Generalized Extrapolation of Temperature and Energy from Light Emissions in a Fusor

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Abstract

IEC fusors are fusion reactors that rely on DC power to directly ionize a pure gas, unlike most other fusion reactors. Although achieving positive energy output is impossible in an IEC, IECs find uses in neutron production and among amateurs. Although there are high-tech solutions to finding the statistical temperature for an IEC, no low-tech solutions exist. The prolific use of IEC's justify the research into a lower tech solution to finding the statistical temperature, which may help enthusiasts find the threshold in which their fusor may start emitting high energy radiation.

Acknowledgments

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1 Introduction

1.1 A brief history of nuclear physics

In the early 20th century, new theories and investigations led to a revolution in chemistry and the addition of two new forces to the standard model in physics. One of the most important discoveries was that electrons were necessarily bound to positively charged protons, and it suggested that atoms could possibly be put back together in a stable manner (although this had been predicted by chemists decades earlier). Stability within atoms is effectively governed by two forces: The strong nuclear force (hereby referred to as the “strong force”) and the slightly weaker coulombic force. The strong force binds baryons together (in this case, neutrons and protons), dominating at a close range but rapidly falling off. The coulombic force binds together oppositely charged particles (in our case, electrons to protons) and repels similarly charged particles (such as protons to other protons). It follows the inverse square law, which states that the force between two particles decreases relative to the distance squared - in other words, if I double the distance between two particles, the electromagnetic force becomes four times weaker. Within an atom, these two forces are at constant odds with each other. Inside the nucleus, the protons are constantly resisting one another, but are bound together by their neutral neighbors, the neutrons. Without the nuclear force, there would be nothing to maintain the internal consistency of the nucleus, and elements with more than one proton would be effectively non-existent. Likewise, on the outside of the nucleus, the electrons are inexorably bound to their positive counterparts, protons. Without the electrons bound to the protons, bonding between atoms could not occur.

As important as they are, these forces have been known for over a century - the more interesting relationship is that between protons and other protons. Among protons, the coulombic force seeks to tear apart protons from one another inside the atom, but these protons could theoretically be bound together by the nuclear force if they became sufficiently close. Of course, the weak nuclear force can transform protons to neutrons and vice versa if an atom is unstable, lowering their energy level. However, it did give rise to modern fusion, in which protons can be bound together through the use of neutrons. To achieve fusion, electrons must first be stripped from both atoms, releasing some energy (this process is known as ionization). Then, the nuclei of the atoms must be smashed together at sufficient speeds for the sheer velocity to overcome the coulombic force. Once the nuclei overcome the distance threshold, the strong force begins to dominate, binding neutrons and protons together.

1.2 Nuclear fusion

While there are many ways for atoms to fuse, the ultimate goal is to create a commercially viable energy source (which is yet to be achieved). In the largest research fusion reactor, the ITER, temperatures reach over 100,000 degrees Kelvin, and plasmas are precisely controlled to the point where any deviation or instability can result in an insufficient plasma. In this reactor, deuterium and tritium gas is cycled in, and is ionized when AC power in massive solenoids induces a magnetic flow. The nuclei, now in a plasma ensemble instead of a gas ensemble, fuse together when within sufficient distance. Helium-5 nuclei decay immediately, ejecting a neutron into the wall of the reactor, heating water (which also acts as a cooling mechanism), evaporating said water to spin a turbine. Theoretically, a successful tokamak nuclear fusion reactor needs only deuterium and tritium, the former abundantly found in any body of water (although needing a form of electrolysis to purify), and large-scale generation of the latter being investigated [Gia17]. There are many alternative types of fusion reactors, such as the stellarator, inertial confinement, and spheromaks.

1.3 Inertial Electrostatic Confinement Fusion

The device that this project focuses on employs an alternate method of fusion: Inertial Electrostatic Confinement (IEC) fusion. IEC devices most often resemble a sphere nested within another sphere [San14]. There are various configurations for IEC fusors, however, we will be primarily exploring the ion-injected configuration with physical anodes and cathodes. In an IEC fusor, a vacuum is generated by sucking out gasses, and a pure gas is pumped in. Then, a large electric potential is generated across the two spheres, such that one sphere becomes a cathode and the other an anode. The electric field then ionizes the pure gas. The positively charged nuclei ions are then accelerated towards the center, where they are confined within the smaller of the two spheres. A large glow can be seen in the center and emanating in tendrils out of the holes of the interior spherical mesh.

1.4 Research objectives

Because fusors need to be vacuum sealed, it is often difficult to get an accurate understanding of the temperature within the fusor. Although fusors are ultimately created to fuse atoms together, IEC fusors are not efficient enough to be a commercially viable source of fusion energy. However, they still have their uses - IECs can be used to investigate the plasma states of various gasses, in commercial neutron generation, [MS00] and used to produce meta-stable Molybdenum-99 [RS]. This motivates the study of the light released during reactions, as the light emitted is a direct reflection of the energy released and the statistical temperature within the fusor. There are a few alternative methods for extracting information about the fusor, often focusing on neutrons emitted during fusion cycles, although various other methods of investigating the ion velocity distributions, and hence, energy, have also been recently investigated [Wol15]. Although there are many high-tech methods for retrieving data from inside the system, there are possible alternate, lower-budget methods for extracting information about the insides of a fusor. Light in the visible range, detectable by any camera, can be correlated to the energy released during collisions, particle accelerations, and ionizations inside the fusor. Although there are certainly professional applications for fusors, most fusors are built by hobbyists. Professionals certainly can use high-tech solutions to obtain data about fusors, most non-professionals do not, motivating the research goal of this project: To develop a low-tech solution to retrieve data about the temperature inside a plasma.

2 Background

2.1 Principles of Plasma

Plasmas are often regarded to be ionized gasses. While ionization is a necessary condition for plasmas to form, plasmas exhibit more properties than just ionization. The first important property to arise from the initial ionization is quasi-neutrality, which dictates that, within a cloud of ionized gas, there are various polarized regions within that cloud. This region creates an electromagnetic field. As a result of the separation between the positive ions and the electrons, there is a massive restoring force that forces them back together [Hut01]. Quasi-neutrality is described by the Debye Length, which can be described in an electrode as

$$\lambda_D^2 = \frac{\epsilon_0 k T_e}{n_e q_e^2}$$

where Epsilon naught is the permittivity of free space, n_e is the density, k is Boltzmanns distribution, T_e is the temperature [Sho03]. At distances outside of the Debye Length, the plasma appears neutral. However, at distances shorter than the Debye Length, one can observe the potential of an electrode or probe. In other words, it is the region in which the effects of the polarization of a gas can be observed [Sho03]. The instabilities and effects that are generated in these regions are known as collective effects and are characteristic of plasmas. We can use this parameter in one of our three necessary criteria to determine if our substance is a plasma or not. Our first parameter is given by

$$N_D = 4/3 n\pi * \lambda_D^3 >> 1$$

Where n is the density and N_D is the number of particles within a sphere of radius of the Debye length. If there are not enough ionized atoms within the Debye Sphere, then it is not a true plasma.

The second parameter is given by

$$\lambda_D^3 << L$$

The Debye Length governs the quasi-neutrality of the plasma - if it becomes too large, then one does not have a quasi-neutral plasma, but a polarized plasma. When a plasma is completely polarized, it stops resembling a cloud of chaotic particles, and instead virtual cathodes and anodes. However, this only occurs at the most extreme of states.

Finally, omega is the frequency of plasma oscillations and tau is mean time between collisions with neutral atoms, our third parameter is given by

$$\Omega * \tau > 1$$

In other words, this equation describes whether or not the collisions follow a plasma distribution or a neutral gas distribution [Che15].

Although these are the parameters needed for plasmas, there are other major differences between neutral gasses and plasmas. Because plasmas are non-neutral, and therefore non-uniform, organized motion within a plasma becomes very important, as non-kinetic interactions become much more pronounced within plasmas. Additionally, plasmas conduct electricity much better than gasses. As the Debye Length grows, the conductivity tends toward infinity as the ions and electrons are completely separated from one another. A clear but not so obvious distinction between plasmas and gasses is that plasmas are composed of various species. In an ensemble of particles within a gas, any collision between two neutral particles are the same, aside from differences in velocity. However, there are two additional variables that govern particulate behavior inside plasmas - mass and charge. A collision between two electrons is very distinct from collisions between a neutral atom and a positive ion. Finally, velocity distributions can vary when working with plasmas, as opposed to the Maxwellian distributions of gasses [GB].

2.2 Bremsstrahlung

Bremsstrahlung, or “braking radiation”, is created when oppositely charged particles collide with and deflect one another [Tur]. First observed by Roentgen in the late 19th century [R6̋7], bremsstrahlung is electromagnetic radiation that is characterized by the change of the emitter’s energy. The single difference between Bremsstrahlung (sometimes known as continuous X-rays) and characteristic X-rays is that characteristic X-rays occur only in very specific spectrums (such as the ionization energy required to liberate a single electron from the valence shell of rubidium). Unlike characteristic X-rays, Bremsstrahlung occurs over a larger spectrum of energy (such as an electron beam being deflected by a large atom of uranium at continuous increments of angle) [McC97].

Given by the following equation, provided the energy of the emitted photon is known, the following equation can be used to find the photons wavelength and frequency:

$$E = hf = hc/\lambda$$

To find the change in kinetic energy between the two particles, we turn to the most elementary equation from electricity and magnetism: the coulombic repulsion force. The coulombic repulsion force says that the force between any two charged objects is given as

$$F = kq_1q_2/r^2$$

Furthermore, the work done to move two nuclei a distance is given as

$$\int_{r_f}^{r_0} F\,dr|_{r_0}^{r_f} = -kq_1q_2/r_f + kq_1q_2/r_0$$

Thus, Bremsstrahlung radiation from a single interaction can be described as

$$W = \frac{kq_1q_2}{r}|_{r_0}^{r_f}$$

Where discrete amounts of energy are irradiated as a function of

$$W = hc/\lambda$$

This equation is extremely handy - it not only describes the work done by two particles to move away from each other, but also the kinetic energy lost due to the particles resisting each other, resulting in gamma rays. This also describes the energy released when an electron is liberated from the shells of an atom (although we have to take rfinal to be infinity), although the ionization occurs not necessarily due to a massive electric potential, but instead due to heat-related vibrations.

2.3 Larmor radiation

In addition to Bremsstrahlung, radiation emanating from accelerating charges is a large source of light. This is one of the most robust descriptions of light emissions, as its equation can describe emissions due to vibrations, the acceleration across a potential, and ionization. We can power radiated P in terms of the permeability of free space μ_0, the charge of the accelerating particle, the acceleration, pi, and the speed of light, such that

$$P = \frac{\mu_0 q^2 a^2}{6\pi c}$$

To see a full derivation, please refer to [Gri]. The result of this equation can be found everywhere in electromagnetism, and is a fundamental result of motion

2.4 The equation of motion

Unlike standard equations of motion for charged particles, we are working with a fluid. Within our fluid, we will need to account for varying temperatures, particle density, and electromagnetic waves, in addition to external electromagnetic effects. However, that is assuming that we are working with an ideal plasma, which we are not. We are working with a mixed-state solution, so we will also have neutral-neutral collisions and neutral-ionized collisions within our plasma. The full equation of motion also must include the stress tensor if we are accounting for magnetic field influences. The magnetic field dynamically influences the flow of particles, and therefore the temperature of the system. In order to fully describe it, one must consider anisotropisms within the plasma. Where n is the particle density, u is the velocity of an individual particle, q is the charge of the particle, E is the electric field influencing the particle, and B is the magnetic field, u naught is the velocity of a neutral particle, and tau is the average time between collisions. Finally, we can fully express our equation of motion including neutral collisions as

$$mn[\frac{\delta \mathbf{u}}{\delta t} + (\mathbf{u} * \Delta)\mathbf{u}] = qn(\mathbf{E} + \mathbf{u} \times \mathbf{B}) - \Delta * \mathbf{P} - \frac{mn(\mathbf{u} - \mathbf{u}_0)}{\tau}$$

However, as the neutral atoms within the fluid are ionized, the equation of motion shifts to

$$Mn\frac{d\mathbf{v}_i}{dt} = en(\mathbf{E} + \mathbf{v}_i \times B) - \Delta p_i - \Delta * \pi_i + \mathbf{P}_{ie}$$

$$Mn\frac{d\mathbf{v}_e}{dt} = en(\mathbf{E} + \mathbf{v}_e \times B) - \Delta p_e - \Delta * \pi_e + \mathbf{P}_{ei}$$

These equations describe a fluid model - however, due to ease of use and an interest in collisions rather than the complex motion of particles in a fluid, we will be working with a kinematic model. Effectively, we will be maintaining standard newtonian distributions, using (eq.3.47) instead of (eq.5.58).

2.5 Inertial electrostatic Confinement

Originally conceptualized and patented by Philo Farnsworth in the mid twentieth century, Inertial Electrostatic Confinement, or IEC, was one of the first explored methods of nuclear fusion. An IEC, unlike many other fusion reactors, ionizes and fuses through an electrical force instead of a magnetic force, unlike almost all of its contemporaries [Che15]. Like all man-made fusion devices, the fusor must be vacuum sealed.

There are two main forms of IEC fusors - virtual and physical. In a virtual IEC, interior grids are created by the concentration of ions in the center of a fusor. Unlike virtual IEC's, physical IECs are composed of two grids, instead of one outer grid. These grids correspond to either ground/positive charge (electron injected configuration), or negative charge (ion injected configuration). The outer grid can be charged by induction (this induced charge is created by an electric field). Although there are numerous configurations for an IEC, we will be focusing on the ion injected configuration. We will be focusing on physical, ion injected IECs. In the center of the fusor is a tower which supports the mesh grids within the fusor. Before the power supply is turned on, the chamber needs to be evacuated of atmosphere. Then, a pure gas is pumped into the high vacuum chamber. Then, another vacuum is generated, with a small amount of the purified gas remaining. Without a sufficiently low vacuum (between $10^{-}2$ and $10^{-}6$), reactions can become unstable.

When the voltage source is turned on, a massive potential is created across the two grids, ionizing gasses that were inserted. A strong potential well is created in the center of the inner mesh grid, trapping ions in the center and continuously smashing other ions against those in the center. Due to conservation of energy, ions are unable to escape from their initial radius (and hence, potential), as whatever kinetic energy they pick up in their move to the center is converted from their initial potential energy. When they exit the center (if they fail to collide) their kinetic energy will be converted to potential - exactly the same potential as they started with, ending in the exact same position.

2.5.1 Linear Energy Transfer [LET] and vacuum

It is rare for a particle to traverse from one side of the IEC to the other with the same amount of energy it began with. The possibility that a particle retains all of its initial energy increases as the particle density decreases. This is one of the most important consequences of having a weak vacuum. By reducing the particle density outside of the inner radius, it ensures that a particle being accelerated into the center does not lose momentum along the path. If a particle collides with another as it is accelerated towards the center, it loses a lot of velocity, and therefore kinetic energy. If too many particles lose energy before they reach the center, the IEC will fail to confine a plasma, as the particles in the plasma will quickly lose energy. For a full derivation of LET, see [Tur].

Having a mean free path equal to the distance of the outer radius, or average distance traveled until a collision occurs, is key to fusion. Fusion can only occur if particles collide at sufficiently high speeds. Provided a large enough potential (and resulting kinetic energy), the ions will be continuously smashed at their highest velocities in the center. Thus, creating a very strong vacuum is exceedingly important. We can use a Poissons equation to describe it.

2.5.2 Poissons equation

In our Geometry, Poisson's equation will have two potentials to consider - a positive outer radius, and a negatively charged inner radius. Furthermore, pressure is not constant. The density of particles varies as plasmas are generated. To keep it simple, we can assume a mid-point, at which $\rho(r) = \frac{\rho}{r^2}$. Let's begin by solving the problem:

$$\frac{1}{r^2}\frac{d}{dr}r^2\frac{d}{dr}V(r) = \frac{\rho}{r^2}$$

$$r^2\frac{d}{dr}V(r) = \rho r + C$$

$$V(r) = \rho ln(r) - \frac{C}{r} + D$$

Now that we have solved the equation, lets find C and D. We begin with our boundary conditions

$$V(A) = -V_0 = \rho ln(A) - \frac{C}{A} + D$$

And

$$V(B) = V_0 = \rho ln(B) - \frac{C}{B} + D$$

Now that we have found the boundary value equations, lets re-express our equations using our boundary equations:

$$V(A) + V(B) = 0 = \rho ln(AB) - C(\frac{1}{A} + \frac{1}{B}) + 2D$$

$$C\frac{B+A}{BA} = \rho ln(AB) + 2D$$

This isn't ideal, as it has two variables in one problem. Let's try the next boundary condition:

$$V(B) - V(A) = 2V_0 = \rho ln(\frac{B}{A}) - C\frac{(B-A)}{BA}$$

$$C = \frac{\rho ln(\frac{B}{A}) - 2V0)}{\frac{B-A}{BA}}$$

Combining these equations, we get:

$$D = C\frac{B+A}{BA} - \frac{\rho ln(AB)}{2}$$

$$D = \frac{\rho ln(\frac{B}{A}) - 2V0}{\frac{B-A}{BA}} * \frac{B+A}{BA} - \frac{\rho ln(AB)}{2}$$

$$D = (\rho ln(\frac{B}{A}) - 2V0) * \frac{B+A}{B-A} - \frac{\rho ln(AB)}{2}$$

So, our final equation can be expressed as

$$V(r) = \rho ln(r) - (\rho ln(\frac{B}{A}) - 2V0)(\frac{BA}{r(B-A)}) + ((\rho ln(\frac{B}{A}) - 2V0) * \frac{B+A}{B-A} - \frac{\rho ln(AB)}{2}$$

$$= \rho ln(r) - (\rho ln(\frac{B}{A}) - 2V0)\frac{1}{B-A} * (B + A - \frac{BA}{r}) - \frac{\rho ln(AB)}{2}$$

As stated previously, Poisson's equation changes radically depending on the voltage of the system, the time since the experiment was started, and initial gas conditions.

2.5.3 Gas Discharges

As discussed previously, there are various methods used to ionize gas in a fusor. The method of interest is through DC gas discharges. We can describe such the voltage needed to break down the gasses as a function of separation distance and pressure [MM14]. Generally, voltages between 300 volts and 1500 volts suffice, but this is only true when there is a sufficiently low pressure or short separation distance [MM14].

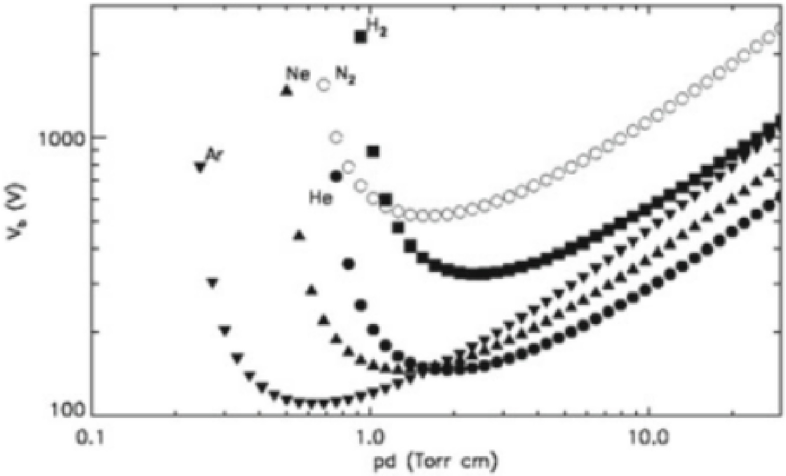

Figure 1: Figure 1: Paschens curve for the gas species Argon, Neon, Hydrogen gas, Nitrogen gas, and Helium [LL05].

3 Methodology

We began our project by retrofitting the fusor, developing a matlab program that took data of interest, then constructed a model to correlate the light inside the fusor to the fusors temperature.

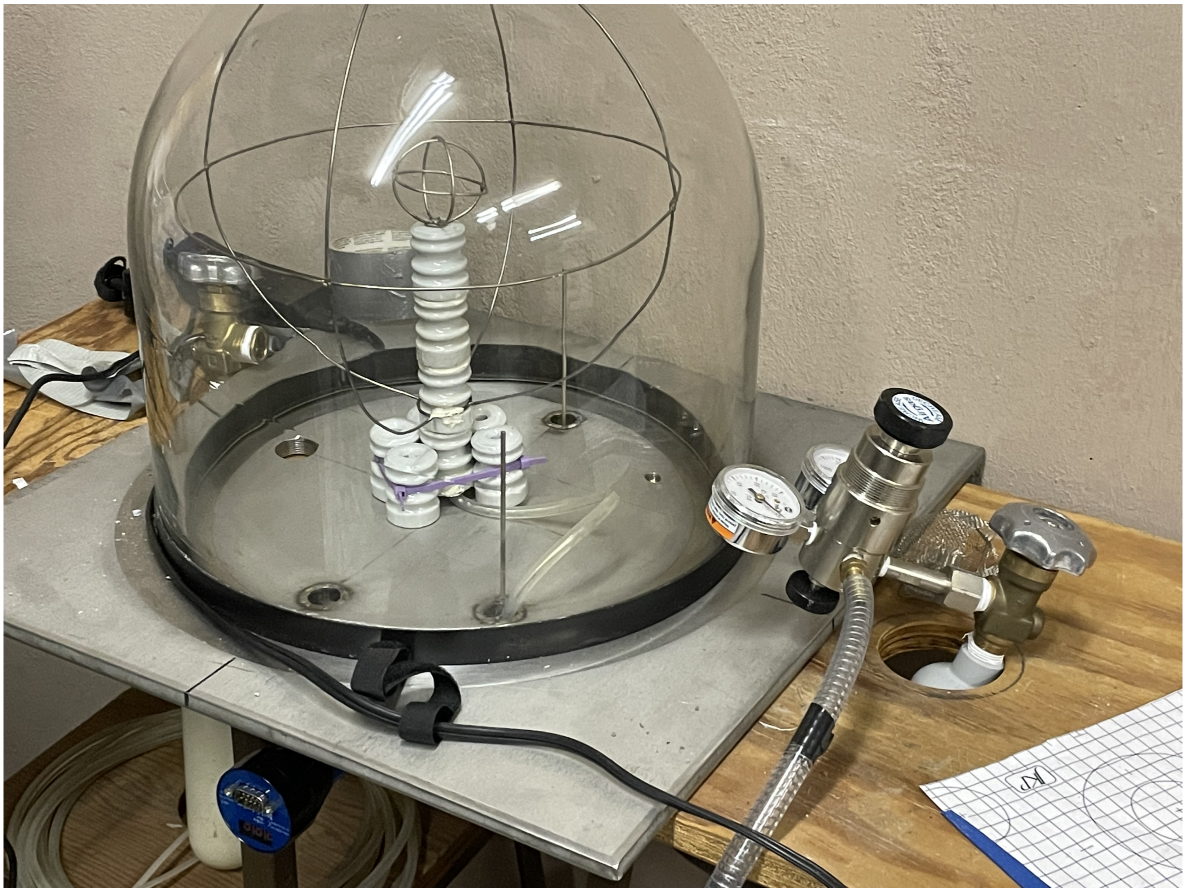

Figure 2: The original setup of the fusor.

3.1 Retrofitting

When the fusor was initially reviewed, there were significant safety concerns in the fusors design and set up. The fusor has a large post in the center which is reinforced by a pentagon of ceramic components at its base. The ceramic pieces are tied together using a set of zip ties. The fusor was initially set on top of the surface of two adjacent stools. Additionally, the Pyrex bell jar was not sealed to the plate. Finally, the fusor was left in this position for over six years.

We began retrofitting by creating what is essentially a reinforced table to replace the adjacent stools, making the whole structure much more stable. Constructed of 2x4's and a plywood surface, this table had a massive hole cut into it from which vacuum sealed apparatus and cathodes/anodes could be easily attached and removed. Bars of wooden 2x4's reinforced the legs of the table, making ninety-degree angles to the legs and the surface. The plywood surface was drilled into the 2x4's. Finally, to ensure that no accidents could occur, the wooden table was screwed into an existing table in the lab. Now that the full fusor apparatus was stable, we shifted focus to the ceramic pole. The pentagon of ceramic components was not entirely stable, and the fusor became lopsided during transportation to a new location due to one of the components being shifted. Additionally, we had concerns that the zip ties could either ignite or melt during operation of the fusor. However, we appreciated the insulation capacity of the ceramic. We used a large amount of ceramic "legos" to form a baseplate of ceramic with a hole in the center for the wire and left a lane open for the insulated cathode wire to exit the vacuum sealed apparatus. To ensure ceramic pieces would remain in place, we used a sealing epoxy that was highly resistant to heat. We also reinforced around the hole in which the tower would be placed, creating a tower. Finally, we placed the tower in the center and wedged it in, sealing the tower to the post with epoxy.

Although we initially explored methods for increasing the vacuum within the fusor, we could not find any significant permanent changes that would allow us to remove the Pyrex bell jar and replace it with ease. However, we did coat the bottom of the base plate of the fusor near where the Pyrex bell jar contacted a very viscous liquid - a vacuum sealing oil. When the vacuum pump turns on, the viscous liquid should make an additional seal to the bell jar when the vacuum tries to suck in additional air. We also had to machine components to assist with vacuum sealing, such as silicone tubes that are tight to the insulated cathode wire. In addition to machining components, we made additional vacuum sealing changes to the fusor, by using a mix of duct tape, gorilla epoxy, vacuum hose clamps, and hose clamps. Additional vacuum sealing precautions are discussed in 5.

We also replaced the gas-regulator with a vacuum gauge. The gas regulator ensures that gas stays constant, so as to reduce instabilities within the plasma due to changes in pressure. However, we ultimately decided that a pressure gauge would be more effective. Our vacuum seals were not as effective as we would have liked, so we prioritized being able to accurately read the pressure inside the fusor before beginning, rather than being able to stabilize the gas flow. The maximum pressure we reached was -26.5 mercury-inches gauge pressure, or 87 torr absolute pressure, on the order of 10^2. The previous group was able to reach an absolute pressure of 10^-2 Torr [MM15]. This is likely due to a more effective vacuum pump.

Prior to testing, the outer mesh broke, forcing us to reweld. In addition, a short term change we had to make to the fusor to get a plasma was by physically weaving a new mesh onto the outer mesh, reducing the separation distance between the physical cathodes and anodes.

3.2 Recording data

Before we programmed a script to take fluorescence data, we first needed a method for obtaining said data. We rigged a camera system around the fusor, placing cameras at various angles to the fusor (90, 45, and 0 degrees from the x=z plane at the height of the cathode) using metal bars. This system allowed us to take consistent data, as depending on the angle and distance from which the picture or video is taken, radically different readings will be recorded.

After hooking up the camera system, we set to work writing a program. Our program takes videos, separates the videos into image files, converts them to grayscale, balances the red, blue, and greens to reflect the true light intensity, and then performs a mathematical analysis of those images to determine the heat inside the fusor. We chose MATLAB as our programming software, as MATLAB can read 16 Bit video files. To obtain accurate data, we needed a large amount of data points such that we can create an accurate qualitative model should the mathematical modeling fail. Obtaining these data points is incredibly difficult unless videos were taken. We also needed that data in 16 Bit, as 16 Bit images yield significantly more information compared to 8 Bit images.

When we first began programming, our focus was on efficiency. We began by processing individual images. Then we created a looped process that would break video files up into libraries individual image files. Finally, we applied our grayscale to the image files once they were separated, preparing the files to be analyzed. The full program for separating image files and analyzing them can be found in 5.

3.3 Method of Analysis

3.3.1 Emission considerations

When working within any environment, it is important to consider all the internal effects, both intended and unintended. Within a fusor, we may have a few sources of electromagnetic radiation with additional sources at higher temperatures. Radiation is primarily emitted through Larmor effects and bremsstrahlung - however, radiation is not uniformly emitted. When considering ions traveling through a fusor, it is important to consider all interactions they may have that will lead to variance in emissions such as direct collisions, fluctuating potentials (leading to differential accelerations), and short range interactions.

The first and most obvious interaction is bremsstrahlung. Although the device operates at low pressures, and therefore low-density gasses, there are still large amounts of bremsstrahlung produced when ions smash into each other and into neutral atoms. The denser the gas cloud, the more bremsstrahlung will be produced.

Emitted bremsstrahlung radiation is an expression of work done by a travelling ion, and therefore energy radiated out of the system. If an ion experiences no energy loss between the point in which it begins acceleration and the point in which it decelerates to v = 0, then it has not interacted and has lost no energy, therefore emitting no radiation (aside from radiation emitted due to acceleration and deceleration). As the gas is ionized into a plasma, interactions become much more likely, as near-collisions can begin creating bremmstrahlung at further distances. We can describe bremsstrahlung emissions using neutral gas density, initial potential energy, and ionized particle density.

Since we are operating at low pressure, we can assume that photons emitted will not be absorbed or affected by the gas or ion clouds within the fusor.

The second form of light emission we want to account for is ionization. The energies required to ionize electrons are always discreet and can be described as the energy required to move an electron from its valence radius to infinity. Although atoms can be directly ionized through a massive electric potential, they can also be "shaken off" by their nuclei vibrating at specific frequencies, which can only occur under specific temperatures.

Light emitted due to ionization is actually due to the Larmor effects. As discussed previously, anytime a charged particle is accelerated, photons are emitted. This is true of both charged particles approaching the barriers and being accelerated and decelerated as well as electrons being liberated from their shells.

Without understanding the role these effects play, we may not be able to precisely characterize the temperature inside the plasma.

3.3.2 Mechanical properties

To construct a rudimentary form of light spectroscopy, we must make many considerations to how we need to set up our system. Most importantly, we need to begin with a number of mechanical properties. We begin with the grayscale. When working with a grayscale, there are various methods used to convert color into a shade of gray. Most grayscale conversions use either an average equation or a weighted equation. The average equation converts the red, light, and green into gray through the equation, where R, G, and B represent red, green, and blue, such that

$$Gray = \frac{R + G + B}{3}$$

Although this equation is accurate to equally balancing a grayscale, it emphasizes each color (and hence, each wavelength) equally [Ima]. The more common conversion from color to gray is known as the weighted, or luminosity, method, in which the colors are weighted such that

$$Gray = 0.299R + 0.587G + 0.114B$$

This balances the RGB to account for how we perceive light. However, this balance is not accurate to the energy inside the fusor. Because we are working with a variety of different sources of radiation, we cannot narrow our visible light spectra down to a small set of wavelengths, and balance the equations of light to focus on that single spectrum. Instead, we can isolate regions of the fusor, and apply different conversions to the system. This effectively allows us to separate certain reactions from others. These effects will hopefully be especially pronounced between the center and outer regions, where collisions dominate in the center and ionization and excitation dominate in the outer regions. Once we can do that, we can work with a Grayscale conversion that is properly weighted to reflect the wavelength of the averaged emission within the visible range to gain a more accurate light intensity. However, with a characteristic plasma in a sufficiently high vacuum, the variance should be minor. This primarily accounts for non-characteristic plasma effects. Knowing how to grayscale to account for readings accurately is only a small part for obtaining accurate readings. Aperture, ISO, and shutter speed must be considered.

A camera's aperture dictates how much light is allowed to come into a camera - it is the camera's exposure to light. The larger the aperture, the more light is allowed per square centimeter. The smaller the aperture, the less light is allowed per square centimeter. Adjusting the aperture is integral to deciding where the grayscale cut off should be - having a higher aperture (such as f/2.8) will allow much more noise into the system than a lower aperture (such as f/16, which allows in 1/128th the amount of light as f/2.8) [Man22b].

ISO value, or International Standard Organization value, dictates how much light is to be allowed into the image, determining the image noise. The higher the ISO, the less the auto correction. In our case, higher ISO's are generally preferable since we don not require very high image contrast and resolution, which is limited in part by the imaging noise [Man22c].

Finally, shutter speed should be considered. Shutter speed is essentially how much light a camera can gather within the speed of the shutter. The shorter the shutter speed, the less time there is for a camera's sensor to detect light, leading to a darker image. The longer the shutter speed, the more time a camera has to detect light, leading to a much brighter image. Likewise, the more frames per second of the camera system, the faster the shutter speed [Man22a].

These three values work in tandem to affect the exposure of the image. Although understanding the mechanical properties of the camera is important, it is paramount that these values be kept constant. Most modern cameras have software that dynamically adjusts to create a more pleasing image. By changing any of these, especially aperture, a much different image will be produced, skewing data.

Although when stated it is obvious, maintaining a constant distance between the camera and the center of the inner mesh is paramount. Light intensity rapidly falls off the further the camera is from the fusor, obeying the inverse square law, such that

$$I(r) = \frac{I_0}{(4\pi r^2)}$$

This law also governs pixel precision - the farther the camera from the fusor, the less precise the image.

Background noise can also distort the light detected by the camera emanating from the fusor. It is imperative to remove as much background light as possible, and set a filtration intensity where all intensities below a certain point will be filtered out of the image during a grayscale calculation.

3.4 Testing and data collection

At pressures exceeding 10 Torr, arcing can be exceedingly dangerous and unpredictable, so purifying the gasses to ensure that we are working with low Z gasses was necessary, lest we damage the plexi glass. We began by evacuating the bell jar. In our experiments, we were only able to consistently reach a vacuum of 49.4 Torr absolute pressure. After we evacuated the bell jar, we injected pure nitrogen gas. Once the pressure reached about 500 Torr absolute pressure, we evacuated the bell jar again. This purifies the bell jar, bringing the purity level to 90% nitrogen. We repeated this experiment two more times, ensuring that the gas that was left was 99.9% nitrogen. Once the gas inside was purified, we turned on the power supply connected to the mesh. We slowly increased the voltage from 500 volts to 3000 volts over the course of a minute. We understood that we were not going to obtain a characteristic plasma, so we did not light-proof the environment as much as would have been ideal. We left the overhead lights on for a minute before turning them off to ensure there would be no mechanical issues that could damage the lab equipment, the apparatus, or us (such as massive discharges that could arc to the baseplate, or damage the plexi-glass. Once no mechanical issues were detected, we began recording data on all three cameras. Once we finished recording data, we slowly brought the voltage down to zero.

4 Results

We failed to record data that would allow us to test our model due to mechanical issues - namely, the base-plates insufficient maximum vacuum. Hence, the focus of this result section will not be whether our modeling worked, but rather if our process worked. See 5 for visual data.

4.1 Mechanical problems and their effects on data

Going into the project, we were unaware of one fundamental issue with the fusor - the baseplate was unable to hold a sufficient vacuum. Although the baseplate was initially successfully constructed with the capacity for a high-vacuum environment, during an upgrade which happened a year later, a weld deformed the baseplate enough such that it was rendered effectively useless during the vacuum process. We were only able to achieve 49.4 torr absolute pressure, which is similar to the previous group's maximum vacuum. However, this was not recorded in the original paper, but in a communique close to the end of the project [McC22]. As discussed in section 2.5. having an exceedingly low pressure is key to ensuring a stable, characteristic plasma is formed.

There is additional noise we did not account for until after data was taken and analyzed - that of refraction and reflection in the apparatus. The metal baseplate reflected a lot of the light back into the camera, especially the camera looking at the x,z plane. Additionally, because the bell jar was curved at the top, the camera facing the x = y plane had a lot of light refracted into it, which skewed the data.

4.2 Generation of non-characteristic plasma

Once we learned of the problems with the baseplate, we abandoned our pursuits to further vacuum seal the apparatus, instead focusing our efforts on achieving non-characteristic plasmas to showcase the validity of using a camera to find the energy within the fusor. We made several changes to obtain any DC-relate gas discharge, referring to the Paschen curve [See 1]. In the Paschen curve, there are four independent variables: vacuum, distance, gas type, and voltage. We realized that amplifying the voltage could have disastrous effects, such as arcing between the wire mesh and the baseplate, damaging the plexi-glass apparatus, or deform the mesh grid, so we decided to maintain the voltage. We were unable to improve the vacuum by a significant amount due to the baseplate. We were also unable to change the gas, as purified non-nitrogen gas is expensive. The only modification we could make was to reduce the separation distance. We quickly weaved a new grid of titanium wiring, which was imprecise and non-uniform, but had a much shorter radius than that of the outer grid. We connected this new mesh to the outer grid, such that it would receive the same DC connection as the outer grid while taking advantage of the stability offered by the outer grid.

Although we managed to create arcing, arcing is not characteristic plasma which is what we modeled. There are a number of large distinctions between arcing and characteristic plasma. Arcing occurs when there is a massive discharge between two points that have a high potential and a ground (for common examples of arcing, look no further than lightning). When this discharge occurs, atoms along the path of least resistance are ionized. This is radically different than a characteristic plasma, which has collective effects, behaves like a fluid, and most importantly, can be controlled. Arcing is highly uncontrollable, and though we may be able to predict where it will happen, the discharges cannot easily be controlled, and generating a permanent arc can be exceedingly difficult. Because of our inability to generate a characteristic plasma, we were unable to obtain clear and concrete data to directly test the model created. However, that does not mean all models that use a form of basic photography as a gauge for energy emissions would not work. Because of this, we focused on building a small model to gauge the energy emissions due to the arcing.

5 Conclusion

There are many projects that could be explored within the scope of fusor technology. First and foremost, a future project should focus on machining a completely new baseplate, or at the very least make it the first step in their project. There are also alternatives than having a single baseplate with a bell jar resting on top of it. For example, one could machine two baseplates, each resting on the y=z axis, with a new plexi-glass jar in between the two. This could theoretically allow for more interesting geometries, such as designs based on tensegrity, as well as provide additional stability and lower concerns of refraction from the bell jar. Furthermore, skewed data due to reflection could be reduced. However, this design would require an additional hole be machined into each baseplate to hold the tower due to structural concerns. Once a new baseplate is engineered, there are a few interesting projects one could focus on, such as exploring and characterizing the relationship between different geometries and maximum plasma intensity. One could also focus on continuing the objective of this project - quantitatively determining the plasma intensity using a low tech camera solution.

Prior to continuing this project, it is paramount that a new baseplate is machined. Although it is certainly possible to get some plasma without it, such plasmas will almost certainly be non-uniform, uncontrolled, and asymmetrical. Without a sufficiently low pressure, generating a stable plasma is impossible. Without a stable plasma, we cannot continue modeling. Thus, continued repairs is paramount to being able to complete the research objective of this project.

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Appendices

Appendix A: Methods employed to vacuum-seal the fusor

Despite the baseplate not being ideal, there were a variety of methods we employed to vacuum seal the fusor as well as a variety of methods we used to find issues in the vacuum sealing. To seal the pyrex bell jar, we slicked the edges with a vacuum sealing oil. When the vacuum is turned on, the oil is partially sucked in, preventing air from flowing in. When we machined a piece that would allow for two tubes to be put inside what was previously a much larger screwhole, the tubes were not perfectly sealed against the tubing holes. To compensate, we used a vacuum epoxy to seal the tubes to the hole.

In early stages, we used a lot of duct tape. Duct tape can be viable for easy fixes to connection points, such as sealing the vacuum generator to its vacuum tube. Using vacuum hose clamps are the most effective method of ensuring vacuum sealing, and they should always be the go to for sealing the chamber.

The first way to find leaks, and most obvious, is to simply listen for the leaks. After beginning the vacuum generation, listen for any leaks - it should sound like a hiss. If pressures drop to a couple hundred torr, then you will be unable to hear noise until you turn the generator off. There are numerous alternative methods to find leaks. The other we employed was placing water at the boundary of the wall and watching for bubbling in the water when the generator was turned on. This bubbling is due to air rushing into the apparatus.

Appendix B: MATLAB computer program

```
obj = VideoReader('FusorImage3Small.mp4'); vid = read(obj); frames = obj.NumberOfFrames;
    ST ='.tif';
    for x = 1 : frames
            // converting integer to string
            Sx = num2str(x);
            // concatenating 2 strings
            Strc = strcat(Sx, ST);
            Vid = vid(:, :, :, x);
            cd frames
            // exporting the frames
            imwrite(Vid, Strc);
            cd ..
end
xlabel('time')
ylabel('Average light intensity over time')
time = 37; //this should be the length of time in seconds
x = linspace(0,time,frames);
y = zeros(1,frames);
            for i = 1 : frames
            // converting integer to string
            Si = num2str(i);
            // concatenating 2 strings
            Strc = strcat(Si, ST);
            RGB = imread(Strc);
            I = rgb2gray(RGB);
            mask = I ¿ 0; // This sets the intensity for it to mask
            props = regionprops(logical(mask), 'Area');
            allAreas = sort([props.Area]);
            maskedGrayImage = I; // First initialize.
            maskedGrayImage( mask) = 0; // Now mask
            y(i) = mean2(nonzeros(maskedGrayImage)); // basic analysis - just average of all non-zero
intensity values. Is a place holder
            imshow(maskedGrayImage);
end
plot(x,y)
//time = frames./fps;
//Data analysis here.
```

Appendix C: Test images and data

Figure 3: Figure 3: Image of the fusor during arcing before and after grayscaling. This image depicts the fusor when the image was taken (with lots of background noise) and after the grayscale was applied using a weighted grayscale equation with an intensity threshold of 140

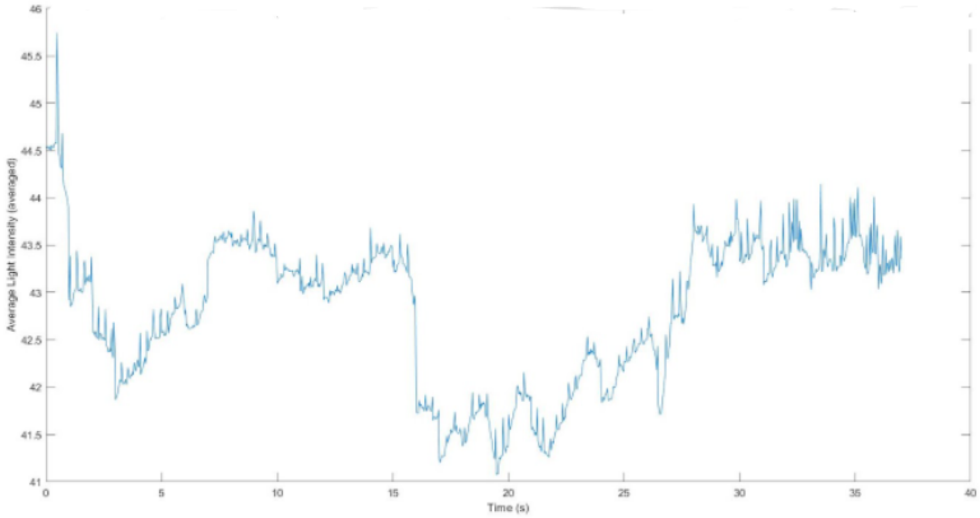

Figure 4: Figure 4: Test run of the fusor at 49.4 Torr absolute gauge with an uneven separation distance of 4 cm. Nitrogen Gas injected. Mean intensity calculation (includes zeros).