SPEAR Coilgun

D. A. Bresie, J. L. Bacon, S. K. Ingram, K. S. Kennington, and D. A. Weeks

Center for Electromechanics
The University of Texas at Austin
BRC, Mail Code 77000
Austin, TX 78712
(512) 471-4496

Abstract--The SPEAR, a recent development in coilgun technology, passively launches a projectile with a solenoidally wound armature. This paper describes the SPEAR, its electromagnetic operation, its construction, and the tests performed to prove its principle. It describes the composite stator sections and the glass reinforced armature coils. It describes how engineers at CEM-UT overcame the problem of keeping solid state switch volume low by employing a modular switch design with a unique snubbing circuit that reduces required volume. Results of test #5, described in the paper, show how well the operation of the SPEAR matches the computer simulation predictions.

Conceptually, the proximity of the approaching armature electromagnetically drives a stator coil's current through zero. At zero crossing the stator freewheel switch turns off, preventing reestablishment of stator current as the armature moves away. As originally designed, the gun was to accelerate a 2 kg package to 2,000 m/s. The part built is expected to achieve 1,000 m/s with a 0.75 kg package. ARDEC sponsored the work under contracts DAAA21-91-C-0087 and DAAA21-90-C-0011.

INTRODUCTION

Electric gun research over the last decade has centered mainly on simple and reliable railguns. An attractive though more complex alternative to the rail gun is an electric gun based on coaxial coils. These coilguns have captured attention because of their promised advantages, absence of high velocity arcing contact [1] and high electrical efficiency [2]. They can also mate more easily with a wider variety of power supplies.

Earlier coilgun programs both at CEM-UT and at other research centers have yet to demonstrate muzzle velocities in excess of 1,000 m/s [3, 4, 5]. Researchers consistently concluded that high coilgun velocity requires many coil stages and that the associated switch timing for each of these stages is critical. The SPEAR concept described in this paper eliminates the need to sense the armature and switch a launcher stage. With correctly designed electromagnetics, switching of the coilgun stages occurs passively eliminating complex control systems. The SPEAR concept not only incorporates this passive electromagnetic switching but also gives the high ratio of conversion of electrical to kinetic energy necessary for high gun efficiency [6].

Manuscript received April 24, 1994.

This work was supported by U.S. Army ARDEC under contract number DAAA21-91-C-0087 and contract number DAAA21-90-C-0011.

The SPEAR Project at CEM-UT has the ultimate goal of accelerating a 2 kg launch package to a muzzle velocity in excess of 2,000 m/s. Achieving this goal has several steps. The first step proves the electromagnetic principle and verifies various system components. The plan then calls for progressively increased energy levels, first with a capacitor bank then with an iron core compulsator. The early tests use a 0.5 m long gun section with 9 coils designed for up to 700 m/s (fig. 1). A second section should boost velocity to 1,000 m/s. Additional sections increase muzzle velocity to the ultimate goal. This paper explains the SPEAR concept, describes the hardware built to demonstrate its principle and presents test results for the first successful test of the system.

SPEAR ELECTROMECHANICS

The SPEAR concept evolved gradually as researchers at CEM-UT sought a coilgun architecture that required no active "sense and switch" control scheme and that allowed utilization of high energy density rotating machinery rather than low energy density capacitor banks for primary energy storage.

MIT's "quench gun" [2] provided valuable background for the SPEAR concept. However, the SPEAR concept differs in several important ways from the quench gun. The quench gun described in the reference utilizes a super conducting barrel, in which a persistent current is established prior to the launch. The full launch energy is stored in the barrel's magnetic field. A persistent current in the armature, has a polarity such that the barrel draws the armature toward it. As the armature passes each successive barrel coil, the superconductivity of that coil is "quenched". Since coils behind the arma-

Fig. 1. External SPEAR arrangement

0018-9464/95$04.00 © 1995 IEEE

ture no longer carry current, no braking force is produced on the armature.

This scheme has the advantage of allowing the launch energy to be stored in the barrel prior to the launch, eliminating the need for high-voltage capacitor power supplies. Active sensing and switching is still necessary, however, to determine when to quench each barrel coil.

Like the quench gun, the SPEAR launcher consists of a set of barrel coils in which persistent current exist. The SPEAR concept, however, does not rely on superconductivity phenomena for proper operation. In a SPEAR launcher the armature carries precisely the amount of current necessary to drive the barrel coil through a current zero as it approaches the centered position of a coil. A silicon controlled rectifier (SCR) in the barrel circuit switches off at this point and prevents the reappearance of the barrel coil's current as the armature moves away (and the consequence braking force). This process continues for each barrel coil as the armature moves down the barrel.

The SPEAR concept offers significant advantages over previous coilgun architectures. First, any type of power supply can charge the barrel. In particular, high energy density rotating machinery works well, whereas many other concepts require the extremely high power levels available only from capacitor banks. Second, the motion of the armature itself controls when the barrel coil current goes through zero, and consequently when the associated SCR turns off. All system timing is an integral part of the electromagnetic operation of the launcher; no active control is required. Finally, unlike the pulsed induction launcher concept, all of the energy initially stored in the barrel is converted to armature kinetic energy, except for that portion which is dissipated thermally. The pulsed induction launcher leaves a residual magnetic field behind in the barrel after the launch.

The gun efficiency trade-off between the SPEAR and induction launcher concept tips in favor of the SPEAR if its L/R time constant is large in comparison to launch time. This occurs more easily in large guns because of favorable scaling.

ELECTRICAL CIRCUIT

Circuit Description

The utilitarian power conditioning feature of the SPEAR stator design allows several charging options. The high coupling between the armature and stator necessary for efficient launch resulted in the stator having a L/R time constant of 20 ms in CEM-UT's SPEAR. Thus for efficiency, the stator needs a charging time well below 20 ms. Compulsators and capacitors are the power supplies at CEM-UT capable of these relatively short discharge times and required deliverable energy. To demonstrate that the SPEAR concept could utilize high energy density/medium power density supplies like compulsators, a launcher system based around CEM-UT iron core compulsator (ICPA) was constructed. The ICPA is capable of storing 60 MJ of energy inertially when its rotor is spinning at 4,800 rpm. At this speed it has an open circuit voltage of 2,000 V, a pulse width of 2.1 ms, and can produce a peak current of approximately 1 MA. Approximately 4 MJ will be removed from the ICPA in order to store sufficient energy in the stator to achieve a 2 kg, 1 km/s launch. In addition to the ICPA, several 100 kJ capacitor modules are used to charge the armature. Finally, 100 kJ capacitor modules have been employed to charge the stator during low energy shots.

The electrical arrangement of components for the SPEAR test bed is shown schematically in fig. 2. To best match the launcher to the ICPA, stator sections composed of nine coils connected in series are charged in parallel. Independent freewheel SCR switches short each stator coil after the gun is charged. Each switch, composed of 6 series by 7 parallel Powerex C713 SCRs, holds off 12 kV symmetrically, has 30 µs turn off time, and can conduct 80 kA for 5 ms.

Progressively increasing the kinetic energy in the armature allowed the first gun tests to be conducted with a capacitor bank power supply. This allowed gun launches relatively early in the program. To reduce stator dissipation an isolation switch, composed of 6 series by 7 parallel Powerex C713 SCRs, was placed electrically in series with the bank. It has the same characteristics as a freewheel switch.

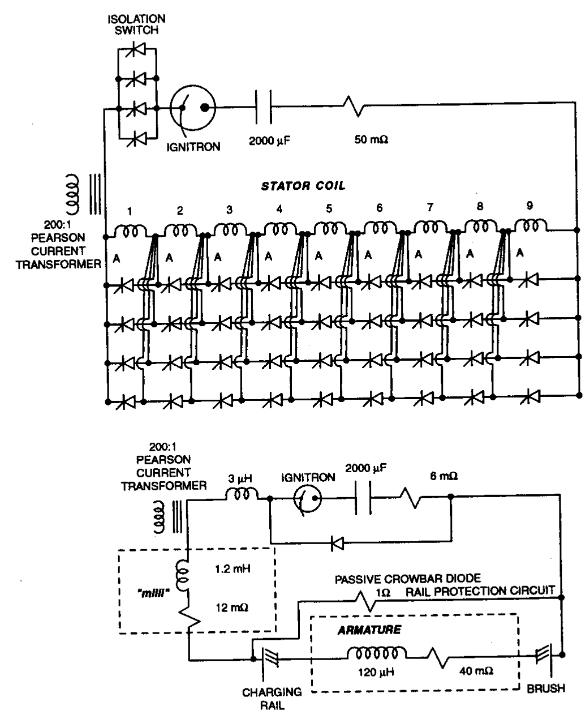

Fig. 2. SPEAR launcher electrical schematic

Capacitor modules switch on with ignitron mercury vapor switches. For later ICPA powered launches, independent rectifiers for each stage will convert the current to dc. Each rectifier leg (4 legs per rectifier) has 2 series and 5 parallel Powerex C702 SCRs. The combined rectifier has a PIV rating of 12 kV and can conduct current that ramps up to 80 kA over approximately 10 ms. For either stator charging arrangement, the armature is charged with one or more capacitor modules. The armature freewheel switch is composed of 5 series by 2 parallel Powerex R9G0 diodes. The armature freewheel switch blocks up to 15 kV and can conduct a 4 ms sinusoidal current pulse of 100 kA.

Launch Process

Stator section charging starts the launch process. Once energized, the power supply begins stator charging by gating the ICPA rectifier SCRs or by gating the capacitor bank's ignitrons. After stator charging, all the stator freewheel switches are triggered simultaneously. Current commutates from the charging path into the freewheel path. Typical launch times for single launcher section is approximately 5 ms. As previously mentioned, the stator L/R time constant is 20 ms so approximately 80% of the initially stored energy is available to be converted to launch package kinetic energy. After sufficient time elapses to complete commutation and to insure that the rectifier or isolation switch SCRs have cleared of minority carriers, the launch starts with the discharge of capacitor modules into the armature. The armature begins to be accelerated while charging. Once the armature reaches peak current freewheeling occurs spontaneously through the its diode switch. As with the stator, the armature freewheel switch L/R time constant is significantly longer than the launch time. If it were not the armature's stored energy will be dissipated and be unable to convert the stators stored energy to kinetic energy. As the armature moves into a stator coil, it drives the stator coil current to zero at which time the SCR freewheel switch opens. The SCR switch must clear (be able to stand-off forward voltage) prior to the armature passing through the centerline of the stator coil or the stator current will be reestablished and the armature will be decelerated. Because the SCR clearing time is fixed, the position ahead of the coils centerline at which current must be driven to zero increases with increasing velocity. So at higher velocities, the armature must drive the stator current to zero at positions of increasingly lower coupling. This requires either an increase in armature energy or a decrease in the stator energy. Thus, for a specific clearing time a point is reached in long guns at which acceleration is no longer practical. Clearly, for higher velocities, faster clearing switches are required.

Critical Hardware

Gun Section

The 120 mm bore SPEAR coilgun barrel is made up of multiple sections placed end to end in a frame and axially preloaded. Fig. 1 shows the external arrangement. Monocast nylon breech and muzzle sections separate the metal gun frame from the active barrel sections. Each of the barrel sections contain 9 coils connected in series with a copper terminal at the ends of each coil. The coils are wound with 6 turns of copper litz wire containing 8 groups of 7, 16 gage wire bundles and wrapped with 0.003 in. thick s-glass tape. A 10.50 in. diameter by 2.125 in. thick filament wound S-glass disc surrounds each coil and provides support for the terminals. During construction, the barrel components, including three longitudinal bore rider retainer pieces were assembled in a mold and vacuum pressure impregnated with an epoxy resin. The outer diameter of the cast barrel section was filament wound with a 0.75 in. thick s-glass over wrap to provide hoop stiffness. Finally, holes were drilled through the overwrap to allow access to the coil terminals.

Switch Module

The freewheeling switch modules and the rectifier modules have similar designs. The freewheeling module has 6 series SCRs and the rectifier has 8 connected as a bridge. They are designed in a modular fashion so that both fabrication and repair would be rapid and efficient. Fig. 3 shows the internal arrangement of a module. Over voltage protection in the rectifier module is provided by a resistor-capacitor snubbing circuit while the freewheel switch requires only resistors.

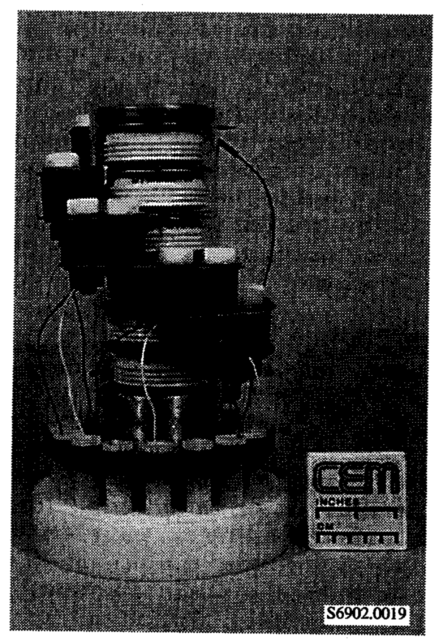

Fig. 3. SCR freewheel module

A pulse transformer provides 8 secondary current pulses to the SCR gates. Each gate circuit contains a current limiting resistor and a diode to prevent reverse biasing to the SCR gate. Modular construction of the switch allows mass production and ease of repair. The aluminum housing of the package performs 3 functions: preload, current conduction, component protection. A hydraulic pressurization tooling gives accurate SCR preloading.

Each switch module is acceptance tested at 12 kA and 5 kV. To date many of the freewheel switch modules have been commutated into over 75 times without any malfunctions.

Armature

The armature, another critical component in the SPEAR system, must operate in a high magnetic field and must be able to withstand a 100 kgee acceleration. Since it has a persistent current throughout the launch, efficiency requires its time constant (L/R) to be longer than the launch time. Toward these goals, advanced materials and construction were used in its design.

The armature windings are of 1100 series aluminum ribbon wire with Poly-thermaleze insulation. The ribbon conductor is edge wound to form a 36 turn coil. Woven glass fiber braid, slipped over the windings provides a structural media for vacuum epoxy impregnation. After impregnation, the windings are overwrapped with glass fiber to give the coil hoop strength. During operation, the armature currents produce a tensile hoop stress in the glass overwrap of near 200,000 psi.

Aluminum contacts on the front of the coil provides electrical connection to the armature circuit. Since the armature begins moving as soon as charging begins, it is charged on the fly. This is made possible with short rails running through the first launcher section that touch the armature contacts. After the charging is complete, an on board crowbar switch maintains the armature circuit. A miniature arc gap switch has been identified for this purpose but has not yet been tested. Testing to date has utilized an external diode stack for crowbarring the armature circuit. Fig. 4 shows the assembled armature.

Initial Tests

In the first successful test of the SPEAR, a single launcher stator section, consisting of nine individual coils charged in series, accelerated a 760 g armature to 148 m/s. Each of the nine coils contributed to the acceleration of the armature and switched off passively. Measured velocity was within 6% of the simulated performance. In addition, the stator section sustained no damage and it is expected that with an additional stator section, a full complement of freewheel switches, and the Iron Core Compulsator that it will be able of accelerating an armature to 1,000 m/s.

Fig. 4. 120 mm SPEAR armature

The stator section was energized with a 2,000 μF capacitor module charged to 7.5 kV producing a peak current of 28 kA. Then, 25.3 kA were successfully commutated into the stator freewheel SCR path. Thirty-six freewheel modules arranged in four parallel paths were used during the test. Upon completing commutation of the stator current, the launch was initiated by discharging a second 2000 μF capacitor module from 8 kV into the armature producing a peak current of 9.97 kA. The armature was accelerated to approximately 148 m/s. In-bore performance was determined from the times at which current was extinguished in each coil.

Experimental Equipment and Setup

The armature, stator, switches, and capacitor banks were connected together as shown schematically in fig. 2. The addition of the 1.2 mH inductor (milli) was necessary to improve the armature time constant during low energy, non-cooled experiments. To prevent leftover energy stored in "milli" from damaging the armature guide/charging rails, a 1 W resistor was placed in parallel with the armature to limit the rail-to-rail voltage on armature exit.

Prior to performing the launch tests, proper stator and armature current freewheeling was verified at the appropriate currents. Because peak stator current exceeds the peak rating on a single SCR, parallel current sharing between the four paths was measured. Typically the current shared within 25% from leg-to-leg. Each parallel path was instrumented to insure that no single path current exceeded the capabilities of the SCRs. Gating of the stator freewheel occurred 840 μs after discharge of the stator capacitor. This was sufficient time for the stator voltage to have reversed to approximately 180 V, thereby forward biasing the stator freewheel SCRs. The commutation event required approximately 160 μs. After the current in the capacitor bank was driven to zero, an additional 90 μs passed prior to triggering the armature capacitor bank to allow the stator bank isolation SCRs to completely recover. Commutation losses required the stator to be overcharged to 29 kA peak so as to have 26 kA in the stator at the time when the armature bank was discharged.

The armature was loaded 0.1 m behind its centered position in coil #1. The make type velocity screens are constructed by separating two sheets of aluminum foil with two layers of paper. A capacitor charged to 300 V was placed across each pair of foils. A sudden drop of the foil-to-foil voltage indicates the penetration of a screen.

Data

A Nicolet System 500 digital oscilloscope recorded the electrical performance data. Signals were down loaded to an IBM compatible PC for archival and plotting. Stator charging is initiated at time zero and peaks in 750 μs at 29 kA. At 840 μs sufficient reverse voltage has accumulated across the stator to commutate current into the freewheel path so the freewheel modules are gated. Stator commutation and armature initiation occurred as described above. From this point, control of the experiment ends and the launch occurs passively. The current in the armature peaks in 2.5 ms at approximately 10 kA. Fig. 5 shows the armature and stator voltages on expanded scale so as to reveal the variation in voltage associated with the turn off of each stage.

Analysis

Stator coil turn off time, ascertained from fig. 5 data, was plotted against coil position in fig. 6. In addition, simulated performance and velocity screen data is also shown. Measured data indicates that the armature accelerated smoothly to 148 m/s in comparison to the predicted 158 m/s, a difference of 6%. It is believed that make screen #1 was penetrated early, by debris which were released as the armature left the charging rails, and consequently is not representative of the armatures true position. Energy balance information is summarized in Table I. The ratio of armature kinetic energy to stator energy after commutation (0.28) best represents the SPEAR gun efficiency in this test. This should improve considerably as the performance increases because the stator dissipation is reduced as a result of shorter launch times.

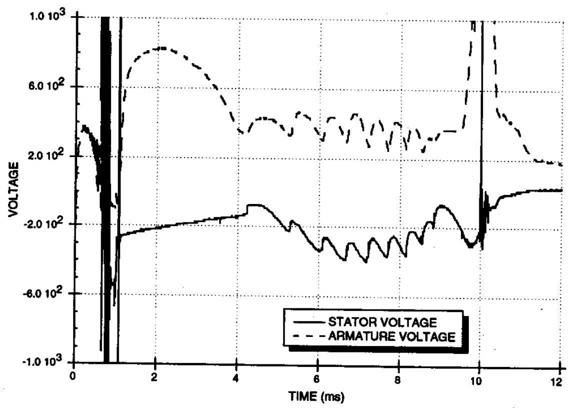

Fig. 5. SPEAR launcher voltages (expanded scale) from test #5

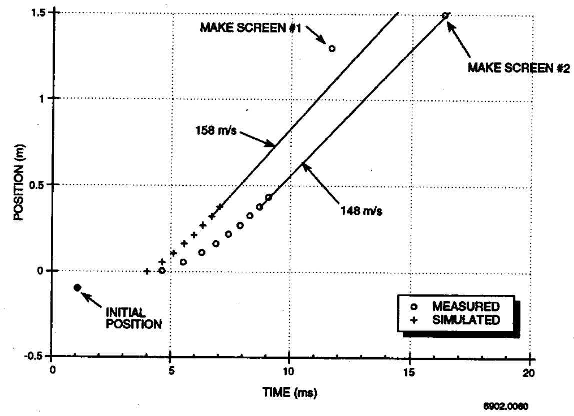

Fig. 6. SPEAR test #5 plot

Table I. Energy balance information for SPEAR launch #5

Description	Energy	Armature Energy/Item Energy
Stator Capacitor Initial Energy	56.25 kJ	0.15
Armature PFN Initial Energy	64 kJ	
Total Initial System Energy	120.25 kJ	0.07
Peak Stator Energy	38.62 kJ	0.22
Stator Energy After Commutation into Freewheel Path	29.64 kJ	0.28
Peak Armature Energy	6.11 kJ	
Armature PFN Residual Energy	23.28 kJ	
Armature Residual Energy	2.17 kJ	
Armature Kinetic Energy	8.32 kJ	

Conclusions And Future Work

A single launcher stator section accelerated a 760 g armature to 148 m/s. Each of the nine coils contributed to the acceleration of the armature and switched off passively. Measured velocity was within 6% of the simulation and the efficiency of conversion of stored stator energy to kinetic energy was 28%. In addition, the stator section sustained no damage. The overall efficiency was 7%.

Scaling relationships developed during the design of the SPEAR launcher indicate that as the size of the launcher increases that higher performance is obtainable without increasing the stresses on components. This suggests that coaxial launch technology may be well suited to electromagnetic space launch systems. Technology of this type has the potential to reduce the cost of access to space by a several orders of magnitude. Other promising applications include long-range artillery and anti-missile defense systems.

ACKNOWLEDGMENTS

The U.S. Army Armament Research, Development, and Engineering Center (U.S. Army ARDEC) sponsored the work described in this paper under contracts DAAA21-91-C-0087 and DAAA21-90-C-0001.

REFERENCES

[1] R. J. Kay, et al, "Design and Performance of Sandia's Contactless Coilgun for 50 mm Projectiles," Transactions on Magnetics, vol 27, no. 1, January 1991.

[2] P. P. Mongeau, "Inductively Commutated Coilguns," IEEE Transactions on Magnetics, vol 27, no. 1, January 1991.

[3] M. W. Ingram, et al, "An Actively Switched Pulsed Induction Accelerator," IEEE Transactions on Magnetics, vol 27, no. 1, January 1991.

[4] R. J. Kay, et al, "Design and Performance of a Multi-Stage Cylindrical Reconnection Launcher," IEEE Transactions on Magnetics, vol 27, no. 1, January 1991.

[5] Z. Zabar, et al, "Test Results for Three Prototype Models of a Linear Induction Launcher," IEEE Transactions on Magnetics, vol 27, no. 1, January 1991.

[6] S .K. Ingram, "Theoretical Analysis of a Collapsing Field Accelerator," IEEE Transactions on Magnetics, January 1993.