

Hall Probe Calibration System Design for the Mu2e Solenoid Field Mapping System

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Abstract— The goal of the Mu2e experiment at Fermilab is to search for charged-lepton flavor violation by looking for neutrino-less muon to electron conversion in the field of the nucleus. The Mu2e experimental apparatus utilizes a complex magnetic field in the muon generation and momentum and charge selection process. Precise knowledge of the magnetic field is crucial. It is planned to map the solenoid field with calibrated 3D Hall probes up to 10^{-5} accuracy. This article describes a new design of a Hall probe calibration system that will be used to calibrate 3D Hall probes to better than 10^{-5} accuracy for the Mu2e Solenoid Field Mapping System.

Index Terms—Solenoid System, superconducting, Magnet Alignment.

I. INTRODUCTION

THE MU2E experiment at the Fermi National Accelerator Lab (FNAL) seeks to find evidence of a charged-lepton flavor violation by looking for neutrino-less muon to electron conversion in the field of the nucleus [1]. The concept of the experiment is to generate a low momentum muon beam, stopping the muons in a target and measuring the momentum of the electrons. The implementation of this approach utilizes a complex magnetic field with both graded solenoidal and toroidal fields.

The solenoids will be mapped using 3D Hall probes calibrated to 10^{-5} and NMR probes mounted to a motion system. The 3D Hall probes will be calibrated twice to ensure high confidence in the subsequent measurement accuracy. The first round will take place at FNAL in a GMW 3474 calibration magnet [2]. The second round will take place at Argonne National Lab in a 4T MRI Magnet.

The 3D Hall probes (Fig. 1) are designed by CERN and manufactured by NIKHEF [3]. Each Hall probe will be permanently mounted to a Hall Probe Holding Fixture (HPHF) (Fig. 2). Each hall probe/HPHF unit will be mounted to the Hall Probe Calibration Equipment (HPCE) which will move the probes within the known magnetic fields whereupon three-

dimensional magnetic field data will be captured to allow for later analysis and determination of the precise orientation of the three Hall effect sensors on each probe. The absolute magnetic field within each calibration magnet will be monitored by way of an NMR probe mounted near the hall probe.

II. MAGNETIC FIELD MAPPING REQUIREMENTS

The 3D Hall probes will be used to map the Mu2e Detector Solenoid B-field; consequently, their requirements are derived from the Mu2e Requirements [4]. They need to measure the $|B|$ field value better 10^{-4} accuracy and the angular error of the B field vector needs to be less than 0.1 mrad.

III. EQUIPMENT

A. Probes

To measure the magnetic field, we use two sensing devices, a NMR probe and Hall sensors. The Metrolab PT2026 NMR is a Precision Teslometer. It is the successor model of the PT2025, and comes with new features that made it the desirable choice. A pulsed wave NMR detector and advanced signal processing allows a fast tracking of magnetic field changes better than 0.01 ppm at 3 T. The PT2026 can measure gradients of 1620 ppm/cm, allowing us to map a larger volume of our calibration magnet. The full range NMR signal search takes only 10 s, thanks to an internal 3-axis Hall sensor. Customized probes with ranges of 0.26-0.78 T, 0.7-2.1 T, and 2.0 - 5.5 T allow full coverage of the Mu2e solenoids' field strengths. Two probe designs are available, a standard head with $16 \times 12 \times 231$ (mm³) or a smaller head with $9.2 \times 6.2 \times 31.5$ (mm³). Each probe has a 10 m long cable, which connects to the MUX6026 four port multiplexer, connected by an additional 10 m cord to the PT2026 where USB and Ethernet interfaces allow remote readout via LabVIEW® based Software applications and drivers.

For the Hall sensors, we use the newest version of 3D Hall Probes developed by CERN for previous experiments such as D0, Atlas, and T2K [5]. Three 1D Hall sensors are orthogonally mounted to a precision glass cube. A temperature probe is

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mounted nearby to compensate temperature effects ($<0.3\%/\text{K}$). The glass cube resides on a printed circuit board containing a Cirrus Logic CS5524-ASZ Analog to Digital Converter for digitization of the analog Hall-sensor signal and a Maxim Integrated Products MAX4582CUE Multiplexer, as well as a SQSP Microcontroller allowing each Hall sensor board to be addressable with a unique Serial Peripheral Interface (SPI) Bus address. Interfaced with a *CANopen* communication protocol up to 60 sensor boards can be read by a computer via a KVASER USBcan II HS/LS adaptor [6].

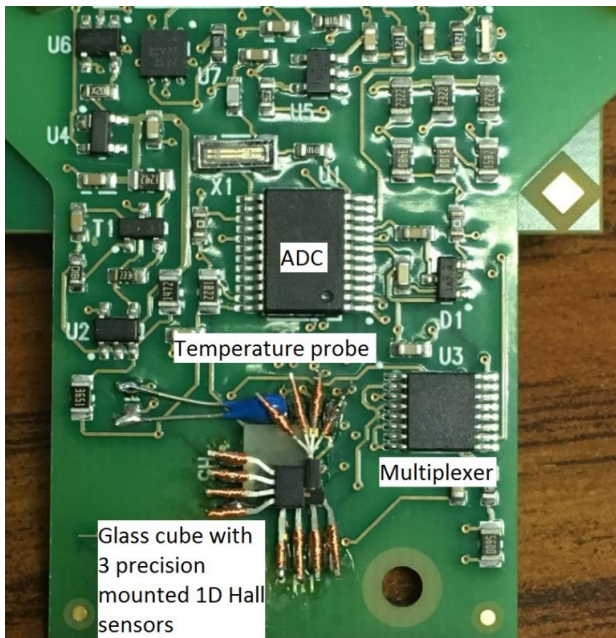


Fig. 1: NIKHEF Hall Probe

B. Calibration Magnets

The GMW 3474-280 Dipole Electromagnet was chosen for the 3D Hall probe calibration. Adjustable poles for an opening gap up to 16 cm and a chamfered pole tip allow high and uniform fields up to 3.5 T (~ 2 T at 5 cm gap). Precision gap spacing is achieved by dedicated brass spacers mounted between the pole tips. A Danfysik 853-300A/40V power supply allows 10 ppm stability over 8 hours, 18 bit current setting, and a built-in IEEE-488 interface (GPIB). De-ionized water is used to cool both power supply and magnet (total heat load $\sim 20\text{kW}$). A current transducer allows readback of the current on the 10^{-6} level. A SIEMENS S7-1200 PLC is used to record the water circuit temperature with 1 K accuracy, and controls the water flow in the heat exchangers between the de-ionized and the Industrial Cooling Water. The magnet is bolted to the floor, a geodesic survey established the exact pole distance of 77.142 mm, the pole tips have a tilt of less than 0.823 mrad.

C. Hall Probe Holding Fixture

The NIKHEF Hall probes will be mounted to the HPCE and the Detector Solenoid Field Mapper (DSFM). The NIKHEF hall probes alone do not provide adequate rigidity to be themselves mounted repeatedly. They require a fixture to

which they can be permanently attached that can, in turn, be repeatedly mounted. This is called the Hall Probe Holding Fixture (HPHF).

The HPHF (Fig. 2) is a triangular plate with threaded holes that correspond to the mounting holes on the Hall probes. Each Hall probe will be mated with an HPHF via three screws and small beads of epoxy that will ensure a rigid connection between the Hall probe and the HPHF. Each HPHF will be etched with a unique number so that each Hall probe will have a traceable history during the calibration process. The underside of each HPHF will contain three precision silicon nitride balls in a triangular pattern.

These precision balls (Fig. 2b) will mate with three features machined into the mounting plate of the HPCE and the propellers of the DSFM: a flat, a V groove, and a cone. These three features form a kinematic mounting system; each feature restricts an additional degree of freedom without over-constraining the system. The result is a repeatable mounting system that provides a consistent relationship between the HPCE and the Hall probes. This is required to

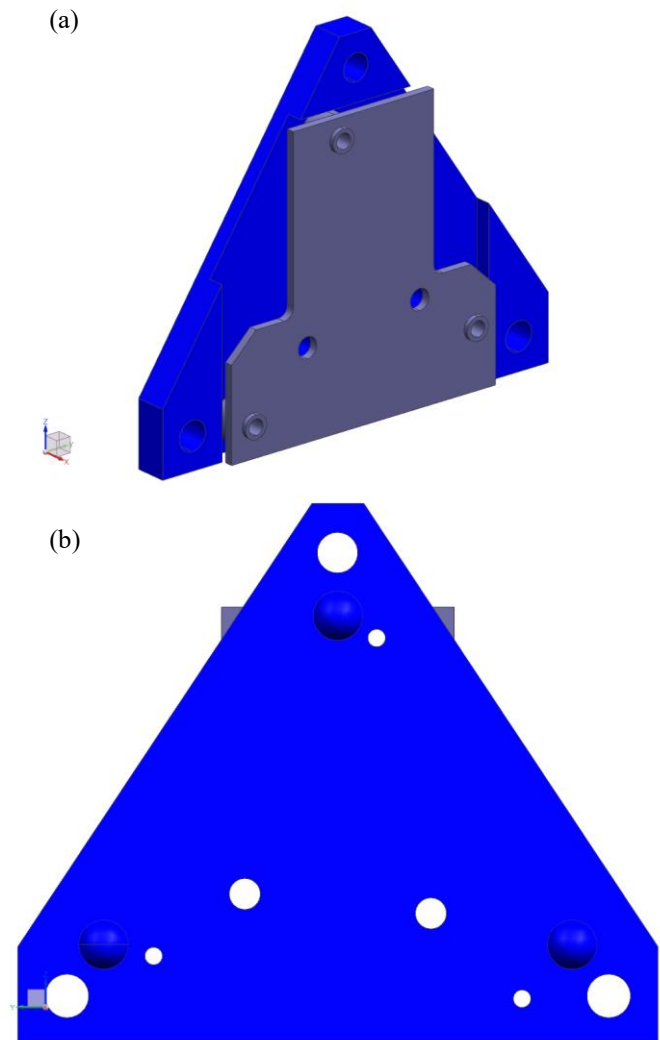


Fig. 2: Hall Probe Holding Fixture (HPHF)

ensure that the magnetic measurements taken are associated with correct spatial coordinates. During calibration, this system will allow successive Hall probes to be mounted to the HPCE without requiring additional metrology to reestablish the location of the Hall probe with respect to the calibration magnet.

D. Hall Probe Calibration Equipment

Two SmarAct SR-7021 [7] rotary actuators perform the two motions necessary to form the required set of angular positions. These two actuators sit in the assembly at a 90° angle, connected by an aluminum bracket to be constructed by SmarAct. The angle will be verified in the initial survey of the device. SmarAct will also provide a plate on which the above pieces will be mounted. This plate serves both as an adapter to allow the device to be attached to the aluminum extrusion frame and as a surface on which survey reflectors can be attached for determining the initial position of the device with respect to the calibration magnets.

The SmarAct SR-7021 is a piezoelectric actuator which provides for continuous rotation in a magnetic environment. It has a load capacity of 2.5 kg. With a resolution of 0.5 microdegrees and a step size of at most 2 millidegrees, the SR-7021 exceeds the requirement of knowing the position to within 5.7 millidegrees (0.1 mrad) while allowing for as many as 180,000 steps in the $\pm 180^\circ$ phi motion and 5000 steps in the $\pm 5^\circ$ theta motion.

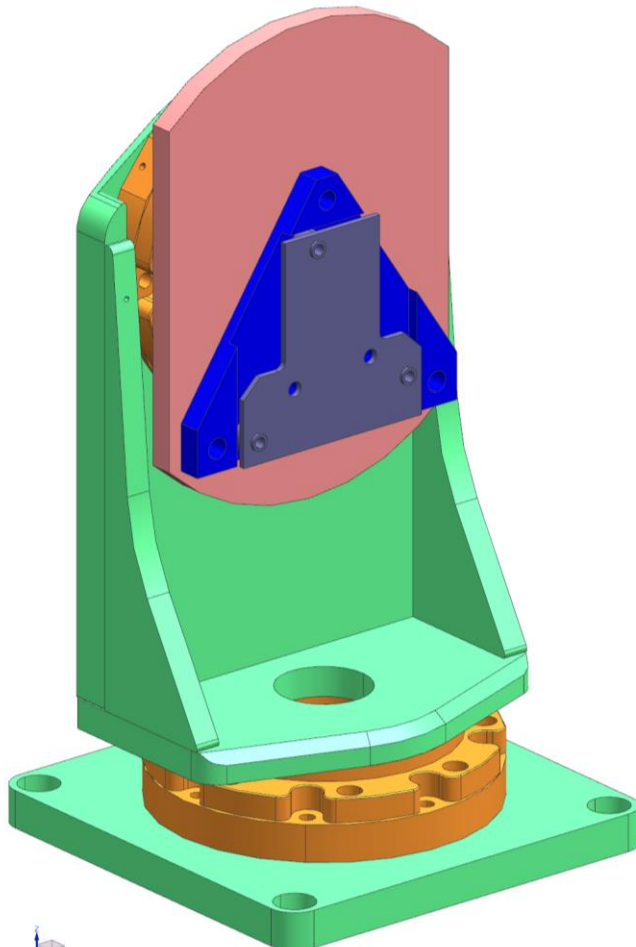


Fig. 3: Hall Probe Calibration Equipment (HPCE)

The device will be supported by two aluminum extrusion frames which will in turn be rigidly fastened to their respective calibration magnets.

E. Temperature Stabilization

To control the temperature effect on the Hall Probe calibration we will enclose the FNAL calibration magnet within an environmental room of 2.5 m x 2.5 m and control the temperature with a T224-31Eo [8] HVAC unit. The system is designed to stabilize the air temperature at 0.2 K, the reading is done via a thermocouple near the rotation stage of the Hall sensors. The radiative heat load of the calibration magnet is estimated to be below 4500 BTU/hr. We will calibrate the Hall probes at several set-temperatures to cover the whole operating conditions of the probes when used at the Mu2e detector building. The building and detector solenoid (DS) specifies a 35 K gradient between the cryostat wall of the DS and the allowed maximal temperature inside the building, efforts to reduce this range are underway.

IV. METROLOGY

A. FNAL Calibration Magnet

In order to perform the magnetic field mapping of the DS tracker region to the 10^{-4} level, the Hall probes need to be calibrated to that or even better precision. The FNAL GMW 3474 calibration magnet [2], has the specifications to reach this goal. The metrology aspect of this paper deals with the dimensional characterization of that magnet, an error estimate of attainable results and the establishment of a suitable coordinate system for further use in placing the rotating stages of the calibration device in the homogeneous field region of the magnet.

The first is whether the API Radian laser tracker we have is sufficient to establish the parallelism between the two pole faces of the calibration dipole to an accuracy of ± 0.1 mrad (or ± 20 arc seconds). To determine this, we performed an error analysis based on the possible achievable point accuracies of our laser tracker instrument. For our tracker, API specifies a Maximum Permissible Error (MPE) of $\pm 49 \mu\text{m}$ in a spherical volume of 5 m around the laser tracker head [9]. That error scales with distance so that on the short distance setup needed for these measurements, less than half of that value can be expected.

The instrument can operate in different modes. The Interferometer Measurement (IFM) mode and static mode were chosen for the highest precision.

A Monte Carlo estimate shows that we can meet the accuracy requirement if point accuracies below $\pm 50 \mu\text{m}$ can be achieved. Based on that information we performed the measurement of the calibration magnet and established a coordinate system for future use.

The API Radian laser tracker was placed about 1 m from the dipole gap. Utilizing the IFM in static mode the left and right pole faces were sampled at about 30 surface locations. A plane was best-fitted to the measurements for each pole surface (plate). A bisecting plane was created from the surface planes. The bisector plane was then shifted (Fig. 4a) to the centers of the pole surfaces ($\pm 38.571\text{mm}$) and compared with the measurements. The distribution of the residuals (Fig. 4b)

indicates that the pole faces are not parallel but intersect with an opening angle of about 1 mrad. Because the same residuals distribution could also indicate an instrument uncertainty (increasing with the distance from the instrument), the measurements were repeated. The results of the repeated measurements confirmed the correctness of the previous results.

The bisector of these two planes was used to establish the calibration magnet coordinate system in which we also located reference markers attached to the magnet yoke. These markers will be used to position the rotary stages for the Hall probe calibration process. Naturally, this information is only valid as long as the pole faces have not been moved out of their position as found during these measurements.

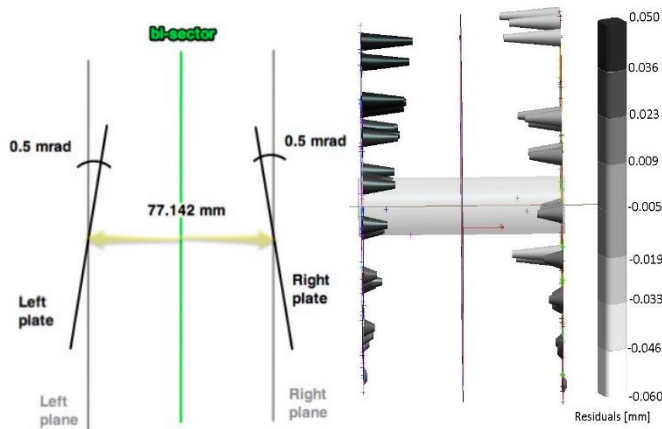


Fig. 4 (a): Left, Bisector Plane; (b): Right, Residuals of the Pole Faces

B. Hall Probe Holding Fixture

As discussed above, each HPHF is fitted with a kinematic mounting system. In order to connect the kinematic system to the Hall Probe location, the mounted circuit board must be referenced with a coordinate measurement machine (CMM) that can perform optical and touch probe measurements. With that, one can define a local coordinate system based on the three sphere locations in which to measure the location of the Hall probes on the order of $\pm 10 \mu\text{m}$ or better. Once a Hall probe circuit board has been married to its fixture they will never be separated again and the calibration characteristics will stay with that unique device. Further, with the implementation of the kinematic mounting system, the calibration coordinate system can be mapped to the mating surface coordinate system to give global Hall probe coordinates without further metrology.

C. Hall Probe Calibration Equipment

SmarAct designs and custom builds the Hall Probe Calibration Equipment. During the design stage, the FNAL Metrology Group asked for the inclusion of reference markers for the assembly. Once the system has been delivered to FNAL we will utilize a coordinate measurement machine (CMM) to establish the locations of these reference markers with respect to the rotation axis of the stages. The goal is to place the rotary stage (i.e. the Hall probe) in the field of the calibration magnet as close as possible to the homogenous center region of the device. Utilizing the previously described magnet referencing

information and the rotary stage CMM measurements we can place the device at the sweet spot of the magnet within $\pm 10 \mu\text{m}$ or better depending on the mechanical adjustment system provided.

V. CONTROL AND DATA ACQUISITION

To achieve the desired angular resolution, the Hall sensor must be rotated at minimum to 1000 positions around each axis. We will require temperature readings over a range of 35 K to allow for the temperature variations inside the Mu2e experimental hall; at least for 10 temperatures we will take a full calibration run. Assuming the reading takes 1 s, this accumulates to a continuous operation of 11.6 days. Custom LabVIEW[®] software will be used to automate and record the stage movements, as well as temperatures. An NMR will be mounted inside the magnet to monitor long-term drift of the calibration field. The acquired data will require a multidimensional fit, similar to work done previously [10].

VI. CONCLUSION

In order to generate an accurate magnetic field map of the Mu2e Detector and Production Solenoids, the Hall effect sensors used to take such measurements must be calibrated to the level of 10^{-5} . This is achieved by moving the Hall probes on a precision stage in a known magnetic field. To acquire data in a stable, well-understood environment, temperature control will be used around the calibration magnet. For repeatability, the Hall probes will be mated to ceramic plates. These plates mount to the calibration equipment and the field mappers using a kinematic mounting system. A Coordinate Measurement Machine and a laser tracker will establish the relative position of all parts of the calibration system. The data gathered from moving the Hall probes in the calibration magnets will be used to ensure high confidence in the field maps.

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