HYPERVELOCITY MACROPARTICLE ACCELERATOR
EXPERIMENTS AT CEM-UT

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Abstract: Several railgun experiments designed to accelerate projectile masses of 2 to 5 g to velocities greater than 6 km/s were performed at the Center for Electromechanics at The University of Texas at Austin (CEM-UT). Two parallel rail-type accelerators with 12.7 mm square bores were used for the experiments. One gun is 2-m long, has molybdenum rails, alumina ceramic insulators, and the other gun is 1-m long, has molybdenum rails, and granite insulators. The greatest velocity achieved to date during the experiments was 5.1 km/s. During the test program, the following ideas to enhance launcher performance were tested: stiff-gun structures to reduce plasma leakage and rail movement; refractory bore materials to reduce ablation and frictional losses; and prefilling the gun bore with gases which will eliminate precursor arcs.

After three experiments utilizing the 2 m long launcher, with peak currents ranging from 660 to 780 kA (bore pressures ranging from 62.6 to 87.5 ksi), a gun barrel comprised of 96% pure alumina ceramic insulators and 99.9% pure molybdenum rails (which is hydraulically contained and preloaded) has survived with minimal damage and no degradation of seals. Evidence to its sealing ability is that it is capable of maintaining 0.4 torr rough vacuum for over one hour after disconnecting a roughing pump used to evacuate the bore prior to gas prefill experiments. Both the ceramic and molybdenum were quickly honed after experiments restoring the bore surfaces and an electrical rail-to-rail resistance of greater than 1 MΩ. No craters or teardrop shaped gouges were visible after each of the experiments. Most of the damage was confined to region of melting centered on the rails starting about 50 cm from the breech and approximately 60 cm in length.

In two of the three experiments utilizing the 2 m long launcher, the bore region in front of the projectile was evacuated to 0.4 torr, then filled to 100 torr with hydrogen gas. A rectangular polycarbonate projectile was accelerated the length of the gun and exited through a Mylar™ window at the muzzle into a diagnostic range evacuated to 1.0×10^{-6} torr. On both experiments, no evidence of a precursor arc was observed on the diagnostics recorded. On a third experiment, the Mylar™ window was removed and the bore was evacuated to 1.0×10^{-6} torr with the diagnostic range. During this experiment, a precursor arc was observed.

Near-term experiments which will be performed on both the 1 and 2 m long launchers include tests designed to reduce secondary arc formation

Introduction

Research in the area of hypervelocity railgun launchers has suggested the need for stiffer gun structures and refractory bore materials. At CEM-UT, a 2 m long railgun featuring alumina ceramic insulators and molybdenum rails has been assembled. The rail

insulator package has been installed in a unique hydraulically preloaded ceramic containment structure which has a calculated static rail-to-rail deflection of only 0.005 in. at 1 MA. Further details of the gun structure are discussed in another paper entitled "Design and Development of Extremely High Velocity Electromagnetic Launchers--GEDI Program".[1]

This paper presents the results of the first three experiments utilizing the aforementioned launcher. In addition, a solution for the shock pressure and temperature in front of the projectile is reviewed. Following the experimental results a plan for future work is presented and conclusions are drawn.

Experimental Work

Prior to the first 2-m long, ceramic insulated railgun experiment, CEM-UT experiments were performed indicating that prefilling the gun bore with sulfurhexafluoride at a pressure of 25 psia would eliminate precursor arcs. Shortly before the initial test, conversations with other experimentalists indicated that at high velocity, the shock pressure and temperature generated in sulfurhexafluoride would cause it to ionize and become conductive.[2,3] In addition, they had eliminated precursor arcs in experiments similar to ours, by prefilling the gun with hydrogen at 100 torr. Because hydrogen generates a lower shock pressure (lower losses and reduced risk of ionization), it was decided to use it to prefill the bore of the 2-m long ceramic insulated railgun in order to eliminate precursor arcs.

In figures 1-10, inner gun current refers to the current in to the railgun breech, sum of inductor refers to the sum of the currents measured out of each energy storage inductor, turret current and total current are redundant measurements and refer to the current going to both crowbar switcher and the railgun, and crowbar current represents the sum of gun current and the current in one of the crowbar switchers.

2-m Long Ceramic Insulated Railgun Experiments

Test #1

On the 26th of April the first experiment was performed on the 2-m long, ceramic insulated hypervelocity railgun. The experimental timing was designed to keep the current decay periods between Balcones homopolar generators/inductors (BHPG)/inductor staging to a minimum. Six (BHPGs) were to provide the gun with a peak current of 780 kA to accelerate a 2.6-g projectile to near 10 km/s. During the first 500 μs of the discharge, less than 30 kA of current droop between staging events was simulated. By this time, the projectile velocity was expected to be approximately 8.5 km/s. Before staging the last BHPG/inductor, the current was expected to droop about 50 kA and prior to crowbar a droop of 80 kA was anticipated.

In addition, the overall trend of the current profile was to steadily increase until approximately 50 μ s before projectile exit. During the last 100 μ s in-bore, there was concern that the larger variations in the current might cause plasma spreading and/or secondary arc formation resulting in no further acceleration of the projectile. But, it was believed that 8.5 km/s was a significant goal and if plasma spreading and/or secondary arcs did not form, it was possible for the projectile exit velocity to be 10.1 km/s.

During the experiment, the staged BHPGs produced a current which peaked at 780 kA (bore pressure 87.5 ksi) and accelerated the projectile to 5.08 km/s as measured by the Hall station high speed streak camera. Table 1 summarizes the performance of this experiment. In figure 1, the various currents measured during the experiment are shown. Unfortunately, an error in the timing of a closing switch, which isolates the fourth BHPG/inductor, caused it to close (time = 330 μ s) 50 μ s prior to the opening switch event, resulting in shunting 50 kA out of the railgun circuit. It was thought that the large drop in current, due to the early closing of the isolation switch, may have caused the armature instability resulting in the spoiled performance. For structural reasons, only four B-dot probes were installed in this gun; two at the breech, spaced 5-cm apart, and two at the muzzle, spaced 10-cm apart. Rail current measuring B-dot probe signals are shown in figure 2. All four probes show no indication of a precursor arc, thus it appears that using a hydrogen prefll of the bore was effective at extinguishing precursor arcs. From probes A and B, it was determined that the thermodynamic kick velocity was 1,300 m/s and that initially the arc was well formed and approximately 4- to 5-cm long. From probes C and D, an exit velocity of approximately 5 km/s was determined and that all of the current did not exit the gun during the time frame of the recording instruments. Also, of interest are the amplitude excursions on B-dots C and D (700 to 1,300 m) which seem to have a structure related to the gun current profile. These same amplitude excursions are also apparent in the muzzle volts signal (700 to 1,300 m) which is shown in figure 3. Unfortunately, high amplitude oscillations were generated on both the muzzle and breech voltage signals due to staging events, so that most of the information available from these signals is obscured during the time the projectile was in-bore. The high amplitude ringing on the voltage probes signal is believed to be generated in the large loop formed by the high voltage leads where they attach to the gun. It is thought that a resonant circuit is formed with the capacitance of the long cables which extend into the screen room. On future tests, muzzle and breech voltage will be measured on an oscilloscope located in a remote screen room to keep the cable lengths to a minimum. After the experiment, the gun and vacuum vessel had equalized at a pressure of approximately 200 torr.

A post-shot performance calculation based on measured gun current was performed with the results plotted in figure 4. The initial step in velocity is the application of the thermodynamic kick of 1,300 m/s. Interestingly, the time at which the postshot predicted velocity is equal to the measured exit velocity is coincident with the time at which the isolation switch closed early (330 μ s) and momentarily shunted current away from the gun.

After cleaning the gun bore, a region of high erosion was observed on the rails. The eroded region

Figure 1. 2 m long ceramic insulated railgun test #94Q4 currents

Figure 2. 2 m long ceramic insulated railgun test #94Q4 B-dot probe signals

was about 60-cm long, starting approximately 50 cm from the breech of the gun. Early in May, 1989 the gun was honed and required 0.015 in. rail material to be removed to reach the bottom of the eroded region. The beginning of the rail erosion, 50 cm from the breech, corresponds to the position predicted by the postshot code at 330 μ s. The extent of damage of this type has not been seen on previous GEDI experiments at CEM-UT which have utilized ETP copper, molybdenum flame sprayed copper rails, and solid molybdenum rails. The rails only melted along the axial center during the experiment, so it is presumed that the current was not well distributed across the rail and that the effective rail height was less than 0.13 m. The reason for the current pinching to the center of the rails is not understood. Although the causal relation between the stationary arc and the current pinching is not known, it is thought that the ablative force in a high melt zone would be large enough to cause a substantial reduction in arc velocity. Yet it is

Table 1. Results from ceramic insulated railgun tests

	Test #1 (94Q4)	Test #2 (9672)	Test #3 (97B3)
Projectile Size L/D Mass Placement Material and Geometry	0.513 x 0.522 x 0.500 in. 0.97 2.56 g 2.25 in. from breech with 1 in. gap between fuse and projectile Polycarbonate annealed for 20 min at 250°F, leading edge angle 10°, 100 lb fit.	0.528 x 0.528 x 0.530 in. 1 2.909 g 2.31 in. from breech and 1 in. gap left between fuse and projectile Polycarbonate annealed for 20 min. at 250°F, leading edge angled at 10° for 0.04 in., 100 lb fit	0.538 x 0.537 x 0.536 in. 1 3.03 g 2.25 in. from breech with 0.75 in. gap between fuse and projectile Polycarbonate annealed for 20 minutes at 250°F, leading edge angled at 10°. 100 lb fit
Armature Mass Location Material	0.06 g (based on density of aluminum of 44.23 g/in. ³) Delrin™ fuse holder combination breech plug 0.005 aluminum shim	0.06 g based on density of aluminum of 44.23 g/in. Delrin™ fuse holder combination breech plug 0.005 aluminum shim	0.06 g based on density of aluminum of 44.23 g/in. ³ Delrin™ fuse holder combination breech plug 0.005 aluminum shim
Total Accelerated Mass	2.62 g	2.97 g	3.09 g
Gasket Style and Material	Epoxy impregnated polyester sheet adhesive cured for 4 hr at 250°F	Epoxy polyester sheet adhesive cured for 4 hr at 250°F	Epoxy impregnated polyester sheet adhesive cured for 4 hr at 250°F
Frame Style	Hydraulic at 30,000 psi	Hydraulic at 30,000 psi	Hydraulic at 30,000 psi
Bore Tolerance Insulator to insulator Rail to rail	0.0002 in. 0.00015 in.	0.0004 in. 0.0007 in.	0.0002 in. 0.00015 in.
Insulator material	96% alumina ceramic	96% alumina ceramic	96% alumina ceramic
Rail material	99% pure molybdenum	99% pure molybdenum	99% pure molybdenum
Bore fill gas and pressure	H ₂ at 100 torr	H ₂ at 100 torr	Air at Chamber pressure
Insulator friction coefficient	0.19	0.19	0.19
Rail friction coefficient	0.24	0.24	0.24
Inductance gradient	340 nH/m	340 nH/m	340 nH/m
Maximum velocity B-probes Hall Station Exit Time Thermodynamic Velocity	5 km/s 5.08 km/s 720 ms 1,300 m/s	5 km/s 5.12 km/s 740 ms 1,250 m/s	4 km/s 4.9 km/s 790 ms 1,250 m/s
Quantity of BHPGs(1-6): 6 Peak Current Crowbar Makes Precursor Current Projectile Kinetic Energy	780 kA 640 ms 0.0 A 33 kJ	670 kA 700 ms 0.0 A 38.1 kJ	600 kA 710 ms 40.0 kA 36.5 kJ
Preshot Observations Vacuum Comments	1 x 10 ⁻⁶ torr	10 ⁻⁶ torr	10 ⁻⁶ torr Did not prefill bore with hydrogen to see if it had an affect on precursor or rail melting
Postshot Observations	1. Noise amplitude high on voltage signals 2. No precursor arc 3. Long arc gouges in rails starting 50 cm from breech and approximately 60 cm long 4. 200 torr system pressure after test (i.e. gun still sealed) 5. B-dots C & D amplitude low and has amplitude variations	1. All of the current did not pass muzzle B-dots during the time frame measured on the oscilloscopes during the experiment 2. A region of the rails approximately 40 cm in length, starting approximately 75 cm from the breech showed extensive melting 3. No precursor arc was observed 4. Chamber vacuum was 200 torr after the experiment 5. Muzzle voltage dropped throughout the time which the projectile was in bore 6. First x-ray head triggered early	1. Precursor arc 2. Secondary arc left gun around 3.5 ms 3. Rail gouge starting 60 cm from breech with length of 40 cm 4. Postshot chamber and gun pressure approximately 200 torr

Figure 3. 2 m long ceramic insulated railgun test #94Q4 gun voltage signals

Figure 4. 2 m long ceramic insulated railgun test #94Q4 post-shot performance calculated performance

just as likely that rail melting and erosion would be high in areas where the arc was traveling slow. It was decided to reduce the designed peak current for the second test to 650 kA and hope that this would reduce the rail erosion.

Shot data from the aforementioned test and several previous have indicated that performance reduced drastically when dramatic changes in the drive current occur. The second test of the 2 m ceramic insulated railgun will attempt to repeat the original designed first experiment. It is believed that the information learned on the first test will allow the isolation switches to be closed at the correct time.

Test #2

The gun was honed to refurbish areas damaged during the first experiment. The diamond-bonded stones on the hone were worn completely off by the time the gun bore was restored. It was observed that molybdenum appeared to be much more abrasive on the

stones after the first experiment as compared to the original untested surface and to molybdenum rails in the granite-insulated railgun.

The second test of the 2-m long, ceramic insulated launcher was performed on July 7, 1989. A peak current of 660 kA (bore pressure 62.6 ksi) was discharged into the gun accelerating the 2.91-g projectile to 5.12 km/s as measured by the Hall Station camera. An experimental summary is provided in table 1. Figure 5 shows the currents measured at various points in the system. All available information indicates that the BHPG/inductor power supply performed correctly. Rail current measuring B-dot probe signals are shown in figure 6. All four probes show no indication of a precursor arc, therefore it appears that the hydrogen prefill of the bore was once again effective at extinguishing or preventing any precursor arcs. From probes A and B, it was determined that the thermodynamic kick velocity was 1,250 m/s and that initially the arc was well formed and approximately 4- to 5-cm long. From probes C and D, an exit velocity of approximately 5 km/s was determined and that all of the current did not exit the gun during the time frame of the recording instruments. Similar to those seen on the previous experiment are the amplitude excursions on B-dots C and D (700 to 1,300 μ s) which seem to have a spatial structure related to the gun current profile. These same amplitude excursions are also apparent in the muzzle volts signal (700 to 1,300 μ s) which is shown in figure 7. The reduction of noise recorded on the muzzle and breech voltage signals in figure 7 is attributed to using the remote shielded oscilloscope as discussed in the preceding text. The steady drop in the average muzzle volt signal between 200 and 700 μ s, suggests an increase in the plasma armatures length, a reduction in its bulk resistivity, or formation of additional arcs. At this point in time it is not clear which mechanism is most responsible for the reduction in the arc voltage. Once again, the pressure in the vacuum chamber and gun was approximately 200 torr after the experiment.

As in the first experiment, a region of high erosion was observed on the rails after the second experiment. The eroded region was about 40-cm long, starting approximately 60 cm from the breech of the gun. The gun was honed and required 0.008 in. rail material to be removed to reach the bottom of the eroded region.

Test #3

The third test of the 2-m long, ceramic insulated launcher was performed on July 11, 1989. It differed from the previous two tests in that the Mylar™ diaphragm between the gun and the vacuum vessel was removed and no prefill gas was used. A peak current of 660 kA (bore pressure 62.6 kpsi) was discharged into the gun accelerating the 3.03-g projectile to 4.91 km/s as measured by the Hall Station camera. An experimental summary is provided in table 1. Figure 8 shows the currents measured at various points in the system. All available information indicates that the BHPG/inductor power supply performed correctly. Rail current measuring B-dot probe signals are shown in figure 9. The signal recording duration was increased to 3.5 ms from 1.6 ms in an attempt to record any slow moving arcs in the gun. All four probes show a precursor arc. From probes A and B, it was determined that the thermodynamic kick velocity was 1,250 m/s and that initially the arc was well formed and approximately 4- to

Figure 5. System currents from experiment #9672 on 2 m long ceramic insulated gun

Figure 6. B-dot signals from experiment #9672 on 2 m long ceramic insulated gun.

5-cm long. From probes C and D, an exit velocity of approximately 5 km/s was determined and that all of the current was not concentrated in the arc behind the projectile. Additional arcs appear to exit the gun at 1.7 ms and 2.75 ms. Similar to those seen on the previous experiments are the amplitude excursions on B-dots C and D (700 to 1,300 μ s and 2.75 to 3.45 ms), which seem to have a spatial structure related to the gun current profile. Unfortunately, the recording period expired before the last observed arc completely exited the gun, so all of the spatial information of this arc may not have been captured. The same amplitude excursions are also apparent in the muzzle volts signal (700 to 1,300 μ s), which is shown in figure 10.

As in the previous two experiments, a region of high erosion was observed on the rails after the third

Figure 7. Gun voltages recorded from experiment #9672.

Figure 8. System currents from experiment #97B3 on 2 m long ceramic insulated gun.

experiment. The eroded region was about 40-cm long, starting approximately 60 cm from the breech of the gun. The gun was honed and required 0.008 in. rail material to be removed to reach the bottom of the eroded region. Interestingly, less wear on the hones was observed in the honing process. It is unclear as to whether the reduction in wear can be attributed to the recently refurbished hones or due to the lack of hydrogen embrittlement of the molybdenum. Since erosion of the aforementioned magnitude nor secondary arc formation had been observed on previous plasma armature railgun experiments at CEM-UT, a relation between the two phenomena was suspected. It was suspected that the slow moving secondary arc might dwell on the rail sections for enough time to melt the surface of the molybdenum. It is then possible for the ablated rail material to become entrained in the armature causing further reduction in its velocity. The amount of ablated molybdenum due to the secondary arc was determined by multiplying an ablation constant for molybdenum, 71 g/MJ [4] times the secondary arc energy (time integral of muzzle power after the primary arc exited the

Figure 9. B-dot signals from experiment #97B3 on 2 m long ceramic insulated gun.

Figure 10. Gun voltages recorded from experiment #97B3.

gun; 1.1 to 4 ms). The calculated ablated molybdenum (2.84 g) was then compared to a crude estimate of the eroded regions volume times the density of molybdenum ($10,241.27 \text{ kg/m}^3$). [5] A triangular shaped cross section was assumed, with a 40-cm length, a 0.63-cm width, and a depth of 0.02 cm (0.008 in.). The resulting volume is 0.512 cm^3 , which corresponds to a mass of 2.58 g. Thus, it appears possible for the secondary arc to be responsible for the rail damage.

In comparison with the previous two experiments, no obvious advantage was gained from not prefilling the bore with hydrogen. Since a precursor arc was observed, it is believed that the hydrogen prefill should be used on future experiments to prevent the instrumentation noise, bore damage, and power loss associated with precursor arcs. The penalty of the increased wear as a result of hydrogen embrittlement has been determined acceptable.

Conclusions and Suggested Future Work

Three experiments were performed in which the projectile was accelerated to approximately 5 km/s. Prefilling the gun bore with hydrogen at 100 torr appears to be effective at eliminating precursor arcs without significant reductions in performance due to a shock pressure front generated in front of the projectile, but an increase in rail hardness due to hydrogen embrittlement may result. In all experiments, slow moving secondary arc formation was suspected to spoil performance. Slow moving secondary arcs may be responsible for extensive rail erosion or conversely extensive rail erosion may be responsible for the formation and/or the reduction of velocity of the secondary armature. After three experiments with bore pressures as great as 87.5 ksi, the ceramic and molybdenum railgun is still capable of maintaining 0.4-torr vacuum for over an hour after disconnecting the rough pump.

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