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Mu2e-II Tracker
Letter of Interest for Snowmass 2021

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The Mu2e-II Experiment will be an order of magnitude upgrade to the sensitivity of the Mu2e Experiment, currently under construction, which will search for the coherent, neutrino-less conversion of a muon into a mono-energetic electron, in the field of a nucleus. As with Mu2e, the Mu2e-II tracker will be responsible for precisely measuring the energy of the conversion electron, distinguishing it from lower energy background electrons. The new tracker will require an improved momentum resolution and improved resilience to radiation. In this letter of interest, we will discuss the requirements for the Mu2e-II tracker and the R&D currently in progress to achieve the required sensitivity.

The Mu2e-II Experiment [1–3] will increase the sensitivity of the Mu2e Experiment [4] at the Fermi National Laboratory by an order of magnitude using most of the high cost infrastructure and apparatus of that experiment. Mu2e-II will either increase Mu2e's search region or improve our understanding of muon to electron conversion process. As with Mu2e, the tracker is the primary energy measurement of the conversion electron. To achieve the required sensitivity, the Mu2e-II tracker must have an improved momentum resolution sufficient to distinguish the signal conversion electron ($\mu + N \to e + N$) from almost all of the decay in orbit (DIO) electrons ($\mu + N \to e + \bar{\nu}_e + \nu_\mu + N$).

Mu2e chose to use a low-mass proportional straw tube tracker. The tracker consists of 20,736 straws with wall thickness of 15 μm, the thinnest walled proportional tube straws used in any experiment to date. The design geometry is a long cylindrical active region with a gap in the middle, purposely blinding the detector to particles with momenta outside a small range around that of the conversion electron and avoiding the beam flash. The Mu2e tracker's designed momentum resolution is better than 180 keV/c.

The increased muon intensity in the Mu2e-II experiment brings with it new challenges of increased DIO backgrounds, radiation, and detector occupancy. The vast majority of the increased DIO backgrounds can be distinguished from the signal by improving the tracker resolution. The methods for improving tracker resolution being investigated fall into 3 categories: reduction to the tracker mass in the electron path, change in tracker geometry, change in detector technology.

Reducing the mass in the active region of the tracker reduces the likelihood of electron scattering, improving the momentum resolution. In the Mu2e straws, the Mylar straw walls makes up the largest fraction of the attenuation length at 67%.

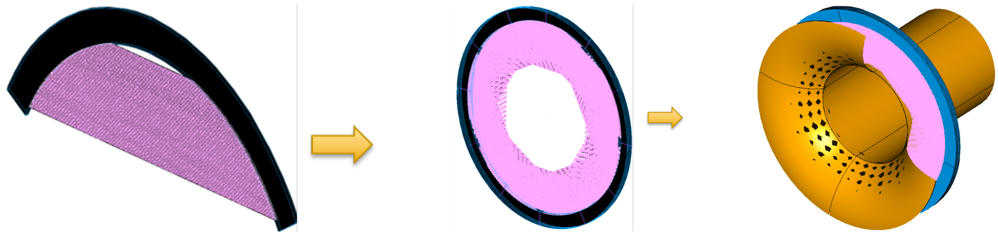
Preliminary simulations show that halving the thickness of the straw walls reduces the standard muon decay background to the level expected in Mu2e. We have succeeded in producing prototype straws with a wall-thickness of 8 μm. These straws are proceeding through a series of mechanical tests, including pressure, tension induced creep rate, sag, gas leak rate, and aging. The results of these tests will be of value to other experiments interested in reducing their detectors active region material budget. These 8 μm straws are spirally wound, a different technology to the welded linear seam of the 12 μm straws developed for NA62 upgrade and COMET[5].

Another opportunity to reduce material and cost of the tracker, would be to remove the 200 Å layer of gold inside each straw. This gold layer contributes 8% of the radiation length and 75% of the material cost of the Mu2e straws. The purpose of the gold layer is to prevent the oxidation of the Aluminum layer that reduces its electrical conduction and causes aging problems. However, thanks to the technical improvements in the material treatment, experiments, such as Belle II[6], have shown that bare Aluminum material can be used for the field cathodes. We produced Mu2e straws without the gold layer in 2017 which we will use to test this assertion.

All components of the tracker must be able to function in Mu2e-II's expected radiation, which is expected to be 10 times that of Mu2e. We will be completing radiation tests to ensure effects on the tracker will be acceptable. Of larger concern, is the radiation hardness of the readout electronics which will be used. Mu2e-II electronics will face challenges by both Single Event Upsets and total dose sensitivity. We will investigate the development of rad-hard front end electronics, including ASICs, DC-DC Converters, and optical components.

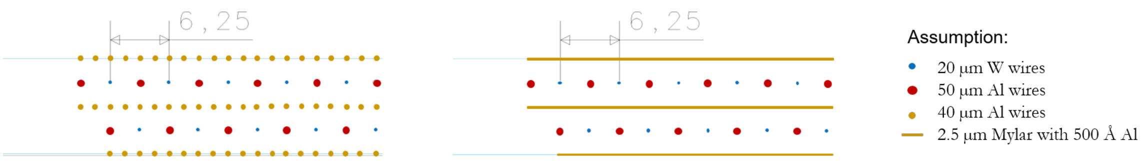
In searching for a detector that fulfills Mu2e-II's tracker requirements, we are not limiting ourselves to a straw tracker. An alternative tracker could be envisioned by separating the gas containing function from the holding structures. Following this paradigm, a drift tracker similar to that of Mu2e could be enclosed in an ultralight gas vessel, similarly to the I-Tracker proposed for Mu2e [7], see fig. 1. The gas vessel proposed for the I-Tracker [7], made of carbon fiber, was able to sustain the differential pressure using an equivalent material thickness of 0.8×10^{-3} X_0 for the inner cylinder and of 0.3×10^{-3} X_0 for the end caps.

With this approach the gas leakage requirements on the single straw tube can be eased and possible alternatives can be identified. Preserving the Mu2e tracker layout, electronics, structures etc., the drift cells can be placed on analogous arched structures to form panels (fig. 1(a)) with similar dimensions and straw disposition. In this configuration, the straws walls are necessary only to define the electric field of the drift cells and need only withstand the electrostatic attraction and gravitational sag. An even further reduction of the straw wall material and a simplified construction could be envisioned by replacing the straw tubes with squared drift cells with the same pitch, as sketched in fig. 2. A possible "all wires" construction is shown in fig. 2(a) assuming thinner wires for the sense wires and larger field wires between adjacent sense wires. The three field wire layers confine the two layers of drift cells. It is important to stress that wire dimensions, materials and wires arrangement have to be optimised. As



(a) (b) (c)

Figure 1. Pictorial views of light tracker alternative: a) single panel; b) a plane built with panels and c) a plane inserted in the gas vessel.



(a) (b)

Figure 2. Sketch of square drift cell scheme for a Mu2e-II tracker option: a) all wire configuration; b) mixed configuration with wires and thin Mylar foils.

starting point, we assume the same wire dimensions (20 μm W wires, 50 μm and 40 μm Al wires) and the same arrangement as the one adopted for the construction of the MEG-II drift chamber [8].

Alternatively, one can think of replacing the three field wire layers with three thin foils of aluminized Mylar, fig. 2(b). Since these aren't subject to differential pressure and only have to sustain the electrostatic forces, Mylar foils 2.5 μm thick with 500 Å of Al[1] on each side could reasonable be used. The outer or middle field wire layers could also be replaced by Mylar foils, ensuring that broken wires will remained confined within a panel and limiting the damage to the tracker (as wire straw tubes). The wires can be anchored by soldering them on ad hoc PCBs to create multi-wires frames. Panels can be simply constructed by stacking up in the right order 3 multi-wires frame with field wires or Mylar foils, 2 multi-wires frame with sense and field wires and 4 spacers. Moreover, since the panel does not need to be sealed, no glue is required between the single layers, which are instead positioned by screws and dowel pins.

This alternative configuration requires a He based gas mixture (we assume a 90% He - 10% $i - C_4H_{10}$ gas mixture as reference point) to maintain the gas multiple scattering contribution at $10^{-3}X/X_0$ level. The single drift cells are equivalent to 1.9×10^{-5} and 3.5×10^{-5} X_0 for the all wire configuration and for the mixed configuration, respectively. The expected material budget for this ultra-light tracker is expected to be of about 3.8×10^{-3} or 4.3×10^{-3} X_0 for the two configuration discussed above, assuming an average value of 35 hits per track. It is worth pointing out that the adoption of the gas vessel not only reduces the material budget but considerably simplifies the construction procedure.

The requirements on the Mu2e-II Tracker will necessitate the advancement of many technologies. Investigations into new thin-walled straws, radiation hard electronics, and alternative tracking technologies will provide valuable knowledge to the detector community. Moreover, we will also investigate the possibility of using different technologies for the Mu2e-II ultra-light tracker. Possible options could be based on Si sensors, like the one designed for the Mu3e experiment, or μ-RWell detectors (in a μ-TPC mode).

[1] At the Mu2e-II occupancy, pure Al could cause space charge effects due to positive ions that cannot quickly discharge, it will need to be tested, however it could be replaced with Cu or Ni.

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