TESTING OF A HIGH PERFORMANCE, PRECISION-BORE RAILGUN

D. R. Peterson, D. A. Weeks, R. C. Zowarka Jr., R. W. Cook, and W. F. Weldon

Presented at the
3rd Symposium on Electromagnetic Launch Technology
Austin, Texas
April 20-24, 1986

Publication No. PR-46
Center for Electromechanics
The University of Texas at Austin
Balcones Research Center
EME 1.100, Building 133
Austin, TX 78758-4497
(512)471-4496

TESTING OF A HIGH PERFORMANCE, PRECISION-BORE RAILGUN

D. R. Peterson, D. A. Weeks, R. C. Zowarka, Jr., R. W. Cook, and W. F. Weldon

Abstract - This paper discusses the results of high-pressure (up to 350 MPa) railgun experiments. The gun is designed both to be capable of high-pressure operation without structural damage and to be readily disassembled for inspection, maintenance and component testing. Considerable effort has been invested to develop techniques to produce and measure smooth, extremely precise ($>5 \mu\text{m}$ of variation) bores. We have not deliberately varied bore precision to determine the effect of precision on performance, but our experience suggests that if two otherwise identical railguns, one with a polished, high-precision bore, were fired under identical conditions, the precisely finished gun would achieve a higher muzzle velocity. Very high accelerations have been achieved ($>10^7 \text{ m/s}^2$). A 2-g projectile has been accelerated to 5 km/s in a 13 mm square-bore gun only 1 m long. Projectiles with an L/D as small as 0.65 have been successfully accelerated. Projectiles with smaller L/Ds have not yet been tested to determine the minimum L/D which can be successfully accelerated. A number of different insulator materials ranging from common float glass to fused quartz have been tested. The best results have been obtained with fused quartz, which shows promise of being reusable. In the course of testing, the importance of gasketing the rail-to-insulator seams to prevent loss of plasma has become apparent. We have made progress in gasket design, but more work is needed. Rail gouging has been a continuing problem. Gouging may be dependent on bore precision, projectile fit, rail mechanical properties, projectile L/D, structural stiffness, operating pressure, velocity, and shape of the current pulse.

RAILGUN DESIGN

The railgun is illustrated in Fig. 1. The cylindrical rail assembly is pressed into the hoop-wound fiberglass-epoxy tube. To clamp the rail assembly components tightly together and compress the rail-to-insulator gaskets, a four-piece bolt-together steel shell is assembled around the fiberglass tube. This design facilitates assembly and disassembly and testing of different components.

Fig. 1. Illustration of a 1 m long, 13 mm, square-bore railgun.

Past experience [1] has shown the importance of good structural design: we have sacrificed some magnetic performance for mechanical performance. The most prominent feature of the gun is the large rail cross section. This cross section is much larger than needed for current duty and has the effect of lowering the inductance. The inductance of several rail cross sections is tabulated in Fig. 2. This extreme rail geometry served several mechanical purposes: the rails are rigidly clamped in place, the rails resist bending, and the insulator holders bear against the rails during firing, protecting the projectile from interference as shown in Fig. 3. Note that the rail-to-insulator seam tends to shear rather than separate as the rail deflects (Fig. 4): the rail-to-insulator gasket remains compressed. Note that the rail slides on the insulator, a feature which helps to prevent rebound damage, especially helpful for brittle insulator materials. Railgun structural stiffness is critical only in the low-velocity section of the gun near the breech. At high velocities ($> 2 - 4 \text{ km/s}$) the projectile runs in an undisturbed bore, outracing structural disturbances originating behind it. We are developing gun designs which achieve the required mechanical performance without sacrificing inductance and which exploit the relaxed stiffness requirements in the high-velocity section of the gun.

The insulators are installed as shown in Fig. 5. This design facilitates the testing of different materials. Insulator tests are discussed later.

The railgun is fired inside a 400 mm diameter, 8 m long vacuum chamber which is pumped down to less than 10^{-3} Pa (10^{-5} Torr) for firing. To date, each time the gun has been fired, a precursor arc has struck in front of the projectile. This precursor, which draws about 50 kA, accelerates to the end of a 1-m gun in less than 20 μs .

Manuscript received March 17, 1986.

The authors are with the Center for Electromechanics at The University of Texas at Austin, Austin, TX, 78758-4497.

$$\frac{H}{S} = 1.5$$

$$\frac{W}{S} = 0.25$$

$$\frac{R}{S} = 2.5$$

$$L' = 380 \text{ nH/m (WITH TUBE)}$$

$$L' = 423 \text{ nH/m (WITHOUT TUBE)}$$

$$\frac{H}{S} = 1$$

$$\frac{W}{S} = 0.1$$

$$\frac{R}{S} = 2.5$$

$$L' = 519$$

$$L' = 556$$

$$\frac{H}{S} = 1$$

$$\frac{W}{S} = 2.5$$

$$\frac{R}{S} = 5$$

$$L' = 342$$

$$L' = 397$$

Fig. 2. Calculated high-frequency inductance of several railgun cross sections showing the effect of extreme rail geometry.

Fig. 3. Illustration of how rail geometry protects a low velocity projectile from being squeezed in the bore as the rails deflect during firing. Deflections are exaggerated.

The muzzle of the gun is equipped with a flash tube (Fig. 6) to shield the steel case from the ends of the rails. Without the flash tube, a muzzle arc can reach from the rails to the steel case, shorting the muzzle of the gun. In this event, the current can commutate from the armature into the muzzle arc [2]. With the flash tube in place, the current driving the muzzle arc gradually commutates (in about 200 μ s) back into the armature, extinguishing the muzzle arc. Although the precursor carries ~10% of the current, Cook [3] has calculated that the effect on gun performance is negligible: the precursor circuit acts like a closely coupled field turn. (The flash tube, incidentally, is shattered by the muzzle blast on more energetic shots.) The flash tube does not eliminate precursor arcs, but it does prevent a precursor from affecting the performance. Our goal is to eliminate the precursor altogether without increasing the vacuum chamber pressure.

Fig. 4. Comparison of geometry in which the rail-to-insulator seam shears and a geometry in which the seam separates.

PRODUCING AND MEASURING HIGH-PRECISION BORES

The practical way to produce a high-precision railgun bore is to finish the bore after the components have been assembled. Attempting to produce an accurate bore by assembling the gun from extremely precise components seems impractical. We have chosen to finish railgun bores by honing because this process can be used with virtually any material and because very high precision and good surface finish can be achieved. With honing, we have produced railgun bores that vary only 5 μ m in size along the length of the gun, as measured with a pneumatic gage [4] (Fig. 7).

We are accumulating evidence that this high degree of bore precision is necessary for sustaining full projectile acceleration above 3 or 4 km/s.

Several hone designs are illustrated in Fig. 8. The important features of a well-designed hone are that the abrasive surfaces be accurately parallel, that fine thickness adjustments can be conveniently made and that the hone be rigid. The temptation is to spring-load the abrasive, eliminating the need for a precise fit to the bore. A spring-loaded hone will,

Fig. 5. The insulator insert is easily changed, facilitating material tests.

Fig. 6. The flash tube shields the steel shell from the rails, preventing a precursor from developing into a muzzle short.

however, tend to follow the existing contours of the bore and will not produce precisely parallel bore surfaces as required.

Presently, more time is spent changing abrasive and adjusting the hone than is spent reciprocating the hone, which is done manually. In an eight-hour shift, about 2,000 mm³ of copper can be removed. After we improve our understanding of the practical aspects of honing, we will build or buy a honing machine.

Fig. 7. Pneumatic gage for precise measurement of a square-bore railgun. The shim allows the gage to be adjusted to the bore size. Assembly screws are not shown.

Fig. 8. Hones for square bore railguns. The abrasive (emery cloth or diamond-coated shimstock) is attached with double-sided tape. The hone on the left is adjustable. (The wedge angle is 75°.) The simple hone on the right is not adjustable: a large set of closely spaced (10 μm or less) hones is required. This type is especially suited for small-bore (10 mm or less) railguns. The setscrews push the hone to one side or the other for honing the corners.

Results

Diagnostics for the 1-m railgun routinely include breech and muzzle volts, individual and total store currents as well as gun current, a set of nine magnetic pickup-coils adjacent to the bore to monitor armature characteristics, and a set of make-screens down range to measure final projectile velocities. Probes oriented to view the armature current and to view the rail current are both used, a technique which has proven to be valuable in diagnosing railgun behavior [2, 3, 5, and 6]. Preliminary indications are that in a well honed, well gasketed gun fired with a carefully fit projectile, the tendency for restrikes to occur in the bore behind the armature is reduced or eliminated [2]. All signal lines are shielded from blast products and electrical noise inside and outside of the vacuum chamber and are recorded on digital storage oscilloscopes or waveform digitizers for later analysis.

Traces for shot #16 of the 1-m gun are shown in Fig. 9. The stores were configured to produce a fast current-rise to 320 kA with a subsequent ramp to 470 kA, thereby producing a steadily increasing base pressure on the projectile. Discontinuous jumps in the breech voltage trace indicates firing of indivi-

dual capacitor stores. Magnetic probes indicate the early appearance of a precursor arc ahead of the projectile carrying about 100 kA of current. The 100 kA of current in the precursor continues to be shunted ahead of the projectile for several hundred micro-conds.

The projectile armature is seen by the magnetic probe accelerating to a final velocity of about 5.0 km/s. Following muzzle exit, the gun is explosively crowbarred, the gun current decays, the voltage traces fall to zero. Muzzle flash is monitored with a fast

Fig. 9. Calculated and measured current and breech voltage (shot #16)

Fig. 10. Calculated and measured projectile displacement and calculated and inferred velocity. (Shot #16)

photodiode indicating negligible radiative power from the precursor and fixing the time of projectile exit.

Actual position, inferred velocity, current, and breech voltage are compared to computer simulations of gun performance in order to diagnose loss mechanisms that may degrade that performance. Fig. 10 show simulation vs. experiment for shot #16 indicating reasonable agreement between theory and experiment. The projectile apparently gained an initial velocity of about 750 m/s when the fuse (which was clamped in the bore) exploded. Thereafter the acceleration was as expected with an effective L' of 310 nH/m in the gun (compared to 320 nH/m measured after the shot).

Fig. 11. Railgun behavior averaged over a number of shots

Insulator Tests

The railgun design facilitates the testing of different insulator materials. The material to be tested is inserted into the gun as shown in Fig. 5. The level of damage sustained by the insulators and the rails may depend on the quality of the rail-to-insulator seal and the bore to projectile seal. The reasoning is that if the quality of the seals is poor,

material is lost from the armature. The armature demands more material to replenish itself, and this material is obtained by ablation from the rails and insulators. We emphasize that the theory that the degree of bore damage depends on the quality of the rail-to-insulator seal and the bore-to-projectile seal has not been tested with controlled experiments. The theory is supported by the plasma puffing experiments of Marshall [7] and the rail damage observations of Bedford [8]. In the insulator tests described below, gasketing techniques, projectile fitting techniques and bore honing techniques were changed from shot to shot so the results are qualitative.

Four insulator materials were tested: fused quartz, G-7 fiberglass laminate, polycarbonate and float glass. (Listed in decreasing order of ability to withstand ablation.) The peak current in the 13 mm square bore varied from 500 to 560 kA. Of the materials tested, fused quartz and G-7 showed the most promise of being reusable at the high current densities of the tests.

Fused Quartz. To the eye, fused quartz showed no effects of ablation. It may be that the transparency of fused quartz is a factor in limiting ablation damage, along with the high melting point.

Post-shot inspection revealed that in places, the fused quartz did not break, in other places it did break. The fact that some regions of the quartz were able to survive the high pressure shot without breaking is encouraging. Perhaps breakage can be eliminated with an improved design.

Quartz breakage appears to be sensitive to bore precision and to the precision with which the projectile is fit to the bore: an oversize projectile appears to result in increased quartz breakage.

The mounting of the 1 x 20 mm quartz ribbon is shown in Fig. 12. Honing of the quartz produces a corner as shown. Brittle materials are notoriously sensitive to such discontinuities. An improved design which eliminates the corner produced by honing is also shown.

A thin quartz ribbon was used to limit bending stresses. Presumably, the deflection produced during firing is determined not by the quartz, but the foundation upon which the quartz is mounted. If this is

Fig. 12. Mounting of fused quartz ribbon railgun insulators. Ribbon thickness increased by 200 μ m from the middle to the edge, impairing the seal. Adhesive installed as shown after assembly fixes the seal. Future improvements to eliminate breakage altogether are also shown.

the case, a thin, flexible ribbon of quartz mounted on a stiff foundation will survive conditions that would cause a thicker quartz ribbon to break in bending. The flexural strength of brittle materials can be improved by polishing the surfaces. We plan to improve the polish of the quartz to determine if less tendency to break results.

The metallic film deposited during firing on float glass (described below) was not observed on the quartz.

Fig. 13. Scanning electron microscope images of float glass railgun insulators. The leftmost picture (x 300) shows the honed glass before firing, the middle picture (x 1000) after firing with a copper fuse, the right picture (x 1000) after firing with an aluminum fuse.

G-7. The G-7 grade laminated fiberglass resisted ablation well, but was difficult to hone. The matrix material tended to powder under the hone, and the lamination boundaries were troublesome, but the results justify further testing, possibly with chopped fiber reinforcing rather than laminated fabric.

Polycarbonate. Polycarbonate is easy to hone, but suffered visible ablation damage at the high current. More sooty material coats the walls of the vacuum chamber after firing than with the other materials tested.

Float Glass. Not surprisingly, the glass is shattered during firing. But the shattering of the glass does not affect the railgun performance: glass-insulated railguns perform well on a one-shot basis. The glass is easily honed to very precise dimensions.

An interesting effect was observed with glass which was not observed with the other materials: after firing, the glass was covered with a thin, metal film. The metal film did not cover uniformly, but was deposited in irregular patches. When a copper fuse is used, the metal film is copper-colored. With an aluminum fuse, the metal film is gray in color, but the film may change to coppery colored for a short distance, then back to gray. Under the microscope, we discovered that the metal film was composed of metal spheres 1 to 10 μ m in diameter 10 to 20 μ m apart (Fig.

13). With the copper fuse, the metal spheres appear to have melted craters into the glass. With the aluminum fuse, no craters are observed.

We do not know if the metal is deposited from the armature as droplets or if the metal condenses as a film which then coalesces. On future shots, we plan to do a quantitative chemical analysis of the metal film, which may show how the composition of the armature changes as it moves down the gun.

The surface of the glass showed visible ablation.

PROJECTILE

We have successfully fired polycarbonate projectiles with an L/D as small as 0.65. Removing the corners (Fig. 14) reduces the mass ~11% without apparent adverse affect. Smaller L/Ds have not yet been tested, but intuitively one would expect a smooth, straight, precise bore and a carefully fit projectile to enhance stability.

Fig. 14. Lightened projectile.

Gouging of the copper rails has been a continuing problem. We have not yet determined the cause: marginal stability of low L/D projectiles, subsonic to supersonic (relative to rail shear waves) transition, projectile instability as the slope of the armature current changes from positive to negative, projectile fit, or rail properties. (Thio [9] reports no gouging of molybdenum rails.)

CONCLUSIONS

The design and fabrication of a launcher with good stiffness which can be disassembled has allowed the investigation of several important research topics:

- The mechanical interaction of the projectile and railgun bore
- Testing of candidate insulator materials for use in high current railguns
- The investigation of plasma seals in high performance launchers

Timely development of broaches and hones for establishing precise bores and the air gauge technology to inspect and insure the close tolerance has led to important discoveries. A classical railgun

simulation considering the driving force as $\frac{1}{2} L'I^2$ and the only retarding force an empirical expression for the friction force of polycarbonate rubbing on copper has predicted the performance of a launcher operating at a peak current of 500 kA and a velocity of 5 km/s.

In the future, attempts will be made to design stiffer guns and to develop techniques that not only yield a precise bore rail-to-rail and insulator-to-insulator but also a very straight bore. Efforts to identify better insulator and rail materials will continue. Further work will include examination of projectile materials and balancing of projectiles. Effectively sealing the plasma armature in the bore will be given careful attention. Loss of plasma creates demands for new armature material. The material is acquired from the rail surface by ablation. The main impetus of the research will remain to produce very straight and precise bores in order to separate the effects of mechanical interaction of projectile and bore and other unwanted effects such as ablation and plasma drag.

ACKNOWLEDGMENTS

This research was supported by the U.S. Army Armaments Research and Development Center and the Defense Advanced Research Projects Agency. The authors are grateful to J. L. Upshaw and his crew who fire the gun, and maintain the capacitor bank, vacuum chamber and other equipment. Inductance calculations were provided courtesy of N. M. Schnurr and J. F. Kerrisk.

REFERENCES

- [1] D. R. Peterson, C. M. Fowler, C. E. Cummings, J. F. Kerrisk, J. V. Parker, S. P. Marsh, and D. F. Adams, "Design and Testing of High-Pressure Railguns and Projectiles," IEEE Trans Magnetics, Vol. MAG-20, March 1984, pp. 252-255.
- [2] J. V. Parker, W. M. Parsons, C. E. Cummings, and W. E. Fox, "Performance Loss Due to Wall Ablation in Plasma Armature Railguns," AIAA 18th Fluid Dynamics and Plasmadynamics and Lasers Conference, July 16-18, 1985, Cincinnati, Ohio.
- [3] R. W. Cook, "Observations and Analysis of Current-Carrying Plasmas in a Railgun," 3rd Symposium of Electromagnetic Launch Technology, April 20-24, 1986, Austin, TX.
- [4] S. A. J. Parsons, Metrology and Gauging (MacDonald and Evans) 1970, Chapter 21.
- [5] J. F. Kerrisk, C. M. Fowler, and D. R. Peterson, "Measurement and Calculation of Magnetic Fields Associated with Railgun Currents," 1983 IEEE Conference on Plasma Science, May 23-25, 1983, San Diego, CA, Paper 6C7, IEEE Catalog 83CH1847-3.
- [6] L. D. Holland, "Distributed Energy Store Railguns Experiment and Analysis," PhD thesis, The University of Texas at Austin, May, 1984, Chapter 6.
- [7] R. A. Marshall, "Plasma Puffing from a Railgun Armature," IEEE Trans. Magnetics, Vol. MAG-20, March 1984, pp. 264-267.
- [8] A. J. Bedford, "Rail Damage and Armature Parameters for Different Railgun Rail Materials," IEEE Trans. Magnetics, Vol. Mag-20, March 1984, pp. 352-355.
- [9] Y. C. Thio, personal communications.