DISTRIBUTED CURRENT FEED AND DISTRIBUTED ENERGY STORAGE RAILGUNS

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DISTRIBUTED-CURRENT-FEED AND DISTRIBUTED-ENERGY-STORE RAILGUNS
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Summary
Distributed-type railguns are combinations of power supplies and railguns designed to maintain a nearly constant current in the armature of a railgun and to overcome the accelerator length limitations of simple breech-fed railguns. This limitation arises from the increasing resistance and inductance of the rails with increasing railgun length. The energy efficiency of a railgun system from the primary energy store to the kinetic energy of the projectile can be improved as compared to the simple railgun in some applications. This is accomplished by a reduction of the stored magnetic field energy in the bore of the railgun at the end of a shot and reduction of the resistive losses in the rails. The improved system performance of the distributed railguns over the simple breech-fed railguns is achieved at the expense of greater system complexity.

The only distributed-type railguns that have been built to date are distributed-energy-store (DES) railguns. These systems presently use capacitors as the primary energy store, which allows the use of closing switches to initiate current from each of the stores. In this paper a new type of railgun, the distributed-current-feed (DCF) railgun, is presented. The DCF railgun system is a compromise in system complexity and efficiency between the DES railguns and the simple breech-fed railguns. Also, the DCF railgun utilizes closing switches in such a manner as to allow the use of a variety of primary power supplies, including homopolar generators (HPGs), for such electromagnetic propulsion tasks as space launches.

Introduction
As railguns move from basic research of the electromagnetic acceleration technology to the development of systems for specific applications, a wide variety of power supply and railgun systems is being investigated. This paper examines the development of the distributed railguns and introduces a new type of railgun system specifically designed for applications requiring long accelerators. The starting point for this discussion is the simple breech-fed railgun system driven by an inductor. With the exception of superconducting inductors, all inductor-driven railgun systems use a primary energy store that can be represented as a generalized capacitor. The energy from the primary store is transferred to the inductor and then to the railgun. Two types of simple breech-fed railgun systems can then be designed, as shown in Figs. 1 and 2. The difference between these two systems is the relative voltage of the primary energy store and the railgun. The system in Fig. 1 represents a system in which the primary store voltage is sufficient to operate the system with closing switches. The maximum voltage in the system during the time the current is rising in the inductor will be the initial voltage of the primary energy store. Examples of this type of system are capacitor-driven railguns and heavy payload systems, such as airplane launchers directly driven by HPGs. In cases where the primary energy store voltage is insufficient to drive the railgun directly, the inductor is brought to peak current and an opening switch is used to create the driving voltage for the railgun, as shown in Fig. 2. The major problem with the latter system is the development of the opening switch. This switch must interrupt currents ranging from a fraction of a megampere to tens of megamperes. In addition to the difficulty of constructing the switch, there are fundamental limits on the efficiency of the transfer of energy from one inductor to the railgun, which is a variable inductive load.

In the following sections an analysis of the distributed railgun systems is presented. In this analysis the system diagrams shown use primary energy stores that match the railgun voltage, as in Fig. 1. The analysis can also be performed for systems that use opening switches as in Fig. 2. The problems associated with using opening switches in distributed railguns are discussed, and a solution to these problems is proposed in the form of the distributed-current-feed type of railgun. A specific system study of the application of the distributed-current-feed railgun to a space launch mission is then examined.

Development of the Distributed Railguns
The performance of the simple breech-fed railguns can be improved in two ways without large increases in
the size of the primary energy store. The first way is to make the armature current more nearly constant with time. In any railgun there will be a maximum force, and thus current, that can be tolerated by either the railgun structure or the payload. The best system performance, that is, a minimum accelerator length, is thus achieved if the armature current is constant during the entire shot. The armature currents in the simple breech-fed railguns are combinations of sine waves and exponentially decaying waveforms. These waveforms can be made more nearly constant by dividing the primary energy store and the inductor into a pulse-forming network as shown in Fig. 3. As can be seen, the armature current is more nearly constant than in the systems shown in Figs. 1 and 2.

Fig. 3. Pulse-forming network and breech-fed railgun

An alternative to the series combination of the pulse-forming network is shown in Fig. 4. The time period of oscillation of each inductor-capacitor set is selected so that the total current into the railgun is closer to a square wave with time than in the simple railgun systems. The dotted current lines represent the current from the individual branches of the pulse-forming network. A capacitor-driven railgun system to drive 1- to 3-g projectiles using the parallel pulse-forming network has been constructed by GA Technologies Corporation.

An improvement in the waveform of the armature current of the system in Fig. 4 can be made by using multiple closing switches. This system is shown in Fig. 5 using several energy stores, each of which is a combination of an energy store and an inductor. With a sufficient number of energy stores turned on in sequence, the armature current can be kept at a nearly constant level throughout a railgun shot. Further improvement of this system in terms of constant armature current would be of limited value. For railguns with accelerator lengths of several meters or less, the multiple-energy-store breech-fed railgun represents an efficient system design. Specifically, increases in efficiency from primary store to kinetic energy of the payload can be increased by 20 percent or more in some applications by the use of two energy stores over the simple breech-fed railguns. The railguns in the DES railgun facility at CEM-UT, reported on elsewhere in this conference, have been operated as multiple-energy-store breech-fed railguns. For some electromagnetic accelerator applications, the length of the accelerator will be greater than a few meters. These applications include acceleration of small projectiles to velocities of interest for impact fusion studies and the launching of large payloads to earth escape velocities. In these instances the breech voltage of the railgun will become excessively large as both the resistance and inductance looking into the breech rise as the length of the rails is increased. For a given rail material, any attempt to reduce the resistance or inductance for a given length railgun will result in a lower driving force on the payload. Also, as the length of the rails increases, the stored magnetic energy in the bore of the railgun rises. For a typical railgun this stored energy will be equal to 200 kJ/m length of the rails for a driving current of one MA. In particular, in a constant-current railgun the stored magnetic energy in the bore will be approximately equal to the kinetic energy of the projectile. Breech-fed railguns can also be limited by the amount of time the rails near the breech can carry the full armature current before melting occurs. These facts led to the development of the distributed-energy-store railgun by Marshall and Weldon. The DES railgun is shown schematically in Fig. 6. Each of the energy

Fig. 4. Breech-fed railgun with parallel pulse-forming network

Fig. 5. Breech-fed, multiple-energy-store railgun

Fig. 6. Distributed-energy-store railgun
In normal operation, the stores of the DES railgun are turned on in sequence as the armature moves down the bore. Several of the stores will be providing current to the armature at any given time. This allows the individual stores to be exhausted before the armature exits the gun, while maintaining a nearly constant armature current. Only a fraction of the gun carries the full armature current, which reduces the resistive losses in the rails and the amount of stored magnetic energy in the bore. An inherent feature of the distributed-store railguns is that the length of the rails is not limited if a sufficient number of energy stores is employed. The DES railgun is the most efficient theoretical system design for applications requiring long accelerators.

The DES railgun presents a problem for systems involving opening switches in the energy stores. After current is initiated from the first energy store, the voltage between the rails behind the armature begins to rise. The voltage at the current connection point of a store behind the armature is given by the equation

\[ V = IR + L'x\left(\frac{di}{dt}\right) + IL'v \]

where

- \( I \) = armature current
- \( R \) = resistance of the rails from the connection point to the armature
- \( L' \) = inductance per unit length of the rails
- \( x \) = distance from the connection point to the armature
- \( v \) = armature velocity.

In a railgun accelerating 1- to 3-g projectiles to 20 km/s, this voltage can range up to 4 kV, while a 25-MA space launch gun will have voltages of 100 kV near the end of a shot. A reusable opening switch at these current and voltage levels presents very significant technical problems. A distributed-store railgun system can be built that uses a single storage inductor and opening switch to drive these types of payloads. The distributed-current-feed railgun is shown in Fig. 7. In the DCF railgun a single primary energy store, a HPGe or other dc generator system, is used to charge a single inductor. This inductor is in two parts. The first part is a normal inductor located near the primary energy store. This part of the inductor connects to the section of the inductor that runs the length of the railgun. The part of the inductor along the gun is most likely a simple coaxial conductor running the length of the rails. Analysis of this type of system shows that a coaxial conductor can provide the correct inductance per unit length for the inductor.

![Fig. 7. Distributed-current-feed railgun](image)

In the DCF railgun, once the current in the inductor is brought to its peak value the switch \( S_2 \) is opened to initiate the armature current. This opening switch operates into the railgun with zero initial voltage between the rails. In some applications the armature of the railgun can perform the function of switch \( S_2 \). As the projectile moves down the bore of the gun, the switches between the inductor and the rails are closed as the armature passes each switch. In this way the length of the rails that must carry the armature current is limited to the spacing between the switches. Thus the DCF system would be capable of driving systems with accelerator lengths of several kilometers as are envisioned for some space launch applications. In the DCF system the energy stored in the bore and in the inductor between the closing switches is dissipated in the rails and the switches during the shot. This overcomes the problem of dissipation of the stored magnetic energy from the whole railgun at the end of a shot common to breech-fed systems.

In most applications the DCF railguns will be less energy efficient than the more complex DES railguns. In applications such as space launch, the decrease in efficiency of the DCF railguns is compensated for by a reduction in the capital investment involved in the system and the reduction of constraints on the power supply. The DCF railgun does not require a high-voltage primary energy store or opening switches that must operate into large rail voltages. In the case of space launch systems, these facts make the DCF railguns conceptually feasible with known technology. In the next section some of the design and operating parameters of a launcher system are presented for a DCF railgun.

A DCF Railgun Launcher

In this section an example of the parameters needed for a railgun system to accelerate a metric ton to 14 km/s using a DCF railgun are presented. The bore of the railgun is taken as 0.5 m square in cross-section and 2 km long. The inductor initially has a total inductance of 1.44 mH, with the section running the length of the railgun having an inductance of 0.2 mH/m. The inductor is charged to its maximum current before the opening switch is operated. Additional system parameters are listed in Table 1. In addition to these parameters, the voltage drop of the switches and the muzzle voltage were taken at a nominal value of 160 V. This assumes a hybrid plasma and metal armature.

<table>
<thead>
<tr>
<th>Distance between Switches, m</th>
<th>Inductance of Railgun, mH</th>
<th>Initial Current, MA</th>
<th>Initial Velocity, m/s</th>
<th>Inductor Resistance, mΩ</th>
</tr>
</thead>
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<tr>
<td>50</td>
<td>0.4</td>
<td>24</td>
<td>0</td>
<td>8.0</td>
</tr>
</tbody>
</table>

Table 1. Parameters of the DCF railgun for space launch mission

A simulation was run on this DCF railgun system that resulted in an exit velocity of 14 km/s at which time the driving current had fallen to 12 MA. The choice of the current level in the armature was made to keep the acceleration of the payload below 1,200 g's. The maximum voltage that occurs during operation of the system is approximately 75 kV, which occurs when the projectile has moved halfway down the bore. The final kinetic energy of the projectile is 102 GJ as compared to the initial energy in the inductor of 500 GJ. This gives an efficiency from inductor to the projectile kinetic energy of 26 percent.

As seen by this example, the efficiency of this
practical design for a DCF railgun is below the theoretical maximum efficiencies of other accelerator schemes such as the DES railguns. The advantage of a DCF-type railgun is that the capital investment in the power supply and switches will be significantly reduced as compared to a DES railgun. To appreciate the relative scale of the cost of energy and the capital cost of the launcher system, the approximately 400 GJ in the inductor of the DCF railgun cost $6,000 at 5¢/kW·h, while one estimate of the capital investment of a railgun earth to space launcher is over one billion dollars. Also, the potential of the DCF railgun is aided by the flexibility in the choice of the primary energy store.

Conclusions

The distributed railguns offer a solution to the limits on performance of the breech-fed railguns as the length of the rails becomes large. These limits are caused by the increasing resistance and inductance of the rails with increasing length. Also, for some launch missions such as space launch, the rails near the breech of a breech-fed railgun will be limited by the amount of time the full armature current can be carried by the rails before melting. Either of the distributed-type railguns is an alternative to overcome this limitation of breech-fed railguns.

A review of the analysis leading to the development of the distributed-energy-store railgun has been presented. A new type of railgun, the distributed-current-feed railgun, was presented as a compromise system in efficiency and complexity between the simple breech-fed railguns and the distributed-energy-store railguns. Finally, the results of a case study for a space launch mission using a DCF railgun were presented.

References


