Tolerance studies of the Mu2e solenoid system

M. L. Lopes, G. Ambrosio, M. Buehler, R. Coleman, D. Evbota, S. Feher
M. Lamm, V. Kashikhin, G. Moretti, T. Page, M. Tartaglia, *Fermilab*,
J. Miller, *Boston University*
J. Popp, *York College CUNY*
R. Ostojic, *CERN*

***Abstract*—The Muon-to-electron conversion experiment (Mu2e) at Fermilab is designed to explore charged lepton flavor violation. It is composed by three large superconducting solenoids: the production solenoid (PS), the transport solenoid (TS) and the detector solenoid (DS). Each sub-system has a set of field requirements. The tolerance sensitivity studies of the magnet system were performed with the objective to demonstrate that the present magnet design meets all the field requirements. Systematic and random errors were considered on the position and alignment of the coils. The study helps to identify the critical sources of errors and which are translated to coil manufacturing and mechanical supports tolerances.**

***Index Terms*—Solenoid, Superconducting Magnets.**

I. INTRODUCTION

THE Mu2e experiment [1] proposes to measure the ratio of the rate of the neutrino-less, coherent conversion of muons into electrons in the field of a nucleus, relative to the rate of ordinary muon capture on the nucleus. The conversion process is an example of charged lepton flavor violation, a process that has never been observed experimentally. The conversion of a muon to an electron in the field of a nucleus occurs coherently, resulting in a monoenergetic electron (105 MeV) near the muon rest energy that recoils off of the nucleus in a two-body interaction. At the proposed Mu2e sensitivity there are a number of processes that can mimic a muon-to-electron conversion signal. Controlling these potential backgrounds drives the overall design of Mu2e. The overview of the Mu2e experiment can be seen in Fig 1. It is primarily formed by three large solenoid systems: the production solenoid (PS), [2] the transport solenoid (TS), and [3] and the detector solenoid (DS) [4].

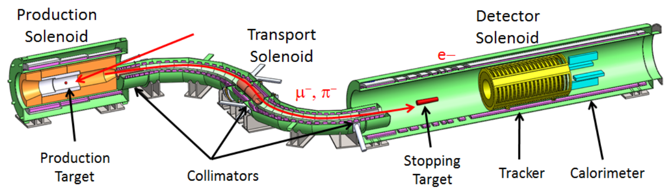

Fig. 1. The Mu2e experiment overview

The magnetic system is formed by 3 coils for PS, 52 Coils for TS and 11 coils for DS. Each subsystem is in a separate cryostat module. TS is divided into two cryostats (named TSu and TSd).

Due to the strict requirements on the field, it is necessary to assess the robustness of the solenoid in presence of geometrical errors in the positions of the coils. Errors can be present both because of the manufacturing tolerances due to the technological fabrication process and because of the mechanical and thermal solicitations present during the operation of the system: particularly, thermal deformations are induced by the cryogenic system.

II. METHODOLOGY

In this work we summarize the changes in the magnetic performance due to misalignment errors in the coils. Two types of errors are studied: systematic and random. Systematic errors are the ones occurring when a group of coils belonging to the same section (TS1, TS2 etc.) has known misalignment errors. Random errors are the ones occurring when each individual coil has an unpredictable deviation from its nominal position. In the case of random errors, each coil is allowed to move in one particular direction. The field is calculated for each geometrical configuration. The process is repeated 100 times, with different individual displacement. The maximum displacements of the coils are limited to a value specified in each case.

For the DS a similar approach was used for the random errors. However, given its cylindrical symmetry some errors were suppressed from the study.

III. TRANSPORT SOLENOID TOLERANCES

The most critical areas of the TS are the straight sections. The magnetic field requirements are described in [1]. The magnetic requirements on those regions are such that the longitudinal field gradient has to be always negative. Positive gradient could potentially trap particles. Figures 2-4 show the longitudinal filed gradient inTS1, TS3 and TS5 (the three straight sections of TS) when the coils are at the nominal position. For each section, the gradient is calculated in five different azimuthal points.

The tolerances on the position (radial, vertical and longitudinal) and angles (yaw and pitch) were studied. Figures 5-7 show variations of the longitudinal gradient in TS1, TS3 and TS5 respectively when the TS coils have errors of ± 10 mm applied to the radial position of the coils. Random errors of up to 10 mm are very larger compared to the typical manufacturing tolerances. The results show that the magnetic design is very robust because, even in the presence of large errors, the longitudinal gradient in the TS straight sections keeps negative. In fact, Table 1 summarizes the results of all the errors studied and the maximum achieved gradient.

TABLE I

SUMMARY OF MAXIMUM GRADIENT IN THE STRAIGHT SECTIONS AND ERROR TYPES.

Error type		**Maximum logitudinal gradient (T/m)**		
		TS1	**TS3**	**TS5**
Radial (mm)	**10**	-0.072	-0.072	-0.083
	2	-0.114	-0.106	-0.115
Vertical (mm)	**10**	-0.103	-0.082	-0.104
Longitudinal (mm)	**10**	-0.023	-0.009	-0.060
	2	-0.111	-0.096	-0.109
Pitch (mrad)	**10**	-0.120	-0.092	-0.116
	2	-0.124	-0.112	-0.120
Yaw (mrad)	**10**	-0.108	-0.086	-0.105
	2	-0.121	-0.107	-0.119

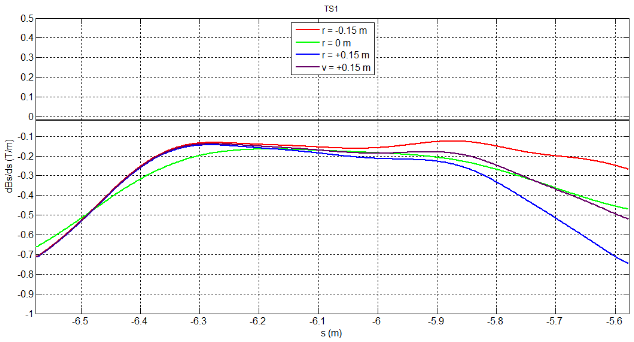

Fig. 2. Nominal longitudinal gradient along TS1.

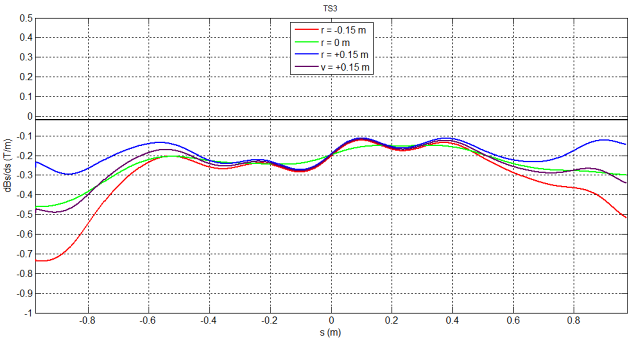

Fig. 3. Nominal longitudinal gradient along TS3.

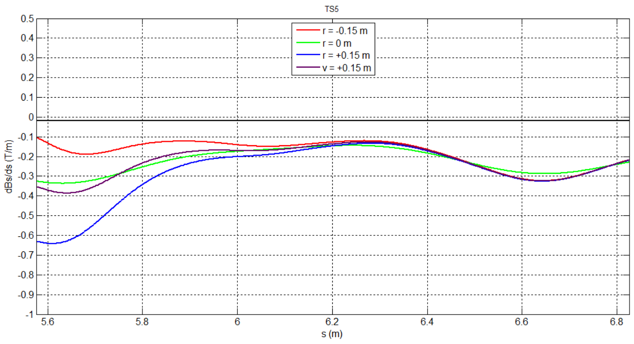

Fig. 4. Nominal longitudinal gradient along TS5.

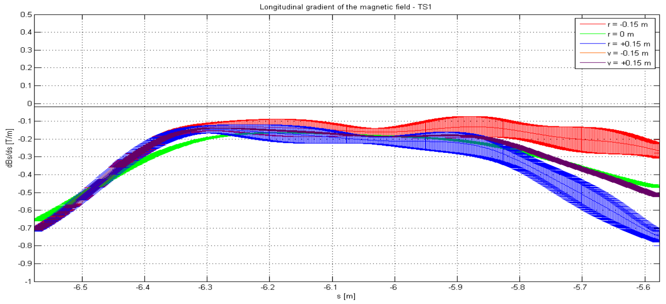

Fig. 5. Longitudinal field gradient along TS1 when radial errors of ± 10 mm are present.

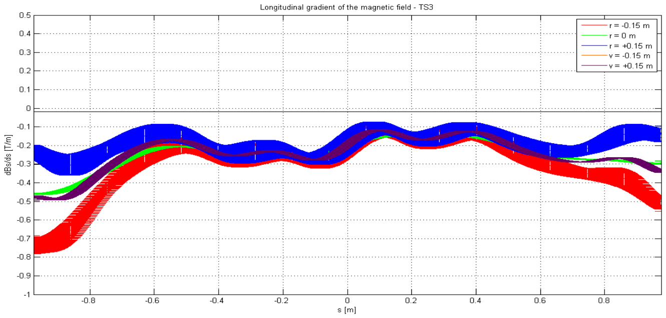

Fig. 6. Longitudinal field gradient along TS3 when radial errors of ± 10 mm are present.

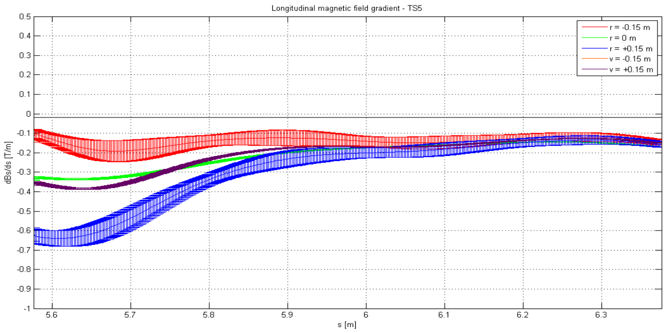

Fig. 7. Longitudinal field gradient along TS5 when radial errors of ± 10 mm are present.

Systematic errors on the TS coils were also studied. These errors, however, have a much smaller impact in the magnetic performance. In particular, the systematic changes needed to correct the magnetic center position [5] do not cause any violation of the magnetic requirements. As an example of systematic error, Figure 8 shows the field gradient in TS1 when TS1 coils are bent vertically by 1^o.

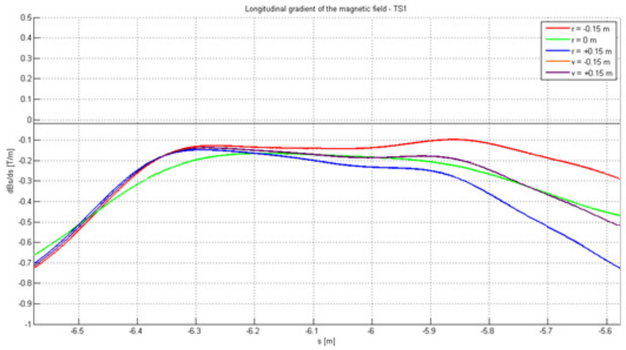

Fig. 8. Longitudinal field gradient along TS1 when the coils are bent vertically by 1^o.

IV. DETECTOR SOLENOID TOLERANCES

The DS is mainly divided into three sections: DS1 (gradient region), DS2 (transition region), DS3-4 (spectrometer and calorimeter region). The magnetic field in these three regions can be seen in figure 9. The general requirement for the DS is that the longitudinal field gradient has to be negative. Figure 10 shows the longitudinal field gradient in these regions.

As can be seen in figure 10, at R=0.7 m the gradient is, at times, often positive. That happens because the bore radius of the coils is 1.05 m, therefore at R=0.7 m is relatively close to the coil's bore and the ripple is given, essentially, by the space in-between the coils. In the same way, at R=0.4 m in the DS1 region, a positive gradient is present. This is due the fact that the TS coils have a bore radius of 0.405 m and TS and DS have an overlap as can be seen in figure 1.

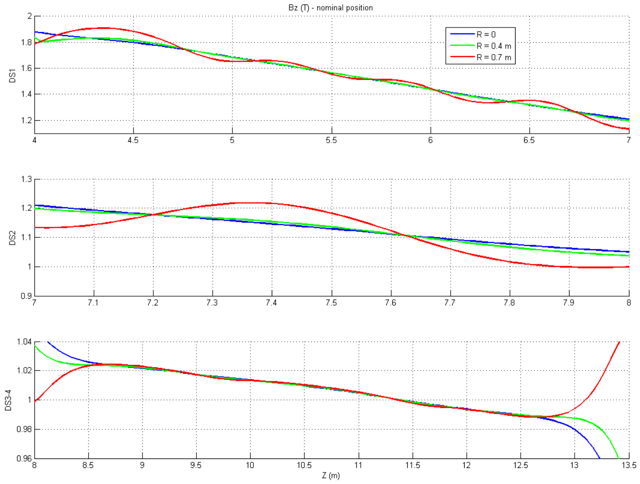

Fig. 9. Longitudinal field in the DS when the coils are at the nominal position.

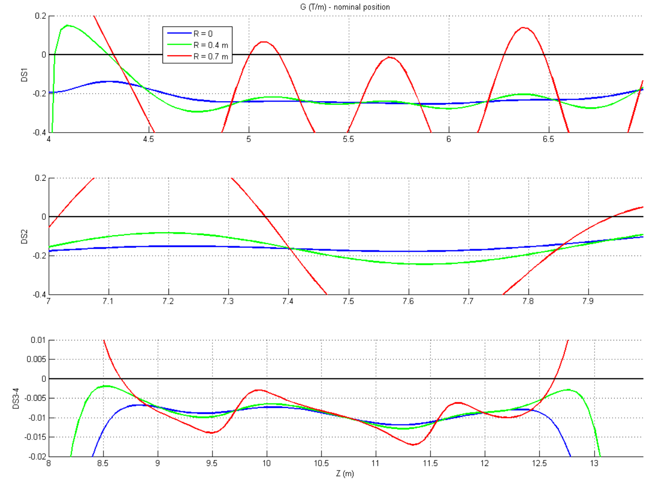

Fig. 10. Longitudinal field gradient in the DS when the coils are at the nominal position.

A. *Cable thickness tolerances*

The DS has 11 coils. They are winded from 2 conductors: DS1 and DS2 types. DS1-type has a bare thickness of 5.25 mm, while DS2-type 7.0 mm (figure 11). Around each conductor is applied 0.250 mm insulation. The coils are winded in the hard-bend mode. Eight of the coils use the DS1-type conductor. The three coils located on the DS3-4 region use the DS2-type conductor. Given the number of turns in each coil, small errors on the conductor thickness will have a direct impact on the length of each coil.

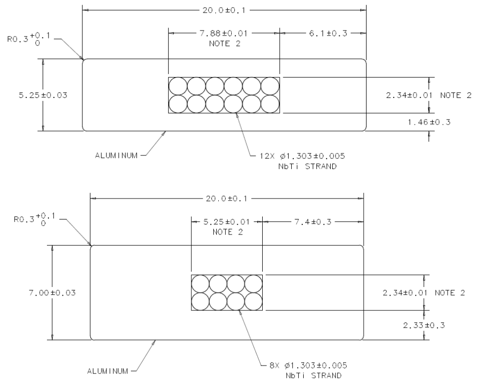

Fig. 11. Top: DS1-Type conductor cross-section. Bottom: DS2-Type conductor cross-section.

The tolerances on the conductor were studied. The only noticeable variation detected is on the longitudinal gradient on the DS3-4 region. The nominal negative gradient there is fairly weak. Figure 12 shows an example of the variation of the longitudinal gradient on that region when the cable thickness can vary ± 50 μm. The negative gradient should be guaranteed up to R = 0.4 m.

As can be seen, 50 μm variation in the cable is the acceptable limit for the thickness of the cable. The manufacturing specification was set in 30 μm.

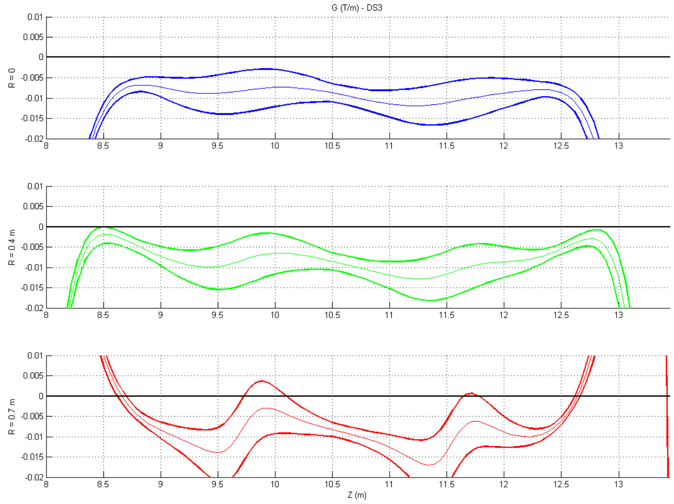

Fig. 12. Longitudinal field gradient in the DS3-4 region when the cables have a variation of ± 50 μm.

B. *Systematic change on the position of the superconductor inside the Al matrix*

In this study it is assumed that the superconducting part of the cable could be displaced with respect to the Aluminum matrix. A systematic change of the position could result in a higher density of turns in one side or the other of the coils. It was considered that only the 3 coils made of DS2-type conductor: coils # 8, 9 and 10 would be affected by that. For this study each individual turn was modeled. Each coil has 244 turns.

Several configurations of coils densities were simulated including linear and quadratic distributions. In all the cases, the variation of the superconductor inside the Al matrix was assumed to be ± 0.3 mm (according to the cable specifications shown in figure 11).

The results have shown that, at this level of errors, no positive gradients (up to R = 0.4 m) arise from this problem.

C. Mechanical tolerances for the coils

In this study the coils were assumed to have perfect length and winding. The coils are positioned off their nominal values. Given the cylindrical symmetry of the problem, changes in the X axis are equivalent to changes in Y axis. The same way, changes in the Pitch and Yaw of the coils are equivalent. Like in the previous section, given the level of errors that was assumed during the analysis, the only noticeable differences can be seen in the longitudinal gradient of the DS3-4 region.

Figures 13 - 15 show the worst cases among all the cases studied. It will be required that the coils be positioned better than ± 5 mm radially and ±1 mm longitudinally. The coils must be aligned within ±2 mrad.

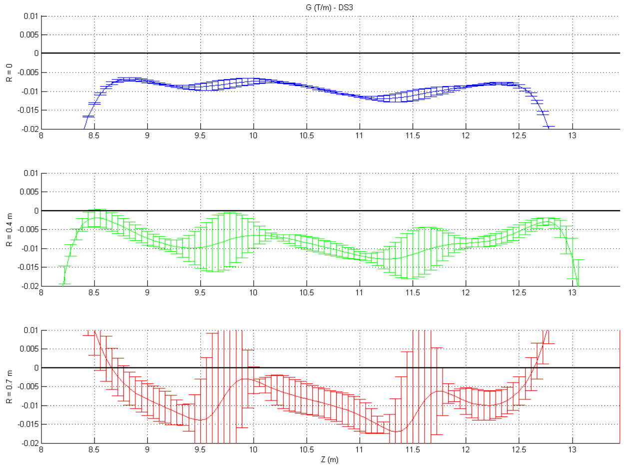

Fig. 13. Longitudinal field gradient in the DS3-4 region when the coils have errors of ± 10 mm in the radial direction.

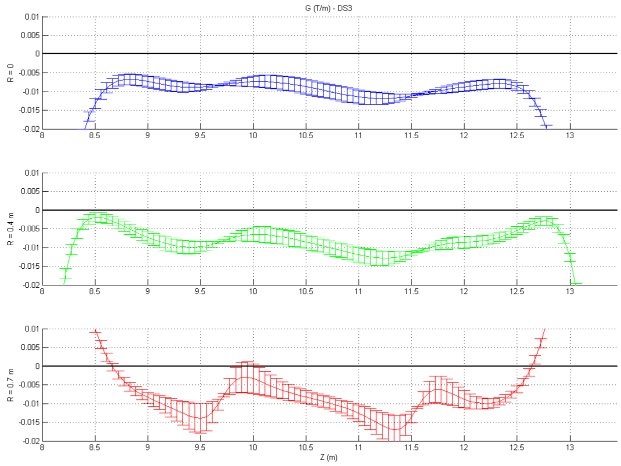

Fig. 14. Longitudinal field gradient in the DS3-4 region when the coils have errors of ± 1 mm in the longitudinal direction.

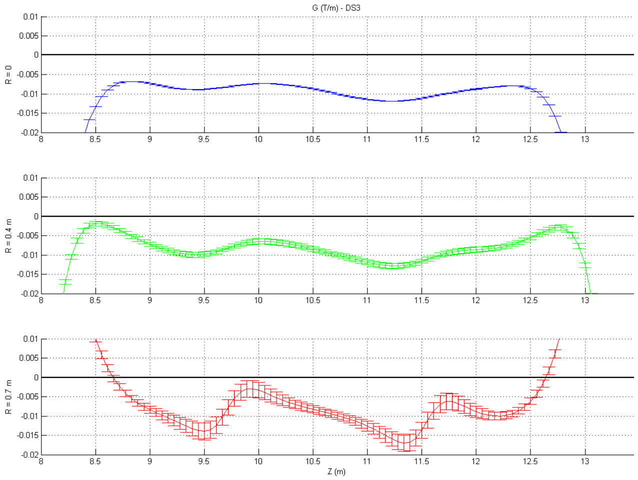

Fig. 15. Longitudinal field gradient in the DS3-4 region when the coils have errors of ± 2 mrad in the pitch angle.

V. CONCLUSIONS

A sensitivity study was performed on the TS and the DS. This study helped to identify the weak spots in the design and correct them.

The most sensitive areas of the TS are the straight sections where positive gradients could potentially trap particles, being a source for backgrounds. The present TS magnetic design has enough margins that make it very robust. Even in the presence of large positioning errors the TS fulfills the magnetic requirements. The mechanical tolerances for the TS coils are given by other sources [5].

The most sensitive region of the DS is the spectrometer and calorimeter regions (DS3-4). Errors on the coils in this area could create a positive gradient that needs to be avoided for the reasons described before. The design is robust otherwise, even with larger errors.

The tolerances on the DS conductors are adequate. It will be required that the DS coils to be positioned better than ± 5 mm radially and ± 1 mm longitudinally. The coils must be aligned within ± 2 mrad.

REFERENCES

[1] Mu2e Collaboration, "Mu2e Conceptual Design Report", arXiv:1211.7019, http://arxiv.org/abs/1211.7019

[2] V. V. Kashikhin et al., “Conceptual Design of the Mu2e Production Solenoid Cold Mass,” Advances in Cryogenic Engineering, AIP Conf. Proc., 1434, 893-900 (2012).

[3] G. Ambrosio et al. – "Challenges and Design of the Transport Solenoid for the Mu2e experiment"- this conference;

[4] S. Feher et al. – "Reference Design of the Mu2e Detector Solenoid" - this conference.

[5] M. Lopes et al. – "Studies on the Magnetic Center of the Mu2e Solenoid System"- this conference