Thu-Af-Po4 ID 184

FERMILAB-PUB-17-633-TD
ACCEPTED

Mu2e Solenoid Field Mapping System Design

S. Feher, P. DeLurgio, L. Elementi, H.W. Friedsam, J. J. Grudzinski, M.J. Lamm, J.M. Nogiec, C. Orozco, B. Pollack, M.H. Schmitt, T. Strauss, R.L. Talaga, R.G. Wagner, J.L. White, H. Zhao

***Abstract*— The Mu2e experiment at Fermilab plans to search for charged-lepton flavor violation by looking for neutrino-less muon to electron conversion in the field of the nucleus. A complex solenoid system and precise knowledge of its magnetic field play a major role in the experimental approach Mu2e has chosen. It is essential to map the solenoid field up to 10^{-4} accuracy. This article describes the design of the Field Mapping System Mu2e will use to measure the magnetic field. Two different mechanical mapper systems, a survey based position determination of the in-house calibrated 3D Hall probes, a motion control system, and a data acquisition and readout system are presented.**

***Index Terms*—Solenoid Magnet, Superconducting, Magnetic Field Map.**

I. INTRODUCTION

THE MU2E experiment is located at Fermilab [1]. The goal of the experiment is to search for evidence of new physics beyond the Standard Model [2] of particle physics by searching for charged-lepton flavor violation (CLFV) [3]. The aim is to observe, as the evidence for CLFV, coherent, neutrino-less muon to electron conversion in the field of the nucleus with an unprecedented sensitivity.

The Mu2e muon production utilizes the Fermilab accelerators to produce a primary 8 GeV proton beam. The proton beam is guided to a target inside the Production Solenoid (PS) to produce secondary particles (Fig. 1). This target area is surrounded with a strong graded magnetic field to collect and guide the muons emerging from the decay process of the secondary particles into a S-shaped muon channel, the Transport Solenoid (TS).

The toroidal field generated by the TS together with collimators provides momentum and charge selection for the muon beam. The muon beam hits the stopping target that is located in the Detector Solenoid (DS) bore. Electrons emerging from the stopping target are further guided into the spectrometer region where their momentum is measured by the tracker and further downstream their energy is measured by the calorimeter.

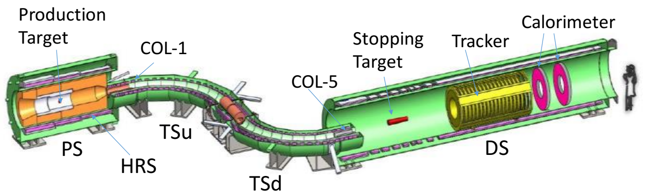

Fig. 1. Mu2e Solenoid system.

Precise knowledge of the magnetic field is crucial in the muon transport process and in the electron momentum measurement. It is planned to map the solenoid field with calibrated 3D Hall probes to 10^{-4} accuracy. This article describes the design of the Field Mapping System (FMS) Mu2e will use to measure the magnetic field in the Mu2e solenoid system.

First the magnetic field requirements are described, followed by the description of the two-different field mapper mechanical designs, the survey and alignment system, the motion control system, and Extensible Magnetic Measurement Application (EMMA) readout system and software.

II. MU2E SOLENOID FIELD MAPPING REQUIREMENTS

The Field Mapping System must perform several functions across the solenoid system. A “map” refers to recording a sequence of magnetic measurements, in a relatively short time frame under stable magnet operating conditions, by utilizing a precise mechanism to position a set of discrete field measurement sensors through the volume of interest:

1. Inside a Heat and Radiation Shield (HRS) that is used to protect the PS (see Fig 1), map the B-field over the PS volume on axis and at a fixed radius as close as possible to the HRS aperture clearing any obstacles, versus axial position and azimuthal angle. The axial range is between the first TS collimator (COL-1) entrance and the end of the PS cryostat. The peak PS field on axis is designed to be in the range of 4.6 T to 5 T; the downstream negative gradient is designed to be within 5% of a uniformly graded field to 2.5 T at the PS-TS interface. The TS field inside COL-1 is designed to have a gradient not less than or equal to 0.02 T/m, and absolute strength within 5% of the nominal value. In the PS and COL-1 region the measured |B| field value needs to be known with 0.1% accuracy and the angular error of the B field vector needs to be less than 1 mrad. The location of the B-field vector needs to be measured to within 1 mm accuracy relative to external fiducials.
2. Map the B-field in the collimator (COL-1 and COL-5) aperture, as close as possible to the collimator inner bore, versus axial position and azimuthal angle (at minimum, on both sides

---

S. Feher is with the Fermi National Accelerator Laboratory, Batavia, IL 60510 USA (e-mail: fehers@fnal.gov).

L. Elementi, H.W. Friedsam, M.J. Lamm, J.M. Nogiec, C. Orozco, T. Strauss are with Fermi National Accelerator Laboratory, Batavia, IL 60510 USA.

P. DeLurgio, J. Grudzinski, R.L. Talaga, R.G. Wagner, J.L. Wjite and H. Zhao are with Argonne National Laboratory, 9700 Cass Avenue, Argonne, IL 60439 USA.

B. Pollack and M.H. Schmitt are with Northwestern University, 633 Clark St, Evanston, IL 60208 USA.

Template version 7.2a, 04 August 2016

This document was prepared by Mu2e collaboration using the resources of the Fermi National Accelerator Laboratory (Fermilab), a U.S. Department of Energy, Office of Science, HEP User Facility. Fermilab is managed by Fermi Research Alliance, LLC (FRA), acting under Contract No. DE-AC02-07CH11359.

of the horizontal and vertical mid-planes). The experimental goal in the PS and collimator region is the same.

3. Map the B-field throughout the volume of the DS at several radii, from (close to) “on axis” to a maximum radius of 0.8 m, versus axial position and azimuthal angle. The DS field mapping has the most demanding requirements, which are imposed by the precision tracking and momentum determination in the spectrometer region. The experimental goal in the tracking and calorimeter regions is: the measured |B| field value needs to be known with 0.01 % accuracy and the angular error of the B field vector needs to be less than 0.1 mrad. The location of the B-field vector needs to be measured to within 1 mm accuracy relative to external fiducials. In other regions of the DS, the goal to measure the |B| field value is relaxed to 0.1%.

The measured B-field map will consist of a set of discrete (measured) data points. One data point is a set of (Bx, By, Bz) values at (x, y, z) coordinate location. The FMS needs to provide the field map in a functional form to the Mu2e experiment in a format where the field map function values can be calculated at any x,y,z location within the volume of the solenoid aperture. The error on the field map function values needs to have the same accuracy as the measured data points described above. To establish the absolute field strength to this level, Nuclear Magnetic Resonance (NMR) probes must be used to measure and constrain the resulting fit. Planned calibration runs involve operating the DS at 50% and 70% and 100% of the nominal operating field, so the DS field mapper must be able to measure over this operating range.

All field measurements must capture the simultaneous values of solenoid system operating currents. The field mapping will be done in ambient temperature controlled air, not vacuum.

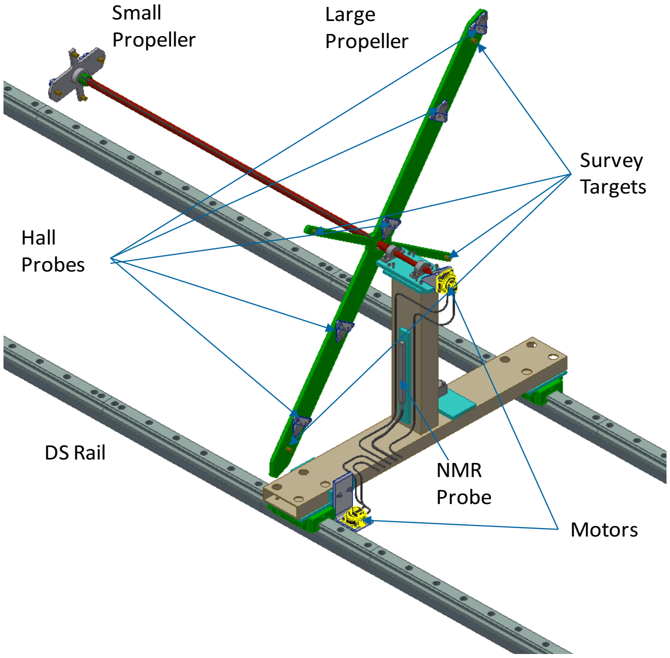

Fig. 2 DSFM is shown.

III. FIELD MAPPER DESIGN

Several Field Mapping devices have been built and used [4-6] – utilizing arms to mount 3D Hall probes, rotate and translate them along the bore axes to get data points everywhere in the solenoid volume – like the Mu2e Field Mapper (FM). Besides the unique solutions the Mu2e FM design took to accommodate the geometrical and other constraints (see section II) there is one major improvement. To get precise knowledge of the B-field vector direction and its location relative to external fiducials the movement of the Mu2e FM Propeller (see Fig. 2) where the Hall probes are mounted is tracked with a laser based alignment system. This approach is more involved in the data taking phase but makes it easier to build the mechanical components and will not rely on precise pre-survey and rigidity of the mechanical system and the use of encoders to figure out the exact location and the angle of the Hall probes.

Both Field Mappers will rotate their propellers +/-180° ($\emptyset$) with the means to position and hold the mapper at discrete locations in $\emptyset$ over the full range $\emptyset=2\pi$. The mapper will be driven along the longitudinal (z-axis) with the means to position and hold the mapper at pre-determined finite increments.

A. Detector Solenoid Field Mapper

The Detector Solenoid Field Mapper (DSFM) mechanical system provides the means for positioning the Hall probes at discrete locations within the solenoid magnetic field (see Fig. 2). The sensors are mounted to large and small propellers of the DSFM which travels on rails located internally in the DS solenoid. The DSFM will map the 3D field components throughout the volume of the DS using five 3D Hall probe sensors located on the large propeller arm at five different radial locations. DSFM will also map the interior of the beam collimator at the entrance to the DS (COL-5) using three 3D Hall probes located on the small propeller arms at three different radial locations.

To assure proper transfer of the Hall probe calibration data from the Hall probe calibration equipment to the DSFM a kinematic mounting technique is used. The large and small propellers are machined to receive the kinematic mount. The detailed description of the kinematic mount is discussed in [7].

The DSFM will include a NMR probe mounted to the mapper base and coincident (radially) with one of the 3D Hall probes providing in-situ measurements of the absolute magnitude of the B-field.

A rack and pinion system was chosen to drive the DSFM by utilizing the DS internal rail system. The DS internal rail system is modified by attaching a non-magnetic gear rack to the side of the rail mounting bar. Non-magnetic piezoelectric motors rotate the propellers and drive the DSFM along the DS rails.

The design is made up of a combination of fabricated and commercially purchased components. Only components made of non-magnetic material were chosen (see Table I).

The cables for the Hall probes will run along the propellers to the rotating shaft and will be looped just below the shaft to provide the necessary slack to allow the 180-degree rotation. The cables need to be routed from the DFSM out to the data acquisition (DAQ) and control electronics which will be located outside of the DS. A cable carrier and tray below the main frame of the DSFM is utilized to provide adequate folding of the cable

TABLE I
FIELD MAPPER MAJOR COMPONENTS

Component	Manufacturer	Description
Ultrasonic motor	Shinsei Co.	PN: USR60-S3N
Survey target	Edmund Optics	12.7 mm clear aperture survey target (PN: RetroReflector46-170
Bearing	THK	Non-magnetic heavy duty bearing
Shaft		Aluminum
Propellers		Aluminum
Carriage/frame		Aluimium
NMR probe	Metrolab	PN: PT2026
Coupling		Aluminum
Gear rack		Brass
Pinion Gear		Stainless Steel
DS Rail	THK	HPM75 Stainless Steel

PN: Part Number

during the DSFM movement. This configuration was carefully tested to confirm that the loads on the motors are sufficient to drive the DSFM.

B. Production solenoid Field Mapper Design

The Production Solenoid Field Mapper (PSFM) mechanical system provides the means for positioning the 3D Hall probes at discrete locations within the solenoid magnetic field. The sensors are mounted to the propeller of the PSFM which travels on rails located externally to the PS solenoid. The PSFM will map the 3D field components throughout the volume of the PS inside the Heat and Radiation shield at three radial locations using three 3D Hall probe sensors. These sensors are located on the propeller arm. The PSFM will also map the B- field inside the TS collimator (COL-1).

The main component of the PSFM is the carbon fiber tube assembly which controls the deflection of the end probes (see Fig. 3). The deflection requirement is based upon the requirement that the probes and related structure do not contact the collimator. Based on the allowable space, the tube assembly is required to have a very high stiffness to weight ratio as the self-weight of the tube drives the deflections. Considering the need for non-magnetic materials, a tube constructed from ultrahigh modulus carbon fiber is required. The effective modulus of the as-built composite tube will need to be greater than 225 GPa which is obtainable with ultrahigh modulus fibers and a high fiber fill ratio.

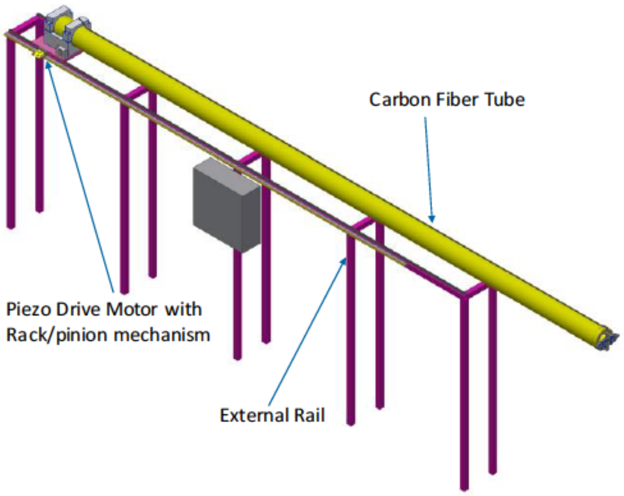

Fig. 3 PSFM is shown.

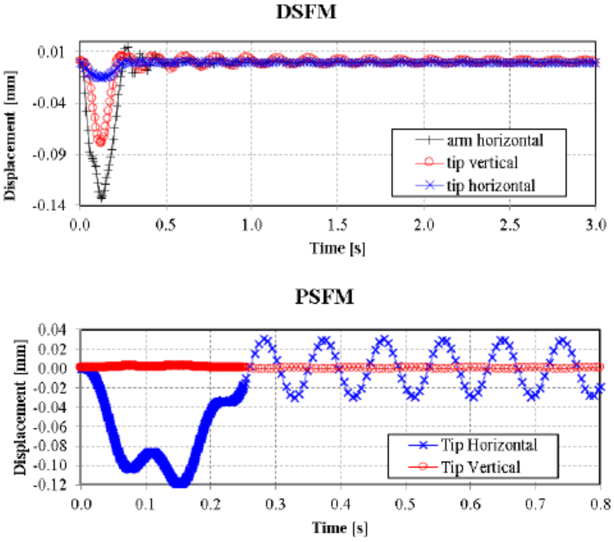

Fig. 4. DSFM and PSFM vibration analysis results.

Even with this stiffness, the deflection of the tube assembly is close to the available clearance in the collimator. For this reason, the arm assembly includes a pivot to align the tube assembly with a positive incline with respect to the horizontal to compensate for the deflection at the end of the tube.

A 203 mm diameter carbon fiber tube that is 6.0 m long is clamped to a fixture on the moving carriage. The carriage is moved along the platform using a rack/pinion system. A piezoelectric motor drives a spur gear along a plastic rack that is secured to the side of the platform.

The cables for the 3D Hall probes, piezoelectric rotation stage, and ultrasonic motor will be carried in non-magnetic cable track guided by a non-magnetic trough. The sensor cables will be routed along the tube assembly and aligned with the axial field direction to minimize Lorentz forces. The cable is placed on the outer diameter of the tube (see Fig. 3) for ease of fabrication as well as to avoid interference with the survey and alignment process.

C. Vibration Analysis

Studies of vibration of the DS mapper showed that the tip vibration amplitude is large if the DS is accelerated and decelerated in an uncontrolled manner. Based on the drive characteristics and using a smooth deceleration profile, a dynamic analysis was performed of the DS and PS mapper and rail system. The analysis was performed using the ANSYS FEA software. The model assumes the mapper is traveling with v=76 mm/s prior to being stopped. The model assumes material damping of β=0.001 which provides little effective damping. This value is assumed to be representative but needs to be validated with the prototype and commissioning work. The model assumes that the drive carriage is fixed at the rail/drive bearing mount and simply supported at the shaft/bearing interface mimicking the design. The horizontal and vertical tip deflections as a function of time are shown Fig. 4. The requirement on the amplitude ($\leq$ 50 µm) for the purposes of the laser tracking system can be met after < 0.5 sec for both DS and PS system.

D. *Survey and Alignment*

The position of the Hall probe locations is ultimately determined using a laser and alignment system. Based on extensive tests of the different Laser Tracker (LT) systems under the influence of a magnetic field (that is present during field mapping up to 200 gauss) the LEICA AT403 system has been chosen. Four RetroReflector46-170 by Edmund Optics reflector targets will be utilized per propeller.

The location of the kinematic mounting features on the propellers relative to the survey targets is needed with high accuracy +/-50 µm established in an independent referencing step through CMM measurements.

Using the laser alignment system, the position of the Hall sensors will be determined within +/-100µm in all spatial dimensions. Using at least three laser tracker targets on the DSFM propeller arms separated by at least one meter the requirement on the angular resolution of <0.1 mrad can be met.

E. *Motion Control System*

Both DS and PS mappers will be driven along the rail system at a maximum speed of 75 mm/sec. When starting or stopping the mapper, the motor will be driven with an acceleration profile defined by a half sine wave with minimum duration of 0.25 seconds. The peak rate of the profile will not exceed a magnitude of 478 mm/s^2.

The motion control system needs to be able to position the mapper and Hall probes to +/- 2 mm and then hold and maintain a stable position within +/-50 µm.

Fig. 5 shows the schematic of the major components of the motion system for control of both the PS and DS field mapping transport systems. The key of this system is the motion controller which gets the position from an encoder and sends out control signals to the motor and its driver. This is a servo-motor control system which requires PID tuning. The components in the dash box are enclosed in an electric box. The list of the different components is in Table 1. The components were selected to meet the performance requirements.

The motion system receives commands from the EMMA framework, executes the commands and sends back the status and position information by TCP/IP.

F. *EMMA based FMS software*

EMMA is a framework developed by the Software Systems Group of Fermilab's Technical Division for magnetic measurement applications [8]. It is a component-based system, where applications are constructed by assembling them from its different functional parts. EMMA is extendable and many different applications can be built by supplying new components and reusing existing system and domain components. An EMMA component is designed following the classical object model, where objects are separate entities with states and defined behavior that communicate via messages. EMMA components may be distributed over multiple nodes. The FMS software system runs on a host computer equipped with two network interface cards and accesses its instrumentation via a private LAN.

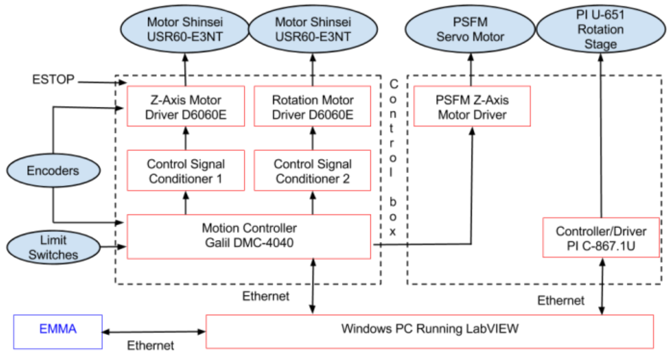

Fig. 5 The schematic for the motion control system used for both DS and PS field mappers.

The FMS instrumentation integrates with the host computer via a private Ethernet subnet consisting of the following devices: i) National Instruments (NI) CompactRIO crate with the VxWorks RTOS and: NI 9881 CANopen module to provide access to Hall probes; NI 9239 24-bit ADC with input isolation and antialiasing filter, to provide readouts of current as a voltage on a shunt resistor. ii) Metrolab PT2026 NMR magnetometer, for precise field measurements. iii) FMS motion system. iv) Leica AT401 laser tracker system, to provide precise positioning of the magnetometer motion system and the Hall probe sensors mounted on it.

The field mapping measurement is fully automated and will not require user interaction. The automation will be provided by a Python script controlling the motion system and readout components.

The archiver will save data in the Technical Data Management Streaming format and the User Interface component will offer several views.

IV. CONCLUSION

The Mu2e Field Mapper System design has been presented. DSFM and PSFM mechanical systems, survey and alignment system, motion control system and the Extensible Magnetic Measurement Application framework based DAQ and readout system are described. The novel approach to use in-situ position measurement utilizing a laser tracker system assures obtaining the 0.1 mrad angular resolution everywhere inside the large solenoid volume.

REFERENCES

[1] Mu2e Collaboration, "Mu2e Technical Design Report", http://arxiv.org/abs/1501.05241, 2015

[2] R. Oerter, "The theory of Almost Everything: The Standard Model, the Unsung Triumph of Modern Physics" *(Kindel ed.) Penguin Group,* p. 2. ISBN 0-13-236678-0, 2006.

[3] R. H. Bernstein and P. S. Cooper, "Charged Lepton Flavor Violation: An Experimenter's Guide," https://arxiv.org/abs/1307.5787 , Jan. 2014.

[4] V.I. Klyukhin et al., "Measurement of the CMS Magnetic Field", IEEE Transactions on Applied Superconductivity Vol. 18, no. 2 (2008) 395–398.

[5] N. Tan et al., "Magnetic Field Mapping of the Belle Solenoid", IEEE Transactions on Nuclear Science, Vol. 48, no. 3 (June 2001) 900–907.

[6] M. Leonova, "MICE Spectrometer Solenoid Magnetic Field Measurements", presented at PAC2013, Pasadena, CA USA, Sept 29 – Oct 4, 2013, Paper THPHO15

[7] C. Orozco et. Al., "Hall Probe Calibration System Design for the Mu2e Solenoid Field Mapping System," *IEEE Trans. Magnet Technology.*, submitted for publication.

[8] J.M. Nogiec and K. Trombly-Freytag,"EMMA: A New Paradigm in Test and Measurement Software", CHEP 2016 Conference, Sand Francisco, October 8-14, 2016