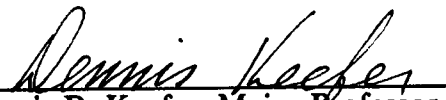
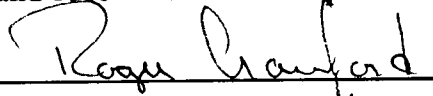


To the Graduate Council:

I am submitting herewith a thesis written by Jaime R. Taylor entitled "A Study of the UTSI Transaugmented and Classical Railgun." I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the Master of Science, with a major in Engineering Science.


Dennis R. Keefer, Major Professor

We have read this thesis
and recommend its acceptance:




Accepted for the Council:


Vice Provost
and Dean of the Graduate School

**A STUDY OF THE UTSI TRANSAUGMENTED AND
CLASSICAL RAILGUN**

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

Jaime R. Taylor

December 1991

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ABSTRACT

In the past few years it has been determined that conventional railguns have nearly reached their velocity limits due to ablation of rail and insulator materials. The UTSI transaugmented railgun was constructed to conduct experiments to investigate the potential of augmentation in increasing the force on the plasma armature without increasing armature current. Preliminary experiments were performed to obtain values for the self and mutual inductances of the UTSI railgun which were needed for performance evaluations. The experiments consisted of generating a current pulse on one of the sets of rails and measuring the voltage and current induced on the other set of rails. From the measurements, the inductances were calculated.

Classical railgun shots were performed to determine an ablation constant, the force on the projectile due to the pressure from the light gas gun and the vaporization of the fuse. Augmented shots in which the operating current on the inner rail was the same as one of the classical shots were performed. Using the parameters obtained from the unaugmented shots, simulations were performed for the augmented shots. The velocity profiles obtained from experimental data were not in agreement with the predicted values. The experimental increase in velocity due to the augmenting field was approximately half the predicted value.

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I. INTRODUCTION

In the past few years, with the advent of the Strategic Defense Initiative and the requirement for launching small payloads or projectiles into space, research into electromagnetic accelerators (railguns) has increased considerably.

Most of the excitement over railgun technology started with the paper by Rashleigh and Marshall in 1978 in which a velocity of 5.9 km/s was reported. [1]* Since then, only a few higher velocities have been reported. The paper by J.V. Parker entitled "Why Plasma Railguns Don't Work (And What Can Be Done About It)" [2] discusses the problems with plasma armature railguns and proposes several methods for solving these problems. One problem is ablation of the conductor, which adds mass to the armature, (mass which needs to be accelerated) and ablation of the insulator, which causes instabilities in the plasma producing secondary arc formation. Since the ablation of material is proportional to the power dissipated in the armature, less ablation occurs if either the current or the voltage are reduced. One way of reducing current in the armature is through augmentation. Augmentation is the addition of current-carrying rails to generate a stronger magnetic field without increasing armature current. This can be done by adding rails which are in series with the original rails (series augmentation) or by adding rails in a separate circuit to externally generate a magnetic field (transaugmentation). [2],[3]

* Bracketed numbers refer to numbered references in Bibliography.

This thesis first reviews the concept of the classical railgun, how it functions and the problems associated with it. It then focuses on the problem of reducing armature current while still maintaining the force on the projectile. One possible solution, augmentation, will be discussed.

A development of how L' the self inductance per unit length and M' the mutual inductance per unit length are used for railgun performance evaluations along with the equations needed to obtain them will be presented. Measurement of the self-inductances and mutual inductance for the UTSI transaugmented railgun will then be presented.

The UTSI transaugmented railgun will be discussed. The forces that govern the motion of the plasma armature and models obtained from these forces will be previewed. The design and experimental setup of the UTSI transaugmented railgun will be presented. The results of these experiments and preliminary conclusions on the results will then be discussed.

A. Background

At the turn of the century, Kristian Birkeland, a Norwegian physicist, patented and built a railgun. "In 1901, while trying to develop a new electric current breaker based on induction, Birkeland noticed that pieces of iron were attracted into a solenoid with such strong force that they flew like projectiles." Birkeland's work, as today's work, revolved around the applications of the gun and

funding through the military. His first gun had a projectile of 0.5 kg and could be accelerated to 80 m/s. His work on railguns ended with a gun capable of launching a 500 kg projectile with a 30 cm bore at velocities of several hundred m/s. [4]

The paper by Rashleigh and Marshall started the current surge of research on railguns. Unlike Birkeland's gun, which had a solid armature, the projectile of this gun consisted of a cube of polycarbonate (Lexan) with copper straps behind the Lexan to make an arc initiator. The Lexan acts as a gas seal for the plasma armature. This is still the basic configuration of railgun projectiles, except that aluminum is usually used instead of copper as the arc initiator, since aluminum has a low ionization energy of 5.96 eV. The Lorentz force acting on the projectile, as presented by Rashleigh and Marshall, is given in equation 1,

$$F_e = \frac{1}{2} L' I^2 , \quad (1)$$

where L' is the inductance per unit length of the gun rails and I is the current through the armature. A derivation for this expression will be given later.

Experimental projectile velocities of 5.9 km/s were obtained and it was concluded that simple railgun theory was reasonably accurate up to velocities of 6.0 km/s. [1] It seemed that the only thing needed to reach higher velocities was to build stronger structures and larger power supplies.

Ten years later, only three laboratories had reported reaching velocities significantly higher than the 5.9 km/s.[2] In 1987 Y.C. Thio reported obtaining a

velocity of 8.3 km/s with a two stage augmented railgun. The staging was done so that the second stage fired after the first stage had passed peak current. The maximum of the total current in the bore was 418 kA. The plasma was generated from a package which contained 50.3 mg of nitrocellulose, 36.8 mg of LiNO_3 , and 35.1 mg of LiH placed in an aluminum foil cylindrical container.[5] In 1982, a set of experiments were conducted by the Lawrence Livermore National Laboratory and the Los Alamos National Laboratory in which an explosive flux compression generator was used to power a railgun. The railgun was 1.8 m in length and peak currents of 1200 kA were obtained. The maximum reported velocity from these experiments was 10.1 km/s, which is also the highest reported velocity for any railgun.[6]

It has been found that the interactions of the plasma and the bore become a serious problem above 6.0 km/s. Since the magnetic field is dependent the current in the classical railgun the obvious way to increase velocity is to increase current. Increasing the current increases the power input to the arc, increasing the power that the arc radiates. The temperature that corresponds to the radiated energy in a 200 kA railgun is 12,000-20,000 K. To dissipate this heat energy, it has been determined that rail and insulator material must be ablated and that the ablation is proportional to the power dissipated in the arc. Material ablated from the conductor adds mass to the armature and this new mass must be accelerated from rest. The acceleration of the ablated mass reduces the force available to accelerate the projectile. Most importantly, the ablation imposes an upper bound

on the velocity for given: 1.) rail materials, 2.) inductance per unit length and 3.) friction coefficient of rails. [3]

Insulator material is also ablated. The typical insulator material has a higher ionization energy than the rail material and is also not as hot as the rail material. The current distribution is close to the insulator, but does not penetrate into the insulator as it does into the rails, which results in the magnetic field being weaker at the insulator boundary than it is at the rail boundary. Therefore, the insulator material that is ionized is not accelerated as much as the rail material, and most of the ionized insulator material in this cold boundary layer does not add to the plasma but drops back into the bore. Rail material, mostly ionized, and insulator material (not all of it will be lost in the bore), partially ionized and non ionized, are mixed within the plasma. This may cause instabilities in the plasma, such as secondary arcs. The secondary arc is a current distribution that has separated from the primary arc. The secondary arc acts as a loss mechanism since it draws current away from the primary arc and must accelerate not only the primary arc but material that is trapped between the primary and secondary arcs. This secondary arc turns out to be an even more critical problem than accelerating the stationary ionized ablated material.[2,3,7,8]

To reduce the effects of ablation either the current or the voltage of the arc must be reduced. At this time, there have been no published results of significant voltage reductions. Suggested techniques have included seeding the plasma with easily ionized atoms and controlling the plasma temperature. Plasma

seeding has been tested but has not been effective. Reducing the current in the arc will also reduce the voltage; a reduction in current of 10% will correspond to a 3 to 4% reduction in voltage. For the UTSI railgun a reduction in peak current from 140 kA to 67 kA (50% reduction) corresponds to a reduction in arc voltage from 160 V to 140 V (13% reduction). It is unlikely that reductions of more than 30 to 50% in arc voltage will be achieved. [2]

Since the current and magnetic field are dependent upon each other in the classical railgun, reducing the current through the armature would reduce the force on the armature. An augmented railgun would be one way to reduce the current through the armature without reducing the force on the projectile. [2] There are two basic types of augmentation that are currently under investigation: series augmented and transaugmented railguns.

With series augmentation, the force (magnetic field strength) due to a specified current is increased by increasing the effective inductance per unit length of the gun by adding an outer set of rails in series to the original ones. The increase in effective inductance can be seen in Equation 2,

$$F_e = \frac{1}{2} (L' + 2M') I^2 , \quad (2)$$

where L' is the self inductance per unit length of the inner rail and M' is the mutual inductance per unit length between the inner and the outer rails. The magnetic field strength is still dependent upon the current.

With the transaugmented case, the force on the projectile is given by

$$F_e = \frac{1}{2} (L' I_1^2 + 2M' I_1 I_2) \quad (3)$$

where I_1 is the primary rail and armature current and I_2 is the outer (augmenting) rail current. Thus, the force is increased without increasing the current in the armature. The force is increased by placing the classical railgun in a magnetic field which is generated by the outer rails. The outer rails are energized independently of the inner rails, meaning that unlike the series augmented railgun, the magnetic field strength can be varied without changing the armature current. This can be done by varying the initial charge on the outer rail capacitors or by varying the time delay between energizing the inner and outer rail. The flexibility of the transaugmented railgun makes it the obvious choice for experimentation.

The magnetic field and the current in the armature are not totally independent for the transaugmented railgun. Part of the magnetic field is achieved by the current through the armature. The other part is achieved by the current on the outer rail, which interacts with the inner rail current through mutual inductance. The outer rail will induce a back emf on the inner rail circuit, and if the current is high enough (two orders of magnitude higher), the current on the inner rail can become negative, causing the projectile to experience a force in the opposite direction.[9, 10] This can be seen in Equation 3 where the force term with M' can be either positive or negative depending on the sign of I_1 and I_2 .

The effect is very small if the rail currents on inner and outer rails are comparable, as in the UTSI transaugmented railgun.

B. Previous Work on Augmentation

Not much work has been published in the way of test results of augmented railguns. The Japan Steel Works tested a series augmented railgun in which they experienced a decrease in rail erosion as compared to the classical case with similar exit velocity. To achieve the same exit velocity with the augmented case required less current through the armature, thus less power in the armature, resulting in less ablation. In the future, they plan on increasing the number of turns of the gun.[11]

In 1984, Westinghouse published results of the ELF-I augmented railgun. The results discussed were mainly concerned with efficiency of the series augmented gun as compared to the classical case. Comparisons of the two guns were made by keeping the current profiles identical. It was reported that the exit velocity of the augmented gun was 83% greater than the classical gun. The comparison made was of the experimental exit velocity of the augmented gun to a simulated exit velocity for a classical gun. First, a simulation was done for the augmented case and it was determined that there was a 35% loss due to friction in the gun. A simulation for the classical case was then done assuming 35% of the electromagnetic force was lost in friction and an exit velocity was

determined.[12] The statement of an 83% increase in exit velocity is questionable because the loss due to friction that was used to simulated the classical case was determined from the augmented experiment. This level of friction loss is unreasonably high. The comparison should have been between two separate experiments, one for the classical case and one for the augmented case. Currently, Westinghouse is performing research on the HART-I augmented railgun, but as of Jan. 1991, results obtained using this gun had not been published.[7]

II. DEVELOPMENT OF L' AND M' THEORY

For railgun performance evaluation, the railgun is usually thought of in terms of a circuit model. From circuit models for the three types of railguns discussed in chapter I, the electromagnetic force Equations 1, 2 and 3 can be derived. In this chapter these equations are derived along with a set of equations that are used later to obtain values for L' and M' from experimental data.

A. The Electromagnetic Force in Railguns.

The force on the armature in a railgun could be calculated using the Biot-Savart law,

$$F_{ab} = \int J_b dv_b \times \left(\frac{\mu_o}{4\pi} \int \frac{J_a dv_a \times r_1}{r^2} \right), \quad (4)$$

where J_a is the current density of the rails, J_b current density of the armature and v_a and v_b are the respective volumes in which they flow.[13] However, the current densities of the armature and the rails are very complex functions of time and space and the computation time required to model the railgun this way (if a reasonable model for the current distribution in the railgun could be obtained) is not feasible for simple performance evaluations. Instead, the electromagnetic force equations from the circuit models are used and values for L' and M' are needed for the particular railgun.

The electromagnetic force for the classical railgun, shown schematically in Figure 1, can be derived from a power argument. In Figure 1 L_o is the storage inductor, R is the resistance of the circuit, C is the storage capacitor for the circuit and $L'x$ is the self inductance per unit length times the position of the armature. The circuit is activated by charging the capacitor to a pre-set voltage and then switching it into the circuit. Typically at the time the current pulse reaches its peak (i.e. the voltage drop across the capacitor is zero) the capacitor is shorted out of the circuit.

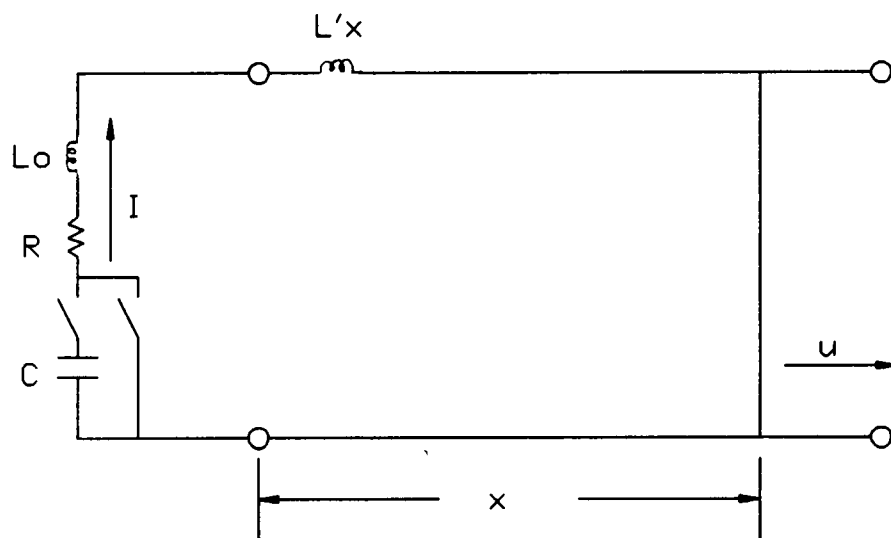


Fig. 1. Circuit model of the classical railgun.

In deriving the electromagnetic force a lossless system is assumed for simplicity. The instantaneous power input to the railgun is the current multiplied

by the breech voltage given by,

$$P = I \left(I \frac{dL}{dt} + L \frac{dI}{dt} \right) . \quad (5)$$

Part of this power is required to change the stored magnetic field energy, represented by W_b , and is given by,

$$\frac{dW_b}{dt} = \frac{d}{dt} \left(\frac{1}{2} LI^2 \right) = LI \frac{dI}{dt} + \frac{1}{2} I^2 \frac{dL}{dt} . \quad (6)$$

Energy is conserved so that the input power must equal the change in stored energy of the magnetic field plus the mechanical work. Subtracting Equation 6 from 5, the change in mechanical work is found,

$$\frac{dW_f}{dt} = \frac{1}{2} I^2 \frac{dL}{dt} . \quad (7)$$

The self inductance of a railgun can be written as the inductance per unit length times the position of the armature, and the time rate of change of the self-inductance can be written as the inductance per unit length times the velocity of the armature. If it is assumed that all the change in mechanical energy goes into accelerating the armature, since the change in mechanical energy equals force times the velocity of the armature, Equation 1 can then be obtained.[8,13]

This derivation can be easily modified for the transaugmented railgun, shown schematically in Figure 2, to include the power input caused by the changing mutual inductance of the two rails and the increased stored energy of the magnetic fields. In Figure 2 L_{o2} is the storage inductor for the outer rails, C_2

is the storage capacitor and $M'_{12}x$ is the mutual inductance between the rails and changes with armature position. The outer rail is energized independently of the inner rails which allows for flexibility in varying the magnetic field. The outer rail capacitor is also typically shorted out of the circuit at its peak current.

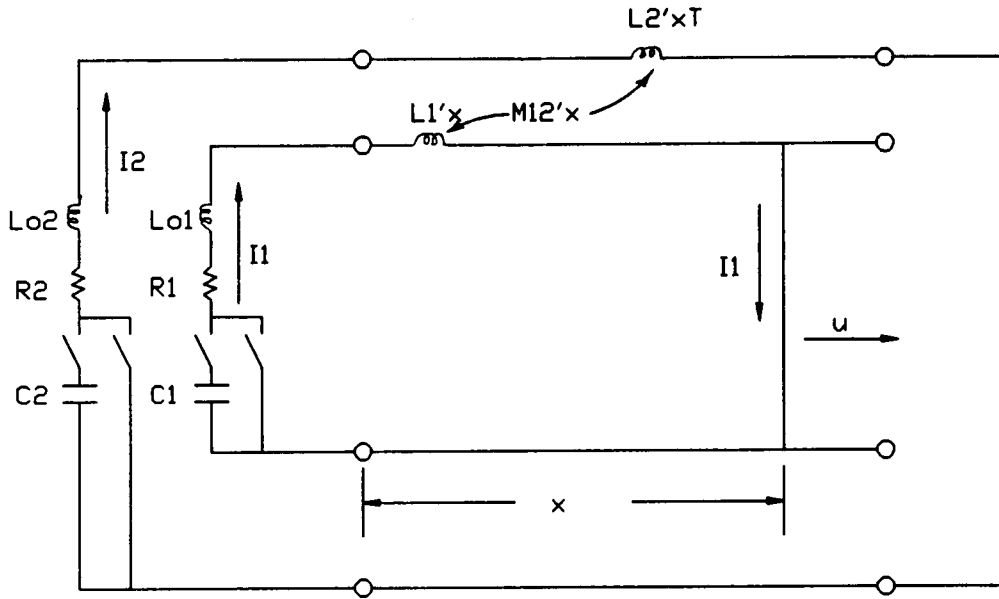


Fig. 2. Circuit model of the transaugmented railgun.

The total power input will include voltages induced on the outer and inner rails,

$$P = I_1 \left(I_1 \frac{dL_1}{dt} + L_1 \frac{dI_1}{dt} + I_2 \frac{dM}{dt} + M \frac{dI_2}{dt} \right) + I_2 \left(I_1 \frac{dM}{dt} + M \frac{dI_1}{dt} + L_2 \frac{dI_2}{dt} \right) . \quad (8)$$

The mutual inductance between the rails changes due to the armature position in the same manner as described for the self inductance of the inner rails. The self

inductance of the outer rails does not change except, perhaps, because of the skin depth. The magnetic field energy for the transaugmented railgun is

$$W_b = \frac{1}{2}L_1I_1^2 + \frac{1}{2}L_2I_2^2 + MI_1I_2 \quad (9)$$

and the change in magnetic field energy is

$$\frac{dW_b}{dt} = \frac{1}{2}I_1^2 \frac{dL_1}{dt} + L_1I_1 \frac{dI_1}{dt} + L_2I_2 \frac{dI_2}{dt} + MI_1 \frac{dI_2}{dt} + MI_2 \frac{dI_1}{dt} + I_1I_2 \frac{dM}{dt}. \quad (10)$$

Subtracting Equation 10 from 8 and making the same assumptions as for the classical railgun Equation 3 can be obtained. Equation 2 for the series augmented railgun, shown schematically in Figure 3, is obtained in the same manner as for the transaugmented railgun except that the current on the inner and outer rails are equal.[13]

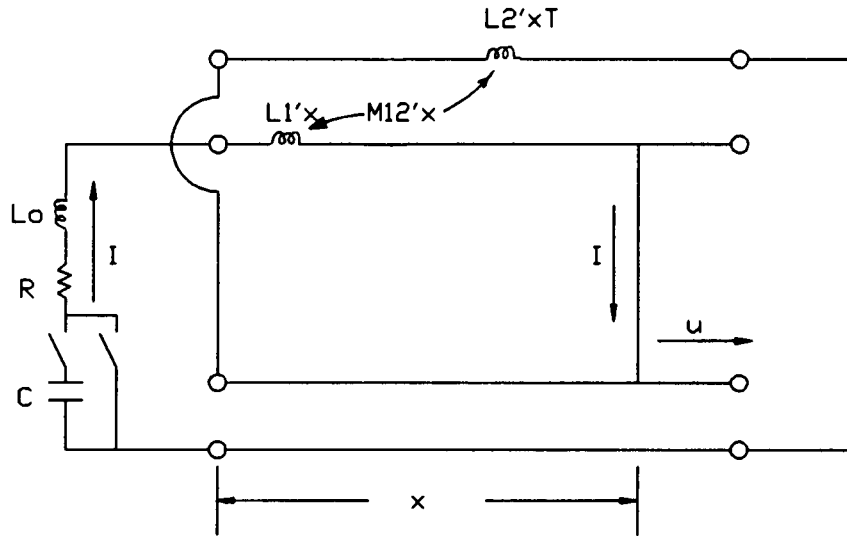


Fig. 3. Circuit model of the series augmented railgun.

B. Theory for Evaluation of L' and M'.

Obtaining the values for L' and M' is not a straightforward measurement. Using transmission line theory, an approximate expression for the self inductance of the rails is,

$$L' = 4 \times 10^{-7} \ln \frac{D}{r} \quad (11)$$

where D is the distance between the center of the rails and r is an effective radius which is difficult to determine due to the geometry of the rails. Using this expression and putting bounds on the effective radius, the self-inductance per unit length of the inner rails for the UTSI transaugmented railgun should fall between 0.1 and 0.4 micro-henrys per meter, with the mutual inductance per unit length, between inner and outer rails, being a fraction of this. These parameters also vary in time due to the current density and skin depth variations. To obtain the values of L' and M' for the UTSI railgun a set of equations are developed for two circuits that are magnetically linked.

If a current path is linked by a changing magnetic flux, then the electrostatic forces on the path are not zero. The electrostatic field conservation equation,

$$\oint E \cdot dl = 0 \quad , \quad (12)$$

is modified to Faraday's induction law,

$$\oint E \cdot dl = -\frac{d\Phi_k}{dt} \quad , \quad (13)$$

where the direction in which the flux is taken to be positive is related to the line integral according to the right-hand rule. The magnetic flux linking the path can be written as,

$$\Phi_k = L_{ik} I_i \quad (14)$$

where Neumann's formula,

$$L_{ik} = \frac{\mu_o}{4\pi} \oint \oint \frac{dl_i \cdot dl_k}{r_{ik}} = L_{ki} , \quad (15)$$

is an expression for the mutual and self inductances of the path, and is dependent purely upon the geometrical configuration of the current paths. The change in flux can thus be written as

$$\frac{d\Phi_k}{dt} = L_{ik} \frac{dI_i}{dt} + I_i \frac{dL_{ik}}{dt}. \quad (16)$$

From this point on, L_{11} will be referred to as L_1 , L_{22} as L_2 , L_{12} as M_{12} , L_{21} as M_{21} and note that from Equation 15 $M_{12} = M_{21}$. From Equation 13, two circuits that are linked by a changing flux as well as their own changing flux and have a resistance associated with them can be expressed in the following form [13,14],

$$V_2 = I_2(R_2 + \frac{dL_2}{dt}) + L_2 \frac{dI_2}{dt} + M_{21} \frac{dI_1}{dt} + I_1 \frac{dM_{21}}{dt} , \quad (17)$$

$$V_1 = I_1(R_1 + \frac{dL_1}{dt}) + L_1 \frac{dI_1}{dt} + M_{12} \frac{dI_2}{dt} + I_2 \frac{dM_{12}}{dt} . \quad (18)$$

These equations are used in the next chapter to obtain values for L' and M' from simple experiments.

III. L' AND M' EXPERIMENTS

To use the electromagnetic force equations, the self-inductance and mutual inductance per unit length of the particular railgun need to be known. The electromagnetic force is the primary driving force governing the motion of the projectile; it is crucial to know the magnitude of this force as a function of time to determine what other forces, such as ablation losses or viscous drag are acting on the armature.

A. Experimental Setup for Evaluation of L' and M'

The evaluation of L' and M' was done directly on the UTSI transaugmented railgun. The UTSI transaugmented railgun is designed to function as either a classical or augmented railgun. The test circuit for the transaugmented railgun can be seen in Figure 2. The inner rail circuit is separate from the outer rail circuit. The outer rails are used only to generate a stronger magnetic field within the armature. Each set of rails has its own power supply and set of inductors.

In this evaluation of L' and M' , two types of experiments were performed for the two sets of rails, as shown schematically in Figures 4 and 5. In these figures R_1 and R_2 are the rail resistances, L'_1 and L'_2 are the self inductances per unit length, and M_{12} is the mutual inductances per unit length of the rails. The

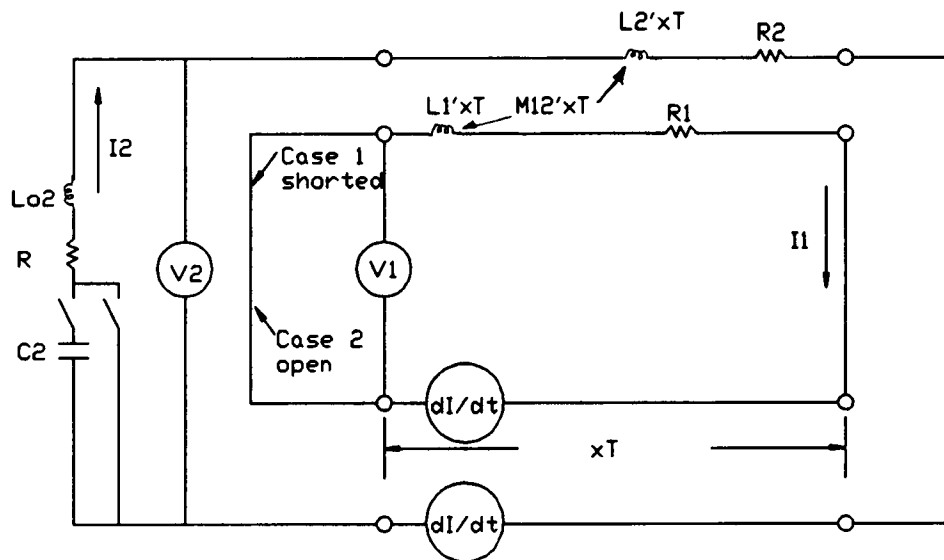


Fig. 4 Circuit diagram for determination of L' and M' with outer rails powered.

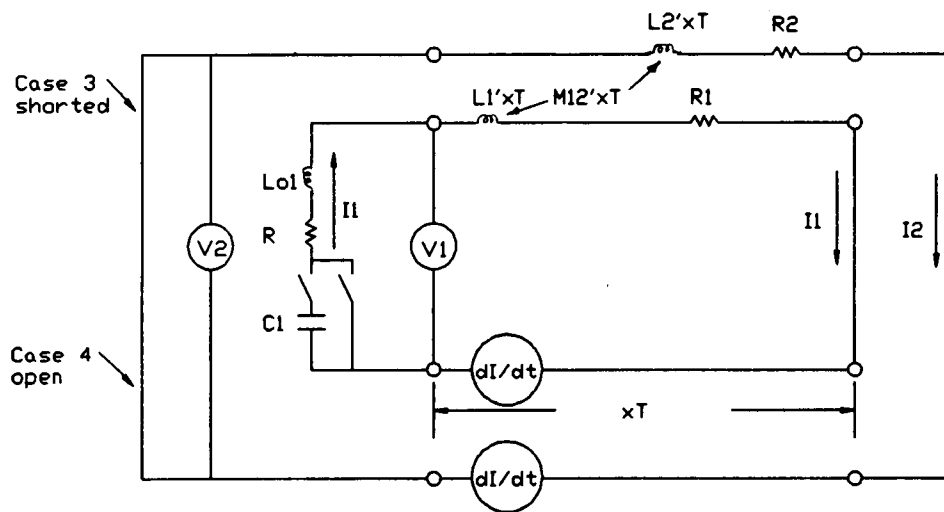


Fig. 5 Circuit diagram for determination of L' and M' with inner rails powered.

first type of experiments consisted of leaving one of the rail circuits open and discharging one capacitor and inductor through the other. Once peak current was reached the storage capacitor was shorted out of the circuit to get the pulse shape similar to that of a typical railgun shot. The other set of experiments consisted of completely short circuiting the non-powered rail.

Rogowski coils were used to obtain measurements for dI/dt on each set of rails. A Rogowski coil is a device which measures the change in magnetic field inside a loop around the rails. As the current is changing in the rails, it induces a voltage across the terminals of the coil proportional to the time rate of change of the rail current, and this induced voltage can be calibrated to give the value of dI/dt . When the capacitor of the powered rail was discharged, a discrete time sequence of 8192 data points was taken with a 200 ns time interval between samples. Actually, 1024 data points were taken before the capacitor was discharged so that a reference zero for the data could be obtained. The way the first 1024 data points are obtained will be discussed later. This was done for both the Rogowski coils and voltage measurements. The data file for dI/dt was then integrated to obtain the current as a function of time. The voltage drop across the rails was obtained by measuring the voltage drop from each rail to ground and then subtracting the two measurements. The points at which the voltage measurements and Rogowski coil measurements were taken can be seen in Figures 4 and 5.

B. Analysis of Data for L' and M'

Once these measurements were obtained, Equations 17 and 18 were used on the open rail set of experiments to determine the self inductance of each set of rails and the mutual inductance between them. The mutual inductances M_{12} and M_{21} should have the same value as shown by Equation 15. A significant voltage drop across the open rail existed when the non-powered rail was open, but the induced current on the rails was assumed small enough in comparison to the current on the powered set of rails to be neglected. Since it was not truly an open circuit (there was a shunt resistance of 1 k ohm used to measure the voltage drop across the open) a small current did exist on the non-powered rail. (This assumption was checked with the data and found to be valid.) Equations 17 and 18 can then be simplified to

$$V_2 = I_2(R_2 + \frac{dL_2}{dt}) + L_2 \frac{dI_2}{dt} , \quad (19)$$

$$V_1 = I_2 \frac{dM_{12}}{dt} + M_{12} \frac{dI_2}{dt} \quad (20)$$

for case 2, and a least squares fit was used to determine the values of L' and M' for the rails. For case 4, the subscripts 1 and 2 need to be reversed in Equations 19 and 20.

The least squares fit used for Equations 17 and 18 can also be simplified to work for Equations 19 and 20. Equation 17 should be satisfied by all 8192 data points taken in each experiment and this set of equations can be written in the

form

$$A x = b , \quad (21)$$

where

$$b = \begin{bmatrix} V_{2a} \\ V_{2b} \\ . \\ . \end{bmatrix} ; \quad x = \begin{bmatrix} R_2 + \frac{dL_2}{dt} \\ L_2 \\ M_{21} \\ \frac{dM_{21}}{dt} \end{bmatrix} ; \quad A = \begin{bmatrix} I_{2a} & \frac{dI_{2a}}{dt} & \frac{dI_{1a}}{dt} & I_{1a} \\ I_{2b} & \frac{dI_{2b}}{dt} & \frac{dI_{1b}}{dt} & I_{1b} \\ . & . & . & . \end{bmatrix} . \quad (22)$$

Since this system is over determined, the solution of Equation 21

$$x = (A^T A)^{-1} A^T b \quad (23)$$

is actually a fit to the data and is known as the least squares solution.[15] This solution, in the shorted rail cases, requires taking the inverse of a 4x4 matrix. To obtain the inverse matrix, a subroutine from Numerical Recipes was used.[16]

The parameters that are to be obtained from the least squares fit are not strictly constant in time, and it is desired to know how they behave as a function of time. The data were divided into blocks of 130 to 150 data points, whatever was needed to make the data blocks of equal size, and the parameters for each block of data were determined. The inverse matrix for the region where dI/dt goes through zero could not be obtained, so this region was not evaluated by the least squares method. The parameters obtained from the least squares fit can then be plotted versus the midpoint of time in each block to give a time

dependent curve for the parameters L_1 , M_{21} , $(R_1 + dL_1/dt)$ in case 2 and L_2 , M_{12} , $(R_2 + dL_2/dt)$ in case 4. The self inductances and mutual inductance can be divided by the length of the particular set of rails to determine a value for the inductance per unit length.

Equation 20 can be interpreted as a differential equation for the mutual inductance, M_{12} . Since the voltage drop and the current are known as a function of time we may define,

$$a(t) = e^{-\int \frac{1}{I_2(t)} \frac{dI_2(t)}{dt} dt} , \quad (24)$$

$$b(t) = e^{\int \frac{1}{I_2(t)} \frac{dI_2(t)}{dt} dt} \frac{V_2(t)}{I_2(t)} \quad (25)$$

then, Equation 20 has the solution,

$$M_{12} = a(t) \int b(t) dt + C a(t) , \quad (26)$$

which can be evaluated numerically. As can be seen in Equation 26, C is an unknown constant in the expression. The term containing the constant decays exponentially in time, so that it is only a problem at the beginning of the curve. The effects of the constant C will be discussed in the results section. A similar solution for M_{21} , can also be obtained for case 4. The values for M , found using a least squares fit for the two cases and by solving the differential equations can be compared for consistency.

Equation 19 is also a differential equation for L_2 , but R_2 and L_2 are coupled so that the equation cannot be solved without making some sort of assumption about R . An attempt was made to use a model in which the skin depth as a function of time and the resistivity as a function of current density were used to obtain a time dependent resistance.[17] Once L was found, dL/dt could be found. The values of L found this way did not agree with the least squares fit and the value of dL/dt that was found was larger than $(R + dL/dt)$ found in the least squares fit. Since there were no assumptions made in obtaining the values with the least squares method it was assumed that the model for R was not accurate. For this reason the values of L obtained using the model for R are not presented.

Using the least squares fit on the shorted rail cases did not give any reliable results because of the number of parameters required for the fit. To make sure the two different sets of experiments (open rail as opposed to shorted rail) were consistent, the time dependent expressions for the parameters, obtained by curve fitting the values in the open rail experiments, were used in a circuit simulation. In equations 17 and 18 for the shorted rail cases, the rails that are shorted have essentially no voltage drop across the short. For case 1, V_1 will equal zero in equation 18. If one takes the experimental value for the current on the powered rail and the parameters obtained from the open rail experiments, then the current in the shorted rail can be found as a function of time. The current distribution obtained from the simulation will be compared to the experi-

mental current distribution to check for consistency. The same procedure will be used for case 3.

C. Results of Measurements of L' and M' .

Time dependent values were found for the parameters in case 2, schematically shown in Figure 4, L_1 , M_{21} , $(R_1 + dL_1/dt)$ and in case 4, schematically shown in Figure 5, L_2 , M_{12} , $(R_2 + dL_2/dt)$ using the least squares fit discussed earlier. Figure 6 gives the time dependent fit for $(R_1 + dL_1/dt)$. The gap in the curve

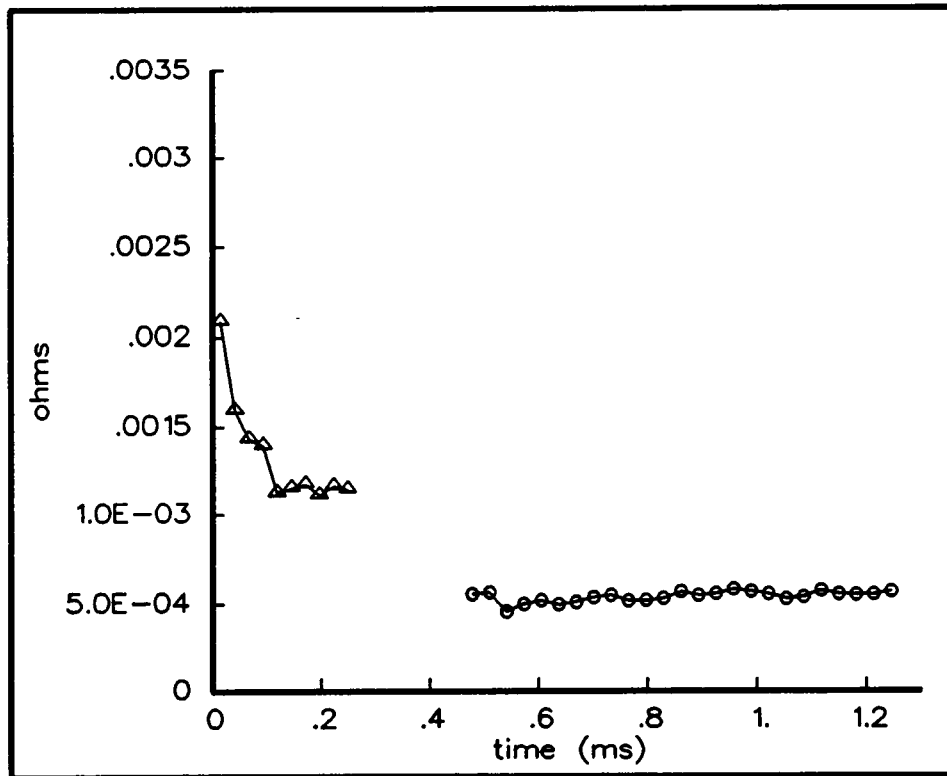


Fig. 6 Plot of $(R_1 + dL_1/dt)$ versus time. The triangles represent the curve before dI/dt goes through zero and the circles represent after dI/dt goes through zero.

occurs since, in this region, dI_1/dt goes through zero and the least squares fit diverges. Figure 7 shows the time dependent fit for $(R_2 + dL_2/dt)$.

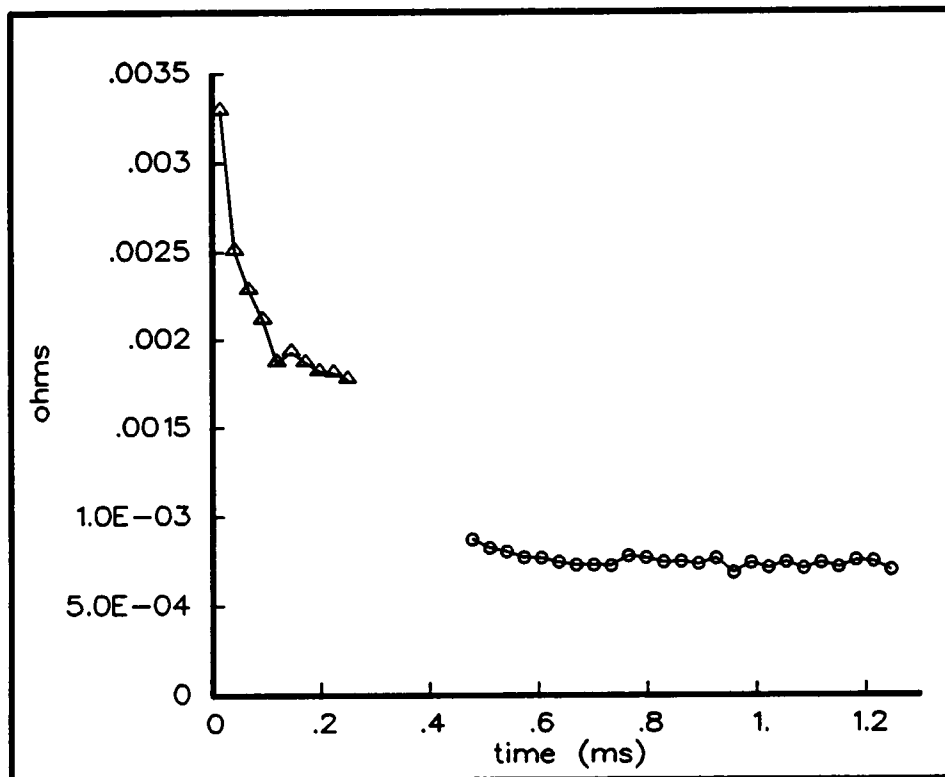


Fig.7 Plot of $(R_2 + dL_2/dt)$ versus time. The triangles represent the curve before dI/dt goes through zero and the circles represent after dI/dt goes through zero.

Figure 8 shows the time dependent values for L_1 , L_2 , M_{12} and M_{21} obtained from a least squares fit, and also from the solution of the Equation 20. The curves that have points marked on them were obtained from the least squares fit and the two solid curves for M that extend across the page were obtained from a numerical solution of the differential equation. Using the least squares fit

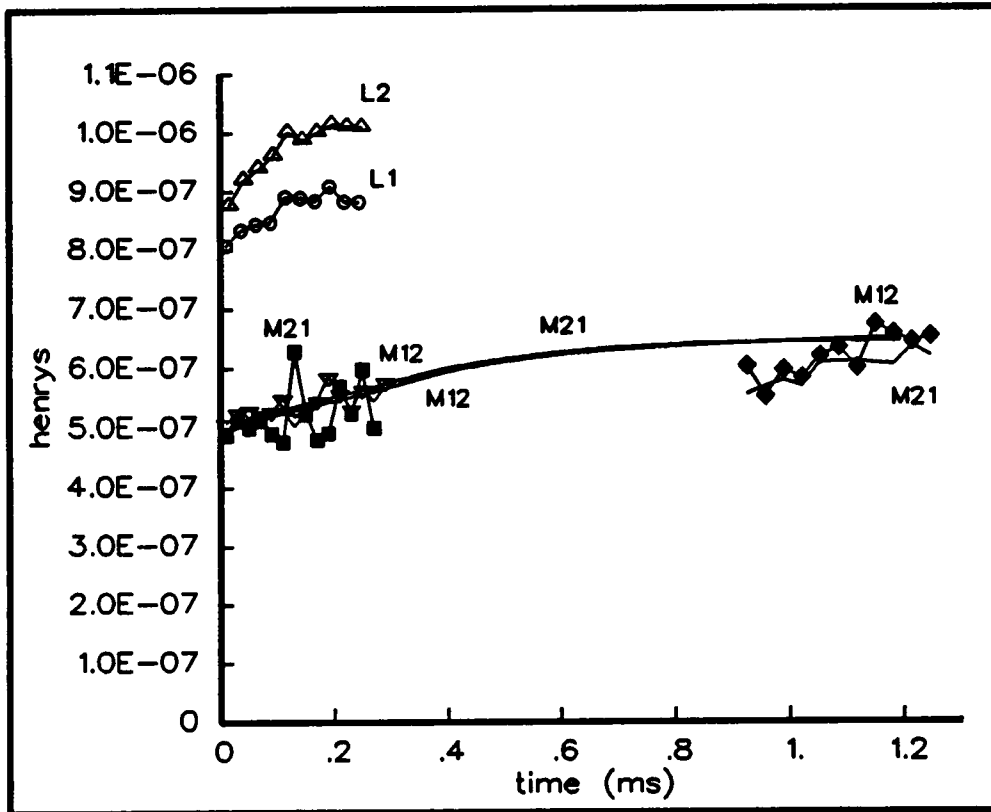


Fig.8 Plots of L_1 , L_2 , M_{12} and M_{21} versus time. Curves with markers were obtained from the least squares fit and the two smooth curves were obtained from the solution of the differential equation.

produced reliable information, for inductances, only in the region where dI/dt was large, which was before dI/dt went through zero. The two small curves in Figure 8, with markers on them for M_{12} and M_{21} in the region where dI/dt is small were obtained from

$$V = M \frac{dI}{dt}. \quad (27)$$

It was assumed that in this region the mutual inductance should not be changing much and the dM/dt term could be neglected. As can be seen in Figure 8, M

obtained by solving the differential equation, is in good agreement with M found with the least squares fit.

In Equation 26, the term containing the constant and the term without the constant were kept separate so that each could be plotted in Figure 9. It can be seen that the term without the constant is in agreement with the least squares fit except for a segment in the first 0.03 milliseconds. Since the constant could not be evaluated a priori, its value was chosen to agree with the least squares fit. The term containing the constant can be seen at the bottom of Figure 9.

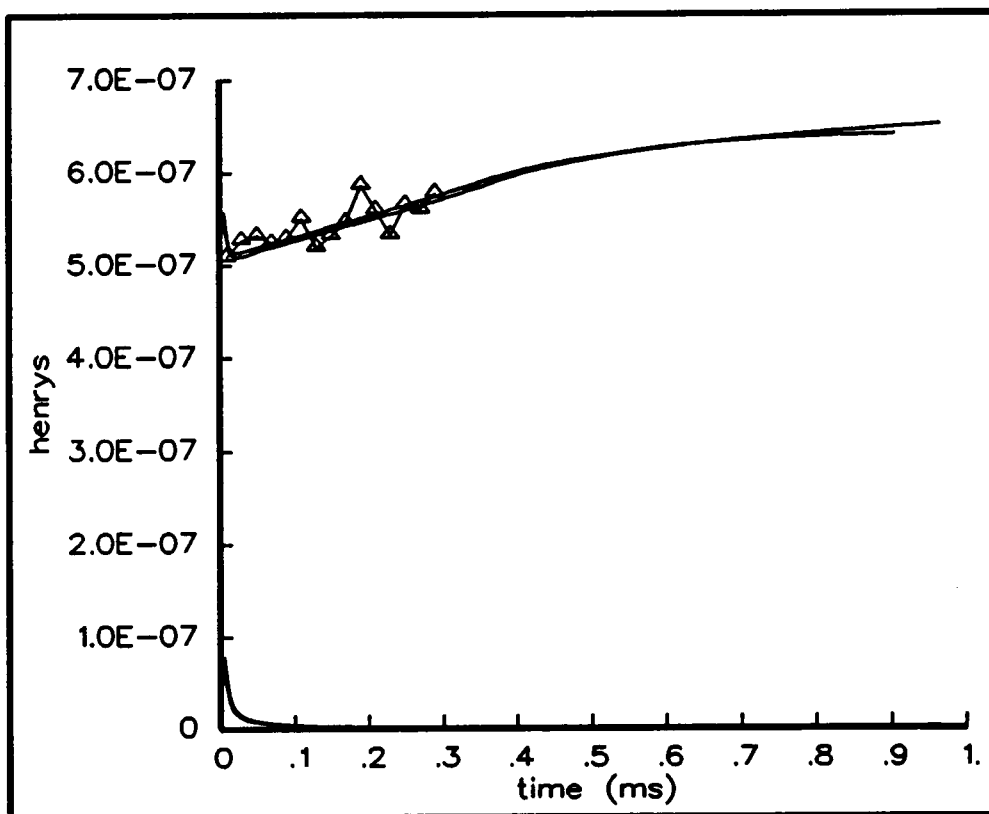


Fig. 9 M obtained from the numerical solution of the differential equation before the term containing the constant was added. The term containing the constant is plotted along with M (curve marked with triangles) obtained through the least squares fit.

In Figures 6 and 7, it can be seen that $(R + dL/dt)$ decreases rapidly and then flattens out at about 0.12 milliseconds. This is most notable in Figure 6. In Figure 8, L_1 and L_2 also flatten out at about 0.12 milliseconds, with the flattening being most noticeable in L_1 . For this reason, it seems the rapid drop of $(R + dL/dt)$ is due to dL/dt . Curve fitting L_1 and L_2 gave a value for dL/dt that was of the right magnitude but was not in agreement with the expected behavior of R as a function of time.

To make sure the values for the parameters obtained above were consistent with the closed circuit experiments, the parameters were approximated by a curve fit and used in a simulation. In curve fitting L_1 and L_2 , an exponential shape was used and it was assumed that they were essentially constant for times greater than 0.2 milliseconds. Results of the simulations can be seen in Figures 10 and 11.

The simulations for the shorted rail experiments did not produce any new information about the values for the parameters. In the region where L_1 and L_2 could not be determined for the open rail experiments, they do not affect the simulation very much since dI/dt is small. Any reasonable assumption about L_1 and L_2 in the region where dI/dt is small would have worked in the simulation.

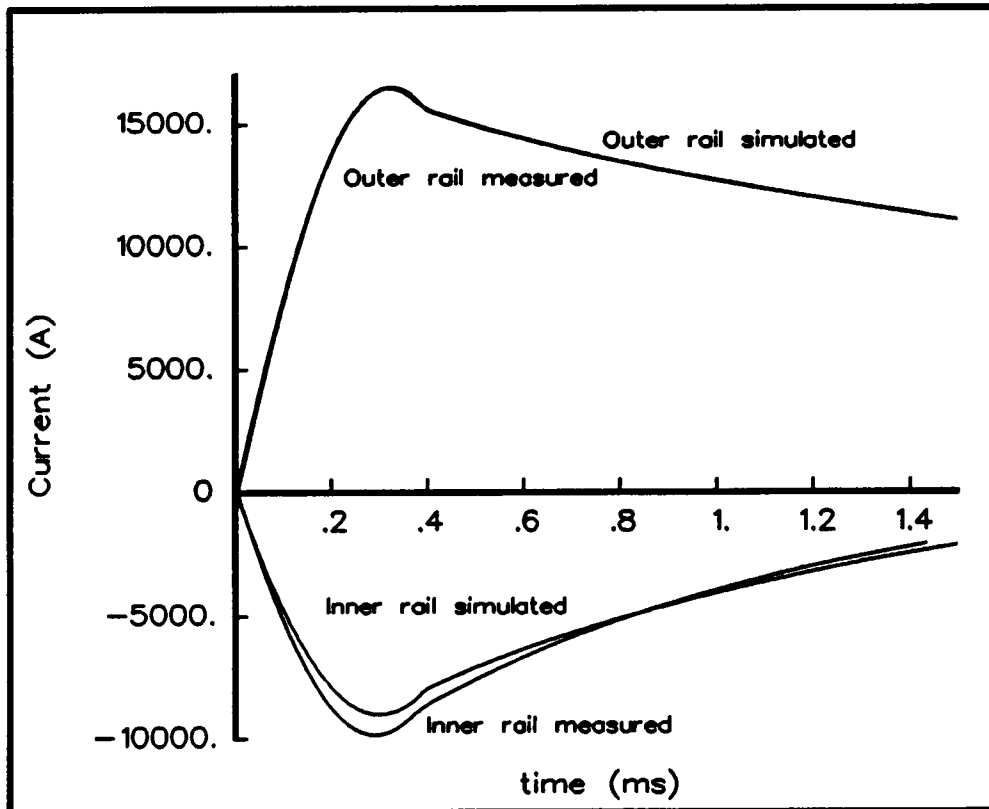


Fig.10 Simulated and measured current distributions for the case of the outer rail powered and inner rail shorted.

D. Conclusions from Circuit Analysis

One purpose in doing the circuit analysis was to find values for M and L_1 that could be used in simulations to predict railgun performance. Another was to make sure that the circuit behaved in the simple manner given by Equations 17 and 18.

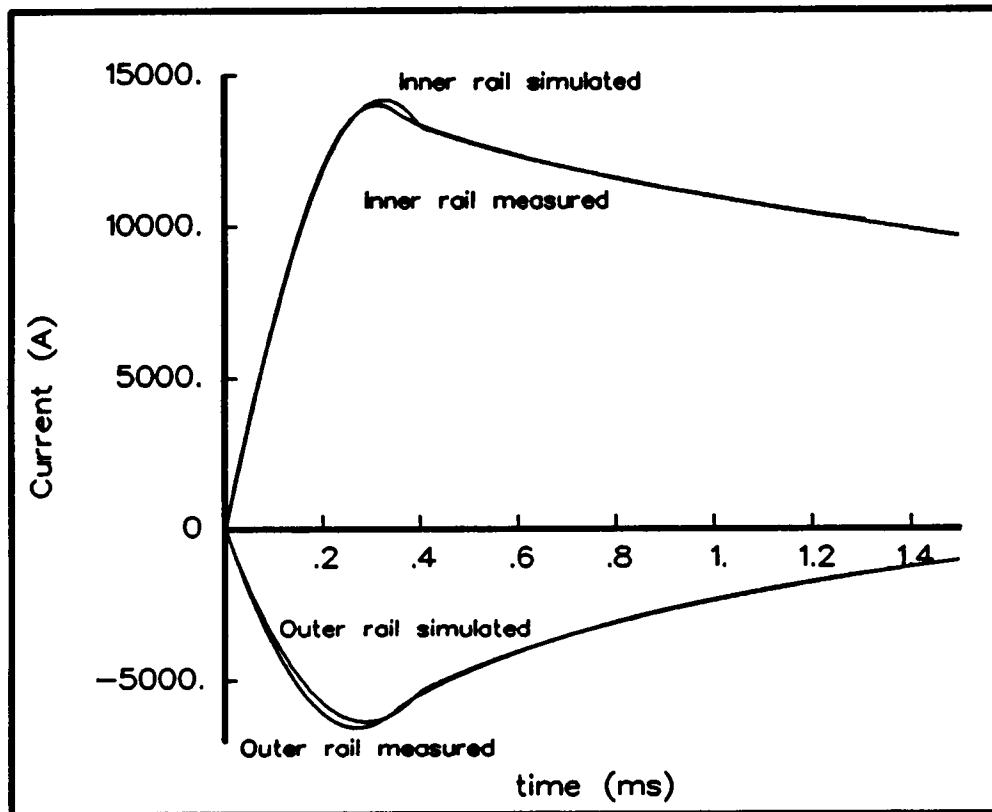


Fig.11 Simulated and measured current distributions for the case of the inner rail powered and outer rail shorted.

From the circuit analysis, the parameters which were most accurately measured were M_{12} and M_{21} . Time dependent values for each of these were found using both a least squares fit and by solution of the differential equation, and they were in very close agreement with each other.

Neumann's formula, Equation 15, can be used to help understand why the inductances increase with time. Neumann's formula is purely dependent upon the geometry of the circuit, being independent of current, frequency and magnitude.

The geometry of the circuit is the path which the current follows, and this does change in time due to the current diffusing into the rails.

The rate at which L_1 and L_2 change was never determined for times greater than 0.3 milliseconds. The least squares fit did not produce reliable information in that region due to dI/dt being small. A differential equation could not be solved directly for L , as one was for M , because there were more unknowns than there were equations. Assumptions were made for R in an attempt to calculate the self inductances, but the values did not agree with what was known about $(R + dL/dt)$ from the least squares fit.

For the predictions of railgun performance, L'_2 is not needed since the self-inductance of the outer rails does not change with armature position. From Figure 8 it can be seen there is no information on L_1 in the region past 0.3 milliseconds. It can be assumed however that the value of L_1 will either level off or continue to increase due to field diffusion in the rails. (i.e. it will not decrease.) The region in which the plasma armature is located is approximately 6.0 cm long and has a duration time, which is velocity dependent, of approximately 0.05 to 0.1 milliseconds. In this region, since there is no current ahead of the armature, the current is just starting to diffuse into the rails, just as when the rails are first energized in the circuit analysis experiments. The value of M' and L'_1 behind the armature would then be approximately the average value of M' and L'_1 from the circuit analysis in the region from 0.0 to 0.1 milliseconds. This gives conservative values of L'_1 and M' . After getting the average in this

region and dividing by the appropriate rail length, the values obtained for the UTSI railgun were:

$$L'_1 = 0.357 \frac{\mu H}{m} \quad ; \quad M' = 0.242 \frac{\mu H}{m}. \quad (28)$$

These values will be used in the next chapter to evaluate the performance the UTSI transaugmented railgun. These values were obtained from a stationary circuit analysis and the railgun is a dynamic system. The dynamics might change the effective L' and M' of the circuit. As stated earlier these are conservative values and should result in conservative estimations for the performance evaluations.

IV. DEVELOPMENT OF PERFORMANCE THEORY

Along with the Lorentz force for each particular railgun configuration other forces act on the plasma armature. Pressure from the light gas gun and pressure generated by the fuse vaporization act to increase armature velocity, and ablation and viscous drag act to decrease armature velocity. From these forces, the Lorentz force and the circuit model for each railgun configuration, railgun performance can be simulated.

In this chapter these additional forces are presented along with the parameters for each force relation. Equations used to simulate railgun performance are presented. Simulations are then done with only the Lorentz force acting on the armature for each railgun configuration and comparisons are made.

A. Forces Acting on the Plasma Armature.

Three different railgun configurations were discussed in Chapters I and II along with the electromagnetic force that acts to accelerate the plasma armature in each case. In addition to the electromagnetic force, forces due to viscous drag and ablation also act on the armature, however their effect is to reduce the force available to accelerate the projectile. Pressure from the light gas gun and pressure due to the fuse vaporization also act to increase the acceleration of the

projectile. Secondary arcs did not occur in the railgun shots that will be analyzed, so they will not be discussed.

The plasma armature experiences a viscous drag that can be written

$$F_v = \frac{C_f \rho v^2 \pi r^2 l}{r} , \quad (29)$$

where C_f is the skin friction, r is the bore radius, ρ is the density of the plasma, v is the velocity of the armature and l is the length of the armature. Taking this shear stress on the boundary,

$$F_v = \frac{C_f m v^2}{r} \quad (30)$$

can be obtained since the density times the volume equals the mass, denoted m , of the plasma. For this analysis, a value of 0.002 was used for C_f which was obtained from Parker's paper "Performance Loss Due to Wall Ablation in Plasma Armature Railguns".[3,8]

The armature also experiences a drag from accelerating ablated mass from the bore surface. The amount of material ablated is assumed to be proportional to the electrical power dissipated in the armature,

$$\frac{dm_a}{dt} = \alpha I V_a , \quad (31)$$

where α is the ablation coefficient and V_a is the voltage across the armature.[3]

From the equation of motion,

$$F_a = \frac{d}{dt}(mv) = m \frac{dv}{dt} + v \frac{dm}{dt} \quad (32)$$

and Equation 31, it can be seen that the ablation drag term will be proportional to the velocity of the armature and the power dissipated in the armature. The ablation coefficient can be determined from material properties and radiation transfer, or through matching data from railgun shots. The value of α used in railgun performance evaluations was obtained from matching data from unaugmented baseline shots. The value of this parameter that was used for the UTSI railgun would suggest that the plasma armature processes a significant amount of mass creating momentum drag. However, the amount of ablated material is not necessarily the same as the amount of mass that is retained in the plasma armature. Material can be ablated and then accelerated (which is where the loss occurs) then eventually left behind in the bore. The units for this parameter are kilograms per joule and typical values are on the order of 10^{-7} . [3,8]

A light gas gun is used to inject the projectile into the UTSI transaugmented railgun. The velocity is measured at the end of the light gas gun to get the injection velocity. It has been determined that there is still some acceleration due to the light gas gun past this point. For the UTSI railgun, the increase in velocity due to pressure from the light gas gun from the beginning of the rails to exit was around 100 m/s. From knowing the initial pressure when the

projectile enters the rails, and the increase in velocity that the projectile experiences, an exponential decay constant β was determined for the pressure.

There is also an added force on the projectile when the fuse vaporizes.[3] Assumptions for the thermal expansion term were made from experimental observation and it was assumed that the pressure could be modeled by,

$$P_t = (\gamma t)^{\eta-1} e^{-\beta t}, \quad (33)$$

where β is the same decay constant used for the light gas gun pressure and

γ and η are shape parameters that determine the magnitude and duration of the pressure pulse. These shape parameters are determined through fitting data on unaugmented railgun shots. The time in which the fuse vaporizes can be determined from the breech voltage measurement of the railgun. The halfwidth of the pressure pulse was set to about the same width as the fuse vaporization. The magnitude was then set so that the simulated velocity profile matched the experimental velocity profile, as determined from the magnetic probe data, early in the shot. The increase in velocity that the projectile would experience due to this pressure pulse alone was then checked to make sure it was reasonable.

The net force on the projectile is then the Lorentz force, F_e , for the particular railgun configuration plus the pressure, P_t , times the cross sectional area

of the bore minus the viscous drag and ablation forces, F_v and F_a . Models can be developed for the three railgun configurations from these forces.

B. Models for Railgun Configurations.

Three types of railgun configurations will be discussed: classical, series augmented and transaugmented railguns. The equations obtained from the circuit models shown schematically in Figures 1, 2 and 3 will be presented. These equations, along with the force equations presented earlier were used to simulate the particular railgun.

The parameters and the values of the parameters used in these simulations are given in Table 1. The values of the capacitance of the two power supplies were given by the manufacturer. The inductance for each of the two storage inductors as well as the resistance of each circuit was determined through curve fitting a simulated pulse with one generated experimentally. The determination of the self inductance per unit length of each rail was presented earlier and a value for k (coefficient of coupling between rails) was also obtained to agree with the mutual inductance per unit length found. For direct comparisons of one model to another, a projectile mass of 1.5 grams was used. For the analysis of a particular experimental shot, the measured mass of the projectile was used which varied from 0.9 to 1.0 grams. The initial pressure in the railgun was obtained from a

pressure transducer located at the end of the light gas gun. The parameters used for the forces in the gun and how they were obtained were discussed at the beginning of this chapter.

Table 1. Values of parameters used in the simple circuit models.

Parameter	Description of parameter	Value of parameter
L_o	-Storage inductance (H)	6.63e-6
C	-Capacitance of circuit (F)	8.4e-3
R	-Resistance of circuit (ohms)	3.6e-3
L'	-Inductance per unit length of rails (H)	0.357e-6
Lo_1	-Inductance of circuit of inner rails (H)	15.0e-6
Lo_2	-Inductance of circuit of outer rails (H)	11.7e-6
L'_1	-Inductance per unit length of the inner rails (H)	0.357e-6
L'_2	-Inductance per unit length of the outer rails (H)	0.429e-6
C_1	-Capacitance of circuit of inner rails (F)	3.6e-3
C_2	-Capacitance of circuit of outer rails (F)	4.8e-3
R_1	-Resistance of circuit of inner rails (ohms)	3.6e-3
R_2	-Resistance of circuit of outer rails (ohms)	3.4e-3
Vo_1	-Initial voltage on inner capacitor (volts)	0.0 to 10kV
Vo_2	-Initial voltage on outer capacitor (volts)	0.0 to 10kV
m	-Mass of projectile (kg)	1.5e-3
k	-Coefficient of coupling between rails	0.62
xT	-Length of railgun (M)	2.0
C_f	-Skin friction	0.002
alpha	-Ablation proportionality constant (-kg/J)	0.14e-7
P_o	-Initial pressure at the end of the light gas gun (Pa)	7.5e+6
beta	-Decay constant for pressure (Hz)	2.0e+4
eta	-Shape parameter for thermal expansion	2.88
r	-Radius of bore (m)	5.0e-3

1. Classical Railgun Model.

In Figure 1, the circuit model for the classical railgun was shown. Three differential equations govern the motion of the projectile, and are found by solving for the time rate of change of current, velocity and position. The time rate of change of current can be obtained by summing the voltage drops around the circuit,

$$(V_o - \frac{1}{C} \int I dt) - \frac{d}{dt}(IL) - IR - V_a = 0 \quad (34)$$

and then solving for the rate of change of current with respect to time,

$$\frac{dI}{dt} = \frac{(V_o - \frac{1}{C} \int I dt) - I(R + \frac{dL}{dt}) - V_a}{L} \quad (35)$$

In Equation 35 when the voltage drop across the capacitor reaches zero or, when making comparisons to experiments, the actual time when the capacitor was shorted out of the circuit, the code will short the capacitor by setting,

$$V_o - \frac{1}{C} \int I dt = 0 \quad (36)$$

In the code, there is a routine that models the voltage drop across the armature, V_a , with a logarithmic curve of the form,

$$V_a = V_{o11} \ln(I) \quad (37)$$

where I is the rail current and V_{o11} is a parameter used to get the characteristic

curve to approximately match railgun data. The total inductance L is the inductance of the storage inductor plus the self-inductance per unit length times the position of the projectile,

$$L = L_0 + L'x . \quad (38)$$

The time rate of change of inductance is thus the self-inductance per unit length times the velocity of the projectile.

Next, setting the Lorentz force, Equation 1, equal to the mass times acceleration and dividing through by the mass, the time rate of change of velocity is given by,

$$\frac{dv}{dt} = \frac{1}{2m} L' I^2 . \quad (39)$$

This is for the ideal model. Equation 39 was modified by adding to the Lorentz force, Equation 1, forces presented earlier to adjust for viscous drag and ablation as well as for the pressure due to the light gas gun and thermal expansion. The modified equation is given by

$$\frac{dv}{dt} = \frac{1}{m} \left(\frac{1}{2} L' I^2 + P_t a - F_a - F_v \right) \quad (40)$$

where a is the cross sectional area of the bore.

The time rate of change of position of the projectile is equal to the velocity,

$$\frac{dx}{dt} = v \quad . \quad (41)$$

Equations 35, 39 and 41 were solved using a simple finite difference technique for the ideal model and Equations 35, 40 and 41 were solved for the modified model. This simple technique was found to be adequate for these equations since they are stable. A current distribution was simulated using Equation 34 without a changing inductance (i.e. $L = L_0$) and was compared with an analytical solution to check the validity of the solution technique. Similar tests were used to test the validity of the other models.

The voltage drop across the armature, V_a , can be thought of as current times a time-dependent resistance with a maximum resistance of approximately 8 milliohms. Since a change in resistance of 8 milliohms from the 3.6 milliohms used in the model affects the exit velocity by less than 0.5%, this term, and the changing resistance of the rails (on the order of 0.3 to 0.1 milliohms) are insignificant in the ideal model. However, when the ablation drag term is included, the voltage drop across the armature becomes very important.

2. Series Augmented Railgun Model.

The series augmented railgun (Figure 3) has an added turn in the rails, and the current in this turn will be the same as in the inner rails since it is part of the same circuit. Again, three differential equations govern the motion of the projectile. The voltage drops around the circuit can be summed and is equal

to zero,

$$(V_o - \frac{1}{C} \int Idt) - \frac{d}{dt}(IL + 2IM) - IR - V_a = 0 \quad (42)$$

The mutual inductance shows up twice, once for the inner rail and again for the outer rail. Solving for the rate of change of current with respect to time gives,

$$\frac{dI}{dt} = \frac{(V_o - \frac{1}{C} \int Idt) - I(R + \frac{dL}{dt} + 2\frac{dM}{dt}) - V_a}{L} \quad (43)$$

Once the voltage drop across the capacitor equals zero the capacitor is shorted out of the circuit in the code by using Equation 36. The rate of change of mutual inductance is the mutual inductance per unit length times velocity,

$$\frac{dM}{dt} = k\sqrt{L_1' L_2'} v \quad (44)$$

The rate of change of velocity can be obtained from Equation 2 and is given by,

$$\frac{dv}{dt} = \frac{1}{2m}(L_1' + 2M')I^2 \quad (45)$$

Equations 41, 43 and 45 were solved with a finite difference method. Only the ideal model was used for the series augmented case.

3. Transaugmented Railgun Model.

With the transaugmented case (Figure 2), four differential equations govern the motion of the projectile due to the two separate circuits. For this

model, there can be a time delay between energizing the circuit of the inner rail and the outer rail. When the inner rail is energized first, a subroutine for the classical case used until the outer rail is energized. When the outer rail is energized first, an analytical solution for the current in an LRC circuit is used to find the current at the time which the inner rails are energized.

The voltage drops around the two loops can be summed and will be equal to zero,

$$(V_{o1} - \frac{1}{C_1} \int I_1 dt) - \frac{d}{dt}(I_1 L_{1T} + I_2 M) - I_1 R_1 - V_a = 0 , \quad (46)$$

$$(V_{o2} - \frac{1}{C_2} \int I_2 dt) - \frac{d}{dt}(I_2 L_{2T} + I_1 M) - I_2 R_2 - V_a = 0 . \quad (47)$$

Now a function, $a(t)$, will be defined to simplify the following equations,

$$a(t) = (V_{o1} - \frac{1}{C_1} \int I_1 dt) - I_1(R_1 + \frac{dL_{1T}}{dt}) - I_2 \frac{dM}{dt} - V_a . \quad (48)$$

Equation 44 can then be solved in terms of I_2 and dI_2/dt ,

$$\frac{dI_1}{dt} = \frac{a(t) - M \frac{dI_2}{dt}}{L_{1T}} . \quad (49)$$

Using this solution, Equation 45 can be solved in terms of I_1 ,

$$\frac{dI_2}{dt} = \frac{(V_{o2} - \frac{1}{C_2} \int I_2 dt) - I_2 R_2 - I_1 \frac{dM}{dt} - V_a - \frac{M a(t)}{L_{1T}}}{L_{2T} - \frac{M^2}{L_{1T}}} . \quad (50)$$

In Equations 46 or 48 once the voltage drop across the particular capacitor reaches zero the capacitor is shorted out of the particular circuit by using Equation 36. The rate of change of velocity can be obtained from Equation 3 and is given by,

$$\frac{dv}{dt} = \frac{1}{2m} (L_1' I_1^2 + 2M' I_1 I_2) . \quad (51)$$

This is the ideal transaugmented model. Equation 51 was modified by adding to the Lorentz force, Equation 3, forces presented earlier to adjust for viscous drag and ablation as well as for the pressure due to the light gas gun and thermal expansion. The modified equation is given by,

$$\frac{dv}{dt} = \frac{1}{m} \left(\frac{1}{2} L_1' I_1^2 + M' I_1 I_2 + P_1 a - F_a - F_v \right) . \quad (52)$$

Equations 41, 49, 50 and 51 were solved with a finite difference technique for the ideal case. Equations 41, 49, 50 and 52 were solved for the modified case.

The three circuit models were used with the ideal force equations to make comparisons between the three models. The transaugmented case was then modified to take into account ablation loss and other force terms by modifying Equation 3 and obtaining a new expression for Equation 49. This modified model was then used to analyze data from the UTSI transaugmented railgun and results from this analysis is given in Chapter V.

C. Comparisons of the Three Ideal Railgun Models.

The previously stated purpose for augmentation is to achieve the same exit velocity with less operating current. The overall energy efficiency of the transaugmented railgun, defined as the ratio of the initial energy of the capacitor to the kinetic energy of the exiting projectile, is no better than the classical case in a 2.0 m railgun. In Figure 14, comparisons of the initial stored energy versus ideal exit velocity can be seen for the classical, series augmented and transaugmented railguns. The curves for the classical and series augmented railguns are straightforward since, for a given initial stored energy,

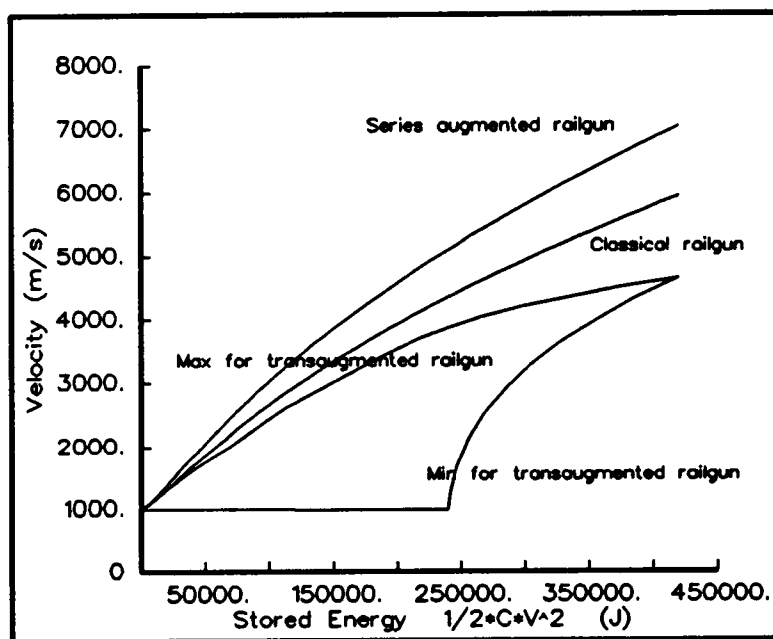


Fig.12 Stored energy versus exit velocity for the classical, series augmented and transaugmented railguns.

there can be only one exit velocity. For the transaugmented case, however, the initial voltage can be distributed in different ways on the two sets of rails, and instead of getting a simple curve for the transaugmented gun, one gets an area (See Figure 12). The minimum exit velocity for a given stored energy was obtained by incrementing the initial voltage on the outer rail until it reached the maximum potential for the UTSI railgun. Then, the initial voltage on the inner rail was incremented up to 10 kV. The maximum exit velocity for a given stored energy was obtained by varying the possible distributions of initial voltage on each rail and finding the one that was a maximum.

The paper by Maruo, Fujioka, Nagaoka, Okamoto, Ikuta and Nemoto reported less rail erosion for the series augmented than for the classical railgun for the same exit velocity.[11] The reason for this can be seen in Figure 13, where the current distributions for the series augmented gun and classical railgun with the same exit velocity are compared. The lower current reduces the power dissipated within the armature, therefore reducing the rate of rail ablation.[2]

Fiske, Wu and Thio reported an increase of 83% in exit velocity for the ELF-I augmented railgun for the same current distribution.[12] A simulation of this was performed using equal peak currents for the series augmented and classical railgun as shown in Figure 14. The series augmented railgun had a 78% greater exit velocity than the classical railgun (Figure 15). The percentage was for velocity increase due only to the electromagnetic acceleration.

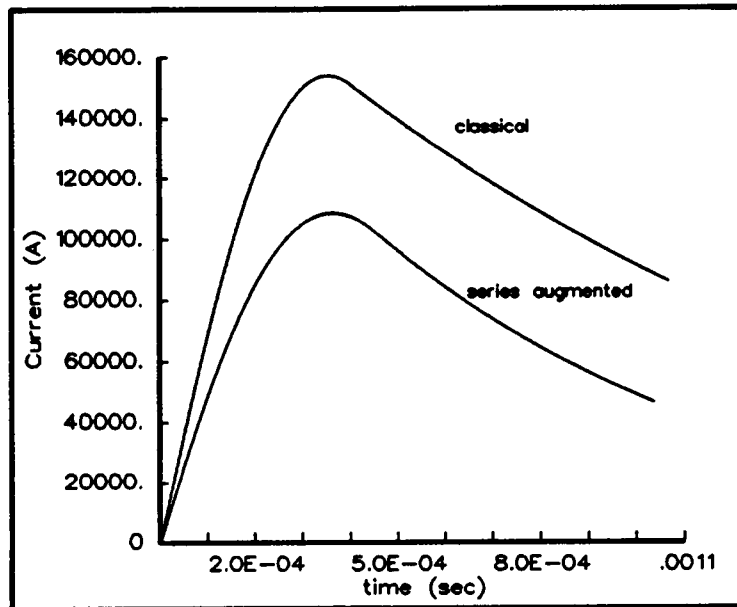


Fig.13 Current for series augmented and classical railguns with same predicted exit velocity.

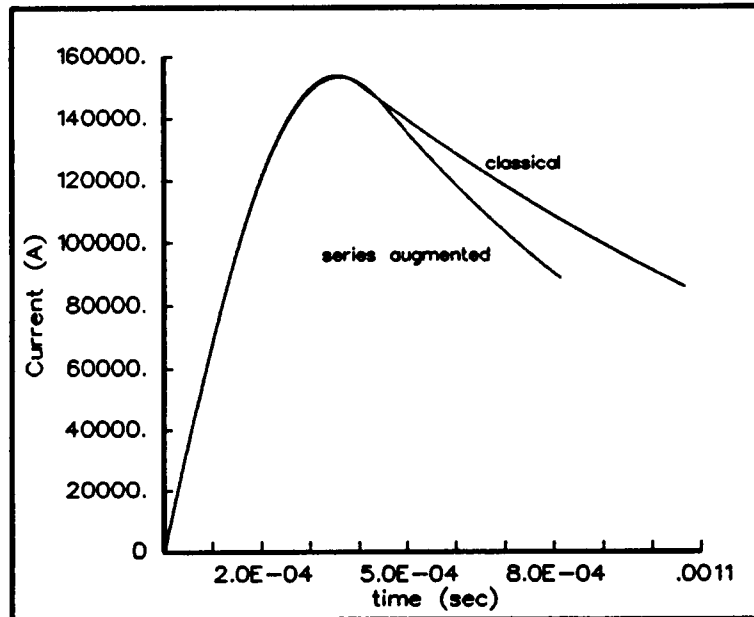


Fig.14 Current for classical and series augmented railguns with the same peak current.

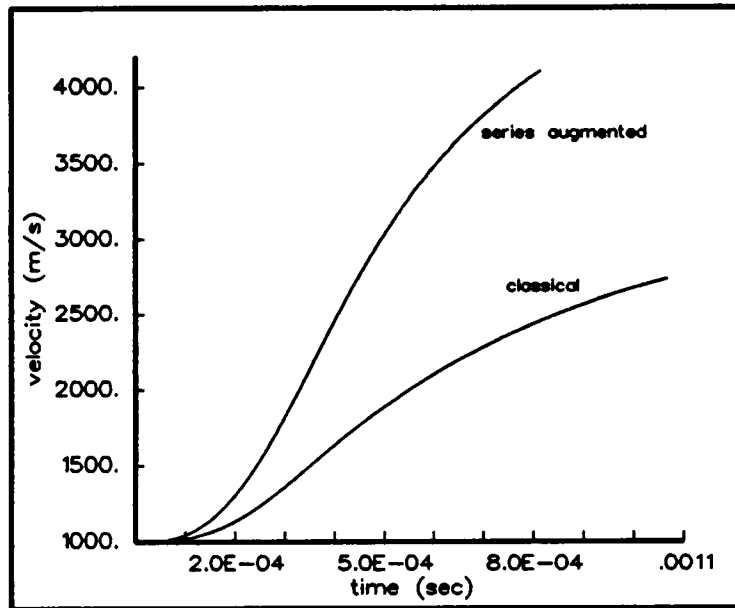


Fig.15 Velocity profiles for classical and series augmented railguns with the same peak current.

With the transaugmented railgun, the current on the outer rail can be increased without increasing the current on the inner rail. The magnetic field will increase the force on the projectile, ideally, without increasing the power dissipated in the armature, meaning no added loss due to ablation. Figure 16 shows the exit velocity as a function of initial charge voltage with no augmenting field and for the outer rails initially charged to 10 kv. It can be seen from this that a maximum increase in velocity of 2.0 km/s can be expected due to the augmented field.

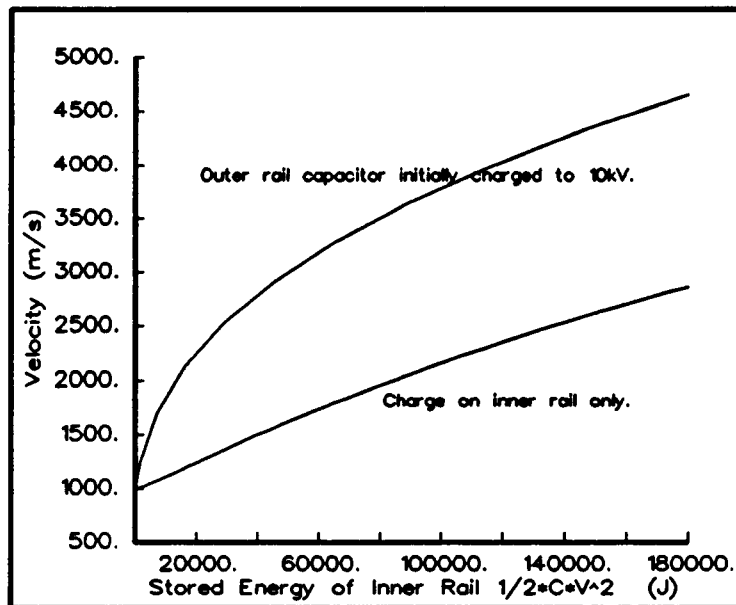


Fig.16 Stored energy on inner rail versus exit velocity for classical railgun in an augmented field and by itself.

The increase in velocity reported by Westinghouse corresponds to the ideal increase that would be experienced as predicted by the Lorentz force. This is consistent with the assumption that there are no changes in the drag forces due to augmentation. If this is the case then with the UTSI transaugmented railgun, it should be possible to increase the exit velocity of an unaugmented shot by approximately 2.0 km/s by adding augmentation.

V. EXPERIMENTS ON PERFORMANCE

The UTSI transaugmented railgun was built to gain a better understanding of the effects of increasing the magnetic field in a plasma armature railgun. The transaugmented railgun is designed so that it can be fired as a classical or transaugmented railgun. Classical railgun shots were to be done so that baseline parameters for loss mechanisms in the particular railgun structure could be obtained. There were no theories or models that would suggest that there should be increased loss due to increasing the magnetic field at the levels which the UTSI transaugmented railgun operates. The loss parameters obtained from the baseline shots were then used in simulation models to eliminate losses for the augmented shots and compare these results to the experimental data.

A. Experimental Setup

1. Design of the Transaugmented Railgun.

The UTSI transaugmented railgun is designed to function as either a classical or augmented railgun. The circuit design for the railgun can be seen in Figure 3. The inner rail circuit is separate from the outer rail circuit. The outer rails are used only to generate a stronger magnetic field for the projectile to travel through.

Figure 17 shows a cross-sectional view of the bore structure.[18] The augmented rails end approximately 0.064 m from the end of the inner rails and are shorted with a copper clamp that goes around the bore structure.

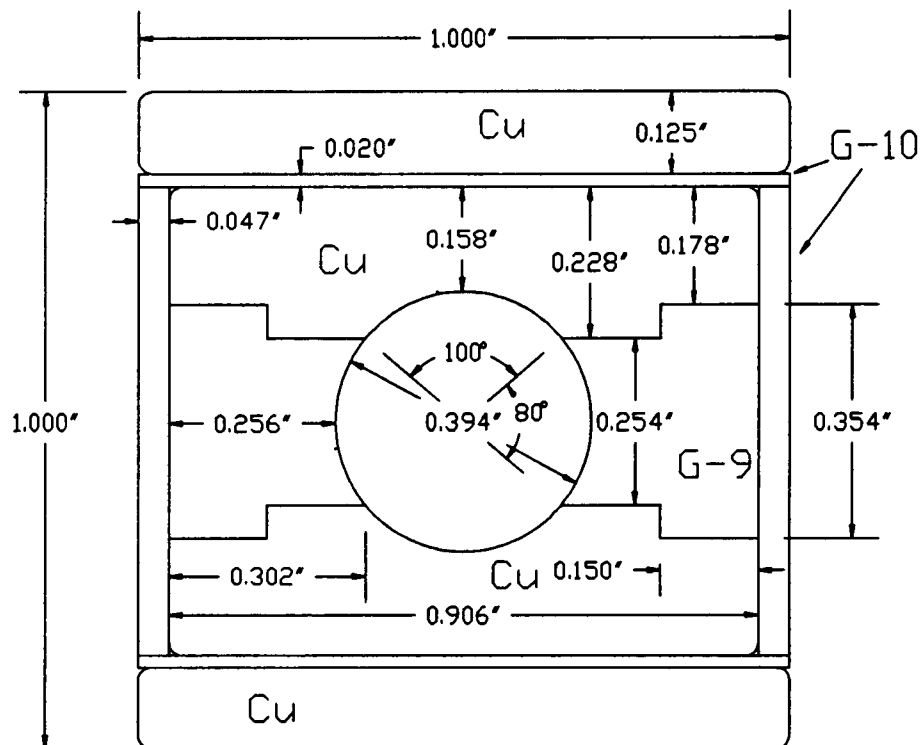


Fig. 17 Bore structure for the transaugmented railgun.

The bore is contained in a structure consisting of four blocks of G-10, V-blocks made of aluminum and hardbacks bolted together with 20.3 cm long 2.54 cm diameter bolts located every 5.08 cm along the length of the railgun. A cross sectional diagram of this can be seen in Figure 18.[19] The square at the center of this diagram is the location of the bore structure.

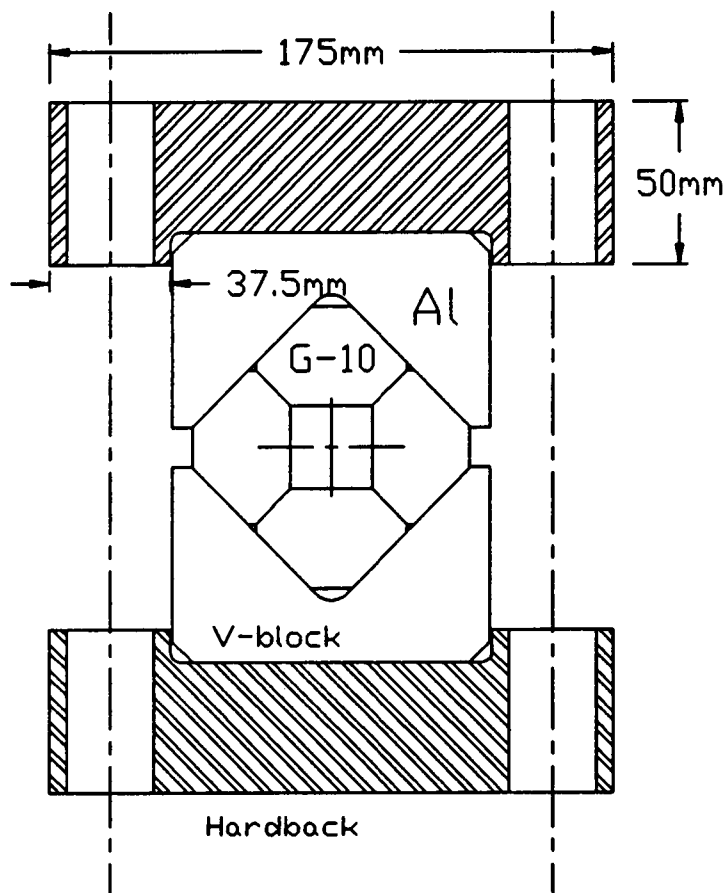


Fig. 18 Cross section of railgun structure.

2. Instrumentation and Data Acquisition

A number of measurements were made for each experiment in order to evaluate railgun performance. Muzzle and breech voltage, inner rail current, outer rail current and voltage, pressure, magnetic field at 23 locations along the bore and exit velocity were recorded for each experiment.

Data points were taken every 500 ns for 4.096 ms to get 8192 data points for each piece of instrumentation on the railgun. The data acquisition was started manually once the capacitor banks were charged, then the bursting of the diaphragm, which gives the projectile acceleration in the light gas gun, was triggered manually. The acquisition system continued to take data (when more than 8192 data points have been taken, it starts storing the data in the first storage position, writing over what had been stored there before) until the first pressure transducer (pt1), located 90 mm before the beginning of the inner rails, detects the projectile. At this time, 7168 more data points were taken, leaving the last 1024 data points that were taken before the projectile reached pt1. There was another pressure transducer located 40 mm past pt1. The two pressure transducers were used to determine the entrance velocity of the projectile into the rails. This was done by knowing the time at which the projectile passed each probe and the distance between probes.

Rogowski coils were used on each set of rails and measure the change in magnetic field around the rails. As the current changes in the rails, it induces a voltage on the coil, and this induced voltage was calibrated to give the value of

dI/dt with respect to time. An integration was done to get the time dependent current in the circuit. Voltage measurements using a shunt resistance of 1k ohm were taken for the augmented rails, the breech end of the railgun and the muzzle end of the railgun.

Magnetic field sensing probes (B-dot probes) were set 100 mm apart down the length of the railgun. The probe consist of a coil of wire which has a voltage induced on it by the changing magnetic fields when the projectile passes the probe.[20] The B-dot axis was aligned perpendicular to the rail so that the current induced on it is due to changing rail current and not the plasma. The current that was in the rail at the time the plasma passed was also the current that was in the plasma. Using deconvolution methods, the current distribution through the plasma at the particular location can be determined.[21] The position of the projectile at a given time was determined from the B-dot records. The velocity profile was then obtained by differentiation of the position-time information. The exit velocity was determined with a passive magnetic induction device (MAVIS). Sketches of this device were obtained from Allan R. Susoeff of Lawrence Livermore Laboratory.[22] MAVIS is a device which has two coils of wire, each fitted inside a magnet and located 20 cm apart. A small piece of conducting material (aluminum) was put on the front of the projectile, and when it passed through the magnetic field, a voltage was induced on the coils of wire. The induced voltage was used to determine when the projectile passed each coil of wire. Since the distance between the coils was known, the exit velocity was accurately determined.

3. Railgun Shots.

Experiments were performed in such a way as to try and isolate the effects of augmentation. This was done by first firing baseline shots in which only the inner rails were used. Then augmented experiments were performed in which the current on the inner rail was the same as one of the baseline shots.

A light gas gun, which injects the projectile into the rails at around 1.0 km/s, was triggered manually to start a typical railgun shot. The pressure transducer pt1, which was used to trigger the data acquisition system, was also used to trigger a delay generator which fires the capacitor banks that power the rails. The inner rails were triggered 125 microseconds after the projectile had reached pt1. For augmented shots, the augmented rails were triggered at two different times. For one set of augmented shots, they were triggered when the projectile reached pt1 and for the other set, they were triggered approximately where the inner rail current was crowbarred. Each of the two power supplies were crowbarred by a time delay of 420 micro seconds after the particular power supply was triggered.

At the end of the railgun, a 20.3 cm diameter 3.35 m long tank, with foam rubber and newspaper stuffed in the end, was used to catch the projectile. MAVIS was also located in the catch tank. Before firing the railgun, the catch tank was evacuated to get oxygen out of the system. It was then backfilled to one half atmosphere of helium to help control precursor arcing across the rails.

A number of baseline experiments in which only the inner rail is fired were conducted to establish the performance of the railgun. (Bore quality, how the railgun acts at the lower currents, etc.) These shots varied in peak current from 67 kA to 137 kA. Then, a series of experiments were performed in which the outer rail current and the time at which the outer rail was fired were varied. These experiments were conducted to obtain a better understanding of how the strength of the magnetic field, as well as the time variance, affects railgun performance.

B. Experimental Analysis

The two low current shots were compared to their expected ideal performance obtained from the Lorentz force. The baseline shots were then used to obtain a parameter for the ablation drag and parameters for the shape of the pressure pulse due to the fuse vaporizing. These parameters were then used in simulations for the higher current shots and the augmented shots to determine if the model was still valid. Table 2 gives a listing of what shots were performed, the peak currents associated with each shot and a brief description of each shot.

From the data collected on each railgun shot, the entrance velocity, muzzle velocity and position versus time curves were obtained. The value for time used in these plots was the value obtained from the midpoint of the leading edge of the B-dot signal minus the 125 micro second time delay in energizing the inner rail. The position verses time curves can be fitted with fourth order curves, then differentiated

Table 2. Listing of Railgun Shots

Date	Rail Current Peak (kA)	Augmented Current Peak (kA)	Brief description of shot
8/16	67	0	This shot was an unaugmented low current baseline shot.
6/17	104	0	This shot was an unaugmented low current baseline shot.
9/19	120	0	The current was increased to test the parameters obtained from the baseline shots.
9/06	133	0	The current was increased to again test for consistency.
7/30	138	0	The current was increased.
9/25	68	30**	Low current augmented shot.
6/28	104	105**	Augmented shot.
7/23	104	105(c)	Augmented rail fired when inner rail crowbars.
7/10	104	142**	Increased current on augmented rails.

**Augmentor fired 125 micro seconds before inner rails.

(c) Augmentor fired when inner rails crowbar.

to obtain reasonable velocity profiles for each shot. The peak velocity from the velocity profile should match up with the muzzle velocity.

The position data as well as the velocity profiles obtained from the position data for the two low current shots were used to find parameters for the ablation coefficient and for the shape parameter for the pressure pulse. Once these parameters were obtained, simulations were computed for the higher current shots and the augmented shots in which the inner rail current was the same as for the particular baseline shot.

C. Experimental Results

The 6/17 and the 8/16 baseline shots were analyzed first to obtain and ablation coefficient and shape parameters. The 6/17 shot is the most important of the two shots because most of the augmented shots were fired with a peak current on the inner rail of 104 kA. In Figure 19, it can be seen that the thermal expansion and the pressure from the light gas gun must play a part in accelerating the projectile, since the velocity due to the Lorentz force is below the velocity from experimental data for most of the 8/16 shot.

The pressure from the light gas gun is measured by pressure transducer pt2 near the point where the projectile enters the rails. This pressure, along with the thermal expansion pressure, were converted to a force and added to the Lorentz force. An exponential decay constant was determined from light gas gun

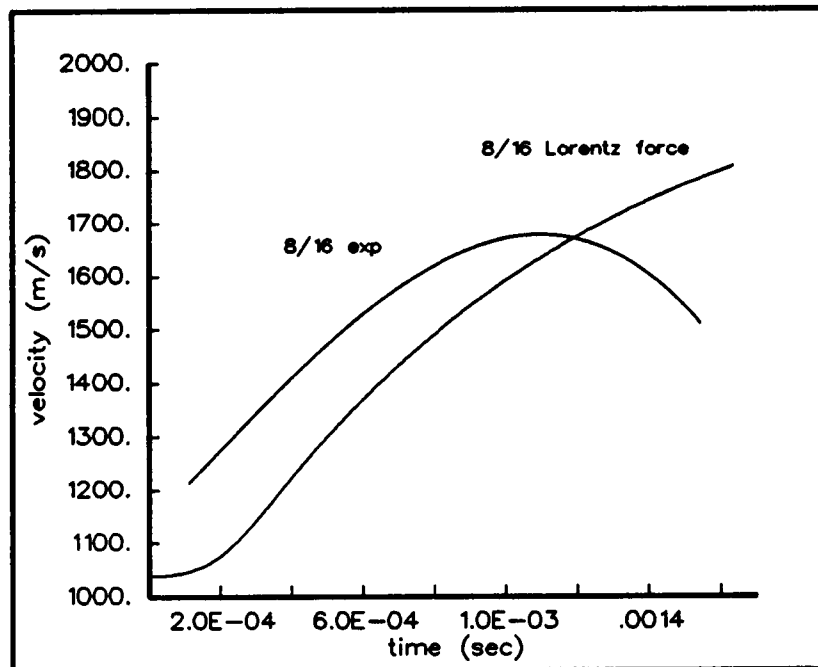


Fig.19 Velocity profile for the 8/16 shot and the velocity due to the Lorentz force.

experiments and the procedures for this were outlined earlier. A shape parameter for the thermal expansion pressure was determined by fitting the simulated velocity to the velocity at the beginning of the curve obtained from the position data. Once this was done, an ablation constant was determined to bring the rest of the curve into agreement with the experimental values. The results of this procedure for the 6/17 and 8/16 shots can be seen in Figure 20, where the velocities are compared, and Figure 21, where the position data is compared with the simulated values. At the end of the velocity curves, the discrepancy is probably due to primary separation, which this simple code does not predict. Primary separation, not to be confused with secondary formation, is the separation of the primary arc from the projectile.

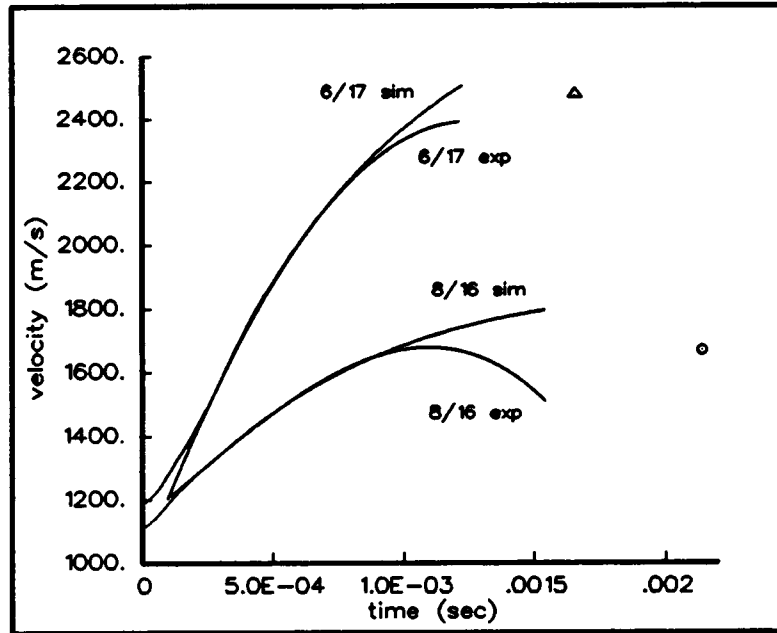


Fig.20 Velocity profiles from the 6/17 and 8/16 shots. Data points shown are MAVIS velocities.

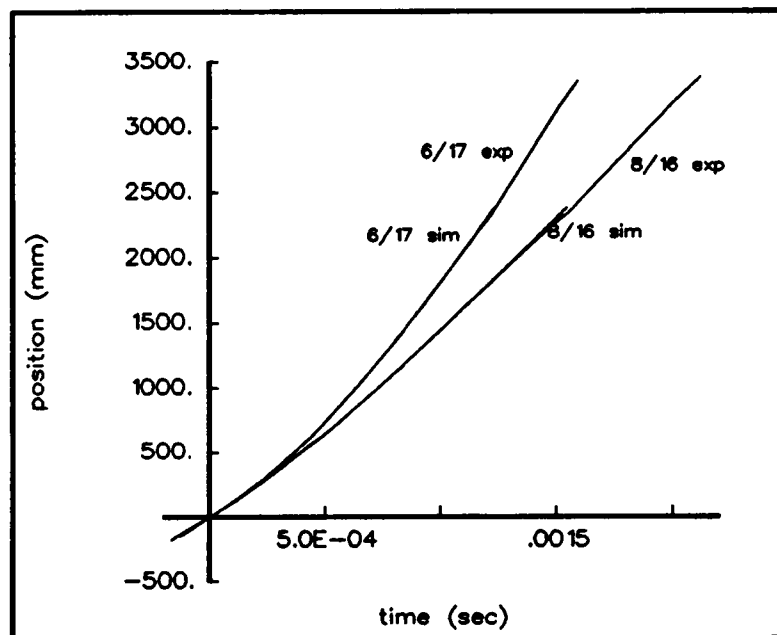


Fig.21 Position data versus simulated position curves for 6/17 and 8/16 shots.

The Lorentz force, ablation drag, pressure due to light gas gun and thermal expansion from the fuse vaporization and the viscous drag, which is essentially zero, are shown in Figure 22. The force due to the pressure seems reasonable since, from observations of pt2, the pressure increases to approximately double its initial value due to the fuse vaporization. The fuse vaporization, as observed from breech and muzzle voltage measurements, also takes place in the time interval of the halfwidth of this curve. The simulation was run with only the pressure pulse term, and an increase in velocity of approximately 200 m/s was obtained. This is in agreement with experiments on the light gas gun alone where an increase in velocity of 91 m/s was seen. It is reasonable to assume that the fuse vaporization can add another 100 m/s.

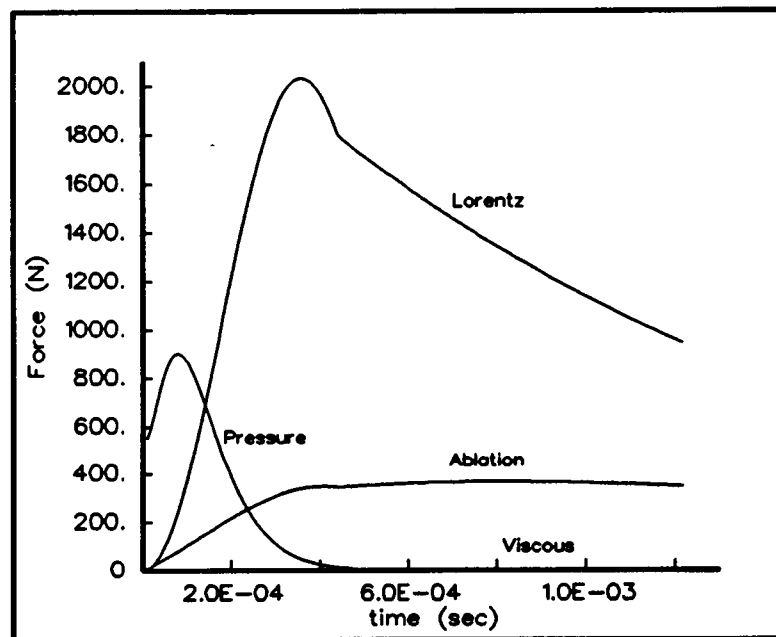


Fig.22 The Lorentz force, ablation drag, force due to pressure pulse and the viscous drag.

Once these parameters were obtained, the 9/19 (120 kA) and 9/06 (133 kA) shots were simulated and their velocity profiles can be seen in Figure 23. Both of these shots differ from their simulated values by approximately the same amount and are considerably off the simulated values. This is interesting because both the 8/16 (67 kA) and 6/17 (104 kA) shots were in good agreement with their simulated values, even though the difference in peak current was 37 kA. It seems that going up 16 kA to the 120 kA shot should still give reasonable results. Since the results did not compare well to the simulation, it would seem that going up another 13 kA to the 133 kA shot would give even worse results but it does not. Figure 24 shows the 120 kA and 133 kA shots with a larger ablation constant than that used for the 67 kA and 104 kA shots. The 120 kA and 133 kA shots are

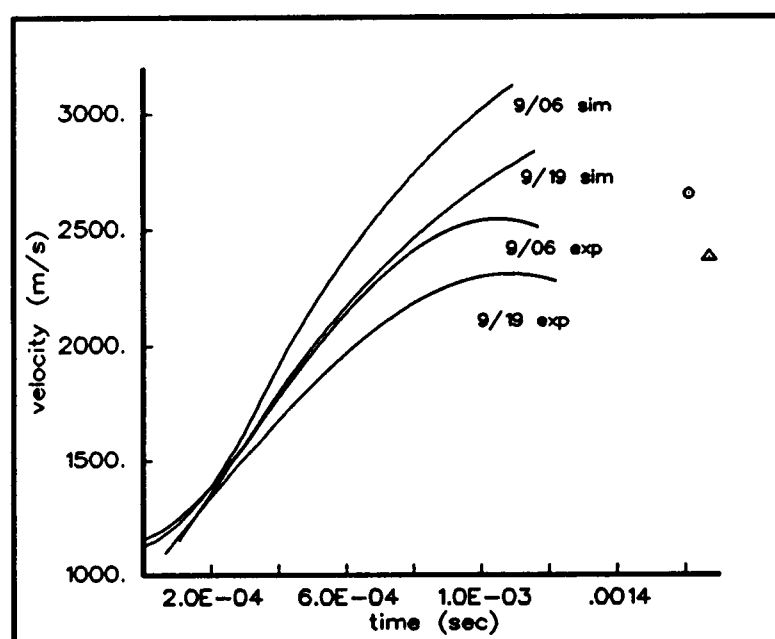


Fig.23 Velocity profiles for the 9/06 and 9/19 shots with parameters found from the 8/16 and 6/17 shots.

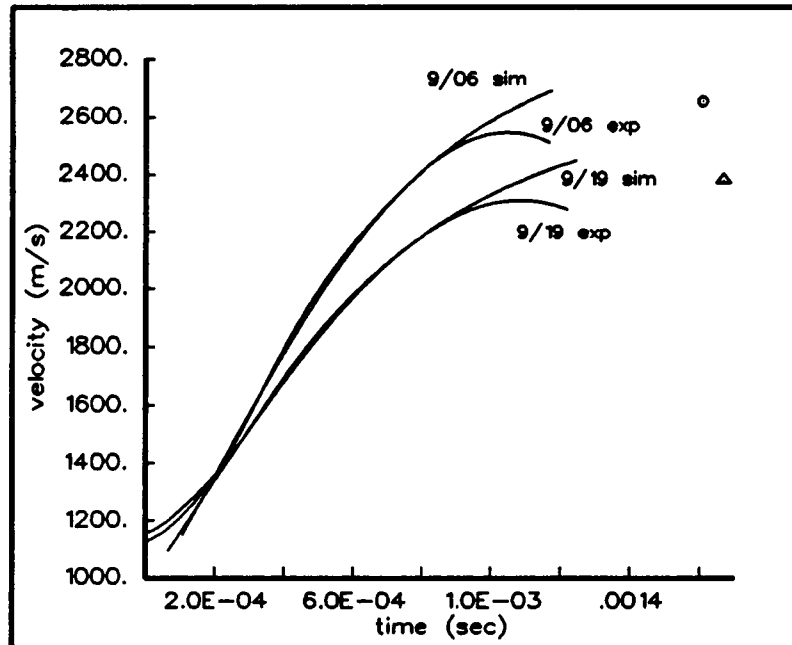


Fig.24 Velocity profiles for the 9/06 and 9/19 shots with an ablation constant that fits the curves.

in agreement with each other. Figure 25 shows the increase in ablation drag needed to bring the shots into agreement with the model. It should not be an increase in ablation that is causing the added loss but whatever the loss mechanism is it should be of the same form as the ablation term, (the loss being constant past peak current) since this does bring the shots into agreement with their predicted values.

In Figure 26, the 6/28 augmented shot is shown. The simulation was done using the parameters obtained from the 67 kA and 104 kA classical railgun shots. It can be seen that the expected velocity is much greater than the actual velocity obtained. This disagrees with the idea that putting the classical railgun in a

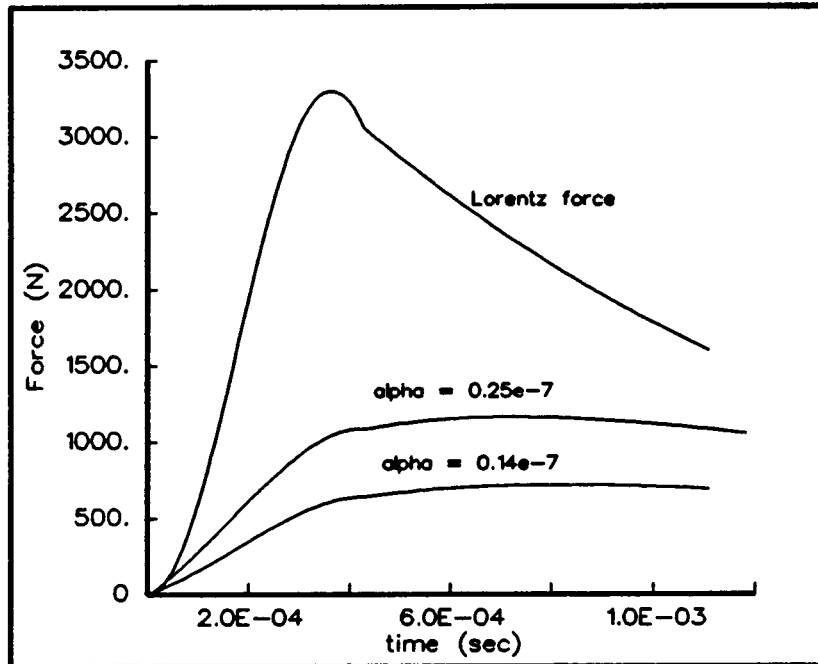


Fig.25 Ablation drag for two different ablation constants on the 133 kA shot.

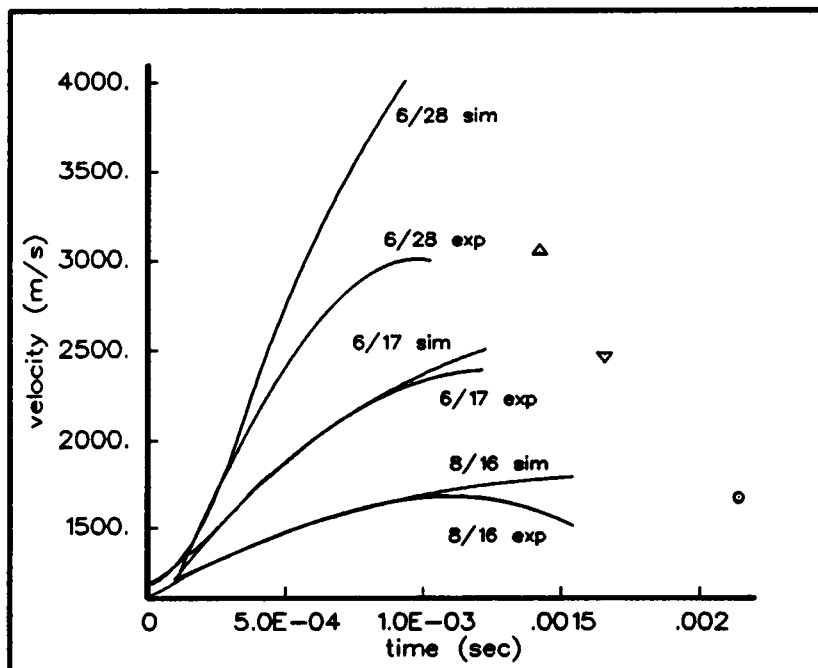


Fig.26 Velocity profiles for the 6/17, 8/16 and 6/28 shots. Data points shown are MAVIS velocities.

magnetic field should not create additional loss mechanisms or increase the ones that already exist. Figure 27 shows that the increased loss is not of the form of the ablation term. An increased ablation constant causes too much drag early on and not enough toward the end of the simulation. Ablation loss is nearly constant once the current hits its peak (see Figure 25). It seems at the beginning of the shot, Figure 26, the experimental velocity is in agreement with the predicted value. Whatever the loss mechanism is, its effect must be continually increasing during the duration of an augmented shot.

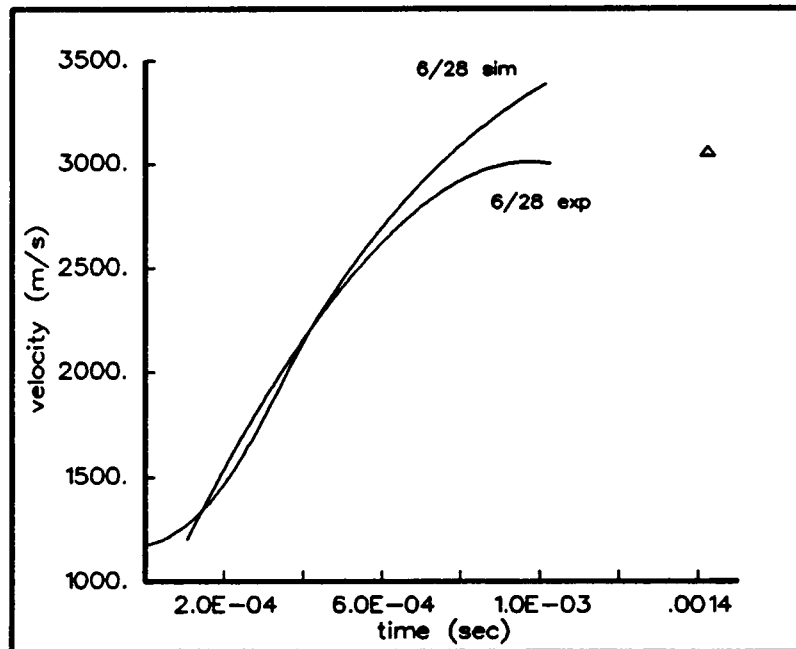


Fig.27 The 6/28 augmented shot with an increased ablation constant to show the loss mechanism is not of this form.

Figure 28 shows simulated and experimental velocity profiles for the 7/10 (104 kA inner rail, 142 kA outer rail) and 7/23 (104 kA inner rail, 105 kA outer

rail with augmentor delayed) augmented shots (See Table 2). The high current classical shots were off their predicted values, but they were not off by as much as the augmented shots 6/28 and 7/10. In the high current shots, the ablation goes up with the rise in current. In the augmented shots, since the inner rail current remains the same, there should be no added ablation.

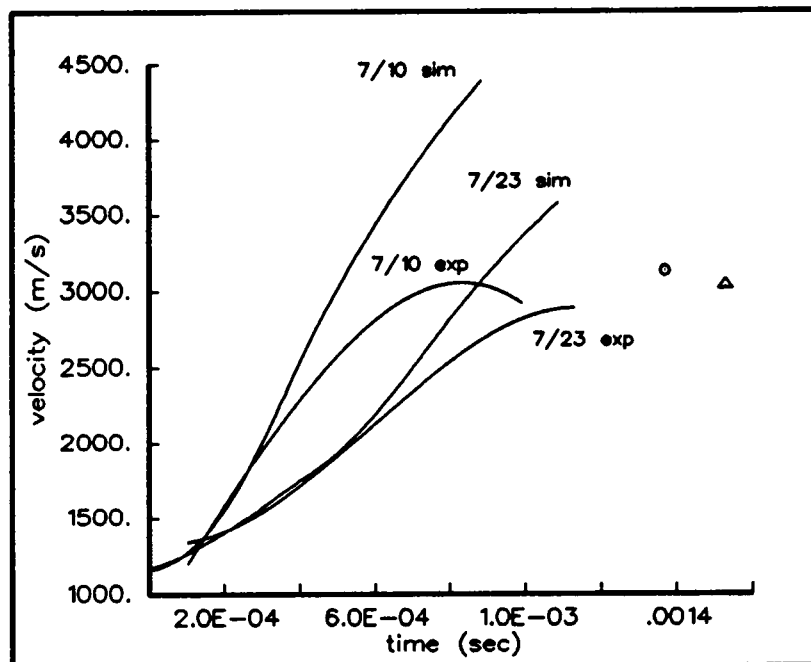


Fig.28 Velocity profiles for the 7/10 and 7/23 augmented shots. Data points shown are MAVIS velocities.

Figure 29 shows simulated and experimental velocity profiles for the 9/25 (68 kA inner rail, 30 kA outer rail) augmented shot and the 8/16 (67 kA) unaugmented shot (See Table 2). The 9/25 shot was a low current shot and was in relative agreement with its predicted performance.

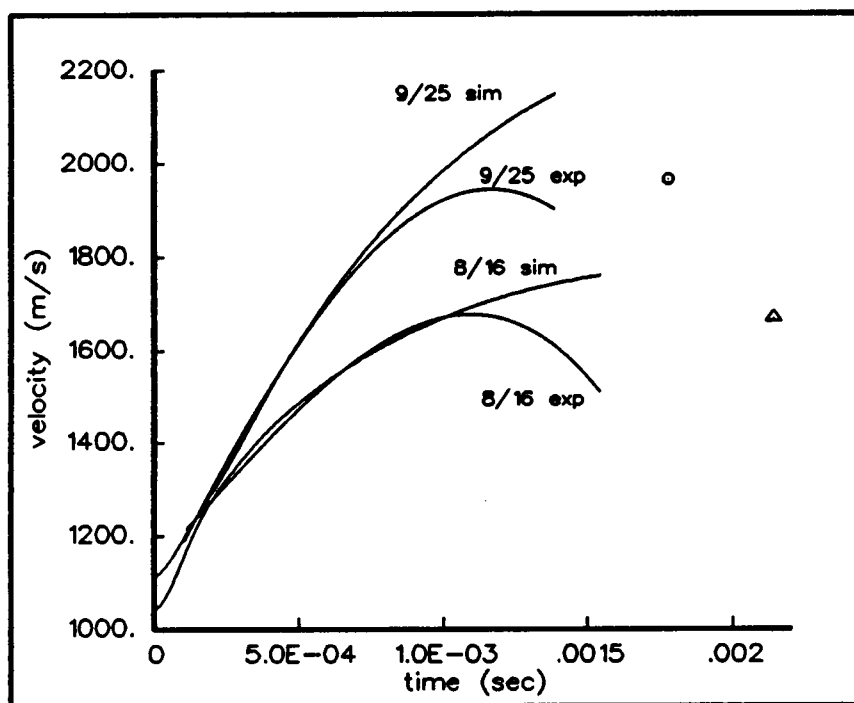


Fig.29 Velocity profiles for the 8/16 and 9/25 shots. Data points shown are MAVIS velocities.

Table 3 summarizes the experiments performed on the UTSI transaugmented railgun. The muzzle velocity shown is the velocity obtained from MAVIS. The theoretical expected change in velocity for each shot was obtained by subtracting the exit velocity in the simulation from the entrance velocity for each shot. The simulations included the ablation drag term and the pressure from the light gas gun and fuse vaporization. The experimental velocity change was obtained by subtracting the MAVIS velocity from the entrance velocity. The efficiency was then the experimental change divided by the expected change. By looking at these efficiencies and the plots that have been presented it can be seen that the higher current augmented shots are well short of their predicted values.

Table 3. Summary of UTSI 2.4 m Railgun Experiments

Shot	Rail Current (kA)	Augment Current (kA)	Muzzle Velocity (m/s)	Δv_E Measured (m/s)	Δv_{theory} (m/s)	$\frac{\Delta v_E}{\Delta v_{theory}}$ (%)
816	67	0	1669	630	722	87.3
617	104	0	2476	1365	1388	98.3
919	120	0	2379	1299	1679	77.4
906	133	0	2655	1602	1983	80.8
730	138	0	2493	1469	2062	71.2
925	68	30	1966	886	1069	82.9
628	104	105	3046	1950	2842	68.6
723	104	105(c)	3030	1920	2408	79.7
710	104	142	3135	2055	3241	63.4

(c) Augmentor Fired When Rail Crowbars

VI. SUMMARY AND CONCLUSION

The UTSI transaugmented railgun did not perform as expected. It is clear from the simulations that the augmenting force is not accelerating the projectile, as much as the Lorentz force predicts. The low current augmented shot is in fair agreement with its predicted value but even it starts to fall away from its predicted velocity fairly early. With the 6/28 and 7/10 shots it is very obvious they did not perform as expected. The pressure pulse and ablation drag constant should not change from the 104 kA baseline shot to the augmented shots for which the inner rail current was unchanged. Even with these forces taken into consideration, the augmented shots were well off their predicted values.

The increase in performance of the augmented shots over the baseline classic shot should have been from the part of the Lorentz force, Equation 3, with the mutual inductance term M' . The value of M' obtained in Chapter 3, Equation 28 is the value for which the most information is known and should be more than reasonably accurate. The value for M' used in the simulations was the average value for M' in the first 0.1 milliseconds of the circuit experiments. The value of M' increased with time in the circuit experiments. Therefore a conservative value of M' was used and should have underestimated the expected velocity.

The value of M' was obtained from experiments in which the circuit was stationary. The railgun is a dynamic system and the effective value of M' could be smaller in this case. An effort is being made to better understand the magnetic field diffusion into the rails and the gun structure for the dynamic case. Work is currently being done to get accurate measurements of the magnetic field in the plasma armature and the region between the inner rails.

There is also the possibility that the gun structure at high current loadings if deflecting and opening leak paths in the rail insulator joints. This could have been the case for the higher current classical railgun shots and the augmented shots. The simple model worked well for the two low current shots, even though there was a 37 kA difference in their peak currents. With the 120 kA peak current shot, there was an increase in peak current of only 16 kA, but the model did not match the experimental values. Also the one low current augmented shot matched its predicted value fairly well and it was only at the higher currents that there were the obvious differences between expected and experimental data. This could be explained if leak paths in the rail insulator joints exist when the peak current gets past some particular value.

One problem with the theory that there are leak paths is the fact that all the shots experienced a primary separation. The separation happens when cold gas builds up between the armature and the projectile. Until current reaches its peak value the electromagnetic force on the armature increases and this cold gas is continually compressed. Once current gets past its peak value the force on the

armature gradually decreases and the cold gas expands causing the primary arc to separate from the projectile. If there were leak paths at higher currents then this cold gas should also have leaked and reduced the possibility of primary separation. This is not the case. The gun structure was re-torqued to a 10% higher value, and the baseline 104 kA unaugmented and augmented tests were repeated with no change in performance. Thus it is unlikely the gun structure is leaking at the rail-insulator interface. Once testing is finished on the UTSI transaugmented railgun, it can be opened to actually see if the structure leaked on any of the shots.

If the gun structure did not leak under high current loadings then one is left with saying the effective M' for railgun shots is lower than that obtained from the stationary circuit experiments.

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VITA

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