THE DES RAILGUN FACILITY AT CEM-UT

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Summary

The Center for Electromechanics at The University of Texas at Austin (CEM-UT) has constructed a facility for the operation of electromagnetic (EM) launcher experiments. The facility was specifically designed to investigate distributed-energy-store (DES) railguns. Experiments conducted in the facility have demonstrated the DES railgun concept using a 1-m long, four-stage DES railgun. Investigations have begun on a 4-m, ten-stage DES railgun to demonstrate operation of such a system at higher projectile velocities. The capabilities and design of the major components of the facility are described. Also presented is a review of the experimental development of the railgun system. The DES railgun facility is a versatile laboratory test bed facility for EM acceleration experiments.

Introduction

The three sections of this paper describe the DES railgun program at the Center for Electromechanics at The University of Texas at Austin (CEM-UT). The railgun facility has been constructed as part of a joint effort with the Vought Corporation. The work has also been supported by the Texas Atomic Energy Research Foundation (TAERF), the U.S. Army Armament Research and Development Command (ARRDCOM) and the Defense Advanced Research Projects Agency (DARPA).

The first section introduces the system by detailing the operational capabilities of the facility. In the following section, the DES railgun concept is briefly reviewed, especially as it relates to the design and operation of the CEM-UT facility. The final section outlines the development of each of the major components of the system and includes a description of the experimental work that has been conducted.

Operational Capabilities of the System

The heart of the DES railgun facility is the set of modular capacitor banks that were developed for DES railguns. The eleven capacitor banks are completely independent energy stores that can be used to operate a DES railgun, to provide any desired current waveform to a single load, or to drive individual loads, such as those found in some coaxial electromagnetic (EM) accelerators. Each of the modules has an energy storage range of from 1 to 60 kJ. The voltage range of the capacitors is up to 10 kV. The peak current limit from each of the energy stores is 200 kA. Because each store contains its own current-limiting inductor, the stores can be operated in parallel. This gives a maximum peak current to a load of approximately 2 MA.

The rise time of the current in each of the stores ranges from 20 to 100 μs, depending upon the configuration of capacitance and inductance in the store. A triggering system, which can use either time delays or signals from a load to trigger the energy stores, can be used to shape the total current from all the stores into any desired waveform. For operation of DES railguns, the system is capable of delivering a nearly constant current of 300 to 400 kA for from 1 to 2 ms.

The DES railgun facility was designed as a laboratory test bed for EM launcher experiments. This fact has affected the system in two respects. First, the energy store, triggering system, and railguns have been designed to permit conducting a wide variety of experiments. How this flexibility affects each of the system components is detailed in the following sections. The second major feature of the facility is the diagnostic system. A complete diagnostic system is required to characterize the operation of both the energy stores and the EM launcher experiment. This leads to a requirement for a large number of data channels in the system. A digital data acquisition system was chosen to perform this task. Part of this system is presently operating during the DES railgun experiments. During the next year, additional data channels and a computer for data reduction will be added to the facility. The details of the diagnostic techniques used on the system are given in the following sections.

DES Railguns

The simple breech-fed railgun consists of a current source feeding the rails of the gun at the breech. This type of system constitutes the simplest form of an EM macroparticle accelerator. Several steps can be taken to improve the system efficiency of the simple railgun in terms of energy transfer efficiency from the initial stored energy to the final kinetic energy of the projectile. In addition, in some railgun applications the length of the accelerator presents practical problems in implementing the breech-fed railgun system. These considerations led to the development of the DES railgun concept. A detailed look at the DES railgun system is presented in another paper.2

The DES railgun is shown schematically in Fig. 1. It consists of separate energy stores connected to the rails at points distributed along the bore of the railgun. The DES railgun has the potential for reducing the amount of energy needed in the primary stores of a given launch mission and removes any limit on the length of the accelerator. The first objective of the program at CEM-UT was to demonstrate that the DES railguns could be operated as theoretically predicted. This objective has been accomplished. A four-stage DES railgun was operated. The discharge of each of the energy stores was triggered based on the position of the armature in the bore of the gun as indicated by magnetic pickup coils.

![Fig. 1. Schematic diagram of a DES railgun](image-url)

In the operation of a DES railgun the total current in the armature can be greater than the peak current available from one energy store. This fact was used in the design of the DES railgun facility. The peak cur-
rent from each store is limited to 200 kA. Calculation of the heating of the rails and subsequent experimental evidence both indicate that the maximum allowable current in 1-cm wide copper rails is greater than 500 kA. Thus, several of the energy stores are turned on in quick succession at the beginning of a shot to achieve an armature current in the 200- to 400-kA range. Subsequent stores are turned on to maintain this armature current level. Operating several of the energy stores simultaneously raises the voltage at the rails as seen by an individual store as compared to a single store operating alone. This increases the efficiency of energy transfer from a store to the kinetic energy of the payload.

The energy stores shown in Fig. 1 show a diode in the circuit. The function of this generalized diode is to prevent the reversal of current in a store once the energy in that store is exhausted. The source of the reverse current is the voltage on the rails caused by the stores further down the bore of the gun driving the armature. Implementation of the diode function can present practical problems in the design of a DES railgun system. For the CEM-UT facility, the cost of semiconductors to perform the diode function on the energy store would have been prohibitive, so they are not included in the present energy stores. In the operation of the 4-m railgun, current reversal does occur in the first four of the ten energy stores. The system was designed to keep the reverse currents in the stores in the range of twenty percent of the armature current at any time during a shot. The design of larger DES railgun systems must either implement the diode function or carefully control the inducances and resistances of the system, including the rail resistance, to keep the total reverse currents to an acceptable fraction of the armature current.

Development of the DES Railgun System

With the assistance of R. A. Marshall, then on the CEM-UT staff, a program to demonstrate the DES railgun concept was begun in 1980. This work was supported by TAERF. A 2-stage DES railgun was constructed to accelerate 1-g Lexan cubes injected at 700 m/s to 900 m/s. This system demonstrated the operation of a plasma armature railgun with two energy stores turning on in sequence. The use of high-energy-density capacitors was successfully demonstrated. An investigation of the high-current switches for the energy stores was carried out. It was found that commercially available spark gap switches had insufficient coulomb capability for the energy store. Mercury vapor-based ignitron switches were chosen for the energy stores. It was also found on this railgun that the signal from a magnetic pickup coil could be used to trigger the current from an energy store at the proper time as the armature moved down the bore of the gun.

Based on the results obtained with the TAERF railgun, development work on the DES railgun facility began. The first steps were the design and construction of a prototype energy store. A circuit diagram of such an energy store is shown in Fig. 2. The energy stores are independent capacitor banks mounted on movable stands that allow reconfiguration of the laboratory for various experiments. Each store includes up to four energy discharge capacitors. The capacitors are 14 cm 35-mil and 61 cm (7.25 in. x 14 in.) of 0.0014 microfarads. The capacitors are rated for 10 kV with a capacitance range of from 60 to 300 µF. The 300-µF capacitors can store a maximum of 15 kJ each, or 60 kJ per energy store.

Flat-plate copper busbars connect the capacitors to the make trigger ignitron, switch 1. With a maximum of only 60 kJ in a store, the capacitors can be connected without fuses. A signal from the trigger system is used to initiate current from the capacitors through the inductors to the railgun. The inductor for each store, L, consists of two parts. The first part is an open helix of 2.5-cm (1-in.) copper rod mounted in an aluminum vessel used for containment of the magnetic field. The second part of the inductor is the coaxial conductor from the energy store to the railgun. The conductor is constructed from 7.6-cm (3-in.) copper pipe as the outer conductor assembled with standard plumbing fittings for argiles. The inner conductor consists of 15-kV jumper cable. The inducance of each store can be varied from 1.5 to 3.5 µH.

When the current in the inductor reaches a peak, the voltage on the capacitors begins to reverse. This causes the diode, D, to conduct and act as an auto trigger to the crowbar ignitron, I2. The crowbar removes the capacitors from the circuit and prevents a large reverse voltage on the capacitors.

Care was taken in the design of the energy stores to contain the magnetic field generated by the currents in the stores during discharge. It was found that the ignitron switches and the trigger electronics could be affected by these magnetic fields. Tests of the ignitron switches revealed that for current pulses similar to those generated by the energy stores, the ignitrons would not perform the diode function shown in Fig. 1. Therefore, the system had to be designed to allow for current reversal in the first few energy stores during a shot of the 10-stage DES railgun.

Experience also showed that D-size ignitrons were the best choice for the energy stores. The smaller A-size ignitrons were prone to shorting after discharge of an energy store, caused by mercury deposits on the glass insulators that support the anodes. Anodes of the D-size ignitrons on the energy stores are heated and the cathodes are cooled using shop air separated by vortex tubes.

Small DES Railgun

The next step in the development of the DES railgun facility was the construction of a 1-m railgun for the summer of 1982. The gun was constructed with four connection points for energy stores. A cross-sectional view of the railgun showing the current feed connection scheme is shown in Fig. 3. The gun was designed for ease of fabrication and assembly and to allow a variable bore size. The gun consists of two layers of 2.5-cm (1-in.) G-10 stacked on a tapped steel plate. The lower rail is set on top of the G-10, and copper pipes are welded to tabs that extend on each side of the rail. These pipes connect to copper rods that are attached to the outer leads of the coaxial connectors from the energy stores. The pipes and rods form part of the double coaxial current feeds that are used to connect the energy stores to the rails.

On top of the lower rail are insulating spacers that form the bore of the railgun. The spacers that are immediately adjacent to the bore run the length of the gun and are approximately the size of the bore. These spacers can be removed from the gun without completely disassembling it. This allows operation of the gun with clean side walls and experimentation with different side wall materials. Above the bore spacers is the upper rail with copper pipes welded to tabs.
attached to the rails. The gun is completed by two more layers of G-10 and a top steel clamping plate. The entire structure is clamped by 19-mm (3/4-in.) bolts spaced every 3.8 cm (1-1/2 in.) along the length of the gun.

The first tests conducted on the 1-m railgun resulted in the acceleration of 1-g projectiles to 700 m/s using a single energy store. With 1.6-cm wide rails, it was found that the 1-g projectile could be accelerated from zero initial velocity without significant damage to the rails if the initial rate of rise of the current in the armature was at least 10^9 A/s with a peak of 200 kA. During the testing of the 1-m gun, three additional energy stores were brought on line, and the gun was operated as a DES railgun. Also during the testing of the 1-m gun, the triggering system, the diagnostic system, and the final design of the 4-m gun were developed. The structure of the gun was tested up to 550 kA in the armature with a 1-cm square bore. The success of these tests led to the present design of the 4-m DES railgun.

Triggering System

To operate a DES railgun or to control the current waveform in any other load, a triggering system is needed to properly time the initiation of the current from each energy store. The electronics of the trigger system must also prevent false triggering of the energy stores, either from electromagnetic noise generated by the high current from the energy stores or, in the case of the DES railgun, by free-running arcs ahead of the projectile. In the DES railgun, magnetic pickup coils are used to determine the position of the armature behind the projectile and turn on energy stores after the armature passes the current feed point for a store. If an arc forms between the rails ahead of the projectile, it will generate a signal in the magnetic pickup coils similar to those caused by passage of the armature. Therefore, a technique is needed to discriminate between the two types of signals to prevent initiating current from a store before the main armature passes its current feed point.

A block diagram of the triggering system for one

energy store is shown in Fig. 4. The magnetic pickup coils are 20-turn coils located 2 cm from the bore of the railgun and having a diameter of 0.75 cm on the level of the bore spacers. The axes of the coils are parallel to the bore. This type of coil generates a signal as shown in the figure, with a peak voltage of several volts for a 2-km/s, 200-kA shot. The peak voltage is affected by the distribution of current in the armature along the bore in addition to being proportional to the magnitude of the armature current and velocity. It was found during the testing of the railgun that the distribution of the current in the armature, and thus the shape and magnitude of the pickup coil signal, depends upon both the sign and the magnitude of the rate of change of the armature current. A strongly negative rate of change of the armature current tends to spread out the current in the armature.

The magnetic pickup coil signal passes through a NIM module single-channel analyzer. The analyzer is used to prevent noise signals from generating trigger pulses. The coincidence gate is used to prevent generation of a trigger signal from a free-running arc. The trigger circuits from the previous store generate an enable signal that creates a window in time during which the present store can be triggered. A free-running arc will generate a magnetic pickup coil signal before the enable signal from the previous store has been turned on. The coincidence gate will then prevent the free-running arc from triggering the energy store. The output of the coincidence gate is fed directly to the trigger circuit of the next store. The variable delay to the initiation of the enable signal is used to set the time delay between firings of the two energy stores.

The Diagnostic System

A system to store the multichannel transient data generated during each experiment is critical to the operation of the DES railgun facility. To characterize the operation of the DES railgun, the current in each energy store, diagnostic signals from the railgun, and timing information from the terminal velocimeters must be recorded simultaneously.

The current from each of the energy stores must be monitored during each experiment. Total armature current in the DES railguns is obtained by summing the current from each of the stores. The currents are measured using Rogowski coils with passive integrators. Three types of diagnostics are presently used directly on the DES railguns. Magnetic pickup coils similar to those described in the triggering system section are used to determine the position of the armature as a function of time. Sets of two pickup coils are used to measure the velocity of the armature in the bore of the railgun. Second, magnetic pickup coils with their axes directed toward the bore of the railgun are used to monitor the total current in the rails.
The third type of diagnostic on the railgun is the voltage probes. Isolation is maintained between the experiment and the data recording devices in the diagnostic system. Thus, the voltage measurements are made using current transformers to measure the current in a 500-Ω resistor connected to the desired point on the experiment. Typically, breech and muzzle voltages of the railguns are recorded during a shot.

The final type of diagnostic used consists of the external velocimeters. These devices measure the velocity of the projectile after it exits from the muzzle. The first velocimeter developed uses breaking laser beams and a photographic system. Recently added to the system is a set of closing switches that are penetrated by the projectile. The switches consist of two sheets of brass foil separated by a Mylar film. A potential of 2.5 kV is placed between the brass foils. This high voltage is used to overcome the noise signals picked up by the switches during a railgun shot. The time between the opening of the switches is used to determine the velocity of the projectile.

All of these diagnostic signals are recorded by digital transient recorders and digital oscilloscopes. A system based on the CAMAC digital interface was chosen for the facility. During the coming year, additional data-recording channels will be added to the system. A computer will also be added to the diagnostic system for data reduction and archiving as the number of data channels is increased.

Four-meter Railgun

During the summer of 1983 the 4-m, ten-stage DES railgun was assembled. The first ten-stage railgun shot was made on July 29. The ten capacitor banks were configured for a maximum of 530 kJ. The first shots were conducted with the capacitors charged to 220 kJ. The 4-m guns has the same cross-section as shown in Fig. 3. The bore of the railgun was 0.95 cm square, and the projectile had a mass of 1 g. The terminal velocity of the projectile was 3 km/s.

The first series of shots with the railgun revealed several anomalies to be investigated. The railgun shots followed the simple computer simulation of the DES railgun for the first third of the shot and then fell significantly behind the predicted velocity. It was found that this was partly due to shorting of several of the current feeds to the rails. Two additional factors contributing to the low velocity have been investigated. The pressure on the projectile at 300 kA is three times the yield strength of the Lexan projectile. Therefore, frictional drag may be of some consequence. A greater effect on the velocity of the projectile or of free-running plasma arcs has been found to be shock heating of the air in the bore of the railgun. This heating had a significant effect on the acceleration of the projectile above 3 km/s. In particular, the maximum velocity of a plasma arc at 300 kA was found to be 6 km/s with air at atmospheric pressure inside the bore of the railgun.

The next series of tests planned for the 4-m railgun will be conducted under vacuum. This will allow the testing of the DES railgun at velocities approaching 10 km/s with 1- to 3-g projectiles.

Conclusions

The Center for Electromechanics has constructed a facility for the operation of DES railguns. Two such railguns have been constructed, and over a year of operating experience with components of the system has been accumulated. The facility is now capable of reliably operating EM acceleration experiments with up to 0.5 MJ in the primary energy store. The facility has been constructed as a laboratory test bed, and as such can be fitted to a wide variety of experiments in the future.

The fundamental concepts of the DES railgun have been demonstrated in the facility. Ongoing basic research in railgun technology is continuing within the facility. The diagnostic system will be upgraded over the next year. Upon completion of the diagnostic system, the facility will offer a unique resource with which to investigate EM accelerator concepts with a reliable, versatile, and inexpensive-to-operate power supply.

References


