SURF Progress Report 1:
Effects of superconducting lead endcaps on boundary conditions of magnetic fields

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I. MOTIVATION

A. Group goal: the half-scale model

The discovery of charge-parity symmetry (CP) violation in the decay of neutral kaons has inspired attempts to extend the Standard Model.[1] Measurements of the electric dipole moments (EDM) of various particles provide important restrictions and clues to guide new models..[2] The neutron electric dipole moment (nEDM) collaboration intends to improve[3] the currently-measured limit[2] on the neutron EDM with new experimental techniques. Trapped ultra-cold neutrons (UCN) precess in the presence of a constant magnetic field or a variable electric field; measuring a change in precession correlated with the electric field would confirm a non-zero EDM.

An important obstacle is eliminating a "geometric phase effect" that creates a shift in the UCN precession and results in a false EDM reading. Since this effect is caused by field gradients, we need to make the magnetic field as uniform as possible. To tackle the engineering challenge of creating an uniform magnetic field, we have constructed a half-scale model of the magnet that will be used in the nEDM experiment. We are both simulating and measuring the effects of various types of shielding (μ-metal, ferromagnetic Metglas, and superconducting lead). The ultimate goal is to determine the optimal magnet design for the nEDM experiment.

B. SURF goal: superconducting endcaps

The current setup (fig. 1) features a cylindrical $\cos\theta$ coil[5] (referred to as the B_0 coil) surrounded by concentric open-ended cylindrical shells for shielding. In order to improve field uniformity, we investigate the effects of superconducting lead endcaps to close the open ends of the lead shield.

Since November 2013 (when I first stared work in this group), we have designed and installed a bottom endcap. Measurements taken afterwards suggested that a top endcap would be more effective. As of July 2014, we have a top endcap installed on the magnet and are preparing to cool the lead shielding to superconducting temperature.

The goal of this SURF is to help develop a reliable simulation of this endcap, measure its effects, explain any inconsistencies, and determine how effective this endcap style will be for the final nEDM experiment.

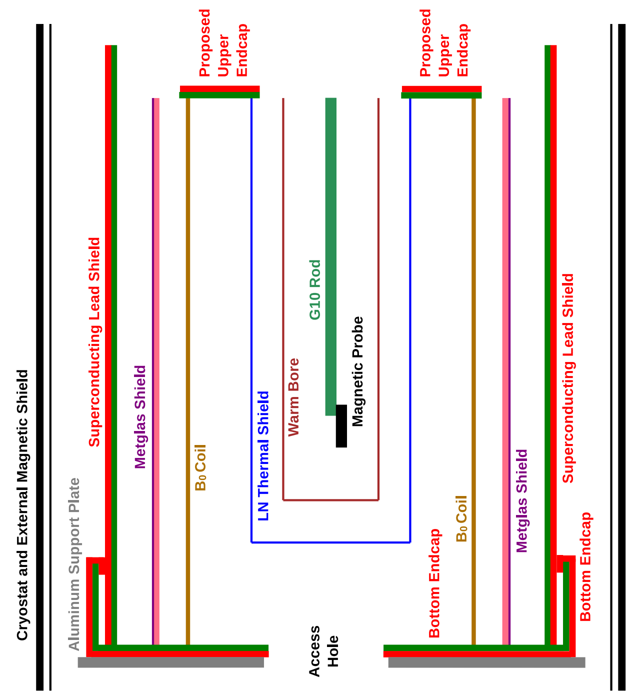

FIG. 1. Stylized diagram of the experimental setup.

II. CURRENT STATUS

A. Data analysis tools

I have developed various programs to streamline the collection and analysis of data. We use National Instruments Labview to interface with temperature sensors, magnetic probes, shimming coils, and other apparatus in the lab. Creating a detailed map of the magnetic field often takes several hours, and the external magnetic field can change dramatically during this time; for example, we have had abberations in our data because a truck parked outside the lab. To avoid this issue, I created a program to monitor the external field at various locations, allowing us to know when the external field has changed dramatically and to throw out data accordingly.

I have also created a specialized plotting program (currently 324 single lines of code) to analyze the data we produce. This plotter manages foreground and background fields, normalizes simulation data by calculating the desired field at magnet center, and handles field slices, making it possible to compare data from multiple simulated and measured maps at a time.

B. Investigating the field offset

We are using `RotationShield`, a "linear matrix solver for systems with cyclic symmetry" developed previously in the group,[6] to simulate our magnet and predict the effects of the superconducting endcap. Before making such predictions for the superconducting state, however, we needed to verify the simulation. The effects of the lead shield are negligible when the lead is above superconducting temperature, so a simulation including only the remaining magnetic shielding (i.e. the Metglas) should agree with measurements taken in the non-superconducting state.

However, we noted a significant discrepancy between the measured and simulated maps. Fig. 2 shows the z component of the magnetic field as a function of z position along the vertical line $x = -0.1$ m, $y = 0$. There is a notable peak shift: the measured peak in B_z occurs about 10 centimeters lower than it should according to the simulation. This presented a problem since we plan to use `RotationShield` to predict the effects of the superconducting endcap, but we could not correctly model our experiment without the endcap. My first task was to explain this discrepancy by investigating every difference between the simulated setup and the experimental setup.

The simulation was created with a Metglas thickness of 3 cm, even though the Metglas is actually less than 1 mm thick, in order to avoid numerical instability in `RotationShield`. Knowing this, I simulated systems with various Metglas thicknesses. Analysis of the resulting data showed that varying the Metglas thickness changed the maximum value of B_z by a relatively small amount, but did not shift the B_z vs. z curve, so this could not be the cause of the discrepancy.

In our magnet, the Metglas shield also extends above the B_0 coil by a few centimeters. However, including this in the simulation also failed to produce a peak shift: even with the Metglas extended 10 cm above the coil (which I ran simply to highlight the effects), the offset was not reduced.

Another possible explanation was that, in the experiment, the Metglas was slightly sheared - one side was up to 2 cm higher than the other. It was not possible to include this in the simulation since `RotationShield` was designed to build interaction matrices for azimuthally-symmetric boundary conditions. However, I ruled out the shearing as an explanation by examining the measured field map at various angles. If the shearing were to produce a peak shift, then data taken along $x = -0.1$ m, $y = 0$ would be shifted relative to data taken along $x = 0.1$ m, $y = 0$, unless the shear was exactly aligned with the y-axis, which was very unlikely. Since there was no shift between the data taken along both axes, the shearing could not explain the offset.

After these three explanations were ruled out, I carefully re-measured the dimensions of the coil and the Metglas to confirm that the dimensions we were using in the simulation were correct. When this did not resolve the offset, we took new field maps.

During the third week, I compared all available measured field maps and noticed that there was an offset between the measurements themselves. In fact, during the same field map, there was an offset between data taken with the magnetic probe moving up (from middle to top) and data taken with the probe moving down (from top to middle). Only the data taken while the probe moved down agreed nicely with the simulation. To investigate this issue, I took new field maps with the probe moving back and forth along a vertical axis. We marked the rod on which the probe is mounted to confirm that the probe was indeed revisiting the correct positions, and also damped any oscillations in the rod to prevent the probe from moving while taking measurements. Finally, the group traced the issue to the behavior of the probe's data collection program, which took an average of measurements collected over the time taken to move to a point rather than measuring once it had reached that point. I confirmed that this eliminated the offset between the going-up and going-down probe paths, and am now in a position to collect new field maps and compare those with the simulated data.

C. Cooldown

During this time, we have also been cooling the lead shield and endcap. Once the lead temperature drops below 7 K, I will be able to take the first field map that includes a superconducting top endcap. By that point, I will also have run high-resolution simulations that include the lead shield and top endcap. In the final weeks of SURF, I will analyze that data and determine whether our endcap simulations are accurate and how effective the top endcap will be for the final nEDM experiment.

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[1] Cronin, J. "Nobel Lecture: CP Symmetry Violation The Search for Its Origin," Nobel Media AB (2013).

[2] Baker, C. A., D. D. Doyle, P. Geltenbort, K. Green, M. G. D. Van der Grinten, P. G. Harris, P. Iaydjiev et al. "Improved experimental limit on the electric dipole moment of the neutron." *Physical Review Letters* 97, no. 13 (2006): 131801.

[3] "Search for the nEDM at Caltech." Kellogg Radiation Laboratory ⟨krl.caltech.edu⟩ (2014).

[4] Malkowski, S., R. Y. Adhikari, J. Boissevain, C. Daurer, B. W. Filippone, B. Hona, B. Plaster, D. Woods, and H. Yan. "Overlap Technique for End-Cap Seals on Cylindrical Magnetic Shields." *IEEE Transactions on Magnetics* 49, no. 1 (2013): 651-653.

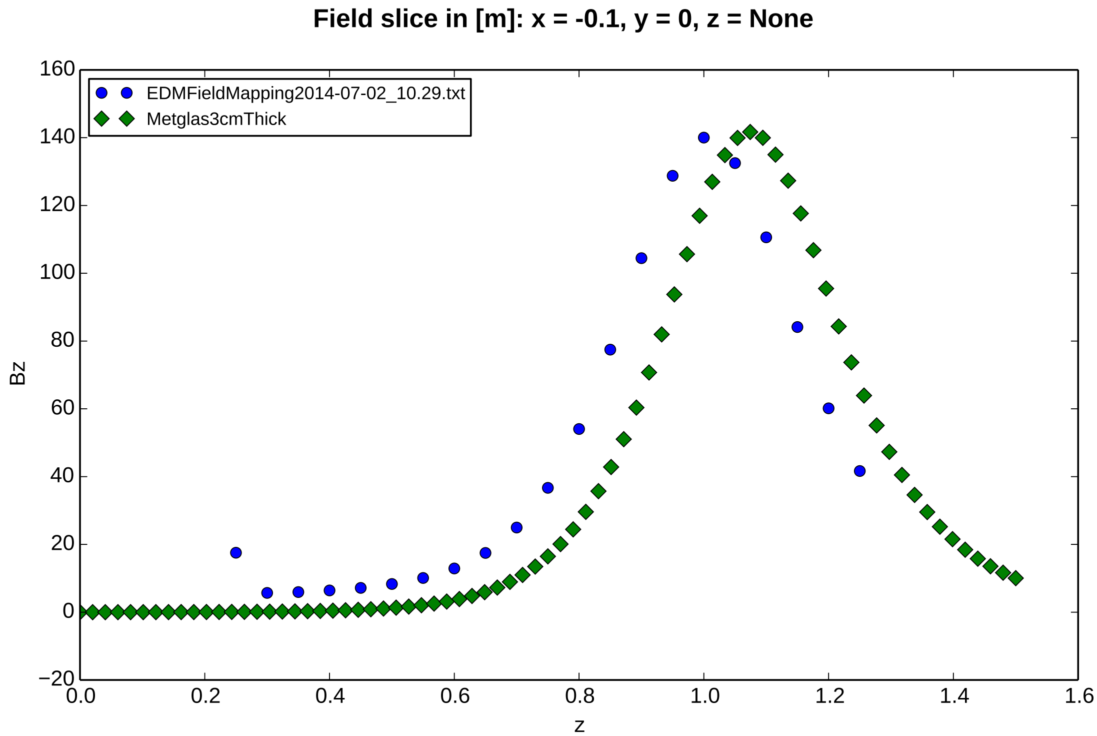

FIG. 2. The magnetic field component B_z [mG] vs. z [m] along the line $x = -0.1$ m, $y = 0$. Green points are predicted by the `RotationShield` simulation, and blue points are from the initial measured field map. The measurement shows the B_z maximum occurring 10 cm lower than it should.

[5] Perez Galvan, A., B. Plaster, J. Boissevain, R. Carr, B. W. Filippone, M. P. Mendenhall, R. Schmid, R. Alarcon, and S. Balascuta. "High uniformity magnetic coil for search of neutron electric dipole moment." *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* 660, no. 1 (2011): 147-153.

[6] Mendenhall, M. P. `RotationShield` source. ⟨https://github.com/mpmendenhall/rotationshield⟩ (2014).