ELECTROMAGNETIC LAUNCHERS FOR SPACE APPLICATIONS: COILGUNS FOR REPETITIVE LAUNCHING

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ABSTRACT

Electromagnetic macroparticle accelerators or electromagnetic launchers (EMLs) are frequently mentioned as a new approach to launching payloads into space, from earth, to interplanetary space propulsion ,or to test facilities for space applications.

The advantages of such EMLs are due to the fact that electromagnetic thrust forces are distributed over the entire space of the vehicle being launched, are substantially more controllable, and permit projectile velocities well beyond the ones achievable with explosives, because of the absence of some thermodynamic constraints.

This paper considers the idea that a solution to markedly improve the technology is to abandon the simple and coarse d.c. railgun in favor of a.c. polyphase induction coilgun launchers powered by heteropolar compulsators The theory of such a coilgun launchers is presented and an example of their conceptual design is given.

BACKGROUND

The old idea [1] of electromagnetic launchers (EMLs) has received new attention in the last two decades due to the fact that electromagnetic thrust forces can be distributed over the entire length of vehicles been launched, are substantially more controllable and permit projectile velocities well beyond the ones achievable with explosives. Under funding from DARPA and the U.S. Army, numerous applications of the EML technology have been reported at the EML Symposia held every two years.

While the vast majority of such papers concern a variety of anti-armor applications, due to the promise of hypervelocity defeating advanced armor, at virtually all of the symposia (beginning with the one in 1980 in San Diego, CA, up to the one in 1995 in Baltimore, MD), the theory that EML technology can provide a cost-effective means of launching and propelling material into space, thus opening the door to exploration of solar system and beyond, was advanced frequently [2, 3].

Several simplistic conceptual designs were performed in order to obtain a first-order calibration of the EML technology involved in achieving an orbital mission. In such a mission, almost the entire propulsion energy needed is provided by EML technology: the projectile is launched from the ground, travels to the atmosphere, and reaches its launch apogee at 200-800 miles for Low Earth Orbit (LEO) or even 22,000 miles for Geosynchronous Orbit (GEO), at which point it fires its circularization rocket.

Another study was performed by NASA Lewis Research Center [4] in conjunction with Battelle Columbus and employed a railgun system, having as a power supply a large number of homopolar generators and inductors distributed along the railgun. The mission of such an EML system was to dispose of nuclear waste by launching it into the solar system. The concept was to process spent fuel rods into a nuclear waste payload and launch the payloads from the earth's surface into the solar system.

A few years ago, a preliminary conceptual design of an electromagnetic accelerator (EMA) was performed at the Center for Electromechanics (CEM), The Univ. of Texas at Austin, under NASA Langley sponsorship [5]. This EML accelerator had a task of accelerating space vehicle models up to 10,000 Gees for studying their flight behavior in actual re-entry conditions (i.e. real velocities atmosphere, and pressures) in a proposed hypersonic real gas-free flight test facility. In the proposed system, the models, ranging in length from 0.1 to 0.6m, and in mass, from 5 to 10kg, were to carry complex measuring instrumentation. In the test, range altitudes from sea level to 120km and test atmospheres of air, nitrogen, and carbon dioxide were to be simulated - for a velocity of interest between 2 and 6km/sec with a possible extension to 11km/sec.

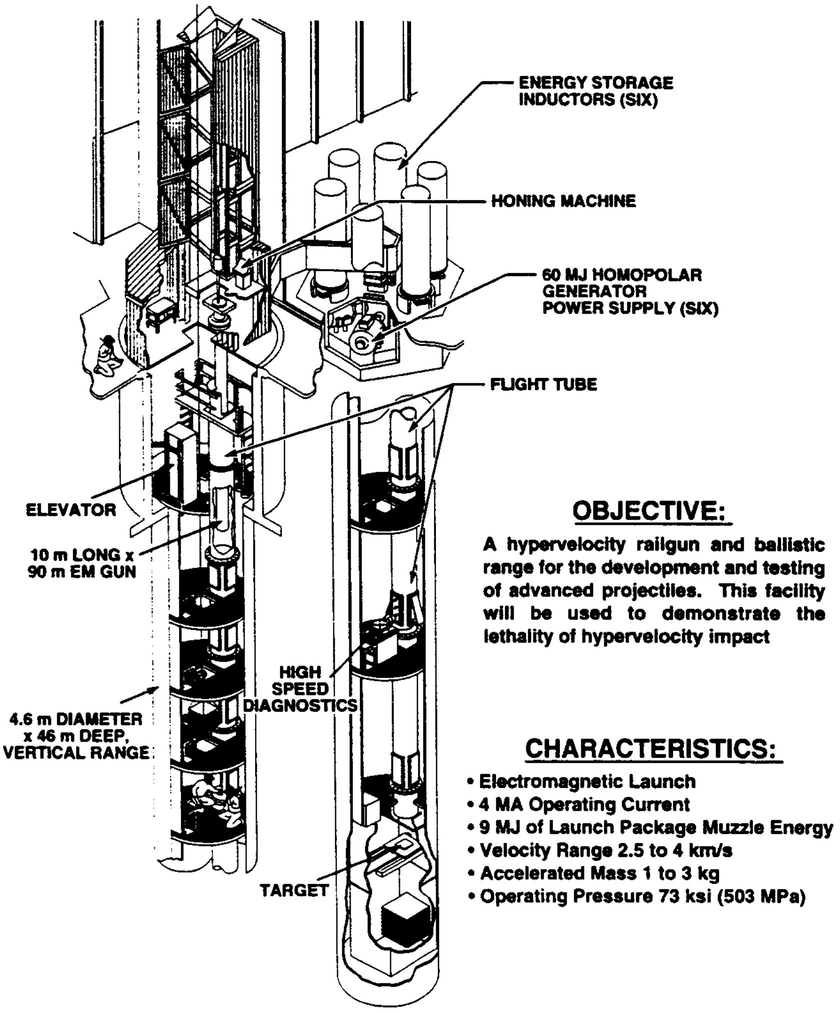
Both basic topological concepts for the accelerators were considered: the coilgun (heteropolar) principle and the railgun (homopolar) principle [6, 7]. The coilgun EML was designed to accelerate a 14 kg mass to a 6 km/sec velocity with the provision that by adding additional accelerator stages and the corresponding power supplies, a 10 kg mass will be accelerated to 11 km/sec. The railgun system was designed only to accelerate a mass of 14 kg to 6 km/sec.

This paper will outline the principle of the coaxial induction accelerators and will show the result of the preliminary conceptual design for such type of accelerator. It is the author's belief that for space applications, the induction coilguns are superior to the railgun EML. Presently, however, the railguns appear to be leading the competition between the two types of accelerators and there are several reasons explaining why they enjoy such popularity.

Railguns are the simplest of the EMLs and it is natural that they should be developed first. They undoubtedly benefit from the fact that virtually anyone with access to a laboratory can fabricate a small railgun which will accelerate a projectile. This advantage of simplicity is compounded by the scaling relationships for the two concepts. Whereas the inductance gradient of the railgun is essentially independent of scale, the comparable gradient for induction launchers is quite sensitive to it, improving dramatically in larger accelerators. Thus, it is quite difficult to build a small-scale coaxial launcher with impressive performance.

Moreover, the railgun, a homopolar accelerator, has had the benefit of the existence of the pulsed homopolar generator in conjunction with an inductor and an opening switch, an inherently compatible power supply that had been developed for other programs (fig. 1). The induction launchers enjoyed no such benefit and have suffered as a result. In fact, much of the effort expended on the development of coaxial accelerators to date, when viewed in this light, appears to have been directed toward forcing the accelerator to conform to existing power supplies.

In this paper, it is considered that the optimal power supply for a coilgun (a heteropolar accelerator) are heteropolar, rotating electrical machines of synchronous, pulsed types [8], in configurations capable of producing accelerated, linearly traveling magnetic fields [9, 10, 11].



OBJECTIVE:

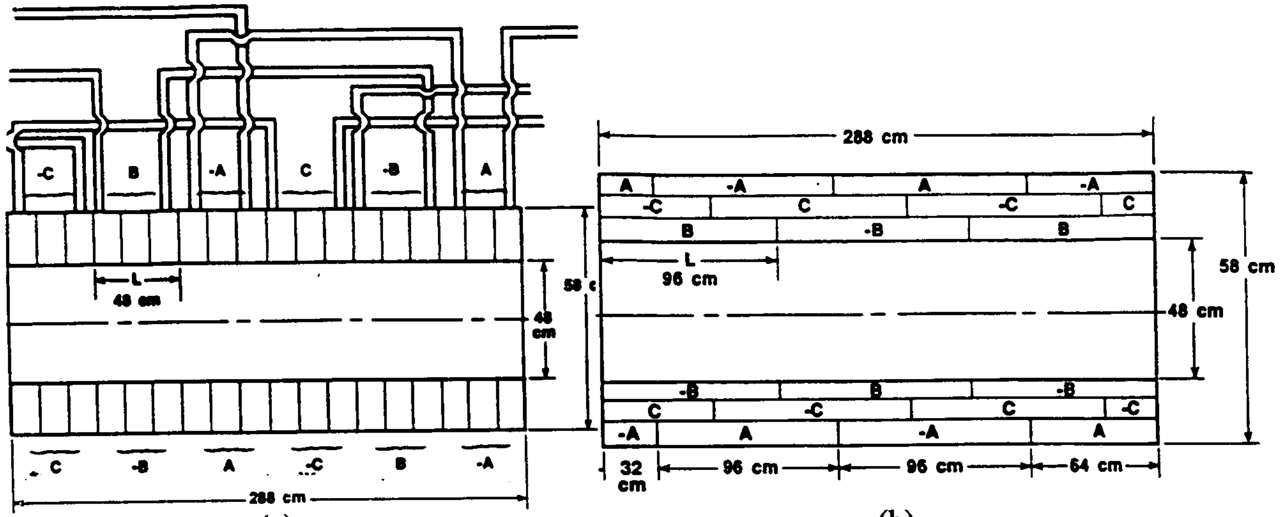
A hypervelocity railgun and ballistic range for the development and testing of advanced projectiles. This facility will be used to demonstrate the lethality of hypervelocity impact

CHARACTERISTICS:

- **Electromagnetic Launch**
- **4 MA Operating Current**
- **9 MJ of Launch Package Muzzle Energy**
- **Velocity Range 2.5 to 4 km/s**
- **Accelerated Mass 1 to 3 kg**
- **Operating Pressure 73 ksi (503 MPa)**

Figure 1. A laboratory railgun electromagnetic launcher (CEM, UT, Austin)

Figure 2 presents a segment of a stator winding of a coaxial launcher with identical coils. The stator winding is assumed to have a constant polar pitch τ. In the typical 3-phase winding of a conventional induction motor, the 3-phase system of currents energizing the stator produce a traveling rotating wave progressing with a speed:



(a) (b)

Figure 2. Segment of stator winding of a coilgun launcher: a) non-layered, b) layered.

$n_s = \dfrac{120f}{p}$ where n_s = synchronous rpm of the field wave (1)

f = frequency of the excitation current

p = number of poles.

In the tubular linear induction launcher in (fig. 2), the velocity of the magnetic field traveling down the launcher is:

$V_s = 2\tau f$ where V_s = traveling field velocity (m/s) (2)

τ = polar pitch (m).

f = frequency of the excitation currents (H_Z)

The velocity, V, can be controlled along the launcher barrel by varying either frequency, f, or the polar pitch, τ, or both. The need for controlling the velocity of the traveling magnetic wave in order to obtain an accelerating field wave arises from efficiency considerations.

From the theory of the conventional induction motor it is known that the efficiency for starting operation (expressed in energy terms) is less the 50%. For each unit of energy stored kinetically in the rotor, an equal or greater amount is dissipated in the Joule heating of the rotor by slip losses.

In exactly the same manner, a projectile accelerated from rest by a constant velocity traveling field will be subject to the same slip losses, which amount to W_{Pj}, for the entire launch period:

$$W_{Pj} = \int_{o}^{t} F_p s V_{TF} dt = m_p V_{TF} \int_{TF_o}^{t} s \frac{dv}{dt} dt. \tag{3}$$

Changing the integration limits:

$$W_{Pj} = m_p V_{TF} \int_{o}^{V_{TF}} \left(1 - \frac{v}{V_{TF}}\right) dv \quad \text{where:} \tag{4}$$

F_p = force applied to projectile (N)

m_p = projectile mass (kg)
V_{TF} = speed of traveling field (m/s)
v = instantaneous speed of projectile (m/s)

and $s = \frac{V_{TF} - v}{V_{TF}} \times 100 =$ slip (percent). (5)

Accelerating from rest to the speed of the traveling field and neglecting friction losses gives a minimum energy loss of:

$$W_{Pj} = m_p V_{TF} \left[v - \frac{v^2}{2V_{TF}} \right]_{o}^{V_{TF}} = \frac{1}{2} m_p V_{TF}^{\,2}. \tag{6}$$

Actually, the projectile does not reach the speed of the traveling field (fig. 3a) and the energy loss is given by:

$$W_{Pj1} = \int_{o}^{V_M} m_p (V_{TF} - v) dv = m_p \left(V_{TF} \bullet V_M - \frac{V_M^{\,2}}{2} \right) \tag{7}$$

where V_M = projectile output velocity (at the muzzle of the launcher).

For a two-staged system (fig. 3b) comprising two traveling field speeds, the energy loss decreases considerably:

$$W_{Pj2} = \int_{o}^{V_i} m_p (V_{TF1} - v) dv + \int_{V_1}^{V_M} m_p (V_{TF2} - v) dv. \tag{8}$$

If the intermediary speed $V_i = \frac{V_M}{2}$ and $V_{TF2} = 2V_{TF1}$, then $W_{Pj2} = \frac{m_p V_M}{2} \left(\frac{3}{2} V_{TF2} - V_M \right)$. (9)

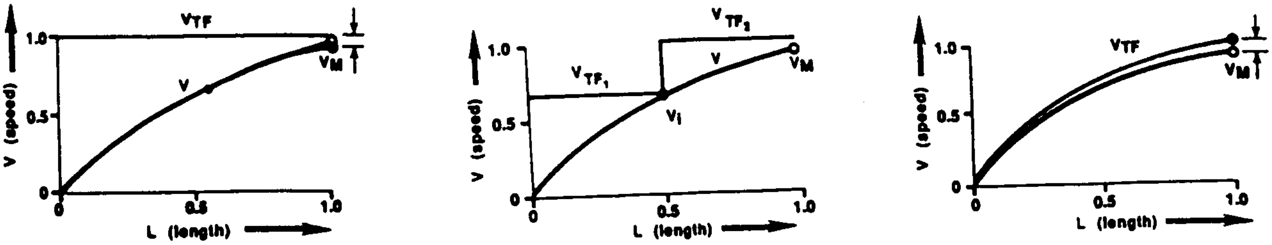
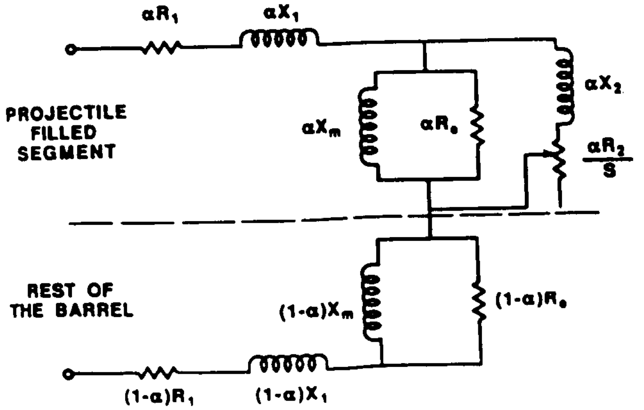


Figure 3. Influence of traveling field velocity change on the launch efficiency.
a) No change; b) Two-step change; c) Continuous change.

The number of stages can be further increased, improving the energy efficiency and reducing to a minimum the Joule loss in the projectile, (fig. 3c). At the limit, this corresponds to a continuous increase in the pole pitch or a continuous change in the frequency of the currents, producing a traveling field. The accelerating traveling field will ideally be followed closely by the projectile, keeping the slip and, consequently, the losses, at constant, low values. The manner of obtaining an accelerating field is to continuously vary the supply frequency. This way, the armature is accelerated down an essentially constant pitch stator winding, the driving frequency increasing with armature velocity. Of course, this is just the opposite of what happens in an alternator or compulsator as inertially stored energy is extracted. A combination of the two solutions above could be chosen - a pole pitch variation combined with a change in the power supply frequency.

ELECTROMAGNETIC PRINCIPLES

Eliminating the use of iron for the magnetic circuit permits an increase in electrical machine performance, especially for pulsed operation. For induction accelerators, this means that the analytical tools of equivalent circuits and the theory and methodology of design related to such tools must undergo significant modifications. The equivalent circuit variants (fig. 4) consider series and take into account both parts of the accelerators - the projectile filled segment and the rest of the barrel, which is many times longer. The first section of the equivalent circuit corresponds to the length of the projectile (neglecting all the edge effects), the second takes into account the rest of the barrel $(L - \ell)$ where, in addition to the energy loss in the stator, only reactive power is consumed.



Figures 4. Series equivalent circuit of the coilgun induction accelerator.

Using a similar treatment as in classical theory of linear induction motors [9, 10], in the short secondary variant, the accelerating force is:

$$F = \frac{\left(I_2^2 R_2 \bullet X_m^{\,2}\right)\left(\frac{\ell}{L}\right)}{V_s^2\left[\left(\frac{R_2}{S}\right)^2 + X_m^{\,2}\right]} \tag{10}$$

Optimizing the system for a maximum force-to-loss ratio, assuming a constant stator resistance, R_1, the value of the product between the force and the speed of the traveling field, FV_s, per unit stator loss results:

$$\frac{FV_s}{R_1 I_1^2} = \frac{\frac{\ell}{L} s \left(\frac{R_2}{R_1}\right)\left[1 + \left(\frac{Xm}{R_1}\right)^2\right]}{\left(\frac{L-\ell}{L}\right)\left[\left(\frac{R_2}{R_1} + s^2\right) + \left(\frac{R_2}{X_m}\right)^2\right] + \frac{\ell}{L}\left[s^2 + \left(\frac{R_2}{X_m}\right)^2\right]\left[1 + \left(\frac{X_m}{R_1}\right)^2\right]} \tag{11}$$

which can be optimized further by considering $R_2 X_m$ as a variable

where: R_1 and R_2 - resistances of the primary and secondary circuits
X_m = magnetizing reactance
s = slip
I_1 = stator current.

Onuki and Laithwaite [10] propose an optimization looking for the minimum stator length with the additional requirement of a permissible heat loss based on Euler-Lagrange's equations:

$$\frac{\partial}{\partial v_s}\left[\frac{m_p V}{2FR_2\left(\frac{1}{X_1} + \frac{1}{X_m}\right)V_{TF}\dfrac{(v_s - v)}{(v_s - v)^2 + \left[R_2\left(\frac{1}{X_1} + \frac{1}{X_m}\right)V_{TF}\right]^2}}\right] + \lambda\frac{\partial m_p(v_s - v)}{\partial v_s} = 0 \tag{12}$$

where: λ = Lagrange multipliers imposing the constraints mentioned above.

It has been shown that efficiency considerations exclude the use of an induction accelerator with uniform properties per unit length of stator. A continuously varying pitch, a continuously increasing supply frequency during the launch, or a combination of both requires changes in the use of the equivalent circuit as a tool for modeling of the machine properties. For a computer-based design, a time marching procedure, continuously changing the parameters of the equivalent circuit as the projectile advances through the barrel was used. Such an iterative procedure takes into account the influence of the transient processes produced by switching the symmetric system of voltages into the accelerator, and also the influence of parameter variations (supply frequency, reactances, polar pitch, resistance change due to field diffusion and temperature rise) [5, 11].

The stator winding is a three-phase tubular winding producing a traveling wave of magnetic flux along the barrel when energized. Usually, one phase of the stator winding is made of a series of alternatively polarized coils spaced apart at a distance equal to the polar pitch and producing alone a standing magnetic flux wave, which pulsates in time with the frequency of the sinusoidal current flowing through the winding. The succession and relative disposition of all three phases is shown in fig. 2a, which illustrates a segment of one of the barrel windings. Each phase coil has an even number of turns, half of direct, half of inverse polarity. The coils of all three phases produce the traveling field wave by superposition.

The serious disadvantage of the standard configuration winding with the interphase connections is that they form an additional outside structure, which the voluminous, and since the connections require the same cross-sectional area as the winding itself, the design of the bus structure is important. Also, the projectile following the traveling wave is subjected continuously to phase-to-phase electric potentials. Because of these drawbacks, the winding selected for design is a layered, distributed winding shown in fig. 2b.

Each layer (inner, middle, and outer) carries only one phase, and the total magnetomotive force (mmf) is obtained by superposition and by the choice of the phase angle between different layers. For a given segment of length *L*, the sum of different mmf's is:

$$mmf = \overline{B} - \frac{1}{3}\overline{C} - \frac{1}{3}\overline{A}. \tag{13}$$

The condition for a symmetric polyphase system of *mmf* is:

$$\overline{A} + \overline{B} + \overline{C} = 0, \text{ at any moment} \tag{14}$$

$$\text{then } \overline{B} = -\overline{C} - \overline{A} \tag{15}$$

or, substituting in the original relation for the winding segment of length *L*:

$$\overline{B} - \frac{1}{3}\left(\overline{C} + \overline{A}\right) = \overline{B} + \frac{1}{3}\overline{B} = \frac{4}{3}\overline{B}. \tag{16}$$

Comparing figs. 2a and 2b, it can be seen that the distance over which phase *B* is spread is twice as much in the distributed winding. Then for equal conditions, the resulting mmf of the traveling wave is only 4/3 X 1/2 = 2/3 or 66% of the original concentrated winding.

However, the loss of 1/3 of the mmf represents a favorable trade-off, not only for the elimination of complicated phase interconnections, but also for an easy manufacturing process. The windings for a phase run continuously, only the polarity being successively reversed. Insulation between phases is applied uniformly. The projectile traveling down the barrel sees along the stator a distributed voltage which, for all positions, is relatively small, requiring comparatively thin layers of insulation.

A PRELIMINARY COILGUN ACCELERATION DESIGN

The system shown in fig. 5 is comprised of a modular coaxial accelerator, each module being energized by its own pulsed electrical machine. The 14-kg projectile (sabot and payload) is accelerated at a constant acceleration of 10,000 gees, to an exit velocity of 6 km/s by the traveling magnetic wave produced by the currents in the three-phase stator. An additional requirement was to launch a similar projectile (14 kg) to almost double the velocity (11 km/s). Table I presents different options in which the second requirement can be accommodated.

Table I. Operating Envelope.

Exit Velocity (km/s)	Projectile Mass (kg)	Acceleration A (gees)	Launch Length (m)	Launch Time (ms)
6	14	10,000	188	61.2
11	14	10,000	620	112
11	14	18,333	336	61.2
11	14	32,800	188	34.4

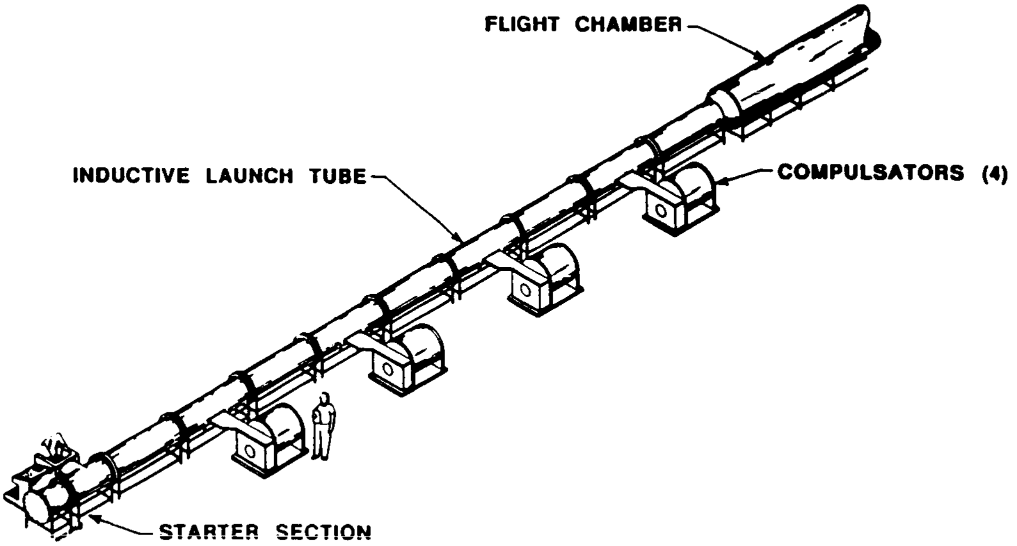


Figure 5. Schematic of a modular coaxial accelerator.

The last design option was chosen, such that the same accelerator is used to launch the 14 kg load at 11 km/s. Due to the modular construction of the barrel, only a small number of connections must be changed. In addition, the number of power supplies, their size, and frequency ratings must be increased.

The three main components of the system are: the launcher, the pulsed electrical machines representing the power supply, and the projectile. The launcher has a ideal length of 188 m and an actual length of 192 m, excluding the "starter coil" which is 1.2 m long and an end coil, 6 m long, the total length approaching 200 m. The standard unit coil which forms the base of the modular construction is 0.15 m long. For the 6 km/s variant, the accelerator is divided into four electrically independent, but magnetically series-connected, segments. Each part is 48 m long and has 14, 8, 7, and 7 segments, respectively, each segment having a different pole pitch in order to match the power supply instantaneous frequency with the velocity of the armature passing through each respective segment.

The power supply is configured of four compulsators storing 179, 211, 242, and 274 MJ. While the projectile is passing through the segment, only half of the stored energy is used. The frequency and voltage of the alternators drops to 70% of the initial value (for instance in the last stage, the frequency drops from 480 to 340 Hz). The current per elementary turn is maintained constant at 477 kA, the impedance dropping at the same rate as the voltage and frequency. The initial voltage of the machines varies from 8.73 kV for the first generator to 29.9 kV for the fourth one.

The above values for the currents and voltages are rms and per phase. Fig. 6 gives the diagram of the frequency and voltage variation for each compensated alternator in the discharge time for each of the parts of the launcher. At the bottom of the diagram, the energy stored by each compulsator is given.

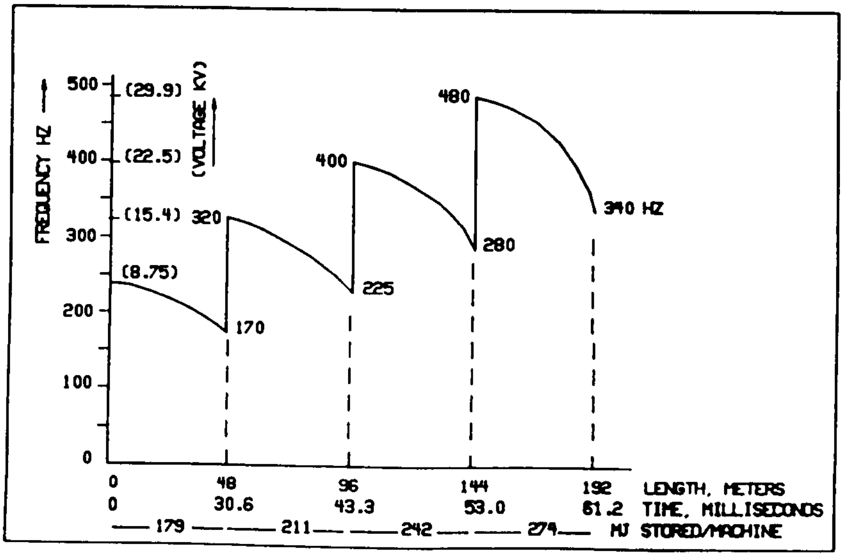


Figure 6. Diagram of frequency and voltage variation for the compulsators used for the modular launcher.

The armature is an aluminum shell. Provisions are made to initially cool the armature to liquid nitrogen temperature. A start-up coil will induce an initial current in the armature, thus assuring the maintenance of the "slip" and the corresponding losses at a reasonable value. When the mass of 14 kg to 6 km/s is accelerated, the exit kinetic energy of the projectile is:

$$W_p = \frac{1}{2} m V^2 = \frac{1}{2}(14)(6{,}000)^2 = 252 \times 10^6 J \qquad (17)$$

For constant acceleration of 10,000 gees = 98,000 m/s^2, the ideal length of the launcher is:

$$S = \frac{V^2}{2a} = \frac{(6{,}000)^2}{98{,}100} = 183.5 \ m. \qquad (18)$$

Connections between segments of the stator winding increase this length to 188 m. Additional starting coils and final segment extends the length to 196 m.

The launch time is:

$$t = \frac{V}{a} = \frac{6{,}000}{98{,}000} = 61.16 \times 10^{-3} s. \qquad (19)$$

The average axial force acting on the projectile in the direction of motion is:

$$F = ma = 1.373 \times 10^6 N. \qquad (20)$$

The need to induce the entire secondary current in the early moments of the launching requires the larger dimensions of the stator coils in the initial stages of the accelerator. A substantial reduction in the size of these coils is achieved by using a "starter segment" whose role is to induce the secondary current in the projectile just before launching.

ACKNOWLEDGEMENT

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