LEGIBILITY NOTICE

A major purpose of the Technical Information Center is to provide the broadest dissemination possible of information contained in DOE's Research and Development Reports to business, industry, the academic community, and federal, state and local governments.

Although a small portion of this report is not reproducible, it is being made available to expedite the availability of information on the research discussed herein.

LA-UR -88-789

LA-UR--88-789

DE88 007900

TITLE: WHY PLASMA ARMATURE RAILGUNS DON'T WORK (AND WHAT CAN BE DONE ABOUT IT)

AUTHOR(S): Jerald V. Parker, P-1

SUBMITTED TO: 4th Symposium on Electromagnetic Launch Technology
The University of Texas at Austin
Balcones Research Center
Austin, Texas

April 12-14, 1988

Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

WHY PLASMA ARMATURE RAILGUNS DON'T WORK (AND WHAT CAN BE DONE ABOUT IT)*

Jerald V. Parker
Los Alamos Alamos National Laboratory
Post Office Box 1663, Mail Stop E526
Los Alamos, New Mexico 87545

Abstract

Plasma armature railguns have failed to achieve the high velocities predicted in the early 1980's. Only a few experiments in the last decade have exceeded the velocity of 5.9 km/s obtained by Rashleigh and Marshall in their pioneering plasma armature experiments.[1] The apparent barrier at 5 to 7 km/s results from viscous and ablation drag on neutral and ionized material in the railgun bore.

It has taken almost five years to understand and demonstrate clearly the inter-relation of ablation, viscous drag, and arc restrike. In the light of this improved understanding, it is time to examine the future potential of plasma armature railguns.

There is little reason to hope that conventional railguns will exceed a velocity of 8 to 10 km/s. New approaches based on reducing the amount of material entering the bore or eliminating electrical conduction appear promising. Based on current understanding a velocity of 20 to 25 km/s appears possible using either advanced materials or novel railgun power systems.

Introduction

Plasma armature railguns have been the subject of active research and development since the Rashleigh and Marshall paper was published in 1978.[1] Following the publication of [1], there was substantial enthusiasm for the development of plasma armature accelerators operating at velocities of 20 to 50 km/s. The basis for this optimism was a general belief that plasma armatures could couple magnetic force to projectiles at almost any velocity up to the speed of light and that the principal velocity limitation was projectile-bore interactions.

After a decade of research, only three laboratories[2,3,4] have reported achieving velocities significantly higher than the 5.9 km/s report by Rashleigh and Marshall. It is now generally accepted that the plasma armature itself has strong interactions with the railgun structure and that these interactions are the dominant factor limiting the performance of plasma armature railguns. The first section of this paper reviews the current semi-quantitative model of plasma armature dynamics. The importance of restrike conduction and the key roles played by ablation and viscous drag in causing restrike are discussed.

The second section reviews the progress which has been made toward eliminating or circumventing restrike and plasma armature drag. A number of ideas suggested in 1985[5] have been evaluated experimentally in the past two years with encouraging results.

Plasma Armature Dynamics

Our understanding of plasma armature dynamics has improved steadily since 1984[6] when the importance of wall ablation was first discussed. Experiments on the HYVAX railgun at Los Alamos culminated in a 1985 paper[5] which identified viscous drag as a second important process and described the phenomenon of current restrike. Although it was recognized at this time that ablation and viscous drag were closely coupled processes, the important relationship between restrike and the ablation-drag process was not appreciated.

By the Third EML Symposium in April 1986, the experimental data base was much broader and a coherent picture of the plasma armature was emerging. The paper of Hawke, et al.[7] summarized an extensive series of experiments at Lawrence Livermore National Laboratory and concluded that restrike was the most important process limiting the performance of their plasma armature railgun. At this same meeting, Parker and Parsons[8] presented an improved, but qualitative, model of the plasma armature. This model explicitly recognized that restrike was a direct result of viscous drag acting on neutral material evaporated from the walls rather than on ionized material ablated from the walls.

Figure 1 illustrates schematically the processes which act upon the plasma armature in a conventional railgun. The armature is depicted in a quasi-equilibrium state achieved after having moved a substantial distance, typically 50-100 diameters. The physical state of each region and the important processes are summarized below.

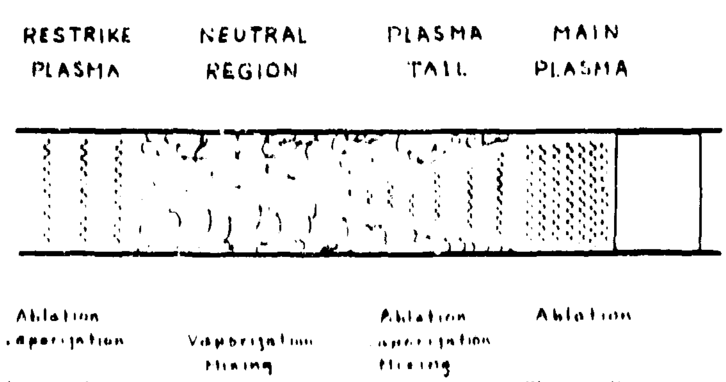

Fig. 1. Schematic of the plasma armature in a railgun. Various regions identified above the schematic and important processes below.

Manuscript received 11 March 1988

*Work supported by the U.S. Department of Energy and the U.S. Air Force Armament Technology Laboratory, Eglin AFB, Florida.

Primary Plasma The plasma properties of the primary plasma have been calculated by numerous investigators and the details are available in the literature. For the present purpose, it is sufficient to note that the plasma is highly ionized, at a temperature of 20,000-30,000°K and is dissipating power at a level of several MW/cm². Most of the primary plasma is strongly magnetized and the boundary layers are thin due to magnetohydrodynamic forces. This results in a rather high drag coefficient (C_f = 0.003-0.005). Intense heat and radiation flux at the walls is ablating material which is ionized and added to the armature plasma. The rate of mass addition ranges from 4 to 8 x 10^{-9} kg/J for plastic insulators up to 30-90 x 10^{-9} kg/J for metal rails. Electromagnetic force accelerates the ablated material almost to the velocity of the main plasma. Viscous boundary forces slowly drag most of this ablated material backward into the plasma tail region.

Plasma Tail As the ablated material is dragged back, it continues to radiate and conduct energy to the walls. The power flux is lower in the tail region, however, and less of the wall material is ionized. The neutral gas from the walls begins to mix into the plasma, quenching the conductivity. A cool boundary layer develops that grows into the plasma until finally the conductivity becomes too low for current to flow. This marks the end of the plasma tail.

The amount of mass evaporated in the tail region is difficult to estimate. Table I summarized the calculated mass addition coefficients for some typical railgun materials in three different modes: ablation (fully ionized, 20,000°K), vaporization (1% ionized, 5000°) and erosion (vapor - liquid). The maximum mass addition rate for vaporization of wall materials ranges from α = 25-40 x 10^{-9} kg/J for single plastics to α = 100-200 x 10^{-9} kg/J for typical metal rails. Since a large amount of the input energy is still stored as ionization and dissociation in the hotter parts of the plasma tail, the mass addition coefficient will be lower than these maximum values but still substantially higher than the ablation values appropriate for the main plasma. A reasonable estimate is that the mass added in the tail region is about twice again the mass ablated in the main plasma region.

Table I

Values of α for Various Materials and Modes

Material	Ablation	Vaporization (1% ionized)	Erosion (gas-liquid)
Copper	28 g/MJ	118 g/MJ	143 - 1630 g/MJ
Tungsten	~ 88	~ 160	188 - 1878
Polyethylene	3.4	28	~ 800 - 6800
Lexan	~ 5.6	~ 40	?
G-10	6.7 ?	~ 40	?

By simple momentum and energy conservation, the conditions at the end of the plasma tail can be estimated. One unit of mass from the main plasma (20,000-30,000°K, v = plasma velocity) mixes with two units of cold gas at rest resulting in three units of weakly ionized gas at a temperature of 6000°K - 10,000°K moving at a velocity about 1/3 the main plasma velocity.

This model of the main plasma and the plasma tail explains the apparent contradiction between the early ablation model[6] that assumed that the armature mass increased continuously as ablated material accumulated, and the experimental observation of nearly constant plasma armature length. In equilibrium, the armature mass is nearly constant. Ablated material is continuously dragged back where it mixes with cool gas from the wall, becomes less conductive, and is lost from the armature. The equilibrium length of the armature is determined primarily by the rate of vaporization from the walls and the rate of turbulent mixing of wall material into the plasma. This model is in agreement with the limited experimental data available which shows a linear scaling of equilibrium plasma length with bore diameter.

Neutral Region The gas entering the neutral region is very hot and moving at a velocity substantially below the plasma velocity. This gas is in turbulent flow and both heat and momentum are rapidly coupled to the walls. This causes further vaporization of material from the walls. Plastic insulators are particularly vulnerable due to their high vapor pressure and poor thermal conductivity. Metal rails may not be vaporized if the rate of conduction cooling into the rail exceeds the rate of heat input from the gas.

A reasonable estimate of the mass density in the neutral region can be obtained by assuming that one half of the energy dissipated in plasma armature is used to ablate the metal rail [illegible] that no subsequent evaporation takes place. The other half of the energy vaporizes the insulator material at the maximum rate of 50-100 x 10^{-9} kg/J. The mass density in the neutral region is thus given by

$$\delta_N = \frac{I V_a (\alpha_a^R + \alpha_v^I)}{2 \pi R^2 v} \qquad (1)$$

where

- I = armature current
- V_a = armature voltage
- α_a^R = rail mass addition coefficient for ablation
- α_v^I = insulator mass addition coefficient for vaporization
- R = bore radius
- v = plasma velocity

For experiment F3 reported by Hawke[7], Eqn. 1 predicts a mass density of 3.4 kg/m³ in the neutral region wall behind the plasma armature.

The gas velocity in the neutral region will continue to decrease due to viscous drag against the walls and due to the admixture of material vaporized from the insulator. A lower bound to the gas velocity is set by the injector gas which is usually moving about 10^3 m/s.

Restrike Plasma The neutral region discussed above is not truly neutral. The gas is neutral only in the sense that the high gas density and weak ionization result in a very low electrical conductivity and no current flow is observed by conventional diagnostics (resolution ~ 1-2 kA). However, if a sufficiently high electric field is applied to this gas, the resultant small current flow will lead to run-away ionization and the reestablishment of a hot, low-density, highly ionized plasma, the so-called restrike arc. The electric field required to cause such a breakdown depends primarily upon neutral gas density and level of residual ionization and secondarily on other factors, such as; gas temperature, gas composition, and electrode surface conditions.

In a railgun the electric field needed to produce a breakdown is generated by the moving magnetic field. A gas moving at velocity v_g, located behind a plasma armature moving at velocity v_a, experiences an electric field

$$\epsilon = \frac{L'I(v_a - v_g) + V_a}{h} \qquad (2)$$

where L is the inductance gradient, I is the current, V_a is the armature voltage, and h is an effective rail separation. As the plasma armature velocity increases, the electric field increases until the breakdown field is reached. Since the gas velocity is lowest near the breech and rail damage is often greatest near the breech, it is quite common for breakdown to occur in the breech region. Breakdown can be observed at almost any location behind the armature, however, because so many variables influence the breakdown strength of the gas. The breakdown electric field can be found approximately from experimental observations of restrike arc formation. For the HYVAX and LTS prototype railguns, the breakdown field was 400-500 V/cm. Lower values are measured when the plasma armature causes gross surface melting of the copper rails.

It is apparent that ablation provides the ionized material in which the restrike arc forms. But this is not the most serious effect of ablation.

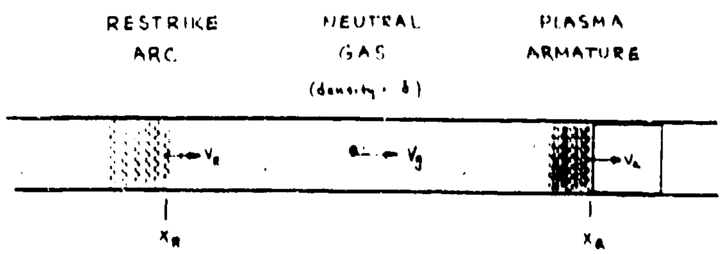

Fig. 2. Simplified illustration of a restrike arc separated from the plasma armature by a column of neutral gas.

Figure 2 shows a simplified restrike situation. For this analysis the neutral gas is assumed to have uniform density δ and velocity v_g. The plasma armature current I_A is less than the input current I_0. The difference $I_0 - I_A$ flows through the restrike arc. The velocity of the restrike arc is determined by the density of the gas which it must accelerate ahead of it and the viscous drag on that gas. The velocity of the restrike arc can be found by equating the magnetic pressure to the pressure required to accelerate the neutral gas and maintain it in motion against the viscous drag force.

$$\frac{1}{2}L'(I_0^2 - I_A^2) = \frac{\gamma + 1}{2}\delta(v_R - v_g)^2 \pi r^2 + C_f \frac{1}{2}\delta v_R^2 2\pi r l_N \qquad (3)$$

where γ is the usual ratio of specific heats, C_f is the drag coefficient, and l_N is the length of the neutral gas region.

To illustrate the magnitude of v_R, Eqn. 3 can be applied to the experiment of Hawke[7] cited earlier. Assume for the sake of argument a complete restrike with $I_A = 0$ and assume further that $\gamma = 1.4$, $v_g = 10^3$ m/s, $\delta = 3.4$ kg/m^3, $C_f = 0.001$, and $l_N = 1.0$ m. Values L' and r are given in [7]. The calculated restrike arc velocity is $v_R = 4.5$ km/s, less than the achieved projectile velocity of 5.1 km/s. Note that this is an upper bound on the restrike arc velocity since viscous drag on the restrike arc itself has been neglected. The critical role of ablation lies in the high mass densities generated in the bore. This mass prevents a restrike arc from overtaking and merging with the plasma armature.

The temporal evolution of the restrike arc is also important in understanding observed railgun performance. Referring again to Fig. 2 the rate of change of the armature current can be calculated from magnetic flux conservation. The magnetic flux between the restrike arc and the plasma armature is

$$\phi = L' I_A (x_a - x_r) \qquad (4)$$

The time rate of charge of φ is equal to the loop voltage. Neglecting resistive losses in the rails, the loop voltage is the difference between the voltage drop across the restrike arc and the plasma armature. Thus

$$L'\frac{dI_A}{dt}(x_a - x_r) + L' I_A (v_a - v_r) = V_a - V_R \qquad (5)$$

Since $V_a \approx V_R$, Eqn. 5 can be rearranged to give an effective time constant for armature current decay.

$$\frac{1}{I_A}\frac{dI_A}{dt} = -\left(\frac{v_a - v_r}{x_a - x_r}\right) = \frac{1}{\tau} \qquad (6)$$

As long as the restrike arc velocity is less than the armature velocity, $\dot{I}_A$ is negative and the armature current will decrease. Note that the time constant for the projectile force $(1/I_A^2\, dI_A^2/dt)$ is one half the value given by Eqn. 6.

A typical time constant for current decay after restrike can be calculated from Eqn. 6 assuming $V_a \sim 6$ km/s, $V_r \approx 1$ km/s and $x_a - x_r \sim 1$ meter. This yields $\tau \sim 200$ μs for the current decay and 100 μs for the force decay. It is apparent why restrike arcs are often correlated with a "sudden" loss of acceleration.

Comparison with Experiments

The simple ablation/drag model, without restrike, has been compared with a variety of experiments by Schnurr[3]. The comparisons are generally quite good if the measured armature current is used rather than the input current. Using the measured armature current provides an ad hoc correction for restrike.

The plasma armature model including restrike is still a semi-quantilative description and detailed numerical comparisons are not yet possible. It is possible, however, to understand many of the observed characteristics of plasma armature railguns and to examine the scaling behavior of the extended model.

Acceleration The only parameter which has a strong experimental correlation with railgun velocity is acceleration. Table II shows this correlation for some of the highest velocity experiments performed. The final velocities shown in Table II scale with acceleration approximately at $a^{1/4}$.

Table II

Summary Of Results

Organization	Velocity	Mass	Peak Current	Peak Pressure	Acceleration
ANU	5.9 km/s	2.5 g	300 kA	16 KSI	735 KGee's
LLNL	6.6	1.0	345	23	2060
Vought	8.2	2.5	560	53	2420
Westinghouse	8.2	1.0	420	41	2880
LANL/LLNL	10	2.8	1200	130	6560

Why should the maximum velocity depend on acceleration when restrike depends on velocity according to Eqn. 2? The answer lies in a closer examination of the breakdown voltage scaling. Most plasma ionization phenomenon are functions of ϵ/n, the ratio of electric field to particle density. Assuming this is true for the restrike breakdown, then Eqns. 1 and 2 can be solved for the velocity which produces breakdown. Let the breakdown field

$$\epsilon_B = \left(\frac{\epsilon}{N}\right)^* \frac{\delta_N}{A}$$

where δ_N is the neutral gas density, A is the average atomic weight of the gas, and $(\epsilon/N)^*$ is the threshold value for electrical breakdown. Combining Eqns. 1 and 2 and assuming the effective rail separation h = 1.4 r for a round bore gives

$$V_r = V_0 + \frac{0.7\left(\frac{\epsilon}{n}\right)^* V_a(\alpha_a^R + \alpha_v^l)}{4\pi r v L'} - \frac{V_a}{L'I} \qquad (7)$$

Equation 7 predicts an armature velocity for restrike which is independent of current but scales linearly with the armature voltage V_a. Since armature voltage increases slowly with current, the observed dependence of maximum velocity on acceleration is partially explained by the high current densities required to obtain high acceleration. Railguns operating at high current actually insulate themselves against restrike by filling the bore with additional neutral gas.

There is a second reason why maximum velocity is a function of acceleration. It was shown above that armature force does not cease immediately when restrike occurs but rather decays over a time $\tau/2$ where τ is given by Eqn 6. Although $\tau/2$ is quite small, there can be a significant velocity increase in this time. For example, for Hawke's test F3, the projectile acceleration deviates from the calculated acceleration when the projectile velocity is 4.3 km/s and the acceleration is 6.5×10^6 m/s. Assuming this deviation marks the beginning of restrike, the predicted force decay time from Eqn. 6 is 150 μs. An additional velocity increase of $\Delta V = 6.5 \times 10^6 \times 150 \times 10^{-6} = 975$ m/s can occur while current is transferring from the armature to the restrike arc. The measured velocity increase after restrike for test F3 is 800 m/s in good agreement with the prediction.

The 10 km/s test reported by LANL/LLNL achieved a peak acceleration of 6.4×10^7 m/s^2 (Table II). If restrike occurred at a velocity as low as 6 km/s, there was sufficient time for the projectile to reach 10 km/s as the current decayed in the armature. It is unfortunate that few payloads can tolerate such high levels of acceleration.

Materials The highest velocity plasma armature railgun tests have all used plastic or glass-reinforced plastic insulators. A number of experiments performed with high temperature materials have given disappointing results. This behavior can be understood from the restrike velocity relationship given by Eqn. 7. If restrike limits velocity, then the best results will be obtained when

$$\left(\frac{\alpha_v^l + \alpha_a^R}{A}\right)$$

is large and the bore has a high particle density to insulate against breakdown. This quantity is maximized by using materials with low atomic weight (small A) and low heat of vaporization

$$(\text{large } \alpha_v^l)$$

The low density plastics such as Lexan best satisfy these requirements.

Attempts to use a mica-based insulator on the HYVAX railgun are consistent with this model. The mica insulator was ablated by the armature but did not vaporize neutral material into the bore after the armature passed. The plasma armature length increased continuously (no quenching) and restrike developed quickly in the plasma tail region. Tests using mica insulation produced lower velocities than comparable tests using G-10 insulation.

What Can be Done to Increase Performance

All of the available evidence points to arc restrike as the principle velocity limiting process in present plasma armature railgun. Both experiment and theory predict that velocities in excess of 6 to 8 km/s will not be achieved unless restrike is controlled.

Techniques for restrike control fall into two broad categories; techniques which eliminate current conduction and techniques which eliminate neutral gas from the railguns bore. Each of these general approaches is discussed below with examples of specific techniques.

In some case, recent experimental work is available to help in assessing the practicability of restrike control.

<u>Controlling Current Flow</u> Restrike arc current can be eliminated in principle by interrupting the current path, either inside the railgun or in the external circuit. A number of the techniques which have been suggested are described briefly below.

<u>Breakdown Voltage</u> The breakdown voltage of the gas in the bore can be increased by raising the atomic number density or adding components which increase dielectric strength. The measured breakdown fields are ≤ 500 V/cm while the fields generated in a high velocity railgun may exceed 3000 V/cm. A straightforward increase in number density by a factor of 10 might provide the required increase in breakdown field. It is unlikely that the neutral vaporization rate can be increased ten times, however, because the armature power dissipation cannot supply the heat of vaporization for this much material. External injection of cold gas has been suggested but does not appear feasible due to the short times involved.

The neutral vapor density might be increased by coating the walls with a reactive material which provids its own vaporization energy through chemical reaction. A 200-300 μm thick layer would provide the required neutral density. Ignition energy is available from the plasma armature. The practical problem of renewing the wall coating would probably limit this technique to laboratory devices.

Adding electronegative atoms is a common technique to increase the breakdown voltage. This idea was evaluated on the HYVAX railgun by coating the insulator surface with epoxy containing 10% lithium fluoride powder. An increase in armature voltage was observed but the effect on restrike was inconclusive. From other experimental data on halogen-gas mixtures an increase in breakdown voltage of more than threefold is unlikely.

<u>External Circuit Changes</u> The classic circuit solution to restrike is a multi-stage, segmented railgun. By segmenting the railgun into many independent stages with independent power supplies, restrike is prevented in all but the active stage. This concept has never been evaluated experimentally because of several practical difficulties. The length of each stage is limited to 1 or 2 meters for effective restrike control. This requires many stages with individual power supplies and switching. There is a serious issue of magnetic energy loss when stages are switched off and an issue of arc damage to the inter-stage insulation.

Recently a new type of segmented design, the Segmented Rail Surface (SRS) railgun, has been developed and tested. Suppression of restrike was demonstrated experimentally as well as increased performance. The SRS railgun resolves several of the issues inherent in a conventional segmented railgun but questions of mechanical and electrical complexity are still present. Details of the SRS railgun are presented in a companion paper[10].

The distributed energy store railgun can also be designed to suppress restrike. To accomplish restrike control the current waveforms must be carefully adjusted to produce near zero current in the region where restrike might otherwise occur. Zero current results in zero magnetic field and thus no inductive voltage to create a restrike. The theoretical feasibility of such a design was shown by Parker[11] for the case of a short, well defined armature. The interaction of the distributed circuit tuning and a long plasma armature has not been addressed. In any case, the analysis in [11] shows that the current in a distributed railgun returns to zero about 4 to 5 stages behind the armature which might require as many as 2 energy storage stages/meter. The distributed energy storage design eliminates the mechanical complexity of a segmented barrel but retains the electrical complexity.

<u>Neutral Gas Velocity</u> The apparent electric field acting in the restrike region can be lowered by increasing the velocity of the neutral gas. One way to accomplish this is to use a high velocity injector whose propellant gases help prevent slowing of the ablated wall gases. This technique is incorporated into the design of the Lethality Test System launcher at Los Alamos National Laboratory and the STARFIRE railgun at Sandia National Laboratory. Both systems are designed with a two-stage hydrogen gun injector operating at 6 to 8 km/s. The LTS launcher project was cancelled before experimental work could begin but STARFIRE is nearly operational and experimental evaluation of this restrike control technique should be available soon.

<u>Eliminating Vaporized Material from the Bore</u> If there is little or no mass in the bore of a railgun, then a restrike arc can accelerate to high velocity, overtake, and merge with the plasma armature. The key question is "what is a <u>little</u> mass?"

The answer is, "as much as the magnetic force can move against the viscous drag force." Assuming for simplicity that the mass is uniformly distributed, the viscous drag force can be written approximately as[5]

$$F_D = 2C_f \frac{m_R}{D} V^2 \qquad (8)$$

where C_f is the drag coefficient, m_R the mass carried by the restrike current, and D the bore diameter. The drag force increases during the launch as m_R and V increase. At the end of launch, the drag force should be a small fraction of the total applied force in an efficient launcher. Choosing 30% as a reasonable loss in drive force, one can solve for the permissible mass, M_R.

$$M_R = \frac{0.075 L' I^2 D}{C_f V^2} \qquad (9)$$

Applying Eqn. 9 to Hawke's test F3' and assuming V = 12 km/s (the design velocity) and C_f = .002 yields $M_R = 4.3 \times 10^{-5}$ kg. Earlier the neutral mass density for test f3 was estimated to be 3.4 kg/m^3. Multiplying by the bore volume gives a total neutral gas mass of 2×10^{-3} kg, about 50 times the tolerable mass according to Eqn. 9. Even if these estimates are in error by a factor of 2 or 3, it is apparent that very large decreases in the ablation and vaporization rates will be required. A number of techniques for reducing ablation are described below and assessed in light of this requirement.

Reduced Armature Power Since the ablated mass is proportional to the energy dissipated in the plasma armature, the reduction of armature power dissipation is important. Power dissipation can be reduced by lowering the armature voltage or the armature current.

Voltage Reduction Lower plasma armature voltage has been a continuing goal of many railgun efforts during the past decade. Various techniques have been suggested, including seeding with easily ionized atoms and careful control of plasma composition and/or temperature. At present, there are no published results demonstrating significant voltage reductions. It seems unlikely that voltage reductions of more than 30 to 50% will be achieved. The most reliable voltage reduction technique is to reduce the armature current. For typical railgun condition, a 10% current decrease yields a 3 to 4% voltage decrease.

Current Reduction Armature current can be reduced by using augmenting turns or externally generated magnetic fields. However, when the armature current is reduced the average magnetic field must be increased in proportion to maintain the accelerating force. The transverse forces on the structure increase rapidly resulting first in more a massive structure and finally in stresses which exceed the strength of available materials. The scaling of transverse force is easily expressed in terms of the reduction in armature current. Let F_T be the transverse force on a conventional railgun operating at current I_o. Then if the armature current is decreased to $I_a = RI_o$, the transverse force on the augmented railgun is given by

$$F_T^a = F_T\left(\frac{1+R^2}{2R}\right)^2 \qquad (10)$$

Reducing the armature current by a factor of 2 ($R = 0.5$) gives $F_T^a/F_T = 1.56$, for $R = 0.333$ $F_T^a/F_T = 2.78$ and for $R = 0.2$ $F_T^a/F_T = 6.76$. Since conventional railguns are already operating near the strength limit of available construction materials, it is unlikely that the armature current can be reduced more than a factor of 2 or 3.

Combining voltage reduction and augmentation may reduce the power dissipation by a factor of 5. Any further improvement must come ultimately from improved materials.

Improved Rail and Insulator Materials The simple linear relation between armature power and ablated mass density expressed by Eqn. 1 is an approximation which neglects the finite heat capacity and thermal conductivity of the wall materials. This approximation is well justified for typical plastic insulators and even for most metals at the heat fluxes generated in a railgun. It has been recognized for some years[9], however, that copper should be able to resist melting and vaporization at high velocity (> 5 km/s). Recently, Rosenwasser[12] published a figure of merit quantifying the ability of materials to resist brief, intense heat pulses. Some of the best refractory ceramics possess a figure of merit comparable to copper due to a combination of high melting temperature and moderate thermal conductivity. For low current and high velocity, it should be possible to operate a railgun without any wall vaporization or ablation.

This conjecture was tested at Los Alamos using the MIDI-2 railgun equipped with copper rails and sialon ceramic insulators. The tests were performed in the "free-arc" mode so that high velocities could be achieved at modest current.

Figure 3 shows a plot of plasma velocity measured at three points along the barrel as a function of plasma current. When the armature current is less than 100 kA, the velocity increases linearly with current as predicted by theory. The curves lie below the theoretical curve by an amount consistent with viscous drag on the armature plasma. For these low current tests, there is no observable change in the ceramic insulators. For tests at 100 kA and above, the insulators develop a greyish coating which is more pronounced at higher current. At the same time the velocity stops increasing with current and the magnetic probe data show the onset of restrike current. Figure 3 presents clear and convincing evidence that it is possible to operate a railgun without ablation at low current and high velocity. The issue is whether material properties can be improved sufficiently to achieve similar results for useful railgun currents and velocities.

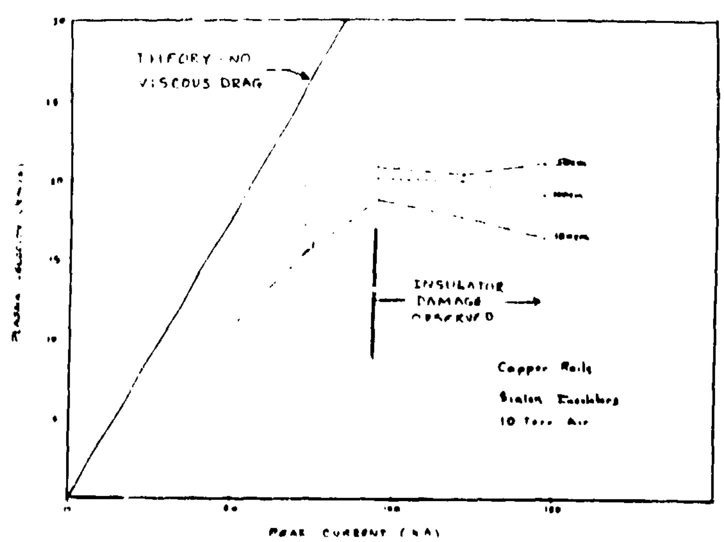

Fig. 3. Free-arc plasma velocity at three axial positions as a function of current showing onset of insulator ablation.

Rosenwasser's figure of merit[12] sets an upper limit on the quantity $Ft^{1/2}$ for a given material, where F is the heat flux and t is the exposure time. The calculated figure of merit for sialon is 0.85×10^7 W $s^{1/2}/m^2$. The onset of damage shown in Fig. 3 occurs at $Ft^{1/2} = 1.0 \times 10^7$ W $s^{1/2}/m^2$, in good agreement with the predicted value.

Sialon, a structural ceramic, does not have a particular high figure of merit. Table III presents the calculated figure of merit for a number of insulator and rail materials.

Table III

Figure of Merit for Some Candidate Railgun Materials

Material	Figure of Merit	Threshold Velocity*
SiO_2 (vit.)	0.24×10^7	3900 km/s
Sialon	0.85	310
Si_3N_4	1.55	100
Al_2O_3	2.06	53
SiC	3.58	18
BN (pyro)	4.2	13
C (diamond)	~21	0.7
Cu	3.5	18
Mo	4.6	10.6
W	5.8	6.7
C (graphite)	7.3	4.2

*) assuming 25 kA/mm armature current

The best candidate insulator is high quality diamond. Although not yet available commercially, thin, high quality diamond films have been grown recently on SiC and other substrates. If diamond films as thick as 200 micron become available on SiC they would provide an unbeatable insulator material.

Is there any near term hope for ablation-free operation? To answer this question, one can calculate the values of $Ft^{1/2}$ which occur during railgun operation. Taking 25 kA/mm as a typical operating current the armature power flux (w/m^2) is approximately $F = 4.1 \times 10^9 + 2.7 \times 10^8/D$, where D is the bore diameter in meters. The exposure time is given by $t = l_a/v$. A reasonable value of l_a is about 5 times the bore diameter so

$$Ft^{\frac{1}{2}} = \left[2.9 \times 10^8 D^{\frac{1}{2}} + \frac{1.94 \times 10^7}{D^{\frac{1}{2}}} \right] v^{-\frac{1}{2}} \qquad (11)$$

where v is in units of km/s.

Inserting the figure of merit values from Table III into Eqn. 11 yields the velocity threshold for ablation-free operation. The calculated threshold velocities at the optimum bore diameter (D ~ 6.7 cm) are shown in the third column of Table III. The bad news is that none of the commercial ceramics are going to work in a conventional railgun. The good news is that the threshold velocity scales as the inverse square of the armature power. Given a factor of 3 reduction in armature power from augmentation and voltage reduction the threshold velocities for commercial ceramics decrease to 3 - 6 km/s and for the rail materials to 1 - 2 km/s.

Conclusions

Conventional plasma armature railguns are limited to velocities of 6 - 8 km/s by arc restrike. To realize the hypervelocity potential of plasma armature railguns, restrike must be eliminated. There are two promising approaches which are based on demonstrated technology. The nearest term solution is some form of circuit arrangement which eliminates current flow in the restrike arc. Both segmented and distributed configurations merit further development, but major issues of electrical and mechanical complexity must be addressed. On a longer term, the development of advanced ceramics coupled with augmentation to reduce armature power shows promise. Special attention will be required to injecting projectiles at a velocity greater than the damage threshold and to preforming the plasma armatures to avoid local bore damage.

With restrike under control, the only plasma related limitation will be viscous drag on the armature plasma. Recent MIDI-2 experiments with a hydrogen plasma armature have demonstrated armature velocities in excess of 30 km/s so armature drag does not appear to be an issue in the 10 - 20 km/s velocity regime.

References

[1] S. C. Rashleigh and R. A. Marshall, "Electromagnetic Acceleration of Macroparticles to High Velocity," J. Appl. Phys. 49, p. 2540 (1978).

[2] R. S. Hawke, A. L. Brooks, F. J. Deadrick, J. K. Scudder, C. M. Fowler, R. S. Caird, and D. R. Peterson, "Results of Railgun Experiments Powered by Magnetic Flux Compression Generators," IEEE Trans. on Magnetics, MAG-18 (1), pp. 82-93 (1982).

[3] M. M. Tower and C. H. Haight, "Development of a High-Energy Distributed Energy Source Electromagnetic Railgun with Improved Energy Conversion Efficiency," IEEE Trans. on Magnetics, MAG-20 (2), pp. 298-301 (1984).

[4] Y. C. Thio, et al., "Feasibility Study of Railguns as a Driver for Impact Fusion," Final Report, DOE/ER/13048-3, Westinghouse Research and Development Laboratory, Pittsburgh, PA, June 1986.

[5] J. V. Parker, W. M. Parsons, C. E. Cummings and W. E. Fox, "Performance Loss Due to Wall Ablation in Plasma Armature Railguns," Paper AIAA-85-1575, 18the Fluid Dynamics and Plasma Dynamics and Lasers Conference, Cincinatti, Ohio, July 1985.

[6] J. V. Parker and W. M. Parsons, "Effect of Ablation on Plasma Armature Dynamics," presented at the DARPA/Service Electromagnetic Propulsion Program Review, Washington, D.C., September 1984.

[7] R. S. Hawke, W. J. Nellis, G. H. Newman, J. Rego, and A. R. Susoeff, "Summary of EM Launcher Experiments Performed at LLNL," IEEE Trans. on Magnetics, MAG-22 (6), pp. 1510-1515 (1986).

[8] J. V. Parker and W. M. Parsons, "Experimental Measurements of Ablation Effects in Plasma Armature Railguns," IEEE Trans. on Magnetics, MAG-22 (6), pp. 1633-1640 (1986).

[9] N. M. Schnurr, J. F. Kerrisk, and J. V. Parker, "Numerical Predictions of Railgun Performance including the Effects of Ablation and Arc Drag," IEEE Trans. on Magnetics, MAG-22 (6), pp 1733-1738 (1986).

[10] J. V. Parker, "The SRS Railgun: A New Approach to Restrike Control," proceedings of this conference.

[11] J. V. Parker, "Electromagnetic Projectile Acceleration Utilizing Distributed Energy Sources," J. Appl. Phys. 53 (10), pp. 6710-6723 (1982).

[12] S. N. Rosenwasser and R. D. Stevenson, "Selection and Evaluation of Insulator Materials for High Performance Railgun Bores," IEEE Trans. on Magnetics, MAG-22 (6), pp. 1722-1729 (1986).