Characterization of a Helmholtz Coil for Maintaining a Flat Magnetic Field

in a Plasma Chamber

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ABSTRACT

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We measure the magnetic field of a set of Helmholtz coils designed to maintain a flat magnetic field in our plasma chamber. We show that the field of the Helmholtz coils is sufficiently large to correct for the magnetic field of the earth (approximately 50 μT) and probably other irregularities as well. We also show that the field is sufficiently flat to distinguish a ^{7}Be plasma from a ^{7}Li plasma using FTICR with a central field of 0.43 T in the plasma chamber. This requires the field created by the Helmholtz coils to be uniform to within about 60 μT. The standard deviation of a 630 μT field produced by the coils was found to be approximately 30 μT.

Keywords: beryllium-7, Helmholtz coil, magnetic field, non-neutral plasma

ACKNOWLEDGMENTS

First I want to thank Dr. Bryan Peterson for his help and instruction, which have been instrumental in the completion of this project. I also want to thank Dr. Grant Hart for his assistance and instruction. Finally, I want to thank my parents for all their support during my undergraduate studies.

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Chapter 1

Introduction

The purpose of our experiment is to measure the half-life of ionized ^{7}Be by containing a non-neutral plasma of ^{7}Be ions for long enough to measure its half-life through a process known as Fourier Transform Ion Cyclotron Resonance Mass Spectrometry (FTICR). This requires confining the plasma in a Malmberg-Penning trap with a flat magnetic field for a period of time about equal to its half-life, which is approximately 53 days. The purpose of this thesis is to characterize the Helmoltz coils used to produce the magnetic field which corrects for the earth's magnetic field and other magnetic asymmetries in the plasma chamber.

1.1 Beryllium-7

Beryllium-7 is the lightest element that decays only by electron capture. It forms naturally in the atmosphere by spallation reactions of oxygen and nitrogen nuclei with cosmic rays [1]. After its formation in the atmosphere it attaches to airborne particles and can be used as a tracer for various atmospheric and terrestrial processes [2]. In the atmosphere ^{7}Be has been used to study short-term atmospheric air mass motion in Tokyo [3] and the influences of the stratosphere on the troposphere in North America [4], as well as numerous other studies. After the particles to which it attaches settle to the earth ^{7}Be can be used to study short-term erosion. As it is continually replaced from the atmosphere it can be used for short-term measurement of erosion with more accuracy than longer half-life elements such as cesium, which are not continually replaced [5] [6].

Beryllium-7 formation also corresponds with solar activity and cosmic ray activity: greater ^{7}Be formation in the atmosphere usually corresponds to periods of less solar activity, as these periods usually result in more of the cosmic rays of the type that react with oxygen and nitrogen to form ^{7}Be [7]. Finally, ^{7}Be is also a factor in solar reactions: it forms from, ^{3}He, ^{4}He fusion, decays into ^{7}Li, and is one source of neutrino emissions in the sun [8].

All these uses of ^{7}Be depend on its radioactive decay; however, ^{7}Be decays only by electron capture, therefore its decay rate depends on the number of electrons in proximity to the nucleus of the atom. The form that it is in can modify the number of electrons available for electron capture and so change the decay rate. Even the way in which it is prepared can affect the decay rate: for example, measurements on the half-life of beryllium-fluoride vary depending on whether the material is in a hexagonal lattice or an amorphous form [9]. Various measurements have been done on ^{7}Be decay rates by making a compound of ^{7}Be and another material or by implanting it into another material: the results are shown in Figure 1.1 and Table 1.1: they show that the decay rate of ^{7}Be varies according to the number of 2s electrons available for the decay [10].

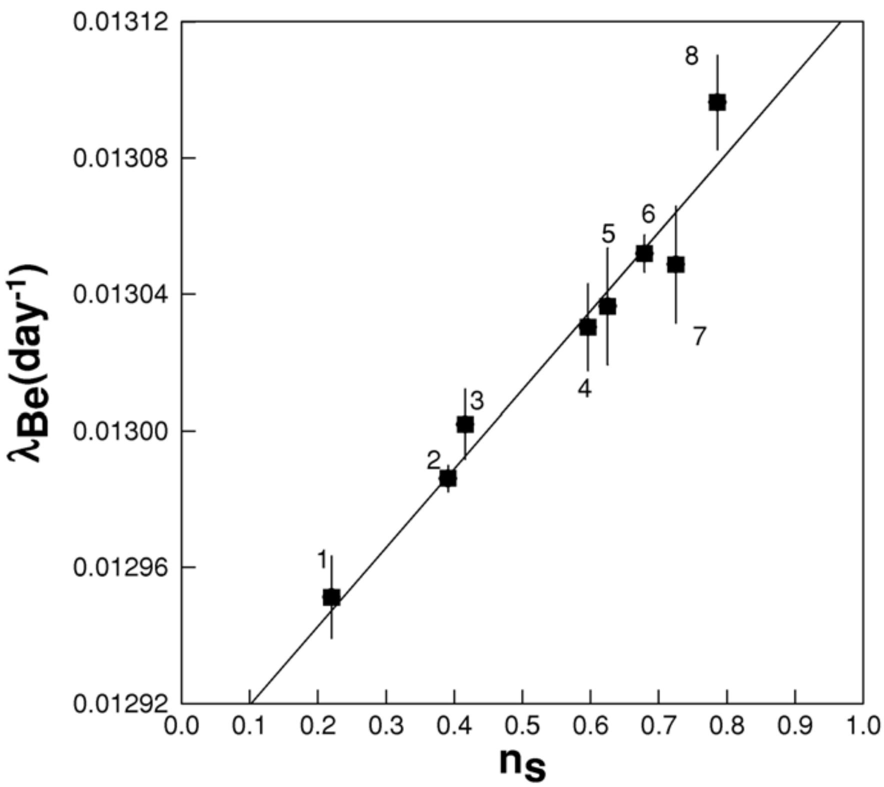

Figure 1.1 Das and Ray's plot of the decay rate of beryllium-7 versus the number of 2s electrons available for decay [10]. In a plasma form we would expect close to 1.00 2s electrons available. Table 1.1 identifies each point.

Figure 1.1 Reference	Medium	Calculated average number of 2s electrons of 7Be	Measured 7Be half-life in days	Reference
1	Average of BeO, BeF_2	0.22	53.520±0.050	[a]
2	^{7}Be in natural beryllium	0.39	53.376±0.016	[b]
3	^{7}Be in Au	0.42	53.111±0.042	[c]
4	^{7}Be in Ta	0.60	53.195±0.052	[c]
5	^{7}Be in Al	0.63	53.170±0.070	[d]
6	^{7}Be in graphite	0.68	53.107±0.022	[c]
7	^{7}Be in LiF	0.73	53.120±0.070	[e]
8	^{7}Be in Al_2O_3	0.79	52.927±0.056	[f]

Table 1.1 Half-life of beryllium -7 in various substances and the calculated number of 2s electrons available for decay. [10]
[a] H. W. Johlige, D. C. Aumann, and H. J. Born, Phys. Rev. C 2,1616 (1970).
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Though the number of electrons available to ^{7}Be for electron capture varies depending on what form it is in, when ^{7}Be forms naturally it often forms in an energetic environment, such as the sun or the earth’s upper atmosphere. In these highly energetic cases it is likely to form in an ionized state and is free of any other atoms which could reduce the number of electrons available to its decay. Therefore we expect the number of 2s electrons to be close to unity. The goal of our experiment is to measure the decay rate of ionized ^{7}Be free of any other material. We have chosen to do this by confining a non-neutral plasma of ^{7}Be ions for a period of time of about 53 days, the approximate half-life, and measuring the change of the ratio of ^{7}Be to ^{7}Li through FTICR.

1.2 Confinement and Measurement Method

We confine the ^{7}Be plasma in a Malmberg-Penning trap in order to measure the half-life. The trap consists of a 4 inch cylindrical pipe which contains a collection of several rings as shown in the figure. Wire is wound around the outside to create a solenoid. We run a current through the wire to create a magnetic field within the chamber directed along the axis of the cylinder. The magnetic field provides radial confinement as the plasma cannot expand radially due to the conservation of angular momentum about the magnetic field [11]. The central magnetic field in our trap is 0.43 T. The rings are used for various purposes: the potential on the D ring is set at 150V to prevent the plasma from flowing out the end of the trap; once the measurement is done it can be lowered to allow the plasma to leave the chamber. The FC, FB, and FA rings are used during the initial fill process to capture the plasma and are kept at 150V to confine it. The interior rings are used for diagnostic and corrective purposes: the X ring is a rotating wall: used to correct for drag caused by collisions with neutral atoms in the trap, and the Z ring is the excitation/detection mechanism for the FTICR.

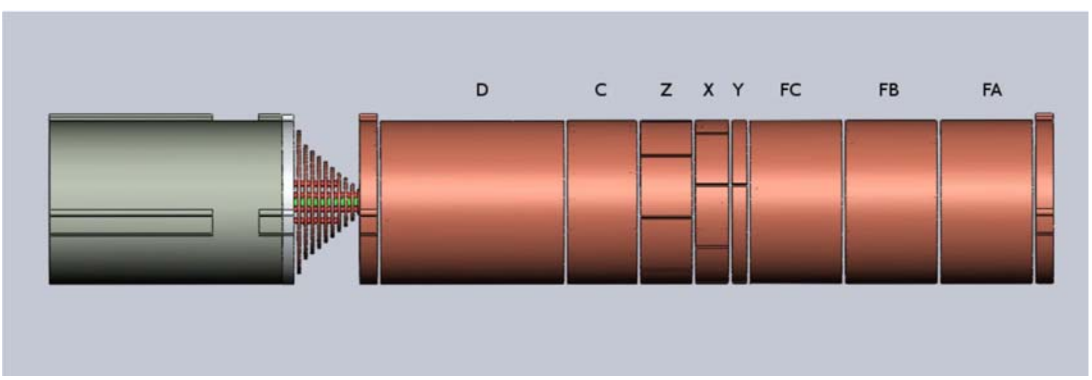


Figure 1.2 The rings in our Malmberg-Penning trap. FA, FB, FC, and D are used during the fill process and for confinement. The X ring is the rotating wall and the Z ring is the FTICR. Y and C are unused at this point, but could be used for various diagnostic or other purposes.

To detect the proportion of ^{7}Be to ^{7}Li we use FTICR, in which we first excite the plasma at a frequency near the cyclotron frequency using the Z ring. This ring is then used to detect the cyclotron frequencies within the chamber. The cyclotron frequency is given by $\omega_c = \frac{qB_0}{m}$, so as long as the magnetic field is constant and consistent across the trap ω_c depends only on the charge to mass ratio [12]; after measuring the particles as they pass by a detection area and doing a Fourier transform we can know the cyclotron frequencies of the particles, and their charge-to-mass ratios. Since ^{7}Be and ^{7}Li have different charge-to-mass ratios we can detect what proportion of each is contained in the trap through FTICR. By observing the change of the ratio of ^{7}Be to ^{7}Li over time we can observe the decay of ^{7}Be and determine its half-life in an ionized state.

There are a few problems, however. The first is avoiding plasma loss. As we are measuring a half-life we cannot simply replace lost plasma with new ^{7}Be: we must keep the same plasma for the full time period. One way we lose plasma is by drag from neutral atoms in the trap. We use a high vacuum trap to help reduce this problem, and the rotating wall located on the X ring in the trap also helps to counter this effect [13]. Another way we lose plasma is through stray magnetic fields: a field directed anywhere but along the axis of the confinement rings will cause an external torque on the plasma, which can cause the plasma to expand radially and leave the trap [11]. In addition, these magnetic fields will cause the central magnetic field to align along a slightly different axis than the axis of the cylinder. This can cause an E × B force which is inhomogeneous within the chamber, which also causes a loss of plasma [14]. The earth's magnetic field is one major source of this E × B force.

The second problem is maintaining resolution in the FTICR. Since the cyclotron frequency depends on the magnetic field, any inhomogeneities in the field will cause variations in the cyclotron frequency and can cause a loss of resolution and sensitivity in the Fourier transform [14]. Since ^{7}Be and ^{7}Li have very similar masses it is essential that we have as flat a field as possible in order obtain sufficient resolution to distinguish the two frequency peaks in the Fourier transform. If the field is not flat enough the two peaks may blend together and we will not be able to tell the two apart. ^{7}Be and ^{7}Li have a mass difference of approximately 9.25×10^{-4} u, which is one part in about 7600; therefore, the magnetic field must be uniform with at least this resolution. This means that our magnetic field variations must be less than approximately 60 μT.

To make certain the magnetic field aligns with the electric field our group has constructed two Helmholtz coils which can be used in tandem to create a magnetic field oriented to counter the earth's magnetic field and make any other necessary corrections. The purpose of this thesis is to test the field of the coils and see if they can be used to counter the earth's magnetic field and still keep sufficient resolution in our FTICR to distinguish ^{7}Li from ^{7}Be in the plasma chamber.

Chapter 2

Measurement

2.1 Helmholtz Coils

The Helmholtz coils we will use to correct for earth's magnetic field are copper wire wrapped onto a rectangular aluminum frame. The geometry of the frame is designed so that a current flowing through the wire will create a flat magnetic field in the center of the coil. The coil will be placed around our plasma chamber so that the area of flat magnetic field is in the chamber itself. Our coils are 77 cm by 76 cm with the 76 cm side (y) having a distance of 40.5 cm between the top and bottom wires (Figure 2.1) and the 77 cm side (x) having a distance of 23.5 cm between the top and bottom wires (Figure 2.2). The wire was wrapped around this aluminum frame 6 times. Together the two coils can be used to create a magnetic field to correct for whatever anomalous fields we may encounter in the experiment.

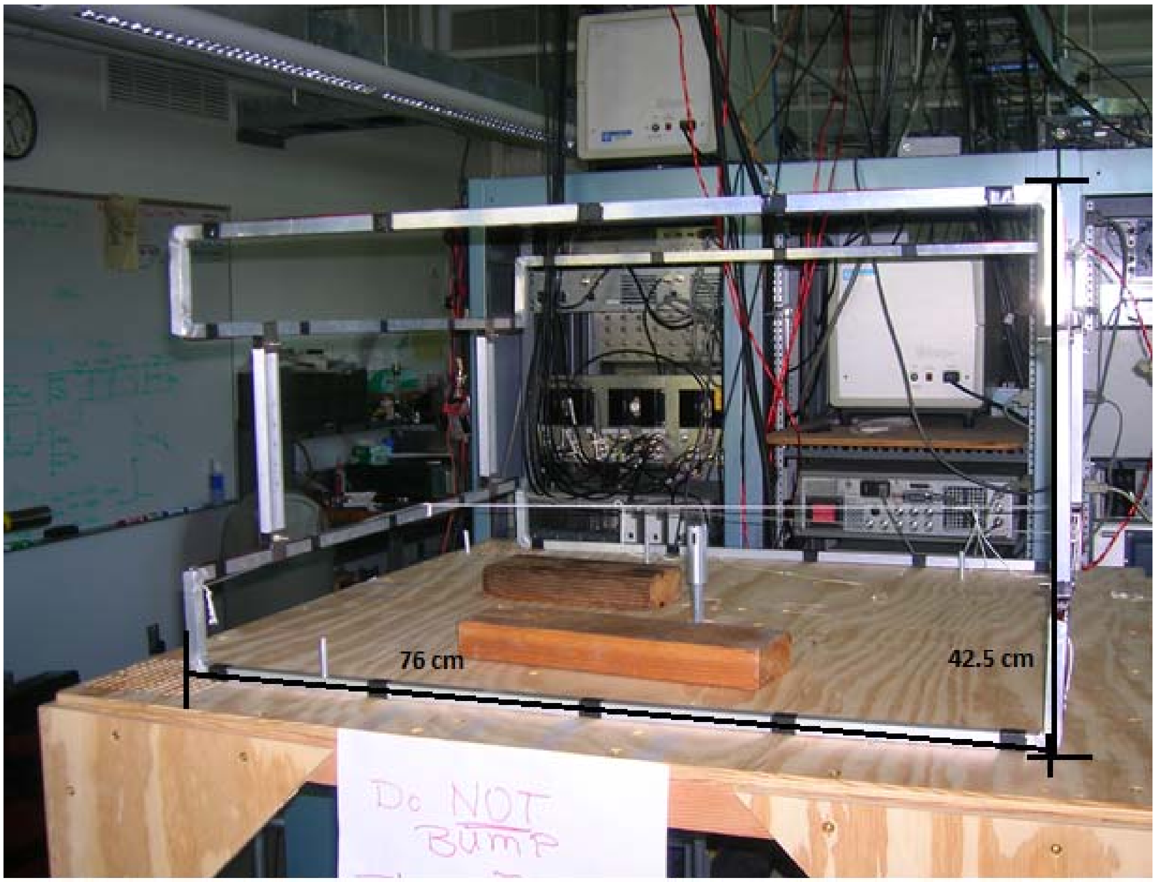


Figure 2.1 The Helmholtz coil showing the y and z sides and their lengths.

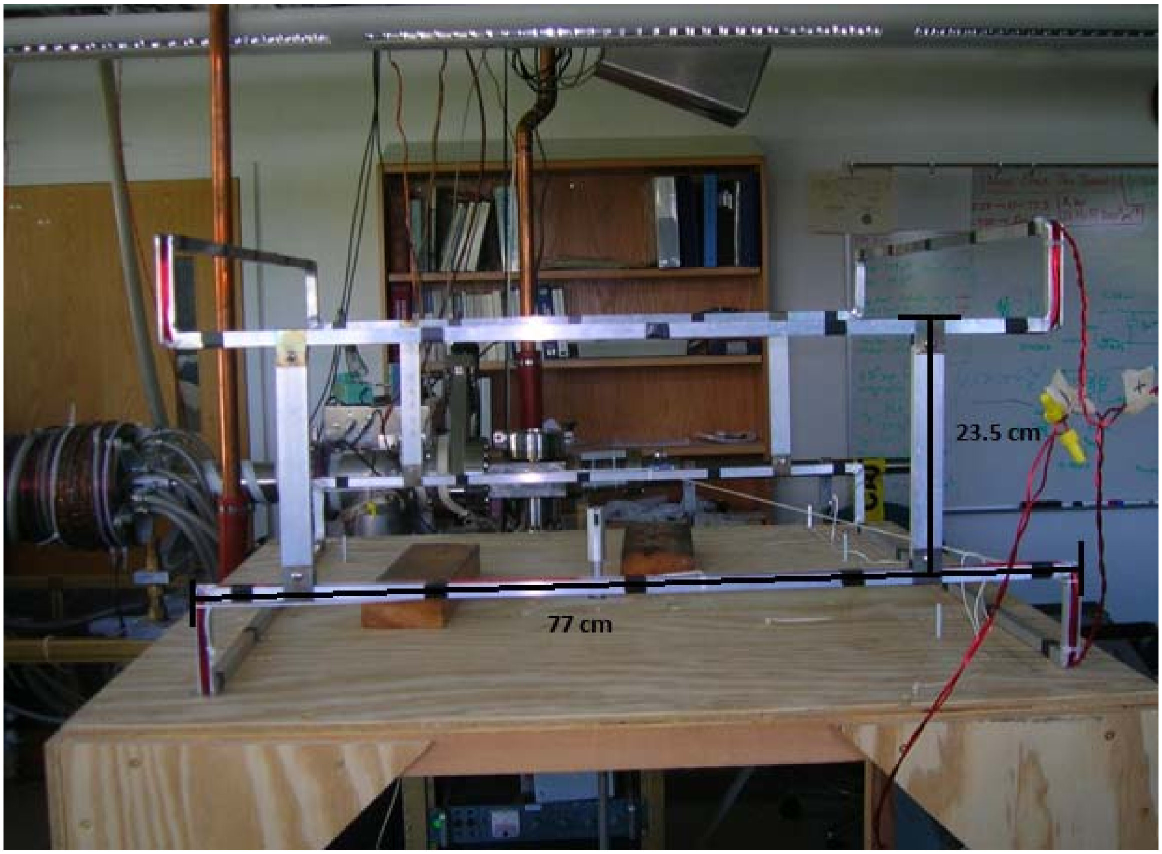


Figure 2.2 The Helmholtz coil showing the x and z sides and their lengths.

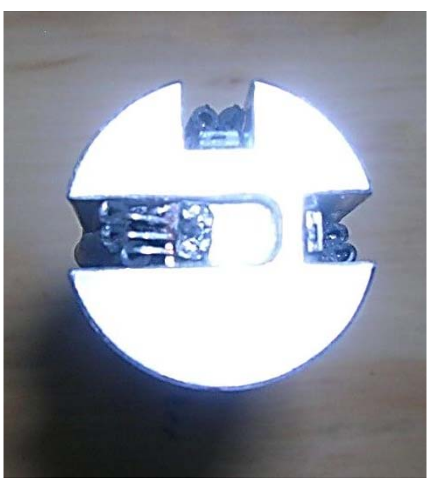


Figure 2.3 (left) The head of the Hall probe viewed from above, showing the three probes designed to measure the magnetic field in the x, y, and z directions.

Figure 2.4 (right) The solenoid used to produce the magnetic field to characterize the Hall probe.

2.2 Hall Probe

In order to measure the magnetic field we used a Hall probe composed of three elements, one to measure in each of the x, y and z directions (Figure 2.2). The probe was powered by a ±15 V power supply and mounted on a 1.25 m pole placed on a lab jack to allow movement up and down. East is +X, North is +Y, and up is +Z. We calibrated the probe using a coil of copper wire to produce a known magnetic field. The coil had 165 turns of wire, an outer radius of 30.2 cm and an inner radius of 28.3 cm. The average radius is 29.6 cm. The magnetic field on the axis of a solenoid outside the solenoid is given by $B = \frac{\mu_0 I R^2}{2(x^2+R^2)^{3/2}}$. For the field at the center of the solenoid it is $B = \frac{\mu_0 I}{2R}$. The mounting of the coil of wire and the probe made it so that the Hall elements were located 21.765 mm out from the center of the solenoid when measuring the fields in the x and y directions and directly on center when measuring the field in the z direction. We took three measurements in each direction, with a current of 1, 0.5, and 0.1 amps through the solenoid, and then we averaged the three to find the proper calibration of the Hall elements in each direction.

Table 2.1a Measured calibration for each Hall probe at different currents.

Hall probe calibration: X direction			
Current (A)	Measured Hall-Probe Voltage (V)	Calculated Magnetic Field (μT)	Calibration (T/V)
1	8.14 x 10^{-4}	347.4	0.4270
0.5	4.16 x 10^{-4}	173.7	0.4175
0.1	8.57 x 10^{-5}	34.74	0.4053

Hall probe calibration: Y direction			
Current (Amperes)	Measured Hall-Probe Voltage (V)	Calculated Magnetic Field (μT)	Calibration (T/V)
1	7.96 x 10^{-4}	347.4	0.4362
0.5	3.99 x 10^{-4}	173.7	0.4353
0.1	9.00 x 10^{-5}	34.74	0.3861

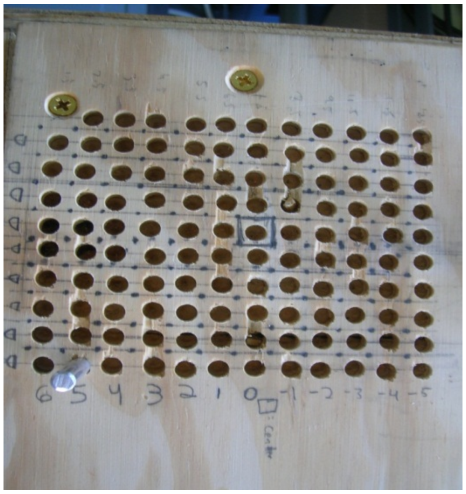
Hall probe calibration: Z direction			
Current (Amperes)	Measured Hall-Probe Voltage (V)	Calculated Magnetic Field (μT)	Calibration (T/V)
1	8.51 x 10^{-4}	350.2	0.4118
0.5	4.22 x 10^{-4}	175.1	0.4149
0.1	8.96 x 10^{-5}	35.02	0.3907

Table 2.1b Overall calibration for each direction of the Hall probe.

Overall Calibration		
Direction	Average Calibration (T/V)	Average Calibration (V/T)
X	0.4166	2.400
Y	0.4192	2.385
Z	0.4058	2.464

2.3 Measurements

Once the calibration of the Hall probe is determined it can be used to measure the magnetic field of the Helmholtz coil. As noted before, the Hall probe itself was mounted on a 1.25 m pole. The pole was marked every one-half centimeter to define the probe's position in the z-direction. A table was also constructed to position the coil during measurement. The table was constructed from wood, having one-quarter inch diameter holes drilled at one centimeter intervals to create a grid which would allow the accurate positioning of the coil. Aluminum pegs were placed in the holes at the proper location and the Helmholtz coil was brought up flush against the pegs, defining the location of the coil for each measurement. Measurements were taken in a one centimeter grid that extended five centimeters from the center of the coil in all directions. This volume covers the entire volume of the plasma chamber and a bit more on each side.



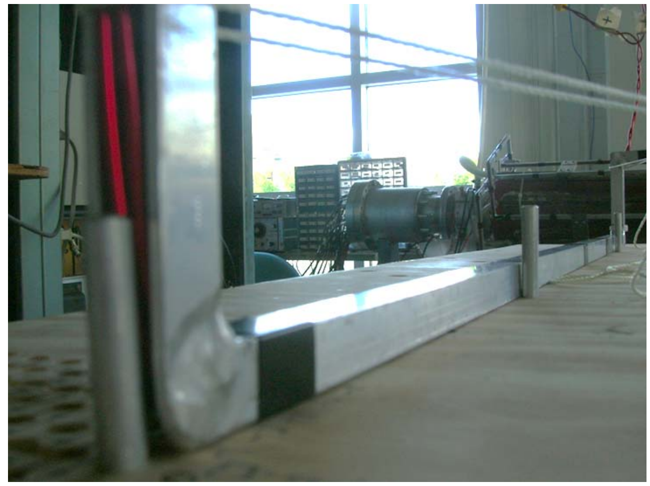


Figure 2.5 (left) Detail of the table used to position the coil correctly showing the grid of holes in which the Aluminum pegs are inserted.

Figure 2.6 (right) Detail of the table showing the coil positioned using the Aluminum pegs to fix its position

Measurements were taken on the magnetic field using a LabVIEW program designed to adjust for both the earth's magnetic field and any random noise that we might encounter. Data was taken at a rate of 1,000 Hz for a period of ten seconds, giving a total of 10,000 measurements for each data point. The points were taken at a resolution of 6.104 μV and were averaged to give the field at a given point. Averaging these points helped to reduce noise. In addition, the voltage across an 18 Ω resistor in the Hall elements was measured and the current calculated to ensure it was not changing drastically. Measurements of the field were taken before the Helmholtz coil was activated, while it was active, and after it was turned off. The before and after measurements were taken so that any drift due to changing currents or temperatures in the Hall probe could be accounted for: we averaged the before and after measurements of the field and subtracted this average from the field measured while the Helmholtz coil was on. We assume that any drift in the offset was linear; therefore, the average of the offset before and after measuring the field should be close to what the offset was during the measurement. This process also allowed us to correct for any background magnetic fields that may have been present and the offset of the Hall probe itself. There was a ten second period left between the turning on or off of the Helmholtz coil and the beginning of the measuring of the field: this was probably longer than was necessary for the field to settle, but was allowed so that the current within the Helmholtz coil would be completely at the new power level during the measurement.

Chapter 3

Results and Analysis

3.1 Results

After measuring the magnetic fields we plotted them in several two dimensional slices for the x, y, and z planes. This allowed us to observe trends in the data and see if the field really was flat. We made 11 two-dimensional plots for each direction of field. The figures below show the field in the horizontal plane located at the vertical center of the coil. These plots show that the field in all directions is fairly flat. The measured field in the Z directions varies between about 610 μT and 650 μT in this plane. In the Y direction the field varies between 0 μT and about 50 μT, with the exception of a few outliers. The field in the X direction is similar to that in the Y direction: it is mostly between 0 μT and 50 μT.

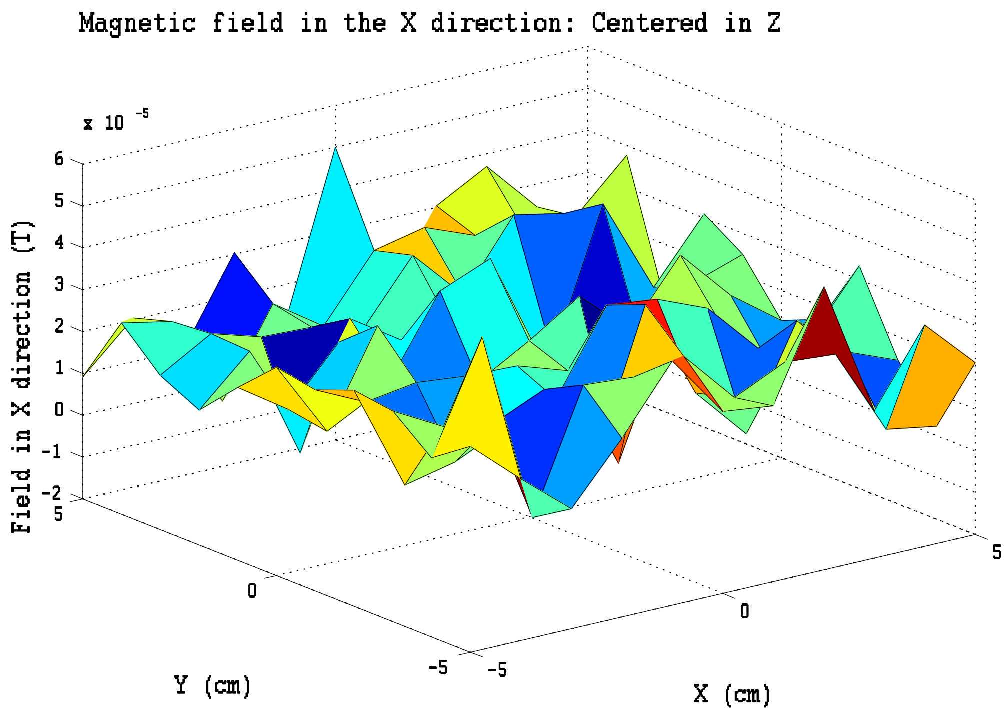


Figure 3.1 The measured magnetic field in the X direction at the vertically centered plane in the coil.

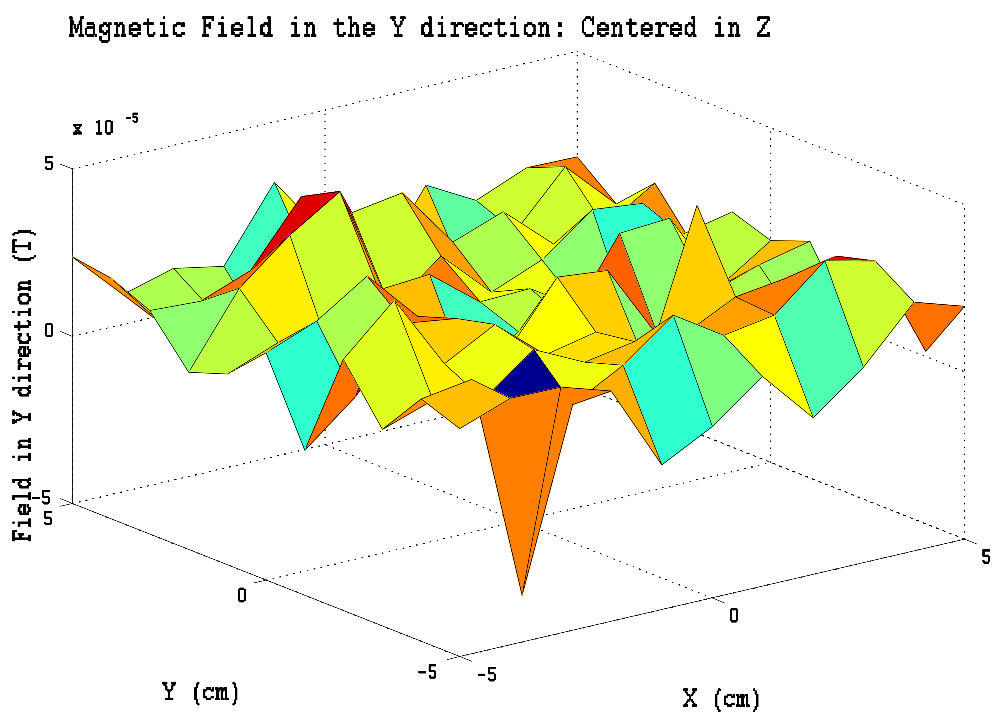


Figure 3.2 The measured magnetic field in the Y direction at the vertically centered plane in the coil.

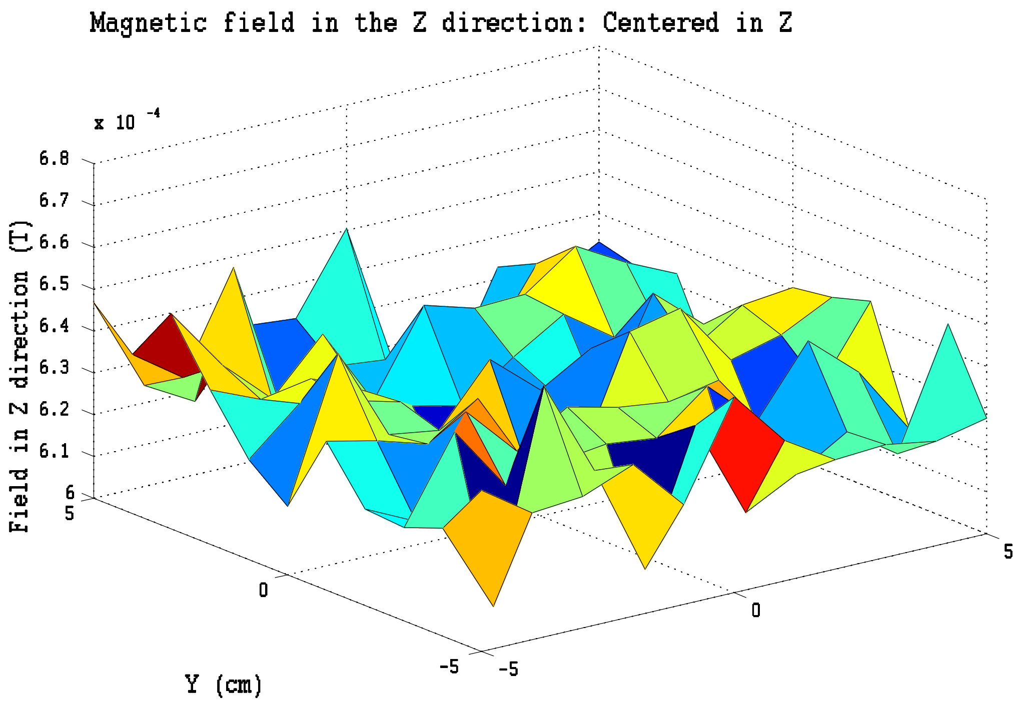


Figure 3.3 The measured magnetic field in the Z direction at the vertically centered plane in the coil.

In order to evaluate the uniformity of the field over the entire system we took each of the planes defined above and found an average magnetic field and a standard deviation. In the X direction the field remains around 20 μT with a standard deviation of about 15 μT. The Y direction is similar, being around 15 μT with a standard deviation of about 15 μT. In the Z direction the field is around 625 μT; however, the standard deviation is still about 15 μT . We assume from this that the offset of the system is around 15-20 μT. The fields that we measured are fairly flat and the variations in them in all directions seem to be small enough to maintain sufficient resolution in the FTICR for our experiment.

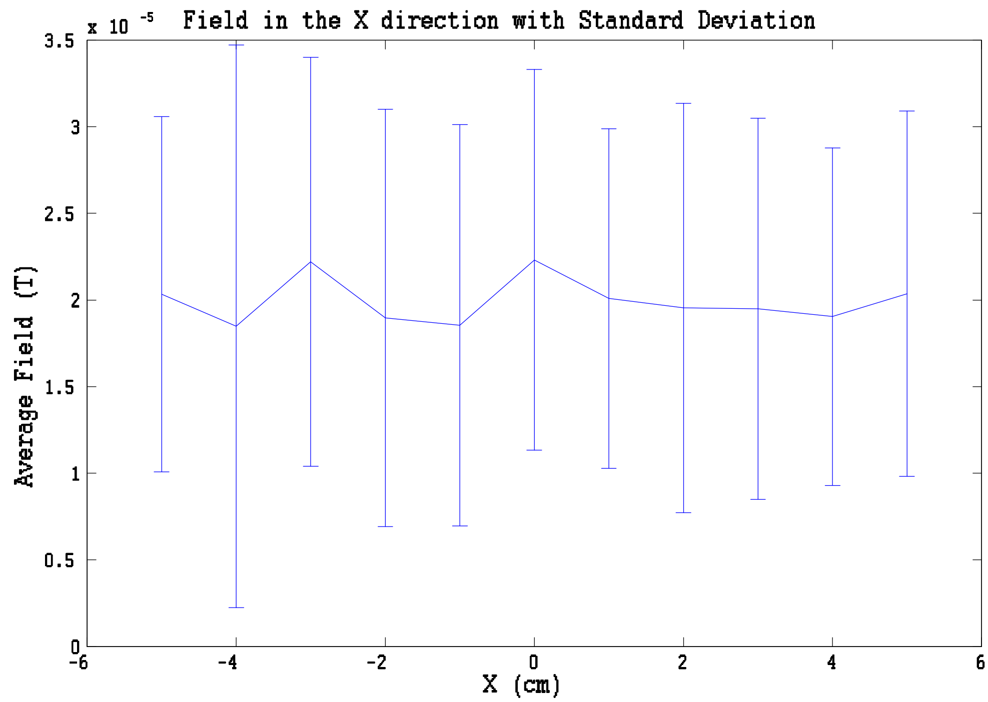


Figure 3.4 Average magnetic field in the X direction showing the standard deviation

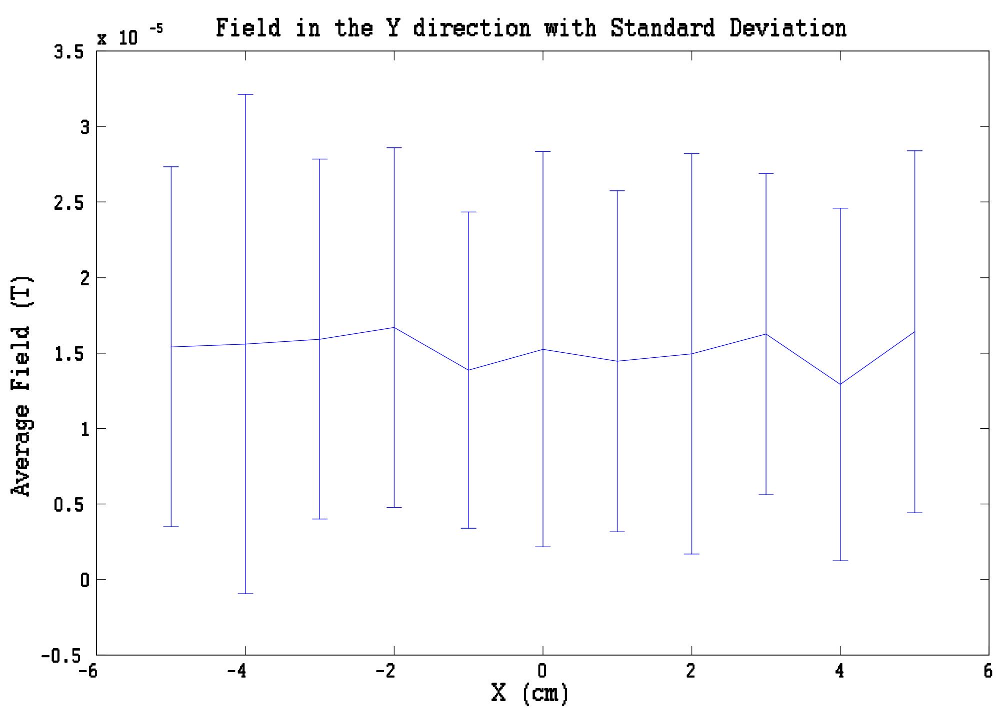


Figure 3.5 Average magnetic field in the Y direction showing the standard deviation

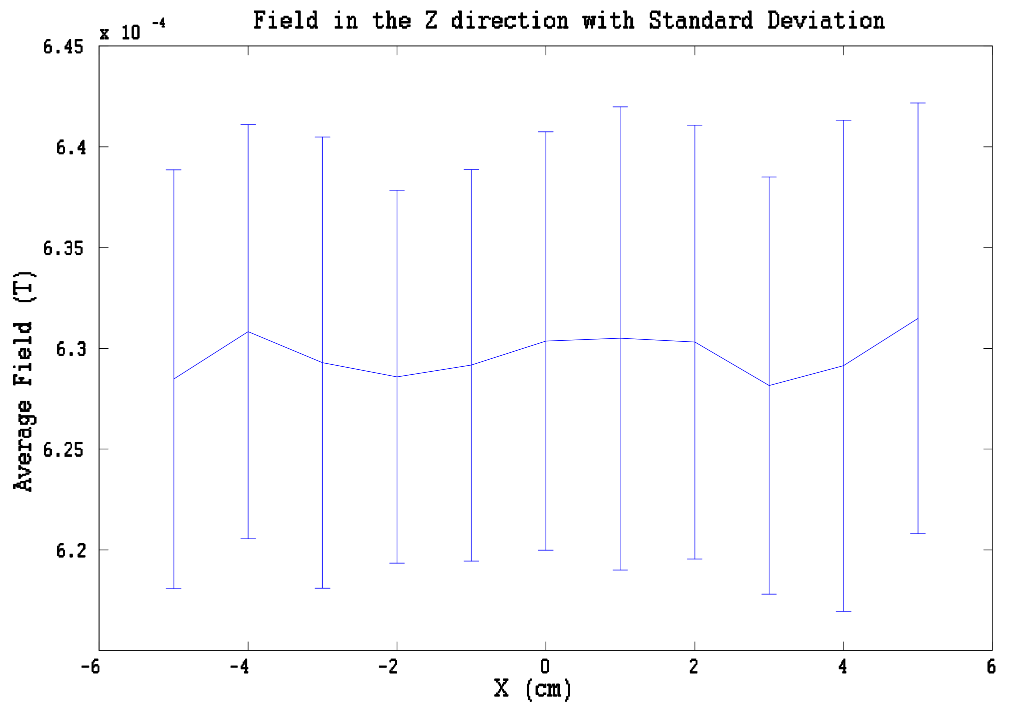


Figure 3.6 Average magnetic field in the Z direction showing the standard deviation

In addition to measuring the magnetic field we also kept track of the current flowing in the Hall probe. Making sure that this current is steady allows us to know that the probe is measuring the magnetic field consistently and helps us evaluate variations in the current as possible sources of error in the measurement.

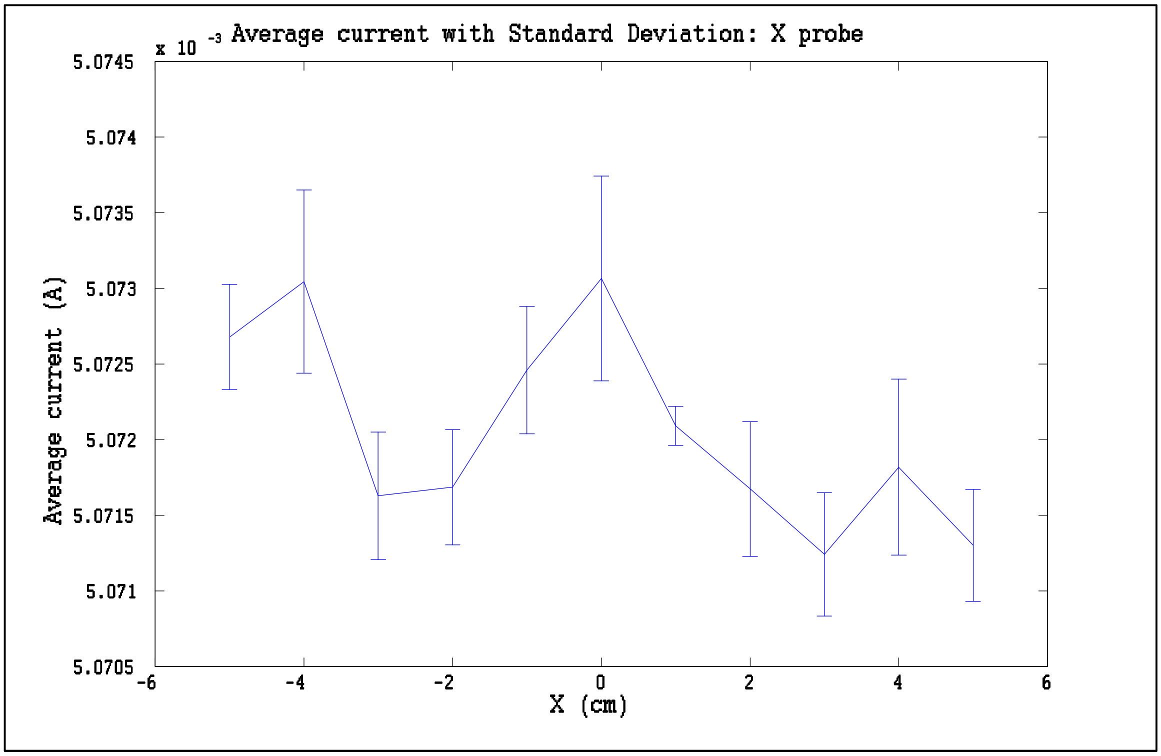


Figure 3.7 Average current in the X direction Hall probe in the X measurement planes with the standard deviation

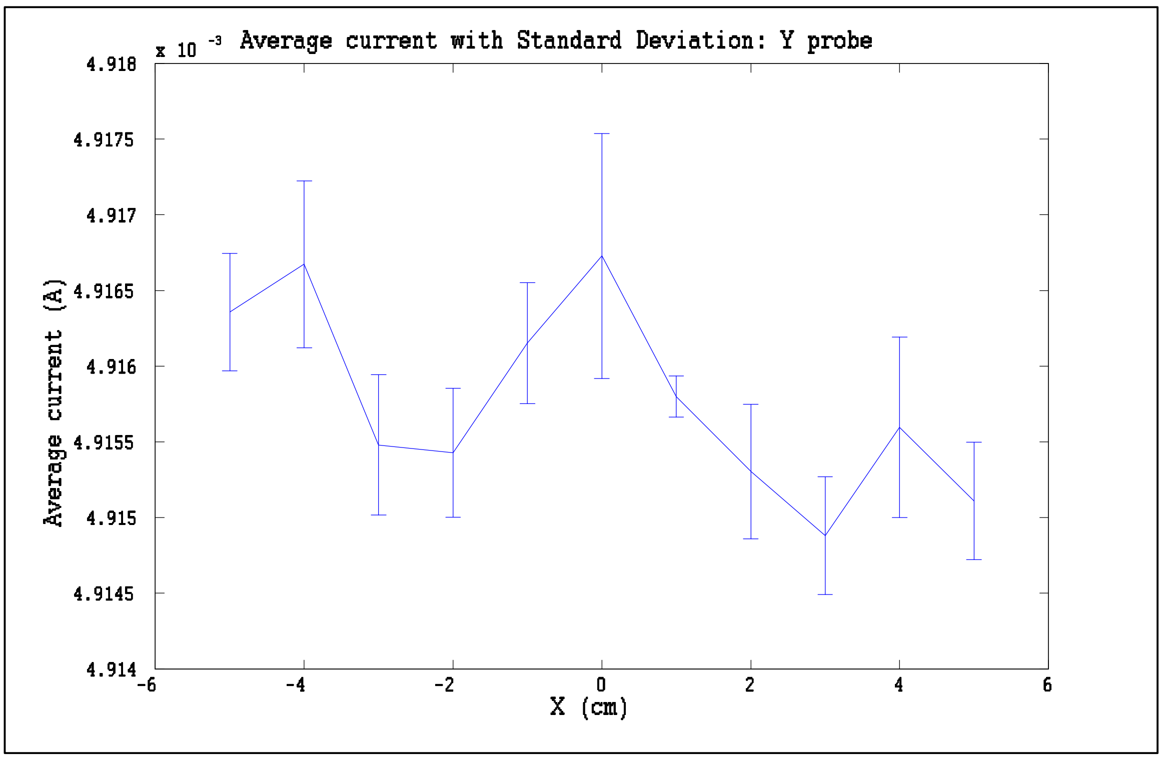


Figure 3.8 Average current in the Y direction Hall probe in the X measurement planes with the standard deviation

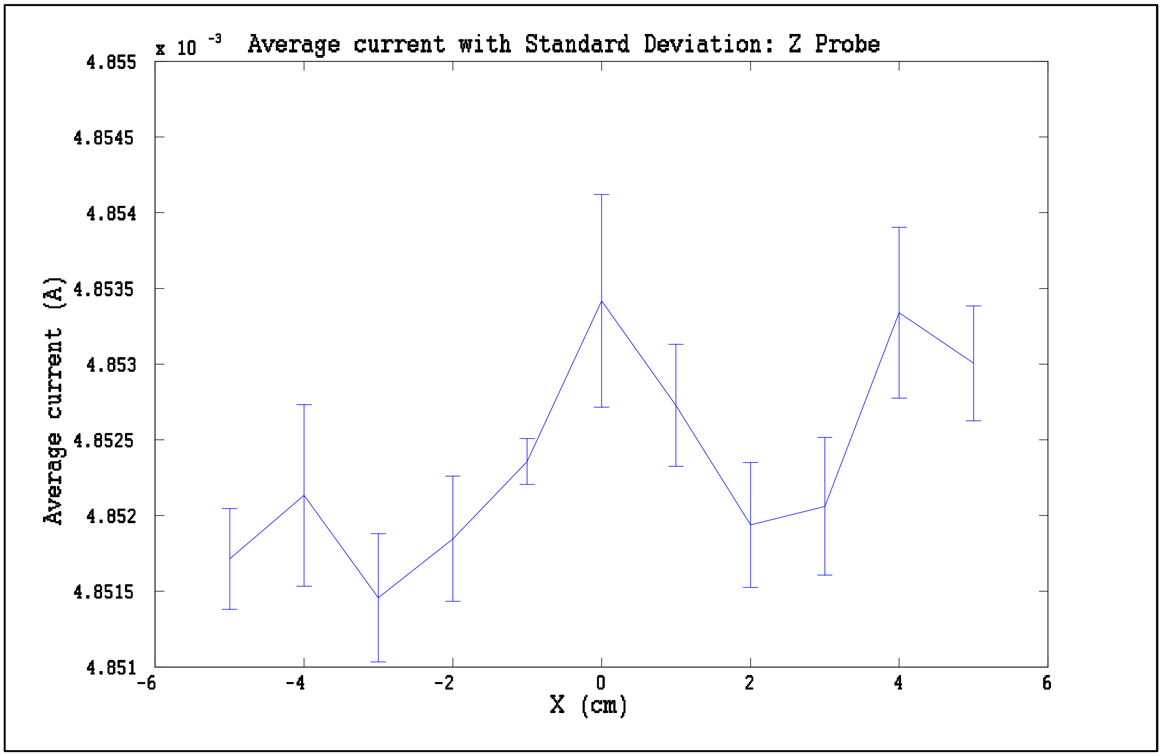


Figure 3.9 Average current in the Z direction Hall probe in the X measurement planes with the standard deviation

3.2 Analysis and Discussion

The current in the Hall probe is fairly consistent, with variations from two to three µA across the board. This is about 0.5% of the total current, and the standard deviations are even less: around one to two µA, so variations in the current should not affect our measurements much. The standard deviations in the magnetic field are 15-20 µT, which comes out to approximately 0.05 % of the magnetic field produced in the chamber by the solenoid. This is approximately one part in 20,000. The accuracy required to distinguish ^{7}Be from ^{7}Li was approximately one part in 7600, or a resolution of about 60 µT, so the field we generate should be uniform enough to distinguish the two using FTICR.

The field we have generated from this coil is quite a bit larger than the field necessary to counter the earth's magnetic field. The magnetic field we generate is about 630 μT, while the earth's magnetic field is roughly 50 μT. By generating a magnetic field with a smaller current we can generate the proper strength field. If the variations in the field are due to the Helmholtz coil they will probably shrink proportionally to the strength of the field, but if they are due to error in the instruments or magnetic fields in the lab will probably remain the same; either way the field should be uniform enough to obtain sufficient resolution with the FTICR. To produce a 630 μT field we used 96 Amp-turns of current. That is approximately 6.56 μT/Amp-turn, meaning that we need to use approximately 7.62 Amp-turns in the Helmholtz coil to generate 50 μT. That is a current of 1.27 A to achieve the desired field. This is only an approximation because the magnetic field of earth is not pointing directly down in this part of the world, and there could be other magnetic fields that point in other directions. In order to counter them all we will need to use both Helmholtz coils to create a field with two components to counter the field in any direction except the one we want it to go: directed along the axis of the plasma chamber. The coils can generate a strong enough magnetic field to counter the earth's magnetic field, and they can also counter any other small magnetic fields that might cause plasma loss in the system.

3.3 Conclusion

The field we have generated from this coil is quite a bit larger than the field necessary to counter the earth's magnetic field, but it can be scaled back to the level that we need in order to counter the earth's magnetic field. The field we generate should also be large enough to counter any other magnetic fields that could be the source of plasma loss in the system. In addition, the field we generate seems to have a small enough variation that we can maintain sufficient resolution in the FTICR. The standard deviations in the field are fairly small, about 30 μT, and we merely needed variations smaller than 60 μT to give us sufficient resolution to distinguish ^{7}Be and ^{7}Li in the FTICR. These coils should serve well to keep our fields correct and prevent any plasma loss as we measure the decay rate of ionized ^{7}Be.

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