ANALYSIS OF PERFORMANCE OF RAIL GUN ACCELERATORS POWERED BY DISTRIBUTED ENERGY STORES

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Summary

It has been established that centimeter sized projectiles weighing several grams can be accelerated by electrical forces to velocities in excess of five kilometers per second in a classical railgun. The technologies required to do this are adequately understood, at least in the case where a single energy store is connected to the breech end of the gun.

There are two disadvantages to using a single energy store. It is generally desirable to keep gun current as nearly constant as possible and this is difficult to achieve with a single store without making the store excessively large. Rail resistance also becomes a dominating factor as higher velocities are reached because higher velocities require greater gun lengths and correspondingly larger gun resistances.

One way to by-pass these limitations is to distribute energy stores along the length of the gun. Not only does this reduce the average rail resistance by reducing the length of rail that carries current at anytime, but it permits inductive energy to be usefully transferred down the gun rather than allowing it to dissipate resistively in the rails.

This paper shows how the performance of such a gun may be simulated, by computing the instantaneous rate of change of current in each energy store and by using these values to obtain projectile acceleration. Two specific rail gun systems are examined, the first being a "scientific railgun" designed to propel a three gram projectile to a speed of 20 kilometers per second, and the second being a "space-launch railgun" to accelerate one metric ton to 7.5 kilometers per second.

Introduction

The basic concept of the parallel-rail railgun accelerator has been known for a long time. The accelerating force is obtained by the interaction of the current in the driven armature with the magnetic field produced by the current in the rails, the armature and rails being connected in series. The recent work done in Canberra has shown that an electric arc can successfully be used as a railgun armature.[1] The other important contribution made was the realization that current control was essential to success, and that the use of an inductor was one way to achieve such control.[2] Projectiles with a mass of three grams were accelerated to velocities of up to 5.9 km/s in the Canberra railgun.

There are other ways of achieving current control in railguns. A program at present being conducted by a LLL-LASL group involves the use of explosive flux compression generators.[3] This very flexible generation scheme makes it possible to generate currents which vary in time in a wide variety of ways.

The use of a single current generator connected to the breech of a railgun has two disadvantages. As gun rails become longer to obtain higher performance, then a larger proportion of the input energy is lost resistively in the rails.[4] The other is that the inductive energy remaining in the gun at projectile exit represents a considerable inefficiency. A way of circumventing both of these problems is to distribute energy stores along the length of the gun.[5,6,7,8] It should be noted that the use of many power supplies along an accelerator is not new. It is commonly employed in atomic particle accelerators, and has been proposed for use in travelling magnetic wave macroparticle accelerators.[9] It has also been used in the MIT Massdriver.[10] The aim in all these cases is to deliver energy to a projectile in small increments many times.

In this paper we present a method by which the distributed inductive energy store railgun can be analysed, and apply this analysis to two railgun systems.

Analysis

The schematic representation of a railgun with inductive energy stores distributed along its length is shown in Fig. 1. Stores have inductance L and resistance R and are spaced at intervals ℓ along the rails. Each is delivering current I_n into the railgun at a voltage of E_n. The projectile has moved a distance x into gun section number 1. It has a mass of m and a velocity of $\dot{x}$. The railgun has an inductance and resistance of L' and R' per unit length.

The current flowing in each gun section is the sum of the currents being delivered by each energy store up to and including the one in that gun section. Current is prevented from flowing backwards in the inductors. The arc armature driving the projectile is assumed to have a volt drop MV (so called because this is the voltage that is measured from rail to rail at the gun's muzzle.)

In order to compute the performance of the rail gun, it is first necessary to find the rates of change of the inductor currents, $\dot{I}_n$. The first step in doing this is to write the equations for the power supply circuits (LH side below Fig. 1) and for the railgun sections (RH side below Fig. 1). These are then solved for $\dot{I}_n$ which are obtained from the matrix equation (1).[11]

The simulation is now performed in the following manner. At any instant, x and $\dot{x}$ are known as are all I_n. When an appropriate value for MV is chosen then all the terms in [A] and [C] are known. Thus [B] is found, enabling new values of current to be calculated for the next step of the simulation. New values of x and $\dot{x}$ are also found from the calculated value of $\ddot{x}$

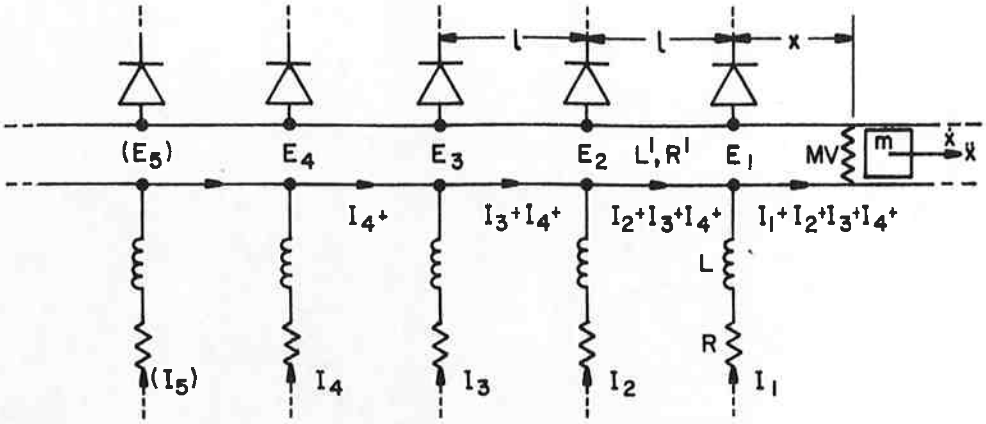

Fig. 1. Circuit diagram showing parameters and variables used in the analysis.

$$\begin{array}{llll}
-E = L\dot{I}_1 + RI_1 & E_1 & = & L'x(I_1+I_2+I_3+I_4+) + (L'\dot{x} + R'x)(I_1+I_2+I_3+I_4+) + MV \\
-E_2 = L\dot{I}_2 + RI_2 & E_2-E_1 & = & L'\ell(I_2+I_3+I_4+) + R'\ell(I_2+I_3+I_4+) \\
-E_3 = L\dot{I}_3 + RI_3 & E_3-E_2 & = & L'\ell(I_3+I_4+) + R'\ell(I_3+I_4+) \\
-E_4 = L\dot{I}_4 + RI_4 & E_4-E_3 & = & L'\ell(I_4+) + R'\ell(I_4+) \\
\cdots\cdots & \cdots\cdots & & \cdots\cdots\cdots\cdots\cdots\cdots
\end{array}$$

Eliminating the voltages E_n gives

$$\begin{array}{rcll}
L(\dot{I}_1) + L'x(\dot{I}_1+\dot{I}_2+\dot{I}_3+\dot{I}_4+) & = & R(-I_1) - (L'\dot{x} + R'x)(I_1+I_2+I_3+I_4+) - MV & \\
L(-\dot{I}_1+\dot{I}_2) + L'\ell(\dot{I}_2+\dot{I}_3+\dot{I}_4+) & = & R(I_1-I_2) & -R'\ell(I_2+I_3+I_4+) \\
L(-\dot{I}_2+\dot{I}_3) + L'\ell(\dot{I}_3+\dot{I}_4+) & = & R(I_2-I_3) & -R'\ell(I_3+I_4+) \\
L(-\dot{I}_3+\dot{I}_4) + L'\ell(\dot{I}_4+) & = & R(I_3-I_4) & -R'\ell(I_4+) \\
\cdots\cdots\cdots\cdots & & \cdots\cdots\cdots\cdots\cdots\cdots &
\end{array}$$

giving

$$\begin{bmatrix}
(L+L'x) & L'x & L'x & L'x\ .\ . \\
-L & (L+L'\ell) & L'\ell & L'\ell\ .\ . \\
0 & -L & (L+L'\ell) & L'\ell\ .\ . \\
0 & 0 & -L & (L+L'\ell)\ .\ . \\
.\ . & .\ .\ .\ .\ . & .\ . & .\ .
\end{bmatrix}
\begin{bmatrix}
\dot{I}_1 \\ \dot{I}_2 \\ \dot{I}_3 \\ \dot{I}_4 \\ .\ .
\end{bmatrix}
=
\begin{bmatrix}
R(-I_1) - (L'\dot{x} + R'x)(I_1+I_2+I_3+I_4+) - MV \\
R(I_1-I_2) \quad -R'\ell(I_2+I_3+I_4+) \\
R(I_2-I_3) \quad -R'\ell(I_3+I_4+) \\
R(I_3-I_4) \quad -R'\ell(I_4+) \\
\cdots\cdots\cdots\cdots\cdots\cdots
\end{bmatrix}$$

Defining the matrix equation as

$$[A][B] = [C]$$

then values of the rates of change of the currents, $\dot{I}_n$, are obtained from the equation $[B] = [A^{-1}][C]$. (1)

which is given by $\ddot{x} = L'(\Sigma I_n)^2/(2m)$.

At each step the value of x is tested and when it gets greater than ℓ, it is replaced by $(x-\ell)$ and at the same time all the currents are shifted one gun stage, i.e., I_2 is replaced by I_1, I_3 by I_2, I_4 by I_3, etc. and I_1 is set equal to the assumed initial value of current from the next energy store. The appropriate dimensions of the matrices are also increased by one because there is now one more power circuit in use.

At each step also, the magnitude of the current in the rearmost energy store is checked and when it goes negative, that store is "removed" by reducing the dimensions of the matrices by one.

The "Scientific Railgun"

As an example of the method, a simulation has been made of a railgun for accelerating a three gram projectile to 20 km/s. The first point to note about the design of the system is that constant average acceleration of the projectile is both desirable and possible. Since energy equals force times distance, this means that the energy stores should be uniformly distributed. Aiming at an average current of around 375 kA (I) and assuming a gun inductance (L') of 0.6 μH/m give a force on the projectile of 42 kN (=0.5 $L'I^2$), giving an acceleration to the projectile of 14 Mm/s^2. Thus, the length of gun required to reach 20 km/s is 14 m.

The kinetic energy of the projectile at exit is 600 kJ. If the gun were to be 100% efficient, and each store held 10 kJ of energy, then these would have to be spaced 0.23 meters apart. For the simulation spacing of 5 stores per meter was assumed.

The arc armature volt drop (MV) is assumed to be 160 V, the value that was observed in the Canberra railgun. The rail resistance (R') is taken as 0.002 Ω/m, being the resistance of copper rails 1.5 mm thick by 13 mm high. The inductor resistance is taken as 0.001 Ω.

The inductor current, when fully charged, has been taken as 125 kA and with the 10 kJ inductor energy gives a calculated inductance of 1.28 μH.

The resulting simulation is shown in Fig. 2. It has been assumed that the projectile is injected into the gun breech with a velocity of 1,000 m/s. The overall efficiency indicated is 70%, 598 kJ kinetic energy being obtained for the expenditure of 850 kJ (10 kJ from each of 85 energy stores). The stage efficiencies rise down the gun, starting from around 20% in the first few stages and rising to 84% in the last stage.

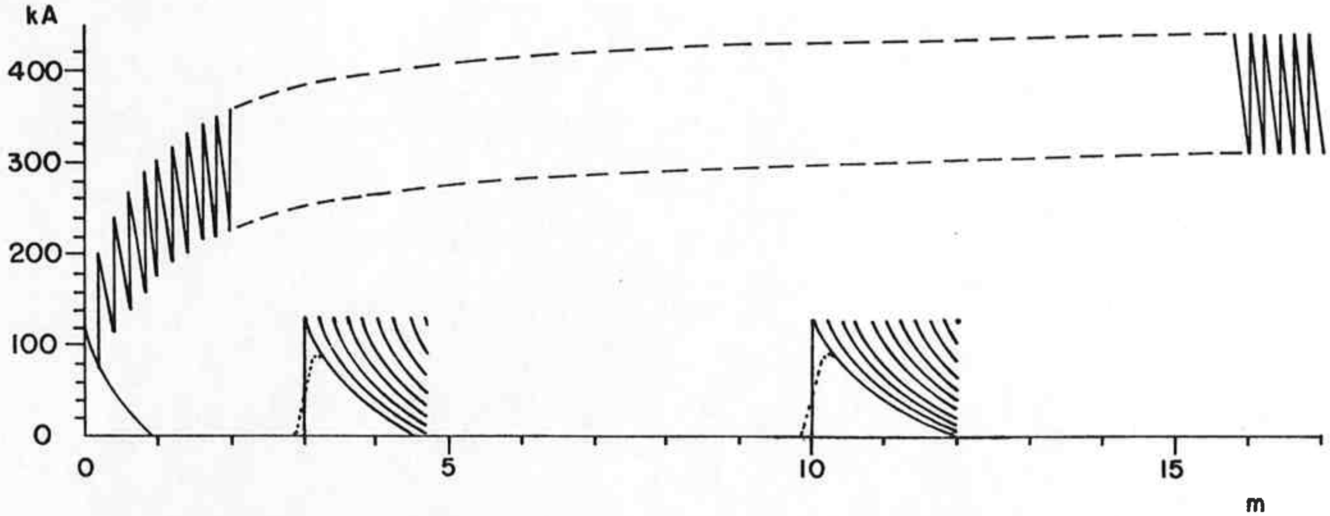

Fig. 2. Simulation of the "scientific railgun" showing current (kA) as a function of projectile travel (m) down the gun. The upper curve shows the total current. The lower curves (only partially drawn) show the currents in individual energy stores. The three gram projectile reaches a velocity of 20 km/s in the 17 m of gun length.

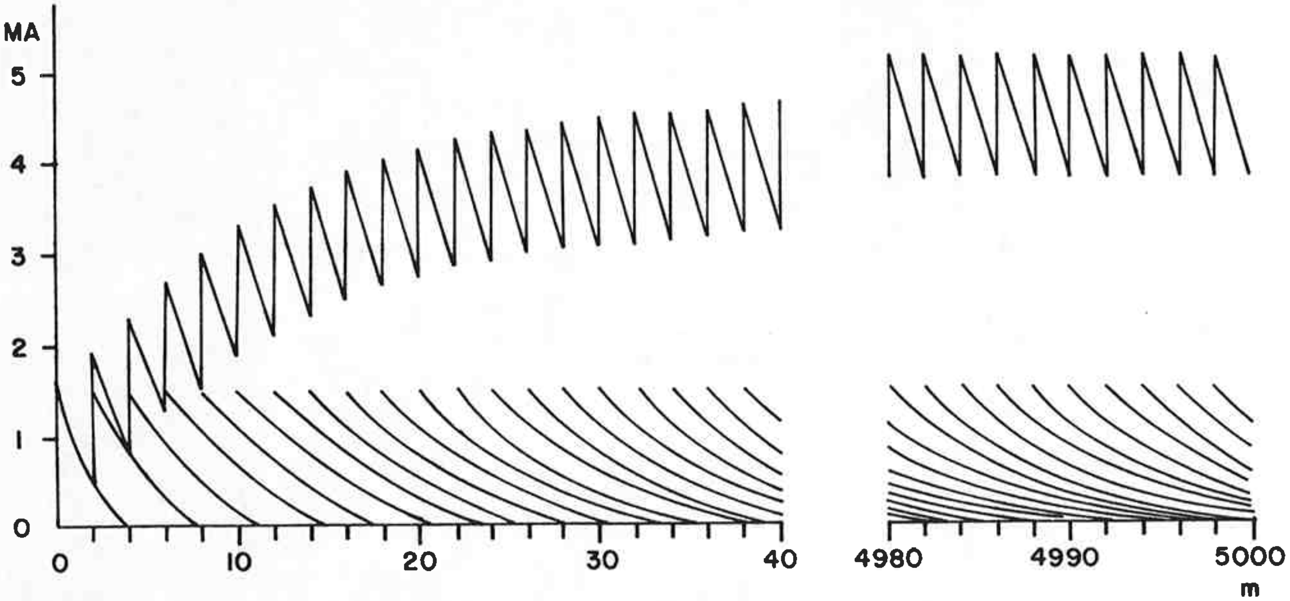

Fig. 3. Simulation of the "space-launch railgun" showing current (MA) as a function of projectile travel (m) down the gun. The curves are discontinuous, the length from 40 m to 4,980 m being omitted. The upper curve is the total current; the lower curves show the currents in individual energy stores. The one tonne projectile reaches a velocity of 7,500 m/s in the 5,000 m gun length.

The "Space-Launch Railgun"

A simulation has also been made of the acceleration of a relatively large mass, 1000 kg, to earth orbit velocity of 7,500 m/s. An acceleration of 500 gravities is assumed which gives a required gun length of 5,700 m. The kinetic energy of the projectile at gun exit is 28.1 GJ which means that about 5 MJ of energy must be delivered to the projectile each meter of travel down the gun barrel. It is assumed that 12 MJ inductors are distributed along the gun at a spacing of 2 m. The total average current required to give the assumed acceleration is 4 MA.

The peak inductor currents are taken as 1.5 MA, requiring an inductance of 10.7 μH.

In the absence of any better information, the arc armature volt drop is again taken as 160 V. Rails of one meter high by three centimeters thick are assumed giving a gun resistance of 2 $\mu\Omega$/m. The coil inductance has the same value as about 20 m of gun, the resistance of which is 40 $\mu\Omega$. Thus, a reasonable value to take for inductor resistance is 20 $\mu\Omega$.

The results of the simulation are shown in Fig.3. The projectile reaches its desired velocity in a gun length of 5000 m, i.e., with the expenditure of 30 GJ, being 2500 energy stores of 12 GJ each. Thus, the overall efficiency is 93.8%. Again, the stage efficiency starts low (~20%) but rises rapidly as speed increases to reach a value of 98% at the exit end of the gun.

Switching

Accelerators of the type described above can only be made to work if the current from each energy store is switched into the gun at exactly the right moment. Synchronism with projectile position is crucial. There are many ways that the arrival of the projectile at any point along the gun can be detected. One obvious way is to interrupt a light beam. There are two other ways in which projectile passage can be used to provide very strong signals. The first is to use the arrival of the high pressure plasma of the armature. A small part of this could be allowed to pass through a vent from the gun base to trigger a switch. Radiation from the arc might be used for the same purpose. The second possibility is to use the magnetic field produced by the driving current to do the triggering. This field rises very fast as the armature passes, and can be used to give a strong, noise immune, signal accurately synchronized with the armature position.[5] This signal could be used directly to activate a switch as indicated in Fig. 4.

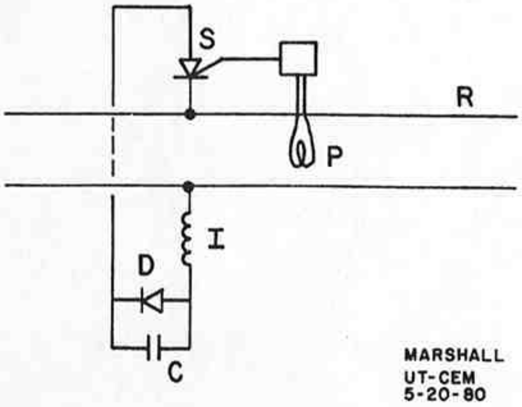

Fig. 4. Schematic of an energy store circuit, showing railgun R, inductor I, capacitor C, diode D, switch S, and pick-up loop P.

When the switch (it can be an SCR) is activated, the energy in the capacitor transfers quickly to the inductor. When the transfer is completed, the diode then effectively removes the capacitor from the circuit. The switch S must also behave like a diode to prevent current from flowing in reverse through the inductor after the latter is discharged.

In the case of the space-launch railgun, the currents are sufficiently high that the use of solid state switches may be expensive. A possible low cost solution may be to have the gun's driving field do the switching directly as shown in Fig. 5.

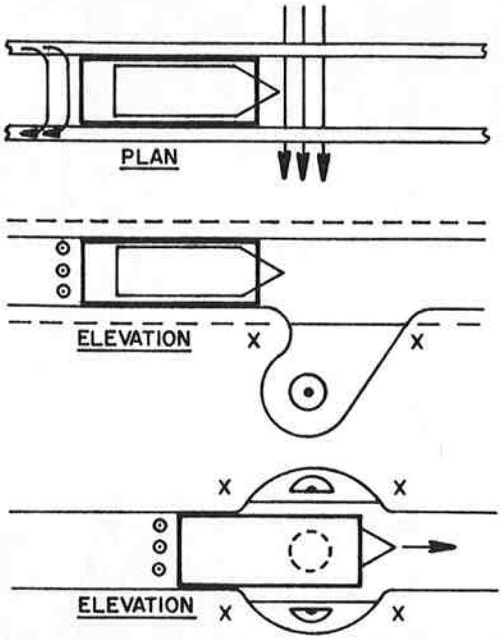

Fig. 5. Direct switching of current into a rail gun using the gun's driving field.

It may be possible to establish an arc, carrying the current from the energy store, between the rails (or electrodes embedded therein) in front of the moving projectile, the arc being stabilized by suitable placement of the current supply leads, xx. As the projectile passes, the arc responds to the driving field and moves in behind the projectile to form part of the armature current. It may be possible to trap the arc as shown in the lower elevation. The projectile would then divide the arc, to have it join the armature behind the projectile after it has passed.[12]

Discussion

The simulations assume that the energy stores consist of precharged inductors which are switched in instantaneously. The method can be expanded to include such effects as the current rise in the inductor which will be roughly as shown by dotted lines in Fig. 2. Note that a parameter not used is the capacitor voltage. In a real system choice of this would be made to provide appropriate rates of rise of inductor currents. Increasing capacitor voltage will probably be desirable with distance down the gun.

Decreasing skin depth in the rails down the gun has not been included, and the assumption of 160 V for the arc drop in the space-launch railgun may not be correct.

No attempt has been made to optimize the two systems studied. If desired, the efficiency of the scientific railgun will improve by using smaller energy stores closer together. The indicated efficiency of the space-launch railgun is surprisingly good. However, the overall efficiency in a real system will be reduced somewhat because the efficiency of transfer of energy from homopolar generators (which will be required as primary stores) to inductors is lower than the transfer from electrostatic capacitors to inductors. The railgun space-launcher would seem to be a good candidate for firing H. Kolm's telegraph pole atmosphere penetrators.[13]

Conclusion

The outlines presented of the two inductively driven railgun systems show how the simple parallel-rail railgun macroparticle accelerator may be used to impart high velocities to "micro-macro" particles (gram-sized) and to "macro-macro" particles (tonne-sized) with good efficiency.

Acknowledgments

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