Properties of Glow Discharge Plasma Created with High Voltage at Low Pressure

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Abstract

This paper outlines the design and build of an experimental plasma chamber, plus the experiments conducted with the chamber. The goal of the chamber is to make plasma physics more accessible and to be able to observe and do research on a state of matter not otherwise found on Earth. The chamber is used to demonstrate magnetic confinement of plasma and the effect of sharp electrode geometries on electric fields. The chamber can be used to create up to 2 Amp arcs or to create sustained glowing plasma throughout the volume of the chamber. It consists of a vacuum system and a high voltage circuit. The vacuum system performs well, reaching less than 300kPa absolute pressure.

Introduction

The aim of this project is to build a vacuum chamber that causes electrical breakdown of the gas inside and produces glowing plasma, allowing plasma experiments to be done. This concept is largely borrowed from a chamber made by GarageLab on YouTube [1]. People come into contact with solids, liquids, and gases constantly in everyday life. This project will allow students to observe and gain knowledge of a fourth state of matter that they do not come into contact with but that is a prevalent state of matter in the universe.

The word "plasma" comes from the Greek *πλασμα*, which means "anything formed or molded." [2] Plasma was first named in 1927 by chemist Irving Langmuir while he was studying electrical discharge through gaseous mercury. He realized that the ionized gas seemed to carry electrons from one electrode to another just like blood plasma carries red blood cells and white blood cells through the body, so he proposed to give the name "plasma" to electrically discharging gases. [3] Plasma is now widely considered to be one of the four fundamental states of matter along with solids, liquids, and gases. Each fundamental state of matter is distinguished from the others by the level of association between molecular, atomic, or subatomic particles in the substance. Solids are melted into liquids by disassociation of molecules and breaking of strong intermolecular bonds; liquids are evaporated or vaporized into gases by further disassociation of molecules and breaking of weaker intermolecular forces; finally, gas is ionized into plasma by the disassociation of the atomic nucleus from its orbiting electrons. This can be done by heating — the sun and some flames contain plasma made in this way [4] — but it can also be done by applying a high voltage across a gas, causing electrical breakdown of the gas and forcing it, a previously insulating substance, to carry current. The most notable aspect of plasma is that it is made up of separated charged particles, meaning that a plasma can carry current, and it both creates and is affected by electric and magnetic fields [4].

Plasma is commonly made on Earth by electric arcs; lightning, shocks from static electricity, Tesla coils, and welding all create examples of electric arc plasma. However, there is a plasma that is more controlled and easily interacted with: glow discharge plasma. Glowing plasma is created at higher voltage and lower current than arc plasma, and is easier to sustain and observe [5]. Glow discharge plasma is researched and used by humans for the purposes of thermonuclear fusion and electric rocket propulsion [4]. Fig. 1 and Fig. 2 below show two examples of plasma creation in the Stanford Plasma Physics Lab for research purposes. One is used for research on thermonuclear fusion, and the other is used for research on ion rocket propulsion. Both utilize high voltages and low pressure environments, similar to the plasma chamber outlined in this paper [6]. This plasma chamber will also provide a testbed for experimentation and plasma research. How is plasma affected by magnetic fields? How does the geometry of the chamber's electrodes change the formation of plasma? These are the questions that this chamber is designed to answer, among others.

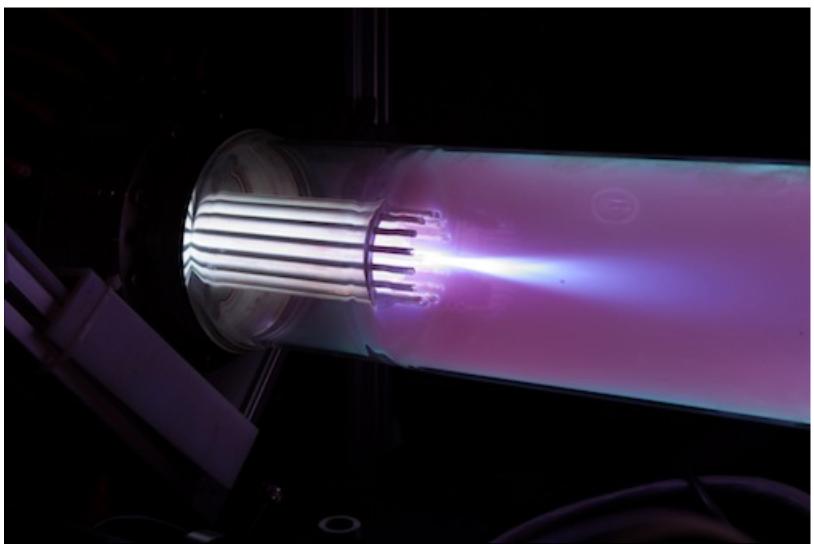


Figure 1 - "The Stanford CHENG Gun (SCG) is a pulsed, direct electrode plasma source that produces a high velocity, high energy density plasma jet in vacuum." (Stanford Plasma Physics)

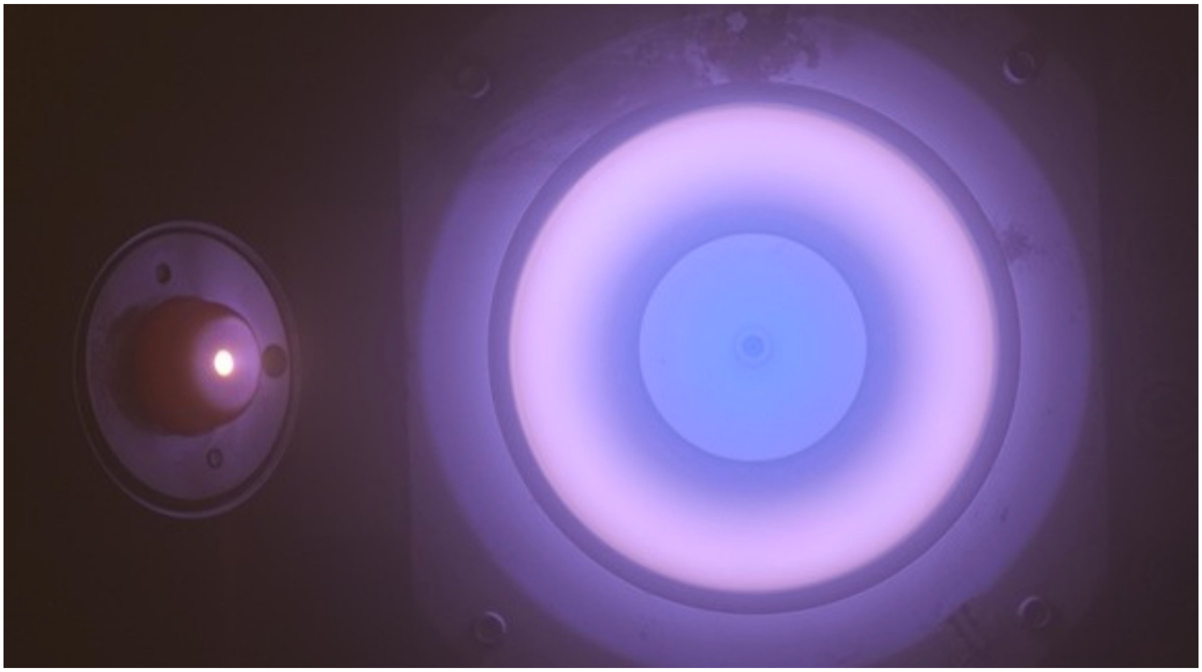


Figure 2 - An ion plasma thruster being tested in the Stanford Plasma Physics Lab (Stanford Plasma Physics)

Design

To be able to make plasma under conditions that are possible to sustain in the lab, the plasma chamber must enclose a low pressure environment and must be able to create a large voltage difference across the low pressure gas inside the chamber. Therefore, as seen in Fig. 5 and 6, the container is made of strong materials, is sealed with neoprene rubber, and has a connection point for a vacuum line to a vacuum pump. Thick aluminum disks are used as walls on both ends of the cylindrical chamber, and they also serve as electrodes to achieve the necessary high voltage difference across the whole chamber. Aluminum is used because it is non-ferromagnetic, so it will not react in unexpected ways to the large electric and magnetic fields created by the chamber. The walls are made of thick acrylic for strength, which is necessary due to the high vacuum environment inside the chamber, and high-strength solid neoprene is used to seal the chamber because it has low compressibility while still retaining malleability for sealing. The vacuum pump attachment point/hole is threaded to allow the connection of a vacuum gauge and a vacuum line running to a vacuum pump. Teflon tape is used to seal the connections between all threaded components. The specific vacuum pump used for this chamber, a Welch DuoSeal 1400 series pump, is a rotary vane vacuum pump. As seen in Fig. 3, rotary vane pumps rotate a vane inside the pump's working chamber that closes off one side of the chamber from the other. As the vane rotates, gas moves into the chamber through the intake, and is then trapped and compressed by the vane as the vane rotates between intake and outtake. By the time that the vane moves by the outtake, the gas is compressed above atmospheric pressure, and it flows out of the outtake in the direction of lower pressure. Vacuum oil provides lubrication, sealing, and temperature control for this type of pump [7].

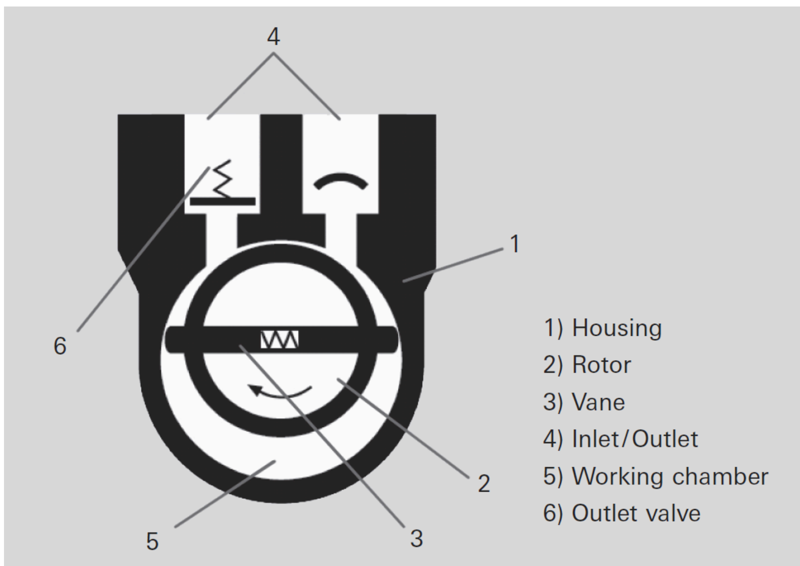


Figure 3 - Diagram of pumping apparatus in a rotary vane pump (Pfeiffer Vacuum)

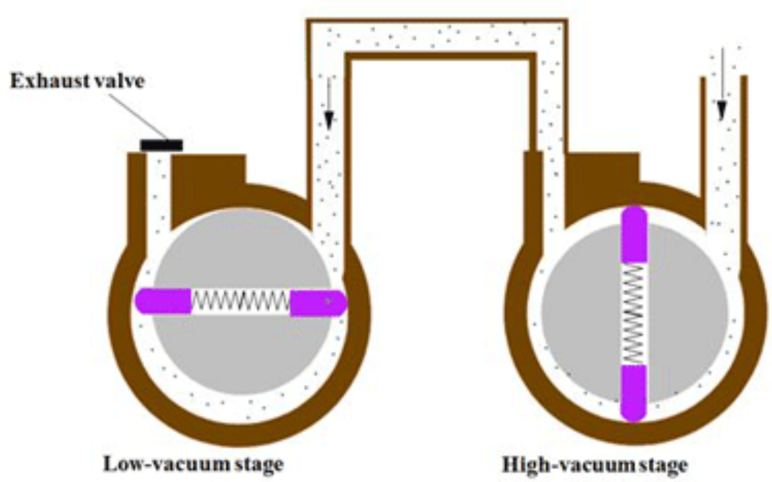


Figure 4 - Diagram of two stage rotary vane pump (Edwards Vacuum via Vac Aero International)

Welch DuoSeal 1400 pumps are also two stage vacuum pumps. This plasma chamber design uses a two stage vacuum pump due to its ability to achieve a more complete vacuum than a one stage vacuum pump. This is possible because a two stage pump includes a "high vacuum stage" and a "low vacuum stage". As seen in Fig. 4, the low vacuum stage pumps the exhaust from the high vacuum stage out through the pump exhaust, causing the high vacuum stage exhaust to be lower than atmospheric pressure and therefore allowing the high vacuum stage to operate at lower pressures than a single stage. This means that lower pressures can be achieved in the vacuum chamber.

This plasma chamber is designed to maximize usable volume for experimentation and observation while minimizing voltage required across the aluminum electrodes and providing the ability to create and maintain a vacuum of desired quality. By using the aluminum electrodes as the walls at either end of the chamber, the entire volume of the chamber may be used to create plasma, and the plasma may be easily observed from 360º around the chamber through the clear plastic walls. The modular design of the chamber is be helpful for conducting experiments and tweaking the chamber as needed. The aluminum electrodes, rubber seal, and plastic cylinder can all be removed to allow modification or adding components for experiments (magnet, etc.).

The chamber design also includes important safety and reliability features. A maker case assembled from laser cut acrylic serves as a base for the chamber and encloses the vacuum piping. Screws are screwed through the top surface of the acrylic box into holes in the bottom aluminum disk, keeping the chamber from falling over. A 3D printed plastic cap that fits over the top aluminum disk and a 3D printed plastic ring that fits around the bottom aluminum disk and can be bolted to the acrylic base cover the high voltage electrodes, keeping viewers safe from potentially deadly electric shock. See Fig. 7 for CAD drawing.

The initial planned circuit design for this chamber consisted of a 540V 35mA DC power supply connected directly to the chamber electrodes, as seen in Fig. 8. This circuit worked well for prototyping and for plasma creation at a smaller electrode spacing than that of the chamber's electrodes. Electrode spacing was decreased in this chamber using an aluminum bar and aluminum foil. However, the goal of the final chamber was to utilize its entire volume. Therefore, a higher voltage source would be needed to cause electrical breakdown of the air across the nearly 8" gap between the chamber's electrodes. The final design uses a 25-1 turn ratio transformer that takes 120V AC input from the wall and outputs 3kV 30mA AC, which is then rectified to a DC signal by a full wave bridge rectifier, which consists of 4 diodes that allow positive current to flow to one end of the load and negative current to flow to the other end of the load during the entire AC cycle. Therefore, a bridge rectifier rectifies the entire AC waveform. The rectified DC signal is then smoothed by a capacitor bank of 9 ETR MPM 2kV capacitors — 3 parallel sets of 3 in series — before running through the chamber. See Fig. 9 for the circuit diagram. This higher voltage circuit is able to create plasma throughout the chamber, fixing the problems of the prototype circuit. However, running at its maximum specifications, the transformer used in this circuit can output 105W of power, making it very dangerous if the electrodes or any live wires are touched. Therefore, safety features are included to keep users safe. The ends of the wires are crimped into screw attachments, which are fastened with screws to the electrodes under the electrode covers; an acrylic maker case encloses the rectifier and capacitor portion of the circuit, and it has a removable capacitor cover to allow for capacitor discharging; and the ends of the transformer's input wires are fastened into a wall plug, allowing for easy and safe connection to a wall outlet. These safety features result in no exposed wires during operation, but they still allow the capacitor bank to be discharged — making this a safe circuit to use.

Drawings

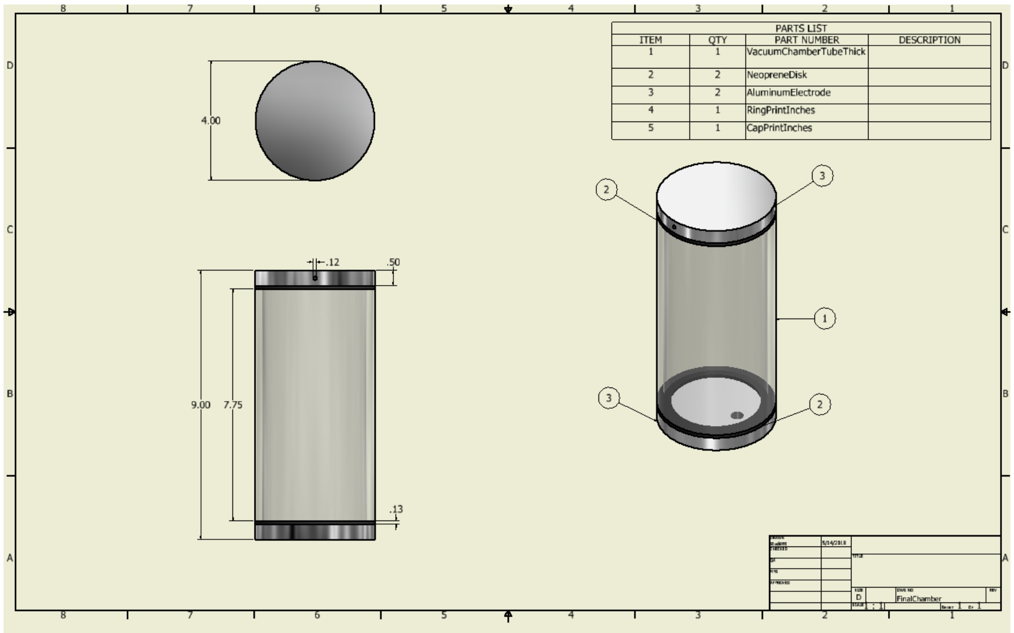


Figure 5 - CAD drawing of chamber with aluminum disks, neoprene seal, and acrylic cylinder

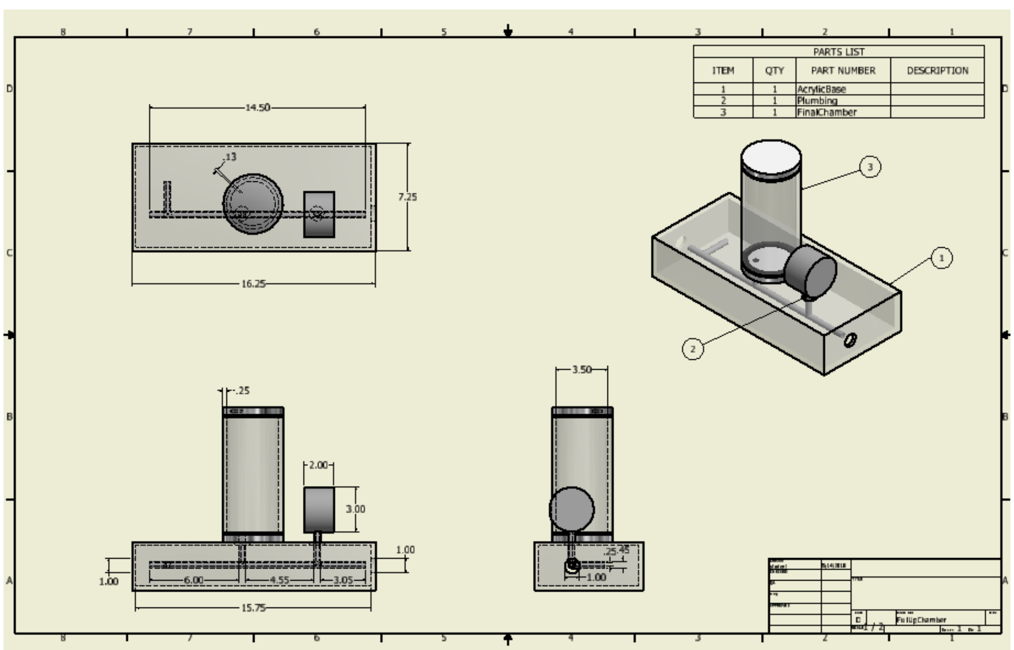


Figure 6 - CAD drawing of chamber including acrylic base and plumbing. Does not include plastic end caps (see Fig. 7).

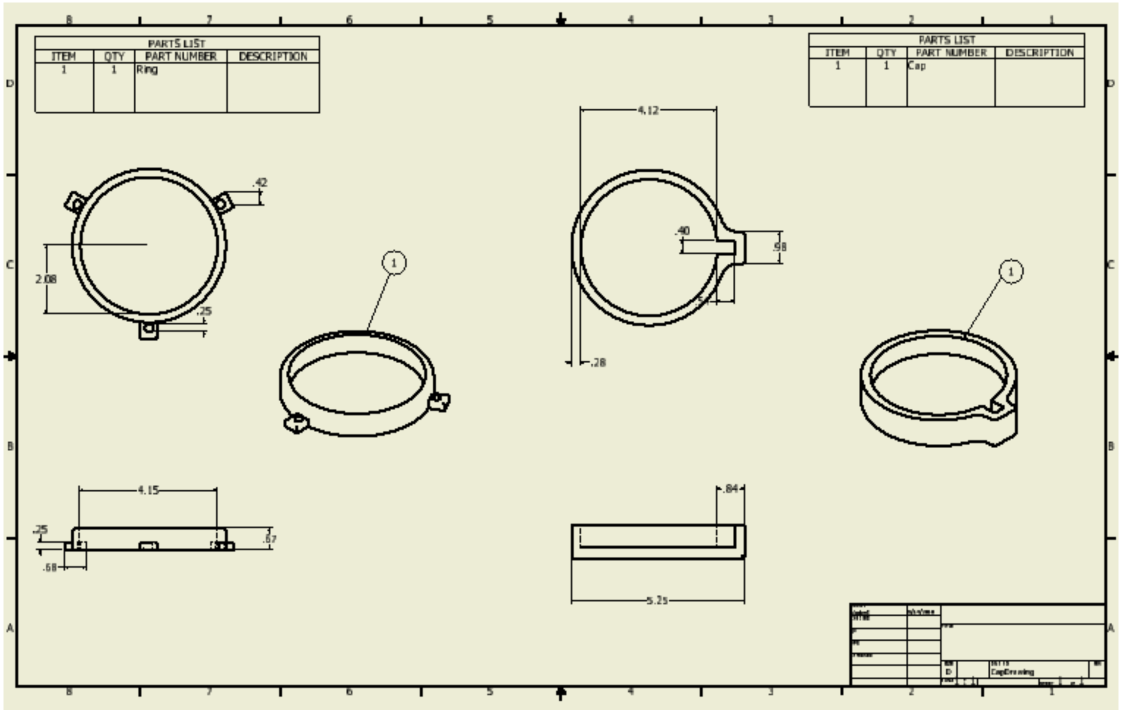


Figure 7 - CAD drawing of 3D printed protective ring for bottom electrode (left) and 3D printed protective cap for top electrode (right).

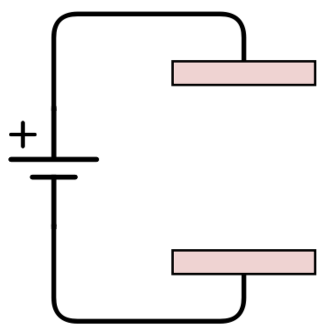


Figure 8 - Circuit diagram of DC high voltage supply and aluminum electrodes at either end of chamber (in pink). This circuit was used for prototyping before the circuit in Fig. 9 was built and implemented.

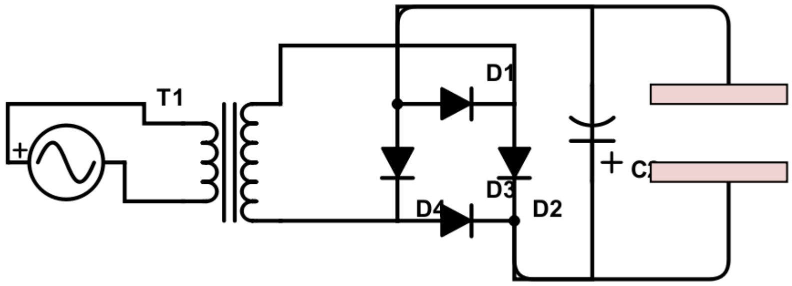


Figure 9 - Circuit diagram of line power supply running through a transformer to step up voltage, and a rectifier and capacitor to convert AC to DC. This setup was used with the final chamber because the circuit in Figure 8 did not provide enough voltage to generate plasma with the electrode spacing used for the chamber.

Theory

The mechanism of creating plasma used for this project is the application of high voltage across a gas, exceeding the breakdown voltage of the gas and causing a sustained electrical discharge through the gas. Specifically, because the plasma should ideally be visible for experiments to be easily conducted on it, this chamber is designed to create a glow discharge. Visible light is created in a glow discharge by the collisions between free electrons and ions. In a plasma, atoms are ionized, but collision events between ions and free electrons do happen. When these events occur, light is emitted in the visible spectrum with a frequency proportional to the energy difference an electron experiences when colliding with an ion [14]. Glow discharge plasma is created with lower voltage and higher current than Townsend discharge plasma, which does not emit visible radiation, and lower current and higher voltage than arc plasma, which does emit visible radiation but is extremely hard to sustain (e.g. lightning or Tesla coil) [5]. The Townsend discharge is notable for the purposes of creating glow discharge plasma because similar physics occur in both plasmas. During creation of the plasma, when an electron is ejected from the cathode in the direction of the anode, it will encounter and collide with un-ionized atoms, imparting enough energy on the atom to free its electrons and ionize it. These electrons then ionize other atoms during their movement towards the anode, producing a cascading effect that provides for the quick ionization of nearly all the gas in a chamber like the one outlined in this paper [8].

For Townsend discharge, glow discharge, and arc discharge, the breakdown voltage of the insulating gas between electrodes must be overcome for current to flow [9]. This breakdown voltage is described for a given gas as a function of pressure and electrode separation by Paschen's law

$$V_B = \frac{Bpd}{ln(Apd/ln(1/\gamma_{se}))} \qquad \text{Eq. 1}$$

where p is gas pressure, d is electrode spacing, and A and B are experimentally determined constants that are dependent on electric field and pressure, but can be considered relatively constant over a range of electric field and pressure values [10][11]. γ_{se} is called the secondary electron emission coefficient, which is a measure of the number of electrons ejected from an electrode or other surface when bombarded by a single electron in a vacuum or near vacuum [10]. This constant varies based on material and electron energy, so it is extremely variable. However, secondary electron emission coefficients are usually between some value just below 1 and a value around 4 [12]. Paschen's law may be differentiated with respect to *pd* and the derivative can be set equal to 0 in order to determine where the breakdown voltage is at a minimum (see Fig. 9 for visualization of Paschen's curve) [10].

$$(V_b)_{min} = \frac{eB \times ln(1/y_{se})}{A} \qquad \text{Eq. 2}$$

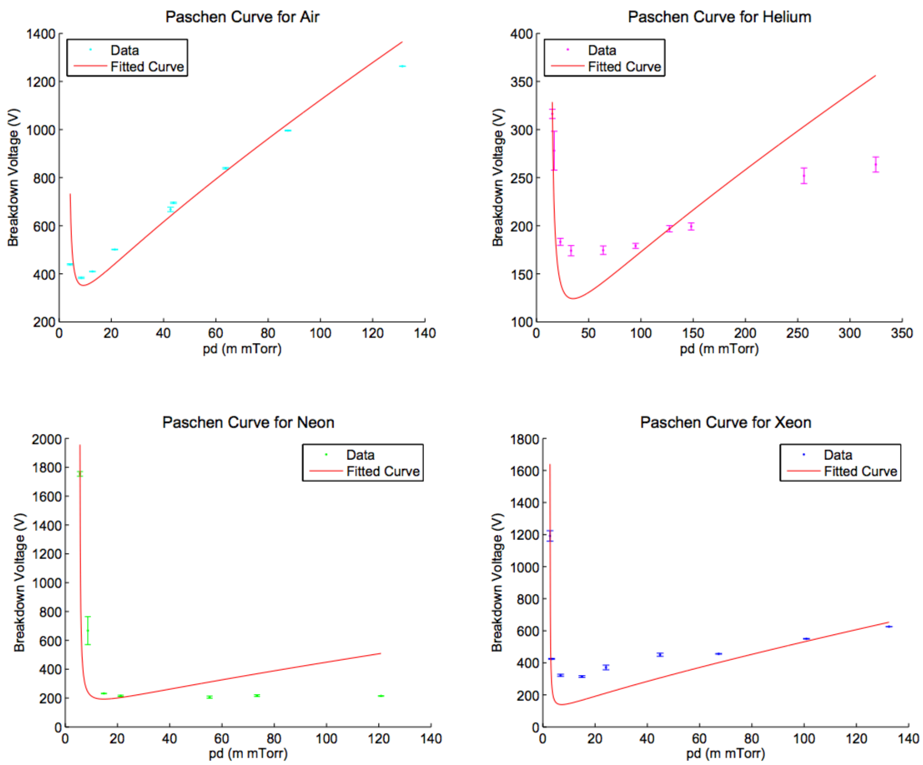


Figure 10 - Empirically determined Paschen's curves for Air, Helium, Xenon, and Neon (Paschen's Law in Air and Noble Gases, Berzak, et al.)

From the Paschen's curve for air in Figure 10, the minimum breakdown voltage is between 300V and 400V, and it is achieved at a pressure-distance product of just below 10 m mTorr, meaning that at an electrode spacing of 8 to 10 inches, a pressure below 10 Pascals may be needed in order to reach ideal conditions for breakdown. However, breakdown can still be achieved at higher voltage with a different pressure-distance product.

The experiments done as part of this project include demonstrations of magnetic confinement and differing electrode geometries. Magnetic confinement is described by the Lorentz force, which states that charged particles moving in a magnetic field will experience a force proportional to the cross product between the particle's velocity vector and the magnetic field vector

$$F = q v \times B \qquad \text{Eq. 3}$$

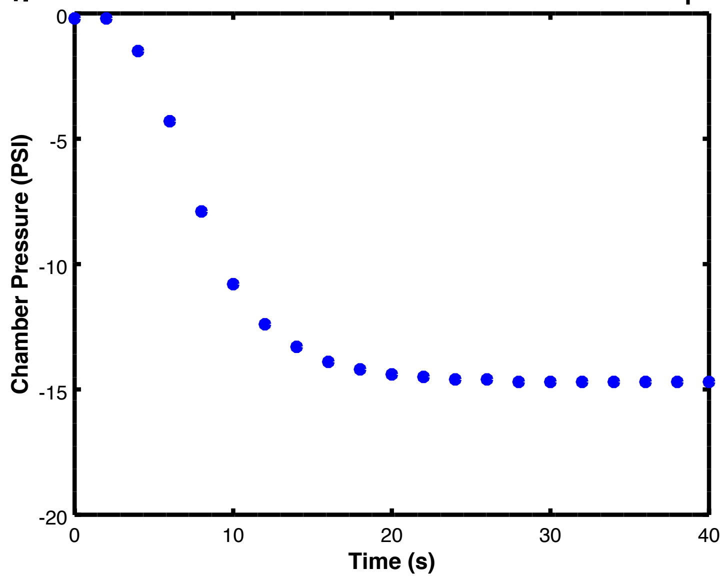
where q is the charge on the particle, v is the particle's velocity vector, and B is the magnetic field vector [13]. Due to this Lorentz force, charged particles will spiral around, and move in the direction of, magnetic field lines.

For the exploration of electrode geometries, the main goal is to determine where electrons tend to leave the chamber's cathode in the direction of the anode with varying cathode geometries. It is expected that rounded or flatter electrodes will have more uniform density of electron ejection across their surfaces, while sharper electrodes or electrodes with holes will eject electrons from their sharp edges. This is the expected result because sharper points cause the electric field strength to be higher around the electrode, creating an easier path for current flow. According to Hiraoka, et al., the breakdown pressure between two high voltage electrodes will decrease with a sharper angled electrode — at least up to an angle of 45º for TIG welding [15].

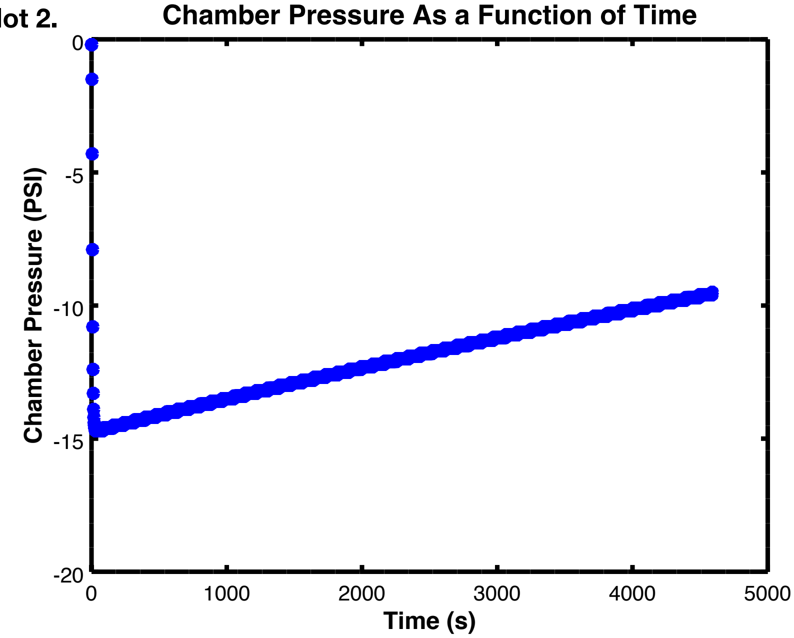
Results

Vacuum Chamber

Plot 1. **Chamber Pressure As a Function of Time While Pumping**



Plot 2. **Chamber Pressure As a Function of Time**



Plots 1 displays the data from a test of the vacuum pump's effectiveness in conjunction with the chamber. From these data, it takes the vacuum pump between 20 and 30 seconds to reach the chamber's minimum pressure. Plot 2 displays data from the same test as Plot 1, but it includes the pressure in the chamber for 1 hour, 16 minutes, and 30 seconds after the vacuum pump is shut off, the chamber is isolated from the vacuum line, and the vacuum line is bled. Clearly, leaks exist in the chamber, but only enough to introduce pressure at a rate of about 4.068 PSI/hour.

Plasma Chamber

Figure 11 - Stable glow plasma filling the chamber at around 300Pa

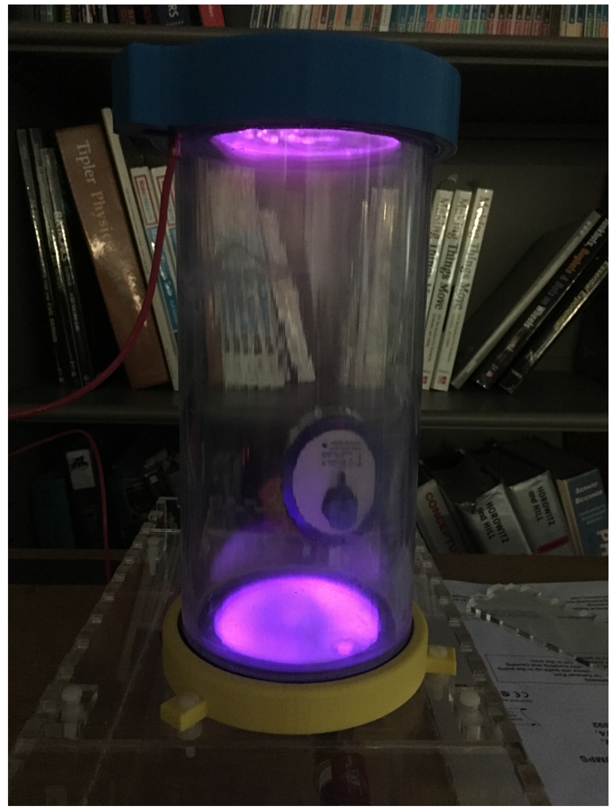


Figure 12 - Glow plasma clinging to the electrodes at extremely low pressure

Table 1 - Electronic Specifications of the Plasma Chamber

Operating Voltage Range	**Residual Voltage of Smoothing Capacitors after Shutdown**	**Maximum Arc Current**	**Glow Plasma Max Current**	**Low Pressure Current Range**
600-700V	**300V**	**Up to 2A**	**560mA**	**200-300mA**

Magnetic Confinement

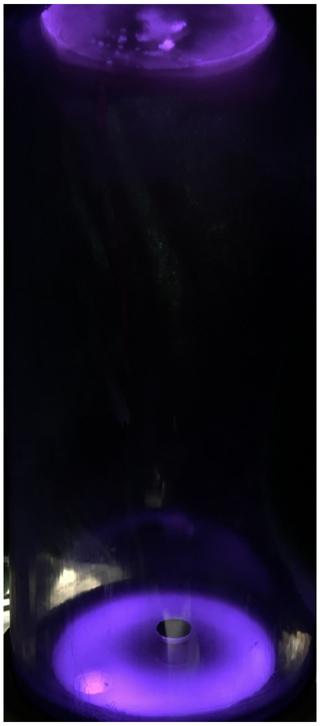


Figure 13 - Single Magnet at Low Pressure

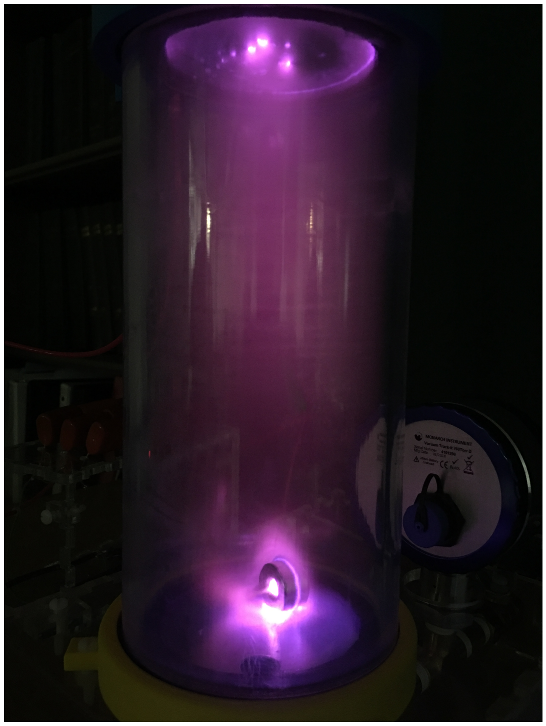


Figure 14 - Torus Magnet with Plasma Band and Jet

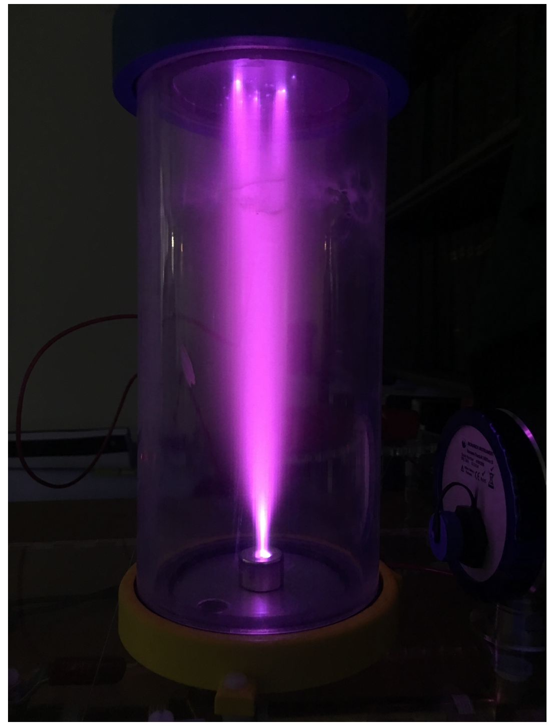


Figure 15 - Plasma Jet from Upright Torus Magnet

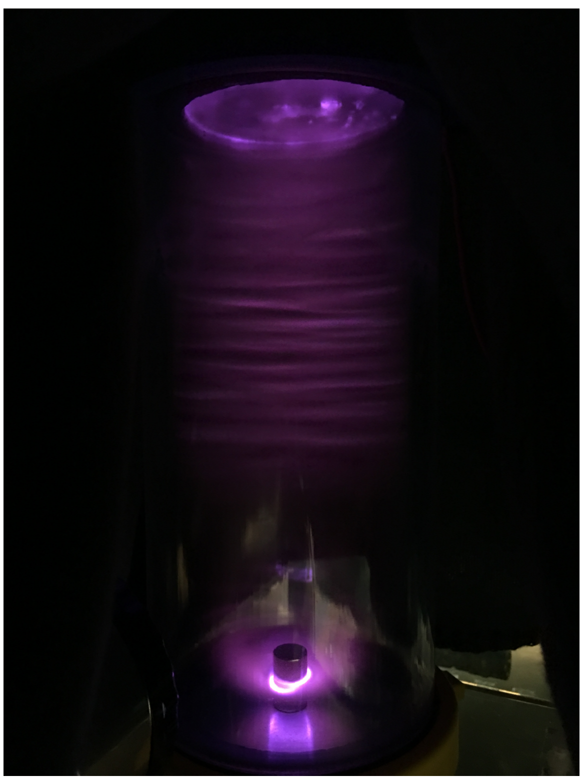


Figure 16 - Double Cylinder Magnet with Plasma Band and Wave Effect

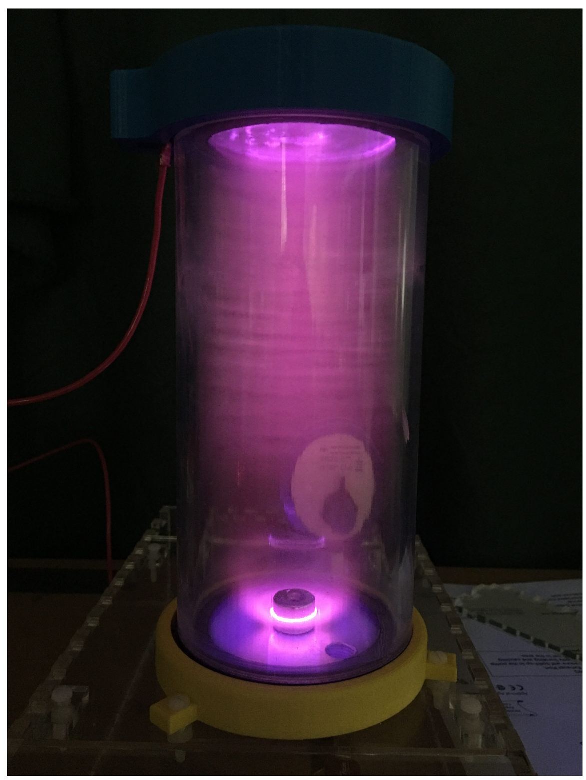


Figure 17 - Torus Magnet with Band at Lower Pressure than Fig. 15

Table 2 - Magnetic Field Values at Distances from the Torus Magnet along Its Axis

Axial Distance (cm)	**30**	**23**	**18**	**8**	**3**	**0**
Magnetic Flux Density (mT)	**0.02**	**0.03**	**0.08**	**0.79**	**8.44**	**8.68**

Table 3 - Magnetic Field Values at Radial Distances from the Torus Magnet

Radial Distance (cm)	**15**	**10**	**5**	**2**	**1**	**0**
Magnetic Flux Density (mT)	**0.03**	**0.16**	**0.96**	**5.85**	**8.7**	**8.71**

Electrode Configuration

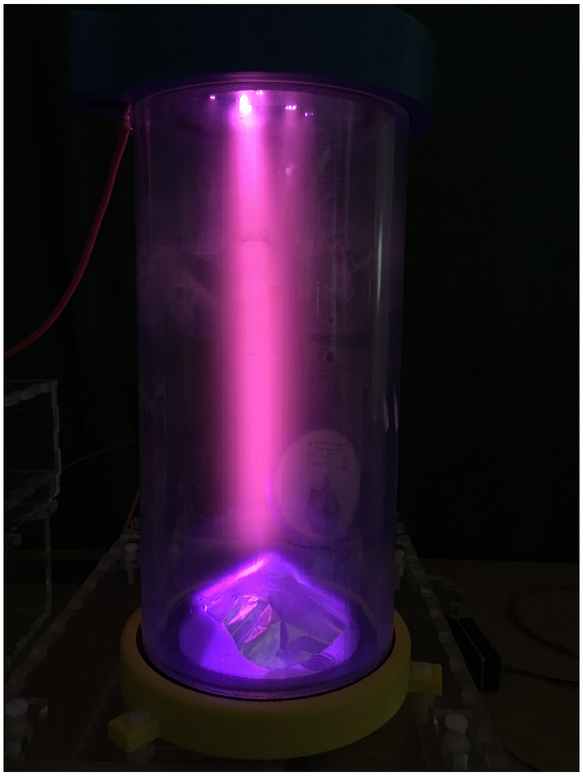


Figure 18 - Rounded Aluminum Foil Electrode

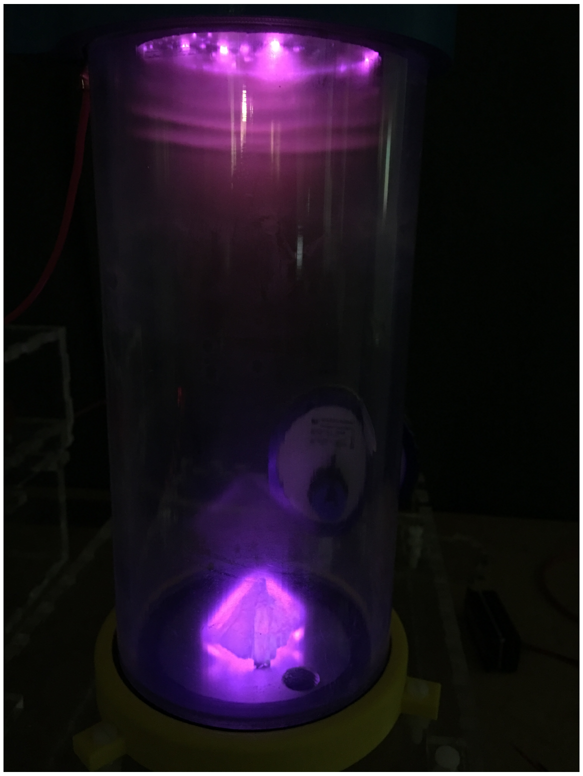


Figure 19 - Pointed Aluminum Foil Electrode at Very Low Pressure

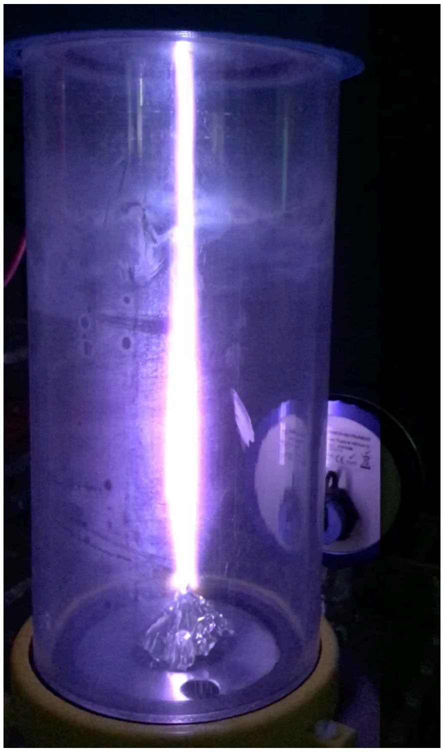


Figure 20 - Arcing at Higher Pressure To Pointed Aluminum Foil

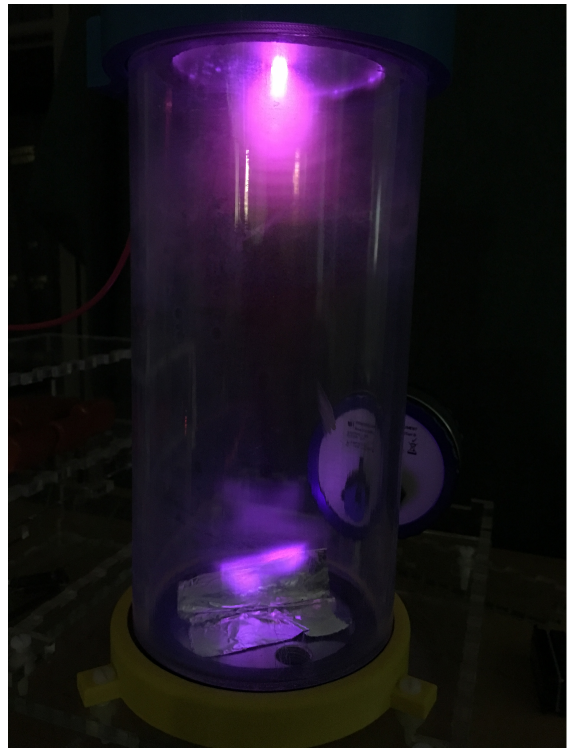


Figure 21 - Pointed Ridge Aluminum Electrode

Figure 22 - Flat Aluminum Foil Electrode with Hole

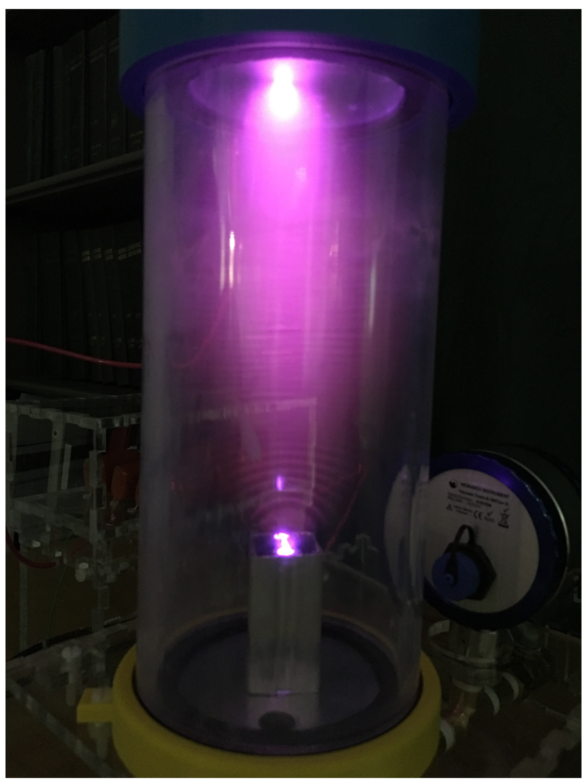


Figure 23 - Aluminum Bar Electrode with Small Central Gap

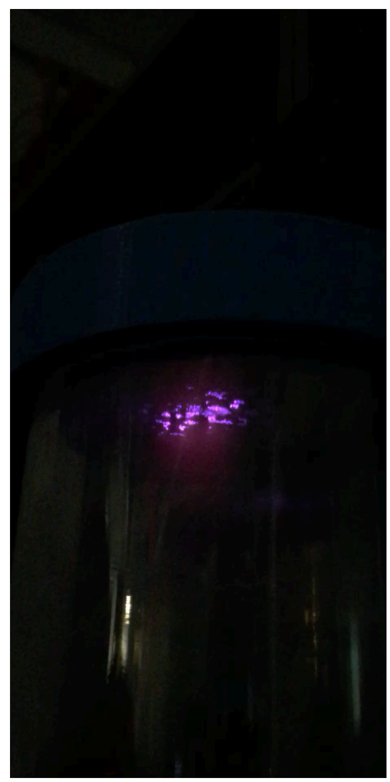


Figure 24 - Plasma Grouping on Electrode Impurities

Conclusion

Vacuum Chamber

While air is being pumped from the chamber, there looks to be an exponential decay of pressure over time (Plot 1). This makes sense due to the fact that there is a higher pressure gradient attempting to push air into the chamber at lower chamber pressures, thus making pumping harder and harder as the internal pressure decreases. The exponential decay seen in Plot 1 means that the chamber quickly reaches near minimum pressure, taking between 20 and 30 seconds to reach a minimum measurable value. Therefore, this chamber is effective for its purpose as a vacuum chamber, as it can reach low pressure quickly and can maintain low pressure with the help of a vacuum pump. If the vacuum pump is taken away, it can be seen from Plot 2 that leaks do exist in the chamber, but that, at a rate of 4.068 PSI/hour, the leaks take a long time to return the internal pressure to near atmospheric pressure. Given that this chamber's chief purpose is not solely to be a vacuum chamber, it performs quite well.

Plasma Chamber

The state of the plasma in the chamber heavily depends on the pressure in the chamber when the plasma is turned on. The transition between arcing and glow plasma happens in this chamber between -99.7 to -100.6 kPa gauge pressure, with the type of glow plasma seen in Fig. 11 being created between this range and a pressure value of roughly -101kPa. At very low pressure (< 300Pa absolute), the plasma will just cling to the electrodes as seen in Fig. 12. This is likely due to a lack of air molecules throughout the chamber to ionize and emit light — near the electrodes, plasma can form out of material ejected from the electrodes as electrons impact the electrodes at high speed. As seen in Table 1, higher currents happen with arcs at higher pressures, reaching large currents of up to 2A. This is due to electrical breakdown of the gas in the chamber creating a short in the circuit. Even the lowest current spikes, at 200-300mA, are much higher than the 30mA rating of the transformer used in the chamber's circuit. This happens because of the electrical breakdown acting like a short. After plasma is created, a large current moves through the chamber, but because of the current limitation on the chamber, voltage between the electrodes drops, and charge must build in the capacitors before more plasma is created. This happens very quickly in a periodic manner, causing the plasma to turn on and off at high frequency. See Appendix B for the waveform created by this shorting and charging action. When the circuit is turned off but pressure is not released into the chamber, the capacitors drop to a voltage of 300V, but no lower. This is because plasma continues until the voltage across the capacitors drops below the breakdown voltage of the air inside the chamber, which is roughly 300V.

Magnetic Confinement

Figures 13, 14, 16, and 17 show plasma wrapping around cylindrical magnets due to the Lorentz force. In the vertical field created by a cylindrical magnet at some radial distance, electrons moving horizontally away from the magnet will be spun around the magnet before flying up to the top electrode due to the large electric field in the chamber. The circular confinement is most intense right at the surface of the magnet due to the decrease in magnetic field with distance that can be seen in Table 3. In Fig. 14 and 15, jets of plasma are created from the hole of a torus shaped magnet. The tight confinement found in the hole of the torus magnet is due to the field pointing along the magnet's axis, spinning the electrons around the axis of the torus magnet. As the electrons get farther away from the magnet, however, the field decreases (see Table 2), and the electrons spread out.

Electrode Configuration

Figures 20, 21, 22, and 23 show that the plasma seeks electrodes with sharp edges and tight spaces. This is due to the fact that any sharp edges on an electrode cause the electric field to be strongest at those points, making arcs and electrical discharge to those points easier. In Fig. 22, specifically, it can be seen that on a flat electrode, the plasma groups around the one hole that is present. Similarly, Fig. 20 shows arcing to the point of the electrode first, and Fig. 21 is an example of plasma forming on a sharp ridge of an electrode before spreading to the other parts of the electrode. With a more rounded electrode (Fig. 18), the plasma spreads more evenly across its surface. However, it's interesting to note that at very low pressure, the same thing can be observed with a more pointed electrode — Fig. 19 shows plasma enveloping the entirety of a pointed electrode fairly evenly. At low pressure it is simply easier for plasma to form in all places on the electrode. Fig. 24 shows the plasma concentration on the top electrode of the chamber — an interesting pattern is observable because the plasma likes to group around impurities in the electrode. These impurities are simply rough spots that act like any other pointy electrode — they make it easier for plasma to form.

Acknowledgements and Thanks

Dr. Dartt - Kindly used a painstaking process to smooth out the chamber's electrodes with his lathe in his garage. Thank you for your help, your time, and your willingness to let me see the smoothing process.

Brian Ward - Bought parts for the project, taught me how to tap a hole, provided tips on the physical design and safety aspects of my project. Thank you for being patient with me and for looking out for my and other people's safety.

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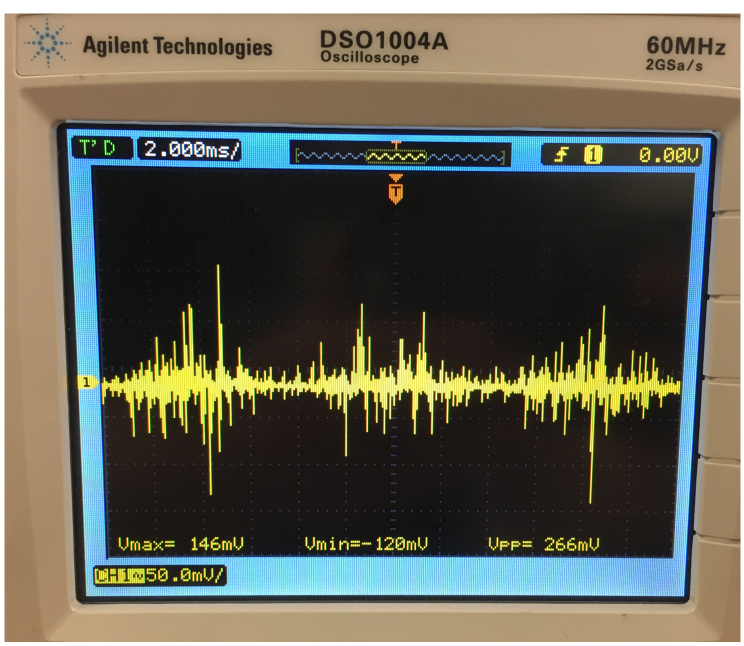
Dr. Dann - Provided me with the right electronics knowledge, referred me to the correct retailers for parts, and found the right parts to order. Also is the one grading this paper, so I need to kiss up.

Appendix A - Parts List

Part	What needed for	Cost ($)	Source
2 4" Aluminum Disks	Endcaps/electrodes	-	Lab
12"x12" Neoprene Mat	Vacuum seal	23.39	McMaster
4" Acrylic Tube	Chamber wall	21.44	TAP Plastics
Vacuum Tubing	Drawing vacuum	~30	McMaster
Track-It Vacuum Sensor	Measuring vacuum	-	Lab
Welch 1400 DuoSeal Vacuum Pump	Drawing vacuum	~800	Ebay
2 1/4" Acrylic Maker Cases	Chamber Base and Rectifier Box	-	Lab
4 Diodes	Bridge Rectifier	-	Lab
12 Capacitors	DC Smoothing	-	Lab
3kV 30mA Transformer	Step Up Line Voltage	-	Lab
3 1/4 in FPT Ball Valves	Seal Chamber and Release Pressure	~30	Ace Hardware/Home Depot
6 1/4 in MPT Nipples	Vacuum Line Connections	~40	Ace Hardware/Home Depot
3 1/4 in FPT Tees	Vacuum Line Connections	~20	Ace Hardware/Home Depot
1 1/4 in MPT Nipple to 3/8 in Barb	Plumbing to Vacuum Tube Connection	-	Home Depot

Appendix B - Circuit Waveform



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