# MAGNETOHYDRODYNAMICS IN TOKAMAK REACTORS AND ITS EFFECT ON PLASMA DENSITY

A Senior Scholars Thesis

by

FRANCO JAVIER MORELLI

Submitted to the Office of Undergraduate Research
Texas A&M University
in partial fulfillment of the requirements for the designation as

UNDERGRADUATE RESEARCH SCHOLAR

December 2011

Major: Mechanical Engineering

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Approved by:

Research Advisors: Steve Suh and Robert Handler
Associate Director for Honors and Undergraduate Research: Duncan MacKenzie

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# ABSTRACT

Magnetohydrodynamics in Tokamak Reactors and Its Effect on Plasma Density.
(December 2011)

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The world's energy consumption is at a crossroads. While petroleum coffers continuously yield enough petroleum to meet the current state of energy consumption, increases in energy consumption and advancements in technology bear significant weight on our ability to maintain current standards. Looking ahead, plasma fusion is a means of yielding vast amounts of clean, renewable and virtually limitless amounts of energy. With many advancements taking place since the 1950's, the current Tokamak reactor claims to be able to produce more energy than it consumes, realizing a dream over 60 years in the making. Many characteristics, including plasma density, have to be tuned to maintain optimal conditions. By using finite element method embodied in COMSOL and first principles, one attempts to show how the plasma density evolves through a Tokomak's modes of operation and to quantify the density against a known standard. The results, although inconclusive seem to point towards a direct correlation between changes in the plasma density and the different modes of Tokamak operation, including pulsing, diverting, beam injection and modes of plasma instability.

# ACKNOWLEDGMENTS

I am especially thankful to Professor Suh, for while he might consider himself as neutral in aiding me towards this task, sometimes just listening and being there is enough. I would also like to thank Professor Handler, one of the smartest guys I know ;O) as well as the financial support of the Texas A&M University Honors and Undergraduate Research Office.

# NOMENCLATURE

| | |
|---|---|
| $D^2$ | Deuterium |
| A | Area |
| $B_T$ | Toroidal Magnetic Field |
| $B_\phi$ | Poloidal Magnetic Field |
| E | Electric Field |
| f | Distribution Function |
| $F_{body}$ | Body Force |
| $F_l$ | Lorentz Force |
| H | Channel Height |
| $He^3$ | Tralphium |
| I | Current |
| I.T.E.R. | International Thermonuclear Experimental Reactor |
| J | Joules |
| J.E.T. | Joint European Torus |
| k | Fluid Conductivity |
| keV | Kilo Electron Volts |
| kg | Kilo Grams |
| kJ | Kilo Joules |
| kW | Kilo Watts |
| m | Meters |
| m | Mass |
| MA | Mega Amperes |
| MeV | Mega Electron Volts |
| MJ | Mega Joules |
| ms | Milliseconds |
| $n^1$ | Neutron |
| $n_e$ | Electron Density |
| $N_i$ | Density of Ionized Atoms |
| $N_n$ | Density of Neutrals |
| P | Pressure |
| q | Charge |
| T | Tesla |
| t | Time |
| $T_0$ | Temperature |
| $T^3$ | Tritium |
| $T_e$ | Electron Temperature |

| | |
|---|---|
| $T_i$ | Ion Temperature |
| TJ | Terra Joules |
| U | Ionization Energy |
| U(y) | Velocity in I Direction |
| v | Velocity |
| V | Volume |
| $\mu$ | Viscosity |
| $\nu$ | Kinematic Viscosity |
| $\rho$ | Density |
| $\rho$ | Fluid Density |
| $\tau_e$ | Fusion Energy Extraction Time |

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# CHAPTER I

# INTRODUCTION

We hear it on a daily basis. The words “Energy Crisis” have come to be engraved in the soul of practically every person using some form of transportation. They tell us it is inevitable. Gasoline prices will rise, and everyday we come closer and closer to one inevitable conclusion, the fossil fuels we have come to depend on will be no more. Chaos will ensue. Wars will be abound and Homo sapiens will come to the brink of extinction, or, at least, that’s what most come to expect. The truth is, no one really knows what will happen. Oh, sure, you can go to your local bookstore and find books upon books of what scholars think might happen, but the future is still uncertain. What is certain is that other forms of energy will have to be harvested. We have to look beyond the next century to come up with solutions to detrimental problems.

Sources of energy are typically classified as either renewable or non-renewable. Non-renewable sources, like fossil fuels are such that when they are harvested, they are not replenished. This is the main problem with todays source of energy. Once petroleum reservoirs have been consumed, there will be no more petroleum left to extract energy

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This thesis follows the style of the *American Society of Mechanical Engineers*.

from. Renewable sources are such that they can be continually harvested and replenished. Solar power is a renewable resource because the sun will always shine (or so for the next couple of billion years); solar power is essentially unlimited. The key to a continued source of energy is a shift from a society that has built it’s framework on a fossil fuel based energy source, to a renewable energy source such as solar or wind power [1,2].

If the solution is so simple, then why is it that one is so reluctant to make the switch? What is stopping us from investing in technology that promotes renewable sources, such as building wind farms off the coast of California, rather than drilling for new petroleum reservoirs in the Alaska wilderness? While the answer is multifaceted and not easy to explain, one can see that the potential specific energy extraction from the carbon-carbon chemical bond found in fossil fuels far outweighs that of wind or solar. The specific energy density for a fossil fuel, such as gasoline is 46.4 MJ/kg. Natural gas has an even larger value of 53.6 MJ/kg. The energy reaching the surface of the earth is about $1kW/m^2$. A $1\ m^2$ solar collector operating at 20% efficiency is able to collect only .2 kW of power. Operating for 1 hr., that same solar collector can only extract 720 kJ. In comparison to an internal combustion engine running at the same efficiency, one kg of octane can provide 10.7 MJ of energy. 1 kg of Octane can provide approximately 15 times the amount of energy as one solar collector running for one hour. The specific energy density inherent to fossil fuels is much greater than those of renewable sources.

The task is to find a renewable source that is as energy dense, if not greater, as current non-renewable sources.

**Nuclear sources of energy**

All forms of energy found on earth came from nuclear sources at one time or another. The fossil fuels we harvest today were once organisms that covered the surface of the planet, deriving their energy from the sun. Today, we understand that the process by which the sun produces its energy is via nuclear fusion. The heavy element, Uranium-235, found in most nuclear reactors around the world was produced during a stars supernova. To date, nuclear fission is the only wide scale use of nuclear energy. Problems abound, while this fuel source has the potential to yield vast amounts of energy ($8.825 * 10^{10}$ kJ/kg), the products of the reaction remain radioactive and poisonous to organic life for thousands of years. A renewable energy source must be clean as well as safe if it is to be widely accepted. Clearly, the problems associated with nuclear fission go without saying. What is needed is a source of nuclear energy that is clean and relatively safe.

There are only two possibilities when it comes to nuclear energy, fission and fusion. While fission access' atomic energy by splitting atomic nuclei, fusion takes advantage of the energy produced when atomic nuclei combine to produce different elements. Such an event it typically characterized by extremely high temperatures and pressures. A fusion bomb, for example, accomplishes its task by using the high temperatures generated during fission to fuse atomic nuclei [3]. This gives the advantage of creating enormous amounts of energy from both fission and fusion, thus increasing the bombs yield. What is needed is a fusion reaction that is controlled and self-sustaining. Harvesting such a power source could potentially thwart the impeding energy crisis and feed the needs of a planet whose energy requirements are constantly on the rise.

## Nuclear fusion and Tokamak reactors

Since the 1950's scientists began toying with the idea of creating a controlled thermonuclear fusion reaction with plasmas. Plasmas have the advantage of being ionized, and thus influenced by magnetic fields. In theory, increasing the temperature imparts the ionized plasma with kinetic energy. If the temperature were high enough, the kinetic energy of the plasma would be greater than the energy associated with the Coulomb force, thus fusing atomic nuclei together, generating energy in the process [4]. This process is typical in a star, where Hydrogen nuclei are fused, creating Helium.

In an attempt to tackle what could potentially be the world's greatest engineering feat, the first order of business was to deduce how to confine the plasma so as to isolate it from the walls of the reactor. Being that the plasma will be under intense temperatures and pressures, there is no known material on Earth capable of withstanding such conditions [2]. It was decided that a toroidal reactor was best suited to accomplish this task. It is well known that the main property of a toroidal field is closed field lines [5], thus using this property would allow one to confine the plasma, isolating it from the inner surface of the reactor. For this reason, a Tokamak reactor is toroidal in shape.

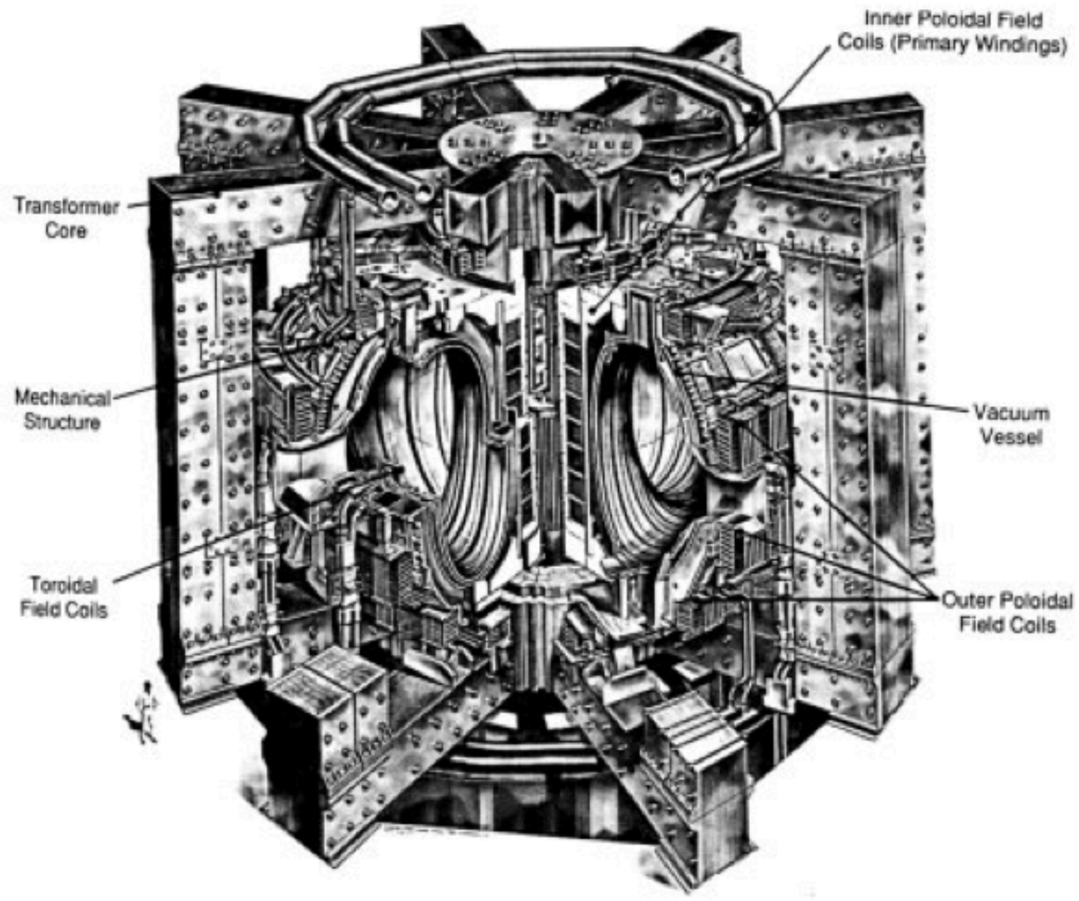

**Figure 1: Depiction of Tokamak reactor.**

Depicted in Figure 1, as an electric current is passed through windings wrapped around the outer radius, a magnetic field that is perpendicular to the direction of the electric current is induced. A simplified model is depicted in Figure 2.

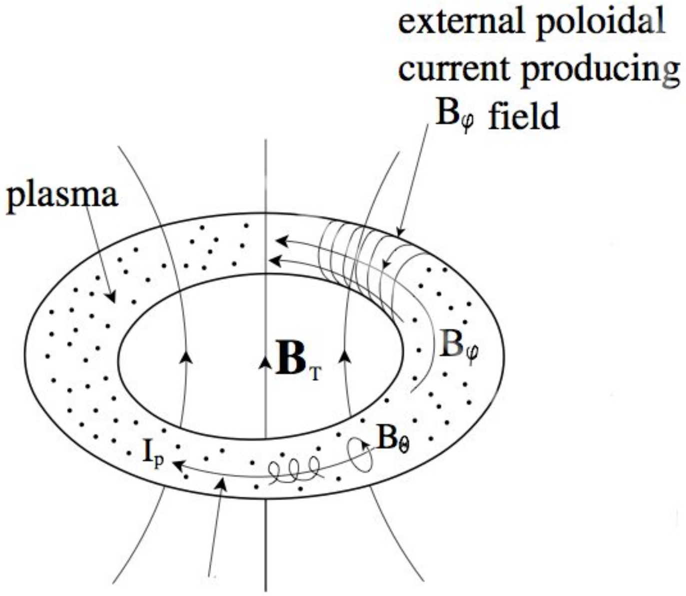

**Figure 2: Simplified Tokamak torus depicting plasma motion as a result of the toroidal current.**

The current induces a magnetic field that curves along the torus tangentially, thus confining the motion of the particles to this same motion [6]. One notes that negatively charged species travel helically in a direction opposite to that of the toroidal field. Positively species will travel similarly, but in a direction complementary to the toroidal field. This is mainly due to the Lorentz force [4] given as

$$\vec{F_l} = q\left(E + \vec{v} \times \overrightarrow{B_t}\right)$$

**Equation 1: Lorentz force.**

where $\vec{F_l}$ is the Lorentz force, q is the charge of the particle, E is the magnitude of the electric field, $\vec{v}$ is the velocity of the particle and $\overrightarrow{B_t}$ is the magnitude of the toroidal magnetic field. Simply, one can see that negatively charged species, such as electrons, will travel in an opposite direction to positively charged species, such as positively charged ions because of the associative negation of the charge. Simply put, electron charge will have a negative in front of the magnitude while positive ions will not. The helical motion of the species is due to the interaction of the poloidal magnetic field and the electric field induced by the motion of the electrons in the plasma.

## Plasma fusion reactants

It is well known that the most abundant element throughout the universe is hydrogen. Stars are known to use hydrogen as a fuel and derive energy from the elemental conversion of hydrogen to helium. Using this same process, Tokamak reactors use isotopes of hydrogen (Deuterium and Tritium) as reactants. Different Tokamak reactors use different isotopic species [3]. Figure 3 depicts the different reactions that can take place.

$$D^2 + D^2 \rightarrow \left[\frac{He^3 + n^1 + 3.27MeV}{T^3 + H^1 + 4.03MeV}\right.$$

$$D^2 + He^3 \rightarrow He^4 + H^1 + 18.3MeV$$

$$D^2 + T^3 \rightarrow He^4 + H^1 + 18.3MeV$$

**Figure 3: Various plasma fusion reaction species**

where $D^2$ is Deuterium, $T^3$ is Tritium and $He^4$ is Tralphium. Deuterium – Tritium reactions are preferred; Deuterium – Deuterium reactions require lager temperatures to achieve ignition. A reaction of this type has a corresponding temperature of $2.042 * 10^{11}$ K [5]. While the main plasma reaction will be confined by the toroidal magnetic field, the main species that will transfer energy from the reaction to the reactor walls are the generated neutrons [7]. Neutrons are neutral in charge, thus they will no be effected by the field. In addition, they carry with them approximately 80% of the product energy. Every neutron will be imparted with $2.25 * 10^{-12}$ J. To put things into perspective, 1 gram of both Deuterium and Tritium could potentially yield enough energy to produce 1TJ [5] (Assuming a complete reaction). It seems almost silly to think that anything can produce so much energy, and yet if progress is to prevail, it is power generation systems of this caliber that could potentially feed new ages of discovery.

## The dilemma

While on paper things seem almost magical, in reality, nothing could be further from the truth. Many technologies had to be perfected to produce the current standard of Tokamak reactor. In the beginning, progress had to be made with respect to magnetic confinement. Rampant instabilities within the confined plasma lead to the degradation of the field [4]. In addition, the contribution to plasma temperature from the Joule effect decreases with high temperatures [3]. To counteract this, methods of supplementing the temperature contribution from the Joule effect were devised. In neutral beam injection, atoms of deuterium and tritium are injected into the plasma stream, thus transferring their energy to the plasma. In radio frequency heating, electromagnetic waves matching the resonance frequency of the ions or electrons create resonance, thus adding energy to the plasma [3]. The same resistance that makes possible plasma heating also leads to current loss, thus the Tokamak operations are pulsed.

Confining the plasma, as well as maintaining the plasma's temperature takes a toll on energy consumption. The J.E.T required a 3.5T field, consuming power in the megawatt range; this is in addition to other power consuming methods [1]. For fusion power to be a feasible means of producing power, the system should produce more energy than it consumes. With previous version Tokamak's, the system always needed more energy than it produced. It hasn't been until recently that the "breakeven" point has been achieved, meaning that the system produces as much power as it consumes [1]. The next generation Tokamak, characterized in I.T.E.R., will implement what has been learned from plasma fusion reactions in the past, and apply them so as to derive more power from the system as is being inputted. The ultimate result of such experimentation is to produce a reaction that is self-sustaining. A reaction in which the plasma itself produces enough energy to stabilize the necessary pressure and temperature to keep the plasma nuclei fusing.

While the dilemmas are numerous (some of which have been described already), the ultimate purpose of this thesis is to attempt to describe one particular characteristic of plasma fusion, the evolution of the density. The density has been discussed before, in reference to the Coulomb force between the atoms. The temperature and pressure affect the density of the plasma. If one imagines the process on an atomic scale, one can imagine that given some finite (perhaps cubic) volume, the larger the temperature, the more likely one will be to find an atom within the imaginary volume, thus characterizing the density as the number of atoms within the imaginary volume. As one increases the temperature and pressure, the number of atoms within the volume increases. This decreases the amount of space between the atoms until the space between the atoms becomes so small, that they have no choice but to fuse. This thesis attempts to characterize how the density evolves with the increase in temperature and pressure, through the transience.

# CHAPTER II

# METHODS

As was mentioned previously, one endeavor's to know how the plasma density will evolve over time. Different Tokomak's have been built with different dimensions and thus, the optimal density sought after changes to varying degrees. It is with this in mind that any subsequent calculations will be based on the J.E.T. (Joint European Torus). These parameters are as follows [1]:

**Table 1: Table of J.E.T. operational parameters.**

| $R_0$ | a (m) | $B_\varphi$ (T) | $I_P$ (MA) | $n_e$ ($10^{-19}$ $m^3$) | $T_e$ (keV) | $T_i$ (keV) | $\tau_e$ (ms) |
|---|---|---|---|---|---|---|---|
| 3.0 | 1.2 x 2.1 | 3.5 | 5 | 3.5 | 6 | 8 | 500 |

where $R_0$ is the major radius, a is the minor radius, $B_\varphi$ is the torroidal magnetic field, $I_P$ is the plasma current, $n_e$ is the number of ionized electrons, $T_e$ is the electron temperature, $T_i$ is the ion temperature and $\tau_e$ is the fusion energy extraction time. From Table 1 one can see that in order to reach the ignition point (the point at which the energy derived from fusion is greater than losses due to conduction, convection and radiation), J.E.T. has to achieve a plasma density of $3.5 * 10^{-19}$ electrons per cubic meter, and sustain it for approximately 500 ms.

One has said that the plasma density is an important characteristic of the fusion reaction, and even what that value has to be to achieve the breakeven point. Considering that Tokamak reactors, through their operation, encounter different modes that tend to bring the plasma back to equilibrium, the push towards a self-sustained reaction causes the density to change in various ways. Pulsing, ohmic heating, modes of instability, diverting, etc… all affect the density, a necessary condition towards sustainment[1,2].

One can imagine that Tokomak's aren't something to be found in a garage sale, or even something that can be built by your average enthusiast. Without access to a national laboratory or a nationally recognized university, the average undergraduate student is bounded to mathematics and modeling, thus the method employed will concern an analysis of the dynamics of charged species, known as magnetohydrodynamics, as well as modeling using finite element method in COMSOL.

First, one requires a mathematical understanding of what is to be expected once the plasma is ignited and subjected to the compression of the toroidal field. Arguably, the most prominent equation in all of fluid mechanics is the Navier-Stokes equation [8], characterized as

$$\rho\left(\frac{\partial v}{\partial t} + v \cdot \nabla v\right) = -\nabla p + \mu \nabla^2 + f_{body}$$

**Equation 2: Navier-Stokes Equation.**

where $\rho$ is the density of the fluid, v is the velocity, p is the pressure, $\mu$ is the fluid viscosity and $f_{body}$ is the Lorentz force, show in Equation 1. In addition to Equation 2, since it is the density that one is concerned with, one requires a second mathematical description of the system to characterize the density. Newton's second law [8] is described as

$$\overrightarrow{F_{body}} = \frac{\partial}{\partial t}\int \vec{V}\rho dV + \int \vec{V}\rho\vec{V}\cdot dA$$

**Equation 3: Momentum Equation (Newton's second law).**

where $V$ is the velocity and A is the area. One must be careful to notice that a plasma has two types of charged species. Electrons are stripped from the Deuterium and Tritium as the temperature of the plasma increases, leaving positively charged atoms of Deuterium and Tritium. The two mathematical descriptions of how the fluid should behave should be done for both species as the body forces on each one will be different. If the fluid were homogeneous in the sense that it were comprised of only one element, then the calculations would be straight forward as in any textbook problem, but the way in which a positively charged deuterium atom feels another positively charged deuterium atom is different than the way it feels another tritium atom, or an electron; this is also true of any other charged particle in the plasma. One must account for the fact that the different species will contribute to the density in different ways, thus an idealized partial model will be used. If there are three times as many deuterium ions than electrons, then ideally one would expect the deuterium to contribute 75% of the density. The following description will give one the degree of ionization [5].

$$\frac{N_i}{N_n} = 2.405\times10^{21}\frac{{T_0}^{3/2}}{N_i}e^{-U/(k_B T_0)}$$

**Equation 4: Saha Equation.**

where $N_i$ is the density of ionized atoms, $N_n$ is the density of neutral atoms, $T_0$ is the plasma temperature, U is the activation energy and $k_b$ is the Boltzmann constant. By understanding how much of the plasma is ionized, one can begin to apply the degree to which the individual charged species contribute to the density.

As was mentioned, a finite element program called COMSOL will be used to employ a numerical scheme that will show how the density evolves as a function of the plasma temperature. To determine if whether COMSOL is effective in it's numerical solution, an analytical solution to Equation 2, known as the Hartmann solution will be used as a standard. Since the solution is similar to the Poiseuille solution between parallel plates, the analytical Hartmann solution is characterized as

$$U(y) = \frac{-kH^2}{2\nu\rho}\left(\frac{V_0}{H} + \frac{k}{2\rho\nu}\right)y + u(F_{lorentz})$$

**Equation 5: Hartmann Solution.**

where U(y) is the fluid velocity, k is the fluid conductivity, H is the channel height, and $\nu$ is the kinematic viscosity of the fluid. If the COMSOL solution is equivalent to the values extracted from the Hartmann solution to within 5%, then the program will be used to solve the system of equations described above.

# CHAPTER III

# RESULTS

Coupling the Navier-Stokes equation with the integral form of the momentum equation will aid one in deriving a solution to the evolution of the density as the plasma temperature rises. The Navier-Stokes equation is an equation of the momentum transport of species, and is also characterized as the first order moment of the Boltzmann equation; the integral operator, when applied to the Boltzmann equation will render the Navier-Stokes equation. Whenever a description is integrated, information is inherently lost, thus a direct solution to the issue at hand can also be recognized through considering the Boltzmann equation [9]. Given as

$$\frac{\partial f(r,v,t)}{\partial t} + (v \cdot \nabla r) f(r,v,t) + \left[\left(\frac{F}{m}\right) \cdot \nabla v\right] f(r,v,t) = \left(\frac{\partial f(r,v,t)}{\partial t}\right)_{collision}$$

**Equation 6: Boltzmann Equation**

where r is the position parameter in x, y, and z, v is the velocity in the x, y and z directions, F is the Lorentz force, m is the mass and f is the distribution function. The solution to such an equation is known as the probability distribution function, a representation of how many molecules (or atoms) of a given substance have a characteristic position and velocity at a given time. The distribution function is depicted in phase space, a seven dimensional space consisting of 3 position parameters (x,y,z), 3 velocity parameters ($v_x$,$v_y$,$v_z$) as well as 1 temporal parameter. Given the distribution function, one can solve for the particle density by integrating over the velocity space. If, for instance the distribution function is defined for a cube with a velocity distribution function [9]

$$\boldsymbol{f(r,v,t) = C_0{}^2 - v_i{}^2}$$

**Equation 7: Velocity distribution function for a cube.**

where $\boldsymbol{C_0}$ is the maximum particle velocity, the particle density is

$$N_0(r,t) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty}\int_{-\infty}^{\infty}(\boldsymbol{C_0}^2 - \boldsymbol{v_x}^2)(\boldsymbol{C_0}^2 - \boldsymbol{v_y}^2)(\boldsymbol{C_0}^2 - \boldsymbol{v_z}^2)dv_x dv_y dv_z$$

**Equation 8: Particle density given velocity distribution function for a cube.**

and analytically, the solution is

$$N_0(r,t) = \frac{1}{27}\left((3C_0{}^2 - v_x{}^2)(3C_0{}^2 - v_y{}^2)(3C_0{}^2 - v_z{}^2)v_x v_y v_z\right)$$

**Equation 9: Analytical solution to the particle density given a velocity distribution function described in equation 7.**

In this particular case one can see that the particle density is directly related to the velocity of the particle in all three directions. This would make sense since the particles are entering and leaving a prescribed control volume, thus the density would be the number of particles within that control volume at some instant of time. Figure 4 shows a graphic representation of the particle density as a function of the velocity in the x direction.

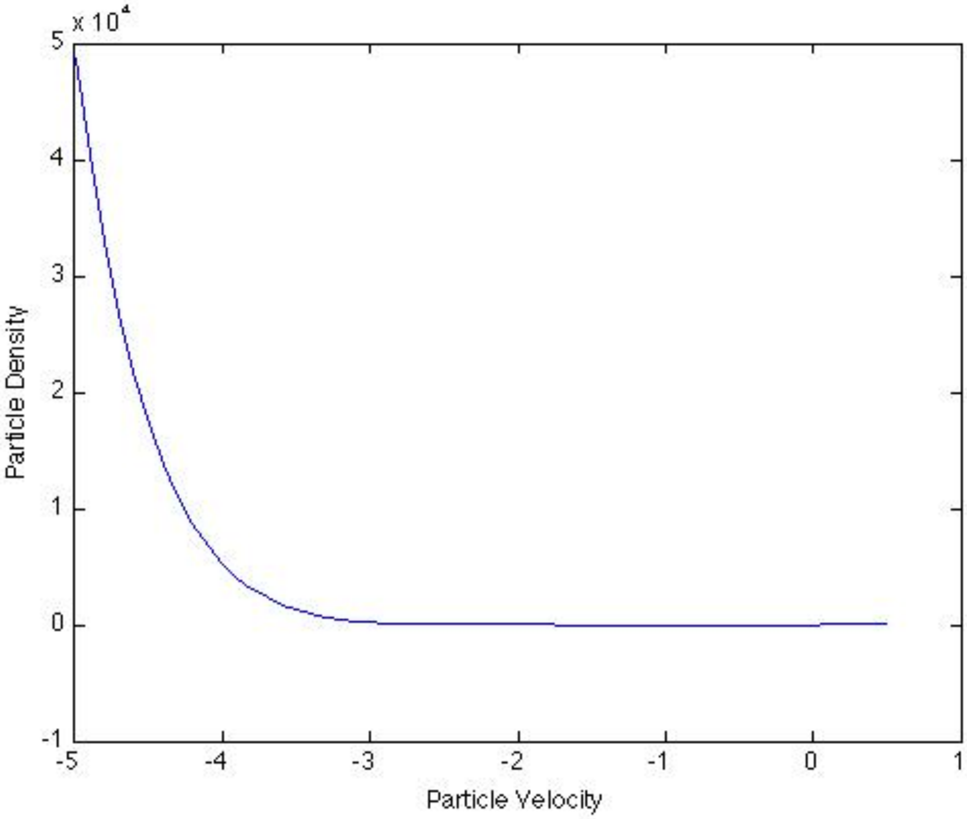

**Figure 4: Relationship between particle density and particle velocity in the x direction.**

From the figure, one notices that in this particular instance, given the distribution function describe in **Equation 7**, as the particle velocity increases, the particle density decreases. This would seem to make sense since the faster the particles are, the less time they stay in the control volume, thus unconfined, the density would decrease. Unlike in a Tokamak reactor where the distribution function will be a function of temperature, the magnetic containment field and the collisional effect of the different species, one expects for the particle density to grow as a function of temperature, thus knowing that the plasma will follow the Boltzmann equation gives one insight into how the density changes through the different operational modes of the reactor.

# CHAPTER IV

## SUMMARY AND CONCLUSIONS

It stands to reason that there is much to be gained from researching plasma fusion. As the demand for energy continues to rise and fossil fuels in petroleum coffers decrease, the need for clean and renewable energy sources will become the focus of national endeavors towards self-sustainment. While there are still many challenges to be faced and problems to be solved, the benefits or fission-based energy cannot be ignored. While in the past, problems in magnetic containment and heating stifled the scientific community, reactors in the planning phase are now ready to take what has been learned in the past and apply it towards experimental reactions that yield more energy than is inputted. There are many contributing factors that must be taken into account upon considering a reaction that will yield (rather than demand) vast amounts of energy. It is generally known that temperature, pressure and time variants must be optimal if a sustained reaction is to come to fruition. The purpose of this thesis was to consider how the plasma density is affected through the pulsed operation of the Tokamak. If it is known, through analytical means that the electron density has to take on some particular value ($3.5*10^{-19}$ $m^3$ for the J.E.T. Tokamak), then it becomes beneficial to map the progression of the density through a given segment in the life of an experimental Tokamak. How the density changes from start up to the specified electron and ion temperatures shown in Table 1. How it changes as the rate of temperature increase from the electron current decreases as well as when there is an influx of atoms from neutral beam injection, or the addition of energy from an external electromagnetic field.

Using finite element modeling in COMSOL and the understanding of several governing equations, one can approximate with some accuracy how the density changes given the mentioned conditions. The Navier-Stokes equations, modified to account for the torroidal magnetic field, coupled with integral form of the Newton's second law, is one method available. With the unknown being both the density of the fluid as well as the velocity field, using the Lorentz force as the external motivator for field motion, one can show how the density changes.

From mathematical principles that consider the fluid to be continuous and non-rarified, to other models, that take a step back and look at the fluid from an atomic point of view, the Boltzmann equation can also be employed to take snapshots of the plasma density. As the solution is a distribution function that can be integrated in order to solve for the particle density, one has the advantage of following the density throughout the course of the plasma's evolution, not just the end result.

We have spoken about the relative importance of the density and how it effects the fusion process, but what perhaps may have not been so clear is why an understanding of the evolution of the plasma, rather than just knowledge of the values at particular instances, is important. One uses an example pertaining to the periodic table to exemplify ones point. It is generally known that the larger the elements get, the more unstable they become. Of the first 92 elements, only the first 90 are found in nature; the rest have either been produced in labs, or are so unstable, that their half-lives are only seconds long. It has been theorized that there are elements beyond uranium, that if produced will be stable beyond expected; these elements are said to lie on the “island of stability”. In comparison, without knowing how the density is evolving throughout different instances of the reaction, one cannot determine, with certainty, if all the measures that have been employed to drive the reaction are necessary. It may be the case that modes of instability, while erratic and unpredictable, aid in maintaining a larger density. It may also be the case that while some measures, such as pulsing the reaction, helps to maintain the temperature at optimum levels, it might also have adverse effects on the density. Without understanding the density at all instances of time, optimizing the reaction becomes a game of “hit and miss”.

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