

Mu2e MAGNETIC MEASUREMENTS

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Abstract

The Mu2e experiment at Fermilab is designed to explore charged lepton flavor violation by searching for muon-to-electron conversion. The magnetic field generated by a system of solenoids is crucial for Mu2e and requires accurate characterization to detect any flaws and to produce a detailed field map. Stringent physics goals are driving magnetic field specifications for the Mu2e solenoids. A field mapper is being designed, which will produce detailed magnetic field maps. The uniform field region of the spectrometer volume requires the highest level of precision (1 Gauss per 1 Tesla). During commissioning, multiple magnetic field maps will be generated to verify proper alignment of all magnetic coils, and to create the final magnetic field map. In order to design and build a precise field-mapping system consisting of Hall and NMR probes, tolerances and precision for such a system need to be evaluated. This paper presents a design for the Mu2e field mapping hardware, and discusses results from OPERA-3D simulations to specify field mapper parameters.

INTRODUCTION

The Mu2e experiment [1] aims to probe the Intensity Frontier to discover new physics beyond the Standard Model (SM).

Muon-to-Electron Conversion

The goal of Mu2e is to measure the ratio of the rate of neutrinoless, coherent conversion of muons to electrons in the field of a nucleus, relative to the rate of ordinary muon capture:

$$R_{\mu e} = \frac{\mu^- + A(Z, N) \rightarrow e^- + A(Z, N)}{\mu^- + A(Z, N) \rightarrow \nu_\mu + A(Z-1, N)}. \quad (1)$$

The conversion process is an example of charged lepton flavor violation (CLFV), a process that has never been observed experimentally.

The conversion of a muon to an electron in the field of an aluminum nucleus results in a mono-energetic electron near the muon rest energy ($E_e = 105$ MeV) that recoils off of the nucleus in a two-body interaction. This provides a very clean experimental signature, which strongly suppresses background electrons near the conversion energy from muons decaying in-orbit around an aluminum nucleus (Fig. 1).

The goal of the Mu2e experiment is to detect a CLFV signal with a single-event-sensitivity of $2.5 \cdot 10^{-17}$.

As a high-precision experiment, Mu2e has a unique discovery potential which in many areas surpasses the

capability of the LHC detectors at CERN. For example, a typical supersymmetry (SUSY) signal would yield a ratio of

$$R_{\mu e} \approx 10^{-15}. \quad (2)$$

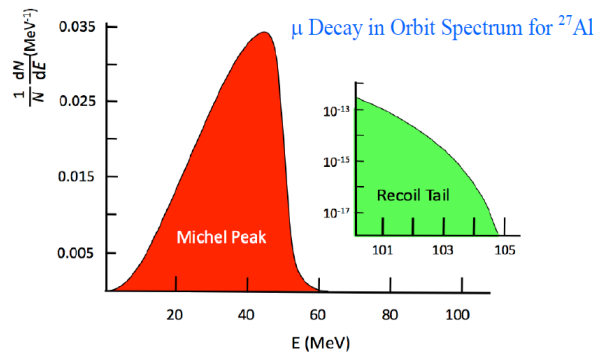


Figure 1: Electron energy spectrum for muon-decay-in-orbit in aluminum. The recoiling nucleus results in a small tail (blown up on the right) that extends out to the conversion energy [1].

This would result in a sample of 40 signal events with only minimal background (<1 event) accumulated over a period of 3 years. This example also illustrates the importance of meeting all the design specifications for the Mu2e detector, in particular the solenoids.

The Mu2e Detector

The Mu2e detector consists of three main superconducting solenoid components (Fig. 2).

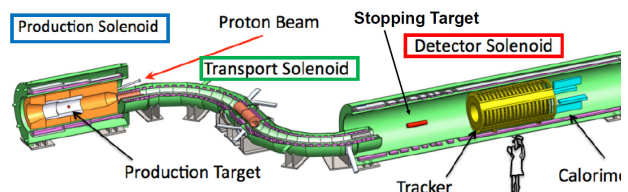


Figure 2: Schematic view of the Mu2e detector with Production Solenoid (PS), Transport Solenoid (TS), and Detector Solenoid (DS).

The Production Solenoid (PS) receives an 8 GeV proton beam, which impacts on the tungsten production target. The PS maintains a strong axial gradient solenoid field (4.6 T to 2.5 T) which magnetically reflects and focuses the emerging charged pions and muons further downstream towards the Transport Solenoid (TS). The TS consists of a set of superconducting solenoids and toroids to form a magnetic channel, which transmits low energy negatively charged muons downstream towards the

Detector Solenoid (DS). Absorbers and collimators within the TS eliminate high energy negatively charged particles, positively charged particles, and neutrals. The DS contains the stopping target, which is built from thin aluminum foils to capture low energy negatively charged muons. A graded field section (2 T to 1 T) collects conversion electrons and guides them towards the tracker and calorimeter detectors, which are installed in a uniform 1 T field.

MAGNETIC FIELD VALIDATION

Stringent physics goals are driving magnetic field specifications for the Mu2e solenoids [2]. In order to efficiently transport negatively charged muons to the stopping target, while at the same time suppressing potential backgrounds, magnetic field requirements need to be validated through magnetic and other measurements.

As a first step, all superconducting coils need to pass pre-assembly verification at the coil manufacturer. This includes basic geometric and electrical measurements, as well as low current non-superconducting measurements (PS and DS coils). TS coils will be assembled into 2-coil modules and tested under superconducting conditions at Fermilab.

Once the detector is in a close-to-final assembly stage at Fermilab, in-situ sensors will be installed to monitor long-term trends. This will include fiber optic coil displacement sensors to assure coil alignment at the level of millimeters and milliradian [3]. This step also includes

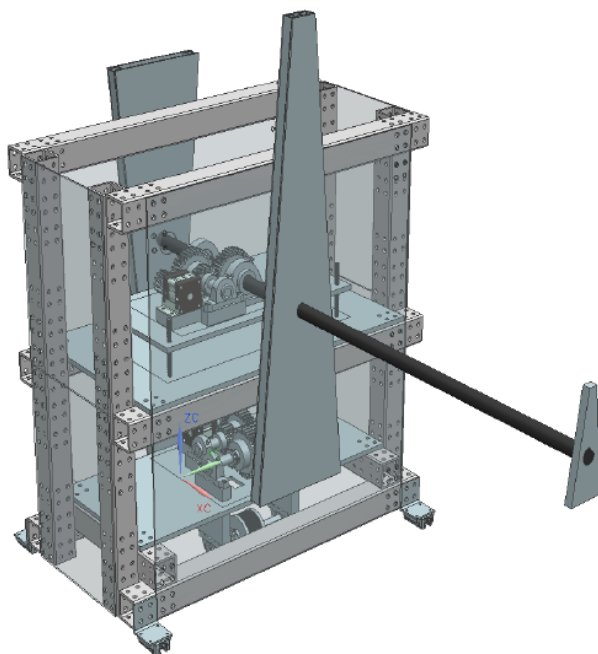


Figure 3: Mu2e DS field mapper design. Probes will be installed on two propeller arms. Propellers rotate to provide azimuthal coverage. The field mapper moves along the magnet axis to provide axial coverage.

the permanent installation of 3D Hall probes to monitor long-term magnetic field stability at the level of 1-5% in the PS, TS, and DS [3].

In order to verify efficient transfer of low energy particles from the production target through the TS to the stopping target, a setup that transmits and detects low energy electrons is also envisioned.

A field mapper is being designed, which will produce detailed magnetic field maps of the PS and DS volumes. The uniform field region of the DS spectrometer volume requires the highest level of precision (1 Gauss per 1 Tesla, i.e., 0.01% precision) and will be the main focus of this article. For comparison, the general field mapping precision for the tracking volume of the CMS detector was 0.07% [4].

Figure 3 illustrates an early design iteration for the Mu2e DS field mapper. A precisely arranged set of Hall and NMR probes will be mounted on a carriage to survey the magnetic field both azimuthally and axially. An axial “Z Drive” will move the carriage along precisely surveyed rails installed along the magnet axis, and stop at predefined positions. At each location the propeller arms will rotate and stop at predefined angles to measure the magnetic field. To minimize positioning inaccuracies, linear and angular encoders coupled to a feedback control

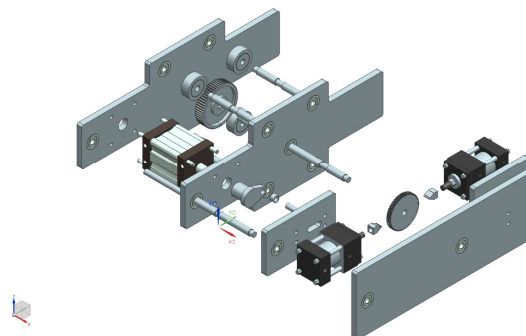


Figure 4: Z Drive components.

system can compensate for gear backlash and wear. Additional active actuators can be added to compensate for rail defects.

Figure 4 shows a detailed schematic view of the Z Drive. The drive must engage a toothed belt to pull the measurement system along the z-axis of the DS with a step size of no more than 25 mm. Additionally the z position of the system must be known to within 0.1 mm. Furthermore, the entire system cannot contain components with a relative magnetic permeability significantly different from 1 to avoid perturbing the magnetic field.

OPTIMIZATION STUDIES

In order to accurately simulate and reconstruct events for the Mu2e experiment, precise knowledge of the value of the magnetic field at any point within the detector is required. Our magnetic measurements will yield a set of

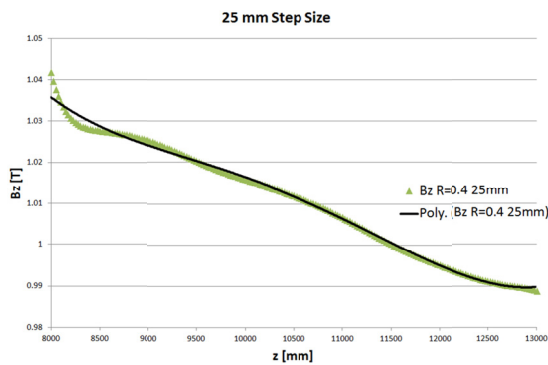


Figure 5: 25 mm step size with 4th degree polynomial fit.

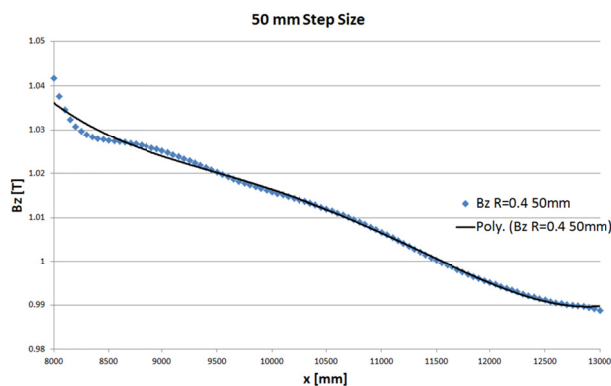


Figure 6: 50 mm step size with 4th degree

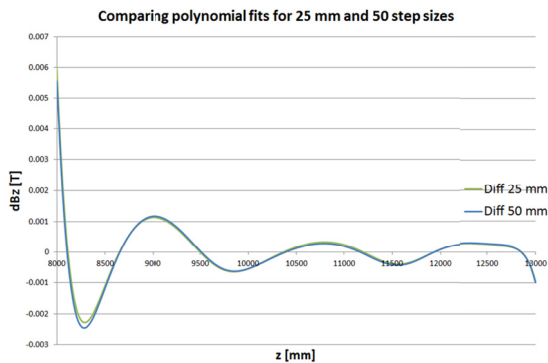


Figure 7: Comparing fit for 25 mm and 50 mm step sizes.

discrete measurement points. The way information is extracted from this map and served to simulation and reconstruction tools will have a large impact on software performance and the accuracy of the physics results.

Using a simulation of the Mu2e magnetic field (OPERA-3D [5]), we study the effect of varying the axial step size between 25 mm (Fig. 5) and 50 mm (Fig. 6). In both cases a 4th degree polynomial fit is used to approximate a continuous magnetic field. Figure 7 compares fitted values with true values of the magnetic field. The fit deviates largely ($> 1\text{G}$) from the true value.

To further improve the quality of the fitting technique, the application of Chebychev polynomials is envisioned since they perform better when approximating continuous functions, while at the same time avoiding Runge's phenomenon [6].

CONCLUSION

Preliminary designs for Mu2e field mapping hardware have been developed. Initial studies to estimate precision of individual magnetic measurements are underway. An analytical treatment of measurement data using polynomial interpolation is being developed.

Field mapping of the Mu2e solenoids is scheduled to commence in 2019. Mu2e will become fully operational in 2020.

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