RAILGUN CURRENT GUARD PLATES: ACTIVE CURRENT
MANAGEMENT AND AUGMENTATION

J. H. Beno
U. S. Army

and

W. F. Weldon
University of Texas at Austin

Published in the: IEEE Transactions on
Plasma Science, June 1989

Publication No. PR-90
Center for Electromechanics
The University of Texas at Austin
Balcones Research Center
EME 1.100, Building 133
Austin, TX 78758-4497
(512)471-4496

**RAILGUN CURRENT GUARD PLATES: ACTIVE
CURRENT MANAGEMENT AND AUGMENTATION**

J.H. BENO

U.S. ARMY

W.F. WELDON

CENTER FOR ELECTROMECHANICS

UNIVERSITY OF TEXAS AT AUSTIN

ABSTRACT: A system of auxiliary conductors, designed to reduce current density peaks in railgun rails, is described and the effects on rail current density and projectile force are discussed. Performance comparisons with simple railguns and typical augmented railguns are made.

1. Introduction

One of the main technological objectives remaining to be met by the research program on railguns is to develop high-energy devices capable of firing hundreds or thousands of shots. Railgun technology is still short of producing guns which exhibit sufficiently minor rail damage per shot to meet this goal. A principle cause of rail damage stems from heating associated with the high current densities which must be transferred across the rail/armature interface at high velocities by sliding contact.

The sources of the rail-damaging heat during projectile acceleration are: 1) heat generated across the rail-armature interface due to the contact voltage drop; 2) resistive joule heating from the current in the rails; and 3) friction. The first two sources of damage are strongly dependent on local current densities. In the past, considerable effort has been spent on passive measures which reduce local peak current densities, e.g., a rail with a cross-sectional shape which has no sharp corners. This paper presents the results of an ongoing study to investigate the potential of using auxiliary current-carrying conductors near the rails as an active means to reduce local rail peak current densities. Since these conductors serve the additional purpose of railgun augmentation, their effects on projectile force are also discussed.

Studies to date have been limited to two-rail railguns with symmetrical bore cross sections. Therefore, only symmetrically shaped and symmetrically positioned auxiliary conductors have been

considered. Additionally, investigations have been limited to the effects on rail current distribution and on railgun force-producing capability in isolation from projectile and power supply considerations. It has been assumed that power supplies exist which can drive the conductors with any currents desired.

For the purposes of this paper, all force calculations are made with local rail current density peaks limited to a specified peak value, which is arbitrarily set to 1 MA/in. The peak current densities in the auxiliary conductors, which are not in contact with the projectile, are then set to be ≤ 2 MA/in.. This approach is an attempt to compare the performance of different accelerators under conditions in which accelerator damage would be approximately equal. As will become evident later in the paper, the actual values of 1 or 2 MA/in. are not important. The relative magnitudes of the peak rail densities and peak densities on nonrail conductors are important, and are discussed in section 3.

2. Current Density, Force and Inductance Calculations

Current densities are calculated with a high-frequency approximation using the technique discussed in our previous work [1], which is based on the analogy between the electrostatic surface charge distribution and the magnetostatic surface current distribution for long parallel conductors. In this technique, it is necessary to specify the appropriate magnetic vector potential, **A**, for each conductor, which is constant everywhere in and on a conductor surface. The surface line current density, **J**, is then computed. Kerrisk [2] and Leuer [3] describe

different methods for calculating current distributions based on the same electrostatic analogy. In all three techniques, at the end of a calculation, one knows the magnetic vector potential and the surface line current density, as functions of position on the rail perimeter, for each conductor.

Once the vector potential and current distribution are known on the surface of all conductors, force can be calculated by first calculating the magnetic energy. Integrating $\mathbf{J} \cdot \mathbf{A}$ over the conductor surfaces yields the magnetic energy, W_m . Projectile force is then obtained using the relation:

$$F = \frac{\partial W_m}{\partial x} \quad (1)$$

where 'x' is displacement along the length of the railgun. For a simple two rail railgun, the magnetic energy in front of the armature (on the muzzle side of the armature) is zero and the force can be taken to be equal to the energy in a unit length of railgun behind the armature (on the breech side of the armature). In a railgun which has nearby auxiliary current-carrying conductors (in an augmented railgun, for example) it is necessary to compute the energy in a unit length of railgun behind the armature and in a unit length of railgun in front of the armature (where both rail eddy currents and currents in the auxiliary conductors exist). Force can then be taken as the difference between the two energies.

Proper specification of the magnetic vector potential for the various conductors is required in order to proceed with the current

density calculations. This deserves some discussion for the various types of railgun situations considered in this paper. For the simple two-rail railgun, the vector potential needs to be specified as equal and opposite on the two rails, in order to produce equal but opposite currents in the two rails. For a railgun with close auxiliary conductors, conductors which are symmetrically positioned with respect to the bore center also have equal but opposite vector potentials. The appropriate vector potentials for each conductor can be determined iteratively in order to produce the total currents desired on each conductor. An iterative procedure is necessitated by the fact that for conductors which have large cross sections in comparison to the separation between conductors, the relation between conductor current and the vector potential is significantly nonlinear [4,5]. The magnetic energy calculation in front of the projectile, for example, requires that the vector potentials be iteratively adjusted until the net rail current is zero and the net current in the auxiliary conductors is the same as it was behind the projectile.

As a basis of comparison for the remainder of this paper, the results for a simple two-rail round bore railgun are presented in figures 1 and 2. The two figures are related and should be considered together. Figure 1 defines the general round-bore railgun and its various geometric parameters. The normalized current density for the top half of the right rail of a particular round-bore gun, calculated using the above procedures, is presented in figure 2. The current density of each half-rail has an identical distribution. The plot is normalized so that the magnitude of the current density on the center of the back of the rail is one. The position scale in figure 2 refers to the arc length, s (in

cm), in figure 1. Position, therefore, has its origin at the center of the inside face of the rail and proceeds around the rail perimeter, ending at the center of the outside face of the rail. Note that the current density on the inside rail corner ($s \approx 1.75$) is approximately four times that on the center of the front of the rail. Another strong peak exists on the outside corner ($s \approx 2.75$). From the plot, it is apparent that the primary region of rail damage is in the vicinity of the inside corner ($s \approx 1.75$) since this region not only has the highest level of joule heating, but is also in contact with the armature. As a result, additional heating occurs due to contact voltage drop and friction. A projectile force of 0.346 MN is calculated based on a peak current density of 1 MA/in. (which occurs at $s \approx 1.75$) with the remainder of the current density scaled in accordance with figure 2. The inductance gradient, L' , is calculated from the force and total current using $F = 0.5 L' i^2$.

It should be noted that the current distribution shown in figure 2 exists considerably behind the projectile, calculated with the approximation that the rails have infinite conductivity. Three points need to be made with respect to this calculation: First (discussed in references 1, 2, and 3) of the various approximations for current distribution commonly used, the approximation used here produces answers which most accurately reflect measured railgun inductance gradients and forces. Second, the region immediately behind the projectile consists of freshly exposed rails, and the conditions closely correspond to an infinite conductivity, or high-frequency, calculation (i.e., little or no diffusion). Third, considerations such as those discussed by Marshall [6] lead to the conclusion that the current peaks on the rail inside corners in the vicinity of the projectile are probably

worse than depicted in figure 2, which is for a region considerably behind the projectile. This is because the current which flows on the rail top and back sides in the region remote from the projectile ($s > 1.75$ in figure 2), must flow over the rail surfaces (around the rail perimeter in figure 1) to reach the projectile. Based on figure 2, more than 60% of the rail current flows on the rail top and back sides. Therefore, in order to provide maximum total current flow with minimum local density peaks, the ideal current distribution would be one with high, uniform levels of current on the inside surfaces of the rails ($s < 1.75$ in figure 1) and zero current on the rail top and back sides ($s > 1.75$). This is also a configuration with a high inductance gradient, which does not naturally occur.

3. Current Density Limits on Conductors

Other Than the Rails

It has already been stated that the purpose of this study is to investigate the potential for using auxiliary conductors in the vicinity of the rails for active current shaping in the rails. Since these auxiliary conductors will not be in contact with the projectile and, therefore, will not suffer the effects of friction and contact voltage drop, it is apparent that larger current density peaks can be sustained on these conductors than on the rails. The objective of this section is to present a first pass thermal analysis so that an appropriate current density limit can be set for the auxiliary conductors relative to the current density limit used for the rails. For this purpose, simplified expressions for the heat generated by the primary sources of rail

heating are presented below. These calculations are made for a segment of the inner surface of a rail which extends the length of the gun and has a height (along the inner perimeter of the rail) of 'h'. The expressions developed are for the heat generated per unit height, Q/h. For a more detailed discussion of thermal issues with solid armatures, see Barber [7].

The joule heating in the rails can be expressed as:

$$Q_1 = \int_0^{t_f} i^2 R dt = \int_0^{t_f} i^2 \frac{\text{length}}{\sigma \text{ area}} dt \quad (2)$$

where 'i' is the total current on the segment of rail, 'length' is the length of rail behind the projectile, σ is the conductivity, and the 'area' is the cross-sectional area of the current carrying portion of the rail. Both the area and length terms are functions of time. The cross-sectional area can be taken as the product of 'h' and the current skin depth. The skin depth, δ , is a function of time, and a suitable expression is provided by Knoepful [8]:

$$\delta = \frac{1}{.88623} \sqrt{\frac{t}{\sigma \mu}} = 0.13217 \sqrt{t} \quad (3)$$

where t is time, μ is permeability, and the calculation, which yielded the value of 0.13217, was done for copper. This skin depth is the magnetic skin depth associated with a conducting half-space and is defined such that the total diffused magnetic flux is equal to the

surface flux density, **B**, multiplied by the skin depth. Now, considering the length term in equation (2), the length of railgun behind the armature increases with time. For simplicity, the railgun's driving current is assumed to be a step function at $t = 0$. Then the projectile acceleration, a , is constant and the length term in equation (2) is equal to $1/2at^2$. The result is that the heat generated by joule heating in the rails, per unit height 'h', can be expressed as:

$$\frac{Q_1}{h} = \frac{J^2 a}{(2)(\sigma)(.13217)} \int_0^{t_f} t^{1.5} dt \quad (4)$$

where J is the current density magnitude ($J = i/h$).

The heat dissipated in the rails as a result of the contact voltage between the rails and the armature can be approximated by assuming half the generated heat goes to the rails and half to the armature. Then the heat dissipated in the rails is:

$$Q_2 = \frac{1}{2} \int_0^{t_f} V i dt \quad (5)$$

where 'V' is the voltage drop across one rail-armature interface.

Expressing the current, i , as the current density J times 'h' yields an expression for contact voltage heating per unit height:

$$\frac{Q_2}{h} = \frac{1}{2} \int_0^{t_f} V J dt \quad (6)$$

A reasonable approximation for the voltage drop is to assume it is constant at approximately 100 V which is typical when the projectile speed exceeds a few hundred meters per second.

The heat dissipated in the rails from friction can be expressed as:

$$Q_3 = \int_0^{t_f} \mu_k F_n v dt \quad (7)$$

where μ_k is the coefficient of friction, F_n is the normal force exerted by the projectile on the rails, and 'v' is the projectile speed. F_n can be expressed as magnetic pressure times an area as:

$$F_n = \frac{\mu_o H^2 \text{Area}}{2} = \frac{\mu_o J^2 \text{Area}}{2} \quad (8)$$

where the second expression comes from the boundary conditions on the magnetic field, H (recall that J is a surface current density). If a projectile similar to that in figure 3 is assumed, the area is

$$\frac{b h \cos\theta}{2 \sin\theta},$$

and the heat generated by friction per unit height, 'h' is:

$$\frac{Q_3}{h} = \int_0^{t_f} \frac{\mu_k \mu_o J^2 b a t}{4 \tan\theta} dt \quad (9)$$

In equation (9) the velocity was replaced by the acceleration, a , multiplied by the time. A typical value for μ_k is 0.3 or 0.4 .

Using the approximations in equations (4), (6) and (9) with some typical railgun data yields an approximation for the appropriate relative current density limits for railgun rails and for the auxiliary conductors. For example, if a section of copper rail has an imposed limit of 1 MA/in., as in this paper, and if the railgun has a 2.257 cm bore radius and accelerates the projectile to 2,000 m/s in approximately 4 ft, the total heat generated from all three sources of heat, per unit height of rail, 'h', is approximately 1.15×10^7 J/m. An equivalent amount of heat can be generated by joule heating alone, (from equation (4)) with a current density of 1.8 MA/in. Therefore, if 1 MA/in. is used as the peak density limit on rails for the calculational purposes, the peak density limit on the neighboring conductors not in contact with the armature should be kept less than 1.8 MA/in. If this is done for all calculations, it is possible to compare railguns which have different cross-sectional geometries under conditions of similar rail and conductor heating. While the actual numbers obtained are dependant on the railgun under study and on the assumptions made, the relative ratio obtained for the peak current densities in auxiliary conductors to the peaks in the rails is usually between 3:1 and 1:1. For the remainder of this paper, the peak current density limit in rails is set to be less than or equal to 1 MA/in. and the limit in other auxiliary conductors is set to be less than or equal to 2 MA/in. Since the specified geometry and vector potentials determine the relative magnitudes of current densities in the rail and auxiliary conductors, this means that the more restrictive of the two limits is used.

While the estimates made in this section are undeniably rough approximations, the results appear reasonable. In the absence of more accurate general guidelines or until a specific railgun geometry is studied and refined, these estimates are sufficient for the purposes of the present study.

4. Current Guard Plates

With sections 2 and 3 above as background, the main topic of current management in rails through the use of active auxiliary conductors can now be addressed. The analogy between charge distribution in a parallel plate capacitor and current distribution in a pair of parallel conductors, leads to the realization that techniques used in capacitor design to combat high charge densities should have analogous counterparts in railgun design. In particular, the use of capacitor guard rings, which are exterior, charged conducting rings around the perimeter of a capacitor plate used to lower the charge concentrations at the plate edges, are well known. In order to reduce local peak charge densities in the capacitor plates, the guard rings are charged with the same polarity as the capacitor plate they surround. This leads to the concept of additional current-carrying conductors adjacent to railgun rails, which have current in the same direction as the rail, to reduce high current densities. With reference to the capacitor guard rings, these additional conductors are designated as 'current guard plates' in the remainder of this paper.

Several different guard plate designs have been investigated and will be briefly described before proceeding to the general design which

is most promising. Guard plates consisting of conductors above and below the rails were considered in an attempt to lower the two regions of peak rail current at the rail corners. Calculations show that the primary effect of this design is to lower the amount of current between the two peaks ($1.75 < s < 2.75$ in figure 2), while leaving the peaks themselves and the amount of current on the rail backside relatively unchanged. Similarly, guard plates consisting of conductors behind the rails, which is the most common design for railgun augmentation turns, reduce the backside rail current but have little effect on reducing the the inside corner peak current. However, since this design is common, it is discussed in the following paragraph. This leads to the wrap-around design of figure 4 which is the general shape considered later in this paper. This shape was found to be most useful for reducing rail current density peaks and rail backside currents. With this design, it was found that a fully diffused (DC) guard plate current is much less beneficial than a pulsed current. If the guard plates are driven in a pulsed mode (which would be the case for guard plates wired in series with the rails, for example), the guard plate current density peaks are located in those places where they have the most effect on the rail peak current densities. Therefore, only pulsed guard plates will be considered in this paper.

At this point, it is of interest to discuss some results for the common augmentation turn guard plate design of figure 5. The results presented are for a railgun identical to that of figure 1, with the exception that augmentation turns are added in the manner of figure 5. The augmentation turns are 1 cm thick. If the railgun peak current densities are limited to 1 MA/in., as was done when obtaining the

results shown in figure 2, the railgun force of 0.316 MN for the augmented railgun, is actually less than that of the railgun without augmentation. This assumes that the railgun and augmentation turn are in series (i.e., carry the same current). The force reduction stems from the increase in the relative size of the current peak on the rail inside corner ($s \approx 1.75$) caused by the augmentation current. Although a current density plot is not provided, the ratio of current density on the rail inside corner to that at the center of the front of the rail is approximately 6:1, compared to 4:1 in figure 2. The effect of defining the magnitude of this heightened peak as 1 MA/in. is to reduce the total railgun current to 0.71 MA. In this calculation, the peak density for the augmenting turn is calculated to be less than twice that of the rail, so further reductions to impose the 2 MA/in. limit -- normally imposed for nonrail conductors -- are not necessary. The inductance gradient is $1.252 \mu\text{H/m}$ (compared with $0.494 \mu\text{H/m}$ for the nonaugmented gun). Based on the inductance gradient, if the augmented railgun is driven at the same total current as the gun in figure 2, the force would increase to 0.872 MN. This, however, requires accepting a higher local peak current density than previously allowed.

Now the guard plate design of figure 4 will be considered. Optimization procedures, using available programs which minimize functions of several variables, were utilized to determine a good guard plate geometric design. Two cases were considered: 1) the design was optimized to produce maximum projectile force with the current density limits of 1 MA/in. in the rails and 2MA/in. in the guard plates and 2) the design was optimized to produce as close to the ideal current distribution (discussed at the end of section 2 above) as possible with

the same imposed current density limits. In both cases, the same set of geometric variables was optimized. This variable set was determined after several calculations to investigate the relative effect of the geometric variables on rail and guard plate current distributions. To simplify optimization procedures, this set was kept as small as possible. The variables selected (shown in figure 4) were the radius of curvature on the guard plate top inside corner, r_t ; the radius of the top portion of the guard plate, r_p ; the angle subtended by the rail, α ; and the relative magnitude of the specified magnetic vector potentials for the rails and guard plates (which affects the total current in each.) All other geometric variables were fixed at appropriate values as follows:

- 1) The other guard plate corner radii were set large enough to insure that local current density peaks were not severe, while the rail corner radii were fixed at 1 mm, which is the same used for the railgun associated with figure 2;
- 2) The separation between the guard plate and the rail was set at 2 mm to allow for insulation;
- 3) The difference between the angle subtended by the rail (α in figure 1) and that subtended by the guard plate was fixed at approximately 20° , so that varying the rail angle, α , also varied the guard plate angle by the same amount;
- 4) The rail and guard plate thicknesses were set at 1 cm;
- 5) The bore radius was set at 2.257 cm, which is the same as for the railgun of figure 2.

Some of the results of this optimization are shown in figures 6 through figure 10. Figure 6 is a scale drawing of the design resulting from force optimization and figure 7 presents the associated rail current distribution. The force and current figures presented here assume the availability of independent power sources for the rails and the guard plates. If the guard plates are in series with the rails, driven by the same source, the force is 1.94 MN, the rail and guard current is 2.1 MA, and the effective inductance gradient is 0.88 $\mu\text{H/m}$. The fact that the guard plate overhangs the rails and intrudes slightly into the bore may be viewed by some as a detrimental complication when actually producing such a railgun design, although rifling has been a necessary part of chemical gun design for many years. Therefore, several optimizations were done in which the guard plate was not allowed to overhang the rails, so that r_p in figure 4 was set equal to the railgun bore radius. These results are presented next.

Figure 8 shows a scale drawing of the optimum guard plate design for maximum force when the guard plate is not allowed to overhang the rail, and figure 9 presents the associated rail current distribution. Again, the force figures presented assume the availability of different power sources. If the guard plates and rails are driven in series, the force produced is 1.42 MN, the current is 1.71 MA and the effective inductance gradient is 0.984 $\mu\text{H/m}$.

The final results presented are for the optimization of current distribution, done for the case in which no guard plate overhang is allowed. Figure 10 presents the current distribution and performance results. Since the railgun cross-sectional shape is similar to that of figure 8, it is not provided. The values of the guard plate geometric

parameters are provided, however, in the caption to figure 10. As in previous plots, the density plot shown in figure 10 is normalized so that the density at the middle of the back of the rail is unity. Note that the ratio of the current density in the middle of the inside of the rails ($s = 0$) to the peak on the inside corner ($s \approx 1.5$) is only approximately 1:2 as compared to that of the simple railgun in figure 2 which was 1:4. Additionally, the top and backside current is negligible compared to the current on the rail inside surface. The force is calculated based on the usual peak densities of 1 and 2 MA/in. for the rail and guard plate peak densities, respectively. However, due to the negligible rail top and back side currents, which aggravate the rail peak current close to the projectile in a railgun without guard plates, it is apparent that the same rail density limits are not appropriate for the railgun of figure 2 and the railgun of figure 10. It is not known what relative limits to place on the two guns in order to make a completely equivalent comparison possible.

5. Conclusions

Several conclusions can be drawn from the results presented in the previous sections. The most obvious conclusion is that the wrap-around design of the guard plates can produce four to eight times the force produced by the usual augmented railgun design--without increasing local peak current densities. The range of performance contained in the factors between four and eight is primarily a function of the complexity of design. The more complex designs involve allowing the guard plates to overhang the rail slightly (intruding into the bore

space, similar to rifling in a conventional gun barrel), and the use of separate power supplies for the rail and guard plate conductors. These added complexities represent unacceptable complications for many applications, but may be justifiable for others. For example, many conceptual designs for high-energy systems already envision several power supplies in order to generate the high power levels required. Additionally, segmenting the guard plate into a few properly proportioned 'slices' which are wired in series with each other and with the rails, may provide the high total currents required in the guard plates, while still requiring only one power source. At the lower end of the performance range, a simple series-wired guard plate with no overhang protruding into the bore still provides substantial performance benefits.

The performance enhancements just mentioned represent improvements obtainable without increasing local current densities. However, figures 7 and 9 indicate that the proportion of current on the rail top and back sides is not improved over that of the simple two-rail railgun of figures 1 and 2. In fact, it appears somewhat worse in figure 7. The extent to which this increases the rail damage which occurs on the rail inside corners cannot be ascertained since the three dimensional current distribution in the vicinity of the armature is not accurately known at this time. However, it appears likely that operating the railgun associated with figure 7 at the total currents indicated, may cause somewhat increased rail damage over the simple railgun of figure 2. In order to equalize the damage levels, it may be necessary to reduce the rail and guard plate currents below the levels indicated in the caption of figure 7. It is anticipated, however, that the

force produced by the railgun of figure 7 will still represent a substantial improvement over that of the railguns discussed in figures 1 and 5.

This leads to consideration of the railgun of figure 10, which has a guard plate optimized for current distribution. In this case, the top and backside current is nearly zero. This means that the rail damage associated with this gun should be less than that associated with figure 2. This would allow for increasing rail and guard plate currents in order to equalize damage for appropriate comparisons. Again, the magnitude of this possible increase is not presently known. However, there is a good probability that the railgun which ultimately produces the most force with a given amount of rail damage will be one which has been optimized for current distribution, such as the railgun associated with figure 10.

6. Acknowledgements

Funding for this project has been provided by the U.S. Army and the Center for Electromechanics at the University of Texas.

7. References

- [1] J.H. Beno and W.F. Weldon, "An Investigation into the Potential for Multiple Rail Railguns," 4th Symposium on Electromagnetic Launch Technology, April 1988 (to be published in IEEE Transactions on Magnetics, January 1989).
- [2] J.F. Kerrisk, "Current Distribution and Inductance Calculations for Rail Gun Conductors," Los Alamos Scientific Laboratory Report LA-9092-MS, November 1981.
- [3] J.A. Leuer, "Electromagnetic Modelling of Complex Railgun Geometries," IEEE Transactions on Magnetics, vol. Mag-22, no. 6, November 1986, pg 1584.
- [4] J.R Auton and C.R. Grant, "A New Method for Treating the Nonlinear Current Systems Posed by Certain Asymmetrical Electromagnetic Launcher Geometries," 4th Symposium on Electromagnetic Launch Technology, April 1988 (to be published in IEEE Transactions on Magnetics, January 1989).
- [5] L.M. Landau, E.M. Lifshitz and L.P. Pitaevskii, Electrodynamics of Continuous Media, New York, New York: Pergamon Press 1984, Section 33.
- [6] R.A. Marshall, "Current Flow Patterns in Railguns," IEEE Transactions on Magnetics, vol Mag-20, No. 2, March 1984, pg 243.
- [7] J.P. Barber, "Metal Armature Critical Issues," Proceedings of the First EM Gun Armature Workshop June 1986, Air Force Armament Laboratory, Eglin AFB, Eglin, Florida.
- [8] H. Knoepfel, Pulsed High Magnetic Fields, Amsterdam, Holland: North Holland Publishing Co. 1970, section 3.12 (eqn. 3.32)

FIGURE CAPTIONS

Figure 1. Round bore railgun. Dark lines show the rail cross-section for the two rail round-bore railgun, defining arc length along the perimeter (s), bore radius (r_b), rail thickness (t), and the angle subtended by the half-rail, (α). The arc length origin is at the inside center of the rail. Although not shown, rail corners are rounded with a radius of 1 mm. The dotted line encloses the bore.

Figure 2. Normalized current density for the round bore two-rail railgun of figure 1. For this plot $r_b = 2.257$ cm (so the bore area = 16 sq cm), $\alpha = 45^\circ$, and $t = 1$ cm. The force developed by this railgun is 0.346 MN, with a current of 1.18 MA and inductance gradient of 0.494 $\mu\text{H/m}$.

Figure 3. A sample armature for use in estimating frictional losses.

Figure 4. Round bore railgun with addition of wrap-around guard plates. Only the right rail and guard plate are shown. The rail variables are the same as defined in figure 1. This figure defines the guard plate variables used for optimization: radius of guard plate top inside corner (r_t), radius of the top portion of the guard plate (r_p), angle subtended by the rail (α), and the relative magnitudes of the rail vector potential (A_r) and guard plate vector potential

(A_g). The vector potentials, as well as the currents, in the rail and guard plate are in the same direction, shown here as into the paper. The separation between rail and guard plate is 2 mm.

Figure 5. A typical design for the augmenting turn on a round bore railgun. Only one rail with its augmentation conductor is shown. The usual rail variables are shown as is the separation distance between the augmentation turn and the rail (d) and the thickness of the augmentation turn (t_a).

Figure 6. A scale drawing of the rail and guard plate system optimized for maximum force. Referring to figure 4, $r_p = 1.97\text{cm}$, $r_t = 0.613\text{ cm}$, $\alpha = 37.8^\circ$, and $(A_r/A_g) = 1.087$. Figure 7 shows the performance data for this gun.

Figure 7. Normalized current density for the railgun with guard plate of figure 6. The force developed with this gun is 2.49 MN, with a rail current of 2.14 MA and a guard plate current of 2.95 MA. This calculation invokes the usual limits of $\leq 1\text{MA}$ and $\leq 2\text{ MA}$ for maximum allowable density peaks in the rails and guard plates, respectively. The scales are the same as in figure 2, for comparison purposes.

Figure 8. A scale drawing of the rail and guard plate system optimized for maximum force. For this optimization, the radius of the top portion of the guard plate, r_p , was fixed at

the bore radius of 2.257 cm. Referring to figure 4, $r_t = 0.514$ cm, $\alpha = 37.9^\circ$, and $(A_r/A_g) = 1.059$. Figure 9 shows the performance data for this gun.

Figure 9. Normalized current density for the railgun with guard plate of figure 8. The force developed with this gun is 1.49 MN, with a rail current of 1.48 MA and a guard plate current of 2.41 MA. This calculation invokes the usual limits of ≤ 1 MA and ≤ 2 MA for maximum allowable density peaks in the rails and guard plates, respectively. Scales are the same as on previous current density plots.

Figure 10. Normalized current density for the railgun and guard plate design which was optimized for current distribution. For this optimization the radius of the top portion of the guard plate, r_p , was fixed at the bore radius of 2.257 cm. Referring to figure 4, $r_t = 0.65$ cm, $\alpha = 0^\circ$, and $(A_r/A_g) = 1.000042$. The force developed with this gun is 1.095 MN, with a rail current of 0.744 MA and a guard plate current of 4.61 MA. This calculation invokes the usual limits of ≤ 1 MA and ≤ 2 MA for maximum allowable density peaks in the rails and guard plates, respectively. The density scale is 1,000 times that of previous plots.

Figure 1. Round bore geometry

Figure 2. Normalized current density

Figure 3. Typical armature design

Figure 4. Guard plate geometry

Figure 5. Normal augmentation design

Figure 6. Guard plate design optimized for force

Figure 7. Normalized current density

Figure 8. Guard plate optimized design for force

Figure 9. Normalized current density

Figure 10. Normalized current density