Solenoid Magnet System for the Fermilab Mu2e Experiment

M.J. Lamm, N. Andreev, G. Ambrosio, J. Brandt, R. Coleman, D. Evbota, V.V. Kashikhin, M. Lopes, J. Miller, T. Nicol, R. Ostojic, T. Page, T. Peterson, J. Popp, V, Pronskikh, M. Tartaglia, Z. Tang, M. Wake, R. Wands and R. Yamada

***Abstract*— The Fermilab Mu2e experiment seeks to measure the rare process of direct muon to electron conversion in the field of a nucleus. Key to the design of the experiment is a system of three superconducting solenoids; a muon production solenoid (PS) which is a 1.8 m aperture axially graded solenoid with a peak field of 5 T used to focus secondary pions and muons from a production target located in the solenoid aperture; an "S shaped" transport solenoid (TS) which selects and transports the subsequent muons towards a stopping target; a detector solenoid (DS) which is an axially graded solenoid at the upstream end to focus transported muons to a stopping target, and a spectrometer solenoid at the downstream end to accurately measure the momentum of the outgoing conversion elections. The magnetic field requirements, the significant magnetic coupling between the solenoids, the curved muon transport geometry and the large beam induced energy deposition into the superconducting coils pose significant challenges to the magnetic, mechanical, and thermal design of this system. In this paper a conceptual design for the magnetic system which meets the Mu2e experiment requirements is presented.**

***Index Terms*—Superconducting Solenoids, aluminum stabilized conductor, particle detector**

I. INTRODUCTION

THe Fermilab Mu2e experiment depends on the production, collection and transport of muons in the right momentum range to form muonic atoms in an aluminum stopping target[1]. The kinematically-constrained process $\mu^{-}Al \rightarrow e^{-}Al$ produces a monoenergetic electron signature which is distinct from background events. A major part of the experiment strategy is to minimize these backgrounds as well as to perform the precise measurement of the muon momentum.

A schematic of the Mu2e layout is shown in Fig. 1. Starting from (A), a 25 kW beam of 8 GeV protons interacts with a gold target (B) located in the radial center of an axially graded solenoid. The axial gradient acts a mirror for forward-going muons and pions, and focuses backward direction particles towards an S-Shaped transport. The transport field and collimation (C) preferentially selects negatively charged muons with momentum suitable for forming muonic atoms in an aluminum target (D). Outgoing electrons produced from the nuclear reaction are collected in the graded upstream field. Their momentum and energy are measured using a tracker and calorimeter in a known magnetic field (E). The magnetic design naturally falls into three couple solenoid systems: the Production Solenoid (PS), Transport Solenoid (TS) and Detector Solenoid (DS). The parameters for PS, DS and TS are given in Table I.

TABLE I PS, TS AND DS PARAMETERS

Parameter	Units	PS	TS (1,2,4,5/3)	DS Grad/Spec.
Cable bare width	mm	30	3.1	30
Cable bare thickness	mm	6	7.4	6/8
Coil inner diameter	mm	1670	810/860	2100
Coil length	m	4	13.2*	11.8
No. of coil segments		3	54	9/3
Operating temp.	K	4.6	5	5
Operating current	kA	8.4	1.3	6.8
Peak axial field	T	5.03	3.4	2.2
% of SSL @ max. temp.		69	56	33/25
Stored energy	MJ	77.3	28.7	28.7

*Path length along the transport center

II. SOLENOID SYSTEM REQUIREMENTS

The Mu2e solenoids and their supporting subsystems are designed to meet a complex set of requirements. Because of the high magnetic field and large stored energy, the solenoids will be made from superconducting NbTi coils, indirectly cooled with liquid helium and stabilized with high conductivity aluminum. For access and detector calibration it must be possible to cool down and energize each solenoid independent of the state of the adjacent magnets.

Significant axial forces will be present between these magnetically coupled systems. The magnets must be designed to withstand these forces when they are being operated in their standard configuration as well as in the various configurations described above. The mechanical support for each of the magnets will be independent and will not depend on adjacent magnets. This simplifies integration issues but complicates the mechanical support system. The bore of the magnets share a common beam vacuum bridge by bellowed connections.

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M. Lamm, N. Andreev, G. Ambrosio, J. Brandt, R. Coleman, D. Evbota, V.V. Kashikhin, M. Lopes, J. Miller, T. Nicol, T. Page, T. Peterson, J. Popp, V. Pronskikh, M. Tartaglia, R. Wands and R. Yamada are with Fermilab, Batavia, IL 60510 USA (phone: 630-840-4098; fax: 630-840-8079; e-mail: lamm@fnal.gov).

J. Miller is with Boston University, Boston, MA 02215 USA

R. Ostojic is with Fermilab, Batavia, IL 60510, on leave from CERN, CH-1211,Geneve 23,Switzerland

J. Popp is with City College of New York, New York, NY 10031 USA

M. Wake. is with KEK, High Energy Research Organization, Tsukuba, Ibaraki 305-0801, Japan

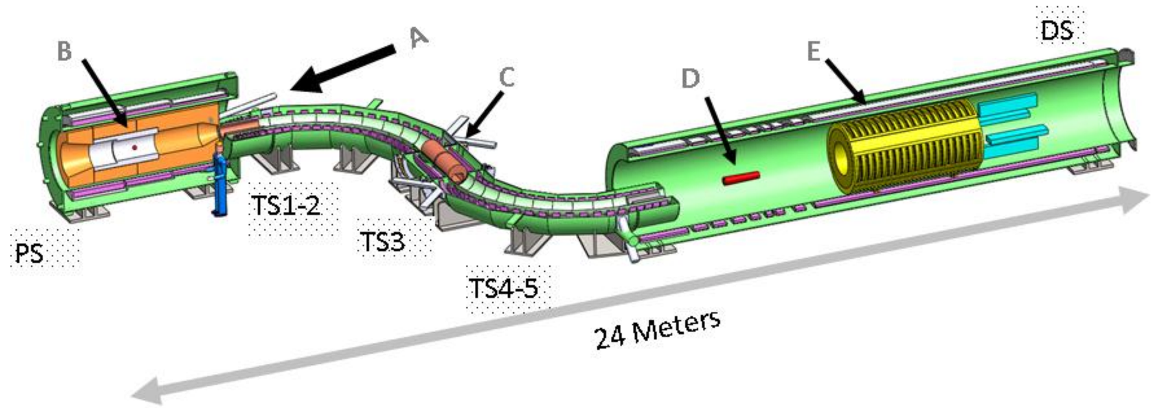

Fig. 1. Layout of Mu2e experiment showing the relative location of PS, TS and DS and function: A: 25 kW 8 GeV proton beam; B: Production Target which generates μ- and background particles; C: Rotating Collimator, D: Aluminum Stopping Target, E: Tracker/Calorimeter for electron momentum identification.

The solenoid coils must be designed for repeated full field quenches and thermal cycles, without degradation in performance, over the lifetime of the experiment. The expected duration of the experiment is 2 years; however the magnets should be designed for the possibility of an extended physics run at the maximum design beam power. The primary consequence of extended running will be the need for repeated thermal cycles to anneal the damage from irradiation (see PS section).

Each of the solenoids performs a different set of functions and each has a unique set of field requirements. A detailed description is beyond the scope of this paper. However, the requirements for each solenoid are described in the table II.

TABLE II MAGNETIC FIELD REQUIREMENTS

Region	Length (m)	Field Requirement
PS Gradient	2.5	|dB/B|<0.05 about an axial field of 1.0 T/m
TS Straight	1-2	negative axial gradient
TS Curved	4.6	Ripple |dB| < 0.02 T
DS Gradient	3.0	dBs/ds = 0.25+/- 0.05 T/m, |dB/B| < 0.05
DS Transition	1.2	Magnitude of gradient decreasing
DS Spectrometer	5.1	|dB/B| < 0.01

Radiation damage to the solenoids must be carefully considered during the design process. The largest radiation dose is estimated to be 0.3 MGy/year at full beam intensity to the PS. Irradiation of the conductor and insulation is not expected to be a major concern over a 20-year life cycle. There is a significant concern about damage to the superconductor stabilizer in the Production Solenoid, causing a significant reduction in electrical and thermal conductivity at low temperature [2]-[3]. The stabilizer room temperature resistivity ratio (RRR) must not degrade below 100 during the operation of the experiment.

III. PRODUCTION SOLENOID (PS)

The PS primary role is to maximize the stopped muon yield by efficiently capturing pions and focusing secondary muons towards the Transport Solenoid. The salient features of the PS are shown in Table II and pictorially in Fig. 2. A detailed design study has been presented elsewhere [4].

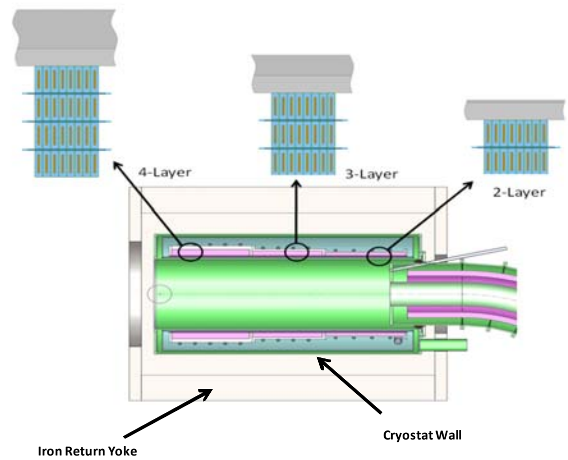

Fig. 2. PS Coil Layout with blowup of individual coil cross sections.

The Production Solenoid must generate a uniform axially graded field ranging from 5 T to 2.5 T. This axial field is made with three solenoid coils of equal axial length and inner diameter, with 4, 3 and 2 layers of aluminum stabilized NbTi superconducting cable. The conductor consists of copper clad NbTi Rutherford cable and stabilized with structurally enhanced aluminum. The PS employs a composite cable insulation made of polyamide and pre-preg glass tapes [5]. All gaps between turns and layers are to be filled with epoxy resin during vacuum impregnation. Each coil has an Al 5083-O aluminum outer support structure to manage hoop stress. The amount of epoxy in the coil relative to the fiberglass insulation and conductor will be carefully controlled so that the coil and aluminum outer shell will have the same thermal contraction coefficient. 1-mm thick aluminum sheets are placed between coil layers which act as thermal bridges connecting via 4 mm plates of aluminum placed between the coil ends and the end flanges. PS will utilize a thermal siphoning cooling scheme.

The PS axial and radial support structure must be able to support the expected >130 Ton of axial force as well as the weight of the coil. The axial suspension point is in the center of the cold mass: 4 INCONEL 718 rods equally spaced azimuthally and connected to the end of the vacuum vessel on both ends [6]. Belleville washers on both ends will allow the rods to always be in tension within the expected force excursions. INCONEL rods at both coils ends will support the weight of the coil and any anticipated radial forces.

The coils will be housed in a stainless steel cryostat. This cryostat must support an anticipated 60 Ton radiation shield located in the bore of the PS. This heat absorber design, described elsewhere [7] will be made of tungsten and copper alloys. The final design will be an optimization of heat absorption efficiency and cost.

The completed Production Solenoid is housed in an iron box that serves as a magnetic field flux return. The pole pieces on both ends of the box serve to shape the field in the Transport Solenoid coils and help to minimize the axial force imbalance due to the TS coupling to the PS axial gradient.

Magnetic, mechanical, thermal and quench analysis have been performed on the PS coil. The axial gradient produced from the 4/3/2 layers meets the 5 percent field uniformity spec. An analysis has been performed to the effect of radiation damage on the stabilizer. It has been shown elsewhere [2]-[3] that aluminum RRR degrades via atomic displacement from radiation. A local RRR degradation can have a significant effect on the peak temperature due to a spontaneous quench. This RRR degradation can be reversed through a room temperature annealing of the aluminum. Result of the study show that with the present heat shield design, the radiation damage will require a once/year room temperature warm up of the PS [8].

Another important study is the thermal margin of the PS. The maximum allowed coil temperature is based on having a minimum 1.5 K temperature margin. There is a linear relationship between the input cooling temperature and the peak coil temperature. We consider the case where there is only a static heat load (beam off) and dynamic heat loads ranging from 100 % to 150 % of predicted. Given the expected input temperature of 4.6 K, the 1.5 K temperature margin can be met with the 150 % heat load. Or put another way, the peak inlet can fluctuate to as high as 4.73 K with expected peak coil temperature.

IV. TRANSPORT SOLENOID (TS)

The primary task for the TS is to transport muons to the stopping target while eliminating background particles. As shown in Fig. 1, the TS are divided into 5 segments TS1-TS5. Curved sections TS2 and TS4 disperse the beam vertically by momentum and sign. Collimators located primarily in the straight sections preferentially select low momentum μ-. The collimator in TS3 is rotatable to allow for the passage of π+ and μ+ for calibration. The curvature and field strength of TS4 is designed to undo the dispersion from TS2. A major source of backgrounds is particles that become out of time with respect to the pulse train. Therefore the field in all TS straight sections is required to have a negative axial gradient in order to avoid trapping or slowing down particles.

The required axial gradients in the straight sections, the toroidal section field uniformity, as well as the magnet coupling between TS and neighboring PS and DS, present a challenging 3 dimensional field specification. The field is generated by a series of 55 solenoid rings. The rings will operate at the same current. Coil segments in TS3 have a slightly larger diameter than adjacent TS2 and TS4, which is needed for generating a large axial fringe field to bridge the axial gap without creating a local dip in the field.

The design concept of a typical solenoid ring is shown in Fig. 3 and in Table I. Each coil will consist of multilayers of structurally doped aluminum stabilized conductor. The coils are wound on an Al 5083-O bobbin. In the toroid region, the coils are wound on Al 5083-O modules (hosing three or four coils) consisting of straight bobbins welded to wedge-shaped spacers in order to approximate the toroid geometry (Fig. 3). Cooling sheets in between the coil and the bobbin are connected to the helium cooling tubes via a thermal bridge. An aluminum bandage will be placed on the outside of the coil to provide pre-stress and support against hoop stress. The aluminum mandrel is expected to shrink slightly more than the coil thus supply axial prestress after cooldown.

TS1/TS2 and TS4/TS5 are each housed in single cryostats. Because of the need to access the rotatable collimator TS3 is located in a separate cryostat.

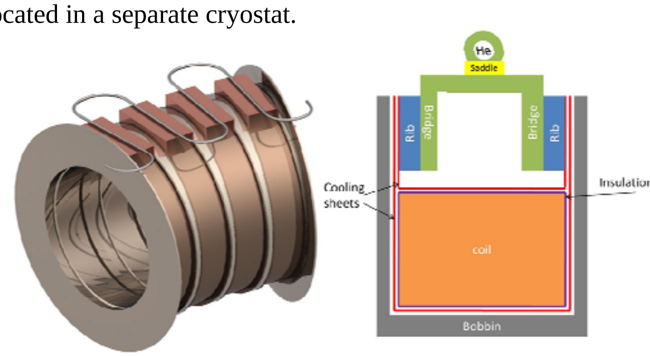

Fig. 3. TS module and coil cross section (not to scale)

The curved shaped design of TS poses a unique challenge on the mechanical design. Thermal contractions are dominated by the aluminum structure and conductor stabilizer. During nominal operation there are over 100 Tons of force between PS and TS, including a small centering force. Fig. 4 shows support structure for TS1 and TS2. The coil modules are bolted together. The supports are connected to the coil mandrels as shown. The forces are reacted against a stainless steel cryostat (not shown for clarity). Except for the fixed point, all support rods are allowed to pivot in the horizontal plane, similar in concept to previous beamline transport [9]. There is a significant coil movement (up to 30 mm axially on the PS end) due to cooldown and excitation. This movement is needed to minimizes areas of local stress while allows support when excited. The peak stress on the support structure is approximately 80 MPa, well with in the allowed values for Al 8030. The movement can be accounted for through room temperature alignment. Additional studies are ongoing to study the effects of coil position tolerance on muon transmission.

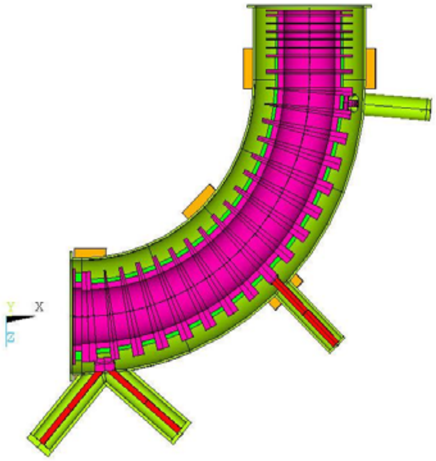

Fig. 4. TS1-2 Cross section, showing coils and mechanical support. Fixed point is a the end nearest TS3, at the "V" support.

V. Detector Solenoid (DS)

The main functions of the DS are to provide a decreasing axial field in the region of the stopping target and a precision magnetic field in a large volume housing the tracker. The DS is tightly coupled to the Transport Solenoid as the last section of the TS protrudes into the DS cryostat. The DS cryostat is mounted inside a square iron yoke.

The main elements of the solenoid are shown in Fig. 5 and the magnet parameters are given in Table I. As shown, DS consists of two sections: a "gradient section", which is about 4 m long, and a "spectrometer section" of about 8 m. The magnetic field at the entrance of the gradient section is 2 T and decreases linearly to 1 T at the entry of the spectrometer section. The transition between sections occurs in a length of 1.25 meters. The gradient section consists of 8 two-layer solenoid rings, wound using a 6 mm wide conductor, similar in dimensions to the PS conductor. Since the stresses on the conductor are significantly smaller than in the PS, pure aluminum stabilizer may be used for the DS conductor. The axial gradient of the field is accomplished by increasing the spacing between the solenoid rings.

The field uniformity in the spectrometer section is achieved with a single layer coil wound with an 8 mm wide cable, tightly packed throughout the winding. In the present baseline the spectrometer section is built in three sections without end flanges between the coils, in a style similar to the CMS solenoid [10]. A 2 layer coil similar in design to the aforementioned gradient section coil has been added to the downstream end to control field uniformity.

The preassembled coils are electrically connected and bolted together in a single cold mass. While a single layer coil allows an efficient use of superconductor for a 1 T field, it adds a complication of a non-compensated return bus. Fortunately, the field of the bus can be made transverse to the solenoid axis and less than 30 Gauss, sufficiently small compared to the required field uniformity of 100 Gauss.

The precision of the magnetic field, both in the gradient and spectrometer sections, are the major design and fabrication challenge for the DS magnet. Detailed sensitivity analysis has established that the length of the coil segment and a missing turn (for example, due to a possible internal joint) are the most critical for field uniformity. A somewhat lesser sensitivity is due to the relative axial position of the coils, while the transverse geometry of the coils after assembly of the support cylinder and final curing (coil radius and ovality) are the least important. A full-fledged tolerance study was performed, based on random choice of geometric parameters of each of the twelve coil sections. The tolerance intervals assumed corresponded to the standards encountered in precision machining. The so-obtained field distributions were statistically analyzed for a large number of cases. The most probable fields in the gradient and spectrometer sections, as well as the peak field deviations were shown to be in all cases well within the field uniformity requirements.

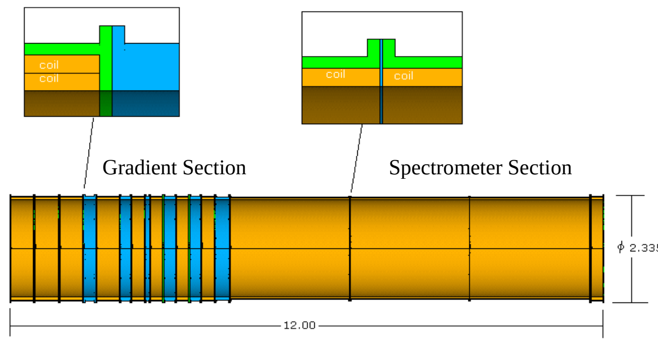

Fig. 5. DS coil layout including blowup of coil-spacer (gradient section) and coil-coil (spectrometer section) interfaces.

VI. Conclusion

A conceptual design of the Mu2e Solenoid system has been completed. The next step is to optimize the design to make the solenoids cost effective. Tolerance studies are continuing to understand the effect of manufacturing sensitivities.

References

[1] R. Tschirhart, "The Mu2e experiment at Fermiab", *Nucl.Phys.Proc.Suppl.* 210-211 (2011) 245-248

[2] J. A. Horak and T. H. Blewitt, Journal of Nuclear Materials **49**, 161 (1973).

[3] M. Yoshida, T. Nakamoto, T. Ogitsu, Q. Xu, T. Itahashi, Y. Kuno, Y. Kuriyama, Y. Mori, B. Qin, A. Sato, K. Sato, and T. Yoshiie, "Low-temperature Neutron Irradiation Tests of Superconducting Magnet Materials Using Reactor Neutrons at KUR," presented at the 2011 International Cryogenic Materials Conference.

[4] V. V. Kashikhin, G. Ambrosio, N. Andreev, M. Lamm, N. V. Mokhov, T. H. Nicol, T. M. Page, V. S. Pronskikh, "Conceptual Design of the Mu2e Production Solenoid Cold Mass," presented at the 2011 Cryogenic Engineering Conference.

[5] ATLAS Central Solenoid Technical Design Report, ATLAS Magnet Project TDR Vol. 4, April 1997.

[6] T. H. Nicol, V. V. Kashikhin, T. M. Page, T. J. Peterson, "Mu2e Production Solenoid Cryostat Conceptual Design," presented at the 2011 Cryogenic Engineering Conference.

[7] V. S. Pronskikh, V. V. Kashikhin, N. V. Mokhov, "Radiation and Thermal Analysis of Production Solenoid for Mu2e Experimental Setup," *Proc. of 2011 Particle Accelerator Conference*.

[8] N. Mokhov and V. Pronskikh, "Mu2e Production Solenoid MARS15 Studies," Mu2e-doc-1060.

[9] "MECO Superconducting Solenoid System Conceptual Design Report", MIT PSFC, June 6 (2002).

[10] CMS, the magnet project: Technical Design Report. CMS Collaboration, CERN-LHCC-97-10, May 199.