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# EFFECT OF THE INITIAL STATE ON THE EFFICIENCY OF ACCELERATION IN ELECTROMAGNETIC RAIL LAUNCHERS

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*The possibility of stabilizing the plasma region in the channel of an electromagnetic rail launcher by limiting the spatial dimensions of this region and by changing the rate of current rise is studied (in the first case, a compound body "limiter–impactor" with an electric discharge between them is considered). The effect of the initial velocity of the compound body and the mass of the limiter on the acceleration dynamics is examined. It is shown that with such an approach, it is possible to considerably decrease the amplitude of fluctuations of the parameters in the plasma armature and the length of the plasma armature, and as a result, to increase the exit velocity of the impactor. The possibility of compacting the plasma region by increasing the current rise rate is examined for a linear change in current. The estimate obtained for the dependence of the time of compaction on the current rise rate coincides with results of numerical calculations.*

**Introduction.** Interest in the problem of acceleration of light bodies to hypersonic speeds is related to the meteoritic problem and its modeling under laboratory conditions and also to studies in the field of high-energy physics. Electromagnetic rail launchers (ERL) have been used most widely in solving these problems. An analysis of their operation shows that the accelerated system "projectile–plasma armature" has long-time "memory" for initial perturbations. Disruption of the equilibrium of forces in the plasma armature at the initial stage of acceleration leads to subsequent large fluctuations of electrical and gas-dynamic parameters, which, in turn, result in additional mechanical loads on the structure, loss of momentum, and an increase in the probability of secondary breakdowns behind the body. Experiments showed that if a compact plasma region was not formed at the initial stage, the efficiency of acceleration decreased markedly. The disruption of the equilibrium of forces is due to the fact that as the current increases from zero, the magnetic force initially is not capable of equilibrating the gas-dynamic pressure, and the plasma bunch formed by electrical breakdown expands rapidly. By the moment when these forces become equal, the length of the bunch is much greater than the equilibrium length, and further current rise leads to compression of the bunch. An oscillatory regime occurs.

Stabilization of the plasma region at the beginning of the process can be achieved by limiting the dimensions of this region and by increasing the current rise rate. Experimentally, these problems were first studied in [1]. The results presented below were obtained by numerical modeling of the operation of ERL within the framework of a generalized model of a current bridge [2] and a quasi-one-dimensional approximation [3].

**1. Use of a Compound Body for Spatial Limitation of the Plasma Region.** We consider a ERL with a channel cross section of $1.5 \times 1.5$ cm and a power source that provides a constant voltage of 4 kV.

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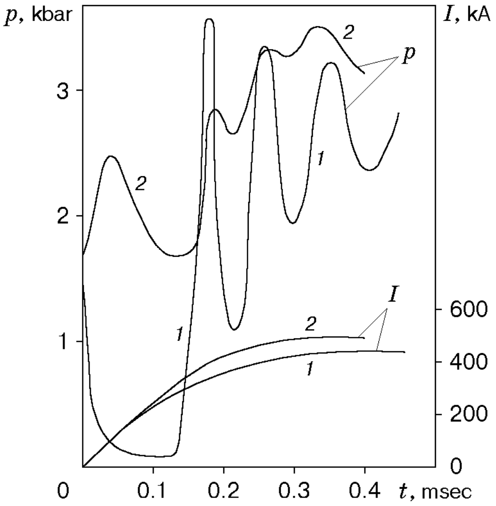

Fig. 1

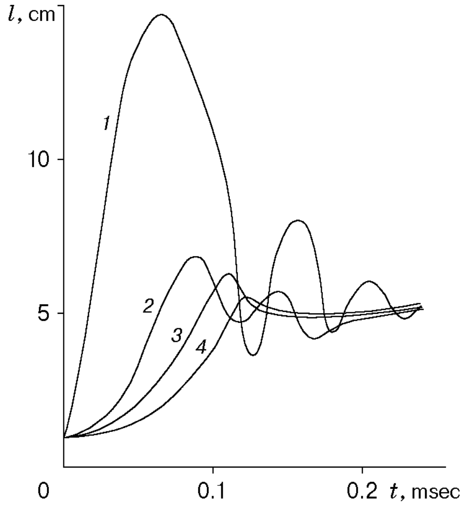

Fig. 2

The assembly inductance and resistance of the external circuit were set equal to 1 $\mu$H and 1 $\mu\Omega$, respectively. It is assumed that at the initial time, a plasma armature is formed as a result of firing of a foil located between the impactor and a body that limits the space, which will be called a limiter. In the calculations, the initial process was simulated as follows. We specified a narrow (less than 1 cm) plasma region with a mass of approximately 0.2 g at $t = 0$. The mass of the accelerated body was set equal to 5 g. The initial velocity of the system "limiter–plasma–impactor" was varied in the range 0–6 km/sec, which implied the presence of a preacceleration section that ensured the specified velocity.

Figure 1 shows the plasma pressure on the surface of the body and the total current for acceleration regimes with an initial velocity of 4 km/sec without a limiter (curves 1) and with a limiter having a mass of 5 g (curves 2). In the first case, initially gas-dynamic expansion of the bunch occurs, and the pressure in it drops rapidly. By the time $t = 0.09$ msec, the magnetic force terminates the plasma expansion, the back boundary of the plasma region begins to catch up with the impactor and forms a powerful compression wave, which reaches the body at $t \approx 0.15$ msec. Then, the process recurs, giving rise to oscillations, which decay due to friction, delivery of the eroded mass to the plasma, and redistribution of the current in the bunch.

In the presence of a limiter, the acceleration process changes qualitatively. The velocity of expansion of the plasma region and the pressure drop in it decrease considerably. By the time $t \approx 0.04$, balance of heat supply and radiation is established, the increase in the temperature ceases, and the pressure begins to drop because the distance between the boundaries of the region increases (the leading body is accelerated and the back body is decelerated). At $t = 0.13$ msec, the magnetic force separates the gas from the limiter and begins to compress the plasma. However, because the bunch was sufficiently compact by that time (7 cm compared to 19 cm in the case with no limiter), the amplitude of the subsequent oscillations is small and they practically do not influence the further process. In this case, the body, traveling a distance of 1 m in the channel, acquires a velocity that is 0.5 km/sec higher than that in the case with no limiter.

Let us consider the effects of the mass and initial velocity of the limiter on the formation of the plasma armature.

Figure 2 shows time dependences of the length of the plasma armature $l$ for an initial velocity of $V_0 = 0$ and masses of the limiter of $M = 0$, 1, 5, and 50 g (curves 1–4, respectively). It is evident that even for $M > 1$ g, the amplitude of the oscillations decreases sharply, and for $M \approx 5$ g, they are practically absent. In the extreme case of a very heavy limiter ($M = 50$ g), formation of the plasma armature proceeds without any gas-dynamic perturbations. Figure 3 shows the acceleration dynamics in two extreme cases: $M = 50$ g (curve 1) and $M = 0$ (curve 2). It is evident that in the case of a heavy limiter, the acceleration velocity is much higher.

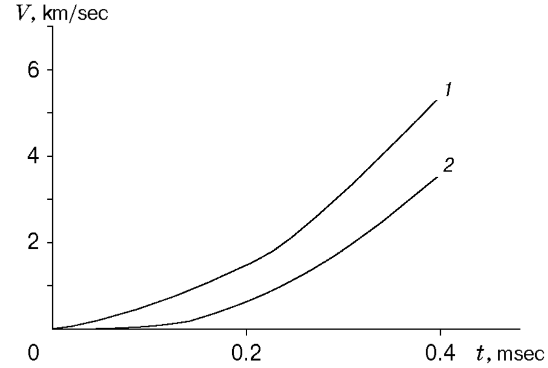

Fig. 3

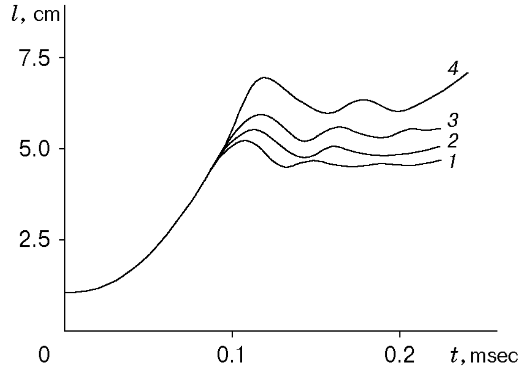

Fig. 4

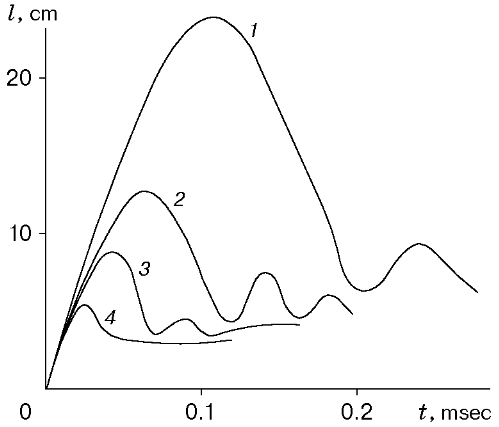

Fig. 5

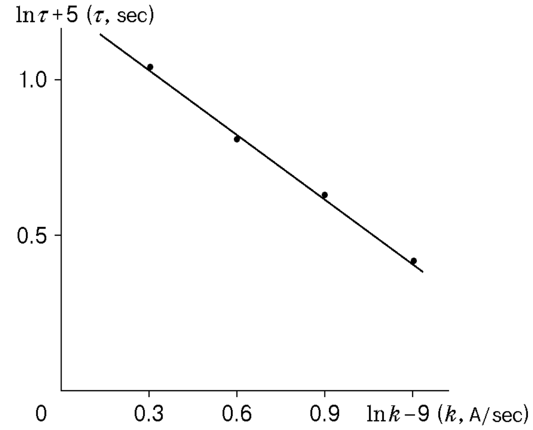

Fig. 6

Figure 4 shows the effect of the initial velocity on the behavior of the plasma armature for $M = 5$ g and $V_0 = 0$, 2, 4, and 6 km/sec (curves 1–4, respectively). The presence of a five-gram limiter ensures compactness of the plasma armature over the entire period of establishment of quasi-equilibrium.

**2. Formation of a Plasma Armature at Different Rates of Current Rise.** In the calculations of the behavior of the accelerated system at different current rise rates, the external circuit parameters were specified so as to ensure a linear change in current $I(t) = kt$. Figure 5 gives the results of calculations for $V_0 = 4$ km/sec, $M = 0$, and $k = 2\cdot 10^9$, $4\cdot 10^9$, $8\cdot 10^9$, and $16\cdot 10^9$ A/sec (curves 1–4, respectively). It is evident that the rate of current change has a significant effect on the processes occurring at the initial acceleration stage because the faster the current rise, the smaller the expansion of the plasma armature before the onset of compaction.

The compaction time $\tau$ can be estimated as follows. If the velocity of expansion of the bunch (approximately equal to the velocity of efflux in vacuum) is $V_{\rm exp}$, then the momentum gained by the gas during acceleration is about $m_{\rm pl}V_{\rm exp}$ ($m_{\rm pl}$ is the mass of the plasma). To compact the bunch, the system should transfer a momentum of the same order to the plasma:

$$\int_0^{\tau} \frac{L_x I^2(t)}{2}\, dt \approx m_{\rm pl}V_{\rm exp}.$$

Here $L_x$ is the inductance per unit length. From this, for $I = kt$, we have $L_x k^2 \tau^3/6 \approx m_{\rm pl}V_{\rm exp}$ or $\tau \approx (m_{\rm pl}V_{\rm exp}/(L_x k^2))^{1/3}$. Hence, the compaction time $\tau$ is determined mainly by the current rise rate: $\tau \approx k^{-2/3}$.

Figure 6 shows a curve of $\tau(k)$ in logarithmic coordinates (points are calculation results and the solid curve is their approximation). The slope of the straight line is about 0.7, which confirms the estimate obtained above.

**Conclusions.** The studies performed showed that the initial stage of formation of the plasma armature has a significant effect on the dynamics of acceleration of the impactor as a whole. Therefore, initial compaction of the plasma armature is a necessary condition for raising the efficiency of operation of ERL. It is shown that the use of a back movable wall (limiter) ensures compaction of the plasma armature at the initial stage of acceleration. As the current rise rate increases, the rate of compaction of the plasma armature increases.

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