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Correctional Magnetic Coils for Beryllium-based Ion Plasma Chamber

Physics 492R Capstone Project Report

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Abstract:

The intention of this project was to develop and assemble two sets of identical magnetic coils for the Beryllium based plasma chamber at Brigham Young University. These coils, assembled simply with 12 gauge wire, power sources, and aluminum channeling (to support the wire), will correct for two very significant anomalies. The first is the Earth's intrinsic magnetic field, and the other, misalignment between the interior of the device and the solenoid surrounding it. These coils, appearing to be very simple, underwent a complex designing process as well. They were developed via a three dimensional analysis that implemented the computing power of Matlab. Completed, these coils will help in furthering plasma based research at BYU by reducing the number of complications affecting the functionality of this particular plasma chamber.

Introduction:

Among physicists, it is commonly known that plasma is the most common form of matter within our universe. After being discovered by a physicist named William Crookes in 1879, much research has been done, and it has become known that about 99% of matter can be traced to and identified as plasma. The reasons why plasmas do not appear to be so prevalent are various. In great part, it is due to their quick decaying time which involves a lack of sustaining optical, electrical, or thermal energy (1). Many research groups today are involved in the process of unraveling the characteristics of plasmas and how they work by sustaining them for prolonged periods of time in controlled environments.

One research group in particular is that of Brigham Young University. Plasma physics research at BYU, both experimental and theoretical, centers on the area of non-neutral plasma. This particular plasma in nature is Beryllium based and is being studied by various professors, as well as graduate, and undergraduate students alike. The goal and purpose of this group ultimately, is to be able to maintain a Beryllium based plasma within the chamber for a period of multiple weeks. This goal will allow the measurement of the half-life of Be^7 in an ionized state (2). Various steps however must be taken first, before being able to accomplish such a feat.

The plasma chamber being used for these various experiments at BYU, is located in the Eyring Science Center of the school's campus. The chamber itself is cylindrical and fairly small, but is surrounded by a large solenoid, which produces a precisely directed magnetic field through the center of the plasma chamber. The plasma chamber is also connected to a pair of power supplies, one on each end of the chamber, which help

to contain the plasma. In order to operate the chamber, first the voltage on the far end of the chamber must be turned on. Then a beam of ions is sent into the chamber. Before the ions are repelled backwards by the high electric potential difference, the other power supply must then be turned on, hopefully trapping a significant amount of particles within the chamber. The particles have large amounts of energy and would want to escape if possible, which follows the very nature of plasmas. However, they are constrained by the magnetic field due to the solenoid as well as an electric field being generated by the end voltages and a fast rotating wall. This prevents the plasma from hitting the wall of the chamber, dissipating, and escaping.

However, there are some complications in this process. First, the ability of the plasma to remain stable within the chamber is based largely on azimuthal symmetry within the chamber. The law of conservation of angular momentum helps by confining the plasma to the middle. As particles move outward from the center of the chamber cylinder, they would have to gain angular momentum, which without an external torque, would violate conservation of angular momentum. The chamber is contained in a high vacuum state when operated. However, there are still unwanted gases and particles within the chamber which are not ionized and therefore can collide with the plasma, which can cause an external torque on the plasma, allowing it to dissipate and escape. It is vital that the highest level of vacuum be attained to reduce this anomaly, as well as to increase the plasma density within the chamber.

The Earth's magnetic field and other unwanted magnetic field also act on the chamber. This can cause a sloshing of the plasma between the ends of the chamber, also generating an external torque. This can greatly reduce the decay time of the plasma as

well. These magnetic fields cannot be eliminated but can be countered via two sets of man made magnetic coils (a modification of Helmholtz coils). There are two perpendicular sets of coils to allow the correction field to point in an arbitrary direction perpendicular to the solenoid field. This allows any type of field error to be corrected. Designing and building these coils was the precise purpose of this project.

Methods:

In the development of this project, it was extremely important to understand various concepts of electricity and magnetism as taught in various physics courses. First, the connection between current and magnetic field must be accurately understood. A wire carrying current, as shown in Figure 1, generates a magnetic field directed in a circular path around the wire, which gets weaker and weaker further away from the wire. For an infinitely long wire, the magnetic field drops off with a mathematical form of (1/r), where 'r' represents the distance away from the wire.
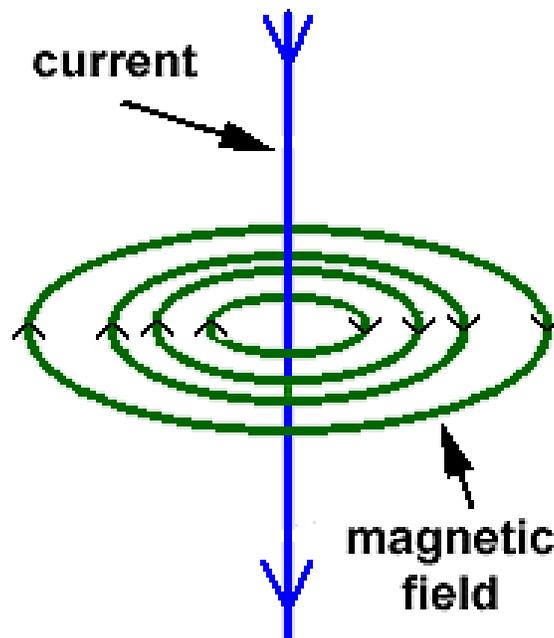
Figure 1

(4)

The mathematics behind this must also be understood in order to know what magnitude of magnetic field must be produced. Using David Griffiths book, "Introduction to Electrodynamics", a simplification of this process is made, which uses a

polar coordinate system to do the calculations, and it is derived that a segment of wire of length "l", carrying current "i", will generate a magnetic field of magnitude "B" at point "a", at a distance of "s" meters away, as shown in Figure 2 (3). It is also essential to correctly understand the direction the magnetic field points. Using the right hand rule and cross product identities, we can see that the current would come out of the page in Figure 2. In this particular design, all of the segments of wire had both horizontal and vertical components that needed to be dealt with.
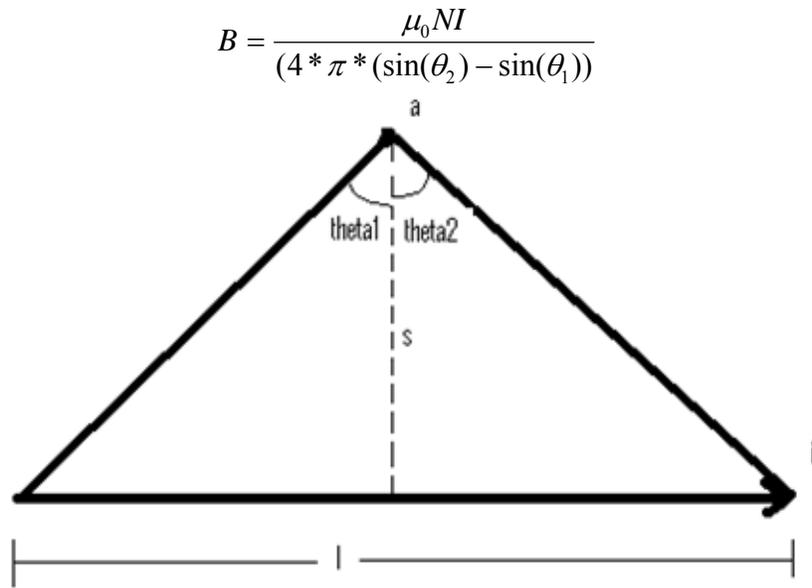
$$B = \frac{\mu_0 NI}{(4 * \pi * (\sin(\theta_2) - \sin(\theta_1)))}$$

Figure 2

Upon knowing this, understanding the function of the Earth's magnetic field was also of great importance. Looking at Figure 3, it is obvious that the direction of the magnetic field varies greatly with position on the Earth's surface. In Provo, Utah it tends to point down into the ground at about a 45 degree angle with respect to the Earth's surface, with a magnitude of approximately 50 micro-Tesla.
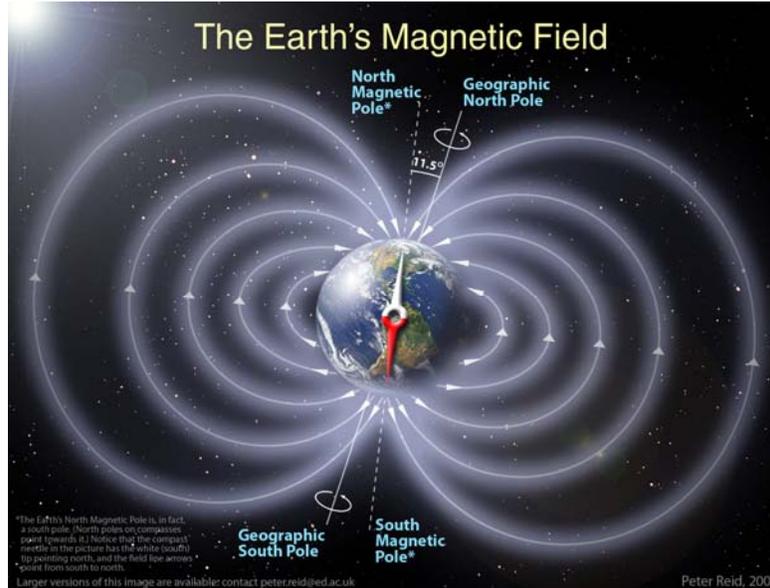
Figure 3

(5)

Having this knowledge, knowing the dimensions of the chamber, and the space restrictions of the apparatus surrounding the chamber, the task of designing the coils could now be explored.

In a perfect world, infinite segments of wire would provide a perfect solution. However, the coils were confined to a space less then one meter in every direction. Similar to Helmholtz coils, the coils here were to be rectangular in shape, with vertical bumps on the ends, which are intended to reduce variations of magnetic field throughout the chamber region (please refer to Figure 10 for illustrative purposes if necessary). An optimal spacing between the coils needed to be found as well. So, with the help of Matlab, the task was approached.

Generating the Matlab code was a giant task in and of itself. Analyzing one segment of wire over a whole plane of space is already a somewhat tricky task, let alone

the task of analyzing 8 or 16 wires simultaneously, which is exactly what was required here. All of the wires were also carrying currents in different directions as well, which also needed to be accounted for. Below, in Figure 4, there are representations of just four segments of wire, as well as the directions of the magnetic field they generate, which allows one to visualize the geometric challenge in designing the coils. Please note that the arrows are not drawn to scale. They simply represent the direction (not magnitude) of the magnetic field at that particular point, due to the corresponding colored wire.
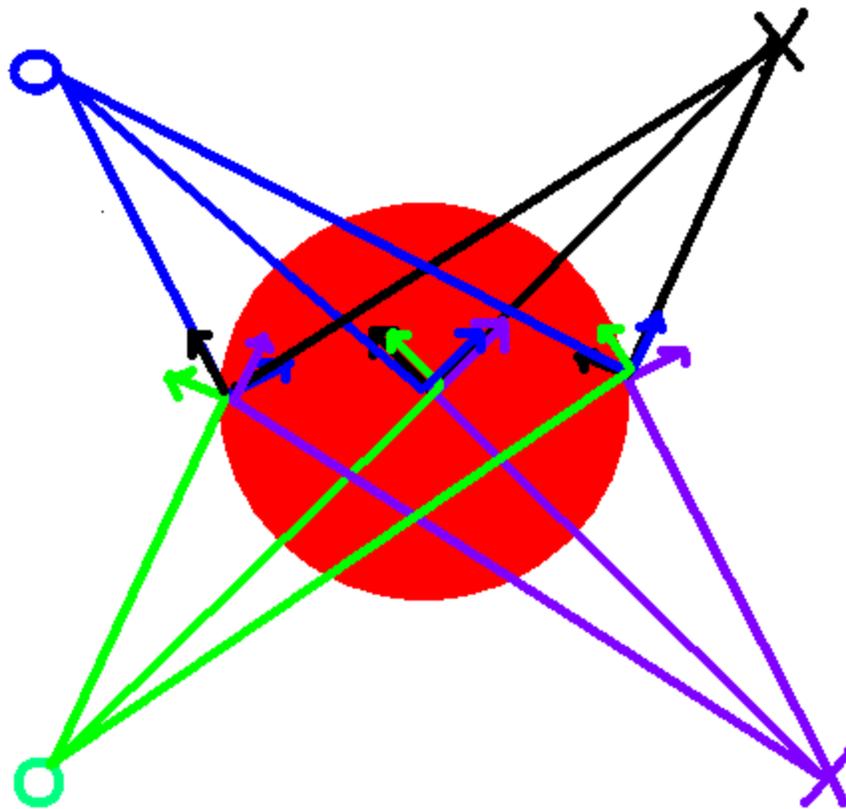

Figure 4

In order to better understand the functionality of the coils, I used two separate viewpoints to do the data analysis. The first represents a horizontal cross section (parallel to the Earth's surface, also shown in part by Figure 4) going through the cylindrical axis

of the chamber, and the other a vertical cross section (perpendicular to the Earth's

surface), also going through the cylindrical axis. Applying the equation for a segment of

wire as mentioned and demonstrated in Figure 3, the code attached in the Appendix was

generated. Each segment of wire was accounted for. A couple 'for' loops were needed

in the code to calculate the magnetic field all over a grid representing the planes

previously mentioned, as each point on the grid carries different characteristics than the

point before. Also, these coils would be able to accommodate multiple loops of wire,

which allowed us simply to multiply our 'B' field by a factor of 'N' loops. The code was

also simplified to allow the user to modify the dimensions of the chamber, the length,

height, and width restrictions, as well as the resolution of the grid with ease. I, in

particular, used a spacing of 1 mm between points. Making full use of the length

dimension, I made one set of coils 77 cm in length, and the other 74 cm, so that it could

fit within the other set which accounted for the ½ inch wide aluminum channel used to

support the wires and maintain the shape of the coils. The width was maximized at 76

cm to minimize error. This however, increased the number of Amp-turns needed to

generate the 50 micro-Tesla as mentioned before. It turned out that even with this

maximized width, only 20 Amp-turns were needed approximately. This was well within

reason considering the power sources to be used. It took a lot of number crunching to

find an optimal spacing between the coils, but it turned out that for this particular

configuration of width and length, a spacing of 21.651 cm worked out best, resulting in a

minimum variation across the whole grid. Knowing this, I then set out to find an

appropriate length for the vertical bumps. Applying the same logic, I found an optimal

length to be 8.7 cm. Running the code with these numbers turned out to be

mathematically better than in any other possible configuration. Changing the numbers

would only increase variation in the magnetic field throughout the chamber as I

discovered many times.

Results and Discussion:

Using the mentioned optimal numbers, generated some interesting, yet pleasing results. As expected, it was discovered in the analysis that symmetry helped out quite a bit, canceling out most of the unwanted magnetic fields. However, to discover this, the magnetic field from each segment had to be broken down into horizontal and vertical components to fully see the results. The vertical results are seen in the following figures. Figure 5 represents the vertical plane of the shorter 74 cm coils. Figure 6 represents the horizontal plane of the shorter 74 cm coils. Figure 7 represents the vertical plane of the longer 77 cm coils. Figure 8 represents the horizontal plane of the longer 77 cm coils. One can easily note that along the length of the chamber there is little variation in the magnetic field. It is along the width or the height where the strong variations occur. On the same note, look at the numbers along the axis. It turns out that even though there is a significant variation, it only has a magnitude of .28%, which is extremely good!

Vertical Plane of Shorter Coils

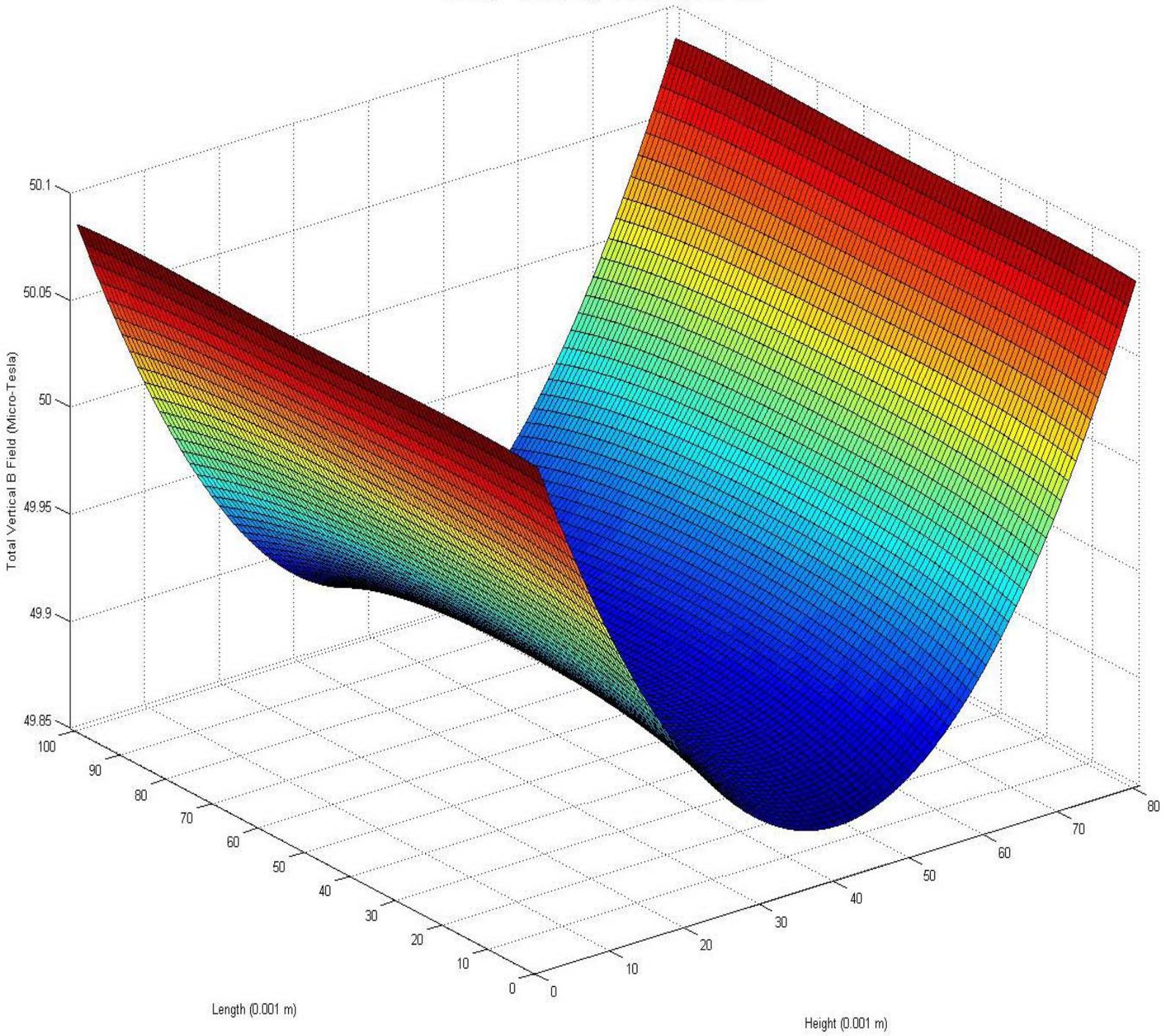Wire Length = 0.74m   Spacing = 0.21651m   Amp*Turns = 20.09

Figure 5

Horizontal Plane of Shorter Coils

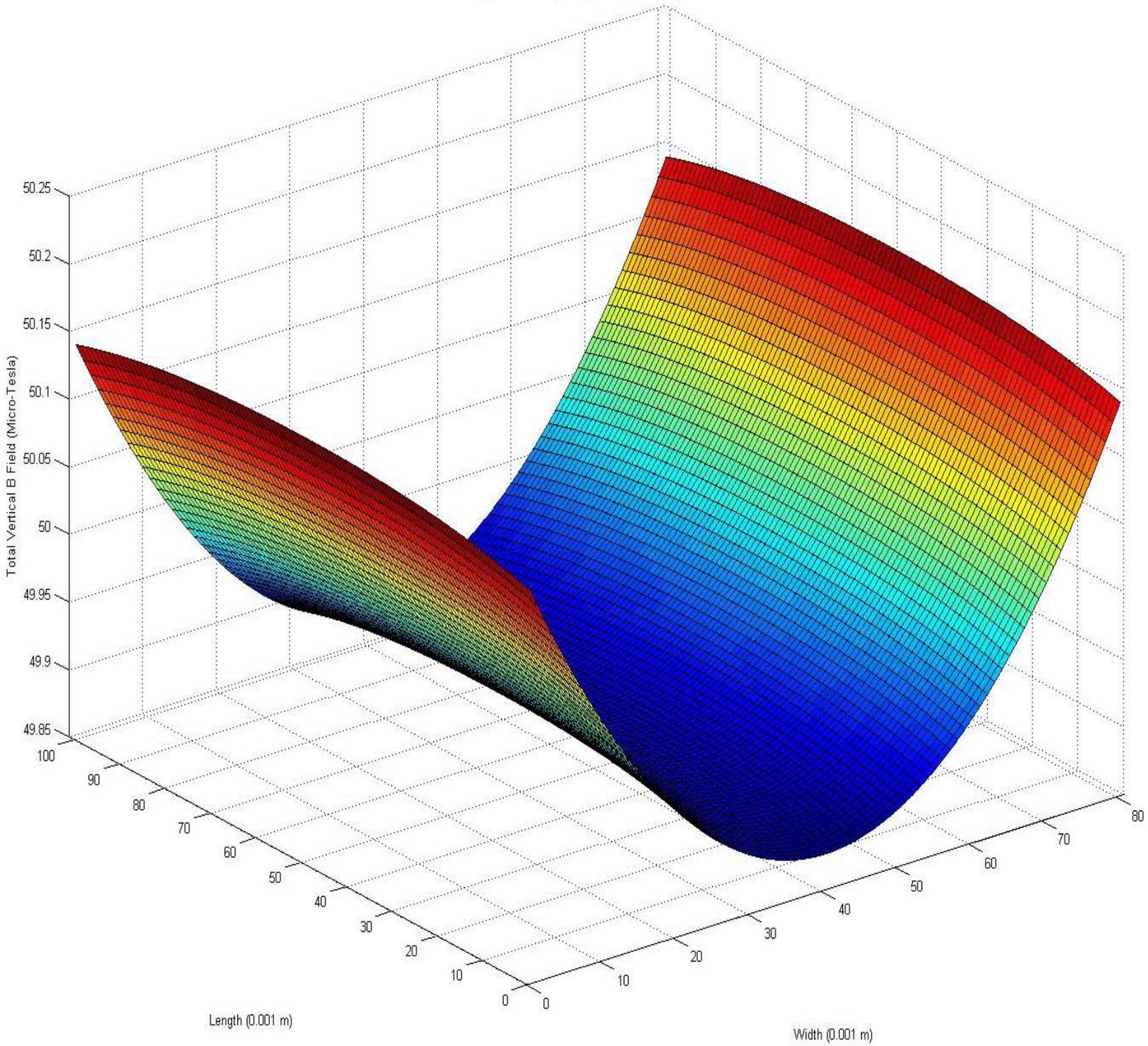Wire Length = 0.74m Spacing = 0.21651m Amp*Turns = 20.09

Figure 6

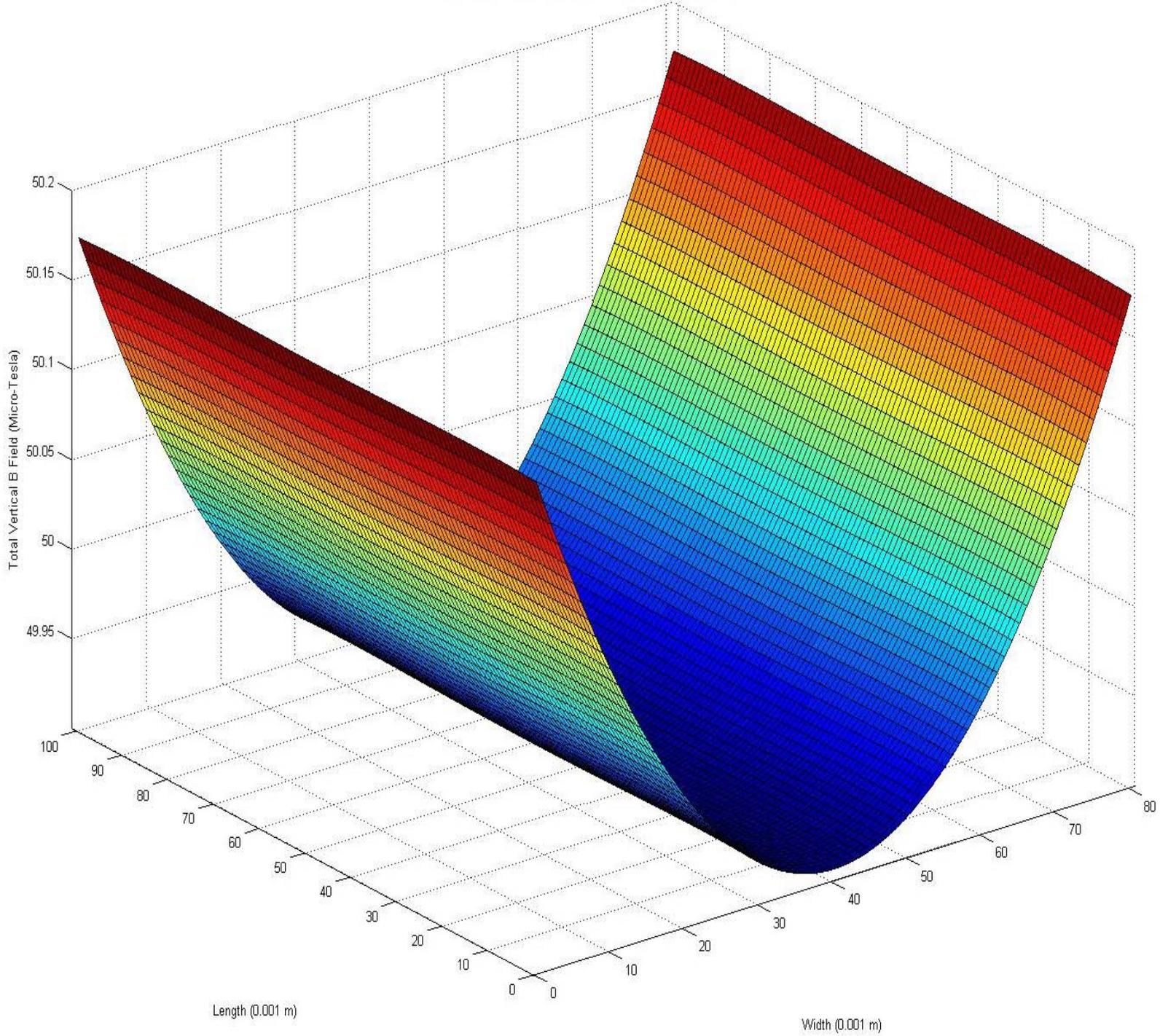Wire Length = 0.77m Spacing = 0.21651m Amp*Turns = 20.23

Figure 7

Horizontal Plane of Longer Coils

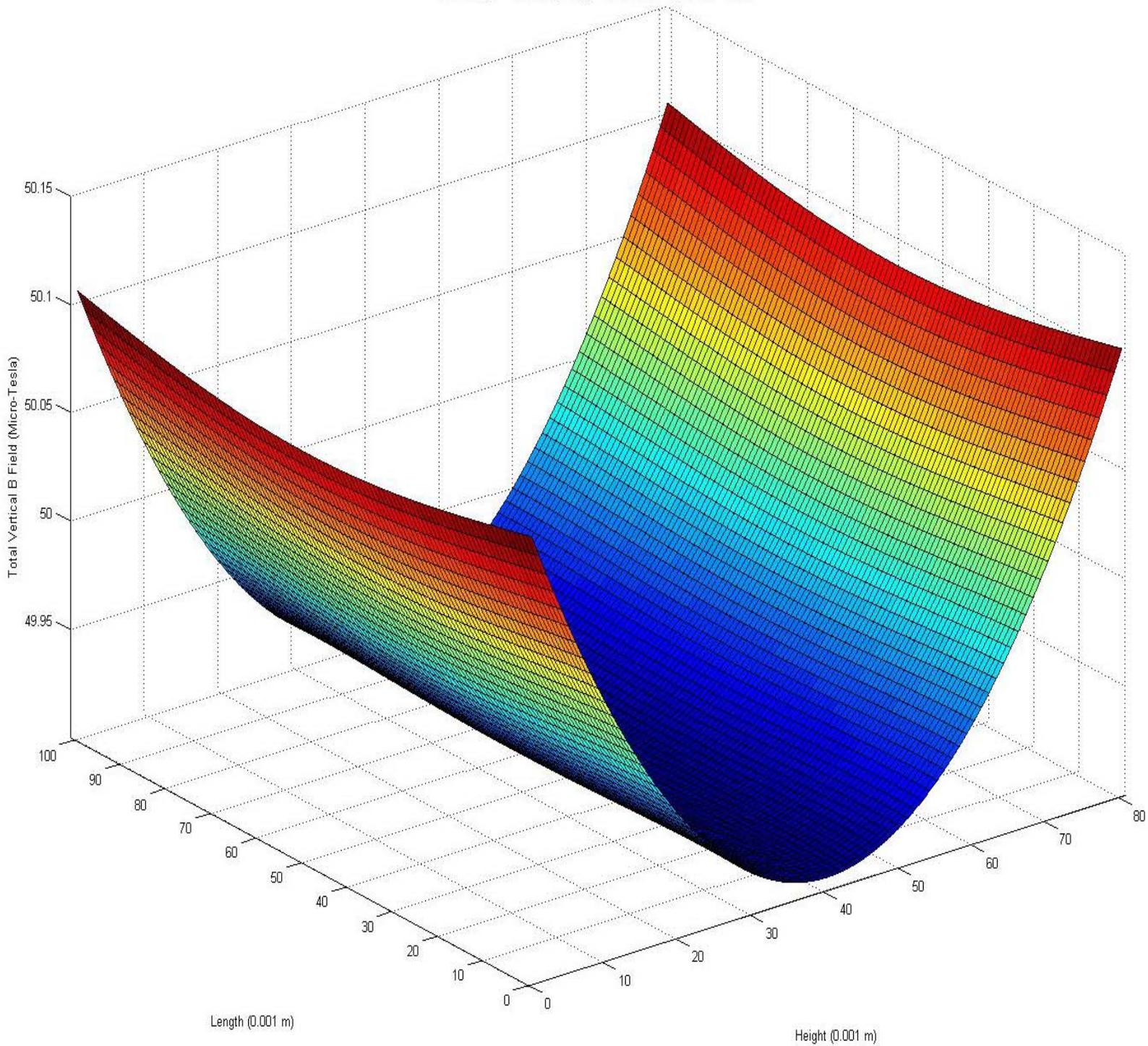Wire Length = 0.77m   Spacing = 0.21651m   Amp*Turns = 20.23

Figure 8

Interpreting the four graphs, we can simply look at the overall picture represented in Figure 9. Although this is a small simplification, it is still useful in being able to visualize the results. Looking down the axis of the chamber, it can be seen that if we are trying to generate a 50 micro Tesla field, it is slightly low in the center, and slightly high on the outer edge, particularly on the top and bottom. As mentioned before, a perfect solution was not possible due to dimension restrictions. However, this result is extremely useful and provides a great correction for the unwanted magnetic field.
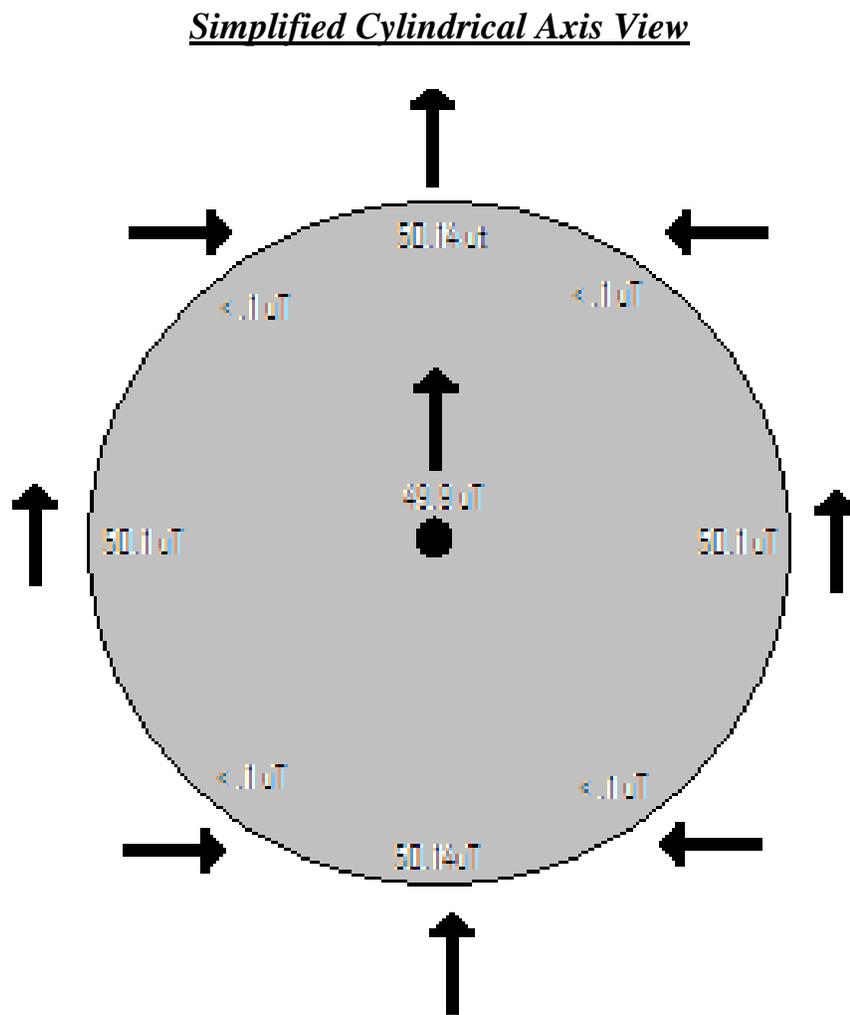
__Simplified Cylindrical Axis View__

Figure 9

They are configured perpendicular to each other, as shown in Figure 10 with controllable power sources, which allow the chamber operator to change the magnitude and direction of the coils' magnetic field as necessary. This will help to optimize the chambers performance as mentioned before. The rate of change of the Earth's field is so small, that for our purposes it is constant (it changes slightly over a period of decades, not days.) The optimal configuration will involve a magnetic field of approximately 50 micro Tesla, antiparallel to the Earth's magnetic field, as well as a variable correction perpendicular to Earth's field which will be caused by misalignment between the solenoid and the rest of the machine. Unfortunately the magnitude of magnetic field needed perpendicular to the Earth's field is unknown and can only be found experimentally. It is assumed that this value for this particular chamber can and will be found in the near future however.
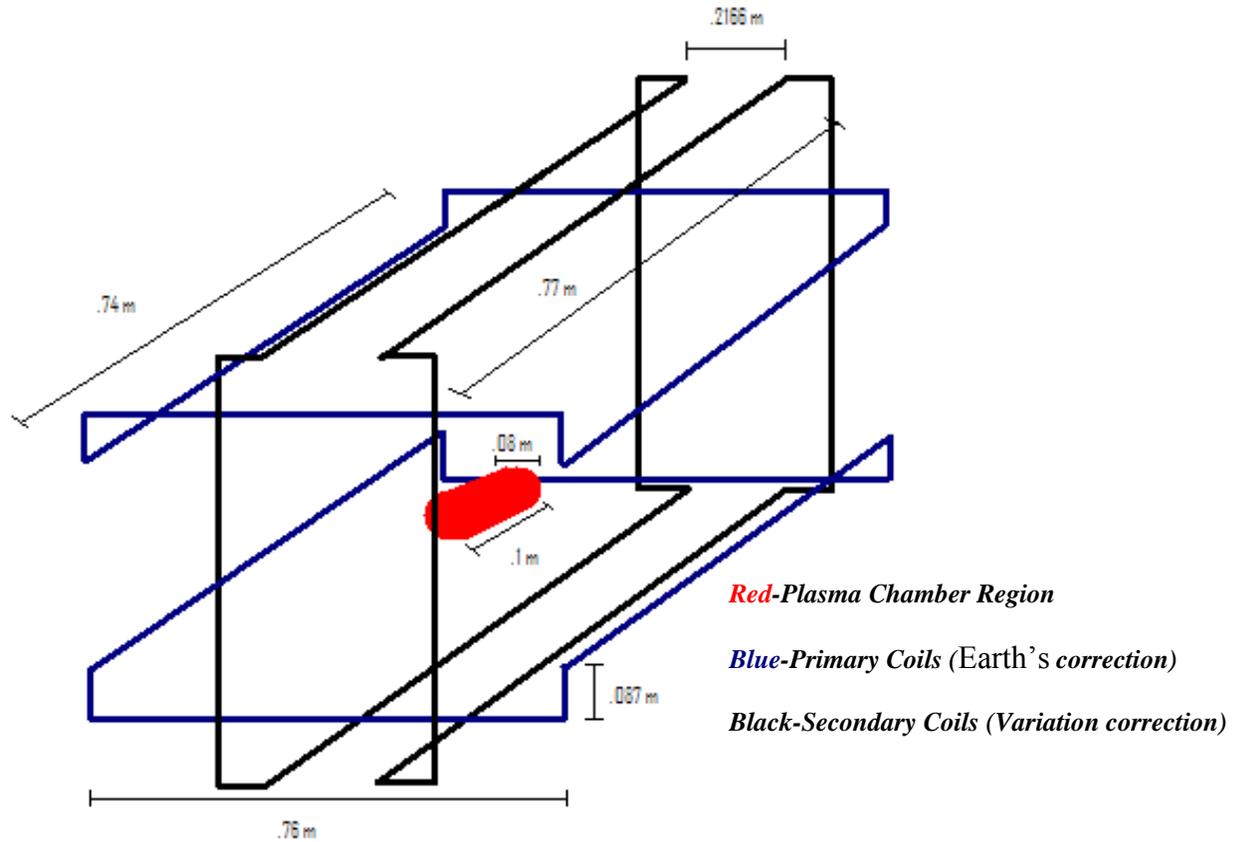
.2166 m

.74 m

.77 m

.06 m

.1 m

.067 m

.76 m

Red-Plasma Chamber Region

Blue-Primary Coils (Earth's *correction)*

Black-Secondary Coils (Variation correction)

Figure 10

As for actually powering the coils, we determined 12 gauge wire would be

adequate to generate the approximately 20 amp turns we needed. We found the wire to

have a resistance of 5.21 Ω/km, which is equivalent to .00521 Ω /m. Since we only

needed about 20 Amp-Turns, I decided the optimal setup involved wrapping the coils

with 4 turns of wire and driving them at 5 amps, which fit well within our power source

restrictions. Since each turn had about 3.5 m of wire and we wanted to run the wire

through the coils in series, we would need about 14 m for each coil. If we wanted to use

the same wire segment to power the coil's parallel counterpart we would need about 28

m, plus the portion of wire running from the actual power source to the coils. Even with

that, only about 30 m of wire would be needed, which has a total resistance of only .1563

Ω, which provided more than adequate conditions to power the coils as needed.

Conclusion:

This project turned out to be very successful, as we were able to design a couple sets of coils that left an error percentage of less than .3% of the 50 micro Tesla magnetic field, compared to 100% before the coils were designed and built. This should help significantly in minimizing the external torque that the plasma within the chamber can feel. As mentioned, this will help reduce the number of speed bumps and hurdles faced in the ongoing plasma research at Brigham Young University. Now, those involved can focus more on other issues, such as generating a higher level of vacuum, or creating plasma with a higher density, in order to generate more desirable results in their future experiments.

References:

1. Perspectives on Plasma – What are Plasmas? 2004.
   http://www.plasmas.org/rot-plasmas.htm

2. Hart, Grant. Mason, Grant. Peterson, Bryan. Spencer, Ross. Non-neutral
   Plasma Physics. 2007. http://www.physics.byu.edu/Research/plasma/

3. Griffiths, David. Introduction to Electrodynamics 3rd Edition. Benjamin
   Cummings Publishing. 1999.

4. Electromagnetism. Figure 4. 2005. http://www.school-for-
   champions.com/science/images/electromagnetism-magnetic_field.gif

5. The Geomagnetic Field. Figure 3. 2008. http://www.kidsgeo.com/images/earths-
   magnetic-field.jpg

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I would like to thank Dr.'s Grant Hart and Bryan Peterson for their time and support in debugging the software needed in this project, as well as their help in acquiring the materials needed to complete this project.

I would also like to thank Brigham Young University for facilitating and allowing the frequent use of their laboratories and facilities.

Finally, I would like to thank all the many Physics professors at Brigham Young University, without whom, this project never would have been carried out.

Appendix:

Matlab Code template

```matlab
close all; clear; clc;
% Define dimensions and variables
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
CL=.1; %chamber length
CW=.08; %chamber width/diameter
R=.001; %resolution/spacing between points (m)
L=.77; %maximum possible length of coils (m)
W=.38; %maximum possible half width of horizontal wire segments (m)
H=W/(2*sqrt(3)); %optimal height between closest wire and center of
chamber (m)
LV=.087; %length of vertical wire segments according to dimension
restrictions (m)
NI=20.23; %Amp*Turns
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%Use polar coordinates
theta01=zeros((CL/R+1),(CW/R+1));
theta02=zeros((CL/R+1),(CW/R+1));
theta03=zeros((CL/R+1),(CW/R+1));
theta04=zeros((CL/R+1),(CW/R+1));
%For each wire create two theta variables that scan through each part
%of the grid
B01=zeros((CL/R+1),(CW/R+1));
B02=zeros((CL/R+1),(CW/R+1));
B01v=zeros((CL/R+1),(CW/R+1));
B02v=zeros((CL/R+1),(CW/R+1));
for i=1:(CW/R+1)
    for n=1:(CL/R+1)
        theta01(n,i) = -atan((L/2-(CL/2-R*(n-1)))/sqrt(H^2+(W-(CW/2-
R*(i-1)))^2));
        theta02(n,i) = atan((L/2+(CL/2-R*(n-1)))/sqrt(H^2+(W-(CW/2-
R*(i-1)))^2));
        theta03(n,i) = -atan((L/2-(CL/2-R*(n-1)))/sqrt(H^2+(W+(CW/2-
R*(i-1)))^2));
        theta04(n,i) = atan((L/2+(CL/2-R*(n-1)))/sqrt(H^2+(W+(CW/2-
R*(i-1)))^2));
        B01(n,i)=10^(-7)*NI/sqrt(H^2+(W-(CW/2-R*(i-
1)))^2)*(sin(theta02(n,i))-sin(theta01(n,i)));
        B02(n,i)=10^(-7)*NI/sqrt(H^2+(W+(CW/2-R*(i-
1)))^2)*(sin(theta04(n,i))-sin(theta03(n,i)));
        %Take only the vertical components by using the cosine identity
        %Change denominator from cm to m by multiplying by 100
        B01v(n,i)=B01(n,i)*(W-(CW/2-R*(i-1)))/sqrt(H^2+(W-(CW/2-R*(i-
1)))^2);
        B02v(n,i)=B02(n,i)*(W+(CW/2-R*(i-1)))/sqrt(H^2+(W+(CW/2-R*(i-
1)))^2);
    end
end
```

```matlab
%By symmetry we can count each wire twice
Bv=2*(B01v+B02v);
%Plot primary
surf(Bv(1:(CL/R+1),1:(CW/R+1))*10^6);
ylim([0 (CL/R+1)]);
xlim([0 (CW/R+1)]);
xlabel(['Width (',num2str(R),' m)']);
ylabel(['Length (',num2str(R),' m)']);
zlabel('Primary Vertical B Field (Micro-Tesla)');
title('Center Horizontal Cross-Section');
annotation('textbox','String',{'Total variation = ',
10^6*(max(max(Bv))-min(min(Bv))), 'Micro-Tesla'},...
    'FitBoxToText','off',...
    'Position',[0 .2 0 .1]);
%For each wire create two theta variables that scan through each part
%of the grid
theta05=zeros((CL/R+1),(CW/R+1));
theta06=zeros((CL/R+1),(CW/R+1));
theta07=zeros((CL/R+1),(CW/R+1));
theta08=zeros((CL/R+1),(CW/R+1));
B03=zeros((CL/R+1),(CW/R+1));
B04=zeros((CL/R+1),(CW/R+1));
B03v=zeros((CL/R+1),(CW/R+1));
B04v=zeros((CL/R+1),(CW/R+1));
for n=1:(CL/R+1)
    for i=1:(CW/R+1)
        theta05(n,i) = -atan((W-(CW/2-R*(i-1)))/sqrt((H+LV)^2+(L/2-
(CL/2-R*(n-1)))^2));
        theta06(n,i) = atan((W+(CW/2-R*(i-1)))/sqrt((H+LV)^2+(L/2-
(CL/2-R*(n-1)))^2));
        theta07(n,i) = -atan((W-(CW/2-R*(i-
1)))/sqrt((H+LV)^2+(L/2+(CL/2-R*(n-1)))^2));
        theta08(n,i) = atan((W+((CW/2-R*(i-
1))))/sqrt((H+LV)^2+(L/2+(CL/2-R*(n-1)))^2));
        B03(n,i)=10^(-7)*NI/sqrt((H+LV)^2+(L/2-(CL/2-R*(n-
1)))^2)*(sin(theta06(n,i))-sin(theta05(n,i)));
        B04(n,i)=10^(-7)*NI/sqrt((H+LV)^2+(L/2+(CL/2-R*(n-
1)))^2)*(sin(theta08(n,i))-sin(theta07(n,i)));
        %Take only the vertical components by using the cosine identity
        %Change denominator from cm to m by multiplying by 100
        B03v(n,i)=B03(n,i)*(L/2-(CL/2-R*(n-1)))/sqrt((H+LV)^2+(L/2-
(CL/2-R*(n-1)))^2);
        B04v(n,i)=B04(n,i)*(L/2+(CL/2-R*(n-
1)))/sqrt((H+LV)^2+(L/2+(CL/2-R*(n-1)))^2);
    end
end
%By symmetry we can count each wire twic
Bv2=2*(B03v+B04v);
%Plot secondary, converting to Micro-Tesla for easier visualization
figure
surf(Bv2(1:(CL/R+1),1:(CW/R+1))*10^6);
ylim([0 (CL/R+1)]);
xlim([0 (CW/R+1)]);
xlabel(['Width (',num2str(R),' m)']);
ylabel(['Length (',num2str(R),'  m)']);
zlabel('Secondary Vertical B Field (Micro-Tesla)');
title('Center Horizontal Cross-Section');
```

```matlab
annotation('textbox','String',{'Total variation = ',
10^6*(max(max(Bv2))-min(min(Bv2))), 'Micro-Tesla'},...
    'FitBoxToText','off',...
    'Position',[0 .2 0 .1]);
%Combination of Main and Horizontal segments
Bvtotal=Bv+Bv2;
figure
%Plot total
%Maximize plot to view characteristics
surf(Bvtotal*10^6);
ylim([0 (CL/R+1)]);
xlim([0 (CW/R+1)]);
xlabel(['Width (',num2str(R),' m)']);
ylabel(['Length (',num2str(R),' m)']);
zlabel('Total Vertical B Field (Micro-Tesla)');
title(['Wire Length = ', num2str(L),'m','  Spacing = ',
num2str(2*H),'m','  Amp*Turns = ', num2str(NI)]);
annotation('textbox','String',{'Total variation = ',
10^6*(max(max(Bvtotal))-min(min(Bvtotal))), 'Micro-Tesla'},...
    'FitBoxToText','off',...
    'Position',[0 .2 0 .1]);
```