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INDUCTIVELESS RAIL LAUNCHERS FOR LONG PROJECTILES

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The paper presents rail launchers having substantially higher efficiency than railguns and much lower mechanical stresses in projectiles and launch tubes.

Based on novel – inductiveless – architecture, which is especially effective for long projectiles, these launchers promise a number of weighty advantages such as:

- Order of magnitude lower rail-to-rail repulsion, resulting in lightweight launch tubes
- No sabots, armature mass share only 25 – 35%
- Suppressed velocity and transient skin effects
- Low stress acceleration of launch packages by forces spread over long armatures
- Negligible parasitic inductive energy – no muzzle flash, no need for energy recovery
- Launch efficiency – ratio of launch package muzzle energy to supplied energy – up to 70%
- Net launch efficiency – similar ratio for in-flight projectile only – up to 50%
- No need for forced cooling of launch tubes due to significantly reduced energy losses

INTRODUCTION

The days of cannon balls are long over. Most in-flight projectiles have large length-to-diameter ratio. For heavy metal rod penetrators, for example, this ratio reaches 20-30. Long projectiles with small cross sections have better ballistic properties, increased range and armor penetration. However, such projectiles are hard to accelerate in powder or other gas guns without sabots adjusting them to larger caliber bores, as the driving force exerted by gas pressure is proportional to the bore cross-section area. Sabots also distribute the driving force (applied to the rear surface of the launch package) over the length of the projectile, thus reducing axial stress in slender projectiles to an allowable level. The downside of the use of sabots is significant parasitic mass they introduce into launch packages – a portion of the launch package muzzle energy associated with it is wasted when the sabot is discarded.

When railguns drive projectiles with metal armatures, magnetic pressure works quite similar to gas pressure. Two key factors – the velocity skin effect and transient skin effect – are responsible for this similarity, because they tend to localize the current and the driving force at the trailing end of the armature. Unsurprisingly, railguns accelerate slender projectiles by using the same subcaliber technique as gas guns – inserting them in larger diameter integrated sabots/armatures to increase their cross section and distribute the force.

In principle, EM launchers could accelerate such projectiles in a quite different mode – without sabots and, nevertheless, with low axial stress – if **jxB** forces could be well spread lengthwise over thin and long armatures, potentially as long as the projectiles (see Fig.1).

So far this remarkable potential of electromagnetic acceleration has remained unrealized. While long armatures could be readily designed for most projectiles, railguns cannot use them to advantage because of the factors mentioned above.

The inductiveless rail launchers presented here enable this highly desirable mode of acceleration. They also provide two additional benefits – radical reduction of repulsion force between the opposite rails in the launch tube, and substantial – 2-2.5 times – increase in the net launch efficiency as compared to the state-of-the-art railguns.

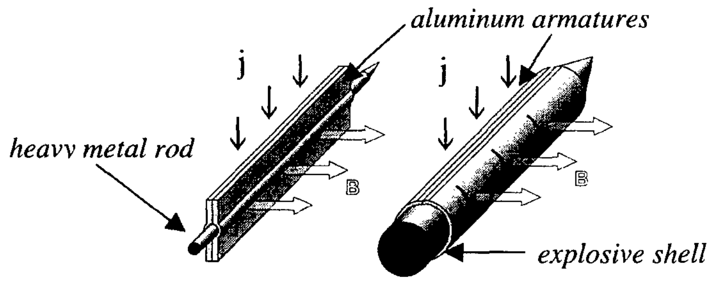

Fig.1. Long projectiles in long but thin armatures can be accelerated at low internal mechanical stress provided that magnetic induction **B** and current density **j** are spread sufficiently evenly over the armature length.

It is convenient to start discussion with the latter issue. Major causes leading to low efficiency of railguns are well known. In addition to losses due to parasitic mass of sabots and resistive losses in the rails and other conductors, a large portion of supplied energy (50% for a rectangular current pulse) is accumulated during the launch in the inductive (magnetic) energy of the rail circuit behind the projectile. On exit, this accumulated energy is wasted dissipating in the muzzle flash or in the ballast resistors used to suppress the muzzle flash.

Two concepts have been proposed to improve the efficiency of railguns by getting rid of this parasitic energy – railgun with nested rails and distributed energy store (DES) by Marshall [1], and muzzle-fed railgun with nested rails and single energy source by Bauer [2]. Marshall's DES railgun is shown in Fig.2. A large number of segmented and nested mini-rails assembled in a chevron-like pattern form two compound rails supplying the current to the armature. Each pair of opposite mini-rails in the assembly receives a short current pulse from a separate energy source (distributed storage capacitors are usually considered for this purpose). The pulse occurs when the armature closes the circuit between the two mini-rails.

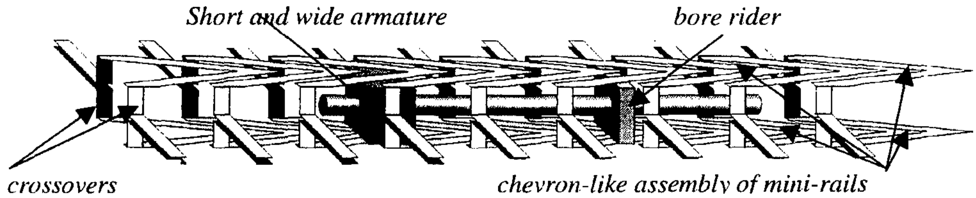

Fig.2. Schematic illustration of the DES railgun. Each pair of mini-rails is connected to a separate pulse power source (not shown). A short and wide armature with large cross-section area simultaneously contacts with several nested mini-rails.

The DES railgun concept eliminates the need to transmit the current along the launch tube, reducing resistive losses in the rails. Also, at any given moment the segment of the launch tube filled with inductive energy is limited by the span of a mini-rail. However, this reduction of accumulated inductive energy does not necessarily mean that the energy lost in a sequence of mini-arcs flashing when the armature breaks contacts with mini-rails is smaller than in conventional railguns. For example, multi-stage railguns with stages arranged in series (i.e., without nesting) loose the same energy in series of smaller arcs occurring on exit from each stage as conventional railguns do in one large muzzle flash. What actually reduces losses in Marshall's concept is increased magnetic (inductive) coupling between nested mini-rails. It improves switching of the current from the mini-rail breaking the contact with the armature to the neighboring mini-rails, because such switching disturbs magnetic fields less.

The DES railgun concept is not readily applicable to tactical guns because it is hard to integrate sizable storage capacitors into the barrel. To circumvent this difficulty, pulse power sources could be situated near the breech and connected to their respective loads by high current cables laid along the barrel. However, the total weight of such numerous cables (each transmitting only a very short pulse of the full high current) appears to be prohibitive.

The launcher illustrating Bauer's concept (dubbed "HYPE" by its author) is shown schematically in Fig.3. HYPE borrows from Marshall's DES railgun the idea of mini-rails' nesting, but instead of multiple pulse power sources uses a single source connected to the muzzle terminals. Two additional continuous rails carry the current from the muzzle terminals to a few mini-rails contacting with the moving armature at the moment.

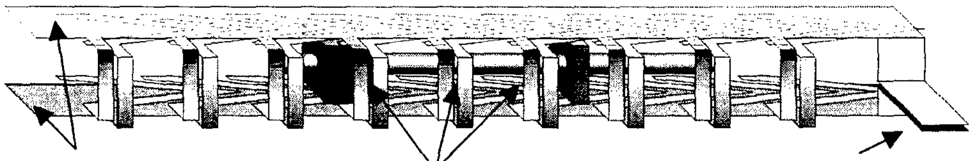

Fig.3. Schematic illustration of a muzzle fed railgun with nested rails and single power source. It can use the same nested rails and armatures as Marshall's DES railgun, but the current is supplied from the muzzle terminals via augmenting rails. To avoid clutter, crossovers on the far side of the launch tube are not shown.

Importantly, each of the two continuous rails is connected to the mini-rails situated on the opposite side of the launch tube. Due to such cross-strap connection, the continuous rails augment the flux created by the mini-rails in and behind the armature (hence the name augmenting rails). The augmenting rails also create magnetic flux in front of the armature, all the way up to the muzzle terminals. Inductive energy associated with this flux has to be supplied by the power source at the beginning of the launch. Contrary to conventional railguns, the portion of the launch tube containing inductive energy shortens as the projectile moves towards the muzzle, until it finally disappears when the projectile exits.

While this concept indeed completely eliminates the residual inductive energy, losses of inductive energy on contact breaks between the armature and mini-rails are about the same as in Marshall's DES railgun. They are lower than in conventional railguns for the same reason – due to increased magnetic coupling of nested mini-rails. As to the ordinary resistive losses in the rails, they are higher in HYPE than in conventional railguns, in particular because the current is delivered to the armature over a longer path (on average), especially if the pulse power sources have in fact to be located near the breech. For this reason, the efficiency improvement over conventional railguns promised by this concept is moderate.

It appears that for both advanced concepts discussed above there was not as much experimental development (especially at higher currents) as their underlying idea – the use of inductively coupled mini-rails – deserved. In addition to restraining factors noted above, there is probably one more reason for that. Launch tubes with segmented rails are difficult to design because of multiple crossovers – conductors carrying current to segmented rails across high magnetic field. The recoil forces acting on crossovers are equal to or even exceed, as in HYPE, the driving force applied to the projectile. It appears that no compelling design solution for high current launch tubes with multiple crossovers has been found so far. Finding a robust design is necessary for any high current experiments involving segmented rails.

The inductiveless architecture presented in the next section continues the line of thought expressed in Marshall's and Bauer's concepts. It adds two new ideas – the use of long armatures and low inductance busses for current transport along the launch tubes. These synergistic ideas bring new merits to launchers with nested segmented rails.

INDUCTIVELESS LAUNCH TUBES

Fig.4 illustrates the inductiveless architecture in a manner highlighting its similarities to and differences from the concepts discussed above. Magnetic flux in a long armature is created by compound rails formed by slanted, densely stacked tongue-like mini-rails, or railettes, as they will be called here. At the interfaces railettes are electrically insulated from each other, while at the tips they pass the current to the armature either via sliding metal-to-metal contact or, preferably, via a thin discharge gap (a plasma brush).

The current in such compound rails can only flow at an angle with respect to the launch direction, and, hence, cannot be transmitted by the rails over the launch tube length. This function is performed in the inductiveless launch tube by a low inductance bus (or several busses) laid along the tube to feed the railettes. The bus receives the current from a supply line connecting a pulse power source to input terminals of the bus; these terminals are located, preferably, between the breech and the muzzle. To reduce the inductance of the supply line and to lower mechanical loads in it, a large number of parallel cables can be used, each carrying a small portion of the total current during the entire launch event.

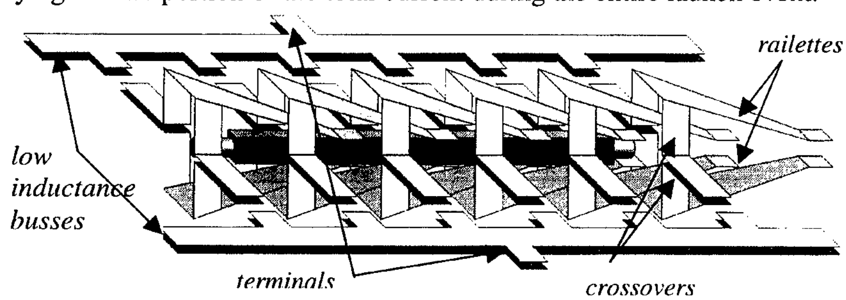

Fig. 4. Skeletal diagram of the inductiveless rail launcher. Densely stacked slanted railettes (to avoid clutter, they are shown rarified) receive current from low inductance busses connected to a single power source. A long armature simultaneously contacts with a large number of railettes. The current flowing in the railettes creates the transverse component of magnetic field in the armature.

Multilayer busses are especially suitable for inductiveless launch tubes because they can have very low inductance and resistance (the latter not only due to larger total cross section area of the bus but also because thin interleaved bus conductors, or busbars, are practically free from the skin effect). Another useful property of multilayer busses is their ability to carry high currents at relatively low mechanical loads.

Due to extremely low inductance attainable with multilayer busses, this architecture is virtually free from accumulation of inductive energy throughout the launch. Yet it can be used with a single power source. Thus it combines the merits of the DES railgun and HYPE.

The conceptual design presented below implements the inductiveless architecture in a different, more robust form. The launch tube in this design consists of stacked metal plates and railettes of alternating electrical polarity. This core assembly is surrounded by a multilayer bus consisting of radially oriented busbars.

Fig. 5 shows the main building block of inductiveless launch tubes - a pair of consecutive plates and railettes (which can be detachable as shown). Fig.6 presents two views of a section of the core assembly along with a pair of busbars carrying direct and return currents.

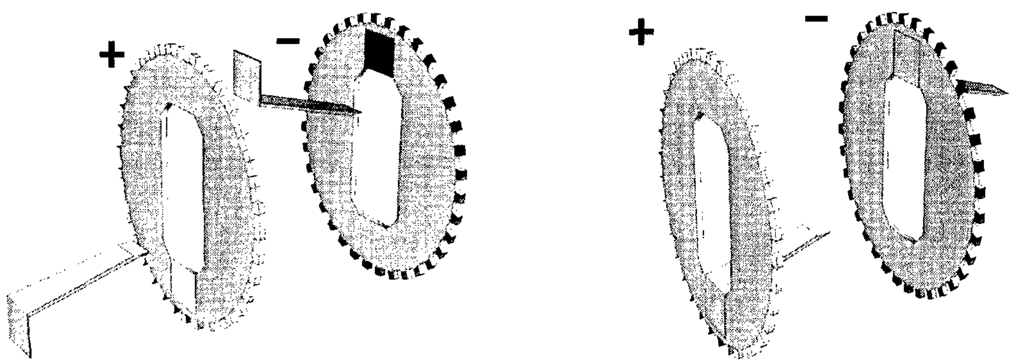

Fig. 5. A pair of plates and railettes of opposite polarity. Positive and negative contacts are shown in white and black.

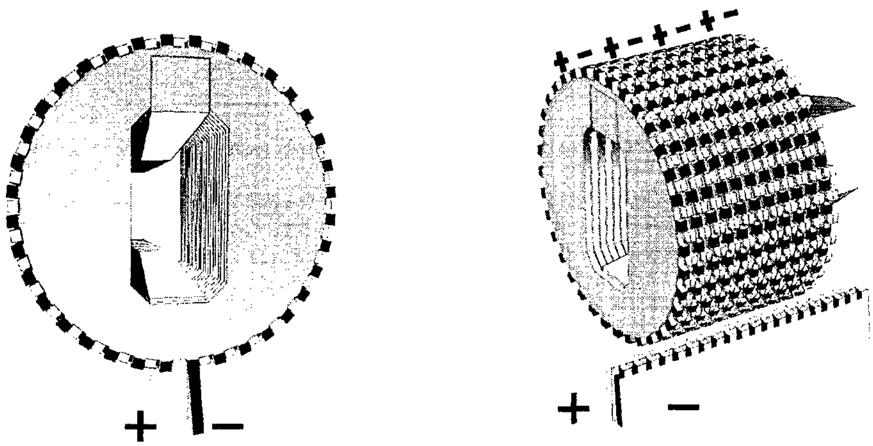

Fig. 6. Short section of launch tube assembled from plates of alternating polarity. Two busbars of opposite polarity belonging to the multilayer bus are also shown. Toothing at the edges (rectangular as shown or of some other shape) helps organize contact interface between plates and busbars.

The plates' geometry – in particular the shape of the bore – depends on the launch packages to be accomodated, and thus may differ from that shown here. Note that positive and negative plates may have exactly the same shape, differing only in orientation. The plates may be not quite flat – in particular, they can be slightly corrugated or conical. It is essential, however, that the plates and railettes are densely stacked forming robust, quasi-monololithic structures of the launch tube and compound rails.This implies that slanted railettes are thinner than plates. Dense stacking of thin railettes results in strong inductive coupling between the current loops containing them. As was discussed above, this reduces losses resulting from the current switching upon breaking of contacts between the armature and railettes.

Candidate materials for plates and busbars are high strength aluminum alloys, and for railettes highly conductive copper alloys because of higher current density near the tips of railettes. The tips can be coated with materials improving contact properties. Insulation between adjacent plates, for example with epoxy or teflon coating, must be thick enough to withstand the maximum voltage applied to the launch tube (which, however, is significantly lower than in railguns). Note that the stacked plates in this design are bifunctional: they serve as electric crossovers passing the current from the busbars to the railettes, and as structural elements supporting the compound rails against repulsion forces. In optimized designs, parameters of the plates, railettes and busbars may vary along the launch tube.

The multilayer bus surrounding the core assembly is shown in Fig.7. In addition to carrying high current to the plates, its busbars tie together the core assembly in the axial direction with the help of radial projections at their ends. Moreover, busbars can prestress the core assembly to keep it quasi-monolithic in the presence of strong recoil forces acting on the plates during the launch (i.e., to preclude occurrence of even instantaneous gaps between the plates). Thus the busbars also perform two functions, electrical and mechanical.

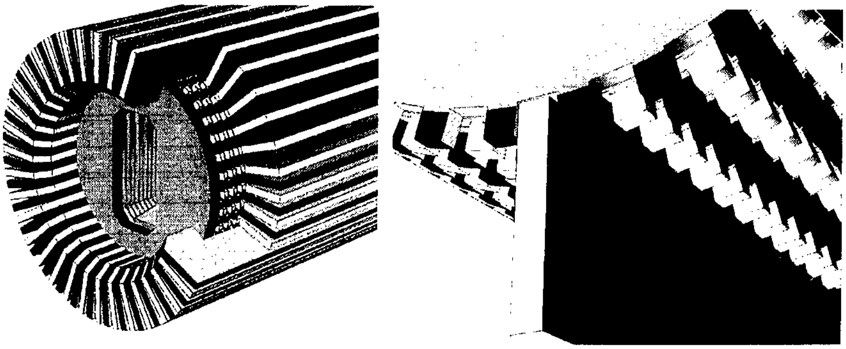

Fig. 7. Cut-out view of busbars near the breech (left), and zoomed view of the checkered pattern of electrical contacts between the plates and busbars (right). Positive and negative busbars and insulating layers between them are shown with white, black and gray edges respectively.

To avoid rail gouging and reduce wear, launch packages in inductiveless launch tubes can be guided not by the rails but by more easily replaceable wall inserts (shown in Fig. 8) made of an insulator with low friction coefficient.

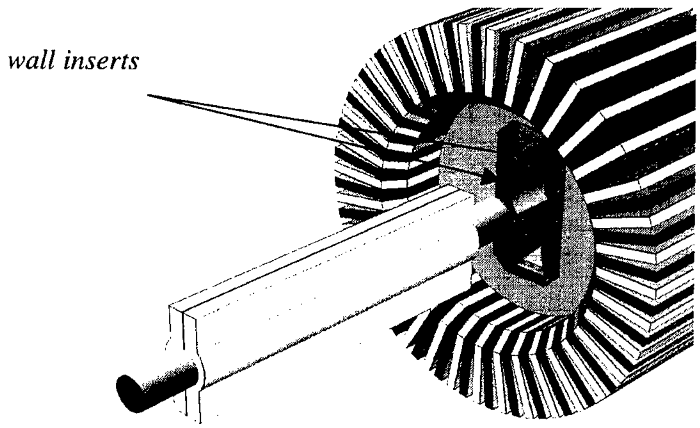

Fig.8. Heavy metal rod in a long armature being inserted in the bore of inductiveless launch tube.

As Figs.5 – 8 show, the launch tube is built with laminated metal structures carrying finely interleaved direct and return currents. Inductances of such structures can be far lower than those of rail circuits in railguns. As was already noted, this greatly reduces the accumulation of parasitic inductive energy as well as mechanical loads accompanying the transmission of high current. As to the thin lamination of compound rails, it enables strong magnetic coupling between neighboring railettes, which reduces current switching losses.

Completing the description of inductiveless launch tubes, Fig. 9 depicts a steel tubular shell, or barrel. Its function is to house the entire launch tube structure, increase its flexural stiffness and provide armor protection. The barrel, however, may have virtually no role in the containment of mechanical loads caused by magnetic pressure – as shown below, rail-to-rail repulsion is reduced so much that it can be contained by the aluminum plates only, while radial forces due to mutual repulsion of the busbars are quite low.

Note that in the barrel shown in Fig.9 the input terminals via which the current is supplied to the launch tube are positioned between the breech and the muzzle. This diminishes the average length over which the current is delivered to the moving armature, further lowering resistive losses. This also facilitates gun designs with an intermediate pivoting point (helping balance the barrel and reduce its forward projecting length).

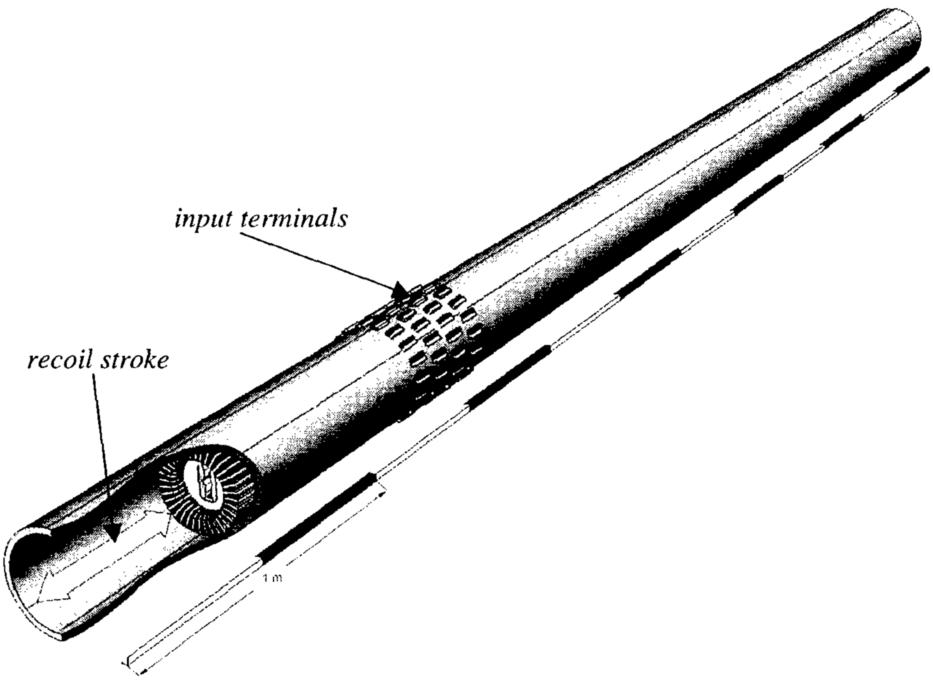

Fig. 9. Launch tube structure in a steel barrel. With sliding contacts between the terminals and busbars inside the barrel, the recoil of the launch tube structure can be absorbed within the barrel, possibly using friction between the structure and barrel (the barrel must have an insulating lining to avoid short-circuiting busbars).

The conceptual design presented here for inductiveless launch tubes has a short list of basic parts – railettes, plates, busbars and wall inserts – that can be readily manufactured and assembled with good precision to provide a highly symmetrical launch environment.

The only essential component missing in Figs. 5 - 9 is the system of distributed ballast resistors connected in series with each plate/railette. As shown in the next section, ballast resistors suppress generation of eddy currents in the launch tube circuitry and help distribute the current from the busbars quasi-uniformly over the length of the armature. Note that the energy lost in ballast resistors would otherwise (i.e., if they were absent) be lost in arcing and contribute to erosion of the contact surfaces. Design consideration for ballast resistors will be discussed below after the basic electromechanical characteristics of inductiveless launchers are presented.

BALLAST RESISTORS AND CURRENT DISTRIBUTION IN LONG ARMATURES

As will be shown shortly, electric current in a long armature can be spread approximately evenly along its length. The corresponding magnetic field created by the current in and around the armature is visualized in Fig.10 as a superposition of two simpler field patterns – the field shown by thin black lines mostly parallel to the armature, and the transverse field shown by gray lines passing through the armature and around the railettes.

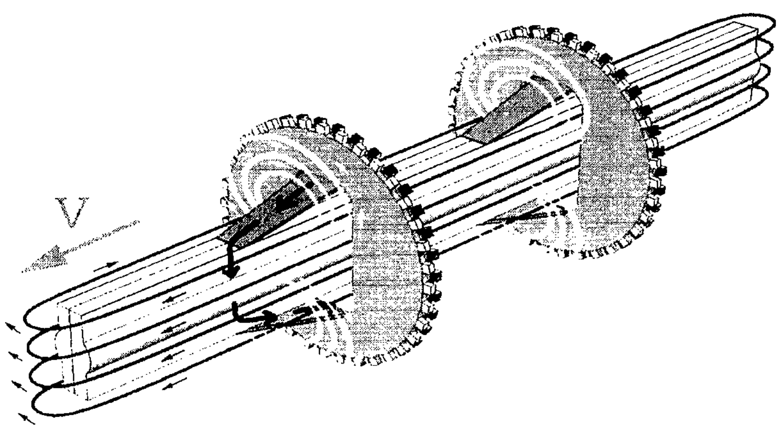

Fig.10. Magnetic field patterns in the inductiveless launch tube. For clarity, only two pairs of plates/railettes are left visible.

It is well known that quasi-static Maxwell equations in their differential form can be difficult to solve numerically in the presence of fast moving metal conductors because of very high magnetic Reynolds numbers. In the case of inductiveless rail launchers the problem is further aggravated because thin lamination of conductors comprising the launch tube necessitates a very fine mesh. Fortunately, lamination makes effective another approach based on circuit equations. In the form appropriate for circuits with sliding elements they are briefly discussed in the Appendix; these equations have been used to find currents in railettes.

The essence of this approach is simple: each pair of plates/railettes together with the adjacent portion of the armature short-circuiting the railettes can be viewed as a current loop. The loops are connected to the common bus feeding them with current, and the current distribution in the loops is controlled, along with their resistances and self and mutual inductances, by the Lorentz electromotive force **vxB** in their sliding elements.

Two typical current distributions in railettes in contact with the armature are plotted in Fig.11 (model parameters for these graphs will be discussed in the next section). The left-hand graphs correspond to the case when the only resistances in the current loops are those of plates and railettes, which are very low. This results in high internal (eddy) currents having opposite directions in the neighboring railettes. As was already noted above, introduction of ballast resistors in the plate/railette loops helps suppress the eddy currents. With sufficient ballast resistors, the current distribution smoothes out as shown by the right-hand graphs. Of course, ballast resistors reduce the launch tube efficiency, but, as also was already noted, some of the energy dissipated in them would be lost anyway in more intensive arcing contributing to erosion of the rails. As follows from the numeric modeling, with sufficient resistances of ballast resistors and good inductive coupling of railettes, the efficiency of inductiveless launchers can be substantially higher than that of conventional railguns.

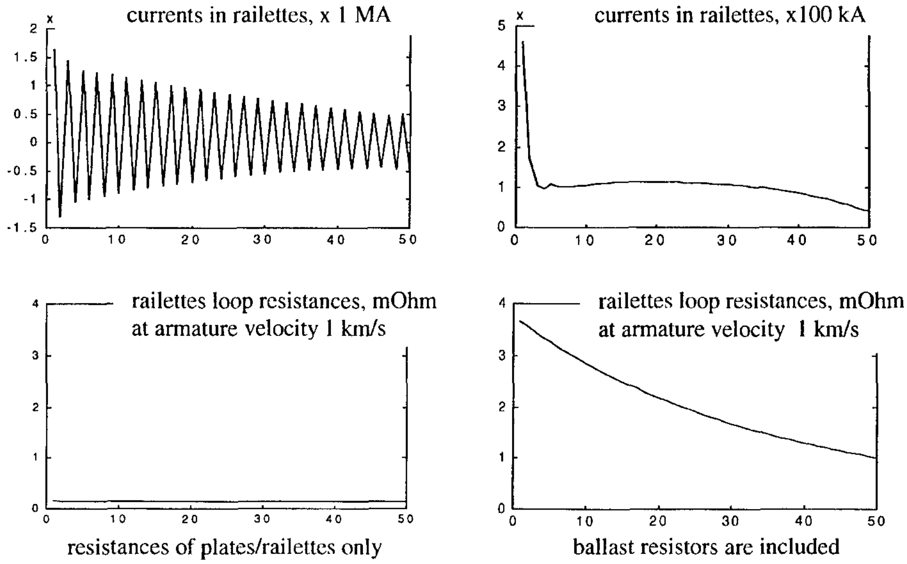

Fig.11. Examples of current distributions for two distributions of circuit resistances. Numbers on horizontal axis increasing from the trailing end to the front end of the armature refer to railettes contacting with the armature at the moment.

With eddies suppressed, the current distribution is nearly constant along the armature, except for a current peak at the trailing end and a reduced current density zone at the front end. As shown in the Appendix, the current distribution remains steady during the launch provided that local ballast resistances increase with the travel proportionally to the expected projectile velocity.

The current peak at the trailing end can locally melt the armature. To avoid that, the armature cross section near the trailing end should be increased, while the current peak amplitude should be lowered to an acceptable level by further increase of ballast resistances. As this would increase energy losses in ballast resistors and hence lower launch efficiency, it is preferable to shape the ballast resistances so that they ramp up towards the trailing end of the armature (as shown on the right lower graph in Fig.11) where they suppress the current peak most effectively.

Note that the ballast resistors belong to the launch tube and move with respect to the armature. For this reason, the increase of resistances at the trailing end (in the frame of reference associated with the armature) means that the resistance of each ballast resistor increases with time as the armature passes by. Such behavior can be achieved, for example, if resistors are made of pure metals and heated red hot by the current pulse, because resistivity of many pure metals increase several times before they melt.

The volume of red hot metal needed to accommodate the required energy loss in the resistors proves to be much smaller than the volume of the aluminum plates. For this reason, ballast resistors can be implemented as metal foils sandwiched between thin ceramic or oxide insulating films and sealed into the aluminum plates (thus resembling heat tapes in ordinary cookers). In another solution, small ceramic chips filled with metal wires or tapes can be integrated into the busbars or plates so that instead of being in direct electrical contact the busbars and plates are connected via such resistor chips.

DESIGN EXAMPLE FOR FTP CLASS INDUCTIVELESS LAUNCHER

To get a better feel of electromechanical properties of inductiveless launchers, a design example with performance parameters set forth by the Focused Technology Program may be useful. Such an example supported by numeric modeling of the current distribution in railettes is presented here, and its characteristics are compared with state-of-the-art railgun technology. For convenience, numeric values quoted below are rounded, and a simple rectangular current pulse is considered.

In this example, a heavy metal rod (diameter 20 mm, length 500 mm, mass 3 kg) inserted in aluminum armature of the same length (like the one shown in Fig.1, with average thickness 8 mm, contact-to-contact distance 80 mm, mass 1 kg – so that the total mass of this launch package is 4 kg, with armature mass share 25%) is launched to 2.8 km/s (16 MJ total launch package muzzle energy, of which 12 MJ is in the rod) by constant driving force 320 ton with acceleration 80 kgees in a launch tube 5 m long. The launch duration is 3.6 ms.

The conceptual launch tube design for this example has already been depicted in Figs.5 – 8, so only dimensions and other numerical details remain to be specified. The core assembly consists of 1000 plates, each 5 mm thick (4.5 mm aluminum and 0.5 mm insulation), with diameter 220 mm and size of the central hole 120 mm by 50 mm. The bus consists of 120 busbars 30 mm wide in the radial direction with average thickness 6.5 mm (6 mm aluminum and 0.5 mm insulation). Inductance gradient of the bus is only 1.8 nH/m – far smaller than 0.4-0.6 μH/m typical for rails in a railgun. The outer diameter of the launch tube structure (without the encasing steel barrel) is 280 mm. Properties of aluminum alloy 7075 T6 were used to estimate mechanical and electrical parameters of plates and busbars.

Copper railettes are 2 mm thick and span 100 mm in the direction of the launch. They form compound rails of trapezoidal cross section (40 mm wide at the base supported by the plates assembly, 20 mm wide at the opposite base interfacing with the armature, and 20 mm high). The armature simultaneously contacts with 50 pairs of railettes. Properties of copper alloy C16200 were used for estimates concerning railettes.

The weight of this mostly aluminum structure is 160 kg/m. A steel barrel with the inner diameter 280 mm and outer diameter 320 mm adds 150 kg/m, raising the weight per unit length to 310 kg/m. The total weight of 5 m long launch tube is thus only 1550 kg.

The graphs in Fig.11 are taken from numerical modeling of this launch tube. The modeling has determined the current and voltage needed to create 320 tons of driving force: 5.2 MA current at voltage rising linearly from zero to 2.7 kV at exit. The total energy supplied to the launch tube is 25 MJ, of which 16 MJ is the launch package kinetic energy, and 9 MJ is lost (7.5 MJ in the ballast resistors and 1.5 MJ in the busbars). It is interesting to note that after the temperature levels out over the cross-section of the launch tube, which takes about 30 s, the average temperature rise resulting from 9 MJ energy loss is ~10° C.

Assuming that ballast resistors are implemented as metal foils sealed in the aluminum plates comprising the launch tube, each of 1000 ballast resistors has to accommodate 7.5 kJ. Assuming also that the allowed metal foil temperature at the end of the pulse is 800° C, the required volume of metal foil is just ~3 cm^3 per plate. For the foil occupying 200 cm^2, or ~80% of the plate area, this translates to 0.15 mm thickness (without insulation, and ~0.5 mm with thin ceramic/oxide insulation). The resistivity of the foil metal and its length-to-width ratio should be chosen from the required ballast resistances varying (in the initial cold state) from ~0.3 mOhm at the breech to ~1.5 mOhm at the muzzle.

To realistically compare the inductiveless launcher characterized by the parameters specified above with state-of-the-art conventional railguns, one should take into account that launch packages designed for railguns are substantially heavier than those for inductiveless launchers. In carefully designed launch packages for railguns parasitic mass ratio of the integrated armature/sabot exceeds 50%, as compared to only 25% for the armature considered here (with parameters also carefully chosen with action and stress limitations in mind).

At parasitic mass ratio 50%, the muzzle energy of the launch package in a comparable railgun must be 24 MJ in order to have the same 12 MJ in the in-flight projectile. This is 1.5 times greater than 16 MJ in the inductiveless launcher. Accordingly, the driving force in the comparable railgun must be 480 tons instead of 320 tons. With this in mind, the current and voltage at exit in a comparable railgun with 0.5 μH/m inductance gradient are estimated as 4.4 MA and 7.0 kV. This corresponds to 43% launch efficiency for the rectangular current pulse considered here, which is a pretty decent allowance given lower launch efficiencies routinely observed in railguns with current pulses shaped more favorably in terms of efficiency (with the current drooping towards the end) than the rectangular pulse.

Thus the inductiveless launcher in our example requires 2.6 times lower voltage and only 1.2 times higher current than a comparable railgun. While a railgun with 43% efficiency would take 55 MJ to launch heavy metal rod with 12 MJ muzzle energy, the inductiveless launcher produces the same result with only 25 MJ, or 2.2 times more efficiently.

Comparing mechanical stresses in inductiveless launchers and railguns, one can easily estimate that repulsion between railgun rails carrying 4.4 MA current and separated by 100 - 120 mm distance would be practically impossible to contain with a structure made of an aluminum alloy. The current supplied to the inductiveless launcher is higher, while its rail-to-rail distance smaller. Why then it is possible to contain rail-to-rail repulsion with aluminum plates in inductiveless launchers? To answer this question, one should take into consideration that in inductiveless launchers the current in any cross section of the compound rail is substantially smaller than the full current supplied to the armature, their ratio being roughly proportional to the ratio of the railette span to the armature length.

As follows from the distribution of current in railettes shown by right-hand graph on Fig. 11, the current in the compound rails at the central region of the armature does not exceed 1.2 MA, which is nearly 4 times lower than the current in a comparable railgun. Recalling that the rail-to-rail repulsion is proportional to the square of the current, it is about ten times lower in the inductiveless launcher after taking into account geometric factors. With such drastically reduced repulsion, the average stress in the most stressed cross section of aluminum plates is, by estimate, just ~40 MPa, which is about one order of magnitude lower than the yield stress, and leaves enough room for stress concentration factor and safety margin. If needed, the barrel encasing the core launch tube structure can provide an additional containment capability.To tap into this reserve, slightly corrugated plates can be used instead of flat ones to transfer the repulsion load to the barrel before being irreversibly deformed.

The rectangular current pulse considered here is not typical for available pulse power sources. With more realistic pulses in which the current droops towards the end of the launch, either the length of the launch tube and duration of the pulse or the maximum driving current may be increased to compensate for the droop. As was mentioned above, such current pulses increase somewhat the launch efficiency of railguns (at the price of lower piezometric quality of the railgun barrels), but these relatively minor corrections can hardly mitigate the significant advantages of inductiveless rail launchers.

APPENDIX :

CIRCUIT EQUATIONS FOR CIRCUITS WITH SLIDING CONTACTS

In structures composed of wire-like conductors in which geometry of current loops can be derived from conductors' geometry, circuit equations can be very effective. For circuits involving sliding contacts these equations must account for Lorentz emf $\mathbf{V}_{rel}\mathrm{x}\mathbf{B}$ due to the relative motion of conductors with respect to the current loop. Retaining this usually omitted term, following the standard derivation of circuit equations and Faraday's law (see, for example, [3]) and taking into account that the magnetic induction linearly depends on the currents, the equations for circuits with sliding elements can be written as:

$$d/dt(Li) + Ri = e + Si$$

in which $i = \{ i_n \}$ is the vector of currents in the loops, e is the vector of external voltages (emf) applied to the loops, L and R – the usual matrices of inductances and resistances. Matrix S with elements given by

$$S_{mn}(t)= \int \mathbf{j}_m(\mathbf{r},t)\ [\mathbf{V}_{rel}(\mathbf{r},t)\mathrm{x}\mathbf{B}_n(\mathbf{r},t)]\ d\mathbf{r}$$

links Lorentz emf acting in a loop to the currents in the same and other loops. In this formula $\mathbf{B}_n$ – vector of magnetic induction created by $\mathbf{j}_n$ – is given by Ampere's law,

$$4\pi\mathbf{B}_n(\mathbf{r},t) = \mu_0 \int (|\mathbf{r} - \mathbf{r}'|^{-3})\ [\mathbf{j}_n(\mathbf{r}',t)\mathrm{x}(\mathbf{r} - \mathbf{r}')\ ]\ d\mathbf{r}'$$

To apply these equations to inductiveless launchers, current loops are defined as consisting of pairs of opposite railettes, crossovers connecting them to the bus, and adjacent segments of the armature short-circuiting the railettes. It is convenient to choose the frame of reference associated with the armature, in which the railettes and crossovers are the sliding conductors, because this choice allows for a steady solution for the currents in the armature.

If a steady solution exists, it can be found from the abridged equation

$$(R - S)\ i = e$$

A steady solution exists, in particular, for the case of constant acceleration. As matrix S is proportional to the armature velocity with respect to the launch tube, it varies in this case linearly with time. If the resistances R in the loops adjacent to the armature as well as voltages e applied to the loops also vary linearly with time, the time dependence can be factored out from the abridged equation. Numerical solution of thus derived system of time-independent linear equations yielded the data used in preparation of this paper.

The increase of resistances of ballast resistors adjacent to the moving armature means they increase along the launch tube proportionally to the expected armature velocity at a given position, varying as the square root of the travel in the case of constant acceleration.

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REFERENCES

1. R.A.Marshall, "The use of Nested Chevron Rails in a Distributed Energy Store Railgun", IEEE Trans. on Mag. Vol.20, No.2, March 1984, pp 389-390
2. D.P.Bauer, "A Novel Railgun Launcher Design", IEEE Trans. on Mag. Vol.31, No.1, January 1995, pp.267-272; see also D.P.Bauer, patent US5375504, Augmented hypervelocity railgun with single energy source and rail segmentation, December 1994
3. L.D.Landau, E.M.Lifshitz and L.P.Pitaevskii, Electrodynamics of Continuous Media, 2nd edition, ISBN 0-7506-2634-8, §§ 33, 61, 63