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# Fusor: Nuclear Fusion Small-Scale Proof Of Concept And Demonstration

[2]Matthew Bloom, [2]Aaron Garofalo, [1]Matthew Michalewicz, [2]Brian Neumeyer, [1,3] Steven Stewart
[1]Electrical Engineering, [2]Mechanical Engineering, [3]Computer Engineering
Oakland University Honors College

Faculty Advisors: Dr. Michael Latcha, Dr. Graeme Harper

## Abstract

The purpose of this project is to design, construct, operate, and observe a Farnsworth–Hirsch Fusor (referred to as “fusor”) that demonstrates inertial electrostatic confinement of plasma. Using previously-created designs from Make Magazine as reference, a slightly larger borosilicate chamber was built to house the reactions. This fusor provides a valuable stepping stone in gaining experience toward constructing a higher-powered fusor that can maintain small-scale nuclear fusion, while also being capable of studying plasma behavior under a greater range of conditions, such as the addition of inert gases and variable vacuum pressures. Materials were chosen carefully for the project to create proper behavior in the system, to ensure no damage to the equipment or surroundings, and to prevent as many uncertainties in measurements as possible. In reference to the chosen materials, it is imperative to mention that air was the only substance used to form the plasma within the chamber. A high-voltage, direct-current power supply based on a rectified neon-sign transformer was used to form a powerful electric field that created and contained a plasma sphere in the center of the chamber, popularly known as ‘star mode’. The goal of achieving ‘star mode’ was attained and the vacuum, secondary voltage, and current were recorded. The current fusor design is referred to as the low-powered fusor, as it is incapable of producing nuclear fusion; however, it demonstrates the concept and the potential to do so, given the higher electrical potential difference required for the high-powered fusor. With the low-powered fusor, the design goal was accomplished. The secondary goal of creating nuclear fusion through the design, construction, and operation of a high-powered fusor is currently in progress. The scope of this report will be limited to the low-powered fusor, with brief mentions and descriptions of the high-powered fusor where applicable.

**Keywords: nuclear fusion, plasma, fusor**

## 1. Introduction

The purpose of a fusor is to create and contain a concentrated ball of plasma. There are three main variables that affect the formation of plasma: pressure inside the chamber, voltage applied, and current flow[1]. While density is the actual variable in consideration, it is immensely easier to measure the pressure of the gas. The relationship between pressure and density of a gas allows pressure to be a suitable substitute for density measurements for the scope of this report. This project examines the relationship between those three variables and plasma production.

The method pursued was to create a rarified atmosphere and apply a powerful focusing electric field to it. On each end of the fusor are aluminum discs. At the center of the fusor is shaped metal wire, called the inner grid. With the voltage applied between the discs and the inner grid, a powerful electric field is produced. The geometry of the inner grid focuses the field into its center. This concentration of the electric field lines creates and contains the plasma[2].

Referencing the designs from MAKE Magazine, the design for the low-power fusor was created. The chamber designed was slightly larger than the MAKE fusor at a diameter of 4.25 inches, compared to 3 inches[3]. This larger design creates more room for other objects inside the chamber, such as sensors or magnetic and electrical field generators. Inside the fusor, there are extreme pressures and temperatures. To manage these conditions, unique materials must be used, such as 304 stainless steel, borosilicate glass, sapphire, and tungsten. Care was taken to ensure the new design would still withstand the pressure differences, draw a deep and clean enough vacuum, meet electrical requirements, and withstand high heat and corrosion from plasma.

The low-power fusor design utilized a vacuum pump, a neon sign transformer (NST), a custom-built rectifier, and a suitable reaction chamber to house an inner grid. These devices operated together to form plasma. Every component on the chamber was oriented using a concentric cylindrical design, meaning that the end plates, borosilicate chamber, and inner grid all shared the same center on the vertical axis. Once assembled, all the components were organized and mounted to a mobile cart workstation.

## 2. Design Overview

The final design incorporated several key components to form focused plasma. The vacuum system held a minimal pressure, decreasing particle density inside the chamber. This is advantageous because it increases the average distance between particles, allowing longer durations of acceleration, further improving the likelihood of creating plasma. In addition, the Variac and neon sign transformer operated together to apply a voltage to the inner grid within the chamber. This voltage difference between the inner grid and the grounded aluminum plates created an electric field necessary for focusing the remaining air particles into the center of the chamber.

The original specifications pertaining to the design of the fusor came from the Make fusor model[3]. In addition, those specifications were cross-checked with suggestions from fusor.net to find the most generally accepted values for the constructed fusor. These specifications are listed below.

- Negative power supply between 5-15 kV @ 5+ mA
- Electrical safety considerations
- Vacuum chamber that can maintain <= 5 mTorr (~.7 Pa)
- Withstand atmospheric pressure (101 kPa)
- Withstand slight heat shocks from ion beams (Pyrex)
- Allow visual observations
- Inner grid that produces an electric field that focuses particles

## 3. Mechanical Subsystem

### 3.1 Initial Design

The idea behind the mechanical subsystem was twofold: to design a vacuum chamber that maintains visibility to observe the reaction, as well as maintain a vacuum up to 15 mTorr, and to design an inner grid capable of producing an adequate electric field within the chamber. In addition, the chamber needed to withstand 1 atmosphere of pressure acting on it from the outside.

To manufacture the chamber, a cylindrical design was significantly simpler than any other design, as the machining process was straightforward and less time consuming. Pyrex was chosen for the material due to its transparent property and because it could withstand the required amounts of stress and thermal shock. The installation of ports on the end plates of the cylindrical design only required holes to be drilled in each end plate. This allows for efficient manufacturability and future modifications, if required. The design uses clamping pressure from nuts and threaded rods on each end plate to create the proper gasket pressure to prevent leaks. A plastic hose was used to plumb the vacuum pump and pressure gauge to the end plates. Ceramic standoffs were used to support the inner grid inside the fusor chamber. The ceramic material prevents the inner grid from creating an electrical short with the aluminum end plate. Lastly, wood plates were used as the base of the fusor design so the entire apparatus could be placed on any surface with no risk of electrical conductivity. A complete assembly can be seen in Figure 1.

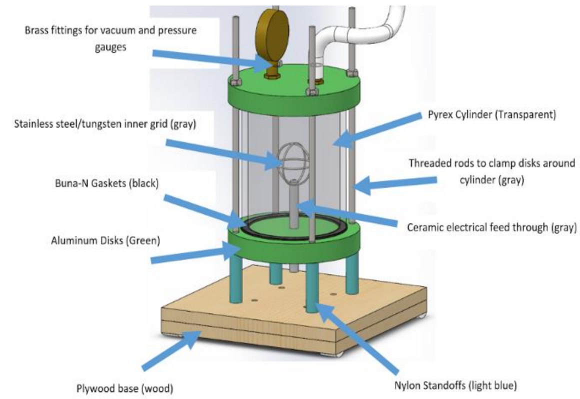

Figure 1. Complete fusor design detailing all mechanical components

## 3.2 Simulation Results

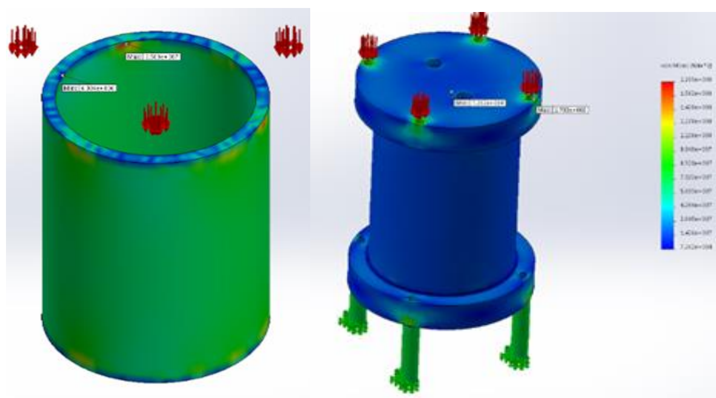
Figure 2. FEA analysis results showing tensile forces acting on the cylinder using Solidworks

A Finite element analysis (FEA) was simulated using a Solidworks model of the fusor. In this case, the only significant loading force is the clamping load on the plates due to the nuts tightened against the threaded rods. This force seals the gaskets between the aluminum end plates and the glass cylinder. For Buna-N rubber to properly seal, the pressure applied to the gasket must be at least 6.9 MPa[4] (1 kpsi). Since the threaded rods are in tension from the load, the simulation was run with a clamping force equivalent to 80% of the rods' tensile strength[5]. At this load, the gasket stress was found to be to be 43.1 MPa (6.25 kpsi), which is over six times the necessary sealing pressure. The other boundary condition was the rigid fixation of the bottom of the nylon standoffs. Once materials and boundary conditions were applied, the model underwent a standard mesh setup before simulation. The result of the analysis is depicted within Figure 2.

Maximum stress is located around the through holes for the threaded rods where the nut clamps down. While this approaches the yield stress of 6061 aluminum (35000 psi/241 MPa), it is localized and can be mitigated by using washers[5]. The rest of the plate has less than 0.1 mm deflection and experiences acceptable stresses, which is necessary for a strong seal.

The maximum stress in the glass cylinder was found to be 25 MPa in the compressive direction, as shown in Figure 2. The documentation from Friedrich and Dimmock, Inc.[6] shows that borosilicate glass has a maximum compressive stress of 100 MPa, which was used in the simulation and was shown to provide a factor of safety of 4. To conclude, all load-bearing components meet the required specifications with an acceptable factor of safety.

## 3.3 Design Success

In regards to performance, the design functioned in accordance with the simulation predictions. No yielding was observed within either the aluminum plates or the borosilicate chamber, which were determined to be the only sites of initial concern. In addition, the clamping force estimated to create a vacuum seal was adequately produced by the nuts, and the vacuum was maintained. Unfortunately, the desired vacuum level was not achieved. This was determined to be largely due to the plastic hose connections from the chamber to the vacuum pump.

### 3.4 Major Revisions

The largest issue with the mechanical design was the low level of vacuum, inadequate for 'achieving 'star mode'. To achieve a more powerful vacuum, the tubing used to connect the vacuum pump to the fusor chamber was replaced with several varying sizes of brass fittings and piping to directly connect the chamber to the pump. This change was only made after extensive testing with the tubing to ensure that it was the source of the leak. After changing to this method of connecting, a vacuum nearly 20 times stronger was observed in the chamber.

Another issue that was addressed was the cleanliness of the chamber and end plates, as well as the removal of vacuum grease. It was found that the grease, residue on the plates, and dirtiness of the chamber were detrimental to the vacuum quality. To correct these problems, the aluminum oxide on the end plates was thoroughly scrubbed and removed, vacuum grease was cleaned off completely, and the chamber was also cleaned extensively before future trials. Results yielded great success and brought down the vacuum pressure down to a minimum of 45 mTorr, with readings as low as 15 mTorr observed during operation.

## 4. Electrical Subsystem

### 4.1 Initial Design

The main objective of the electrical areas of the system deal with providing enough power to produce fusion. For the low-powered fusor, the requirements are much lower, since the product is plasma instead of fusion. A suitable power supply was required to meet these requirements, which can provide a maximum of 5-15 kilovolts (kV)[3]. It must also produce direct current (DC) and be fully variable from 0 volts to its full voltage. Finally, the hot terminal of the power supply must be negative, with the positive terminal grounded. The potential drop must be from the outer shell to the inner grid, so that the particles are accelerated towards the center to encourage collision. A standard positive-hot, negative-grounded power supply with the positive voltage applied to the outer shell and the inner grid grounded could not be used due to safety concerns. If the outer shell had the voltage applied to it, it would be lethal to touch. Since the voltages are so high, there would also be a very high chance of voltage arcing to other components of the system, which could damage them and would present another element of danger.

The voltage and current that the supply provides must be in DC. If alternating current (AC) were used, the potential difference would be reversed for half of the cycle, causing particles to be repelled from the center when the voltage is positive. However, it is possible to effectively convert AC to DC with the use of diodes. One of the defining aspects of diodes is that they only allow current to flow in one direction. It is possible to utilize a pair of diodes in a manner so that one diode rejects the reversed voltage and current and allows the positive, while the other does the same, but with the opposite polarity. This method is known as voltage rectification, and it allows a steady current and voltage drop in one direction.

The chosen power supply was a neon sign transformer rectified by two high-voltage diodes. The diodes are directed in a way that current flows from the fusor's inner grid toward the transformer's ground, effectively converting it from AC to DC. The NST used was an older style transformer with a magnetically shunted iron core. This type of transformer is useful due to the nature of its operation. When the voltage is high enough and plasma is created, the resistance will drop to near zero. If the same voltage were maintained, an extremely large amount of current would be demanded, which could cause the chamber to explode due to the high-energy dissipation. When the plasma is created, the NST will shunt the magnetic flux away from the windings, which reduces the output voltage to safe levels, thereby reducing the current[7]. The voltage was controlled by a Variac, which allowed a variable input from 0 to 130 volts. As the Variac dial is rotated, the winding ratio of the internal transformer is changed, resulting in a controllable voltage multiplier from input to output. This allowed the voltage to be slowly and safely turned up to its maximum value. The Variac was not a necessary component for successful operation of the fusor; its role was mostly for safety. The Variac also allowed voltage to be increased slowly and allowed observations to be made for any undesired effects that occurred. It also allowed the voltage to be intentionally kept at a lower value for testing. The voltage was applied to the inner grid of the fusor and the outer shell was grounded, creating the required potential difference. A circuit containing all the critical elements is displayed in Figure 3.

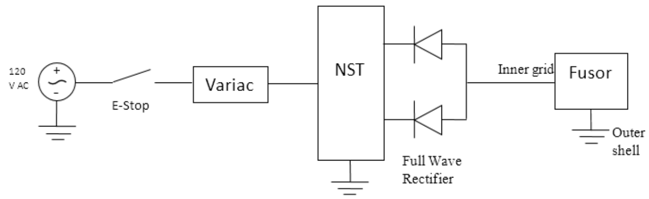

Figure 3. Circuit diagram for electrical subsystem

To measure the voltage applied to the fusor, a voltage divider was made to step the voltage down to safe levels, allowing a measurable output. These resistors are in parallel with the fusor chamber, and since voltage is the same across parallel elements, this allows the determination of the fusor voltage. The equation for the output voltage of a voltage divider is shown by equation (1):

$$V_{out} = \frac{R_2}{R_1+R_2} * V_{in} \tag{1}$$

For this project, $R_1$ was chosen to be a high voltage ceramic resistor with a resistance of 500 MΩ. It is capable of dissipating 10 W, which is suitable for the levels of current expected. This type of resistor was chosen to be able to handle the high voltage drop across it. It is also physically very long to prevent the high voltage from arcing over the resistor. This resistor was in series with a standard resistor denoted as $R_2$, which has a resistance of 470 kΩ. This value was chosen since it is approximately 1/1000 the value of $R_1$. When the equation above is computed with these values, the output voltage is also about 1/1000 the value of the rectifier output voltage $V_{in}$, which allows for an easy conversion to find the actual voltage across the fusor. Since the voltage across $R_2$ is stepped down to a voltage of around 10 V, it can be measured using standard instrumentation.

## 4.2 Simulation Results

### *4.2.1 transformer voltage simulation*

A simple transformer circuit was constructed using PSpice to determine the behavior of the output voltage with a voltage divider. An ideal transformer was considered due to lack of specific knowledge of the inner mechanisms of the transformer. To achieve the desired turn ratio of the transformer, a relationship between the two inductances can be set. This relationship is shown in equation (2):

$$V_1/V_2 = N_1/N_2 = \sqrt{L_1/L_2} \tag{2}$$

If the primary winding inductance $L_1$ is set to a simple value of 1 mH, then from the equation the secondary winding inductance $L_2$ would have a value of 15.625 H. This would achieve the desired turn ratio of 1:125 of the NST.

To simulate the negative voltage that the neon sign transformer produces, the input voltage was negative. Diodes were also added to achieve full wave rectification of the voltage. The models used were basic diodes, with the known values being modified and the other parameters being left at their default values. Finally, the resistor values were added in. It is impossible to model the chamber of the fusor itself in PSpice, so only the open voltage applied to the fusor was simulated.

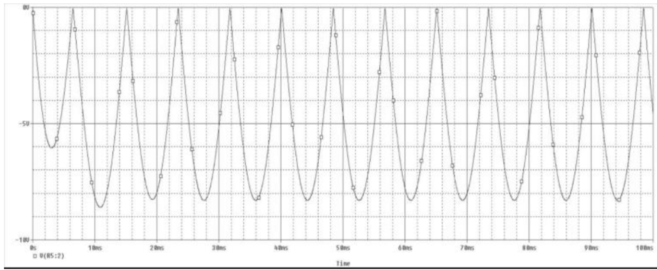

Figure 4. Simulated waveform of transformer voltage over time

The simulated voltage behaves as expected, as shown in Figure 4. It is a full wave rectified output producing negative voltage. The magnitude of the voltage is not fully accurate as to what was expected, but this is a result of the small resistances added to each winding. If it were possible to remove these resistances, the voltage would likely have peaked around -10.5 V. However, the overall behavior would not change and can be used to compare with experimental results.

### *4.2.2 matlab electrical field simulation*

There are many variations of inner grid geometries. A relatively simple grid was chosen to be used. The inner grid proposed to be used is popular among fusor engineers. It consists of three concentric rings that are perpendicular to each other, as shown in Figure 5. While the two end plates do contribute to the electric field, they essentially serve as planes of infinite charge and direct the electric field between them. The main interest lies in the basic geometry of the inner grid and the grid's effect on the electric field.

$$E_r = \frac{Q}{4\pi\varepsilon_0}\frac{2}{\pi q^{\frac{3}{2}}(1-\mu)}\frac{1}{\mu}\left(2RK(\sqrt{\mu})(1-\mu) - E(\sqrt{\mu})\big(2R - \mu(r+R)\big)\right) \quad (3)$$

$$E_r = \frac{Q}{4\pi\varepsilon_0}\frac{2}{\pi q^{\frac{3}{2}}(1-\mu)}aE(\sqrt{\mu}) \quad (4)$$

$$q = r^2 + R^2 + a^2 + 2rR \quad (5)$$

$$\mu = \frac{4r}{q}R \quad (6)$$

The purpose of this arrangement is to focus particles into the center to create a plasma ball. With a single ring, unless the particle is perfectly aligned with the axis, it will veer off into the ring itself. For this reason, it was decided to use three rings. To verify the preliminary simulation of a single ring, a Wolfram Alpha program was used as seen in Figure 5[8].

The equations that were used to model the electric field come from Mandre[9]. The axial and radial components of the field are found separately with equations (3) and (4). Equations (5) and (6) serve to simplify equations (3) and (4). The variables r and a are determined by the radius and along the ring's axis, respectively. The variables $\varepsilon_0$, q, R only serve to change the magnitude of the field; however, the scope of this simulation focuses on the shape. They are the permittivity of free space, total charge on the ring, and radius of the ring, respectively. K and E are the elliptic integral functions of the first and second kind, respectively.

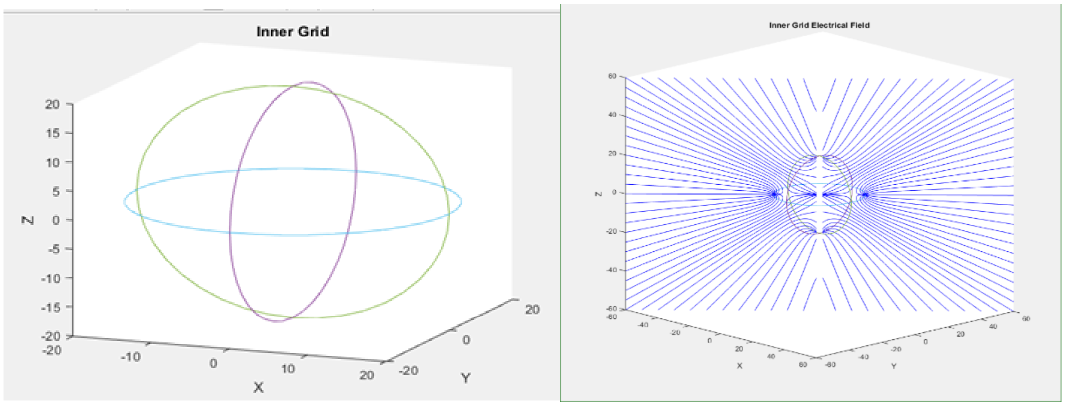


Figure 5: Inner Ring Geometry (Left), Inner Ring Electric Field Lines (Right)

A cross section of the electric field is shown in Figure 5. The closer the lines are to each other, the stronger the field in that region. As expected, field lines near the ring will contact the ring, rather than the central plasma ball. This transfers the particle's energy into the grid, instead of keeping it in the plasma, resulting in a large source of inefficiency. However, lines that fall between the rings will converge on the center of the inner grid.

It is interesting to note that many videos of this grid show glowing not only in the center of the grid, but also around the grid, especially where two rings intersect. This model illustrates the cause of those glowing spots; they are caused by concentrations of the electric field around the wire rings. In the model, an observer may note that there is a region with no field lines. This is a limitation in Matlab caused by the converging of the field lines. It can be mitigated by increasing the size of the mesh; however, this mesh coarseness was at the limit of the available computational ability. The general trend of the field may still be observed.

## 4.3 Design Success

The constructed power supply functioned as was required. An oscilloscope was utilized to verify that the output voltage matched what was expected from the simulated results.

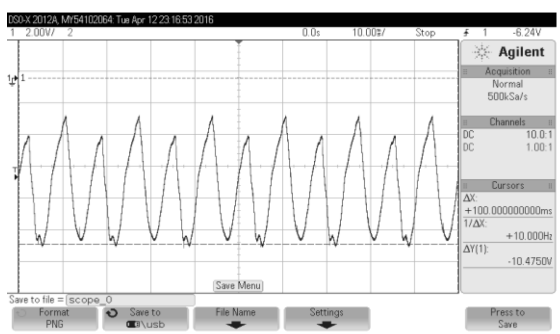


Figure 6. Oscilloscope reading of output voltage from rectifier

Figure 6 shows the waveform recorded from the oscilloscope. The behavior of this waveform accurately follows what was predicted, ensuring that the power supply would be sufficient for the system. No major revisions were required of the electrical subsystem.

## 5. Technical Discussion

### 5.1 Initial Run

The initial run of the fusor was successful in producing plasma. The pressure of the chamber was found to be around 1800 mTorr. The theoretical voltage was transformed into 15000 VAC RMS, which was rectified to 7500 VDC at 30 mA.

As expected, with the vacuum chamber evacuated and the voltage steadily increased from zero, a glow from plasma was observed around the inner grid. This glow is shown in Figure 7. No glow was formed at zero voltage, and the brightest glow was seen at the maximum voltage. While plasma was produced, 'star mode' was not achieved. This means that the plasma was concentrated around the inner grid wires, not focused in the center of the inner grid. The plasma concentration around the wires had a thickness of approximately 1 millimeter. The reason 'star mode' was not observed was that the pressure was not low enough. This indicates that there was an issue with the vacuum pump or gasket seals. As expected, the color of the plasma was a hue of purple. This is because nitrogen is the primary element of air, which gives off a blue-purple glow when ionized[10]. The presence of other elements like oxygen would push the color into the purple range, which is what was observed.

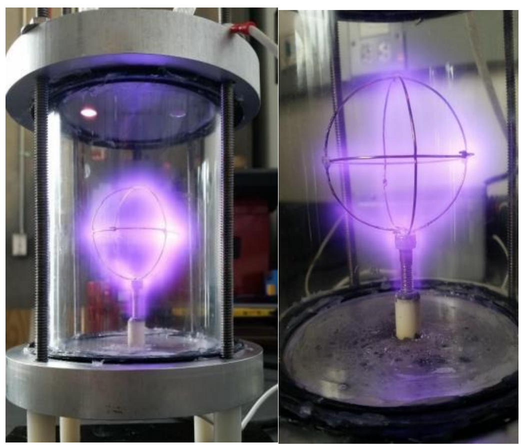

Figure 7. Initial testing results

The initial experimental raised a few additional questions. At the brass nozzle inlet connected to the vacuum gauge, there was a yellow-orange corona glow. This can be seen in Figure 7. It is hypothesized that this was due to a leak somewhere, which also would explain the higher than normal pressures. This matter was resolved in the subsequent runs, detailed in the next section.

At the base of the ceramic feed through on the aluminum plate, a Lichtenberg figure appeared. A Lichtenberg figure is a branching, tree-like pattern that is the result of high voltage electrical discharge through an electrically insulating material[11]. This is undesirable, since it means that there is less power being delivered to the inner grid. There was no arcing between the inner and outer grid; however, a small amount of sparking was observed near the ceramic feedthrough in Figure 7. It was hypothesized that this was due to aluminum oxide on the surface of the aluminum disk breaking down. Aluminum oxide is an electrical insulator, which would allow the Lichtenberg figure to appear[12]. The oxidation of the aluminum plate was due to prior experiments with boiling water at room temperature that were run to test both the validity of the vacuum seal of the chamber itself and the performance of the vacuum pump.

### 5.2 Subsequent Runs

After the initial results of the fusor were collected and observed, adjustments and improvements were made to the design, and included in subsequent tests. The plasma was concentrated in the center of the grid in a more-defined spherical ball rather than on the rings. Pressure was held below 100 mTorr and reached a minimum of 45 mTorr without the applied voltage and 15 mTorr with the applied voltage. For more robust joint integrity, an inner grid was manufactured using no silver solder. This also resulted in longer operating duration due to its higher melting point.

These results confirmed successful modification of the device. Further improvements were limited by the capability of the vacuum pump.

Subsequent runs clearly demonstrated the full capability of the fusor to produce ‘star mode,’ which can clearly be observed in Figure 8. As runs of longer duration and higher voltages were conducted, a darkening of the glass cylinder became more-noticeably apparent, suggesting that this phenomenon was proportional to the applied voltage. This can be seen in Figure 8. This darkening was determined to be a deposition presumably caused by either the gaskets or the vacuum grease. The deposition was focused in a band centered around the inner grid, due to the repulsive effect of the outer aluminum discs along with the attractive effect of the inner grid. Hydrochloric acid was found to be the most effective in cleaning the deposited material.

Figure 8. Final design, ‘star mode’ achieved (left) and particle deposition induced darkening phenomenon (right)

## 5.3 Engineering Standards And Safety

Standards were upheld in various ways throughout the entire design process, the most prominent of which was consulting numerous online and in-text resources to ensure values and equations had valid basis. Numerous simulations were conducted prior to the construction or acquisition of materials to ensure the legitimacy of the design. During the initial test, faculty members from the Oakland University Department of Safety were on standby to ensure safe practice. Once a Standard Operating Procedure had been established, extensive testing through repeated experimentation was carried out to observe changes in the reaction based on modifications to the design. Furthermore, experts in the field of engineering were brought into the scope of the project throughout its development to provide professional opinion and oversee the construction and continued operation of the fusor.

Many components of the design were chosen to contribute to overall safety within the experiment. The greatest contributor was the Variac, which allowed for different levels of voltage rather than simply an on or off condition. Additionally, the emergency stop was incorporated to immediately stop the experiment should an unsafe condition arise. Finally, electrical components required sufficient spacing to prevent the occurrence of high voltage arcing. The full assembly is depicted in Figure 9.

Furthermore, every chemical element requires a specific energy threshold to be met to undergo nuclear fusion. Electrical inputs for the low-powered fusor did not come close to breaching this threshold for even the most easily fused elements: isotopes of hydrogen. By limiting the fusible material to only atmospheric air, the outcome of actual nuclear fusion occurring was virtually impossible.

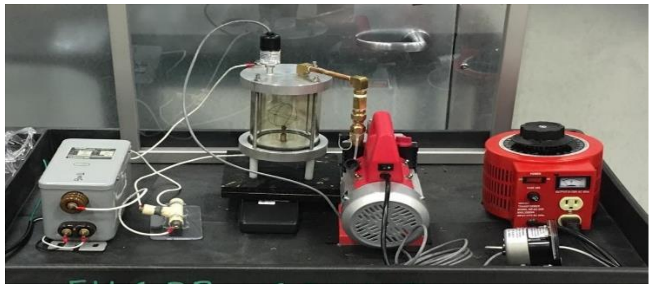

Figure 9. Complete fusor assembly

## 6. Conclusions and Recommendations

The main objectives of building, operating, and testing a low-powered fusor were achieved. Though there was some difficulty receiving funding and other approvals from Oakland's safety committees, these challenges were eventually overcome. The delays, however, caused further auxiliary objectives to remain out of scope such as the construction and operation of a fusion-producing fusor.

Major revisions to the fusor resulted in the overall success of the low-powered fusor, as it achieved 'star mode.' The pressure maintained was not quite below the originally desired 15 mTorr, but it proved acceptable for clearly concentrating the ball of plasma. A strong electric field was adequately maintained to allow plasma formation to occur. In addition, the revisions were noted to apply them to the high-powered fusor and avoid similar problems encountered with the assembly.

Throughout the entirety of this endeavor, safety was maintained as a top priority. Using methods described above, there was little to no risk of injury for members of the team. As the project progressed and further experimentation was conducted, safety considerations were updated and modified to account for changes in design and operation. Several professionals in the engineering field gave critical insight to meeting general guidelines for safety as well.

Moving forward, magnetic fields will be introduced into the inner grid within the low-powered fusor to run final experiments before focusing solely on the construction of the high-powered fusor. To this end, brackets have already been made and magnets have been ordered. The high-powered fusor chamber is in the preliminary stages of construction. The cylindrical design remained the preferred choice for consistency and predictability. Materials have already been acquired and machined to size, and the larger power supply is in the process of being acquired. Deuterium was selected as the reactive material due to its market availability and cost effectiveness. The high-powered fusor will utilize only enough voltage difference to observe a fusion reaction through neutron detection; however, it is imperative to note that the observation will occur in a safe manner. This means that adequate shielding will be in place, the observation period will be very short, and running the fusor will take place in a controlled environment.

## 7. Acknowledgments

Success of this endeavor would not have been possible without the immense support of Oakland University and the Honors College. Through the School of Engineering and Computer Science, the means to purchase materials, receive feedback from professionals in the field, and utilize machines and tools necessary for fusor construction and design were available. The Honors College also contributed a generous amount of funding for the project, as well as provided an endless source of encouragement. Specifically, Dr. Michael Latcha and Dr. Graeme Harper were integral parts of the team and share in the project's success. Many others contributed to the achievement of this undertaking, and while not specifically listed, the magnitude of their efforts is greatly appreciated.

## 8. References

1. Ligon, T., 1998, "The World's Simplest Fusion Reactor, And How to Make Work," Analog Science Fiction and Fact./>:

2. Miley, G. H., and Murali, S. K., 2013, “Inertial Electrostatic Confinement (IEC) Fusion: Fundamentals and Applications,” Springer, New York, NY, pp. 400.

3. Spangler, Dan. Build a Nuclear Fusor. Make. N.p., 22 Oct. 2013. Web. 1 Jan. 2016. <http://makezine.com/projects/make-36-boards/nuclear-fusor/>

4. "Online Catalog." McMaster-Carr. N.p., n.d. Web. 1 Jan. 2016. <http://www.mcmaster.com/>

5. Leader Global Technologies. "Gasket Stress Calculations and Bolting Data."Leader-gasket. N.p., n.d. Web. 1 Jan. 2016.http://www.leadergasket.sk/download.html

6. Friedrich & Dimmock, Inc. "Comparative Values of Borosilicate Glass." Friedrich & Dimmock Glass. N.p., n.d. Web. 1 Jan. 2016. https://www.fdglass.com/pdf/simax.pdf

7. Hull, Richard L. "High Voltage Power Transformers for the Researcher: An Investigation of the Neon Sign Transformer." Electric Spacecraft Journal 1.36 (2002): 15-17. Print.

8. Ramsden, Phil. "Electric Field around a Charged Ring." Wolfram Alpha. N.p., 10 Dec. 2012. Web. 1 Jan. 2016. <http://demonstrations.wolfram.com/ElectricFieldAroundAChargedRing/>.

9. Mandre, Indrek. Off-Axis Electric Field of a Ring of Charge. Ephi - the Simple Physics Simulator. N.p., 1 July 2007. Web. 1 Jan. 2016. <http://www.mare.ee/indrek/ephi/efield_ring_of_charge.pdf>

10. Wiberg, Egon, Nils Wiberg, and A. F. Holleman, 2001, Inorganic Chemistry. San Diego: Academic., Chap. 9

11. “What Are Lichtenberg Figures, and How Are They Made?” What Are Lichtenberg Figures, and How Are They Made?, from <http://capturedlightning.com/frames/lichtenbergs.html>

12. “Resistivity of Aluminum Oxide.” Resistivity of Aluminum Oxide, from <http://hypertextbook.com/facts/2006/EuniceHuang.shtml>