Electromagnetic launcher for heavy projectiles

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Abstract. In this paper, we present the electromagnetic launcher with capacitive power source of 4.8 MJ. Our installation allows studying of the projectile acceleration in railgun in two regimes: with a solid armature and with a plasma piston. The experiments with plasma piston were performed in the railgun with the length of barrel of 0.7-1.0 m and its inner diameter of 17-24 mm. The velocities of lexan projectiles with weight of 5-15 g were in a range of 2.5-3.5 km/s. The physical mechanisms that limit speed of throwing in railgun are discussed.

1. Introduction

Until now, the record speeds of projectiles throwing with weight of 1 g in electromagnetic launcher (EML) were about 6.5 km/s. These values are two to three times less than the expected [1]. The substantial erosion of the barrel walls under the action of extreme heat loads, which results in increase of total accelerated mass [1], is considered to be the main obstacle to achieving design projectile speeds.

In the work [2], it was suggested that the speed of projectile in EML is limited by the value of sound velocity in plasma of railgun channel. The sound velocity, estimated for typical working conditions of EML, do not exceed 7 km/s [2]. This fact indirectly confirms the fairness of the hypothesis [2]. The sound velocity in plasma increases with decreasing medium molecular weight of heavy particles \( \mu_m \) and with increase of the plasma temperature. The sound velocity in the railgun barrel can achieve 10−12 km/s if the plasma temperature is of about 30 kK and its medium molecular weight is of about 7 atomic units [2]. Light plasma (\( \mu_m \sim 7 \) a.u.) can be created with the use of lithium initiator. Obtaining the high temperature of plasma is a more complex problem, since it requires a very high rate of energy input in the railgun. By estimations, in this case the growth rate of current in EML must be above 20 kA/\( \mu s \). It is extremely hard to provide dynamic strength of the barrel under such extreme regimes of acceleration.

The study of some processes during high-speed impact requires a relatively low speed of projectiles, at the level of 4−5 km/s, but with their weight of more than 10 g. At such speeds of projectiles the limit, which is associated with the sound velocity in the channel plasma, can be overcome due to the use of the low-molecular weight initiators. Earlier we explored acceleration in EML the projectiles with weight of \( \sim 2 \) g up to velocities of about 5 km/s. In work [3] we described the results of these experiments and also a numerical simulation of the targets destruction due to the high-speed impact. This paper presents the results of our research aimed to resolve of the task of the throwing of the relatively heavy projectiles with weight above 10 g.
2. Experimental set

We have created an EML with capacitive energy source (CES) of $E_0 = 4.8$ MJ when it is fully charged to 6 kV. CES was sub-divided into seven modules, each with its own independent triggering system and delay timer. Installation allowed studying the projectile acceleration in railgun in two regimes: with a solid armature and with a plasma piston (PP). Energy of CES is sufficient for throwing of projectile with a mass $m_b$ of 0.3 kg at a speed of 3 km/s.

This paper describes the results of experiments with PP, where we used three modules of CES with nominal stored energy $E_0$ of 1.2 MJ. The length of the railgun barrel was 0.7 – 1.0 m, its internal diameter was 17 – 24 mm. Electrodes were made of copper, and insulators were made of lexan. After assembly, the channel was placed into the power housing, which was made of stainless steel.

The weight of lexan projectile was 5 – 15 g; length of the heaviest projectile was of 32 mm. The discharge in railgun was triggered by using of graphite disk, which provided the initial contact between the electrodes. The application of graphite initiator with weight of about 1 g allowed producing of the comparatively "light" plasma on the initial part of the channel. In the experiments [3] we used as the initiator the lithium plate, which weight was of about 10% of projectile weight. The sound velocity in lithium plasma is higher than in carbon plasma. Additionally, lithium requires the significantly less energy to create the PP in comparison with carbon. On the other hand, the lithium initiator explodes faster than graphite initiator that creates more difficulties in the retaining of impulse pressure in the channel breech.

We equipped the railgun with diagnostic system, consisted of: Rogowski coil - to measure breech current, transducers based on current transformers to determine breech and muzzle voltage, magnetic probe (MP) - to control the motion of PP along the channel. MP had form of 7 mm wide loop, padded along the insulation wall of the channel. After departure from the channel, the motion of projectile and its collision with target was controlled by high-speed videography (100,000 frames per second). The target represented itself duralumin disk with thickness of 60 mm and diameter of 150 mm. The time of projectile collision with target was determined by contact sensor.

3. Experimental results and discussion

In our experiments maximum throwing speed (3.5 km/s) was obtained for the projectile with weight of 5 g. Previously, when throwing lighter projectile ($m_b = 1.3$ g) we have achieved the speed of 5.4 km/s [4]. In experiments [3] we used CES with nominal stored energy of 0.8 MJ.

Figure 1 shows the oscillograms of the current in railgun $I$, breech voltage $V_b$, muzzle voltage $V_m$, and the signal from MP $V_p$. Energy of CES with charging voltage of 3.6 kV was $E_0 = 0.68$ MJ. In this test the projectile with weight of 14.3 g was accelerated in the channel with length of 1 m up to the speed of $u_m = 3.0$ km/s, its kinetic energy $E_k$ was 65 kJ.

Neglecting the voltage drop at the electrodes, it follows from the equation of circuit that the rate of change of magnetic flux and consequently projectile acceleration is proportional to the difference of input and output voltage ($V_b - V_m$). This difference sharply increased to $\sim 0.45$ kV (Figure 1) through $\sim 20 \mu$s after the start, then it changed more smoothly with achieving maximum value of 0.9 kV at time $t = 370 \mu$s. The sharp rise in muzzle voltage $V_m$ and drop of signal from MP $V_p$ at $t_e = 620 \mu$s is explained by the departure of projectile from the channel.

If we neglect the loss of momentum due to the friction between projectile and channel walls and disregard an increase of throwing mass due to its erosion, the acceleration of projectile (a) and its velocity ($u_t$) is defined from equations [1]:

$$a = \frac{L'}{2m_b} I^2(t)$$
\[ u_t = \frac{L'}{2m_b} \int I^2(t')dt' \]  

(2)

In these equations \( L' \sim 0.65 \mu \text{Hn/m} \) is inductance gradient of the railgun.

From equation (1) and Figure 1 it follows that the maximum projectile acceleration at the maximum current \( (t_m = 350 \mu s, I_m = 730 \text{ kA}) \) was \( 1.6 \times 10^7 \text{ m/s}^2 \), and the peak plasma pressure \( p_m \) was 0.53 GPa. In this experiment the average values of acceleration and plasma pressure were approximately three times less than the maximum values, and were respectively \( 5 \times 10^6 \text{ m/s}^2 \) and 0.16 GPa. Plasma pressure in the final stage of acceleration \( (t_e = 620 \mu s) \) was 0.2 GPa.

In this experiment the net energy efficiency of launcher, i.e. the ratio of \( E_k \) to \( E_0 \) was 9.5%. Theoretical speed of projectile \( u_t \) was calculated using the formula (2) and oscillogram of the railgun current, which is presented on Figure 1. In the moment of the projectile departure from the channel its theoretical velocity reached 4.3 km/s, which corresponds to projectile kinetic energy \( E_t = 132 \text{ kJ} \).

The difference between \( E_t \) and \( E_k \) is a mainly estimation of the sum of the friction forces work of projectile on the channel walls and energy losses due to the increase of kinetic energy of the PP. In this experiment the sum of energy losses reached to 67 kJ. By the time of the projectile departure from the channel the charge of CES was about 10% of the initial, so almost all electromagnetic energy, remaining in the circuit, proved to be stored in the inductance. When the projectile left the railgun, the current \( I \) was equal to 460 kA (Figure 1), and magnetic energy \( E_m = 0.17 \text{ MJ} \). Thus, about 56% of the energy stored in CES mainly was spent on creation of PP and heating of electrodes.

In this experiment the real projectile velocity was \( \sim 70\% \) of the calculated one. Our results may clarify one possible mechanism of loss of momentum projectile. It can be seen from Figure 1 that at time \( t_b = 290 \mu s \) on the voltage oscillogram of MP there is a "plateau" lasting of about 20 \( \mu s \). This peculiarity is being registered during the stage of increasing current, therefore at moment \( t_b = 290 \mu s \) the braking of current jumper occurs. It follows from the equation (2) that at the moment \( t_b = 290 \mu s \) the calculated speed of projectile was of about 1.5 km/s.

Figure 2 shows the central part of the channel, where the projectile velocity by estimations increased from 1.5 to 2 km/s. At the surface of the insulator there are many "notches", the
similar damages with smaller size and not so numerous also present on the electrode surface. We did not observe the similar damages near the entrance of the channel; near the exit of the channel the intensity of such walls damages was noticeably less. The time of projectile passing through the zone of damaged walls in central part of the channel corresponds to the time of braking of current jumper.

Many researchers have observed the damages on inner walls of railgun, similar to those shown in Figure 2. For example, in work [4], when the projectile velocity was of about 1.5 km/s, the damages like gouging appeared on copper electrodes of railgun with duralumin armature. The characteristic size of these damages was of about 10 mm. In work [5], we have explained the occurrence of these injuries due to the development of resonant deformation of barrel (RDB) under the action of moving front of high pressure.

Effect of RDB appears when the speed of the high-pressure front becomes comparable with the sound speed in the wall of the channel. In the real design of railgun the analysis of RDB is a very complex problem. In the channel with thin cylindrical walls RDB develops when the velocity of high-pressure front reaches one of the two critical speeds [6]. The first critical speed corresponds to bending resonance of the channel; the second critical speed causes an axial vibration resonance. Occurrence of RDB results in creation of dynamic asperities on the channel surface. The projectile collides with these asperities, and the explosive ejection of walls material into the channel takes place. It causes the drastic slowdown of PP (current jumper); additionally, the temperature of the plasma and its electrical conductivity considerably decreases. In work [5] we have shown that the effect of RDB explains qualitatively many observed features of railgun operation when the projectile velocity is above 2 – 3 km/s. In particular, a sharp braking of PP can cause a power surge at the entrance to the channel, and as a result, the appearance of breakouts and shunt discharges in this part of the channel. Similar current structures significantly reduce the efficiency of EML.

The height of the dynamic asperities that occur on the surface of the channel due to RDB increases with local pressure, therefore the degree of damage to the walls near the exit of the channel is noticeably smaller than in its central part.

Figure 3 shows the duralumin target after the experiment under consideration. After the experiment the diameter of the target was reduced to 100 mm. The diameter of the crater on the target and its depth were 52 mm and 26 mm respectively. Figure 3 also shows the projectile with weight of 15 g, which is similar to projectile used in this experiment. For comparison, in our experiments [3] the lexan projectile with weight of 2.6 g and velocity of 4.7 km/s embossed the cork with diameter of 30 mm in duralumin target with 40 mm thick.
4. Conclusion
The results of experiments on the acceleration in railgun with plasma piston the projectiles with weight of $5 - 15$ g up to velocity of $2.5 - 3.5$ km/s are presented. It was concluded that resonant deformation of barrel under action of moving front of high pressure is one of the main sources of loss of projectile momentum in railgun.

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