FOCUSING EXPERIMENTS IN PLASMA COAXIAL RAILGUNS

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Abstract - The "projectile" being accelerated in a plasma coaxial railgun is a complex mixture: besides plasma, it contains solid particles of fuse, liquid and vapor metal. Materials accelerated are not limited to the fuse metal, the rail material through ablation also contributes to them.

For such a situation "plasma focusing" is a simplified term, borrowed from electron beams in vacuum technology (and electron lenses) where the Busch's theorem describes the tendency of electrons to approach the axis (or to focus) in the presence of radial and axial components of magnetic fields and under the assumption that on the time scale of interest, the ions remain essentially motionless.

The present work is the first in a series of papers trying to classify and to explain a larger spectrum of problems affecting a mixture of metals in different states (solid, liquid, and vapor) in which magnetic fields, transient diffusion, and other phenomena may be used to contain or focus a flowing stream under thermal expansion.

The main variable used in experiments to affect the focusing was the topology of magnetic fields, temporal and spatial. Emphasis was given to the effects of penetration of magnetic field in the bulk of the "projectile" being accelerated.

Experiments were conducted on a 0.5-m coaxial railgun with inner and outer coaxial radii of 0.25 and 0.31 in., respectively. The rails were constructed from stock sizes of copper pipe with a CVD tungsten coating on the inner rail surface to minimize arc damage during the shots. External magnetic fields were applied to a 3-mg metallic vapor arc accelerated with a 250 kA capacitive discharge. Plasma characteristics were measured with magnetic pick-up coils and langmuir probes. Confinement and focusing of the arc was examined with break screens and metal deposition analysis.

INTRODUCTION

In the large family of plasma accelerators, the coaxial accelerators are a privileged part due to the properties of the magnetic fields in such structures. The scope of such devices is to accelerate at hypervelocities a projectile of plasma which should in the right conditions produce an extensive damage to a target, damage comparable to the one produced by a solid projectile accelerated by a similar electromagnetic railgun.

To achieve such a goal it is necessary that plasma stores an important amount of kinetic energy. Then it is tempting to assume that plasma can be kept tightly together and by "focusing" it can be concentrated even more in a smaller space and accelerated as a projectile against all the thermodynamic forces trying to blow it apart.

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The term "focusing" is borrowed from the technology of electron beams in vacuum -- where, in the presence of external axial and radial magnetic fields, the electrons are forced to approach the axis. Busch's theorem shows that a beam of particles, entering from a field-free region with no angular velocity into a complex magnetic field distribution, leaves with no angular velocity.

Even if, by some methods, the plasma can be "focused" and concentrated (projectile-like), when it leaves the muzzle of the gun it will expand again and the advantages of the operation will be lost -- unless a certain degree of stability is built in its confinement.

A important step in this direction was achieved by Alfvén, et al. [1], which reported shooting magnetized plasma rings from a coaxial plasma gun. Such toroids have a Tokamak-like stability built-in, having (individually) a longitudinal magnetic field and being wrapped in a poloidal field, larger parts of both fields being generated by currents in plasma itself.

The nature of plasma for the focusing experiments treated in the present paper permits a qualitative improvement over the one just mentioned because it is not a pure hydrogen plasma (as reported in [1]), but being obtained by exploding a metallic fuse at the breech of the gun, is a mixture of metal vapor, metal liquid droplets, and even small solid chunks of metal. Such composition seems to be more amenable to modeling using classical electrodynamics and magneto-hydrodynamics, and also their higher mass permits a larger kinetic energy storage. It would be promising if the experiment of shooting magnetized plasma rings could be repeated for this type of plasma.

METHODOLOGY

In order to "focus" or to "agglomerate" plasma, external magnetic fields will be used. The variable parameters will be related to the topology of the magnetic fields -- spatial and temporal. The space topology refers to changing the ratio between axial and aximuthal components, as well as the intensity and the distance over which magnetic fields are applied. Special effects may be obtained using ferromagnetic materials. The temporal topology refers to the time variation of fields and their diffusion in the neighboring conducting materials.

Two distinct methods of producing plasma were mentioned above. One is injecting a pure gas with high degrees of ionization. The gas can be hydrogen as in Alfvén, et al. experiments [1] or argon (Liu, et al. [2]), and with proper simplifying assumptions a workable mathematical model is possible. The second method creates a plasma with higher potential of damaging the targets by exploding a metal fuse at the railgun breech, accelerating the mixture of solid, liquid and vapor metal, and with the external magnetic fields creating a structure with a "certain degree of stability." This structure is capable of surviving after leaving the railgun muzzle.

Being interested in ways which can do the most damage to a target, the second method of producing plasma will be considered.

Experiments have shown that after the fuse explosion, two fronts propagate along the railgun. The first (initial) plasma front is low current and travels with high speed. A second front contains the main body of plasma, has higher conductivity than the initial front and travels with velocities five to fifteen times lower.

While the initial front is lending itself to be studied with methods of usual plasma physics, the second front behaves as a high conductivity fluid, and at least in the first approximation seems to obey macroscopically the laws of magneto- hydrodynamics [3,4,5]. It is interesting to note that in this macroscopic modeling, the bulk of molten and vapor metal, coexisting with solid chunks of metal fuse, behaves as several successive secondaries of an induction motor. As the front continues to advance the main bulk of plasma expands and slips with respect to the maximum value of the magnetic field, which advances with the velocity of the front. In continuous electrodynamics [3], a generalized slip is defined as

$$s = (\mu_0 \sigma_{av}/k)(V_{front} - V_{mixture}) \quad (1)$$

where

σ_{av} = average conductivity of the layer of plasma considered ($1/\Omega \cdot m$)

$V_{front}, V_{mixture}$ = velocities of the front and of the given layer of plasma, respectively [m/s]

$2\pi/k$ = wavelength of the spatial magnetic field distribution

Then, the time average focusing pressure trying to compress plasma toward the inner electrode

$$P_f = \frac{\mu_0 k^2}{4} \frac{\sqrt{1+s^2} - 1}{\sqrt{1+s^2}} \quad (2)$$

The force per unit area acting in the direction of the axis of cylindrical structure is

$$P_a = \frac{1}{4} \frac{\mu_0 H_m^2 s}{\sqrt{1+s^2} \operatorname{Re} \sqrt{1+js}} \quad (3)$$

where H_m is the peak value of the magnetic field of the front. The formulas in Eqs. (1), (2), and (3) have been obtained considering a sinusoidal distribution of the magnetic field.

Since obtaining a structure of plasma with a certain degree of stability when leaving the muzzle of the railgun is one of essential promise in this study, one of the first steps was to repeat Alfvén [1] experiment in the conditions of metal plasma.

EXPERIMENTAL SET-UP

To produce a stable toroidal plasma, Alfvén introduced a radial magnetic field at the muzzle of a coaxial rail accelerator. The velocity of the ionized plasma crossed into this field resulted in a $J \times B$ force, inducing azimuthal current. The location of this field at the muzzle lowered the final velocity of the plasma.

The same type of induced azimuthal current can be produced by introducing an axial field at the breech of the gun from a finite length solenoid. The axial field is high in the breech region and decreases toward zero at the muzzle. This configuration has the advantage of allowing the toroidal plasma to accelerate in the gun after the azimuthal current has been induced, and is easier to incorporate into existing coaxial guns. Nevertheless, it is expected that the external field will reduce the final plasma velocity.

All experiments were conducted at CEM-UT using a 120 kJ capacitor bank charged to half energy (7 kV) to discharge the gun. Store current and gun current were measured with Rogowski coils. To prevent muzzle arcs, the gun was explosively crowbarred with a preset time delay. The voltage at the crowbar location was measured with an isolated current transformer monitoring current through a 500- Ω resistor across the crowbar buswork.

Axial magnetic field was produced in the breech region by a solenoid powered with a 1 F, 50-V capacitor bank. The coil was 320 turns of eight-gauge wire wound in 12 layers to a coil length of 10 cm. The finished coil had a measured inductance of 2 mH and resistance of 144 m Ω . Peak current at full bank voltage was 380 A with a rise time of 45 ms producing a field of 0.8 T in the breech of the gun. Shots were performed in a vacuum of 10^{-5} torr.

The initial series of experiments were three shots of a 0.5-m gun using cruder solenoids producing fields of less than 200 G. The only diagnostics consisted of a set of two brass make-screens, and plasma confinement was evaluated from visible damage to the first screen. The sequence of shots showed increasing screen damage with increasing magnetic field, yet the screen damage could not be definitely attributed to plasma confinement since other parameters (muzzle tubes and screen placement) had varied.

A new series of shots was attempted with the higher field magnet holding all other physical parameters fixed. A new design of the gun was used in these experiments and the cantilever support of the inner conductor proved problematic. The inner and outer coaxial rail would short electrically at some time during the shot deforming the rails, sputtering rail material, and preventing any clear interpretation of screen damage. To finally eliminate the problem, the length of the gun was reduced to 25 cm, and a 1-m section of flexible bus-work consisting of 19 parallel RG-8 coaxial cables was fabricated to mechanically decouple the gun from the explosive crowbar.

In the next series of experiments, a diagnostic tube was added to the muzzle, containing three langmuir probes and three pick-up coils to determine plasma length

and velocity. In addition, photo-diodes were directed at the end of the muzzle tube and at the first make screen to detect plasma and impact luminosity.

Assembly procedure is illustrated in Figs. 1 through 3. The gun is assembled to the vacuum flange with current feed connections, the magnet is placed at the breech and the muzzle diagnostic tube is added at the end. The whole structure is then mounted in the chamber (Fig. 4) and all electrical connections are made. The complete assembly ready to fire is shown in Fig. 5.

Fig. 1. Coaxial railgun mounted on vacuum flange.

Fig. 2. Placement of external magnet.

Fig. 3. Muzzle diagnostic tube assembly.

Fig. 4. Vacuum chamber.

Fig. 5. Assembled experiment.

All data from the shots was stored digitally on Nicolet Model 4094 oscilloscopes, with an effective bandwidth of 500 kHz. All signal lines were shielded in vacuum from plasma products and electrical noise using shielded twisted pair wire and custom isolated vacuum feedthroughs.

RESULTS

Seven successful shots were completed using the high field magnet. The application of axial fields up to 0.7 T to the breech of the gun produced no measurable difference in the discharge characteristics of the gun. Also, no obvious difference in screen damage was observed over an order-of-magnitude decrease of external axial magnetic field, although reduction of muzzle sputtering products evident on the screens when the field is applied suggests that the plasma does accelerate slower. A typical screen showing metal spray on aluminum foils is shown in Fig. 6.

Fig. 6. Velocity make-screen following a shot.

Langmuir probes and pick-up coils gave no clear indication of localized toroidal plasma rings. If such rings are being produced, either the diagnostics are not sensitive enough to detect them, or the oscilloscopes are not fast enough to distinguish the signals from noise. The coil signals for a centimeter length cylinder of plasma passing at a typical velocity of 10 km/s will have a time width of less than $2 \mu\text{s}$, which is the limit of the oscilloscope time resolution. The plasma length at these field strengths should be much longer however.

The azimuthal current induced by the axial field is clearly evident in helical swirl patterns observed on the inner coaxial rail. Figure 7 shows such a swirl at a location where the arc had concentrated. Quantitative determination of induced azimuthal current may be possible on future shots with greater sensitivity in the pick-up coils.

Plasma confinement was not at all evident when the screens were located 24 cm from the end of the muzzle diagnostic tube. On one shot, however, the make screens were moved to within an inch of the tube, and the gun was discharged with an applied field of 0.15 T. A toroidal hole was punched in the screen (see Fig. 8), indicating that the

Fig. 7. Swirl pattern from arcs on inner coaxial rail.

Fig. 8. Screen damage with screen 1 in. from diagnostic tube.

plasma was not collapsing inward completely during the transit of the 30-cm tube.

The pick-up coils on the diagnostic tube were successful in observing substantial current flow between the make-screens and the coaxial rails. Apparently the presumed breakdown of the make-screens due to impacts can actually occur when conductive plasma links the screens to the gun electrically. In fact, when the cryo pump failed on one shot and the gun discharge occurred in a vacuum of 100 microns, the breakdown of the screens was coincident with the crowbar of the gun at $58 \mu\text{s}$. This result suggests that make-screen information is largely unreliable in measuring plasma velocities. Although highly luminous "impact" flash was observed on the first screen with the photodiodes, it is not clear that the light may not be due to the electrical arc which occurs between the screens and the gun.

Considering the difficulties with the make-screens and muzzle diagnostics, it is impossible to give accurate velocity for the bulk plasma, although the timing between all observed events suggests velocities between 5 and 10 km/s.

Although 3 mg of aluminum fuse material was ionized in each shot, much of it was found plated out on the coaxial rails. A quantitative analysis was completed by removing this aluminum plating from the outer rail in a KOH bath following several shots and analyzing the solution spectroscopically. The results showed that the plating on the outer rail represented roughly one-third (1 mg) of the ionized fuse mass.

CONCLUSIONS

Plasmas have been accelerated in a coaxial railgun with an externally applied axial magnetic field, and azimuthal plasma motion (current) has been observed. The induced azimuthal current appears to confine the plasma to a cylinder surface while traversing an insulating tube of the expense of some forward acceleration during the railgun discharge. Full analysis of the confining effects of this azimuthal current, although as yet inconclusive, hold the potential of providing a means of condensing and focusing a plasma accelerated in a railgun.

Shooting magnetized rings (Tokamak-like), of the mixture of plasma, liquid and metal-vapor, and solid chunks of fuse represented a step in obtaining structures with a certain degree of stability, promising survival of plasma after leaving the railgun.

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