Mu2e: Tracker and calorimeter study in MARS

(With focus of study on geometry and simulation)

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Mu2e is an experiment at Fermilab that will search for charged lepton flavor violation (CLFV) at an increasing sensitivity that will be able to probe energies as high as 10 000 TeV. The CLFV that will be sought is the neutrino-less conversion of a muon into an electron in the vicinity of an aluminum nucleus. This process is normally forbidden in the Standard Model of physics, yet discoveries since the development of the SM, and more, lead more than one reason to point to theories beyond the Standard Model that account for CLFV, some of which have already been proven. The focus of this study is on the development of the tracker and calorimeter that will be used to detect the conversion electrons, specifically on the geometry and simulation in the MARS code. Geometrical models created with the purpose of ignoring backgrounds as much as possible, coupled with measuring particles momenta, trajectory, and end energy are the main strengths employed to detect our goal. Results are discussed and data given of a toy model simulation and a full model simulation in MARS.

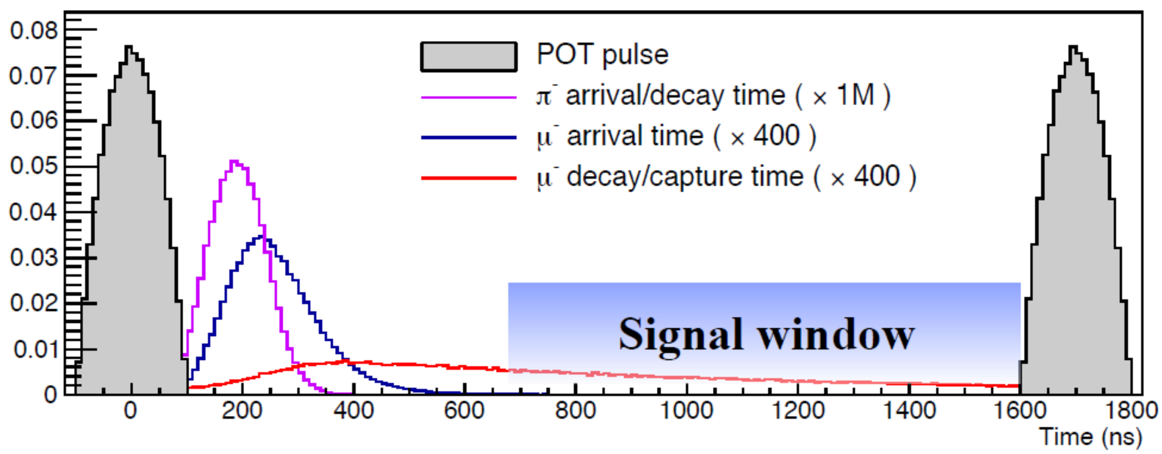
Table of Contents

I. Mu2e INTRODUCTION / OVERVIEW

Mu2e is an experiment at Fermi National Accelerator Laboratory that looks for an ultra-rare process: the neutrino-less conversion from muons to electrons. Neutrino-less muon to electron conversion is known as charged lepton flavor violation (CLFV). In the Standard Model of physics this ultra-rare conversion process is predicted to happen at a rate of less than 10^{-50}. Beyond the standard model (BSM) theories predict the conversion rate to occur at approximately 10^{-16}. From the Standard Model, lepton flavor conservation exists in the presumption that the neutrinos have zero mass[1]; since then, there has been the discovery of neutrino oscillation, thereby concluding that the neutrino has some mass. Also, neutrino oscillation violates lepton flavor conservation, which is a crack in the Standard Model (SM) and clearly a path to new physics. Naturally after discovering LFV in neutrinos, one would look for CLFV in heavier particles like the muon; one would investigate the muon before the heavier tau because heavier particles imply probing to higher energies ($E = mc^2$). The Mu2e experiment aims to increase the sensitivity, and thus the limit of experiment to 10 000 TeV. By running the experiment for three years of data acquisition (DAQ), optimization for detecting this ultra-rare process can be maximized.

The design of the detector is of significant importance to Mu2e and that is the focus of this work, particularly the tracker and the calorimeter in the detector solenoid of the experiment. The geometrical design and materials that make up the tracker and calorimeter must be created with optimizing the ability to detect the conversion electrons of 105 MeV. There occurs in this experiment, to say the least, significant background, which can over-dominate, mimic, and cloud the detector's ability to recognize the conversion electron. Some of the dominant backgrounds are: decay in orbit (DIO), 53%; radiative muon capture (RMC), 14%; beam electrons, 9%; and muon decay in flight, <7% .[1] The methods for subverting these backgrounds as best as possible in the detector solenoid are to set up the working time window after 700 ns,[2] and, the study done here specifically, to use geometrical design to ignore particles without the conversion energy and combine information from tracker and calorimeter. The tracker will measure the momentum and trajectory, while the calorimeter will measure the energy before the particle reaches the beam stop; the combination of this data will optimize the ability for Mu2e to detect this ultra-rare process.

FIG. 1. Working window set up 700 nanoseconds after proton on target (POT) pulse.



II. TRACKER DESIGN & BUILDING FOR SIMULATION

The tracker provides the primary momentum measurement for conversion electrons.[4] The Mu2e tracker sits surrounded by a superconducting solenoid with a uniform magnetic field of 1 Tesla. The tracker is situated in the experiment to operate in optimal working time window of $670 < t < 1\,595$ ns, where $t = 0$ is the arrival of the peak beam pulse at the aluminum stopping target.[4] Also, before the particles reach the stopping target, selected particles with determined momenta and negative charge will be selected in the transport solenoid. In order to study backgrounds, the tracker will need to work in the time window of $500 < t < 1700$ ns.[4]

A. Geometry study

The geometrical design of the tracker is created with the intention to measure conversion electrons, while ignoring other particles having less momentum. The tracker has an inner radius of 390 mm, which is positioned in order to not intersect with a traveling electron with energy less than the conversion electron energy of 105 MeV. Two designs were studied. A simplified version of the tracker from the conceptual design report (CDR) with twenty discs that has an outer radius of 700 mm, a thickness of 40 mm and an inner cut out shape of a twelve-sided polygon making the inner radius 390 mm. The other design studied models of the CDR tracker more accurately and is made up of rotated trapezoidal panels. Three trapezoids are rotated 120 degrees relative to one another, forming an inner shape of a triangle; this is called a plane. Two planes are placed front to back and the back plane is rotated sixty degrees relative to the front; this makes up a panel. Then two panels are placed front to back with the back panel rotated 30 degrees relative to the front, this creates one station. The tracker is then comprised of twenty stations. The overall shape has an outer radius of 700 mm and an inner radius of 390 mm. In order to model the straws that create the panels, divisions along the x and y direction were coded in accurate number to the trapezoidal shape. The geometry for the tracker was written in ROOT, which is a C++-like language and placed into the tgeo_init.cc file in the mars15 directory.

FIG. 2. Simplified tracker YZ plane.

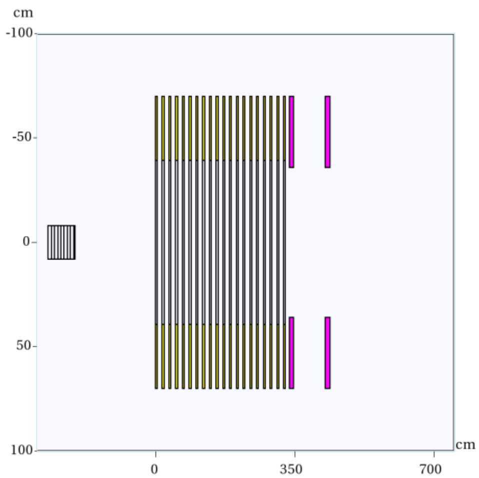


FIG. 3. Simplified tracker XY plane.

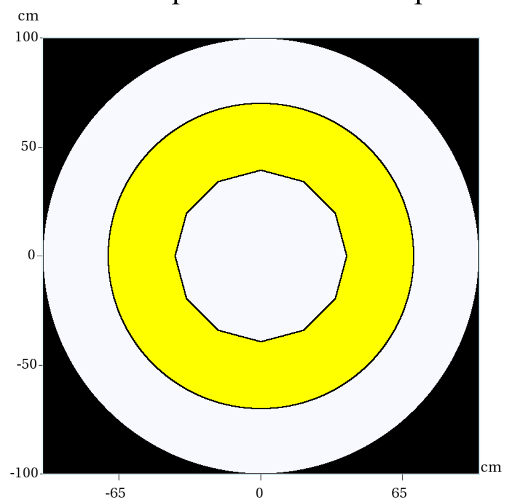


FIG. 4. Tracker design with trapezoid panels YZ plane, from L to R, stopping target, tracker, calorimeter.

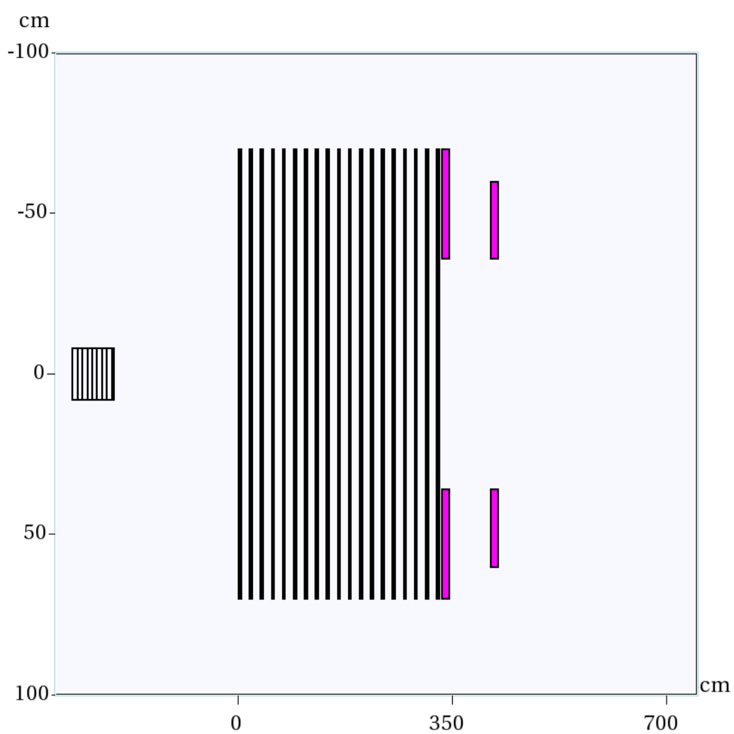


FIG. 5. Tracker design with trapezoidal panels XY direction; view panel rotation creating one station.

(Note: Division segments upon zoom are evenly spaced, and the corners of panels do not touch.)

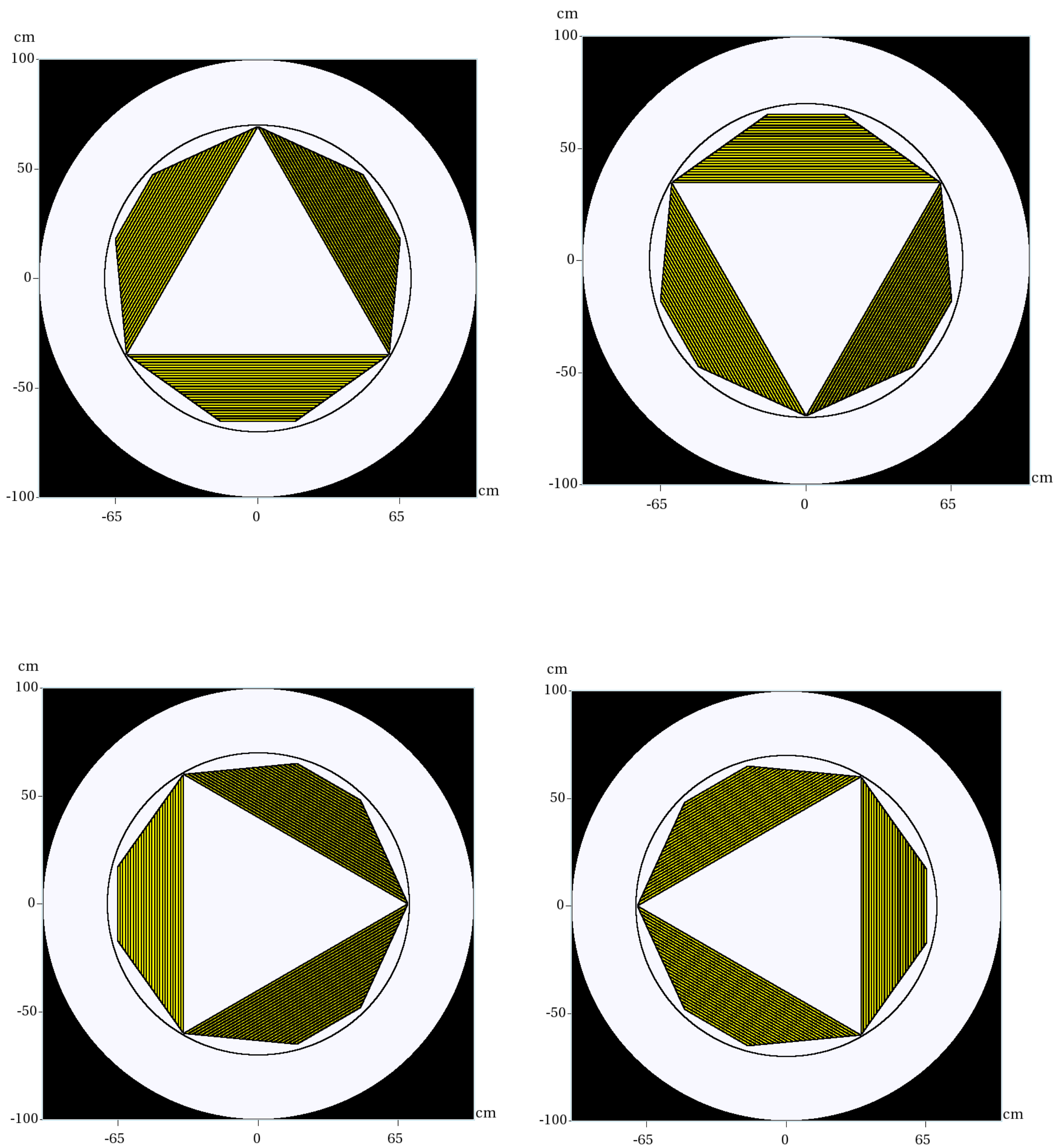
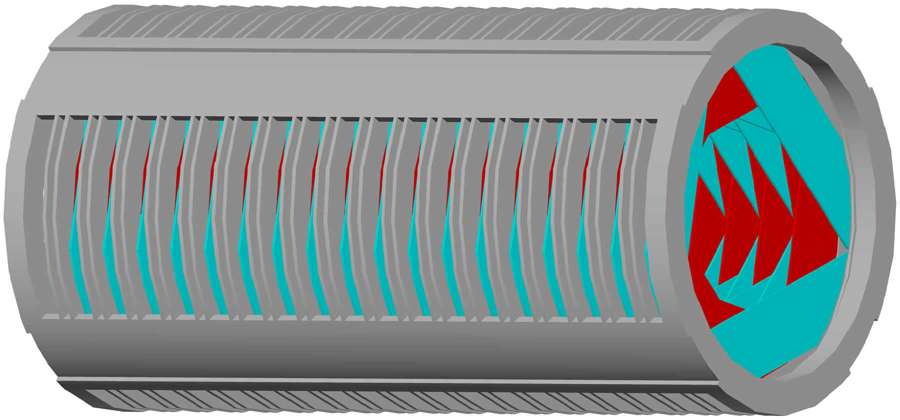


FIG. 6. Assembled tracker from CDR.



B. B field study

In order to input the magnetic field into the toy model, a B field study was done in order to find the gradients at positions throughout the detector solenoid reading in the magnetic field map file. The detector solenoid consists of the aluminum stopping target of sixteen foils. Positioned longitudinally 2 100 mm downstream from the stopping target is the tracker, and 80 mm down from that are the two calorimeter rings separated by 800 mm. The magnetic field from the stopping target to the tracker decreases linearly from 1.5 Tesla to 1 Tesla upon reaching the tracker.[4] Through the tracker the magnetic field is approximately linear, although at very small scales there is small nonlinearity, which overall oscillates in a range of 0.5% deviation from 1 Tesla, and cancels opposing fields. From the tracker through the calorimeter the magnetic field linearly decreases again. In order to find the function for the gradients of these fields, ROOT was used to do a linear fit on the graph and then the functions were inputted into bcalc.cc file in mars15 directory.

FIG. 7. Magnetic field function through the detector solenoid.

Middle of stopping target to entrance of tracker: 5 946 cm – 7 956 cm

Through the length of tracker: 7 956 cm – 12 946 cm

From exit of tracker to exit of calorimeter: 12 946cm – 15 946 cm

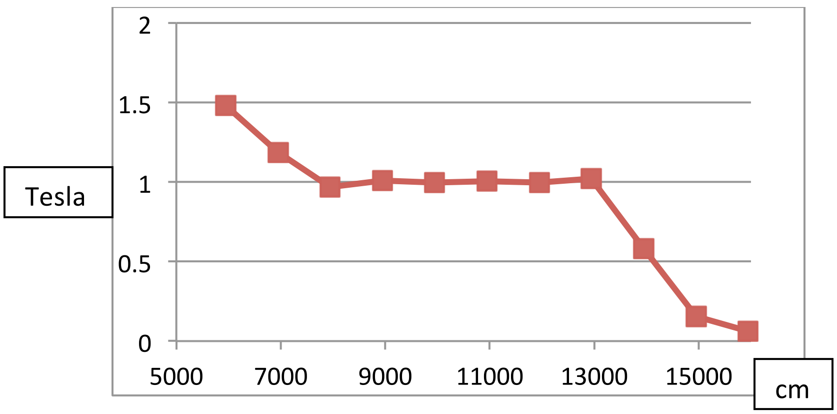


FIG. 8. Magnetic field in the tracker, 1 Tesla; there are some asymmetries (note scale).

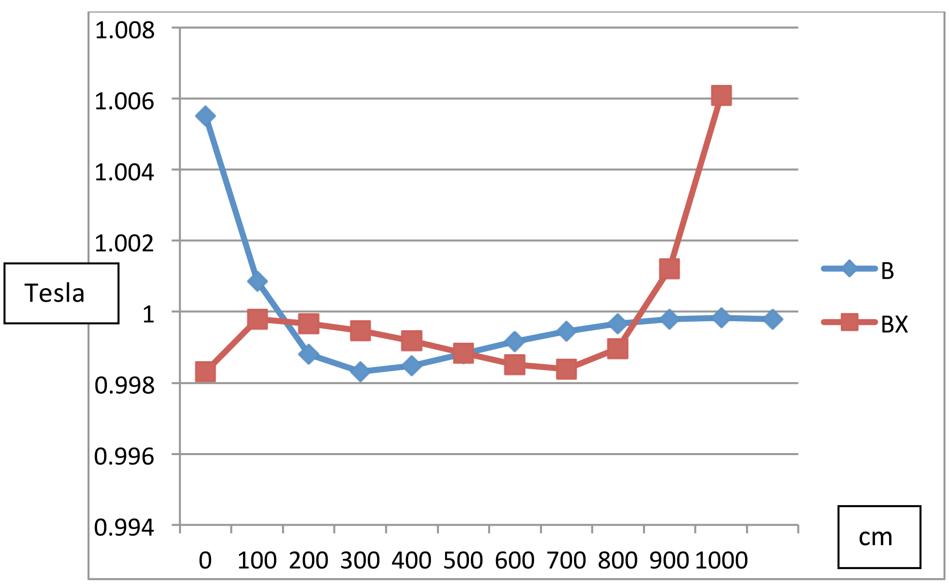
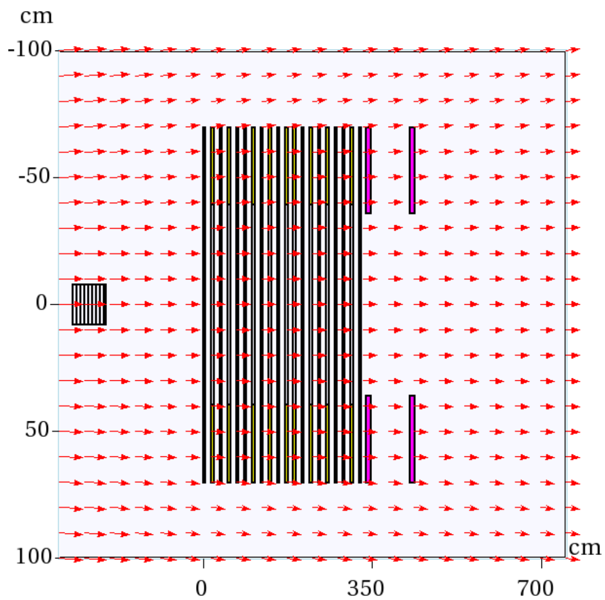
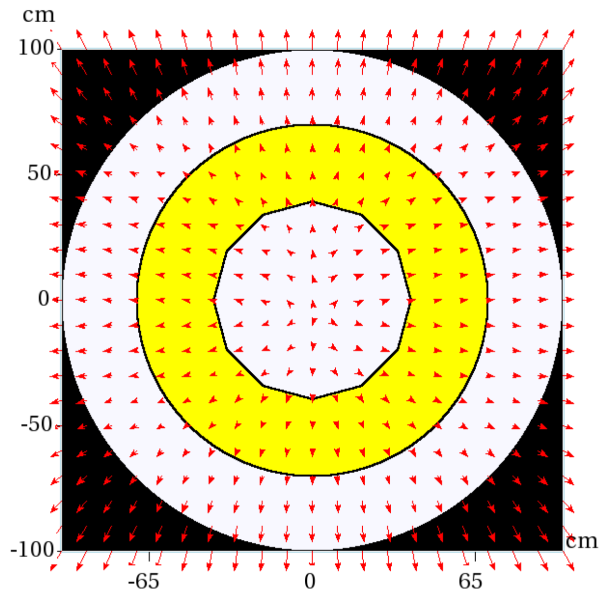


FIG. 9. YZ plane of detector with B field. (Simplified toy model)

FIG. 10. XY plane of tracker with B field. (Simplified toy model)





III. CALORIMETER DESIGN & BUILDING FOR SIMULATION

In the Mu2e experiment, upon entering the detector solenoid, the particles first hit the aluminum stopping target; then travels through the tracker and finally reaches the calorimeter. The calorimeter is where the particle's energy will be acquired. Finally, the particle will proceed to a beam stop. The calorimeter has the concern of measuring false conversion electron energy due to accidental hits combining with lower energy particles and stemming from pattern recognition errors in the overwhelming amounts of hits it will be receiving. To rectify this concern, the calorimeter will read redundant measurements and couple this information with data from the tracker. Also, the calorimeter has the function of providing trigger to the experiment.[4]

A. Geometry

The current geometrical design for the calorimeter is a pair of discs with an inner radius of 360 mm, an outer radius of 700 mm for the front disk, and 600 mm for the back disk, with a thickness of 110 mm. The first disk is to be placed longitudinally 80 mm from the exit of the tracker, and the second disk 800 mm behind the first disk. According to the CDR, the disk configuration produces an efficiency of 84%, which is a substantial gain compared to the 78% efficiency of the prior vane model.[4]

B. Materials

The material that makes up the calorimeter is especially important to study in order to prove that it will not decay, melt, or break down in the required three year period that Mu2e will need to run in order to acquire enough data for decent analysis. The latest design material for the calorimeter from the CDR consists of LYSO crystals that have been studied in the field of detectors greatly.[4] Similar to the tracker, the LYSO material was inputted into the MATER.INP file and inputted as a card in MARS.

IV. SIMULATION

A. Single particle simulation in MARS model

To study the simulation in the toy MARS model we ran single particles such as one electron, one muon, one pion, and one positron through the detector, starting from the middle of the stopping target to see if the particle interacted and moved as we expected it to. The toy model only consists of the aluminum stopping target, the tracker, and the calorimeter in a vacuum. The results are shown in the following figures for an electron with 44 MeV, 60 MeV, and 105 MeV. Here we are looking to confirm that as the particle spirals through the tracker, the geometry is ignoring backgrounds of electrons that have a momentum of less than 105 MeV/c. When looking at the following figures, one can clearly see electrons with energy less than 105 MeV do not intersect with the tracker. Upon simulations, it was found the muon, pion, and positron will all have less momentum, or energy than the electron; therefore, they will not generally produce a dominant background through DIO or RMC.

FIG. 11. 44 MeV electron moving from middle of stopping target through tracker and calorimeter, YZ direction.

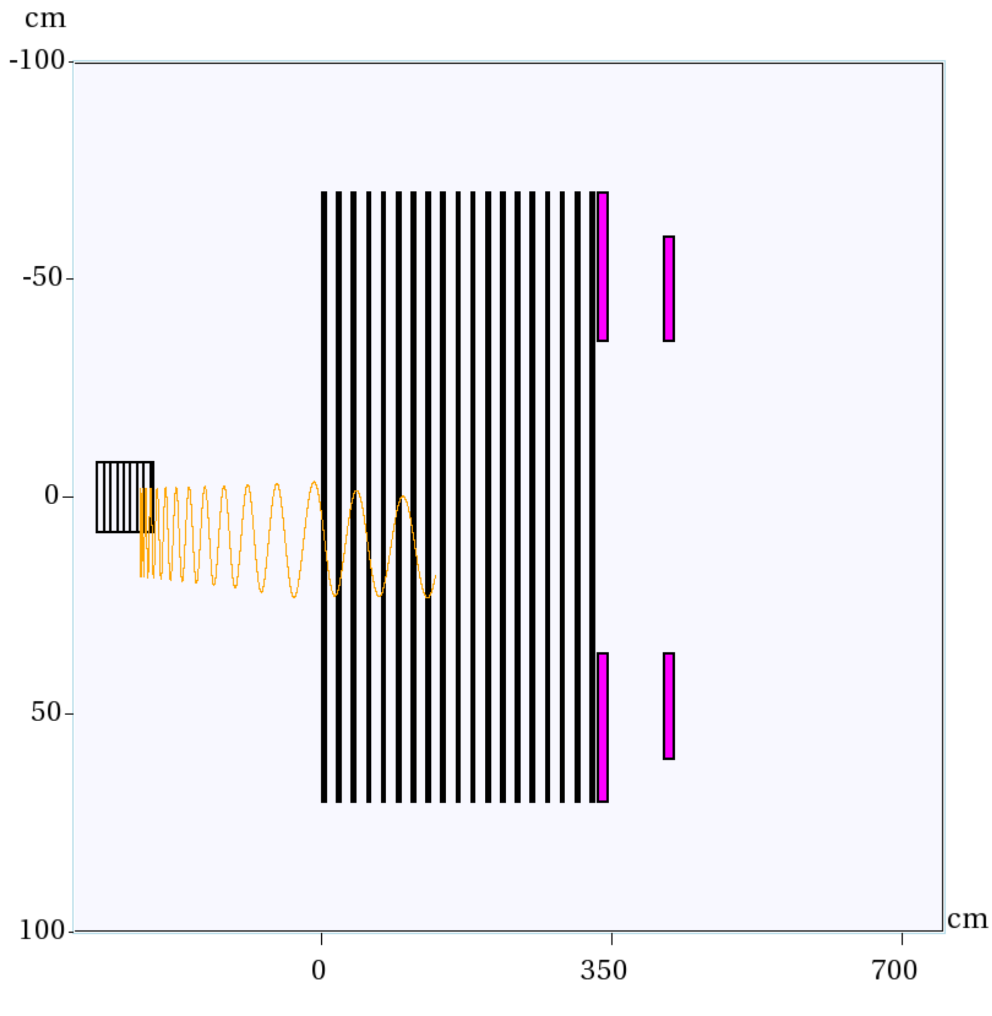


FIG. 12. 44 MeV in trapezoid tracker model XY direction.

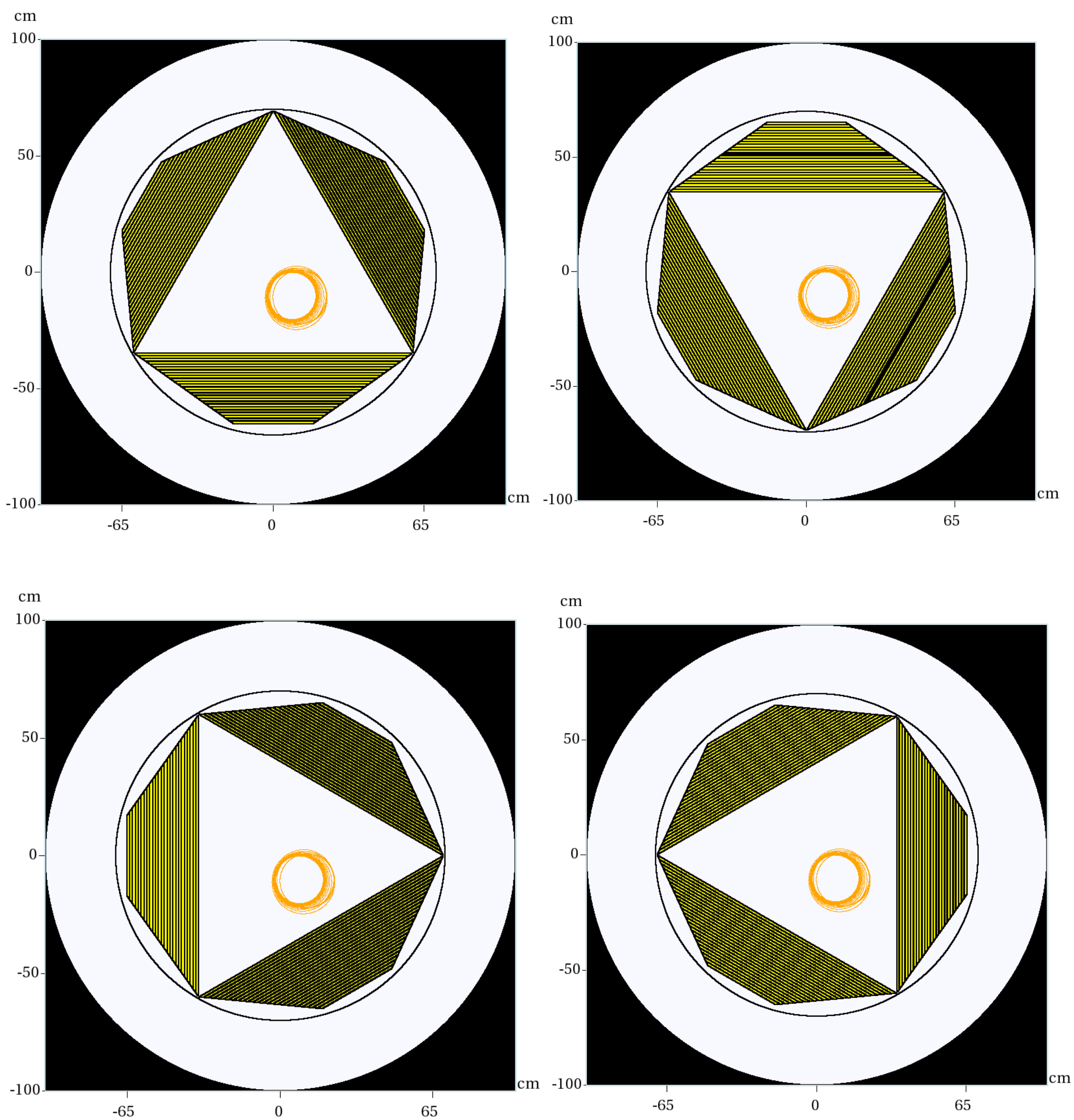


FIG. 13. 60 MeV electron in trapezoid panel tracker toy model, YZ direction (second run).

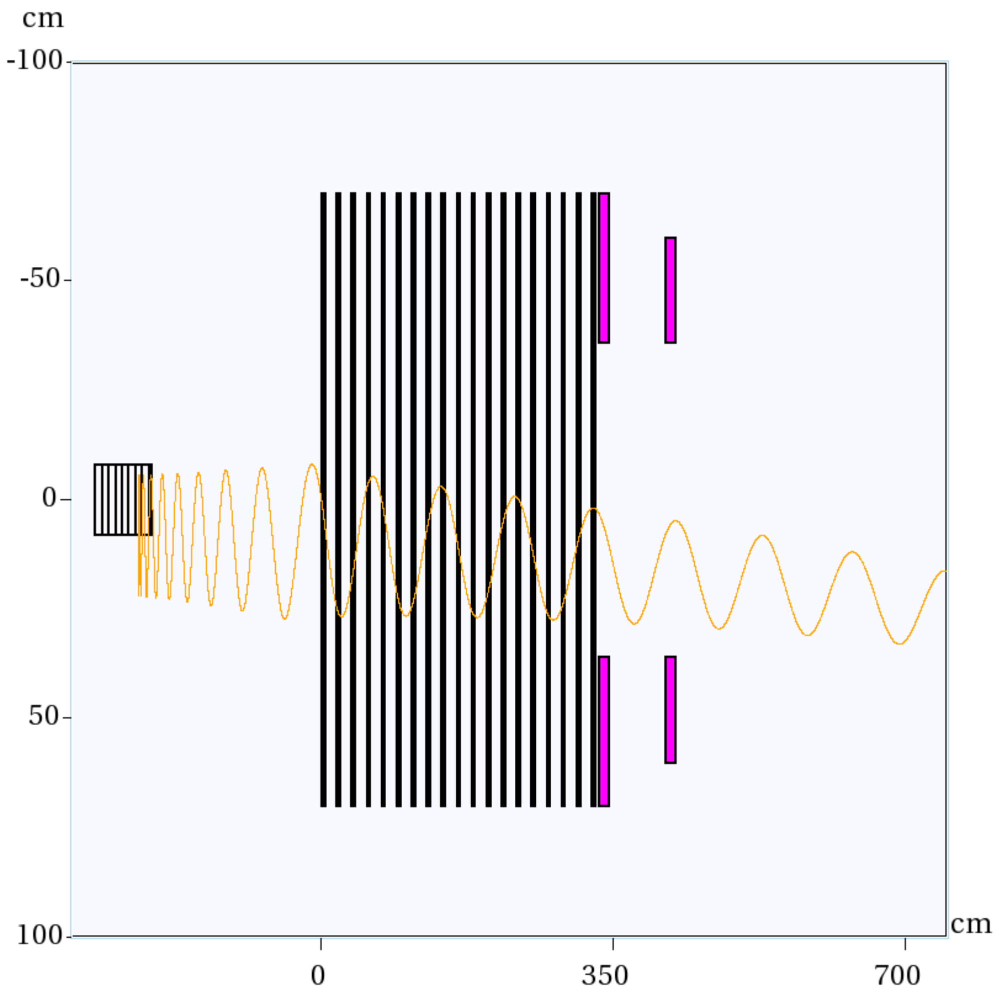


FIG. 14. 105 MeV electron moving through tracker; note the phtons that are emitted in blue due to interactions with the tracker.

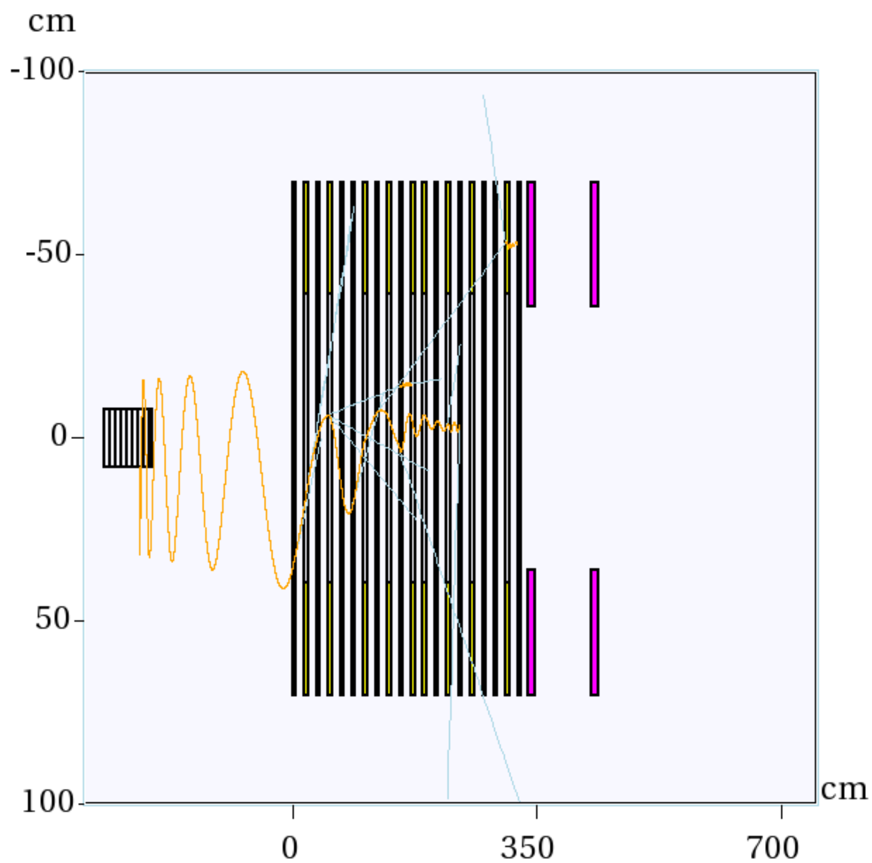


FIG. 15. 60 MeV electron traveling through tracker in XY direction; the photon emitted happens in the calorimeter (first run).

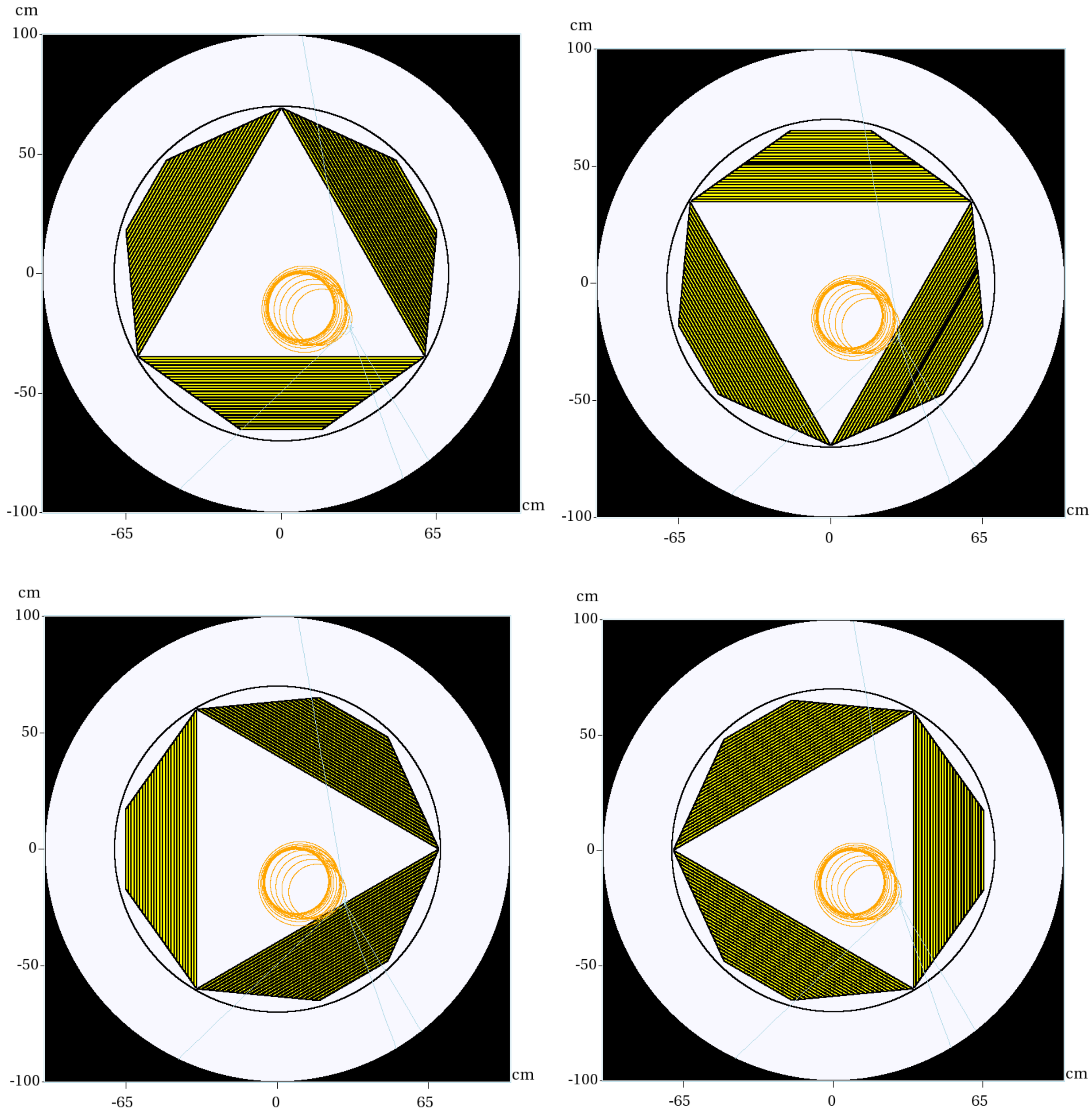


FIG. 16. 105 MeV electron sent through trapezoid panel tracker in toy model.

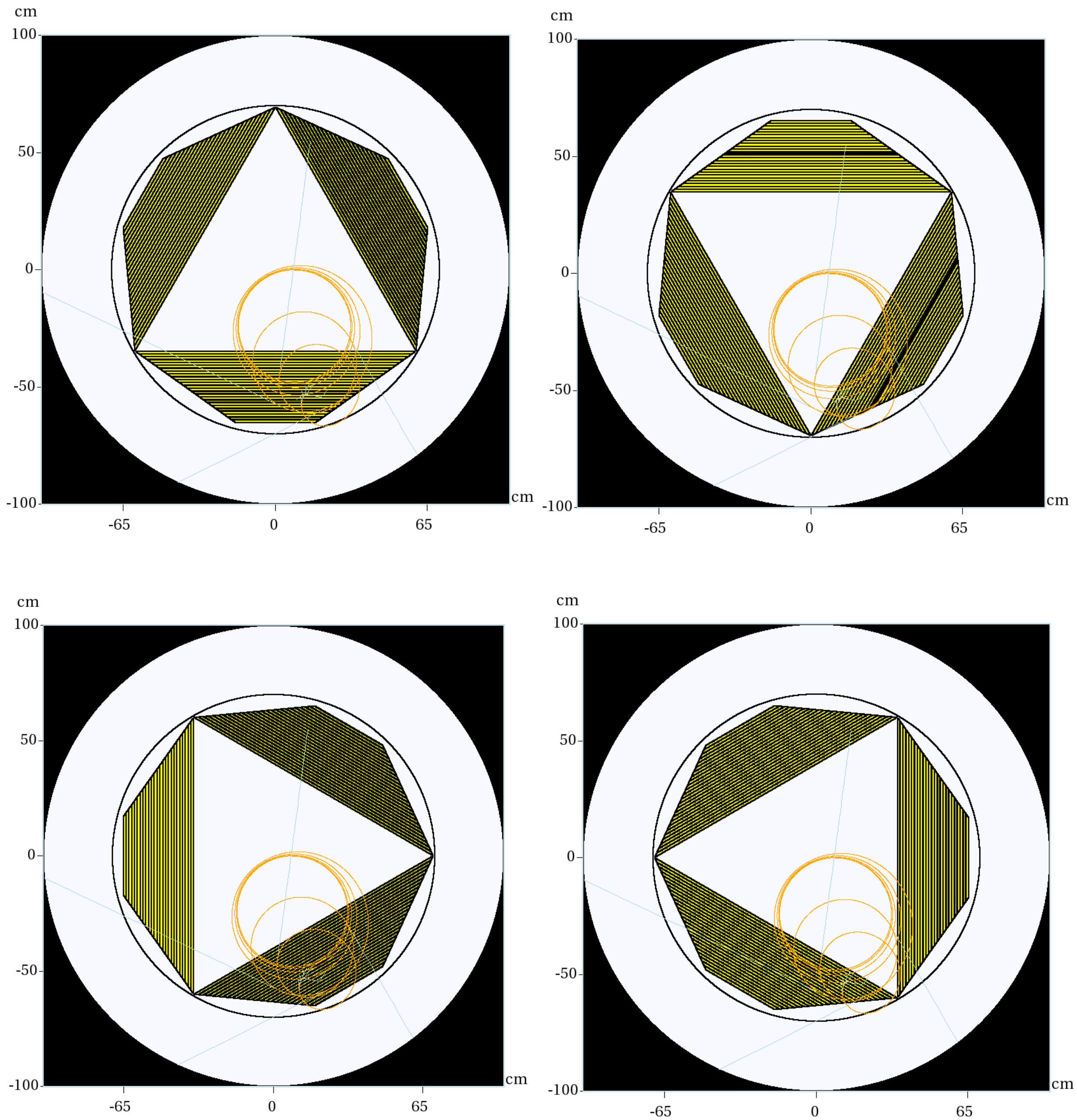


FIG. 17. Mu2e full model, observing a 105 MeV electron sent from stopping target.

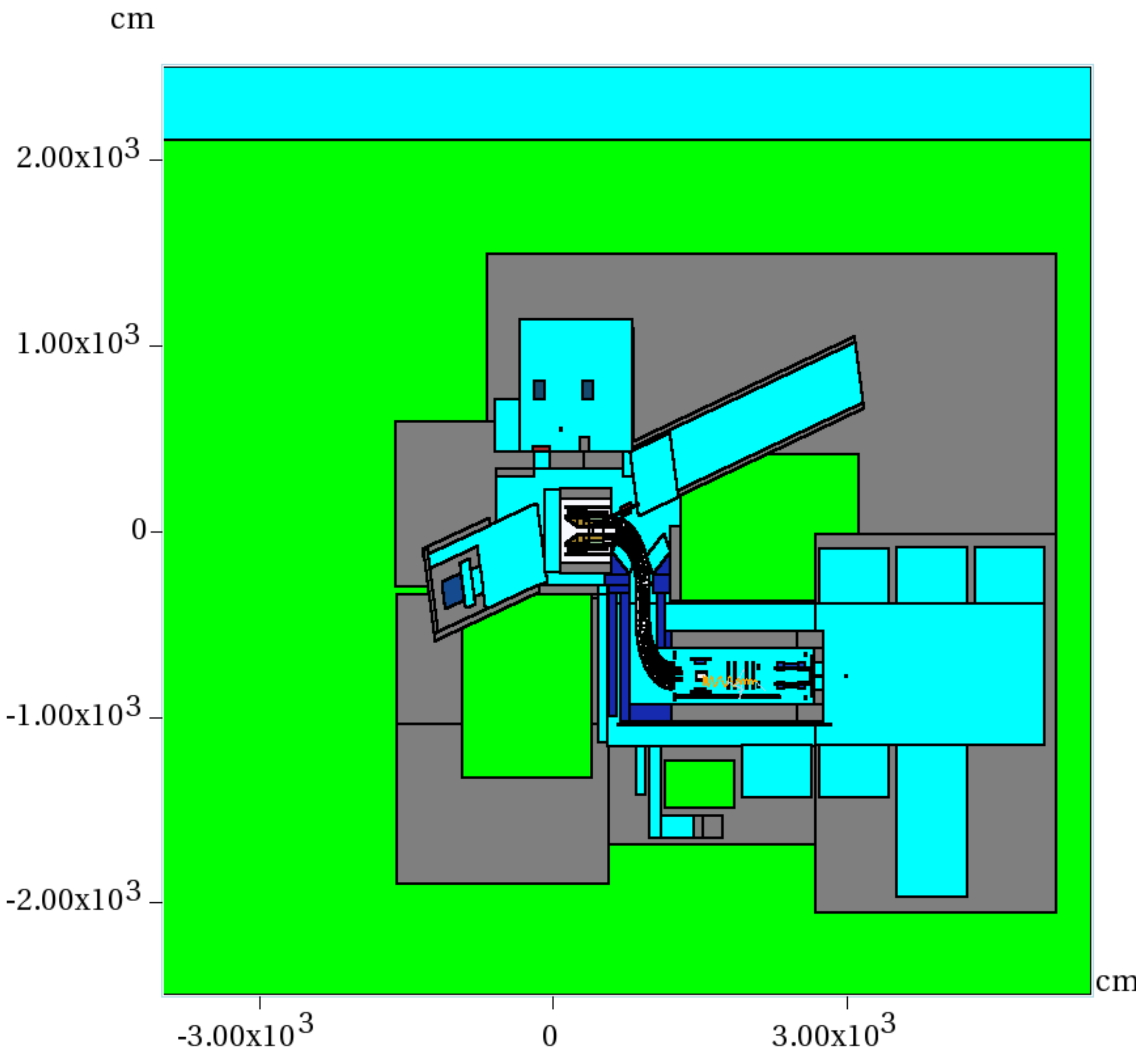


FIG. 18. 105 MeV moving from stopping target through tracker and reaching first calorimeter.

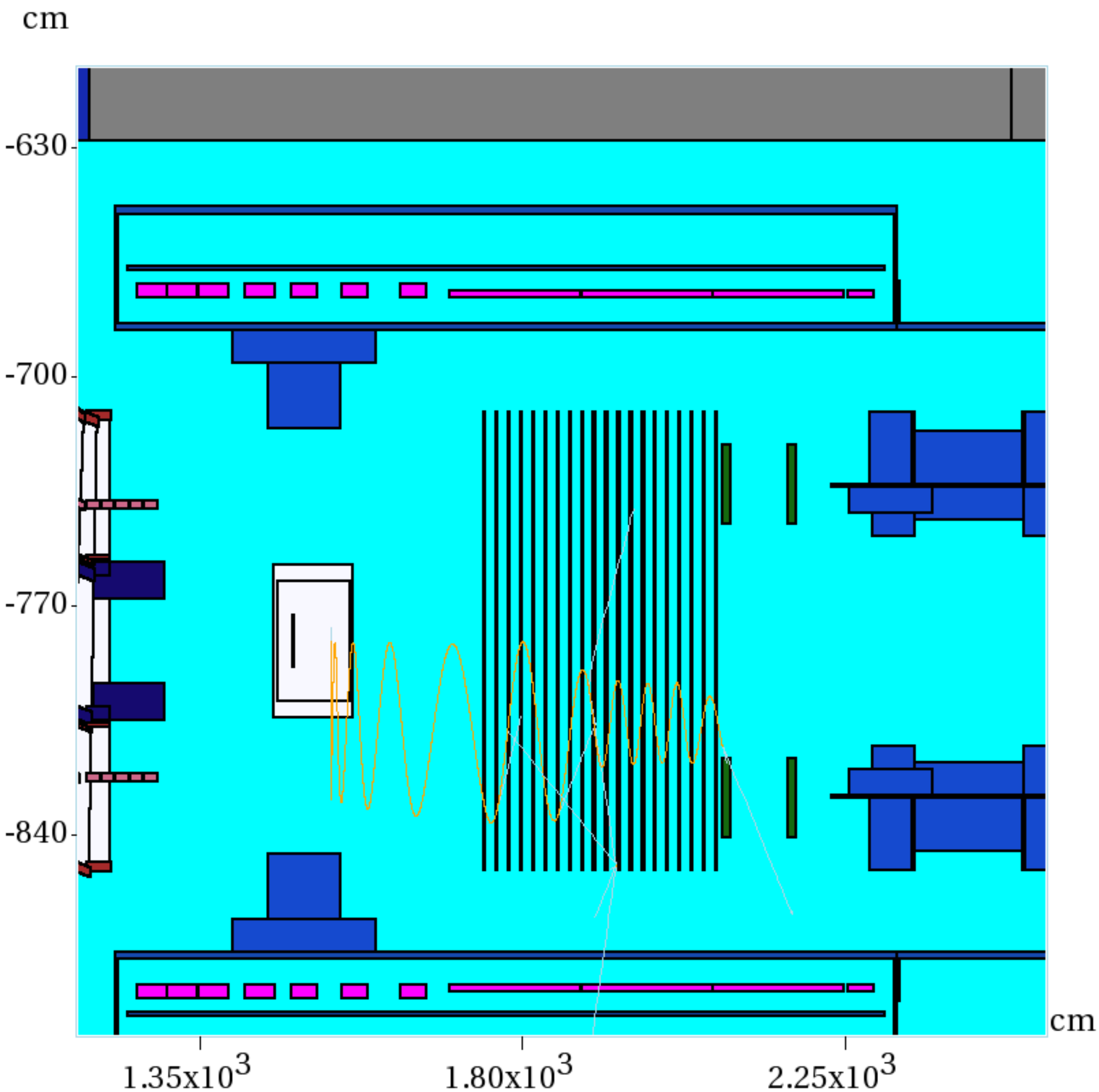


FIG. 19. 105 MeV electron moving through tracker and reaching first calorimeter.

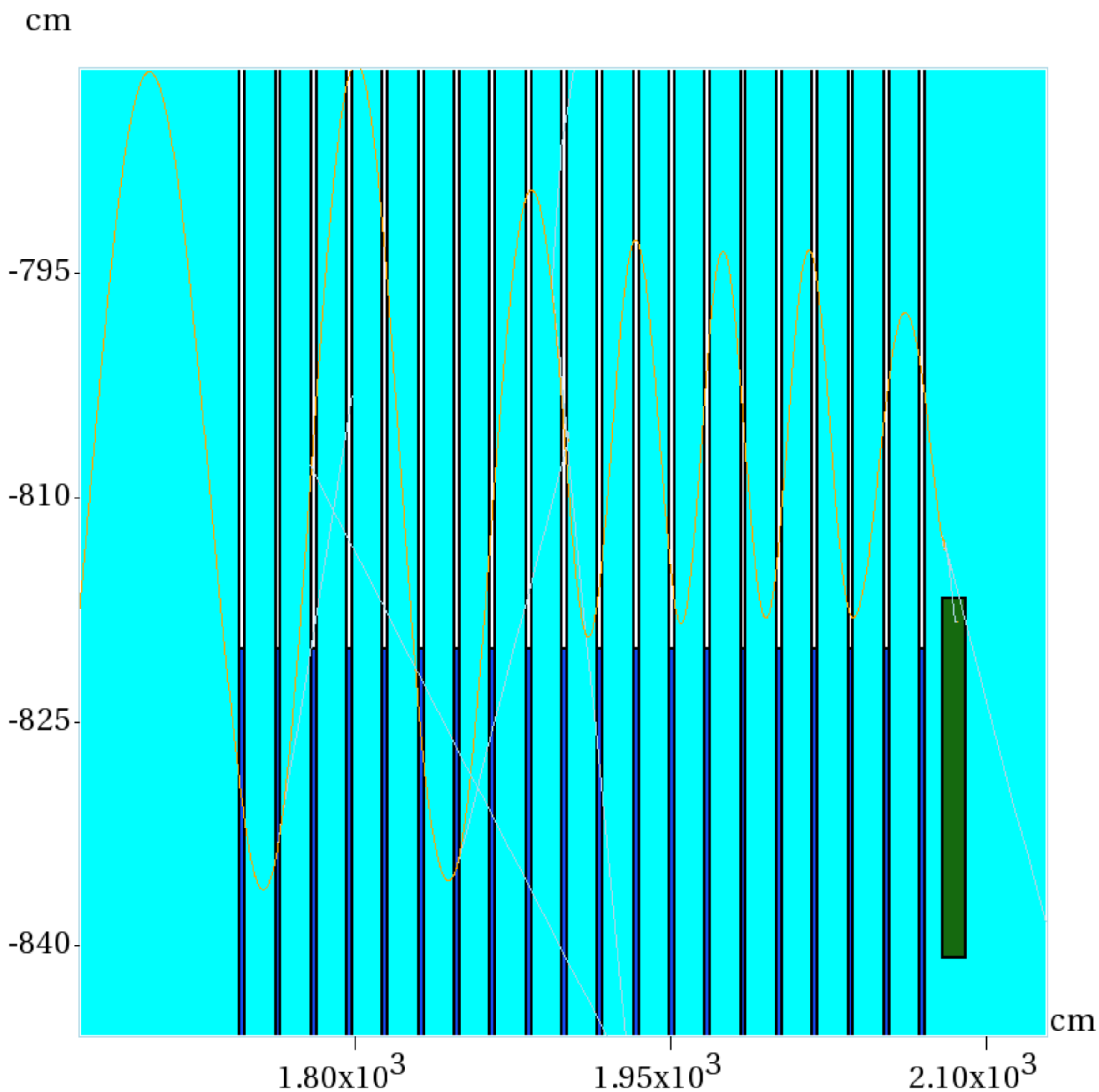
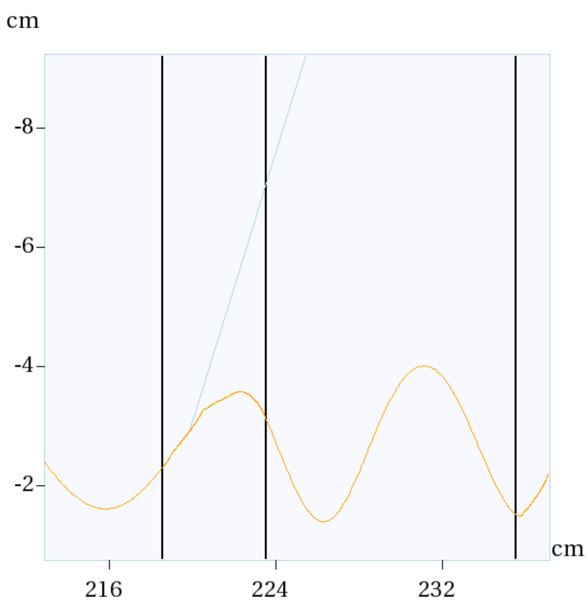
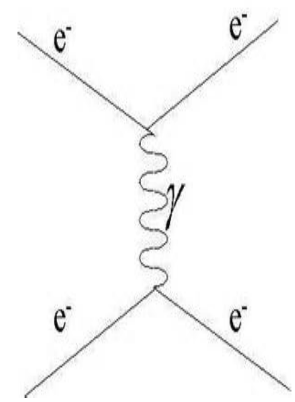


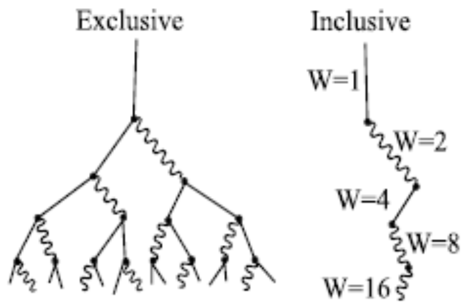
FIG. 20. Electron (orange) scattering into a photon (blue) and electron [LEFT].
FIG. 21. Feynman diagram of electron-electron scattering [RIGHT].





In the MARS simulation, one can clearly see through the particle interactions that the code is built upon Feynman's inclusive approach for particle reactions[3]; the inclusive approach is also known as discrete interaction. In physics interactions, a discrete interaction is when a particle collides with a nucleus[3]; at this collision, also modeled as a vertex, the probability of the next action is expressed through cross section probabilities. By default, MARS looks for discrete interactions, and then continuous interactions can be searched if desired. An example of a continuous interaction is Coulomb scattering or a magnetic field. As stated in the MARS manual, the inclusive approach is used for simulation because there are fewer particles to handle, and allows acquiring more data of interest, such as energy deposition, particle flux, momentum, etc.[3]

FIG. 22. From MARS manual for visualization of inclusive versus inclusive approach.

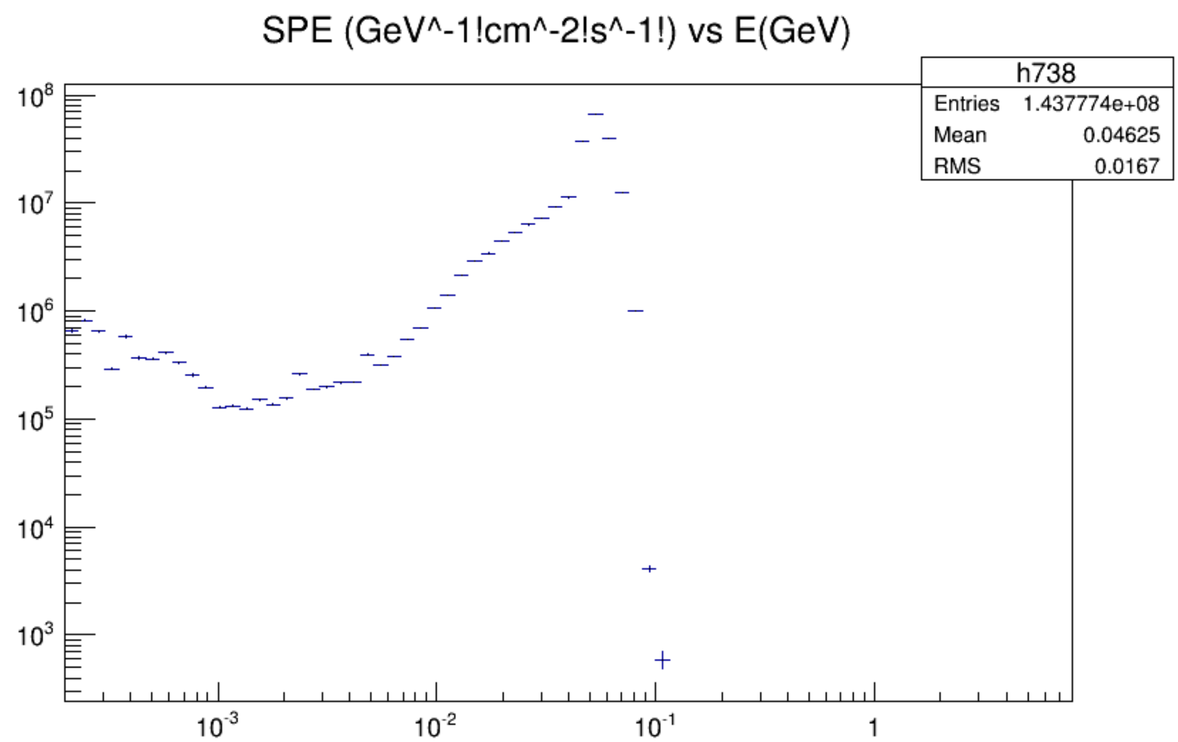


"Left diagram is a full EM shower; each particle with a weight = 1. The right diagram is the inclusive equivalent, with a single representative particle exiting each vertex, with a given weight."[3]

B. Mars model full simulation

It takes approximately three days to run the full simulation of beam energy and particles through the MARS model of the Mu2e experiment. The main results we will be looking at are energy limit cross sections of particle interactions, and the deposits of power in histograms in the tracker and calorimeter. We want to know the energy of the particles we see interact because the conversion electron energy is 105 MeV and is like a signature to find the conversion electron. And we want to see the power deposited into the materials in order to know that the materials to acquire data for the experiment will not decompose in the duration needed.

FIG. 23. Tracker energy cross section.



As one can see, the tracker observes an electron with about 105 MeV; this is most likely a source of background such as DIO because MARS does not code for the neutrino-less conversion from a muon into an electron (either way the information is still useful to study DIO).

FIG. 24. Calorimeter disk 1 power deposition histogram.

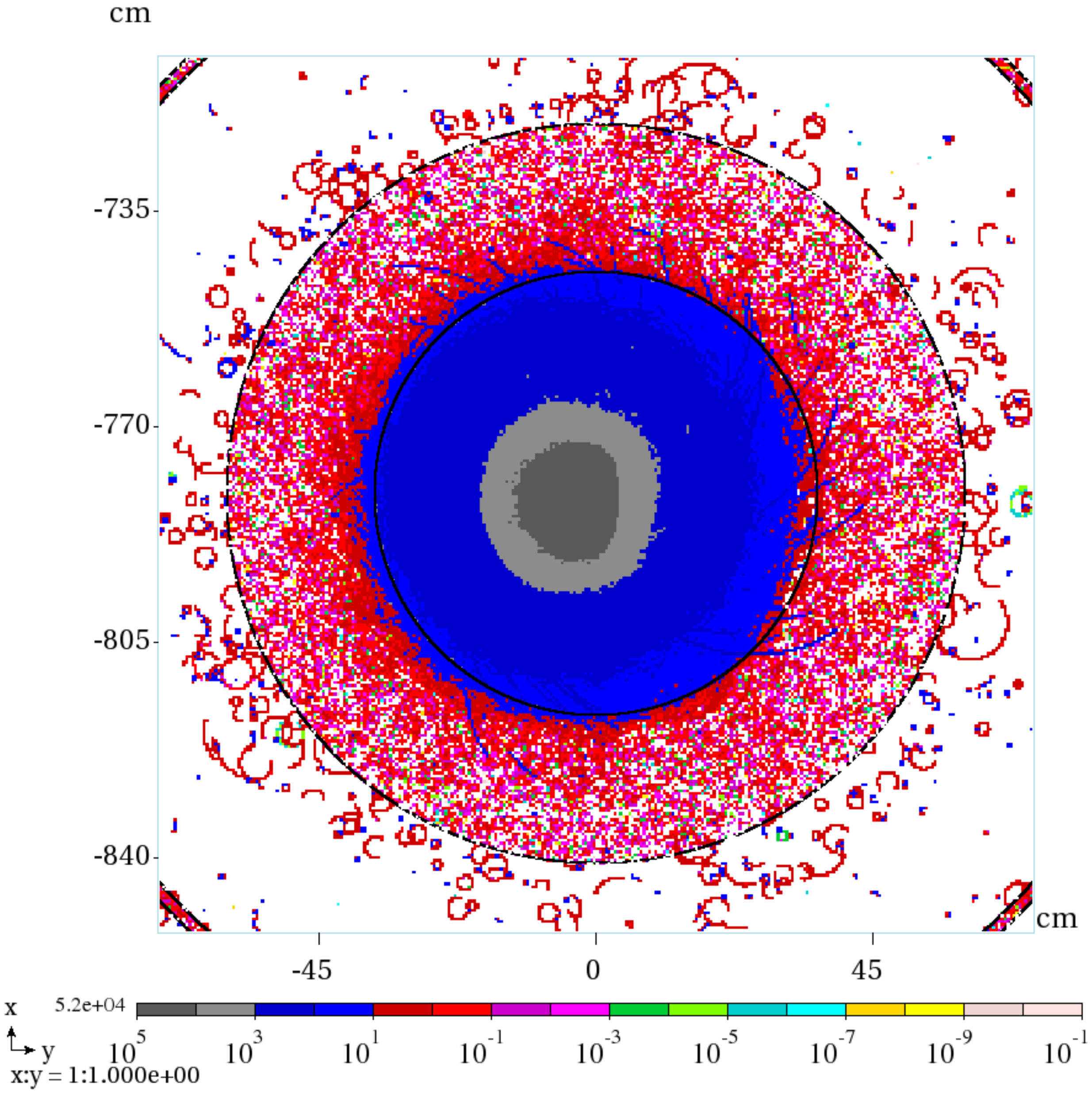
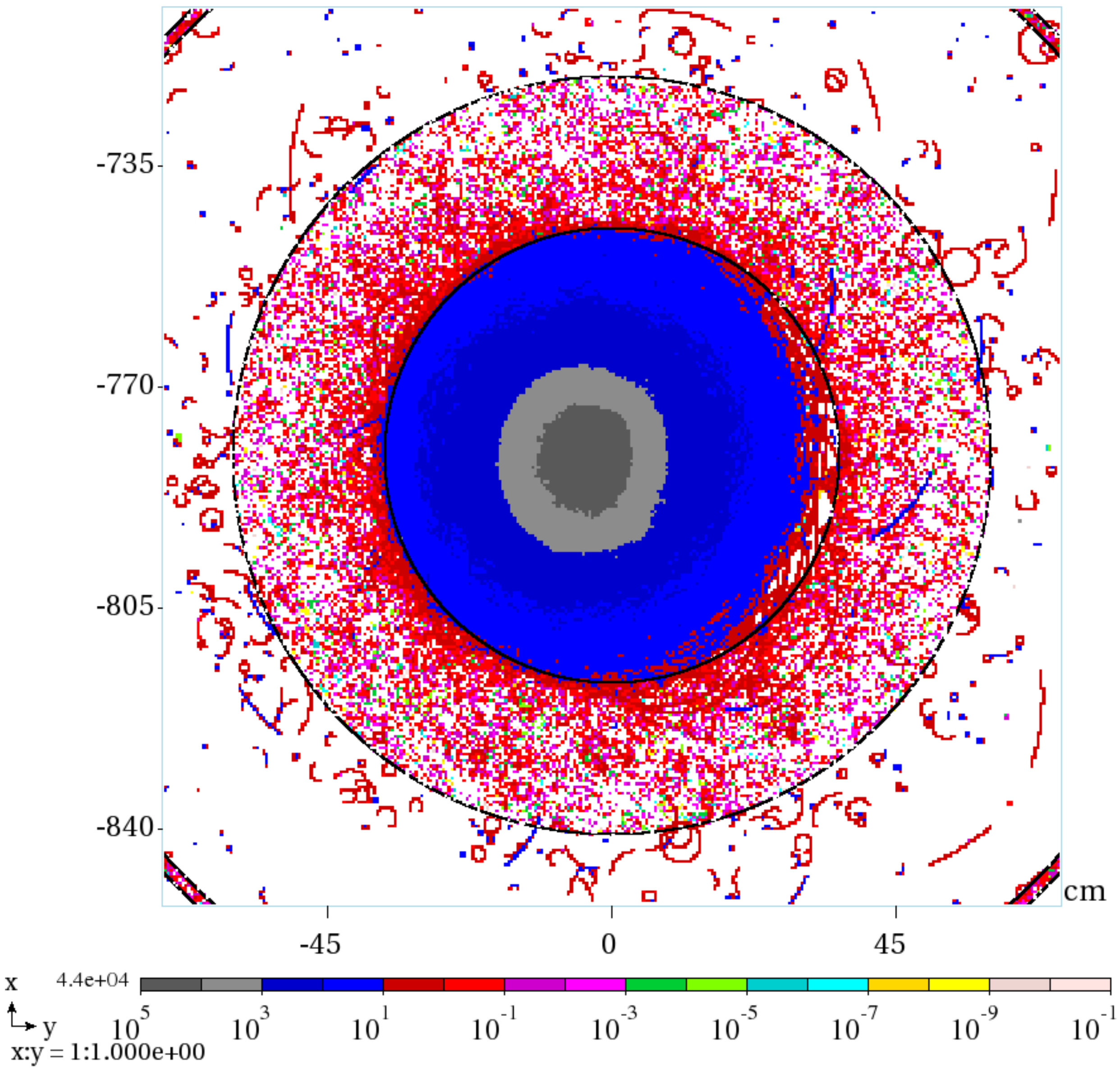


FIG. 25. Calorimeter disk 2 power deposition histogram.



These histograms state that for the first disk, there is an average power deposition, also known as dose rate of 2.55 kRad/yr, while the second disk yields an average dose rate of 1.31 kRad/yr. The peak dose rate for the first disk is found to be approximately 22 kRad/yr, while the second disk has a peak dose rate of approximately 18 kRad/yr. The peak dose rates are found using the MARS graphical user interface (GUI), which is not as precise as using a file data output, which was used to find the average dose rate. There is reason to believe that the LYSO crystals are able to handle this amount of energy, although long term periods need to be still studied.[5]

V. CONCLUSION

The results from the toy simulation prove that the geometry of the tracker clearly ignores electrons with energy less than the 105 MeV of the conversion election. In the full simulation, it is very interesting that a cross section of energy of approximately 105 MeV was observed. This could be from decay in orbit background, or may even point to an explanation not yet formulated. Also, in the full simulation, the power deposition on the calorimeter proves to be in an acceptable range for the experiment. Mu2e finding CLFV at a rate beyond the Standard Model will provide us with a deeper understanding of particles, their interaction, and their relationships. This understanding is crucial for the future of physics to develop the theories that underlie our reality.

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