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RAIL GUN POWERED BY AN INTEGRAL EXPLOSIVE GENERATOR*

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ABSTRACT

We propose the use of a rail gun powered by an explosive magnetic flux compression generator built into the rail gun itself in which the rails of the gun are driven together behind the projectile by explosives. The magnetic field established between the rails by an initial current supplied by an external source at the breech of the gun is trapped and compressed by the collapsing rails to accelerate the projectile down the bore of the gun.

Whether used externally or integrally to power rail guns, the use of explosive magnetic flux compression generators appears promising.

I. INTRODUCTION

Kreisler[1] and Hawke and Scudder[2] list a number of applications that call for projectiles (macrons) that move at very high speeds. In particular, they note ranges of macron speeds required for various applications. As examples, equation-of-state measurements could be extended with suitable projectiles traveling at speeds in excess of 10 km/s, whereas impact fusion might be attainable at speeds greater than 100 km/s. Kreisler[1] gives a compact survey of various methods by which such particles might be accelerated. Some of the methods are by electrostatic acceleration, magnetic acceleration, and use of light gas guns.

The current interest in macron acceleration has been stimulated by the successes achieved in two recent experimental programs: the rail gun program of Marshall et al.[3] and the mass launcher program of Kolm et al.[4] The projectiles are accelerated magnetically in both programs, but the rail gun

* Many of the ideas presented in this paper were discussed at an informal session of the Second International Conference on Megagauss Magnetic Field Generation and Related Topics, May 29-June 1, 1979, Washington, DC.

uses direct-magnetic-field drive and the mass launcher employs magnetic-field gradients. The differences in the two techniques may be seen in Fig. 1, which shows schematically the systems employed by Fowler et al.[5] for direct drive and Chapman[6] for gradient drive. In the direct-acceleration arrangement (Fig. 1a), the projectile plate carries current and is accelerated down the rails away from the heavy base plate. Current was supplied by a capacitor bank. The accelerating force arises from the magnetic field that is confined to the region between the base plate and projectile. In case (b), a magnetic-field channel is constructed so that a magnetic-field gradient is developed opposite the direction of projectile motion. Here, the projectile does not carry current directly. To a first approximation, the projectile is accelerated by forces proportional to the local average field and the field gradient across the sample. Joule heating, from eddy currents in case (b), was a serious factor in both schemes, leading to vaporization of the projectiles at high speeds.

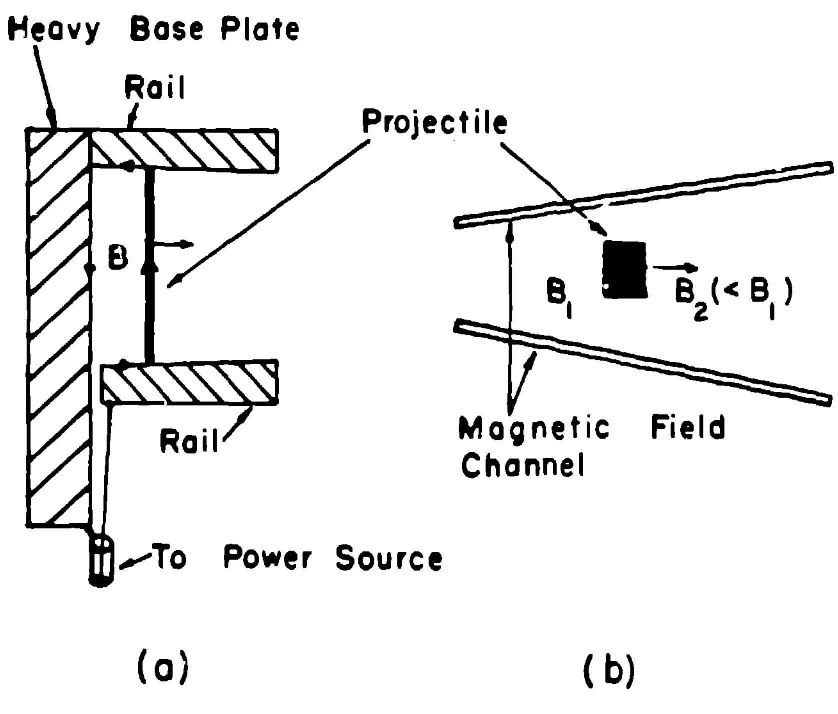

Fig. 1. Schematic drawings of projectiles accelerated by (a) magnetic fields and (b) magnetic field gradients.

In the direct-feed case, thin plates were successfully accelerated to about 3 km/s, but were completely vaporized when attempts were made to accelerate them to 8 km/s. As noted in Ref. 5, for this situation, there is a one-to-one correspondence of plate temperature with the ratio of plate velocity to its thickness, provided the current density throughout the plate is uniform and plate-edge effects are negligible. These thin plate results were consistent with this theory. It was felt then that efforts to increase plate thickness to obtain higher velocities before vaporization would not be too successful because the current would concentrate near the plate surface, leading to harmful ablation of projectile material. However, experiments with the rail gun seem to imply that such ablation would not be particularly harmful. This implication is consistent with recent work by Sherwood et al.[7] in which electromagnetic implosion of a cylindrical liner yielded inner radial velocities of about 10 km/s, even though calculations indicated that the temperature exceeded the melting point on the outer liner diameter. It might be profitable to repeat some of this earlier work with thicker plates and larger energy sources. Somewhat later, Guenther et al.[8] used the vaporization products obtained by deliberately exploding thin plates to drive thin plastic materials placed ahead of the plates. Speeds of these plastic projectiles reached several kilometers per second. In all of these experiments, acceleration was to be accomplished over short distances with single, intense magnetic pulses.

In the mass launcher, Kolm et al.[4] avoided the very large stresses needed to accelerate in a single short pulse by using a series of staged field coils, each giving an acceleration pulse as the projectile passed through the coil. The eddy current heating that would eventually melt and vaporize the projectile would be eliminated by using a superconducting coil as the projectile driver.

In the rail gun, Marshall et al.[3] avoided the large stresses by controlling the magnitude of the projectile driving current and greatly increasing the length of the rails. Figure 2a shows this basic rail gun assembly. Power was supplied from an inductive store that was energized by the Canberra homopolar generator. Much attention was devoted to the design of the armature to carry the current between the rails. Initially, metal armatures were used. Later, plasma-arc armatures were used.

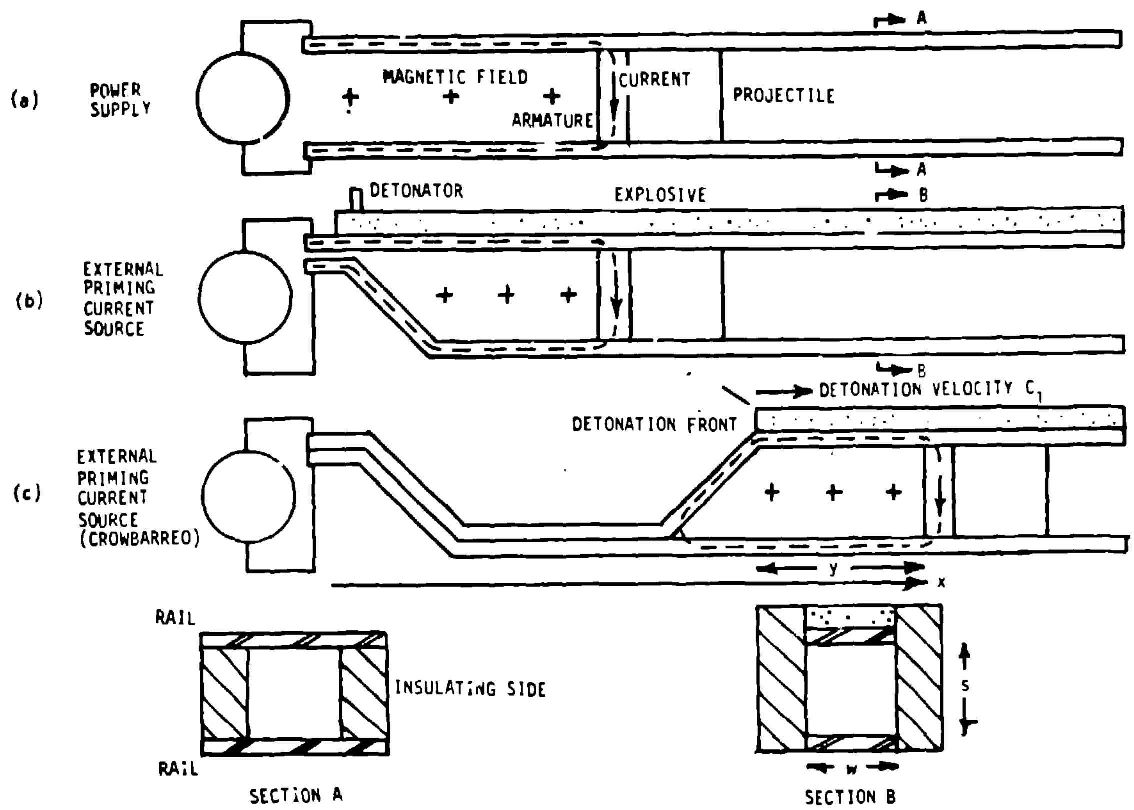

Fig. 2. Schematic drawings of externally powered (a) and hybrid (b) and (c) rail runs.

II. FLUX COMPRESSION GENERATOR POWER SUPPLY

Among the power supplies that have been used to power rails guns are the inductive store of Marshall et al.[3], capacitor banks by a number of workers, and flux compression generators.[9]

We propose the use of a rail gun powered by an explosive magnetic flux compression generator built into the rail gun itself, as in Figs. 2b and 2c, in which the rails of the gun are driven together behind the projectile by explosives. The magnetic field established between the rails by an initial current supplied by an external current source at the breech of the gun is trapped and compressed by the collapsing rails to accelerate the projectile down the bore of the gun. A rail gun powered by such an integral explosive generator is referred to as a hybrid rail gun.

Whether used externally to supply power to a conventionally fixed-rail gun or integrally to power a hybrid rail gun, the use of explosive magnetic flux compression generators appears promising, based on preliminary, idealized calculations. Plans are in progress to pursue both of these approaches.

External generators will be used to power the guns in a cooperative program with R. S. Hawke and J. K. Scudder of Lawrence Livermore Laboratory, and the hybrid approach is now being planned as a Los Alamos Scientific Laboratory (LASL) experiment. As planned, strip generators such as those described by Fowler et al.[10] will be used for both systems. They have the advantage of very long burn times (hundreds of microseconds) that are thought to be necessary for successful rail gun application.

III. ANALYSIS OF EXPLOSIVE-GENERATOR-POWERED RAIL GUN

In Fig. 2c, at time t, the position of the projectile is x; the distance between the explosive detonation front and the projectile is y; and the current is I. The detonation front moves with constant velocity C_1. The boundary conditions are that, at some particular time, t_0, the projectile position is x_0; the distance between the detonation front and the projectile is y_0; the current is I_0; and the projectile speed is C_0 ($C_0 < C_1$).

At any instant of time, the inductance L of the rail run is (in SI units)

$$L = \alpha\mu_0 \, sy/w, \qquad (1)$$

where α is a dimensionless constant depending on the ratio s/w, $\mu_0 = 4\pi \times 10^{-7}$, the magnetic permeability, and s and w are the separation and width of the rails. Values of α are available in Ref. 11.

If there is no magnetic flux lost from the trapped magnetic field, the magnetic flux $\phi = LI$ is constant, and equal to the flux at time t_0,

$$\alpha\mu_0 \, sy \, I/w = \alpha\mu_0 \, sy_0 \, I_0/w,$$

so that the current is

$$I = I_0 \, y_0/y. \qquad (2)$$

The average magnetic field B between the rails is

$$B = \phi/sy, \quad (3)$$

and the magnetic pressure P acting to accelerate the projectile down the rails (and, incidentally, acting to drive the rails apart) is

$$P = B^2/2\mu_0. \quad (4)$$

Using the above equations, the equation of motion of a projectile of mass m may be written

$$d^2x/dt^2 = D_1\, y_0/2y^2 - f/m, \quad (5)$$

where

$$D_1 = \alpha^2 \mu_0\, s y_0\, I_0^2/mw, \quad (6)$$

and f is the force caused by mechanical friction between the projectile and the bore of the rail gun, gas ahead of the projectile, etc., acting to resist the projectile acceleration.

For the case f = 0, Eq. (5) may be integrated twice using the relation

$$x = x_0 + y - y_0 + C_1(t - t_0), \quad (7)$$

with the initial conditions stated above to obtain the projectile velocity and the time in terms of y.

Solutions are expressed in terms of auxiliary y dependent parameters G and H, together with constants x_1, t_1, E_1, F_1, and the previously defined parameter D_1 determined from initial values. These new parameters are defined below. Velocities and times are then given by

$$dx/dt = \begin{cases} C_1 - G/y, & t_0 \leq t \leq t_1 \\ C_1 + G/y, & t > t_1 \end{cases} \quad (8)$$

and

$$t = \begin{cases} t_1 - H, & t_0 \leq t \leq t_1 \\ t_1 + H, & t > t_1 \end{cases} . \quad (9)$$

The constant parameters are defined as follows:

$$E_1 = D_1 + (C_1 - C_0)^2. \quad (10)$$

$$F_1 = D_1/2E_1^{1/2}. \quad (11)$$

$$t_1 = t_0 + y_0 \left\{C_1 - C_0 + F_1 \ln[(C_1 - C_0 + E_1^{1/2} - F_1)/F_1]\right\}/E_1. \quad (12)$$

$$x_1 = x_0 - y_0 (C_1 - C_0)^2/E_1 + C_1 (t_1 - t_0). \quad (13)$$

The y dependent parameters are given by

$$G = (E_1 y^2 - D_1 y_0 y)^{1/2}, \text{ and} \quad (14)$$

$$H = \left\{G + F_1 y_0 \ln [(G + y E_1^{1/2} - F_1 y_0)/F_1 y_0]\right\}/E_1. \quad (15)$$

Equations (7) through (9) prescribe x, dx/dt, and t for the projectile in terms of y, the separation between the detonation front and the projectile.

At time t_1, the projectile velocity is equal to the explosive detonation speed C_1, and the separation between the detonation front and the projectile is minimum. Previous to t_1, the projectile is traveling slower than the explosive detonation front, the separation between the detonation front and the projectile is decreasing, the trapped magnetic field is being compressed, and the magnetic pressure accelerating the projectile is increasing. After t_1, the projectile is traveling faster than the explosive detonation front, the separation between the detonation front and the projectile is increasing, the trapped magnetic field is expanding, and the magnetic pressure accelerating the projectile is decreasing. If there are no mechanical losses and no flux losses from the trapped magnetic field, the projectile velocity will approach asymptotically the velocity

$$(dx/dt)_{max} = C_1 + E_1^{1/2}.$$

In a real rail gun, the projectile will, at some point, begin to decelerate after initially outrunning the explosive detonation wave.

It is useful to have the explosive detonation speed start out at a relatively slow speed and increase as the detonation front proceeds along the rail. One way of accomplishing this is to use segments of explosives of different detonation speeds, as in Fig. 3b. The equations obtained above may be used in this case, but must be written separately for each segment of explosive using the appropriate constants. The initial conditions for each segment are obtained from the final conditions of the preceding segment.

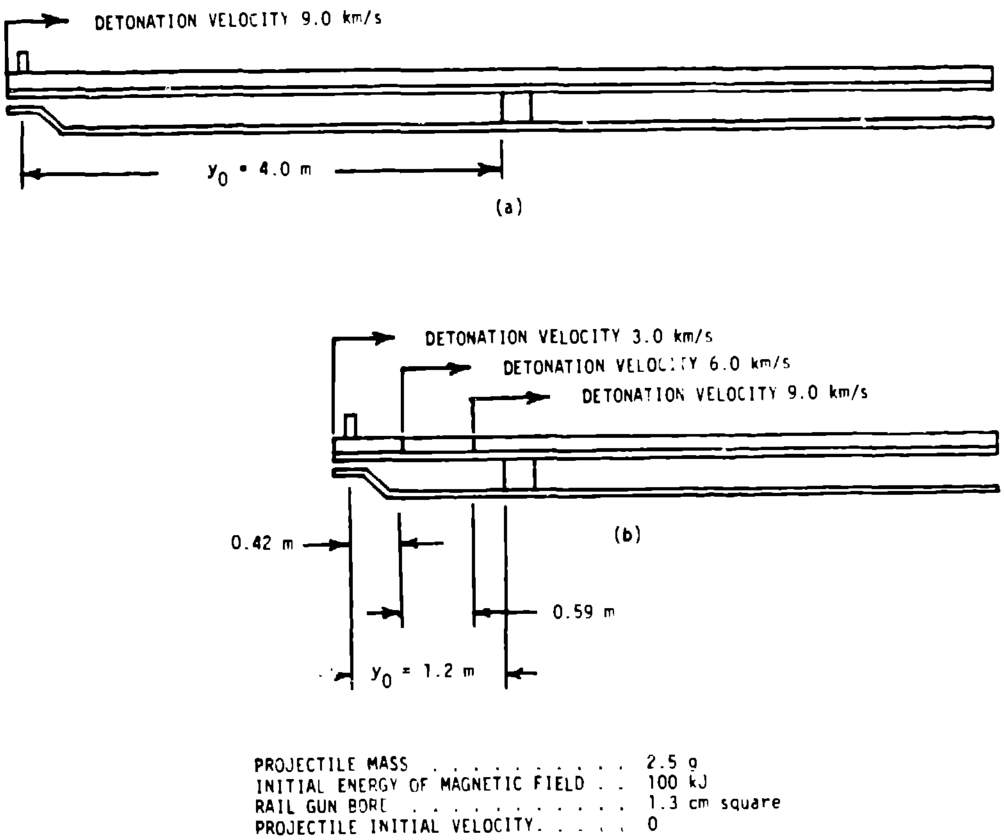

Fig. 3. Parameters for example performance curves in Fig. 4.

Performance curves for the rail gun arrangements shown in Figs. 3a and 3b are given in Fig. 4. The use of staged explosives results in a shorter gun.

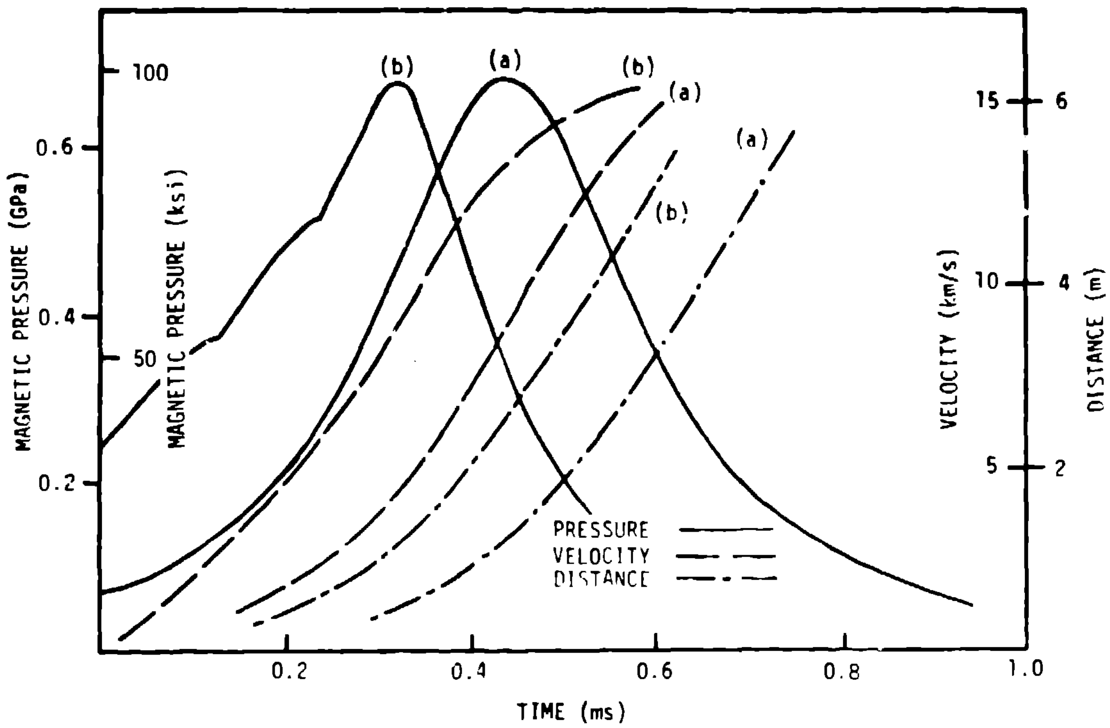

Fig. 4. Calculated performance curves for rail guns shown in Fig. 3.

IV. DISCUSSION

Both the externally driven and hybrid-type rail guns using the flux compression generators show considerable promise. Some of the favorable aspects and potential problems of this approach are discussed.

Ideally, projectile velocities exceed the detonation velocity of the explosives. Explosive strips can be detonated at arbitrary phase velocities greater than their normal detonation velocity. Thus, in principle, arbitrarily large effective detonation velocities and, thus, projectile velocities can be achieved.

The continuous collapse of the rails behind the projectile has several advantages. The active inductance of the rail gun is never very large. Therefore, relatively little magnetic energy must be stored inductively. Similarly, no part of the rails is exposed to current for a very long time. Heating effects, as well as integrated forces that displace the rails, are greatly reduced.

Aside from the obvious disadvantage of destroying the rails, there are some potential difficulties with the hybrid gun. These include the possible formation of harmful jets at the rail collision juncture and the loss of flux trapped in the rails. Jets could actually overtake the projectile, particularly when it is moving slowly, and would lead to undesirable flux losses. Flux losses from any cause result in projectile speeds slower than those calculated ideally, and therefore lead to the possibility of the detonation front overtaking the projectile.

We now lean toward the following approach. External flux compression generators will first be used to accelerate the pellet to several kilometers per second, after which the rail generator will be started. The rail explosive will be staged, starting with low detonation velocity explosives and finishing with fast detonating explosives. H. L. Flaugh, LASL Design Engineering Division, has undertaken the design and production of the staged explosives to drive the rail gun, and J. M. Christian, LASL Dynamic Testing Division, is developing the technique to assess the performance of the explosive-rail assemblies.

Strip generator systems can be built that require a millisecond or more to complete detonation, but it is likely that flux losses would be prohibitive for much longer times. Therefore, the ultimate speeds obtainable by this method are directly related to the stresses that the projectiles are able to withstand during acceleration.

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