19th International Symposium of Ballistics, 7–11 May 2001, Interlaken, Switzerland

MULTISTAGE METHOD FOR ACCELERATION OF BODIES BY A RAILGUN

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The use of a railgun operating in the plasma armature mode for achieving hypersonic (greater than 10 km/sec) velocities of macrobodies is considered. The main physical models describing the operation of such an apparatus and factors imposing restrictions on its characteristics are outlined. Based on a cascade scheme of throwing plates (shells) with the help of explosives, a multistage method for accelerating macrobodies in railguns with a pinched plasma armature is proposed. The method allows one to compact the plasma armature, partly avoid adverse effects of electrode erosion and loss of stability, and optimize the shock-wave interaction between the plasma and the projectile. Experiments are performed on the two-stage throwing of bodies of mass 1 g with pinching the plasma armature with a striker speeded up at the first acceleration stage. An increase in the velocity by 75% is obtained.

Over twenty years, achieving super-high velocities in railgun-assisted throwing of macrobodies in apparatus operating in the plasma armature mode still remains a challenging problem. The velocity 5.9 km/sec of a polycarbonate dielectric body of mass 2.5 g achieved by 1978 [1] still characterizes the level of velocities reproducibly obtainable in the present-day experiments [2–4]. The importance of works in the field of electromagnetic railgun-assisted acceleration of macroparticles is related, first of all, to the fact that all present-day gasdynamic methods of high-velocity throwing of bodies (employing light-gas guns, explosives, gas-cumulative jets, generators of intense shock waves, etc. [5, 6]) either have a restricting factor, the velocity of sound in the working medium, or face serious difficulties in detaching the accelerated body from the pushing stream. For bodies weighing several grams, the researchers failed to overcome the 10–12 km/sec threshold of velocity.

Simultaneously, in electrodynamic methods, among which railguns have gained the widest utility, there are no fundamental restrictions on the velocity and mass of projectiles. However, there are a number of detrimental factors that, accompanying acceleration, greatly hamper realization of wide potentialities of the technique. The operation of a railgun working in the plasma armature (PA) mode consists in the following (Fig. 1). A dielectric body is placed in the gap between current-carrying electrodes-rails, and a PA is

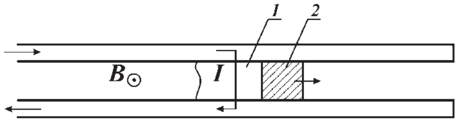

Figure 1. A railgun working in the PA mode. 1 – plasma armature; 2 – projectile.

generated at its rear boundary (by injecting a plasma bunch or with the help of its self-formation after explosion of a metal foil several tens of micrometers in thickness). Between the electrodes, a potential difference is applied, which, after the initiation of the PA, results in closing the discharge circuit, and the PA starts accelerating under the action of the pondermotive force **F=I×B,** pushing the body.

J.V. Parker proposed a physical model that describes phenomena occurring in the railgun. This model crowns a several-year period of studies aimed at obtaining hypersonic velocities of throwing [7]. The essence of this model consists in the following (Fig. 2). Intense erosion of channel walls leads to involvement of a parasitic mass into the PA and, owing to the viscous friction and inertia, gives rise to a wake with high electric conductivity that shunts the main accelerating discharge, thus causing the current split; as a result, the pondermotive force decreases and an additional ablation of the electrode material takes place. For this reason, erosion of wall material was believed to be the main negative factor affecting the operation of the apparatus under consideration.

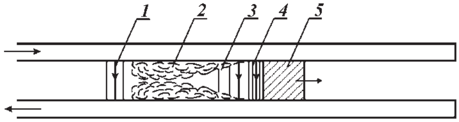

Figure 2. Development of a plasma armature after Parker. 1 – shunting discharge; 2 – wake; 3 – delocalized rear part of the plasma armature; 4 – the main discharge; 5 – projectile.

With due regard for available knowledge, the studies aimed at diminishing the adverse effect of wall erosion were concentrated around the following lines.

- Synthesis of new erosion-resistant materials;
- Diminution of thermal loads on the channel:
  - preliminary acceleration of the projectile;
  - applying an additional magnetic field;
  - optimization of the electric-current path;
  - reduction of the voltage drop across the discharge gap;
  - suppression of the electric conductivity in the PA wake.

However, the works carried out along these lines also failed to overcome the velocity barrier.

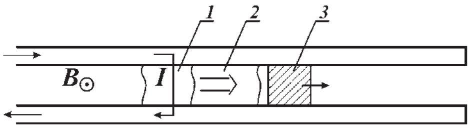

Figure 3. Schematic of the discharge model with a quasi-steady plasma flow. 1 – plasma-dynamic discharge; 2 – buffer zone; 3 – projectile.

In their experimental and theoretical studies of the structure and dynamics of PA during acceleration of macroparticles in a railgun channel, B.E. Ostashev, E.F. Lebedev and V.E. Fortov [8] advanced the following model for the development of a plasma anchor in a railgun. An MHD-analysis of stability of the conducting wake behind a plasma-dynamic discharge (PDD) showed that the latter is absolutely unstable with respect to occurrence of parasitic shunting currents in it. The PDD can exist in the current-shell mode (the properties of such a PDD resemble the properties of an H-pinched discharge) only for rather a short period. Surprisingly, to improve the stability of such a discharge, it is required to intensify erosion. It is a discharge with a quasi-steady plasma flow that constitutes a stable form (Fig. 3).

The physical model for a railgun working in a typical operating mode can be described as follows (see Figs. 1 and 3). A PDD 1 moves predominantly under the action of the pondermotive force (Fig. 1). Owing to instability of erosive wake and to the tendency to the transition from the current-shell mode to the mode with a quasi-steady plasma flow demonstrated by PDD, the PDD gradually shifts upstream the flow of erosion products directed toward the projectile (Fig. 3). The flux dm/dt 2 entrained into the PDD and accelerated there by the pondermotive force carries away some momentum and decelerates the discharge. On the other hand, this flux is decelerated on the rear side of the projectile surface 3 and gives rise to a gasdynamic force accelerating the body. In contrast to the Parker model, the gas of erosion products thus accelerated is not accumulated immediately in the PDD but, instead, gets set in motion by the discharge. Hence, the PDD is not a "current armature": that immediately accelerates the projectile but, instead, is a factor that forms a pushing "piston". In this case, the PDD is separated from the projectile by a buffer zone free of any current, whereas it is the gas decelerated by the body surface that forms the "piston". It is the loss of momentum for accelerating the flow that restricts the velocities of PDD and projectile. The authors of [8] consider the problem of complete elimination of factors destabilizing the state of PDD that cannot be resolved.

Particular attention of researchers was given to development of multi-stage schemes of acceleration, for these schemes hold most promise in solving the problem of interest. The following measures were undertaken to further develop the technique.

- a longitudinal sectioning of electrodes [7];
- preliminary acceleration of the projectile with the help of a gasdynamic scheme followed by its entry into the railgun channel (a three-stage gun, in the case of a two-stage light-gas gun) [9];
- further development of the previous scheme with involvement of a duet body to compact the PA during its initiation in the channel (Fig. 4) [10];
- use of a gas-cumulative jet additionally accelerating the projectile [11];
- acceleration at the first stage according to the ordinary scheme of a railgun with a breech current input and additional acceleration at the second stage with muzzle current input, which should, in the opinion of the authors, to prevent the PA from delocalization [12];
- to two-stage schemes, a scheme with high-velocity injection of a weakly conducting gas into the wake of a flying projectile can be classed [13].

Nevertheless, to the best of our knowledge, no success in reliable breaking through the 6–7-km/sec threshold of velocity for bodies weighing several grams was achieved.

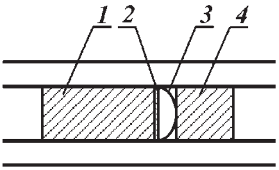

Figure 4. Duet body. 1 – striker; 2 – closing plug; 3 – PA initiator; 4 – projectile.

Home
Table of Contents

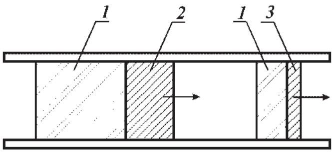

Figure 5. Two-stage charge-assisted acceleration scheme. 1 – explosive; 2 – striker; 3 – projectile.

Gasdynamic schemes of multi-stage acceleration of macrobodies were successfully used in ballistic experiments for a long time. In late seventies, two of the present authors (Fomin V.M. and Sapozhnikov G.A.) proposed a scheme of two-stage acceleration of plates and shells separated by gaps with imtermediate layers of an explosive [14]. The main mechanism of obtaining high velocities in this scheme consists in a pulsed interaction of plates (shells) with a decreasing mass (and increasing velocity, as follows from the law of conservation of momentum) and in throwing of plates in cascades by explosion products obtained in the regime of strong detonation [15]. Using the same mechanisms, the authors of [14], however, paid primary attention to searching effective ways for “transportation” of explosive energy from the charge periphery to plate (shell) to be accelerated with the help of intermediate agents, other plates (shells). It is well known that for large values of the loading factor $\eta = m_{exp} / m_p >> 5$, where m_{exp} and m_p are the masses of the charge and projectile, respectively, the efficiency of the energy transfer toward the body (a plate or shell) is rather low. The latter follows from the fact that the energy released by remote parts of the charge almost does not enter its active part. To transfer this energy to the projectile, it was proposed to deliberately divide the charge into several layers and attach an intermediate plate (stage) to each of them (Fig. 5). Using this method, the authors enhanced the energy transfer from peripheral parts of the explosive to the projectile and improved the working characteristics of explosive-based accelerating systems [15, 16].

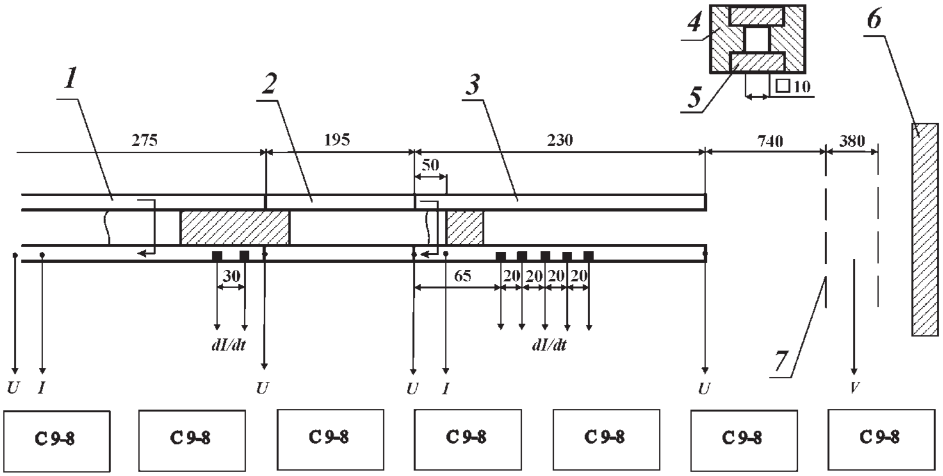

Figure 6. Scheme of the experiment and cross section of the channel. 1 – first stage; 2 – insert; 3 – second stage; 4 – insulators; 5 – electrodes; 6 – anvil; 7 – cut-wire targets; C 9-8 digital oscilloscopes; black squares – magnetic probes; all dimensions are in mm.

Home
Table of Contents

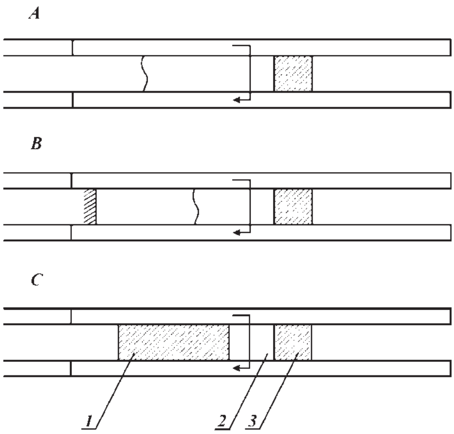

Figure 7. Organization of the rear boundary of the plasma armature in the second stage of the accelerator: (A) – "plasma-body", free boundary; (B) – "plasma-body", rigid boundary; (C) – "body-plasma-body", moving boundary; 1 – striker, 2 – PA (the arrow shows the direction of the electric current), 3 – projectile.

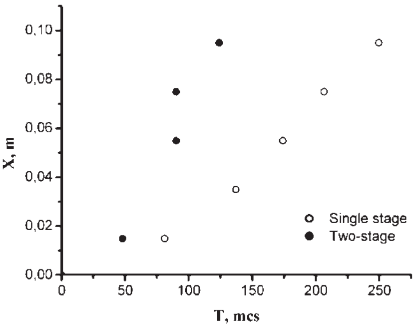

Figure 8. Location of the plasma armature as deduced from indications of magnet probes.

Here, we propose using the above mentioned layered systems to magnetoplasma acceleration of bodies in railguns. The key element of such a layered system has the form "body-plasma-body". A distinctive feature of this system is energy addition to an intermediate plasma layer, which is distributed in time and actually controllable. In addition, "pinching" of the PA between the striker and the projectile allows one to compact the PA, partially eliminate detrimental effects of electrode erosion and loss of stability of the PA (since it successfully solves the problem of the conducting wake and buffer zone), optimize the shock-wave interaction between the plasma and the projectile and, finally, substantially increase the body velocity.

This system was experimentally studied on a two-stage railgun with the total length of the acceleration path 0.7 m and a capacitive source of 0.8 MJ. The capacities of the capacitor bank of the first and second sections were 0.036 and 0.0085 F, respectively. The specific (per unit length) inductance was 0.42 μH/m. The active length of the copper electrodes of the second section was 230 mm. The insulators were made of fiber-glass plastic. Both stages (sections) were electrically isolated from each other with a 195-mm-long dielectric insert made of caprolon. Both the striker and the projectile were made of lexan. The plasma armature was initiated by an exploding 30 μm-thick copper foil. The scheme of the experimental setup is shown in Fig. 6. The striker was accelerated at the first stage to a velocity of 1.7 km/sec and interacted, via the PA, with the projectile in the second stage of the accelerator (Fig. 7C). The expected time at which the striker started interacting with the PA was chosen on the ascending branch of the current in the second stage. In the course of experiments, the following physical quantities were measured: currents I and voltages U at the input and output of both stages, indications of magnetic probes dI/dt installed inside the channel, and velocity V of the projectile. Special tests in a shortened channel without the second section were carried out to determine the striker velocity; this

Home
Table of Contents

velocity was additionally measured by magnetic probes [17] spaced 30 mm apart and installed inside the channel at the exit from the first stage. The magnetic probes were small disclosed Rogowski coils. Five magnetic probes were also mounted in the second section of the accelerator to monitor the speeding up of the projectile. The projectile velocity was determined with a relative error of 1% by a cut-wire method with targets installed at 380 mm interval; afterwards, the velocity found was multiplied to the channel exit using the formula $V_p = V \cdot \exp(\alpha x)$, where V is the velocity determined with the help of cut-wire targets, $\alpha = 0.11\ \mathrm{m}^{-1}$ is the ballistic coefficient for a cubic body, and $x = 0.740$ m is the distance from the channel exit to the first cut-wire target. Comparative experiments on acceleration of the projectile without "pinching" the PA by striker were also performed, the launch being organized either from free or rigid boundary (Figs. 7A and 7B, respectively). The peak value of the current in the second stage was 125 kA. This value did not depend on particular organization of the rear boundary of the PA. The obtained experimental data are listed in the Table 1 (here E is the energy stored in the capacitor bank), and the kinematics of motion of the projectile as revealed by magnetic probes is shown in Fig. 8. The coefficient of energy transfer in the scheme "plasma-body" is defined as $\beta = E_p / E$. For the scheme "body-plasma-body", two limiting cases are possible: 1) if, after interaction, the striker completely looses its velocity; then $\beta = E_p / (E + E_s)$; 2) if the velocities of the bodies at the exit from the second section are identical, then $\beta = E_p + \frac{1}{2} m_s V_p^2) / (E + E_s)$.

Table 1

Striker			Plasma	Projectile			PA rear boundary	β , %
m_s, g	V_s, km/sec	E_s, kJ	E, kJ	m_p, g	V_p, km/sec	E_p, kJ		
–	–	–	20.6	1.0	0.43	0.09	free	0.45
–	–	–	20.6	1.0	1.0	0.50	rigid	2.4
2.7	1.7	3.9	20.6	1.0	1.75	1.53	moving	6.1÷22.8

As follows from the Table 1 and Fig. 8, the use of the spatially distributed acceleration scheme with a "pinched" PA allows one to substantially increase the projectile velocity (by a factor of 4 as compared to the "plasma-body" variant with a free rear boundary and by 75% with a rigid wall).

The possibility of cyclic adding more sections is an advantageous feature of the acceleration scheme under consideration; in it, the first stage (striker acceleration) can be gasdynamic. With the present acceleration scheme, the following scenario can be proposed to overcome the 6–7 km/sec velocity barrier: the first two stages of the accelerator work to overcome the critical velocity; in these stages, the striker, having interacted at an optimal velocity with the projectile via the PA, impart it with a necessary (supercritical) kinetic energy which, afterwards, permits more effective cumulation of energy at the next stage, etc. Here, the behavior of the pinched PA in the vicinity of the critical velocity, at which erosion of channel walls is essential, is highly important, whereas in the experiments performed in this study the effect due to the associated parasitic mass was small. Decrease of the added mass during a two-stage acceleration is effected due to increase in the flight time and compactness of the PA.

Varying the velocity of the striker, its mass, the moment at which its interaction with the PA begins, and the energy-input function, one can optimize the acceleration process. The latter gives grounds to believe that the critical velocities for railguns can be indeed overcome.

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Home

Table of Contents