Improving Ion Injection into a Cylindrical Malmberg-Penning Trap

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ABSTRACT

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In this research, ionized boron carbide is used as the current choice ionic plasma. A powerful electric pulse must be generated to ionize and inject the sample into a cylindrical Malmberg-Penning trap, the goal being to approach the Brillouin density limit. Utilizing inductors and capacitors, a pulse forming network (PFN) was designed and made to provide a longer pulse to generate sufficient plasma. After further development of the PFN and insertion into the trap, the anticipated electrical behavior did not match the actual resulting waveform. The system and the PFN are being studied and will be modified to obtain correct functionality.

Keywords: plasma, Brillouin limit, boron carbide, metal vapor vacuum arc, pulse forming network

Contents

Chapter 1

Introduction

1.1 Importance of Plasma

The majority of all the known matter in the universe is in a state of plasma. On the earth most matter is in the first three states: solid, liquid, and gas. Plasma, which is commonly referred to as the 4th state of matter, still influences much of what happens on earth. When an electrical charge builds up it can cause an arc between two points, which is a kind of plasma. Lightning, which is an example of plasma, has a significant effect in nature. Another common way that earth is affected by plasma is the ionosphere. An additional manifestation of plasma on earth is in the northern lights. Amongst all these things, it is clear why this is an important topic of research.

Researching how plasma behaves is also important in order to understand stars. Research in this area can help us understand how our sun behaves and potentially may allow us to use its energy to our benefit as well as protect us from possible harm from its radiation. Solar physics research tries to explain solar radiation, solar flares, and fusion reactions [1]. Modeling these effects can be important to understanding why and how these things happen. Measurements of our sun's radiation coupled with knowledge of the elements, particularly beryllium and boron, help us understand what is happening inside it. The Standard Solar Model (SSM) utilizes calculations and measurements in ^7Be decay and reactions of ^7Be and ^8B in order to model the behavior of our sun [2].

Plasmas have lots of application in technology. Since electric arcs are plasmas, welders make use of plasmas to connect two pieces of metal. There are many other applications of plasma like plasma cutters, neon lights, florescent light bulbs, plasma televisions, and other industrial applications that utilize plasma.

There is a large focus in plasma research to utilize fusion reactions as a form of energy. The difficult part is getting more energy out than the energy it takes to get the fusion reaction to occur. Obviously it is possible since this is exactly what stars do. The challenge is then trying to contain such a system while maintaining the plasma in order to break even in the used energy. One international collaboration trying to do exactly this is the International Tokamak Experimental Reactor (I.T.E.R.) [3].

1.2 Non-Neutral plasmas

A neutral plasma has an overall neutral charge. More specifically, it is quasi-neutral containing both positively and negatively charged particles, which are usually electrons and ions normally of a single species. These plasmas may contain charge imbalances locally, but the overall plasma will have equal positive and negative charge.

A non-neutral plasma is obtained when charge is removed from a neutral plasma or when only one type of charge is inserted. They usually only contain one species of charge and are thus charged and non-neutral. An interesting result of having a single species of ions is that they can theoretically be confined for an infinite time, because non-neutral plasmas diffuse slower than a neutral plasma because of conservation of canonical angular momentum [4]. Fourier Transform

Ion Cyclotron Resonance (FT-ICR) Mass Spectrometry [5] is another tool that can be easily used with non-neutral plasmas.

It is for these reasons that research of non-neutral plasmas have gained popularity. It allows for creation and study of particles that would otherwise react with particles of other species. One example of this is the study of positron plasmas at the University of California, San Diego where they work on containing positron particles and must get them in a low energy state [6]. Another great example is the study of antiprotons and antihydrogen at CERN [7, 8]. In most cases, a non-neutral plasma, whatever the species of charge, is easily trapped and contained for a significant period using a Malmberg-Penning trap.

1.2.1 Malmberg-Penning Trap

A Penning trap is a typical method to confine ions. It uses a strong magnetic field to trap the ions radially, and it uses a quadrupole electric field to contain the ions axially; the ions are contained near the center saddle point of the electric field. It is better for the plates that produce the electric field to be shaped hyperbolically. A Malmberg-Penning trap is a version of the Penning trap that uses rings along the axis instead of the hyperbolic plates (Figure 1.1). The charged rings, a metal tube with separated sections, are then used inside to create an electric field that traps the ions in an electrostatic well thereby trapping them along the axis. This configuration also has a smaller but similar quadrupole electric field. However, by using rings instead, it allows for more convenient working and testing environments with greater access to the plasma to take measurements of different effects. These charged rings also separate the ions from the electrons if both are present, which prevents the recombination of the ions. This is a feature of Penning traps, which makes it easy to trap a single species of charge.

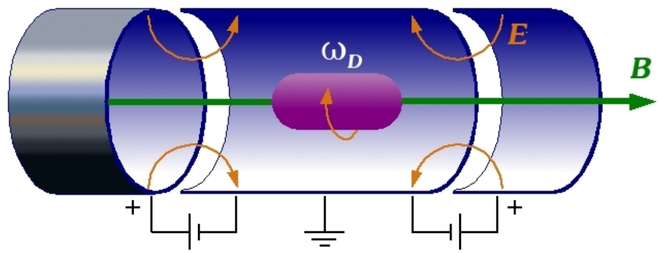


Figure 1.1 General design of a Malmberg-Penning trap with a strong axial magnetic field to provide radial confinement and rings to create an electrostatic potential well for axial confinement.

1.2.2 Brillouin Limit

One goal of the ion project at BYU is to study the Bernstein modes of oscillations of different plasmas. This experimental setup is in a unique position to study the $m = 0$ mode that is axially symmetric. This is described and explained in greater detail in William Hall's Senior Thesis [9]. This has importance in this thesis, because in order to study such modes it requires that the density of the plasma has reached or is a significant fraction of the Brillouin limit. Two other goals of the ion project at BYU are to study the ^7Be decay when in the ionized plasma state in order to improve the SSM as well as to study the effects of a dense plasma on an FT-ICR analysis. Both these goals also require a very dense plasma close to the Brillouin limit. This Brillouin limit comes from the electrostatic repulsive force of the charge itself of the plasma. The following derivation is taken from William Hall's thesis. Taking an infinite cylindrical plasma with a constant velocity, the forces in the radial direction can be balanced:

$$\sum F = m\frac{v^2}{r}$$
$$\Rightarrow qE_r - qv_\theta B_z = -m\frac{v_\theta^2}{r}. \tag{1.1}$$

Solving Poisson's equation in cylindrical coordinates, and remembering we have a plasma with uniform azimuthal velocity, we get:

$$\begin{aligned}\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial V}{\partial r}\right) &= \frac{nq}{\varepsilon_0}\\ \Rightarrow \frac{nqr^2}{2\varepsilon_0} &= r\frac{\partial V}{\partial r}\\ \Rightarrow \frac{nqr}{2\varepsilon_0} &= \frac{\partial V}{\partial r} = -E_r. \end{aligned}\tag{1.2}$$

Utilizing equation 1.2 in equation 1.1, we obtain:

$$\begin{aligned}\frac{nq^2 r}{2\varepsilon_0} - qv_\theta B_z &= -m\frac{v_\theta^2}{r}\\ \Rightarrow \omega_p^2\frac{r}{2} &= -\frac{v_\theta^2}{r} + \frac{qv_\theta B_z}{m}\\ \Rightarrow 0 &= \omega^2 - \omega\omega_c + \omega_p^2 \end{aligned}\tag{1.3}$$

where $\omega_p^2 = \frac{ne^2}{m\varepsilon_0}$ is the plasma frequency and $\omega_c^2 = \frac{e^2B^2}{m^2}$ is the cyclotron frequency. The solution to this quadratic is:

$$\omega = \frac{\omega_c}{2}\left(1 \pm \sqrt{1 - 2\frac{\omega_p^2}{\omega_c^2}}\right). \tag{1.4}$$

To have a real solution, the value under the radical must be greater than or equal to zero, implying:

$$2\omega_p^2 \leq \omega_c^2.$$

Remembering the definition of ω_p, we can solve for the maximum possible number density, which yields:

$$n \leq \frac{B^2\varepsilon_0}{2m}. \tag{1.5}$$

This equation constitutes the Brillouin density limit for a non-neutral plasma. This derivation has assumed an infinite plasma with a constant density, but it has been shown that the Britllouin limit still holds in cases of non-uniform density and non-infinite plasmas [10].

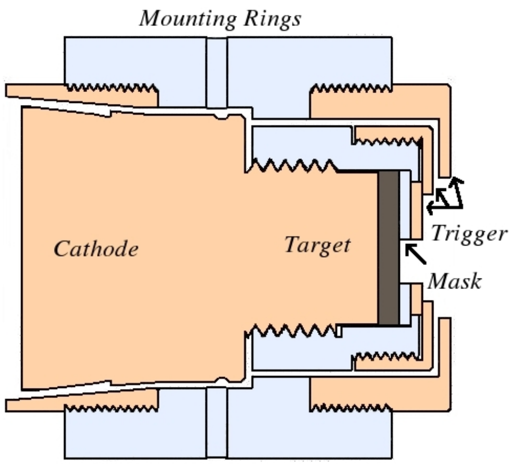
Chapter 2

Experimental Setup

The ion experiment at BYU utilizes a Malmberg-Penning trap. The system as a whole consists of a vacuum chamber that is pumped using an ion pump, a metal vapor vacuum arc (MeVVA) source combined with a high voltage bias and extractor grid, a quadrupole magnet to remove and filter contaminating ions from the plasma, and a metal tube separated into individually insulated rings that are connected to separate adjustable voltage sources or used for diagnostics. A large solenoid is then used outside the rings to contain the plasma radially. A rotating wall is included to increase confinement time, which is similar to the one used by the UCSD ion experiment [11]. The opposing end of the chamber has destructive charge collecting rings. A non-destructive FT-ICR helps assess what particles are currently trapped if there are any charges trapped at all. There is more detail on the system in its entirety in David Olson's Masters Thesis [12].

2.1 MeVVA Source

The MeVVA source consists of the electrical pulse from a step-up transformer, a pulse forming network (PFN) that will be discussed later, and the source material housing, with the target or source material.



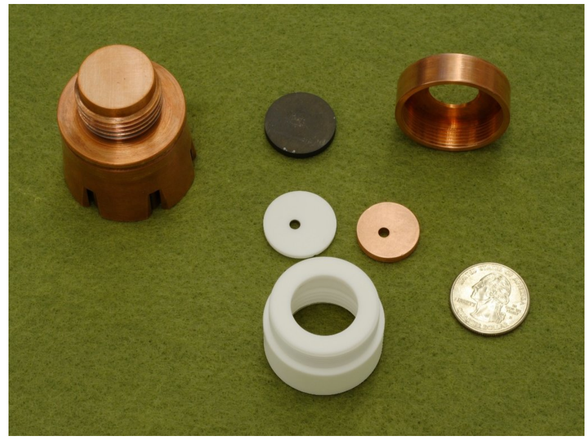


Figure 2.1 Schematic and image of MeVVA source with the target source colored black. The threaded components hold it together. The white components insulate the cathode from the trigger.

2.1.1 Pulse Transformer

The pulse transformer was designed with a 0.2 μF high voltage capacitor to store the energy needed, which is charged to about 2300 V. The transformer itself has 2:12 windings with an air core, where the primary windings connect to the capacitor and the secondary windings connect to the source housing (Appendix A). The discharge through the transformer primarily is initiated through an air spark gap. When the energy is released through the transformer it creates a trigger arc in the source housing.

2.1.2 Source Housing

The source is located in a removable cathode assembly (Figure 2.1). The removable components are the cathode base, the target or source, the target mask, the trigger disk, and the locking ring and cap to hold it all together. The material that the base, trigger disk, and cap are made of is oxygen-free high-conductivity (OFHC) copper.

The assembly is cylindrical in order to allow the pieces to thread together and be held in place. The base, locking ring, and cap are all threaded. The locking ring is made out of Macor™. The locking ring screws onto the base, which holds the source and mask together. The cap then screws onto the locking ring in order to hold the trigger disk in place. The base is then in electrical contact with the source, and the cap is electrically connected to the trigger disk.

The mounting system is located and remains inside the vacuum; it has the cathode ring, mounting rings, and the trigger ring. The mounting rings insulate the other two rings that way when the cathode assembly is inserted it makes a connection and leaves the cathode and trigger rings separate. This is on a mounting bracket held in place by screws.

Currently the source is a boron carbide wafer. When this is used the arc will initially start between the trigger and cathode which will be provided by the pulse transformer described previously. The arc vaporizes and ionizes some of the source. Placed just beyond the cathode assembly are the extractor and ground screens. The extractor is used to control the electric field in that region in order to extract the ions from the plasma and allow them to pass through. The extractor reduces the number of electrons that pass through by controlling the electric potential that they have to overcome. The ground screen then helps give an electrical reference to the rest of the system to reduce interference. This also brings the charges that pass through back to their normal trajectory.

2.2 Trap

The trap itself consists of a solenoid, an array of axial rings, and charge collectors (CC). The solenoid contains the plasma radially with a maximum magnetic field of 0.45 Tesla. The rings are made of OFHC copper and have a consistent 4 cm radius. Glass beads, stainless steel rods, and copper end brackets hold the rings together. There are 3 fill rings and 5 confinement rings giving a total of 8 rings (Figure 2.2).

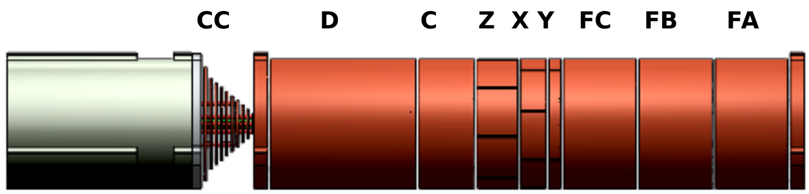


Figure 2.2 Confinement rings that contain the plasma (right) and the charge collecting (CC) rings (left). FA, FB, and FC are the fill rings. The D ring is the dump ring that releases trapped plasma to the CC. The rings Z, X, Y, and C are used for diagnostics and plasma measurements.

2.2.1 Rings

The rings labeled Fill A (FA), Fill B (FB), and Fill C (FC) are the 3 fill rings. They each have a length of 5 cm and are ordered from the closet ring from the source, FA, to the farthest fill ring from the source, which is FC. The fill rings are used to contain the plasma from escaping towards the source during the trapping and confinement process. The rings after the fill rings continuing from closest to source to farthest are labeled for historic reasons rings Y, X, Z, C, and D. Ring Y is 1 cm long and is split into 4 sections, which is available for future diagnostics. The X ring is 2 cm long and is separated into 8 sections for use with the rotating wall. Next is ring Z that is 3 cm long and is used with the FT-ICR diagnostics. The C ring is not segmented at all and is 4 cm long. It is used to observe the change in charge within the ring in order to study oscillations. The dump (D) ring is used to prevent the ions from escaping to the CC at the left of the figure. The D ring is 10 cm long.

Each ring can be monitored or controlled through coaxial cables with BNC connectors. These connections are how the rotating wall is controlled, how diagnostics are made with the FT-ICR, and how the capture sequence is run controlling the voltages of rings. The experiment is controlled using a network of timing instruments, which are controlled by a computer. The high precision timing is controlled by a Xilonx Spartan 3E FPGA.

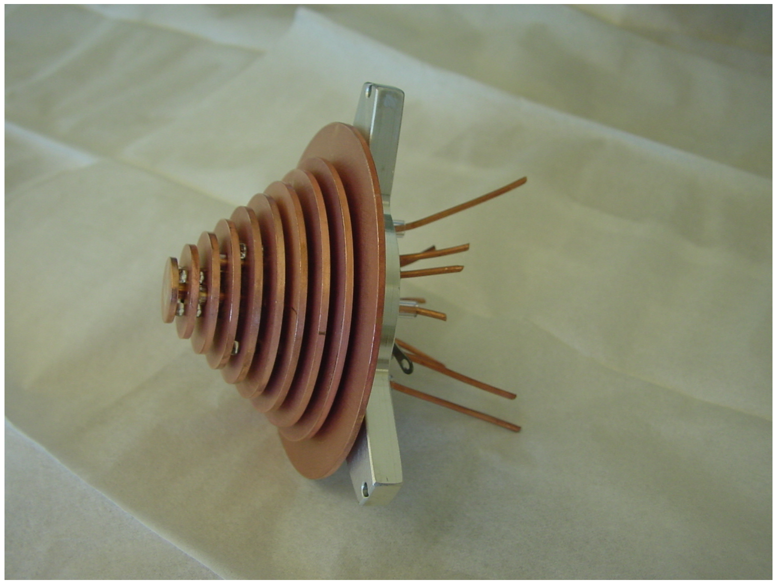


Figure 2.3 Charge collection disks that have different radii to make a map of the charges received from lowering the D ring to dump the plasma.

2.2.2 Charge Collectors

Figure 2.3 shows the CC up close. It is made of 10 concentric copper plates at the end of all the rings. They all have different radii as shown. Each of them are connected by BNC cables to an active integrator. Each ring is connected to its own integrator, which have each been calibrated, in order to tell how much charge hit it at that ring's radius. After a simple calculation, it gives the total number of charges that it received. Thus when combining all the rings, a map can be made of approximate radii of all the different charges and the density of those charges. This can be used for diagnostics to knotw when to start the trapping sequence as well as to tell approximately how many ions there are that made it through the magnetic field and can be trapped and contained. The rings can also be used after having confined the plasma and then dropping the D ring in order to tell where and how much charge was trapped. Thus we can see the radial profile of the plasma when we dump. Simple MATLAB fitting techniques then can find the central charge density.

2.2.3 Electron Dump

This process is the method that removes electrons from the Malmberg-Penning trap. Our trap naturally keeps positive and negative charges separate; the ions are contained under the rings with lower voltages in a potential well and the electrons may be trapped in their own potential well under the end rings held at a higher voltage. When we dump to see the charges that were contained, all the negative charge held under the end rings are included in the measurement of the CC. Thus, in order to remove the electrons all the rings are brought down in voltage together until there is no potential well continuing to contain the electrons under the end rings and they are allowed to leave, while the ions are still held in an electrostatic well in the center. All the rings are then brought back up to their previous voltages, and there should not be any electrons remaining.

Chapter 3

Testing

3.1 Plasma Density

All of our goals require that the plasma is close to the Brillouin limit. Our current boron carbide plasma is made of about 80% boron and 20% carbon. Then according to the Brillouin limit in equation 1.4, we will need a density around $5.13 \times 10^{13}\, m^{-3}$ as calculated by William Hall. With this described setup, the system was tested to see how much charge could be trapped. William Hall described the results in more detail. To trap the desired ions, a significant increase of positive charge was needed.

3.2 What is a PFN?

To produce the required positive charge, a significant increase in the arc time is required. A PFN is made with multiple capacitors and inductors. General Atomics' website has some great examples of these types of networks [13]. Our PFN is what General Atomics lists as a type B network where one end of all the capacitors are connected to ground and the inductors are placed between the capacitors on the other terminal of the capacitors (Figure 3.1). The end of the last inductor, L3,

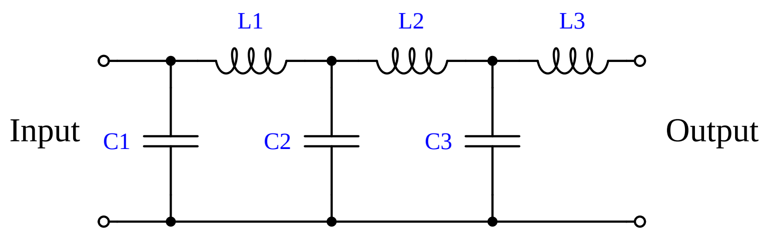


Figure 3.1 PFN layout with 3 inductors and 3 capacitors

is the output connection of the PFN. This PFN setup starts discharging the moment the circuit completes but takes a moment for its current to build. Once the first capacitor's charge only has a portion left, the second capacitor is then discharging thus allowing a continual flow of current for a period of time before reversing the flow.

The network can be modeled using Kirchhoff's laws

$$rI_1 + \frac{Q_1}{C_1} - \frac{Q_2}{C_2} + L_1\frac{dI_1}{dt} = 0 \tag{3.1}$$

$$rI_2 + \frac{Q_2}{C_2} - \frac{Q_3}{C_3} + L_2\frac{dI_2}{dt} = 0 \tag{3.2}$$

$$rI_3 + RI_3 - \frac{Q_3}{C_3} + L_3\frac{dI_3}{dt} = 0 \tag{3.3}$$

where r is the internal resistance of each inductor, R is the load resistance, Q_n are the charges, C_n are the capacitances, L_n are the inductances, and I_n are the currents through each inductor. The current I_3 is the output of the circuit to the load.

3.3 Designing and Using a PFN

William Hall was the student to originally design the PFN. It was designed to provide a burst of steady current for 100 μs for a resistance of about 100 Ω, which was a guess of the approximate resistance of the plasma during the arc since it is currently unknown. The original design used three equal capacitors and three equal inductors as in Figure 3.1. Each capacitor was 0.1 μF and each inductor was 2.3 mH. The model and the measured response when tested were almost

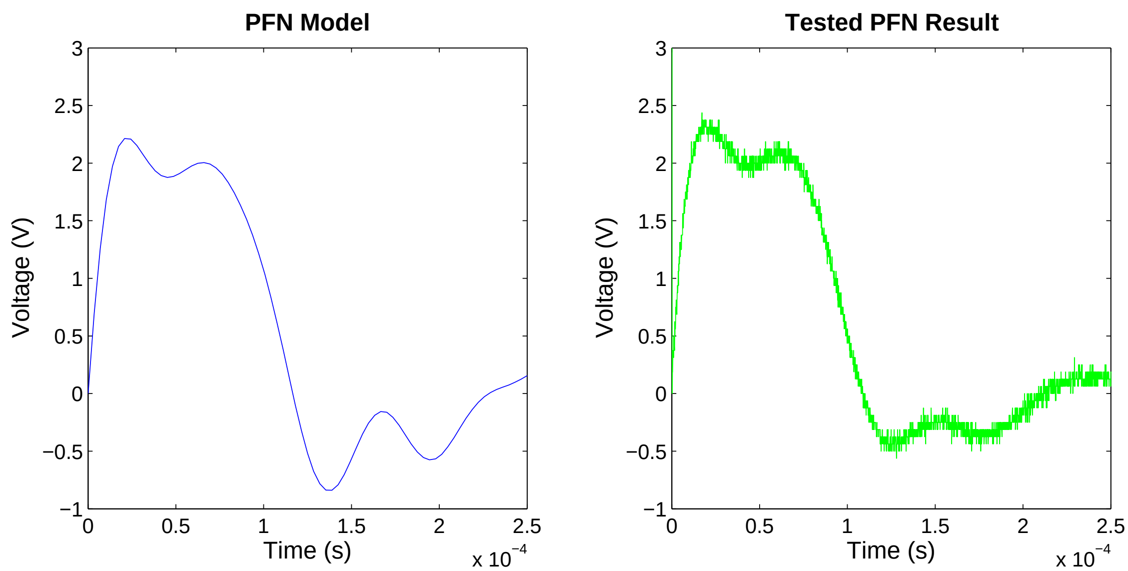


Figure 3.2 The PFN model (left) and tested result (right). The resulting pulse was around 100 μs. The implementation of the PFN matches the model.

identical (Figure 3.2). Once the PFN was attached to the cathode and extractor, it was tested again to confirm correct behavior to ensure no other electrical components interfered with its design. In Figure 3.3 it is visible that it still behaves appropriately with a small addition of current on the front end, which is actually desirable so that the arc has current being provided the whole time.

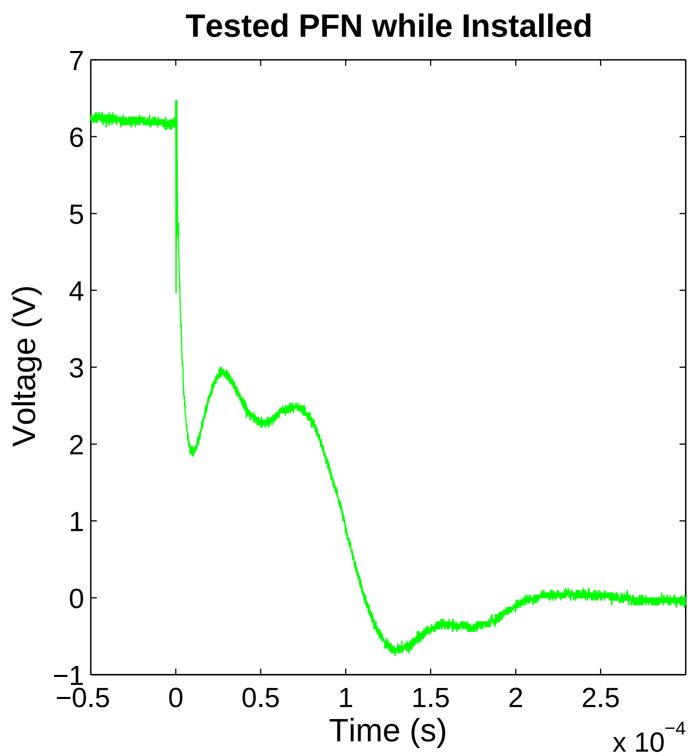


Figure 3.3 The PFN was tested while installed into the system without triggering the transformer. It had additional current at the front and then followed the desired model. The extra current on the front end is desirable to maintain the arc until the PFN provides additional current.

Chapter 4

Results

4.1 Behavior of Arcs

The system was tested again to detect how much positive charge was possibly available to be trapped. It was uncertain if the addition of the PFN improves the results. The voltage of the cathode did not behave as expected (Figure 4.1) compared to the model (Figure 3.2). After significant testing, the reason for this specific behavior was still unknown. We decided to test and redesign it while it was installed since the behavior of the PFN was significantly different.

4.2 Adjusting the PFN

Regarding the small oscillation in Figure 4.1, we considered that it might have to do with internal oscillations in the PFN. The models for the PFN, which only model the key components of the circuit due to its complexity (Appendix A), could not generate an oscillation with such a high frequency. We decided to keep the PFN the same and only remove a single capacitor (Figure 4.2) in order to hopefully not have as much internal energy loss. We found that the positive charge received by the CC was increased for those attempts (Figure 4.3). Due to the few number of

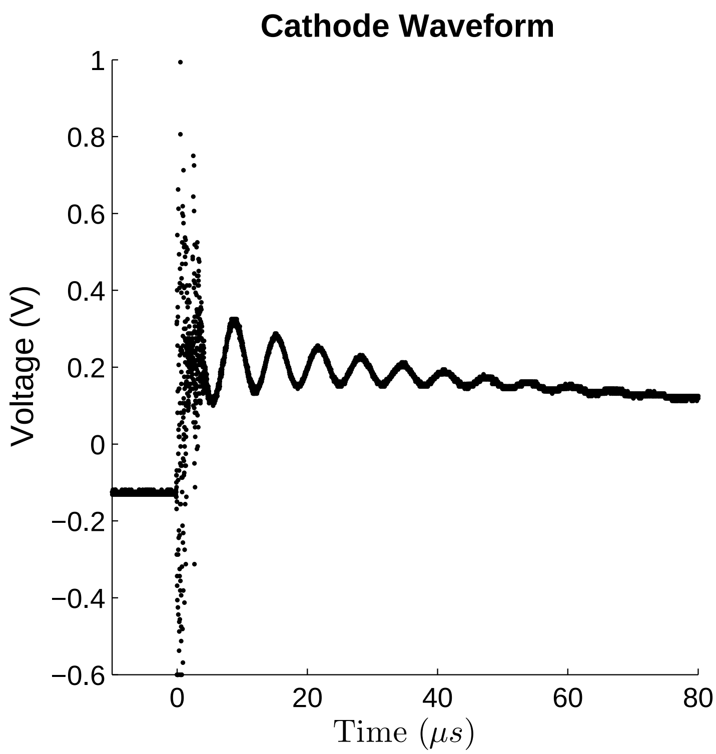


Figure 4.1 Voltage at the cathode. The cathode was connected to the output of the PFN and should have been provided a voltage similar to the model. However, this was different from the model in many ways. One difference is in the small oscillation. It came from the presence of the PFN in combination with the initial pulse from the transformer.

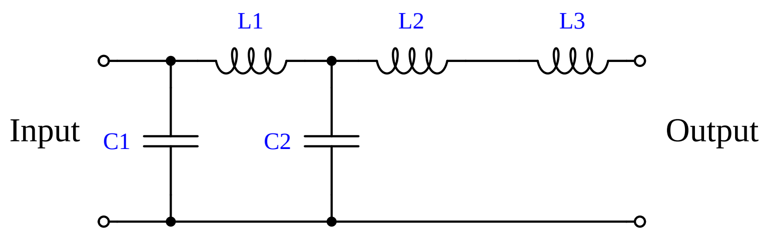


Figure 4.2 The PFN layout with the removal of the third capacitor

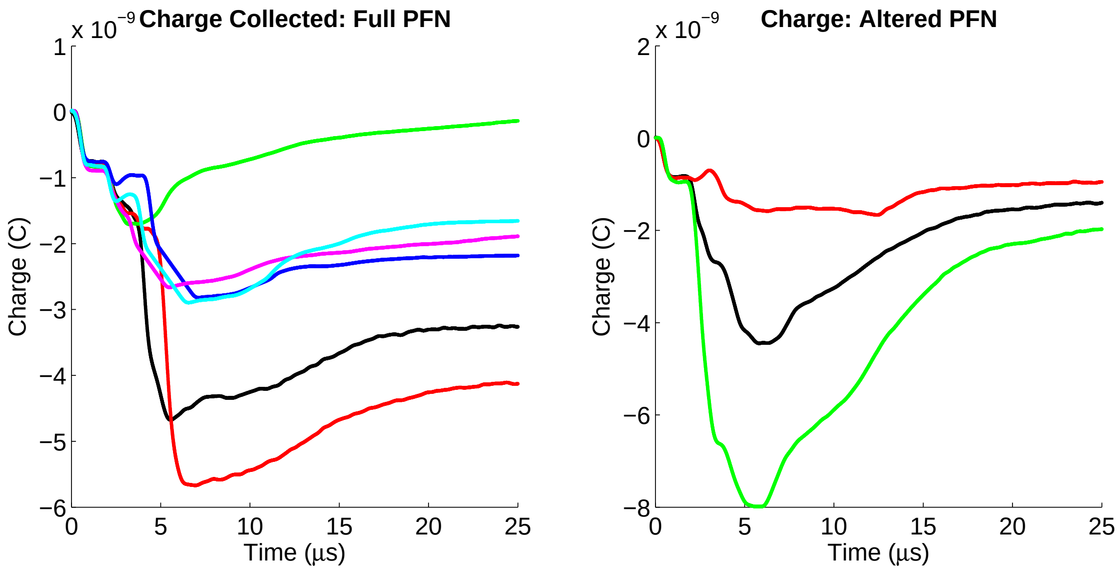


Figure 4.3 Charge received by the CC with 3 capacitors in the PFN (left) and 2 capacitors (right). The average positive charge received before changing the PFN was 1.11 nC and after the change was 3.09 nC. Thus it appeared that the removal of one capacitor may have improved the output of ions.

attempts at that time, that result was uncertain. The reason for that result was not clear.

4.3 Trapping Plasma

After adjusting the PFN, the process of trapping plasma was tested. Since the PFN was inserted and changed the potentials inside the chamber, we had to recalibrate the timing of our confinement rings as described in William Hall's thesis. The confinement rings were activated and the were

	Percent success rate	Average trapped charges detected
3 capacitors	57%	6.749×10^6
2 capacitors	40%	6.474×10^6

Table 4.1 Success in trapping charge of the 2 configurations of the PFN. It appears that the change in the PFN may have had a negative effect on the process of trapping plasma.

connected to the integrators to measure the charge after confining the plasma. It was tested with the PFN containing 3 capacitors and then tested again only containing 2 capacitors. The results were not promising. Looking at Table 4.1, it can be seen that the success rate decreases and the amount of contained positive charge also decreases. We believe this to possibly be a flaw in the code controlling the confinement rings and potentially the process of dumping the electrons. This is currently being investigated.

4.4 Discussion and Conclusion

The adjusted PFN may be injecting more ions into the system; at the same time however, it is probably injecting more electrons. A possible problem may be contained in the electron dump process. We are concerned that during this process ions are possibly being lost as well or the electrons are just not being removed completely. There may have also simply been problems with the catching sequence. These sequences are controlled by the FPGA. Current investigation is underway of this component of the experiment.

It is uncertain that the inclusion of the PFN improved the injection of ions. Until diagnostics on the FPGA are done, the reason for such complications are unknown. The PFN will require further diagnostics afterwards to make sure the additional current performs as expected.

Appendix A

MeVVA Circuitry

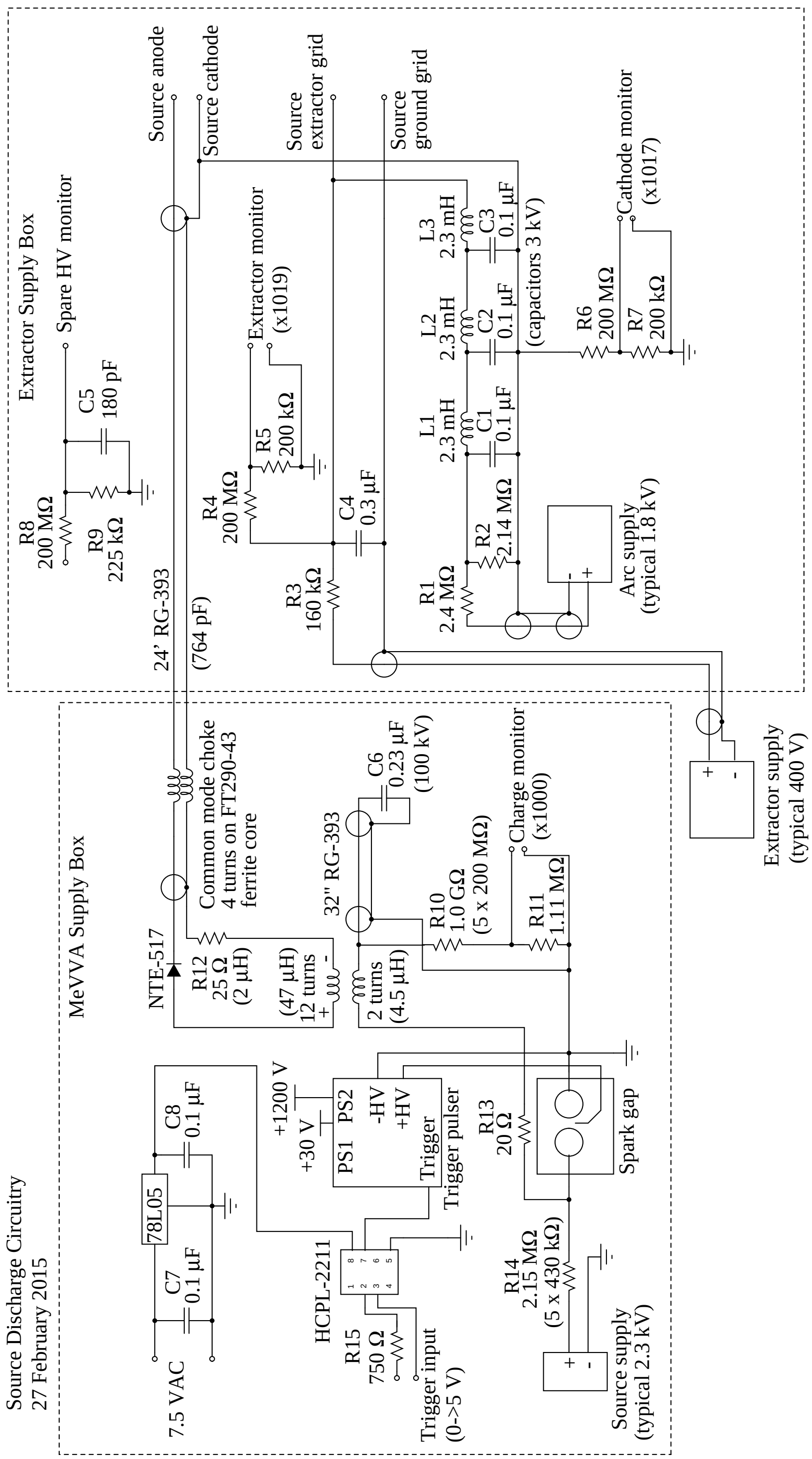


Figure A.1 Full MeVVA source discharge circuit

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