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 a crucial component of Mu2e and requires accurate characterization to detect any potential flaws and to produce a detailed 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. To generate a final magnetic field map of the Mu2e solenoids, a continuous field has to be extracted from a discrete set of measurement points. A design for the Mu2e field mapping hardware, and results from simulations to specify parameters for Hall and NMR probes are presented. A fitting procedure for the analytical treatment of our expected magnetic measurements is introduced.

Index Terms—Solenoids, Superconducting Magnets, Magnetic field measurement

I. INTRODUCTION

The MU2E experiment [1] aims to probe the Intensity Frontier to discover new physics beyond the Standard Model (SM).

A. 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:

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

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 \( E_e = 105 \text{ MeV} \) 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 \( 2.5 \times 10^{-17} \).

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 (SU3) signal would yield a ratio of \( R_{\mu e} \approx 10^{-15} \). 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.

B. The Mu2e detector

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

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 particles, while the Transport Solenoid (TS) and Detector Solenoid (DS) are used to transport and focus particles to the detector region.
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.

II. 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 in the TS to assure coil alignment at the level of millimeters and milliradian [3]. This step also includes 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 [1].

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].

Fig. 3 illustrates an early design iteration for the Mu2e 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.

III. SENSITIVITY AND PRECISION ESTIMATES

In order to achieve “1 G per 1 T” accuracy for the volume field map in the DS, probes need to be precisely positioned. Probe positioning effects were studies with the OPERA-3d Post-Processor tool [5]. Fig. 4 and Fig. 5 study the effect of probe positioning inaccuracies along the central axis of the DS. In order to achieve <1 G accuracy, probes need to be positioned with an accuracy of <400 µm. Similarly, for probe positioning along the magnet axis at a radius of R = 0.8 m, probes would need to be positioned with an accuracy of <100 µm (Fig. 6 and Fig. 7).

Radial positioning requirements appear to be less stringent. Fig. 8 and Fig. 9 examine the effect of radial probe displacement in the center of the DS tracking volume. The effect of a missing turn in the central portion of the tracking volume in the DS was studied. This part of the DS consists of 3 coils each 1.83 meters in length with an inner radius of ~1 meter. Each single-layer coil contains 244 turns of superconducting cable. For this study, a single turn in the center of the middle coil was removed from the simulation. This (purely hypothetical) case would result in a field deviation of ~70 G (Fig. 10).

IV. ANALYTICAL TREATMENT OF MEASUREMENTS

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 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.

A single global grid to parameterize the Mu2e magnetic field with the accuracy required for simulation and reconstruction would be difficult to generate and handle. Instead, we propose to follow the method of cubic spline interpolation (CSI) [6]. Originally, spline was a term for elastic rulers that were bent to pass through a number of predefined points ("knots"). These were used to make technical drawings for shipbuilding and construction by hand.

For example, to mathematically model the magnetic field of Mu2e from a discrete set of \( n+1 \) measurements in one dimension \((z_i, B_i)\) (where \( i = 0, 1, \ldots, n \)), a polynomial of degree 3 (cubic spline) will take a shape that minimizes the bending under constraint of passing through all measurement points.

This method naturally lends itself to model magnetic fields, since field lines naturally follow a smooth curve in Mu2e.

In order to minimize the uncertainties introduced by the CSI method, individual magnetic measurements need to be as precise as possible (accurate placement of sensors, redundant measurements, high-precision probes) and the distance between individual measurement points as small as experimentally possible. Given the specification of "1 G per 1 T", together with the assumption on the precision of individual measurements, the required density of measurement points can be estimated. This will define how many probes are necessary for the Mu2e field mapper and where they need to be mounted.

V. CONCLUSION

Conceptual designs for Mu2e field mapping devices have been developed. Initial studies to estimate precision of individual magnetic measurements are underway. An analytical treatment of measurement data using cubic spline interpolation is being developed and will ultimately yield specific design recommendations for the field mapper.

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

REFERENCES

Fig. 4. Magnetic flux density ($B$) in the DS along the central axis.

Fig. 5. Magnetic field deviation ($dB$) for a 400 $\mu$m shift along the central axis.

Fig. 6. Magnetic flux density ($B$) in the DS along the magnet axis at $R = 0.8$ m.

Fig. 7. Magnetic field deviation ($dB$) for a 100 $\mu$m shift along the magnet axis at $R = 0.8$ m.

Fig. 8. Magnetic flux density ($B$) in the DS along the radial axis in the center of the tracking volume.

Fig. 9. Magnetic field deviation ($dB$) for a 3 cm shift along the radial axis.

Fig. 10. Field deviation in case of a missing turn in the center of the DS tracking volume.