University of Texas at Arlington SPS Research Report
December 2013
Primary Researchers: Timothy Hoffman, Elijah Murphy
Secondary Researchers: Frank Allen, Soha Aslam, Arthur d'Auteuil, Andrea Marlar, Blake Watson

Introduction:

This project is meant to investigate the physical properties of a hypotrochoidal electromagnet. The electromagnet is based on the property of currents in wires to produce magnetic fields. In standard electromagnets, the wire is wrapped in coils in order to intensify and direct the magnetic field. Our winding method uses a shape known as a hypotrochoid, which is a special type of roulette curve generated by a point attached to a circle rolling within larger circle. We obtain this shape by coiling wire around a torus (or torus-like object). It is possible that this winding method will still intensify and direct the magnetic field in a novel (possibly helical) fashion. Specifically, our investigations are meant to characterize these electromagnets.

Simulation:

We spent a significant amount of time working on the simulation portion of this project. Much of the time was devoted to finding a program that would plot a magnetic field for a given coil of wire. However, this was unsuccessful as we could find no such programs. Even after consulting several professors, many of whom research in the field of electromagnetics, we were unsuccessful in finding a program that could accommodate our needs. For this reason, we have forgone the simulation portion of the experiment, in favor of creating our own maps from theory.

Theory:

Since simulation did not seem viable, we turned to theory. Still using the hypotrochoid (eq 1) as the shape of our magnet we wrote out the dipole and quadrupole moments of the magnetic vector potential.

$$x(t) = (R - r)\cos(t) + d\cos\left(\frac{R - r}{r}t\right)$$
$$y(t) = (R - r)\sin(t) + d\sin\left(\frac{R - r}{r}t\right)$$
$$z(t) = h\sin\left(\frac{2r - R}{r}t\right)$$

Equation 1. Parametric form of a hypotrochoid with a sinusoidal third dimension added.

Where R is the radius of the large circle, r is the radius of the small circle, d is the distance of the generating point from the center of the small circle, h is the amplitude of the third dimension, and t is the angle between the center of the small circle and the horizontal axis.

This method also turned out to be nontrivial as the dipole moment has over 30 terms and the quadrupole moment has over 100. These moments must be turned back into rectangular coordinates and then curled in order to finally obtain the theoretical magnetic field. This problem has so far stonewalled us due to a lack of understanding of the equations that govern the hypotrochoid. In the future, we would work further on the theoretical equation and hopefully input it into a program (such as ROOT or Mathematica) in order to map the entire theoretical magnetic field. This would allow us to compare our theory with experimental data in order to support the experimental results.

Experiment:

Prototypes:

We currently have a total of five prototypes. The five prototypes are: "original" (figure 1), "Small" (figure 2), "Medium" (figure 3), "Large" (figure 4), "Flat" (figure 5). The fifth prototype turned out to have an electrical short in it and is currently inoperable. More prototypes can be constructed in the future, if a broader selection is needed. The Original prototype was built early on as our first foray into this project. However, the small wire took issue with the large current that we pushed through the coil and would sometimes begin to emit a metallic odor. In order to remedy this problem we constructed the other prototypes mentioned above with much thicker wire at various sizes in order to investigate their varying magnetic fields.

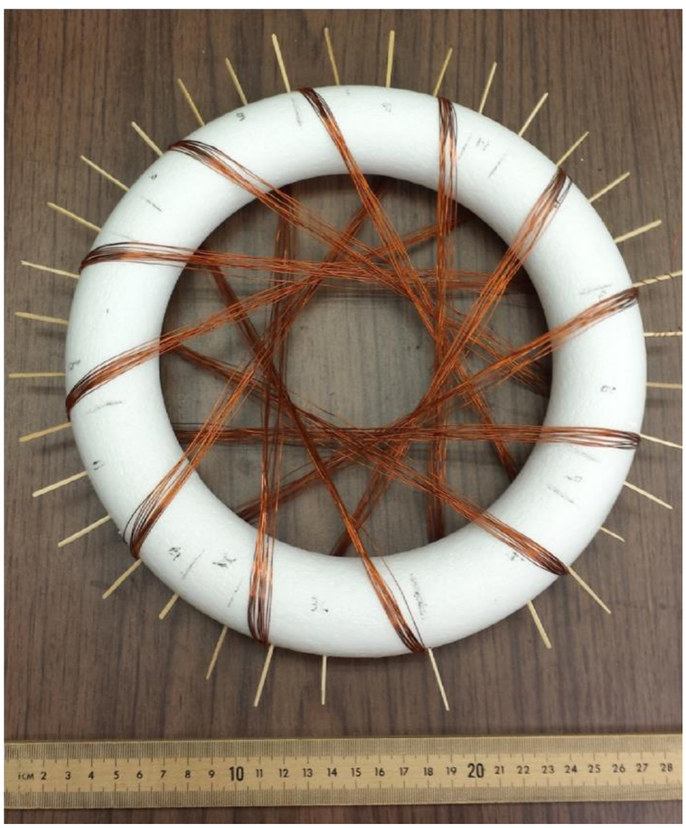

Figure 1. The "Original" prototype consisting of twelve loops and twelve winds of 45 gauge wire. The outer diameter of the torus measures 26 cm.

Figure 2. The "Small" prototype consisting of twelve loops and ten winds of 16 AWG wire. The outer diameter of the torus measures 21 cm.

Figure 3. The "Medium" prototype consisting of twelve loops and ten winds of 16 AWG wire. The outer diameter of the torus measures 26 cm.

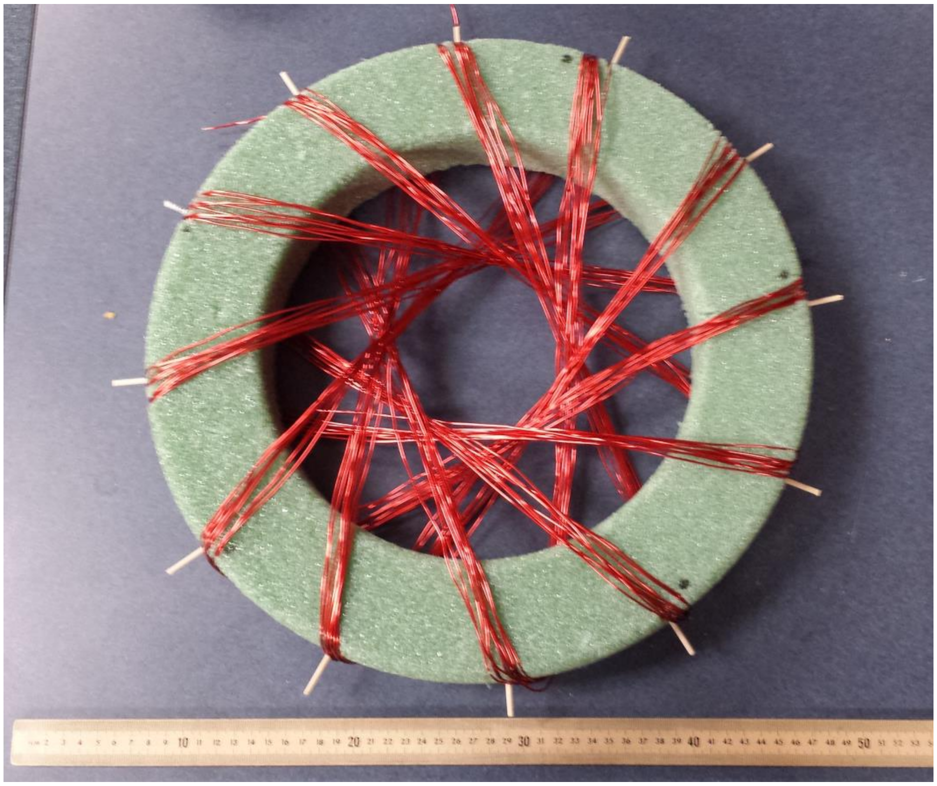

Figure 4. The “Large” prototype consisting of twelve loops and ten winds of 16 AWG wire. The outer diameter of the torus measures 40 cm.

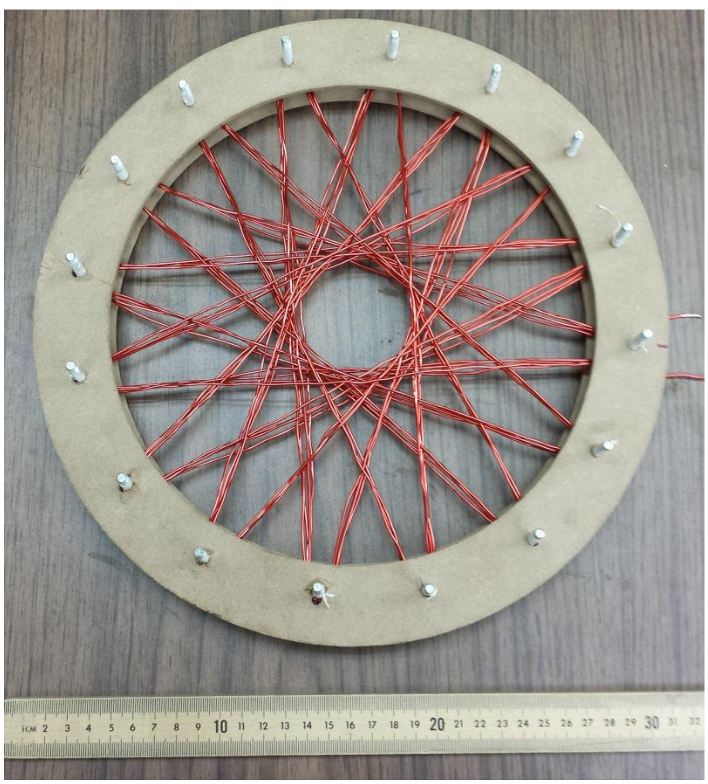

Figure 5. The “Flat” prototype consisting of twelve loops and ten winds of 16 AWG wire. The outer diameter of the torus measures 27 cm.

Experiment to Date:

We tested the prototypes discussed above using a power supply obtained second-hand from our physics department. This power supply has a range of 0-30 Volts and 0-3 Amps, but does not have an accurate display and its output can occasionally fluctuate wildly without being touched. In order to obtain an accurate measurement of the output voltage and the current being generated, we connected two digital multimeters to the circuit to be used as an ammeter and voltmeter. The resulting circuit is shown in Figure 6.

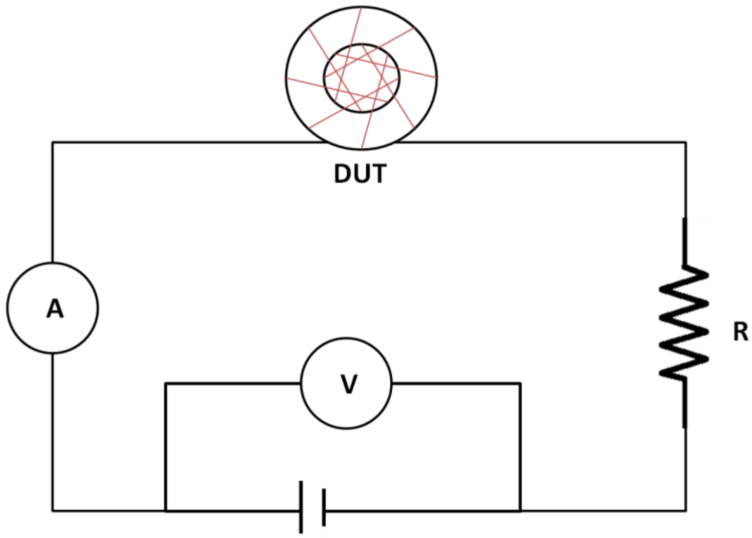

Figure 6. Schematic of the testing circuit. A represents the digital ammeter, V represents the digital voltmeter, DUT is the device under test, and R encapsulates all resistors of the entire circuit.

In order to measure the magnetic field being produced, we borrowed a Gaussmeter from Dr. Liu of UT Arlington. The Gaussmeter was suspended over the prototypes via a lever support system. This allowed us to maintain a desired position over the apparatus during each testing. The problem came, however, when we discovered that the gauss meter was not very precise; repeated measurements of the magnetic field of the prototype in the same location could have varying values by up to $\pm 30\%$. This meant that many of our results were not repeatable. In December a new Gaussmeter became available from the department which did not have this issue. Using this Gaussmeter, we obtained the measurements shown below in Table 1 of the data section. However, this Gaussmeter still did not suit our needs, because the probe was only sensitive to one axis of measurements. This meant that in order to generate a three-dimensional magnetic field, we had to rotate the Gaussmeter to the three orthogonal axes. This proved difficult, however, because it was not possible to be sure that we were perpendicular to the other axes. Those six degrees-of-freedom create a system where it is difficult to control orthogonality using a single-dimensional probe.

Data:

We have obtained basic data for all working prototypes (Table 1). The basic data represents the maximum magnetic field measured for each prototype from the center point of each torus. This data shows the trend of magnetic field strength decreasing as the size of the torus is increased. This is an expected result, because as the wires move further from the center, the magnetic contribution diminishes.

	Volts (V)	Current (A)	Magnetic Field (G)
Original	6	1.03	8.8
Small	2.7	1.05	9
Medium	2.8	1.04	7.4
Large	3.4	1.01	4.9

Table 1. The relationship between the prototype and the magnetic field. The voltage and current are given as a comparison. Note, the flat prototype had a Short and did not function.

Notice that field strength increases for decreasing torus radius.

We also obtained graphs of the magnetic field versus the current passing through the circuit. This was done to show that any conclusions made thus far could be applied to the magnetic fields at any reasonable current by applying a linear relationship between the current and magnetic field. These data are shown in Figures 7 and 8.

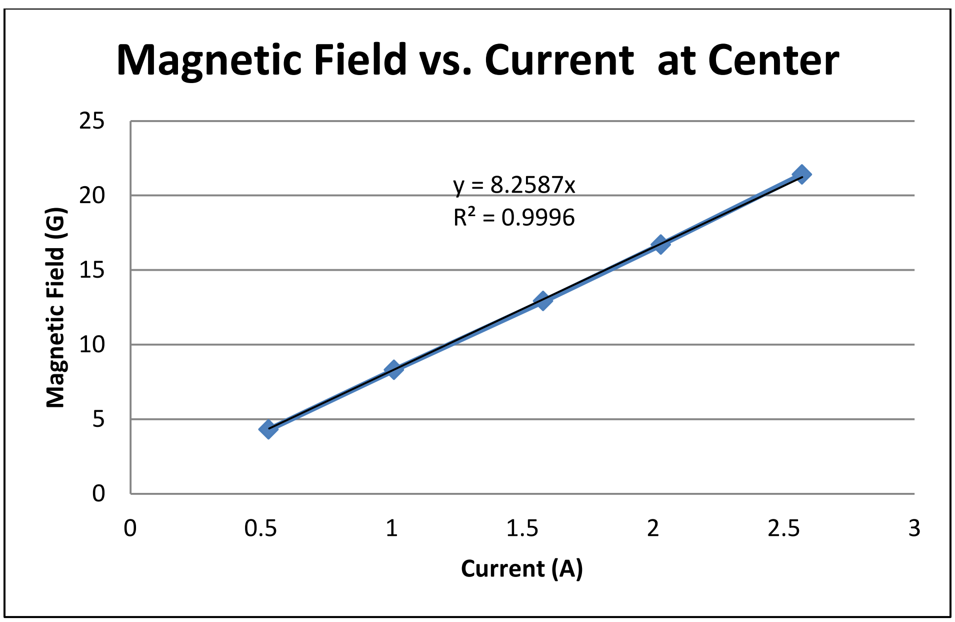

Figure 7. The magnetic field as a function of current at the center of the Medium torus.

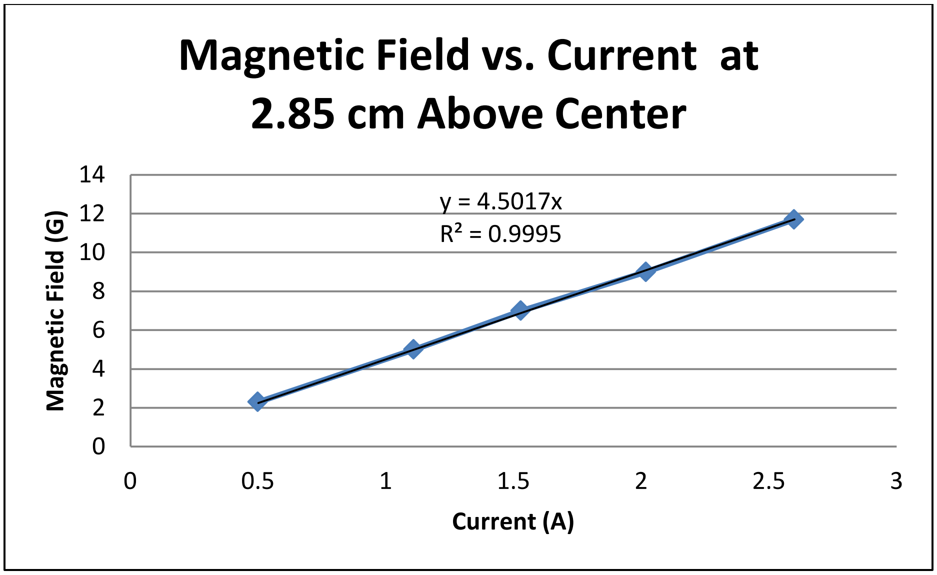

Figure 8. The magnetic field as a function of current 2.85 cm above the center of the Medium torus.

The z direction (which is defined to be perpendicular to the plane of the torus) of the Medium torus (Figure 9) was mapped; this map gives a general feel for the magnetic field produced by the torus. The brightness denotes magnitude so that lighter regions are larger and darker regions are smaller (even negative) in magnitude. This map shows the field pointing up from the center of the torus, looping around the torus, and pointing downward along the outer perimeter. Since the new Gaussmeter was only obtained in December, there has not yet been time to measure the x and y directions of the magnetic field. However as has been stated previously, large errors would be introduced by assuming that we could place the Gaussmeter probe at orthogonal angles. This could be remedied in the future by obtaining a three-axis Gaussmeter that would be capable of measuring the magnetic field in all three Cartesian directions simultaneously. Note that the during the measurements that produced Figure 7 there was a ± 0.2 G noise and the voltage and current varied from 3.05 to 3.25 Volts and from 1.03 to 1.13 Amps respectively. This variation came from our power supply, and in the future a better power supply would need to be obtained in order to increase precision and accuracy in the experiment.

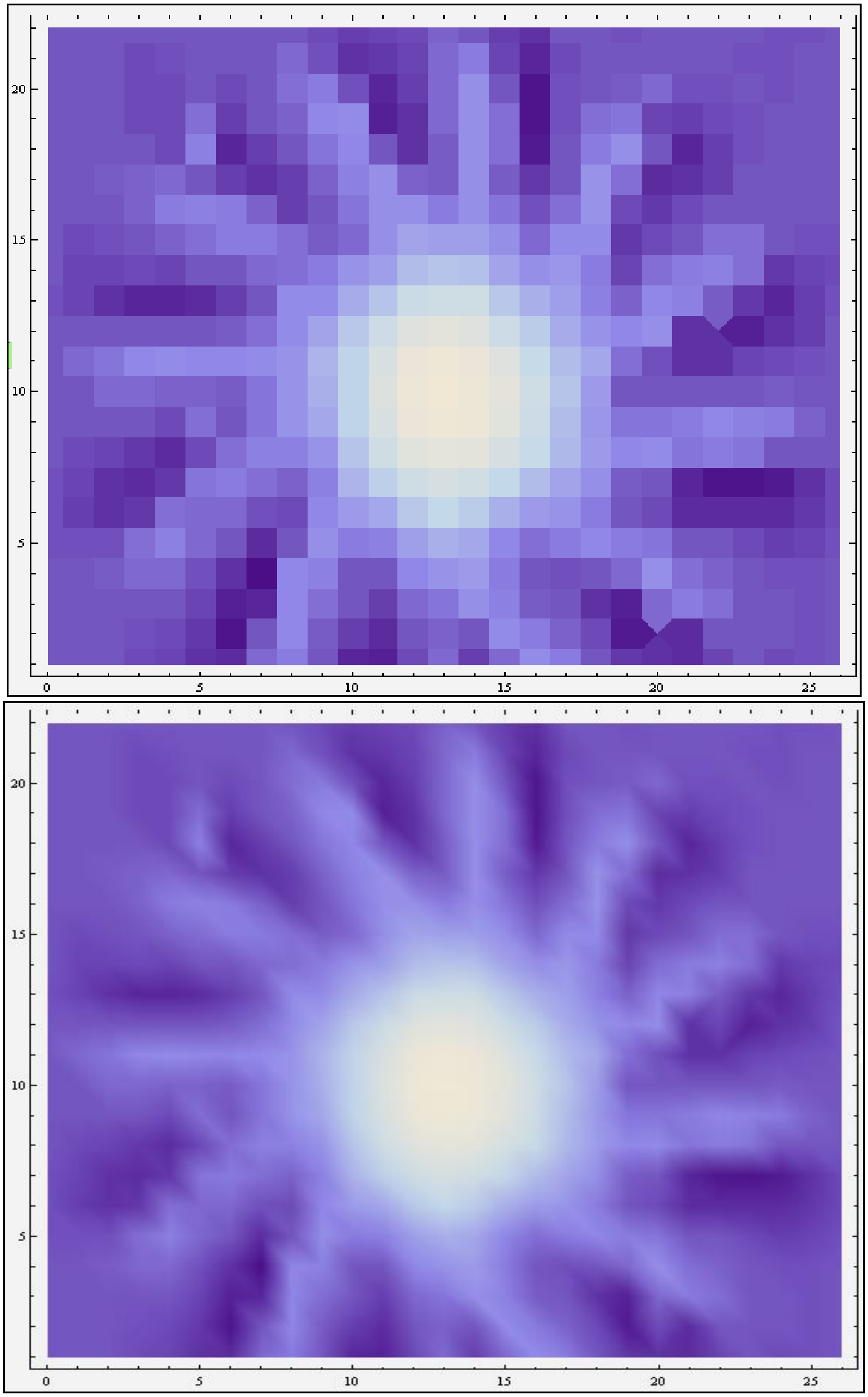

Figure 9. The distribution of magnetic field in the z direction for the Medium prototype at 6 mm above the center of the torus. Here, brightness denotes magnitude where lighter is larger. The top image shows the raw data while the bottom uses Mathematica's interpolation order setting of 1 to smooth the picture.

Procedure:
The magnetic field is mapped in the following way: The electromagnet itself is placed over a grid (22×27, 1cm × 1cm squares) with the Gaussmeter probe fixed above the grid. The center of the magnet is then moved to each intersection of the grid and the resulting magnetic field observed by the (still fixed) sensor recorded. This leads to 594 data points for each height in each direction, or more than 1700 total points for each field at each height using a single-axis probe. In this way we can map the exact magnetic field without moving the probe (which would have caused the probe to rotate, reintroducing our previous problem with orthogonality). Note that this method would not have worked with the original single-axis probe since this method does not address the reproducibility problem encountered with the first probe. Once the data are gathered, Mathematica is used to plot the magnetic field. Figure 10 shows the apparatus used in this test. Note that the use of a three-axis probe would cut down on the amount of work by a factor of three whilst simultaneously increasing the accuracy, precision, and reliability of the experiment.

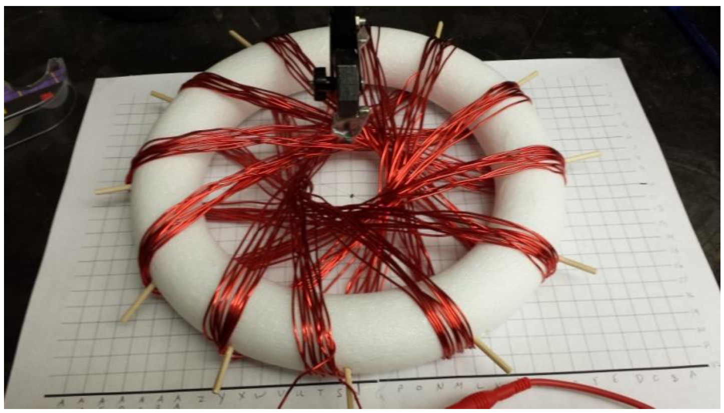

Figure 10. The set-up of the Gaussmeter probe held in place above the torus and grid. The torus is moved along the grid, simulating the movement of the probe, without interfering with the orientation or position of the probe.

Data Summary:

From the data we have collected, we can determine that the magnetic fields of the coils are linearly dependent upon the current going through the wire. This is expected due to Ampere's Law of electromagnetism. This principle was verified in Figures 7 and 8. We can therefore justify that any of the conclusions made can be extrapolated for a reasonable range of currents. We have also determined that the maximum magnetic field strength of the tori are related to the size of the torus. Specifically, as you increase the radius of the torus, the magnetic field generated, at a constant current, is decreased. This is consistent with what would be expected from a traditionally wound coil, such as a Helmholtz coil. Finally, we have shown that the magnetic field flows around the magnet similar to a traditional toroidal magnet; strongest at the center and weakest near the perimeter.

Expenses:

Purchase Item:	Amount::	Description:
Hardware Supplies	$24.95	Lever arm assembly and mounting equipment
Digital Multimeters	$335.89*	Digital Multimeters for measurements
Mounting Assembly	$7.01	Gaussmeter Probe Clamp
Copper Wire (16 AWG)	$69.45*	Copper wire for electromagnets
Digital Protractor	$38.01*	Protractor for precise angle measurements
Refreshments	$95.87	Food for meetings
Construction Supplies	$20.00	Toroids and Points (sticks)
TOTAL COST	**$591.18**	
Power Supply (Potential)	$100.00*	New Power Supply
Gaussmeter (Potential)	$780.00*	Three-axis Gaussmeter with USB data recorder
TOTAL COST (Potential)	**$1471.18**	*amounts do not include shipping and handling.

Table 2. Approximate expenses throughout the project.

To date, we have purchased almost $600 worth of materials, including the hardware for our apparatus, the wire for the coils, and equipment for measuring properties of our apparatus, such as digital multimeters. Potential future purchases would include a three-axis Gaussmeter and a new power supply. The Gaussmeter would be a necessary purchase because it would alleviate most of the obstacles that we encountered with the single-axis probe. This Gaussmeter would also reduce the amount of data needed by a factor of three, thereby drastically reducing the amount of time needed to collect data. The power source is also a needed purchase because it would be capable of going up to 10 Amps, allowing us to increase the magnetic field accordingly and reducing the signal to noise ratio of our data. This power supply also has a digital reading, allowing for more accurate determination of the output voltage and current, alleviating the need for the multimeters in the circuit, also cutting down on excess error.

Potential Timeline

Because of the coming spring semester, times must be extended to account for classes and other responsibilities. Note that purchases cannot be ordered until the university reopens at the earliest.

January 1-24:
Continue work on the theoretical magnetic field. Complete Mathematica program for mapping the experimental magnetic fields. Adjust apparatus for measuring magnetic field in preparation for the three-axis Gaussmeter and power supply.

January 8 (University reopens)
Order the power supply and three-axis Gaussmeter

January 25-March 16
Mapping and data processing for two prototypes

March 16-April 6
Data Analysis

April 6-20
Paper Write-up

April 21
Final paper submission

Conclusion:

Through this project, we have investigated some of the properties of the magnetic field of a hypotrochoid electromagnet. We have determined that many of the properties are consistent with those of a Helmholtz coil. However, more investigation would be needed to determine the true nature of the magnetic field. We have been unable to simulate a magnet of this nature and have not been able to curl our vector potential for the magnetic field either. One potential goal of this project was to try to use one of our magnets in combination with Dr. Weiss's positron accelerator housed at UT Arlington to see if the magnet could focus the beam of positrons. This has been found to be unrealistic, as this integration of machinery could take several months; putting the research of Dr. Weiss and his students completely on hold for the duration of the incorporation. Additionally, the size of torus required to create this coil would be very large (on the order of a meter). We can say, however, that much of our data supports the postulation of our magnet focusing the beam. Future work with this project could include a more thorough mapping of the magnetic fields for the various coil configurations. This would include three-dimensional vector maps and showing the magnitude and direction of the magnetic field lines at various points around the tori.

Acknowledgements:

Special thanks to Dr. Liu, Dr. Weiss, Dr. Brandt, Dr. Yu, and Dr. Jackson for lending us their equipment and guidance.