Designing a Uniform Magnetic Field for nEDM Experiments

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August 11, 2022

1 Introduction

The search for a separation of positive and negative charge, called the electric dipole moment (EDM), within the neutron is one of the most pressing issues in nuclear/particle physics. The discovery of charge separation in the neutron would be a major step forward in explaining the imbalance between matter and antimatter in our universe. According to the Big Bang theory, equal parts of matter and antimatter should have been created in our universe, but now it is predominantly matter. A non-zero EDM in the neutron would be evidence of processes required to convert antimatter into matter during the formation of the Universe. According to Sakharov, these baryon number (B) violating processes require parity (P) violation and charge-parity (CP) violation, equivalent to temporal (T) symmetry violation, which are both present under the standard model of physics, but with not nearly enough strength to explain the asymmetry. Thus detection of a finite nEDM would help to explain the Baryon Asymmetry of the Universe (BAU) [1][2].

In testing the EDM of the neutron, physicists have exposed neutrons to magnetic fields and measured the precision frequency of the particles. The precision frequency is measured through a nuclear reaction with polarized He-3 atoms. If the neutron had an EDM, its spin axis would also precess when exposed to an electric field, albeit on a much slower scale. After measuring the precision frequency, the large electric field is reversed, and the frequency is measured again to see the difference from background effects. Were an electric dipole moment to be present in the neutron, the precision frequency would shift according to the strength of the applied electric field. The precision frequency can be calculated using the following formula: $\omega_L \hbar/2 = \pm\vec{d} \cdot \vec{E} + \vec{\mu} \cdot \vec{B}$. In this equation, ω_L is the precision frequency, $\hbar/2$ is the spin angular momentum of the neutron, $\pm\vec{d} \cdot \vec{E}$ is the electric dipole moment, and $\vec{\mu} \cdot \vec{B}$ is the magnetic moment dot the B field [1][5].

Due to neutrons being hypersensitive to magnetic fields, a slight change in the magnetic field could produce results mimicking the presence of an EDM, causing a systematic error in the experiment. Therefore, the design of a uniform magnetic field is crucial in testing for EDMs. A double cosine theta coil will be used in this project. This is a unique coil containing two cylindrical layers which produces a uniform magnetic field on the inside of the coil. This design prevents a fringe field from being formed which blocks interference with nearby devices. Through Nuclear Magnetic Resonance, the electric dipole moment of the neutron can then be measured [3][4].

2 Procedure

1. We will use Autodesk Inventor to develop a skin for a pre − existing skeleton. This skeleton is the decided shape of the magnetic field. The skin will be made of resin from 3-D printing and will contain small clips to hold the wires in place.
2. We will wrap wire around the skins precisely where the clips are placed to create a uniform magnetic field.
3. The robotic magnetic field mapper will be used to measure the magnetic field. Then, computer programs will be used to compare what was measured with what was expected for the magnetic field.

This project is important in the manipulation of neutrons. These neutrons will then be used in nuclear physics experiments including determining the electric dipole moment of the neutron.

3 Mapping a Magnetic Field

Starting off in the laboratory, we began with learning about the different instruments we had to work with. This included becoming familiar with how power supplies and multimeters worked. We coiled various objects around the lab in wire and connected it to the power supply. From this, we were then able to measure the B field with an application on our cellular device called Physics Toolbox. Physics Toolbox has a built in magnetometer which we used to measure the magnetic field in relation to time. Since most of the materials in the laboratory are nonmagnetic - to reduce the amount of interference with magnetic materials - the objects we coiled ranged from plastic cylinders to nonmetal rod like structures. Since the wire used for coiling was covered in an insulating material, before hooking the self-made magnet up, we had to scrape the ends of the wire off. This ensured that the power would connect directly to the wire. With these, we tested the field with varying amounts of current and voltage and checked the magnetic field produced. Becoming familiar with these devices allowed us to become familiar not only with the lab environment, but also with what instruments we had to work with in relation to our research project.

Next, we took the multimeter and measured the resistance using different resistors found in the lab. We related how the resistors looked in terms of shape and size with the amount of resistance produced. Using the resistor in this sense allowed us to become more familiar with its capabilities. This proved to be especially helpful in the coming days to work out issues involving other coils we were mapping for more detailed research. After we did this we continued to coil materials around the lab, moving towards coiling magnetic materials we could find. This included coiling objects such as nails and spoons. After running a current through these objects, we tested if there was a magnetic attraction between the coiled material and another metal object. We followed this with viewing the magnetic field using our cellular devices.

Since we knew we were designing a double cosine theta coil for our main project, we also coiled a smaller cosine theta coil for practice using materials found in the lab. We found a cylindrical shape of plastic material used in an older project to use as the base of our coil. Using wire also found in the lab, we coiled the cylinder based on where we knew the equipotential lines to be. This coiling process took a couple of tries since we had to find a way to keep the wire in place while also preventing it from bending in a way that it was not supposed to. Although the cylinder base did have grooves, these grooves were not substantial in keeping the wires in place. Therefore, tape was used. However, this tape proved to be somewhat ill-suited to the coil design, as well. At one instance we also attempted to use glue to keep the wires in place. But we reverted back to tape when we found that the glue provided no additional support. After a couple tries of coiling the magnet, we completed the cosine theta coil and began the process for measuring the magnetic field produced. As with the other objects we coiled, we connected the cosine theta coil to the power supply and ran a current through it. After looking at the field on our devices, we decided to map out the field points. We measured the appropriate distances and measured the points needed to map out the field using a caliper. After determining the points, we used a Matlab program to plot the field. However, due to technical issues, the program did not run as expected and it was determined that the points we calculated were wrong due to us coiling the cosine theta coil in the wrong manner. The way in which we had coiled it did not position the wires precisely in the correct place. We later recoiled the cosine theta coil so that the wires were in the correct position and used tape as reinforcements.

As part of a larger side project, we were tasked with mapping out the field points produced by the recoiled cosine theta coil. To do this, we had to set a reference point to the origin inside of the coil. We set this point as the middle of the coil. We were going to be using the Physics Toolbox application on our cellular devices, so we then had to find where the sensor for the magnetometer on that application was. We did this by taking a small steel rod and tracing our device. Wherever the magnitude of the magnetic field spiked was where the sensor was located. This is due to the fact that this piece of magnetic material channeled the Earth's magnetic field and redirected it in one direction. This was picked up by the sensor in our phones.

Next, we measured out points on the inside of the coil we created which represented where we were going to measure the magnetic field. We had to measure points in the x, y, and z directions then note the points given to us by the magnetometer for the Bx, By, and Bz directions. In the x-direction, we decided to mark points in 0.5 inch increments. So, from the front to the back of the coil, we measured the field at each 0.5 inch marking. In the z-direction, we measured the field at the bottom of the coil, middle of the coil, and top of the coil. In the y-direction, we moved the phone to the far ends of the coil and measured the field there. Since the coil was a relatively small cylindrical shape, we were only able to measure the far right and far left in the middle of the coil. The shape restricted us to be able to only measure in one place relative to y in the bottom and top of the coil. We measured all of the following field points with the coil connected to a power supply running 2 amps of current through the coil, continuously.

Since the field points were taken every millisecond, we first took the measurements by rounding up a number to what was recorded on the magnetometer. However, after becoming more familiar with the application, we found that data could be recorded and exported as an excel later. We decided to try this method of data collection. At first, we recorded the phone while sliding it at the different points chosen for measurement. We also used a stopwatch while recording this data and lapped the clock every time we stopped at a point. This way, we were able to see at what time the phone was stopped which also indicated the specific data at that point. However, this method of data collection proved to be unreliable since the measurements at specific points would not provide the correct average and therefore, not provide us with the correct reading.

Following this stage, we decided it would be best to collect data at each point separately. Although somewhat time consuming, collecting data in this manner provided for the most accurate results. A phone was placed at each predetermined point, individually, and data was collected for 2 seconds. The data was then exported to an excel spreadsheet and each column with points for Bx, By, and Bz was averaged.

The following day, the setup was changed to further produce accurate results. From the previous set up, it was determined that measuring the origin of the bottom of the coil was particularly difficult. So an encasing of sorts was used to hole the magnet up. The phone used for taking measurements was also attached to a cardboard piece to allow for more uniform measurements. Previously, it was hard to get measurements at the same height. However, with this new set up - putting the phone on a flat surface - allowed measurements to be taken at the same height. Additionally, 1 inch boxes were used as the standard measurement for height. In doing this, measurements could be expanded in the y-direction. This meant points could be taken in the far right, middle, and far left points in the coil for the bottom, middle, and top tiers of the coil. Measurements were also taken with the power supply switched off so that the Earth's magnetic field and any disturbance from background devices could be taken into account.

The next part of this project was to use Matlab to plot the magnetic field points. The points were inserted into a program and were plotted to show the vector field. This aspect of the project, although not directly related to our main project, allowed us to learn more background in magnetism. It also allowed us to become familiar with mapping magnetic field points and with how robotic mappers function. This is especially useful since in measuring the electric dipole moment of the neutron, a robotic magnetic field mapper will be used to measure the field. Following this, programs would compare what was measured to what was expected for the magnetic field. So, the aspect of manually mapping the magnetic field of a cosine theta coil allowed us to dig deeper into what goes into measuring the EDM of the neutron.

4 3D Printing the Magnetic Field

We were also simultaneously able to start working on the main project relating to neutron electric dipole moments during our work on mapping magnetic fields. An aluminum skeleton with specific dimensions was made to be the core of the magnetic field for this project. From here, skins created using Autodesk Inventor/Fusion 360 (online design programs) and printed using a 3D resin printer would be made to surround the aluminum skeleton and complete the design for the magnetic field. Based on designs from previous work in this project, I was tasked with creating and adjusting the designs for these skins that would then fit precisely into the pegs of the aluminum skeleton.

Due to the shape of the skeleton, it was decided that the best way to print the skin would be to do so in sections of $\frac{1}{4}$ of the skeleton. This way, one section could be perfected and printed 4 times to complete the skin. This would need to be repeated for the inner section of the skeleton, as well, since the curvature of the outer and inner parts of the skeleton are slightly different. For this aspect of the project, adjustments have been made to better the fit of the skin onto the skeleton. For example, pegs on the skin have been made slightly smaller to better fit into the skeleton and will contain mechanisms which allow it to be latched onto the inner portion of the skin. This will allow for the skin to fit tightly onto the skeleton, preventing the chance of the uniformity of the field to be disrupted. The skin will also contain a lip to cover the bottom and top of the aluminum skeleton.

Another design aspect of this project is the inclusion of small clips onto the skin being developed. This is the main focus of the project as of now. Since the uniformity of the field is important and due to the nature of a double cosine theta coil, the wires must be coiled at specific equipotential lines. If the wires slightly move away from their specified position, there would be a change in the magnetic field. In learning from previous designs, simply applying grooves to the skin so that the wire may fit in-between is insubstantial. Therefore, small clips are being designed to line the skins. These clips will be just big enough to keep the wire in place as it is coiled around the skin. The dimensions for this clip are being perfected before they can be inserted into the design of the skin. Additionally, we have recently settled on a design for the clips which includes adding a trench to which the wire would fit into. This trench would act like a groove of some sorts. The trench would be attached to a digout which is a small box cut out of the resin skin. The clip would sit in this digout rather than being directly attached to the trench. This would allow for the clip to be flexible in hugging the wire and adjusting for it to be fit in. A diagram of this design is provided below.

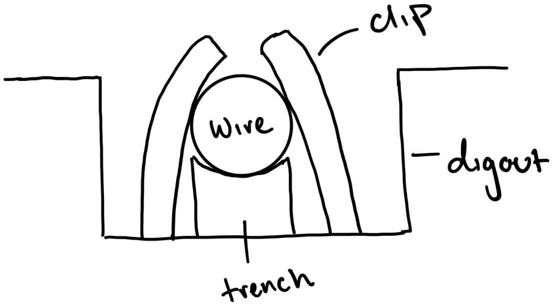

Figure 1: Front view of proposed clip design.

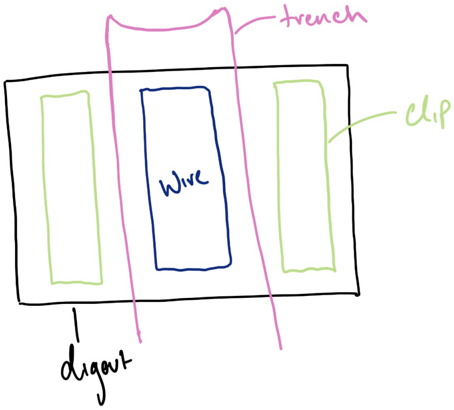

Figure 2: Overhead view of proposed clip design.

Using this base design, we strategized a plan for printing the clips. This plan included printing the components of the clips in parts. Therefore, we started by printing prototypes for the trenches first using the correct dimensions. After perfecting the dimensions for the trenches, we added the clips to the design. The construction of these clips in Fusion 360 was slightly different from that of previous designs. For this clip, a plane was hand drawn and a shape for the clip was drawn onto that plane. From there, the shape was swept and extruded to create the clip. Constructing the clip this way allowed us to create the exact curvature needed to fit the trench and skin. A picture of this design in Fusion

360 can be seen below. In this figure, the trenches can be seen with the clips.

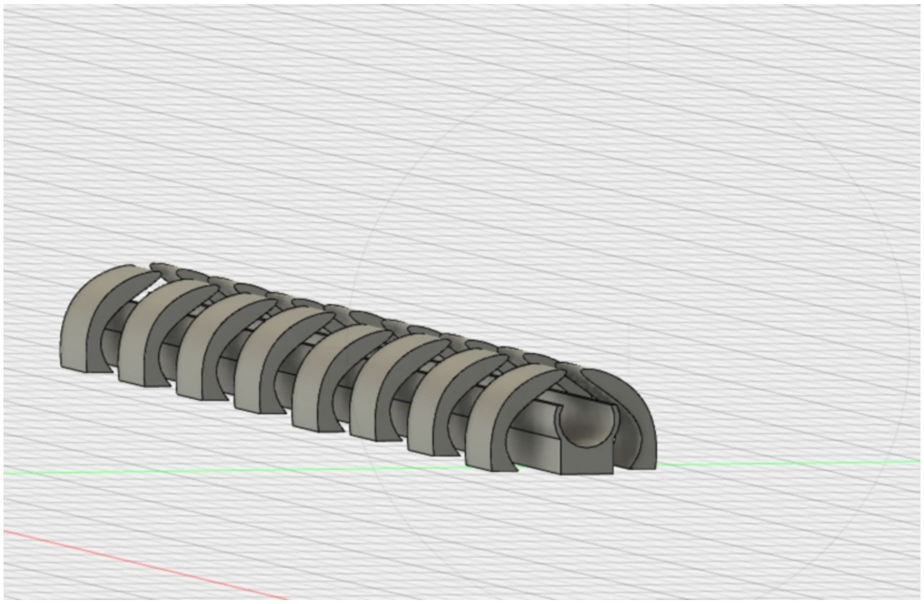

Figure 3: Clip design in Fusion 360.

The design of the clips were formed to fit a 24 gauge wire. For the first print, the spacing between the individual clips was slightly off - being too far apart. Due to this the clips were not holding the wire as tightly as needed. So, the spacing was adjusted to slightly bring each clip closer to its counterpart. After the second print using the adjusted measurements, the 24 gauge wire fit in perfectly. However, there were some issues concerning resin from the 3D printer spilling into the trenches. This prevented the wire from fitting in the best it could. To fix this, we printed the designs at a higher resolution.

Following the clip designs, we further adjusted the dimensions of the skins. We mainly focused on perfecting the outer skins. First, we shortened the length of one of the sides to match a previous print we had done. We then realized that shortening that side created a gap between two skins placed next to each other. We wanted to minimize this gap as much as possible. So, we worked in Fusion and lengthened the specific side to fill in the gap.

Following adjustments made to dimensions of the skin, we printed prototypes of the skin with the clips covering the surface. We printed two of these copies to see if the wire would wind correctly with the clips on the skins. Our conclusion from these prints was that the clips worked well attached to the skin. Additionally, due to the placement of the clips, the position of the print in the 3D printer along with the addition of supports altered the curvature of these prints compared to previous ones. Instead of the supports pushing down on the curvature, they were pushing up. This caused the curvature of the print to be less curved which did not fit the curvature of the aluminum skeleton as best as necessary. Therefore, we opted to change the position of the print in the 3D printer to be standing on its side. This way the supports were not pushing up on the curvature but were holding the print from the side. This solved our problem and we continued printing future prints in the same manner. Below is a picture of the first two prints containing clips. This image is also an example of how the skins would cover the aluminum skeleton.

Figure 4: Prints of skins containing clips.

Our next task included placing the clips on the skins exactly where the equipotential lines of the magnet were and constructing a lip to cover the top and bottom of the skeleton. We first drew the equipotential lines in Fusion 360. We determined the number of windings we wanted to have based on an older prototype of the magnet. The final decision was to have 19 coils on each side for a total of 38 coils. Based on this, a lip was created and the equipotential lines were drawn on using the 3 point arc tool. Then, the placement of the lines were swept in the same dimension of the diameter used for creating the trench for the clips. Clips were placed over these troughs. For the design of the lip, rather than having it extrude halfway on the inner and outer skins over the top and bottom of the skeleton, it was decided to print on lip extruding so that it may cover the entirety of the top of the skeleton. This prevented any gap that may have formed while designing. This also allowed for the clips on the lip to be placed without a break in the design.

We also later decided that it would be more beneficial to vertically combine two skins and print them as one to reduce error margins. Knowing the placement of the equipotential lines, we placed clips on the skin aligning with the curves drawn on the lip. Below is a completed design of the outer skin containing the lip and clips in Fusion 360.

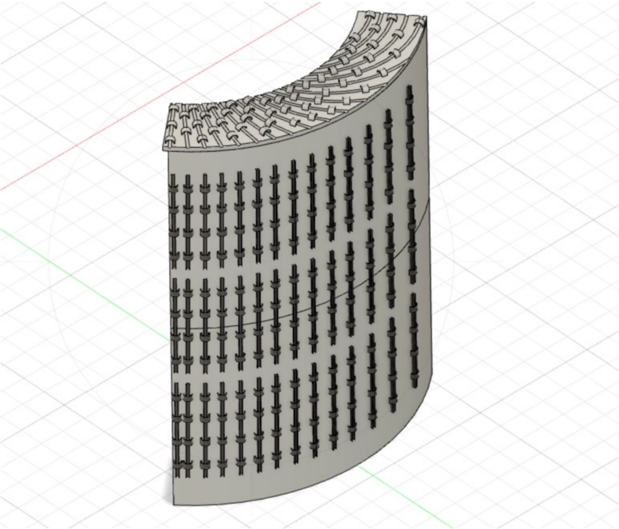

Figure 5: Outer skin design containing lip and clips.

We printed two of these designs. The first did not hug the skeleton as tightly as we wanted so we adjusted the dimensions by lengthening the top and bottom by 1mm. The second print fit the skeleton much better. The result is shown below.

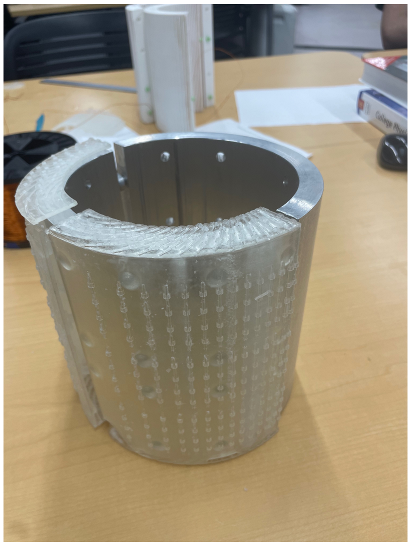

Figure 6: Final print of outer skin design containing lip and clips.

5 Next Steps

Next steps in this project include making necessary alterations and printing the above design of the outer skin three more times to completely cover the skeleton. These alterations include adjusting the design of the clip. When printing this design, some clips were removed from the original clip design since it was determined not as many clips were needed to hold the wire. However, since the clips are attached to the trench in the design, removing these couple clips weakened the structure of the entire clip. This resulted in the clips breaking more easily when trying to clip wire in. For further designs, an attempt to sweep the clip in Fusion 360 can be made to strengthen the structure. Additionally, the design of the outer skin was the main focus of this project which left the inner skin incomplete. Therefore, further work should include adjusting any necessary dimensions of the inner skin to better fit the curvature of the aluminum skeleton. Due to the present design of the lip, only clips would need to be added to the inner skin and printed four times to complete the magnet. After completing the printing process for the magnet, it would need to be wound with 24 gauge wire. From here, a magnetic field can be generated and mapped using the robotic mapper. Using computer programs the measured field can be compared to the expected field and the design can be further refined based on these results.

6 References

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