ELECTROMAGNETIC LAUNCH RESEARCH AT THE UNIVERSITY OF TEXAS AT AUSTIN

Presented at

The Third European Symposium on
Electromagnetic Launch Technology

London, England
April 16-18, 1991

Prepared by

William F. Weldon

Jack S. Josey Professor of Energy Studies
Director, Center for Electromechanics

Publication PR-140

Center for Electromechanics
The University of Texas at Austin
Balcones Research Center
Bldg. 133, EME 1.100
Austin, TX 78758
512/471-4496

ELECTROMAGNETIC LAUNCH RESEARCH AT THE UNIVERSITY OF TEXAS AT AUSTIN

William F. Weldon

Jack S. Josey Professor of Energy Studies
Director, Center for Electromechanics
The University of Texas at Austin
Center for Electromechanics
Balcones Research Center
Austin, Texas 78712

Abstract: The Center for Electromechanics at The University of Texas at Austin (CEM-UT) has been involved in the development of rotating electrical machines for pulsed power applications since 1973 and in the development of electromagnetic launch technology since 1979. The CEM-UT single shot laboratory gun, a 90 mm round-bore railgun 10 m long, is reviewed. The extensive operating experience with the ferromagnetic compulsator built at CEM-UT in the mid-1980's is reviewed and two new compulsator projects are described. Finally, future trends in the evolution of power supplies for electromagnetic railguns are surveyed.

INTRODUCTION

The Center for Electromechanics at The University of Texas at Austin has been involved in the development of specialized rotating electrical machines utilizing inertial energy storage for pulsed power applications since 1972 and in the development of electromagnetic (EM) launch technology since 1979. This work has included the successful development of seven generations of pulsed homopolar generators (HPGs) [1-7], three generations of inductive energy stores [8-9], mechanically and explosively actuated switches as well as high current solid-state switches, the invention and subsequent development of five generations of compulsators (CPAs) [10-14], structurally stiff and lightweight, high performance railguns, and solid railgun armatures. This paper presents a review of recent progress at CEM-UT.

THE ELECTROMAGNETIC RAILGUN

The simplest of the EM launchers, the railgun, has enjoyed the greatest popularity and success, at least partially because of the availability of pulsed power supplies well suited to the nature of this dynamic load. The force produced on the armature is given by the well-known expression

$$F = \frac{1}{2} L' I^2 \tag{1}$$

where

F = force in newtons
L' = inductance gradient along the gun, dL/dx
I = current in the gun

The voltage required to drive the current in the gun is approximately

$$V = \underbrace{IR'x + V_A}_{\text{dissipative elements}} + \underbrace{IL'\upsilon}_{\text{speed voltage}} \tag{2}$$

where

V = breech voltage
R' = resistance gradient down the rails and back, dR/dx (note: this is actually a dynamically changing value due to magnetic diffusion and heating)
x = position of the armature in the gun (measured from the breech)
V_A = voltage drop across the railgun armature (this is also a dynamic term)
υ = velocity of the armature, dx/dt)

Thus to achieve a constant acceleration, the instantaneous power which must be supplied to the railgun is

$$P = VI = \underbrace{I^2R'x}_{\substack{\text{dissipated}\\ \text{in}\\ \text{rails}}} + \underbrace{IV_A}_{\substack{\text{dissipated}\\ \text{in}\\ \text{armature}}} + \underbrace{I^2L'\upsilon}_{\substack{\text{increased}\\ \text{armature/projectile}\\ \text{kinetic}\\ \text{energy}}} \tag{3}$$

An ideal acceleration profile to extract maximum performance from a railgun is shown in figure 1. The acceleration should be turned on at the maximum rate allowed by the launch package, then held constant for the majority of the launch, being turned off at the end of the launch at the maximum rate allowed by the launch package. The current profile required to accomplish such a launch closely follows the shape of the acceleration curve as shown. The voltage required to produce such a current (1) must first be high, to force the current to rise at the desired rate, then (2) fall to a lower value to limit the current to the desired maximum value, after which it will rise (3) to hold the current constant against the rising speed voltage of the armature and, to a lesser degree, the rising resistive voltage drop of the rails and possibly armature, and finally (4) reverse to a negative value to force the current to zero before the armature exits the railgun. This last effect is one of the most difficult to achieve, but serves to both reduce the acceleration at the desired rate and to eliminate arcing at the muzzle due to energy stored magnetically in the railgun or power supply system. This then outlines the electrical requirements on an ideal railgun power supply which will be discussed further in the next section.

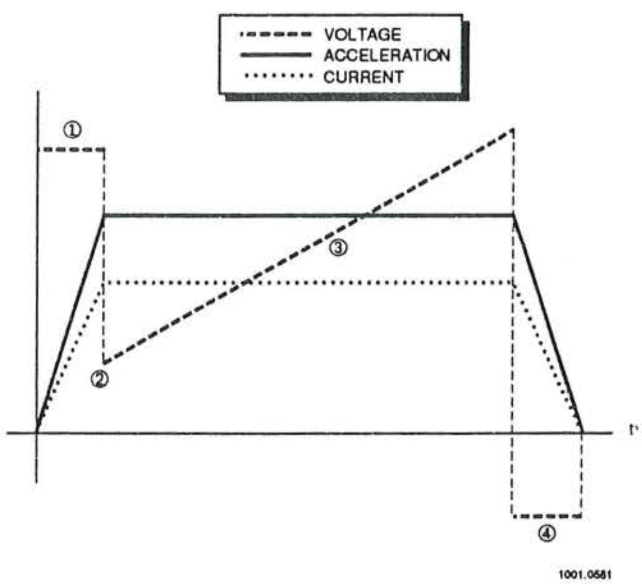


Figure 1. Ideal railgun performance requirements

An assumption implicit in the above discussion is that the railgun itself acts as a perfectly rigid structure producing a driving force on the projectile armature in proportion to the square of the applied current and responding in no other way. In actuality, as the armature accelerates down the railgun, the forces acting to separate the rails become much larger than the accelerating force. This can be envisioned as shown in figure 2, by considering that the path of the current through the rails and armature results in an elevated magnetic field in the bore of the railgun which in turn results in an effective "magnetic pressure" acting outward on the current carrying elements. It is the action of this magnetic pressure on the armature that produces the desired acceleration. Although the armature area over which this pressure acts is constant throughout the launch, the area of rails subjected to high magnetic pressure constantly increases as the armature moves down the gun.

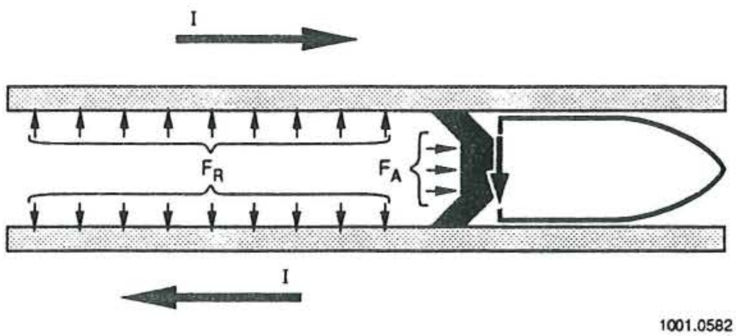


Figure 2. Magnetic pressure in bore of railgun

If the railgun structure is not sufficiently stiff, the rails will move outward under this loading. While this outward rail motion obviously causes mechanical problems such as the fit of the projectile in the bore, a less obvious problem is that it presents an additional load on the power supply. Lateral movement of the rails results in an additional factor being introduced into equations (2) and (3), a transverse L' or dL/dy designated as L'_T in the modified power equation below.

$$P = I^2 R' x + IV_A + I^2 L' \upsilon_\chi + I^2 L'_T \upsilon_y$$

where

υ_χ = velocity along the bore of the railgun
υ_y = transverse separation velocity of the railgun rails

Of course, this additional power requirement does not produce useful or desirable work and, unfortunately, becomes a maximum at the same time the other power requirements are a maximum, thus increasing the peak power required of the power supply.

CEM-UT has pioneered the development of stiff railgun structures designed to minimize transverse rail movement.[15] Past stiff railgun designs, although effective research tools, have been too bulky and heavy for practical field use (fig. 3).[16] Recent developments at CEM-UT have produced lightweight, stiff railguns with exceptionally high values of L' (fig. 4).

POWER SUPPLY OPTIONS

The short duration, but extremely high, power requirements of railguns make pulsed power supplies (which store energy at low power levels between shots, then deliver it at high power during the acceleration of a projectile) attractive. Effective energy storage mechanisms include inertial, magnetic, electrostatic, and electrochemical. Each method offers certain advantages and commonly used figures of merit include stored energy density and delivered power density. Table 1 compares the present state of the art for pulsed power supply technology.

In practice, only the CPA is suited to directly driving the railgun as witnessed by the fact that only its optimal discharge time (per pulse energy density/power density) matches the pulse width requirement of a railgun. Homopolar generators and batteries develop insufficient power to directly drive a railgun and are typically used to charge an intermediate inductive store which, through an opening switch, develops the power required to drive the railgun. The energy decay time (L/R time constant) for a typical inductive energy store is usually short; therefore, these devices are typically used only as intermediate energy storage devices.

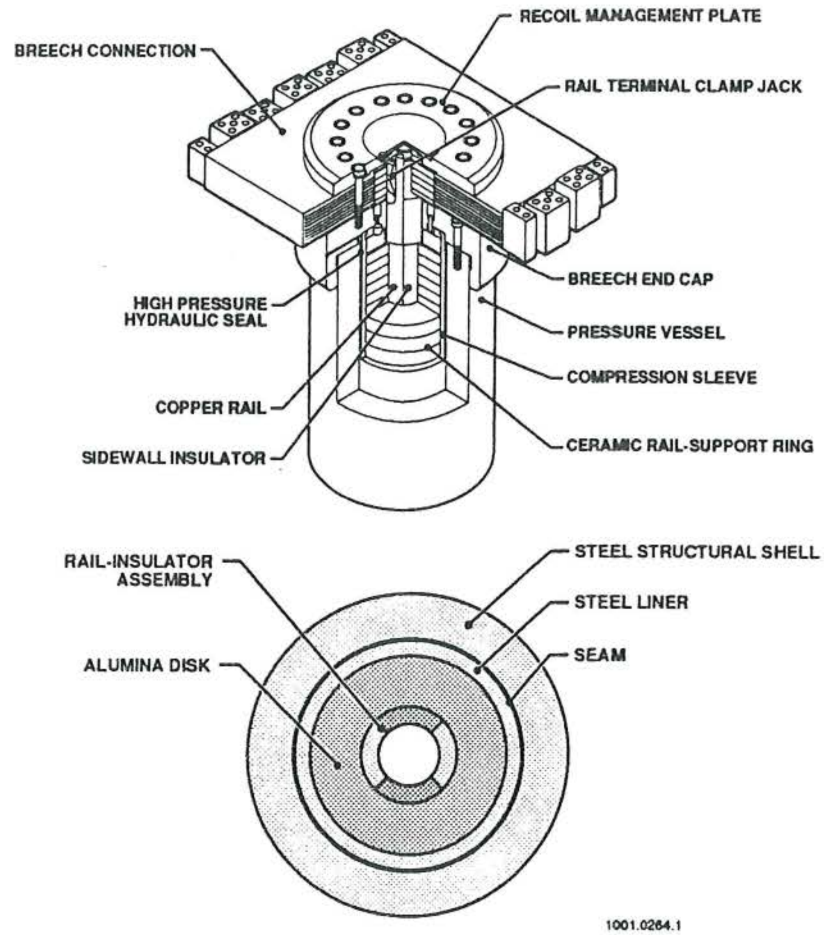


Figure 3. 90 mm bore x 10 m long hydraulically preloaded railgun

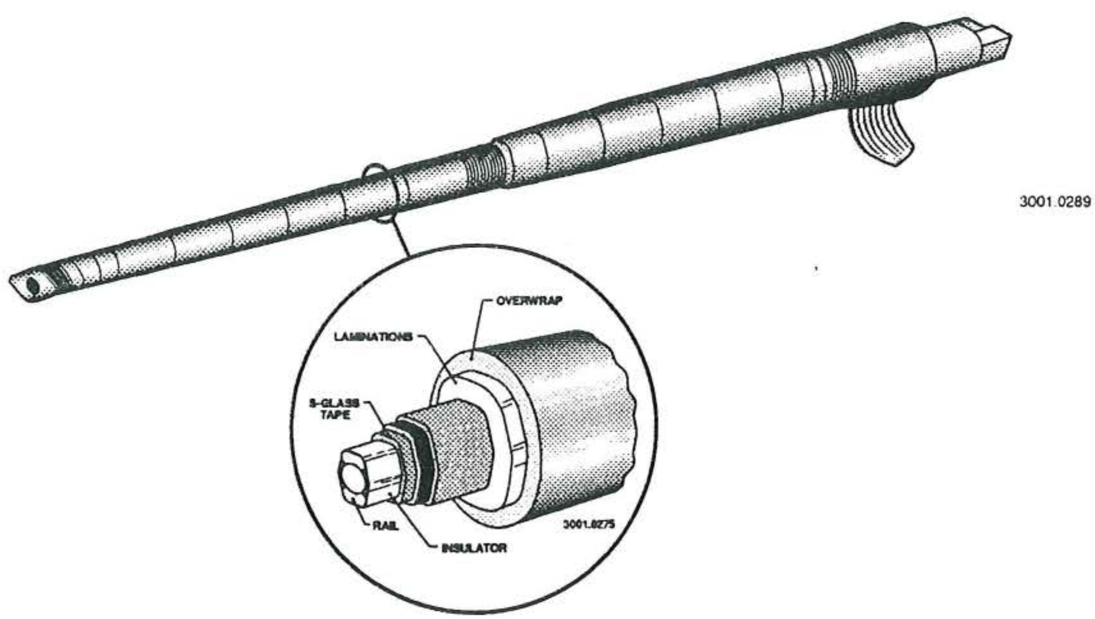


Figure 4. Lightweight, high performance railgun

Table 1. Pulsed power technology state of the art

	ROTATING MACHINES		STATIC DEVICES	
	COMPULSATOR	HOMOPOLAR GENERATOR	BATTERY	CAPACITOR
stored energy density	3.5 kJ/kg ferromagnetic, 12 kJ/kg composite	4 to 6 kJ/kg ferromagnetic	150 kJ/kg (usable)	0.7 kJ/kg
power density	164 kW/kg ferromagnetic, 1 to 1.25 MW/kg composite	50 kW/kg ferromagnetic	1.5 kW/kg	5.6 MW/kg
optimal discharge time	2 to 6 ms	80 ms	10 s	125 μs
typical module size	0.25 to 36 MJ/pulse	5 to 10+ MJ	2.4 MJ	50 to 100 kJ
typical voltage and current	2 to 6 kV 0.5 to 3.5 MA	50 to 100 V, 1.5 MA	12 V, 2 kA	10 to 20 kV, 25 kA
suitability for repetitive operation	inherently high 150 to 400 Hz	low	moderate	moderate

Conversely, capacitors typically have optimal discharge times too short to directly drive railguns and inductance must be inserted into the circuit to slow down the energy delivery. Although HPG or battery powered systems and capacitor powered systems both require inductors, the required performance and consequent size and weight of inductors for the two types of systems are radically different. The energy storage inductors used with batteries or HPGs must store the entire energy being transferred and must have L/R time constants long compared to the charging time. Thus, they are relatively large and massive. Inductors used in capacitor-charged systems on the other hand, do not store a significant fraction of the energy being transferred and can, therefore, be much smaller and lighter.

The CPA is also unique among pulsed power supply options in its inherent ability to reverse the applied voltage, driving the gun current to zero at the end of the pulse. This occurs because of the alternating voltage produced by the CPA. Other power supply options must achieve this task with resistors, crowbar switches or commutation circuits, any of which are slower and/or less efficient than the CPA technique. Thus, the CPA is unique among railgun power supply options in its passive operation, smooth acceleration profile, elimination of muzzle arc, efficiency and small volume. In addition, it may be driven directly by prime movers appropriate for advanced mobile weapon systems such as gas turbines or diesel engines as well as being motored from battery stores. For these reasons, the CPA has been selected by CEM-UT for development as a railgun power supply.

9 MJ SINGLE SHOT LABORATORY GUN

In 1987 when the U.S. Army Armament Research, Development, and Engineering Center solicited proposals to develop a single shot laboratory railgun capable of developing 9 MJ of muzzle energy at projectile velocities ranging from 2.5 to 4 km/s, CEM-UT responded by proposing to use an existing pulsed power supply consisting of six, 10 MJ HPGs [7] developed by CEM-UT and Parker Kinetic Designs and six, energy storage inductors developed for a Strategic Defense Initiative Organization sponsored hypervelocity railgun project, GEDI [17] (fig. 5). A single stage explosively actuated opening switch capable of interrupting 1.2 MA against recovery voltages up to 12 kV with opening times adjustable from 100 μs to 300 μs was developed for commutating the inductor currents into the railgun breech [18]. Figure 6 shows a typical railgun current pulse generated by staged operation of the six opening switches. The 90-mm bore, 10-m long hydraulically preloaded railgun shown in figure 3 is presently used in the facility.

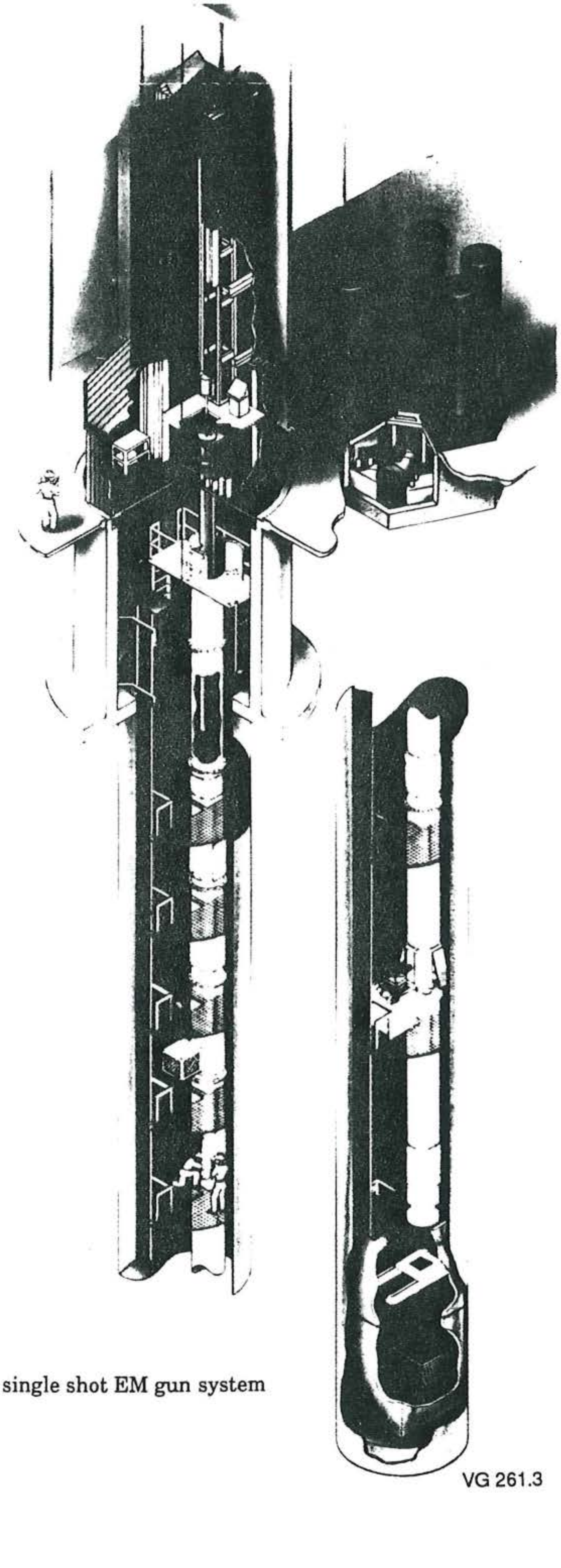


Figure 5. 9 MJ single shot EM gun system

VG 261.3

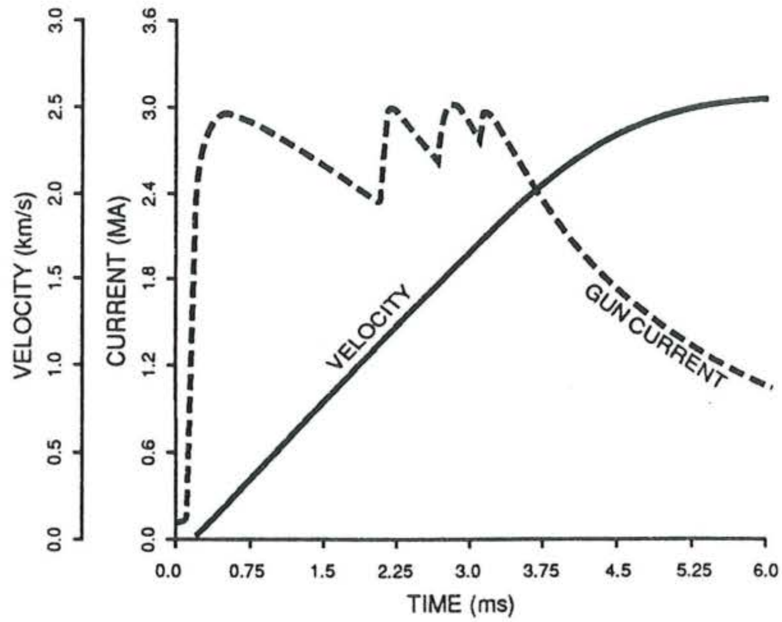


Figure 6. 8.1 MJ muzzle energy railgun shot - current and velocity profiles

The 9 MJ Single Shot Laboratory Gun facility was originally used to develop solid armatures for tactical applications, but is now being used to launch successively more complex integrated penetrator, sabot, armature packages. The highest launch energy achieved to date is 8.1 MJ (2.4 kg at 2.6 km/s) and launches are routinely being made in the 4 to 6 MJ range as required for the projectile development program.

FERROMAGNETIC COMPULSATORS

A passive, ferromagnetic CPA completed in 1986 stores 38 MJ and is designed to deliver 1.2 MJ/pulse at 2,000 V and 950 kA (fig. 7). Operating at 240 Hz, the machine stores sufficient energy to produce a burst of ten pulses. It was originally designed to accelerate 80-g projectiles to 2 km/s at a rate of fire of 60 Hz in a 20-mm railgun. After exceeding these goals, it has found a variety of applications as a versatile and reliable laboratory power supply. Most recently, it has been used to test high current solid state switches and to fire three-shot bursts in a 15 mm bore railgun at 10 Hz.

Although ferromagnetic CPAs are heavier than the composite CPAs presently being built, they are quite attractive as low maintenance, highly versatile power supplies for fixed applications. An example of such an application is a system of four passive, ferromagnetic CPAs investigated by CEM-UT for the RARDE EM Gun Range at Kirkcudbright. These machines, each 1.4 m diameter. x 1.5 m long (slightly larger than the CPA in fig. 7), would produce the desired muzzle energy in an 8 m railgun barrel over the full performance range as shown in figure 8a. Furthermore, a single unit would be an attractive railgun power supply in its own right, producing muzzle energies well in excess of 2 MJ over an equally wide performance range (fig. 8b).

ADVANCED (COMPOSITE) COMPULSATORS

In order to maximize power and energy density, recent development efforts at CEM-UT have focused on nonferromagnetic CPAs utilizing composite materials. The high specific strength of such composites makes dramatic gains in CPA performance possible. This is perhaps best illustrated by the results of the Hardison study comparing mass and volume of advanced CPAs to other power supply systems for a variety of electric gun missions [19]. Figure 9 shows the results of the study for all 18 missions. The results for a 9 kJ/kg capacitor based power supply are shown for comparison.

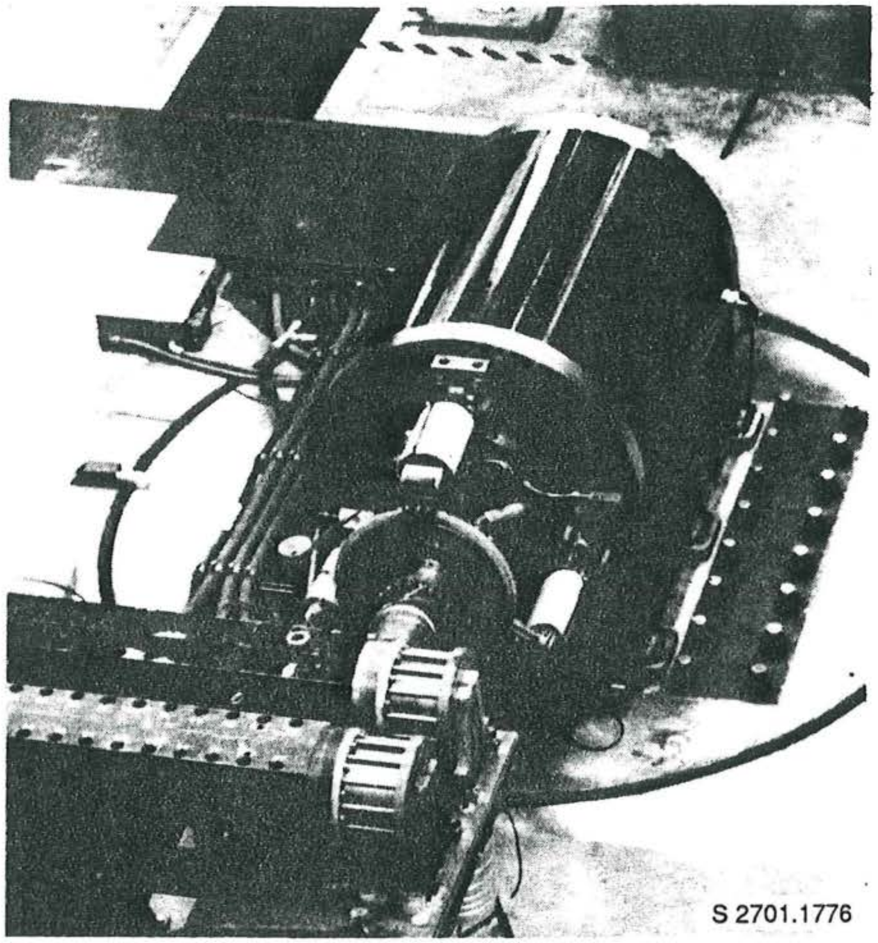
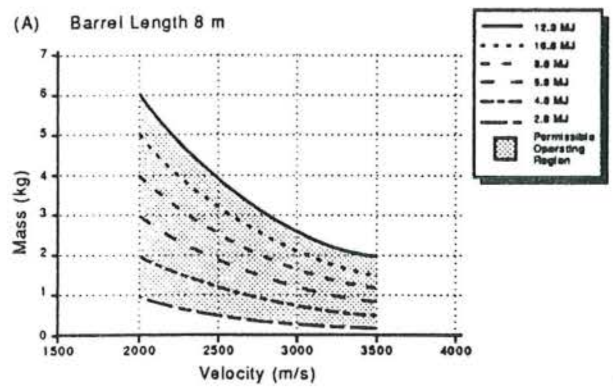
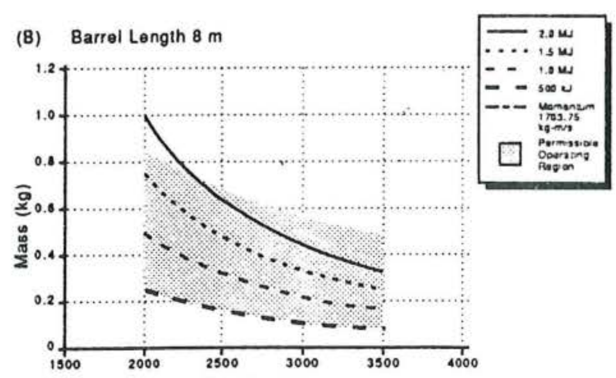


Figure 7. Iron-core compulsator



1001.0628.2

Figure 8a. Performance of system of four modular compulsators



1001.0628.1

Figure 8b. Performance of a single modular compulsator

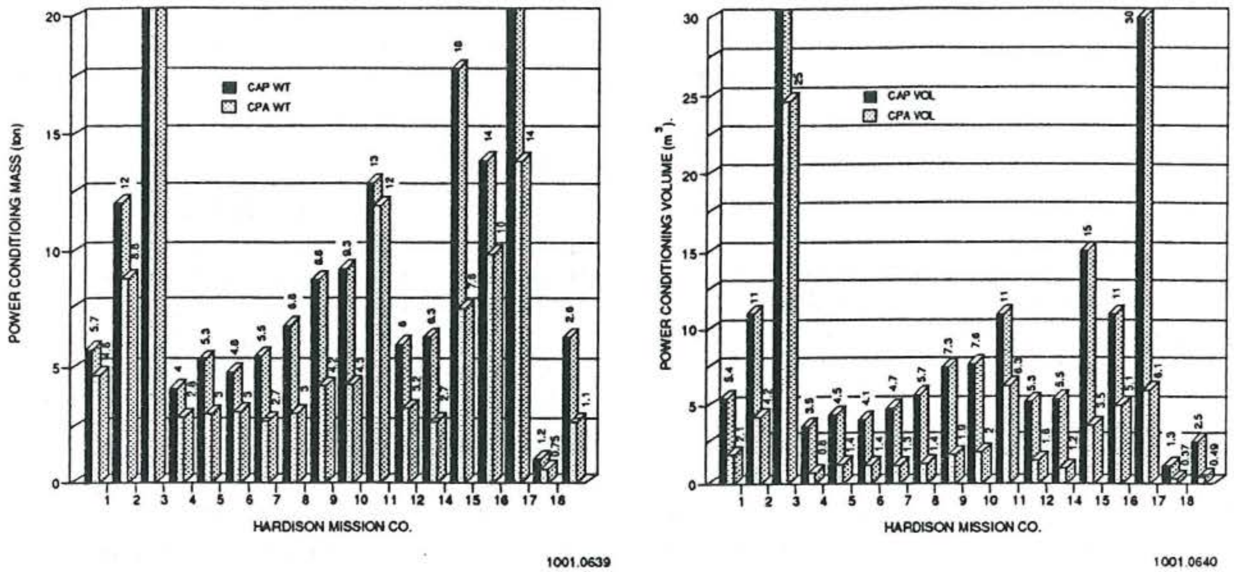


Figure 9. Hardison study -- mass and volume of advanced compulsators compared to capacitors

Two advanced CPAs are presently under development at CEM-UT. The smaller machine is intended to drive a small caliber machine gun firing 32-g projectiles at 2 km/s at a 10 Hz rate of fire [20] (fig. 10). The project weight goal of 1,000 kg has been beaten with the CPA weight of 750 kg. The CPA stores 8 MJ, delivers a peak power of 700 MW and incorporates such advanced features as self-excitation, ceramic shaft and bearings, all composite rotor, and lightweight, filament wound, augmented railgun. System testing is scheduled for spring of 1991.

The larger advanced CPA presently nearing completion is the power supply for the 9 MJ range gun (fig. 11) intended to produce 9 MJ of muzzle energy at velocities ranging from 2.5 to 4.0 km/s with a three shot per minute repetition rate from a stand-alone skid [21]. This CPA also makes extensive use of composite materials, is self-excited, and has provisions to reclaim the excitation energy after each pulse. This provision substantially increases the per-shot efficiency to about 33%. The machine shown in figure 12 stores 210 MJ and delivers up to 36 MJ per pulse at 5.8 kV and 3.2 MA. Two shots can be extracted from the stored inertial energy while power for the continuous firing requirement is provided by a General Electrical LM-500 gas turbine.

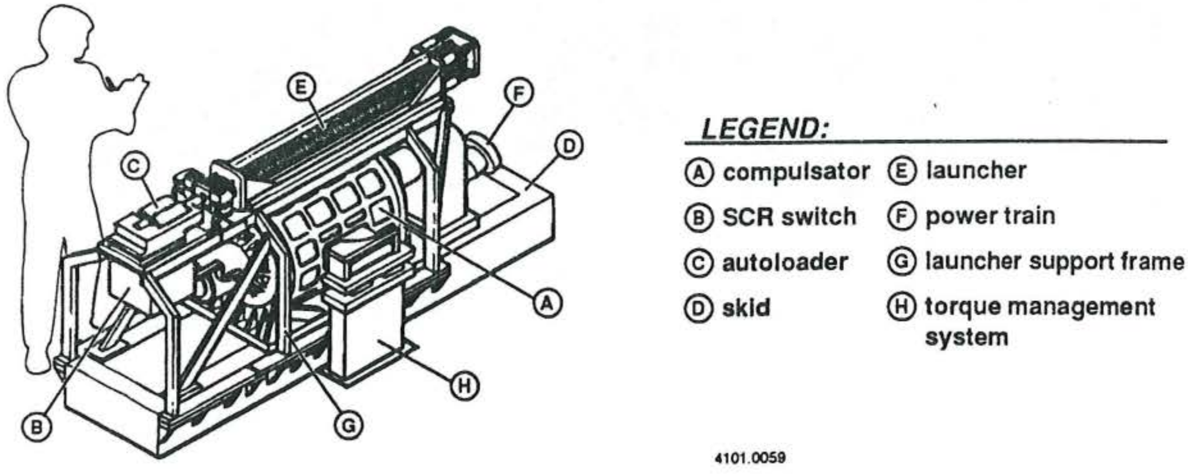


Figure 10. Small caliber compulsator powered railgun

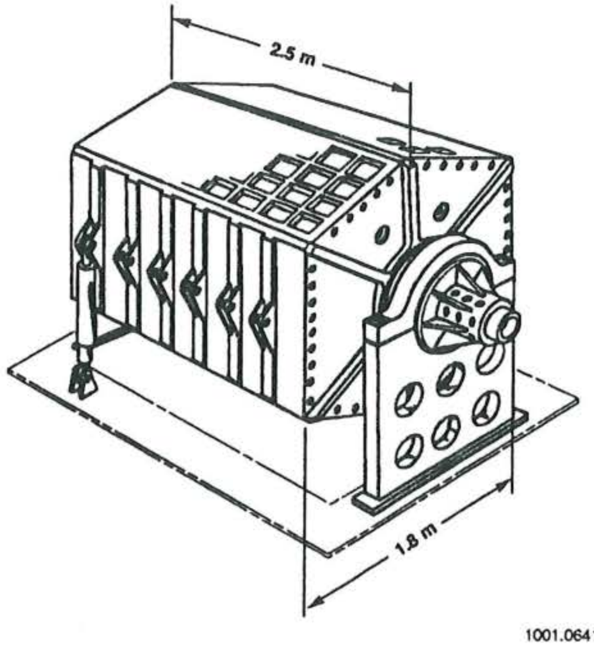


Figure 12. 9 MJ range gun compulsator

For mobile applications, dual CPAs with counterrotating rotors or a single CPA with counterrotating elements is required to eliminate reaction torque on the vehicle. While both of these configurations have been explored for HPGs, they have not yet been applied to CPAs. Work must continue to reduce required auxiliaries. Ceramic rolling element bearings being demonstrated on the small caliber CPA presently represent the limit of the state of the art. Larger ceramic bearings must be developed. It is believed that presently identified technology can provide size reductions between 2.5 and 4.0 compared to the advanced CPAs presently nearing completion.

Finally, as impressive as the performance of current and next generation railguns is, the problem of transferring enormous currents across the gun bore/armature interface will continue to limit the longevity of such guns. The prospect of noncontacting EM launchers will continue to become more attractive as we learn more about them. CEM-UT is involved in optimizing the geometrical and electromechanical parameters between the armature and stator of coaxial induction accelerators [23] and in developing the highly specialized power supplies required to make such accelerators practical [24].

REFERENCES

[1] H. G. Rylander, H. H. Woodson, E. B. Becker, and R. E. Rowberg, "Homopolar Motor Generator Designs for Cheap Inertial Energy Storage," Conference on Technology of Controlled Thermonuclear Fusion Experiments and the Engineering Aspects of Fusion Reactors, Austin, TX, November 20-22, 1972.

[2] W. F. Weldon, M. D. Driga, H. H. Woodson, and H. G. Rylander, "The Design, Fabrication, and Testing of a Five Megajoule Homopolar Motor-Generator," International Conference on Energy Storage, Compression, and Switching, Torino, Italy, November 5-7, 1974.

[3] T. M. Bullion, M. D. Driga, J. H. Gully, H. G. Rylander, K. M. Tolk, W. F. Weldon, H. H. Woodson, and R. C. Zowarka, Jr., "Testing and Analysis of a Fast Discharge Homopolar Machine (FDX)," Second IEEE International Pulsed Power Conference, Lubbock, TX, June 12-14, 1979.

[4] T. M. Bullion, R. C. Zowarka, Jr., T. A. Aanstoos, W. F. Weldon, H. G. Rylander, and H. H. Woodson, "Five-Megajoule Homopolar Upgrade," Third IEEE International Pulsed Power Conference, Albuquerque, NM, June 1-3, 1981.

[5] J. H. Gully, E. G. Estes, W. A. Walls, and W. F. Weldon, "Compact Homopolar Generator Development at CEM-UT," IEEE Transactions on Magnetics, Vol. Mag-20, No. 2, pp 203-206, March 1984.

[6] J. H. Price , J. H. Gully and M. D. Driga, "The High Voltage Homopolar Generator," IEEE Transactions on Magnetics, Vol. Mag-22, No. 6, pp 1690-1694.

[7] J. H. Gully, D. J. Hildenbrand, and W. F. Weldon, "Balcones Homopolar Generator Power Supply," IEEE Transactions on Magnetics, Vol. 25, No. 1, January 1989.

[8] M. D. Driga, T. A. Aanstoos, K. E. Nalty, R. C. Zowarka, Jr., A. Y. Wu, and W. F. Weldon, "Homopolar Generator Charged Inductors," IEEE Pulsed Power Conference Arlington, VA, June 10-12, 1985.

[9] R. L. Laughlin, "Fabrication and Testing of a 6 mH, 1.2 MA, 100 kV Inductor," Sixth IEEE Pulsed Power Conference, Arlington, VA, June 29-July 1 1987.

[10] W. L. Bird, W. F. Weldon, H. G. Rylander, H. H. Woodson; (The University of Texas at Austin) B. M. Carder, B. T. Merritt, and W. F. Gagnon (Lawrence Livermore Laboratories), "The Compensated Pulsed Alternator: Preliminary Test Results," Eighth Symposium on Engineering Problems of Fusion Research, San Francisco, CA, November 13-16, 1979.

[11] M. L. Spann, W. L. Bird, W. F. Weldon, and H. H. Woodson, "The Design, Assembly, and Testing of an Active Rotary Flux Compressor," Third IEEE International Pulsed Power Conference, Albuquerque, NM, June 1-3, 1981.

[12] D. E. Perkins, S. B. Pratap, M. L. Spann, R. F. Thelen and M. D. Werst, "The CEM-UT Rapid-Fire Compulsator Railgun System-Recent Performance and Development Milestones," presented at the Fifth EML Conference, Destin, FL, April 2-5, 1990.

[13] A. W. Walls, S. B. Pratap, G. W. Brunson, K. G. Cook, J. D. Herbst, S. M. Manifold, B. M. Rech, R. F. Thelen and R. C. Thompson, "A Field Based, Self-Excited Compulsator Power Supply for A 9 MJ Railgun Demonstrator," Fifth EML Conference, Destin, FL, April, 2-5, 1990.

[14] J. R. Kitzmiller, R. N. Faidley, R. L. Fuller, G. R. Headifen, S. B. Pratap, M. L. Spann and R. F. Thelen, "Final Design of an Air-Core Compulsator Driven 0.60 Caliber Railgun System," Fifth EML Conference, Destin, FL, April 2-5, 1990.

[15] W. F. Weldon, J. L. Bacon, D. A. Weeks and R. C. Zowarka, Jr., "Stiff Railguns," presented at the Fifth EML Conference, Destin, FL, April 2-5, 1990.

[16] J. H. Price, E. P. Fahrenthold, D. R. Peterson, W. F. Weldon, R. C. Zowarka, Jr., C. W. G. Fulcher, M. W. Ingram, "Design and Testing of Large-Bore, Ultra-Stiff Railguns," IEEE Transactions on Magnetics, Vol. 25, No. 1, January 1989.

[17] J. L. Upshaw, R. C. Zowarka, Jr., R. W. Cook, and D. A. Weeks, "Design and Development of Extremely High Velocity Electromagnetic Launch Accelerators--GEDI program," IEEE Transactions on Magnetics, Vol. 25 No. 1, January 1989.

[18] D. R. Peterson, J. H. Price, J. L. Upshaw, W. F. Weldon, R. C. Zowarka, Jr., J. H. Gully and M. L. Spann, "Heavy-Duty Explosively Operated Pulsed Opening and Closing Switches: Reducing Cost and Turnaround Time," Fifth EML Conference, Destin, FL, April 2-5, 1990.

[19] "Electric Gun Propulsion and Power Conditioning," Report of the Propulsion and Power Conditioning Panel of the Electric Energy Gun System Study to David C. Hardison, David Elliott, ed. Jet Propulsion Laboratory, JPL D-6272, May 15, 1989.

[20] J. R. Kitzmiller, J. H. Gully, M. L. Spann, W. F. Weldon, and D. J. Wehrlen, "Testing the 60 MJ Pulsed Homopolar Power Supply at the University of Texas, Center for Electromechanics," Seventh IEEE Pulsed Power Conference, Monterey, CA, June 11-14, 1989.

[21] W. A. Walls, M. L. Spann, S. B. Pratap, K. G. Cook, W. G. Brinkman, J. D. Herbst, S. M. Manifold, B. M. Rech, R. F. Thelen, and R. C. Thompson, "Design of a 20 GW, Self-Excited, Air-Core Compensated Pulsed Alternator Railgun Power Supply," 1990 International Conference on Electrical Machines.

[22] Joseph Henry Beno, B. S., M. S., "Current Management For Improved Railgun Performance," Ph. D. Dissertation, The University of Texas At Austin, August 1989

[23] D. A. Bresie, J. A. Andrews and S. W. Ingram, "Parametric Approach to Linear Induction Accelerator Design," Fifth EML Conference, Destin, FL, April 2-5, 1990.

[24] S. B. Pratap, "Limitations on the Minimum Charging Time for the Field Coil of Air Core Compensated Pulsed Alternators," Fifth EML Conference, Destin, FL, April 2-5, 1990.