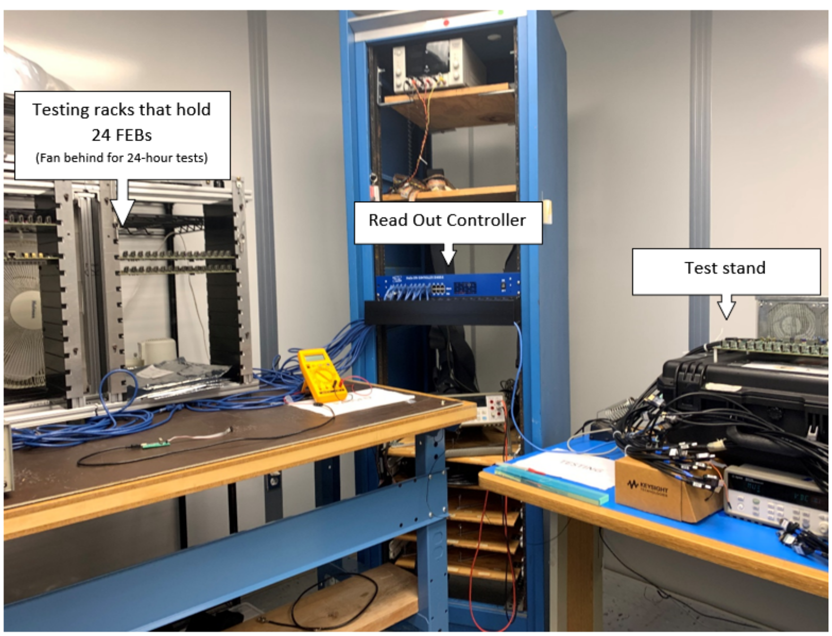

Figure 5.1: *Front End Board testing setup at K-State*

This station consists of a multichannel multimeter testing arrangement, software developed specifically to test the boards, two FEBs from pre-production run one for reference, seventeen Controller Mother Boards (CMBs), thirty-five CMB adapters, firmware for the most current on-board microcontroller, racks for testing multiple FEBs, and a readout controller [5]

Russell Taylor and his team designed the board in K-State's Electrical Design Lab. Glenn Horton-Smith, Kreswell Neely, myself, and several others developed and troubleshot a testing setup at Kansas State. This testing setup consists of a computer, a rack that can hold multiple boards, a readout controller to control voltages delivered, a black box to house the counter motherboards, and necessary cables.

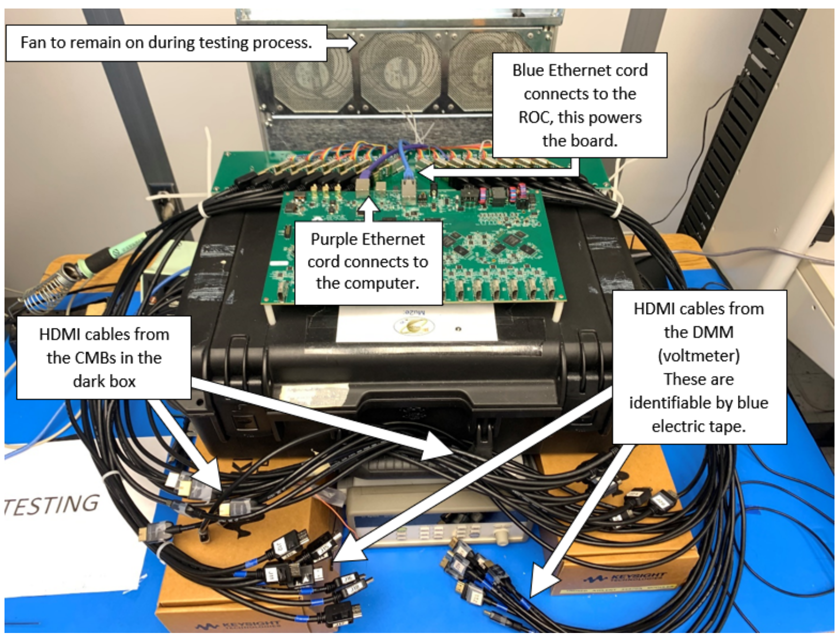

Figure 5.2: *Front End Board test stand at K-State*

With this equipment, we can test prototype boards and the final production front end boards. Each circuit board must be tested to ensure that it is free of factory errors and operates correctly under the same stress applied to it when installed and running. Manuals for the testing process are on the Mu2e internal database. Because of the unavailability of particular circuitry, the production of the front end boards has been pushed back to about another year from the publication of this report.

Chapter 6

Future Work

There are still several areas of CRV performance that have not yet been investigated. Specifically, there is great potential in studying the effects on the number of coincidences found when one or more SiPMs are missing. To conduct this study, one can run an analysis over all the SiPMs or counters in the CRV. Then, look at the 3- or 4-fold coincidences and see how often each SiPM is "hit" to show that coincidence. With this information, one can create a map of the Cosmic Ray Veto to see where the hits are on the different modules and to determine any specific hot spots. A list of all the coincidence clusters can be produced by the coincidence cluster finder module created by Ralf Elrich[1]. Now that you have a list of clusters of coincidences and SiPMs used to detect those hits, you can count how many times any particular cluster is hit in a simulated run and then see if each SiPM in the cluster is needed to keep the 3- or 4-fold coincidence needed to veto the cosmic event. The removal of SiPMs might lead to an increase in the background of the experiment. It is vital to the required sensitivity that any added background must be 0.01% or smaller.

[1] This module can be found under CRVAnalysis in the Mu2e computing environment.

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