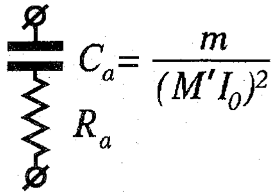

Fig. 2. Starting-point of an equivalent electric circuit for the armature of a special augmented railgun.

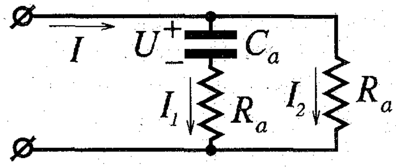

Fig. 3. The most rough simplified equivalent electric circuit of a real railgun armature.

[20], [21] is equivalent to the leakage of our "capacitor" even in the absence of any mechanical losses, so we should add one more ohmic resistor to our equivalent circuit of the armature (Fig. 3).

This analysis can be applied for the simple railgun as well, although in that case the propulsion force equals

$$F_{pm} = {}^1/_2 L' I^2 \propto I^2 \tag{8}$$

and the kinetic energy has the form of

$$K = \frac{L'^2}{8m}\left(\int I^2 dt\right)^2 . \tag{9}$$

The only difference is that the armature of a common railgun behaves as an effective "variable capacitor" with the energy of

$$K = \frac{q^2}{2C(t)} = \frac{L'^2}{8m}\left(\frac{\int I^2 dt}{\int I\, dt}\right)^2 \cdot q^2 \tag{10}$$

and time dependent capacitance value of

$$C(t) = \frac{4m}{L'^2}\left(\frac{\overline{I}\,\Delta t}{\overline{I^2}\,\Delta t}\right)^2 \approx \frac{4m}{\left(L'\,\overline{I}\right)^2} \tag{11}$$

where $\overline{I}$ and $\overline{I^2}$ are the average values of current and current square during the chosen time interval Δt .

As in the case of the special railgun, the effective "capacitance" of a simple railgun, within the order of magnitude, turns out to be equal to the accelerated mass divided by square of the linear magnetic flux in a rail circuit. In both systems, as a result of current flowing, we get some armature velocity and consequently back emf increase. In other words, as a result of a charge passing through the rail circuit and the armature we get a voltage increase; this allows us to characterize the armature of any railgun as some effective "capacitor".

It is obvious that the circuit in Fig. 3 still remains extremely rough because it does not allow for the gradually decreasing voltage drop along the armature which has been measured in real experiments. A more sophisticated approximation should contain a multi-cell circuit, ideally infinite, with appropriately chosen different values of "capacitors" and resistors in each elementary cell (Fig. 4). It is also possible to use sources of back emfs instead of capacitors; for total equivalence each emf value should be equal to the charging voltage of the corresponding capacitor.

Both variants of circuits represent only a single layer of the armature, so the total circuit should be a 3-D multi layer structure with a cubic elementary cell comprised of 4 capacitors (or sources of emf, as it was proposed in [24]) and 12 resistors. But even a single layer equivalent circuit (Fig. 4) allows us to visualize the dynamics of kinetic energy acquisition in a railgun launcher.

Suppose the total armature current remains constant and each part of the armature has the same velocity. In such a case we get the difference of back emfs (or capacitor charging voltages) in each elementary contour of the equivalent circuit growing with the increase of armature velocity (Fig. 4). So the higher the velocity, the higher additional currents in horizontal resistors (along the armature). As long as the total current and propulsion force remain the same, the velocity increase gives rise to an increase in the fraction energy put into Joule heating, which, from an energy point of view, is equivalent to the increase in drag force. This conclusion is more apparent if we look at the single 2-D cell which is equivalent, from a viewpoint of electrical connections, to the circuit represented in Fig. 3. If we charge our shunted "capacitor," the relative role of working current "leakage" should increase with the capacitor voltage increase. What is more, for given values of resistors and total working current I, there exists a maximum possible charging voltage, (and in the case of moving armatures, a maximum velocity) when the current I_1 through capacitor becomes zero (Fig. 3).

The methods of analysis by means of equivalent circuits also remains valid for any real railgun. Action of friction and other nonelectric losses simply lower the value of acquired kinetic energy and increase the rate of its dissipation. These effects can also be treated as an increase of capacitor "leakage," and can be taken into account by appropriate choice of smaller effective values of shunting resistors compared to the previous idealized (non-frictional) case.

IV. Simple estimations of an electromagnetic drag force

Unfortunately, the precise magnitude of the electromagnetic drag force discussed here cannot be obtained either by direct measurements, or analytically. So, for qualitative analysis, we offer a simple analytical expression as a first

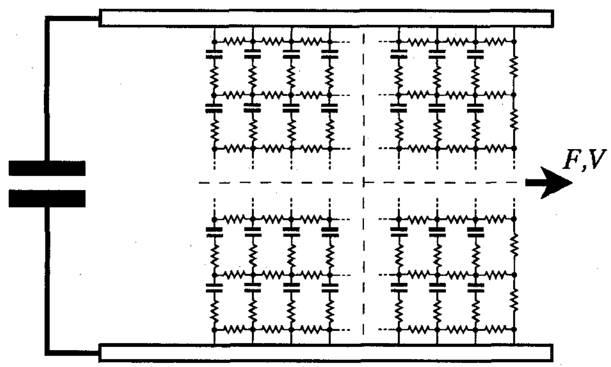

Fig. 4. More detailed 2-D equivalent circuit of a simple railgun armature.

order correction to the ponderomotive force at low values of armature velocity and analyze what physical parameters of a railgun play an important role in this undesirable phenomenon.

Consider the armature as a rigid rectangular frame moving with the velocity of V and each side of the frame has the ohmic resistance of R_a. For a simple railgun, the back emf equals 0 at the front edge and $L'VI$ at the rear edge of the armature. This difference brings about additional circular current

$$\Delta I \approx \frac{\Delta E}{4R_a} = \frac{L'VI}{4R_a}. \tag{12}$$

The magnetic field induction, B, equals $\frac{L'I}{l}$ at the rear edge of the armature (l is the distance between rails) and 0 at the front edge. From this, one can easily obtain the expression for total drag force:

$$F_{dr} = \Delta B\ \Delta I\ l \approx \frac{L'I}{l}\Delta I\ l = {}^1\!/_2 L'I^2\ \frac{L'}{2R_a}\ V. \tag{13}$$

So the relative role of such an electromagnetic drag force equals

$$\frac{F_{dr}}{F_{pm}} = \frac{L'}{2R_a} \cdot V. \tag{14}$$

This calculation implies that all eddy currents are localized just inside the armature and neglects the magnetic field of armature itself. This analysis is not appropriate for the case of thin solid armatures when the fraction of eddy currents in the rails becomes significant or even dominant in the resulting electromagnetic drag. But as long as we are able to get a rough value within an order of magnitude, even maximum possible deviations from assumed physical conditions in real devices are not of a major importance.

In case of a common railgun with independent augmentation [22], [23] we get the same value of back emf difference

$$\begin{aligned}\Delta E &= E_{b\ rear} - E_{b\ fr} = \\ &= L'VI + M'VI_0 - M'VI_0 = L'VI\end{aligned} \tag{15}$$

and consequently exactly the same as obtained in earlier (12) and (13) for the values of eddy current and electromagnetic drag force respectively. So the ratio of electromagnetic drag and ponderomotive force determined by (3) equals

$$\frac{F_{dr}}{F_{pm}} = \frac{{}^1\!/_2 L'I}{{}^1\!/_2 L'I + M'I_0} \cdot \frac{L'}{2R_a} \cdot V. \tag{16}$$

All the expressions for drag forces can also be derived independently from energy balance in equivalent circuits. Assuming exactly the same conditions as in the previous derivations, (constant discharge current, rigid armature, and the shape of square frame) all values of resistors of the equivalent electric circuit are equal to R_a.

For the armature at rest, the application of Kirchoff's law results in the following relationship between the current values (see Fig. 5a):

$$I_1 \cdot R_a = I_2 \cdot 3R_a. \tag{17}$$

In the case of the armature in motion, when the equivalent capacitor is charged to $L'VI$ (Fig. 5b), we get the same value for the circular eddy current as obtained in our previous estimations:

$$\Delta I = \frac{L'VI}{4R_a}. \tag{18}$$

So, in comparison with the stationary case the additional power of Joule heating is equal to

$$\begin{aligned}N &= \left((I_1 - \Delta I)^2 - I_1^2\right) R_a + \\ &+ \left((I_2 + \Delta I)^2 - I_2^2\right) 3R_a = \frac{(L'VI)^2}{4R_a}.\end{aligned} \tag{19}$$

Using the well known relationship between the power and the corresponding force $N = F \cdot V$, i.e. in our case

$$N = F_{dr} \cdot V = {}^1\!/_2 L'I^2 \cdot \frac{L'}{2R_a} \cdot V^2, \tag{20}$$

we get for electromagnetic drag force exactly the same as obtained in (13).

Analogous expressions for the drag force and its ratio to the propulsive ponderomotive force can be easily obtained in a similar manner for other basic railgun schemes [22].

V. Discussion

All the expressions for the ratio of electromagnetic drag and ponderomotive force have the form of

$$\frac{F_{dr}}{F_{pm}} = \frac{V}{V_*} \tag{21}$$

where V_* is the combination of parameters with the dimension of velocity. With due regard for all said above we use for further analysis the expression of V_* as a rough approximation for the maximum attainable velocity.

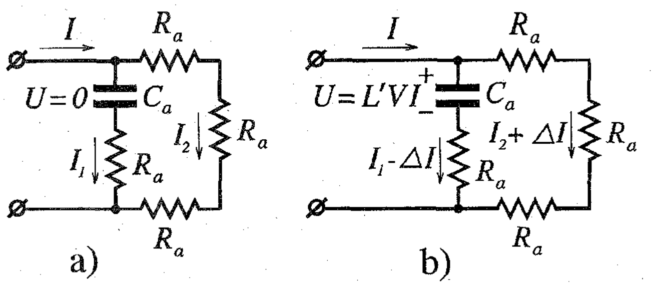

Fig. 5. Current distribution in a stationary (a) and moving (b) railgun armature.

To accelerate a projectile in any railgun scheme and armature type it is necessary to create a gradient of magnetic energy density $\Delta\left(\frac{B^2}{2\mu_0}\right)$, where $\mu_0 = 4\pi \cdot 10^{-7}$ H/m, which determines the value of a propulsive ponderomotive force

$$F_{pm} \propto B \cdot \Delta B \propto B \cdot I. \tag{22}$$

The drag force due to eddy currents is proportional to

$$F_{dr} \propto \Delta B \cdot \Delta I \propto (\Delta B)^2. \tag{23}$$

The ratio of drag and propulsive ponderomotive force is always proportional to

$$\frac{F_{dr}}{F_{pm}} \propto \frac{(\Delta B)^2}{B} \cdot \Delta B = \frac{\Delta B}{B}, \tag{24}$$

that is augmentation should decrease the relative role of electromagnetic drag and increase the maximum attainable velocity [25].

For a common railgun the value of maximum velocity turns out to be proportional to

$$V_* \propto \frac{2R_a}{L'}. \tag{25}$$

According to the equation, the higher resistance of plasma armatures compared to solid ones results in higher maximum velocities of projectiles ([9], [10], [26]–[28] for example). Even higher velocities in "free-arc" tests (see [29] and [30] for example) can also be explained from viewpoint of eddy currents generation. The absence of a projectile results in a lower plasma density [29], which corresponds not only to lower viscous friction but also lower electric conductivity as well (see, for example, [31]).

Analysis of 3 basic railgun schemes by both the method of analytical expressions and equivalent circuits demonstrates the advantage of railguns with a "traditional direction" of current supply (simple or augmented [22]). The tendency for the discrepancy increase between estimated and obtained velocities in railguns with two-sided current supply, in spite of high stability and compactness of plasma armature even at the descending branch of discharge current [32], is explained here by a higher contribution from electromagnetic drag for this electromagnetic configuration.

In all previous estimations we considered the armature as a rigid body and calculated the total drag force as a difference between backward additional force acting on the rear part and forward additional force on the front part of the armature. But in the case of plasmas we do not deal with a rigid body, so nonuniform force distribution causes a relative lagging of the back of the armature resulting in separation of the plasma with formation of distinct discharges. The effects of eddy currents explains the formation of secondaries even in the absence of a conductive erosion tail [17], [33], [34]. The same explanation, as a partial case of our general approach, was suggested by Calvin and Virostek on the basis of Lorentz force distribution derived from experimental data for a plasma armature railgun but they did not identify the nature of the drag force [21].

The basis problem of high velocity sliding contact [35]–[37] may also be associated with the increase in voltage gradient along the armature as the velocity increases. The maximum values of eddy currents, both in rails and the armature, are near the interface boundary where we get the maximum value of heat release. At some threshold voltage difference, determined by velocity, melting must occur, creating degraded electric contacts which results in a sharp increase of the muzzle voltage, formation of arcing contact, and decrease of the acceleration efficiency (see [35]–[37] for example).

We believe that all aspects of performance loss in previous railgun experiments can be explained by the phenomena of eddy currents generation and associated electromagnetic drag.

VI. Conclusions

Generally accepted expressions for electromagnetic force in railguns (such as (3) and (8)) are valid only for the armature at rest and tend to overestimate the value of propulsion force after the acceleration process had started [18]. Necessary corrections can not be represented by analytical expressions and must be obtained by detailed 3-D nonsteady simulations for each particular case.

We see no way of eliminating electromagnetic drag entirely. In our opinion, neither power source optimization, nor application of sectioned or thin metal armatures, nor application of railgun schemes with different directions of current supply will result in any considerable improvement of the kinetic energy acquisition in a macroparticle acceleration process.

As it follows from our analysis, there exist only two more or less practical ways of increasing the efficiency of a railgun: to increase the specific resistance of armature and to organize the acceleration of a relatively low armature current in a very high external magnetic field similar to that described in [25]. However, the magnitude of a field necessary for the acceleration of massive projectiles to hypervelocities is far larger than experimentally practiced. Even in the case of a destructive railgun, which operates at enormous magnetic fields, the total time at which the projectile is accelerating is insufficient to achieve the highest velocities. Use of high resistance armatures is questionable because high resistance inevitably increases the power of Joule heating and consequently the thermal load inside the barrel.

A full assessment of the performance of railgun devices requires an accounting of all the numerous performance loss mechanisms (see [13]–[17], [33], [34], [36] for example). However, even ignoring all of the other effects, the effect of electromagnetic drag alone may fundamentally limit the efficiency and ultimately the maximum velocity of railgun armatures.

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