SEQUENCING THE CREATION AND CHARACTERIZATION OF A NON-NEUTRAL PLASMA

by

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ABSTRACT

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Beryllium-7 (^{7}Be) is the lightest element that decays only by electron capture. The half-life can measurably change depending on the density of electrons available for capture. This density is affected by chemical bonding, insertion into a lattice, or the application of high pressure. We hope to determine the half-life of singly ionized ^{7}Be where the electron configuration is well known. We will measure this by trapping a ^{7}Be plasma in a Malmberg-Penning trap. To measure any differences in the half-life, we must contain it for up to one accepted half-life of 53.3 days. This will give a precise half-life which can then be used to compare with other measurements of the half-life. I will discuss the hardware and software needed to properly sequence the creation and characterization of the plasma as well as some preliminary results.

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Chapter 1

Introduction

The accepted half-life of beryllium-7(^{7}Be) is 53.3 days, however there have been measurements taken that show a slight fluctuation in this value. ^{7}Be does not have enough energy to make an electron-positron pair, so it can decay only by electron capture. It is the lightest element that decays in this manner. The electrons that are captured by the nucleus for about 95% of the decays are 1s (K) electrons. The other 5% of the decays occur when a 2s electron (L) is captured [1].

The electronegativity of ^{7}Be is low when compared with most elements. When placed in an environment with atoms of higher electronegativity, such as carbon or oxygen, the electrons from the ^{7}Be will tend to leave and attach with the other atoms, reducing the number of electrons available in the decay of the ^{7}Be.

Singly ionized ^{7}Be may have a longer half-life because it has only one L electron, changing the percentage of decays of the L electrons [2].

1.1 The Significance of ^{7}Be

1.1.1 Solar Cycle

Many different nuclear reactions happen within the sun and other stars. One of these is the transformation of ^{7}Be. In the p-p cycle, ^{7}Be decays into either lithium-7 (^{7}Li) by electron capture, or it captures a proton and becomes boron. In these two process, a neutrino (ν) is release.

$$^3He +^4 He \rightarrow^7 Be + \gamma \tag{1.1}$$

$$\begin{aligned} ^7Be + e^- \rightarrow^7 Li + \nu \quad or \quad ^7Be +^1 H \rightarrow^8 B + \gamma \\ ^8B+ \rightarrow^8 Be + e^+ + \nu \end{aligned} \tag{1.2}$$

Both cycles start with Eq(1.1) and then go through the individual paths. In these processes, the energies of the neutrinos released are different and measurable [3]. For 10% of the ^{7}Be decays, the neutrino has an energy of 0.383 MeV. The other 90% have an energy of 0.862 MeV. When the boron decays, the energy of these neutrinos has a range between 1 and 14 MeV, and peaks around 5 MeV. These neutrinos are measured by two different groups. BOREXino [4] is the group that collects the neutrinos from the ^{7}Be decays and Sudbury Neutrino Observatory captures the boron neutrinos [5]. If the half-life of ^{7}Be is extended, then the number of electron capture decays will decrease and the ratio of ^{7}Be to boron neutrinos will be smaller. If the half-life is decreased, the ratio will increase.

1.1.2 LDEF

In 1984, NASA launched the spacecraft Long Duration Exposure Facility (LDEF) to better learn how materials are affected by being in space. After it was retrieved almost six years later, results showed that the amount of ^{7}Be accumulated on the surface was several orders of magnitude larger than expected at a low earth orbit. ^{7}Be is created in the upper atmosphere, primarily between 20 and 50 km, through high energy collisions of cosmic rays with oxygen and nitrogen. At lower altitudes, the atmosphere is too dense, and causes the rays to lose the energy needed for the reaction. At higher altitudes, because the atmosphere is not as dense, not very much ^{7}Be will be created. The amount of ^{7}Be was calculated by assuming that composition of the atmosphere is the same as the atmosphere becomes less dense. By looking at the amount of ^{7}Be at 20km, it is possible to figure out how it should decrease with elevation. When LDEF was inspected, the question arose about why there was 1000 times more ^{7}Be than expected.

One expanation of this over abundance of ^{7}Be at 300 km is that it was carried up through atmospheric activity. ^{7}Be in the atmosphere often connects to aerosols and falls to the earth in precipitation. It is thought that some of the ^{7}Be is transported upward from that region [6] [7]. Another possibility is attributed to the solar cycle. There is a possibility that more ^{7}Be is made at higher elevations when there is an increase in solar flare activity. Research has been done to determine if, during the flight of LDEF, there was more solar activity than normal [8]. The exact reason for the large amounts of ^{7}Be in the low earth orbit is still unknown.

1.2 The Experiment

To understand ^{7}Be, we are conducting an experiment to help determine the half-life. In this experiment, singly ionized ^{7}Be will be used since its electron configuration is well known. This gives us a starting point when looking at the decay rates of the ^{7}Be in other samples.

In the experiment, we will use a non-neutral plasma so there will be no free electrons in the system. This will stabilize the decay rate and the ^{7}Be should decay at the same rate throughout the plasma. We will capture the plasma in a trap created by several containment rings and coils. By using the electric and magnetic fields, the non-neutral plasma will remain in a containment chamber. Using this method makes it difficult to measure the gammas released as the ^{7}Be decays into ^{7}Li. Instead of measuring the gammas, we will measure the abundance of the ^{7}Be and ^{7}Li by using Fourier transform ion cyclotron resonance mass spectrometry (FT-ICR/MS). This measures the relative amounts of ^{7}Be and ^{7}Li. By watching this ratio change in time, the number of decays will be calculated. To calculate the half life, the plasma will need to be contained long enough to get accurate measurements. This could possibly take up to one half-life, or 53 days.

Chapter 2

Experimental Process

2.1 Hardware

2.1.1 Malmberg-Penning Trap

To study a non-neutral plasma, John Malmberg developed a way to contain it for an extended amount of time using a modified penning trap [9]. By using static electric and magnetic fields, he was able to keep the non-neutral plasma contained in a cylindrical region without losing it. Fig.2.1 is a schematic of what the trap does. We will be using a similar trap to study ^{7}Be. Our trap was designed and built to capture ions [10]. The magnetic field will keep the plasma contained radially while the electric field confines the plasma axially. By manipulating the current, we can change the strength of both the electric and magnetic fields. The nominal maximum magnetic field is 0.4295 T at 250 A through the primary magnet.

We will look at singly ionized ^{7}Be, which has a positive charge. By placing positive voltage at the ends of the chamber, these ions will be confined to the chamber. The negative ions and electrons will be extracted by the positive end potentials while the neutral atoms will not be affected by the fields and will go straight through the

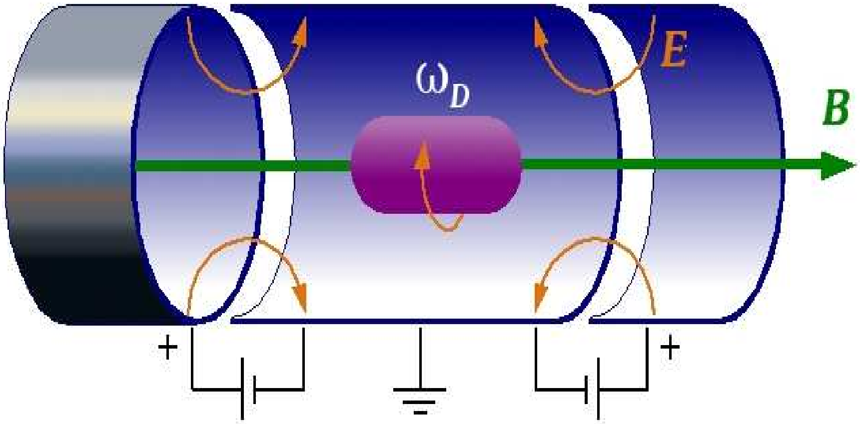

Figure 2.1 A diagram of the Malmberg-Penning trap. The configuration of the electric fields and magnetic fields manipulate the plasma to revolve around the magnetic field.

chamber. This will leave only positively charged ions. These ions will feel the force of the magnetic field $q(\mathbf{v} \times \mathbf{B})$ to provide radial confinement.

2.1.2 Creating the Plasma

The source of our plasma is a boron carbide (B_4C) target. The target is enriched so 97% of the boron will be ^{10}B. It is then bombarded by protons, which causes the fusion reaction

$$^{10}B + p^{+} \rightarrow \alpha +^{7} Be. \tag{2.1}$$

After bombardment, the target is placed in the metal vapor vacuum arc (MeVVA) source [11]. This source applies a large voltage, between 5-7 kV, from an electrode to the target, which will cause an arc to the B_4C target. This will do two things: first it will ablate the atoms, and second, it will ionize the released atoms. This ablated material contains ^{10}B, ^{11}B, ^{7}Be and ^{12}C. These free ions will travel through a quadrupole designed to extract only ^{7}Be for the chamber [12]. It is difficult to remove the unwanted ions, by using only the quadrupole, because of the high initial density

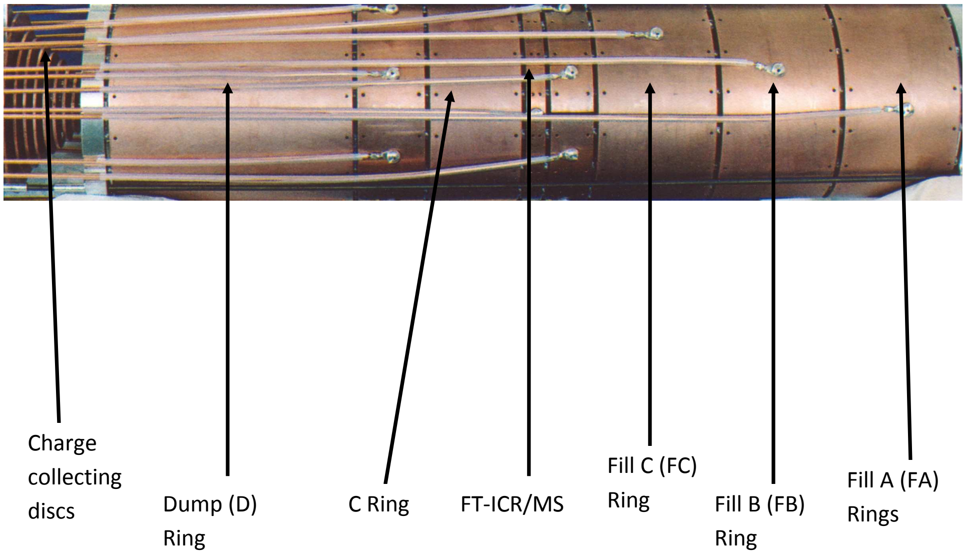

Figure 2.2 Ring configuration inside the trap. The FA, FB, and FC rings are used to capture the plasma and, along with the D ring, contain it axially. The FT-ICR/MS will measure the decay rate of the ^{7}Be. The C ring is used to measure the charge inside the chamber. The charge collectors measure the charge when the plasma exits the chamber

of ions we have. After the plasma is contained in the trap, a driving frequency equal to the cyclotron frequency of the unwanted ions will be applied which will force the ions, except ^{7}Be, to the walls and out of the system.

2.1.3 Capturing the plasma

Once the plasma comes through the quadrupole, it will be contained in a chamber. Within the confinement area, there are several rings which will change states, or the electrostatic potentials, depending on what we need it to do. Fig. 2.2 shows the different rings being used to confine and diagnose the plasma. The process of taking the plasma from the source to the confinement chamber is called the catch-stack sequence. What we call the D (dump) ring will have 150 V for the entire experiment until we are finished and need to get rid of, or dump, the plasma. The FA, FB and FC rings (the three fill-end confinement rings) will change state to capture and consolidate the plasma. When we first create the plasma, FC will be high and FA and FB will be low. Once the plasma has passed the FA ring, the FA ring will go high and the plasma will be captured between FA and FC. At this point, FC goes low and FB goes high, followed by the re-energizing of FC. This puts the plasma between the FC and D rings. This sequence allows us to capture multiple pulses of ions from the source if necessary. While contained, we will take data and analyze the plasma using Fourier transform ion cyclotron resonance mass spectrometry (FT-ICR/MS) [13]. This will measure the relative amounts of ^{7}Be and ^{7}Li. By watching this ratio change in time, the half-life of the ^{7}Be can be calculated.

2.1.4 Dumping the plasma

After the desired time has elapsed, the plasma is release by dropping the voltage on the D ring and collecting the charge using a set of discs connected to charge integrator amplifiers(see Fig.2.3). As the plasma travels outward, it circles around the magnetic field lines. As the field gets weaker, the radius of the plasma increases slightly. The discs are set up in such a way that they collect the charge at different annuli which creates a radial profile of the plasma. This allows us to see where, inside the chamber, the charge is located. By collecting the charge, the total number of ions contained can be calculated and help to determine the behavior of the plasma while inside the chamber.

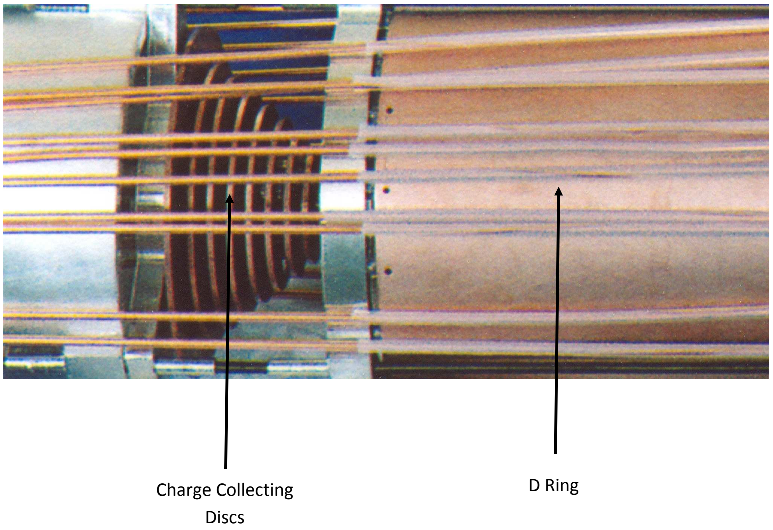

Figure 2.3 These charge collecting disks are connected to the integrator amplifiers. These help determine the number of ions captured.

2.2 Hardware Controls

2.2.1 Power Supplies

During the experiment, we are using several power supplies to control the strength of our magnetic fields and ring potentials used to confine the plasma. For our main magnetic coil, we will be able to produce a magnetic field with strength up to 0.43 T. There are two correction coils that will smooth the axial magnetic field inside of the trap. There are also two coils that are used to correct for the magnetic field of the earth and for any misalignments of the components. Each of these coils is driven by a separate power supply that is computer controlled to specify the current. The last power supply will be used produce the potential for the electrostatic confinement rings.

2.2.2 Controls

We control the parameters of the main magnet power supply through an RS-232 interface. The remaining power supplies are controlled using commands over a IEEE-488 (GPIB) bus. A National Instruments PCI-6110 multifunction data acquisition board (DAQ) board provides 8 digital I/O lines that are used for some of the experiment control. This board is not fast enough to control the sequencing of the ring voltages and other control lines so we are using a Xilinx Spartan 3-E Starter Kit board that has been programmed to provide the proper sequencing. This board uses a 50 MHz clock giving us 20 ns resolution in the timing. A Kinetic Systems 3072 CAMAC module provides a 48-bit output register that is used to program the desired timing in the Spartan 3-E FPGA controller. Communication with the CAMAC module is also done through the IEEE-488 bus.

Chapter 3

Controlling Sequence

Primary control of the experiment is provided through a LabVIEW program. This provides the overall sequencing of the experiment and the sequencing of diagnostic data.

3.1 Setup Parameters

Once the program is running, the first thing that the user will do is to set the proper parameters for the power supplies, the timing values, and the acquisition parameters. These will be used in performing the experiment.

3.1.1 Power Supply values

There are six different power supplies being used that are user controlled from the computer. Their default values are saved in a file (Default Power.txt) and are loaded at the start up of the program (see Appendix B). For the main coil, we are using a ESS Power Supply. This will be set at 250 A at up to 60 V. It will operate in constant current mode. The two correction coils (horizontal and vertical) are used to cancel the magnetic field of the earth and correct for any misalignment of the components. The horizontal correction is powered by an Agilent 0-20 V/7.5 A power supply and the vertical correction is powered by an Agilent 0-8 V/16 A power supply. These two supplies operate in constant current mode. Two coils (east and west) are being used to smooth the magnetic field inside of the containment chamber. These are powered by Hewlett-Packard 0-60 V/0-50 A power supplies. Again, these operate in constant current mode. The final power supply is used to power the rings (ring power). This is a Agilent 0-20 V/7.5 A power supply. This will operate on constant voltage mode. For the ring power, there needs to be more voltage than this supply can give and so it is connected to an amplifier with a gain of 30. This makes it possible to get the needed 150 V out. In addition to the increased voltage, the amplifier also has the switching capabilities to control the FA, FB, FC, and D rings. By controlling the switching, a plasma can be captured and contained.

3.1.2 Timing values

There are several timing values used in the experiment. Default values have been tested, saved in a file (Default Timer.txt), and are loaded at the beginning of the experiment. However there may be values that need to be changed. Catch delay (Catch Delay) is the time we wait to put voltage on the FA ring after the source has been triggered. This captures the plasma between the FA and FC rings. There is minimal time delay between raising the FA ring and lowering the voltage on the FC ring. The fill c delay (Fill C Delay) sets the time to wait after the FC ring drops for the FB ring to go high. Shift delay (Shift Delay) is the time waited after the FB ring goes high for the FC ring go high, forcing the plasma to the middle chamber. These first three values create the timing for the catch-stack sequence. The fill integrator clear delay (Fill Int Clr Delay) is the wait time from when the FB ring control signal goes low to turn on high voltage to when the integrator on the C ring gets cleared. The time is chosen so the integrators are cleared just before the voltage on FB starts to rise. By doing this, we can read the induced charge on the C ring created by the plasma, which has a positive charge, traveling through it. The integrator hold delay (Int Hold Delay) is the time the integrators wait from when the FC ring goes high to when it holds the value from the catch-stack sequence.

The dump integrator clear delay (Dump Int Clr Delay) is the wait time between clearing the integrators and dropping the D ring. Again, clearing the integrators removes the charge buildup on the discs so the charge collected comes only from the plasma. The dump wait (Dump Wait) is the time delay between dropping the D ring and holding the values on the integrators.

The read delay (Read Delay) sets the time between either changing the channel or holding the values and reading the values from the integrators. The read happens on the falling side of the signal. The write clock delay (Write Clock Delay) determines the time between reading the value from one channel to changing to another channel. For the dump, there are nine different channels that will be scrolled through and the values written. For the catch-stack, only one channel is read.

The source interval (Source Interval) is not being used at this time, but may be if there is an effective way to trigger the source from the computer. The sample interval (Sample Interval) is the time between FT-ICR/MS samples.

In calculating the timing values, we need to include the delay it takes the high voltage switching to happen. For example, when the FC ring switches from high voltage to low voltage, there is a 144 μs delay before that change begins and a total of 282μs until it is finished. For a complete list of these delay, see Appendix D.

3.1.3 Acquisition values

There are a few acquisition parameters that the user will also be able to control. The first is how many pulses from the source will be captured. This is determined by how much density is wanted inside the trap. Once the plasma is in the trap, the user can determine how often the FT-ICR/MS takes measurements. The duration of these measurements take will also be controlled. The user will also be able to determine the frequency of the rotating wall, which will be implemented at a later time.

3.2 Initialization

The next thing to do is initialize the power supplies and write the timing values to the Spartan 3-E Field Programmable Gate Array (FPGA). The end of chapter 2 discussed how the equipment communicates with each other. Using the GPIB, all but the main power supplies are set to the assigned voltages and currents. The main magnet power supply is set using the RS-232. The CAMAC module then writes the timing values to the FPGA, which stores them to use in the sequences when they are called.

3.3 Loading a plasma

Once the values have been initialized, it is time to capture the plasma. This is done by using the catch-stack sequence. The beginning state for the sequence is that the FA and FB ring are low and the FC ring is high. On the falling edge of the source trigger pulse, the sequence starts. The first thing will be to wait the time set by the catch delay. After that has expired, the FA ring goes high. This captures the plasma between the FA and FC rings. After waiting for the fill C delay, the FC ring will go low. Next, the shift delay time will expire and the FB ring will go high, followed by the FC ring. Fig. 3.1 shows the timing sequence of a catch-stack sequence. The number of times this sequence is performed is determined by the number of pulses. Once it has gone through the correct number of cycles, the FPGA will send a done signal the sequence will stop.

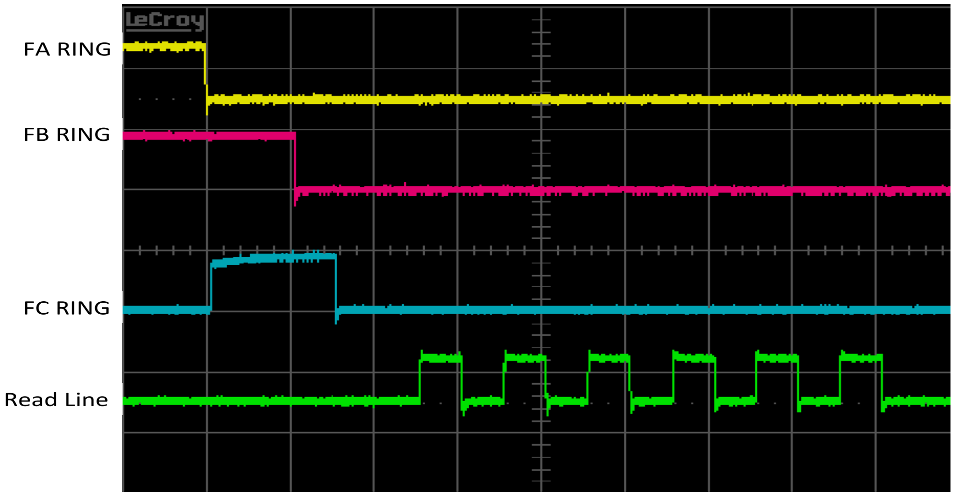

Figure 3.1 The catch-stack sequence: The lines represent, from top to bottom: FA ring, FB ring, FC ring, and the read line. When the voltage is in the upper state, the voltage is off. There is minimal time delay between the high voltage on the FA ring and the low voltage on the FC ring. The time between the low voltage on the FC ring and the high voltage on the FB ring is the Fill C Delay. The time between the high voltage on the FB ring and the high voltage on the FC ring is the Shift Delay. The read line reads in the value from the C ring on the falling edge.

In performing the catch-stack, additional measurements—pedestals—will be taken to correct for slow charge buildup. The apparent charge on the C ring will be measured before any plasma is captured. This is called the pedestal with no plasma (FillPedNoP). This will be saved in a file and used to give a reference point for other measurements. The charge will then be measured again as the plasma goes into the chamber. Once the desired amount of plasma is contained, another pedestal will be taken(FillPedWP).

3.4 FT-ICR/MS

Once the plasma is contained, we will use Fourier transform ion cyclotron resonance mass spectrometry (FT-ICR/MS) to watch the change in relative amounts of ^{7}Be and ^{7}Li. For more on the FT-ICR/MS, see [13]. This is the longest part of the experiment because we now wait and watch the decay rate of the ^{7}Be. The plasma should be able to be contained for up to a half-life of 53 days, and the FT-ICR/MS will take data until enough is acquired to accurately measure the half-life.

3.5 Emptying the chamber

After the plasma has been held for a sufficient time, the dump sequence will begin. Similar to the catch-stack sequence, we will begin by taking a pedestal with the plasma (DumpPedWP). Since there are nine rings, each of which is connected to an integrator, there will be nine values retrieved. After the pedestal is taken, the integrators will be cleared as the plasma is allowed to leave the trap. The plasma will be collected on the rings, and the values will be held as they are read. These values are saved in a file, and another pedestal is taken with out plasma (DumpPedNoP). These two pedestals will be used to correct for any charge gained on the integrators while waiting for Int Hold Delay. Fig. 3.2 shows the timing for the dump sequence.

3.6 File names

In order to keep the data organized, we will be using a time stamp to name everything. When the experiment first starts up, a folder is created using the time and date. All

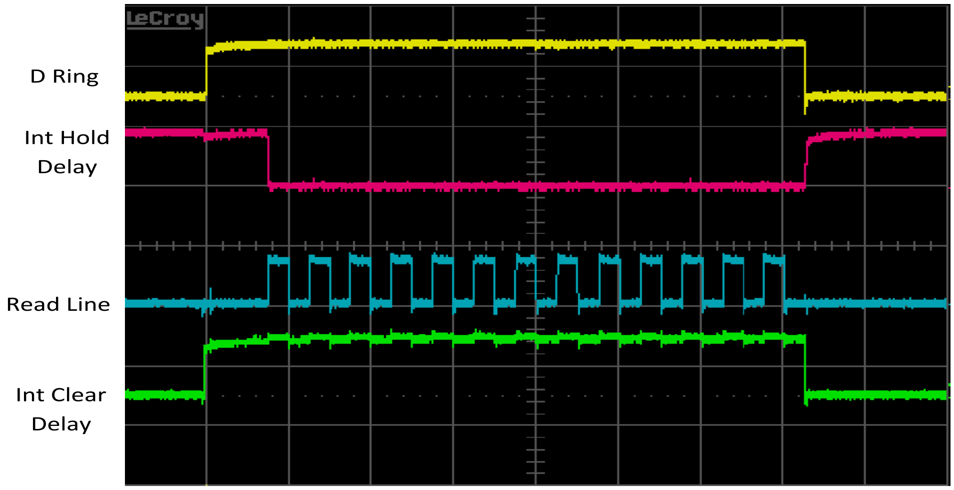

Figure 3.2 Dump sequence: The top line is the control line for the dump ring. It loses voltage at the jump up. The second line is the integrator hold line. When this goes down, it holds the values that have been read on the discs. The third is the read line, and on the falling edge, one of the integrators is read. The bottom is the integrator clear line. This discharges the discs so the charge collected is only from the plasma.

data will be saved in this folder. The data that we get from the experiment will also have a time stamp, but to differentiate from the other files they have an additional suffix. When all of the values are initialized, they are then written to a file with the time stamp and a suffix of parameter. The values from the catch-stack sequence will have a stacking suffix. The FT-ICR/MS will have several files, each with a time stamp and the suffix of fticr. Since we will be taking measurements at 5MHz, these files will be larger than the others, so each iteration of the FT-ICR/MS will be is own file. The dump sequence has the additional suffix of dumping. All these files are saved as .dat files (see Appendix C).

3.7 PCI-6110 control lines

Different lines are used to perform specific tasks. The start line is used to tell the FPGA when to start a specified sequence. The different sequences are numbered, and by writing in the number of sequence to be executed, the start line will signal the FPGA to start it. The done line signal comes from the FPGA and indicates the sequence is complete. The read line is used to read in values from the integrators. For the catch-stack sequence, there are six pulses from the read line. The program needs two samples to work, and the PCI-6110 needs an additional two samples. Another two were put in as an extra precaution. In the dump sequence, nine samples are needed, one for each ring. Two samples were added for the PCI-6110 to work and, again, two more for added protection. There is also a reset line which stops and clears the FPGA of any sequence being. It does not, however, reset any of the timing values that have been written to the FPGA.

Chapter 4

Testing and Results

4.1 Power

By using the LabVIEW program, we have verified that values for the power supplies can be written and initialized. We have also verified that the default values are loaded into the power supplies. We are able to write new values to the file and then write the new values to the supplies. These values appear on the power supplies, which permits ease in adjusting them. We are able to control the power supplies.

4.2 Timing

The timing values have also been tested and shown to work. Referring back to Fig.3.1 and Fig.3.2, we see that the timing sequences are working as expected. When we change a values, the appropriate delay correctly shifts the signal received by the oscilloscope. All of the timing values have been tested in this way. We used the catch-stack and dump sequences in testing these changes. The pedestals use the exact same code as the catch-stack and dump sequences, so we know that the values also change for those as well.

4.3 Capturing a plasma

After verifying that we were able to set, initialize, and change the values of the power and timing, we attempted to capture a plasma. We found that after the MeVVA was triggered, enough electronic noise was created to stop the sequence. We will not be able to capture a plasma until this electronic noise has been removed.

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Appendix A

Names and purposes the used VIs in the programming

Acquisition Time–this sets the duration of an FT-ICR/MS sample.

Calling–This is what runs the whole program. Run this one first.

Capturing–this does both pedestals and the catch-stack sequence

Catch and Stack–this catches a pulse from the source and stacks it in the main chamber

Catch–this just catches a pulse from the source

Dump–this dumps the plasma from the main chamber

DumpPedNoP–measures the charge on the integrators with no plasma inside

DumpPedWP–measures the charge on the integrators with a plasma inside

Dumping–this does both dumping pedestals and the dump sequence

Editing Panel–here is where the editing of the parameters takes place

File Names–this is where the naming of the folder and files takes place

FillPedNoP–measures the charge on the C ring with no plasma inside

FillPedWP–measures the charge on the C ring with a plasma inside

Frequency–this determines the frequency of the rotating wall

Get and Hold–this gets the plasma and just holds it in the main chamber

Ion Global–this is where the parameters for the whole experiments are set up and defined

Load–this loads the sequence into the FPGA

Number of Pulses–sets the number of pulses from the source

Open Signal– part of the FT-ICR/MS

Power Global–this is where the power supply values are written to global values

Power Supply–this is where the power supply values are changes

Read from DAQ and Write file–part of the FT-ICR/MS

Reset–stops and clears sequence in FPGA

Stack–moves a plasma from between the FA and FC rings into the main chamber

Start–starts the sequence written to the FPGA

Testing–used to catch a plasma and immediately dump it

Timer Global–writes the timing values

Timers–sets the timing values

ToggleDigitalLine–changes the sequencing numbers

Write Catch Delay–write Catch Delay to FPGA

Write Clock Delay–writes Clock Delay to FPGA

Write Dump Integrator Clear Delay–writes Dump Int Clr Delay to FPGA

Wrtie Dump Wait–writes Dump Wait to FPGA

Write Fill C Delay–write Fill C Delay to FPGA

Write Fill Integrator Clear Delay–write Fill Int Clr Delay to FPGA

Write Integrator Hold Delay–writes Int Hold Delay to FPGA

Write Read Delay–write Read Delay to FPGA

Write Sample Delay–N/A

Write Shift Delay–writes Shift Delay to FPGA

Write Source Interval–N/A

Write to DAQ Card–part of the FT-ICR/MS

WriteAddressRegister–writes sequence number to FPGA

fticr–runs the FT-ICR/MS

initialize–writes the timing values and power supply values to the appropriate places

write to data–write initial data to correct file

Appendix B

Default Values

Power Supplies

Ring Power = 5 V

West Correction = 0 A

East Correction = 0 A

Horizontal = 15.8 A

Vertical = 15.8 A

Main Magnet = 250 A

Timing Values

Catch Delay = 7.7e-6 s

Fill C Delay = 80.0e-6 s

Shift Delay = 140.0e-6 s

Fill Int Clr Delay = 64.0e-6 s

Dump Int Clr Delay = 5.0e-6 s

Int Hold Delay = 123.0e-6 s

Read Delay = 6.0e-6 s

Write Clock Delay = 6.0e-6 s

Source Interval = no default value

Sample Interval = no default value

Frequency

Rotating Wall = not yet available

Appendix C

File Naming

The files for the data are names in the following ways:

/home/ion/data/trials/Y:m:d:h:m:s/Y:m:d:h:m:s:[modifier].dat

Y = year = yyyy

m = month = mm

d = day = dd

h = hour = hh (24 hr)

m = minute = mm

s = second = ss

the first date and time is when the test was started

the second date and time is when the data was taken

[modifier]

for the dump sequence = Dumping.dat

for the catch-stack = Stacking.dat

for the FT-ICR/MS = fticr.dat

for the starting parameters = Parameters.dat

Default Value Files

/home/ion/data/Default Timer.txt

/home/ion/data/Default Power.txt

/home/ion/data/Default Frequency.txt

Appendix D

Delays

For the FA ring

- 150 V → -1 V takes 4.2 μs
- -1 V → 150 V takes 724 μs

For the FB ring

- 0 V → 150 V
  - start rise 208 μs
  - rise done 240 μs
- 150 V → 0 V
  - start drop 148 μs
  - drop done 298 μs

For the FC ring

- 0 V → 150 V
  - start rise 215 μs
  - rise done 260 μs
- 150 v → 0 V
  - start drop 144 μs
  - drop done 282 μs