MAGNETIC PROPULSION FOR A HYPERVELOCITY LAUNCHER

J. P. Barber
(International Applied Physics)

R. A. Marshall
(The University of Texas at Austin)

S. Rashleigh
(Max-Planck Institute)

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Center for Electromechanics
The University of Texas at Austin
Balcones Research Center
EME 1.100, Building 133
Austin, TX 78758-4497
(512)471-4496

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John P. Barber

International Applied Physics, Inc., U.S.A.

Richard A. Marshall

*Center for Electromechanics
University of Texas*

Scott Rashleigh

*Max-Planck Institute
Stuttgart, Federal Republic of West Germany*

ABSTRACT

The concept of using electromagnetic forces to launch projectiles to high-velocity has been pursued since the laws of electro-motion were first derived by Oersted and Ampere in the early 1800's. During the 1960's, there were a number of attempts to develop practical hypervelocity accelerators using electro-magnetic forces. These investigations did not meet with notable success [1,2]. There has been greatly increased interest in electromagnetic propulsion in recent years for a variety of applications including hypervelocity weapons, meteoroid simulation at impact velocities above 10 km/s, high pressure shock physics, and space propulsion. This paper describes an electromagnetic launcher which was developed at the Australian National University (ANU) in the early 1970's, [3] and was successfully used to accelerate projectiles to hypervelocities [4].

INTRODUCTION

Magnetic fields may be thought of as two-dimensional gas. A magnetic field exerts pressure perpendicular to the magnetic field lines, but not along the magnetic field lines. The pressure exerted by a magnetic field is related to the magnetic flux density as shown in Fig. 1. As the magnetic flux density approaches 100 T (1 MG), the pressures become very high. Magnetic flux densities in the range from 30 T to 70 T produce pressures comparable in magnitude to those produced in high performance gas guns. Magnetic pressures have a great advantage over gas pressures in that magnetic pressure fields propagate at the speed of light (3×10^8 m/s) while gas pressures typically propagate at the sonic speed of the medium ($\sim 5 \times 10^3$ m/s). Therefore, the ability of magnetic fields to apply pressure to projectiles at high velocity is greater than that of gases. This fact has generated considerable interest in the use of magnetic fields for hypervelocity launching.

Figure 1 — Magnetic pressure as a function of magnetic flux density.

Figure 2 — The DC electric rail gun principle.

There are a variety of techniques for generating magnetic fields and for using these magnetic fields to exert pressure on projectiles [3]. The DC electric rail gun is one of the simpler, more easily understood methods and it also has great potential for high acceleration performance. The ANU project concentrated on the rail gun concept.

DC ELECTRIC RAIL GUN PRINCIPLES

The principle of operation of a DC electric rail gun is illustrated in Fig. 2. The accelerator consists of two parallel electrodes, or rails, with a projectile placed between them. Current flows up one rail, through the projectile, and back down the other rail. The current flowing in the rails and through the projectile generates a magnetic field between the rails and this magnetic field exerts pressure on both the rails and the projectile. If the projectile is free to move it will be accelerated along the rails.

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A more convenient way of considering the performance of a DC electric rail gun is to consider the inductance of the current path in the accelerator. If the rails are parallel, the inductance per unit length of the accelerator, L' , will be constant, and the force on the projectile can easily be derived as;

$$F = L'I^2/2 \quad (1)$$

where I is the current flowing in the accelerator. For a projectile of mass m , the acceleration may be simply written as:

$$a = L'I^2/2m \quad (2)$$

The inductance per unit length of a parallel rail system depends only on the geometry and spacing of the rails. For practical geometries, the inductance per unit length varies between approximately $0.2 \mu\text{H/m}$ and $0.8 \mu\text{H/m}$. (Various field augmentation techniques have been suggested which could effectively increase these values by factors of approximately two.) Equation 2 is shown plotted in Fig. 3, which illustrates that very high currents are required to achieve high accelerations with gram-size projectiles.

Figure 3 — Current requirements for rail gun accelerations.

Figure 4 — The Australian National University rail gun circuit.

Let us consider a typical hypervelocity launch requirement in which we wish to launch a multi-gram projectile to a velocity of 10 km/s in a launcher approximately 10 m long. The average acceleration required is $5 \times 10^6 \text{ m/s}^2$ and we see from Fig. 3 that currents ranging from 10^5 to 10^6 A are required. The projectile will have a kinetic energy of several hundred kilojoules. Practically achievable single shot system efficiencies may increase primary energy storage requirements to 10 times that value. Although all this energy need not be wasted it must be initially stored and available during acceleration. These power supply requirements have greatly limited DC electric rail gun development.

High accelerations generate high launch stresses in the projectile. The performance of high-velocity accelerators is generally limited by projectile break-up

during launch. Accelerator performance is optimized by maximizing the impulse imparted to the projectile while minimizing the peak launch force. The optimum acceleration profile for meeting this criteria is clearly constant acceleration. Equation 2 shows that, for a parallel rail DC electric gun, constant acceleration may be obtained by maintaining the current constant during acceleration. The most attractive method of driving a rail gun is therefore with a constant current.

The approximate impedance of an electric rail gun may be derived by considering the mechanical power supplied to the projectile. This power is simply the force applied to the projectile times the velocity of the projectile. The force is shown in Equation 1 and the power, W , may be written as;

$$W = L'I^2 v/2 \quad (3)$$

This power must be equal to the electrical power, which may be written as:

$$W = ZI^2 \quad (4)$$

where Z is the apparent impedance. Equating Equations 3 and 4 we obtain;

$$Z = L'v/2 \quad (5)$$

The total impedance of the gun will be higher than that predicted by Equation 5 due to resistive terms and the inductance of the gun and interconnection system. Equation 5 demonstrates a fundamental property of electric rail guns—the impedance rises at least linearly with projectile velocity. Therefore, voltage sources, such as batteries and capacitors, will produce a rapidly decreasing current when used to drive a rail gun. Inductive energy stores, on the other hand, tend to produce a constant current and the voltage developed rises as the impedance rises.

The development at the Australian National University of a very large and high-current homopolar generator together with the early recognition of the potential of inductive driving led to the successful development of a hypervelocity electric gun.

THE AUSTRALIAN NATIONAL UNIVERSITY RAIL GUN FACILITY

An electric rail gun facility was designed, fabricated, and tested at the ANU in the early 1970's. The facility was assembled to investigate the feasibility of large inductively-driven electric rail guns for hypervelocity launching. The system was based on an inductively-driven rail gun concept in which the inductor was charged using the ANU homopolar generator. The ANU generator could store up to 500 MJ of energy and deliver current pulses up to 1.6 MA. The facility was used to power a variety of accelerators ranging from a few millimeters bore size up to almost 20 mm bore size. Accelerators ranging from less than a meter to several meters long were employed. The following paragraphs describe the system in detail.

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The sequence of operation of the accelerator system is shown in Fig. 4. The homopolar generator is charged to a predetermined voltage and energy, and is then switched into the inductor circuit using the electrolytic circuit breaker (ECB). When the current in the storage inductance reaches the required value, the clamp-switch is closed. This switch is designed to isolate the accelerator system from the generator during accelerator operation. The safety resistors limit the post-clamp current in the generator circuit to a safe value.

The task of switching the rail gun into the inductive energy storage circuit is formidable. The gun must be kept out of the circuit during charging to prevent excessive resistive heating of the projectile. The gun must then be switched into the circuit rapidly when the inductor is fully charged. Rapid current switching of inductive circuits carrying high current places severe demands on switching components. No commercially available switches capable of efficiently switching the current could be identified. A special purpose "rail switch" was, therefore, developed. The rail switch is basically a low performance, massively constructed rail gun. When the clamp-switch is closed, the rail switch projectile is simultaneously released. The rail-switch projectile accelerates down the rail-switch rails and switches the rail gun into the inductor circuit. Current then flows through the rail gun and the projectile is launched.

When the projectile reaches the muzzle of the gun, the post-clamp switch is closed to prevent the residual energy stored in the inductance from dissipating in an arc at the muzzle of the gun.

The accelerator system was designed to operate at a maximum of 500 kA. The storage inductance stored 2.75 MJ and could deliver a maximum of 400 kJ to the projectile. The storage inductance was a simple four-start, seven-turn solenoid, one meter in diameter and two meters long. The clamp switch was a hydraulically-operated, multi-element mechanical switch clamped into the bus-bar system near the terminals of the storage inductance.

The rail switch served multiple purposes in the circuit. During charging of the inductor, the rail switch projectile was mechanically restrained and served as a shorting bar in the circuit. The charging time was typically 0.5 s and the resistive heating problems were enormous. To accommodate the heating, the switching projectile and switch rails were made from copper and had a current-carrying cross-sectional area of 20 cm². The switching projectile weighed up to approximately 0.5 kg. The rail switch not only had to carry current during the charging cycle, it had to switch current into the rail gun in times short compared to the acceleration time of the projectile. This was accomplished by releasing the switch projectile at the appropriate time during inductor charging. The switch projectile then accelerated down the rail switch crossing an insulating insert at the breech of the rail gun. Current was rapidly switched into the rail gun and the rail switch projectile was subsequently stopped before it reached the muzzle of the rail switch. The switch achieved typical switching times of 50 μ s and current rates of change of 5×10^9 A/s. A photograph of the storage inductor, the clamp switch, and the rail switch is shown in Fig. 5.

A variety of guns of different geometries and sizes were connected to the rail switch and employed for launching projectiles. A typical 3.7 meter long gun attached to the switch is shown in Fig. 6. In general, a projectile consisted of a current-carrying armature and a non-current-carrying payload section. Both metallic and plasma (arc) armatures were used and the results are described in the next section.

Figure 5 — Photograph of the storage inductor and clamp switch.

Figure 6 — A rail gun installed at the Australian National University facility.

RESULTS AND DISCUSSION

The first series of experiments conducted with the ANU rail gun facility employed multi-leaf metallic armature projectiles as illustrated in Fig. 7. The payload was usually eliminated in order to achieve maximum acceleration and velocity. Good electrical contact must be obtained between the armature and the rails with a metallic armature projectile. Good contact was achieved by designing the armature to have multiple independent contacts and by applying high normal loads to the contacts. Multiple contacts were obtained by employing multiple leaves and slitting the edge of the leaves to form multiple fingers, as shown in Fig. 7. High, normal contact forces were obtained by employing chevron-shaped leaves which allowed a component of the magnetic accelerating force to appear as a normal force between the armature contact and the rail. The results of a series of experiments with this type of projectile are shown in Fig. 8. The projectile, which consisted only of copper-armature leaves, weighed two grams. The velocities achieved varied from 1200 m/s at 105 kA to over 2500 m/s at 203 kA. Very good electrical contact between the armature and the rail was achieved at velocities up to 1100 m/s. Above 1100 m/s transition to arcing contact occurred, but acceleration continued.

Experimental observation of the progressive failure of multi-leaf projectiles during launch, indicated that most of the accelerating current was carried in the trailing leaf. Theoretical analysis of electrical skin-effects confirmed this observation. The projectile was re-designed to eliminate all but the trailing leaf

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Figure 7 — A metallic armature projectile.

Figure 8 — Performance of a 2 g copper armature projectile (the lines are computed performance and the points are experimental data points).

as shown in Fig. 9. As might be expected, these projectiles worked very satisfactorily, but two problems still remained: the contact arc transition still occurred at 1100 m/s; and the limited current-carrying capacity of the single-leaf projectile limited the maximum velocities achievable.

The armature was subjected to excessive electrical heating in attempts to increase velocity by driving more current through the single-leaf armature. Armature failure resulted and an arc struck between the rails behind the payload. Current continued to flow and the payload continued to accelerate. These observations led to the development of plasma armature concepts.

A plasma armature is illustrated in Fig. 10. The first plasma armature projectiles were developed from the single-leaf metallic armature projectiles. The single-leaf was deliberately designed to fail at a predetermined time during the acceleration—a "flying fuse." This time was selected to permit the rail switch projectile to clear the switching gap and achieve adequate stand-off voltage for plasma armature accelerator operation. Using this technique, payloads consisting of polycarbonate cubes were successfully launched to velocities of over 4 km/s. A typical test result is shown in Fig. 11. It can be seen from Fig. 11 that the entire mass of the payload and metallic armature are accelerated during the first part of the acceleration. At some point during the acceleration, after arcing has begun, the armature mass "decouples" and only the payload appears to continue acceleration. The performance would obviously be improved greatly if only the payload were accelerated during the entire acceleration. This observation led to the final projectile concept investigated.

The voltage across the gun breech must be kept low (less than approximately 50 volts) for a few hundred microseconds after gun operation commences to permit the rail switch to switch the current and stand-off the gun voltage without internal arcing. In the "flying fuse" concept, this was accomplished by launching a metal armature/fuse with the payload. The next step was to clamp the fuse into the breech of the gun and mount the payload immediately in front of the fuse. When the fusing element blows out, a few hundred microseconds after rail switch operation, the plasma arc will

Figure 9 — A single-leaf projectile.

Figure 10 — A plasma armature projectile.

Figure 11 — Performance of a flying fuse projectile.

Figure 12 — Rail gun performance for a flap-back fuse projectile.

immediately make contact with the back of the payload, and the acceleration will begin. This concept was successfully implemented and the results of a high velocity acceleration are shown in Fig. 12. A payload mass of 2.5 g was launched to 5.9 km/s, with an initial current of 290 kA. Orthogonal shadow-graphs of the projectile in flight are shown in Fig. 13.

CONCLUSIONS

The Australian National University experiments clearly demonstrate that the DC electric rail gun principle can be used to launch projectiles to hypervelocities. The expected and desirable constant acceleration performance obtainable with inductive driving has been demonstrated. Both metal and plasma armatures have been employed successfully to launch projectiles. Plasma armatures were used to obtain the highest velocities (5.9 km/s) and show great promise for allowing even further increases in muzzle velocities.

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Figure 13 — Orthogonal shadowgraphs of a rail gun-launched polycarbonate cube traveling at 5.9 km/s.

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