Development of Economic Spherical IEC Fusion Device

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Development of Economic Spherical IEC Fusion Device

Submitted to the Faculty of the

Worcester Polytechnic Institute

In partial fulfillment of the requirements for the

Degree of Bachelor of Science

by

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April 29, 2015
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1 Abstract

Inertial electrostatic confinement (IEC) fusion devices are often used commercially for generation of neutrons. These devices represent applications of fusion and plasma physics principles, and involve a practical knowledge of high voltage and vacuum systems. It is, then, beneficial for students in research sciences to be able to construct such a device within reasonable economic means. With regard to Deuterium-Deuterium fusion ($^2H + ^2H \rightarrow ^3He + ^1n$), a common metric for experimental success is neutron production. In this project, a practical IEC device is constructed out of accessible materials. The confinement of Deuterium and background gas plasma is analyze with respect to optical intensity, up to 3000 Volts. The selection of a highly transparent anode is recommended for most efficient plasma confinement. Recommendations for continued study on the device are made, so as to directly observe neutron production at fusion temperatures(approx. 20 - 40 keV).
2 Introduction

In the early 1900’s, research on the theory of quantum tunneling, as well as experiments discerning the masses of light elements, led to the discovery that large amounts of energy can be produced by fusing light nuclei. This release in energy can be attributed to the relative strengths of the Coulomb force and the strong interaction between nucleons. At large distances, the electrostatic force causes protons to repel each other, but if this force is overcome by highly energetic particles, then the protons may attract due to the powerful but short range nuclear force. The extra energy from the net attraction of these lighter nuclei is then released in various forms, such as radiation, heat, and thermal neutrons.

Since this discovery, there have been many attempts at controlled thermonuclear fusion, none of which have achieved a “break even” point, in which equal power is released as is put into the system. The two largest fields of research in the production of fusion energy are inertial and magnetic field confinement. Inertial confinement fusion utilizes fast pulsed lasers, attempting to compress a plasma to an ultrahigh density wherein fusion may take place, whereas magnetic confinement fusion utilizes an often large array of electromagnets to confine a plasma in a particular geometry. A prominent example of this is the ITER tokamak in France, which takes the form of a large closed torus [4]. The trouble with these approaches is that, despite their immense promise, they have large operational costs that are typically in the range of billions of dollars [9].

Alternative methods for heating plasma to fusion conditions are vital to the search for inexpensive controlled fusion. The Inertial Electrostatic Confinement (IEC) style of device proves to be a worthy candidate due to its simplicity. The nature of the devices can be explained through a typical “gridded” IEC, wherein a gas of light nuclei is ionized by a spherical mesh grid that has been given a negative bias. The ions are then, in theory, accelerated towards the center of the device where they either fuse or move to a location on the opposite side of the grid that corresponds to the potential of their birth. This type of device was discredited early on, due to the notion that an electric field alone was not enough to confine a plasma. Since then many experiments have shown that, in a dynamic setup, it is possible to both confine a plasma and achieve fusion in an IEC. A lack severe lack of increased fusion production at high energies has since discredited the archetypal IEC as a fusion power source, however it has vast applications as a conduit for plasma research, as well as in practical neutron generation.

This project is intended to apply principles of plasma physics and fusion technologies to the construction of an inexpensive, spherical, inertial electrostatic confinement fusion device, and to experimentally quantify the relationship between grid design to incidence of fusion. We have studied the basic principles of fusion, plasma physics, and inertial electrostatic confinement. Following background research, we constructed a vacuum chamber and system, a deuterium gas management system, both anode and cathode grids, an insulated ceramic
stalk, a high voltage system, and method of recording fusion data. Due to shortcomings in acquisition of materials, voltages of just 3000 Volts were reach. This allows for verification in our high voltage system, characterization of plasma with and without deuterium within contrasting electrode designs, and extrapolation to higher voltage systems.

3 Background

3.1 Principles of Fusion

Man-made Fusion is a controlled process wherein two lighter nuclei are combined to form a heavier atom, releasing energy. This is accomplished by getting nuclei close enough that the short-range strong nuclear force can overcome the coulombic repulsion between nuclei. When this is done using light nuclei, they form a heavier nucleus with a higher binding energy per nucleon. The difference in binding energy is then released into the systems and can be used for various purposes. In the context of inertial electrostatic devices, the energy is often released in the kinetic energy of product neutrons. Neutron sources such as these are valuable to nuclear labs worldwide.

3.1.1 The Binding Energy Ladder

In order to understand the release of energy in nuclear fusion, one must become accustomed to the concept of binding energy. Binding energy is described by Albert Einstein’s famous relationship [10],

\[ E = \Delta mc^2. \]  

The \( \Delta m \) here represents the difference in mass between a nucleus from the mass of its constituent nucleons. Binding energy if often referred to in units of electron volts (eV). A convenient comparison to atomic mass units (amu) states that 1\( amu \) = 931.5\( MeV \). The following table lists some standard atomic weights.

<table>
<thead>
<tr>
<th>Element</th>
<th>Symbol</th>
<th>Charge (Z)</th>
<th>Atomic Mass (amu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron</td>
<td>n</td>
<td>0</td>
<td>1.008665</td>
</tr>
<tr>
<td>Proton</td>
<td>p</td>
<td>1</td>
<td>1.007276</td>
</tr>
<tr>
<td>Hydrogen</td>
<td>(^1H)</td>
<td>1</td>
<td>1.007825</td>
</tr>
<tr>
<td>Deuterium</td>
<td>(^2H)</td>
<td>1</td>
<td>2.014102</td>
</tr>
<tr>
<td>Tritium</td>
<td>(^3H)</td>
<td>1</td>
<td>3.016050</td>
</tr>
<tr>
<td>Helium-3</td>
<td>(^3He)</td>
<td>2</td>
<td>3.016030</td>
</tr>
<tr>
<td>Helium-4</td>
<td>(^4He)</td>
<td>2</td>
<td>4.002603</td>
</tr>
</tbody>
</table>
The light nuclei to be fused in this experiment is Deuterium. The binding energy of deuterium can be calculated simply as,

$$B_{2H} = (m_p + m_n) - m_{2H} = 2.21045 MeV.$$  \hfill (2)

Likewise, the binding energy of helium-3 is a much larger 28.3 MeV, making the D-D reaction favorable for fusion research.

A deuterium-deuterium (D-D) fusion reaction can be written as

$$^2H + ^2H \rightarrow ^3He + ^1n \quad \hfill (3)$$

By comparing the masses before and after the reaction using the previous table, we can see that the reaction releases an energy difference of approximately 0.004349 amu or 4.051 MeV. This energy is released in the form of $\gamma$ radiation and in the kinetic energy of the reaction products.

### 3.1.2 The Coulomb Barrier

Before one can consider utilizing the energy released in the D-D fusion reaction, they must first consider how to bring the nuclei close enough together, such that the strong force overcomes the coulomb repulsion. Figure 1 is a 1-D depiction of this repulsion.

![Figure 1: 1-D representation of coulomb repulsion](image)

The electrostatic force between two D-D is described by the charge of their nuclei, denoted "Z", and their distance apart. The force between two deuterium nuclei is

$$F = \frac{k_e q_1 q_2}{r^2}. \quad \hfill (4)$$

The work done in moving the two nuclei is then

$$U = \int Fdr = \frac{k_e Z_1 q_1 Z_2 q_2}{r_o} \approx 1.434 MeV. \quad \hfill (5)$$
In other words, in this classical description we must impart approximately 1.434 MeV to a single deuterium nucleus to allow it to fuse with another deuterium nucleus. This is equal to having a temperature in our experiment of approximately $1.6 \times 10^{10} K$.

This criteria can be relaxed a bit, when one considers the phenomena of tunneling. In this case, tunneling refers to particles "tunneling" through the coulomb barrier, if they do not have quite the appropriate energy to overcome it. The probability of tunneling through the coulomb barrier can be approximated using the proportionality

$$P \propto e^{-\frac{2\pi}{\lambda}},$$

where $\lambda$ refers to the DeBroglie wavelength of the nucleus, defined as $\lambda = \frac{\hbar}{p}$. Taking this probability of tunneling to account, we can again overestimate the energy needed to imparted in our system, but this time with slightly relaxed requirements. The average temperature in this case is then

$$T \approx 40 \times 10^7 K,$$

which is about 35,000 eV [10]. This energy will serve as a point where we certainly expect to observe fusions.

### 3.1.3 Ion Temperature

Our IEC system, as to be described in section 4, will generate a plasma in a spherical capacitor. Within this plasma will be gas ions following a distribution of energies. Of these ions there will be atmospheric gasses along with our added, fusible gas, deuterium. And so we are concerned with knowing what our probability of fusing is at different energies, along with how many ions in our population will be at said energies.

Fusion reactivity is described as the average value of the product of nuclear cross section and ion velocity $\langle \sigma \nu \rangle$ as the average kinetic energy in our system increases, so too will the reactivity. This relationship was graphically described in Kenneth Krane's "Introductory Nuclear Physics", and can be seen in Figure 2 below.
To find the number of fusions that will occur at a particular volume, we first assume that the ion energies follow a Maxwell-Boltzmann distribution, we can plot the number of particulars we expect to see if the average energies of the system are 5 keV, 10 keV, and 20 keV respectively. In Figure 3, the shaded regions correspond to the product of the number of ions at a given energy, and the reactivity at that energy. In other words, the area under that region is the amount of fusions we expect to see.

Evidently, at an average ion temperature of 20 keV, we expect substantial fusions.
3.2 Discussion on Plasma

As seen in the Section 3.1.3, the energies required to produce fusion are extremely high. In all cases these energies are high enough to ionize the gas and form a plasma. As a consequence it is important to first establish a basic understanding of plasma physics. Analysis of plasmas will introduce some fundamental properties of plasma related to IEC fusors. These properties deserve a full derivation, but for the purposes of this paper they will just be stated here with an intuitive explanation and reference to the full mathematical derivations.

3.2.1 Debye Length

The first property is the Debye length $\lambda_D$.

$$\lambda_D^2 = \frac{\epsilon_0 T}{2n_0 e^2} \quad (8)$$

The Debye length is the length over which the Coulombic force is reduced to $\frac{1}{e}$. This reduction occurs due to shielding from opposite charged particles mitigating the force from other like charged particles. What this means is that if the plasma’s dimensions are much much greater than the Debye length it is safe to analyze the dynamic properties of the plasma without taking the Coulombic interactions within the plasma into account.[7]

This is important as much of the theoretical work on IEC fusors is done on a scale much much larger then the Debye length. Such an assumption will be used for the remainder of this paper and all plasma body sizes will exceed the Debye length.

3.2.2 Equation of Motion

As plasmas are made up of charged particles they respond to electric fields. In addition they act as fluids, as a result individual elements experience pressure gradient forces as well as collision forces. Finally, as a hot fluid, a convection effect takes place in the plasma as heat is transferred through the plasma. When these effects are taken together it is possible to see that

$$m \left( \frac{\partial \vec{v}}{\partial t} + \vec{v} \cdot \nabla \vec{v} \right) = -e\vec{E} - e\vec{v} \times \vec{B} - m\nu\vec{v} - \frac{1}{n} \nabla (nT_e) \quad (9)$$

This is the macroscopic equation of motion for the plasma and most of the properties discussed in the following sections have their basis in it. In addition, from it we can see a crucial aspect of plasma’s behavior that is utilized in IEC fusors, specifically plasma’s direct response to electric fields. If these fields are powerful enough they can contain the inertial motion of the ions and confine them.
3.2.3 Plasma Frequency

One of the unique properties of plasmas that differentiate them from normal fluids is that they oscillate due to charge buildups within the plasma. As a side note, this does not conflict with the Debye length property as it deals with microscopic perturbations of the plasma and thus does not alter the macroscopic properties of the plasma in most cases.

\[ \omega^2 = \frac{n_0 e^2}{m_e \epsilon_0} \]  

(10)

Which is the plasma frequency for small oscillation in the plasma. While this normally does not impact the operation of IEC fusors the property has some potential to be amplified via an externally modulated electric field to increase density [1]. The application of these principles, however, is outside the scope of this project.

3.3 Inertial Electrostatic Confinement and Potential Wells

Inertial Electrostatic Confinement fusors operate by using two or more electrodes, normally in spherical symmetry, to develop a deep potential well anywhere from 40 – 150kV. Either a neutral gas is introduced which experiences electrical breakdown due to the high electric fields or ions are introduced from an external source. Regardless the positive ions are accelerated towards the center of the fusor to the bottom of the potential well and impact with enough energy to fuse.
3.3.1 History of IEC’s

In the early 1950’s, Philo Farnsworth first proposed his designs for an inertial electrostatic confinement device to the ITT corporation, a global manufacturer. This information was not made public, however, until his patent was granted in 1966. This design for an electrostatic confinement fusor can be seen in Figure 5.

Farnsworth can not take full credit for the premise of electrostatic plasma confinement, however. Lavrent’ev, in the former soviet union, proposed both electrostatic confinement, and the magnetic enhancement of such confinement during approximately the same time period [4].

During the conception of these devices, they were often discredited in the scientific community due to Earnshaw’s theorem. This theorem can be written as

\[ \nabla \cdot \mathbf{F} = \nabla \cdot (-\nabla U) = -\nabla^2 U = 0. \]

(11)

This states that for some electrical force \( \mathbf{F}(\mathbf{r}) \) derived from a potential \( U(\mathbf{r}) \), there will be no divergence. This can be alternatively viewed as, a plasma confined by electrostatics will always have at least one degree of instability, hence the system will crumble. The pioneers of early IEC’s understood this, but they also knew that if the ions were set in motion by the initial electric field, then it would be possible to achieve confinement. The next important studies were made accessible by Langmuir, wherein he analyzed current flow in a concentric spherical capacitor, seen in Figure 6.

3.3.2 Plasma Confinement

In order to fuse, ions must be confined to a relatively small area by the powerful electric fields generated by the potential well. This is in part because the ions have a far larger scattering cross section than a fusion one. What this means is that on average ions will be ejected from the center of the IEC without fusing. In this process there are several ways that energy can be lost, the most common of which are up-scattering in energy, charge exchange reactions and impacting the electrodes. Up-scattering occurs when an ion interacts with another ion
in such a way as it gains additional energy during the collision. Charge exchanges occur when an ion interacts with a neutral atom and steals an electron, leaving a low energy ion and a high energy neutral that escapes. Finally when an ion impacts the electrode it looses energy to the heating of the electrode, this heating can eventually lead to electrode breakdown.

The major focus of research into IEC fusors is how to mitigate these losses while increasing the energy density of the plasma. This is generally called plasma confinement. Physically plasma confinement is due to the fact that when a ion is scattered from the center without gaining energy it is slowed by the electric field and than accelerated back towards the center and thus confined with no energy leaving the system. Confinement time can be thought of as the number of times an ion will pass through the center before loosing its energy. [4]

Quantitatively confinement time is

\[ \tau_e = \frac{W}{P_{\text{loss}}} \]  

Where \( W \) is the total energy in the volume and \( P_{\text{loss}} \) is the rate of loss of energy due to all of the aforementioned sources as well as radiation and bremsstrahlung. In order to determine if confinement is good enough to produce break-even fusion we must evoke the Lawson criterion which says \( n \tau_e = 10^{14}\text{cm}^{-3}\text{s} \) for kinetic energies \( T > 15 \text{ KeV} \). An important fact about the Lawson criterion is that it is independent of the confinement scheme, so any modification which increases either the density or confinement time brings us closer to the goal of break-even. [4]
3.3.3 IEC Electrode and Well Design

Up to this point the actual shape and design of the electrodes has mostly been ignored. However, in order to continue discussing the theory behind IEC operation it is necessary to introduce some fundamental attributes of a standard IEC device.

IEC devices are almost always set up in spherical symmetry. In traditional IEC’s the Electrodes take the form of two or more wire grids with very high optical transparency. This usually means they look like irregular metal cages or spiderwebs. The high transparency allows ions to pass through them without interacting with them while maintaining a near symmetric electric field.

The grids are than biased to high potential. The sign of the bias on the inner grid determines the kind of fusor one is constructing. If the inner grid has a negative bias than (e.g. the electric fields point towards the center), the fusor is called ion injected. The ions enter the field and are trapped in the potential well and begin to oscillate as described in the plasma confinement section.[4] This type of fusor is convenient due to its simplicity of construction. Both electrodes can be real and made of physical materials, although they don’t need to be. The draw back of both electrodes being real is that the area of convergence is large, which means that plasma density tends to be lower. Some research into replacing the center electrode with a set of electromagnets that confine an electron cloud that serves as a ”virtual” electrode. It is called virtual to distinguish it from the physical electrodes (the grids), while still conveying information about the nature of the well.

Should the inner grid have a positive bias (e.g. the electric field points from the center out) the fusor is said to be electron injected. This means that electrons must be added externally. These electrons fall into the harmonic oscillator potential of the well created by the electrodes. After a time, the charge of the electrons in the center is significant enough to rival the charge on the inner grid. As such the electric field between the
electrodes will vanish. However there will be very strong electric fields pointing from the inner grid to the electron cloud, a virtual electrode.

The Virtual electrode produces a potential well strong enough to inertially confine ions with sufficient energy to fuse when they reach the center. Virtual electrodes are in general preferable to real ones for several reasons. The first is that losses due to collisions are less frequent and not nearly as much power is lost. In addition virtual electrodes tend to be smaller and thus will confine the ions in a smaller area than could be done with a traditional, real, electrode. They do however have one very large issue: it is possible that in the course of operation the ion density becomes such that the virtual electrode is lost and the electrons scatter. It has been mainly this effect, combined with its increased impact in scaling laws that have made ion injection the preferred form of IEC fusors. [4]

There has been some research into electron injected IEC devices that should make them be able to compete with ion injected. POPS is one such area of research. It aims to use electron injection to create a specific potential oscillator potential which can than be excited by external RF electric fields.

### 3.3.4 Idealized Potential Well

An idealized representation of the distribution of the potential well is the spherical capacitor. We will do the calculation for it here. First we begin by setting up the physical situation. Imagine two spherical shells with a common center as depicted in Figure 8.
The derivation starts by writing down Poisson’s equation in spherical coordinates for a vacuum.

\[
\frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial V}{\partial r} \right) = 0 \tag{13}
\]

Which instantly reduces to

\[
r^2 \frac{\partial V}{\partial r} = C \tag{14}
\]

Now if we devide and integrate again we get

\[
-\frac{C}{r} + D = V \tag{15}
\]

In order to determine the constants C and D we have to use the boundary conditions depicted in Figure 8, specifically that

\[
V(a) = -V_0 \tag{16}
\]

and

\[
V(b) = V_0 \tag{17}
\]

by applying these conditions and doing the algebra we find that

\[
C = \frac{2V_0ab}{(b-a)r} \tag{18}
\]

and

\[
D = -\frac{2V_0a}{b-a} + V_0 \tag{19}
\]

This means that the potential is

\[
V = -\frac{2V_0ab}{(b-a)r} + \frac{2V_0a}{b-a} + V_0 \tag{20}
\]

This can be seen graphically for the experimental parameters used in the methodology section of this paper in Figure 9.

An important result of this graph is that, within the parameters of the approximation, most of the gas will ionize and gain the majority (75%) of its energy in the last 7 CM of its path from the outer grid.
3.3.5 Potential Wells with plasma

The actual potential within IEC fusors exhibit different properties then those in the idealized situation above. A major factor that influences these properties is the fact that vacuum does not exist and plasma is free to move within the well. When the current of ions entering the center is high enough the ion cloud is large enough to deflect additional ions. The ions already there are still contained by the potential well of the electrons, but they themselves form a new potential well. This new potential well can than trap an additional electron cloud forming a new virtual electrode. These nested wells can, in theory, increase the volume of the fusion plasma. The term for such nested wells is "Poissors".[8]

It is possible to find a differential equation that can be solved using easily measurable quantities, namely the ion and electron currents and masses. We start by realizing that the potential is described by Poisson’s equation:

\[
\frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial V}{\partial r} \right) = -4\pi \left( \rho_i - \rho_e \right)
\]  

(21)

The electron currents can be expressed in terms of the velocities and densities.

\[ I_e = 4\pi r^2 \left( \frac{\rho_e}{2} \right) v_e \]  

(22)

The ion current can be expressed exactly the same way. Now from conservation of energy we can see that:
Figure 10: The nested potential wells caused by alternating areas of positive and negative plasma particles called Poissors

\[ \frac{1}{2} m_e v_e^2 - eV = E_{0e} \] (23)

and

\[ \frac{1}{2} m_i v_i^2 + eV = E_{0i} \] (24)

Where \( E_{0e} \) and \( E_{0i} \) are the total electron and ion energies respectively. We want to be able to express this in terms a dimensionless less quantity that can be easily solved for. We will call it \( W \):

\[ W_e = \frac{\frac{1}{2} m_e v_e^2}{\Lambda} \] (25)

Where \( \Lambda \) has units of energy and will be determined later. Using this we can write the velocities in terms of \( W \) and \( \Lambda \):

\[ v_e = \left( \frac{2\Lambda}{m_e} \right)^{\frac{1}{2}} W^{\frac{1}{2}} \] (26)

and

\[ v_i = \left( \frac{2\Lambda}{m_i} \right)^{\frac{1}{2}} \left[ W_0 - W \right]^{\frac{1}{2}} \] (27)

Where

\[ W_0 = \frac{1}{\Lambda} [E_{0e} + E_{0i}] \] (28)

combining equation 14 (for both ions and electrons), 18, and 19 we find that
\[ 4\pi e [\rho_i - \rho_e] = -\frac{2eI_i}{(2\Lambda/m_e)^{1/2} r^2} \left[ \frac{1}{W^{1/2}} - \frac{G_0}{(W_0 - W)^{1/2}} \right] \]  

(29)

We define \( G_0 \) as the ion to electron current ratio.

\[ G_0 = \frac{I_i}{I_e} \left( \frac{m_i}{m_e} \right)^{1/2} \]  

(30)

Now if we employ Poisson’s equation and allow \( e \left( \frac{\partial V}{\partial r} \right) = \Lambda \left( \frac{\partial W}{\partial r} \right) \) than we can obtain

\[ \frac{\partial}{\partial r} \left( r^2 \frac{\partial W}{\partial r} \right) = \frac{1}{W^{1/2}} - \frac{G_0}{(W_0 - W)^{1/2}} \]  

(31)

This transformation places the requirement on \( \Lambda \)

\[ \Lambda^{1/2} = \sqrt{2eI_e m_e} \]  

(32)

we can make this into a normal second order differential equation by letting

\[ z = \ln \frac{r}{r_0} \]  

(33)

and so

\[ \frac{d^2 W}{dz^2} + \frac{dW}{dz} = \frac{1}{W^{1/2}} - \frac{G_0}{(W_0 - W)^{1/2}} \]  

(34)

This differential equation can be solved for \( W \) which is directly related to the energy distribution for a particular system. The solution does still depend upon various inputs such as current, voltage and boundary conditions.[?]  

It is now possible to state a seemingly obvious, but important result from this derivation. Equation 23452 tells us that the kinetic energy of a single electron (or ion) is directly related to \( \Lambda \). From equation 2345245 we see that \( \Lambda \) is directly dependent on the Ion current flowing into the center of the well. This means that when IECs operate at higher voltages both the density of ions crossing the center and their energy increases. The collisions in the center would thus be both occur more often and at higher energies, improving the fusion yield.

4 Methodology

Due to the considerations presented in Section 3.3.3 the fusor was built in an ion injected configuration. Our completed experimental setup can be seen in Figure 11.
4.1 Select Vacuum Chamber and Vacuum System

A Pyrex bell jar and aluminum base plate were used to form the vacuum chamber used in this experiment. The bell jar was selected based on availability and the fact it allowed us to take visual measurements of the plasma more easily. The bell jar was 60 cm across its base and 80 cm tall. The base plate was chosen based on cost and ease of machining, it had a thickness of 2 cm.

In order to achieve a stable plasma and thus fusion the pressure in chamber had to be brought down to at least $10^{-3}$ torr. Ideal pressure ranges would have been in the range of $10^{-6}$, however equipment issues prevented us from achieving this.

A mechanical roughing pump was used to set up the vacuum. It was attached to the chamber via a mechanical vacuum feed-through in the aluminum baseplate.

4.2 Gas Management

The fusible material used in this experiment was Deuterium gas. Deuterium was leaked into the chamber via a mechanical feed-through.

During the experiment the volumetric flow in and out of the chamber was held in constant equilibrium so that the pressure would not change. This was necessary in order to prevent variations in the pressure from affecting the plasma density and fusion reactions. Before adding deuterium, our chamber pressure reached about $10^{-3}$ torr. After beginning to leak deuterium, the pressure could only be held at approximately $10^{-2}$ torr.
4.3 Grids and Stalks

Our anode and cathode grids were made of 308L stainless steel. This is the low carbon form of this steel wire, which was chosen to minimize sputtering. Sputtering is a phenomena that occurs at sufficiently high voltages, and subsequently high energy plasma discharge, can cause anode and cathode material to be ejected upon collision with an incident ion [4]. Stainless steel is a desirable material due to its high melting point of about 1700 Kelvin. So long as the stainless steel is a few centimeters away from the confinement region of our plasma, it will sustain its shape for the duration of the experiment.

The stainless steel wire was then formed into three large and three small circles, which were then spot welded together to form the cathode and anode, respectively. The anode and cathode were then mounted on a stalk, consisting of ceramic, electric fence insulators, and fastened with vacuum epoxy. The insulated stalk is meant to prevent arcing between the high voltage and the aluminum baseplate.

For determining how to optimally confine plasma in future IEC projects, we compared the spot welded grid design with one of significantly lower transparency. A stainless steel mesh was formed into a sphere around the anode, and plasma confinement was tested and compared in both systems.

4.4 Electrical System

In order to achieve fusion energies, it was necessary to obtain a power supply that could out put at least up to 50 kV. Initially, it was anticipated that the power supply for a modern neutron generator could be repurposed for the sake of this experiment. After receiving the generator, it was found that the output connections for the power supply could not be used in this experiment without harmful modifications.

We were not able to reach our power output goal of at least 20 kV in this experiment. For the sake of verifying out work in confining plasma for use in tabletop nuclear fusion, we chose to test our system at the highest voltage available to us. This came as approximately 3000 Volts, by using an available, Northeast Scientific Corporation, regulated high voltage power supply.

A ceramic, high voltage feedthrough, rated to 25,000 Volts, was fitted through the baseplate and again sealed with vacuum epoxy. The power supply was connected to each of the two prongs on the external side of the feedthrough. Inside the chamber, the positive DC signal was applied to the outer cathode, and connected with silicone rubber insulated high voltage wire. The negative DC voltage was fed up the insulated stalk to the inner anode. The potential generated between the grids is described in Section 3.3.4.
4.5 Neutron Detector

The Neutron Detector we intended to use to verify was a Ludlum 2241-4 Neutron Meter. It consists of a moderating material which slows neutrons so that they be absorbed by the contained Boron-10. The absorption results in the release of a $\gamma$, which a conductor converts to a signal which reads out both neutron counts, and Rem/hr. If neutrons were measured, it would be an assured verification of fusions being generated in the dense cloud of ions in the center of the potential well.

5 Results and Discussion

When stepping up the voltage applied to the grids between 0 and 50 kV, we would anticipate seeing a peak in fusions between 20 and 30 kV, as evident in Section 3.1.3. After this point, it was expected that the loss of ions due to collisions would vastly overtake the number of fusions, and the plasma would become more difficult to confine in our comparatively basic setup [4].

Due to limitations in availability of a high voltage power supply, we were not able to conduct our experiment at what would be considered fusion temperatures. What remains is to verify that we were able to confine a plasma up to the maximum voltage available to us. In addition, it is pertinent to compare the anode and cathode design with respect to surface area, so that the design exhibiting the best confinement can be use in future, higher voltage tests.

Using pictures taken on an Iphone camera, ImageJ was used to produce " .tiff" files depicting plasma confinement in both deuterium and non-deuterium environments, with both transparent and non-transparent anode configurations. A contour plot of grayscale with respect to physical distance was then produced using MatLab, in order to observe plasma confinement. Areas that have a higher optical intensity can be associated with an increase in energy and frequency of ion collisions, which can produce visible light [6]. The configuration with the best confinement of D-D plasma will be used in future experiments. The graphics generated are included in the following sections.

5.1 No Deuterium & Transparent Grid

This configuration exhibits our best confinement. The plasma consists solely of ionized background gasses. And at the relatively low pressure of approximately $10^{-3}$ torr. The hottest part of the plasma is the dense, 2 cm sphere of collisions at the center of the anode.
With deuterium leaked into the vacuum chamber we were only able to attain pressures of about $10^{-2}$ torr with our rough vacuum pump. It is evident that the whiter, deuterium plasma is not as well confined as the background gas plasma. This can be attributed predominantly to the higher pressure in this environment, but could also be improved at higher voltages. Another way to mitigate this issue without changing equipment would be to increase the size of the grids in order to compensate for the increase in pressure when deuterium is added.
5.3 No Deuterium & Mesh Grid

The background gas plasma is again tested using the less transparent, stainless steel mesh. The confined region is larger here, and slightly less intense than that of the previous background gas test. This is due predominantly to ions losing kinetic energy after collisions with the mesh. Although the mesh did well to maintain the shape of the confined region, the fact that the plasma is brought much closer to the anode is not desirable, as the grid will be more prone to melting. The bright jet seen at the lower left of the anode is due to a deformation in the spherical mesh, resulting in leaking of the plasma.
5.4 With Deuterium & Mesh Grid

With added deuterium, the mesh grid appears to result in better confinement of the deuterium plasma. Although we anticipated, as in Figure 13b, that the deuterium gas would again extend past the boundary of the anode, it appears that collisions with the grid help confine the deuterium plasma better than in the case of the transparent anode.
6 Conclusions and Recommendations

Regarding the comparison of the transparent grid with the stainless steel mesh, we predict better confinement in future devices with highly transparent grids. This is most evident when observing the no deuterium graphic, Figure 12b, versus the no deuterium graphic Figure 14b. Although the confinement with deuterium seems to improve with the addition of the mesh, lower vacuum pressure and higher voltages will improve confinement far more than the added spherical mesh. This is because the addition of the mesh promotes ion collisions, which quickly corrode the steel and reduce the ion kinetic energies. If optimal vacuum pressures were achieved (below $10^{-3}$ torr), and fusion temperatures were reached, the limitations of the spherical mesh will compound.

Our experiment was limited to rough vacuum, and a voltage of 3000 V. These voltages are far too low to produce fusion, and so the properties of plasma confinement in our device were further investigated. These investigations, at least up to the voltage reached, verified, the high voltage configuration used to produce our potential well. The plasma showed little to know signs of instabilities up to 3000 volts. In order to better observe the properties of the deuterium plasma, however, it would have been beneficial to construct larger grids. The grids we used were limited to fit the dimensions of the bell jar.
For optimal confinement of plasma to theoretical fusion temperatures, it is recommended that one uses a transparent spot welded grid design. For maintaining a well confined plasma, it is recommended that turbo vacuum is used.

6.1 Recommendations for Future Works

1. In order to study our IEC design at fusion temperatures, future projects must apply a voltage difference of at least 20,000 eV, and up to 40,000 eV.

2. In order to lower ion mean free path, a turbo vacuum should be obtained before further studying of D-D fusion in this device.

3. Use Ludlum Neutron Meter to observe neutron counts as a function of voltage, comparing the production of neutrons in the D-D fusion reactions in the spot welded grids and spherical mesh grids.

4. Introduce a modulated electric field to try to match the plasma frequency and improve periodic neutron production in deuterium plasma (POPS) [2].
References


