AN ABSTRACT OF THE THESIS OF

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Abstract Approved:

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Abstract

Our research was focused mainly on the field of plasma physics and the creation of plasmas in a laboratory environment. We first began our project with the goal to develop a tabletop Tokamak, a doughnut shaped device that magnetically confines plasmas at pressures greater than one atmosphere. After researching this topic, it was determined that it would be impossible for a team to design and build a Tokamak without serious financial and scholarly help. To continue our research, we instead intended to build an induction lamp that would let us take current, potential, and resistance measurements of a plasma as well as examine the working parameters of a magnetically induced plasma. While we were unable to complete the induction lamp design, we did complete experiments on plasmas confined in cylindrical tubes and determined the necessary electrical potential and current needed to sustain low-pressure plasmas as well as the change in resistance before and after the plasma ignites.

Key words: plasma physics, Tokamak, induction lighting, low-pressure plasma

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Experiments into Plasma Physics

by

Christopher S. Smith

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I understand that my project will become part of the permanent collection of Oregon State University, University Honors College. My signature below authorizes release of my project to any reader upon request.

Christopher S. Smith, Author

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1. Introduction

Plasma is a state of matter that is not often experienced in day-to-day life, but is more prevalent than all of the solids, liquids, or gases combined throughout the universe. The most common place for plasma to exist is within a star, but in this state it is very difficult to run experiments upon. Plasma forms when molecules are energetically excited to the point that their electrons become free from the positive atomic nuclei. The two common methods to excite these molecules are thermally, in the case of stars, and with a powerful electric potential in the lab. This process drastically changes the conductivity of the matter because instead of having neutral atoms or molecules, there are highly charged free particles that can flow past each other. This makes plasmas extremely susceptible to electric and magnetic fields.

The goal of our research was to build a plasma containment system and to analyze some of its properties. Fortunately, plasmas are relatively easy to make in the lab under certain circumstances. The most common gas to create plasma with is hydrogen because the single protons can react almost as quickly as the newly freed electrons to any external fields. Also, hydrogen is the simplest atom to ionize and requires the least amount of energy to strip off all of its electrons because there is only one proton to attract the electron. The most popular method of plasma creation is the tokamak. A tokamak uses a high pressure (greater than one atmosphere) of hydrogen placed within a doughnut-shaped torus and wrapped with coils of wire to create a magnetic field for containment. This design resembles a solenoid that has been twisted so that both open ends meet. The plasma is ignited by a powerful electric field. A magnetic field created by the coils contains the plasma within the torus and keeps the plasma from losing energy by coming into contact with the container walls. While tokamaks can create large plasmas and can even mimic the pressures and temperatures in stars, we were not able to construct one because of the sheer amount of engineering and lack of knowledgeable assistance.

Once we decided that a Tokamak was unfeasible, we began to design a low-pressure plasma generator using a simple vacuum tube. Vacuum tube plasma physics was a hot topic for physicists in the early 1910’s and 1920’s but was displaced when atomic physics was developed. By decreasing the pressure to much lower than one atmosphere, it doesn’t take as large a potential to ionize the gas. Also, with a lower pressure it isn’t necessary to use a magnetic field to contain the plasma and keep it from contacting the container walls. By using a glass vacuum tube it was possible to see the light given off by the plasma. The excited electrons briefly reattach to a proton and emit light before becoming ionized again. Because of the danger of using the extremely explosive hydrogen gas in an environment with electrical sparks, we decided on using neon both for safety reasons and its commercial availability. The energy to ionize the first electron from a neon atom is 21.56 electron volts.

The information and experiments with the vacuum tube led us to our final design. Much like the Tokamak, the latest design is a torus but made of glass and with no coils for a magnetic containment field. The gas is at a pressure of two torr and the excitation comes from a ferrite core that is attached to a circuit. When the 80-kilohertz signal from the circuit is passed around the ferrite core, a powerful magnetic and electric field is generated like in a common electromagnet. The magnetic field induced in the ferrite cores creates an electric field that ionizes the gas and accelerates the electrons and positive ions. The electrons and ions flow in opposite directions, due to their opposite charges, around the torus. Free electrons that become captured by ions or electrons that were not fully ionized but were excited to higher energy levels give off light as they fall back to lower levels.

The technology driving this system is much younger than the setup itself. Induction lamps are commercially available and are often used in large warehouses because of their resilience over conventional fluorescent lights. Barring a break in the tube, induction lamps last much longer than other lamps because there are no metal connections in the tube that will break down over long exposures to high voltages. With our research, we hope to gain a better understanding of low-pressure plasmas and perhaps design more efficient induction lamps.

2. Design and Research

Plasma is a state of matter in which all of the atoms of a substance are fully ionized. To ignite plasmas, atoms must be ionized until there are nothing but positive ions and negative electrons present. This state of matter is vastly different from most forms because it is highly susceptible to electric and magnetic fields. Plasma has very negligible resistance due to the collisions of atoms and electrons striking each other. The greatest uses of plasmas currently are in fluorescent lighting and also fusion power. A fluorescent light works by ionizing gas and emitting light as the electrons fall back into the atomic orbital. In fusion physics, plasmas can be accelerated to very high velocities so that atomic collisions will fuse and give off more energy.

2A. Tokamak Research

When the Plasma project was first begun, our initial research looked into the Tokamak generator. The Tokamak generator is a high-pressure (greater than one atmosphere) plasma generator most commonly used in fusion experiments. This system is powered similarly to our design with the gas being excited by a powerful electromagnetic field that runs the length of the torus. However, due to the pressure of the system, energy loss from collisions between the ionized atoms and the container walls becomes a significant issue. The solution to this is a second field that magnetically contains the plasma and limits its contact with the walls. In our conference class, we began by researching the basics of plasma physics.

The first thing we looked into was how do the charges move and what models are currently applied to represent how they react to electromagnetic fields. We learned that there are two main approaches to plasma modeling: examining the interactions of individual electrons and ionized nuclei under the influences of a magnetic field in close association with each other and through a sophisticated fluid dynamics model. While the first model seems simpler, the sheer number of particles that are needed in a tokamak makes the math nearly impossible to do. The second model is more commonly used but still surprisingly difficult.

It turns out that magnetically confined plasmas are similar to confined liquids. Plasmas behave in similar ways to fluids and can be modeled as idealized fluids under pressure. However, there is an added complexity due to the fact that the electrons and positive nuclei are moving in opposite directions to each other and thus both affect the drift velocity of the other. This new complexity, however, is not very difficult as the electrons and positive charges can be modeled separately with the effects of the other merely adding to the drag coefficient already present in the fluid dynamics equations.

Once we felt that we had a somewhat tentative grasp on the models available, we turned to the challenges of building the tokamak. We considered many issues such as: heating the gas, time scales of ignition, physical and magnetic containment projections, construction of the torus and the external sensors, leak detection of the torus, coil size, and above all, cost. We briefly considered incorporating a fuel injection system so that the tokamak could potentially be used in fusion experiments, but that was relegated to a minor goal. At this point fusion seemed like a much farther cry than merely building a tokamak for plasma experiments.

After discussing these challenges, different aspects of the plasma physics were assigned to group members to research. Firstly, fusion confinement in a tokamak is quantified by the necessary energy and particle confinement times of the plasma. This means that for fusion plasma, the amount of energy necessary to contain the plasma is dependent upon the energy needed to achieve fusion as well as the length of time that the reaction will run for. The necessary energy for fusion between deuterium and tritium is 4 kilo-electron volts and for deuterium-deuterium it is 35 kilo-electron volts. Also, the necessary energy to sustain the plasma lessened due to the fusion process depositing energy back into the system minus the energy lost due to brehmstahlung. There is a quality safety factor to the toroid design that is equal to the minor radius over the major radius multiplied by the toroidal field strength over the poloidal field strength. Thus, the tokamak is safest when it has a large minor radius and toroidal field. The major radius and poloidal field affect the strength of the toroidal field and the pressure of the magnetically confined plasma, respectively. (Hazeltine)

An interesting fact that we discovered is that the phrase “tokamak equilibrium” is a misnomer. The plasma contained in the tokamak is far from stable due to energy lost to collisions made between charges and the container walls as well as collisions between particles. Tokamaks are only considered stable because the amplitude of the unstable disturbances is bounded at an acceptable level, much like a simmering pot versus a pot boiling over. They do not have exceedingly long run times because of this, with most fusion experiments only lasting upwards of milliseconds.

The toroidal shape of the tokamak is also important because it is a flux surface. The magnetic field of the toroidal coils is completely contained within the torus, but there are some interesting effects. The field lines within the torus are far from ideal although they do constitute completely closed lines. Instead, the lines are threaded throughout the torus in a completely random fashion that also changes with time. This is referred to as magnetic chaos and is a topic all to its own. (Hazeltine)

While this all seemed very straightforward at first, doing some of the calculations for a Tokamak proved it to be nearly impossible with the resources at hand. It was calculated that the Tokomak would require the nearly one hundred pounds of copper for the inductor loops that had to allow nearly one thousand amps to pass through them. All of this copper would be necessary to dissipate the power without heating the copper to the point of melting. We were never able to receive any advice from any of the facilities that have built tokamaks and discovered that the premise for our project was decidedly improbable due to our lack of experience, funds, and knowledge. As such, the tokamak idea was shelved but much was learned about plasmas in the process.

2B. Low Pressure Research

With the Tokamak firmly out of the picture and with some advice from professors, our attention was turned to the field of low-pressure plasmas. While not as exotic as a Tokamak, low-pressure plasma generating devices are very common and gave us many opportunities to learn about the plasma itself. Because of the low pressure, the ionized atoms and electrons have fewer collisions with the container and energy loss is too small to be appreciable. From this, it wasn't necessary to create a second field to restrict the plasma within the container and the primary field was our focus.

Our initial setup was fairly unsophisticated (Fig. 1). Using a vacuum pump and a glass tube that was 12 inches long and 1 ½ inches in diameter, we pumped regular air out and ran tests to see how the necessary DC voltage to achieve excitation changed with pressure. We were only considering the relative voltage change for multiple pressures because air is mixture of gases, unlike the pure neon we used for the final experiments. After experimenting, we found that the lower the pressure of the gas, the lower the DC voltage it took to ignite the tube (Table 1). However, with fewer atoms, the intensity of the light was severely diminished. To see if this was also true with neon, we attached a neon tube to our setup so that we could evacuate the tube, fill it with neon, and evacuate it again to the desired pressure. Once again, we saw that with a higher pressure it required a higher DC voltage, but the light was much brighter. Using these experiments, we decided that the pressure for the torus would be 22 millimeters mercury (mm Hg).

Table 1: Voltage and Resistance at Differing Pressures

Pressure (mm Hg)	Voltage (V)	Resistance (Ohms)
22	475	230
2	425	205

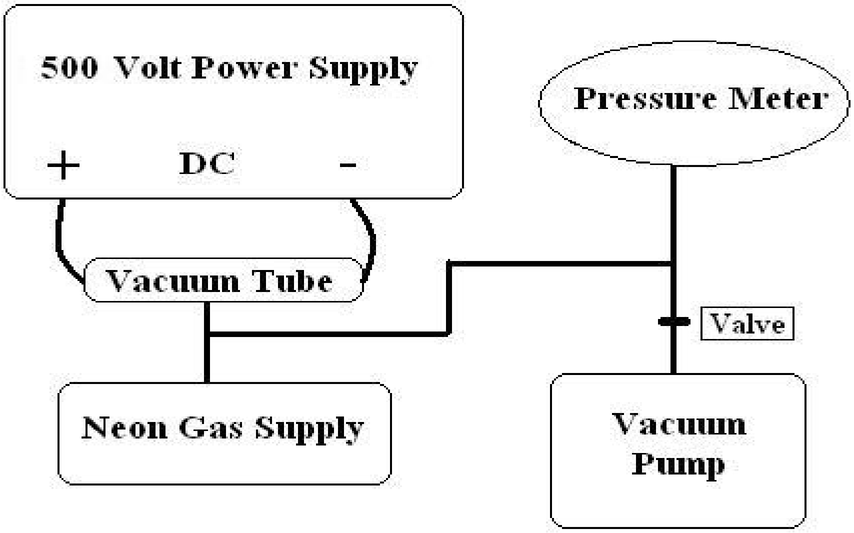

Fig. 1:Initial Vacuum Testing Schematic

An interesting phenomenon that was seen during the vacuum tube experiments was a ripple effect seen in the tube. In our original setup, there wasn't a valve to separate the depressurized tube from the vacuum pump and thus the pump had to be left on while the experiments were run. Because the gas was constantly being moved due to the pump, after the voltage was applied a strange rippling pattern would form throughout the tube. The ripples were evenly spaced and would at times form a standing pattern, as seen in Figure 2. This pattern was finally quelled by adding a valve so that the vacuum tube could be isolated from the pump.

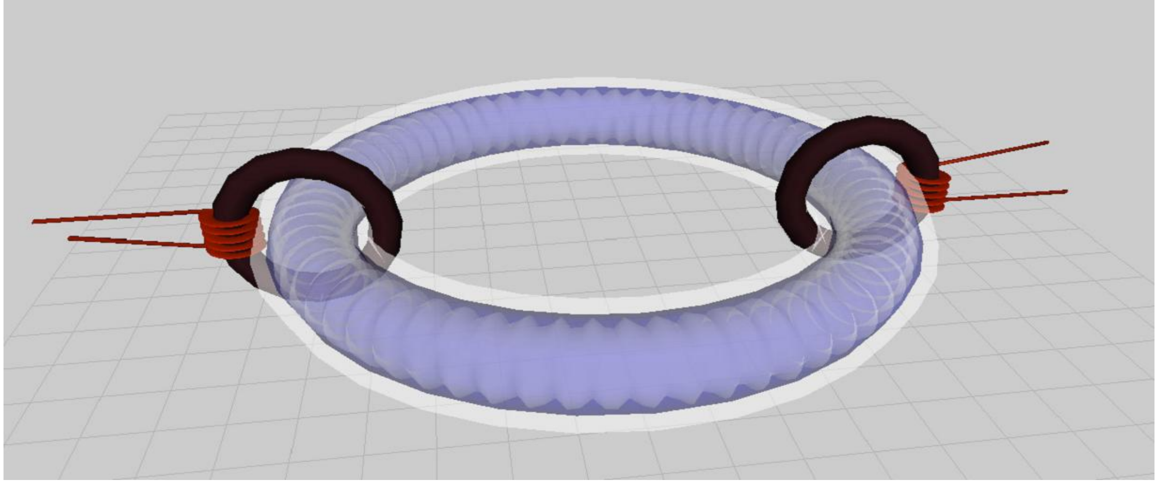

Fig. 2: Rendition of fringes inside of Torus tube

Figure 2 also shows the ferrite cores wrapped with wire that ignite the plasma. When current passes through the wraps of coil it acts as a solenoid and induces a magnetic field in the ferrite cores. This field is entirely contained in the ferrite cores and due to the cores having very high resistance there are no eddy currents to counteract this field. The magnetic field passing through the cores creates an electric field that is pointed along the path of the torus, ionizing the gas and accelerating the free particles around the loop.

After deciding on an appropriate pressure, we began experimenting on commercial neon tubes to see the difference between a DC voltage ignition and AC voltage ignition. We purchased two tubes, one nine inches long with a diameter of ¾ of an inch and a second twelve inches long with the same diameter. Using a DC power source, both tubes required over 500 volts of DC potential to ignite. However, the car adaptor's twelve volts DC passed through a small internal circuit could power the tubes. The signal coming out of the circuit was AC with an interesting waveform and 80 volts root mean square (rms). The frequency of the signal was 60 kHz. This information gave the engineers on our team a design basis that became the circuit they built to excite the gas in the torus.

One thing we didn't consider until we began experimenting was the difference in the required DC potential and AC potential. To ionize the atoms in a gas, it requires nearly five times the DC potential compared to the AC rms potential. Also, the plasma reacts to AC potentials differently at different frequencies, usually around a resonant frequency. With a DC potential, all of the electrons gather on one electrode and the positive ions gather at the other electrode. Once this happens, there are very few charge carriers left in the gas. This means that the effective resistance of the gas is much higher than with an AC power source and requires a higher potential to keep the necessary current flowing. Thus, by using AC we do not need to supply a larger potential.

The circuit the engineers built works off of an input frequency signal and a DC power supply for the initial potential and current. The signal is ramped up through a series of transformers and can either be applied to the leads of one of the neon tubes or through a wire wrapped around a ferrite core that will radiate the electric field at radio wave frequencies (300 kHz) that will excite the torus. When the circuit is connected to the tube leads, the input potential and current needed to ignite the tube are dependent on the number of turns around the ferrite cores (See Figure 4). From experimentation, the fewer the turns around the ferrite core there are, the higher the input voltage and current must be to sustain the system.

While the low-pressure plasma can be sustained by a significantly lower pressure than the high-pressure plasma, a special power supply had to be built to create a large enough current source for the neon tubes (Figure 4). The plasma can be maintained with a current of 100 milliamps but to obtain this with only one turn requires an input current of over 150 milliamps. A low voltage and high current power supply was passed through a transformer, a diode rectifier, and a large capacitor to create the high voltage and current that was needed. Unfortunately, it was found that the transformer that was being used had a common ground between the two sides. This was creating a short circuit through one of the diodes in the rectifier when a load was attached to the circuit.

3. Data and Results

Our first low-pressure experiment involved the vacuum tube that allowed us to set a pressure and determine the ideal pressure for the future torus. Initially we used air so the gas was a mixture primarily of nitrogen with some oxygen and carbon dioxide we tested it again with primarily neon and some small percentage of air mixed in. We saw that with lower pressures came lower ignition voltages, but an increased fragility of the system due to the pressure’s affect on the glass tube. The relationship between ignition voltage and pressure of the gas was linear with higher pressures requiring higher voltages. This is logical because with a higher pressure there are more atoms in the same volume. Free electrons are more likely to collide with a charged ion and become bound to it before being ionized again. This affects the mean free path of the electrons with higher pressures increasing the chance of a collision and slowing down the drift velocity of the electrons.

Our second experimental set-up used a 10-centimeter green neon tube and a 15-centimeter red neon tube. The green tube used a compound coated on the inside of the tube to convert the normally red neon light to green, but this did not affect the necessary voltage to ignite the tube. Our first real experiments came with the final build of the engineer’s power circuit. The power circuit allowed us to measure supply voltages and currents as well as the primary voltage before it was multiplied though the ferrite core transformers. By changing the number of turns around the ferrite cores, we could see the resulting change in the efficiency of the circuit and the necessary currents and voltages needed to maintain the green neon tube plasma (Table 2 and Figure 3).

Table 2. Data from Inductance Experiments

Inductance		Data	Green Tube					Vresistor/ R	R=100 Ω	
# of Turns	f (kHz)	Vin (V)	Iin (mA)	Pin (W)	V01 (V)	V02 (V)	Vresistor (V)	Iresistor (mA)	Pout (W)	Efficiency
20	67	40	150	6.0	19.8	265	0.50	5.00	1.33	0.22
18	67	42	162	6.8	21.6	265	0.97	9.70	2.60	0.38
16	67	48	157	7.5	21.0	265	1.26	12.60	3.35	0.45
14	67	50	206	9.9	27.5	265	1.42	14.20	3.76	0.37
12	67	48	226	10.9	30.9	265	1.00	9.95	2.64	0.24

In Table 1, Vin was the supply potential, Iin was the supply current, Pin was the supply power, V01 was the primary voltage measured between the power circuit and the transformer, V02 was measured across the neon tube, Vresistor was the resistor placed in series with the neon tube, Iresistor was the current through the resistor, Pout was the power reaching the neon tube, and efficiency was power out divided by power in. See Figure 4 for the relations between components.

The number of turns around the ferrite cores was then plotted versus the efficiency coefficient. The input voltage, current, and power were measured at the power supply. V01 was measured prior to the ferrite cores and V02 was measured across the green tube. However, the values are suspect because we were not sure of the impact of the oscilloscope being in parallel with the tube. The resistor voltage and current were measured on a resistor in series with the tube and the power output was calculated from those measurements.

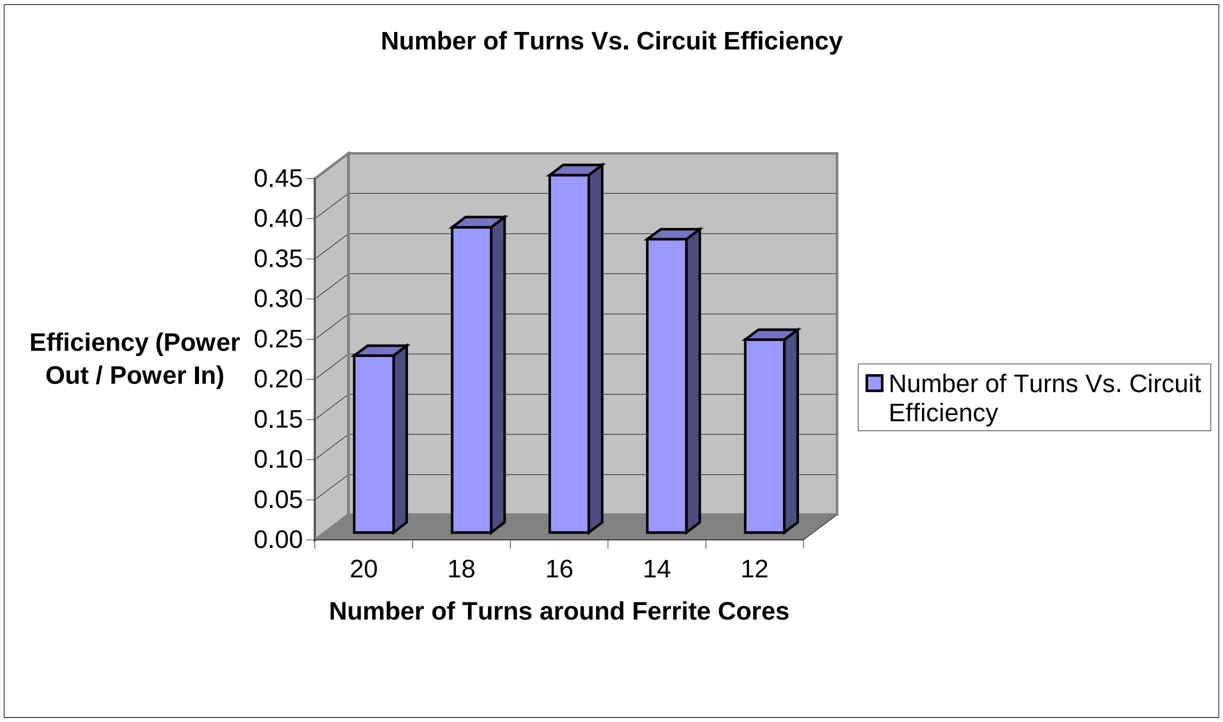

Fig. 3 Graph of Number of Turns vs. Circuit Efficiency

As can be seen, the efficiency has a maximum when the number of turns around the ferrite cores is sixteen. The drop-off around this number is nearly symmetrical. This is similar to the impedance matching of a co-axial cable. When the plasma is lit, it creates load impedance that is much lower than the infinite impedance it had before it was lit. But this lit impedance is still finite and is affected by the source impedance of the ferrite cores. From the data, the impedance of the cores changes with the number of turns around the cores and is most like the plasma’s impedance at 16 turns. However, the efficiency of the circuit has a physical limit due to the ferrite cores themselves. The cores have a set resistance that has to dissipate power from the current induced in them. Thus they heat up and a great deal of power is lost because of it.

Another note about the impedance matching is that the efficiency of the circuit also increased when the green and red tubes were both lit and placed in parallel to each other. First, the frequency was changed and the supply voltage was raised until the tube was still lit. After these data points were taken, then the power supply was set, the frequency was changed and the primary voltage was measured before the ferrite core transformer. Results are shown in Table 3.

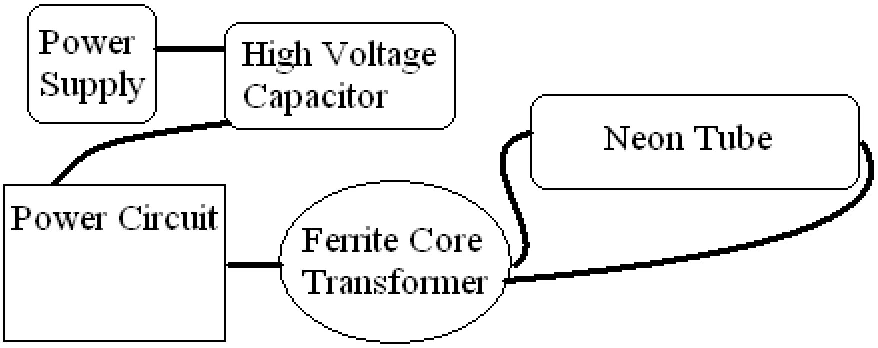

Fig. 4: Block Diagram of Final Setup

Table 3. Frequency Dependence of the Power Circuit

Frequency Data		Both Tubes	
f (kHz)	V primary (V)	Vsupply (V)	I supply (A)
63.3	27.4	44.0	0.220
63.6	27.2	42.0	0.221
64.5	27.6	41.5	0.221
65.6	27.3	41.5	0.222
65.9	27.3	40.5	0.220
66.3	27.1	40.1	0.216
67.0	27.5	40.1	0.212
67.3	30.6	40.0	0.210
68.0	30.9	40.0	0.210
68.8	30.4	41.0	0.198
69.5	30.0	42.0	0.186
70.2	29.2	43.5	0.173
71.5	27.9	45.0	0.152
72.9	26.6	47.8	0.128
73.5	26.0	48.1	0.121
74.8	24.2	50.0	0.106
76.1	23.2	51.0	0.095
77.1	22.7	52.0	0.091
78.6	20.4	54.1	0.075
79.3	19.9	55.5	0.071
80.1	19.2	56.1	0.067
81.5	18.1	57.0	0.062
82.8	17.0	57.9	0.058
83.9	16.1	58.1	0.055

85.8	14.7	60.0	0.051
85.9	15.0	60.0	0.051

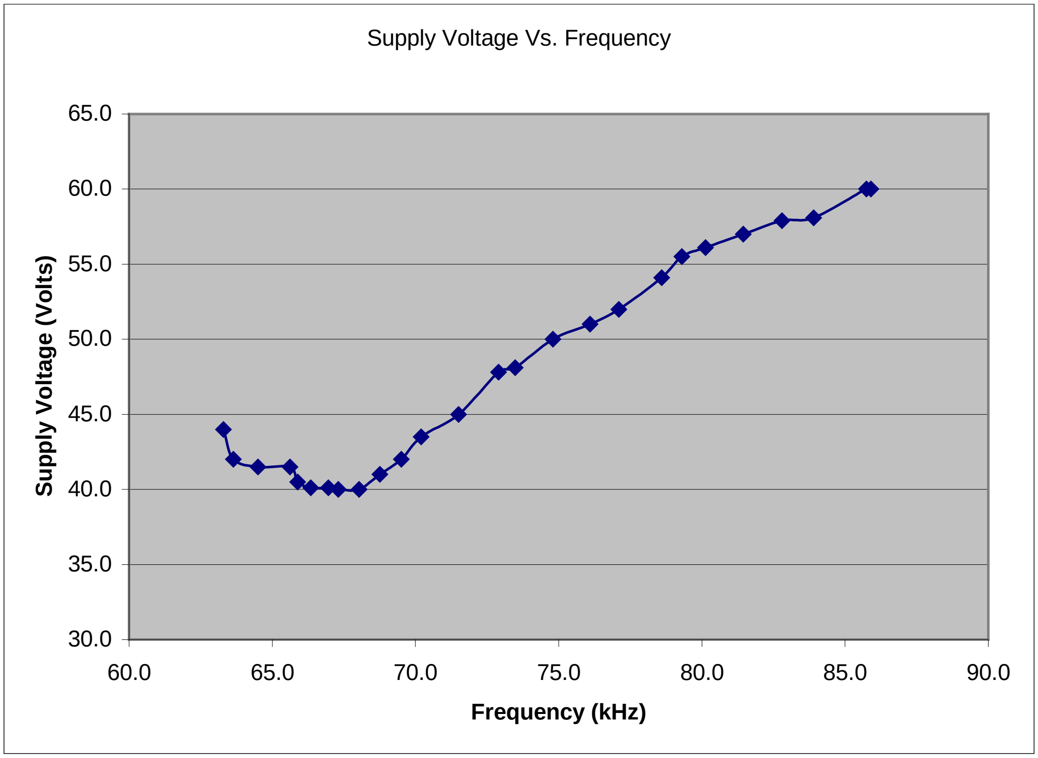

Fig. 5 Graph of Supply Voltage vs. Frequency

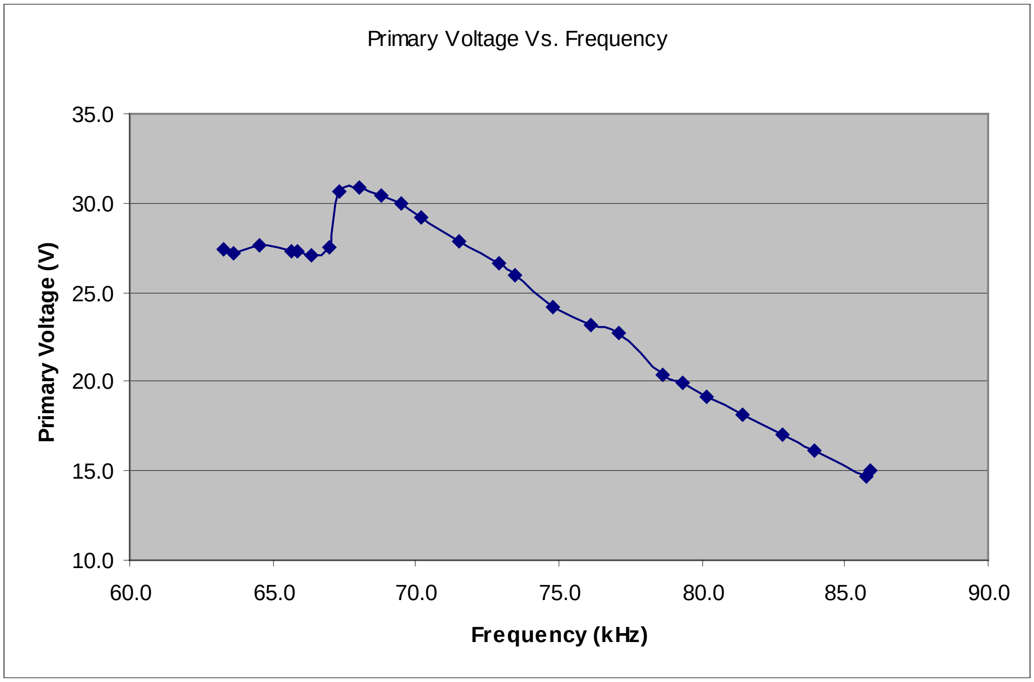

Fig. 6 Graph of Primary Voltage vs. Frequency

Data could not be taken at frequencies lower than 63.3 kHz because the lights were not capable of being fully ignited and thus the voltage and current measurements would fluctuate wildly. Both lights also had differing working frequencies, with the red tube beginning to dim at 67.3 kHz. Both tubes were half lit at 76.1 kHz with the green tube turning off at 79.3 kHz and the red one following at 85.75 kHz. We deduced the frequency dependence to be caused by the power circuit having a resonant frequency due to the inductors, capacitors, and resistors.

The frequency dependence of the Figure 5 and 6 is a direct response to the power circuit developed to power the neon tubes. It is a LRC circuit designed to be run at the set frequency of 67 kHz. The data shows how the impedance of the circuit changes as the frequency moves away from the resonant frequency and the primary voltage measured before the induction transformer dropped though the supply voltage increased.

The two tubes also had different number of turns around the ferrite cores from each other, with the 10-centimeter green tube having 14 turns and the 15-centimeter tube having 21 turns. The ratio of the number of turns was equal to the ratios of the two lengths, 2:3, as we expected. Thus, the voltage needed to light the two tubes was dependent only on the lengths as the widths were identical. Thus, the voltage necessary to excite the neon plasmas is dependent upon the amount of gas to be ignited.

Unfortunately, the ultimate goal of our project was unsuccessful. We hoped to take the knowledge we had gained from using cylindrical tubes and exciting the gas with electric fields and apply that to exciting a doughnut-shaped torus filled to 22 mm Hg with neon gas and excite it with a magnetic field. This setup closely resembles the magnetic driven and contained plasma inside of tokamak fusion generators. Instead of simply putting energy into the system so that the electrons remained energized, the magnetic field induced in the ferrite cores creates an electric field that drives the charged electrons and positive nuclei and this kinetic energy keeps them excited. This is illustrated in Figure 7 where the magnetic field going around inside the ferrite core creates an electric field inside the tube.

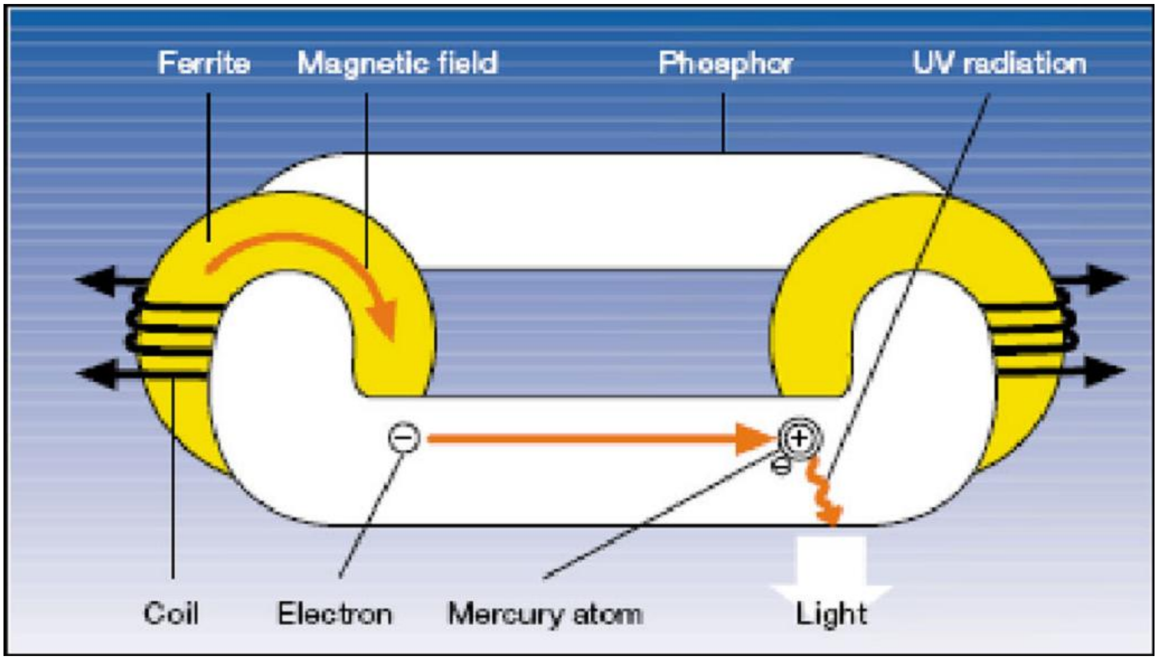

Fig. 7:Picture from Renewed Interest in Induction Lamp Technology, *Illinois Mathematics and Science Academy Journal*

4. Conclusion:

While our final goal of creating a magnetically induced plasma wasn't successful, many interesting facts about plasmas were learned. First, in high-pressure plasma systems, the system can actually by modeled as a dynamic fluid that is compressed into a magnetically confined pipe. Tokamaks work by both inducing a current that keeps the plasma flowing as well as a secondary field that confines the plasma away from the walls and reduces energy loss from collisions with the surface. While tokamaks are relatively common as a plasma-generating device, their complexity and the cost were great barriers for a team of undergraduates to construct even a small version.

For creating an induction lamp to examine the characteristics of a magnetically induced plasma, we accomplished much but did not succeed in the final task of inducing the current with a magnetic field. We designed and built a power circuit capable of transforming an DC input of 20 volts and converting it to an AC signal of 250 volts rms at 67 kHz. Low-pressure plasmas seem to be more responsive to alternating current than direct current, perhaps because of charges gathering on electrodes and screening charge carriers. The resistance of a gas drops considerably when it becomes a plasma due to the creation of free electrons when the gas molecules ionize.

It is my sincere hope that others will continue this research and continue working to induce plasma with the ferrite cores at radio wave frequencies. The obstacles left are cutting the ferrite cores so that they can be reattached without gaps between them and modifying the power circuit so that it can run at radio frequencies without burning out from dissipating power. Even by just using the experimental setups that we have created, quite a bit of quantitave data can be taken such as pressure and resistance measurements, measurements for other gases, and using the power circuit that was built. The largest difficulty for our team was collecting the necessary equipment and I would like to see others take this project to the next level.

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