Tabletop Fusion Reactors: Construction and Testing of a Demonstration Inertial Electrostatic Confinement Fusor

by
Logan Reese Holler

A THESIS

submitted to

Oregon State University

Honors College

in partial fulfillment of
the requirements for the
degree of

Honors Baccalaureate of Science in Physics
(Honors Scholar)

Presented June 1, 2023
Commencement June 2023

AN ABSTRACT OF THE THESIS OF

Logan Reese Holler for the degree of Honors Baccalaureate of Science in Physics presented on June 1, 2023. Title: Tabletop Fusion Reactors: Construction and Testing of a Demonstration Inertial Electrostatic Confinement Fusor.

Abstract approved:____

Nuclear fusion reactors comprise a significant field of study due to their potential to provide a limitless, clean, and sustainable source of energy. The inertial electrostatic confinement fusor is a type of fusion-generating device that accelerates deuterium gas to the conditions required for fusion. The goal of this research was to construct a demonstration fusor as an intermediary point in creating a full fusor. We first tested the pressure vessel's vacuum capabilities and the turbomolecular pump's functionality. The resulting vacuum was significantly below the required pressure, showing its ability to function under fusion conditions. High voltage was supplied by a neon sign transformer, which underwent worst-case scenario testing without fault. We introduced a spherical grid to accelerate ions toward the center of the fusor. The demonstration fusor was able to create and maintain a plasma ball, confirming successful construction. The collected data will inform a system model for the full fusor's start-up, incorporating variables such as pressure, voltage, and current. Our results verify the demonstration fusor is ready for further development into an inertial electrostatic confinement fusor. The completed fusor can be utilized as a neutron generator within material testing research for power-generating fusion reactors.

Keywords: Inertial Electrostatic Confinement, Fusor, Fusion, Neutron Generator

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

Logan Reese Holler, Author

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Chapter 1 – Introduction

1.1 – Motivation

Since fusion's first discovery as the source of solar energy in the 1930s, scientists have sought to build a fusion-capable device, resulting in the first fusion reactor patented in 1951 [1]. Over the years, the field of fusion research has seen significant advancements in both the theoretical and experimental departments with a final goal of producing power. The growing global energy needs, combined with the climate crisis, have created a pressing demand for a new source of power. Nuclear fusion power production has become a desirable option to meet these demands. If successfully harnessed, fusion power will provide a consistent supply of energy to power grids, unlike current wind and solar-powered systems. Fusion is also a safe, carbon-neutral, clean energy source, unlike coal, gas, or even modern fission plants.

The tokamak and inertial confinement fusion designs are considered the most promising options for contemporary fusion power plants. Both methods still require extensive research and development. Neither design has produced power due to the largest tokamaks still being under construction, while inertial confinement reactors are still collecting data on proper fuel pellet arrangements [2]. Given the immense scale of these fusion projects, it benefits us to understand fusion's components on a smaller scale to better simulate what will be happening in a full-sized reactor. For this task, our lab opted to use one of the multiple alternative small systems called an inertial electrostatic confinement (IEC) fusor. The IEC fusor is a system that uses an electric potential generated from a high-voltage source to control its deuterium plasma; this contrasts with large fusion reactors which also utilize magnetism. The purpose of this research is to construct and test a modular demonstration IEC fusor. IEC fusors can produce the same reactions as full-scale fusion reactors within an easier-to-manufacture device which justifies the chosen system. The fusor will support the studies of material degradation due to emitted radiation, plasma dynamics, and operate as a scientific instrument acting as a togglable neutron and gamma-ray source for irradiation experiments. Plans include working in conjunction with large fusion reactors and contributing to materials testing necessary for their reactor systems.

1.2 – Nuclear Fusion

Nuclear fusion is the process of two nuclides combining to create a heavier atom, the same process that fuels the stars. Fusion starts within plasma where two light nuclei, called the parent nuclei, collide with enough energy to overcome their repulsion of one another. The byproduct of this reaction is a heavier atom called the daughter nucleus, a subatomic particle, and energy as shown in Figure 1.

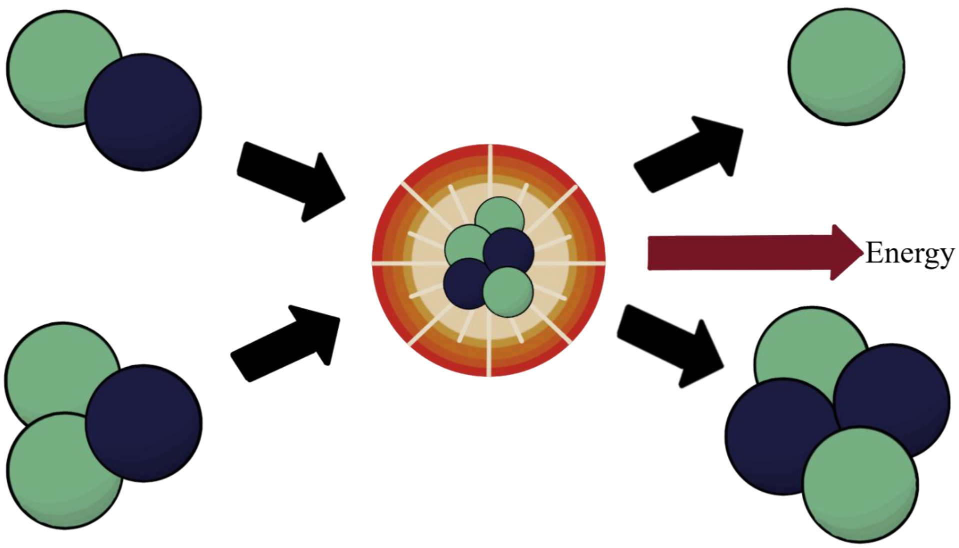

Figure 1: A diagram showing the fusion process. The dark blue spheres represent protons while the green spheres represent neutrons. On the left side of the diagram, two parent nuclei move toward one another and collide. In this collision, the two nuclei fuse into a larger nucleus. This large nucleus is unstable and breaks apart into one heavier daughter nucleus, one subatomic particle, and a release of energy. For the shown fusion reaction a neutron would be emitted as the subatomic particle.

Interestingly, the combination of the daughter nucleus and subatomic particle will have less mass than the sum of both parent nuclei. The energy released in fusion comes directly from this difference in mass, the mass difference converts to an immense amount of energy which is then released in the reaction [3]. This released energy is then transferred between the daughter nucleus and the subatomic particle which are both formed through the reaction. In the case of harnessing fusion on Earth, the main reactions analyzed by the scientific community are deuterium-deuterium fusion (D-D), deuterium-tritium fusion (D-T), or deuterium-helium-3 (D-He3) fusion due the incredible amount of energy that can be produced by a single fusing of these atoms[4]. From D-D fusion a neutron of 2.45

MeV or a proton of 3 MeV is produced, for D-T fusion a 14.06 MeV proton is produced, and for D-H3 a 14.7 MeV proton is produced as shown in the reactions below.

$$ {}_{1}^{2}D + {}_{1}^{2}D \rightarrow {}_{1}^{3}T + {}_{1}^{1}p \quad (3\ MeV) \tag{1.1} $$

$$ {}_{1}^{2}D + {}_{1}^{2}D \rightarrow {}_{2}^{3}He3 + {}_{0}^{1}n \quad (2.45\ MeV) \tag{1.2} $$

$$ {}_{1}^{2}D + {}_{1}^{3}T \rightarrow {}_{2}^{4}He + {}_{0}^{1}n \quad (14.06\ MeV) \tag{1.3} $$

$$ {}_{1}^{2}D + {}_{2}^{3}He3 \rightarrow {}_{2}^{4}He + {}_{1}^{1}p \quad (14.7\ MeV) \tag{1.4} $$

For these reactions *D* stands for deuterium, *T* for tritium, *p* for proton, *He3* for helium-3, and *n* for neutrons. The energy displayed on the right describes the energy imparted into the proton or neutron produced in the reaction. Most fusor designs aim to use D-D fusion as deuterium gas is easily attainable for small systems. Helium-3 is a rare isotope on Earth making it extremely expensive and tritium has tight regulations around the isotope due to contamination risks, resulting in both isotopes rarely being used in fusors. Most large fusion reactors aim to use D-T fusion due to the comparatively high energy release as shown in the equations above. These reactors tend to be large teams working with high budgets, where approval for working with tritium is easier to obtain if proper handling methods are implemented at the site. It is also worth noting that there is no variance to the associated energy for the products of fusion as one would expect with traditional nuclear reactions. This is because fusion reactions can only result in a mono-energetic particle, defined as a single energy particle. As a result, we can expect to get the same energy output from every reaction we get, so to increase the power output the only method is to induce more fusion events. This is one reason why high-energy reactions are suitable for fusion reactors as they produce more energy.

Additionally, high-energy reactions are needed as they must compete with the Coulomb repulsion to produce power. As the protons naturally repel one another, it is necessary to put in an initial amount of energy to overcome the repulsive barrier and collide so that they may fuse. In fusion research the ratio of the total energy into the system versus the total energy produced is called the fusion energy gain factor, normally denoted as Q. It is worth noting that a Q value does not include the energy to start up the reactor, rather only accounting for the energy to sustain a steady state reaction. Following this notation, a Q value less than one is acting in a loss of energy, a Q value greater than one implies a gain of energy, and a Q value of one is “break-even” where there is no gain or loss of energy [4]. As a Q value of one is the initial goal of every fusion reactor currently, the break-even point has a special name of “ignition”, which signifies a landmark success for a fusion reactor. To date, there has been one reactor to achieve a Q value greater than one, this reactor is discussed more in 1.4.2. After achieving a Q value of one, the goal then becomes to increase the value of Q so that more energy is being produced as the number of fusion events increases. Once fusion has begun, the goal of the fusor is to maintain the plasma in a form such that the produced energy can sustain a chain reaction of fusion events and therefore release more energy.

1.3 – Plasma

When enough energy is applied to a gas, the nucleus of the atom begins to move incredibly fast, to the point that the nucleus and the atoms’ electrons are able to separate from one another. This state, wherein nuclei separate from their electrons, is called plasma. In this form, the nucleus is referred to as an ion and the electrons that break away from their nucleus are called free electrons. As ionization is not a threshold state of matter, the number of ionized atoms will increase as the energy of the system is increased. Inside a fusion reactor, the fuel of the reaction is heated tremendously so that the particles are moving fast enough so that they collide with enough energy to induce fusion. As fusion is centralized around colliding the ions, fusion reactors focus entirely on controlling the plasma, particularly the ions inside, to increase the probability of collision. Within stars, plasma is compressed via the immense amount of mass located at the core of a star, but our reactors are not able to generate this same mass density. To achieve the same compression, fusion devices use electrostatics or magnetism. The ions in the plasma can be compressed since the ions carry a net positive charge and interact with the electrostatic fields, magnetic fields, or conservation of momentum via lasers. Within fusion reactors, the goal is to squeeze all of the plasma to a point or along a path so that all of the ions are located close to one another while accelerating them. Magnetic fields are used to both compress and accelerate the ions around the desired path. For inertial solutions, lasers shoot against the plasma fuel pellet using the conservation of momentum to compress the fuel and heat the ions to plasma conditions. IEC fusors accelerate the ions but use a different method. The field generated by the electrostatic potential exerts a force on the ions toward the center of the device. The ions will accelerate to the center of the device and then fly past. As an ion goes past the center of the grids, it will then interact with the field on the other side and be forced back to the origin as shown in Figure 2. This will result in a cyclic path for the ion. If we analyze the path of all the ions there will be an increased density of ions at the center. Through the electrostatic potential, the plasma in IEC is able to generate enough energy and a high enough density to induce fusion conditions.

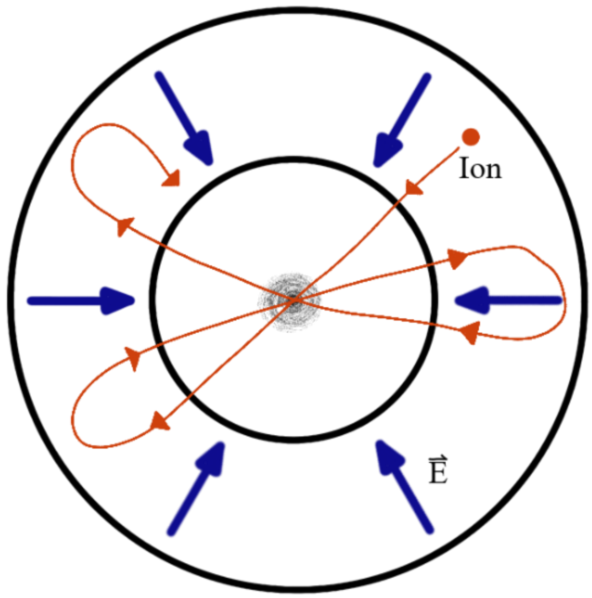

Figure 2: The blue arrows represent the electric field that is generated. The symmetry of the concentric spheres allows for all paths to point to the center of the grids. A shown single theoretical ion caught within the field would be accelerated along the path in orange. As every ion in the plasma will be following a similar path, there will be a high density of ions located at the center, displayed as the dark gradient at the center of the grids. The density of the ions in the plasma should decrease inverse exponentially away from the center.

1.4 – Nuclear Fusion Reactor Design

All fusion reactors aim to generate a high-energy pure plasma that is compressed to the point of inducing fusion within the plasma. Particles need to be accelerated to incredibly high velocities to achieve fusion. This is because the cross section, defined as the probability of interaction with another particle or nucleus, of the fusor fuel increases with the velocity of the fuel nucleus. A higher cross section implies that the reaction is more probable to occur. The relation of the particle's center of mass kinetic energy to the cross section, shown in Figure 3, displays the goal of fusion: to accelerate the ions to high kinetic energies to increase the probability of interaction.

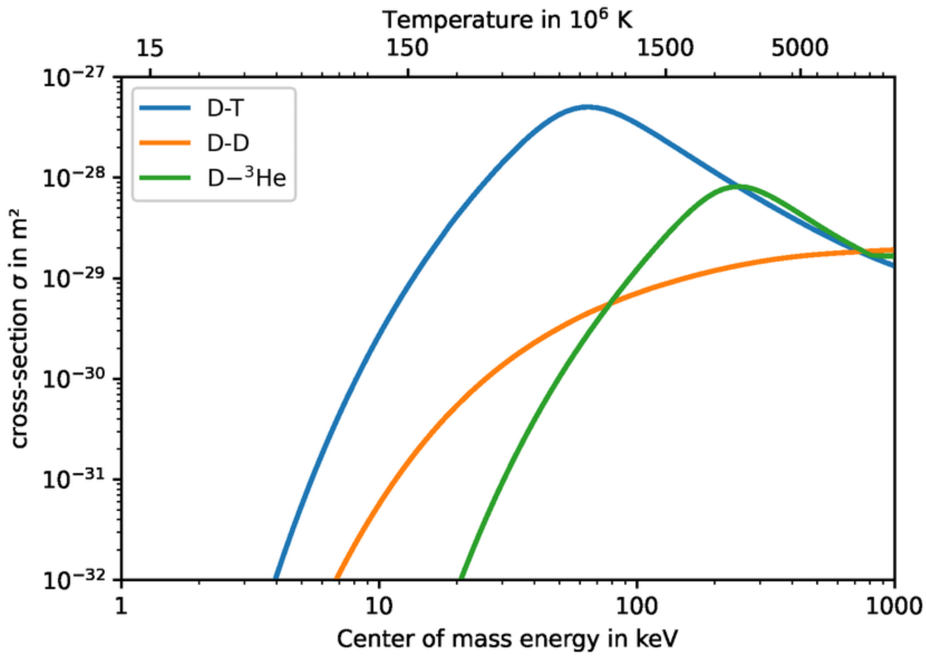

Figure 3: The cross section and temperature of a deuterium nucleus in a fusion reactor are dependent on its energy. As this graph relates to ions, the amount of energy the nucleus has is directly correlated to the temperature. Reactors aim to keep the plasma under an energy level of 100 keV due to associated losses in cross section as shown in the graph. Reproduced from [5].

Another factor is the dependence on how compressed the plasma can become, increasing the density of ions increases the probability of interactions. Each fusion reactor seeks to compress the plasma as tightly as possible through different methods. The key to this process is preventing the plasma from interacting with its environment which would cause it to lose kinetic energy or even potentially destroy its containment vessel. While these two concepts are the most important for designing a system, every design must also account for how they will inject additional fuel into their system as they consume their fuel, how they will confine the plasma of their system, and how they will build proper shielding of the high energy radiation coming out of the system. As all contemporary experiments strictly seek to achieve positive Q values, one major issue of fusion energy will be a method of extracting the energy produced within the chamber. Currently, none of the modern design philosophies have a method to extract the released power and is therefore a task left to the future of fusion once reactors are Q positive.

1.4.1 – Inertial Electrostatic Confinement Fusors

For this research project, the designed system will fall under the fusor family, particularly constructing an IEC fusor. A fusor is a system that uses electric fields to accelerate ions to nuclear fusion conditions. The electric fields are generated by charging a metal grid to a high negative voltage to accelerate ions to the center of the grid while increasing the ions' center of mass kinetic energy. As the ions in the plasma are positively charged, the generated electric field needs to point toward the center of the grid to create a central location where the ions will collide. The use of a spherical grid also allows for universal capture of the ions which will be forced to the center regardless of the path the ion takes away from the core, as shown in Figure 2. The first creation of an IEC fusor was from the Farnsworth-Hirsch configuration which was patented in 1968 by Philo Farnsworth [6]. The designed setup included charged concentric metal grids designed to accelerate deuterium particles generated from ion guns. From the Farnsworth fusor came a new design that eliminated the ion guns, instead using deuterium gas which would be controlled via an electric field generated by the grids, a design proposed by Robert Hirsh [7]. The design and resultant electrostatic potentials are shown in Figure 4. A negative polarity high voltage central grid is made concentric to a grounded outer grid, this results in electric field lines that point radially towards the center of the grids. The grounding of the outer wire simply allows the generation of slightly more symmetric field lines rather than letting the higher voltage be generated from the grounded walls of the chamber.

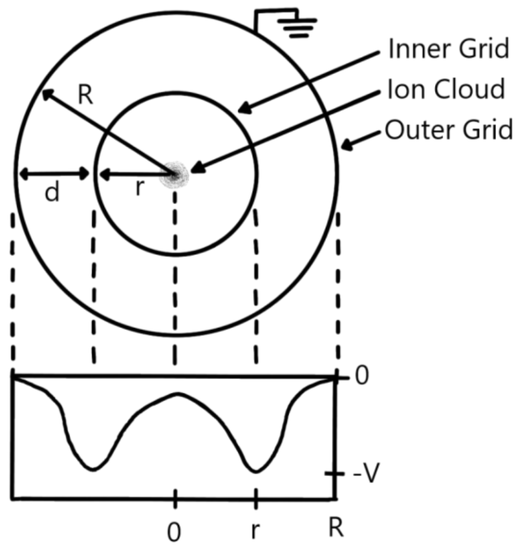

Figure 4: Showing the electric potential within the system with respect to its location radially from the center of the grid. The outer grid located at radius R is held at Earth ground and the inner grid with radius r will have a negative electric potential. The rise in the electric potential at the origin is also due to the increased density of ions, which hold only positive charge, located at the center of the system.

IEC fusors are currently not contenders for potential fusion power generation and will likely never have net positive power output [8]. This is due to the high inefficiency of the system design utilizing the grids to induce an electric field. The use of metal grids provides a physical barrier along the path of the ions which causes energy loss as collisions occur with the grid. Another standing issue is the spherical electric field generated by the use of thin wires. The ideal case would be an ion-path transparent, fully spherical charged grid for perfect uniform acceleration. As that is not possible, it is necessary to balance the losses due to grid collisions with regard to imperfect field generation. Despite these flaws, fusors still have utility as neutron generators for various experiments. Fusors have a wide application in both research and commercial uses due to their mono-energetic neutron generation capabilities; this allows for constant neutron activation of a target to observe how the neutrons interact with the materials. The closest connection for research is to larger fusion reactors that need to test reactor components which will be expected to remain durable under constant neutron bombardment during the fusion reactors' sustained operation. There is also potential for IEC fusors to investigate medical isotope production or neutron radiography, though such processes would require minor modifications to the fusor to complete these tasks.

1.4.2 – Reactors

The goal of a fusion reactor is to compress the fuel while heating it to temperatures that drastically exceed the temperature of stars. The reason for such high temperatures is that we seek to replicate the stellar fusion conditions but we are not able to produce the same level of pressure that would be found at the core of a star. Consequently, we must opt to increase the energy of the ions so that they overcome their repulsion forces and begin to fuse. While fusion reactors can function with all four fuel types detailed in section 1.2, the primary reaction for fusion research is that of D-T fusion due to the increased level of energy output as shown in equation #1.3. The reason that D-He3 fusion is not commonly suggested is that He-3 is an expensive isotope that is hard to come by naturally on Earth and so the costs of the fuel currently exceed the production value.

The first fusion reactor was the stellarator proposed by Lyman Spitzer which sought to twist the plasma in a helix shape [2]. The stellarator design is focused on heating and compressing the plasma to induce fusion conditions for the ions in the plasma using magnetism. The stellarator design was quickly optimized and modified into the modern tokamak design which uses the same magnetism principle as the stellarator. The key difference between the two is the shape of the confinement and magnet structure. Stellarators use a helix-shaped confinement to induce twisting in the plasma, tokamaks instead use a torus-shaped containment and use their magnet structure to twist the plasma. The largest tokamak experiment currently in development is called the International Thermonuclear Experimental Reactor (ITER). Currently, thirty-five nations are collaborating on the ITER tokamak reactor which is predicted to have a Q value of ten making it one of the largest net-positive tokamak designs [9]. Should the design be successful, the plan is to use ITER in the development of smaller test reactors and then use it in the development of fusion power plants.

The second most common design for fusion reactors is the inertial confinement reactor. This design focuses more on compressing the fuel rather than superheating it by using high-energy lasers to cause the fuel pellet to collapse. The largest inertial confinement reactor is located at the National Ignition Facility which houses 192 of the strongest lasers in the world. Their model is based on firing all of the lasers at the same time at different points around the fuel pellet and having the lasers reflect off of the pellet [10]. Due to the conservation of momentum, the fuel inside of the pellet should become increasingly compressed until D-T fusion is possible and helium is released. On December 5th, 2022, Lawrence Livermore National Labs achieved the first-ever Q positive reaction utilizing inertial confinement. This ignition event is the first time in history that a Q value greater than one has ever been recorded [11]. This is a landmark success for fusion devices proving they can produce energy.

IEC fusors have the potential to benefit both of these designs through their developmental phases working through both of their standing issues. For tokamaks, IECs are usable for plasma modeling and control, particularly as magnetic systems can be added on top of the electrostatic confinement to better mimic tokamak's behavior. For inertial confinement, IECs with a high enough voltage grid could compress the plasma to a level that could simulate the compressed fuel pellet in an inertial confinement test. Both tokamak and inertial confinement designs can be better informed by IECs by exploring the effects of neutron irradiation on reactor-building materials. This is because the reactors lack a way to control where the generated neutrons go, particularly since neutrons are neutral particles, meaning they do not interact with electric or magnetic fields. All materials closest to the fusion reactions need to be tested for receiving high neutron fluxes. IEC reactors are well suited for this task as a high neutron flux can easily be produced allowing for materials to be irradiated. As IEC reactors operate with the fusion processes in equations 1.1 - 1.4, they can produce a specific subatomic particle, or daughter nucleus, to irradiate a material with.

1.5 – Utilized Fusor Design

The IEC fusor that we are constructing is the Hirsch fusor design, utilizing high negative polarity voltage to induce fusion at the center of our chamber. This fusor design was chosen by Jacob Van de Lindt who first began the project but was forced to change projects to modeling the IEC fusor due to the COVID-19 pandemic [12]. The Hirsch fusor was preferred due to its relative simplicity when compared to the Farnsworth fusor design. It also has relatively good documentation online as a community of scientists has set up an online forum of amateur IEC fusor creators who have been building and analyzing fusors for the past few decades. For these designs, the only major issue to contend with is the need for a high voltage, negative polarity, direct current (DC) power supply which is not a common device in contemporary machines and was predominantly used in older technologies such as X-ray generation machines. However, there are recent research teams producing modern power supplies that are able to continue advancing the field of IEC fusors [13].

As the proposed fuel is pure deuterium gas, the common reaction should be D-D fusion with the subatomic particle we measure being the 2.45 MeV neutron detailed in equation #1.2. The Oregon State University Nuclear Science and Engineering (NSE) department has an interest in the device as it can act as a quick-start monoenergetic neutron generator. Modifications to the reactor system are also simple which would allow the NSE department to add modules to the reactor for any additional data that they would like to extract from the system.

Chapter 2 – Methods

2.1 – Initial Construction Plans

The original plans for the Oregon State fusor were drafted by Jacob Van de Lindt. The fundamental requirements for a fusor to operate are as follows: a pressure vessel capable of holding high vacuum, a vacuum pump, a gas feedthrough for the deuterium gas, metal grids capable of holding high voltage and low current, and a power supply capable of providing negative polarity direct current (DC) high voltage. Additional components are required for monitoring the system and to allow for data collection. Upon taking control of the research, the current systems in place were the pressure vessel, a vacuum pump, and a step-up transformer. The pump was already integrated into the system but the step-up transformer did not have a method for powering the internal grids nor a rectifier to convert the alternating current (AC) to DC. Upon first research findings, it was determined that the provided vacuum pump would not be able to achieve the level of pressure required for fusion conditions and the step-up transformer was not capable of operating in fusor conditions. Upon documentation of the above points, we decided to fully restructure the system in place, excluding the initial pressure vessel. We introduced our own goal to make the system more modular, allowing for the alteration of constructions for optimization tests. The proposed fusor system should be predominantly operated through D-D fusion as pure deuterium gas will be the fuel within the system. The D-T and D-He3 reactions detailed in equations #1.3 and #1.4 will only occur from helium-3 and tritium produced by D-D fusions in the system; there should be minimal levels of tritium and helium-3 in the system due to relatively small operation timeframes. With these considerations in mind, the first constructions of the fusor began with the first target being the construction of the demo fusor. The overall design of the fusors systems is shown in Figure 5 which includes all design considerations for the demo fusor.

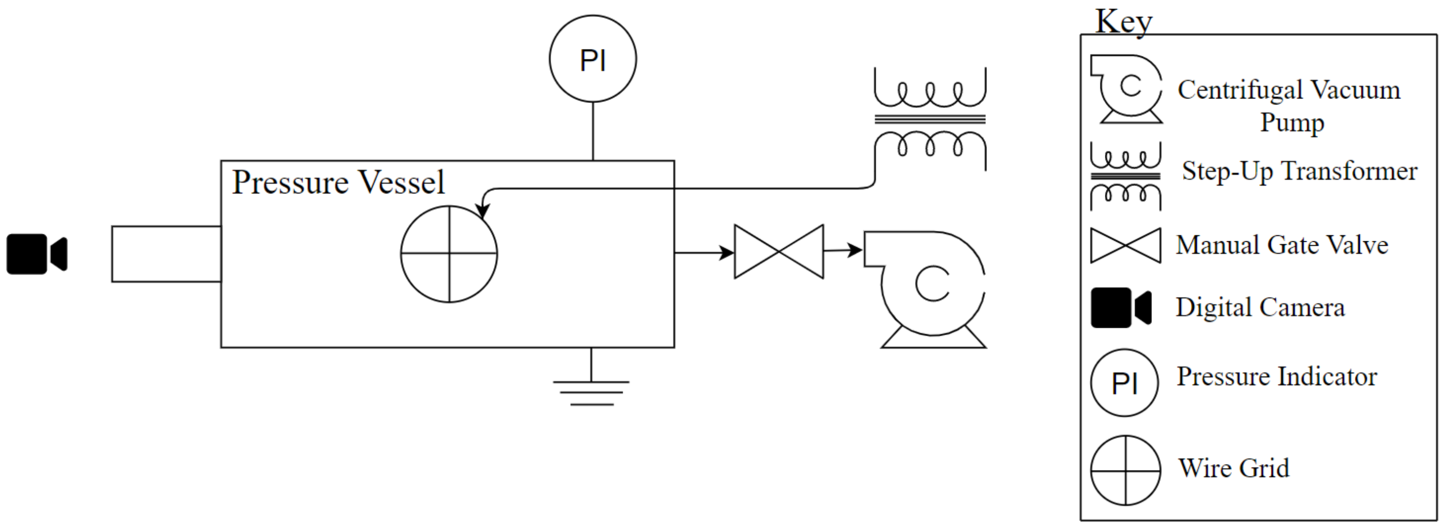

Figure 5: The overall system design for the demo fusor. The main component to which all systems are connected is the pressure vessel. This includes all the required tools for plasma generation and testing. The centrifugal vacuum pump and valve are used to control the flow rate of the gas out of the chamber. The step-up transformer is used to power the grids which then accelerate the ions to create plasma. There are also the components of the digital camera and pressure indicator which are used to help in controlling the system during plasma tests. The digital camera looks through an add-on viewport on one end of the chamber. The wire grid should be located central to the grounded pressure vessel to better form the generated electric field.

2.2 – Overview of Demo Fusor Versus Functional Fusor

Fusors have two goals within their development timeline, the first goal is to develop a demo fusor that can behave and operate like a fully operational fusor but is not able to produce a countable number of neutrons. The primary reason for this issue is that demo fusors lack the level of voltage necessary to accelerate the ions' center of mass energy to fusion levels. For this paper, a functional fusor refers to a fusor that is set up to the point that it is capable of generating neutrons from D-D fusion reactions. As we do not expect a demo fusor to achieve fusion results, it is not necessary to implement a form of deuterium gas injector yet. Once the demo fusor is transformed into the functional fusor, the gas feedthrough system will need to be introduced. Another consequence of minimal neutron production is the fact that neutron and gamma-ray shielding does not need to be introduced as the majority of risk is mitigated by the stainless steel vessel as well as by maintaining a distance of five feet between the operators and the fusor's core. The purpose of the demo fusor is to act as a check-in point in the development process to ensure that proper progress is being made in the development of the functional fusor. The demo fusor and the functional fusor should operate under the same methods of plasma generation. As such, demo fusors also allow operators to become familiar with the process of fusor mechanisms in a safer environment while using more replaceable components in the event of device damage while the fusor is powered.

The demo fusor has the operational goal of ensuring that all major and minor systems of the fusor are functioning as intended. The demo fusor is useful in spotting future issues that may emerge as the project progresses. The successes of a demo fusor's major systems are marked as the ability to hold the pressure vessel near high vacuum, to read the pressure inside of the chamber, charge the central grids to the desired voltages, have the grids maintain form as the temperature of the wire increases, and ensure no arcing from the grid to the pressure vessel. Minor system successes are determined by the ability to measure the voltage of the wire grid, the current flowing through the grid, and remote observation of the plasma formed in the core of the fusor. This plasma acts as a clear indicator of success. The formation of plasma at the center of the grid indicates all major systems are operating without critical failures. The minor systems are continuously checked for success as they simply act as input-output devices, thus a reading indicates the success of the system. Upon plasma formation, the construction has been completed to the demo fusor target and can then be adapted to a functional fusor.

The transition from a demo fusor to a functional fusor is primarily a change between power systems and the gas inside of the chamber. The first task is to increase the center of mass energy of the deuterium to above 20 keV to cause substantial fusion reactions [14]. The second alteration is a new system designed to introduce deuterium gas to the chamber, allowing for the desired D-D fusions to occur. As fusion will begin with these two alterations, proper neutron and gamma irradiation shielding would need to be introduced. It would also be ideal to reform the control system so that the majority of the fusors subsystems are operated through a single terminal. This would also allow for more accurate measurements of pressure, voltage, current, and neutron counts and be able to correlate each set of the collected data.

2.3 – Vacuum System

The functional motivation for the vacuum in the fusor is to increase the mean free path (the average distance a particle travels between collisions) of ions in the chamber. The particles in the plasma need to have long enough mean free paths such that they are able to accelerate to fusion levels before colliding with another particle. One method is to reduce the total number of particles which will increase the mean free path length of each particle. However, operating the chamber at too low of pressure would result in there not being enough fuel ions in the plasma system to achieve practical fusion levels. The mean free path would not be the same across the entire plasma as the ions would conglomerate at the center of the grids with decreasing density radially. This allows ions to accelerate outside of the center and then be recirculated. Another requirement is the pressure around the grids needs to be lowered substantially as operating high voltage systems at air pressure would result in melting the grid connections due to the high currents needed for fusion conditions. One important concept is the distinction between microns and torr which relates microns to millitorr approximately 1:1000, respectively. Torr is used when discussing high vacuum systems while microns will be used when discussing plasma condition pressures as it allows for the use of whole numbers. For both the demo fusor and the operational fusor, the goal is to operate around eight microns of gas pressure in the chamber [7]. At this pressure, we can balance voltage and current to the pressure and achieve ideal fusion results. As the applied voltage becomes higher with better sources it is possible to lower the pressure.

A goal of the fusor is to be able to lower the pressure past what is required to operate. To combat this it is necessary to get a pump that is able to achieve vacuum levels below operational pressures on its own. For this task, our team purchased a Pfeiffer Vacuum HiCube 80 Eco turbomolecular pump seen in Figure 6.

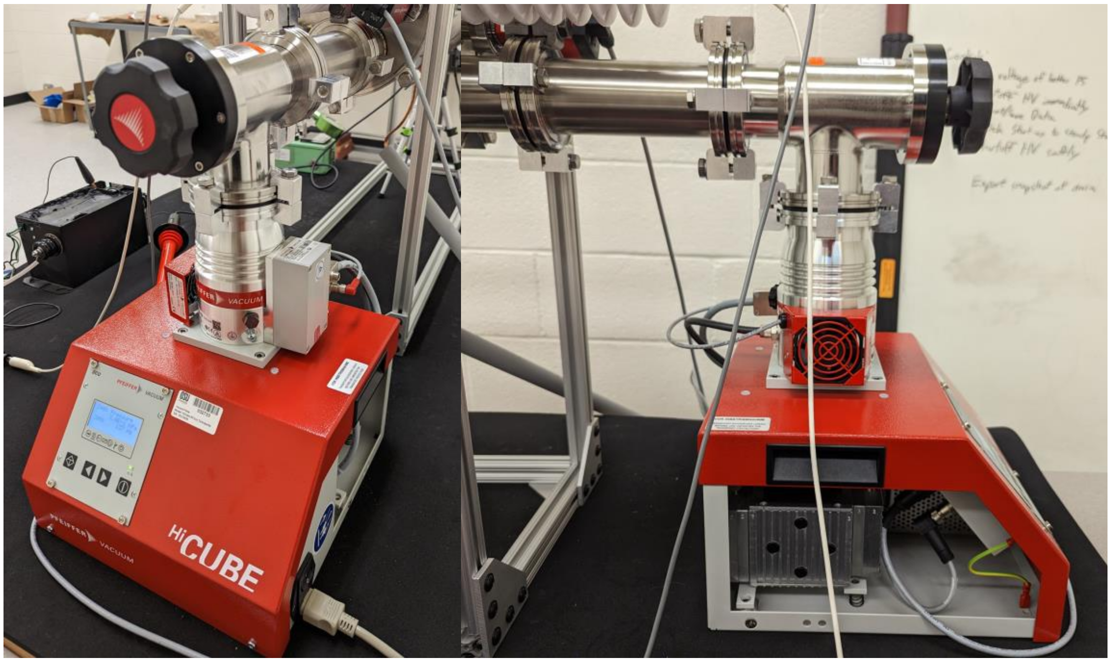

Figure 6: Imaged is the HiCube 80 turbomolecular pump configuration. The system uses two pumps, a turbomolecular pump, and a backing pump. The turbomolecular pump is the flared silver cylinder on top of the case and the backing pump is only visible in the right image as the silver cube seen inside the case. The pump system is controlled by a display and control unit embedded into the case which is visible in the left image. Finally, the turbomolecular pump connects to a valve seen above the turbomolecular pump which then connects to the chamber.

This pump has a target vacuum pressure of 7.5E-8 torr which takes the pressure close to the edge between high vacuum and ultra-high vacuum. There are a collection of reasons why such a low pressure is useful within the chamber. For both fusor types, when in the operating pressure range, small variations in pressure can result in the fusor’s pressure becoming too high and the plasma ball not forming. The reason that pressure can increase would be due to vapors escaping from the walls of the chamber, predominantly water vapor trapped in the stainless steel. By increasing the pump’s power, more water vapor can be extracted from the chamber. This can be enhanced by a process called a bake-out where heating the walls of the chamber will heat the absorbed water and allow it to escape the walls. This reduces the number of particles leaking into the chamber when the valve is closed and the turbopump no longer lowers the pressure.

2.4 – Grid Systems

The grids are one of the most important parts of the fusor as the grid determines the shape of the electric field that accelerates the ions to fusion levels. As mentioned, a perfect grid would be a perfect sphere of negative polarity charge that did not interact with the ions. Since this is not possible, an approximate grid needs to be made out of wiring. The wires that make up the grid have to be large enough to provide ample current and not melt if the grid temperature increases. The addition of more wires, or larger wires, will make the electric field more spherical, however, increasing the size of the grid introduces more physical barriers for the ions to collide with. We designed a grid utilizing three rings of tantalum wire placed along all three Cartesian axes as shown in Figure 7.

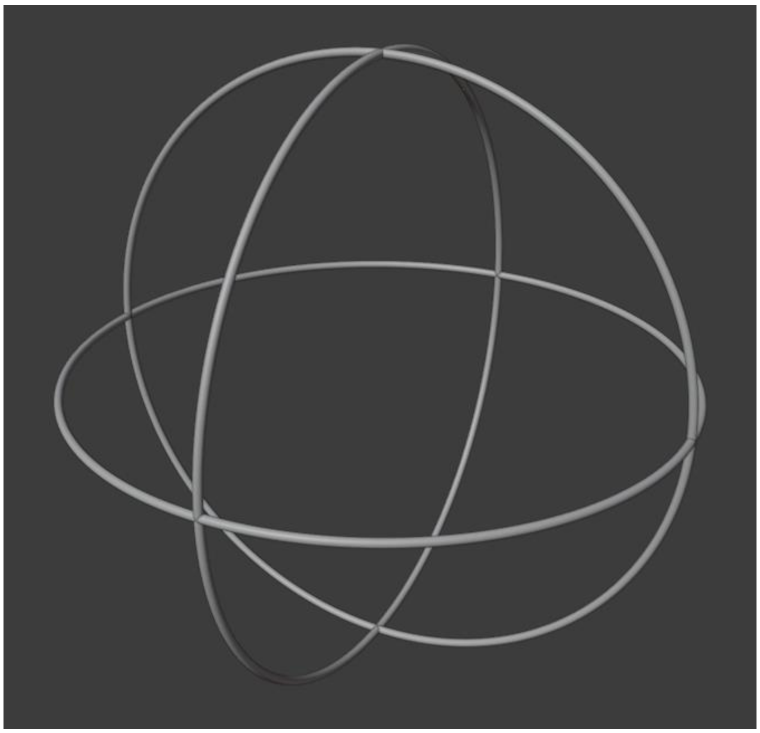

Figure 7: The design primarily used for the fusor grid modeled in Blender. Three concentric spheres of the grids are used to form a spherical grid. For different tests, small alterations were made to the system, particularly the size of the sphere as well as the number of wires used. Although each joint is shown as being perfectly embedded, in actuality, the welds left small deformities in the grids which altered the electric field slightly. These changes should minimally impact the performance of the plasma.

If the pressure is too high, it is possible that the grids themselves could become incredibly hot. It becomes important to use a metal that has a high melting point so that the current flowing with high voltage does not deform or melt the wires. For this task tantalum wires were used due to tantalum's naturally high melting point. The joints where each ring is connected were joined via silver solder which has a lower melting point compared to the tantalum.

Ideally, the grid would be able to directly connect to whatever system is introducing power from outside the chamber to inside. In reality, this would not be possible as it would put the high-voltage grid too close to the chamber walls which would cause arcing to occur. To keep the grid centralized, a hollow ceramic stalk and 3D modeled and printed base were used. The stalk used was ceramic as ceramic is a non-conductive material that can withstand cracking from very high temperatures. A nonporous alumina ceramic tube was also chosen due to having a small neutron capture cross section for fast neutrons. This leads to the ceramic lattice not frequently being disrupted from the continuous neutron generation. However, the ceramic will also act as a physical barrier for ions and as such should be small to reduce efficiency losses [15]. A tungsten wire, chosen for its high melting point, was then fed from the grid, through the ceramic stalk, and attached to the high-voltage connection. As the wire could not get too close to the chamber walls, a small hole was cut into the ceramic from which the wire was fed through. As the stalk is a thin cylinder, it would not be possible to connect it to the chamber wall on its own. For this task, a 3D base was modeled and printed which would hold the ceramic stalk in place. The only requirements were that the base would fit on the plate between the feedthrough and the vacuum pump piping, as well as be able to hold up the ceramic rod without drooping. The best style of the base was developed through trial and error and is shown in Figure 8.

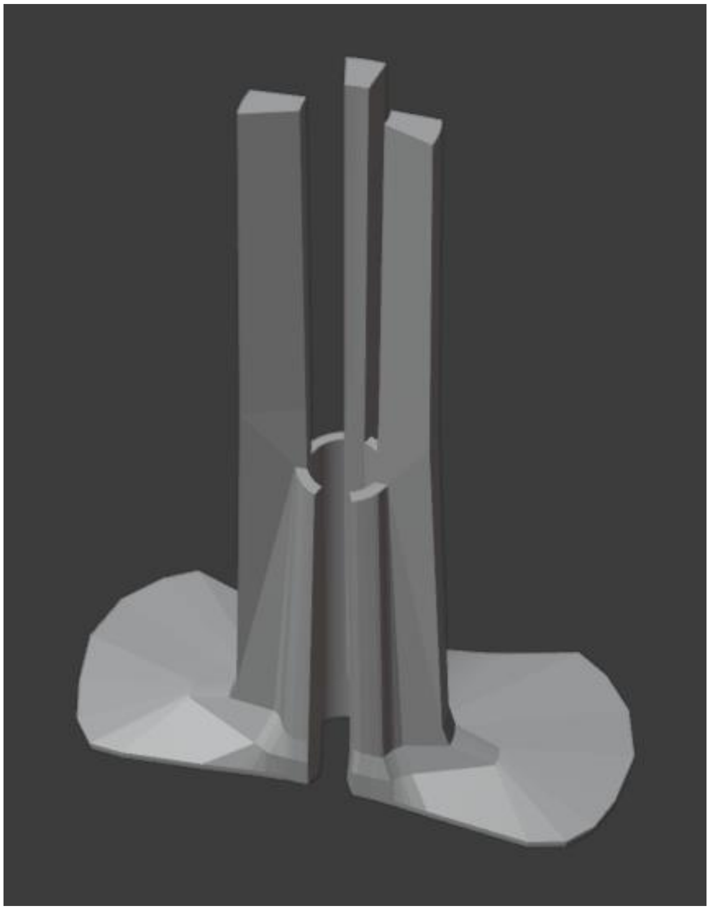

Figure 8: The base used to support the grid modeled in Blender. The wings of the base are connected to the plate while the ceramic rod is held inside the hollow cylinder. The empty gap on the side of the base is added so that the wire can enter the ceramic rod. This also prevents the plastic from connecting to wires which may become hot to the point of melting the base. The wire then connects to the grid on the opposite side of the base.

As it was a concern that the 3D printing plastics would melt when subjected to the functional fusors temperatures, the material of the base would have to change. For this process, the same 3D model of the base was used. The aim would be to use a similar ceramic to the stalks so that the thermal expansion coefficients would be similar. This way the base and stalk would expand at the same rates and no compression cracks would form. The conductivity of the high voltage in both cases is not a concern as the ceramic and plastics used in 3D printing are not conductive materials. However, for the demo fusor, the 3D-printed stalk was used and fully functional in these operational conditions.

2.5 – Power Systems

The power systems for any IEC will always be the most hazardous part of the entire build. The voltages required to operate a fusor are at a level that contact with any hot lead would be lethal nearly instantaneously. This is because the high voltage is constantly sourced at 30 mA of direct current which is associated with muscle lock. Once muscle lock occurs the individual would have sustained contact with the hot lead from which the constant voltage would then induce atrial fibrillation or stop the heart entirely [16]. With this in mind, safety becomes paramount to the design of each power system alongside its functional design. Safety guidelines enforce distance from any high-voltage system. Distance is one of the most effective and simplest protections from high voltage. In case of the chamber walls becoming charged via arc or faulty power designs, the grid and all systems are connected to Earth ground. In case of an emergency where someone would have to interact with something potentially charged, 80 kV high voltage insulating gloves are required to be worn. For the fusor's construction, the first challenge to address is transporting the power from outside of the chamber to inside of the chamber. For this task, a high-voltage feedthrough needed to be added to the chamber. A 100 kV feedthrough, seen in Figure 9, was chosen as this would allow for the fusor's power supply to be variable across a large range of voltages while keeping the metal grid and any connected devices safe from electrocution.

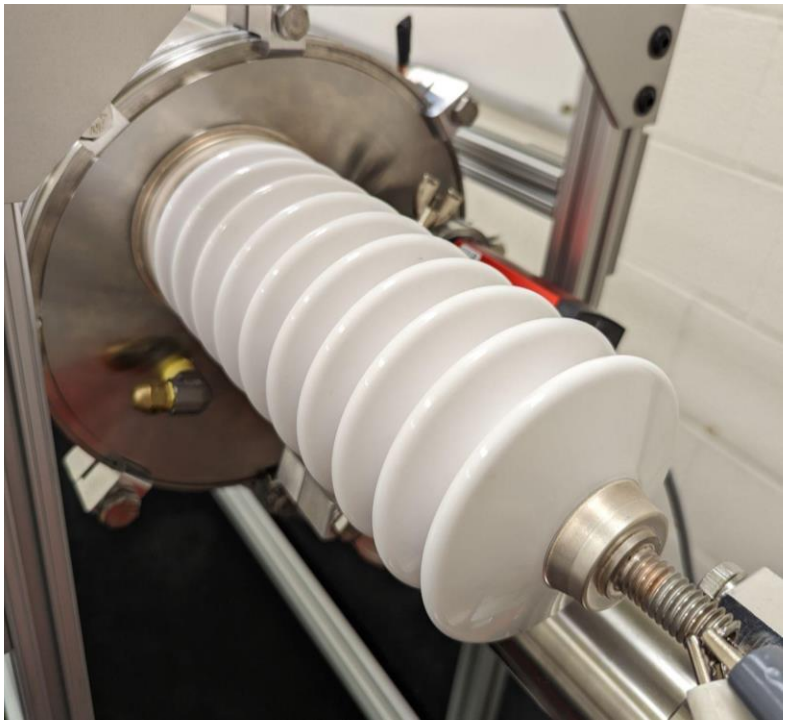

Figure 9: The 100kV high-voltage feedthrough into the pressure chamber. The device uses flared ceramic in order to prevent arcing from the wire in the center toward any surrounding systems. The NST is connected to the outer terminal of the feedthrough which then passes the power to the grid. For the functional fusor, additional arc shielding may be required to prevent arcing to the vacuum pump piping, which would destroy the vacuum pump systems.

The goal of the power supply is to provide a negative polarity DC at high voltage to the grid inside the chamber. The negative polarity is necessary to control the ions which are positively charged. This way the ions are forced toward the center of the grid as shown in Figure 2. Direct current is necessary as the internal grid needs to be charged to a high voltage rather than have the current flowing through. As the current provides a high voltage to the grid, a moderate current is necessary to accelerate the ions to the fusion levels discussed in 1.4. These would be the requirements for designing both the demo fusor and functional fusor's power supplies.

2.5.1 – Demo Fusor Power

The demo fusor's power supply essentially acts as a trial run to ensure that the initial setup for the fusor is done properly and to troubleshoot errors with the system. As such, there is no need to supply incredibly high voltage to the grid, rather just enough power to form a plasma. However, this voltage is still at lethal levels of voltage and current, as such a foot pedal was installed for the demo fusor so that, in the event of electrocution of the operator, the foot pedal would no longer be depressed and would cut off the power supply. Since the current supplies high voltage to the grid, a minimum level of current is required to ensure the grid is properly charged. Through experimentation, it was determined that fusors should aim for 15 milliamps to achieve fusion goals [17]. Although the demo fusor does not aim to achieve fusion, staying above this current simply ensures that plasma will be able to form in the chamber. A suitable candidate for this role in the demo fusor comes in the form of a Neon Sign Transformer (NST). These devices are ideal as they are specifically designed to maintain plasmas within neon signs, a similar event as to what will be occurring in our fusor. An issue is that the voltage and current need to be variably controlled but the NST outputs a single voltage and current. To allow this control, the NST is connected to a Variac Variable Voltage Regulator (VVR) to allow us to increase the output of the transformer slowly. The NST we are using is a step-up transformer that can supply a root-mean-square voltage of 15,000 volts at 30 milliamps of AC output.

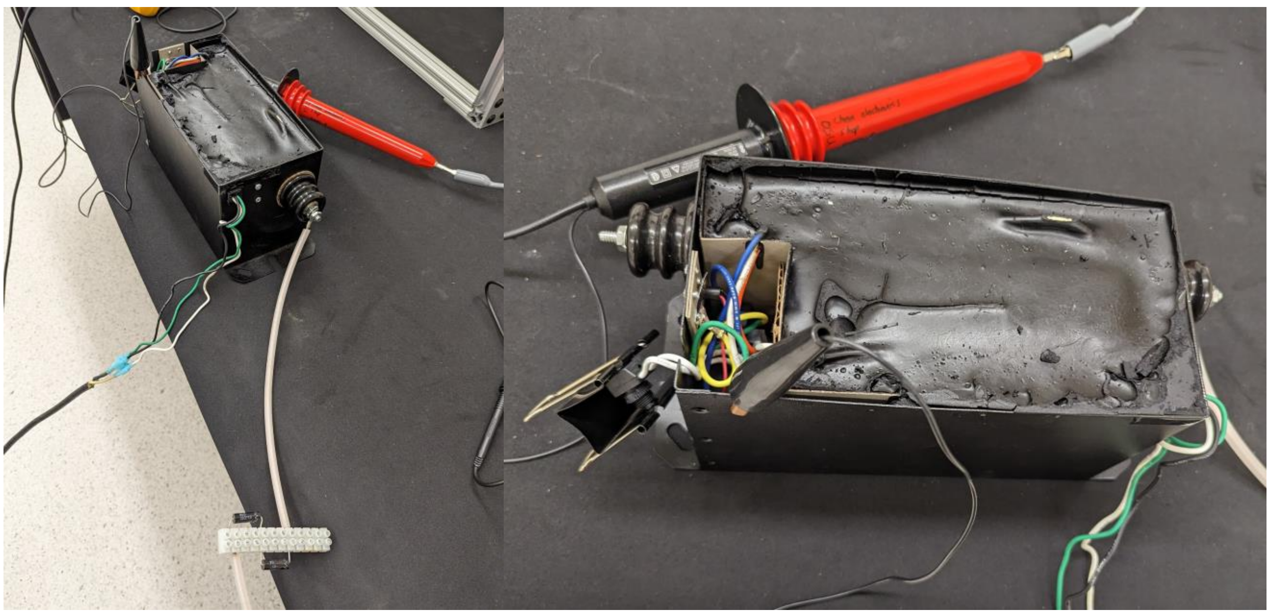

Figure 10: The left image shows the NST connected to the diode ladder which rectifies the output voltage. The use of black insulating rubber and insulated wires is to prevent any chance of arcing to the table itself. The top of the case is removed so that voltage can be measured from the case ground and so that a clip can depress the safety-bypass button. This button prevents the shut off of the transformer in the event of sustained arcing events to which high voltage plasma would simulate during backflow. The safety bypass being engaged does not increase the risk to operators as it only affects the system while powered. The top of the case being removed does not increase the risk of failure or injury, again because operators should never be interacting with the transformer while powered.

To convert the AC into the required DC, a diode circuit was constructed to rectify the product of the NST. The combination of these systems is seen in Figure 10 where the AC output flows into the diode ladder. The rectifier only allows for half of the waveform to travel through its configuration. As maximizing voltage is not necessary to the demo fusor, a half wave rectifier was used rather than a full wave rectifier which limits the usable voltage to half the total output but at the benefit of being a simpler system. Using the half-wave rectified DC does have a drawback in that the supplied power to the grid comes in pulses rather than as a continuous current. There is also the issue of the ripple effect, essentially a small unwanted AC signal that fails to be filtered out but is mitigated as much as possible by the diodes [18]. These both are reasons why the demo fusor is not capable of generating neutrons in our configuration. Another issue with our NST is due to fault protections built into the system. The ions in the center of the grids act as a virtual anode; as the grid voltage increases, so do the number of ions which then generate a stronger electric potential. If the number of ions becomes too great, the NST may detect this virtual anode as an arc fault and shut itself down. For lower voltages this can be dealt with by activating the service bypass mode which removes some protections, however, the transformer will still stop at very high voltages if the pressure is not lowered enough. Once the NST can sustain the plasma with the fusor in its configuration, the goal then becomes to begin altering the fusor into the functional fusor.

2.5.2 – Functional Fusor Power

For this project, only the demo fusor was able to be constructed; however, I will also discuss the goals and project constraints for the system used to modify the demo fusor into its functional fusor form. The selection for the functional fusor power supply must meet the same requirements of the demo fusor but be able to do so to greater effect. Although the goal is to increase the voltage as much as possible, as always, the first consideration for the power supply should be its safety. As the goal is to take the functional system to a drastically higher voltage than the demo fusor, to maintain laboratory-safe conditions a high-voltage power supply will be purchased rather than constructed. As an upper limit, a power supply capable of providing greater than 100 kV is not necessary as the risk of such high voltage begins to outweigh the benefits of higher voltage. For our project, a power supply with a target maximum voltage somewhere in the range of 60 - 80 kV was set as the goal to generate high levels of neutron generation. The power supply also needs to be capable of variable voltage output as we need to slowly increase the voltage of the grid to condition the plasma as the voltage is increased. There is also a limit to the current of the power supply; again, fusor conditions begin to take off at 15 mA but generally aiming for more current is better with good operation at 30 mA [24]. The manufactured DC power supplies' constant DC voltage should also help with this conditioning as there will be no current pulsing as is present in the demo fusor. This way the electric field should remain drastically more constant and allow for even acceleration of the ions. As mentioned, a higher current is good as more high-voltage electrons on the grid help produce more symmetric electric fields.

The power supply will also need to be operational with a virtual anode forming at the center of the grid which will impact its voltage output [25]. In essence, the virtual anode can be thought of as a capacitor when analyzing the power flowing to the grids. As the virtual anode forms, the effective voltage of the grids will drop as though a capacitor is being charged. If the ball of ions becomes too large while charged, it could discharge to the grid and send a positive charge to the power supply. In the demo fusor, the diodes will be able to neutralize this effect but the functional fusor power supply will need to be purchased with this limitation or it must be designed out of the system with diodes. While the power supply will need to be designed for this potential backflow event, it may also need to be able to operate in rapid discharging too. In a perfect system, no arcing should occur within the chamber. However, there is a high possibility that improper geometry or increased pressure could lead to arcing in the system. As such, the system will need some form of arc protection or be capable of sustaining power during a brief arc event. This device will be the most complex in the functional fusor and as such will be the most expensive to purchase and the most difficult to introduce safely. Design, integration, and operation should be checked through multiple safety briefings before any actual experimentation occurs with such a device.

2.6 – Deuterium Gas Feedthrough

As mentioned, the target reaction within this fusor will be generated via D-D fusion reactions. The fuel of the fusion reaction will then come directly from pure deuterium gas which is stored in a pressurized bottle. The bottle will need to be designed so that it may leak deuterium fuel into the chamber while the fusion reactions are occurring. This slow addition of deuterium gas during operation will be necessary as the D-D, D-T, and D-He3 reactions will slowly use the deuterium ions in the chamber. The goal is to keep a consistent pressure in the chamber so that the reaction rates can remain uniform thus providing a constant source of neutrons. As the bottle will be pressurized while the chamber is held at a high vacuum, a system will need to be in place so that the deuterium gas does not flood the chamber. For this process, an electronic valve and a needle nose valve are proposed to control the flow rate of the deuterium gas. The needle nose valve will reduce the overall flow rate to the device which is necessary due to the vast difference in pressure. The electronic valve would be used to allow for more modular, remote control of the gas flow system. The electronic valve could theoretically be replaced with a manual valve, however, this increases risk as it would involve an operator approaching the device while in operation. This increases the chances of electric shock to an operator as well as the risk of irradiation as changes to the flow rate should only occur during device operation meaning ionizing radiation would be generated. As the relative pressures between the deuterium bottle and chamber pressure change, the opening of the electronic valve will need to change in proportion to maintain steady-state conditions which could be integrated with computer controls. While there is currently a gas port located on the device, there have been no other design considerations as to the rest of the fuel-supplying subsystem.

2.7 – Radiation Detection

As neutrons are the desired product from our fusion reactors, a neutron detector will be the main focus of our detection system. However, there will also be other products from the reactions such as high-energy gamma rays, protons, and potentially beta emissions from the tritium. For these other reaction products, a general Geiger-Müller (GM) counter is capable of detecting these particles like the one in Figure 11. Within this laboratory setting, both detectors should be used for measuring overall irradiation risk.

Figure 11: The Geiger-Müller counter used for all radiation experiments during the demo fusors operation. The device was only used with 1x counting rates chosen. The pancake detector can then be held in hand and moved freely around the fusor. Predominantly this detector was held over the viewport looking into the chamber as this was the highest density location for radiation to be emitted from the chamber.

As GM counters are not capable of detecting neutrons, there is no risk of a double count occurring within the device [19]. The GM counter can also be a secondary verification to ensure the neutron detector is functioning properly. The flux of neutrons should increase proportionally to the number of other radioactive products produced. If one detector reads increased counts while the other does not that would signify one device giving a faulty count. The GM detector also acts as a general warning to operators as, if the detector has a sustained increase of uptick of counts, operators then have a direct warning to shut down the device and/or evacuate the room. The neutron detector is the primary detection component for the device as it marks the success of the functional fusor. It is also how the device can be used within OSU as a neutron generator as the total neutron flux can be monitored for irradiation experiments. For this lab, a He-3 neutron detector is used alongside a bonner sphere. The He-3 detector can only detect thermal neutrons (0.025 eV and below); as the fusor will produce neutrons at higher energies than thermal, the bonner sphere is used to slow down the neutrons. It does this by allowing collisions between the neutrons and the bonner sphere material, a design discussed more in 2.8. With these two devices, the overall radiation generated within the laboratory space can be monitored and metrics on production rates can be produced. However personal safety is also an important consideration for radiation detection and needs to be included in design principles. All individuals consistently present in the room must always wear personnel dosimetry in compliance with rules and regulations from the US Nuclear Regulatory Commission (NRC), Oregon State Radiation Safety Manual, and general requirements from the Radiation Center [20,21]. Personnel dosimetry is used to track user irradiation annually as the fusor is used in demo fusor and functional fusor forms. While the fusor will be producing harmful radiation, with proper shielding the received dose to operators should be under the annual dose limits imposed by the NRC.

2.8 – Radiation Shielding

The particles generated from fusion all inherently pose biological risks to humans and as such proper shielding needs to be emplaced for proper operator safety. As the intent of the device is to generate radiation, the first line of defense becomes distance from the radiation generator. As the radiation should be emitted uniformly from the sphere of plasma, the density of radiation should decrease according to the inverse square law. By imposing distance requirements, the flux of radiation where the operator is working should be incredibly reduced. For the demo fusor, distance is the only shielding in place as any potential radiation production would be low. While operating the functional fusor, distance will not be the only use of shielding for the operator, physical barriers will be required as well. As the most common type of emitted radiation, neutron shielding becomes the first goal of the physical barriers. Neutrons will require a special style of shielding as they do not carry a charge and cannot be stopped using electricity or magnetism-based Shielding materials. In this case, using a material with a large composition of light elements with a large cross section will result in safely reducing the energy of the neutrons. The material that is chosen should slow neutrons via elastic collisions which thermalize neutrons until they can be absorbed by a compound with a high absorption cross section. Example materials are water which is commonly used as a neutron moderator in fission reactor plants or light plastics like borated polyethylenes [22]. The second most concerning radiation is that of gamma rays. Gamma shielding is a more straightforward process for the fusor and works via attenuation of the gamma rays. In general, most gamma-ray shields use layered materials so high energy gammas can be attenuated then the second material attenuates lower energy gammas. This concept of two-layer gamma shielding is particularly necessary for non-ideal scenarios where the flux is not perfectly normal to the plane of shielding [23]. As the radiation for the fusor is emitted spherically, we will not have an ideal flux for shielding. It is also worth noting that the slowing of the neutrons in a neutron moderator has the potential to release trace gamma rays, so gamma shielding should be placed to attenuate those rays as well. Combining these concepts the final proposal for shielding comes to be a three-layer system with neutron shielding first, high energy gamma second, then low energy gamma. It is worth noting the chamber also contains a viewport to allow visible observation of the plasma. As the viewport is made of glass this will result in radiation being attenuated less than the steel of the chamber, thus creating a port for high-energy radiation to escape. This viewport must be oriented away from where the operators are located, in its current configuration the viewport is aimed toward a concrete wall, as concrete is a good gamma ray and neutron shield.

2.9 – Additional Components

The fusor will have some additional minor components that are not critically necessary for the fusor but assist with the operation. The first of these devices is a Pfeiffer PKR 360 Pirani/cold-cathode gauge which is used to measure the pressure inside the chamber. This device is naturally connected to the HiCube 80 Eco turbomolecular pump as shown in Figure 12 and can be connected to the future computer control system to give two readouts of the pressure in the chamber. While not fully necessary, knowing the pressure of the system allows for more optimal control and understanding of the above systems. As mentioned previously, there is a viewport into the chamber, and as irradiation of the operator is a major concern, it is also not possible to have an observer approach the viewport. For this task, an AIDA HD-100A camera is set up looking into the chamber to allow for full viewing of the plasma as seen in Figure 12. The video is observed and recorded using the Open Broadcasting System (OBS). The use of video allows for physical confirmation of the creation of plasma. Once experienced with controlling the plasma, the camera also allows for an operator to monitor the voltage and pressures in relation to the plasma formation. Changes in both pressure and voltage will impact the conditions of the plasma inside. As the creation of a steady state is the primary goal, the ability to ensure systems remain in the correct proportion is necessary. The future electronic valve, the power supply, the neutron detector, and data recording will all be controlled from a computer system running LabView processing the devices through a LabJack T7 DAQ card system. The goal is to employ this system so that it can record the pressure, gas flow rate, neutron counts, voltage, and current at the same time so that direct analysis can be made of the data. For the data collected from the demo fusor, Python shall be used to produce the graphs.

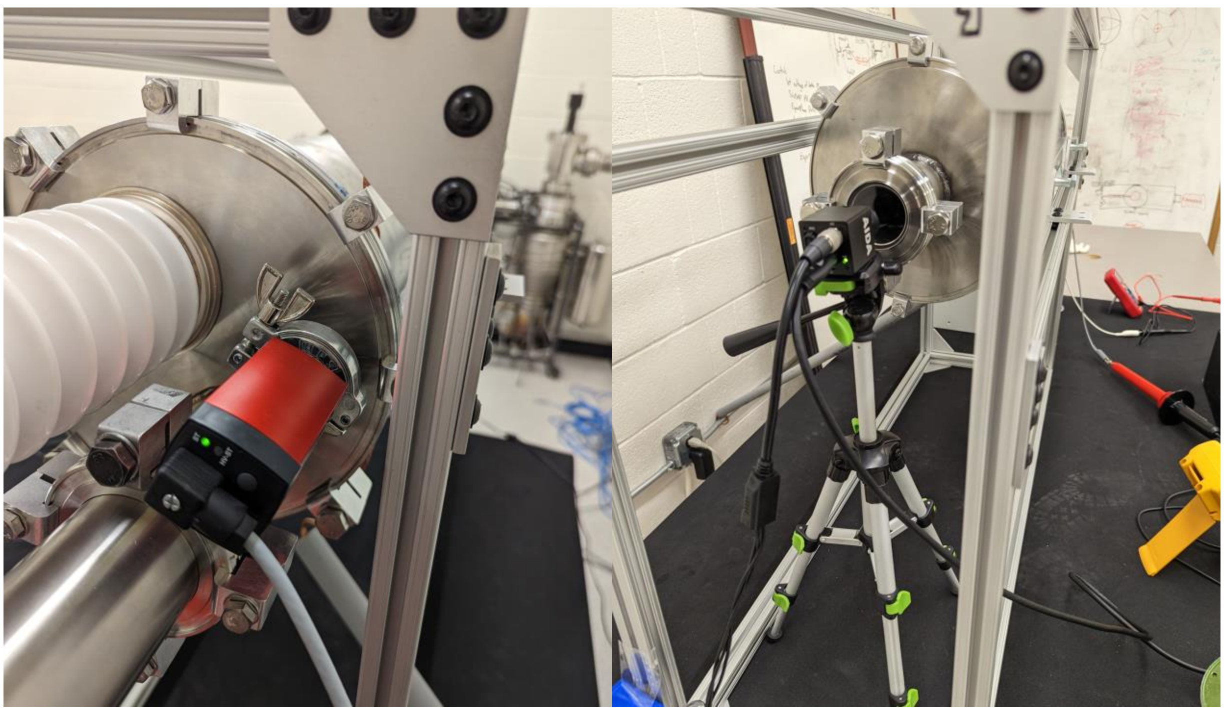

Figure 12: The image on the left shows the Pirani/cold cathode gauge as it connects to the chamber. The wire coming out of the gauge then connects to the display and control unit attached to the vacuum system case. The AIDA camera is on a stand allowing it to see into the chamber. It then connects to the lab computer via a video capture card which is read by OBS. In the event of arcing to the chamber walls, the camera display may be interrupted. This is due to the arcing current flowing through the chamber supports disrupting the camera feed.

Chapter 3 – Results and Discussion

3.1 – Subsystem Confirmations

Before combining all subsystems into the completed demo fusor, every subcomponent had to be tested in isolation to ensure that they would operate as anticipated without failure. The goal was to test every major component in different configurations to confirm that all installations were correct and would be sufficient for the demo fusor's operation. This included testing some of the major systems in intentional failure conditions to understand their behavior in the event of an accident with the system.

3.1.1 – Vacuum System

The vacuum system consists of both the pressure vessel as well as the turbomolecular pump, both of which are required for the demo fusor and functional fusor. The interdependency of these subsystems could result where a fault in one could be read as a fault in both. However, if we could test one system then the other could be then be verified without issue. To do this we first tested the pressure vessel to confirm that it could hold a high vacuum. This was tested by using a Pfeiffer vacuum leak detection system operated by a Pfeiffer Vacuum technician on our system. The system connects to the pressure vessel and pumps it down to vacuum. Helium is then sprayed around each weld and connection point. If there is a leak into the chamber then the helium would enter the chamber and be tracked by the vacuum leak detector. As no helium was detected by the device, we could confirm that the welds and clamps were properly set and could therefore proceed to test the turbomolecular pump. The detector also had a separate pressure sensor which was able to confirm that our Pirani gauge was correctly calibrated and reading high vacuum. The failure test for the pump was to introduce a major leak into the chamber while the pump attempted to pull a vacuum. This was done two ways: by leaving the venting port on the pump open and by opening the gas port on the chamber. In both events, the pump read out an error and would not pump to a high vacuum but also did not critically fail. The next task was a full bake-out of the chamber resulting in the lowest read pressure of 0.47 microtorr. Achieving such a low pressure ensures that the turbomolecular pump is operating as expected at its maximum and that the chamber is capable of sustaining conditions more extreme than standard operation. This is drastically lower than the required pressure of 5 millitorr to 15 millitorr where fusor operation tends to occur. Such low pressure is beneficial as it means that, when deuterium is introduced, it will be the dominant gas in the system thus reducing the number of other gasses present in the system. Fewer contaminants within the system should result in higher fusion rates when transitioned into the functional fusor.

3.1.2 – Power System

For the demo fusor, the power system is composed of the NST transformer, a diode ladder, a high voltage feedthrough, a voltmeter, and an ammeter. Again, safety is the primary concern for this system so an order of operation was generated for every experiment utilizing high voltage to ensure that operators would not be interacting with any high-voltage wires. The first goal was to test the NST to confirm that it is operational, particularly when operating in worst-case scenarios. For the fusor, the worst-case condition would be if there was sustained arcing from the grid to the chamber walls. To simulate this event the NST was connected to a Jacob's ladder to simulate the potential arcing within the chamber to see how the NST would behave. The NST was able to maintain the power supply as the arcing events occurred as shown in Figure 13.

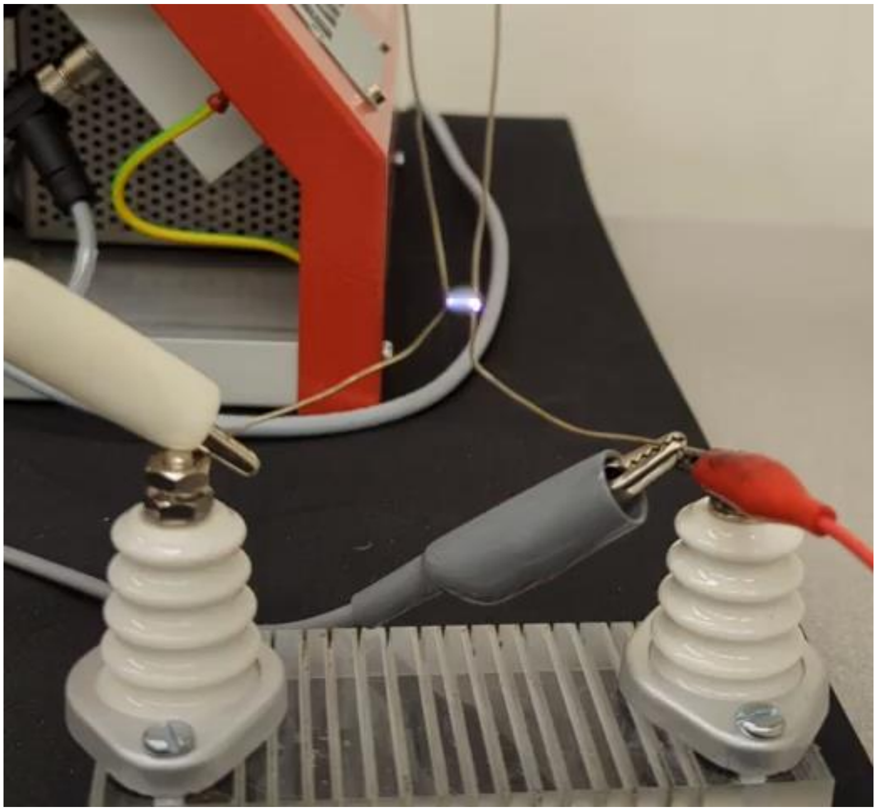

Figure 13: The Jacob's ladder arcing experiment with an arc occurring at the bottom of the ladder assembly. The right leg is charged by the NST while the left leg connects to the case ground. This way the energy dissipates the high voltage in a safe manner. The arc would start near the bottom of the ladder and then climb higher, sustaining the arc for the entirety of each arcing event.

The voltage at which arcing occurred was variable to the setup of the Jacob's ladder however most arcing occurred around 5 kilovolts. This would be around the voltage that a good plasma ball would be generated and therefore means the NST would be able to sustain this fault. The arc test was then retested with the diode ladder introduced to the power supply which was able to produce the same arcs. This implies that DC arcing was also viable for the NST and would function for the fusor. The last step was to connect the system with the feedthrough and test if the grid was being charged as expected. Using a voltmeter and ammeter the grid was measured and confirmed to be being charged by the NST which was the final confirmation that the power system was fully functional.

3.1.3 – Additional Systems

The primary additional components for the demo fusor were the AIDA camera and the Pfeiffer PKR 360 Pirani/cold-cathode gauge. The secondary system was the addition of a GM counter during experimentation. As mentioned in 3.1.1 the Pirani/cold-cathode gauge was also tested during vacuum pump testing and confirmed as functional and calibrated. The AIDA camera was simple to ensure as it was able to connect to the computer via an external video card. OBS was able to naturally intake the video card output within its system programming and did not need to be modified further. OBS was also able to record and save the video generated by the camera which marked the success of the video subsystem. The final demo fusor subsystem was that of the GM counter used for general safety procedures and occasional radiation count tests. The GM counter was provided by the OSU Nuclear Science and Engineering (NSE) department. All system calibration is done by the NSE department using their own radioactive sources. As such, the only setup for the GM counter was to request one for use from the NSE department which was completed in advance of the first plasma test. There was a neutron detector also provided by the NSE department for the first plasma test, simply to ensure operational safety in regulation with the Radiation Center guidelines but this was not a permanent addition to the demo fusor lab.

3.2 – Plasma Generation

With all systems confirmed as operational and attached to the chamber as shown in Figure 14, a full plasma test could be performed. For the demo fusor, the primary goal was to generate the first plasma within the chamber but we could also record additional information that would help with the functional fusors development. With every major system in place, the test could then be performed to ensure that all systems were operational when synched together. The mark of this success would be through the generation of a plasma ball at the center of the grids.

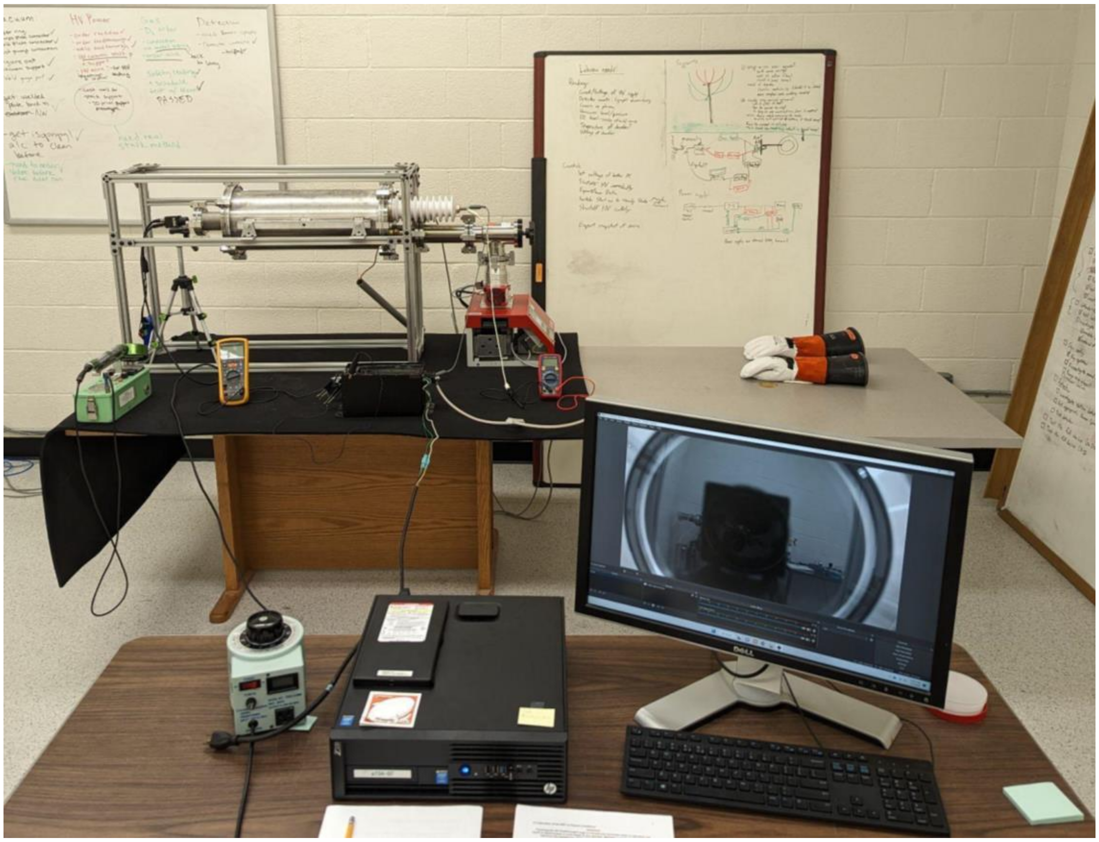

Figure 14: The full demo fusor setup. Starting in the upper left there is the AIDA camera and GM counter next to the viewport of the chamber. The pressure vessel is being held up by the supports. On the right side of the vessel are the high-voltage feedthrough, the vacuum system, and the Pirani/cold cathode gauge. In front of the supports are the NST, diode ladder, voltmeter, and ammeter. The wires continue over to the operator station closest to the image where the VVR and OBS recording studio is controlled. This was the complete setup for the demo fusor during all plasma testing.

The first major tests did not result in any form of plasma being generated. This result was due to the lack of modular control of the turbomolecular pumps' venting pipes, either resulting in too low of pressure while on or too high of pressure while off. By introducing a valve to the vacuum piping, the flow rate of outgassing was able to be reduced while keeping the pump on. To reduce the flow rate the turbomolecular pump's operational speed was reduced to 40% with a speed of 600 Hz. Once this issue was rectified we were able to generate plasma, as seen in Figure 15, but produced it in a diffused distribution. It is also worth noting that the voltages for these tests are the voltage the transformer is putting out to the grid in a high vacuum, there will be a discussion of the variation of grid voltages with respect to the pressure in section 3.4. Although plasma was able to be generated by the system, it was not in the location that was needed for this to be marked as a successful test of all subsystems. Upon investigation, it was suggested that the formation resembled plasma generated from a positively charged grid which we were able to confirm. This was due to the diode ladder becoming flipped at some point during the testing resulting in the grids being charged with a positive polarity.

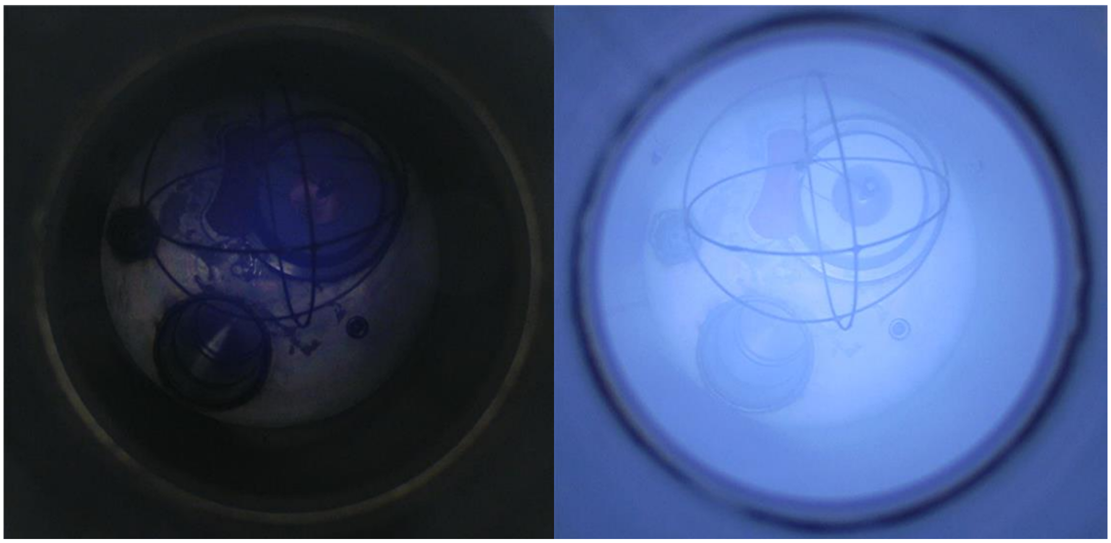

Figure 15: The creation of plasma but in a diffused form about the whole assembly. The image on the left displays the generation of plasma at 15 microns of mercury with grid voltages of 500 volts. The image on the right displays plasma at 50 microns with a grid voltage of 5000 volts.

By simply reversing the diode ladder only the negative polarity was transmitted into the grids rather than the positive polarity. The plasma experiment was repeated, but now with all other previous issues resolved. In the second test, the plasma was able to be properly generated within the grid. Figure 16 shows the plasma in the center of the grid as we expect from the demo fusor's successful operation.

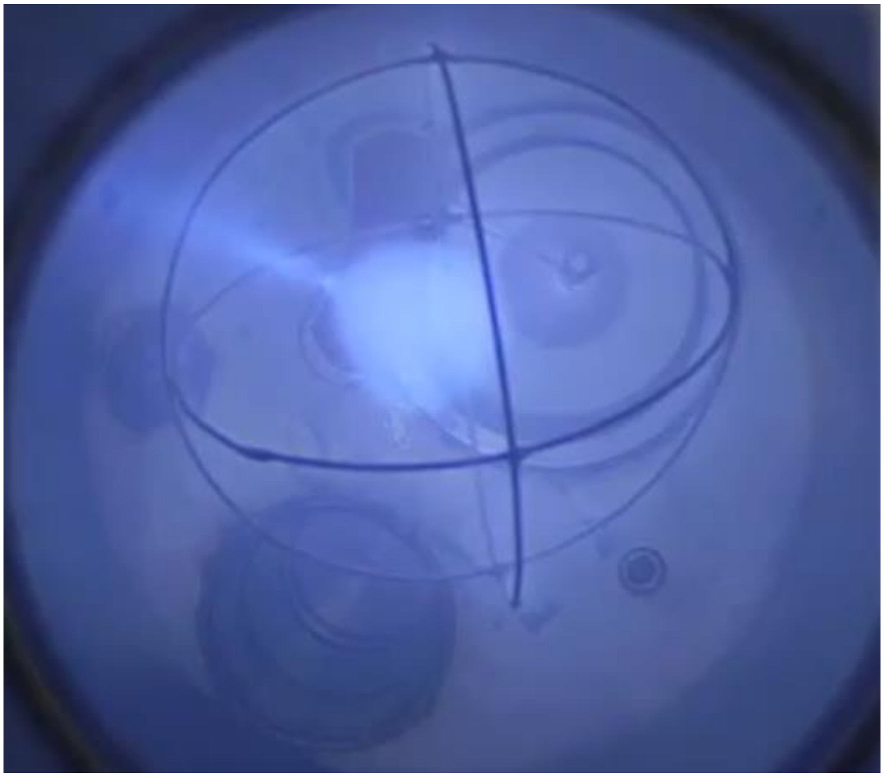

Figure 16: The best plasma formation within the grid. This is at 7 microns of pressure with a grid voltage of -6500 volts. In the upper left section of the image, there is a stream of ions coming off of the main ball of plasma. This formation is referred to as jet mode for the fusor.

By containing the plasma into a single ball, it confirms that the chamber is holding the high vacuum properly (thereby increasing mean free path, as discussed in 2.3), vacuum pressure is being sustained, the grid is being charged, and the air is being ionized. This confirms that all subsystems are operating as intended and the demo fusor can be adapted into the functional fusor. Note in Figure 16 the existence of the ion jet coming out of the plasma ball. This is indicative of a misshapen electric field being generated which would result in most ions taking this path causing this stream to occur. To remove this jet from the plasma one easy method is to reduce the size of the grids which would change the proportion of the grounded chamber in relation to the charged grids. In this event, any small geometry errors in the grid or in the grid's placement can be minimized. By increasing the distance between Earth ground and the charged grid, the electric field can be made more uniform.

3.3 – Radiation Counts

Although there is no expectation of the demo fusor to produce any hazardous levels of radiation, measuring any and all potential radiation coming off the machine was still a goal. As fusion events are inherently probabilistic, there is a minute chance that a fusion event occurs. As the goal of this device is a neutron generator, the first radiation measurement was using a neutron detector. As expected for the demo fusor, the neutron detector never registered being hit by a neutron flux above background levels. This confirms that the device was safe from neutron irradiation. The next measurement was using the GM counter provided by the NSE department. At the operator station, there was no increase in the counts registered by the GM counter, registering an average background count of 120 counts. This was also true for any counts registered along the metal pressure vessel. However, as discussed in 2.8, the viewport of the chamber was expected to be a beam of radiation. Figure 17 shows the counts coming out of the viewport and compares them to the background counts of the room.

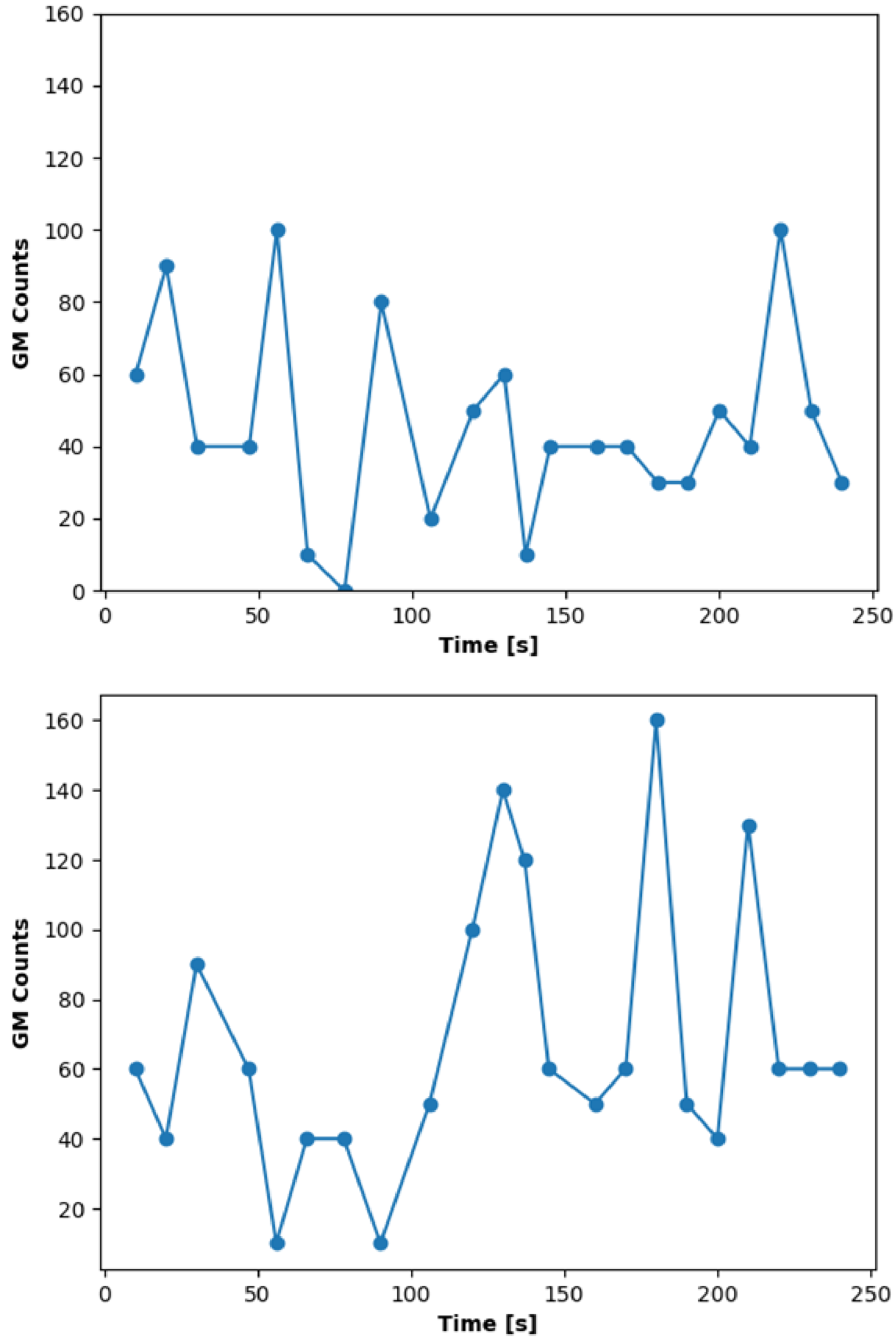

Figure 17: The two measurements of counts as recorded by the GM counter. The top graph shows the counts recorded as the background radiation within the laboratory. The second graph is the radiation counts as measured coming through the viewport of the pressure vessel. The average for the counts were 46 and 68, respectively. These averages, alongside the fluctuation in counts registered by the GM counter over the four-minute time span, indicate that radiation from the fusor is not significantly above background levels of radiation.

The trend in Figure 17 suggests that an operator would have no increased risk of irradiation while working with the demo fusor, especially with the current radiation safety guidelines in place. Even if an operator were to remain in front of the window during operation, the highest measured risk would only be two times the natural background radiation which would pose a negligible increase to operator irradiation risk [26]. As such, even in an accident scenario, an operator could take the full dose of the device for prolonged exposures and be safe. Another way we can confirm the increased event of radiation coming through the window is from the AIDA camera feed. While the plasma is formed, the video feed occasionally has white specks appear. Since the white specks exist temporarily we can confirm that these are gamma rays interacting with the camera’s sensor [27].

3.4 – Comparative Relations

For the demo fusor, there is no simple way to collect data to mark the demo fusor's success as the creation of plasma is the goal. Plasma creation is hard to measure; the measurement of ‘better or worse’ plasma does not have empirical methods for determining these concepts. However, some of the collected data can still be corroborated so that future use with the functional fusor has data on how the fusor should behave with certain voltages and pressure. As voltage is one of the most important parameters of the system, it is worth documenting how the voltage changes with respect to pressure. It is worth noting that all voltages listed in the graphs are negative polarity though they are plotted as positive values. By measuring different pressures we are better able to understand fusor voltage behavior as the pressure of the system changes as shown in Figure 18.

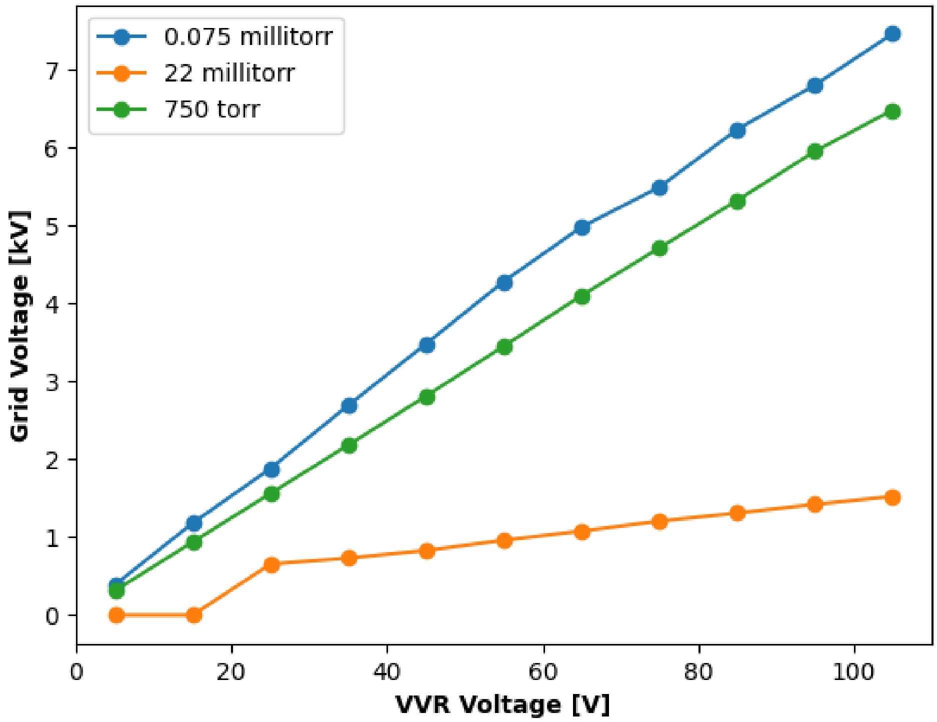

Figure 18: The measured negative voltage on the grid with respect to the output voltage as reported by the VVR's personal display. The relation is linear as would be expected since the output voltage and input voltage should be directly correlated. The first two measurements of the 22 millitorr are at zero as no plasma was generated at that voltage, but theoretically would continue the linear relation had the plasma been formed. The 22 millitorr slope should match that of the functional fusors operation.

As the pressure decreases the actual output of the NST increases as seen between the 750 torr to 0.075 millitorr results. The 22 millitorr reduced result is due to the plasma formation decreasing the output voltage of the NST. As the pressure decreased, the relative voltage for the grid increased. This is due to the fact that a high vacuum reduces the number of charged particles within the chamber, particles that would be interacting with the grid, which then reduces the potential of the grid. This is something to keep in mind for the functional fusor, the output voltage as read by the device will not be the actual voltage of the grid. This is something to also consider for all future data as the output voltage read by the power supply will be lower than what the grid is being charged to. For the next data set the voltages on the plots will be the voltage as read on the grid by the voltmeter rather than the output of the VVR. Figure 18 can be used to compare the plotted voltages to the NST's theoretical and actual outputs for those values, a concept useful for the functional fusor. The maximum error of the cold/cathode gauge is ±30% for each data point as listed by the Pfeiffer Vacuum data sheet. This error does not impact the results as the primary study is simply the comparative relationships rather than extracting exact values from the data.

From here the goal became to relate the generation of plasma in the grid with respect to the components we could control. In this case, the main comparisons came from the effects of voltage and pressure on the formation of the plasma. The first case, shown in Figure 19, can directly show the effects of voltage on the plasma if the pressure is kept near constant.

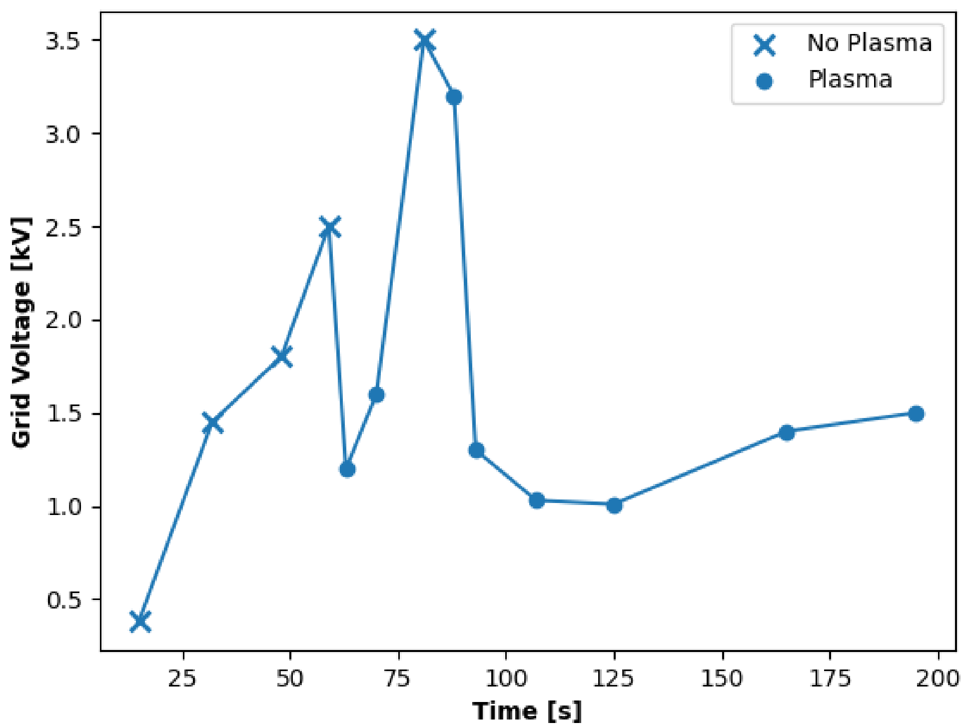

Figure 19: The generation of plasma in relation to the measured negative voltage on the grid. Up to the first plasma formation, the pressure was at 12 microns; and once plasma formed it remained at a constant 15 microns. In the 80-second region, the voltage was too high for the pressure causing the transformer to fail and deform the plasma. Decreasing the voltage after the first plasma generation allowed steady control of the system.

Figure 19 shows the direct effect of the plasma on the voltage of the grid, matching the expectation of the virtual anode formation. This shows the behavior of the system which is useful to operators for understanding when the plasma is being formed. If the voltage begins to drop rapidly without manual manipulation, this implies that the plasma has begun to form. If the voltage begins to spike this could imply multiple faults with the system. Once the plasma has been formed, the expectation is that the voltage should increase with the VVR voltage, with some potential deviations as the plasma reforms. If the plasma deforms, it is not necessary to end the experiment, simply decreasing the VVR voltage will allow for the plasma to be reformed. In a deformation event, the grid could have arced to the chamber walls, the pressure could have gotten too low causing the plasma to dissipate, or backflow from the virtual anode to the NST could have caused it to fault as is seen in Figure 19. As measuring time for each voltage and current measurement for a single observer became too difficult, and was not necessary for understanding the fusor operation, the measurements were classified by the order they were taken. However, the overall timescale for the rest of the graph is on a similar scale as that of Figure 19. For the voltage, the Fluke Insulation Multimeter used had a listed error of ±(1% + 3), and for current the AstroAI Multimeter had an error of ±(1.2% + 8). Once again, the error is not a major concern for this data as we are not interested in extracting exact values from the data, rather, observing the overall behavior of the device.

An additional parameter to test in relation to the plasma's formation is current through the grid. This was done using a secondary multimeter to monitor the current from the diode ladder into the HV feedthrough. This way the voltage and the current could be related to one another to monitor how they reacted to changes in the system.

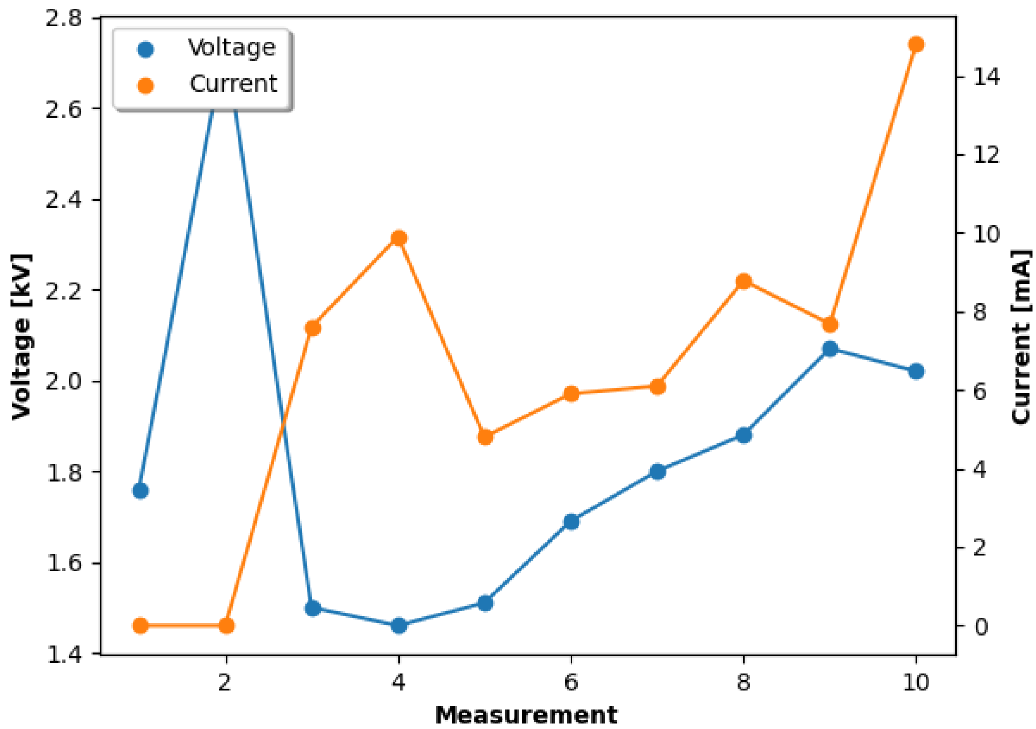

Figure 20: The result of measuring current and negative voltage as the plasma formed and supplied voltage was increased. After the second measurement, we see the plasma form. This is characterized by the rapidly decreasing voltage and the current increasing to measurable values. Until the plasma forms, the applied current is in the microamp range as the grid is rapidly charged. After measurements 5 and 9 there are deviations from the expected behavior due to the plasma leaving jet mode and reentering jet mode, respectively. The pressure for these tests was measured at 11 microns of pressure after the plasma formed.

The current of the fusor's grid is relatively proportional to the voltage being supplied during optimal operating conditions as seen in Figure 20. The final measurement of 14.8 mA of current confirms that the grids are capable of maintaining the functional fusor's current requirements. This also shows the effects of the formation of the plasma and how it will impact the power supply as its shape changes. As the plasma ball dissipates its jet, as well as when reforming it, current and voltage will change as well. This was due to the alteration in the ion geometry. With the plasma in jet mode, there is a stream of ions near one section of the grid which the transformer reacts to. When the jet dissipates, the transformer no longer needs to overcompensate for that disruption to the grid's charge. This reduces the overall voltage requirement of the grid to contain the plasma into the smaller ball and a temporary increase in current as the charge redistributes.

Having viewed how the different quantitative components of the fusor relate to one another, it is then important to understand how maintaining a stable plasma condition alters the system. This is harder to determine as monitoring the plasma is subjective to the operator. In this case, steady-state plasma was determined to occur when the size, brightness, and geometry of the plasma did not change. This test was done by forming the plasma at the upper end of the allowed pressure (generally around 20 microns) and making it a stable formation. The valve was then opened slightly so that the chamber would be vented at about 2 microns per minute. As the pressure dropped, the voltage would have to then be increased to maintain the plasma ball in its configuration. The geometry of the plasma ball used for this test is shown in Figure 21.

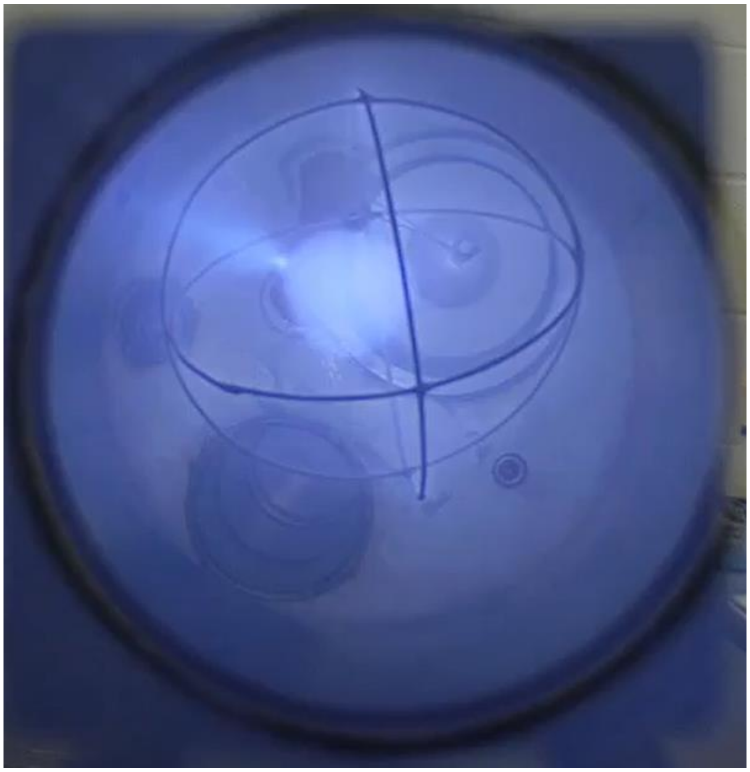

Figure 21: This was the plasma that was sought to be maintained within the grid during plasma tests. The goal of this test was to maintain this plasma throughout the experiment. During this test, the plasma would fluctuate in size and brightness but through voltage and pressure control these parameters were made to keep as constant as possible. Due to the size of the grid, the jet remains for all pressure and voltages but this is okay so long as the jet can be sustained as constant.

The plasma was in a smaller ball with the jet mode. This then depends on the operators to be familiar with the systems as every subsystem would be changing proportionally to one another. After small changes were made to the system, the ball would be returned to this form then data would be collected from each system. Figure 22 shows the results of a steady state test, showing how the voltage, current, and pressure all relate to one another as the plasma sustains a constant brightness and shape.

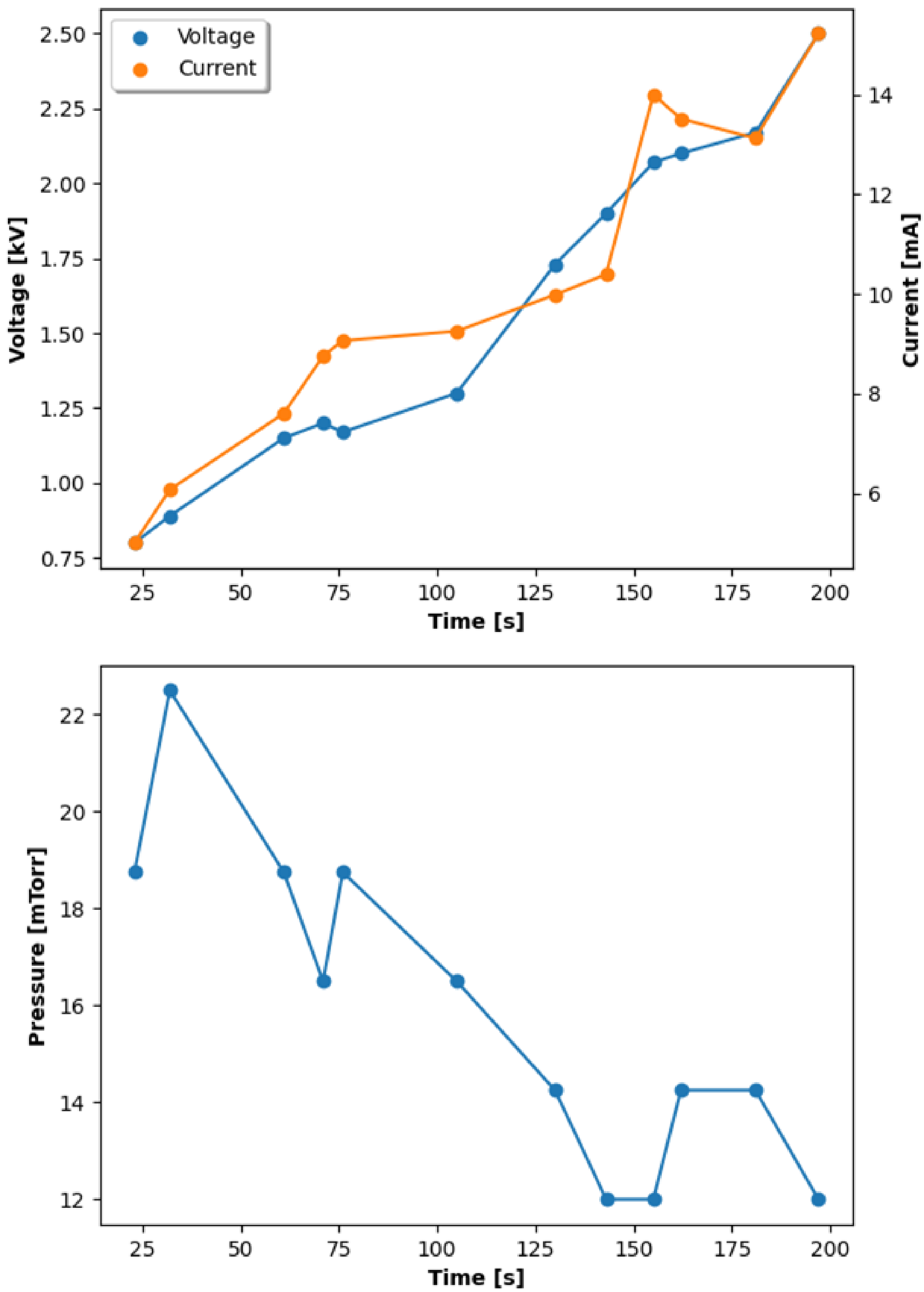

Figure 22: The top figure shows the voltage and current during a steady-state plasma test. The pressure was made to continuously drop. The lower graph shows the pressure of the system decreasing during the test. The pressure decrease is not constant as the plasma generation itself will increase the pressure in the chamber. The goal would be for the functional fusor to follow these same behaviors during its operation as it attempts to enter its own steady-state generation.

The voltages and pressures are not increasing at the same rate as the plasma is dynamic and small variations will impact how the grid voltage changes and how the current flows through the grid. The purpose of this test was to model the functional fusor characteristics. At the pressures used for the demo fusor, the high voltage system associated with the functional fusor would cause backflow or arcing. The goal of the functional fusor is then to continuously decrease the pressure while keeping the plasma from fully dissipating. Since the functional fusor needs to slowly increase its voltage, it will need to start at pressures in the demo fusor range. This early stage of the functional fusors operation can be replicated with the demo fusor which can achieve some of the same early-stage operations as the functional fusor. Although this test cannot reach fusion levels of voltage, it can provide insight into how the functional fusor will need to be set up when it performs the same test. The data collected should model almost exactly the same as the start of the functional fusor. The pressure during plasma formation should be the same for the operation of the functional fusor. The voltage and current should also follow the demo fusor's proportional trends during steady-state experiments, especially as the functional fusor starts at the same power levels as the demo fusor.

Chapter 4 – Conclusions

4.1 – Demo Fusor Success

The demo fusor was able to control and sustain plasma within the chamber without failing any subsystems. Therefore, all demo fusor subsystems are working properly and in coordination. The vacuum system and pressure vessel were able to maintain the high vacuum needed for fusion conditions. The spherical grid was constructed with minimal errors in the geometry, resulting in a well-generated electric field. The high-voltage feedthrough, diode-ladder rectifier, and NST power supply were able to properly power the grid with negative polarity DC charge. The data collected demonstrates that the minor subsystems for monitoring and data collection were integrated correctly with the fusor. The steady-state plasma test marks the successful completion of the demo fusor construction. All subsystems successfully operated with one another, allowing for the formation and containment of plasma within the chamber. This achievement confirms the effectiveness of the demo fusor's design and demonstrates that the various subsystems are capable of working together harmoniously. As such, the experiment can be deemed a success.

The data collected allows for the operators of future fusor iterations to understand the behavior of the plasma as certain constraints change with time. This provides a better understanding of the limiting factors when upgrading the demo fusor to a functional fusor. Although the functional fusor will require the power supply to be changed, the functional fusor must operate in the same conditions as the demo fusor during its start-up. As such, the voltage and current, in relation to pressure, will be the same during functional fusor operation. This can act as a benchmark for the success of the functional fusor as, when the device is completed, it should be able to reproduce the same data as the demo fusor. The trends in the final experiments should match that of the demo fusor when all other components stay the same; despite potential data variation due to the fluidity of the plasma.

4.2 –Future Research Goals

The conclusion of this research leaves the fusor capable of being transformed from the demo fusor into the functional fusor with minimal changes to the tested subsystems. The changes required to adapt the device into a functional fusor are still complicated in design but are achievable by an undergraduate researcher. The first remaining design consideration is the introduction of a high-voltage power supply capable of fusion levels of voltage. Second, is the introduction of a deuterium gas piping system that can slowly leak fuel into the chamber. These are the only operational requirements to make the functional fusor produce neutrons. As the functional fusor will be a radiation production device, ample neutron and gamma-ray shielding will need to be introduced to protect operators who work with the device. There is also a need for neutron and gamma-ray detectors in the system so that the flux of the device can be monitored. Lastly, integrating all systems with a single computer overlay would allow for easy data collection and direct analysis, which would be superior to the current operator-observed data.

As mentioned above, the first goal of the demo fusor would be its advancement to a functional fusor status. Beyond that, future research would need to be organized and approved. For the NSE department, the functional fusor can be used in a multitude of research applications. For example, the device can operate as a neutron source for neutron irradiation experiments. For our fusor, there are plans for modularity with multiple grid sizes and shapes for the functional fusor. This creates a better model of the functional fusor's neutron production rate changes with grid geometry changes. Assuming changes are substantial enough, this allows for the single fusor to offer multiple distinct neutron fluxes based on the application requirements. A variable neutron flux can be used to study the structure and/or properties of certain materials within many scientific fields such as condensed matter physics, biology, materials science, or geology. In the realm of fusion, there is hope to use this device to contribute to the understanding of fusion reactor materials which will undergo high neutron fluxes. A final potential future research opportunity would be investigating the use of the functional fusor to produce Technetium-99m (Tech-99). Tech-99 is a rare isotope of Technetium that has extensive use within the field of medical diagnostics. The isotope is produced from Molybdenum-99 which is irradiated by neutrons, a task normally performed only in large-scale nuclear reactors. The primary issue with this is that Tech-99 has a short half-life, meaning much of the isotope has decayed away by the time it arrives at a hospital. If the functional fusor can produce Tech-99, this would allow more tabletop systems capable of producing the isotope, which has potential use within hospitals due to their size. The functional fusor will have an extensive list of potential applications, even beyond the ones listed above, which require little to no modification of the fusor's design. The current results and proposed experiments justify continued fusion research with the inertial electrostatic confinement fusor.

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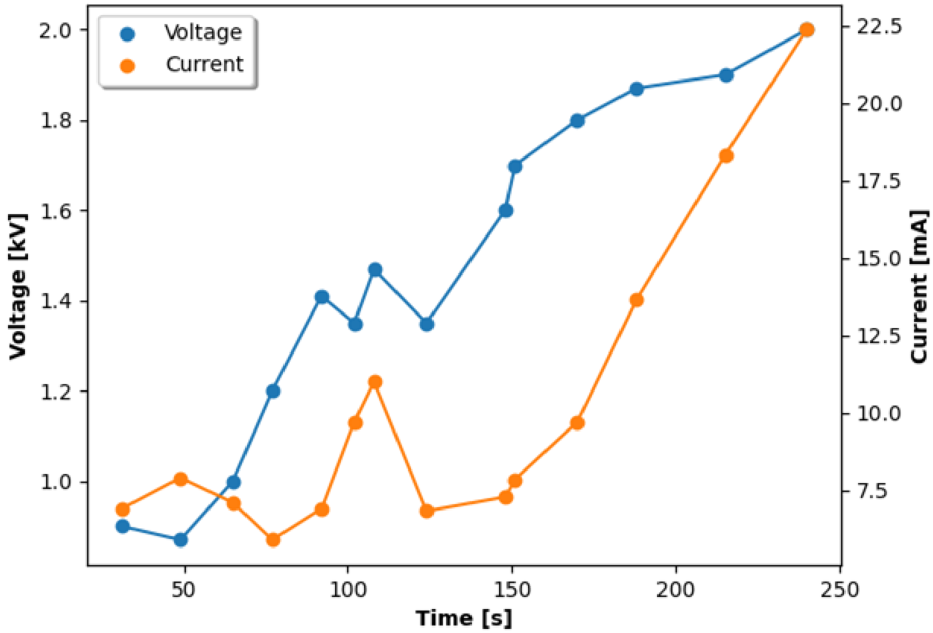
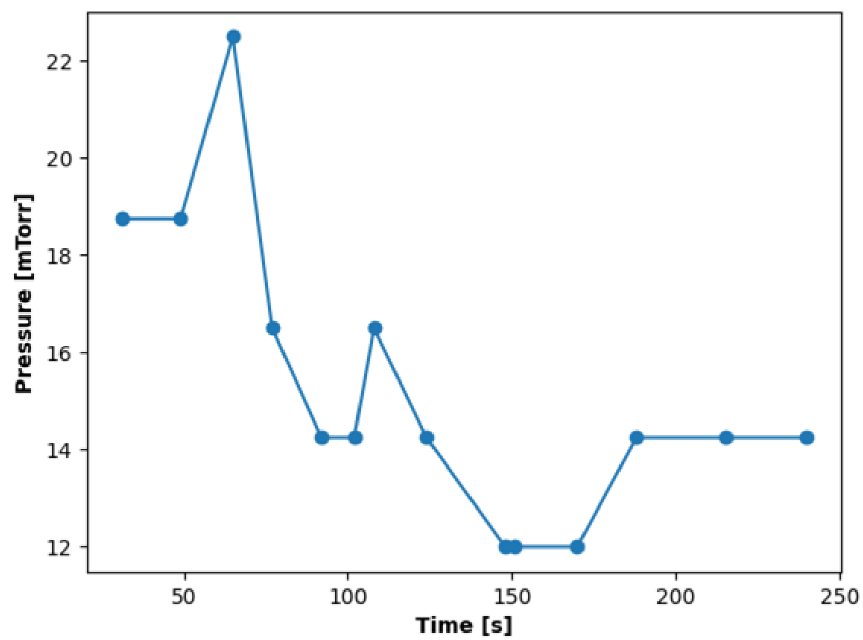
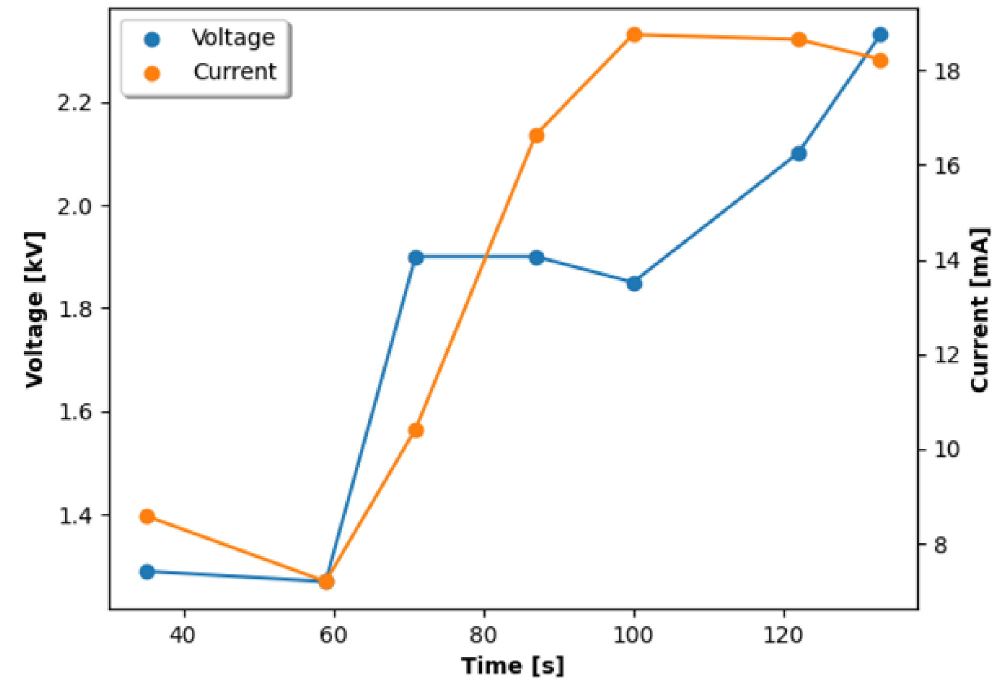
Appendix: Steady-State Tests

Additional steady-state tests were done with the demo fusor. This is introduced as a reference to the functional fusor team for how the pressure, current, and voltage should change in relation to one another as the vessel stays in a steady state. These graphs should model the behavior at the start of every functional fusor test. The first graph has an NST failure at the 60-second mark characteristic of the decrease in current and voltage which was required to reform the plasma.



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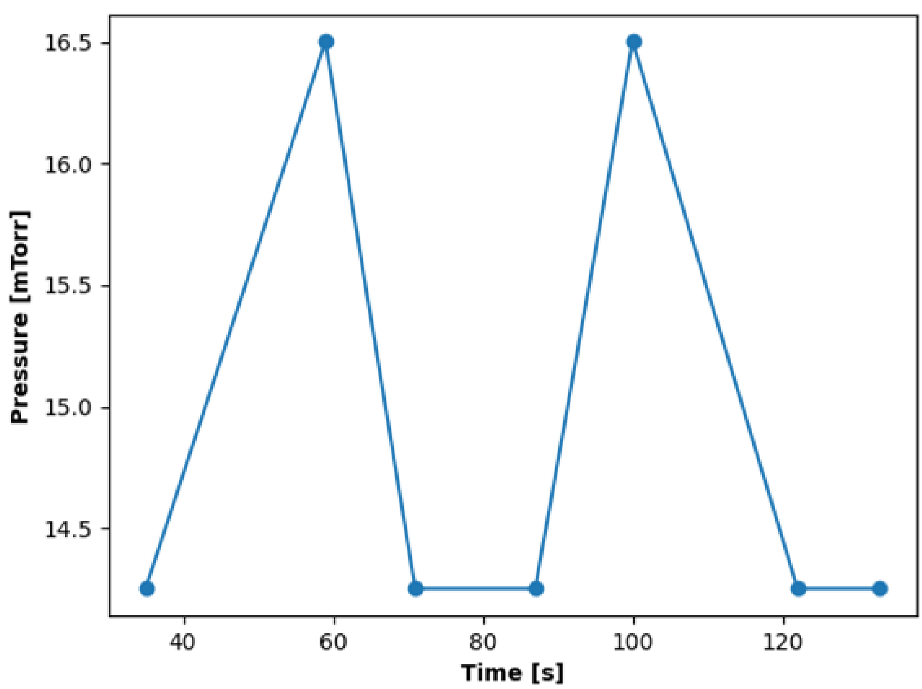
Current
Voltage [kV]
Current [mA]
Time [s]


Pressure [mTorr]
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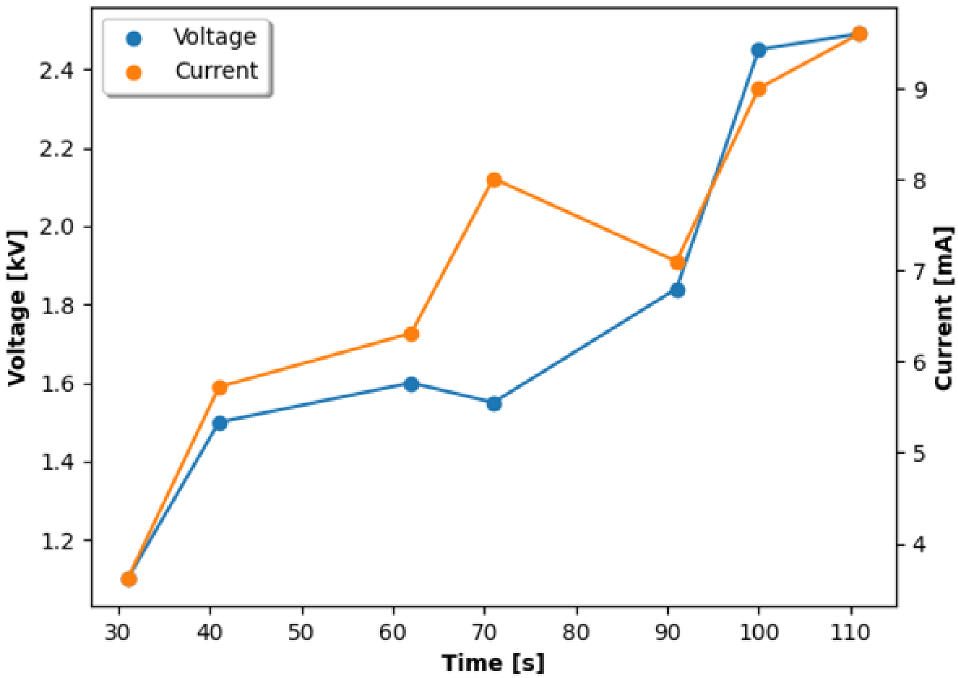
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Current [mA]
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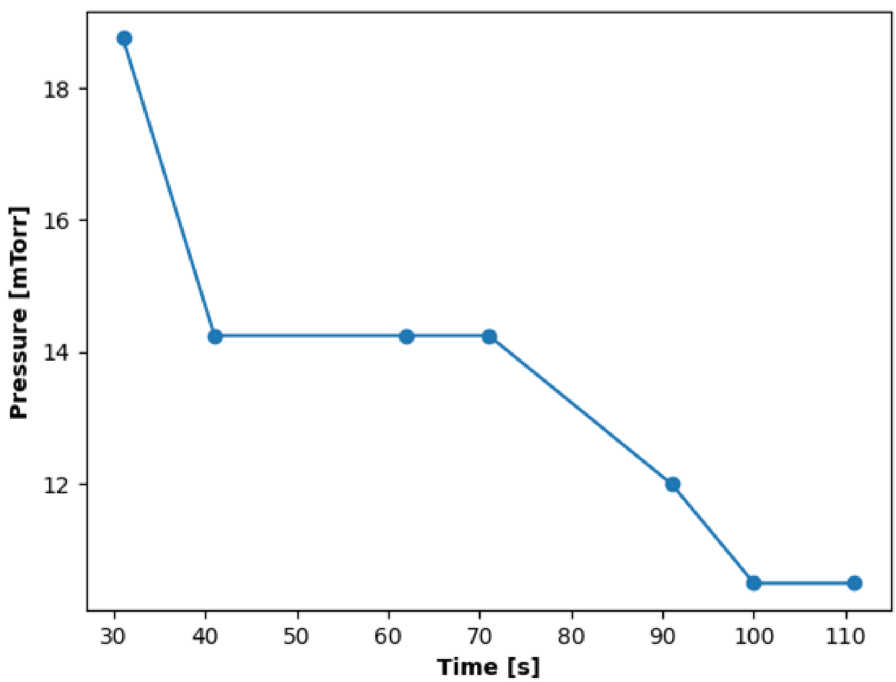
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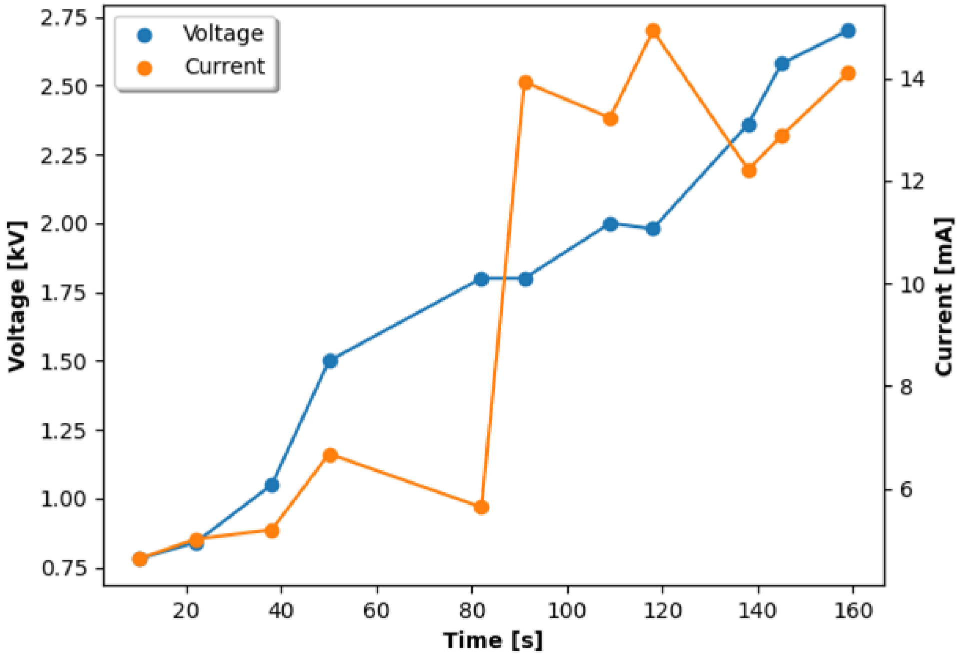
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Current
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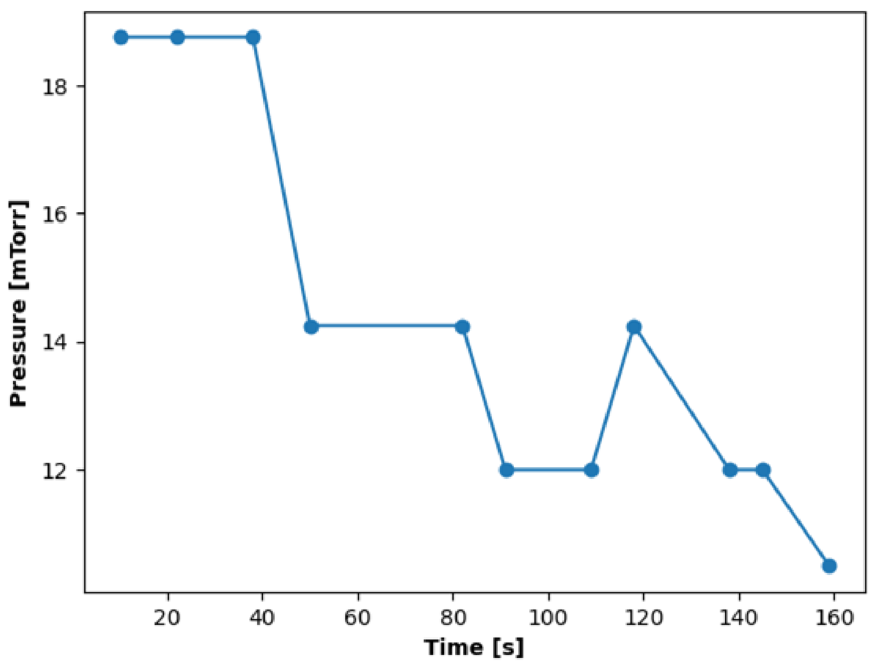
Pressure [mTorr]
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16
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