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Abstract - The goal of many railgun investigations is to arrive at a railgun design that is capable of launching projectiles to extremely high velocities (10 to 100 km/s). Often a second goal is for the railgun design to allow for repetitive launches without a total rebuild of the railgun. These two goals are the objectives the Center for Electromechanics at The University of Texas at Austin (CEM-UT) has pursued over the past several years. As part of the investigation, a serious study of coaxial railguns was conducted. Coaxial railguns were studied because the coaxial geometry offers two attractive features. One feature is the simplified construction, and the other is an inherent lower L' value. Studies were conducted on 0.5- and 5.0-m long coaxial railguns. Results were mixed in that high velocities were obtained (37 km/s), and several shots were done on one gun without cleanup or rebuild, but plasma mass amounts were small and not tightly patterned. Experiments are still underway, on a limited basis, to attempt to focus and bunch the plasma during launch and as it exists the muzzle.

INTRODUCTION

For several years, CEM-UT has been engaged in the development and testing of electromagnetic launchers where the goal was to achieve extremely high velocities (10 to 100 km/s) with lightweight projectiles (0.1 to 1 g). Begun in October of 1983, under the sponsorship of the Armament, Munitions, and Chemical Command (AMCCOM), the program continues as a research program. The project has included the investigation of several launcher and power supply designs. One design studied was that of coaxial railguns. With one of the project goals being to accelerate 0.1 g to 50 km/s, it was felt that a very dense plasma might serve as the projectile if it could be magnetically focused or condensed. To shoot such a plasma several railguns were considered. Literature studies on accelerating plasmas turned up a large amount of work done in the early 1960s where small coaxial plasma guns were utilized to investigate various impulsive hydromagnetic accelerator configurations for ultimate use in controlled thermonuclear fusion reactions [1]. Extremely high velocities of plasmas were reported and useful diagnostics were described with regard to experimental data collection. [2] These earlier experiments utilized short accelerators driven at relatively low current levels. It was therefore decided to investigate coaxial accelerators of longer designs driven at higher current levels. Because CEM-UT experience with coaxial guns was very limited, it was decided to build a small (0.5-m) coaxial gun powered by an existing CEM-UT capacitor energy store to verify performance and to validate construction methods.

Regardless of whether the accelerator would ultimately be a coaxial or parallel launcher, a decision was also made to design and construct a high vacuum test facility, so that all accelerations could be tested in an atmosphere-free environment, where the uncertainties associated with the aerodynamic stability of a specific projectile could be eliminated. A small vacuum system was built for use with the 0.5-m coaxial railgun and provided practical high vacuum

experience for CEM-UT personnel. Both vacuum systems required the design of electrical vacuum feedthroughs capable of handling extremely high currents (200 to 1,000 kA) at high voltage levels. The high current levels were supplied by either a storage inductor charged by a homopolar generator (both developed by CEM-UT) [3] or a 0.6-MJ energy store composed of ten independent capacitor banks [4] (also developed at CEM-UT). The capacitor banks were relocated to a mezzanine constructed over the homopolar generator/inductor (HPG/I) and the vacuum test range. The arrangement allowed the railguns to operate from either power supply with a minor modification in buswork. The buswork in both cases was coaxial and 1-MA rated. Buswork current was measured with Rogowski coils. Because no leakage flux is present with a coaxial gun design (the flux is trapped between the inner and outer conductors), B coils were developed for axial insertion into the bore of the coaxial launchers. For free flight measurements, high voltage, noise-immune make screens were used.

Design work on the high vacuum and dual power supply system took place during November and December of 1983. Concurrently, the 0.5-m gun and vacuum system was designed and constructed. Tests of the 0.5-m gun began in late March of 1984 and initial results indicated the coaxial concept as viable. Work began immediately on construction of the 5.0-m coaxial railgun. The power supplies relocation and installation along with the fabrication and installation of a large vacuum system took place over the first half of 1984. Fabrication of the 5.0-m coaxial railgun took place over the summer of 1984, with first tests conducted in September 1984. The initial test of the 5.0 m also included the first gun test of an explosive crowbar switch. The crowbar switch was designed and developed to effectively crowbar excess power supply energy from the gun after the fuse-initiated plasma left the end of the launcher. This was needed because excess power supply energy was dissipated by means of less energetic muzzle plasma arcs sustained from rail erosion. The sputtered rail material would coat portions of the vacuum range and cause velocity screen damage in addition to the penetration caused by the fuse-initiated plasma. This secondary damage was obscuring the ability to evaluate penetration capability of the main plasma.

The initial tests of the 5.0-m coaxial railgun were encouraging with regard to velocity measurement (37 km/s), but penetration of targets was poor due to a large, in-bore plate out of the fuse material (i.e. low plasma mass). Efforts to increase the mass by means of preventing this plating out (plasma focusing) have so far not proved very successful. Overall conclusions as to whether coaxial plasma railguns can someday be viable low mass accelerators cannot be made without additional testing.

DESIGN CONSIDERATIONS

With the goal of accelerating 0.1 to 1.0 g to 100 km/s, CEM-UT reviewed many potential railgun designs and found nothing approaching those design parameters. It was felt that dense plasmas could be accelerated to extremely high velocities. Because plasmas do not require an open bore in the sense that projectiles do, coaxial railguns could be considered. The coaxial geometry offers two attractive features:

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1. simplified construction because the outer conductor provides a natural pressure vessel which does not suffer the sealing problems of rail-to-insulator joints found in parallel railguns,

2. a lower L' value allows plasma arcs to be driven to higher velocities with lower supply voltages.

Another feature considered was the availability of gun materials in standard copper pipe and tubing. A simulation code was developed during the initial design investigation that allowed performance evaluation of coaxial staged-energy-store railgun utilizing the CEM-UT ten bank energy store.

The bore dimensions of the 5.0-m gun were determined by sizing the inner conductor to accommodate the maximum current levels available from CEM-UT's power supplies (approximately 1 MA). Wanting the gap spacing between coaxial conductors to be as small as possible (literature studies had shown that plasmas traveled non-uniformly in wide gap coaxial devices), [1] the outer conductor dimension was chosen to be the closest standard copper pipe size where the inner diameter of the outer conductor (1.37 in.) was just larger than the outer diameter (1.125 in.) of the inner conductor. The 5.0-m length was set somewhat arbitrarily. The 0.5-m gun conductor diameter dimensions were selected to model the current per periphery of rail and the arc pressure in the 5-m gun.

Because of the difficulty of using distributed energy stores in association with a coaxial design, as well as the problem of multiple current vacuum feedthroughs, it was decided to consolidate the outputs of ten individual capacitor banks into central coaxial collection plates (Fig. 1), with a robust

coaxial buswork then extending to and through the vacuum wall and terminating at the breech connection. Just prior to the vacuum feedthrough a explosive crowbar switch was designed for installation into the coaxial buswork. The design was an explosively operated version of the magnetically operated switch of Boissady and Rioux-Damidaou. [5] The design incorporated several attractive features:

- small (several grams) explosive charge
- simple and inexpensive
- precise timing
- low inductance and resistance
- two simple and easily replaced components expended each shot

The principle of operation is the same whether the switch is magnetically or explosively operated. Contact is made by projecting a metal ring into the gap between the coaxial electrodes (Fig. 1). The oversize ring deforms as it wedges into the gap, ensuring good contact as the switch closes and current begins to flow. The resulting magnetic pressure also acts to close the switch. A metal-to-metal switch develops much less voltage than switches which use a triggered arc or an arc passing through a ruptured dielectric for conduction. The crowbar switch operates outside the vacuum vessel close to the coaxial vacuum feedthrough.

The vacuum test range was designed around the following system requirements:

- contain sections to house the buswork feedthrough and gun breech, the gun, diagnostics, and a catch chamber

Fig. 1. Energy store collection buswork layout.

- pump down to between 1×10^{-6} and 1×10^{-9} in approximately 0.5 hr
- provide a sufficient number of instrumentation feedthroughs, observation ports, and access ports
- be supported by steel framework equipped with casters and leveling jacks
- be equipped with an automatic vacuum sequencing unit that controls automatic pumpdown of the entire system at once and also provides complete manual control of all values with a lamp panel schematic display

Thought was given to the pumping system, and it was decided that cryogenic high vacuum pumps would perform the best given the harsh working environment created by railgun shots.

FABRICATION

The initial 0.5-m coaxial railgun design was one of simplicity in that for the most part it was built using off-the-shelf materials such as copper pipe, rod, and fittings. The small size permitted the inner coax rail to be cantilever supported within the outer coax rail. Armature loading was facilitated by easy removal of outer coax conductor. Later, a extremely precise bore 0.5-m gun was fabricated to allow tests with solid projectiles shaped as right hollow cylinders. Also additional modifications were done to the design to facilitate plasma focusing experiments.

The 5.0-m coaxial railgun outer conductor was made using 1.66-in. O.D. copper pipe with a wall thickness of 0.146 in. The inner conductor was made of 1.125 O.D. copper tube with a wall thickness of 0.065 in. Both conductors were precision straightened and the inner conductor ground to insure a uniform roundness. The outer conductor was supported inside of a stainless steel tube (2 in. diameter with a 0.1 in. wall thickness). The stainless tube served as a safety shield should the outer conductor be stressed beyond material limits, and the tube also served to straighten the outer gun coax. Special clamps fixed to the outer coax, and loaded against Belleville spring washers, acted to load the stainless tube column in compression and the copper outer rail conductor in tension providing a straightening and securing action on the outer conductor. Radial drilled aluminum disks were fabricated and clamped to the outside of the stainless tube at varying intervals. These disks acted as pilot fixtures for the drilling of holes through the stainless tube and outer conductor. The holes allowed ceramic pins to be used to support the inner coax at specific points down the 5-m length. Some of the holes were for placement of B-dot probes diagnostics. The aluminum disks contained the mounting hardware for both pins and probes. The 5-m coaxial launcher is seen in Fig. 2. To insure good alignment between the coaxial vacuum feedthrough and the coaxial launcher a breech busbar connection with radial pivots was designed and fabricated. Fuse armatures were trapped by flanges on the outer conductor and trapped by a spring loaded ceramic insulator against brass ferrule soldered to the inner conductor.

The vacuum feedthrough was fabricated using copper bar and pipe along with stainless steel vacuum flanges and insulators. The vacuum is accomplished with Viton® O-rings. Stainless steel flanges were silver brazed, one to the outer diameter (OD) of the inner conductor, one to the inner diameter (ID) of outer conductor and one to the OD of the outer

Fig. 2. 5-m coaxial launcher.

conductor. Two of the flanges are connected to one another by insulated bolts. The flange O-rings press against smooth insulator surfaces which separate the steel flanges electrically. The flange connected to the OD of the outer conductor is bolted to the vacuum vessel with insulated bolts and also is separated by an insulation plate that provides an O-ring surface but isolates the outer conductor from the vacuum vessel potential. This high current high voltage electrical vacuum feedthrough has been tested numerous times without failure.

TESTING AND RESULTS

0.5-m Coaxial Railgun

In its original configuration the 0.5-m gun was fired 14 times. Shot parameters such as fuse mass, energy stored, bank voltage, etc., were varied as part of the test program. The parameters measured on the launcher consisted of total rail current, breech and muzzle volts, flux in the bore of the coaxial gun, and free flight measurement of plasma velocity. The current was measured with Rogowski coil passive integrator systems. The voltage was measured indirectly by clamping an accurately measured resistance across the circuit to be monitored and then measuring current flow through the known resistance. With the use of Pearson current monitors this measurement can be made accurately with a high degree of electrical isolation from the pulsed power circuit. Flux in the bore measurements were done with very small B-dot coils. These B-dots were contained in small diameter glass tubes that were mounted to the gun in such a manner that they penetrated the outer coax conductor through small holes (Fig. 3). Perturbations of the plasma in the region of the probes was not desired but was expected. The final diagnostics on the 0.5-m launcher was the velocity screens. The screens were made of two pieces of 0.8-mil aluminum foil insulated with 1.5 mil sheet of Mylar drafting Vellum. (Later shots involved other materials) A potential of 500 V was applied across the screens to improve signal to noise ratio of the make switch voltage traces. The position of the screens in the railgun range, as well as the location of the B-dot coils is shown in Fig. 4.

Design consideration was given to the fuse elements for plasma arc initiation. Vaporization rates, fuse geometry, and enthalpy changes of the different thermodynamic states were considered in fuse fabrication. The fuse material selected for the initial tests was aluminum.

Fig. 3. B-dot geometry

Fig. 4. Small coax range layout

Preparation for all shots (both with 0.5 and the 5.0 m guns) involved mechanical cleaning of the gun followed by thorough wipe off of the copper surfaces with a degreaser such as chlorothene. A low energy discharge through the gun, with a short attached to the muzzle, allowed for a pretest calibration of the

B-dot probes prior to each shot. The gun was then loaded with a fuse and the vacuum chamber sealed and pumped down. After the vacuum seals were verified, remaining busbar connections and the breech voltage diagnostic were connected. With all diagnostics, triggers and bus connections properly made and set, the capacitor banks were then charged and the gun fired. Later shots (#8 to 14) on the 0.5-m gun, and all shots with the 5.0-m gun, involved the preshot preparation of the explosive crowbar switch.

Experimental observations and data analysis was recorded for all shots. This shot data is summarized in the table below. The vacuum level prior to the shot was 9×10^{-8} torr and after 1×10^{-6} torr. For the first shot, two energy stores were charged to 5 kV (representing a stored energy of 27.6 kJ). The signals into the digital oscilloscopes were arranged such that a time zero event was recorded with each of the B-dots. In this way, time zero was identified independent of scope triggers. The plasma front arrived at B-dots #1 in 30 μ s. The front passed B-dot #2 in 47 μ s indicating an average velocity of 5,900 m/s between B-dots #1 and 2. The third B-dot recorded a flux passing at 57.5 μ s indicating an average plasma front velocity of 9,500 m/s between B-dots #2 and 3. Because the plasma passed B-dot #3 at the time of peak current in the gun (i.e., the current through the plasma armature should have been relatively constant), the rise time of this B-dot probe multiplied by the velocity gives us an indication of plasma length

$$l = 9,500 \text{ m/s} (39 \times 10^{-6} \text{ s}) = 0.37 \text{ m.}$$

The make screens triggered 6 μ s apart, indicating an average velocity of 16.7 km/s between the screens (Fig. 5). The first screen was triggered at 134.5 μ s, which is 77 μ s after B-dot #3 recorded the incidence of the plasma front. The distance from the third B-dot to the leading velocity screen is approximately 55 cm. If the plasma was traveling between 9,500 and 16,700 m/s in this region, the front should have reached the first screen in

$$t = \frac{0.55 \text{ m}}{13,100 \text{ m/s}} = 42 \mu\text{s},$$

Table 1. Data Summary of 5-m Coaxial Tests

Shot #	Bank Voltage kV	Energy Stored in Bank kJ	Time to Peak Current μ s	Peak Current kA	Mass Vaporized at Breech g	Average Velocity of Leading Edge of Plasma in Bore (seen between 1st and 3rd B-dot m/s)	Estimated Exit Velocity (2x Average Vel) m/s
1	5	27.6	100	187	0.011		
2	7	54.0	96	262	0.027	7,700	15,400
3	7	54.0	88	250	0.014	1,200	2,450
4	5	27.6	INSTRUMENTATION PROBLEM: DATA LOST				
5	5	27.6	91	187	0.011	#3 B-dot failed	
6	5	27.6	91	188	0.011	#3 B-dot failed	
7	7	54	INSTRUMENTATION PROBLEM: DATA LOST				
8	7	54	92	275	0.011	10,200	20,400
9	9	90	94	345	0.011	6,700	13,400
10	7	54	95	255	0.014	8,400	16,800
11	7	54	90	246	0.015	3,600	7,200
12	7	54	88	245	0.014	#3 B-dot failed	
13	7	54	84	265	0.014	Instrumentation change	
14	7	54	90	265	0.014	Instrumentation change

Fig. 5. Velocity screen traces from test #1 of 0.5-m gun

and if the total column had to bunch-up on the screen to deliver enough energy to burn through another,

$$t = \frac{0.37 \text{ m}}{13,100 \text{ m/s}} = 28 \mu\text{s}.$$

were required to short-circuit the first screen. This accounts for 70 of the 77 μs and is possibly a good explanation of the recordings. In the first experiment, a 0.023 g, cross-shaped foil, 0.02 mm thick, was loaded in the gun.

The unburned fuse material was collected after the shot. This includes pieces clamped under the center ferrule and the ends of the fuse clamped under the outer copper flange. The mass of the recovered pieces was 0.012 g. This indicates 0.011 g were vaporized to initiate the plasma arc. Not all of this mass was delivered to the railgun bore. A portion of the foil material was plated onto the conical chamber that directs the plasma into the bore. For this reason, the mass of the plasma is not well known.

Table 2. Data Summary of 5-m Coaxial Launcher Tests

Shot #	Bank Voltage kV	Energy Stored in Bank kV	Time to Peak Current μs	Peak Current kA	Mass Vaporized at Breech g	Average Velocity in Bore of Leading Edge of Plasma (seen between 1st and 5th B-dot m/s)	Estimated Exit Velocity (2x Average Vel.) m/s
1	6	99.5	105	480	0.083	18,500	37,000
2	6	99.5	115	440	0.079	17,400	34,800
3	6	120.0	DATA LOST DUE TO INSTRUMENTATION PROBLEM				
4	6	139.8	125	470	0.080	24,200	48,400
5	6	143.0	315	380	0.055	11,400	22,800
6	7	221.3	450	410	0.037	13,600	27,200
7	7	221.3	400	430	0.060	11,600	23,200
8	7	221.3	420	470	0.055	11,900	23,800

5-m Coaxial Railgun

The objective of the 5-m railgun testing was to accelerate 0.01 g of plasma matter up to a velocity of 50 km/s and have it exit the muzzle of the railgun in free flight. Having never tested a coaxial railgun with a crowbar switch, a low energy shot was planned for the initial test. It was felt that if the initial shot proved successful a test schedule would be worked up that would hold the mass of the fuse constant while increasing the energy. When the optimum energy level was determined the mass of the fuse was to be varied in an attempt to optimize the greatest amount of mass that could be successfully accelerated to velocities approaching 50 km/s. Other tests were planned to check the 5-m guns repeatability performance, and still others were planned to optimize the current waveform of the railgun power supply. Though as many as 30 tests were envisioned, only eight were conducted before it was decided that much remained to be done before a concentrated plasma with enough mass and velocity could be delivered on target. This decision led to CEM-UI solid projectile testing using parallel railguns not covered in this article. In all, eight tests were performed on the 5-m coaxial railgun. Fig. 6 shows the 5-m coaxial railgun and range layout.

A comparison of make screen velocity measurements has not been summarized because the materials used to make the screens, and the way the screens were hooked to their power supplies and oscilloscopes, were changed between various tests of 5-m railgun. The changes were done for easier post-shot screen damage analysis as well as making the screens more immune from extraneous noise. Velocity make screen oscilloscope traces for the first shot (typical of all eight shots) are seen in Fig. 7. Plots of experimental data (total current, gun current, crowbar voltage and current, and B-dot current) plotted against the same time scale were done for each shot. Some of this data is summarized in the following table.

Regarding performance, the velocity of the plasma in shot #1 (37 km/s measured by the make screens) was the fastest recorded of the eight shots even though that shot and shot #2 were done with the least amount of energy tested. It is not felt the (99 kJ) energy level was necessarily the optimum energy level. Two

possible factors that contributed to the steadily decreasing performance of the 5-m gun were: 1) after test #1 the velocity make screens were constructed using brass shim stock to allow for easier post shot analysis, the brass shim was not only thicker than the aluminum but stronger with regard to penetration by plasma, (i.e. it took more energy from the plasma to burn through the brass layers), 2) with each shot the surface of the inner and outer conductors became more and more scarred particularly around the area of the ceramic pins used to support and center the inner conductor.

Fig. 6. 5-m coax range layout

Fig. 7. Velocity screen traces from test #1 of 5-m railgun

In the analysis of the test data from test #1 it was seen that the velocity make screens triggered some 27 μ s apart indicating a free flight velocity of 37 km/s. Current measurements taken in-bore the 5-m gun by B-dot probes indicate the plasma arrived at B-dot #1 in 67 μ s and passed B-dot #5 in 283 μ s. The distance between the two probes (2 m) divided by the difference in the times ($283 - 67 = 216 \mu$ s) indicates an average velocity in-bore of 18,500 m/s. At first glance this velocity seems to contradict the measured make screen velocity of 37 km/s. It must be remembered, however, that the in-bore measurement is an average velocity and given the current's waveform, the actual final velocity can be shown to be twice the average velocity.

Another task the B.dots perform is to measure current passing through the plasma as the plasma travels down the bore. The current data collected during the coaxial railgun tests showed that the majority of the gun current dwelled in the breech and initial region of guns bore. This is supported by the fact

that the majority of the aluminum fuse, which vaporizes to form the plasma initially, appears to plate-out on the copper surfaces of the gun breech and the initial portion of the inner coax conductor. It was thought that the center coax support pins in the early portion of the gun, observed to be plated or coated with aluminum after each of the initial shots, were providing current pathways which robbed current from the plasma armature. Removal of the initial support pins in a later test did result in a greater current being measured by B-dot #1 and the plating action being extended further down the gun. One might think that removal of all bore obstruction (i.e. ceramic support pins, fuse clamping devices, B-dot probes, etc.) would result in less or no plating out of the vaporized fuse material and prevent of the formation of pathways for establishing stationary current paths. Tests using the 0.5-m clear bore coaxial railgun have shown, however, that the plating out will still occur, and if a crowbar switch is used to prevent excess bank energy from spewing or sputtering off rail copper, no appreciable plasma mass is delivered on target. Experiments aimed at preventing the vaporized fuse material from plating out by use of externally applied magnetic fields (plasma focusing attempts) have not yet been attempted with the 5.0-m gun. Several plasma focusing experiments were performed using the 0.5-m coaxial railgun. The tests results have been inconclusive to date. A much more in depth report on the focusing experiments is the subject of another paper [6].

CONCLUSIONS

A great deal of work is left to be done on making coaxial railguns viable mass launchers. The work performed at CEM-UT has shown that a plasmas can be launched in free flight at a substantial velocity and impact a target. The plasmas to date, however, have been of very low mass. Many questions remain unanswered as to how the plasma mass can be increased. Large coaxial guns present the difficult task of supporting the inner coax conductor without introducing obstructions into the bore. If the plasma mass can be increased and successfully launched the problem of keeping the plasma tightly coupled during free flight must also be addressed.

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