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Report FTCPRL-9101**

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**APPLICATION OF RAILGUN PRINCIPLE TO
HIGH-VELOCITY HYDROGEN PELLET INJECTION
FOR MAGNETIC FUSION REACTOR REFUELING**

**Prepared by
Professor Kyekyoon (Kevin) Kim
Principal Investigator
Department of Electrical and Computer Engineering
Fusion Technology Laboratory
University of Illinois
Urbana, Illinois 61801**

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ABSTRACT

This report contains three documents describing the progress made by the University of Illinois electromagnetic railgun program sponsored by the Office of Fusion Energy of the United States Department of Energy (Program Manager: Dr. T. V. George) during the period from July 16, 1990 to August 16, 1991. The first document (#FTCPRL-9102) contains a brief summary of the tasks initiated, continued, or completed, the status of major tasks, and the research effort distribution, estimated and actual, during the period. The second document (#FTCPRL-9103) contains a description of the work performed on time resolved laser interferometric density measurement of the railgun plasma-arc armature. The third document (#FTCPRL-9104) is an account of research on the spectroscopic measurement of the electron density and temperature of the railgun plasma arc.

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**Fusion Technology and Charged Particle Research Laboratory
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**APPLICATION OF RAILGUN PRINCIPLE TO
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PROGRESS REPORT FOR JULY 16, 1990 - AUGUST 16, 1991

Prepared

by

**Professor Kyekyoon(Kevin) Kim
Principal Investigator**

and

**Dr. Jianhua(David) Zhang
Senior Research Engineer**

**Fusion Technology Laboratory
Department of Electrical and Computer Engineering
University of Illinois at Urbana-Champaign
Urbana, Illinois 61801**

1. Tasks Initiated, Continued, or Completed

- a) A new hydrogen pellet generator-gas gun combination (Fig.1) that allows one to fabricate frozen hydrogen (and isotope) pellets of variable diameters and lengths was designed, fabricated, and successfully tested. This hydrogen pellet generator improves the strength of the frozen hydrogen pellets produced, and reduces the liquid helium consumption.
- b) A 1.2-m railgun with advanced spacers and trans-augmentation has been designed, fabricated, and tested in order to resolve plasma-arc velocity saturation due to gun-wall ablation and viscous drag, and to further improve the railgun performance by increasing the magnetic field strength inside the railgun bore.
- c) Pulse-shaping networks that provide lower current to the main rail and higher current to the augmentation rail, respectively, were fabricated, installed, and successfully tested.
- d) Density profiles of the plasma arc armatures (Figs. 2-4) along the railgun axis have been measured under different operating conditions using laser interferometric method.
- e) Density and temperature of a free arc (Figs. 5-6) have been measured under a variety of operating conditions by measuring Stark broadening and

line emission intensities at different time intervals during the railgun operation.

- f) Insulating refractory materials, such as alumina and mullite, have been employed and tested to replace the previously tested graphite spacers, on both the 1.2-m-long and 2-m-long railguns, not only to prolong the useful life of the insulating spacers, but also to minimize the gun wall ablation.
- g) Free arc velocities have been measured at different operating conditions on the newly designed 2-m-long railgun system with and without the mullite spacers using a streak camera. **With the proof-of-principle mullite spacers, a record free-arc velocity in excess of 36 km/s (Fig. 7) has been achieved on a 2-m-long railgun at 3 kV, 9kA, and a helium pressure of 0.2 Torr (measured at a streak duration of 400 μ s).** Under the same conditions, a free-arc speed of 11 km/s was measured with the previously used Lexan sidewalls. A more accurate measurement using B-dot probes is being implemented to double-check the free-arc speeds because a measurement error might have occurred due to the non-linearity of the streak pictures. The mullite spacers have improved the plasma arc speed due to reduced gun-wall ablation. This improvement will most likely lead to higher hydrogen and deuterium pellet velocities.
- h) The much-higher free-arc velocities measured at very low pressures led to the consideration of using perforated sidewalls to release the propellant gas

pressure behind the pellet. A set of perforated Lexan sidewalls have been fabricated with the capability of spacing variation. The preliminary results indicate that hydrogen pellet acceleration continuously increases with increasing rail current, and that the manner in which the hydrogen pellet velocity increases appears more promising with the perforated railgun than with the nonperforated railgun at higher currents (Fig. 8).

- i) CAMAC data acquisition system was installed to upgrade the data collection and processing capabilities. With the full operation of this system we will be able to monitor and record all the important experimental conditions and parameters.
- j) The trans-augmented railgun system including diagnostics has been upgraded to avoid possible arc-induced damages at very high voltages and currents. Fiber optics has been employed to physically separate the railgun system and the diagnostic instruments in the screen cage.
- k) The timing circuit that automatically measures pellet input velocity at the railgun breech and that also accurately controls arc initiation behind the pellet has been upgraded. This new version combines the pellet detection with the automatic timing and delay control and triggering, and helps prevent pellet disintegration and mistriggering of the arc initiation circuit.
- l) A crude model designed to predict the amount of arc-induced hydrogen pellet erosion during pellet acceleration has been formulated. According to this

theory, substantial pellet ablation occurs due to the high density of the plasma arc armature.

2. Status of Major Tasks

- a) A new hydrogen pellet generator capable of producing frozen hydrogen and deuterium pellets of variable diameters and lengths has been designed, fabricated, and successfully tested.
- b) A free-arc velocity of 36 km/s has been achieved on a 2-m-long railgun with the mullite spacers, indicating that mullite is a strong candidate as a material for ablation-free insulating spacer.
- c) A 1.2-m-long railgun system with trans-augmentation has been upgraded. Testing of the trans-augmentation scheme on the 1.2-m-long railgun will be carried out in the near future. The working optimal configuration will be implemented on a 2-m-long gun to achieve the highest possible velocities of solid hydrogen and deuterium pellets.
- d) Experiments designed to measure the plasma-arc armature temperature and density under different operating conditions have been performed using spectroscopic and laser interferometric techniques.

- e) B-dot probes have been designed, fabricated, and tested on the 1.2-m and 2-m railguns. They are employed to measure the railgun and plasma armature currents, and plasma armature velocities.
- f) Study of the heat dissipation and wall contamination with and without the perforated sidewalls is under way. Investigation of the effect of perforation on the elimination of secondary arcs will also be carried out.
- g) The effect of rail repulsion on the pellet erosion and plasma blow-by is being studied. A compact and stiff railgun barrel capable of withstanding severe mechanical, electrical, and thermal shocks will be investigated.

3. Research Effort Distribution - Estimated and Actual

See the attached schedule chart on the following pages.

Fig. 1 Cryogenic Pellet Generator/Gas Gun Assembly

Fig. 2 Recorded Fringes at 3 kV

Fig. 3 Density Distribution and Light Output of Plasma Arc with Lexan Peilet

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Fig. 5 Electron Density of Railgun Plasma vs. Distance

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Fig. 8 Velocity increase of hydrogen pellet on 1.2-M railgun

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Schedule of Estimated & Actual Effort Distribution - Page 1

[illegible]

Schedule of Estimated & Actual Effort Distribution - Page 2

Projected Effort
Actual Effort

**Fusion Technology and Charged Particle Research Laboratory
Report FTCPRL-9103**

**Department of Energy Project
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**TIME RESOLVED LASER INTERFEROMETRIC DENSITY MEASUREMENTS
OF A PLASMA ARC ANODE IN AN ELECTROMAGNETIC RAILGUN**

Prepared

by

**Professor Kyekyoon(Kevin) Kim
Principal Investigator**

and

**Richard G. Haywood
Research Assistant**

**Fusion Technology Laboratory
Department of Electrical and Computer Engineering
University of Illinois at Urbana-Champaign
Urbana, Illinois 61801**

I. INTRODUCTION

This work describes research on plasma electron density measurement in a plasma armature railgun. The objective of this research is to develop an effective diagnostic technique for railgun analysis. Laser interferometry is employed to make the measurements. The railgun is located at the University of Illinois Fusion Technology and Charged Particle Research Laboratory. It is hoped that a fueling device based on the railgun principle will eventually be a subsystem for nuclear fusion power generation.

Although laser interferometry has been used for many years as a plasma diagnostic technique, it is believed that this is only the second attempt to use it on a railgun-type system, and the first to use it on a railgun that accelerates a projectile. Electron density has been measured on a railgun simulator which has no projectile (Headley 7). It turns out that the large bore diameter and high electron densities in many railgun systems have the effect of attenuating any probe beam that might be used to measure railgun plasma characteristics. There is a tradeoff between sensitivity and attenuation, which is explained in more detail in Chapter VII. The railgun system on which this research is done has a relatively small bore diameter (3.2 mm), and even though there is attenuation, enough light goes through to make measurements possible. Similar applications of interferometry

have been attempted, as on a dense plasma focus (Boulais), and on other arc-type devices (Loree, et al., Gibes).

In order to meet the energy demands of the next century, it is advisable to conduct research into nuclear fusion (Holdren). One of the most promising ways to achieve nuclear fusion is by confining a very high temperature deuterium/tritium plasma in a magnetic containment field in a device known as a tokamak. One of the many problems to be worked out is how to refuel the plasma inside the magnetic containment field. It turns out that pellets of frozen deuterium or tritium, if accelerated to a high enough velocity, will penetrate the magnetic field before melting (Kim and Honig). Once the pellet has penetrated the magnetic containment field, it is available to sustain the fusion reaction.

The obvious method for accelerating pellets, using a gas gun something akin to a BB gun, has a velocity limitation which is a function of the speed of sound in the gas used. Since a velocity on the order of 10 km/s may be needed for successful refueling of large fusion reactors, and gas guns have only achieved velocities on the order of 2 or 3 km/s, the use of a gas gun alone is not practical. Various other schemes have been proposed, among them centrifugal acceleration and the use of a railgun. Railguns appear to be the most promising technology for achieving very high velocities (Honig 1). The primary advantage of a railgun over many other methods is that, short of the speed of light, there is no known fundamental limit on the velocity which may be achieved.

The theory of operation of railguns in general is as follows. It may be helpful to refer to Fig. I.1. (Figures and tables are placed at the end of chapters.) A conducting armature of some sort is placed between two parallel conducting rails. When current is supplied to the gun, it runs down one rail, through the armature, and back along the other rail. This creates a magnetic field as shown in Fig. I.1. The charge carriers in the armature feel a Lorentz force towards the end of the gun, since they are moving perpendicularly to the magnetic field. If a projectile is placed in front of the armature, or if the projectile and the armature are the same object, then the projectile is accelerated down the gun. The expression commonly used to determine the force exerted by the railgun on the projectile is

$$F = \frac{1}{2} L' I^2 \quad (I.1)$$

where L' is the inductance of the rails per unit length, and I is the current running through them (Honig 9). There is some approximation involved in the above expression, but for most purposes it is a good starting point.

The primary purpose of the railgun at the Fusion Technology and Charged Particle Research Laboratory is to accelerate frozen hydrogen pellets. However, room temperature plastic or foam pellets are also used for experimental purposes. There are two major phases in this acceleration. Initially, the pellet is accelerated in a single stage gas gun, shown in Fig. I.2. The gas gun is simply a reservoir for the propellant gas with a fast valve

on it. High pressure gas, usually helium or hydrogen at about 800 psi, is let into the reservoir. When the pellet is formed in the barrel by a pellet generator, in the case of hydrogen, or simply placed in the barrel by a pellet loader, in the case of room temperature pellets, the fast valve is triggered and the pellet is driven down the barrel. Typical velocities for the pellet after this stage are 800 to 1000 m/s for foam and frozen hydrogen pellets, and about 200 m/s for plastic pellets. The gas gun has two primary functions. First of all, it is a very simple way to start the acceleration of the pellet earlier, so that the final velocity of the pellet when it exits the system will be higher. Second, having the pellet velocity as great as possible when the pellet enters the railgun has the advantage that the pellet will spend a minimum of time in the railgun. This assures that pellet melting and rail erosion by the arc will be kept to a minimum. After being accelerated by the gas gun, the pellet then enters the actual railgun. Figure I.3 shows the basic block diagram of how the gas gun and the railgun are connected. The key dimensions of the railgun are a bore diameter of 0.125 in., and an active acceleration length of 1.17 m. A cross section of the railgun is presented in Fig. I.4. Once the entrance of the pellet into the railgun is detected, the gas behind the pellet is ionized by a high voltage pulse and an arc forms between the rails. Then the main current is applied to the rails from the high current pulse-shaping network. This current follows the path between the rails that is already ionized, and keeps the arc going. The current is

adjustable, with values between 6 and 15 kA being used in this experiment.

In summary, the armature in this railgun is a hydrogen or helium plasma, which is started in the gas from the gas gun and picks up material from the pellet and railgun walls as it progresses down the gun. If everything goes correctly, the plasma pushes the pellet and the pellet is accelerated to a much higher velocity. Hydrogen pellets are protected from excessive melting by a layer of gas that evaporates at first and surrounds it (Kim and Honig), and by the short time that they are actually in the railgun. A more detailed description of the system is available (Kim, et al.). It is the plasma armature which is the focus of this research, specifically determining its electron density profile. When the density of the plasma is known, changes in the density profile may be related to changes in pellet propulsion efficiency, and this knowledge will be used to improve the system.

This thesis is organized into chapters and sections, with the next chapter being largely theoretical, and the later ones explaining the practical application of the theories. Finally, the experimental results will be presented and discussed, and possible sources of error will be given.

Figure I.1. Railgun Concept.

Figure I.2. Gas Gun Diagram.

Figure I.3. Railgun Block Diagram.

Figure I.4. Railgun Cross Section.

II. MATHEMATICAL BACKGROUND

Before experimental results are presented, it is necessary to lay down a mathematical foundation for checking the feasibility of the experiment and for explaining the results. This will consist first of a brief explanation of interferometric theory and then the relationship between the index of refraction of the plasma and its electron density. Unless otherwise noted, all quantities and equations are in mks units, and all coordinates are Cartesian. Vector quantities are indicated by boldface type.

A. Interferometry

In this application of interferometry, a Mach-Zehnder configuration is used. A light source is split into two beams. Refer to Fig. II.1. One beam, the object beam, passes through the plasma being measured. The other beam, called the reference beam, traverses approximately the same distance but does not travel through the plasma. The phase of the object beam is altered by the plasma as will be discussed in the next section. When the beams are both projected onto the same screen with a small angle (Θ) between them, linear interference fringes result from the constructive and destructive interference of the light (Boulais 4, Steel 8). Refer to Fig. II.2, which is adapted from Boulais. The two waves with identical wavelength and with wavevectors of $\mathbf{k}_1$ and $\mathbf{k}_2$ overlap on the screen at an angle. The intensity of the light

on the screen will vary sinusoidally. In practice, this sinusoidal pattern must be multiplied by the transverse Gaussian intensity distributions of the two beams (Tolansky 42). If the phase of one beam changes, the fringes will appear to move across the screen. If the fringes move enough so that they look the same as before, one fringe shift has occurred. The direction of movement may be most easily determined by noting that if one of the wave vectors is advanced, then the fringes will move in the direction of the component of that vector parallel to the screen. For example, if the path length through which beam 1 has to pass is shortened, then $\mathbf{k}_1$ will be advanced and the fringes will move down the screen.

To determine the mathematical relationship between the index of refraction and the fringe shift, the differences in the optical path length in the two arms of the interferometer must be examined. In the arm with the object beam, the wavelength of the light that goes through the object is shortened proportionally to the object's index of refraction. Thus more wavelengths per unit length will fit in an object with an index of refraction greater than 1.0, resulting in a longer optical path length. The phase difference in wavelengths may be expressed by the difference in path length between the beams, measured in fractions of a wavelength

$$d\delta = \left(\frac{N(y)}{\lambda} - \frac{1}{\lambda} \right) dy \quad (\text{II.1})$$

where (y) is the coordinate axis parallel to the beams. The number of fringes shifted (δ) is related to the wavelength of the light used (λ) and the index of refraction $(N(y))$ by integrating (II.1) over a path (L)

$$\delta = \frac{1}{\lambda} \int_L [N(y) - 1] dy. \quad (\text{II.2})$$

Note that δ is proportional to a line average index of refraction measurement over L . Since in this work we are only interested in this line average index of refraction, which will be called N , (II.2) can be simplified to

$$\delta = \frac{d}{\lambda} (N - 1). \quad (\text{II.3})$$

In (II.3) d is the length over which the measurement is taken, in this case, the diameter of the railgun bore.

For this work, the relationship of the angle between the beams (Θ) and the fringe spacing is irrelevant; nevertheless, it is given in Fig. II.2. When the experiment is conducted, the mirrors which guide the beams are adjusted to give fringes which are convenient for the recording method used.

B. Plasma Density

It has been shown that interferometry can be used to measure the index of refraction of an object. Since the purpose of this thesis is to measure the electron density in the plasma, it now remains to be shown what the relationship is between the electron density and the index of refraction. When analyzing the plasma,

it will be possible to relate the index of refraction to the relative dielectric constant (ϵ_r) by the following fundamental relationship

$$N = \sqrt{\epsilon_r} \quad (\text{II.4})$$

assuming that magnetic permeability is constant throughout. Thus we must determine the relative dielectric constant of the plasma. The absolute dielectric constant is related to ϵ_r and ϵ_0 by

$$\epsilon = \epsilon_r \epsilon_0, \quad (\text{II.5})$$

where ϵ_0 is the dielectric constant of free space.

The dielectric constant actually will depend on the density of three types of particles in the plasma: electrons, ions, and neutral particles. It will be assumed that the plasma is strongly ionized, so that neutral particles may be neglected. The justification for this will be given when possible sources of experimental error are discussed in Chapter VI. Ions and electrons change the index of refraction of the plasma when their charges interact with the electromagnetic wave propagating through the plasma. The effect of ions is commonly neglected, as their mass-to-charge ratio is much greater than that of the electron; hence, they are less prone to being manipulated by forces that interact with charges. The remaining factor to be determined is the analysis of the relationship between electrons and the wave propagating through the plasma.

The electrons in the plasma react to the electric field in the wave propagating through the plasma. The fundamental relationship is

$$m_e \frac{d\mathbf{v}}{dt} = -e(\mathbf{E} + \mathbf{v} \times \mathbf{B}) - m_e \mathbf{v} \nu_m \quad (\text{II.6})$$

where e is the electron charge, $\mathbf{E}$ is the electric field, $\mathbf{v}$ is the electron velocity, $\mathbf{B}$ is the magnetic flux density, m_e is the electron mass, and ν_m is the electron collision frequency. Only electron-ion collisions have to be accounted for, as the collision cross section of electrons is much smaller than that of ions, making the electron-electron collision frequency negligible.

In order to determine what factors in (II.6) have a significant effect on the dielectric constant, it is necessary to examine the expression for the dielectric constant,

$$\epsilon_r = \left[1 - \frac{\omega_p^2}{\omega^2(1 \pm \omega_b/\omega)[1 + j(\nu_m/\omega)]} \right], \quad (\text{II.7})$$

which may be derived from (II.6) and Maxwell's equations (Jahoda and Sawyer 4-9). In (II.7) ω_p is the plasma frequency, ω is the frequency of the incident light beam, ω_b is the electron cyclotron frequency, j is the square root of -1 , and ν_m is the electron-ion collision frequency. The plasma frequency and electron cyclotron frequency are defined as follows (Chen 351):

$$\omega_p = \sqrt{\frac{n_e e^2}{\epsilon_0 m_e}} \quad (\text{II.8})$$

$$\omega_b = \frac{eB_0}{m_e} \quad (\text{II.9})$$

where n_e is the electron density, and B_0 is the magnetic field applied to the system, caused in this case by the current flowing along the rails. An attempt will be made to show that ω_b and ν_m

are much smaller than ω in (II.7), as this would make the expression much simpler, allowing interpretation of the experimental results without taking so many factors into account. In this experiment a visible laser will be used as a probe, at a wavelength of 632.8 nm, which corresponds to a radian frequency (ω) of 2.97×10^{15} radians/second.

In order to find the electron cyclotron frequency, an approximate idea of B_0 is required. The expression for B_0 is

$$B_0 = \frac{L'I}{d} \quad (\text{II.10})$$

where L' is the railgun inductance per meter, d is the bore diameter, and I is the current flowing through the rails. Equation (II.10) may be derived from (I.1) and (II.6). Using values of $L'=0.35 \mu\text{H/m}$, $I=20 \text{ kA}$, and $d=3.2 \text{ mm}$, the value for B_0 is 2.2 Tesla. Numerical techniques may also be used to derive a similar value for the magnetic field (Hoole 115). The Mathematica program used for the numerical approach is given in the Appendix. The simplification made is that current density is uniform throughout the rail. This is not strictly accurate; however, it will be acceptable as an approximation. The numerical approach of dividing the rails into many smaller rails and summing the magnetic field contributions of the smaller rails as if they were one-dimensional wires is used in this analysis. The value 1.7 Tesla is obtained for a current of 20 kA. Comparing 1.7 Tesla to the result of (II.10), it can be seen that there is good agreement considering the approximations made. These values for the

magnetic field are on the high side, as the current value used was very high. Calculating the electron cyclotron frequency using (II.9), the radian frequency is 3.8×10^{11} , which is insignificant compared to the frequency of the probe beam. Therefore, the effect of the magnetic field on the index of refraction will be discounted.

The electron-ion collision frequency is difficult to determine exactly, but a good approximation may be found. The collision frequency may be written as (in cgs units and eV) (Book 27)

$$\nu_e = 2.9 \times 10^{-6} n_e \lambda_{ei} T_e^{-\frac{1}{2}} \quad (\text{II.11})$$

where λ_{ei} is the Coulomb logarithm for electron-ion collisions, given by

$$\lambda_{ei} = 23 - \ln(n_e^{\frac{1}{2}} Z T_e^{\frac{1}{2}}). \quad (\text{II.12})$$

In hydrogen $Z=1$. A reasonable value for n_e is 10^{18} cm^{-3} , and for T_e is 2 eV. Note that the Coulomb logarithm is relatively insensitive to the values used for its variables. Thus an approximate value for ν_e is $3.4 \times 10^{12} \text{ Hz}$. The associated radian frequency is much lower than ω . The dielectric constant may now be written in the simplified form

$$\epsilon_r = \left[1 - \frac{\omega_p^2}{\omega^2} \right]. \quad (\text{II.13})$$

It has been shown that interferometry can be used to measure the index of refraction and that in a plasma the index of refraction is related to the electron density. We can rewrite (II.13) as

$$N^2 = 1 - \frac{n_e}{n_c} \quad (\text{II.14})$$

where

$$n_c = \frac{\omega^2 m_e \epsilon_0}{e^2} \quad (\text{II.15})$$

is the cutoff density past which the wave will be attenuated by the plasma (Hutchinson 95-100). The cutoff density will be discussed in Section A of Chapter III, where suitable choices for a light source are discussed. Further simplification may be made on (II.14) if $n_e \ll n_c$ (or $\omega_p \ll \omega$). If we assume an n_e of 1×10^{18} per cubic centimeter, ω_p is 5.6×10^{13} using (II.8). Thus we may make the following approximation. Taking the first terms of a Taylor series expansion of the square root of (II.14) yields

$$N \cong 1 - \frac{n_e}{2n_c}. \quad (\text{II.16})$$

From (II.3), (II.15), and (II.16) an expression may be derived which relates fringe shift to electron density. This expression is

$$n_e = \frac{4\pi\omega c m_e \epsilon_0 \delta}{e^2 d}. \quad (\text{II.17})$$

When the experiment is conducted, δ is measured, and since all other factors in (II.17) are known, n_e can be determined.

Figure II.1. Mach-Zehnder Interferometer.

Figure II.2. Interference Diagram.

III. EXPERIMENTAL CONSIDERATIONS

There are many decisions to be made when setting up an interferometry experiment. The main ones are the type of interferometer setup, the data recording methods, and the light source to be used. The latter consideration will be discussed first.

A. The Light Source

When choosing a light source for plasma interferometry, several primary criteria were taken into account. These are

- the intensity of the light source as related to the requirements of the fringe recording schemes employed,
- the electron density range measurable by the system,
- the frequency of the light being higher than the frequency below which the light source will be attenuated by the plasma (the cutoff frequency),
- and the coherence length of the light source as related to the path length difference in the arms of the interferometer.

It should be obvious that the light source most likely to satisfy all these criteria, especially coherence, will be a laser. The factors which must be determined are the wavelength and power output of the laser. Power output is easier to decide, and depends on the sensitivity of the recording techniques used and

the budget for buying the laser. This project will use two different recording techniques, the details of which will be revealed in Section C of this chapter. There is no need to overpower the light from the plasma, as the greater coherence of the laser results in a beam with less divergence (Verdeyen 30). A satisfactory signal-to-noise ratio may be obtained by placing the fringe recorder or detector far enough away from the plasma so that the light from the plasma has spread out over a much greater area than the light from the laser.

This project uses a Uniphase 106-1 helium-neon laser, with a power output of 10 mW and an operating wavelength of 632.8 nm. The type of laser was chosen for largely practical reasons, mainly price and power, but also reliability and ease of use. It turns out, however, that given what was known at the beginning of the project, this wavelength is ideal. The two limiting factors on the wavelength of the laser are the cutoff frequency and the recording techniques used. By examining (II.17) it may be seen that fringe shift is proportional to the wavelength of light used. The minimum acceptable wavelength is set by the minimum recordable fringe shift. As will be seen later, the minimum fringe shift that is reasonable to expect is 1/10 fringe. An initial estimate for the electron density in this system is 10^{17} cm^{-3} to more than 10^{19} cm^{-3} (Choe and Kim 39). By plugging values into (II.17), it becomes evident that 1/10 of a fringe shift corresponds to $1.1 \times 10^{17} \text{ cm}^{-3}$, which is very close to the minimum expected density. The upper limits of the density will

result in 10 or more fringe shifts, which are also recordable, up to the cutoff density.

To determine the cutoff density, or in other words the maximum measurable density, the equations for electromagnetic wave propagation need to be examined. The electric field in an electromagnetic wave propagating in the z-direction may be represented by

$$E = E_0 e^{ikz} e^{-j\omega t} \quad (\text{III.1})$$

where k is the component of the wave vector in the z-direction. The quantity k , also referred to as the propagation constant, is represented by

$$k = \omega \sqrt{\mu \epsilon}. \quad (\text{III.2})$$

In (III.2), μ stands for the magnetic permeability of free space. If ϵ were to become negative, the propagation constant would become imaginary. Equation (III.1) indicates that this would cause the wave to attenuate. The relationship between dielectric constant of the plasma and the frequency of the light propagating through it is given by (II.13). If ω_p should become greater than ω , then ϵ_r and hence ϵ will become negative, and the wave will be completely attenuated. By relating (II.8) and (II.13) to the wavelength of the laser used in this experiment, the cutoff density is found to be $2.8 \times 10^{21} \text{ cm}^{-3}$.

If an interferometer is to work properly, the light source must have a coherence length greater than the difference in length of the interferometer arms. The difference in path length in most interferometer setups will be only a few millimeters. The

effective difference in length of the arms will be increased by windows and lenses if they are present only in one arm. This experiment will have at most 2 cm of extra windows and lenses which the object beam has to go through. The laser chosen for this project has a coherence length of 25 cm, which indicates that coherence length will not be a problem. The ultimate test is if fringes form. If they do, then the system works.

B. Interferometer Configuration

There are many different interferometers, with two major types being used for this type of work. In cavity-type interferometers the plasma being studied is usually part of the laser cavity, and density change modulates the output beam (Gerado and Verdeyen). In the second major category the laser beam is split into two beams after leaving the laser and then recombined after one has passed through the plasma. In this latter group, two common configurations are the Michelson and Mach-Zehnder interferometers. The Michelson interferometer shown in Fig. III.1 can be compared with the Mach-Zehnder interferometer shown in Fig. II.1. The two major differences are that in the Michelson interferometer the light travels twice through the object under study, and only one beam comes out, the second goes back towards the laser. Otherwise these two interferometers have similar properties. This experiment uses the Mach-Zehnder configuration, which gives two output beams which carry the same information. The Mach-Zehnder interferometer has the advantages of not needing

an isolator to keep reflected beams from modulating the laser output, and its physical configuration is adaptable to going around the railgun.

C. Fringe Recording

Recording the fringe shifts is critical to the success of the experiment. In this experiment, the time-resolved electron density profile of the plasma will be obtained. Figures. III.2 and III.3 give diagrams (not to scale) of the geometry employed. The density profile will be taken along a direction parallel to the arc travel at a small point in the middle of the arc. No attempt will be made to determine an instantaneous spatial density profile in any direction. However, as the density is measured at one point and the arc moves relative to that point, it will be possible to infer a spatial density profile along a line parallel to the railgun. In this experiment, the primary obstacle to be overcome when taking data is the speed at which everything happens. Foam pellets travel around 1000 m/s and the arc is about 10 cm long, giving a 100 μ s observation time. With plastic (Lexan) pellets, the arc is close to 2 cm long, but it is traveling slower, giving roughly the same observation time. The experimental data in Chapter V will reveal that the arc takes between 30 and 130 μ s to pass the interferometer, depending on experimental conditions.

Two recording methods are used in this experiment, a streak camera and multiple photodiodes. Both of these methods are

adaptable to high speed recording. They also are able to give a positive indication of direction of fringe movement, in addition to the number of fringes moved. This is important for plasmas whose densities are not monotonically increasing or decreasing, because single photodiode systems often have ambiguity in the direction of fringe movement and the actual number of fringes moved in one direction (Lochte-Holtgraven 607). This results in ambiguity as to the plasma density, as demonstrated in Fig. III.4. The top third shows a hypothetical graph of the light intensity versus time at a stationary point on a hypothetical screen onto which the fringes are projected. In Fig. II.2 this point would be somewhere on the screen. The variation in light intensity signifies fringe movement in one direction or another. There are many possible interpretations of which way the fringes are moving. The middle third of Fig. III.4 shows one such interpretation, which is often used when no better information is available. It is assumed that the fringe recording starts when the density is a minimum, and fringes move one way to a point which signifies maximum density, then move the other way to a point which signifies minimum density. An equally valid interpretation is presented in the bottom third of the figure. Without some means of checking the direction of fringe movement, there will always be some uncertainty as to the density profile of the plasma.

The principle of operation of a streak camera is that an image is swept across a screen at a constant rate. Figure III.5 shows a simplified schematic. The image is focused on the

photocathode, which releases electrons. These are accelerated by an applied electric field in the image tube. An electric field perpendicular to the direction of electron travel is used to steer the beam across a phosphor screen. Film is usually placed next to the screen to record the image. Figure III.6 shows a typical fringe pattern from this interferometer, and what it looks like after passing through a slit. These dots are directed onto the photocathode of the streak camera. When the streak camera is triggered, the dots are swept across the screen. This results in a pattern such as in Fig. III.7. The fringes move up or down; hence, the dots move up or down. It is then easy to interpret the fringe shift versus time. By placing a grid over the exposed film, fractional fringe shifts may be determined. Depending on the quality of the image exposed on the film, it should be possible to discern a fringe shift of $1/10$ of a fringe. If many fringe shifts occur in a short period of time, this method might not work as well, as the fringes could become muddled together. For this case, another method may be used, the photodiode detection method.

For the photodiode method, two photodiodes are used to look at the fringes. Figure III.8 demonstrates how this is done. The dimensions of the active area on the photodiode are much smaller than the spacing between the fringes. The spacing between the two diodes along the coordinate parallel to the direction of fringe movement is variable, but must be a fraction of the fringe spacing. Output from the photodiodes can be amplified and fed

into a recording device such as an oscilloscope. The amplifiers may either be linear, or have highly nonlinear or TTL output depending on the equipment used and the dictates of experimental conditions. In a noisy environment, the nonlinear amplifiers which give TTL output may make data interpretation easier. The two traces should be almost identical but offset in time. The direction of fringe movement is easy to determine by noting which photodiode has an output which comes ahead of the other timewise. Figure III.8 shows the output, which indicates three fringe shifts to the left, and then three fringe shifts to the right. It is obvious that the photodiode recording method is suited for recording many fringes, as the resolution and recording time are only limited by the bandwidth and data capacity of the equipment used. However, when small fringe shifts are to be recorded, the streak camera method is better. If the amplifiers have only two output states as with TTL output devices, then it will be very easy to miss fractional fringe shifts. In theory, the linear amplifiers should be able to detect fractional fringe shifts, as the intensity profile of the fringes is sinusoidal and sinusoidal output will result. In practice though, unless the system does not have very much noise, the streak camera will be better, because the information content of the fringes recorded on film is much higher, as the complete pattern is recorded, not just two tiny points. Thus it will be easier to spot trends and, in effect, average out noise when looking at the film.

Figure III.1. Michelson Interferometer.

Figure III.2. Interferometer Geometry.

Figure III.3. Side View of Laser and Railgun Geometry.

Figure III.4. Density Interpretations.

Figure III.5. Simplified Streak Camera Diagram.

Figure III.6. Fringe Patterns.

Figure III.7. Streaks on Film.

Figure III.8. Photodiode Recording.

IV. EXPERIMENTAL SETUP

The experimental setup is divided into two main blocks of equipment. The first is the actual railgun and support systems, located on a Newport optical table. The second consists of the control and data acquisition systems. These are located primarily in a screen room to provide shielding from electromagnetic interference. Figures IV.1 and IV.2 depict these two categories at a block level. This chapter will cover the functions and details of each block, in the general sequential order of one firing of the railgun. The order of events when the railgun is fired is as follows:

- the shutter covering the streak camera is opened,
- the gas gun is fired, propelling the pellet,
- the first timing assembly detects the arrival of the pellet in the railgun,
- the timing relationship for arc initiation is calculated,
- the arc and main current are initiated after the pellet has proceeded far enough,
- arc detectors 1 and 2 detect the arrival of the arc (not the pellet),
- the streak camera or other recording method is triggered to allow fringe recording, and outputs from arc detector 3 and the laser intensity detector are recorded,

- the second timing circuit times the pellet after it leaves the railgun,
- and the shutter in front of the streak camera is closed.

For each shot, several sets of data are recorded. These are

- output from the first timing system,
- main and arc initiation current profiles,
- output from all three arc detectors and the laser intensity detector,
- the fringe pattern as seen by the recording method used (usually the streak camera),
- and output from the second timing system.

Many experiments have been conducted; some of them did not have the complete setup. Between experiments many factors were changed, the pellet type and size, gas gun parameters, interferometer lenses, and detector types. In this chapter the major variables in each part of the system will be outlined, and then when experimental results are presented the specific conditions will be given. In addition to the main experimental thrust, several experiments of a different nature were conducted, mainly to check for possible sources of experimental error. These will be discussed Chapter VI.

A. The Pellet

The pellet type is one of the key factors in this system. Even though the eventual objective of the railgun is to accelerate frozen hydrogen or a deuterium/tritium mixture, frozen pellets

were not used for most of these experiments. The primary reason is that freezing hydrogen is expensive, freezing deuterium is more so, and freezing tritium is a health hazard. Room temperature pellets are much cheaper and easier to work with. There are many different possibilities, each with advantages and disadvantages. The only common factors are that they are nonconducting and are all 0.125 inch or less in diameter.

Pellets were made from foam, Flexible Products Company NP95. These pellets have the advantage of being very light, with approximately the same density as deuterium. A typical foam pellet will have a mass of 5 ± 2 mg. They have two primary disadvantages. The first is a lack of physical strength, which makes them susceptible to breaking up and being rendered useless. The second disadvantage is that it is very hard to make them uniform. There is considerable variation in density between pellets, and even within a pellet itself.

Pellets may also be made from Plexiglass and Lexan. The Lexan is the superior choice, due to its greater strength (Witherspoon, Burton and Goldstein). Lexan pellets have the advantage of being very uniform when properly machined. They are, however, denser than foam or hydrogen. Several pellet designs were tried. The first was simply a Lexan cylinder, with the diameters from 0.118 inch to 0.123 inch, and lengths from 0.125 inch to 0.1875 inch. These were much heavier than the foam pellets. In order to reduce the weight, a hole was drilled in the

center of the pellet. Figure IV.3 shows a typical design for a pellet with a mass of 16 mg.

B. The Gas Gun

The gas gun has been briefly discussed in the Introduction, its diagram is shown in Fig. I.2. The variables in gas gun operation are the reservoir size, the fast valve, the gas pressure, and the gas itself. There are two reservoirs used, one with a volume of 20 cm³, and the larger one with a volume of 250 cm³. Two valves were tried. The slower valve has a response time of 5 ms to 8 ms, and the faster valve has a claimed response time of less than 1 ms, but this has not been verified. Gas pressure may also be varied, typically in the range of 200 to 1200 psi. The gasses used to propel the pellet are helium and hydrogen. In theory, the pellet moves faster with hydrogen, as the speed of sound in hydrogen is faster than that in helium. Overall, the setup of the gas gun does not affect this experiment in a fundamental way, except in how fast the pellet enters the gun. Pellet type was found to be the primary determinant of pellet velocity from the gas gun.

C. The First Timing and the Arc Initiation Assemblies

The first timing system has two functions. First it indicates the speed at which the pellet enters the railgun, which is useful for determining how well the gas gun is working. Second, the speed of the pellet is used to properly time the arc

initiation pulse. Figure IV.4 shows the first timing and arc initiation assemblies. Timing is accomplished by the two laser beams, which are broken by the pellet. The timing circuit, shown in Fig. IV.2, calculates the proper time for arc initiation. This is generally after the pellet has passed the arc initiation point. A high voltage pulse from the arc initiation pulse-shaping network ionizes the gas behind the pellet by striking an arc to the grounded rail, in a way very similar to the operation of a spark plug in an internal combustion engine. When the arc initiation current is at its maximum, the main current is applied to the rails. Since there is an area of low-impedance ionized gas near the arc initiation needle, the main current chooses to go through that area.

D. The Current Pulse-Shaping Networks

The design of the pulse-shaping networks will not be covered in any detail, as their designs are not very relevant to this work. The main current pulse-shaping network is shown in simplified form in Fig. IV.5. The capacitors are charged up, and when the current is needed, the pulse-shaping network is connected to the railgun. There are five LC units, which in total give a 980- μ s current pulse of amplitude 2.35 times the voltage to which the capacitors are charged. The arc initiation network is more simple, and shown in Fig. IV.6. It supplies a current pulse 10 μ s long.

E. Arc Detectors 1 and 2

The functions of the first two arc detectors are to determine the speed of the arc armature and to trigger data recording from the other instruments and detectors. The light from the arc is carried to a detector from the railgun by an optic cable. This cable is placed next to the Lexan spacer between the rails, and the detector is in the screen room. Refer to Fig. IV.7 for a diagram. The detectors used in this experiment are Hewlett-Packard model R-2501. These give a TTL output, indicating either presence or absence of an arc, not the level of light output.

F. The Interferometer

Many diagrams for the interferometer have already been presented, each of them demonstrating a concept. Figure IV.8 gives a more detailed view, with Fig. IV.9 providing the details of the railgun and vacuum chamber. The 10-mW helium-neon laser is mounted on the optical table on a two-axis translation stage for adjustability. The beam goes to a cube-type beam splitter, mounted on an adjustable platform. The reference beam goes under the railgun, and the object beam goes through it. The beams are then combined in a second beamsplitter cube. All mirrors and beamsplitters are mounted on adjustable mounts to facilitate proper alignment of the interferometer. There are several possible ways for the beam to go through the railgun bore. The first method added small quartz windows in the Lexan spacer. This turned out to be unsuitable, as the quartz soon blackened from

soot in the plasma arc and became opaque. The Lexan sidewalls do not blacken significantly, presumably because a thin layer is melted from them every time the arc goes by, thus cleaning them. After that, two 1.5 mm diameter holes in the Lexan spacer were drilled for the laser beam to go through. This had the problem that gas from the arc could easily escape from the railgun through the holes. Escaping gas is undesirable for two reasons. First, it could alter characteristics of the arc and hence have an adverse effect on the measurement. Second, this gas darkened the windows on the vacuum chamber in which the railgun is located. The final solution adopted was to use two very small holes 0.020 inches (0.5 mm) in diameter. Although some gas will escape, its effect on the experiment will be discounted as the area through which gas can escape is much smaller than the size of the plasma. Darkening of the vacuum chamber windows is not a problem with very small holes in the Lexan sidewall. The laser beam will not be able to pass through such a small hole unaided, as its diameter at the laser is 0.68 mm, and it diverges at a rate of 1.2 mm per meter. The diameter of the laser may be reduced by focusing it down, in other words by transforming the beam to another one with a smaller waist (Kogelnik and Li 1319) Refer to Fig. IV.10 for the Gaussian beam geometry involved. Note that the vertical dimension is greatly exaggerated in this figure. The beam travels a distance labeled Z on the diagram, which is about 50 cm in this experiment, before going through the railgun. Using

$$w_1 = w_0 + 2Z \sin\left(\frac{\text{divergence}}{2}\right) \quad (\text{IV.1})$$

the beam diameter is 1.28 mm at the first lens. The equation which relates w_2 to w_1 is (Verdeyen 30)

$$w_2 \cong \frac{2\lambda_0}{\pi} \frac{f}{2w_1}. \quad (\text{IV.2})$$

For the helium neon laser and lenses of focal length of 150 mm, the spot size at the focal point is about 24 μm . Thus the beam will easily fit into a 0.5 mm hole. In reality, the minimum spot size will be slightly removed from the focal point, but for the purposes of this experiment that fact is irrelevant. When the interferometer is set up, the position of the lenses is adjusted to give the best results. Note that although the spot size after the first lens is smaller than the minimum size of the beam coming out of the laser, its divergence is greater. The second lens, if properly placed with respect to the first lens, will allow the beam to diverge at the same rate that it did coming out of the laser. Thus it will appear as if there were no lenses in the way of the laser beam, which is the desired effect, as the object beam must recombine with a reference beam which has been diverging all the way. Using lenses to reduce the laser beam diameter has the collateral advantage that all of the beam goes through a much smaller slice of the plasma, precluding the possibility that density variations on an axis perpendicular to both arc motion and beam direction would have an effect on the measurement.

G. Arc Detector

The third arc detector measures relative arc light intensity versus time, rather than providing a triggering signal. Like the first two, it is actually in the screen room. A fiber optic cable guides the arc light from the railgun into the screen room. Arc detector 3 measures light coming out of the same hole in the Lexan spacer through which the interferometer laser beam goes. The actual detector circuit is based on the Hewlett-Packard HFBR-2406 fiber optic receiver. This receiver, in contrast to the R-2501, provides an output voltage proportional to the input optical power. The circuit used, shown in Fig. IV.11, is very similar to the circuit recommended by Hewlett-Packard.

H. The Laser Intensity Detector

The laser intensity detector is used to determine attenuation of the object beam by the plasma and to detect passage of the pellet. It is based on the same circuit as the third arc detector. The physical setup is shown in Fig. IV.12. The second beamsplitter in the interferometer sends identical output in two directions. In one direction fringes are formed and recorded. In the other direction, the object beam is separated from the reference beam by a knife edge. The object beam then travels through an optical line filter for light of wavelength 632.8 nm, separating the object beam from most of the arc light. Finally, the object beam is focused on the face of a fiber optic cable and carried into the screen room.

I. The Second Timing System

After the pellet leaves the railgun, its velocity is determined when it breaks two laser beams, in a manner similar to that for first timing system. Refer to Fig. IV.4.

J. The Streak Camera Lens and Shutter System

If the output of the interferometer is being recorded with photodiodes, the optical processing that needs to be done after it leaves the interferometer is limited. However, if the streak camera is used, considerable manipulation must be done to the beam from the interferometer before it can be recorded. Referring back to Chapter III and to Figs. III.5 through III.7, the fringes must be converted to dots and then focused on the photocathode of the streak camera. The streak camera then amplifies the image and puts it on film.

Figure IV.13 shows the equipment which is placed in front of the camera. The shutter is used to protect the photocathode of the camera, as it was found that if the laser were allowed to linger for long periods on the photocathode, extraneous spots would appear on the film. The shutter opens right before the gas gun is fired, and closes after the shot is over. The shutter is the plunger of a solenoid, it is pulled up by application of current to the solenoid, and falls down by gravity when the current is no longer applied. Figure IV.14 shows the circuit used to control the shutter.

It must be noted that the lenses were chosen from those that were at hand, and the distances between them were determined pretty much by trial and error. There were no formulas used in the design, as were used for designing the interface between the object beam and the railgun (Fig. IV.10). The first convex lens narrows the beam to allow the shutter to block it. The third lens is a convex cylindrical lens. It is placed with its long axis perpendicular to the fringes, as shown in the inset of Fig. IV.13. The cylindrical lens converts the linear fringes to a series of dots when they are focused. The second lens, the concave one, adjusts the distance between the cylindrical lens and the point at which the fringes are focused. By adjusting the distances between the lenses, the size of the fringe image on the photocathode can be changed.

----- Indicates control or signal lines going to or from screen room.

Figure IV.1. Railgun Block Diagram.

Figure IV.2. Block Diagram in Screen Room.

Figure IV.3. Typical Lexan Pellet Design.

Figure IV.4. Timing and Arc Initiation.

Figure IV.5. Main Current Pulse-Shaping Network.

Figure IV.6. Arc Initiation Pulse-Shaping Network.

Figure IV.7. Arc Detector Setup.

Figure IV.8. Interferometer.

Figure IV.9. Railgun Vacuum Chamber.

Figure IV.10. Laser Beam Diagram.

Figure IV.11. HFBR-2406 Circuit.

Figure IV.12. Laser Intensity Detector.

Figure IV.13. Lenses and Streak Camera.

Figure IV.14. Shutter.

V. EXPERIMENTAL RESULTS

The experiments performed for this thesis consist of two main blocks. The first block was done with foam pellets and the second with Lexan pellets. It should be possible to measure plasma density behind a hydrogen pellet in the future. The most general discovery from these experiments, other than the density range of the plasma, is that railgun operation is very inconsistent from shot to shot. This is especially true with foam pellets, probably because as mentioned earlier, the foam pellets are nonuniform. Foam pellets break up much more easily, as has been experimentally verified. Results for both foam and Lexan pellet operation will be presented.

Since the streak camera method of recording was used almost exclusively, most of the data come from analysis of streak camera pictures. On a typical picture, see Fig. V.1a, the time axis is horizontal, and the density axis is vertical. Time goes from left to right, and the upward fringe deflection signifies increasing density. When the pellet (or a piece thereof) passes the object beam, fringes disappear and are replaced with a faint grey spot (shows up as a break in Fig. V.1a). This spot results when only the reference beam falls on the film. Note that the pictures were taken with black and white film, which shows continuous shades of grey. It is impossible to reproduce grey scales on standard printers or copy machines. An attempt has been made to display a

picture by using a dither technique, but there is an unavoidable loss of resolution, especially next to the pellet. Data are taken from measurements of magnified grey-scale color copies of streak camera pictures. Figures V.1b and V.1c are representations of fringe pictures at 2.5 kV and 5 kV, respectively. Note that the fringe shift is greater for the 5 kV picture.

As explained in Chapter IV, there are many variables in railgun operation. The primary ones, other than the pellet type, are the gas pressure used in the gas gun (should affect pellet input velocity), the gas itself (hydrogen or helium), and the voltage to which the main pulse-shaping network is charged. Many combinations of these variables were tried, and the only one which had a definite effect on the results is the voltage. It is not surprising that the gas used in the gas gun had no discernible effect, as most of it is removed before the railgun by the perforated coupling piece between the gas gun and the railgun. The plasma probably consists mostly of copper from the rails and hydrogen and carbon from the spacers. If the variability from shot to shot can be greatly reduced, it may be possible to discern any effect that other variables have, such as the type of gas. However, it is possible that this system exhibits some chaotic behavior, no matter how carefully the conditions are controlled. As the results are better for Lexan pellets, they will be presented first.

A. Lexan Pellet Results

For Lexan pellet operation many shots were made. The railgun operated properly for 31 of these. Even if the railgun worked, the triggering and recording were not always operational. Nine shots have been chosen for analysis from these, as they had almost fully working recording and exhibited typical behavior. Table V.1 gives a summary of these shots. Helium at 800 psi was used throughout in the gas gun. The velocities listed are final pellet velocities. They should be a good indication of the relative arc velocities, as the arcs were measured towards the end of the current application. Also listed are approximate arc lengths. These lengths are somewhat uncertain because of inexactness in the velocity measurement, the fact that the arc is undergoing acceleration while it is being measured, and uncertainty as to where the actual end of the arc is.

Table V.1 shows that the trend of maximum line average density of the plasma-arc armature is increasing with increasing voltage. Pellet velocity goes up with increasing voltage. This is expected, as the current is linearly related to the voltage to which the capacitors are charged, and the force on the pellet is related to the current by (I.1). In practice, acceleration does not go up as the square of the voltage as implied by (I.1), as other effects have to be accounted for. One of the main effects is that ablated material from the rails and spacers is carried along by the arc. This material increases the mass that must be accelerated. Figure V.2 shows the trend of maximum line average

density versus voltage. As can be seen, the density increases approximately linearly with voltage. There is not enough data to determine if a linear relationship is true in general. A nearly linear relationship can be justified in theory. The length of the arc shows no obvious correlation to the voltage. On the average, it is 1.7 cm long, or about 5 times the diameter of the railgun barrel. Since the diameter of the railgun is constant, we can assume that the area which the current goes through remains roughly the same. The electron density is related to the current (and hence the capacitor voltage) by

$$n_e = \frac{I}{A e v_d}, \quad (V.1)$$

where A is the area through which the current goes and v_d is the drift velocity of the electron, expressed by (Headley 126, Cobine 35)

$$v_d = \frac{e \Delta V}{m_e d v_e}. \quad (V.2)$$

The electron-ion collision frequency, ν_e , is given by (II.11) and (II.12). The electron-ion collision frequency is a slowly varying function of both temperature and electron density. It is unknown, but will be assumed to be constant over the range of operation of the railgun. If the voltage drop across the plasma, ΔV , is relatively constant, then the electron drift velocity will be constant, and the electron density in (V.1) will be linearly related to the voltage.

Figure V.3 shows the relationship between voltage and pellet acceleration. There are more points than in Fig. V.2, as fringe recording was not necessary to obtain acceleration data. Acceleration data were obtained from the initial velocity of the pellet, the final velocity of the pellet, and the time duration of the current. The acceleration is more consistent from shot to shot at low voltage values. The same type of behavior is seen in the maximum density plot.

The figures for each shot are divided into three parts. In the first part (such as Fig. V.4a), the density versus time is shown as derived from the fringe movement. The error bounds for these plots are about $\pm 1 \times 10^{17}$ per cubic centimeter at any one point, but nearby points should be more accurate relative to each other. The error analysis is presented in Chapter VI. The second and third parts of the figures are shown below the first, as in Fig. V.4b. These are photocopies of the display on an oscilloscope. They are the results of the laser attenuation detector on the top, and arc light detector on the bottom. The traces are 400 μ s wide. For the attenuation detector, maximum light is at a level at which the trace starts. Zero light is at a level to which it falls, as that is where the pellet blocks the light. The arc light detector is not intended as an absolute measure of the light from the arc, and the vertical scale varied according to experimental conditions. The arc light output is only intended for comparison to the density trace in the same figure, not for comparison to other figures. It appears that some

light from the arc bled into the laser attenuation detector, but the point at which the pellet passes is quite clear. Note that the arc followed right after the pellet in all of these figures. There is no light output information for shot 3, due to equipment malfunction.

By comparing the density plots to light output, it can be seen that they have the same general shape and time duration. All of the plots have a maximum density near the pellet, and a taper away from that. Presumably this indicates that the pellet is confining the plasma; therefore, the plasma is pushing the pellet. The positive relationships between density and voltage, and acceleration and voltage indicate that the expected railgun action is taking place.

B. Foam Pellet Results

Foam pellets were originally used. Some results were obtained; however, the success rate with foam pellet shots was very low, probably due to the variability of foam pellets, as well as to their tendency to break up or let the arc blow by. Streak pictures were observed which had several grey spots typical of pellet passage following the arc, indicating arc blow by and pellet breakup. The railgun operation success rate with foam pellets, usually low, dropped dramatically when voltage was increased past 4 kV.

Table V.2 summarizes the foam pellet results. Velocities here, where available, are from arc sensors 1 and 2, which are

placed shortly before the interferometer. Note that the foam pellet velocity is much greater than the Lexan pellet velocity under similar circumstances, due mostly to the foam pellet's smaller mass of 3 to 7 mg as opposed to Lexan's 16 mg. The velocity of the foam pellets coming out of the gas gun is higher than that of the Lexan pellets. The maximum densities are smaller, probably due to the longer arcs having more area for the current to go through. Speculation on arc length differences will follow shortly.

Figures V.14 to V.20 for the foam experiment are organized similarly to those for the Lexan experiment. The one difference is that instead of a laser attenuation detector, the top trace of the oscilloscope shows output from one photodiode indicating the fringe pattern. In general, the environment was too noisy and fringe shifts too small to be observed with one photodiode, as a result, the top trace can be ignored. By comparing the density plot to the light output, a correlation can often be seen between minima in the density and dips in the light output; shots 12, 13, and 16 are good examples. Direct numerical comparison is not valid, as the density measurement is along an extremely thin line through the plasma, and the light output measurement measures light from a somewhat larger area (the diameter of the hole in the sidewall and a cone behind it).

The general profile of electron density differs greatly between the foam and Lexan pellet experiments. For the foam experiment the arc is not as simple as for the Lexan experiment.

The trend of greater density for greater voltage remains, but the arc is often divided into two or more sub-arcs. In addition, density is not always highest right behind the pellet. When the graphs say that density is zero, it may be just an order of magnitude or two down from the maximum density, not actually zero. Other than the nature of the arc, the difference between the two experiments is the speed of the arc. It is possible that for the foam pellets a point has been reached at which the arc is constrained not only by the pellet, but also by matter ablated from the sidewalls and the rails. It is obvious that not all of the arc, or even most of the arc, is pushing the pellet.

The length of the arc pushing foam pellets is much greater than that of the Lexan pellets. In addition, there seems to be a trend for longer arcs at higher voltage. Both of these observations are explainable by the ablated matter hypothesis. The arc could be longer because the ablated matter has a mass closer to that of the pellet. With Lexan, the pellet is the limiting factor and the arc is packed up against it. Higher voltage could ablate more matter and thus put more drag on the arc, stretching it out.

An alternate (but not mutually exclusive) explanation of the differences between the foam and Lexan pellet results is that foam pellets are likely to be evaporated more by arc heating than the Lexan pellets. This evaporated material could help to drag the plasma arc out to a longer length. The pellet would become

smaller, contributing to pellet breakup and allowing the plasma to blow by.

TABLE V.1. Lexan Summary.

Shot #	Voltage (kV)	Max. Density ($10^{18}/\text{cm}^3$)	Velocity (m/s)	Arc Length (cm)	Figure Number
1	2.5	.94	235	2.2	V.4
2	2.5	.94	222	1.9	V.5
3	3	1.25	320	2.6	V.6
4	3	1.25	292	1.8	V.7
5	4	1.35	377	1.1	V.8
6	4	1.44	344	1.3	V.9
7	4.5	1.52	333	0.9	V.10
8	5	1.7	471	1.7	V.11
9	5	2.03	435	1.6	V.12

TABLE V.2. Foam Summary.

Shot #	Prop. Gas	Volt. (kV)	Max. Density ($10^{18}/\text{cm}^3$)	Vel. (m/s)	Arc Length (cm)	Figure Number
10	Helium	3	0.50	1000	7.7	V.14
11	Hydrogen	3	0.39	-----	-----	V.15
12	Hydrogen	3	0.39	-----	-----	V.16
13	Helium	3.5	0.60	1000	9.1	V.17
14	Hydrogen	4	0.80	1154	10.7	V.18
15	Hydrogen	4	0.73	1250	12.8	V.19
16	Helium	4.5	1.18	1250	14.4	V.20

Figure V.1a. Example of Recorded Fringes at 3 kV (Shot 4).

Figure V.1b. Example of Recorded Fringes at 2.5 kV (Shot 2).

Figure V.1c. Example of Recorded Fringes at 5 kV (Shot 9).

Figure V.2. Lexan Density Trend.

Figure V.3. Lexan Acceleration Trend.

Figure V.4a. Density of Shot 1.

Figure V.4b. Light Information of Shot 1.

Figure V.5a. Density of Shot 2.

Figure V.5b. Light Information of Shot 2.

Figure V.6a. Density of Shot 3.

Figure V.7a. Density of Shot 4.

Figure V.7b. Light Information of Shot 4.

Figure V.8a. Density of Shot 5.

Figure V.8b. Light Information of Shot 5.

Figure V.9a. Density of Shot 6.

Figure V.9b. Light Information of Shot 6.

Figure V.10a. Density of Shot 7.

Figure V.10b. Light Information of Shot 7.

Figure V.11a. Density of Shot 8.

Figure V.11b. Light Information of Shot 8.

Figure V.12a. Density of Shot 9.

Figure V.12b. Light Information of Shot 9.

Figure V.13. Foam Density Trend.

Figure V.14a. Density of Shot 10.

Figure V.14b. Light Information of Shot 10.

Figure V.15a. Density of Shot 11.

Figure V.15b. Light Information of Shot 11.

Figure V.16a. Density of Shot 12.

Figure V.16b. Light Information of Shot 12.

Figure V.17a. Density of Shot 13.

Figure V.17b. Light Information of Shot 13.

Figure V.18a. Density of Shot 14.

Figure V.18b. Light Information of Shot 14.

Figure V.19a. Density of Shot 15.

Figure V.19b. Light Information of Shot 15.

Figure V.20a. Density of Shot 16.

Figure V.20b. Light Information of Shot 16.

VI. POSSIBLE SOURCES OF ERROR

Every experiment has possible sources of error; this one is no exception. These sources of error fall into two general categories. First there are errors from the experiment itself. Second there is some error in analyzing the data. If possible additional experiments have been conducted to determine the range of error introduced by the experimental factors. If no such experiment is practical, theoretical considerations are invoked to dispel reasonable doubt about the results. The major possible sources of experimental error are

- vibration of the optical components,
- fringe shifts due to the pressure change behind the pellet,
- neutral particles altering the fringe shift,
- and object beam deflection.

Error introduced by the data analysis procedure will be covered in Section E.

A. Vibration

If vibration of the interferometer components causes the difference in optical path length in the arms to change by any significant part of a wavelength, then the measurement may be compromised. It is possible to develop elaborate theoretical models, based on the transmission of sound waves through the air,

and vibrations through the table, stiffness of the optical components mountings, and so forth. However, these will be, at best, approximations. The best way to determine for sure if vibration is a problem is to conduct an experiment to measure it. This was done by altering the interferometer slightly, so that the object beam passes not through the plasma, but through a hole in the railgun mountings, as in Fig. VI.1. Other than that, the path is the same and the object beam passes through the same optical components. When the railgun is fired, fringe movement can be measured. If no fringe movement is registered until the arc is well past the point where it would be measured, then vibration will not be considered a problem. This experiment was conducted at many different voltages with a photodiode measuring the fringe movement. Figure VI.2 shows typical results. The top trace is photodetector output, which is flat, indicating that the fringes are not moving at all. For comparison purposes, when vibrations are induced in the system, the top trace shows a roughly sinusoidal trace with an amplitude of three divisions. The bottom trace is from a photodetector measuring light output from the arc. This merely verifies that the arc is passing the interferometer as fringe movement is being measured.

B. Fringe Shifts Due to Pressure Change

A gas, not just a plasma, when introduced into one arm of an interferometer, can cause fringe shifts. It is important to be reasonably sure that any such effects are accounted for. In the

railgun system used here, a neutral gas is used to start the pellet, as in the gas gun. A coupling piece between the gas gun and the railgun is designed to vent the pressure behind the pellet. To check if enough pressure is left to have an effect on the measurement, the railgun was operated without forming an arc, so that the pellet passed through the interferometer on momentum gained from the gas gun alone. This was tried for several different gas gun pressures, and no fringe movement due to gas from the gas gun was observed.

C. Neutral Particles

It is possible for neutral particles to be part of the arc that is driving the pellet. Although it is very difficult to determine what these particles are, a rough idea may be obtained of their quantity from theoretical calculations. Methods are available, such as two-wavelength interferometry (Bennett, Burden and Shear), which can make a more quantitative measurement. It must be noted that the contribution to the index of refraction of neutral particles is opposite in sign to that from electrons (Huddleston and Leonard 438). It can be shown that, on a per particle basis, the contribution of electrons to the index of refraction is much greater than that of neutral particles (Headley 96). Thus if there is significant ionization of the plasma, the possibility of neutral particles altering results can be dismissed. To obtain an estimate of the ionization, Saha's

equation may be used (Chen 1), since the arc is assumed to be at thermal equilibrium (Choe and Kim 40).

$$\frac{n_i}{n_n} \approx 2.4 \times 10^{15} \frac{T^{3/2}}{n_i} e^{-U_i/KT}. \quad (\text{VI.1})$$

The ionized atom density is n_i (in cm^{-3}), the neutral atom density is n_n , T is the temperature in Kelvin, K is Boltzmann's constant, and U_i is the first ionization energy of the gas in electron volts. Note that the ionization ratio depends primarily on the temperature of the plasma. There is also some dependence on the density of ionized particles. The expected elements in the arc are hydrogen and carbon from the Lexan insulators, and copper from the rails. Figure VI.3 shows the ratio of ionized to neutral atoms for these three elements, at the moderate density of $5 \times 10^{17} \text{ cm}^{-3}$. An estimate of the temperature of the railgun arc is several electron volts. Figure VI.3 shows that neutral particles are in the minority above 1.5 eV as a worst case, so neutral particles will not be taken into consideration.

D. Object Beam Deflection

If there exists a large enough density gradient along an axis perpendicular to the object beam, the beam can be deflected from its path, as if it passed through a prism. Figure VI.4 clarifies this. Note that beam deflection is in the opposite direction from what would be expected with a prism or gas, as higher electron density results in a lower index of refraction. Although in certain situations beam deflection can be a useful diagnostic

technique, in the case of interferometry it complicates the results. The plasma density is assumed to be symmetrical and close to constant in the vertical direction, so upward or downward deflection of the beam can be ruled out. An experiment was conducted to determine if there was any significant horizontal deflection of the object beam. Figure VI.5 shows the experimental setup. The interferometer is no longer set up, instead all of the beam goes through the plasma. The streak camera has the usual lenses and shutter in front of it. When the plasma is about to pass the laser, the streak camera is triggered. If the beam were to be deflected, a curved trace would be seen on the streak camera film. There was no deflection of the beam when this experiment was conducted. It must also be noted that if the object beam were to be deflected, the angle at which it recombines with the reference beam would change. Figure II.2 reveals that this would cause the spacing of the fringes to change. Such an effect would be readily apparent, and since it was never observed, the absence of beam deflection is confirmed.

E. Data Analysis Error

The most practical data recording method in this experiment is the streak camera method. The steak camera records fringes on Polaroid 667 film. The image on the film is then magnified 400% by a color copier. This copy is then scanned into a Macintosh II computer, with a 256 level grey-scale. It will be assumed that no significant error is introduced in the magnification and scanning

processes. The scanned image is then evaluated with an image processing program, NCSA Image 3.0. The program allows contrast adjustments and magnifications. It also allows a cursor to be moved across the picture giving the X-Y position. Figure VI.6 shows a section of fringes as recorded by the streak camera and processed as above. Note that printers and most copy machines are fundamentally black and white devices, as opposed to the grey-scale capability of the computer. Hence there is a loss of resolution in the transfer to paper. In order to facilitate explanation of the analysis, there is no movement in the section of fringes displayed in Fig. VI.6, as the plasma was not passing the laser at the time. The accuracy to which a fringe shift can be determined depends on the accuracy of the distance D as marked on the figure. On the computer screen the distance D takes more than 40 pixels. It is possible to determine the center of the fringe to better than ± 2 pixels. Thus the maximum error is plus or minus one tenth of a fringe. It is probably less, but 1/10 fringe is a conservative estimate. An alternate method of analysis is to measure the magnified color copy directly. Fringe spacing is usually between 3 and 4 mm, and it is reasonable to measure the deflection to the nearest ± 0.25 mm. Thus the 1/10 fringe error is still reasonable.

Figure VI.1. Modification for Vibration Test.

Figure VI.2. Vibration Test Results.

Figure VI.3. Graph of Ionization Ratios.

Figure VI.4. Beam Deflection Details.

Figure VI.5. Beam Deflection Experiment.

Figure VI.6. Sample Fringe Picture.

VII. SUGGESTIONS FOR FUTURE WORK

Perhaps the first future application of the technique developed in this work should be the examination of plasma arc characteristics when ceramic spacers are used instead of Lexan. Ablation from the ceramic spacers is almost nonexistent. If the plasma arc does not form multiple arcs at high velocity, the speculation that they are caused by ablated material will be verified.

It may be possible to increase the sensitivity of the density measurement, so that lower densities may be measured. Since the diameter of the railgun bore is fixed, the only way to do this is to employ a laser with light of longer wavelength. The risk here is that for light of lower frequency, the cutoff density will be lower. Figure VII.1 shows cutoff density versus wavelength. Even though the maximum density measured in this experiment was about 2×10^{18} electrons per cubic centimeter, it must be remembered that that is a measurement of line average density. It is possible that in certain spots density is significantly higher. In addition, it has been demonstrated that higher voltages result in higher electron densities, so if voltage is increased, the higher electron density will block more frequencies of light. In any case, it would be beneficial to use a laser of higher power, as the laser used in this experiment was only adequate. It is always

easy to cut back on the power output of a laser if it is too high for the recording method used.

As mentioned earlier, two-wavelength interferometry may be employed to determine the neutral particle density, as well as electron density. The index of refraction of neutral particles depends on what elements they consist of and what temperatures they are at. Thus, before two-wavelength interferometry will be successful, it is necessary to determine what elements are in the plasma, as well as their temperatures. Finding the composition of the plasma is a very difficult proposition, and may never be completely solved.

If a way can be found to allow laser light through larger areas of the sidewalls of the railgun without distortion, it should be possible to obtain an instantaneous density profile by using a pulsed laser spread out over a significant area. This will be very challenging, as a large hole or open area on the spacer will have an effect on the arc. The Lexan spacer itself is not suitable for undistorted optical transmission, and quartz darkens easily.

In-depth analysis of the results of this work is difficult, as so little is known about the plasma. Use of B-dot probes to measure current density will help, as will measurement of plasma temperature, pressure, and voltage drop. The more pieces of the puzzle that are found, the easier a full understanding of the railgun plasma armature will become.

Figure VII.1. Cutoff Density Plot.

VIII. CONCLUSIONS

In this work the basics of railgun operation and the mathematical background for interferometry of plasmas have been introduced. The experimental considerations and construction have been discussed. Results for the experiments with both foam and Lexan pellets have been presented, and possible sources of error have been explained.

The line average electron density in the armature of the present railgun system has been found to be in the range of 10^{17} and 10^{18} electrons per cubic centimeter. It has also been found that in some cases the plasma forms several arcs, probably to the detriment of railgun operation. The concept of interferometric measurement on a railgun has been shown workable, at least in some railguns. When other diagnostic techniques are developed, it may be possible to use several methods to obtain a more thorough understanding of the railgun plasma armature. Different methods can be used to complement each other and to fill in the total picture that describes the railgun plasma armature.

APPENDIX. MAGNETIC FLUX CALCULATIONS

(* Program to calculate magnetic flux between rails
at 1 A current. Executed using Mathematica.
Written by Richard Haywood. *)

```
(* Initial set-up *)
u0=4 Pi 10^-7;
RailSide=.25 .0254;      (* converted to meters *)
BoreRadius=1/16 .0254;
Area=(RailSide^2 - (BoreRadius^2 Pi/4));
                        (* area of one rail *)
Current=1;              (* assume current of 1 amp *)
Density=N[Current/Area];
```

```
(* Definitions for current densities *)
J1[x_,y_]:=If[x<0 || y<0 || x>RailSide
  || y>RailSide || Sqrt[x^2+y^2]<BoreRadius,
  0,Density];
J2[x_,y_]:=If[x>0 || y>0 || x<-RailSide
  || y<-RailSide || Sqrt[x^2+y^2]<BoreRadius,
  0,-Density];
```

```
(* Set up division of rail into smaller units *)
BoxPerRail=15^2;
BoxPerSide=Sqrt[BoxPerRail];
BoxSide=RailSide/BoxPerSide;
BoxArea=RailSide^2/BoxPerRail;
```

```
(* Calculate magnetic field from rails *)
(* First Rail *)
Blx[x_,y_]:=u0/(2 Pi) (If[J1[x,y] == 0,
  Sum[J1[xx,yy] Sqrt[(x-xx)^2+(y-yy)^2]^(-2)
  (yy-y) BoxArea,
```

```

    {xx, BoxSide/2, RailSide-BoxSide/2, BoxSide},
    {yy, BoxSide/2, RailSide-BoxSide/2, BoxSide}]],
    0])
B1y[x_, y_] := u0 / (2 Pi) (If[J1[x, y] == 0,
    Sum[J1[xx, yy] Sqrt[(x-xx)^2 + (y-yy)^2]^-2
    (xx-x) BoxArea,
    {xx, BoxSide/2, RailSide-BoxSide/2, BoxSide},
    {yy, BoxSide/2, RailSide-BoxSide/2, BoxSide}]],
    0])
(* Second Rail *)
B2x[x_, y_] := u0 / (2 Pi) (If[J2[x, y] == 0,
    Sum[J2[xx, yy] Sqrt[(x-xx)^2 + (y-yy)^2]^-2
    (yy-y) BoxArea,
    {xx, -BoxSide/2, -RailSide+BoxSide/2, -BoxSide},
    {yy, -BoxSide/2, -RailSide+BoxSide/2, -BoxSide}]],
    0])
B2y[x_, y_] := u0 / (2 Pi) (If[J2[x, y] == 0,
    Sum[J2[xx, yy] Sqrt[(x-xx)^2 + (y-yy)^2]^-2
    (xx-x) BoxArea,
    {xx, -BoxSide/2, -RailSide+BoxSide/2, -BoxSide},
    {yy, -BoxSide/2, -RailSide+BoxSide/2, -BoxSide}]],
    0])

(* Magnetic flux in tesla per amp at point centered
between rails *)
Btot = Sqrt[B1x[0, 0]^2 + B1y[0, 0]^2] +
    Sqrt[B2x[0, 0]^2 + B2y[0, 0]^2]

0.0000828 (* Multiply by current to get total
field *)

```

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**SPECTROSCOPIC MEASUREMENTS OF THE ELECTRON DENSITY AND
ELECTRON TEMPERATURE OF A PLASMA ARMATURE IN AN
ELECTROMAGNETIC RAILGUN**

Prepared

by

**Professor Kyekyoon(Kevin) Kim
Principal Investigator**

and

**William C. Manns
Research Assistant**

**Fusion Technology Laboratory
Department of Electrical and Computer Engineering
University of Illinois at Urbana-Champaign
Urbana, Illinois 61801**

1. INTRODUCTION

An electromagnetic railgun is a mechanism which can accelerate projectiles to very high (>5 km/sec) velocities. While the previous statement may cause some to immediately think in terms of its military applications, there are many other nonlethal applications in which the accelerating capabilities of the railgun could be employed. Among these are the launching of payloads into orbit, the rapid solidification of solids for the creation of superalloys, and impact studies and simulations for the development of solutions to the space debris problem and for equation of state research. Another application which has been the subject of considerable research over the past decade is as a refueling mechanism for magnetically confined fusion reactors by the high speed injection of frozen, millimeter-sized hydrogen isotope pellets [1-4].

Ever since Spitzer et al. [5] first proposed pellet injection as a refueling technique, extensive effort has gone into the investigation of pellet acceleration methods. To date, the record velocity for a deuterium pellet is 3.3 km/sec using a two-stage light gas gun [6,7]. This still falls short of the estimated 5-10 km/sec which will be required for future fusion reactors [8]. Significant increases in pellet velocities using gas gun techniques are not expected unless a sabot is used to protect the pellet from the large shock forces encountered.

A railgun is made up of a pair of parallel rigid conductors which are separated by some type of insulating material in such a way as to form a bore. A conducting movable armature is needed to carry the current between the two rails. The theory of operation is presented in Fig. 1.1. (Figures appear at the end of chapters.) As current flows down one rail, through the armature, and back to ground through the second rail, a magnetic field is induced such that the current density vector and the magnetic flux vector within the bore are at right angles. The resultant $\mathbf{J} \times \mathbf{B}$, or Lorentz force, on the charge carriers then acts to propel the armature, and any object in front of it, down the length of the rails. While a solid conducting piece can be used as the armature, the problem of maintaining good electrical contact with the rails at high speeds has led to the use of plasma armatures. Since the theoretical speed limit of a plasma armature is well above 100 km/sec, it appears highly likely that a plasma armature railgun could be used to obtain the speed required for refueling.

For a constant rail current, assuming no energy loss, the force which the railgun can impart to the pellet is given in Eq. (1.1).

$$F = \frac{1}{2} L' I^2 \quad (1.1)$$

Here L' is the inductance per unit length of the rail pair, and I is the current. This formula implies that the force and,

therefore, the velocity of the pellet, can be increased by increasing the current or the inductance, a more difficult adjustment. In reality, however, due to the various energy loss mechanisms, the velocities achieved in experiments to date have fallen short of the predicted values. First attempts to model the plasma made by McNab [9], Powell and Batteh [10,11], and Thio [12] neglected many effects. In efforts to reconcile theory with experimental results, Parker et al. [13] proposed the addition of a viscous drag term and the addition of ablation products from the sidewalls and rails which add to the mass of the plasma. Hawke [14] mentions the formation of secondary arcs which steal current from the main arc. All of these effects slow down the plasma armature. In any case, it is clear that one of the major issues in facilitating the development of reliable, hypervelocity railguns is an accurate description of the conditions within the plasma armature.

In an effort to obtain this information, this research is concerned with the measurement of the electron density and electron temperature of the free-running, i.e., no projectile, plasma armature in a small-bore electromagnetic railgun. Until recently, relatively little effort had been directed to the area of plasma diagnostics for railgun systems [15-18]. Most of the problem is due to the nature of the plasma itself. The high temperatures involved and the fact that the gun bore must be kept clear necessitate the use of nonintrusive diagnostic techniques. One of the most obvious characteristics of the plasma, and one

which easily lends itself to the techniques required, is that it is luminous. Therefore, to investigate the plasma parameters, spectroscopic methods will be employed. These methods and the subsequent determination of the plasma parameters are derived from astronomical techniques and from studies of stabilized, essentially steady-state plasmas. The determination of the electron density is achieved through the half-width measurement of the Stark broadened hydrogen beta line. This method is one of the most accurate and convenient for dense plasmas [19]. The electron temperature will be determined from the relative intensities of the hydrogen alpha and beta lines [20].

This thesis is organized into chapters and sections. Chapter 2 includes a more detailed discussion of Stark broadening as well as the methodology for determining the electron density and temperature. Chapter 3 describes the experimental equipment used in this research. The experimental procedure, data reduction, and results are presented in Chapter 4. Finally, Chapter 5 contains conclusions and recommendations for further experiments.

Figure 1.1 Railgun Theory of Operation

2. STARK BROADENING AND PARAMETER EVALUATION

This chapter is divided into two sections. The first gives some background on the process of Stark broadening of spectral lines. In the second, the methodology used for the evaluation of the electron density and electron temperature of the plasma armature will be described.

2.1 Stark Broadening

The broadening of emitted spectral lines occurs from a variety of factors. Natural broadening is the result of the nature of the atom. The energy levels that electrons make transitions between are not exact, but have a spread around average values. Thus even if there were no other interactions, the lines emitted would still exhibit some width. The width due to natural line broadening, however, is usually negligible when compared to that from other broadening mechanisms [19].

The two most important mechanisms are Doppler and Stark broadening. Doppler broadening is due to the relative motion of the radiating system and the observer. A purely Doppler broadened line would produce an intensity distribution with a Gaussian shape. Stark broadening, or pressure broadening, is the result of interactions of the radiating atoms with surrounding charged particles, i.e., electrons and ions. Lines broadened in this manner exhibit an approximately Lorentzian-shaped profile. When

both mechanisms are present, the overall line profile is a convolution of the two shapes called Voigt profiles. Under certain conditions, however, the effect of one type of broadening is negligible compared to the other. Stark broadening, which is dependent on the electron density, is dominant at low electron temperatures and high densities [19]. As will be seen in the experimental results, these are the conditions which are present in the railgun plasma armature. Doppler broadening, which is independent of electron density, is dominant at the reversed conditions and can be neglected in this case.

Stark broadening theory was originally derived from two very different approaches, the quasi-static approximation and the impact approximation. In the quasi-static approach, the radiators are considered to be continuously under the influence of the perturbers throughout the emission process. These perturbers are also assumed to be moving so slowly during the emission that the perturbing fields can be taken as quasi-static. The impact approach takes the opposite view that the radiator is basically unperturbed most of the time, but can be disrupted by fast moving perturbers. It was finally realized that the two approaches were basically the extremes of a more general theory. The quasi-static approach described broadening from the heavy, slow moving ions, while the impact approach described broadening from the fast moving electrons. A refined Stark theory which simultaneously takes into account the effects of both ions and electrons was developed mostly by Griem [21]. The quantum mechanical

calculations are very complex and have only been done for a few atoms. Hydrogen, having the simplest configuration, is one of these atoms. It is also the one which experiences the largest broadening. In hydrogen, the Stark effect is linearly proportional to the electric field due to degeneracies in the energy levels. For other multielectron atoms it is quadratic, proportional to E^2 , and therefore much smaller [22].

2.2 Parameter Evaluation

This section will describe the methodology used to evaluate the electron density and electron temperature of the plasma armature. Since the relationships used involve both the density and temperature, the measurements are not really independent. It is therefore necessary to find results that are self-consistent. Concerns about the application of these methods will also be discussed.

2.2.1 Electron density

Probably the best line for the observation of Stark broadening is the hydrogen beta line. It is conveniently located in the visible region at 4681 Å and its shape, with two slightly different intensity maxima, is very characteristic and easily detectable. Most importantly, it provides the best agreement between theoretical calculations and experimental results leading to the most accurate determination of the electron density [19]. The density is determined from a measurement of the width of the

beta line at the points where the intensity is equal to one-half of its maximum value, and can be written in terms of this full width at half-maximum, or FWHM, as

$$N_e = C(N_e, T) [\text{FWHM}]^{3/2} \quad (2.1)$$

The $C(N_e, T)$ term is a slowly varying coefficient that is only a weak function of both the density and temperature [21].

Table 2.1, taken from Griem [21], demonstrates the variation of $C(N_e, T)$ over a range of density and temperature conditions.

Table 2.1 Coefficients $C(N_e, T)$ for Electron Density Determination from FWHM Measurements

Temp. (K)	Ne (cm ⁻³)		
	10 ¹⁵	10 ¹⁶	10 ¹⁷
5000	3.68 x 10 ¹⁴	3.44 x 10 ¹⁴	
10000	3.58 x 10 ¹⁴	3.30 x 10 ¹⁴	2.98 x 10 ¹⁴
20000	3.55 x 10 ¹⁴	3.21 x 10 ¹⁴	3.03 x 10 ¹⁴
40000	3.52 x 10 ¹⁴	3.30 x 10 ¹⁴	2.87 x 10 ¹⁴

A few questions must be addressed before the application of Eq. (2.1). The first is the determination of the FWHM. Since the hydrogen beta line exhibits two slightly different maxima, the question arises as to which value should be used. The asymmetry is usually ignored in theory with an average of the two

intensities used instead [23]. This average is still not the final value used for determining the FWHM, however, since it is the height above the underlying continuum which is the important quantity. In a plasma composed of pure hydrogen, the determination of the underlying continuum would only be a matter of how far away from the line center one had to be before the contribution from the far wings of the broadened line was considered negligible. The plasma armature, however, is mostly composed of helium along with components from the copper rails and the Lexan sidewalls. In fact, it is the hydrogen which is ablated from the Lexan that is being measured to determine the electron density. This is appropriate since Wiese [19] advocates the admixture of at least some hydrogen, as long as it does not significantly change the plasma parameters, in order to use the beta line for density measurements. The other components in the armature, however, may produce lines which appear as impurity lines when they fall near the beta line. These lines are also broadened and their line wings can overlap with the beta line wings effectively raising the continuum level. The width of the wavelength window being viewed is also a limiting factor. Both of these effects can lead to an overestimation of the continuum level. This would in turn lead to an overestimation of the FWHM and the electron density.

Another question arises in the choice of the coefficient, $C(\text{Ne}, T)$, in Eq. (2.1). Since it is a function of both the electron density and electron temperature, how does one choose the

correct coefficient without a priori knowledge of the parameters one is trying to measure? Fortunately, for small values of FWHM, the variation with density and temperature is also very small as shown in Fig. 2.1. Using an average value for $C(\text{Ne}, T)$, a nominal value for the density is obtained. As described in the next section, a measurement of the relative intensities of the hydrogen alpha and beta lines is used to determine the electron temperature. With this temperature value, one can go back and refine the density measurement by choosing the proper coefficient.

2.2.2 Electron temperature

One of the oldest methods for determining the electron temperature is through the comparison of the relative intensities of two spectral lines [21]. For this measurement, the hydrogen alpha and beta lines will be used. Equation (2.2) gives the intensity ratio of two lines belonging to the same atomic species [20].

$$\frac{I_1}{I_2} = \frac{A_1 g_1 \lambda_2 U_2 n_1}{A_2 g_2 \lambda_1 U_1 n_2} \exp \left\{ \frac{-(E_1 - E_2)}{kT} \right\} \quad (2.2)$$

Here 1 and 2 refer to the first and second lines (alpha and beta), I is the total intensity, A is the transition probability for spontaneous emission, g is the statistical weight of the upper state, λ is the wavelength, U is the partition function, n is the number density of particles in the ground state, E is the energy

level, k is the Boltzman constant, and T is the temperature in Kelvin. The Boltzman constant and temperature are usually combined to express the temperature in the unit of electron volts ($1 \text{ eV} = 11,600 \text{ K}$). If the two lines belong to the same ionization stage, as in this case, then the partition function and densities cancel, leaving Eq. (2.3) [20].

$$\frac{I_{\alpha}}{I_{\beta}} = \frac{A_{\alpha}g_{\alpha}\lambda_{\beta}}{A_{\beta}g_{\beta}\lambda_{\alpha}} \exp\left\{\frac{-(E_{\alpha} - E_{\beta})}{kT}\right\} \quad (2.3)$$

Solving for the temperature yields Eq. (2.4).

$$kT = \frac{E_{\beta} - E_{\alpha}}{\ln\left[\frac{I_{\alpha}A_{\beta}g_{\beta}\lambda_{\alpha}}{I_{\beta}A_{\alpha}g_{\alpha}\lambda_{\beta}}\right]} \quad (2.4)$$

All of the known quantities for the hydrogen alpha and beta lines are given in Table 2.2 [24]. Inserting the values gives Eq. (2.5).

$$kT = \frac{0.66 \text{ eV}}{\ln\left[\frac{I_{\alpha}}{I_{\beta}}(0.46)\right]} \quad (2.5)$$

Thus, a measurement of the relative intensities of the two lines leads to the determination of the electron temperature in the plasma armature.

Table 2.2 Constants for Hydrogen Alpha and Beta Lines

Quantity	Alpha	Beta
$A \text{ (sec}^{-1}\text{)}$	4.410×10^7	8.419×10^6
$E \text{ (eV)}$	12.084	12.745
$\lambda \text{ (Å)}$	6562.80	4861.32
g	18	32

Again, a few questions should be addressed before applying Eq. (2.5). First, the I 's are total intensities which include contributions over the entire line profile. The intensities used will be obtained by evaluating the area under the curve between two diode numbers in a computer data file. As with the density measurement, uncertainties arise in determining the continuum level, i.e., the diode numbers between which this integration takes place. Second, after determining the intensity of the alpha line, it must be multiplied by 1.25 before inserting it in Eq. (2.5) to account for the efficiency of the spectrograph grating. (The spectrograph and grating are described in detail in the next chapter.) A graph of the efficiency of the grating versus wavelength, supplied by the manufacturer, is shown in

Figure 2.2. Finally, it can be shown that in order for Eq. (2.5) to be a sensitive function of the electron temperature, the difference in energy levels should be at least of the same order as the temperature being measured [25]. In this case, $\Delta E = 0.66$ eV may be on the low side.

Figure 2.1 Calculated Densities for Selected Conditions

Figure 2.2 Grating Efficiency

3. EXPERIMENTAL EQUIPMENT

The equipment used in this research is divided into two main groups. The first consists of the railgun system and its associated subsystems. The second group includes the diagnostic equipment used to examine the spectral output of the plasma armature.

3.1 The Railgun System

A schematic of the hydrogen pellet accelerating system at the Fusion Technology and Charged Particle Research Laboratory of the University of Illinois is shown in Fig. 3.1. It is a two-stage system with the gas reservoir and fast valve acting as a gas gun first stage to preaccelerate pellets up to 1 km/sec before entering the railgun second stage. This preacceleration is necessary in order to reduce ablation and rail erosion near the breech which would occur from a slowly moving plasma armature [4]. A coupling piece is used to provide a smooth transition from the gas gun to the railgun bore. The oscilloscopes, amplifier, and timing circuit are located in a screen cage to shield them from electromagnetic interference effects. Some of the subsystems and diagnostics shown in Fig. 3.1 are used only when pellets are being fired. Since this research was concerned with free-arc operation, only pertinent subsystems will be described here. A thorough presentation of the others is given in Kim et al. [26].

3.1.1 Railgun

The main component of the railgun system is, obviously, the railgun itself. It has a bore diameter of 0.125 inch (3.2 mm) and a length of 1.2 meters. The rails are made of 0.25 x 0.25 inch square copper rods with the bore groove machined out of one edge. The bore is completed with appropriately machined dielectric material made of Lexan. The rails and insulating sidewalls are bolted into two aluminium "vee-blocks" to hold the assembly intact. A cross-sectional view of the railgun is shown in Fig. 3.2.

The railgun is placed in a vacuum chamber located on a Newport optical table. Flanges on the top of the chamber provide for the connection of power cables to the railgun, as well as other control and signal lines. Pyrex windows on the sides of the chamber allow for the viewing of the armature motion by a streak camera described later. The chamber can be evacuated down to less than 1 mTorr or backfilled with helium or hydrogen gas to specified pressure levels.

3.1.2 High current pulse-shaping network

The purpose of the high current pulse-shaping network is to deliver an approximately rectangularly shaped current pulse to the railgun. This is achieved by using up to five pairs of capacitors and inductors connected in series. The actual design is covered elsewhere [27]. The capacitors have a nominal value of 500 μF each, while the custom wound inductors have a nominal value of

12 μH each. Capacitor/inductor pairs can be added or removed to lengthen or shorten the duration of the pulse from 238 μsec to 985 μsec . All of the experiments performed during the course of this research used 3 capacitor/inductor pairs which resulted in a 615 μsec duration pulse. The amplitude of the current pulse delivered is approximately 2.35 times the voltage to which the capacitors are charged. An example of the high current pulse is shown in Fig. 3.3 for a bank voltage of 2 kV.

3.1.3 Arc initiation subsystem

In most plasma armature railgun systems, the arc is initiated via a metal foil attached to the rear of the projectile. When the foil contacts both rails, the circuit is completed and current flows. Almost instantaneously, the current density in the foil becomes too large and the foil vaporizes. The spark from the vaporization of the foil serves to initiate the plasma. The use of a fuse, as it is known, presents two problems if the railgun is to be used as a refueling mechanism for fusion reactors. The first is the actual attachment of the fuse to a cryogenic pellet. More importantly, the plasma armature produced will consist mainly of high Z (atomic charge) particles from the foil. These particles, introduced into the reactor plasma, absorb much of the energy in electronic transitions possibly lowering the temperature below that required for fusion [27]. To eliminate this problem, a unique scheme is utilized which uses a high voltage spark from a tungsten needle to break down the gas in the gun bore. The plasma

armature is now composed of mostly low Z helium or hydrogen particles. The needle is mounted through the sidewall, 3 inches from the breech, with the tip flush to the bore so that the barrel remains unobstructed.

The arc initiation subsystem also has a pulse-shaping network similar to the high current pulse-shaping network, but consisting of only one capacitor/inductor pair. The 0.5 μF capacitor and 20 μH inductor provide a current pulse of 10 μsec duration when the capacitor is charged to 5 kV. At the peak of the arc initiation pulse, the ignitron switch is closed and the current from the high current network is allowed to pass to the railgun. The current flows between the rails through the low impedance path of the plasma as the armature moves down the length of the rails.

3.1.4 Streak camera

A streak camera sweeps an image across a screen at a constant rate. Film is placed behind the screen to record the image. Thus a record of the arc position as a function of time is obtained. An example of a streak camera photograph is shown in Fig. 3.4. The duration of the streak is set so that it is longer than the time taken for the plasma to travel the length of the railgun. Where the streak turns up in the photograph is then an indication that the plasma has reached the gun muzzle. Also observed in the photograph is that the streak is almost linear implying that the plasma is traveling at nearly a constant velocity. This fact is important since the streak camera ceased operating early in the

data collection. The velocity of the plasma was then determined by other methods.

3.1.5 B-dot probes

B-dot probes are so named because they produce an output voltage proportional to the time rate of change of the magnetic flux linking the probe. The probes were composed simply of 160 turns of wire attached to the ends of a coaxial cable. The loop was encased in epoxy to provide insulation and structural integrity. As a consequence of Maxwell's equations, the probes only respond to the components of the magnetic field which are perpendicular to the plane of the loop. This property is used when mounting the probes in the railgun sidewalls to detect the passage of the armature while ignoring the effects of the rail current, Fig. 3.5. Two probes, one near the arc initiation needle and the other near the muzzle, 37 inches (93.98 cm) apart, were used. An example of the B-dot probe signals is given in Fig. 3.6. B-dot probes can be used to provide another measure of the plasma velocity. They can also be a very effective tool in detecting the occurrence of any secondary arcs which may become present in the railgun.

3.2 Spectrum Diagnostic Equipment

A block diagram of the equipment used in the acquisition and analysis of the spectral output of the plasma armature is shown in Fig. 3.7. The light from the plasma will first impinge on a

spectrograph and then the electronic spectrum will be collected by a device known as an Optical Spectrometric Multichannel Analyzer (OSMA). The OSMA transfers the data to a computer where the spectrum can be analyzed.

3.2.1 Spectrograph

The spectrograph, a Jarell-Ash Mark X Model 82-484, is a crossed Czerny-Turner design with aspheric mirrors, a focal length of 275 mm and an aperture ratio of $f/3.8$. A diagram of the optical path and the main components of the Mark X is shown in Fig. 3.8. The most important of these components is the grating, which is essentially a mirror with thousands of grooves "drawn" on it, and serves as a light separating device. The more grooves/mm on the grating, the larger the dispersion of the incident light. The grating is mounted on a platform which can be rotated, changing the angle of the grating with respect to the other mirrors, and thus the wavelength of light which is allowed to escape through the exit.

Two different gratings were used throughout the course of this research. One had 1200 grooves/mm with a dispersion of 3 nm/mm, while the other had 300 grooves/mm and a dispersion of 12 nm/mm. Both were blazed at 500 nm. The blaze wavelength is a measure of the region of peak efficiency for the grating. The two gratings help to provide what are essentially zoom and wide-angle pictures of the spectrum. Since the photodiode array in the OSMA is 18 mm wide, a wavelength window of $3 \text{ nm/mm} \times 18 \text{ mm} = 54 \text{ nm}$ wide

is produced with the 1200 groove grating. This configuration is used for close-up observation of the hydrogen beta line for density measurements. Similarly, the 300 groove grating produces a wavelength window 216 nm wide. Both the hydrogen alpha and beta lines can be observed for temperature measurements with this grating in place. The spectrograph is equipped with a four-digit counter, which is calibrated with the 1200 groove grating to read directly in nanometers the center wavelength of the spectral region being viewed. When using the 300 groove grating, the counter reading must be multiplied by four to obtain the correct center wavelength.

A mechanical shutter similar to those found on a high quality camera was attached to the entrance port of the spectrograph in front of the entrance slit. The purpose of the shutter was to prevent light from entering the spectrograph and reaching the very sensitive OSMA detector when the experiment was not in progress.

3.2.2 Optical spectrometric multichannel analyzer (OSMA)

The OSMA is a computer-controlled multichannel image detector capable of detecting, measuring and manipulating spectra. The system is composed of a Princeton Instruments IRY-700 detector head, an FG-100 high voltage pulse generator and an ST-110 detector controller. The detector head is mounted onto the exit port of the spectrograph. A schematic of the main components in the detector head is shown in Fig. 3.9. The proximity-focus micro-channel-plate (MCP) image intensifier is optically coupled

to a ReticonTM diode array with an optical fiber coupler window. In CW mode, the photocathode potential is held 180-200 volts more negative than the MCP input allowing the photoelectric spectrum to continuously reach the MCP. In the GATED mode, the photocathode is approximately 20-40 volts more positive than the MCP input and thus the image cannot reach the MCP. When triggered, the FG-100 pulse generator applies a negative pulse of -180 to -200 volts to the photocathode allowing the photoelectric spectrum to reach the MCP. The MCP intensifies the electron spectrum, and it is then accelerated and focused onto the phosphor where it is converted to a photon spectrum with further optical gain. This photon spectrum is transmitted to the individual diodes in the diode array through the phosphor and the optical-fiber coupler. A Peltier effect, thermoelectric cooler is utilized to reduce the temperature of the array. Water is circulated through the back plate to more efficiently remove the excess heat. To prevent condensation on the MCP faceplate, dry nitrogen is flushed through the detector head.

As mentioned above, the FG-100 pulse generator is used to provide high voltage negative pulses to the photocathode in the detector head. The output can be chosen to have a fixed width of 10 nsec or to be variable from 20 nsec to 4 μ sec. The FG-100 can be externally triggered on the rising or falling edge of an input trigger up to a rate of 1 kHz with the variable pulse output selected. A low-level output which can be used for measuring pulse width and for timing purposes is also provided. The actual

timing and other parameters used will be discussed in Sec. 4.1, Experimental Setup and Procedure.

The ST-110 detector controller not only provides power and temperature thermostating, but serves as an interface between the computer/operator and the IRY-700 detector in performing the experiment. In this capacity, it is responsible for certain experiment synchronization and triggering signals, exposure time control, and data digitization and transmission to the computer. The diode array operates in a self-scanning mode, i.e., the diodes are continuously being exposed and then their values read out. This reading-out, or scan time, takes 33 msec. The exposure time is set by the operator in multiples of the scan time. Until a command is sent by the computer, the values of the diodes will be read out and stored in the ST-110, but not transmitted to the computer. When the computer does give the command, at the occurrence of the next scan time, the values of the diode array will be read out, stored in the ST-110, and then transmitted to the computer. Once in the extended memory, the spectrum is displayed on the CRT screen and can be stored onto floppy disk.

3.2.3 Computer system

The computer used is a Tektronix 4052A with an extended memory pack attached. A floppy disk drive and a hard copy unit, which can make printouts of the screen display, comprise the rest of the system. Two programs originally written when using the OSMA to study a dense plasma focus were used in the data

collection and processing. The programs are written in BASIC which allow for easy modification and both incorporate user-defined keys (UDKs) to call various subroutines.

Program "O" is used to acquire spectra with the OSMA system. Subroutines control the collection of background and calibration spectra in the CW mode, and experimental spectra in the GATED mode. Other subroutines set and record experimental parameters and store and recall data from disk.

Program "P" is used in the manipulation and data reduction of the spectra acquired with program "O." As in "O," subroutines store and recall data from disk. Another initiates a cursor mode which is used to display the magnitude and horizontal position at the crosshairs which follow the spectrum. These data are used in converting the horizontal axis to a wavelength scale with another subroutine and for determining line widths. The area under the curve between two diode values, used in the temperature evaluation, is computed by another subroutine. Finally, an additional subroutine was written and added to program "P" which can list diode numbers and their values, unilaterally change the values between two diode numbers, or change individual diode values.

Figure 3.1 Hydrogen Pellet Accelerating System

Figure 3.2 Railgun Cross Section

Figure 3.3 High Current Pulse for 2 kV Bank Voltage

Figure 3.4 Streak Camera Photograph

Figure 3.5 B-dot Probe Orientation

Figure 3.6 B-dot Probe Signals

Figure 3.7 Spectrum Diagnostic Equipment

Figure 3.8 Spectrograph Components and Optical Path

Figure 3.9 IRY-700 Detector Head Components

4. EXPERIMENT

This chapter describes the experimental setup and procedure used to collect data on the railgun plasma armature. The data reduction techniques used along with the final density and temperature results will also be presented.

4.1 Experimental Setup and Procedure

The setup used to conduct the experiment is shown in Fig. 4.1. With the impact transducer on the end flange of the vacuum chamber replaced by a quartz window, the spectrograph and OSMA detector head are positioned on the optical table so that they are looking down the railgun bore. The rest of the spectrum acquisition apparatus is the same as that shown in Fig. 3.7. In order for the acquired spectra to later be displayed versus wavelength, a source which emits lines at known wavelengths is required. This is the purpose of the calibration lamp and He-Ne laser. For density shots, a xenon lamp was used as the only calibration source, since it emits a very good signature of spectral lines around 4861 Å. Temperature shots require lines spread over a larger region since both the alpha and beta lines need to be observed. This led to the use of the He-Ne laser as a calibration source emitting light at 6328 Å; however, since more than one line is necessary for the wavelength conversion, a source at a lower wavelength is still required. The smaller dispersion

of the 300 groove grating tends to blend together the narrowly spaced lines of the xenon lamp making identification less precise. To remedy this, the xenon lamp is replaced by a mercury lamp with stronger, more isolated lines. The lowest usable mercury line occurred at 5461 Å. While it would have been better to have a line closer to the beta line wavelength, this was not considered to be a big problem since exact wavelength calibration is not critical to the temperature measurement. The power of the laser beam was a problem, however. It was so high in comparison to the other sources that it had to be attenuated. This was accomplished with the aid of two linearly polarized filters. The rotation of the plane of polarization of one of the filters relative to the other produced a continuously adjustable attenuator. To direct the light from the calibration sources into the spectrograph, mirrors are used. One of these is placed between the quartz window and spectrograph, and is mounted on a set of optical rails to reduce the experiment's preparation time. Once the mirror was adjusted to the correct angle, it could be slid into position for calibration shots and then slid away for shots of the plasma armature.

Two timing schemes are used to acquire spectra with the OSMA in GATED mode. For gated shots of the calibration source(s), the timing diagram of Fig. 4.2 is used. The external pulse generator is set to run at a 1 kHz pulse repetition frequency. Each time the FG-100 is triggered during the exposure time, light from the source(s) is integrated on the diode array. The high voltage

pulser is prohibited from pulsing during the array readout with the NOTSCAN signal from the controller connected to the ENABLE port of the pulser. For gated shots of the plasma armature, the timing diagram of Fig. 4.3 is used. The external pulse generator is set to single-pulse mode. The rising edge of this pulse is used to trigger the arc initiation circuitry. A delay generator provides a 4 μ sec delay for proper timing between the arc initiation and ignitron switch signals. The falling edge of the single pulse serves as the trigger for the FG-100 to pulse the photocathode in the detector head. By varying the width of the pulse from the external pulse generator, a spectrum of the armature at different positions along the length of the rails is obtained.

As described in Section 3.2.2, the diode array operates in a self-scanning mode, which alternates between exposure time, when light can be integrated on the diodes, and readout time. For shots of the plasma armature, it is essential that the trigger from the external pulse generator occur during the exposure time for any meaningful data to be collected. To assure that this happens, two steps were taken. First, when initializing the experimental parameters with program "O," the exposure time is set to a large multiple of the readout time (e.g., 1000x). Second, the TRIGGER OUT signal from the ST-110 controller is observed on the oscilloscope. When this signal goes "low," indicating that the diodes are in the exposure time, the railgun can be fired by pressing the single pulse trigger on the external pulse generator.

In previous experiments which studied the performance of the free-running plasma armature, the usual procedure included the backfilling of the vacuum chamber with helium gas. This procedure is followed here by backfilling the chamber with 20 Torr of helium gas in order to take advantage of the Paschen curve characteristics of helium. Paschen's law states that the breakdown voltage of a gas is essentially only a function of the gas pressure, p , times the electrode separation, d [28].

$$V_B = f(pd) \quad (4.1)$$

The Paschen curve for helium, taken from Honig [27], is shown in Fig. 4.4. The minimum of this curve occurs between 3 and 6 Torr·cm. In the bore, the smallest separation between the rails is 0.225 cm, which corresponds to pressures of 13.4 and 26.7 Torr, respectively. The previous experiments with free-arc operation determined that a pressure of 20 Torr is optimum. With the vacuum chamber backfilled, the position of the tungsten needle becomes the most favorable for the breakdown of the helium fill gas, and the reliability and repeatability of the railgun are increased.

Once the chamber is backfilled, the general procedure used for data collection is as follows:

- Program "O" is recalled on the computer and the experimental parameters initialized.
- The detector head is set to CW mode, the lights in the room are turned off, and a background spectrum of the

ambient radiation is taken which will be subtracted from all subsequently acquired spectra.

- A CW spectrum of the calibration source(s) is taken and stored on disk. This spectrum is displayed on the computer CRT screen beneath spectra acquired in the GATED mode to provide a rough calibration check.
- The detector head is switched to GATED mode and another spectrum of the calibration source(s) is acquired and stored using the timing scheme in Fig. 4.2. This spectrum will be used when converting the diode numbers to a wavelength scale.
- The calibration source(s) are turned off and the movable mirror slid away so that the spectrograph and detector are looking down the railgun bore.
- The pulse width of the external pulse generator is set to the desired width and the generator set to single-pulse mode.
- The capacitor bank in the high current pulse-shaping network is charged up to the desired voltage. The arc initiation and the ignitron circuits are charged to 5 kV and 1.6 kV, respectively.
- A spectrum of the plasma armature is acquired using the timing scheme of Fig. 4.3. The spectrum is displayed on the computer CRT screen and can be stored on disk.
- The room lights are turned on.

Due to the high velocity of the plasma and the timing scheme used, only one spectrum can be acquired per firing event. To obtain a profile of the electron density and temperature of the plasma armature along the length of the rails, therefore, requires repeated firing of the railgun under the same experimental conditions. The only change made is in the delay time before the OSMA acquires the spectrum. To acquire another spectrum for a different delay time, the pulse width of the external pulse generator is reset to the new desired width and the generator is set to single-pulse mode. After the lights in the room are turned off, the procedure is as listed above starting with the charging of the capacitors in the high current pulse-shaping network. A group of spectra, taken in succession, recording the emission of the plasma from the railgun breech to the muzzle, was considered as one data run. Associated with each data run was a calibration spectrum. The wavelength calibrations remain in effect as long as the position of the spectrograph is not changed or the counter on the spectrograph adjusted. Thus, the same calibration can be used for more than one data run.

4.2 Data Reduction

As with most experiments, the raw data collected must undergo some analysis and/or processing before the final results can be presented. The program "P," discussed earlier, is used for the data reduction of all the spectra. The first step is the creation of conversion files, which correlate diode numbers in the array

with wavelength values. A gated spectrum of the calibration source(s) is recalled from disk, and the cursor mode is used to identify the diode numbers of specific lines whose wavelengths are obtained from a calibration handbook. A subroutine uses these diode numbers and wavelengths to convert the x-axis into a wavelength scale. This conversion file is stored on disk, and is valid for all data runs associated with this calibration spectrum. Figure 4.5 shows a spectrum of the xenon lamp acquired by the OSMA. The same spectrum displayed versus wavelength using its conversion file and the spectral output as given by an Oriel Corp. calibration handbook [29] are shown in Figs. 4.6 and 4.7. The errors in wavelength values after conversion are generally less than 1 Å when the xenon lamp and 1200 groove grating are used, i.e., for density shots. Since the determination of the electron density is dependent on the evaluation of the FWHM of the hydrogen beta line, it is advantageous to attain as small an error as possible in the conversion process.

4.2.1 FWHM measurement

Perhaps the easiest way to explain how the FWHM values are determined is by stepping through a sample measurement. A spectrum from one of the density data runs is recalled from disk and displayed on the computer screen. Shot B33 from data disk #11 is shown in Fig. 4.8. The conditions for this spectrum were a bank voltage of 3 kV, backfill pressure of 20 Torr, and delay time of 100 μsec. The cursor mode is used to determine the heights of

the two peaks of the beta line. These heights, in arbitrary units, are 1871 and 1789 for B33. The level of the underlying continuum is also obtained using the cursor. This is the step which is prone to the largest uncertainty since the continuum level is basically determined by a "best guess" as to where the spectrum radiation has flattened out. The continuum level for B33 was taken at 934. The very low level seen at the far left in Fig. 4.8 is caused by a misalignment of the exit mirror in the spectrograph and is present in all acquired spectra regardless of the wavelength counter setting. Due to this misalignment, the first 35-40 diodes in the array are not illuminated with any radiation from the light sources. The continuum level is then subtracted from the average of the peak values to give the height of the line above the continuum, $1830 - 934 = 896$ for B33. This value is divided by 2, and then the continuum level added back to determine the height of the half-maximum points, 1382 for B33. The spectrum is now displayed versus wavelength using its associated conversion file. Figure 4.9 shows B33 displayed on a wavelength scale. The cursor mode is used once again to determine the wavelengths of the half-maximum height points. Finally, the difference between these two wavelengths yields the FWHM value. In the example of shot B33, the half-width value was determined as $\text{FWHM} = 4888.85 - 4835.47 = 53.38 \text{ \AA}$.

Occasionally, an interpolation is required to determine wavelength values for either or both of the half-maximum points. This should not be a source of significant error since the

difference in wavelengths between two adjacent diodes is approximately 0.7 Å.

This procedure for evaluating the FWHM values was repeated for every shot in each density data run. For all of the measurements, the continuum level was determined by looking at the left-hand side of the beta line which is relatively free of the "impurity" lines which are more apparent on the right-hand side. As mentioned earlier, these lines are due to components from the sidewalls and rails that are ablated away by the plasma armature as it passes.

4.2.2 Intensity measurement

As with the FWHM measurement, probably the best way to explain the technique used in the temperature determination is through an example. A spectrum from one of the temperature data runs is recalled from disk and displayed on the computer screen. Figure 4.10 shows the raw spectrum of shot BA32 from data disk #12. The conditions for this shot were a bank voltage of 3 kV, backfill pressure of 20 Torr, and delay time of 70 μsec. The hydrogen beta line is seen on the far left and the hydrogen alpha line on the far right. The most outstanding feature of the spectrum, however, is the presence of what was identified as a helium line at 5875.6 Å which dominates the spectrum. The additional subroutine given in Appendix C is used to remove this very high intensity line by unilaterally changing the values of the diodes in the array where it appears. For BA32, the values

from diode number 393 to 447 are set to 490. Again the value is in arbitrary units. When the spectrum is redisplayed on the screen, the self-scaling mechanism of the computer allows the features of the alpha and beta lines to be seen much more clearly as shown in Fig. 4.11 for BA32.

Temperature measurements require that the intensities of the alpha and beta lines be integrated over the entire profile. The presence of the impurity lines which were observed on the upper side of the beta line in the density shot now becomes a problem. If the area from these lines were included, the beta line intensity would be greatly overestimated leading to errors in the temperature determination. One of the characteristics of the hydrogen beta line which is broadened due to the linear Stark effect, however, is that the profile is essentially symmetric except for the slightly different intensity maxima [21]. Using this fact, the impurity lines are removed when the profile on the left is mirrored onto the right by changing individual diode values with the assistance of the additional subroutine. The mirroring of the diode values is continued until the continuum level for the beta line is reached. As with the density measurement, the determination of this continuum level is one of the steps which is prone to the largest uncertainty in the measurement. It is worth noting that the continuum level under the beta line is not the same as that under the alpha line, since the continuum seems to experience a quantum step down at approximately 5150 Å.

The alpha line is virtually isolated in comparison to the beta line. Usually, a few diode values on the upper line wing near the end of the diode array need to be adjusted, however, so that when the integration is performed the beginning and ending diode values match. The same idea of creating a symmetric profile is followed when adjusting the alpha upper line wing diode values. Figure 4.12 shows the modified spectrum of shot BA32, again with the helium line removed. A subroutine is now used to calculate the intensities of the alpha and beta lines. For BA32, integration from diodes 54 to 96 gives a beta line intensity of 25,828. Integration from diodes 625 to 695 gives a value of 61,985 which must be multiplied by 1.25 to account for the grating efficiency. The alpha line intensity is thus evaluated at 77,481. Substituting these values into Eq. (2.5) returns an electron temperature of 2.05 eV. If desired, the modified spectrum can be displayed versus wavelength using its associated conversion file as shown in Fig. 4.13.

This procedure for determining the electron temperature was repeated for every shot in each temperature data run. It should be stated that all of the diode value adjustments were done to a file in the extended memory of the computer. The original spectra data were not destroyed, but remained saved on disk. The modified spectra could have also been stored, but this was not usually done due to space limitations on the disk. A record of all of the adjustments was kept, however, so that the modified spectra could always be reproduced at a later date.

At this point, some may wonder why separate shots of the beta line were taken for density measurements when it is already present in the temperature shots. The reason is mostly due to the dispersion of the two gratings and the techniques used in the temperature evaluation. The larger dispersion of the 1200 groove grating used for density shots usually spreads the impurity lines far enough away from the beta line so that none of the mirroring techniques used in the temperature evaluation were necessary. In the few cases in which the mirroring technique had to be used to determine the FWHM, it involved the adjustment of only a few diode values. The accuracy in wavelength conversion for the 1200 groove grating, as shown earlier, was also a consideration. The smaller dispersion of the 300 groove grating used for temperature shots translates into less accurate wavelength determination since each successive diode corresponds to an increase of approximately 2.8 Å. Interpolation to determine the wavelengths of the half-maximum points now becomes the rule, rather than the exception, leading to larger uncertainty in the FWHM values. The half-widths of the few beta lines from temperature shots measured were found to be of the same order, but consistently larger than those from density shots.

4.2.3 Armature position

Before presenting the final results, one last problem must be addressed, namely, the correlation between the delay time prior to spectrum acquisition and the position of the plasma armature in

the railgun. Originally, the plan was to use streak camera photographs to determine an average velocity for the plasma since the traces are approximately linear. The product of the average velocity and the delay time would then give the approximate position of the armature when the spectrum was acquired. After the streak camera ceased operating, the average velocity approach was still used, but the method of obtaining its value had to be changed.

The streak camera photograph of Fig. 3.4 shows that when the plasma reaches the muzzle, it does not dissipate immediately, but essentially sits at the end of the rails until the current from the high current pulse-shaping network is expended. The arrival of the armature at the muzzle is easily observed with the OSMA. Since the plasma is no longer confined within the small diameter bore of the gun, the density and, therefore, the width of the beta line are dramatically reduced. Figure 4.14 shows the spectrum for shot B37 on data disk #11. This is the final shot in the same data run as the FWHM example, and has the same conditions except the delay time is 180 μ sec. An average velocity for the armature can be determined by dividing the distance travelled from the arc initiation needle to the muzzle, $120 - 7.62 = 112.38$ cm, by the delay time.

Even under the same experimental conditions, the armature does not always travel at exactly the same velocity. The physical condition of the railgun has some effect on the speed. As the gun is repeatedly fired, soot and other ablation products are

deposited on the surfaces of the sidewalls and rails inside the bore. Over time, this can act to slow down the plasma. It was also observed that the tightness of the bolts holding the vee-block assembly together had some effect on the velocity. Tighter bolts tended to slow down the plasma. A sufficient number of data runs were performed at each set of experimental conditions so that runs with similar speeds could be grouped together under one velocity. For a bank voltage of 2 kV on the high current pulse-shaping network, the velocity of these groups ranged from 4.57 km/sec to 4.93 km/sec. When the bank voltage was increased to 5 kV, all the data runs had essentially the same velocity of 8.03 km/sec.

The B-dot probes would seem to provide another method for determining an average velocity. However, since the plasma is not really travelling at a constant velocity, but slowly accelerating, the velocity obtained from the B-dot probe data is always faster than for the previous method. This presents a problem at the longer delay times. At these delay times, where good spectrum data were still being acquired, if the B-dot velocity were used, the approximate position determined for the armature would have placed it outside the railgun. It was empirically found that if the B-dot velocities were multiplied by 0.8, then much better agreement between the two methods was achieved.

The information from the B-dot probes was still utilized, but in a different fashion. Since the railgun must be fired a number of times to complete one full data run, shot-to-shot variations

are cause for concern. The B-dot probe signals were always checked before the acquired spectrum was stored on disk to insure that the speed of the plasma was not varying in comparison to the other shots in the data run, and that no secondary arcs were visible. If either of these effects were observed, the spectrum was discarded, and the shot repeated.

4.3 Results and Discussion

The results of the electron density and electron temperature measurements of the plasma armature are presented in graphical form in Figs. 4.15-4.22 for high current network voltages of 2,3,4, and 5 kV and a backfill pressure of 20 Torr. Each graph contains a number of data runs taken at the same experimental conditions. The legends give the names of the data runs followed by the number of the data disk on which the data are stored, e.g., BET,9 includes density shots BET1 to BET5 on disk #9. As one might expect, the electron temperature increases as the voltage is increased. The density also increases, most likely, from the higher temperature ablating away more particles from the sidewalls and rails, and due to the snow-plowing effect of the accelerating plasma.

The shape of the curves in the density plots implies that the plasma armature requires some time to reach a "steady-state" condition. This buildup time increases as the voltage is increased, probably because the velocity of the armature is also increasing. The buildup effect seems to be absent at the lower

voltages of the temperature data, but reappears at the two higher voltages. This would imply that the "steady-state" temperature is reached faster than the "steady-state" density. Beyond the midpoint of the railgun, the temperature values generally experience a large increase at 2 and 3 kV, while no data are shown for the 4 and 5 kV plots. In the spectra of these shots, the intensity of the alpha line does not increase at the same rate as that of the beta line. Consequently, the ratio of the alpha to beta line intensity steadily decreases. When Eq. (2.5) is used to evaluate the temperature, the natural log term in the denominator also steadily decreases, which in turn produces higher temperature values. For the higher voltages, the denominator may even turn negative implying a physically impossible negative temperature. The cause of this phenomenon is not fully understood at this time.

Some additional experiments were performed at 2 kV with the backfill pressure increased to 50 Torr. The results for these conditions are shown in Figs. 4.23 and 4.24. In comparison to the 2 kV, 20 Torr data, the density is seen to be slightly higher due to the larger backfill pressure. The increase in pressure apparently has little effect on the temperature, however, because the "steady-state" value remains around 1.5 eV.

Discounting temperatures beyond the railgun midpoint, plots of the "steady-state" electron density and temperature versus the bank voltage of the high current network produce some very interesting results. Figures 4.25 and 4.26 indicate that both parameters demonstrate a basically linear relationship to the

voltage. Although some assumptions must be made, a linear relationship between density and voltage can be explained as follows. The electron density is related to the current by Eq. (4.2)

$$n_e = \frac{I}{A e v_d} \quad (4.2)$$

Here A is the area through which the current flows, e is the charge of an electron and v_d is the electron drift velocity.

Cobine [30] has expressed the drift velocity as

$$v_d = \frac{e \Delta V}{m_e d \nu_e} \quad (4.3)$$

where ΔV is the voltage drop across the plasma, m_e is the electron mass, d is the railgun bore diameter and ν_e is the electron-ion collision frequency, which is a slowly varying function of both electron density and temperature. If the electron-ion collision frequency, the voltage drop and the area through which the current flows can all be assumed as nearly constant, then the drift velocity becomes a constant, and the electron density will be linearly related to the current which, in turn, is linearly related to the bank voltage as noted in Sec. 3.1.2. This linear relation between density and voltage was also seen by Haywood [18]

when he used an interferometer to measure the electron density of a plasma armature which was accelerating small Lexan projectiles.

Finally, some discussion of the accuracy of the experimental results should be presented. Griem [21] states that for the hydrogen beta line, the agreement between calculated half widths and electron density are reliable to within 5%. Therefore, if the FWHM can be measured with a high degree of accuracy, the density values obtained should be very reliable. It was already shown that the errors produced by the wavelength conversion process are very small; therefore, the main source of error in this experiment is the determination of the underlying continuum. A reasonable estimate for this error is another 5%. The electron densities obtained should, therefore, be accurate to within 5 to 10%. Electron temperature values are inherently less precise, because the uncertainty of relative line intensity measurements is about 10% [21]. The determination of the continuum level and the mirroring technique used are likely to increase the error by another 10%. Accordingly, the electron temperature values obtained should have an error between 10 and 20%.

Figure 4.1 Experimental Setup

Figure 4.2 Timing Scheme for Calibration Source(s)

Figure 4.3 Timing Scheme for Plasma Armature

Figure 4.4 Paschen Curve for Helium

Figure 4.5 Xenon Lamp Spectrum vs. Diode Number

Figure 4.6 Xenon Spectrum vs. Wavelength

Figure 4.7 Xenon Spectrum from Oriel Calibration Handbook

Figure 4.8 Spectrum of Shot B33

Figure 4.9 Shot B33 vs. Wavelength

Figure 4.10 Spectrum of Shot BA32

Figure 4.11 Shot BA32 (He Line Removed)

Figure 4.12 Modified Shot BA32 (He Line Removed)

Figure 4.13 Modified Shot BA32 vs. Wavelength

Figure 4.14 Spectrum of Shot B37 at Railgun Muzzle

Figure 4.15 Density vs. Distance for 2 kV and 20 Torr

Figure 4.16 Temperature vs. Distance for 2 kV and 20 Torr

Figure 4.17 Density vs. Distance for 3 kV and 20 Torr

Figure 4.18 Temperature vs. Distance for 3 kV and 20 Torr

Figure 4.19 Density vs. Distance for 4 kV and 20 Torr

Figure 4.20 Temperature vs. Distance for 4 kV and 20 Torr

Figure 4.21 Density vs. Distance for 5 kV and 20 Torr

Figure 4.22 Temperature vs. Distance for 5 kV and 20 Torr

Figure 4.23 Density vs. Distance for 2 kV and 50 Torr

Figure 4.24 Temperature vs. Distance for 2 kV and 50 Torr

Figure 4.25 Density vs. Voltage

Figure 4.26 Temperature vs. Voltage

5. CONCLUSIONS

Spectroscopic measurements were performed to determine the electron density and the electron temperature of the free-running plasma armature in an electromagnetic railgun. These parameters were investigated as the armature progressed along the length of the rails. For both the density and temperature, the plasma required some time to buildup to "steady-state" quantities, with the temperature attaining its value slightly faster. These "steady-state" values were found to range from $8 \times 10^{16} \text{ cm}^{-3}$ and 1.5 eV to $2.2 \times 10^{17} \text{ cm}^{-3}$ and 2.7 eV as the voltage on the high current pulse-shaping network was increased from 2 to 5 kV. The relationship between the parameters and the voltage was also observed to be essentially linear.

As far as future work is concerned, since the primary purpose of this railgun system is the acceleration of frozen hydrogen pellets, the next logical step would seem to be the determination of the plasma armature parameters with a pellet in the system. Obviously, this would require side-on observation of the plasma through a hole in the Lexan sidewall. An optical fiber would have to be employed to carry the light signal from inside the vacuum chamber to the spectrograph and OSMA detector. Without many such holes, the investigation of the density and temperature along the entire length of the rails would no longer be possible. However, the variation of these parameters, at one point along the length

of the armature, may become feasible, if the proper timing can be worked out. To this end, two closely spaced B-dot probes might be able to serve as plasma detector, OSMA trigger, and provide a measure of the instantaneous plasma velocity.

The methods used to evaluate the electron density and electron temperature may also have to be altered for measurements with a pellet in the system. First, side-on observation of the plasma may require the use of an Abel inversion process to determine the true line profile before any other measurements can be performed. Second, Haywood [18] reported densities as high as $2 \times 10^{18} \text{ cm}^{-3}$ in his work with Lexan projectiles. This is almost an order of magnitude larger than the values for the free-running armature. In this case, the hydrogen beta line may be too widely broadened to use for density measurements. The possibility does exist of using the hydrogen alpha line widths at these higher densities. Although the accuracy of the results is reduced from those with the beta line, the interference from impurity lines is also much smaller. Third, for the temperature measurement, much of the processing could be reduced, or even eliminated, if another isolated helium line could be found in close enough proximity to the 5875.6 Å line that was discarded for this experiment. The two helium lines could then be used in the same fashion as the hydrogen alpha and beta lines to determine the electron temperature. As an alternative, one could try using the helium line present along with the hydrogen alpha line in attempting to determine the electron temperature. However, this would require

much more knowledge about the exact composition of the plasma, degrees of ionization for each element, absorption oscillator strengths, etc.

Once the diagnostic system has been shown to provide reliable measurements of the armature parameters, the effects on the plasma can be studied in a variety of other experiments aimed at achieving the highest possible acceleration. Among these are the use of perforated or ceramic sidewalls, variations of the high current pulse shape, and use of a second set of rails which carry a large current to augment the magnetic field inside the railgun bore. It is hoped that, in the future, the results of these and other experiments can be used to improve the efficiency of the railgun through the optimization of the plasma armature.

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