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# A Coilgun Design Primer

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**Abstract**-**This** paper explains how an inductive coilgun works and presents the factors which go into its design. Our purpose is to obtain algebraic expressions which, although crude, provide useful predictors of behavior, illustrate the dependence on parameters, and suggest ways to optimize the design. Detailed simulation of the gun's behavior is obtained from the computer code, **SLINGSHOT**, a successor to the code **WARP-10** developed by Mel Widner [1]. **SLINGSHOT** was designed to be user friendly, run quickly, and provide a range of design options.

## I. COILGUN FUNDAMENTALS

The basic geometry of an inductive coilgun is shown in Fig. 1. It consists of a sequence of equally shaped and spaced coils surrounding a flyway in which a cylindrical armature moves. The coils are connected to an external electrical circuit. The projectile consists of the armature (the part carrying current) plus a payload which is not shown but is included in the mass. The armature is electrically coupled to the coils only by their mutual inductance, there is no physical contact.

Fig. 2 illustrates how the coilgun works. Fig. 2a shows the magnetic field configuration produced by several coils in the absence of an armature. Coils which have yet to be energized are not shown. The remaining figures are in the reference frame of the moving armature. New coils are energized as the armature reaches them, maintaining the field picture. Fig. 2b shows the magnetic field shortly after the coils are energized. A thin surface current induced in the armature excludes the field from its interior. If the armature were a perfect conductor, the current would remain on the surface and the field would be forever excluded. Since the armature is not perfectly conducting, the field diffuses into it in time as shown in Fig. 2c. The magnetic field would eventually reach the state shown in Fig. 2d in which it has completely diffused into the projectile, resulting in a field similar to that of Fig. 2a. In this state, where the armature is fully "saturated", no force is produced on the projectile.

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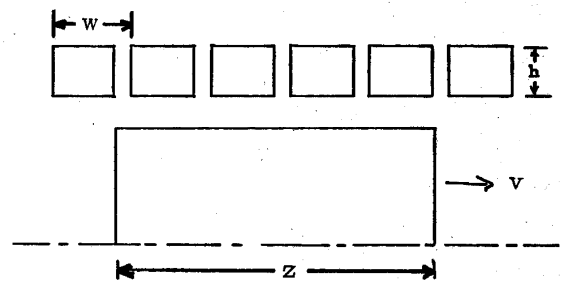


Fig. 1. Basic coilgun geometry.

In order to continue accelerating the projectile, the firing position of the coils must advance on the armature as shown in Fig. 2e. The rear section of the armature is saturated with magnetic field in a force free configuration. The force on the armature arises forward of this region, near material which still contains no magnetic field. The velocity at which the firing position of the coil relative to the armature is advanced is called the slip velocity, denoted by "u". As the moving projectile encounters new coils, a switch is closed at the proper time which energizes the coil and induces the currents in the armature needed to maintain the desired field configuration and its resultant forces.

Coilgun operation involves the interaction of the current density, **J**, and the magnetic field, **B**, which are related by

$$\mathbf{J} = \text{curl } \mathbf{B} / \mu \tag{1}$$

where $\mu$ is the permeability of space, equal to $4\pi x10^{-7}$ henry/meter. The source of the field in Fig. 2a, for example, is the current in the coils. The current is entirely azimuthal, that is circulating around the axis. Forces result from the current density crossed into the magnetic field:

$$\mathbf{F} = \mathbf{J} \times \mathbf{B} = \text{curl } \mathbf{B} \times \mathbf{B} / \mu . \tag{2}$$

In order for the magnetic field to produce a force, both it and its curl must be present. The mere presence of a magnetic field does not in itself imply that a force exists. The equation governing the diffusion of the magnetic field into a material with conductivity $\sigma$, is

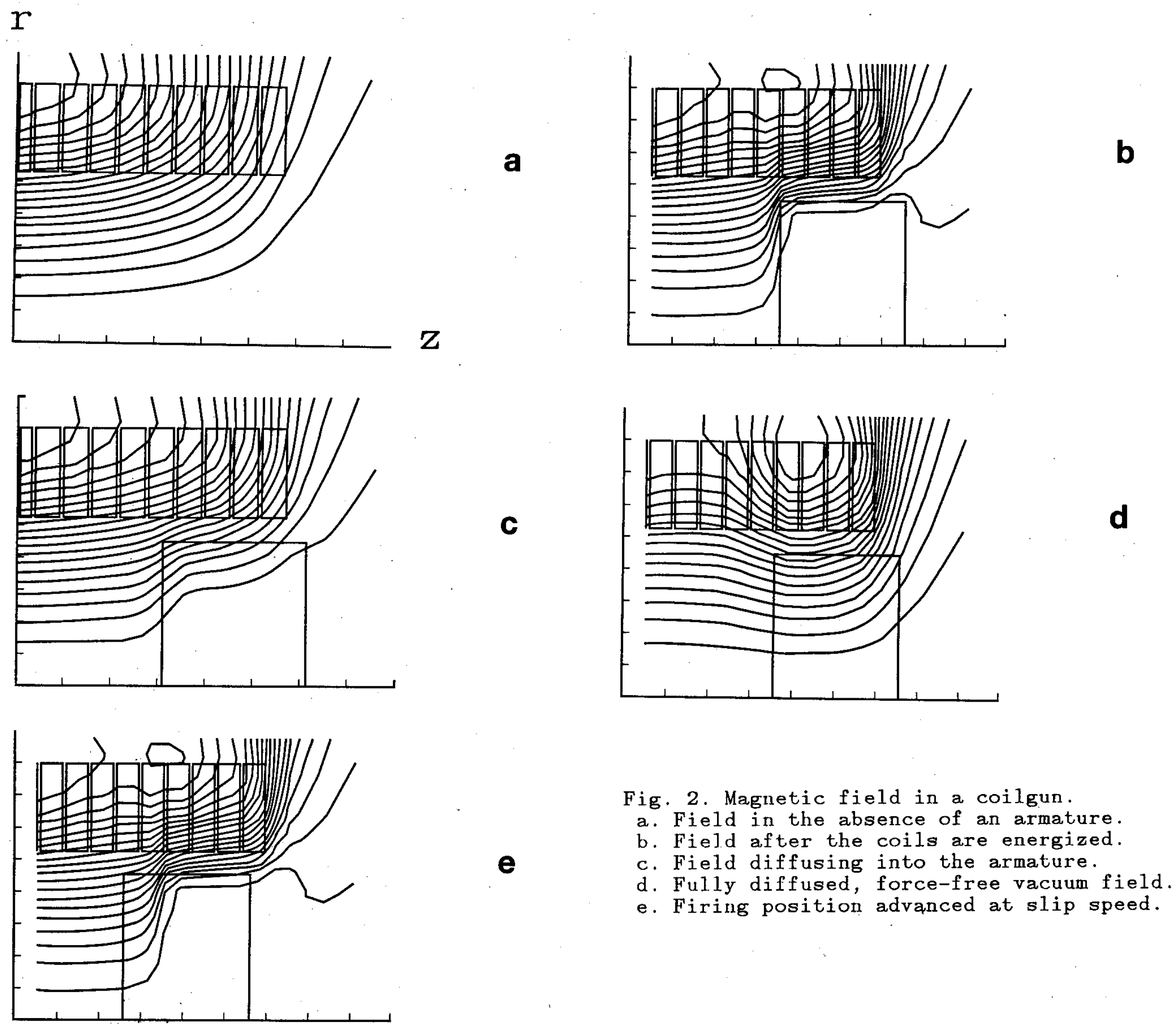


Fig. 2. Magnetic field in a coilgun.
a. Field in the absence of an armature.
b. Field after the coils are energized.
c. Field diffusing into the armature.
d. Fully diffused, force-free vacuum field.
e. Firing position advanced at slip speed.

$$\partial \mathbf{B}/\partial t = -\text{curl } \mathbf{J}/\sigma = -\text{curl curl } \mathbf{B}/(\sigma\mu). \quad (3)$$

Notice that if $\sigma$ is infinite, the magnetic field does not change in time, being unable to penetrate any superconducting material in which it is not initially present. When the field has fully diffused, as in Fig. 2d, current no longer flows in the armature. Thus, by (1), curl $\mathbf{B} = 0$ and no force is produced.

Equation (2) shows that the axial force, the one pushing the projectile, is given by the radial magnetic field times the current density. The radial force, which compresses the projectile, arises from the axial magnetic field times the current density. Of course, the coils also experience forces due to their own currents interacting with the magnetic field.

Fig. 2b suggests another way to look at coilgun operation. By virtue of its surface current, the armature has excluded the field that would ordinarily be inside it. The surface current creates its own magnetic field which cancels the coil field inside the armature and enhances it outside. Fig. 3 illustrates how the field in Fig. 2b results from the vector sum of the coil currents and the armature currents. Thus, the projectile can be considered an electromagnet being pushed by the magnetic field of the coils. Later, when the armature is fully saturated with the coil field, no current flows in it so it contributes no magnetic field of its own.

## II. ENERGY AND KINEMATIC CONSIDERATIONS

We shall examine a coilgun with stages labeled by the index "k". The stages have width "w", height "h", and mid-coil radius, "r". Since a stage consists of supporting structure as well as conductor, we shall assume the conducting portion is three quarters as wide as the full stage, 3w/4, but occupies the full height. Let E be the initial stored energy per stage, $\eta$ the electrical-to-mechanical energy efficiency,

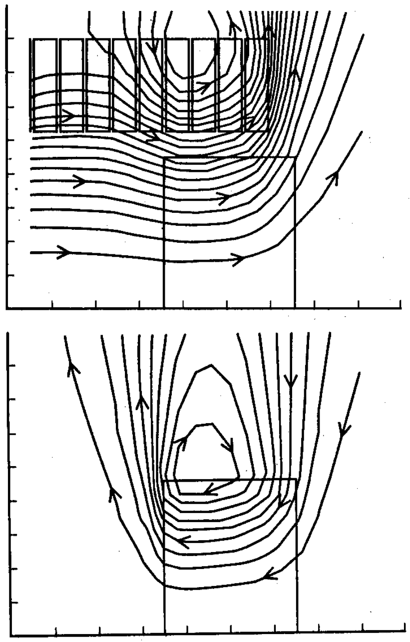

Fig. 3. Field in Fig. 2b is produced by the vector sum of fields from the coil currents (top) plus the armature current (bottom).

s the distance the projectile has moved, v its velocity, and m its mass. Both E and $\eta$ are assumed to be the same for all stages. The power per stage fed to the projectile is the effective energy divided by the time taken to pass the stage, $\eta E/(w/v)$. Setting this equal to the force times the velocity we find that the acceleration, a, is the same at each stage and satisfies

$$maw = \eta E. \quad (4)$$

Since we are assuming a gun with many stages, we shall ignore the first several stages, as the behavior for these tends to be quite different from when the currents in the armature have been established and essentially uniform acceleration has been achieved. Let $v_0$ be the velocity at which this happens. Constant acceleration implies

$$v = v_0 + at \quad (5)$$

$$s = at^2/2. \quad (6)$$

Since resistive losses go as the square of the current, operating the gun with each stage at the highest possible voltage minimizes the current and gives the best efficiency. We shall, therefore, assume that the voltage is the same for each stage and is equal to some value, V, determined by engineering considerations. The electrical energy for each stage is stored in a capacitor and is related to the voltage and capacitance, C, by

$$E = CV^2/2. \quad (7)$$

As illustrated in Fig. 4, the coil is fired when the armature is at a location determined by the slip velocity and the rise time of the circuit. Let L be the inductance of a single turn coil and $N_k$ be the number of turns in the actual structure. Because the coil fires with the projectile completely inside it, some fraction of the area is taken up by the projectile, reducing the effective inductance. Denoting this fraction by $\beta$, the rise time, $\tau_k$, of the $k^{th}$ coil can be estimated by

$$\tau_k = \pi/2 \ N_k(\beta LC)^{1/2}. \quad (8)$$

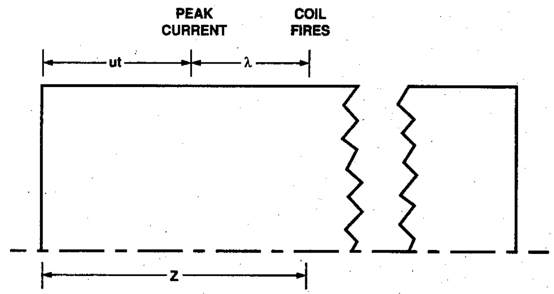


Fig. 4. Location on armature of coil firing showing rise length.

The length of armature that moves past the coil during the rise time is called the rise length, $\lambda$, and is assumed to be the same for all stages. It is equal to the product of the rise time and projectile velocity:

$$\lambda = v\tau_k = \pi/2 \ N_k v(\beta LC/2)^{1/2}. \quad (9)$$

After the capacitor is discharged, its electrical energy is converted to inductive energy in the coils. Letting $I_k$ be the peak current in the $k^{th}$ coil, we have

$$E = \beta L(N_k I_k)^2/2. \quad (10)$$

Notice that $N_k I_k$ has the same value for all coils.

Unless some of the electrical energy is recovered, the portion not used to accelerate the projectile will heat the coils. If $\rho$ is the specific density of the coil material, and c its specific heat, the coil temperature rise, T, can be found from

$$E(1-\eta) = 2\pi rh(3w/4)\rho cT. \quad (11)$$

Let $z_k$ be the required length of armature at stage k. Referring to Fig. 4, we have

$$z_k = ut + \lambda. \quad (12)$$

The inductance of a single turn rectangular cross-section coil is a function of the coil radius, height, and width for which no analytic formula exists. Nor does one exist for the magnetic field at the coil surface which depends also on the coil current.

Summarizing what we have so far:

$$v = v_o + a(z_k-\lambda)/u \tag{13}$$

$$s = a(z_k-\lambda)^2/(2u^2) \tag{14}$$

$$\eta E = maw \tag{15}$$

$$2E = CV^2 \tag{16}$$

$$4\lambda^2 = (\pi N_k v)^2 \beta LC \tag{17}$$

$$2E = \beta L(NI)^2 \tag{18}$$

$$2E(1-\eta) = 3\pi rhw\rho cT \tag{19}$$

$$B = B(r,w,h,I) \tag{20}$$

$$L = L(r,w,h). \tag{21}$$

## III. DESIGN CONSIDERATIONS

We shall now make some assumptions and approximations. If the coil shape is not very elongated, the inductance of a rectangular cross-section coil can be approximated by the formula for a circular cross-section coil with minor radius "a" and major radius "b":

$$L_{circle} = \mu b \ln[1.39b/a]. \tag{22}$$

To use this, set "b" equal to the radius of the coil center, r, and set "a" to the value that gives the same cross-sectional area, $\pi a^2 = (3w/4)h$:

$$L = \mu r \ln[2.84\, r/(wh)^{1/2}]. \tag{23}$$

The magnetic field inside the coils can be related to the field in an infinitely long solenoid in which all the coils carry the same current. Since only a few coils are actually carrying current, and the current they carry will be less than the peak, we shall approximate the field by half the solenoidal field:

$$B = 1/2\ \mu N_k I_k/w. \tag{24}$$

This is, of course, a crude approximation, but SLINGSHOT runs indicate that it is reasonably accurate. It serves as a useful reference field.

As a trade off between increased magnetic field tolerance and efficient coupling to the armature, we shall assume the height of the conducting part of the coils is equal its width, which we took to be 3/4 of the length of the stage:

$$h = 3/4\ w. \tag{25}$$

With this specification, the inner radius of the coil is $r_i = r - 3w/8$ and the outer radius is $r_o = r + 3w/8$.

To keep the acceleration reasonably smooth, the length of a stage should be no more than half the rise length so that several coils are contributing to the force at any time. To minimize the number of stages, we shall take the rise length to be exactly two stages long:

$$\lambda = 2w. \tag{26}$$

Finally, the projectile will, in general, occupy about half the area enclosed by the center of the coil. We shall, therefore, set the inductance area factor, $\beta$, equal to 1/2.

Equations (13)-(19), (24), and (25) now constitute a system of nine equations for fifteen unknowns ($s$, $v$, $z_k$, $N_k$, $I_k$, $a$, $m$, $E$, $V$, $B$, $C$, $L$, $w$, $r$, $T$) and five parameters ($u$, $\eta$, $\rho$, $c$, $v_o$). All but the first five unknowns are constants, both in time and coil index. We shall specify the five quantities $m$, $r_i$, $w$, $V$, and $B$, and solve for the remaining nine.

$$L = \mu r\Gamma \tag{27}$$

$$a = \eta wrB^2\Gamma/(\mu m) \tag{28}$$

$$N_k v = 4V/(\pi rB\Gamma) \tag{29}$$

$$T = 8(1-\eta)B^2\Gamma/(9\mu\rho c) \tag{30}$$

$$E = w^2 rB^2\Gamma/\mu \tag{31}$$

$$C = 2w^2 rB^2\Gamma/(\mu V^2) \tag{32}$$

$$N_k I_k = 2Bw/\mu \tag{33}$$

$$s = (v-v_o)^2/(2a) \tag{34}$$

$$z_k = 2w + u(v-v_o)/a \tag{35}$$

$$k = [s/w] \tag{36}$$

where now $\Gamma = \ln[3.28r/w]$ and $r = r_i + 3w/8$.

Since the number of turns per coil cannot be less than one, setting $N_k$ equal to one (or somewhat less, as the N in these expressions need not be an integer) determines the maximum achievable velocity. Any velocity between $v_o$ and the maximum can be realized by stopping at an intermediate stage with more than one turn. The total gun length, required armature length, and the number of stages are found from (34), (35), and (36).

Three coilgun designs are presented as examples in Table 1, an experiment designed to achieve hypervelocity with a 400 gram projectile, a long range gun for naval applications using a 60 kg projectile, and a 1000 kg payload earth-to-orbit (ETO) launcher.

A voltage of about 20 kilovolts is convenient for laboratory experiments. Above about 40 kilovolts, measures must be taken to avoid electrical breakdown. Such measures are acceptable for the ETO launcher but would be undesirable aboard a ship. The maximum magnetic field experienced by the coils should lie below 40 Tesla, which is pushing the capability of existing coils but is probably achievable in future designs. Without energy recovery, cooling requirements become important above a coil temperature rise of 100 degrees, especially for repetitive shots. The optimum slip velocity depends on the armature material and geometry, but is typically around 5 m/s, decreasing as the armature increases in size.

The upper portion of the table gives the input parameters to equations (27)-(36) while the lower portion gives the values computed using these equations for the remaining variables. If a reasonably accurate efficency is used as input to the equations, the final velocities are generally within ten percent of those predicted by the full simulation code, SLINGSHOT.

## IV. CONCLUSIONS

We have presented a qualitative explanation of how a coilgun works and have derived some crude algebraic expressions for determining its performance. Examples include a laboratory hypervelocity experiment, a long range naval strike weapon, and a large earth-to-orbit launcher.

## REFERENCES

[1] M. M. Widner, "WARP-10: a numerical simulation model for the cylindrical reconnection launcher," IEEE Trans. on Magnetics, vol 27, no. 1, pp. 596-600, January 1991.

**Table 1**

Predicted Gun Behavior

| | EXP | NAVY | ETO |
|---|---|---|---|
| m(kg) | 0.4 | 60 | 1000 |
| $r_i$(m) | 0.03 | 0.105 | 0.5 |
| w(m) | 0.04 | 0.06 | 0.1 |
| V(kV) | 15 | 40 | 180 |
| B(T) | 20 | 40 | 25 |
| $v_0$(m/s) | 100 | 100 | 100 |
| u(m/s) | 5 | 4 | 2 |
| $\eta$ | 20% | 25% | 30% |
| a(kGee) | 38 | 8.0 | 2.3 |
| v(km/s) | 3 | 3.5 | 6 |
| N | 5 | 1 | 1 |
| s(m) | 11.2 | 73. | 756 |
| E(kJ) | 30 | 1135 | 7670 |
| C(mf) | 0.27 | 1.42 | 0.47 |
| L(nh) | 74 | 310 | 1940 |
| NI(kA) | 1270 | 3820 | 3980 |
| T(°K) | 27 | 150 | 82 |
| $\lambda$(m) | 0.08 | 0.15 | 0.2 |
| z(m) | 0.12 | 0.29 | 0.71 |
| h(m) | 0.03 | 0.045 | 0.075 |
| stages | 280 | 1220 | 7560 |