CONSTRUCTION AND CHARACTERIZATION OF A SPECIALIZED MALMBERG-PENNING TRAP FOR CONFINEMENT OF A NONNEUTRAL RADIONUCLIDE PLASMA

by

David K. Olson

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Bryan G. Peterson, Advisor

Justin B. Peatross, Thesis Coordinator

Scott D. Sommerfeldt, Department Chair
The design for a Malmberg-Penning trap is dependent on the characteristics of the plasma being studied. $^7$Be is a radioactive isotope that decays to $^7$Li by electron capture. A $^7$Be plasma requires special consideration in designing a trap. Specifically, a strong, uniform field is required in the center, where the plasma will be confined, to distinguish between $^7$Be and $^7$Li particles. We have completed the assembly and initial testing of a trap designed specifically for confining a $^7$Be plasma. Results of this testing show that we have a strong magnetic field with $\mu$T variability. This uniform field will allow us to make accurate measurements of the radioactive decay of $^7$Be in a plasma state.
Writing this thesis was a long process, and I’m especially grateful to my research advisors Dr. Peterson and Dr. Hart for their patience and assistance in its revision and completion. I would also especially like to thank my father for his help and encouragement to me. Finally, I would like to express my deep appreciation to all of my family and friends who encouraged me in writing this thesis and for the suggestions offered in its revision.

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Chapter 1

Introduction

Beryllium-7 ($^{7}$Be) is a very interesting radioactive isotope of beryllium. Scientists in different fields have found important uses for it in helping us understand physical behavior in our world. We do not, however, understand the isotope itself as well as we would like. We have begun a project here to study $^{7}$Be in a nonneutral plasma confinement system, based on the Malmberg-Penning trap. In this thesis, we will show how we have designed our trap and how it enables us to study this particular plasma.

1.1 Historical Background

We know that the vast majority of the material in the universe is in a plasma state. In other words, nearly all matter in the universe is ionized. Because plasma is so common, understanding it helps us understand a great deal that happens around us. One method of studying plasma is to create one using only a single type of charge, positive or negative. Such a plasma is termed nonneutral. Confining nonneutral plasma for long periods of time is much simpler than confining neutral plasma. Studying them allows us to more easily observe certain behaviors of plasma, especially long term behaviors.
CHAPTER 1. INTRODUCTION

Nonneutral plasma physics is a relatively new field. Leon Brillouin published one of the first significant papers relating to the field in 1945. In this paper, he discussed the importance of studies done by Larmor on the mechanics of electron motion in a magnetic field by applying Larmor’s Theorem to a beam of electrons, beginning the formal study of nonneutral plasmas. In the 1960’s, interest in nonneutral plasmas increased because of the possibilities of fusion power and developments in the study of accelerators and ion sources. Interest continued to develop into the 1970’s, when physicists began looking for ways that nonneutral plasma could be confined and studied.

1.1.1 The Malmberg-Penning Trap

In 1975, J. H. Malmberg and his associates published a description of a new method they had designed for confining nonneutral plasma. They made their trap from a simple, cylindrical tube. A solenoid coil around the tube generated a magnetic field, creating a type of Penning trap that confined plasma radially. That is, since charged particles spin around magnetic field lines, the magnetic field controls the radial movement of the particles, preventing them from drifting away. In order to completely confine the particles, Malmberg added plates to each end of the cylinder. He then applied a voltage to the plates such that the charged particles would be repelled. These voltages controlled the axial movement of the particles, keeping them trapped inside the cylindrical container. Such an apparatus is now known as a Malmberg-Penning trap. (See Fig. 2.1.)

1.1.2 Plasma Confinement Using the Malmberg-Penning trap

Research found Malmberg’s trap to have a number of advantages for the study of waves in a plasma medium. The Malmberg-Penning trap could create relatively idealized situations for study of basic plasma phenomena. One of the most crucial differences between this trap and other confinement methods was that the confined
plasma would be more or less at rest with respect to the laboratory environment. Since the plasma was at rest, wave propagation was much easier to analyze, and nonlinear phenomena that occurred were much easier to see and understand.

Since the publication in 1975, the Malmberg-Penning trap has become one of the common methods for nonneutral plasma confinement. Use of these traps helped physicists to understand more clearly principles of many fields, including fluid dynamics and wave propagation. Physicists have studied such phenomena as vortices, Landau (collisionless) damping, and fluid echoes.\(^3\)

### 1.2 Beryllium-7

\(^7\)Be is the lightest known radioactive isotope that undergoes only orbital-electron capture decay. The \(^7\)Be atom decays into \(^7\)Li with a half life of approximately 53 days. Study of the \(^7\)Be isotope revealed that when combined with other materials, the decay constant is actually dependent on the chemical state of the atom. Therefore, the half life of \(^7\)Be is dependent on both the types of atoms to which \(^7\)Be is bonded and the arrangement of those bonds around the \(^7\)Be atom.\(^4,5\) It may therefore also be possible that the half life may change if \(^7\)Be is in a plasma state.

In 1955, Arnold and Al-Salih detected \(^7\)Be in our atmosphere.\(^6\) Presumably, high-energy cosmic rays interact with nitrogen and oxygen in the upper atmosphere, creating \(^7\)Be in addition to many other materials through spallation reactions. Because of the high energies of these reactions, the isotope is ionized when it is created. Normally we assume that the ions quickly combine with oxygen, fluorine, or small aerosol particles shortly after their creation. The added mass creates a downward transport mechanism, carrying the \(^7\)Be to lower altitudes.\(^7\)

Because production of \(^7\)Be comes from interactions with air molecules, the rate of production should be proportional in some way to the density of air. Thus, at higher altitudes where air is thinner, the production rate should be less. Current models
suggest that the highest production of $^7$Be in our atmosphere occurs between 20 and 50 km—in the lower stratosphere. At this altitude, $^7$Be can be found in concentrations of $10^3$ atoms per gram of air. These models also suggest that although production rate decreases with altitude, so does the density of air, and so the concentration of atoms per gram of air should remain fairly constant. Experiment has verified this hypothesis to be true in the lower stratosphere. Eventually, rainfall removes the $^7$Be molecules from the atmosphere. The entire cycle of the creation of $^7$Be to its removal by rainfall covers a period of 35–40 days, or a little less than one half life.

1.3 Why $^7$Be Should Be Studied

1.3.1 Uses of $^7$Be in Various Fields

Because $^7$Be washes out of the atmosphere through rainfall, eventually it reaches the surface of the earth. In 1999, Walling, He, and Blake published a paper discussing measurements made by geologists in assessing soil redistribution through erosion. Traditionally, the isotope $^{137}$Cs has been used to trace soil movement. However, the half life of $^{137}$Cs is long enough that only medium-term (∼45 years) rates of movement can be effectively determined. Walling and his colleagues proposed that $^7$Be, which has a much shorter half life, can be used as well, so that short-term rates of erosion can be mapped. Preliminary experiments performed by them confirmed the value of tracing $^7$Be that has fallen from the upper atmosphere through rain washout.

Shortly after Walling’s experiments, S. A. Fitzgerald and her associates used this idea to map sediment deposition and resuspension in the Fox River, located in northern Wisconsin. Certainly, further studies will be done by geologists employing the use of $^7$Be as a tracer.

Meteorologists have also found use for $^7$Be while it is still in the atmosphere. In 1996, a group of scientists noticed that there were temporal variations in distributions of $^7$Be-aerosol combinations in the atmosphere. In 1999, a research team in Spain
found that these variations had weekly and seasonal trends. Further research by the Spanish team implied that these trends could be accounted for by local meteorology. By understanding more completely the conditions of $^7$Be in the atmosphere, it may be possible to do the reverse, and predict meteorological trends by following $^7$Be variations.

1.3.2 NASA’s Discovery Regarding $^7$Be in the Upper Atmosphere

On 7 April 1984, the space shuttle Challenger launched the Long Duration Exposure Facility (LDEF). This unmanned satellite was designed to provide information about the effects that long exposure to space has on the materials used to construct spacecraft and their various components. The satellite spent nearly six years in orbit around the earth, also giving scientists an opportunity to study the effects of induced radioactivity on a craft placed in orbit around the earth for a long period of time. After retrieving the LDEF from orbit in 1990, NASA scientists, in collaboration with the Naval Research Laboratory, made a startling discovery. Gamma-ray spectra revealed a surprisingly high concentration of $^7$Be on the surface of the leading end of the satellite. The scientists found that the amount of $^7$Be was a few orders of magnitude more than what the accepted models of its production at the satellite’s orbital altitude predict.

According to the accepted models, the production of $^7$Be in the 300 km range of the atmosphere should be much less than the peak production of it at an altitude of 20 km. Concentration of $^7$Be should be on the same order at both altitudes, somewhere around $10^3$ atoms per gram of air. However, NASA’s measurements revealed that the concentration of $^7$Be at the orbital altitude of the LDEF was $3.8 \times 10^6$ atoms per gram of air, or three to four orders of magnitude greater than the measured values of $^7$Be concentration at an altitude of 20 km.

There are many possible explanations for the unexpected concentrations of $^7$Be
CHAPTER 1. INTRODUCTION

high in our atmosphere. $^7$Be could possibly be brought from another source external to the earth. $^7$Be is found in the solar core, for example, and it has been suggested that it is transported to the earth during some solar flare activity. Experiments on the composition of the solar wind such as the Genesis project may give more evidence on whether or not this is possible. A followup paper to NASA’s article suggests that though this type of transport may contribute to the amount of $^7$Be in the atmosphere, most of it comes from interactions in the atmosphere.

Another possibility is that the $^7$Be comes from elsewhere in the atmosphere. NASA proposed in their article that some unknown transfer mechanism brought $^7$Be from the lower atmosphere to higher altitudes. This theory would imply that there are characteristics of our atmosphere that are not well understood.

G. W. Petty proposed another possible explanation for NASA’s findings in 1991. In his paper, Petty hypothesized that $^7$Be atoms at very high altitudes are found primarily as free atoms. This assumption provides a model suggesting that gravitational fractionation accounts for most of the $^7$Be found on the LDEF. The diffusion models provided by Petty do, in fact, closely resemble the calculations done by NASA in their analysis of the LDEF. However, the assumption that $^7$Be exists as free atoms may be incorrect. At these altitudes, free electrons are very sparse. It is possible for the atoms to take electrons from free neutrals, such as oxygen, but the accepted models assume that the chances of this occurring are less than the probability of the ion bonding to free oxygen, fluorine, or aerosol particles. The idea can be examined, however, by establishing the chemical behavior and relationship of $^7$Be to other elements found in the atmosphere while in an ionized state.

1.3.3 Studying the $^7$Be Isotope

Because important uses for $^7$Be have been and will probably continue to be found, we need to have a clearer understanding of the characteristics of this particular atom.
We must first understand how $^7\text{Be}$ behaves in the atmosphere—its creation, its movement, and its removal. Through the study of $^7\text{Be}$, we will be able not only to explain why there is so much of it in the atmosphere, but we may also be able to discover new processes of transport in our atmosphere, or maybe from outside the earth. Or perhaps we will discover a new characteristic of the atmosphere that allows this isotope to exist monatomically. Since $^7\text{Be}$ is first created in a plasma form, it should first be studied as a plasma. This study will not only help us understand the $^7\text{Be}$ isotope better, but will also help us understand plasma behavior. We will also see what effects ionization and plasma behavior have on radioactive decay.

1.4 Designing a Trap for Studying $^7\text{Be}$

In order to study the $^7\text{Be}$ ion plasma, we first needed to design a trap that would allow us to confine and analyze it. Because of the properties of this isotope, there are certain qualities that the trap must have in order to provide meaningful data. The next chapter presents the needed characteristics and describes how we designed our trap to be able to study $^7\text{Be}$. My part in this project consisted of assisting in the construction of the trap and analyzing the magnetic field. This analysis shows that we have made a Malmberg-Penning trap capable of studying this particular isotope. Further study of other plasmas, radioactive or not, can be done by others by making simple modifications to the design of our trap.
Chapter 2

Design of the Trap

The basic design of a Malmberg-Penning trap is simple. A conductive cylinder has an applied axial magnetic field. Voltages are applied to isolated segments at both ends to close the trap. When confining an ion plasma, the voltages are positive. An electron plasma would require negative voltages. The axial field keeps the particles from moving radially, while the voltages keep the particles confined axially. The trapped particles coalesce to form a cylindrical-shaped plasma in the trap that rotates at a frequency $\omega_D$ due to $E \times B$ drift (Fig. 2.1). The trap is evacuated so that the plasma can take form and not collide with neutral particles. Instruments are placed inside the cylinder to take measurements and probe or manipulate the plasma. These instruments are placed in such a way that physical contact with the plasma is avoided, or at least unobtrusive to the behavior of the plasma. In order to get the plasma to form in the trap, however, certain criteria need to be met. A series of considerations determine how the trap should be built in order to confine the plasma.

2.1 Considerations for the Type of Plasma

The most important factor of the Malmberg-Penning trap in order for it to work successfully is the magnetic field. The strength of the field to be applied to the trap
is dependent on the density of the desired plasma. Brillouin showed that there is a maximum density that can be confined by a given trap configuration.\textsuperscript{1} This maximum depends on the plasma frequency $\omega_p$ and the cyclotron frequency $\omega_c$, determined by the type of plasma being confined. This relationship is given by the Brillouin Limit:

$$\frac{2\omega_p^2}{\omega_c^2} \leq 1$$

In SI units, $\omega_p^2 = \frac{n_i Z^2 e^2}{m_i \epsilon_0}$ and $\omega_c = \frac{ZeB}{m_i}$, where $n_i$ is the density of the ion plasma in ions/m$^3$, $m_i$ is the mass of the ion, and $Z$ is the integral charge of the ion. ($Ze$ is thus the total charge of the ion.) Substituting and simplifying these equations,

$$\frac{2n_i m_i}{\epsilon_0 B^2} \leq 1 \quad \text{or, solving for } B, \quad B \geq \sqrt{\frac{2n_i m_i}{\epsilon_0}}.$$ 

The minimum strength of the magnetic field, then, is determined by the required plasma density for the experiment, and by the species of ion in the plasma.

Similarly, the required size of the trap is affected by the plasma effects being studied. A larger trap allows for more confined particles at a given density. Different plasma behaviors become more pronounced with higher particle numbers and densities. The width and length of the trap should be chosen to conveniently fit the length

Figure 2.1: Basic design of a Malmberg-Penning trap.
CHAPTER 2. DESIGN OF THE TRAP

and width of the size of the plasma that results from the design of the trap. Since a larger radius makes getting a strong magnetic field more difficult, the trap requires a better magnet and becomes more expensive. It is also important to make the trap small enough to get an adequate magnetic field, but still large enough to avoid any contact between the plasma and the trap wall. Other factors that may apply to the trap size may include lab space, budget, and convenience.

2.2 Considerations for the Radioactivity of $^7\text{Be}$

2.2.1 Multiple species in the plasma

Because of its radioactive decay, the $^7\text{Be}$ plasma will actually be made of two different elements: $^7\text{Be}$ and $^7\text{Li}$. Analyzing the changing ratio of each element in the plasma reveals the rate of radioactive decay. Since we are interested in how much of each element is present in the plasma, the trap needed to be designed so that we would be able to distinguish between the two materials.

The principle method by which we view the content of a plasma is Fourier Transform Ion Cyclotron Resonance Mass Spectroscopy (FT-ICR/MS).\textsuperscript{19} Simply, this process involves measuring the frequencies at which the particles in the plasma are rotating around the magnetic field lines. The cyclotron frequency is dependent on both the strength of the magnetic field and the mass of the particle in the field:

$$\omega_c = \frac{qB}{m} \quad \text{or} \quad f_c = \frac{qB}{2\pi m}.$$  

Distinguishing between $^7\text{Be}$ and $^7\text{Li}$ then becomes a matter of distinguishing between the two cyclotron frequencies given in the measurements.

Considering the similar masses of the two types of particles, the frequencies at which they rotate in a given magnetic field are nearly the same (Table 2.1). Thus, any change in the magnetic field strength will have a significant effect on what we observe in the trap. A small fluctuation in the field in the region over which measurements
Table 2.1: Masses and cyclotron frequencies for each element (singly ionized) in the plasma at a magnetic field of 0.5 T.

<table>
<thead>
<tr>
<th></th>
<th>Mass</th>
<th>Frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^7$Be</td>
<td>$1.16516 \times 10^{-26}$ kg</td>
<td>1.09425 MHz</td>
</tr>
<tr>
<td>$^7$Li</td>
<td>$1.16501 \times 10^{-26}$ kg</td>
<td>1.09439 MHz</td>
</tr>
</tbody>
</table>

The resulting lack of resolution prevents the acquisition of clear data concerning the number of each kind of particle in the plasma. To be able to distinguish between the two types of particles, the field must be as constant as possible over the sampling region.

2.2.2 Radiation issues

The actual radiation emitted from the plasma will not be a major concern for our experiment. Orbital-electron capture leaves a free space in the orbital electron shell. This space puts the $^7$Li atom in an excited state, and so an electron may cascade to the open spot in the orbital shell. The cascading causes a 75.6 eV UV photon emission in addition to the 0.4 MeV $\gamma$-ray and neutrino typical of this type of radioactive decay. Neither $\gamma$-ray nor UV emission is a concern in our experiment for two reasons. First, $\gamma$-ray emission happens in only about 10% of the decays that occur. Our design predicts a decay rate of 150 decays/second, and so only 15 $\gamma$-rays will be emitted every second, or only 4 nCi are radiated by the plasma. Second, the amount of copper surrounding the trap is more than sufficient to block the few $\gamma$-rays and the UV photons that are emitted as a result of the decay. Neutrino flux from the reaction is minimal compared to the normal background flux we see every day, and so is also of no concern.


2.3 Physical Design of the Trap

For our particular experiment, we are looking for a plasma made up of about $10^9$ particles. The plasma will be 10 cm in length and 2.5 cm in radius, giving a central density of $n_0 = 4.9 \times 10^{12}$ ions/m$^3$ (assuming $n_{tot} = 7.4 \times 10^8$ ions). Our choice of having a less dense plasma is deliberate so as to keep plasma effects from becoming too strong. As mentioned previously, plasma effects become more pronounced at higher densities, and the observed phenomena become more complex. The stronger plasma effects would have a negative impact on the results of FT-ICR/MS. However, because we are interested in the radioactive decay of our plasma, the density needed to be high enough to observe the decay rate clearly. Our density is higher than the density of $^7$Be in the atmosphere for this reason.

Taking into account the aforementioned considerations, a plasma of this density requires a magnetic field of at least 0.12 T at the Brillouin limit. We can confine our density at just 5% of the Brillouin limit by using a field of just under 0.5 T. The stronger field will also allow us to confine more particles while staying well away from the Brillouin limit if we desire.

With this density as our goal, a convenient size for our trap is a 4 inch diameter tube with a magnet length of 60 cm. In order to prevent field error, the tube is made of non-magnetic stainless steel. Inside the tube is a series of rings to which measuring devices can be attached. The inner diameter of these rings is 3 inches, leaving enough room for the 5 cm (2 inch) plasma diameter. The entire tube is evacuated to a pressure on the order of $10^{-9}$ torr or better.

2.3.1 Wiring and Power

One of the major challenges of this design is creating a 0.5 T magnetic field. Cryogenic magnets are not suitable for this experiment not just because of their cost, but also because traps using them are repressurized every time the cryogenics are
refilled with liquid helium, limiting the period of confinement possible for the plasma. We are particularly interested in observing the plasma over a long period, and so a copper magnet is preferable. Using a simple solenoidal coil of wire and 250 A of current, a turn density of 1.15 turns/cm in 13 layers (a total of 14.73 turns/cm) will provide this magnitude of magnetic field. (This value is different from that of an ideal solenoid because we have taken the thickness of the layers into account.) It is easier to deal with wire connections if there are an even number of layers, and so our design uses only 12 layers (13.6 turns/cm) giving us an adequate magnetic field of 0.4490 T. The quantity of wire needed to make the coils for this field has enough resistance to require a 15 kW power supply to provide the high current. The wire used must be heavy enough to handle such a large amount of power.

For our magnet, four \( \frac{1}{4} \)-inch square copper wires are wound parallel to each other across the 60 cm length. To obtain the needed turn density, there are 12 layers of the wires. The wires are connected in series to make one long winding through the whole magnet. The free ends are connected to the 15 kW power supply, providing 250 A of current at just under 60 V. Wound properly, this magnet should provide a field of about 0.4409 T at the center.

This power supply is stable to within 0.1% in its constant current supply. With this kind of variation in the current to the main winding, we may see variations as much as 300–400 \( \mu \)T in the magnetic field within a relatively short period of time. This variation is not a problem for our experiment, because the variation occurs across the entire magnet. The relative variation in the center of the trap would remain unchanged in spite of a small variance in the power supply’s current.

### 2.3.2 Cooling System

The 15 kW of power applied to this magnet dissipates mainly as heat. At this power, the wire used to make the magnet could reach temperatures at which the wire
insulation could be damaged. To remove the heat and cool the magnet, a square copper tube is wound between the sets of four wires. We use a set of 12 parallel tubes for cooling, with one tube wound in each layer of the magnet. Chilled water runs through the tubes to carry away the heat. At a rate of six to ten gallons per minute, the water should carry enough energy away to operate the magnet at room temperature. The chilled water is obtained from the cooling system for the building.

2.3.3 Field Correction

As was discussed earlier, a constant field is necessary to distinguish between the $^7\text{Be}$ and $^7\text{Li}$ contained in the plasma. At 0.5 T, the differences between cyclotron frequencies is slight: just 140 Hz, or one part in 10,000 (Table 2.1). Clearly, a very small change in the magnetic field will make it difficult to discern between the two particles. A change of 53 $\mu$T is sufficient to lose nearly all resolution, making $^7\text{Li}$ indistinguishable from $^7\text{Be}$.

The normal field of a reasonably long solenoid magnet is not flat enough to guarantee a variation of less than 53 $\mu$T across a 10 cm region. Adding coils of wire to the ends of the magnet boosts the field on both sides enough to provide a flat field across the center. Coils of 12 gauge wire are used in our design on either end of the magnet. Calculations show that 6 layers of wire are needed with 15 A of current to boost the field sufficiently, even providing a flatness of as little as 10 $\mu$T.

2.3.4 Internal Design

Though this project did not involve the building of the interior structures of the trap, a brief description of its design helps complete the discussion of designing a Malmberg-Penning trap. A series of rings mounted along the axis of the trap provides a convenient way of probing and analyzing the confined plasma. Some of these rings are segmented, allowing more specific control or analysis around the entire circumference of the plasma. There is also a system used to correct for the earth’s
magnetic field inside the trap. The rings are insulated from each other, and from 
the conductive wall of the trap itself. Coaxial cable passes between the rings and 
the wall, out of the way of the plasma inside the trap. The cables are accessible 
to the laboratory through a set of BNC feedthroughs at the end of the trap. The 
feedthroughs are designed and mounted in such a way that leaks in the vacuum system 
are not an issue.
Chapter 3

Constructing the Trap

We began assembling the trap in January 2002, and finished shortly before the summer. The coils were wound by mounting the trap on a large machine lathe and turning the entire trap by hand.

3.1 Winding the Primary Magnet

Before winding the primary coil, aluminum brackets were mounted on the trap to keep the turns of wire in the 60 cm segment for the magnet. The brackets were designed in a star pattern to help us turn the wires around and to keep track of which layers in the magnet were associated with which ends of the copper tubing. The face of these brackets toward the wires was covered with rounded pieces of a nylon plastic to prevent the insulation of the wires from being scraped off by the corners of the aluminum frame.

The set of four wires were wound simultaneously along with a length of the cooling channel. The wire is a 2 gauge square copper wire with an armored Polythermaleze® insulation.* This wire has a weight of 242.82 lbs and a resistance of 0.12929 Ω per 1000 feet of wire. Each of the four wires was wound continuously through twelve

*Polythermaleze is a registered trademark of Phelps Dodge Magnet Wire Corporation
layers of windings. The cooling channel is an uninsulated, square copper tube, approximately \( \frac{1}{4} \) inch on a side. Separate lengths were used in each layer. (It should be noted that the width of the wire is actually just slightly more than the width of the tube. This difference did not provide any significant field error.) The spools of wire and tubing were mounted vertically on a wheeled cart to help ensure the wires did not twist as they were wound around the trap. (See Fig. A.1.)

A potential source of shorts in the winding came from fragments of metal from nearby machines. We prevented metal fragments from falling into the windings by working only when the machines were not being used and covering the magnet when not working. We placed a thin sheet of mylar between each layer to prevent connection between layers in case the insulation was broken in any part of the wire due to any fragments that may have fallen into the trap despite our efforts. The mylar also helped to keep the successive layers of wire from twisting into any gaps between windings of the layer below.

Adding the mylar layer created a concern for the efficiency of the cooling system. Any gap between layers of wire that would be filled with air would reduce the effectiveness of the magnet’s cooling system to draw heat away from the coils. To improve cooling efficiency, we spread a thermally conductive paste both underneath and over each layer of mylar. (See Fig. A.2.)

The final step in preparing the primary magnet was to connect the four wires in such a way that it would be a single series winding when connected to the power supply. The beginning and end of each of the four coils of wire were on one side of the magnet, providing a simple way to connect the coils together. We took the end of one coil and connected it to the beginning of the next coil. The connections were kept short in length, as they would not be able to be well cooled. One of the spools of wire we used did not have enough length to finish all twelve layers, so extra wire
had been taken from one of the longer spools to finish its winding. This break added one more connection to be made, for a total of four. The connections between the coils did not significantly raise the resistance of the entire coil.

The main winding was built closely to the specifications we had designed. The actual windings had an average of 17.5 turns per wire per layer, providing a total of 70 turns per layer (See Table B.1). Note that every group of four turns is separated by a $\frac{1}{4}$-inch gap because of the cooling channel. Having four wires between each winding of the cooling system means there is about an inch spacing between these gaps. (Fig. A.3)

With a $\frac{1}{4}$-inch width, each layer had an increase in diameter of $\sim \frac{1}{2}$-inch. The inside diameter of the first layer is 4 inches. The outside diameter of the outer layer is 10.752 inches. The 0.752 inch excess in winding diameter is due primarily to the mylar and conductive paste between the layers of wire.

With the specifications of the trap, we find that the total length of the wire in the primary coil is approximately 1,540 feet. This length of wire weighs 374 pounds, and has a resistance of 0.2 $\Omega$. (The cooling channel, pipe, and all other parts in the assembly do not add significantly to the total weight of the trap. The entire assembly of the magnet weighs about 400 pounds.)

### 3.2 Winding the Correction Coils

When the primary winding was completed, we began mounting the correction coils. These coils used a 12 guage round, insulated copper wire, and coils were placed on each end of the magnet. This wire weighs 19.98 pounds and has a resistance of 1.589 $\Omega$ per 1000 feet. Mylar sheets were again used between layers, but in these coils a transparent silicone sealant was used rather than the thermal paste used in the primary magnet. The silicone sealant allowed us to glue each coil to prevent any shifting while we wound the six layers in each coil.
The correction coils span different regions in the different layers (See Table B.2). Each begins at the far end of the trap of the respective side, so more windings are placed on the extremes of the magnet. Overall, the widest part of the correction coils spans a 4 inch region, and the outside diameter at the correction coils is 10.975 inches (Fig. B.1).

After completing the correction coils, the entire exterior of both the primary magnet and the correction coils was covered with the silicone sealant. This coating protects the interior of the magnet from dust and particles that could damage it. (Fig. A.4)

The two correction coils are driven independently by connecting them to separate power supplies. Separate connections as opposed to a series or a parallel connection with the same power supply allows us better control of the final magnetic field in the trap. By using two power supplies instead of a single one, we can adjust the current specifically to each end. Independent control allows us to make adjustments for any difference in the magnetic field between ends of the primary magnet and in the correction coil windings.

### 3.3 Building the Cooling System

Cooling water is supplied to the magnet with $\frac{1}{2}$-inch reinforced hose. The hose connects to the $\frac{1}{4}$-inch square tubing in the magnet with a set of 24 brass adapters we made. To reduce turbulence in the flow of cooling water, we beveled the inside of the ends of the adapters connecting to the hoses. These 24 pieces were soldered on to the ends of each cooling channel. (Fig. A.4)

To supply the magnet with cooling, we ran two pairs of $\frac{3}{4}$ inch reinforced hose to two pairs of manifolds. The manifolds are built of PVC, plastic, and brass. The hoses attach to the manifolds and are held with a non-magnetic stainless steel hose clamp. Each pair consists of a feed supply and a return supply for each end of the magnet.
CHAPTER 3. CONSTRUCTING THE TRAP

The feed manifold on each end is also equipped with a release valve in the event the cooling system needs to be drained. (Fig. A.5)

Each set of manifolds divides the cooling water to six of the layers in the magnet. The layers alternate between the two sets of manifolds. This alternating pattern prevents one end of the magnet from cooling better than the other. $\frac{1}{2}$-inch reinforced hose connects the manifolds to the magnet’s cooling channels. Again, each connection is held with a non-magnetic stainless steel hose clamp.

We provided additional cooling to the exterior of the magnet by soldering lengths of the square tubing to sheets of copper two inches wide. These were wound around each of the correction coils to draw heat away from them. We also wrapped a length of $\frac{1}{4}$-inch reinforced hose around the lengths of wire in the series connections of the primary coil’s windings as well as the connections to the power supply. This way we can also draw some heat away from the extensions that are not directly in contact with the rest of the cooling system.

3.4 Mounting the Trap

We used an aluminum support frame to mount the trap. Aluminum mounting brackets with curves designed to hold the trap were bolted to the top of the frame. We lined the curves of the brackets in which the magnet rests with a padding to keep the trap from being damaged by the mounting brackets in any way. (Fig. A.6)

Aluminum panels mounted on the side of the frame provided a place to attach the cooling manifolds. These panels are held with non-magnetic stainless steel screws. Likewise, the bolts holding the manifolds are non-magnetic.

Finally, lengths of heavy cable provide power to the primary magnet from the nearby 15 kW power supply. These cables are twisted around each other to reduce field error from the current running through them. Twisted pair wire runs from the correction coils to their power supplies as well.
3.5 Testing the Trap

The primary power supply provides 250 A of current to the primary magnet at approximately 58 V. This voltage is within the specifications of the power supply, and so there will be no difficulty in maintaining this current for the duration of the experiment. Running at full power, including the correction coils, the cooling system is adequate to keep the temperature at or just slightly above room temperature, and so heating will not be a problem in the experiment either.
Chapter 4

Characterization of the Magnetic Field

We mapped the magnetic field inside the trap to determine if our magnet would have the characteristics we needed to hold and analyze a $^7$Be plasma. We constructed a special Hall probe, using three hall elements on perpendicular axes. Using this probe, we analyzed the magnetic field along and above the axis of the trap and determined that the center 10 cm region appears to have less than 50 $\mu$T variation from its average field.

4.1 Design of the Hall Probe

We made the Hall probe using a 2 meter, hollow aluminum rod with a specially designed cap on the end. The design of the cap provided a way to mount the Hall elements perpendicular to the axial and two orthogonal radial directions, and allowed the leads of the elements to be inside the cap (See Fig. A.7). For easy reference, we labeled these components as green (axial), blue (horizontal radial or off-axis azimuthal), and red (vertical radial or off-axis radial). We securely fixed the three Hall elements on the face, side, and top of the cap (Fig. 4.1). The wires to power the Hall
Figure 4.1: Hall element configuration. The leads are fed through a hole in the center of the cap.

elements and measure the voltage (twisted pairs to reduce field error) ran through the rod to the other end. This end was attached to a distribution box that connected the Hall probe to a set of three constant current power supplies and to a 6.12 digit multimeter. In addition, an 18 Ω resistor was placed in parallel with the current leads to watch for any variation in the current from the power supplies to the three Hall elements. If variations were seen, they would be considered in relation to any variations seen in the measured Hall voltages.

Measuring from the position of the axial Hall element on the face of the cap, we marked the rod every half centimeter. These marks provided a distance measurement of the position of the Hall elements from the end of the trap. Measuring from the
end of the trap, the distance to the center of the magnetic field is 49 cm. The center
10 cm could be measured by scanning the field from 44 cm to 54 cm from the end of
the trap.

The final addition to the Hall probe assembly was a pair of plastic disks, cut to
match the inside diameter of the trap and the outer diameter flange. The latter disk
securely attached the probe assembly to the trap and the former disk supported the
end of the probe, preventing it from sagging when measuring the field away from the
end of the trap. Both disks included holes for the rod to pass through directly at
the center of the trap’s axis and 2.5 cm away from the center. With this spacing,
we could measure the center of the magnetic field and the field near the edge of the
plasma. (Fig. A.8)

4.2 Calibrating the Hall Probe

To ensure that our Hall probe assembly would work properly and provide the
needed resolution for our project, we set up a simple calibration system to determine
how the Hall voltage related to our field. We examined two separate cases: low (mT)
fields and high (T) fields. We also analyzed noise in the electronics and stability over
time in the hall elements.

4.2.1 Low Field Calibration

To calibrate at low field, we passed a known current through a coil of wire. The
probe assembly was held with the axial Hall element at the center of the coil, and
voltage readings from the element were taken at incremental currents applied to the
coil. Given that there were 200 turns in the coil, the magnetic field at the Hall element
can be calculated by $B = \frac{\mu_0 n I}{2R}$ where $n$ is the number of turns and $R$ is the radius of
the loop. The coil used provided magnetic fields in the mT range.

In making these measurements, we immediately noticed two significant problems.
The largest problem was that the variation in voltage readings at a given magnetic
field would increase over time. We discovered that the cause of this was a poor
design in the Hall probe power supply. The zener diodes used to set the current were
sensitive to temperature changes, and as the power supply warmed up the voltage
would steadily increase. We replaced the diodes with resistors, and the problem
immediately disappeared, though we were still required to allow the whole system to
warm up over a period of a couple of hours to ensure stability. Next, we found that the
rod served as a good antenna for the 60 Hz signals from the building’s power lines. We
avoided this problem by averaging data over time. The averaging also gave us a way
to reduce the error in our measurements from short term fluctuations in the magnet’s
current and the electronics of the Hall probe assembly. Spacing measurements in time
did, however, introduce error due to longer term drift in the 15 kW power supply.

Using the coil, we found the Hall elements gave very linear data with low fields
(Fig. 4.2). From the data obtained, we find that the calibration constants at low
magnetic fields for the three Hall elements are 1.252 V/T, 1.230 V/T, and 1.188 V/T
for the axial, horizontal, and vertical elements respectively. These calibrations used
a conservative measurement of the radius of the loop to make sure they would be
generous in their measurements of the fluctuations in the magnetic field.

4.2.2 High Field Calibration

Because measurements of our trap’s field would be significantly greater than
the mT fields we measured in the calibration, we also examined the relationship be-
tween voltage and magnetic field at higher field strengths. Because known coils that
would provide up to 0.5 T fields were not available, we made these measurements
using our trap. Since the actual magnitude of the fields of the trap are not known,
we estimated the field using a Maple script that found the magnetic fields using the
actual dimensions of the trap. The code provided the magnitude of the field at the
center of the trap at a given current. The actual fields at a given current are prob-
Figure 4.2: Low field calibrations for each of the three Hall elements.

ably, if anything, less than these obtained values, and so using a calibration derived from this method would possibly show a greater change in magnetic field for a given voltage difference. These magnetic field measurements then are a liberal estimate of the fluctuations actually present in the trap’s magnetic field.

For this measurement, we examined only the green (axial) element. The probe was mounted on the trap with the axial element sitting at the center of the trap, 49 cm from the end. Examining the Hall voltage related to the current running through the trap, we found that at high field strengths the relationship was also very linear. However, we found that the slope of this relationship was less than at low fields (Fig. 4.3). The calibration for high fields is 1.113 V/T.

4.2.3 Hall Probe Noise

In spite of our efforts to minimize noise in our Hall element signals, some noise was inevitable. We examined the behavior of the Hall probe without the trap’s magnetic
field around it (Fig. 4.4). These fluctuations are less than 20 $\mu$T in magnitude, and so were not a significant source of error in our mapping of the magnetic field.

4.3 Mapping the Field

To measure the actual field values of the trap, we wrote a LabVIEW™ program that would automatically tell us where to place the probe, take data for the field at that position, and then tell us to manually move the probe to another position. (See Appendix C.) As mentioned earlier, a large number of measurements were taken and averaged to eliminate error from power line signals. We took data using the main winding alone, each correction coil alone, and the entire system together.

We found that at full power, the Hall voltage was enough that we lost the final decimal place in the multimeter readings. Rather than introduce more uncertainty, we made all measurements at half the current the trap would actually use. All of the following figures shown give values of the magnetic field at this current. Since the
Figure 4.4: Background noise fluctuations in magnetic field measurements for all three Hall elements.
field should double at the full 250 A, all the field values at full power are twice what is reported here. We looked for fluctuations greater than 25 $\mu$T to ensure that we would not have changes above 50 $\mu$T at full power.

### 4.3.1 Main Axis Field

Figure 4.5 shows the data from measurements of the axial magnetic field created by the main winding and both correction coils. These plots use the high field calibration values for the Hall probe. The main winding itself clearly does not provide a flat enough field, but adding the two correction coils boosts the field on the ends, creating a more constant field across the center.

Using the calibrations we obtained for the Hall probe, the magnitude of the magnetic field appears to be about 0.22 T at the center of the trap (0.44 T at the full 250 A). It is possible that our field is actually slightly less than this. If this really is the case, and our magnet is not as strong as we hope, it may affect the density of our plasma. It is not a factor, however, in determining if the field is constant enough to be able to see a difference in the peaks for $^7$Be and $^7$Li in FT-ICR/MS.

Our primary interest is in the field across the center 10 cm of the trap, where the plasma will be. We made finer measurements across the range from 44 to 54 cm from the end of the trap to observe the field across just this range. In particular, we used measurements of the center 10 cm to find the optimal current settings for the two correction coils. This method of adjusting the field in the correction coils and measuring the center region determined that the best configuration of the correction coils was to apply 7.90 A to the east coil (the coil on the end from which we measured the distances, designated the east coil because it is located on the east end of the room) and 8.10 A to the west coil. (These values should be doubled when running the trap at 250 A.) Using these settings, the field across the 44-54 cm region appears to be constant to within the necessary 25 $\mu$T (Fig. 4.6).
Figure 4.5: Magnetic fields from the three windings of the trap.

The fluctuations outside of this range are probably a result of the amount of time between measurements. The fluctuation in the current powering the main winding could potentially cause more change in the magnetic field than what we see in this data, and is probably the source of the points lying outside the $25 \mu T$ range. As discussed earlier, these variations are not a concern to the experiment, since they are constant variations across the entire magnet. Comparing this data to previous data using nominally the same currents in each coil of the trap, we see that this is the case, and that nearly all of the variation falls within $\pm 20 - 25 \mu T$ of the mean field. The large changes appear to vary between the three different measurements, implying they are a result of the current changing in the power supply (Fig. 4.7).

This data also shows that the correction coils boost the field enough to raise the ends of the center section above the field at the center. We can then adjust the current to these coils slightly to flatten the field even more if necessary. If the power supplies
CHAPTER 4. CHARACTERIZATION OF THE MAGNETIC FIELD

Figure 4.6: Corrected magnetic field at the center of the trap.

Figure 4.7: Variation of the magnetic field in the center of the trap.
cannot adjust the current by a small enough value, we can add a large resistor in parallel to bleed off a little of the current.

4.3.2 Off-Axis Field

In addition to the main axis of the trap’s magnetic field, we examined what the magnetic field looks like at the edge of the region where the plasma will be. For the off axis measurements, we also looked at the radial and azimuthal directions to see if any fields in these directions would affect our trap. All of this data was taken at 2.5 cm above the main axis using the high field calibration for the axial field and low field calibrations for the azimuthal and radial fields.

4.3.2.1 Axial Field

At the edge of the plasma, the field starts to have more variation. We see a small drop in the magnetic field happen about every 2.5 cm across the center of the trap (Fig. 4.8). This variation is due to the cooling system of the trap. Since the cooling channel is wound between sets of four wires, each 1/4-inch wide, we have a space every inch along the length of the magnet where there is no current. These spaces account for the drops in the field with the same spacing.

4.3.2.2 Radial Fields

While we expected to find no significant magnetic field at all in the radial and azimuthal directions of our trap, the Hall elements measuring the vertical and horizontal fields did measure magnetic fields at about 1% of the magnitude of the axial field (Fig.s 4.9 and 4.10). The data also reveals the same drops every inch due to the cooling channel as seen in the axial fields. This similarity leads us to believe that the fields measured by these elements are actually due to a slight tilt (it could be as small as 1° or less) in the orientation of the radial and azimuthal Hall elements, causing them to not be exactly perpendicular to the axis of the trap. This measured field in these directions, then, is just a measurement of a small component of the axial field,
and not an actual radial and azimuthal field in the created by the magnet for the trap. The actual radial and azimuthal fields are probably negligible. Further testing may be done to ensure that these fields do not affect the confinement system in any significant way by confining an actual plasma inside the trap.

Figure 4.8: Axial off axis field.
Figure 4.9: Azimuthal off axis field.

Figure 4.10: Radial off axis field.
Chapter 5

Conclusion

Though its construction was difficult, we were able to successfully create a magnet suitable for studying the $^7$Be plasma. This magnet has several qualities that are necessary and beneficial for this particular project. These include built-in protection (the thick copper wall created by the magnet windings) from the small amount of radiation that will be emitted by a $^7$Be plasma and the ability to confine the plasma for long periods of time, since the trap’s design does not use cryogenic magnets.

The key property of our magnet is its very low variation across the center 10 cm region of the trap. When we examined the magnetic field in this region, we found that the variations were generally less than the maximum amount of variation before losing resolution in our Fourier analysis of the composition of the plasma. The data alone shows more variation at two different points across the center 10 cm, but we are confident that these changes are attributable to fluctuation in the 15 kW power supply that powers the main winding itself, and not an artifact of the magnetic fields along the trap. Our analysis of the radial fields also implies that the magnitude of the magnetic field in these directions is minimal, and will not be a factor in using this trap.
CHAPTER 5. CONCLUSION

Obtaining this flatness in the magnetic field was quite dependent on a good configuration of field correction coils at the ends of the magnet. These coils boost the normal solenoid magnetic field created by the primary winding enough to keep the drop in magnitude from occurring in the center of the trap. By using two different power supplies, we are able to drive the correction coils separately, which allows us to control the field at each end of the trap independently. The currents to these coils can be adjusted further to improve the variation in the field if necessary.

The primary difficulty in this analysis is the lack of accuracy with the instruments available to us. The Hall elements used were subject to errors in alignment and noise. The actual magnitude of the fields inside the trap are still unknown because we were unable to calibrate the Hall elements at high field values. The amount of time required to measure the magnetic field at a given position in the trap allowed for drift in the power supply’s output to the primary magnet, making it difficult to ensure that fluctuations in the measurements were due to the magnetic field itself, and not the driving equipment.

In spite of these issues, we conclude that our trap has the necessary properties for the study we propose to do. The next step for this project will be to create an ion source and actually confine a plasma inside the trap. $^7$Be is difficult to make, and so confining another ion first would be a reasonable step toward the goal of the project. $^9$Be is a good choice for testing the trap’s ability to confine a plasma, because it has a mass similar to $^7$Be and does not need to be made with a proton accelerator as $^7$Be would. This step would have a number of advantages in our experiment. It would ensure that our resolution is in fact enough to distinguish between Fourier transform peaks for $^7$Be and $^7$Li. It would also allow us to tune the power supply voltages for the two correction coils more precisely to maximize the resolution in our Fourier analysis. It would also allow us to see how the trap behaves, and how well it confines
a plasma without needing to create the $^7\text{Be}$ before running the actual experiment. The experience and knowledge gained will in the end make the project more efficient and effective.

In the end, we will observe the behavior of $^7\text{Be}$ in a plasma state. Our observations may help us better understand radioactive decay and radioactive plasma behavior. By understanding these things, we will be able to understand better how ionization affects the behavior of particles like this in the atmosphere. We may also be able to find an explanation for the abundance of $^7\text{Be}$ in our atmosphere.
Appendix A

Project Photos

Figure A.1: Beginning the main winding. The cooling channel sits between pairs of the four wires.
Figure A.2: A layer of mylar sheet as insulation. A coating of thermal paste was applied on top of this sheet as well.

Figure A.3: The complete primary coil winding.
Figure A.4: Correction coils and cooling adapters.

Figure A.5: The cooling system manifolds.
Figure A.6: The entire assembly of the magnet system for the trap.
Figure A.7: The Hall probe cap to which the Hall elements are mounted.

Figure A.8: The Hall probe assembly, including cap, rod, and support disk.
Appendix B

Detailed Trap Specifications

Figure B.1: Trap dimensions.
Main Winding:

2 ga. square with armored Polythermaleze insulation

bare wires: 0.255 to 0.260” on a side (nominal is 0.258”)

0.063” radius on corners

insulation: 0.003 to 0.005”

0.12929 Ω / 1000’ at 20° C

242.82 lb / 1000’

\[ \rho = 1.822 \times 10^{-8} \Omega m \] (using square area approximation)

\[ \rho = 1.728 \times 10^{-8} \Omega m \] (using area with rounded corners)

temperature coefficient is 0.00393

---

Table B.1: Windings in the primary coil.

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APPENDIX B. DETAILED TRAP SPECIFICATIONS

Correction Coil Windings

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Table B.2: Windings in the correction coils.

Correction Winding:

12 ga. round magnet wire

Bare wires: 0.0800 to 0.0816” in diameter (nominal is 0.0808”)

1.589 Ω / 1000’ at 20° C

19.98 lb / 1000’
Cooling System: starts at \( \sim 14^\circ C \)
- input 67 psi
- output 40 psi
- \( \Delta P = 27 \) psi

Thermal Conductivities:
- \( Cu \): 395 W/m/K (Book value says 338.9 – 390.8 W/m/K)
- Polyester: 0.1675 W/m/K (Polythermaleze layers)
- Polyamide - imide: 0.2596 W/m/K
- Polyimide: 0.1465 W/m/K

Table B.3: Specifications for cooling system and thermal conductivity.

\( ^{7}\textbf{Be} \): atomic mass = 7.016928 amu = \( 1.1651609 \times 10^{-26} \) kg
- half life = 53.29 d
- decay energy = 0.862 MeV
- gamma energy = 0.47759 MeV
- gamma intensity = 10.35%

\( ^{7}\textbf{Li} \): atomic mass = 7.016003 amu = \( 1.1650123 \times 10^{-26} \) kg

Table B.4: Details for \( ^{7}\text{Be} \) and \( ^{7}\text{Li} \).
Appendix C

LabVIEW Code

The following is some of the LabVIEW code used in this project. These VI’s are dependent on internal VI’s developed by Dr. Bryan Peterson and Dr. Grant Hart as well as standard National Instruments VI’s that are not included in this thesis. These are the VI’s I developed only, so this is by no means a comprehensive review of the LabVIEW code developed for this project.
APPENDIX C. LABVIEW CODE

Figure C.1: full hall probe calibration.vi
APPENDIX C. LABVIEW CODE

high field hall probe calibration.vi
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Figure C.2: high field hall probe calibration.vi
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Printed on 8/1/05 at 2:45 PM
Figure C.3: ion magnet characterization.vi
APPENDIX C. LABVIEW CODE
References


