A Same-Scale Comparison of Electromagnetic Launchers

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Abstract— **A same-scale comparison of conventional railguns, augmented railguns, and helical launchers is presented and discussed. While the ideal launcher is always 100% efficient, practical launchers have an efficiency which is a function of the projectile velocity and a new parameter called the characteristic velocity. The characteristic velocity is the velocity needed for 50% maximum efficiency. The motivation for a same-scale comparison is an accounting for the velocity-dependent efficiency effect. The same scale concept states that launcher comparisons should be done on an equal bore diameter, launcher length, projectile mass, and velocity basis. Other parameters developed by the authors and included in the analysis, are the launcher constant and the mode constant that account for the launcher geometry and the mode of operation, respectively. The analysis uses experimental data collected by the authors with conventional railgun, augmented railgun, and helical gun launchers.**

I. INTRODUCTION

A broad range of applications has been proposed for electromagnetic launchers (i.e., EML's) including low/high/variable speed, small/mass, and single-shot/rep-rated systems. The state of EML technical knowledge is insufficient to address the majority of concerns associated with all these applications. For example, despite more than a century of research and development [1], it was only recently that general efficiency and scaling relationships were discovered for the EML [2]. It is natural to use energy conversion and volumetric efficiencies (acceleration per amp per volume) to evaluate an EML geometry. Efficient operation reduces pulse power supply size, primary power requirements, switching requirements, physical launcher size, support structure size, and cooling requirements, and leads to longer launcher lifetimes.

The EML's considered in this investigation are those with constant inductance gradient, including the conventional railgun, the augmented railgun, and the helical gun, all of which are illustrated in Fig 1. Efficiency and scaling relationships for constant gradient EMLs are derived from basic principles in this investigation. Force, efficiency, and scaling relationships are given in terms of circuit parameters such as inductance gradient, back-voltage, and system resistance and are, therefore, sufficiently general to be applied to any constant gradient EML geometry. Expressions for the back-voltage and kinetic power are also given and expressed in circuit parameter terms.

This investigation reports the efficiency of constant gradient EMLs is a function of armature velocity and a parameter called the *characteristic velocity*. The characteristic velocity, in turn, is the product of two other parameters called the *launcher constant* and the *mode constant*. The launcher constant reflects the geometry of the launcher, while the mode constant reflects the manner in which the EML is operated (or powered). Constant current and zero exit current operation modes are investigated. The characteristic velocity reflects both the operation mode and geometry of the launcher and, mathematically, is the launcher velocity needed for 50% maximum efficiency. The *ideal* EML is defined by 100% maximum efficiency operation, regardless of velocity.

Since efficiency is a function of velocity, launcher geometry and operating mode, the concept of *same-scale* comparisons is developed and states that bore diameter, bore length, armature mass, and armature velocity must be the same when comparing EML geometries. The same scale comparison of constant gradient EMLs is performed using new experimental data and data previously reported in the literature.

II. THEORY

A. Efficiency

A detailed theoretical analysis is beyond the scope of the present text but is given in [2]. The constant gradient EML electric-kinetic conversion efficiency is defined as the ratio of the output energy and the total input energy given as

$$\eta \triangleq \frac{W_k}{W_k + W_r + W_i + W_c + W_f} \tag{1}$$

where η is the efficiency, W_k is the kinetic energy, W_r is the resistive energy losses, W_i is the inductive energy stored or lost to commutation (all other inductive energy storage is assumed zero), W_c is the contact energy losses, and W_f is the friction energy losses. High efficiency results if the kinetic energy is much greater than the sum of the resistive, inductive, contact, and frictional energy terms. Assuming efficient sliding contacts and negligible frictional losses, (1) simplifies to

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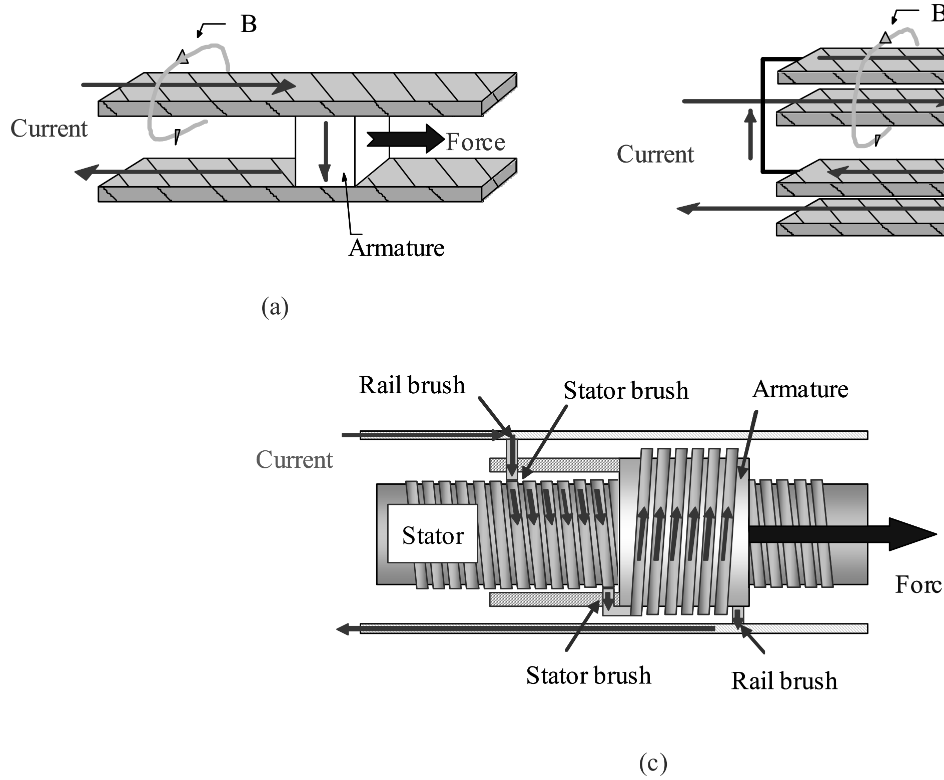

Fig. 1. The constant gradient EML geometry of the (a) conventional railgun, (b) augmented railgun, and (c) helical gun.

$$\eta = \frac{1}{1 + \frac{W_r}{W_k} + \frac{W_i}{W_k}} \quad (2)$$

In applying (2) to the EMLs of Fig 1, the way the launcher is operated determines its energy state and the substitutions for the terms in (2). Two modes of EML operation are considered: the constant current (i.e., CC) mode in which current is constant during the entire acceleration event interrupted only when the armature leaves the launcher, and the zero exit current (i.e., ZC) mode in which current is increased to a given level but is zero as the armature exits the launcher. The current can decay to zero naturally, as prescribed by the electrical circuit, or it can be forced to zero with an external circuit [3]. Mechanical methods physically interrupting current flow are not acceptable.

1) Constant Current Operation

In CC operation mode, the armature kinetic energy of the conventional and augmented railgun is given as

$$\begin{aligned} W_{krg} &= \frac{1}{2} L I^2 \\ &= W_{irg} \end{aligned} \quad (3)$$

where W_{krg} is the railgun kinetic energy and W_{irg} is the railgun inductive energy. Eq (3) shows that the railgun armature kinetic energy is equal to the inductively stored energy. Therefore, with $W_{krg} = W_{irg}$, (2) is reduced to

$$\eta_{rgcc} = \frac{1}{2 + \frac{W_{rrg}}{W_{krg}}} \quad (4)$$

where η_{rgcc} is the railgun efficiency in CC mode and W_{rrg} is the railgun resistive losses. Another expression for the railgun kinetic energy is given as

$$W_{krg} = \frac{1}{4} I^2 L' v_{\max} \tau \quad (5)$$

The resistive energy term in (2) is given by the definition

$$W_{rcc} \triangleq \int I^2 R dt = I^2 R \tau \quad (6)$$

where R is the total system resistance and assumed constant and W_{rcc} is the resistive energy losses. An average value can be used when the system resistance is not constant. Eqs (5) and (6) are substituted into (4) yielding the railgun efficiency

$$\eta_{rgcc} = \left(\frac{1}{2}\right) \frac{1}{1 + \frac{2R}{L' v_{\max.}}} \quad (7)$$

The helical gun is the next EML geometry to be analyzed and suitable expressions are sought for the terms of (2). In CC mode, the helical gun kinetic energy relationship is given as

$$
\begin{aligned}
W_{khg} &= MI^2 \\
&= W_{ihg}
\end{aligned} \tag{8}
$$

where W_{khg} is the helical gun kinetic energy and W_{ihg} is the helical gun inductive energy lost during acceleration. The helical gun efficiency expression, therefore, has a form similar to the railgun efficiency of (4), namely

$$
\eta_{hgcc} = \frac{1}{2 + \dfrac{W_{rhg}}{W_{khg}}} \tag{9}
$$

where η_{hgcc} is the helical gun efficiency in CC mode and W_{rhg} is the helical gun resistive losses. Another helical gun kinetic energy expression is found to be

$$
W_{khg} = \frac{1}{2} M' I^2 v_{\max} \tau \tag{10}
$$

Substituting (6) and (10) into (9) and rearranging terms yields the helical gun efficiency in CC mode as

$$
\eta_{hgcc} = \left(\frac{1}{2}\right) \frac{1}{1 + \dfrac{R}{M' v_{\max}}} \tag{11}
$$

2) Zero Exit Current Operation

The ZC operation mode simplifies some of the previous analysis since there will be no inductive energy storage in the launcher at armature exit. If the current decays to zero naturally, as prescribed by the L/R time constant of the system, the inductive energy will be used toward acceleration. If the current is forced to zero with the aid of an energy recovery circuit [3], the inductively stored energy is removed from the system and the efficiency equation. In both cases, $W_i = 0$ and (2) reduces to

$$
\eta_{zc} = \frac{1}{1 + \dfrac{W_r}{W_k}} \tag{12}
$$

where η_{zc} is the efficiency in ZC mode. The launcher velocity is not linear since the current is not constant, so the familiar kinetic energy expression

$$
W_k = \frac{1}{2} m v^2 \tag{13}
$$

must be used. The kinetic energy expression for the conventional and augmented railgun is given in this case as

$$
W_{krg} = \frac{1}{4} L' v \int I^2 dt \tag{14}
$$

The resistive energy definition of (6) with constant system resistance becomes

$$
W_{rzc} = R \int I^2 dt \tag{15}
$$

where W_{rzc} is the resistive energy in ZC mode. Substituting (15) and (14) into (12) yields the conventional and augmented railgun efficiency

$$
\eta_{rgzc} = \frac{1}{1 + \dfrac{4R}{L' v_{\max}}} \tag{16}
$$

where η_{rgzc} is the railgun efficiency in ZC mode. The substitution $v = v_{\max}$ is made since maximum efficiency is the only case of interest.

The efficiency for the helical gun EML operating in ZC mode is found by substituting the term $L' = 2M'$ in (16) to yield the final helical gun efficiency given as

$$
\eta_{hgzc} = \frac{1}{1 + \dfrac{2R}{M' v_{\max}}} \tag{17}
$$

III. Discussion

Examination of the railgun efficiency of (7) and (16) and the helical gun efficiency of (11) and (17) show that efficiency for these devices can be generalized to the expression

$$
\begin{aligned}
\eta &= \left(\frac{\mu}{4}\right) \frac{1}{1 + \dfrac{\mu\lambda}{v_{\max}}} \\
&= \eta_{\max} \frac{1}{1 + \dfrac{\mu\lambda}{v_{\max}}}
\end{aligned} \tag{18}
$$

where μ is a term reflecting the mode of operation ($\mu = \mu_{cc} = 2$ for CC mode and $\mu = \mu_{zc} = 4$ for ZC mode), λ is a term reflecting the launcher's geometry, and $\eta_{\max} = \mu / 4$ is the maximum efficiency. In this investigation, μ is termed the *mode constant*, and λ is termed the *launcher constant*. The launcher constant is the ratio of the system resistance and the inductance gradient. For conventional and augmented railguns the launcher constant is given as

$$
\lambda_{rg} = \frac{R}{L'} \tag{19}
$$

whereas for helical guns the launcher constant is given as

$$
\lambda_{hg} = \frac{R}{2M'} \tag{20}
$$

Eq (18) shows that efficiency is clearly a function of the armature velocity. Although velocity-dependent EML efficiency will be experimentally verified in the following section, it should not be surprising since rotational DC motors are known to be inefficient in the start-up process [4]. A similar scenario occurs for the EMLs in this investigation. There are two limiting cases of efficiency in (18) with respect to velocity, specifically $v = 0$ and $v = \infty$. At low velocity, EMLs are inefficient while at high velocity, EMLs approach maximum efficiency.

Low velocity and *high velocity* are relative to the product of the mode constant and launcher constant. Normalizing (18) with respect to $\eta_{\max}$ yields the normalized EML efficiency of

$$\begin{aligned}\frac{\eta}{\eta_{\max}} &= \frac{1}{1+\dfrac{\mu\lambda}{v_{\max}}} \\ &= \frac{1}{1+\dfrac{\sigma}{v_{\max}}}\end{aligned} \tag{21}$$

where $\sigma = \mu\lambda$ is termed the *characteristic velocity*. If $v_{\max} \ll \sigma$, the velocity is considered low and the efficiency is low. If $v_{\max} \gg \sigma$, the velocity is considered high and the efficiency is high. When $v_{\max} = \sigma$, the launcher operates at 50% maximum theoretical efficiency.

Low σ geometries are synonymous with high efficiency. Fig 3 plots the normalized efficiency of (21) versus velocity for $\sigma = 1, 10, 100, \text{and } 1000$. As can be seen in that figure, low σ launchers approach maximum efficiency more quickly than high σ launchers. The characteristic velocity can, therefore, be used to characterize the EML. The launcher constant λ can also be used to characterize an EML if one assumes a fixed operating mode (i.e, CC or ZC) and armature velocity.

The Fig 3 data also suggests that an *ideal launcher* is one that operates at 100% maximum efficiency, regardless of velocity. For example, a railgun or helical gun operating in CC mode at 50% efficiency would be considered an *ideal railgun* or an *ideal helical gun*. Although the ideal launcher

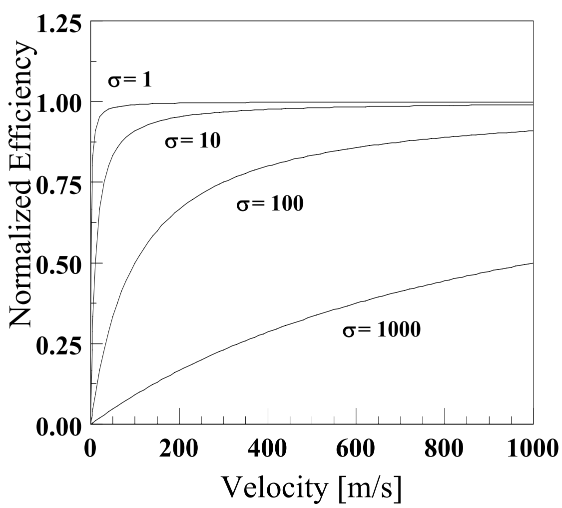

Fig. 3. Normalized efficiency versus velocity for various characteristic velocities.

may be difficult to achieve in practice, the Fig 3 case with $\sigma = 1$ is very close to ideal and is approximately 90% normalized efficient for $v \geq 10$ m/s. In comparison, a launcher with $\sigma = 1000$ must operate at 10,000 m/s for 90% normalized efficiency. A low σ EML geometry approximates the ideal launcher.

The main point of this section regards the process by which EML geometries are compared. From (21), the efficiency of a constant gradient EML is a function of both the armature velocity and the launcher's characteristic velocity. To factor in both electric-kinetic conversion efficiency and the physical size of the launcher (i.e., its volumetric efficiency), EML comparisons should be done with equal bore diameter, bore length, armature mass, and armature velocity. A comparison under these conditions is termed a *same-scale* comparison.

IV. Experimental Results

This section presents new and recently published experimental results by the authors with conventional railgun, augmented railgun [5], and helical gun EML geometries [5-8]. The first experimental data set is from a one-turn augmented railgun (ARG). The ARG launcher has a 40 mm bore diameter, 750 mm bore length, 350 gram armature mass and is powered by a single module pulse forming network (i.e, PFN) operating in ZC mode. Table I lists the PFN charge voltage, peak armature current, armature velocity, and measured electric-kinetic efficiency for each of the ARG experiments. Experimentally measured efficiency is given by

$$\begin{aligned}\eta &= \frac{W_k}{W_u} \\ &= \frac{\frac{1}{2} m v_{\max}{}^2}{W_0 - W_f}\end{aligned} \tag{22}$$

where W_k is the kinetic energy of the projectile, W_u is the total electrical energy used, W_0 is the initial electrical energy stored in the PFN, and W_f is any electrical energy remaining in the PFN that is not used.

The first part of the analysis is an examination of efficiency versus velocity using the ARG data from Table I. The measured efficiency and theoretical efficiency of (7) are plotted in Fig 4 versus velocity. The launcher constant used for plotting (7) is 300 [m/s] and is derived from static measurements of the inductance gradient ($L' = 1.2$ μH/m) and average system resistance (R =0.4 mΩ), although both of these parameters are known to vary during the experiment. As can be seen in Fig 4, the velocity-dependent efficiency effect predicted by (7) is clearly evident. The ARG efficiency increases with velocity. The theoretical results are in good agreement with the experimental data at low velocity. There is 16.3% error between the predicted and measured results at the highest velocity. While this error is acceptable, it is attributed to increased system resistance from joule heating or

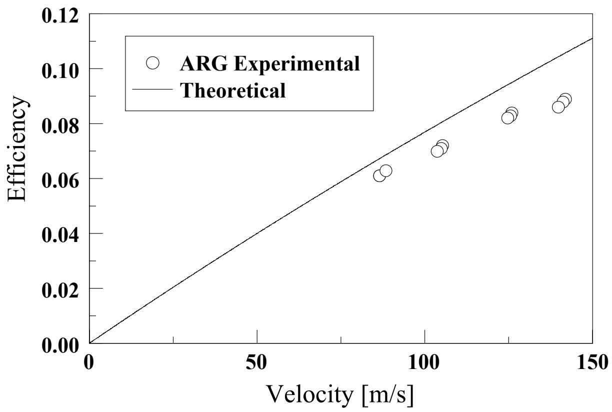

Fig. 4. Illustrating velocity-dependent efficiency for a one-turn augmented railgun.

decreased inductance gradient from high frequency skin effects. Both of these effects are present at high velocity because of the high current and because of the so-called velocity skin-effect [10].

The second part of the experimental data analysis is a comparative analysis of *same-scale* EMLs. Table II is a performance summary of a helical gun, a one-turn augmented railgun, and an ideal conventional railgun. Although there is some variation in the armature mass, the EMLs are considered same-scale with nominal 40 mm bore diameter, 750 mm bore length, 500 gram armature (i.e., projectile) mass, and 150 m/s velocity. Table II lists launcher specifications and experimentally measured data, as well as static measurements of the inductance gradient and average system resistance.

The LCG-6 and LCG-7 data of Table II are helical gun experiments conducted with mechanically identical armatures. The difference between the armatures is the LCG-7 armature is liquid nitrogen cooled to reduce its resistance, whereas the LCG-6 armature is room-temperature with no cooling. The liquid nitrogen cooling reduced the armature resistance from 8.0 mΩ to 1.3 mΩ, a factor of almost 8 [9]. The armature

TABLE I
AUGMENTED RAILGUN (ARG) EXPERIMENTAL RESULTS

Experiment	V_{charge} [v]	I_{peak} [kA]	v_{max} [m/s]	η
1.1	1700	204	86.4	0.061
1.2	1700	204	86.4	0.061
1.3	1700	204	88.4	0.063
2.1	1900	226	105.2	0.072
2.2	1900	226	104.9	0.071
2.3	1900	226	103.6	0.070
3.1	2100	255	125.8	0.084
3.2	2100	255	125.5	0.083
3.3	2100	255	124.7	0.082
4.1	2300	270	141.8	0.089
4.2	2300	270	141.2	0.088
4.3	2300	270	139.7	0.086

resistance decrease reduces the system resistance approximately 40% (the stator resistance constitutes approximately 50% of the system resistance). The σ and λ values are directly proportional to the system resistance and are similarly reduced.

The CRG data of Table II are from a simulation of an ideal conventional railgun. The ideal CRG simulation is frictionless, lossless, and powered with an ideal constant-current source. While constructing a launcher to meet these specifications would be difficult, the absence of same-scale railgun investigations in the literature dictated the need for the simulation. The CRG inductance gradient and system resistance are conservative estimates based on [11] and the authors' experience with the ARG.

Pulse power supplies for the LCG and ARG EMLs are capacitor based pulse forming networks (PFN's). The interested reader should consult [12] for PFN construction details. The V_{charge} data of Table II is the PFN charge voltage. The LCG-6 and LCG-7 experiments use an eight-module PFN and, therefore, have eight different charging voltages. The maximum and minimum module charge voltages are given in Table II. The ARG experiment used a single-module PFN, as stated previously.

TABLE II
ELECTROMAGNETIC LAUNCHER PERFORMANCE COMPARISON

Parameter	LCG-6	LCG-7	ARG	CRG
Bore diameter [mm]	40	40	40	40
Bore length [mm]	750	750	750	750
Projectile mass [g]	526	515	350	500
Inductance gradient [μH/m]	113	148	1.2	0.45
Operating mode	CC	CC	ZC	CC
R (min) [mΩ]	18.1	11.3	0.4	0.4
R (max) [mΩ]	21.9	12.1	2.0	0.4
R (avg) [mΩ]	20.0	11.7	0.4	0.4
λ [m/s] (Eq 19 or 20)	88	40	300	889
σ [m/s]	176	80	1200	1778
I_{peak} [kA]	12.4	11.5	270	183
V_{charge} [V]	300 to 550	250 to 550	2300	98
v_{max} [m/s]	137	164	141	150
Theoretical efficiency (Eq 9,11,16, or 17) [%]	21.8	33.7	7.2	3.9
Measured efficiency [%]	18.2	32.0	8.8	3.9
Efficiency error [%]	16.6	5.1	16.3	0.0

LCG = long (i.e., helical) gun; ARG = augmented railgun; CRG = simulated ideal conventional railgun. See text for complete description of experiments.

The Table II data show the LCG-6 and LCG-7 EMLs to have an inductance gradient more than 2 orders of magnitude greater than the ARG and CRG launchers. In addition, the σ and λ values for LCG-6 and LCG-7 are more than an order of magnitude lower than the ARG and CRG σ and λ values, which means the LCG will be more efficient at fixed velocity, a fact verified in Table II. LCG-6 and LCG-7 are the most efficient launchers in Table II at 18.2% and 32%, respectively, and are the most efficient ever reported at this scale. The agreement between theoretical and experimental efficiency is good with a maximum error of 16.6% and a minimum error is 0% (exact agreement) with these errors attributed to changes in the σ and λ due to joule heating and/or skin effects. Thom and Norwood [13] also postulate that commutation effects could lower the effective inductance gradient of helical coil launchers.

Table II also lists the V-I operating characteristics of the various launchers. The LCG peak current is more than 20 times lower than the ARG peak current while accelerating a 40% larger mass. The maximum LCG PFN charge voltage is approximately 3 times lower than the ARG voltage. This, however, is misleading, given that the ARG operates in ZC mode. The ARG charge voltage would be comparable to the LCG voltage if it were operated in CC mode.

The CRG current is 16 times higher than the LCG current. The CRG operating voltage (operating voltage is used instead of PFN charge voltage since the CRG is driven with an ideal current source) is a factor of 5.6 lower than the maximum LCG voltage. It is only a factor of 2.6 lower than the minimum LCG voltage. Caution is used when interpreting this result since the CRG is powered with an ideal current source. A system resistance increase of 1 mΩ would increase the operating voltage 183 V from ohmic voltage drop (since $I = 183\,\text{kA}$). Considering that current is constant, Joule heating could easily increase the resistance by this amount. Table II data show the CRG is the most inefficient launcher considered in this investigation. This is not surprising given its σ of almost 1800 m/s. The large current needed for this velocity would almost certainly cause significant joule heating leading to larger σ and λ and, ultimately, lower efficiency. The combined evidence suggests that low σ and low λ launchers can not only be operated at significantly lower currents, but at voltage levels that are slightly higher than (given an ideal power source), or comparable with, (given a non-ideal power source), low gradient launchers.

V. Summary

EML efficiency is a function of the armature velocity and the launcher's characteristic velocity. The characteristic velocity σ characterizes the launcher since it is the product of the mode constant μ and the launcher constant λ. The EML must operate at its characteristic velocity to achieve 50% maximum theoretical efficiency. The concept of an ideal launcher is developed in this investigation. The ideal launcher operates at 100% of its maximum theoretical efficiency at all velocities. A low σ or low λ geometry approximates the ideal launcher. This investigation also shows that EML comparisons should be done on a same-scale basis, meaning equal bore diameter, bore length, armature mass, and velocity. Same-scale comparisons account for both electric-kinetic conversion efficiency and volumetric efficiency.

A comparative analysis of a same-scale conventional railgun, augmented railgun, and helical gun is presented. The comparative analysis verifies that efficiency is a function of armature velocity and shows that low σ or low λ geometries, such as the helical gun, are many times more efficient than conventional and augmented railguns. Furthermore, the comparative analysis shows that low σ or low λ EMLs can operate at an order of magnitude lower current and with voltage comparable to, or slightly higher, than conventional and augmented railguns.

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