RAILGUN ENERGY STORES AND SYSTEMS

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Summary

Sufficient experimental railgun work and railgun analysis has now been performed to make it desirable to present an overview of what is offered by various options. These are examined.

The single, pulsed homopolar generator-inductor-railgun system is well understood. It offers the means of imparting energies of multi-MJ to projectiles with masses of many kg. Hypersonic velocities can readily be obtained.

When acceleration of masses in the gram range is required, the capacitor-inductor-railgun has advantages because switching is simpler. Capacitors make convenient energy stores in the sub-MJ range.

If very high velocity is required, then the use of distributed energy stores is indicated because it overcomes limitations imposed by rail resistance, and enables the driving current to be kept up during projectile acceleration. Capacitor-based stores are, again, convenient for distributed energy store (DES) systems.

If very high energies, in the GJ range, are required, then distributed homopolar energy stores will be appropriate. An application would be launching large masses from the earth's surface directly into space.

When high repetition rates are required for a railgun system, average powers required may become so high that the direct use of chemical energy is desirable. A flux compressor consisting of an inverse railgun is suggested for this application. The performance of a compressor railgun system is analysed.

Introduction

In a gun of any sort there must be adequate coupling between the gun's energy source and the projectile. In an ordinary gun this relationship is very direct: the propellant burns to generate high pressure gas that pushes on the rear face of the round. In electric guns the connection is less direct and therein lies the challenge. For any particular acceleration requirement, how can the most appropriate electrical system be chosen?

The simple answer to the question is that all the options have not yet been examined, so it is not possible to make an absolute judgment. However it is possible to make a first guess at what might be suitable by looking at the energy required. If the desired kinetic energy of the projectile is less than about one MJ, then regular energy discharge capacitors are likely to be acceptable. On the other hand if the energy is greater than 10 MJ, capacitors are likely to be too unmanageable and some other kind of energy store will be required. If the energy required is in the multi-GJ range, the use of homopolar generator (HPG) energy stores is indicated.

The question is further complicated if high repetition rate is required because then the average power requirements must be considered as well as the peak power.

It is also not necessarily clear yet which type of electrical accelerator is best suited to any particular requirement. Whether the choice will be the mass driver[1] or other travelling wave type[2], an induction gun[3], plasma squeeze accelerator[4], or railgun[5] will depend more on the question of what energy store is available and how the energy will be transferred to the accelerator than on the intrinsic merits of the accelerator itself.

The travelling wave and induction gun have the advantage that physical contact between the gun and projectile is not required. The same is true of the plasma squeeze gun although contact between the projectile and the driving plasma is necessary. The railgun requires contact between the projectile and the gun bore. In the plasma armature railgun the projectile should seal the bore[6]. With a solid armature good contact between armature and rails is necessary[7]. Nevertheless the railgun is the simplest of the electric guns and it is relatively easy to couple energy stores to it. For these reasons we continue to examine railgun systems.

In this paper a summary is presented of the railgun-energy store systems that have been examined to date, and their range of usefulness is assessed. No existing system is particularly suitable when high average powers are required. One possible means of meeting this requirement is discussed.

The Single HPG Charged Inductor System

Over a period of twenty-five years beginning during WWII, sporadic attempts were made to build railgun systems. Only limited success was obtained, mostly because adequate energy stores were not then available. A major factor in the success of the Canberra railgun was the availability of the HPG at the Australian National University.[8] It was necessary to include a fast secondary energy store in the form of an inductor.

A diagram of the basic system requirements is shown in Figure 1. By appropriate switching, energy is transferred from the HPG to the inductor to the railgun. The energy remaining in the inductor after projectile exit can either be dumped by closing a post clamp switch at or near projectile exit time, or by reclosing the divertor switch to direct the energy back into the HPG.

A diagram showing the curve of current versus time is shown in Figure 2. This system offers the best way of getting into the medium kinetic energy range, i.e., one to ten MJ, at present. Much experience has now been accumulated on the Canberra 500-MJ HPG[9] and the

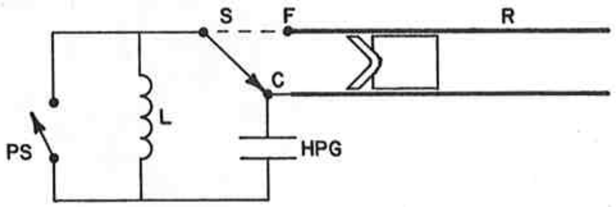

Fig. 1. Homopolar generator-inductor-railgun system showing the homopolar generator HPG, divertor switch S, inductor L, railgun R, and post clamp switch PS. C is the "charging position for S, F the "firing" position.

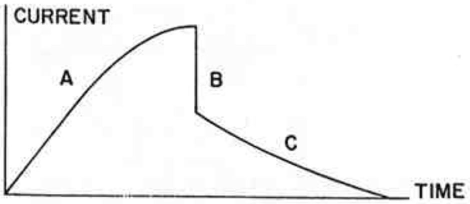

Fig. 2. Current versus time for the HPG-inductor-railgun system for inductor charging A, gun firing B, post firing C.

CEM-UT 5-MJ machine[10] now being upgraded to 10-MJ[11]. The next generation of compact HPGs will be available soon. The Canberra railgun has provided the basic information for the design of divertor switches. It has also demonstrated metal-on-metal railgun armatures for velocities up to around one km/s[12] and plasma armatures for velocities up to 5.9 km/s[13]. Energy storage inductors present no basic problems.

The Capacitor Charged Inductor System

Provided that the current and energy for some required railgun system can be obtained from a capacitor bank, then the most convenient way to charge an inductor is to use such a bank. Because capacitor voltages are much higher than the voltages produced by HPGs, the inductor can be charged at the same time as current is passed through the railgun. No divertor switch is required. In most cases it will be desirable to crowbar the capacitor when it has reached zero voltage.

A diagram of this system is shown in Figure 3. The associated current flow curve is shown in Figure 4.

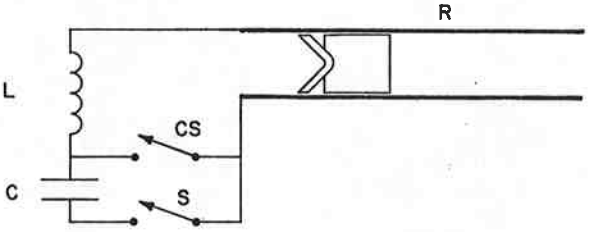

Fig. 3. Capacitor charged inductor railgun system showing the capacitor C, start switch S, inductor L, crowbar switch CS, and railgun R.

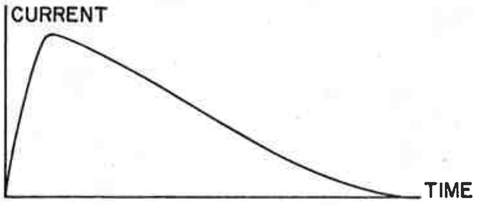

Fig. 4. Current versus time for the capacitor-inductor-railgun system.

Several of these systems are in use[14,15] and more are planned.

For submegajoule energies, the capacitor-inductor system provides the simplest power supply for a railgun. Switching can readily be handled with ignitrons and spark gaps. Currents flow for relatively short times so joule heating of components is not a problem. Short current flow times also allow components to have higher resistances without causing undue losses, thus the most desirable form of inductor, the coaxial, which produces no external magnetic field, can be used successfully.

The Distributed Capacitor Inductor System

Computer simulations of the single capacitor-inductor-railgun system show that it is difficult to get indefinitely large velocities by this method. To keep gun current high requires use of an excessively large energy store, and rail resistance becomes a dominating factor as gun lengths become great. Both these effects, which reduce efficiency, can be overcome by using distributed energy stores (DES) along the gun.[16,17,18] A further advantage is that, in effect, the lengths of railgun between energy stores behave like a part of the adjacent inductor and the magnetic energy in each rail length is also fed along the gun as the projectile progresses.[19]

A schematic of this system is shown in Figure 5. Each individual energy store behaves like the single store discussed in the previous chapter. Each store is triggered as the projectile passes its input connections; the energy flows from the capacitor into the inductor and the gun; when the capacitor is discharged it is crowbarred, the energy in the inductor continuing to flow into the gun. Current is prevented from flowing in reverse in an energy store after it is discharged.

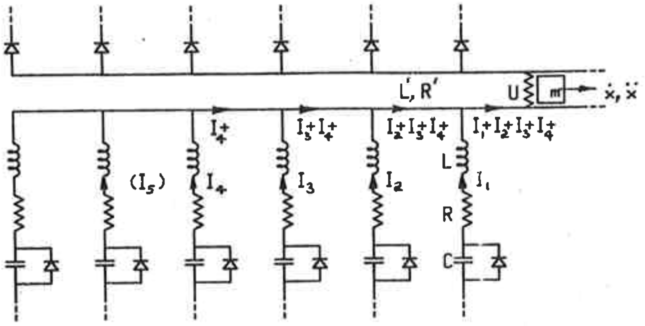

Fig. 5. The capacitor-inductor distributed energy store railgun

A simulation of the performance of a railgun with 20 energy stores distributed at 5 per meter is shown in Figure 6.[20] Each store is assumed to have a 10-kV, 160 μF capacitor, the stored energy being 8 kJ. The inductance size of 3.2 μH has been chosen to limit the

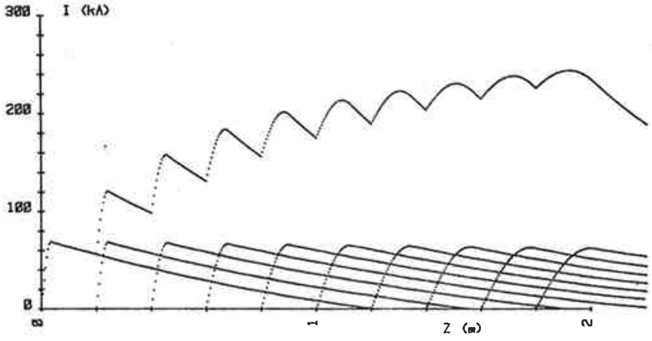

Fig. 6. Computed values of current versus time for a DES railgun with 20 stores. The top curve is total current in the armature. The bottom curves are the currents in the individual energy stores.

peak current in each energy store to 70 kA. Inductor resistance is 1 mΩ. Gun inductance is 0.6 μH/m; gun resistance, 2 mΩ/m. An armature arc drop of 160 V is assumed. Projectile mass is 1.3 grams, i.e., 1-cm cube of polycarbonate. With a projectile injection velocity of 1000 m/s, the exit velocity from a gun with a length of 4.4 m is computed to be 10.4 km/s.

A railgun is being built at CEM-UT using the above parameters. Two stages have been completed and tested, and the performance has been similar to that predicted. A photograph of the installation is shown in Figure 7.

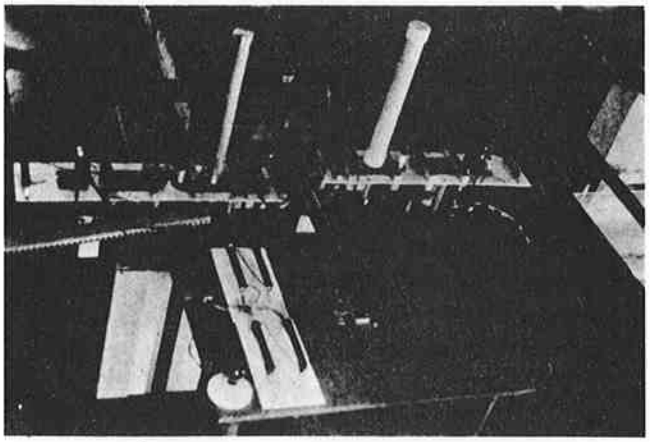

Fig. 7. The two-stage railgun showing: (A) railgun, (B) injector, (C) first energy store, (D) second energy store, (E) capacitor for first energy store, and (F) crowbar diode string for second energy store

Again, there will be a limit beyond which one would not willingly go with this system. If, for example, an accelerator capable of giving a velocity of 50 km/s to a 5-gram projectile were required (for impact fusion, say) then the use of capacitors to deliver the required kinetic energy of 6.25 MJ would be quite thinkable. On the other hand, use of capacitors for a system requiring tens of gigajoules would not be reasonable, and the HPG DES system is indicated.

The Distributed HPG Inductor System

The use of HPGs as the basic energy store for a DES railgun requires a switching system as shown in Figure 8. At a suitable time before the projectile arrives at a particular energy store position the switch S is closed in the charge C position, enabling energy to be transferred from the HPG to the inductor L. As the projectile passes the energy store the switch is reconnected to the fire position F, thus connecting the inductor to the railgun. When the current in the inductor has fallen to zero, the switch is opened to prevent energy from further down the gun from flowing back into the energy store in question. Suggestions have been made as to how this switching could be performed.

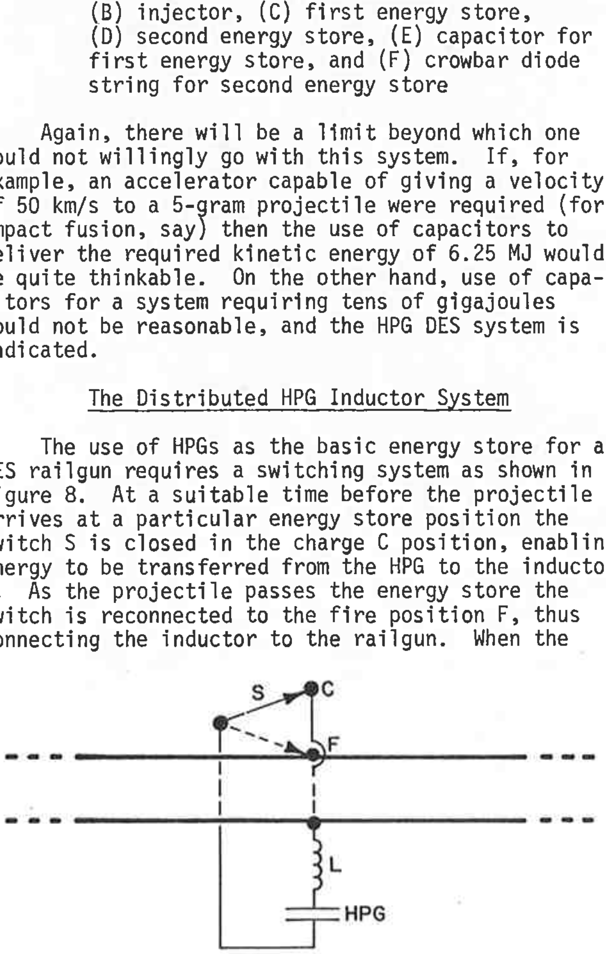

Fig. 8. Circuit requirements for HPG based energy store

A simulation has been made of the acceleration of a relatively large mass, 1000 kg, to a velocity of 7.5 km/s. This is the sort of performance that might be required for an earth-to-space launcher. The system uses 2,500 energy stores with 12 MJ at 1.5 MA of current in each inductor. These are spaced 2 m apart along the 5,000-m long accelerator. The curves of current versus time are shown in Figure 9. The total initial energy in the inductors is 30 GJ. The kinetic energy of the projectile at launch is 28 GJ.

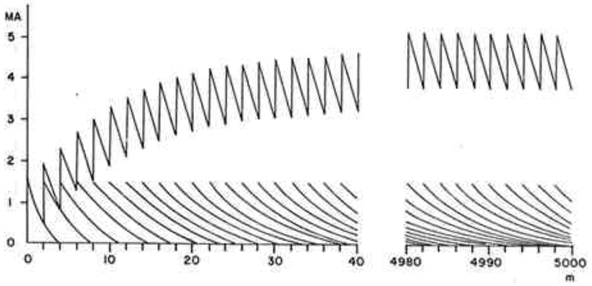

Fig. 9. Simulation of a "space-launch railgun" showing current (MA) as a function of projectile travel (m) down the gun. The curves are discontinuous, the length from 40 m to 4,980 m being omitted. The upper curve is the total current; the lower curves show the currents in individual energy stores.

Flux Compressor Powered Railguns

The railgun systems discussed above all have one thing in common. Immediately prior to the firing of the gun, all the energy used is stored in some physical device or devices--capacitors for the production of lower kinetic energies, HPGs for higher kinetic energies. (A lesser subdivision is that HPGs are indicated for mobile applications and capacitors for fixed installations.)

These systems with suitable engineering can almost certainly be made to perform in a repeatable reliable manner at low repetition rates. As the required rep rate becomes progressively higher, however, a point will be reached where the average power flow through the electrical supply system (the primary generator and HPGs or capacitors) will become sufficiently large that the bulk and cost of these supply systems will dominate the total system. Flux compressors powered directly by chemical energy offer the possibility of producing very high powers with modest cost and bulk.

The LANL/LLNL railgun experiments have shown that one-shot, explosive-powered flux compressors match well to railguns.[21,22] Suggestions have been made for coupling a repetitive-shot flux compressor to a theta gun.[23] We here suggest a further type of repetitive-shot flux compressor and show how it may be coupled to a railgun.

The Inverse Railgun Flux Compressor

A schematic of an inverse railgun flux compressor (the compressor) is shown in Figure 10, where the distance from armature to the output end is x, the in-

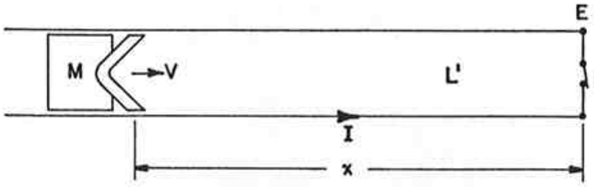

Fig. 10. The elements of the inverse railgun flux compressor

ductance per unit of rail length of L', and current I is flowing. In the lossless case with the output of the compressor shorted, the magnetic flux in the loop is constant, i.e.,

$$\text{Flux} = LI$$

$$= L'xI$$

giving $xI = \text{constant.}$

It is interesting to note in passing that this compressor behaves like a gas compressor in which the gas has $\gamma = 2$.

The electromagnetic energy in the compressor loop is given by

$$W = 0.5\ L'xI^2,$$

but

xI is constant

$$\therefore \quad W \propto 1/x.$$

Thus for a compression ratio (initial x/final x) of 10, for example, one tenth of the final required energy must be injected electrically and nine tenths of it comes from the mechanical effort required to do the compressing.

The Compressor-Driven Railgun

A schematic of a compressor-railgun combination is shown in Figure 11. The parameters shown are defined in Table I, which also lists the parameter values chosen for the simulation detailed below.

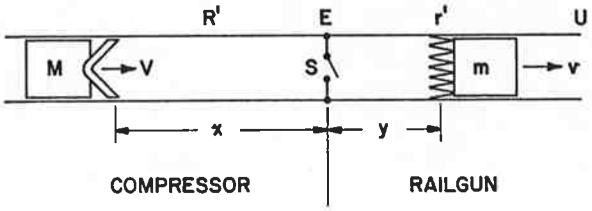

Fig. 11. The elements of an inverse railgun flux compressor coupled to a railgun

The principle of operation is as follows. With the switch S closed, the compressor is "charged" with an initial amount of flux (current) and kinetic energy is injected via the compressor armature. At some time towards the end of the compression the switch is opened and the current allowed to flow into the railgun at the same time as the railgun projectile is injected into it. Electrical energy then transfers from the compressor to the railgun to accelerate the projectile in the latter.

The equations involved are

for the compressor

$$E = L'x\dot{I} - L'VI + IxR' \qquad (1)$$

Table I

M	Compressor projectile mass	2.7 kg
V	Compressor projectile velocity	v_0 = 1000 m/s
X	Compressor projectile position	x_0 = -15 m
R'	Compressor resistance	20 μΩ/m
I	Current	I_0 = 200 kA
m	Railgun projectile mass	0.1 kg
v	Railgun projectile velocity	v_0 = 1000 m/s
y	Railgun projectile position	y_0 = zero
r'	Railgun resistance	1 mΩ/m
U	Railgun armature volt drop	200 V
L'	Inductance of both compressor and railgun	0.5 μH/m
C	Value of V at moment of switching	200 m/s
E	Voltage across compressor-railgun terminals	

and for the railgun

$$-E = L'y\dot{I} + L'vI + Iyr' + U \qquad (2)$$

where $\dot{I}$ is the time rate of charge of current.

In the compressor during flux compression, E is zero giving from (1)

$$\dot{I} = (L'V + R'x)I/L'x \qquad (3)$$

When the compressor and railgun are electrically connected (S open), $\dot{I}$ is found by eliminating E from (1) and (2) giving

$$\dot{I} = (L'I(V-v) - I(R'x+r'y)-U)/L'(x+y) \qquad (4)$$

The performance of the system may be computed using (3) and (4), noting that the force on the armatures is $1/2\ L'I^2$, as always.

As an example of how a compressor-railgun system would be expected to function, a simulation has been conducted using the parameters listed in Table I. The parameters chosen are consistent with the aim of accelerating a 0.1-kg mass to a velocity greater than 3 km/s. The resistance values chosen are roughly what one would expect for a compressor and railgun for these duties. The results of the simulation are shown in Figure 12.

The energy input to the compressor is 1.35-MJ kinetic plus 0.15-MJ electrical, giving a total input of 1.5 MJ. At the moment the switch opens 16 ms later, the electrical energy in the compressor is 1.12 MJ. The residual kinetic energy is small, 0.05 MJ. The kinetic energy delivered by the railgun is 0.70 MJ, being 0.1 kg travelling at 3.75 km/s, indicating an efficiency of 47%.

While this example chosen does not necessarily portray a practical device it does show what is possible. The 15-m-long compressor is used as a computational convenience. In practice it could consist of folded or ganged elements. Its nature is like a Kolm momentum transformer. It is also a close analog to a two-stage light gas gun where the second-stage working fluid is a magnetic field rather than helium or hydrogen.

The armature assembly can be fired into the compressor by using a chemical propellant, thus high average powers associated with automatic guns are attainable. It is also possible that DES railguns using flux compressors may also have applications.

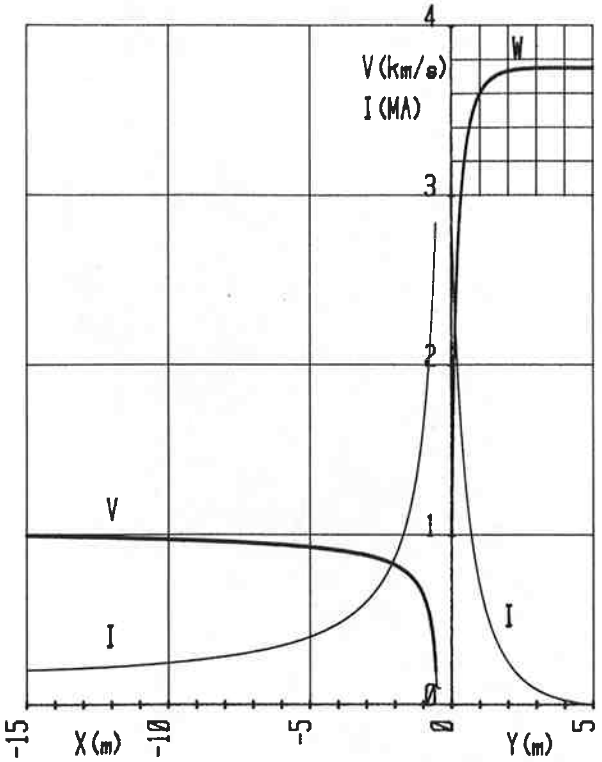

Fig. 12. Flux compressor railgun simulation. Curve V shows the velocity of the compressor armature versus position. Curve W shows the railgun projectile velocity. Curves I show the associated currents.

Conclusions

The conclusions can best be summarized by the diagram in Figure 13 that shows the regions of usefulness for the railgun systems discussed. The four systems using physical energy storage divide the velocity energy domain into four general regions, and all apply to systems with relatively low average power. If high average power is required, then chemically powered energy stores will have applications over the whole domain.

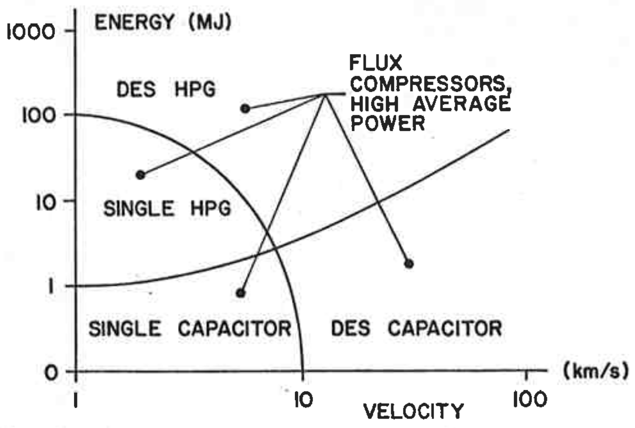

Fig. 13. Regions of usefulness for five energy store railgun systems

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