Muon-to-Electron Conversion Experiment (Mu2e) Detector Solenoid Design

Bryce T. Austell

Office of Science, Summer Internships in Science and Technology Program

University of Illinois at Urbana-Champaign

Fermi National Laboratory

Batavia, Illinois

August 3, 2010

Prepared in partial / fulfillment of the requirement of the Office of Science, Department of Energy's Summer Internships in Science and Technology Internship under the direction of Dianne Engram at the Equal Employment Office and Ryuji Yamada at the Technical Division at the Fermi National Laboratory.

Participant: __________________________

Signature

Research Advisor: __________________________

Signature

**TABLE OF CONTENTS**

## ABSTRACT

Muon-to-Electron Conversion Experiment (Mu2e) Detector Solenoid Design. BRYCE T. AUSTELL (University of Illinois, Urbana-Champaign, IL 61820) RYUJI YAMADA (Fermi National Laboratory, Batavia, IL 60510).

The conversion of a muon to an electron is achieved by the acceleration of the muon through three different solenoid compartments in the Mu2e experiment. The three solenoids are the production solenoid, transport solenoid, and detector solenoid. The detector solenoid consists of several coils and superconducting magnets which allow for detection. Most of the project was carried out using a finite element analysis (FEM) program called COMSOL with which analyses involving preliminary magnetic fields, axial stresses, and coil deformation were performed in order to assess the validity and practicality of the detector solenoid design. Much of the summer was dedicated to understanding COMSOL and learning how to use the computer assisted drawing (CAD) tools associated with the program. The optimal design for the detector solenoid was achieved through these methods and is to be implemented in the near future.

## 1. INTRODUCTION

Elementary particles come in different families called quarks, neutrinos and charged leptons. Members of the quark and neutrino families are capable of morphing from one family member to another and also from one kind of quark to another kind of quark. The charged leptons, the electron, muon and tau, seem different. These types have never been observed switching family identities.

If it is true that the charged lepton family really is different, if the electron, muon and tau do not change from one to another, it means there is no sensible model to unify the different forces of nature and there may be something slightly incorrect with the theories of the fundamental laws of physics. Therefore, physicist need to search in order to see if muons and electrons do very rarely interchange identities or if they do not change identities at all.

By producing huge numbers of muons, elementary particles of matter that are heavier copies of electrons, in a controlled environment, physicists of the mu2e experiment hope to observe the direct conversion of muons into electrons.

Mu2e is proposed in order to find the direct, neutrinoless conversion of a muon to an electron in the field of a nucleus at the very specific detection level of two out of $10^{17}$ stopped muons. This conversion has never been observed and recorded before, but is expected to occur in many theories that attempt to go beyond the present understanding of the standard model and high energy physics. If observation of the process can occur, its occurrence and rate will heavily aid in determining which , if any, of these new theories is correct. The superconducting solenoids make up most of the experiment. The magnets create a specified magnetic field that varies nearly monotonically from the 5T in the production solenoid (PS) to 1 T in the Detector Solenoid (DS). The magnetic field is controlled over a volume around a curvilinear axis with a developed length of about 27 m. Protons will strike a target inside the 1.5 m diameter warm bore of the PS, creating pions. The pions decay to muons, which follow the field lines through the 0.5 m diameter warm bore of the Transport Solenoid (TS), where they are filtered, via bending and collimation, and strike a target within the 1.9 m warm bore of the DS.

Charged Lepton Flavor Violation (CLFV) is not specifically denied in the Standard Model (SM) of high-energy particle physics, but it is certainly dynamically suppressed. CLFV processes still to date remain unobserved. Although the SM is very well tested in many scientific realms, it seems that it is possible and even likely to be incomplete. In some of the Beyond the Standard Model scenarios, the speeds for CLFV processes are within the range of the upcoming and future experiments. Specifically, if SUSY particles maintain masses and couplings within the discovery reach of the LHC or the Tevatron, many scenarios predict CLFV rates that are easily observable. Even more so, many CLFV searches have a sensitivity to new physics that exceeds the reach of even the LHC [1].

One specific example of a CLFV process is neutrino-less muon-to-electron conversion in the Coulomb field of a nucleus. In order to find and discover this process, a beam of slow muons is stopped in a series of thin target foils. Then specific muons are obtained and capture by atomic orbits. During a muon decay in orbit, the electron daughters have a continuous energy spectrum that has an endpoint that is just less than the mass of the muon . In the conversion process, it seems as if the final state has just two bodies. These two bodies are a recoiling and an electron, intact, atomic nucleus. From this process comes an electron that is mono-energetic with an energy amount equal to endpoint-energy amount of that of the continuous spectrum. The center core of the Mu2e detector is a magnetic spectrometer of low-mass which can measure the electron momentum with a resolution of order 0.15%. At the conclusion of the Mu2e experiment, the collaboration will publish the measurement of the energy spectrum of electrons. This data will be able to answer whether or not there will there be an excess at the endpoint.

The Mu2e experiment will begin with a beam of slow muons. One of the technical challenges with Mu2e is to build the muon beam line that will deliver a beam of slow muons onto the target foils. The 8 GeV (kinetic energy) proton beam will be delivered by the Fermilab accelerator complex onto a target that is housed inside a complex system of curved solenoids with a graded magnetic field and determined number of coils. Interactions between the target nuclei and protons produce pions that are captured by the solenoids. When those pions decay to muons, the muons are captured by the magnetic field and are transported to the target foils.

A strong advantage of placing the Mu2e experiment at Fermilab is that the experiment will reuse many parts of the accelerator complex that will become available following the conclusion and completion of the Tevatron project. Certainly some significant research and development challenges remain, one example being how to specifically design the solenoids for proper magnetic field specifications. These problems and the design specifications primarily for the DS will be met and investigated with these studies and analyses found in this report.

## 2. MATERIALS AND METHODS

### *i. Structure and Scope of the Detector Solenoid*

1. Detector Solenoid Overview

The Detector Solenoid (DS) is part of the mu2e magnetic system. See figure 1. The Detector solenoid primarily is made of a series of wide aperture superconducting solenoids; a chimney for superconducting leads, helium supply and return lines and instrument ports; a cryostat for the solenoid; iron magnet return yoke; internal mechanical supports; external mechanical supports to building.

## 2. Role of DS in Mu2e

The DS is used for several purposes in the mu2e experiment:

1) First of all, the DS efficiently focuses muons on to the stopping target. These muons are generated from the production target and transported through the Transport solenoids, in the momentum range to be stopped in the stopping target. 2) The DS also focuses conversion electrons from the stopping target towards the tracker spectrometer and electron calorimeter in an efficient matter. 3) In addition, the DS provides a uniform solenoid field as part of the tracker spectrometer. 4) It acts as an interface through the cryostat wall for the stopping target and any remote handling machinery. 5) Finally, the DS acts as an interface through the cryostat wall and cryostat supports for the shield which protects the solenoid from primary and secondary beam radiation.

## 3. DS Magnetic Field Requirements

Magnetically, the DS has three primary requirements all initially derived from the MECO magnetic requirements [1]. These three requirements consist of 1) An axially graded solenoid field which matches the transport field. 2) A uniform field of approximately 3 meters as part of the spectrometer for the conversion electron tracker. 3) A less stringent but uniform field for the electron calorimeter.

## 4. DS Physical Requirements and Dimensions

The length of the coil in the mu2e DS design is the same as that found in the MECO design [1]. Table II maintains a list of physical dimensions and requirements.

## 5. COMSOL Multiphysics

In order to create the correct magnetic flux density, magnetic field requirements, deformity stresses, and axial forces for the Detector Solenoid, several calculation tests and analyses were required to run during the conceptual design stage.

COMSOL was the main program used for these calculations in addition to ProEngineer and ANSYS. Using COMSOL's complex Finite Element Analysis, both a two-dimensional magnetic field analysis and three-dimensional field analysis, axial force analysis, and geometric analysis were performed for the Detector Solenoid and Transport Solenoid.

Much time is spent learning the complexities and functions of the COMSOL program, but its capabilities and boundaries are certainly broad and encompassing. COMSOL Multiphysics has redefined modeling for cross-discipline studies as well as for single-physics applications. COMSOL is applicable to traditional physics disciplines as well as emerging technologies such as advanced materials, alternative energy sources, biotechnology, micro-electromechanical systems (MEMS), nanotechnology, and optoelectronics. For the mu2e experiment, the COMSOL Multiphysics and AC/DC modules are used in which Electromagnetics and Magnetostatics Multiphysics applications are often used [2].

*ii. Calculations and Analyses with COMSOL Multiphysics: Iron Endplates*

One of the first issues to solve was whether or not a 30 cm iron endplate was required for the Detector Solenoid design. To solve this issue, the mu2e group used COMSOL Multiphysics in order to calculate both the magnetic flux density and the Lorentz force distribution on the Detector Solenoid. These calculations were performed for both created geometries: the DS with iron endplate and the DS without an iron endplate.

*iii. Calculations and Analyses with COMSOL Multiphysics: Axial Forces with Iron Endplates*

In order to determine if the axial forces were within reason and allowable for both the Detector Solenoid and the Transport Solenoid, several Lorentz Force Calculations were performed. These force calculations were performed with COMSOL Multiphysics.

*iv. Calculations and Analyses with COMSOL Multiphysics: Coil Force Calculation Comparison*

The mu2e experiment requires several safety precautions in which axial forces must be accounted for when certain events occur. For example, the axial forces on the coils must be bearable for the DS and TS when the TS current is reverse or turned off. The forces must also be bearable when the DS current is turned off.

*v. Calculations and Analyses with COMSOL Multiphysics: DS and TS Current Manipulation*

In order to accurately create the magnetic flux density and the magnetic field according to the necessary requirements, the DS and TS currents can be changed up and down and directionally. These changes in currents change the magnetic field and therefore can be manipulated individually (variable number of coils for the DS and 10 coils for the TS) in order to achieve the correct field shape.

*vi. Calculations and Analyses with COMSOL Multiphysics: Coil Force Calculation Comparison*

Another design to be analyzed for the mu2e experiment is the 7-coil Detector Solenoid graded design. Using COMSOL Multiphysics, the magnetic field can be calculated and it can be decided if there is a 3 m region for the tracker and 1.2 m region for the calorimeter in which there is a 1 T field within +/- 0.2%.

**3. RESULTS**

*i. COMSOL Data Collection and Calculations*

COMSOL Multiphysics 3.5a aided in calculating the axial forces, coil deformation, magnetic flux density, Lorentz force distribution, geometry, mesh, and external current densities. All of these functions were used thoroughly in the following studies. Their results and conclusions can be read on the consecutive pages.

*ii. Calculations and Analyses with COMSOL Multiphysics: Iron Endplates*

Here it is determined that the Lorentz force distribution calculates a 142.8 ton force on the DS in a direction toward the TS when the Iron endplates are present. In addition, magnetic flux density is depicted in Figure 2 as well as graphed in Figure 3.

In Figure 3 the magnetic flux density, norm is displayed for the Detector Solenoid With Iron. This plot meets the requirements in that the 1 T region is approximately 6 m +/- 0.2% and that the gradient from the 2 T region to the 1 T region is standard and drops in approximately 4 m. Below the plot, the locations of the 5 coils can be seen as well as the gap between DS coils 3 and 4.

Here it is determined that the Lorentz force distribution calculates a 91.8 ton force on the DS in a direction toward the TS when there is no iron endplate. In addition, magnetic flux density is depicted here in Figure 4. As can be seen in the figure, the 2T region is seen in the very beginning of the 1 m region, similarly to the DS with the iron endplate.

In Figure 5 the magnitude of the magnetic field with iron is represented. The radii of 0, 0.25, 0.5, and 0.7 m are represented. All share the same shape after the drop from 2T to 1T begins.

In Figure 6 the magnitude of the magnetic field without iron is represented. The different radii of 0, 0.25, 0.5, and 0.7 m are represented by the four different plots.

*iii. Calculations and Analyses with COMSOL Multiphysics: Axial Forces with Iron Endplates*

The axial forces on the DS due to the iron plates are listed  in Table III.  At one extreme, the 30 cm iron end plate carries a 142.8 ton axial force. At the low end, the 5 cm iron end plate carries an 85.2 ton force. The consecutive images and Figures 7, 8, and 9 show the magnetic flux density and magnetic field lines as displayed by COMSOL. The images are shown for the largest 30 cm iron endplate, the smallest 5 cm end plate (found to have the least axial force), and the DS with no iron end plate.

*iv. Calculations and Analyses with COMSOL Multiphysics: Coil Force Calculation Comparison*

See Table IV. Here the force both on the Detector Solenoid and on the Transport Solenoid have both been calculated at different radii of 2.07 m and 1.57 m. The two different radii represent different distances of the coils from the iron casing. For both cases, the forces do not greatly change. They also show a similar trend as they decrease in quantity when the TS is off and then decrease and change direction when the TS is reversed. With the 0.05 m iron endplate, the smallest force is found on the DS and the TS. The forces are 88.32 tons toward the TS and 99.78 tons toward the DS respectively. This is a smaller force than compared with the 30 cm endplate (looking at the case of DS on and TS on).

*v. Calculations and Analyses with COMSOL Multiphysics: DS and TS Current Manipulation*

The Detector Solenoid and Transport Solenoid external current densities can all be altered according to each specific coil. By altering the current densities of a specific coil, the magnetic flux density value and plot will change. As part of the mu2e work, the original current densities were estimated to make a shape that roughly met the requirements set. In order to meet the requirements, the current densities in the DS 1 and TS 4 and TS 5 were altered from their original external current densities. The result of the original current densities can be seen in Figure 10. After trial-and-error fluctuation of these current densities, the initial field in the TS region was stabilized at 2.0 T. The proper gradient was achieved for 4 m and the steady 1 T region was reached for 6 m at +/- 0.2% of the magnetic field. See Figure 11. In Table V, the final external current densities and geometries for the DS and TS coils can be seen. Also, Figures 12, 13, and 14 illustrate the ability to create the 1 T region within +/- 0.2 % of the magnetic field. This can be done using COMSOL Multiphysics. This same procedure can also be applied to a 7 coil graded design that is under review. This process can be applied to any geometry that is finally chosen for the DS design.

*vi. Calculations and Analyses with COMSOL Multiphysics: Coil Force Calculation Comparison*

Another design to consider with the mu2e experiment with regards to the DS is whether or not to choose a 7-coil graded design in which the same specifications can be met. The current densities and geometries have been produced as to propose a viable alternative to the 5-coil design. See Figure 15 for the parameter list. Figure 16 also illustrates the ability of the 7 coil graded design to fit the +/- 0.2 % of the 1 T region. The 7 coil graded design can also fit the +/- 5 % gradient region for 3 m. This can be met at a radius of r = 0, r = 0.5, and r = 0.7 m. The magnetic flux density can also be adjusted to fit the correct specifications for the mu2e DS.

## 4. DISCUSSION AND CONCLUSION

*i. Structure and Scope of the Detector Solenoid*

The entire length of the coils in the Detector Solenoid is 11.9 meter long. There are two different magnetic field regions. The first upstream region has magnetic field distribution starting from 2 Tesla and gradually decreasing to 1 Tesla. From discussion and calculations about whether or not a 5 coil design or 7 coil graded design should be used, the decision has been made to use the 7 coil graded design as it allows for +/- 5% gradient for 3 m during the decrease from

2 T to 1 T. Therefore, 7 coils are required. See *study vi* results and conclusion. The magnetic field can still be adjusted via external current density adjustments as to allow for the correct field shape to be created.

*ii. Calculations and Analyses with COMSOL Multiphysics: Iron Endplates*

Overall, the difference between the detector solenoid with the iron and without the iron is minimal in that the magnetic field distribution located after the 2T to 0T drop is nearly identical. The difference in magnetic field prior to this instance do not have a drastic effect on the detector solenoid. Therefore the difference between the detector solenoid without iron and with iron in terms of magnetic field are non-consequential. However, it is important to note that the axial forces on the two cases are different. The axial force on the DS with the iron end cap is much greater in magnitude than that of the DS without the iron end cap. This concludes that no iron end cap would be more reasonable than a 30 cm end cap. Other geometries of end caps will be determined later.

*iii. Calculations and Analyses with COMSOL Multiphysics: Axial Forces with Iron Endplates*

With this study, it is determined that the largest axial force on the DS is due to a 30 cm iron end plate. With no iron end plate, the axial force on the DS is approximately 91.8 tons. The smallest force on the DS was determined to be with the 5 cm iron end plate. This 5 cm iron endplate is the smallest due to its shielding ability and its thin geometry as compared with the 30 cm iron end plate. Therefore, the most reasonable iron end plate size to use in the DS geometry is the 5 cm iron end plate.

*iv. Calculations and Analyses with COMSOL Multiphysics: Coil Force Calculation Comparison*

In this study, it is determined that the large radius of 71 cm and the small radius of 50 cm both have very similar values for the axial forces. Therefore, it is unnecessary to evaluate both cases as the axial force values will be approximately similar in all cases. It can also be determined from this study that in accidents, the axial forces on the DS when the TS current is turned off or set in reverse are manageable and bearable. Finally, the 5 cm iron endplate study shows that once again, the smallest axial forces are present on the DS with this geometry.

*v. Calculations and Analyses with COMSOL Multiphysics: DS and TS Current Manipulation*

The DS and TS current manipulation reveals the direct relationship between the external current densities and the magnetic field. The current was correctly manipulated to create the field shape that meets the mu2e experiment requirements. Therefore, it can be determined that the design can be flexible because the magnetic field can be manipulated with the current densities. The more coils that are present as well, the higher degree of manipulation that is available for the magnetic field shape.

*vi. Calculations and Analyses with COMSOL Multiphysics: Coil Force Calculation Comparison*

The 7 coil graded design tests and calculations reveal that it is the best design for the DS. It is one of the only designs that allows for both +/- 0.2% in the 6 m 1 Tesla region as well as the +/- 5% gradient region for 3 m when the magnetic field drops from 2 Tesla to 1 Tesla. Overall, this 7 coil graded DS geometry and design is the most flexible and fitting design to meet all of the mu2e project specifications.

## 5. FUTURE WORK

The Mu2e experiment has several more steps to accomplish in order to bring the project to completion. In the short run, the DS group needs to finalize the conceptual design and outline the DS physical dimensions, forces and field from TS, weight from itself and absorber detector, the expected radiation loads, technical specification of DS, the conductor properties, the coil properties, the cryostat, iron geometry, cryogenic system, mechanical studies, thermal studies, radiation studies, quench protection studies, magnetic field studies, and alternate design considerations [3]. In the long run the Mu2e project aims to finish its conceptual design and then allow time for construction and finalization within the next 8 years.

## 6. ACKNOWLEDGEMENTS

I would like to acknowledge and thank Dianne Engram, Jameison Olsen, and the rest of the SIST committee for their tremendous amount of guidance and effort that made this summer a great experience at Fermilab. I would also like to thank my supervisor, Ryuji Yamada, for his help in guiding the mu2e DS studies and interest in educating summer students about superconducting magnets and COMSOL. His guidance was certainly educational and important. I would also like to thank another one of my mentors, Cosmore Sylvester, for guiding me through my research and time at Fermilab. Finally, I would like to extend my gratitude to Dr. Davenport for his assistance finalizing the U.S. Department of Energy and Fermilab paper and presentation.

## 7. REFERENCES

[1]"Mu2e Detector Solenoid Requirements Document." *Fermilab: Detector Solenoid Requirements* (2010): 1-9. Print.

[2] *FEMLAB 3: Multiphysics Modeling*. Stockholm, Sweden: Comsol, 2003. Print.

[3]Smith, Bradford A. "Superconductin Magnet Systems for the Muon-Electron Conversion Experiment." *IEEE Transactions on Applied Superconductivity* 13.2 (2003): 1377-380. Print.

**FIGURES**

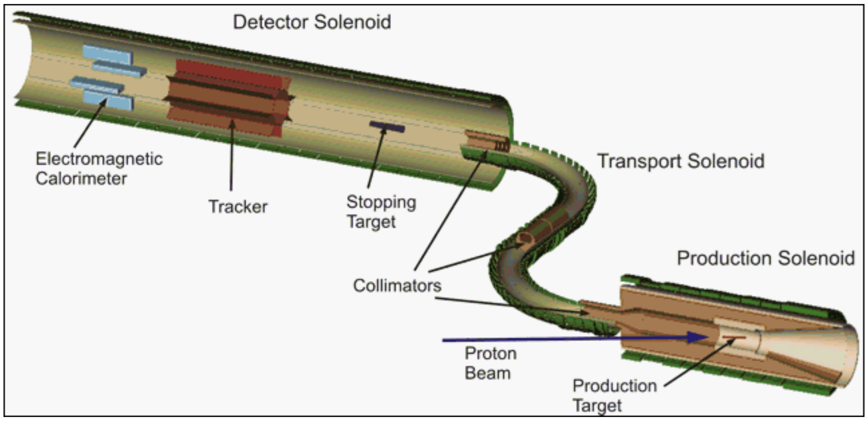



Figure 1: Here the structure of the layout of the Mu2e apparatus is displayed. The muon will be initially sent through the production solenoid, followed by the proton beam traveling through the transport solenoid and then arriving at the detector solenoid, which is the focus of the COMSOL studies.

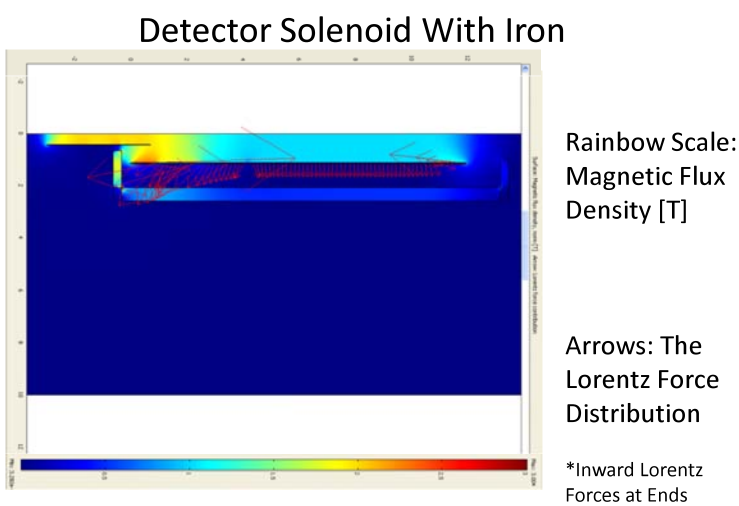



Figure 2: Here the Detector Solenoid with iron is depicted. The iron endplate consists of 30 cm at both ends. The magnetic field is depicted by the rainbow field scale while the Lorentz force distribution is depicted by the red arrows on the coils.

Detector Solenoid With Iron

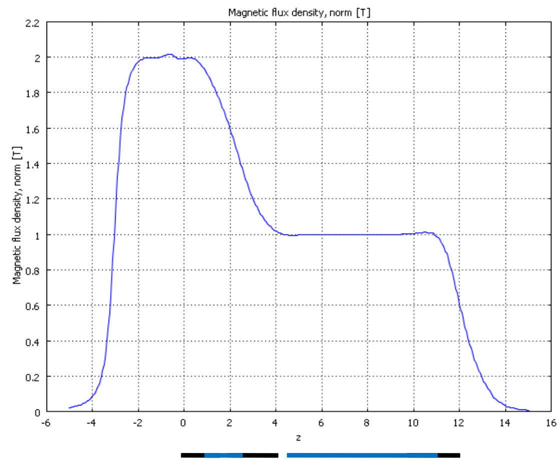
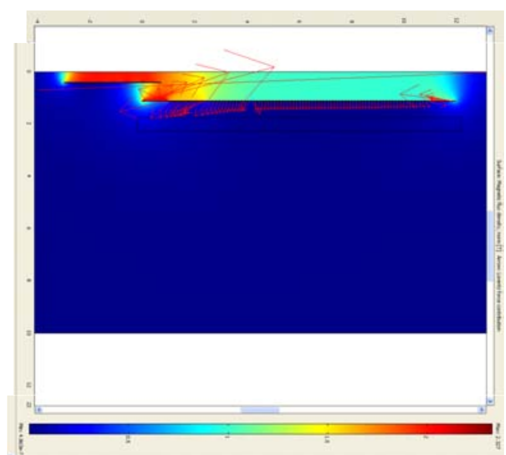



Figure 3: Here the Detector Solenoid has iron and the magnetic flux density for the detector solenoid and transport solenoid is displayed.

Detector Solenoid Without Iron



Rainbow Scale: Magnetic Flux Density [T]

Arrows: The Lorentz Force Distribution

Figure 4: Here the Detector Solenoid has no iron endplate and the magnetic flux density is depicted with the rainbow scale while the Lorentz force distribution is depicted with the red arrows.

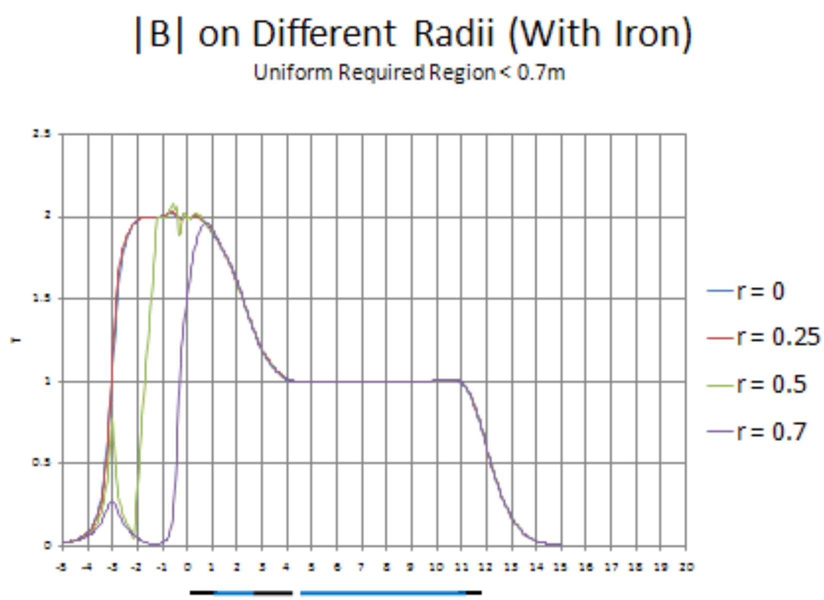



Figure 5: Magnetic Field of Different Radii With Iron

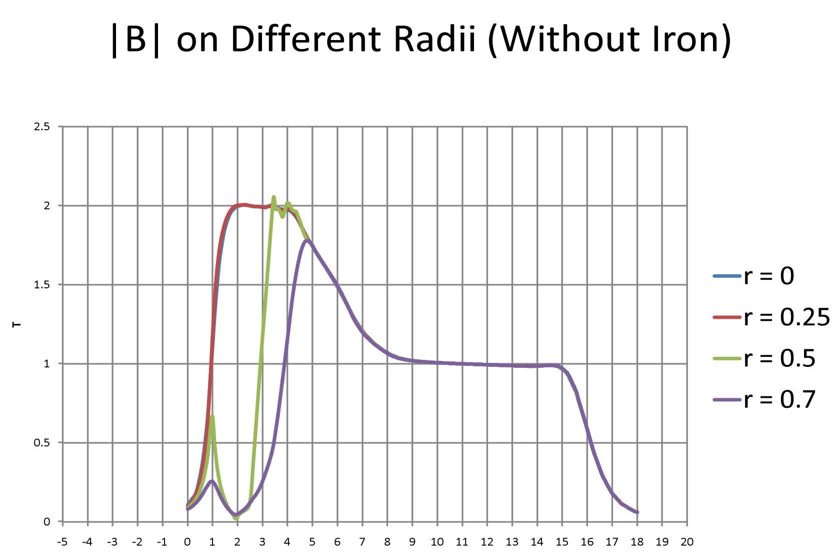



Figure 6: Magnetic Field of Different Radii With Iron

30 cm Iron End Plate: Force = 142.8 Tons

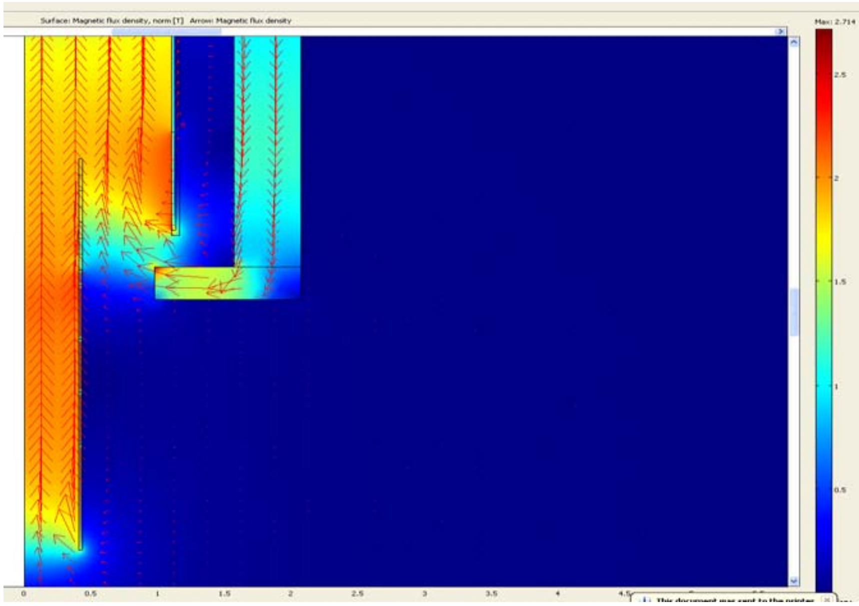


Figure 7: Magnetic Flux Density and Magnetic Field Lines for the 30 cm Iron Endplate DS

5 cm Iron End Plate: Force = 85.2 Tons

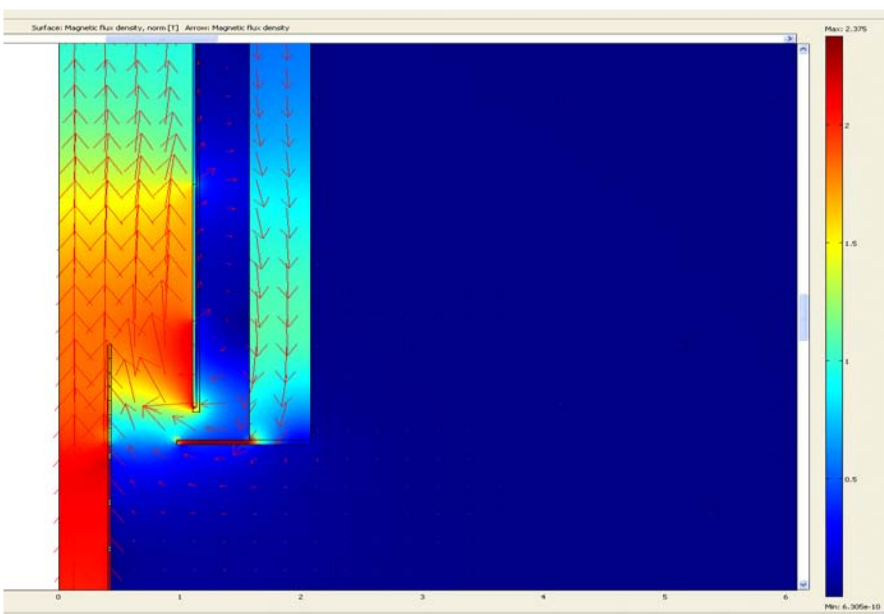


Figure 8: Magnetic Flux Density and Magnetic Field Lines for the 5 cm Iron Endplate DS

No Iron End Plate: Force = 91.8 Tons

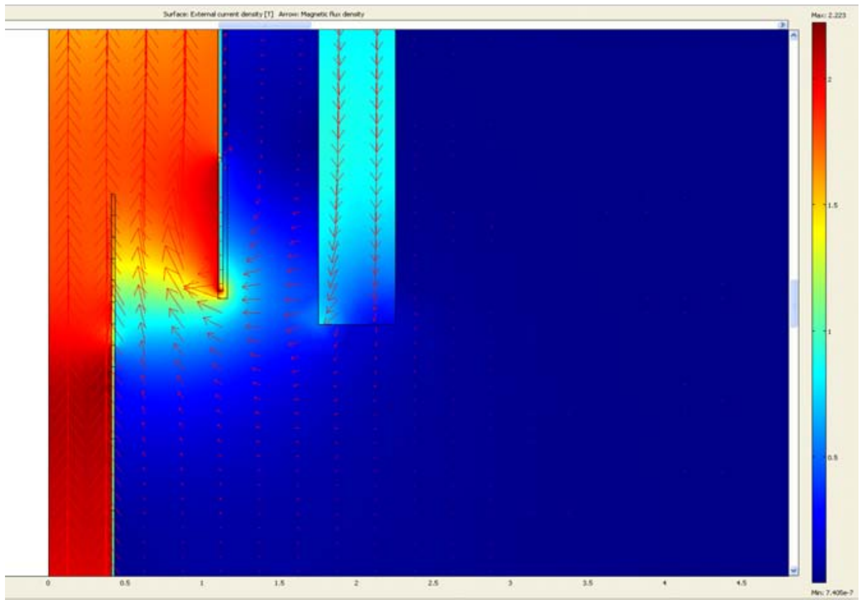


Figure 9: Magnetic Flux Density and Magnetic Field Lines for the DS with no Iron Endplate

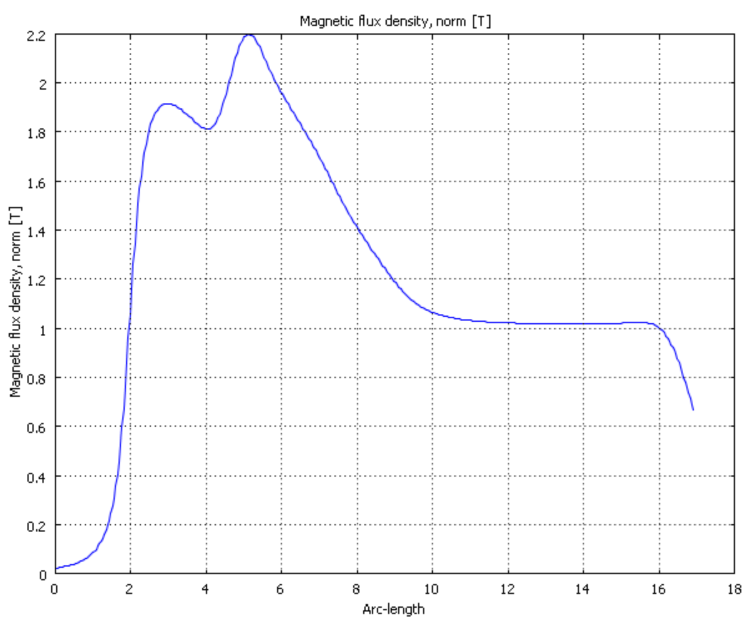



Figure 10: Original Magnetic Flux Density, norm with estimated external current densities

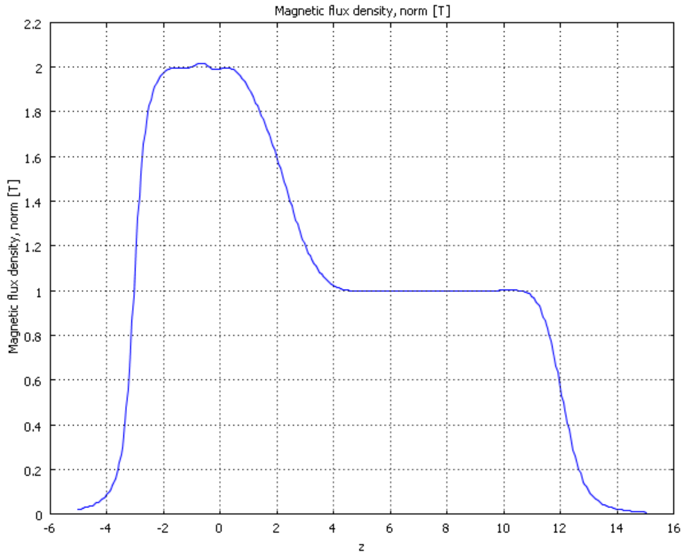
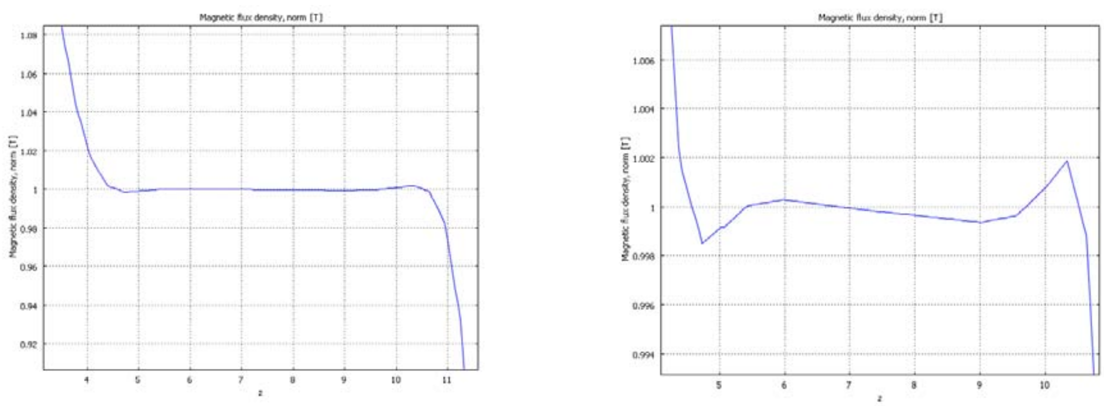



Figure 11: Final Magnetic Flux Density, norm with corrected external current densities to match the mu2e experiment specifications




Figures 12, 13: One of the mu2e experiment specifications includes an approximate 6 m region in which the magnetic field adheres to =/- 0.2 % of 1 T. These plots depict that this external current density and magnetic field results from COMSOL reflect that level of accuracy.

The DS maintains a 1 T region within 0.2 %, represented by the colored regions.

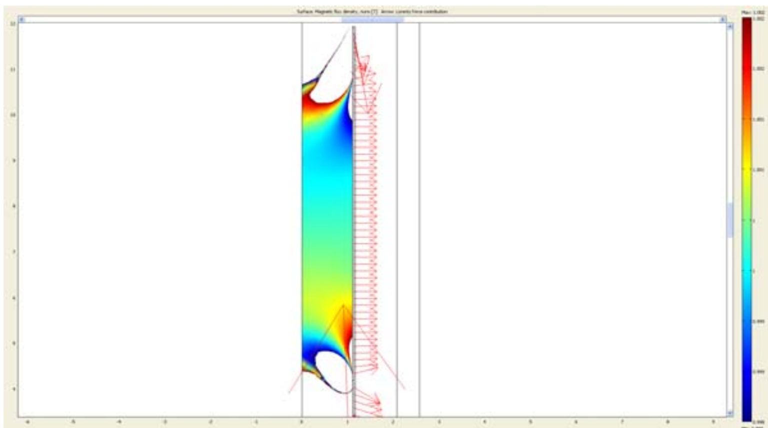
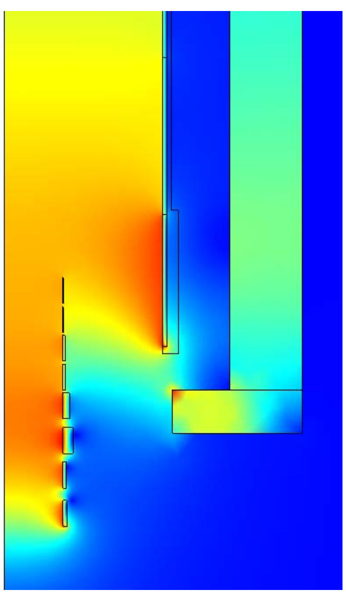


Figure 14: COMSOL depicts the region in which the DS maintains +/- 0.2% of the 1T B field.

# Parameter List



• With adjusted TS4 current densities, gradient of transition region between 2T and 1T meets 3m length requirement.
• The flux at the TS region is high due to TS4 (almost 2.2 T)

| Coil | z-start (Local coord.) | z-end | Length (m) | r-start | r-end | Width (m) | Current Density (A/m^2) |
|---|---|---|---|---|---|---|---|
| TS4.1 | -0.9472 | -0.7672 | 0.18 | 0.405 | 0.435 | 0.03 | 8.47E+07 |
| TS4.2 | -0.682 | -0.502 | 0.18 | 0.405 | 0.4302 | 0.0252 | 8.13E+07 |
| TS4.3 | -0.442 | -0.262 | 0.18 | 0.405 | 0.475 | 0.07 | 3.67E+07 |
| TS4.4 | -0.2 | -0.02 | 0.18 | 0.405 | 0.4526 | 0.0476 | 3.71E+07 |
| TS5.1 | 0 | 0.18 | 0.18 | 0.405 | 0.4218 | 0.0168 | 4.50E+07 |
| TS5.2 | 0.2 | 0.38 | 0.18 | 0.405 | 0.4218 | 0.0168 | 4.38E+07 |
| TS5.3 | 0.4 | 0.58 | 0.18 | 0.405 | 0.4106 | 0.0056 | 4.00E+07 |
| TS5.4 | 0.6 | 0.78 | 0.18 | 0.405 | 0.4106 | 0.0056 | 3.25E+07 |
| | | | | | | | |
| DS 1 | 0.3 | 0.92 | 0.92 | 1.1 | 1.13 | 0.03 | 8.00E+07 |
| DS 2 | 1.22 | 1.84 | 0.92 | 1.1 | 1.13 | 0.03 | 5.25E+07 |
| DS 3 | 2.14 | 2.77 | 0.93 | 1.1 | 1.13 | 0.03 | 4.42E+07 |
| DS 4 | 3.07 | 3.74 | 0.97 | 1.1 | 1.13 | 0.03 | 3.50E+07 |
| DS 5 | 4.04 | 4.04 | 0.3 | 1.1 | 1.13 | 0.03 | 2.65E+07 |
| DS 6 | 4.49 | 11.4 | 7.21 | 1.1 | 1.13 | 0.03 | 2.65E+07 |
| DS 7 | 11.7 | 11.9 | 0.5 | 1.1 | 1.13 | 0.03 | 4.35E+07 |

DS Meeting 7/28/2010 11

Figure 15: The current density and geometry of the 7-coild graded design for the DS

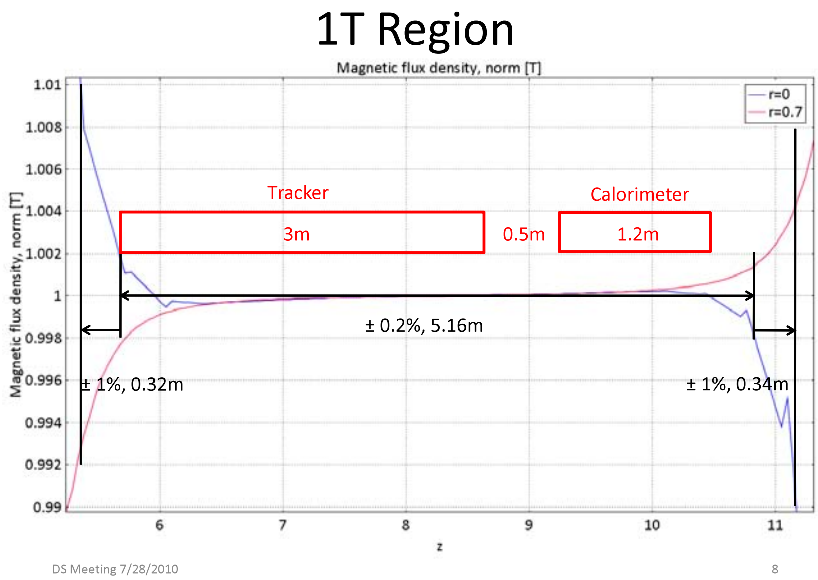



Figure 16: The +/- 0.2% of 1 T region is just long enough to hold the 3 m tracker as well as the 1.2 m calorimeter and 0.5 m gap for flexibility in placing the detector devices.

**TABLES**

| | |
|---|---|
| Peak Field Along TS Axis | 2T |
| Gradient Linearity on axis | 5% |
| Value of gradient on axis | <0.3 T/m |
| Field value in spectrometer | 1T +/- 0.02 |
| Goal Field Uniformity in Spectrometer | 0.20% |
| Req. axial length of uniform field | 3 m |
| Req. radius of uniform field | 0.7 m |
| Accuracy of longitudinal location of uniform Field | 0.5 m |
| Req. uniformity in calorimeter region | 1% |
| Req. axial length of field | 1.5 m |

Table I: Magnetic Requirements

| | |
|---|---|
| Cryostat Inner Diameter | 1.9 m |
| Coil Length | 11.9 m |
| Maximum Cryostat outer Diameter | 2.66 m |
| Outer Dimension of Iron Box | 4.6 m |
| Thickness of Iron Box | 0.5 m |

Table II: Required Physical Dimensions of DS

## Axial Forces on DS Due to Iron Plates

| Type of End Plate | Axial Forces (Toward Transport Solenoid) |
|---|---|
| 30 cm Iron End Plate | 142.8 Tons |
| 15 cm Iron End Plate | 114.8 Tons |
| 5 cm Iron End Plate | 85.2 Tons |
| 15 cm Iron End Plate with 15 cm Buffer | 106.6 Tons |
| 5 cm Iron End Plate with 25 cm Buffer | 90.9 Tons |
| No Iron End Plate | 91.8 Tons |

Table III: Axial Forces on DS Due to Iron Plates

# Coil Force Calculation Comparison

| | DS | TS | Large Radius Axial Force (71 cm Iron) | Small Radius Axial Force (50 cm Iron) | 5 cm Iron Endplate (50 cm Iron) |
|---|---|---|---|---|---|
| DS Force | On | On | -149.40 Tons | -142.70 Tons | -88.32 Tons |
| | On | Off | -78.31 Tons | -63.23 Tons | -50.14 Tons |
| | On | Reverse | 4.24 Tons | 10.56 Tons | 15.45 Tons |
| TS Force | On | On | 92.25 Tons | 92.36 Tons | 88.78 Tons |
| | On | Off | 0.00 Tons | 0.00 Tons | 0.00 Tons |
| | On | Reverse | -93.15 Tons | -93.15 Tons | -90.17 Tons |
| No Endplate | On | Off | 10.15 Tons | 10.15 Tons | |

Table IV: Coil Force Calculation Comparison with Large and Small Radii and 5 cm Iron Plate

| Solenoid | I Density | Height | Width |
|---|---|---|---|
| **Ds 5** | 3.75E+07 | 1 | 0.03 |
| **Ds 4** | 2.67E+07 | 6.73 | 0.03 |
| **Ds 3** | 2.60E+07 | 1.73 | 0.03 |
| **Ds 2** | 4.45E+07 | 1.47 | 0.03 |
| **Ds 1** | 6.65E+07 | 0.93 | 0.03 |
| **Ts 1** | 1.30E+06 | 0.15 | 0.03 |
| **Ts 2** | 4.80E+06 | 0.15 | 0.03 |
| **Ts 3** | 7.50E+06 | 0.15 | 0.03 |
| **Ts 4** | 1.20E+07 | 0.15 | 0.03 |
| **Ts 5** | 2.10E+07 | 0.15 | 0.03 |
| **Ts 6** | 3.50E+07 | 0.15 | 0.03 |
| **Ts 7** | 2.50E+07 | 0.15 | 0.03 |
| **Ts 8** | 5.40E+07 | 0.15 | 0.03 |
| **Ts 9** | 6.15E+07 | 0.5 | 0.03 |
| **Ts 10 (1)** | 6.35E+07 | 0.5 | 0.03 |
| **Ts 10 (2)** | 6.55E+07 | 0.5 | 0.03 |
| **Ts 10 (3)** | 6.50E+07 | 1 | 0.03 |

Table V: The final external current densities and geometries for the DS and TS coils (meeting the correct mu2e experiment specifications).