Behavior of Calibration Electrons in the Mu2e Tracking Chamber

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July 30, 2010

ABSTRACT

The paper describes the simulation of calibration electrons as they pass through the tracking chamber of the Mu2e detector. MATLAB[1] was used to construct a program that simulates this behavior. The paper provides an analysis of scattering and energy loss effects and a description of methods of determining electron paths. The final objective of the project involves creating a continuous simulation of calibration electron paths in the detector. These electrons pass through a calorimeter, the tracking chamber, and a proton absorber before reaching a magnetic bottleneck. This reverses the z-component of their velocity and sends them back through the detector. Since the tracking chamber detects collisions with rows of straw tubes, and because these straw tubes will not recognize more than one collision for each calibration process, it is of interest to determine the likelihood that the incoming and outgoing tracks of a given electron will intersect with the same straw tube. Modification of the system to decrease the probability of such an occurrence by rotating the tracking chamber is considered. This paper provides a discussion of a simulation of calibration electrons in the tracking chamber in addition to commentary on its inclusion in the continuous detector simulation.

I. Background and Introduction

The collaborators of the Mu2e experiment at Fermilab[2] propose to search for neutrino-less muon decay to an electron in the presence of a nucleus,

$$\mu^- \text{Al} \rightarrow e^- \text{Al}.$$

Neutrino-less muon decay violates lepton flavor conservation as described by the Standard Model, but post-Standard Model physics suggests it can occur. Violation of lepton flavor conservation has been observed through neutrino flavor oscillations. However, it is yet to be observed experimentally with charged leptons. Confirmation of this muon decay process would suggest a need to modify the Standard Model of particle physics.

In the experiment, a beam of collimated, slow-moving muons hits an aluminum target. Some of the muons remain at the target and decay. The preferred muon decay mode is

$$\mu^- \text{Al} \rightarrow e^- \nu_\mu \overline{\nu_e} \text{Al},$$

which produces electrons with approximately half of the muon energy. However, for the neutrino-less decay

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[1] Mathworks. MATLAB. Computer Program. Mathworks, 2009.
[2]The Mu2e Collaboration, *Mu2e Proposal*, Fermilab, 10 Oct 2008.

mode, the electron energy is very close to the muon energy. The signal event for the experiment is the detection of an electron in this energy range.[3,4,5]

Electron behavior, including that of the calibration electrons, must be simulated prior to experimentation. The electrons will experience scattering effects and energy loss when passing through the tracking chamber. This paper describes the simulation of electron paths through the tracking chamber region in the detector of the experiment apparatus.

II. Simulation Methods

MATLAB is used to simulate the tracking chamber structure and the calibration electron's path. The program determines the electron track based on its initial position and momentum, as well as Coulomb scattering effects and energy loss in the tracking chamber.

The Tracking Chamber

The tracking chamber consists of an octagonal structure with eight vanes extending from the vertices of the octagon. The structure is 2.5 meters long in the z-direction, and the vanes and sides of the octagon are each 0.2954 meters wide.

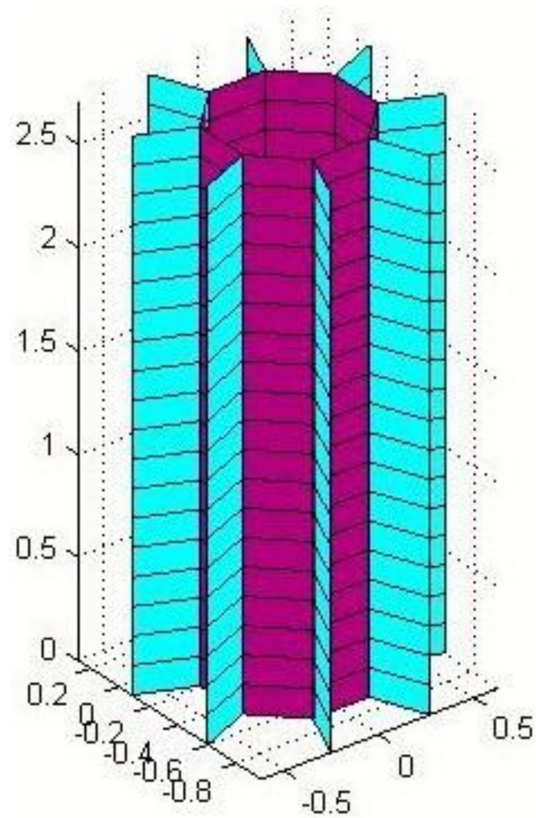


Figure 1. The tracking chamber.

Cylindrical straw tubes fabricated from either Kapton or Mylar extend along the z-direction to detect the x- and y-positions of collisions. They are arranged in three rows in a pattern of interlocking cylinders. Each tube has a wall thickness of 25 μm and an inner radius of 0.25 cm. A 20 μm diameter cathode is in the center of each tube. The remaining space in the tubes is filled with a mixture of argon and ethane gas.[6] When the electron passes through the straw tube, its charge excites the gas and a signal is sent down the wire.

To determine the z-coordinate of a collision, 5 mm wide cathode pads are arranged perpendicular to the straw tubes.[7]

[3]Gollin, George. "Summer 2010 Mu2e Investigations." Department of Physics, University of Illinois at Urbana-Champaign, 11 May 2010.
[4]Bluhm, Grace. "Mu2e Experiment at Fermilab: Calibration with Linac and Collimation System." *2009 REU Program.* Department of Physics, University of Illinois at Urbana-Champaign, 7 Aug 2009.
[5]Pershey, Daniel. "Analysis of a Novel Proton Absorber Geometry for the Mu2e Experiment." *2009 REU Program.* Department of Physics, University of Illinois at Urbana-Champaign, 7 Aug 2009.
[6]Mukherjee, Aseet. "T-Tracker R&D." Mu2e Collaboration Meeting at Fermilab. Batavia, IL. 2009.
[7]Eastwood, Michael. "LTracker Geometry." Mu2e Collaboration Meeting at Fermilab. Batavia, IL. 7 Aug 2009.

This simulation uses the physical properties of 1 mm thick polymethylmethacralate (PMMA)[8] to approximate the detector material. Random error is included to accommodate the uncertainties in detection for the straw tubes and the cathode pads.

The Undeflected Electron

A charged particle in a constant magnetic field propagates in a helical path. Because the electrons are traveling within 0.001% of the speed of light, relativistic equations are necessary to describe the electron tracks.

Coulomb Scattering

Coulomb scattering occurs when electrons collide with the atomic nuclei of the tracking chamber material. The root-mean-square scattering angle is calculated as

$$\Phi_{sc} = \frac{21}{\sqrt{2}} \frac{1}{p\beta c} \sqrt{\frac{s}{X_0}} \quad (9),$$

where p is the electron's momentum, β is the ratio of electron velocity to the speed of light (v/c), s is the distance the particle travels through the material, and X_0 is the radiation length attributed to the material. The root-mean-square scattering angle is calculated and used as the width of a normal distribution. This value is used to determine a new path for the electron based on each collision.

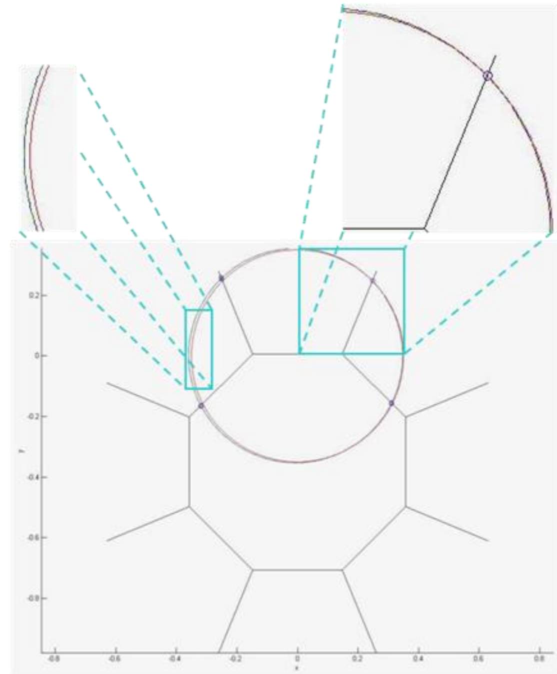


Figure 2. Two-dimensional view of Coulomb scattering in the tracking chamber. The electron's path arbitrarily begins at the zero value of the unit circle and completes one revolution in this image. The inner circle represents the undeflected path of the electron, while the outer path is a fitted circle for the scattered collisions of the electron. The deviation from the undeflected path is evident at the midway point.

In the simulation, the effects of Coulomb scattering are visible in the results, as shown in figure 2.

Energy Loss

Three types of energy loss occur in relation to electrons: Čerenkov radiation, ionization energy loss, and bremsstrahlung (radiation loss). Čerenkov radiation is a very small effect with losses on the order of 400 eV/cm, so it was not included in the energy loss calculations. Ionization energy loss and radiation loss, however, are on the order of MeV/cm, so these are the primary concern in determining energy loss in the tracking chamber.

The Bethe-Bloche formula for relativistic electrons describes fast-moving

[8]Weinberg, Erick J., and D.L Nordstrom. "Atomic and Nuclear Properties of Materials." *Physical Review D: Particles and Fields*. 667:1. Woodbury, NY: The American Physical Society, 2006. Print.
[9]Perkins, Donald H. Introduction to High Energy Physics. Reading, MA: Addison Wesley Publishing Company, Inc., 1972. 38. Print.

electron ionization energy loss and is written as follows,

$$\frac{dE}{dx} = \frac{2\pi e^4}{m_0 v^2} NB$$

$$B = Z\left[ln\left(\frac{m_0 v^2 T}{2I^2(1-\beta^2)}\right) - \ln(2)\left(2\sqrt{1-\beta^2} - 1 + \beta^2\right) + 1 - \beta^2 + \frac{1}{8}\left(1-\sqrt{1-\beta^2}\right)^2 \right] \quad (10)$$

where e is electron charge, m_0 is the rest mass of the electron, v is velocity, N is number density of the medium in atoms per cubic centimeter, Z is the effective atomic number, T is kinetic energy, and I is the average ionization potential of the material.

Bremsstrahlung (radiation loss) is calculated as,

$$\frac{dE}{dx} = \frac{4N_0 Z^2 {r_e}^2}{137A}\left[ln\left(\frac{183}{Z^{1/3}}\right) + \frac{1}{18}\right] \quad (11)$$

where N_0 is nuclei per gram, r_e is electron radius, and A is atomic mass.

The two effects are calculated and the total energy loss is included in determining a new path following each collision.[12]

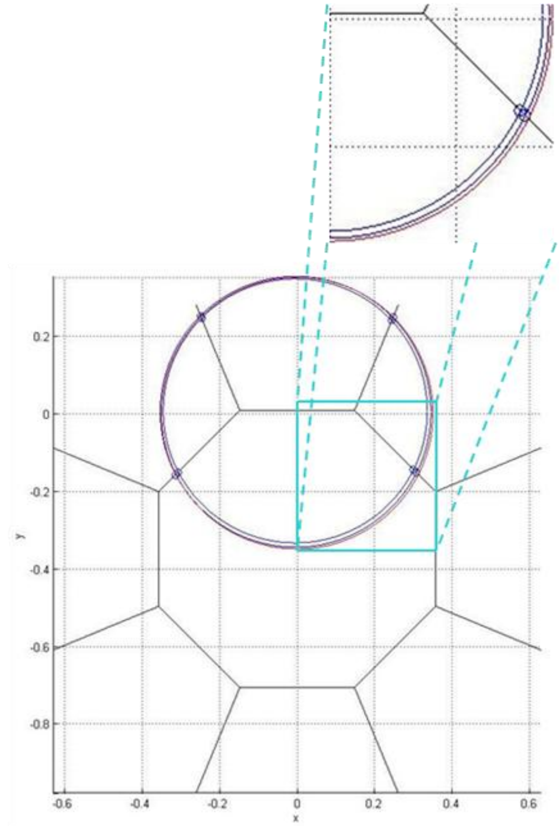


Figure 3. Two-dimensional view of ionization energy loss and bremsstrahlung loss in the tracking chamber. The electron’s path arbitrarily begins at the zero value of the unit circle and completes two revolutions in this image. The outer circle represents the undeflected path of the electron, while the inner paths are a fitted circle based on the scattering and energy loss associated with the collisions. The energy can be observed in the gradual decrease of path radius.

The results are visibly evident in the simulations, as shown in figure 3.

The histogram in figure 4 shows the result of multiple trials for a detector wall width of 1mm.

[10] Nassiri, A. "LS Note 165: Stopping Power and Scattering Angle Calculations of Charged Particle Beams through Thin Foils." Argonne National Laboratory, Advanced Photon Source. Argonne National Laboratory, March 1991. Web. 16 Jun 2010.

[11] Perkins, see reference (2)

[12] Bichsel, H., D.E. Groom, and S.R. Klein. "Passage of Particles through Matter." *Physics Letters B: Review of Particle Physics*. 667. Amsterdam, Netherlands: Elsevier, 2008. Print.

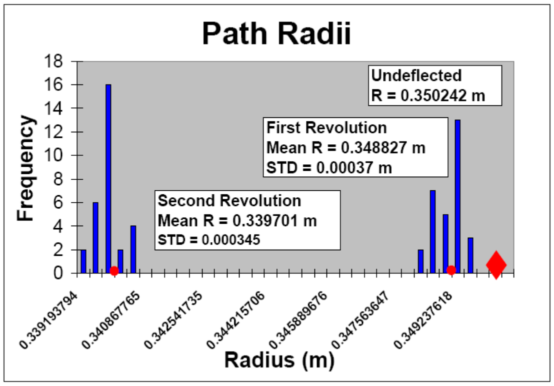


Figure 4. Histogram of 30 trials representing the frequency of occurrence versus radius. The undeflected radius of 0.3502m is represented by the red diamond. The mean fitted radius for the first revolution is 0.3488m, with a standard deviation of the first revolution radii of 0.00037m. The second revolution mean fitted radius is 0.3397m, with a standard deviation of the second revolution radii of 0.00035m.

Figure 5 shows the decrease in kinetic energy as the electron passes through the tracking chamber material.

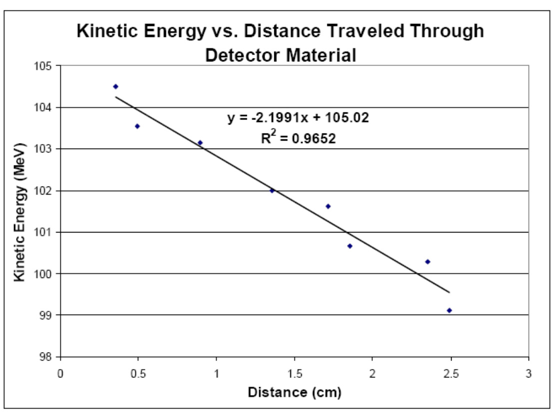


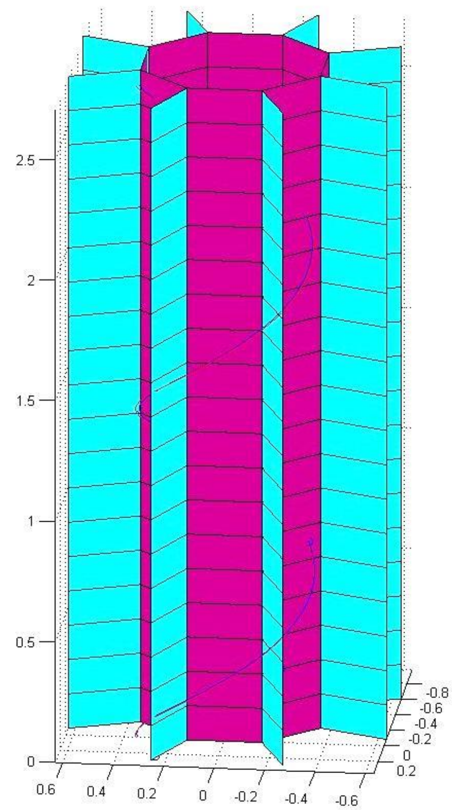
Figure 5. Kinetic energy (MeV) versus distance traveled though detector material (cm). At energies in the 100MeV range, an approximately constant change in kinetic energy is expected and observed. The electron experiences an energy loss of approximately 2.199 MeV/cm.

Helix Fitting

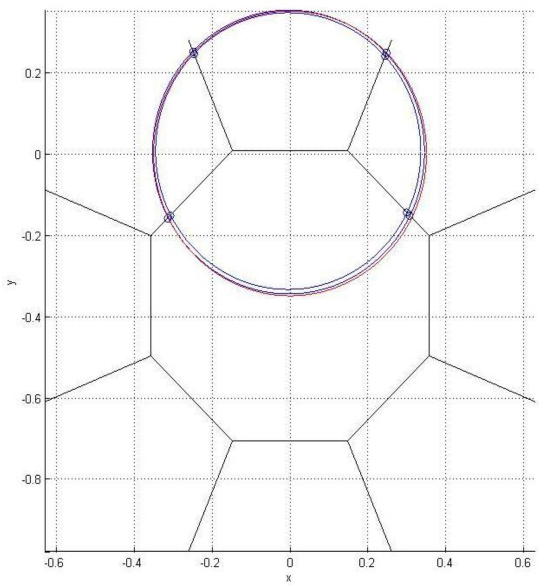
A circle is fitted for the collisions associated with each revolution.[13] Additionally, scattering in the z-direction is fitted to a linear approximation.

III. Results and Discussion

The program provides an output of the undeflected center and radius of a path, the fitted center and radius for each revolution, and the residual from the undeflected path for each collision. These are plotted for visual benefit.



[13]Bucher, Izhak. *Circle Fit: circfit.m*. Computer Program. Mathworks, 2004. MATLAB m-file, 631 bytes.



Figures 6 and 7. Sample visual output. Figure 6 shows a path with two revolutions as it passes through the tracking chamber. Figure 7 shows a two-dimensional view.

IV. Conclusions

The program produces a simulation of electron behavior in the tracking chamber based on initial position and momentum, Coulomb scattering, and energy loss.

Current work in progress includes encapsulation of this program to fit into a continuous simulation describing the electron behavior in the detector. Because the electron passes through the detector twice, it is important to consider multiple incidents on the same straw tube. By simulating the behavior throughout the detector, the tilted chamber solution may be tested as a remedy to this issue, and a more realistic depiction of the electron tracks may be obtained.

V. Acknowledgments

The REU program hosted by the University of Illinois at Urbana-Champaign Department of Physics is supported by National Science Foundation Grant PHY-0647885. The first author would like to thank the Department of Physics, University of Illinois at Urbana-Champaign for its support. She would also like to thank Sheryl, Scott, and Brent Shafer, and Reed Plimpton for the encouragement and support, and Daniel Pershey for his help in the lab.

Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation or the University of Illinois at Urbana-Champaign.

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11. Bichsel, H., D.E. Groom, and S.R. Klein. "Passage of Particles through Matter." *Physics Letters B: Review of Particle Physics*. 667. Amsterdam, Netherlands: Elsevier, 2008. Print.
12. Bucher, Izhak. *Circle Fit: circfit.m.* Computer Program. Mathworks, 2004. MATLAB m-file, 631 bytes.