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The Mu2e Straw Tracker Detector Status and Prototype Results

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Abstract

The Mu2e experiment will search for charge-lepton flavor violating (CLFV) muon to electron conversion. It aims to achieve a four-orders of magnitude improvement in sensitivity over previous experiments, allowing it to probe new physics at mass scales up to 10^4 TeV. A precision momentum measurement is needed to resolve the monoenergetic electron that is the signal of CLFV conversion from muon decay-in-orbit backgrounds. This is achieved in Mu2e using a low-mass cylindrical straw tracker operated in vacuum, consisting of 21,000 thin-wall mylar straws held at tension. The Mu2e tracker is now in production and will be completed during 2025. We will discuss the design and status of the experiment and the tracker detector, and show results from data taken with the first tracker module.

1. Introduction

In the Standard Model, even with the addition of neutrino masses and oscillations, charged lepton flavor violation (CLFV) is predicted to be unmeasurably small, with branching fractions less than 10^{-50} [1]. Any detection of CLFV would thus be evidence of new physics. The Mu2e experiment at Fermilab will search for the neutrino-less conversion of a negative muon in the field of a nucleus [2], and aims to achieve a four-orders of magnitude improvement in sensitivity over previous experiments to this CLFV process.

The signal of muon conversion is a monoenergetic electron with an energy of approximately 105 MeV. This signal sits at the endpoint of a steeply falling spectrum of electrons from muons that decay in orbit (DIO). Separating the conversion signal from this background requires a precision momentum measurement and a low mass detector. This is achieved in Mu2e using a straw tracker operated in vacuum.

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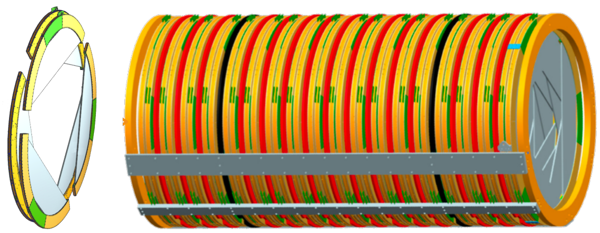

Figure 1: Left: Arrangement of six panels of 96 straws into a circular plane. Right: the full tracker consisting of 18 stations (36 planes).

2. Straw Tracker Design

The Mu2e straw tracker consists of around 21,000 straws, each 5 mm in diameter with 15 μm thick mylar walls and 25 μm tungsten sense wires, oriented transverse to the field axis. It is built out of 96-straw submodules called 'panels'. These form 120°arcs with front-end electronics held at the outer radii and the straws arranged in two staggered layers. Six panels are assembled together to create a circular 'plane', and two planes back-to-back make up a 'station'. The complete tracker cylinder is made up of 18 stations, as shown in Figure 1, and is 3.2m long and 1.6 m in diameter. The tracker sits in a nearly constant 1 T field, and conversion signal electrons will make multiple loops within the detector.

The straws do not instrument the inner 380 mm radius of the tracker cylinder. This makes the tracker blind to the majority of the lower momentum DIO electrons and other beam related backgrounds, greatly reducing the radiation load and hit rate.

Preamps sit directly at both ends of the straws, with each preamp instrumenting two channels. The analog signals are then routed to a central digitizing and readout board (DRAC), as shown in Figure 2. Commercial ADCs are used to digitize the waveforms at 40 MHz to provide a measurement of the energy deposited in the straw and to allow rejection of signals from protons. Most of the remaining functionality is contained within three Microchip Polarfire FPGAs, including the time digitization and the interface with a CERN VTRX optical transceiver for data readout over fiber. The firmware TDCs provide a resolution of approximately 50 ps, and by digitizing the time from both ends of the straw separately we can use time-division to reconstruct the longitudinal position along the straw. We also make a coarse measurement of the time-over-threshold, which provides a measure-

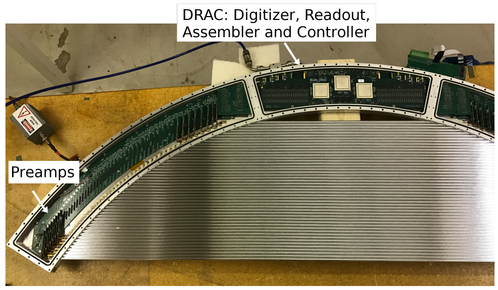

Figure 2: A preproduction panel and front-end electronics.

ment of the drift radius that does not require knowing the particle's arrival time at the straw and can be used to seed the track reconstruction.

3. Prototype Testing

We performed a 'vertical slice' test (VST) of a tracker plane, i.e. a test of the full integrated system from signals produced in the straws to data written to disk. Six fully instrumented pre-production panels ($\sim$ 600 straw) assembled into a plane were operated together. The setup, including the associated infrastructure is shown in Figure 3. Data from radioactive sources and cosmic ray particles were read out by the streaming data aquisition over the optical fiber and used to calibrate the straw response and test reconstruction algorithms.

The VST plane was operated in a vertical configuration so that multi-straw cosmic ray tracks could be reconstructed. The reconstruction was done using a Minuit-based maximum likelihood track fitter that used both drift time and time-division information. An example of a reconstructed cosmic ray track is shown in Figure 4. These tracks were then used to extract the single straw performance of the VST plane. The design requirements for the single straw performance are to provide a measurement of the drift radius with resolution $<$250 μm, a longitudinal position measurement with resolution $<$4 cm, and have an efficiency of $>$90% for minimum ionizing particles, all of which were achieved for cosmic rays in the VST, as shown in Figures 5, 6, and 7.

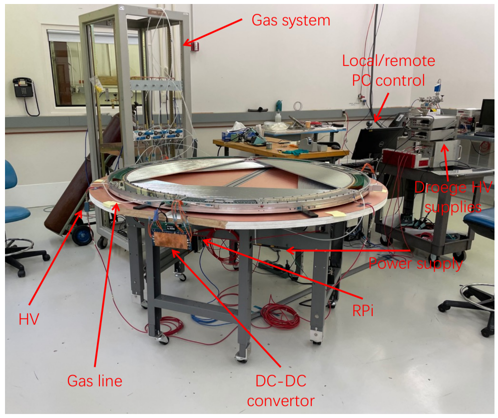

Figure 3: VST setup of first preproduction plane, in horizontal configuration.

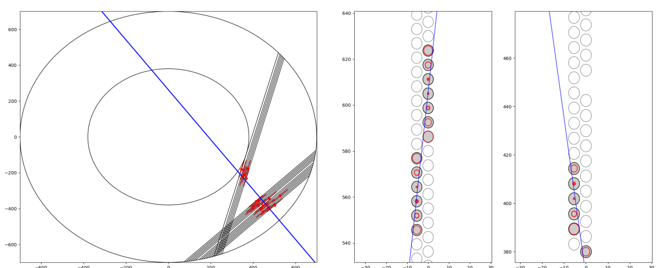

Figure 4: Event display showing example reconstructed cosmic ray track (blue) in vertical slice test, with measured position in each straw (red). Left shows longitudinal reconstruction from time-divison, and right two show estimated radii using drift times, projected into the coordinate systems of the two panels in this event.

4. Construction Status

A large fraction of the construction of the Mu2e straw tracker has been completed. All of the front-end electronics have been produced and processed, and testing and installation is now ongoing. All of the straws and panels have also been produced, and the 36 planes needed for the full tracker have been mechanically assembled. After construction of each panel an x-ray scanner was used to measure the positions of every straw and wire within it [3]. Mechanical and optical metrology measurements are then performed during and after the assembly of the planes and stations, which together will provide initial constraints for later track-based alignment algorithms. Currently the majority of the planes are undergoing long term leak testing as shown in Figure 8, and the first full station module has been assembled. We

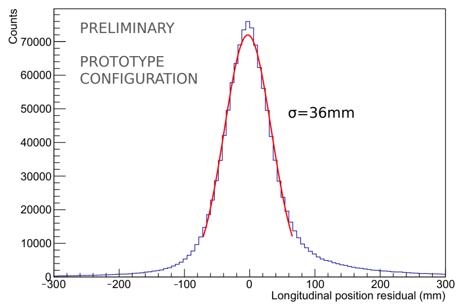

Figure 5: Longitudinal position residuals for middle 80% of straws from reconstructed cosmic ray tracks in the VST, with σ from gaussian fit to core.

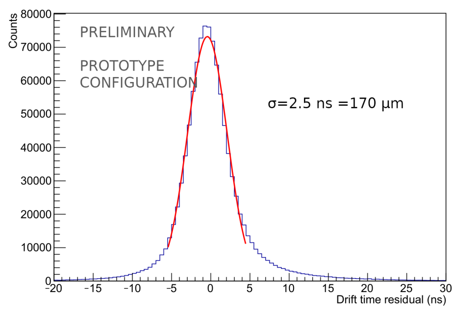

Figure 6: Drift time residuals excluding inner 0.5 mm from reconstructed cosmic ray tracks in the VST, with σ from gaussian fit to core, and position resolution calculated using effective drift velocity.

expect to complete the full tracker by the end of 2025.

5. Conclusion

The Mu2e straw tracker will provide the high precision momentum measurement needed to separate the CLFV conversion signal from the DIO background. Vertical slice tests have demonstrated that the single-straw performance in a realistic configuration meets requirements. Construction of the Mu2e tracker is nearing completion and we expect to be running cosmic ray tests of the full tracker in the detector hall in early 2026.

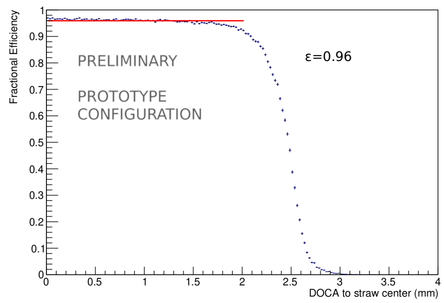

Figure 7: Efficiency as a function of distance of closest approach (DOCA) determined using reconstructed cosmic ray tracks in the VST. Reported ϵ from average of inner 2 mm.

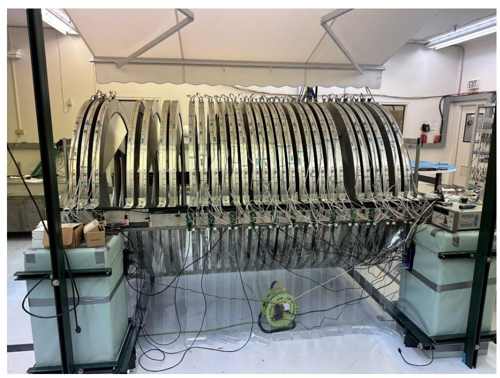

Figure 8: A set of assembled tracker planes undergoing long term leak testing. Note that the configuration of the planes in this testing setup is different than their final configuration in the full tracker shown in Figure 1.

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References

[1] W. J. Marciano, T. Mori, J. M. Roney, Charged lepton flavor violation experiments*, Annual Review of Nuclear and Particle Science 58 (Volume 58, 2008) (2008) 315–341. doi:https://doi.org/10.1146/annurev.nucl.58.110707.171126.
URL https://www.annualreviews.org/content/journals/10.1146/annurev.nucl.58.110707.171126

[2] L. Bartoszek, et al., Mu2e technical design report (2015). arXiv:1501.05241.
URL https://arxiv.org/abs/1501.05241

[3] S. Oh, C. Wang, An x-ray mapper for the mu2e experiment, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 807 (2016) 64–68. doi:https://doi.org/10.1016/j.nima.2015.09.083.
URL https://www.sciencedirect.com/science/article/pii/S0168900215011547