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Nuclear and Particle Physics Proceedings 273–275 (2016) 2530–2532

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The Straw-tube Tracker for the Mu2e Experiment

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Abstract

The Mu2e experiment will search for neutrinoless conversion of muons into electrons in the field of an aluminum nucleus. Precise and robust measurement of the outgoing electron momentum is an essential element to the experiment. We describe the design of a low mass tracking system to meet this requirement. We have chosen to use about 20,000 thin-walled Mylar straws held under tension to avoid the need for supports within the active volume. The electronics system enables the time-division technique to measure hit position along the wire. Charge will be measured using ADCs to provide particle identification capability.

Keywords: Mu2e, Straw detector

1. Introduction

The Mu2e is proposed experiment at Fermilab to search for charged lepton flavor violation phenomena in muon-to-electron conversion, with four order of magnitude better sensitivity beyond the previous experiments. Muons are produced from the decay of pions from 3.6×10^{18} proton hits to the pion production target. They are stopped in thin Aluminum stopping targets and captured in the nuclei, subsequently decaying to electrons with two neutrinos (Decay-In-Orbit: DIO), or decaying neutrinolessly in the field of nuclei which is a signature of charged lepton flavor violation.

The momentum of electrons from the muon decays are measured by tracking detector system. The signal of Mu2e experiment is 104.9 MeV monoenergetic electron above background events from the tail of DIO distribution or other flat background sources. Therefore, precise measurement of electron momentum is one of the important requirement of Mu2e experiment.

The current status of design efforts of Mu2e tracking detector system utilizing straw-tube detector and development of straw detectors are described in Sec. 2 and Sec. 3, respectively. The efforts on front end electronics system development is described in Sec. 4.

2. Development of Tracking detector system

It is important to place less material inside the tracking detector system to minimize the multiple scattering by the detector material which degrades the momentum measurement resolution, and increase the background hit rate. To address this issue, the detector solenoid inside which the tracking detector locates is kept as vacuum except the straw detector which is the active components of tracking detector system. Less material can be used by employing straw detector system compared to a conventional drift chamber because major volume could be vacuum.

Table 1 shows the key parameters of Mu2e tracking detector system. The 23,040 straw detectors are active detector of tracking detector system. 96 parallel aligned straws compose a single panel of detector, as shown in Fig. 1. 12 panels with different rotation angles compose a station as shown in Fig. 2, where 20 stations compose the tracking detector system as shown in Fig. 3. The design of station is made so that the tracking detector system is blind to the electrons with $\leq$ 90MeV transverse momentum.

Stations are aligned along the beam axis with equal spacing inside 1 T homogeneous magnetic field generated by superconducting solenoid. The electrons from

http://dx.doi.org/10.1016/j.nuclphysbps.2015.09.448

muon decay propagate from the muon stopping target located at the upstream of tracking detector system, to the downstream of detector, producing spiral trajectories due to magnetic field. The electrons generate hits at the straw detectors, which are read out by frontend electronics to be reconstructed as track in offline.

Table 1: Key parameters of Mu2e tracker.

Parameters	Values
Number of straw	23040
Straw diameter	5 mm
Sense wire	25μm gold plated tungsten
Drift gas	Ar : CO_2, 80:20
Gas gain	$3 \sim 5 \times 10^4$
Maximum drift time	50 ns
Detector length	3196 mm
Detector diameter	1620 mm

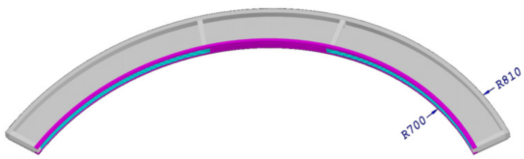

Figure 1: (Color online) A straw panel without covers or straws. Inner magenta regions are stainless steel alloy; outer gray are aluminum frame; and cyan parts inside steel alloy are plastic. Dimensions are in millimeters. Straw detectors connect two plastic parts in parallel. The front-end electronics locate at the aluminum frame beyond plastic parts.

Mechanical and thermal stability are important issue for robust operation of tracking detector system. Specially the thermal analysis showed that major heat source is the readout electronics located at the center of panel. A colling system utilizing SUVA is being designed to help the cooling of the tracking detector system.

3. Straw detector

Straw detectors are sensitive and active detector components of tracking detector system. At the center of the ϕ5mm and t15μm metalized Mylar straw is the ϕ25μm gold plated tungsten sense wire. A Ar : CO_2 80:20 gas mixture is flowing inside the straw. Estimated gas gain to generate electron/hole pair with this gas mixture is $30,000 \sim 50,000$.

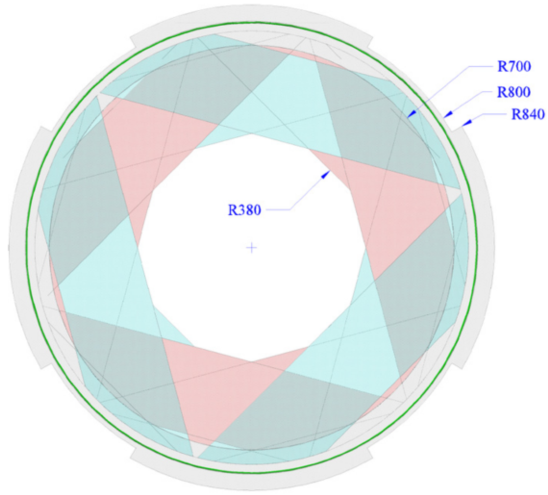

Figure 2: A station of tracking detector with 12 panels overlaid. Dimensions are in millimeters.

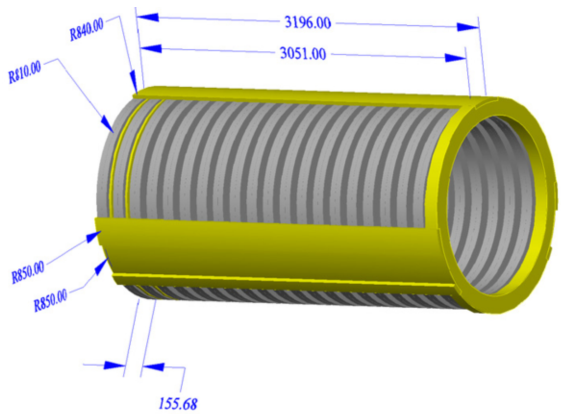

Figure 3: (Color online) Mu2e tracking detector system with 20 stations. Grays are stations without showing detailed structure of panel, and yellow is supporting and service structure. Dimensions are in millimeters.

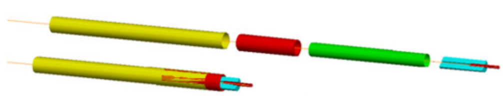

Figure 4: A dissembled (top) and assembled (bottom) straw detector. From the left part of the dissembled plot, ϕ5mm and t15μm metalized Mylar straw, brass tube, kapton sleeve, injection molded plastic with ϕ1mm brass pin are shown. At the center of straw, ϕ25μm gold plated tungsten sense wire is included.

Because straws locate inside vacuum and they should sustain 1 atm air pressure, it is important that straw does not leak for the life time of experiment. A straw leak test is performed at Rice university, by putting a straw inside a copper vessel filled with pure nitrogen gas. The straw is filled with CO_2 gas with 2 atm pressure or without it, and the CO_2 sensor measures its partial pressure to get the leak rate of straw. The leak rate was less than 3.5×10^{-4}ccm which was acceptable for life time usage of straw. Further robust test is on going.

Straws are expected to sustain tension connecting both end of panel and not to get displaced or broken by making creeps. Therefore it is important that the tension of straw does not drop below certain required level after life time usage of straw. A test on straw creep is performed in Duke university. Four different initial tension of 300, 400, 500 and 600 gram-meter (gm) were applied to 120 cm long straws, and the straw tensions are measured by applying acoustic oscillation and measuring the resonant frequency. The tensions are measured for more than 700 days until now, and a sharp decrease of tension at the initial 200 days was observed, followed by a quasi-linear decrease of tension. An extrapolation of measured tension data results that 600 gm initial tensioning is required to get > 200 gm tension after life time operation of straw. The test is still going on to get better extrapolation of tension expectation.

4. Frontend electronics

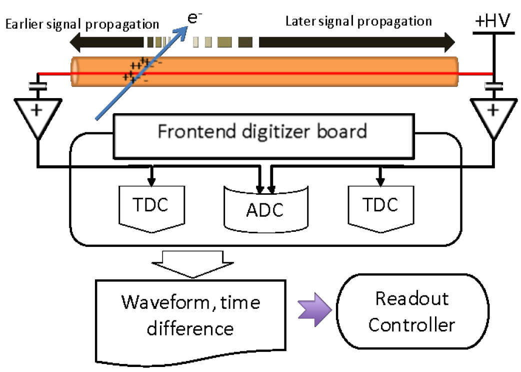

Figure 5: A conceptual diagram of signal flow of front end electronics of Mu2e tracking detector system.

The frontend electronics system of tracking detector system manipulates electric signal from the straw detectors by amplifying and digitizing it. The conceptual diagram of signal flow is shown in Fig. 5. Signals from straws are read from both end of straw, amplified by custom preamplifier which locates at the end of straw on the panel. The amplified signal is sent to digitizer electronics which locates at the center of of panel.

A time division technique is employed to get the hit position information along the straw, which enables better track reconstruction and momentum measurement. The time difference of signal propagation along straw is related to the hit position along straw, and is measured by using a precise Time-to-Digital Converter (TDC). It is required to get < 35ps resolution on time difference measurement by TDC, to get less than a centimeter resolution in hit position measurement. A TDC design implemented in FPGA by using logic chain delay and bin width correction algorithm is employed [3]. The Analog-to-Digital Converter (ADC) is included in the digitization. The sum of preamplified signal is feed to ADC to get pulse height information, which is used to discriminate electron hits from proton hits with much larger energy deposition in the straw. A commercial 12 bit, 50MS/s ADC chip is employed. Both TDC and ADC designs including preliminary custom preamplifier are tested with straw detector and calibration source.

5. Conclusion

It is important to have a high performance tracking detector system in Mu2e experiment to measure the momentum of electron from muon decay. The straw-tube detector is used to construct the tracking detector system, which enables less materials inside the detector region and enhance the performance. Various tests on the performance of straws are still going on, when the preliminary results are meeting requirements. A time-division technique is applied in the design of frontend electronics system to help better reconstruction of track. From the simulation study, it is expected to get 116 keV/c core resolution of electron momentum measurement. Expected experiment sensitivity of Mu2e with this tracking detector system is 2.9×10^{-17}.

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