OBSERVATION AND ANALYSIS OF CURRENT CARRYING PLASMAS IN A RAILGUN

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Abstract - Observation of current-carrying plasma arcs driving solid projectiles in round-bore and square-bore railguns have been made with magnetic induction coils. Both free-running precursor arcs as well as projectile armature arcs are observed. Qualitative behavior of the plasmas is inferred from data and compared to basic physical models. The non-uniform nature of the force on the armature is investigated. Experimental details as well as difficulties in calibration and in quantitative analysis of magnetic probe signals are discussed. Evidence suggesting evolution in the structure of free-running arcs is presented.

INTRODUCTION

The highest performance yet achieved in practical railguns is obtained using plasma armatures. To optimize this performance, a thorough understanding of plasma behavior in an operating railgun is necessary. Outstanding work by Powell [1], McNab [2], Jamison [3], and Marshall [4] and others has established a solid foundation in the theoretical understanding and experimental observation of these plasmas. This paper reports further observations and suggests refinements which may explain qualitatively these observations.

The observations were made on railguns tested at the Center for Electromechanics at The University of Texas at Austin (CEM-UT). Two specific guns were used: a 60-cm round-bore gun and a 1-m long square-bore gun. The guns were driven at currents between 150 and 600 kA from a 0.6 MJ, 10-kV capacitor bank or a 3-MJ inductor charged with a homopolar generator. All shots are made in a vacuum of better than 10^{-5} torr.

The magnetic probes were of two types: axial probes with the coil axis oriented parallel to the bore, and vertical probes with the coil axis oriented perpendicular to the plane of the rails. Axial probes were 25 to 40 turns of 40 gauge magnet wire while the vertical probes were 100 to 300 turns. Both types of probes were wound on 2-mm diameter graphite forms potted in epoxy, shielded in a Pyrex® sleeve, and connected through a vacuum chamber wall via shielded twisted pair cables. Custom flanges were constructed to isolate the signal lines from blast plasma. It is easy to show that the axial probes "see" only the armature current, while the vertical probes "see" components of both rail and armature current.

In general, the magnetic probe signals depend on the current distribution. To examine this effect, the expression for the signal voltage expected from the axial probes was derived for the limiting cases of a current loop and finite current sheet distribution of rail current (see geometries in Figs. 1 and 2) assuming a constant rail current.

For a current loop, the signal voltage can be expressed (SI units):

$$\epsilon(t) = NA v(t) \frac{\mu_0 I}{4\pi} \frac{wz(x(t) - x_0)}{r^2 R} \left[\frac{1}{R^2} + \frac{2}{r^2} \right] \quad (1)$$

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where

N = number of turns in coil
 A = coil cross section
 $v(t)$ = armature velocity
 I = total armature current
 w = rail spacing
 z = probe height from center bore
 $x(t)$ = armature displacement from breech
 x_0 = probe displacement from breech

$$r = \sqrt{(x(t) - x_0)^2 + z^2}$$

$$R = \sqrt{r^2 + \left(\frac{w}{2}\right)^2}$$

For a finite current sheet, the signal voltage is expressed

$$\epsilon(t) = NA v(t) (x(t) - x_0) \frac{\mu_0 I}{4\pi} \frac{w}{h} \left[\frac{1}{r_1^2 R_1} - \frac{1}{r_2^2 R_2} \right]$$

where

h = height of the rails
 d = probe height from center bore
 $r = r(z = d \mp h/2)$
 $R = R(z = d \mp h/2)$

Fig. 1. Geometry for current loop calculation of axial probe signals.

Fig. 2. Geometry for current sheet calculation of axial probe signals.

The two expressions are graphed in Fig. 3 for identical square-bore typical values. Clearly the sheet model predicts greater voltage by a factor of about five with maxima closer together. Then, unless the current distribution is well known, it would be impossible to use these probes to measure total current.

Fig. 3. Comparison of current sheet and current loop predictions of axial probe signals.

The vertical probes are integrated and thus the signal voltage is proportional to the magnetic field at the probe location. An expression for the magnetic field "seen" by these probes was derived for a current loop rail current (Fig. 4):

$$B_z(x_0, \frac{w}{2}, z, t) = B_z^{\text{rails}} + B_z^{\text{arc}} \quad (3a)$$

where

$$B_z^{\text{rails}} = \frac{\mu_0 I}{4\pi} \frac{w}{\left[\left(\frac{w}{2}\right)^2 + z^2\right]} \left[\frac{(x(t) - x_0)}{\sqrt{(x(t) - x_0)^2 + \left(\frac{w}{2}\right)^2 + z^2}} + 1 \right] \quad (3b)$$

$$B_z^{\text{arc}} = \frac{\mu_0 I}{4\pi} x$$

$$\frac{w(x(t) - x_0)}{[(x(t) - x_0)^2 + z^2] \sqrt{(x(t) - x_0)^2 + \left(\frac{w}{2}\right)^2 + z^2}} \quad (3c)$$

Fig. 4. Geometry for current loop calculation of vertical probe signals.

The two contributions and their sum are shown in Fig. 5. When the armature is well past the probe location ($x(t) \rightarrow \infty$), the integrated vertical probe signal is proportional to the rail current. With an RC integrator circuit, the voltage would be

$$e(t) = \frac{NA}{RC} B_z(t) \quad (4)$$

Fig. 5. Predicted vertical probe signal showing components from armature and rails.

Additionally, it is seen that when $x(t) = x_0$ the probe signal should be exactly half the value at $x(t) \rightarrow \infty$, and this can be used to determine the time the armature passes the probe, assuming that armature current is localized in a thin sheet behind the projectile.

In practice, the calibration of the vertical probes to rail current is accomplished by shorting the gun at the muzzle, and calibrating the vertical probe signals to a known discharge current.

Two particular shots are shown here as representative of the types of analysis done with magnetic probe data. The first shot is from a 60 cm, round-bore gun which suffered severe leakage of the plasma armature producing a "precursor" arc ahead of the projectile. The second is a typical shot from a 1 m, square-bore gun.

ROUND-BORE SHOT #11

In this shot, a balsa projectile with a copper foam fuse epoxied to the back was accelerated to a velocity of about 2.2 km/s. Three axial probes and one vertical probe were used.

Precursor activity is seen in Fig. 6 where the first 250 μ s of axial probe data is shown. Probe #1 located 2 cm ahead of the fuse registers increasing current in the fuse as the first three of ten capacitor stores were triggered at 20- μ s intervals. At about 50 μ s the fuse ionizes and part of the plasma leaks past the projectile and accelerates down the gun registering on all three probes. From the 20-cm probe spacing and time of signal rise, it is estimated that the leading edge of the precursor plasma attains a velocity of about 60 km/s. The bulk of this plasma progresses at a slower and apparently terminal velocity of about 15 km/s.

Features common to the three probe signals suggest that small current arcs continue to form in front of the projectile and proceed down the gun at about 13 km/s, until about 120 μ s when the passage of the main armature appears in the first probe.

Fig. 6. Round bore shot #11, axial probe data, ($t = 0 - 250 \mu s$)

The passage of the main armature is more clearly seen in Fig. 7 where the entire probe signals are shown with their time integrals superimposed. Passage of the armature by the three probes occurs at 120, 260, and 350 μs .

An interesting effect observed on many shots is the fracturing of the first precursor into discrete, current-carrying sections. Examining the first large precursor arc, the departing plasma registers as a single negative pulse on the first magnetic probe. Passing the second probe, however, that same arc has developed a definite structure indicating that the current distribution has started to show three maximum locations, a fast fragment, the main arc-body, and a tail fragment. At the third probe, the first precursor almost appears to have become three separate arcs, the maxima separated in time by about 10 μs intervals indicating a spacial separation of about 15 cm between maxima.

SQUARE BORE SHOT #6

This shot accelerated a 2.8-g projectile to a velocity of about 4.3 km/s in a distance of 1 m. The probe signals are shown in Fig. 8. Five axial probes and four vertical probes are used. The vertical probe signals were actively integrated and calibrated, so that the traces should (and do) agree with gun current.

From the raw signals, it can be clearly seen that a small precursor current begins at 80 μs and dwells in the rails for the entire shot at a current level of about 60 kA. A slight wave in the first axial probe signal following the armature passage suggests a very small restrike occurring in the breech of the gun, while the last two vertical probes support this by failing to show full gun current in the rails. Clearly some of the current is shunted far behind the projectile.

From the traces, the armature position vs time can be obtained and the velocity vs time inferred in an obvious way. These measures can be compared to theoretical prediction to fully evaluate gun performance. To date, the performance of the 1-m square-bore gun has proved to agree with simulations to the accuracy with which the performance can be measured (all velocities have been less than 5 km/s to date).

A more subtle and interesting use of the probe data is to evaluate the effective L' of the gun since

$$V(t) = \int_0^t \frac{F}{m} dt$$

and

$$F = \frac{1}{2} L' I^2 + \text{friction} + \text{ablation} + \text{viscous drag} \dots$$

then a graph of the velocity vs the time integral of the squared current should be linear with a slope of $L'/2m$. Any deviation from linearity would indicate effects of friction or ablation. Such a graph for shot #6 is shown in Fig. 9 where it can be seen that the slope varies slightly around an average value indicating $L' = 0.3 \mu H/m$, which compares well to the measurement of $L' = 0.32 \mu H/m$ made with an inductance bridge at 100 kHz. The deviations seem to correlate to trip marks found in the rails and some apparent decrease in friction when the projectile exceeds the transverse sound speed of the bore material.

Since the precursor activity is observed on all shots, inquiry was made into its cause and ultimate effect on gun performance. Possible causes include - high voltage arcs (tracking) occurring at the front of the projectile and plasma leakage past the projectile

Fig. 7. Round bore shot #11, axial probe data.

Fig. 8. Square bore shot #6, shot record.

Fig. 9. Square bore shot #6, velocity vs integral squared current.

through cracks and seams in the gun either from thermal pressures or from electromagnetic forces. The question of electromagnetic forces is addressed here.

The precise force on an element of the armature can be expressed as the Lorentz force:

$$\vec{F} = \vec{J} \times \vec{B}_R$$

where B_R is the field generated by the rails. If one computes B_R in a current loop model, the magnetic field is found to diverge at the rail-armature interface. On the other hand, if the rails are taken to be infinitely high current sheets (a two-dimensional approximation used in almost all plasma models), B_R is found to be constant across the armature.

Clearly the rail-current in an actual railgun is neither a filament nor an infinite sheet, but something between the two (to an approximation). In fact, it can be shown that for a finite current sheet (Fig. 10), B_R for any point (y, z) on a flat armature can be written

$$B_z(0, y, z) = \frac{\mu_0 I}{4\pi H} \left[\tan^{-1} \left(\frac{H-z}{y} \right) + \tan^{-1} \left(\frac{z}{y} \right) + \tan^{-1} \left(\frac{W-z}{W-y} \right) + \tan^{-1} \left(\frac{z}{W-y} \right) \right]$$

where

I = total current
 H = rail height
 W = rail spacing

This field is illustrated in Fig. 11. Although not diverging, the field peaks at the rail-armature interfaces. The force variations in any railgun armature with this sort of rail-current will depend upon the armature current distribution, yet if that current distribution approaches a uniform sheet current per-

Fig. 10. Geometry for finite current sheet force calculations

pendicular to the rail currents, the force across the sheet will also vary directly as the field from the rails varies. A sheet current model for the armature may be a good approximation at early times when the aluminum foil fuse explodes or at early times in the formation of precursor arcs before the current can diffuse into the plasma and before the plasma reaches an equilibrium configuration.

A flat sheet current in a freely accelerating plasma armature would experience higher forces at the rail-armature interfaces which would tend to deform the edges ahead of the rest of the plasma. Further, such a deformation, if it persisted, could be considered a kink instability which would grow until the plasma disrupted.

This might explain the appearance of a fast edge, a slower main body, and a fracturing mechanism in precursor arcs. It might also explain the ease with which the plasma leaks past projectiles, though thermal pressures must also be considered.

Although this analysis is too simplistic to draw any hard conclusions, it does serve to illustrate a basic deficiency in the assumption of infinitely high rails to predict plasma armature behavior in a railgun.

The ultimate effect of the precursor has been analyzed from basic electromagnetic arguments and from careful Lagrangian analysis. Both methods indicate that the precursor modifies the basic railgun force equation to

$$F = F_0 \left(1 - \left(\frac{I_p}{I_T} \right)^2 \right)$$

where

$$F_0 = 1/2 L' I_T^2$$

I_T = total current
 I_p = precursor current

Fig. 11. Magnetic field at the armature for a finite current sheet railgun current.

Apparently a precursor carrying 10% of the total gun current will only reduce performance (acceleration) by 1%. Thus, good railgun operation can be obtained by merely minimizing precursor current, not eliminating it entirely. Success of recent square-bore gun shots with $I_p \sim (1/6)I_T$ has verified the validity of this analysis experimentally.

CONCLUSION

Current-carrying plasma armatures are easily observed using magnetic probes, which prove to be one of the most valuable tools in diagnosing performance of a railgun. Secondary arcs including precursors and restrike arcs can be identified, and current in the armature can be quantified. Performance limiting effects may be indirectly observable. The non-uniform force on the arcs may contribute to the fracturing of precursor arcs. Interpretation of probe signals at CEM-UT has shown consistent precursor activity, which has a negligible effect on the operation of the present generation gun. No loss mechanisms are apparent for velocities below 5 km/s, except friction between bore and projectile, which agrees well with a simple empirical model.

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