Design of the Mu2e Straw Tracker

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New Perspectives at Fermilab
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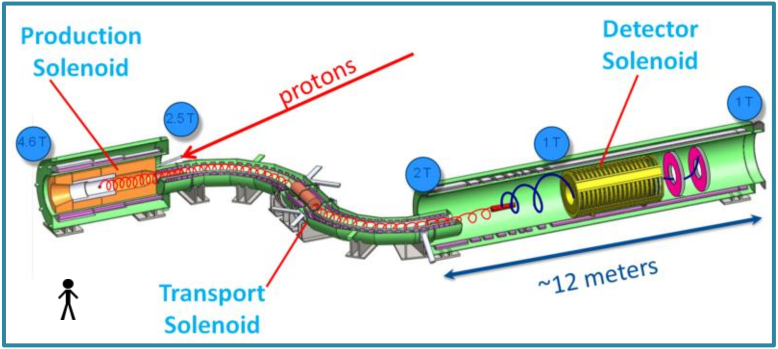
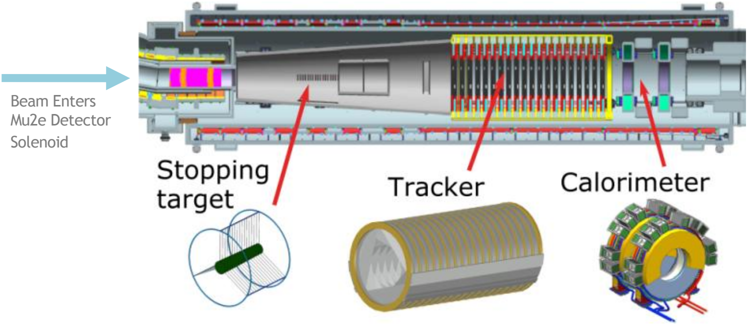
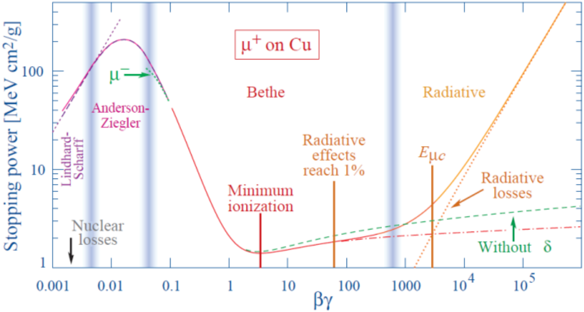


- The Mu2e experiment searches for charged lepton flavor violation, when a muon converts to an electron inside an aluminum atom
- In the Detector Solenoid, tracker and calorimeter measure properties of signal electrons from this process
- Electrons move downstream from stopping target, and tracker determines momenta by fitting their helical trajectories through a magnetic field



- Sensitivity goal for the muon conversion measurement sets challenging physics goals for the tracker
  - Must determine electron momenta with better than 0.2% resolution
  - Use minimal material to avoid signal electron energy loss
  - Maintain efficiency at high hit rates
  - Operate in a strong magnetic field and high radiation environment

Energy Loss in Material



Example of energy loss for muon

For comparison, Mu2e electron has γβ=205

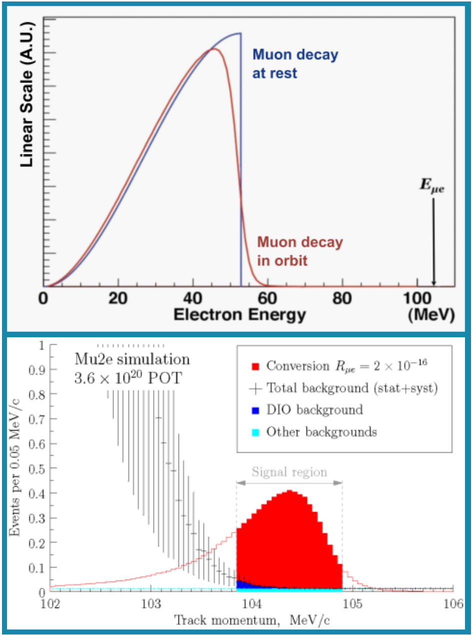
- Particles lose energy as they pass through material, and Mu2e must minimize this effect for signal electrons
- Energy as a function of distance traveled decreases more rapidly for material with more protons, characterized by radiation length X_0

$$E(x) = E_0 \exp\left(\frac{-x}{X_0}\right)$$ with X_0~8.9cm for aluminum

- The Mu2e tracker can only use a very small amount of metal – even just 3cm of aluminum would cause 30% energy loss for electron

Signal Electron vs. Background Spectrum

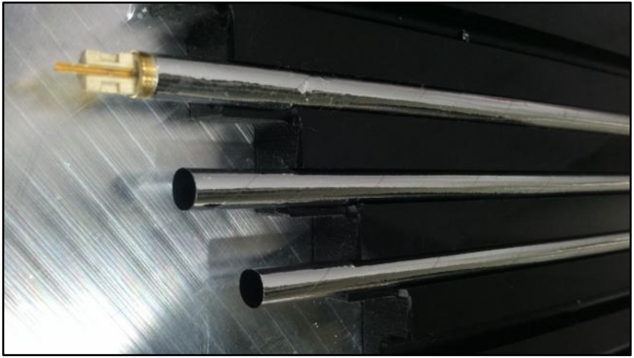
- Muon conversion produces a mono-energetic electron with kinetic energy nearly equal to the muon rest mass, $E_e \sim 105 MeV$
- Energy from normal muon decay at rest is shared among electron and neutrinos, with maximum $E_e = m_\mu/2$
- For muon orbiting a nucleus in the aluminum target, decay spectrum has high energy tail that extends out to signal region
- Tracker must measure momentum with better than 0.2% resolution to separate conversion electrons from normal muon decay products



How is momentum measured with sufficient precision to identify conversion electron candidates?

Mu2e Tracker Components – Straws

- The tracker will use over 20,000 straw drift cells to locate high energy electrons based on ionization events along their trajectories



Mu2e Straws

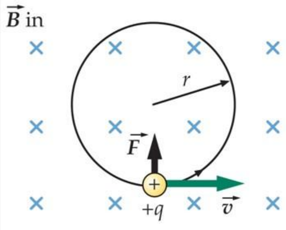
Mu2e Tracker Components - Panels

Mu2e Panel

- A panel holds 96 straws parallel under tension, and has space for readout electronics
- Panels of straws arranged in a circle around the beamline intercept only electrons with large transverse momentum
- Low energy electrons from muon decay, and beam muons, will pass through the hole along the axis of the detector

A Mass Spectrometer for a Massive Quantity of Electrons

Abstract Scenario



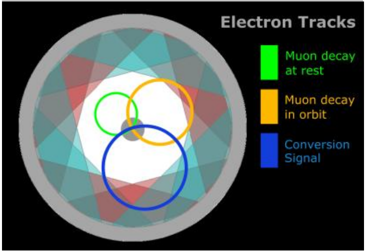
- A particle of mass m and charge q moves perpendicular to a magnetic field. What is the radius of its trajectory?
- Magnetic force provides centripetal acceleration

$$F = |q\vec{v} \times \vec{B}| = \frac{mv^2}{r}$$

- Track radius found from known momentum, or vice versa

$$r = \frac{mv_\perp}{qB} = \frac{p_\perp}{qB}$$

Beamline View of Mu2e Tracker



- In Mu2e detector, magnetic field is uniform 1T and signal electron has q=-e
- For limiting case where all momentum is transverse, $p_\perp$=105MeV/c

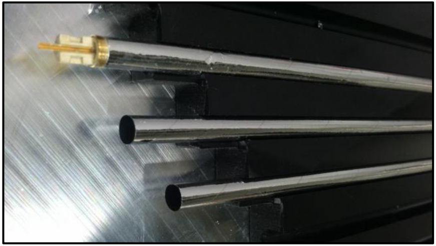
$$r = \frac{p_\perp}{eB} = 35cm$$

- Mu2e tracker instrumentation is positioned to contain these trajectories

How is a conversion electron trajectory located within the tracker?

Mu2e Tracker Components – Straws

- The tracker will use over 20,000 straw drift cells to locate high energy electrons based on ionization events along their trajectories
- To minimize multiple scattering, which alters electron momentum, straws use minimal material and are surrounded by vacuum
- Straws account for only about half of the active detector mass, comparable to the drift gas inside

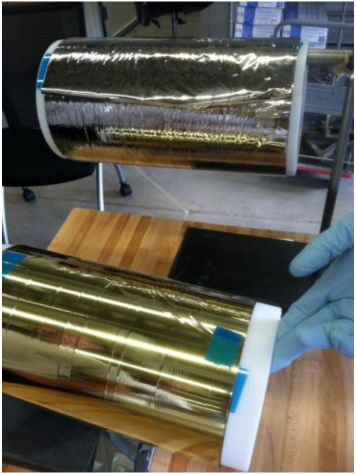


Mu2e Straws

~~Straw into Gold~~ Gold into Straws

- Straws are made of low-mass metalized Mylar
- Wound from 15μm thick strips, with layers of aluminum to separate drift gas from vacuum and gold for conductivity
- Similar in diameter to drinking straws, with lengths varying from 44 to 114cm

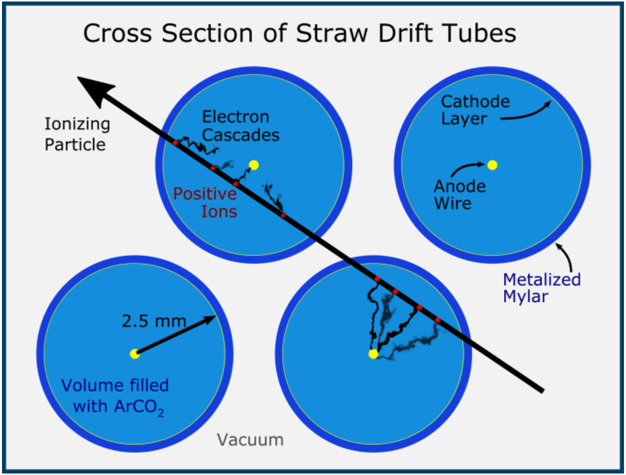
Pallet of Straws



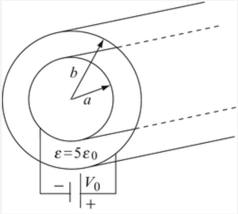
Metalized Mylar – Raw Material for Straws

Signal Electron Path Through Straws

- A high energy electron ionizes Ar:CO_2 gas in the straws, producing a cascade of secondary electrons that drift toward a central 25μm sense wire



Abstract Scenario



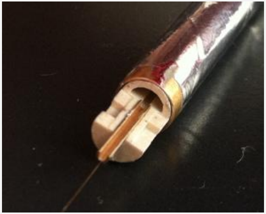
- Electric field between conductors with cylindrical symmetry can be found with Gauss' Law

$$\oint \vec{E} \cdot d\vec{A} = \frac{Q_{enc}}{\varepsilon}$$

- Effective charge λ found by relating field to potential difference

$$\Delta V = -\int \vec{E} \cdot d\vec{l} = \frac{-\lambda}{2\pi\varepsilon} \ln(r) + const.$$

Mu2e Straw and Sense Wire



- Straw is grounded (cathode) with radius r_s=2.5mm, and sense wire is at 1450V (anode) with radius r_w=12.5μm

$$E(r) = \frac{V_w}{r \ln(r_s/r_w)}$$

- Due to this electric field, secondary electrons drift toward sense wire
- Displacement of wire inside straw, or increase in voltage, can cause electrical breakdown

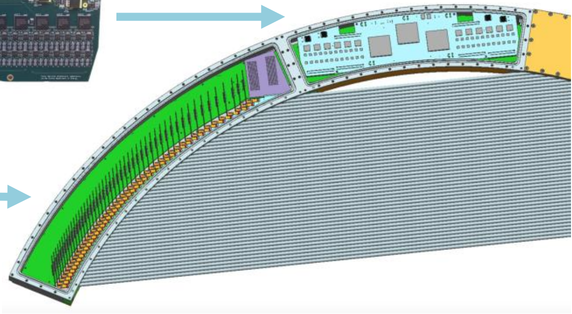
When an ionization event takes place in a straw, how is it detected?

Tracker Electronics

- Just outside active detector region, front-end electronics will amplify and digitize the signal from ionization events
- Highly segmented detector capable of readout efficiency in high hit rate averaging around 15 kHz/cm^2
- Electronics must also withstand neutron and photon flux produced when muons interact with stopping target nuclei

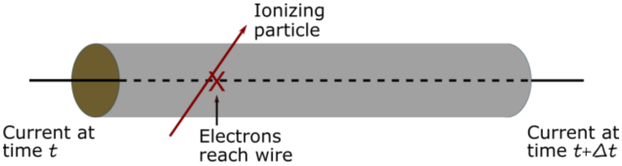
DRAC – Digitization and Readout Control


Preamps connected to straws



Ionization Signal

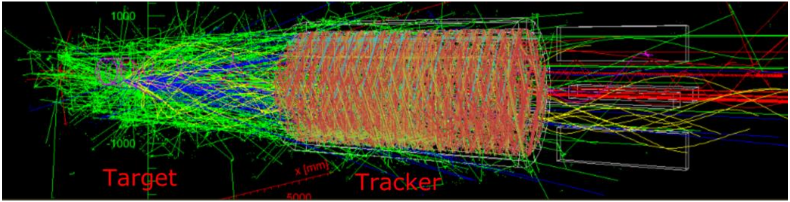
- Readout at both ends of the straw constrains hit position along straw axis, within several cm



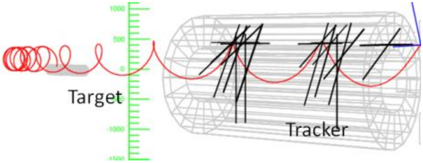
- Timing of the current pulse from an electron cascade gives the distance from ionization event to wire, based on electron drift velocity
- Measure current pulse time to within 2ns for 100μm resolution in hit position

With so many particles passing through the tracker, how do we know if a hit is from a conversion electron or another particle?

Finding a Conversion Electron in a Haystack



- Particle trajectories are simulated segment by segment using Monte Carlo methods in GEANT4, based on measured properties of the tracker
- Analysis goal: distinguish pattern of conversion electron hits
- Group hits by time and fit geometrically, using several iterations to reach a helix with <0.2% momentum resolution



Exciting Times Ahead...

- Mu2e has the potential to discover charged lepton flavor violation in muon to electron conversion, a previously unobserved process that would indicate the existence of new physics
- To reach a single event sensitivity of $3x10^{-17}$, electron momenta must determined with better than 0.2% resolution
- The Mu2e solution to this challenge is an innovative straw tracker design
  - Drift cell straws have ultra low mass to minimize energy loss and multiple scattering
  - A central hole to avoid beam particles and low energy electrons
  - Highly segmented active detector volume to maintain efficiency at high hit rates

...check back in 2021 to see the initial physics data!