Prototyping of Superconducting Cage for nEDM Measurement

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1 Introduction

The electric dipole moment (EDM) is a property of particles characterized by electrically positive and negative poles, that defines their torque in electric fields. One of the questions currently being investigated in particle physics is whether the neutron has a non-zero electric dipole moment. Such a discovery would have important ramifications due to the violation of charge and parity symmetries by the neutron's EDM (or nEDM). One illustrative example of this violation is that a time-reversed version of a neutron would have its magnetic moment change direction, but not its EDM, leading to a non-symmetric situation with the initial system in relation to T (time) symmetry, which implies a CP violation. This CP symmetry violation is especially important in regards to baryogenesis, the theorized process by which the early universe had more matter than antimatter and thus, after the two had interacted and nullified each other, was left with the matter that would become our material universe.[2] According to the Sakharov conditions, a set of conditions that allow for this baryon asymmetry, a violation of CP symmetry is required of sufficient magnitude that the estimated difference in matter over antimatter was produced. While sources of CP symmetry violation are already known of, they are much too small to explain baryogenesis, and observing a non-zero nEDM may provide the required CP symmetry violation to satisfy it.[3] Experiments to measure the nEDM at Oak Ridge Laboratory's (ORNL) Spallation Neutron Source (SNS) involves inducing Larmor precession of the neutron spin in a strong electric field. While the outside magnetic field will be small, the neutron's large magnetic moment will create a precession in the field from this spin, and the resulting modulated signal can be detected to measure the nEDM.[2]

The requirement for constant magnetic fields within the small size of the cryostat in which the experiment is being performed could be fulfilled by designing a superconducting cage. Due to the ability of superconductors to maintain a current for an almost indefinite amount of time, exposing such a material to an outside B field would induce a current by Lenz's Law that opposes any change in the B field; thus, the B field would be maintained even when the external source is removed. Forming the superconductor into a cage allows for multiple current loops to form around each hole in the cage, "pinning" magnetic field lines such that they stay constant over space and time within the cage[1], thus creating the necessary field for the nEDM experiment that remains unaffected by external B-fields. Using a prototype superconducting cage design composed of lead, this project will accurately obtain temperature and magnetic field strength data on the cage during testing in liquid helium, and thus determine whether the design is able to produce the desired fields.

2 Procedure

2.1 Cage Design

The first step of prototyping was designing the superconducting cage, which occurred before I joined the project. The cage was constructed of leaded PCBs with a grid of small holes, after which multiple pieces were soldered together to create the cage itself. This cage was then attached to a resin stand using epoxy, though after it shattered in the first liquid nitrogen test, the stand was replaced with a metal part and attached with varnish instead. This apparatus was affixed with epoxy to the end of a long metal rod with a hollow interior, so that it could be safely lowered into a dewar holding the liquid helium during testing. Two thermometers (a DT-471-DI, "Probe A", and a DT-470-SD, "Probe B", both from Lake Shore Cryotronics and controlled with a Model DTC-500-SP) and a magnetometer (a Mag F probe from Bartington, for use with the Mag-01H single-axis magnetometer) were attached to the cage and had their cables run through the rod. Each thermometer was attached with varnish to the farthest (for Probe A) and closest (for Probe B) face of the cage, to be able to measure when the front and back of the cage reached the critical temperature and thus confirm the cage is superconducting. The thermometers and magnetometer are attached to separate, external control devices (the DTC-500-SP and Mag-01H) that convert the data from the sensors into voltages, which are then sent to a National Instruments DAQ device (an NI 9239) that converts the two data streams into a single data stream that can be read by a computer through a single USB port. Note that the two thermometers input into the same converter, but only one of their signals is outputted at a time; during testing, we will manually swap between the two to check both thermometers.

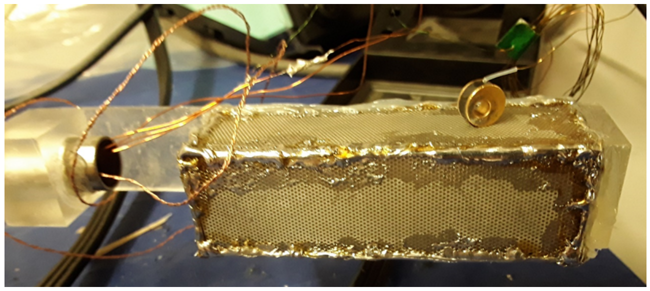

Figure 1: Early version of superconducting cage, with resin stand. Probe A is on top of the cage in this image; this is not where it will be attached during testing. Magnetometer is not shown as it is inside cage, and Probe B is outside the image bounds.

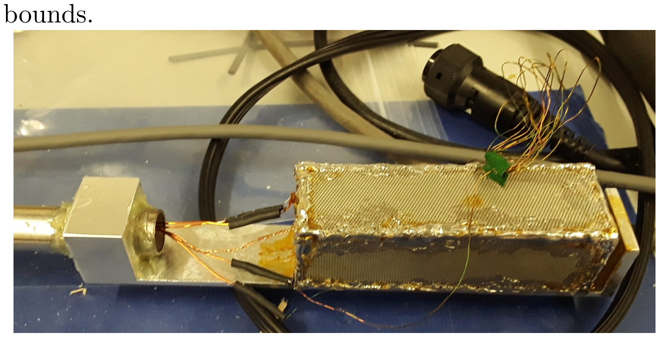

Figure 2: Later version of superconducting cage, with metal stand. Probe B is visible near to the top left corner of the cage, while Probe A is not visible as it is attached to the hidden side of the rightmost face of the cage. Magnetometer is not again not shown as it is inside the cage.

2.2 Data Acquisition Software

While the NI 9239 is capable of storing data from the sensors into a buffer, this buffer cannot be read by a computer without the use of a program. Originally, this was performed using a combination of DAQExpress, a program which contained the NI-DAQmx driver necessary to access the NI 9239, and a previous student's executable version of a C program, called from a separate MatLab program. The executable generated a text file list of 2000 data points, every four data points being a list of the readings from the NI 9239's four channels at some unknown time, and the MatLab program reorganized this list into a clearer format, with 500 lines that each contained four data points from all of the channels. This set-up was unusable, as we could not know when each data point had been read, nor be sure of how consistently data was being taken. While we attempted to investigate whether we could average the data from the output, and thus loop the calls to the executable, it was decided to instead rebuild the code anew ourselves.

The new data acquisition program was written in Python, utilizing (and requiring the installation of) the nidaqmx Python library to communicate with the NI 9239. This library, a repackaging of the NIDAQ C++ library for use in Python, was specifically used to create an object representing the device and its channels, setting its sample rate of the sensors, and requesting to read the data in the buffer. The program operates by first creating an interpolated curve function translating voltage signals to temperature, based on a document describing curve points for the outputted voltage signals from the converter equipment when receiving the thermometer's temperature readings. Then, the program asks the user to provide a sample rate in samples per second, as well as the number of samples that will be gathered. Next, the program starts a for loop that will count up to the requested number of samples, assuring that this many samples are gathered. Within the for loop, a while loop is used to wait until a specific time period has passed since the last loop iteration, equal to the reciprocal of the sample rate. When this amount of time has passed, a thread is started that contains the actual read operation, and the next iteration of the loop begins. The thread contains the function call to read all data from the buffer but not saving this data (which clears any accumulated data in the buffer), read the data from the buffer (as a new set of data will be in it already), and write the gathered data to a text file in a readable format along with a timestamp of when the computer requested the data. Additionally, the thread has function for translating the voltage signal data from the thermometers into a temperature using the previous interpolated curve function, and notifying the user when this temperature has gone below the critical temperature (set in-code) or returned to above it. After all iterations of the loop have been processed, the program ends, and a text file is left containing all the data collected.

During the process of developing the program, certain decisions were made to alleviate issues and errors. One of the more significant was the original usage of MatLab integration, through a MatLab engine, within the Python code to call a MatLab program when converting voltage signals from the thermometers to temperatures. This was later removed to reduce complexity and because it was believed to be causing a reduction in performance. The addition of clearing the buffer through reading all available data without storing it was implemented to prevent an error caused by the mismatched rate of how fast data was being added to the buffer and how fast data was being read (and thus deleted) from the buffer; clearing the accumulated data help prevent the buildup of entries that caused the error. The last changes worth discussing are related to performance. It was noticed that the program would take longer than expected to read an amount of samples, especially at much higher sample rates; 10000 samples at 1000 samples/sec, expected to take 10 seconds, took 140, while 100 samples at 10 samples/sec took 10 seconds as expected. By changing the read operations to be executed in a thread instead of within the for loop itself, performance was massively increased, reducing 10000 samples at 1000 samples/sec to 40 seconds. The remaining performance issues were believed to be caused by the computer's CPU itself, as during the while loop the CPU was likely getting overwhelmed and would hang temporarily before continuing the program, leading to the timing discrepancy we were seeing. As this issue was occurring with the CPU itself and would happen regardless, there was no change made to fix it. Because the performance issues only became problematic at high sampling frequencies, and we would be testing at low frequencies, the increase in time taken to sample would not affect us.

2.3 Experiment Setup

Two sets of tests have been planned for the superconducting cage prototype – one using liquid nitrogen, and one using helium. Both tests consist of dipping the cage into a container of cryogenic liquid, using the rod to support the cage and keep it stable within the liquid. Sensor readings would be taken from the magnetometer and thermometer, using the NI 9239 and the Python code written for it. We would also expose the cage to an external field magnetic field, though the method by which this will done has not yet been determined.

The liquid nitrogen test consists of a small container of liquid nitrogen being used as the cryogenic liquid. Due to the small size of the container and the length of the rod that the cage is attached to, a wooden stand was built to hold up the rod during testing. Liquid nitrogen is only 77 K, so the lead of the cage will not reach the critical temperature of 7.2 K, and thus won't be superconducting. Using liquid nitrogen instead allows for the identification of any issues with the design, more specifically any materials that do not stand up under cryogenic temperatures.

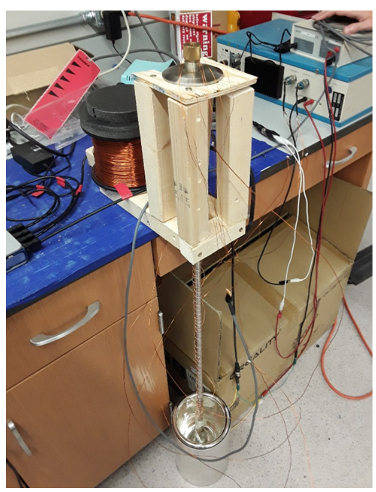

Figure 3: Image of the setup for a liquid nitrogen experiment. The wooden stand is shown in the center, with the rod extending down from it to the liquid nitrogen container. The control equipment is seen at the top right corner, while a small part of the NI 9239 is seen at center left.

The liquid helium test consists of a large dewar of liquid helium being used as the cryogenic liquid. The length of the rod is such that it can be threaded through the hole in the dewar and let the cage reach the liquid inside, while keeping the whole container sealed. Liquid helium is 4.2 K, which allows the lead to reach critical temperature and for the whole cage to become superconducting. This test will thus consist of waiting for the cage to reach the critical temperature, then use an external magnet to see if the cage can create the induced, opposing B-field that it was designed for. The creation of said B-field will confirm the viability of the design in the SNS nEDM experiment.

3 Results

All tests were performed at a 10 Hz sampling rate, with varying numbers of samples gathered. The magnetometer was present during these tests, but as the magnetic field of the cage was not the focus of the tests, its data has been omitted here except when relevant. It should also be noted that the thermometers had not yet been attached with varnish to the cage during the first test; instead, both thermometers hanged alongside the cage, with Probe A hanging down to a lower elevation than Probe B and thus acting as the "bottom" thermometer and "top" thermometer respectively. Additionally, all tests observed significant frost accumulation on the cage and rod above and close to the liquid nitrogen's surface, but this did not appear to affect any of the equipment.

The first test was performed in two parts, a 605.25 second segment that was intended to continue for a longer time period, and an 858.73 second segment started shortly after the first segment ended and manually ended early, along with two single-point reads from much later. After the test was completed and the cage was left unattended overnight as the liquid nitrogen evaporated, the resin stand was found to have shattered, requiring its replacement. In both segments, the data indicated that the temperature fluctuated around 78.3 K, with the first segment varying by 1 K at most with momentary spikes of up to 205.83 K and as low as 30.22 K during swapping between thermometers, and the second varying by 1.5 K (with an outlier spike to 83.57 K). The last two readings gave 93.23 K and 128.9 K, with the large difference between each thermometer as well as from their previous values may have been due to the liquid nitrogen evaporating, allowing Probe B to warm up again while Probe A was still submerged. The first segment did have manual swapping between the two thermometers, leading to some of the irregularities found in the first segment's data.

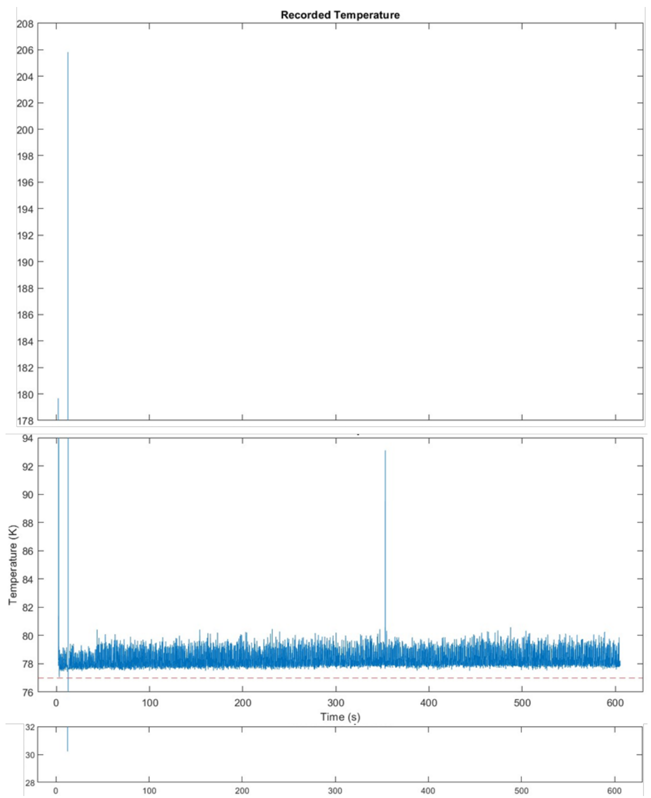

Figure 4: Graph of temperature data from both Probe A and B (with swaps between the two while sampling) during the first test's first part. The graph has been broken on the y-axis to remove extraneous intervals. Note that the dashed red line represents the temperature of liquid nitrogen, 77 K.

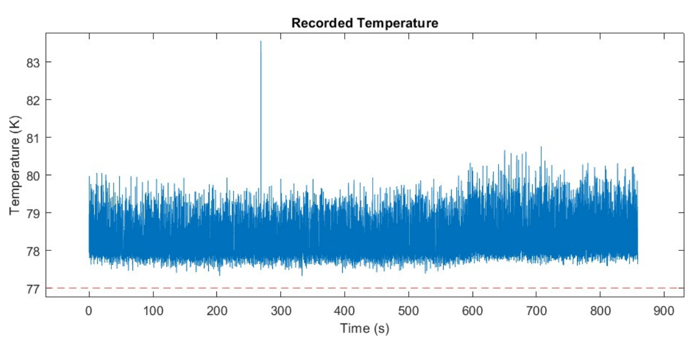

Figure 5: Graph of temperature data, possibly from Probe A, during the first test's second part.

The second test was performed in two parts, a 230.38 second segment that was terminated manually as the control devices had not been turned on (meaning the output signal was simply random noise), and a 1,132.40 second segment intended to last 1,800 seconds but which terminated early due to an error caused by the external computer going to sleep and restricting resources. During the test, the metal stand held up, making it a suitable replacement for the resin stand. The data indicated that the temperature fluctuated around 77.7 K by at most 0.5 K, with the minor variance likely caused by electrical noise rather than true temperature fluctuations. All measurements were made with Probe A – no manual switching between the two signals occurred.

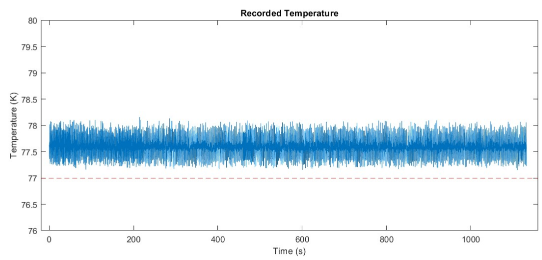

Figure 6: Graph of temperature data from Probe A during the second test's second part.

The third test was performed in five parts, which can be divided into 4 different sub-tests of the cage. The first was an approximately two-hour sampling from Probe A (accidentally, as intended to be the "top" thermometer, i.e. Probe B) during insertion into the liquid nitrogen and while it cooled, made up of two consecutive sampling periods of 3,632.32 seconds and 3,634.95 seconds. During the insertion into the liquid nitrogen, the temperature read by the sensor decreased drastically from 300 K to 77.6 K, with variance of 0.12 K after the temperature stabilizes.

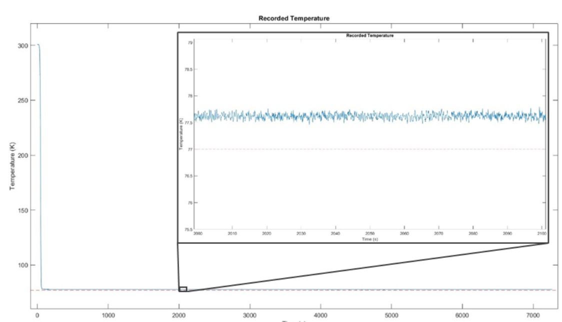

Figure 7: Graph of temperature data from Probe A during the third test's first sub-test. An insert of the data from t=2000 to t=2100 is shown here to represent the temperature fluctuations of the cage while at equilibrium.

The second sub-test was another hour-long sampling from Probe B after the liquid nitrogen surface had lowered enough that Probe B was exposed to the air and allowed to warm. Specifically, this sampling period was for 3,633.28 seconds, starting 25 minutes after the previous sub-test. The readings showed that the temperature increased steadily over time from 87.6 K to 93.7 K, with a variance of 0.15 K.

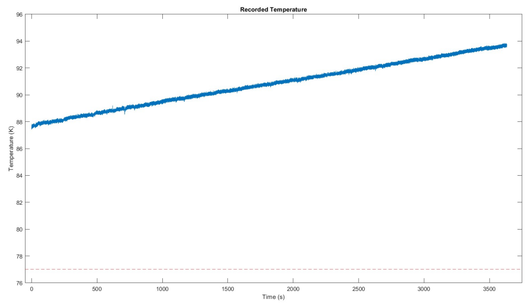

Figure 8: Graph of temperature data from Probe B during the third test's second sub-test.

The third sub-test was a shorter sampling from the magnetometer while the cage was exposed to a magnetic field to confirm that the magnetometer was accurately reading the magnetic field strength. This test lasted 1211.67 seconds, taking place directly after the previous test. The source of this magnetic field was a large coil of wire used for storing copper wire, with the current provided by an external power supply whose output could be controlled manually. The results showed that the magnetometer correctly read the field strength when the power supply was made to apply zero voltage, maximum voltage, and reduced voltage. The slow reduction in the measured field strength over time is likely caused by the resistance in the wire increasing as it is heated up by the current, leading to a lowered current output and a consequently lower strength magnetic field from the coil.

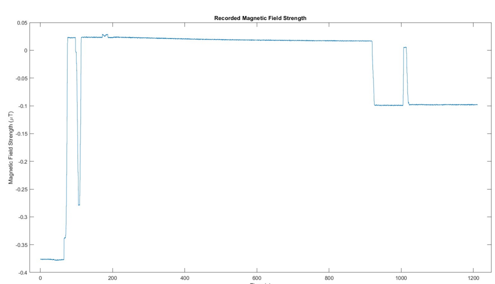

Figure 9: Graph of magnetic field strength during the third test's third sub-test.

The final sub-test was another hour-long sampling taken from Probe A which, during the entirety of testing, was below the surface of the liquid nitrogen while it evaporated. This test lasted 3,632.95 seconds, starting five minutes after the previous one. As expected, the results showed that Probe A had only risen slightly to 77.65 K with 0.2 K variance, due to its continuous emersion in the liquid nitrogen compared to Probe B.

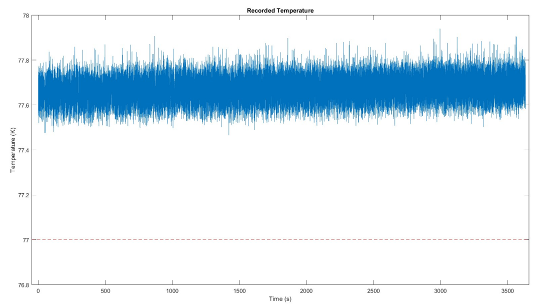

Figure 10: Graph of temperature data from Probe A during the third test's fourth sub-test.

4 Future Work

The next step in this project is running a liquid helium test of the device, in order to specifically test whether the superconducting cage is capable of producing the desired constant magnetic field. Currently, the cage is attached to a long rod in order to facilitate inserting it into a dewer holding the liquid helium, and allowing for data to be taken from the sensors after insertion via the wiring passing through the rod. A method for inducing the external magnetic field has not been selected yet, but would most likely consist of a current applied onto a simple wire coil to create an electromagnet. An alternate method for determining the magnetic field, by using a field mapper to measure the internal field from outside the cage, is also being considered.

References

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[2] J. S. Nico and W. M. Snow. "Fundamental neutron physics". In: *Annual Review of Nuclear and Particle Science* 55 (2005).

[3] E. Sather. "The mystery of the matter asymmetry". In: *Beam Line* 26 (1996).