Magnetic Impurity Detection for nEDM Experiments

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The neutron Electric Dipole Moment (nEDM) is an elusive quantity that, if found, would violate CPT symmetries. The LANL nEDM measurement involves measuring precession frequency changes in polarized Ultra Cold Neutrons (UCN). Changes in precession frequency indicate the presence of an EDM within the neutron or a variation in the magnetic field inside the measurement cell on the order of a femto-Tesla. Due to the magnetic sensitivity of the experiment utilization of non-magnetic materials in components is imperative. To ensure the magnetic constraints on the components used in the apparatus fall within this threshold a method was devised to scan materials for magnetic impurities. During this SULI appointment I was directly involved in the design, fabrication, and construction of a sensitive scientific instrument that will be able to detect magnetic impurities in materials on the order of nano-Tesla.

I. INTRODUCTION

Charge, Parity, and Time reversal (CPT) symmetries lie at the core of many universally accepted theories in modern physics. The existence of an EDM in a subatomic particle such as the neutron would directly violate CPT symmetry and could potentially harm the validity of many accepted theories today, such as Quantum Field Theory. Due to the many interesting consequences that come with the existence of the nEDM the scientific community is very motivated to measure this quantity. Currently, there are six large scale collaborations around the world that are looking for the nEDM. Los Alamos as well as Oak Ridge National Laboratories are among the laboratories associated with this effort. The LANL and ORNL nEDM search efforts are each large-scale scientific collaborations in their own right and are very complicated technically and scientifically. Therefore, the exact details of these experiments will be omitted as the concern of this paper is with constructing a method to aid in these experiments, about the experiments themselves. The main concept that motivates this project is the need for magnetic purity on the order of femto-Tesla inside the measurement cell, as a variation in the magnetic field in the measurement cell on this order can generate false positives. In order to suppress the prevalence of false positive EDM measurements from uniformity issues in the magnetic field, the components must produce a magnetic field less than 2 nano-Tesla (nT) in for copper and less than 50 nT for stainless steel.

The magnetic field needs to be uniform on the order of femto-Tesla inside of the measurement cell. The materials scanned are going to be used to construct different components of the apparatus that will be near the measurement cell. It can be shown that if a magnetic impurity is present the strength of the signal generated by the impurity will decrease via a power law with distance. While steel is magnetic, it will be sufficiently far away from the measurement cell as it will be used for structure support. Steel needs to have a net magnetization less than 50 nT. Copper will be fairly close to the measurement cell, therefore the magnetic restrictions on this material are much more stringent. The copper components need to have a net magnetization below 2 nT.

II. METHODS

The goal of this experiment is to construct a magnetic signal detection system that is able to detect magnetic impurities in materials on the order of nT. Since the signal is so small, much consideration must be given to noise reduction. To minimize noise from Earth's ambient magnetic field, a nickel iron alloy known as Mu-Metal is used to encapsulate the entirety of the signal detection apparatus. This room made of Mu-Metal will be referred to as the Magnetically Shielded Room (MSR) from now on.

Within the MSR is a round wooden table where the samples to be scanned are placed. This wooden round-table was belt driven by a brush-less DC motor such that it was able to spin with a sample on it with an angular velocity anywhere from 0.25 to 0.1 revolutions per second. Having the sample spin is advantageous because it allows the background noise to be averaged out from the magnetic signal being measured. This creates a delta function-like signal that is very easy to differentiate from background noise.

Two fluxgate magnetometers were used to measure the magnetic signal from samples as well as the ambient magnetic field within the MSR. The first magnetometer was placed directly above the sample and was used to measure the signal from the sample, while the second was placed 12" directly above it to measure the noise inside of the MSR. The magnetometers were always stationary while the sample spun with the round-table for all measurements. Each sample was scanned at 0.1, 0.05, and 0.025 revs/s. Two photo-diodes were placed throughout the MSR to keep track of the position and speed of the round-table. One photo-diode was placed directly on the side of the table and the second was placed underneath the table. Pieces of reflective tape were placed at certain places on the table that caused a large signal in the photo-diode data. This allowed us to count the number of revolutions the table made throughout the measurement in order to calculate the speed of the table. Continuous, circular data acquisition was used to preserve as much data as possible. Oversampling was implemented to further improve our signal to noise ratio. A large copper coil was constructed (14 turns) that surrounded the round-table. A current was run through this coil to produce a magnetic field that was used to measure the magnetic susceptibility of samples.

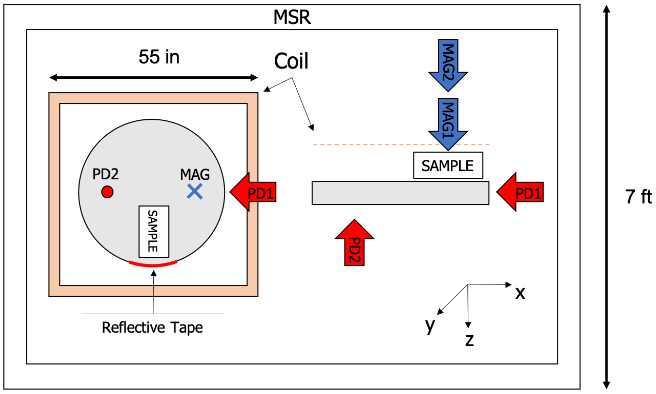

FIG. 1. MSR Round-Table set up. The coordinate system in the lower right is relative to the magnetometers.

III. ANALYSIS

A. Raw Data

The goal of analyzing the MSR data was to find a signal on the order of nT. First, we plotted the raw magnetometer data, only converting to nT from Volts using the following conversion:

$$[nT] = [V]/Gain * 1e9 \tag{1}$$

This allowed us to see a very large signal with the steel components. The raw data didn't show apparent signals with the copper components, the ones that are of the most concern, therefore further analysis had to be done.

B. Raw Data Overlay

We then sectioned off the data into one revolution intervals using the photodiode data and overlaid the raw magnetometer data on top of each other for each revolution of the table. This was done to ensure we were getting a consistent signal. If the signal was very consistent, then the raw data overlay would look like a signal from a single revolution.

C. N Oversampling

The raw data was rather noisy. In order to cut down on the noise, we N Oversampled which is a technique that involves taking data at a rate much higher than we actually need it to be and averaging out N points. This drastically reduces the noise seen in the raw data and helps sharpen the signal peaks.

D. Binned Statistic

To reduce the sheer amount of data plotted we used a method known as binned statistics. The data is put into a number of bins, in this case we used 72 bins, which was about a 5 degree rotation in the table. Once the data is placed into a bin a statistic is computed with the data that was placed in the bin, in this case the mean was computed for plotting the points, the standard deviation was calculated for error propagation and for error bar plotting.

IV. RESULTS

A. Steel

For steel, a magnetic signal of 5 nT was observed. The measurement was carried out at multiple distances for testing purposes. In the actual experiment the steel will be about 1' away from the measurement cell, which is the distance that 5 nT was measured. Meaning it is safe to use steel i-beams for a support structure in the nEDM experiments.

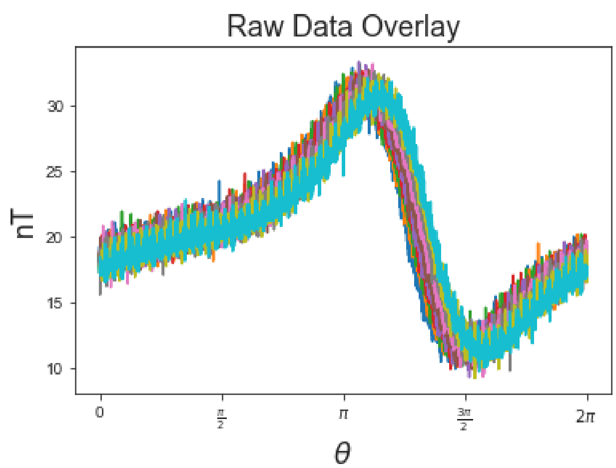

FIG. 2. Steel: Raw Data Overlay

B. Copper

For copper, a signal of around 0.175 nT was observed. Extra care will be taken with copper since it will be so close to the measurement cell. Another factor that makes copper more prone to magnetic impurities is the fact that it will have to be machined. The process of machining copper might have an increased probability of contamination the copper. Therefore, the copper will have to be scanned multiple times, before and after any machining.

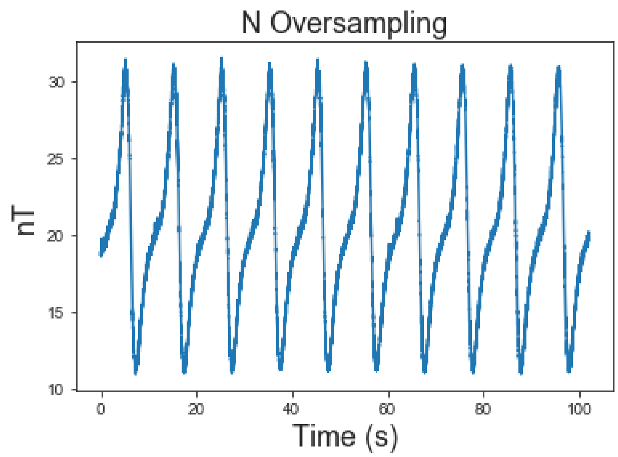

FIG. 3. Steel: N Oversampling

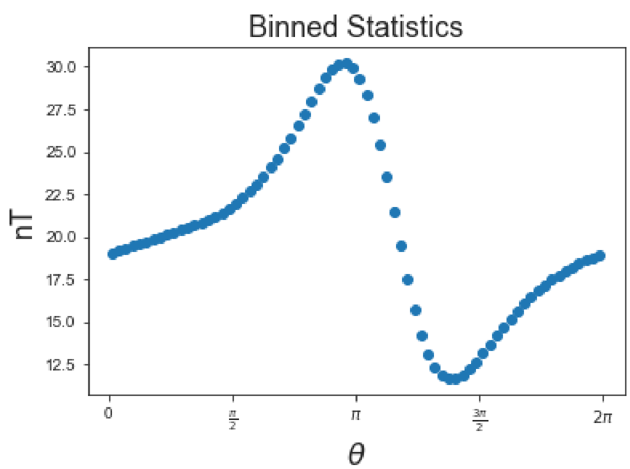

FIG. 4. Steel: Binned Statistics

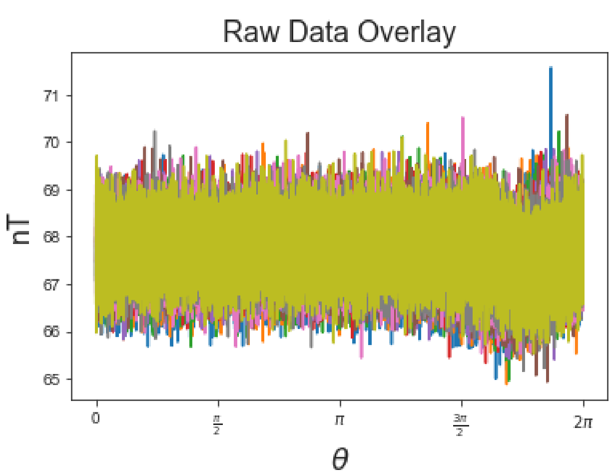

FIG. 5. Copper: Raw Data Overlay

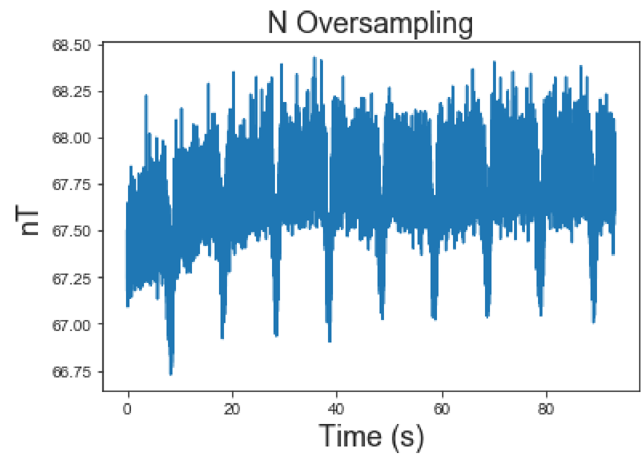

FIG. 6. Copper: N Oversampling

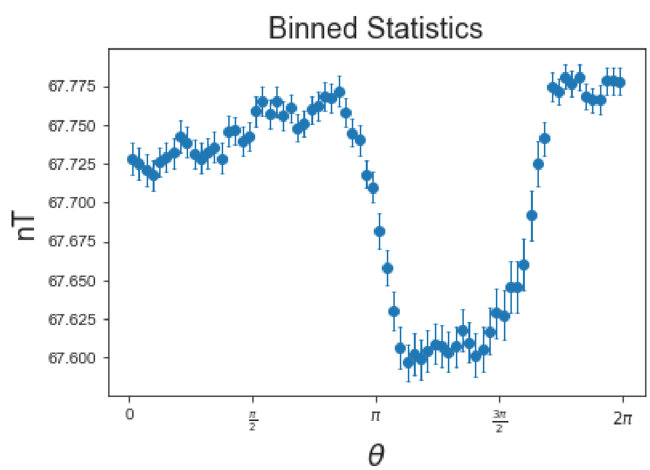

FIG. 7. Copper: Binned Statistics

V. DISCUSSION

After initial scans, the steel i-beam and copper are well within the constraints to be used in nEDM experiments.

A. Issues

One of the major issues that occurred early on the in the fabrication and construction process was how to drive the round-table. The easiest and simplest solution was to use a belt driven system with a DC motor. However, a brush-less DC motor is essentially a giant magnet, therefore it had to be located outside of the MSR. Finding a motor and belt that had enough torque and length to adequately drive the round-table was very challenging. Early on in the data acquisition procedure a buffering issue was causing a large loss of data throughout the entirety of a run. The solution was in the size of the buffer store. We were writing data too quickly to the file which was causing the large loss in data. As of now, the second magnetometer used for noise detection is not sensitive enough and has drift issues in low field (see Fig. 8).

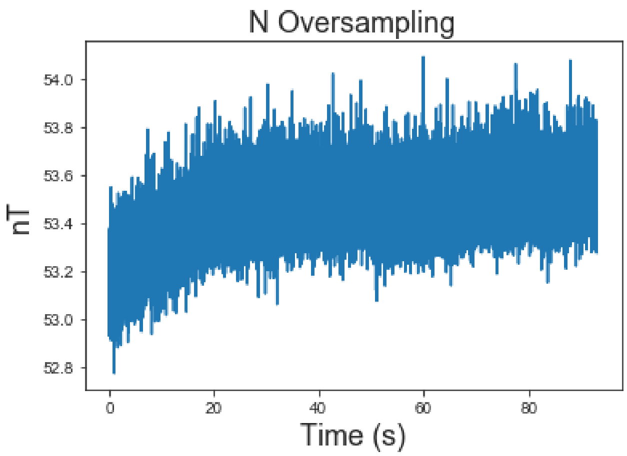

FIG. 8. MSR low field drift

B. Future Work

In the future, to test the precision of the device, a magnetic sample with a well known magnetic signal will be scanned. A solenoid will most likely be used as it is very easy to calculate the magnetic field generated from them. Another area for improvement in the device is a fluxgate position monitoring system. It would be convenient to be able to correlate a signal with specific positions on the sample. We also plan on purchasing higher quality magnetometers to eliminate low field noise and reduce white noise.

VI. CONCLUSION

The MSR round-table apparatus was able to detect signals in magnetic as well as non-magnetic materials on the order of nT. We were able to show that it is promising to be able to use steel and copper materials in nEDM experiments. This apparatus will be used throughout the research and development process in both the LANL and ORNL nEDM efforts to ensure the magnetic purity of components is adequate. Throughout this SULI program I have been directly involved in the design, fabrication, construction, DAQ, and data analysis of the MSR round-table apparatus. This program as given me a greatly beneficial experience conducting modern day physics experiments at a professional level. This experience has been a vital part in my development as a scientist, and greatly aided my perspective in having a career as a scientist at a DOE laboratory.

VII. ACKNOWLEDGMENTS

I would like to thank my mentors Dr. Takeyasu Ito and Dr. Steven Clayton as well as my collaborators Taufique Hassan and Max Becher for helping and guiding me throughout this project. I would also like to thank Los Alamos National Laboratory for hosting me and the Department of Energy for funding my stay.