ELECTRIC PROPULSION APPLICATIONS IN PLASMA-DRIVEN ELECTROMAGNETIC RAILGUNS

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ABSTRACT

The effects of material ablated from rails, and the formation of secondary arcs are at present widely recognised to be the phenomena that hinder the expected performances of the plasma-driven railguns investigated.

In this paper the application of an external magnetic field on arc-driven railguns, in order to reduce the plasma armature length and consequently limit these parasitic effects, is proposed.

The analysis of the EAR (External Augmented Railgun) performances, and a comparison with the conventional and SAR (Series Augmented Railgun) behaviour is carried out. Furthermore some preliminary design criteria are given.

NOMENCLATURE

μ = Magnetic permeability in the vacuum
e = Electronic charge
V_i = Ionization potential
l_a = Arc length
h = Distance between the rails
w = Height of the rails
b = Thickness of the rails
l = Length of the rails
L' = Per unit inductance of the rails
ρ = Arc mass density
σ = Conducibility of the plasma arc
ρ_p = Pellet mass density
h = Planck's constant
σ_s = Stefan's constant
σ_r = Conductivity of the rails
K = Boltzmann's constant
m_a = Mass of the plasma arc
m_{ab} = Ablated mass
m_p = Mass of the pellet
m_e = Electron mass
m_o = Hydrogen atomic mass
n_e = Electron density
n_a = Atomic density
ν_{ei} = Electron ion frequency collision
ν_{ea} = Electron atom frequency collision
Q_{ea} = Electron atom collision cross section
α = Degree of ionization
T = Temperature
P = Pressure

INTRODUCTION

The arc-driven railguns are electromagnetic launchers capable of accelerating masses ranging from a few milligrams to several kilograms to velocities of several km/sec. As is well known, a railgun is substantially formed, see fig. 1, by two parallel rails that carry current to a solid or plasma armature behind the mass to be accelerated. Because of the electromagnetic force acting on it, the armature slides along the rails accelerating the mass. Some interesting applications that have been proposed for these devices, are those in the fields of nuclear fusion [1], [2], [3] and of space missions [4], [5].

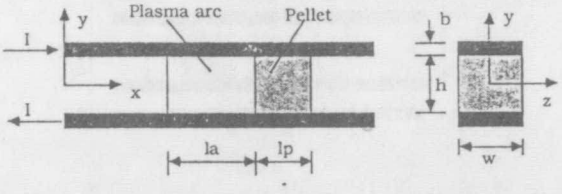

Fig. 1 Schematic draw of a railgun

The analysis of the several railgun experiments that have been carried out in these past years, shows that at velocities of up to 3 Km/sec the railgun behaviour is not significantly affected by parasitic effects. Nevertheless as velocity increases an acceleration decrement becomes more and more relevant so that, near 6 km/sec , the velocity ceases to increase. As a consequence of this fact the experimentally obtained launch speeds were all close to 6 km/sec independent of the delivered input energy or the rail length.

This limit is due to the interactions between the plasma armature and the rail and insulator walls. The plasma armature ablates material from bore walls, therefore a mass to be accelerated is added to the plasma arc and instability phenomena can occur so causing a plasma leakage from the rear of the armature. The region behind the armature is then filled with plasma, and the formation of secondary arcs shunts a part of current from the primary arc and significantly reduces the propulsive force.

The secondary conduction is proportional to the rail to rail voltage, and this voltage increases with velocity. Therefore, it seems that as velocity approaches 6 km/sec, this phenomenon causes a reduction of the propulsive force below the drag force.

Several approaches to the solution of these problems have been suggested, including the use of ablation resistant materials, the use of hybrid armatures, or the augmentation of conventional railgun by adding one or more additional rail turns, but none have demonstrated the possibility of completely overcoming the parasitic phenomena.

In this paper the application of an external magnetic field on plasma-driven railguns in order to have shorter armature lengths and consequently reduce the drag force and ablated mass effects is proposed. The analysis of the EAR performances, and a comparison with SAR and conventional railgun behaviour is then carried out.

RAILGUN AUGMENTATION ANALYSIS

Augmentation of railguns by adding one or more rail turns, see fig. 2, was proposed in order to reduce, for an equal accelerating force, the input current and consequently the power dissipation in the plasma armature and the rails.

The series augmented railguns must have a limited number of 2 or 3 augmenting turns because of the increased transverse force acting on the rails [6], and because the mechanical and electrical complexity introduced by the augmenting rails complicates the structural design of these systems.

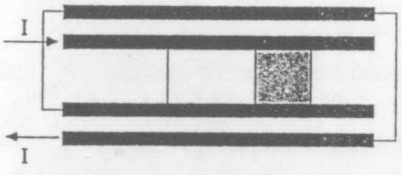

Fig. 2 Schematic draw of a Series Augmented Railgun

The performances of the experimentally investigated laboratory devices [7], [8] did not demonstrate any particular benefits compared to those of conventional railguns.

This lack of effectiveness can depend on the fact that the augmentor rails increase resistive losses even at reduced current values, as suggested by Kotas et al. [9], and that an ablation reduction does not eliminate secondary arc conduction, as shown in the experiments [10] carried out with low ablation ceramic insulators.

In order to reduce these hinderances we propose the application of an external magnetic field, see fig. 3, having the same direction of the self induced magnetic field of a conventional railgun.

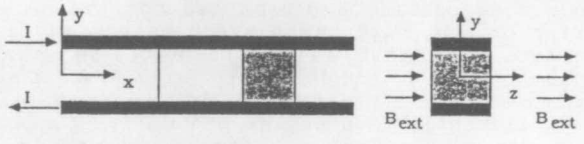

Fig. 3 Schematic draw of an External Augmented Railgun

A first evaluation of the EAR characteristics and a comparison with the behaviour of SAR and conventional railguns can be carried out considering a constant supplying current I_o, all the rail pairs as completely coupled magnetically and having the same inductance gradient L', and neglecting the plasma armature resistance with respect to the rail resistance.

The accelerating force on the armature can be found integrating J x B in the armature volume V. This force can be estimated considering, in the armature, a uniform distribution of the current density J and a constant magnetic field B obtained averaging the magnetic field B_b backward and B_f forward the armature.

Therefore for the SAR we have :

$$F_s = \int_V J \times B_{as}\, dV = (2n - 1)\, L' I_o^2/2$$

$$B_{bs} = nL'I_o/h \qquad B_{fs} = (n - 1)L'I_o/h$$

$$B_{as} = (B_{bs} + B_{fs})/2 = (2n - 1)\, L'I_o^2/2h$$

where h is the rail height and n is the number of augmenting turns, while for the EAR we have:

$$F_e = \int_V J \times B_{ae}\, dV = (L' I_o^2 + 2B_{ext}I_o h)/2$$

$$B_{be} = L' I_o/h + B_{ext} \qquad B_{fe} = B_{ext}$$

$$B_{ae} = (B_{be} + B_{fe})/2 = (L'I_o/h + 2 B_{ext})/2$$

where B_{ext} is the applied external magnetic field.

In order to carry out a parametric comparison of the performances of the two devices we define $B_{ext}h = mL'I_o$, where m is the proportional constant between the external field and the augmenting turn field. We have:

$$F_e = 2m (L'I_o^2) / 2$$

The breech voltage can be evaluated adding the Bhv term and the resistive voltage drop term V_r for each rail pair.

In Table I a comparison among some characteristic quantities of the SAR and EAR railgun for the same accelerating force is reported.

	Simple	SAR	EAR
Accel. Force	1	1	1
Input Current	1	$1/\sqrt{(2n-1)}$	$1/\sqrt{(2m)}$
Breech Voltage	1	$\sqrt{(2n-1)}+nV_r$	$\sqrt{(2m)}$

Tab. I Comparison of some characteristic quantities of conventional, SAR, and EAR railguns.

It is possible to observe that the EAR configuration allows:

- with respect to conventional railguns

a) an input current reduction, for the same propulsive force;

- with respect to SAR

a) an input current reduction of the same order of magnitude;
b) the absence of additional resistive losses in the augmenting turns;
c) a reduction of the breech voltage that could result in a less probable formation of secondary arcs;

It can be noticed that the EAR railgun needs a superconducting magnet to apply the high external magnetic field required to have good performances.

To evaluate the order of magnitude of the external field $B_{ext} = mL'I_o/h$, we consider a proportional constant $m = 1$, and typical values of $L' = .4\ \mu H/m$, $I_o = 500$ KA, and a bore of 1cm obtaining $B_{ext} = 20$ T.

A positive characteristic of the EAR configuration is the short plasma armature length that allows a reduction of the ablation and drag effects. In order to show this we will compare the performances of augmented and conventional railguns taking into account the plasma armature behaviour.

MODEL

For the analysis of EAR and SAR railguns, we have modified the formulation of a simplified model of the plasma armature [11] that takes into account the drag force, and considers the ablative effects adding all the ablated mass to the plasma armature, but neglects the secondary conduction phenomenon.

In that model we considered the part of plasma close to the pellet, where quite the whole arc mass is concentrated, and the pressure is nearly constant and equal to the pressure exerted on the pellet, as for the 'actual arc', thus assuming constant values for its characteristic quantities. Furthermore we assumed the following hypotheses (fig. 1) :

- Rails extended enough in the z direction so as to consider the magnetic induction B as having only a z-component.
- The arc current is uniformly distributed and is directed only in the y direction.
- The arc configuration is steady during the motion of the arc, and the plasma arc is in thermal equilibrium.
- Thermal exchange primarily by radiation.

On the basis of the previous assumptions and now considering augmented railguns with only one augmenting turn (n = m = 1) , the railgun model is expressed by the following equations:

- the electrical equilibrium equation of the equivalent electric network, see fig. 4

$$\frac{d}{dt}[(L_o + L'x + L_s + 2M_m(x))I] + (R_o + R'x + R_p + R_s)I + B_{ext}h\dot{x} = 0 \qquad (1)$$

where L_o is the external inductor, with resistance R_o , supplying the launcher, $L' = \mu h/2w$ is the per unit length inductance of the rails, modified in order to take into account the fact that the rails are not infinitely wide [12], $L_s = L'l$ is the self inductance of the augmented turn, l is the rail length, $R_p = h/(\sigma w l_a)$ is the plasma armature resistance, B_{ext} is the external field, and x is the plasma armature velocity.

The resistance of the augmented turn $R_s = 2l/(b\delta\sigma_r)$, and the per unit length resistance of the rails $R' = 2/(b\delta\sigma_r)$ are considered functions of the current density penetration depth [13] $\delta = (\pi t/\sigma\mu)^{\frac{1}{2}}$.

The mutual inductance $M_m(x)$, between the two turns of the SAR is calculated using the formulas of Grover [14] for go and return conductors of equal cross section, and is approximately one half of the difference between the inductance of the conductors together and apart.

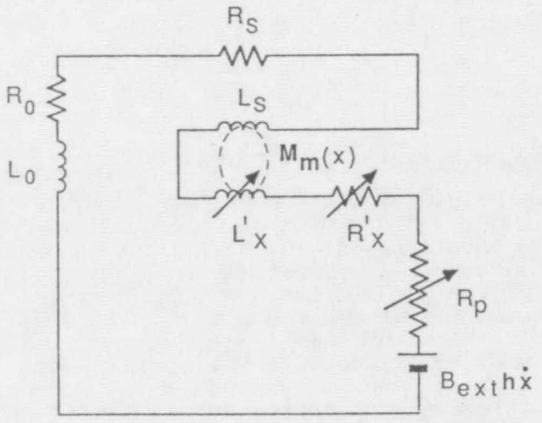

Fig.4 Equivalent electric network

It can be noticed that if $M_m(x)$, L_s and R_s are zero the model reduces to the EAR model, if B_{ext} is zero the model reduce to the SAR model, while if these parameters are all zero we have the conventional railgun model.

- The mechanical equilibrium equation

$$F = (m_p + m_a)\ddot{x} = \frac{L'I^2}{2} - \dot{x}\frac{dm_a}{dt} + - F_{Da} - F_{Dp} + F_e + F_s \qquad (2)$$

where $F_e = B_{ext}hI = L'I_oI$ is the force due to the application of the external field, $F_s = L'_sI^2/2 \doteq L'I^2$ is the force due to the augmenting turn, F_{Da} is the drag force on the plasma armature, F_{Dp} is the drag force on the pellet.

The term $\dot{x}\, dm_a/dt = ß\ I\ V_p$ takes into account the ablation effect at the barrel walls and depends on the ablation coefficients ß of the wall material , and on the arc voltage $V_p = R_p\ I$.

The drag force can be estimated [15], as $F_{Da} = Av^2m_a(w+h)/(wh)$, where $A = [\ 2\lg(a/(\delta_{aw})) + 1.74]^{-2}$, and $a/(\delta_{aw})$ is the ratio of the bore size divided by the bore roughness. For most smooth gun bores $a/(\delta_{aw}) = 4000$. Neglecting the drag force on the pellet [16] and substituting the previous relations, we obtain:

$$F = (m_p + m_a)\ddot{x} = \frac{L'I^2}{2}\left(3 + \frac{2I_o}{I} \right) - \dot{x}ß I^2R_p - A\dot{x}^2m_a\frac{(w+h)}{wh} \qquad (3)$$

- the equilibrium equations of the characteristic quantities of the plasma:

$$P = m_p\ddot{x}/(wd) = \mu I^2/[2w^2(1+\varepsilon)] \qquad (4)$$

$$P = \rho(1+\alpha)KT/m_o \qquad (5)$$

$$\frac{\alpha^2}{1-\alpha^2} = \frac{(KT)^{2.5}}{P}\left(\frac{2\pi m_e}{h^2}\right)^{1.5}\exp\left(\frac{-eV}{KT}\right) \qquad (6)$$

$$\rho = m_a/(whl_a) \qquad (7)$$

$$S_a = 2(wh+hl_a+wl_a) \quad (8)$$

$$S_a\sigma_s T^4 = \frac{hI^2}{\sigma w l_a} \quad (9)$$

$$n_e = \rho_a/m_o \quad (10)$$

$$\sigma = n_e e^2 /[m_e(\nu_{ea} + \nu_{ei})] \quad (11)$$

$$\nu_{ei} = 1.8\cdot10^{-6}\, n_e\, T^{-1.5}\, \ln\Lambda \quad (12)$$

$$\nu_{ea} = 6.21\cdot10^{3}\, n_a\, T^{0.5}\, Q_{ea} \quad (13)$$

$$\Lambda = 1.24\cdot10^{7}\, T^{-1.5}\, n_e^{-0.5} \quad (14)$$

The equations (1),(3)-(14) , were integrated with the initial conditions $I(0)=I_o$, $x(0)=0$, $\dot{x}(0)=0$, $m_a(0) = m_{ao}$, where we assume an initial arc mass $m_{ao} = .01\ m_p$.

The model was tested simulating the CEM-UT experimental results [15]. The arc was practically composed of material ablated by the rails and insulator walls, therefore, since the rail material has an ablative coefficient greater than the insulator [15] (3-4 times), a copper plasma was considered postulating only one possible ionization level. Simulated results in Fig. 5 show good agreement with the experimental data.

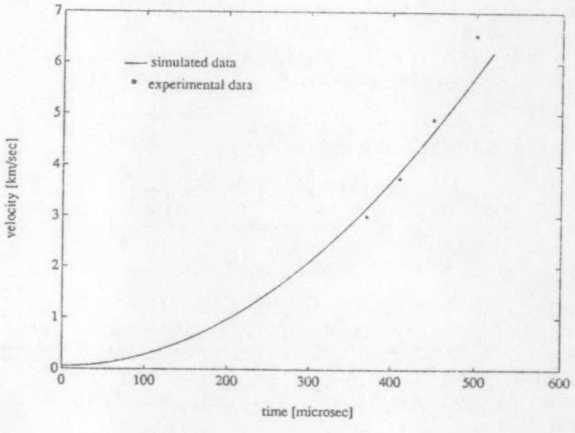

Fig. 5 Comparison between calculated and experimental data

RESULTS

We analysed how the external magnetic field influences the conventional railgun behaviour, and compared it to the SAR behaviour for equal accelerating force, for the two different railgun sizes shown in Table I and II

w = 5 mm	h = 5 mm
l = 2m	b = 10 mm
σ_r = .58· 10^8 $ohm^{-1}m^{-1}$	
L_o = 10μH	R_o = .3mΩ
m_p = 100mg	ß = 8 g/MJ

Tab. I - Small bore railgun parameters

w = 50 mm	h = 50 mm
l = 8m	b = 10 mm
σ_r = .58· 10^8 $ohm^{-1}m^{-1}$	
L_o = 60μH	R_o = 1.4mΩ
m_p = 5g	ß = 8 g/MJ

Tab. II - Large bore railgun parameters

In fig. 6, 7, 8 the comparison among the values of velocity, arc length, and ablated mass obtained with a propulsive force of 10^4 N, for small bore EAR, SAR and conventional railguns are reported.

Fig. 6 shows that the EAR railgun allows a significant improvement in the obtained maximum velocity. The SAR has low ablated mass of an EAR, see fig. 8, which means a lower ablative effect, but since it has a longer arc length, see fig. 7, it has stronger drag force effects and its performance is globally worse than that of the EAR.

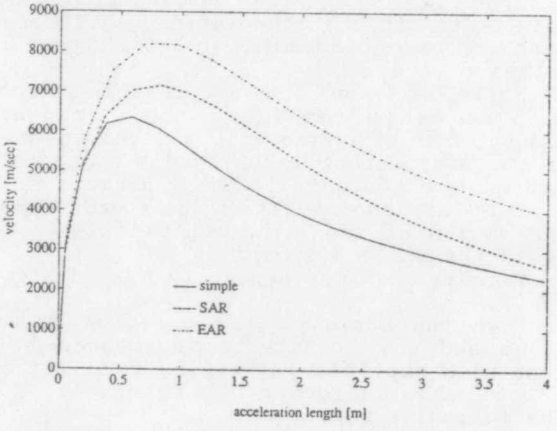

Fig. 6 Comparison among velocity vs. acceleration length of simple, SAR and EAR small bore railguns.

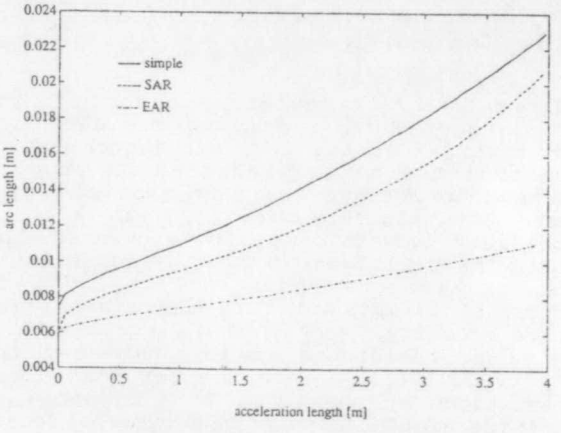

Fig. 7 Comparison among arc lengths vs. acceleration length of simple, SAR and EAR small bore railguns.

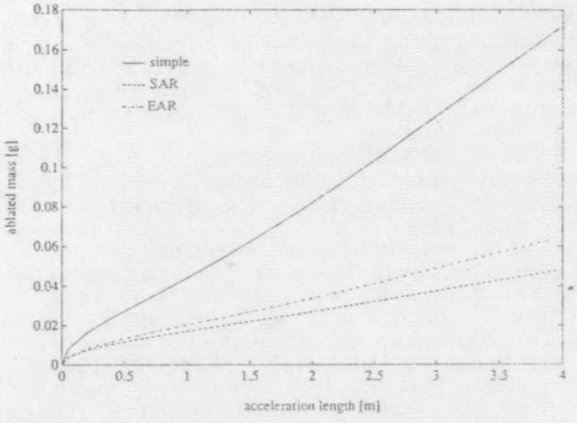

Fig. 8 Comparison among ablated mass vs. acceleration length of simple, SAR and EAR small bore railguns.

In the simulated data the SAR railgun reaches a higher velocity than the conventional railgun because it has a lower ablated mass. This trend, observed for several rail ablative and drag coefficients, does not correspond to the experimental observations and is probably due to the fact that, in the adopted model, the secondary conduction effects have been neglected.

The velocity decreases beyond the acceleration length correspondent to the maximum velocity, hence the indication of the rail length at which a given speed is reached can help for design of the rail length in order to have the correct final speed. In fig. 9 the acceleration length that gives 6.5 km/sec is reported for different propulsive forces.

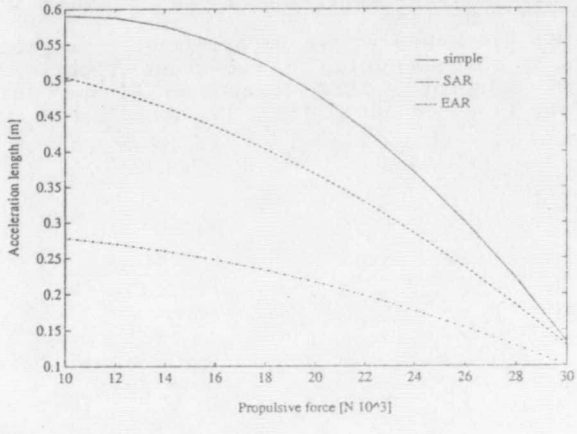

Fig. 9 Comparison among acceleration length in order to have 6.5 km/sec vs accelerating force of simple, SAR and EAR small bore railguns.

In fig. 10, 11, 12 the comparison among the values of velocity, arc length, and ablated mass obtained with a propulsive force of 10^4 N, for large bore EAR, SAR and conventional railguns are reported.

The figures show that for this bigger railgun bore size the differences among the final velocities of the examined railguns are less evident even if the trend of the

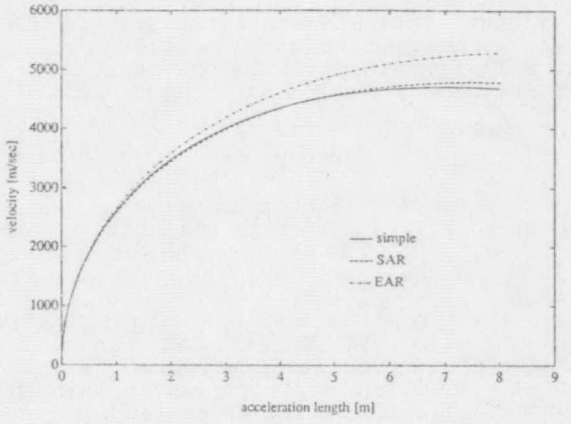

Fig. 10 Comparison among velocity vs. acceleration length of simple, SAR and EAR large bore railguns.

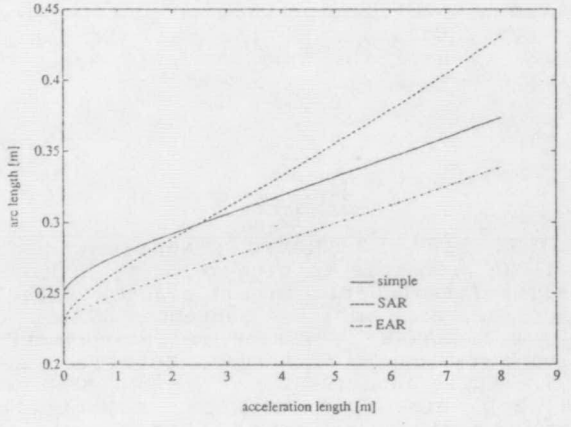

Fig. 11 Comparison among arc length vs. acceleration length of simple, SAR and EAR large bore railguns.

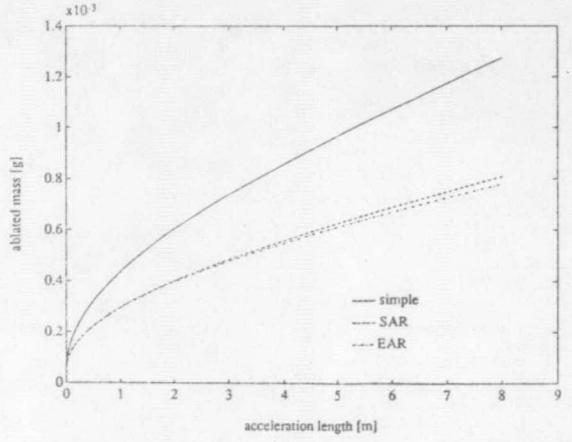

Fig. 12 Comparison among ablated mass vs. acceleration length of simple, SAR and EAR large bore railguns.

different quantities remains the same as the previous case. The velocities of SAR and conventional railguns are nearly the same because the SAR has a less ablated mass, see fig.12, but has a longer arc length, see fig. 11, than conventional railguns. This means less ablative effects but a stronger drag force and a similar overall behaviour of the two railgun configurations.

CONCLUSIONS

The application of an external magnetic field on plasma-driven railguns in order to limit the parasitic phenomena that influence railgun performances was proposed.

The proposed railgun configuration reduces the arc length and limits the ablative and drag force effects, allowing one to reach better performances than with conventional and Series Augmented railguns.

The benefits of the external field application are significant for small bore railguns, while for large bore railguns the EAR, SAR and conventional railguns have similar performances.

The velocity decreases beyond the acceleration length correspondent to the maximum velocity, hence a preliminary design indication of the rail length in order to have the correct final speed is given.

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