SYSTEM DESIGN OF THE ULTRAHIGH VELOCITY GEDI EXPERIMENT

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

Publication No. PR-45
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Abstract - System and component design for the ultrahigh velocity, guided electromagnetic defensive interceptor (GEDI) experiment is underway and initial fabrication has begun. Figure 1 is an artist's sketch of the experimental facility. The objective of the GEDI experiment is to accelerate a 1-g mass to 50 km/s. Prime power for the experiment will be supplied by the 60 MJ, 9-MA Balcones homopolar generator (BHPG) power supply located at the Center for Electromechanics at The University of Texas at Austin (CEM-UT). This power supply consists of six 10-MJ HPGs which can be connected in various series/parallel configurations or sequentially discharged for pulse shaping. Power conditioning consists of six room-temperature copper coaxial inductors, six two-stage opening switches, and six crowbar switches with a 1 m diameter x 40 m long vacuum chamber, and high speed diagnostics completing the system. The system which will be used to develop and test ultrahigh velocity electromagnetic accelerators (EMAs) was designed to be a versatile, easily maintained laboratory system. This power supply represents a substantial capability and can be used to drive a variety of experiments such as a large bore tactical-type railgun which is being designed to launch a 2-kg projectile at 3 km/s. Design parameters, component specifications, and program status are presented.

Fig. 1. GEDI power supply.

PRIME POWER SUPPLY

The six homopolar generators that comprise the BHPG system are 10-MJ, 100 V, 1.5 MA, drum-type

homopolars. The machines were designed and paid for by CEM-UT and are being built by Parker Kinetic Design (PKD). Characteristics of the CEM-UT system are shown in Table 1. Six machines, rather than one large machine, were built because of the versatility of being able to connect them in various series/parallel configurations and the ability to do pulse shaping by sequentially discharging the machines. The homopolars, which are being installed below grade, will have their output terminals at grade for convenience as shown in Fig. 2. They are in the final stages of assembly with delivery and installation to follow.

Table 1. CEM-UT BHPG characteristics.

MAXIMUM ENERGY STORAGE	60 MJ
MAXIMUM DISCHARGE CURRENT (Six machines in parallel)	9 MA
MAXIMUM DISCHARGE VOLTAGE (Six machines in series)	600 V
MAXIMUM ROTOR SPEED	6,200 RPM
MAGNETIC FLUX DENSITY IN AIR GAP	1.8 T
EFFECTIVE CAPACITANCE (per machine)	2,000 F
IMPEDANCE (per machine)	7.1 $\mu\Omega$ /112 nH
MAXIMUM SLIP RING SPEED	186 m/s (610 ft/s)
APPROXIMATE DIMENSIONS	1.2 m dia. x 1.8 m l. (42 in. dia. x 72 in. l.)
APPROXIMATE WEIGHT (per machine)	10,000 kg (22,000 lb)
MOToring TIME TO MAXIMUM SPEED	2 min.
DISCHARGE TORQUE	216,140 N-m (159,419 ft-lb)
CYCLE RATE	FULL DISCHARGE EVERY 5 MIN.

Fig. 2. BHPGs in pit.

Two Turn Coaxial Inductors

To provide intermediate energy storage and pulse compression as required by HPG driven railgun acce-

Manuscript received March 17, 1986.

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lators, six inductors, one each per HPG, have been designed and are being built. The design criteria for the inductors called for a 50% transfer efficiency, or 5 MJ at 1.2 MA from the HPG. A two turn coaxial geometry, shown in Fig. 3, was chosen because of the minimal external fields associated with coax's and the ability to utilize high dielectric strength insulation and replace the insulation if required. However, because the inductance is proportional to the number of turns squared, limiting the design to two turns resulted in rather large and heavy devices. Table 2 shows the specifications of the inductors.

Table 2. Inductor specifications.

INDUCTANCE (per inductor)	6 μH
DC RESISTANCE (per inductor)	8.3 $\mu\Omega$
OUTER DIAMETER	1.4 m (55 in.)
LENGTH	5 m (200 in.)
WEIGHT (per inductor)	11,124 kg (24,526 lb)

For efficient energy transfer between the low voltage, low-impedance HPGs and inductor, the resistance of the load during the charging cycle must be minimized. In a cryogenic inductor, aluminum, which is lighter and less expensive, is the material of choice. Because this is a laboratory system, the complexity of a cryogenic system was undesirable and therefore copper, operating at room temperature, was the material of choice. Copper alloy CDA 10300 was selected because of the superior weld quality obtainable in this alloy. Therefore, the design was based upon a yield strength of 69 MPa (10 ksi) and a resistivity of $17 \times 10^{-9} \Omega/\text{m}$, which are the properties of fully annealed copper. Although the inductors are designed to operate at room temperature, provisions have been made to cool the center rod of the inductor with LN_2 because the center rod has the smallest cross sectional area, and therefore the highest current density of 6.57 kA/cm² (42.4 kA/in²). By cooling the center post a 4% increase in transfer efficiency is realized.

Because the need for compactness was not necessary, like that of the first coaxial inductor built by CEM-UT [1], a two-turn design which can be readily assembled and disassembled was implemented. This also allows for the inspection and possible replacement of the interturn insulation. In a coaxial inductor with more than two turns, disassembly is not feasible because of the required number of bolted joints and because of the vacuum impregnated, fiberglass reinforced insulation system. Conductor thickness and interturn separation were minimized because of partial flux linkages (internal inductance) that occur. In the theoretical case of an instantaneous discharge, magnetic diffusion effects result in energy in partial flux linkages being trapped and dissipated in heating of the conductor rather than producing usable energy. For the rapid discharge into a railgun, 70% of the energy stored in internal inductance is trapped. Therefore, internal inductance must be minimized. The outer conductors are being rolled out of 1.27 cm (0.5 in.) thick x 229 cm (90 in.) wide x 439 cm (173 in.) long plate. Two cylinders are rolled to the same diameter and welded along their seams. These two cylinders are then stacked, one on top of the other, and the girth joint is welded. The center rod will be made by silver brazing two pieces together and the inner tube is made by silver brazing centrifugal castings together. The endplates are made of 5 cm (2 in.) thick plates for structural reasons. The dc inductance is calculated by using the following formulas for each area of the inductor.

For air

$$L = (2 \times 10^{-7}) N^2 L_a \ln(R_o/R_i)$$

Inner conductor

$$L = (0.5 \times 10^{-7}) L_a N^2$$

Fig. 3. Cross section of two turn coaxial inductor.

End plate

$$L = (2 \times 10^{-7}) (T/3) N^2 \ln((R_{oo} + R_o)/R_i + i))$$

Outer conductor

$$L = (0.5 \times 10^{-7} N^2 L_a) (4 R_{oo}^4 \ln(R_{oo}/R_o) / (R_{oo}^2 - R_o^2)^2 + (R_o^2 - 3 R_{oo}^2) / (R_{oo}^2 - R_o^2))$$

where:

- N = Number of turns in the inductor
- L_a = Length of coil
- R_o = Inner radius of outer turn
- R_i = Outer radius of inner turn
- T = Thickness of endplates
- R_{oo} = Outer radius of outer conductor
- R_{ii} = Inner radius of inner conductor

Magnetic fields decrease linearly with radius (1/r) and magnetic forces resulting from these fields are highest at the inner conductors and decrease with the square of the increasing radius (1/r²). To determine the pressure applied on a surface of the inductor, the magnetic flux density must first be found.

$$B = \mu_o NI / 2\pi r$$

where:

- B = Magnetic flux density (W/m² or T)
- $\mu_o = 4\pi \times 10^{-7}$ (H/M)
- N = Number of turns enclosed in loop
- I = Current (A)
- r = Radius from center of inductor (m)

Now the pressure can be determined by:

$$P = B^2 / 2\mu_o$$

where:

$$P = \text{pressure (N/m}^2 \text{ or Pa)}$$

Inner coaxial conductors are compressed by the magnetic field with a load of 4.6 MPa (670 psi), the load being taken by the thick walled center post and inner tube. The outer cylinders are loaded in tension but the fields are low, 68 kPa (10 psi) at this large radius, and the resulting stresses are acceptable. Endplates experience a load profile that starts at the inner radius with a magnitude of 4.6 MPa (670 psi) and decreases to 68 kPa (10 psi) at the outer radius as shown in Fig. 4. The areas of highest stress are at the corners where the endplates are attached to the inner conductors. To strengthen these areas, a fillet weld will be used as shown in Fig. 5. During assembly of the inductor, the center rod will be loaded in tension so that when it is clamped in place and released it will preload the insulation. This will help the loading that is applied to the endplates to be transmitted to the center rod.

Fig. 4. Pressure profile on endplates.

Fig. 5. Fillet weld.

The back voltage that the inductors will be subjected to, because of the 50 km/s velocity, is on the order of 40 kV. The inductor insulation is designed to withstand 2.5 times this back voltage or 100 kV. A mock-up has been constructed of the area at the top of the inductor where the center post meets the outer endplate to test the insulation. This mock-up is shown in Fig. 6. The insulation has withstood 40 kV without the Mylar® wrap on the center post. At this time we are awaiting a larger power supply so that we can test up to 100 kV.

SWITCHES

The GEDI program will require two switches per generator, one switch being a normally closed inductor charging switch, the other being a normally open switch between inductor and load.

Fig. 6. Insulation test mock-up.

Opening Switches

Ideally, the GEDI opening switch must handle charging currents of up to 1.5 MA for periods of 0.25 s, transfer current to a load in approximately 20 μ s, and recover to 100 kV. Realistically, these requirements can be relaxed initially for testing at lower current levels, and the experience gained from initial testing will be used to design the final switch.

Individually, each of the above named switch attributes has been achieved or approached in previously published reports. For example, exploding foil fuses have generated MV level pulses with transfer times in the μ s range, while mechanical charging switches have carried 500 kA currents with times to peak of 0.25 s. To combine the different features of different opening switches, a staged switch scheme is typically used, where a slow, low voltage, first-stage switch commutates current into a fast, high voltage, second-stage switch.

For the GEDI experiments, two approaches are being followed for the design of the primary charging switch. One approach is the use of a mechanical opening switch similar to the switch developed at CEM-UT for use on the compact HPG, the other approach is the use of an explosive first-stage switch akin to those designed by Ford and Vitkovitsky at Naval Research Labs [2]. Both approaches have advantages and drawbacks. The mechanical opening switch's advantage is multiple operations before refurbishment is required. The mechanical switch's drawbacks are damage due to electrical breakdown, and relatively complicated fabrication. The advantage of the explosive opening switch is relatively simple fabrication, while the drawbacks of the explosive switch are mandatory reloading between shots, and the necessity of handling explosives.

The initial design of the explosive opening switch was based on Ford and Vitkovitsky's "cookie cutter" design, with three topologies shown in Fig. 7. In these switches, Detasheet acts as a pressure source moving a paraffin piston. This paraffin ruptures the aluminum, cools the arc, and insulates the separated metal edges. In addition to the use of paraffin for arc control, the switch topologies are designed to make use of magnetic assist for arc blow out, and magnetic insulation for voltage standoff assistance.

Fig. 7. Explosive switch topologies.

After further investigation of the properties of Detasheet, it became apparent that even in its thinnest form, Detasheet is too powerful an explosive for our needs. Further, concerns exist as to the propagation of the explosive front in Detasheet for proper sequential opening of the gaps in the switch. To make better use of the explosive energy for cutting metal, we decided to pursue the use of explosive shaped charge for an opening switch. Figure 8 is the current rough design of the GEDI explosive switch. Six to eight lines of explosive shaped charge cut the aluminum plate, and embedded the debris in a polyethylene sheet. The lead casing of the explosive shaped charge is likewise driven into a backing piece of plastic. Sequencing of the shaped charge lines can be done by explosive delay lines, or by external firing modules for detonators. As with the previous switches, both magnetic blow out assistance and magnetic insulation are incorporated into the switch design.

Fig. 8. Latest explosive switch design.

Fuse Design

The generation of significant back voltage (40 kV) in the GEDI gun requires even higher voltages (100 kV) be generated in the opening switch in order to commutate to the high voltage loads. One known technique of generating such voltage pulses is through the use of an inertially confined exploding foil fuse. The basic mechanism of voltage generation is the rapid increase in resistance of a gas under high temperatures and pressures. A water tamped foil fuse upon explosion, can produce 10 to 20 kV/cm of length. Unfortunately, the attainment of high resistance is a transient behavior, with the resistance decreasing as the superheated plasma expands and cools. Research will need to be conducted to see how long the high resistance state of the plasma can be maintained.

Isolation Switch

Each generator/inductor pair will need to be isolated from its neighbors when time distributed switching of the generators is desired. For low level testing of the experiment, existing commercial ignitrons from GE are available and adequate for our purposes. However, for longer pulses and higher currents, reservations exist about the ability of the ignitrons to carry the current without damage to the ignitron. One substitute that could potentially replace ignitrons for the isolation switch, with a decrease in circuit inductance, is the use of a triggered railgap switch. These switches have typically been used for much lower coulomb levels than are expected in this experiment. Given that the explosive switch will require reloading, designing an expendable railgap switch that requires replacement between shots is a consideration.

GEDI is an experiment. The approach taken by CEM-UT is to build precise bore launchers of high structural stiffness to minimize the mechanical interaction between projectile and railgun bore. Every effort has been made to insure precise measurement of voltage, current, and final velocity of the projectile. The theories of ablation, restrike, and plasma drag need to be studied in very precise experiments that have the potential of exploring the power levels and velocities of interest. In this way the severity of the loss mechanisms may be verified experimentally.

One example of the operating philosophy is to accept the fact that restrike is a problem and a loss mechanism. Also observe that the launch time in a hypervelocity gun is a small time interval. Experiments have shown that restrike arcs have finite formation times and with a 5 km/s launch in a 1 m long gun, the restrike develops to shunt at most 25% of the current from the main armature in the launch time.

Assume the restrike robs 25% current from the primary arc in the launch time. For the constant current case

$$v = \sqrt{2ax}$$

where

v = velocity
a = acceleration
x = launcher length

also

$$a = \frac{kL'I^2}{m}$$

where

L' = Inductance gradient
I = gun current
m = projectile mass

therefore

$$v_{\text{final}} \propto I$$

The projectile kinetic energy is then proportional to the current squared. With the restrike taking 25% of the current from the main arc the efficiency of the launch drops to 56% of that seen with no restrike.

To eclipse the first GEDI program milestone of 1 g to 10 km/s in an electromagnetic railgun 50,000 J of the 26.4 MJ inductive energy must be delivered to the projectile. Even if the 50,000 J needs to be increased to 8 kJ to account for restrike losses the overall efficiency of 0.34% is required. An efficiency of 4% is being realized in 5 km/s launchers performed in the laboratory at this time.

By taking this approach, the severity of the different loss mechanisms may be characterized in the short term. The major research effort may then concentrate on the most pressing problem area.

ACCELERATOR

Gun geometries and components are being investigated with capacitors and CHPG power to attain the goal of accelerating 1 g to 50 km/s. Outlined are some of the important aspects of reaching this goal.

1. Exceptional structural strength and stiffness
2. Designed to allow disassembly for maintenance and inspection
3. Gun mounted on a rigid stiffback with provision for gun straightening adjustments at mounting points
4. Optical tooling system for measuring gun straightness
5. Honing system for producing polished and precisely straight and true bore
6. Low pressure 2-m railgun to inject projectile at 5 to 10 km/s into main railgun
7. Main railgun to be constructed without transverse in-bore seams
8. Development of a 1-g projectile for a 12-mm square bore which will not tumble or shatter
9. Erosion-resistant materials for rails and insulators
10. Bore-projectile friction
11. The diversion of armature current into spurious paths
12. Realistic simulation programs
13. Structural analysis
14. Accurate, convincing diagnostics

The first six phases of the program are shown in Table 3.

Table 3. Railgun Development

	DESCRIPTION	COMMENTS
Phase I	1-m gun powered by capacitor	- Material testing - Diagnostic development
Phase II	2-m gun powered by capacitor	Goal: 10 km/s
Phase III	2-m gun powered by homopolar generator	- Square current pulse, soft driven
Phase IV	1- or 2-m gun powered by capacitor injected by 2-m gun powered by homopolar	- Avoid problems of commutating inductor into injected gun - Mechanical decoupling of first and second stages - Second stage breech connections critical - First stage soft driven, second stage hard driven
Phase V	5-m gun powered by Balcones homopolars, injected by capacitor-driven 2-m gun	- Demanding switching requirements Goal: 20 km/s
Phase VI	25-m gun powered by Balcones homopolars	- Goal: 40 km/s very high back voltage

The railgun will be fired in a vacuum range similar to the chamber now in use at the CEM-UT facility for experimentation on 1- to 5-m railguns (Shown in Fig. 9). The new vacuum chamber will be 1 m (40 in.) in diameter and 40 m (130 ft) long. The range may be pumped to 1×10^{-6} torr and is capable of holding a 25-m gun.

Fig. 9. Vacuum range

CONCLUSION

The Center for Electromechanics is in the process of design and fabrication of a 60-MJ power supply to be used as the power source for an ultrahigh velocity electromagnetic accelerator. The HPGs are in the final stages of fabrication with delivery in April, 1986. The material for the inductors has been ordered with fabrication to begin May, 1986 and delivery in October, 1986. Completion of the entire facility is to be in November, 1986 with the first experiments taking place in January, 1986.

ACKNOWLEDGEMENTS

Funding for this program is being provided by the Strategic Defense Initiative Office (SDIO) and the Defense Advanced Research Projects Administration (DARPA) through the U.S. Army research and Development Center (ARDC). Contract No. DAAA21-85-C-0212.

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