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MACROPARTICLE ACCELERATION IN A PLASMA ARMATURE RAILGUN

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Magnetic plasma accelerators (MPA) or, using other terminology, plasma armature railguns, are structures of the simplest design which are able to accelerate macroparticles with a mass of several grams to hypervelocities. In many experiments with railguns, velocities of 5–7 km/sec are attained. Further increase of the in-bore velocity is problematic because of severe erosion of the bore materials and instability of the plasma armature.

A detailed numerical analysis of the temperature distribution in the rails has shown [1] that: 1) the rail contact surface was strongly heated and partially melted during the shot, 2) the parts of rails which were closer to the breech of the railgun were more prone to melting, 3) as the initial velocity rose, the maximum of the melted material shifted in the direction of the macroparticle motion, while the depth of the melt decreased (from 60 μm at the initial velocity $V_0 = 0$ to 20 μm at $V_0 = 2$ km/sec), 4) increase of the injection velocity to a value of 2 km/sec and up does not change the temperature distribution in the rails. These conclusions are confirmed by both a visual inspection and X-ray structural analysis of the rails and the insulators after the experiments [2]. However, efforts to lessen the undesirable influence of the initial section through the use of a pre-injector, which provides for the injection of a macroparticle with an initiator into the railgun bore at some initial velocity, gave rise to the problem of arc initiation and formation of a plasma armature.

Another problem preventing macroparticles from attaining a velocity of 10 km/sec and higher is the instability of the plasma armature, which becomes especially apparent every time the current gradient changes in the accelerator circuit.

In this paper, results of experiments on the process of arc initiation and plasma armature formation are given in relation to the macroparticle initial velocity and the plasma armature behavior during the change of current gradient in the accelerator circuit.

A series of experiments was carried out using the installation EMMU-10, whose schematic diagram is shown in Fig. 1. The power supply was configured on the principle of the so-called "long line," enabling the formation of the properly shaped current pulse in the railgun circuit. The power supply parameters are given in Table 1.

The battery modules were electrically independent and could be connected to the circuit simultaneously or one-by-one at some intervals. The following parameters were recorded in the experiment: currents (the input current I_{U}, the output current I_{L}, the leakage current I_{leak}, and the individual battery module currents I_1, I_2, I_3, and I_4) using a Rogowskii coil, the input voltage U_{in} and the output voltage U_{out} by means of voltage dividers, the in-bore velocity of the plasma armature using inductive probes $\text{ID}_1, \ldots, \text{ID}_n$, and the macroparticle in-flight velocity through the use of frames with tearable wires CD_1 and CD_2 and using rapid survey by means of high-speed cameras GLV-2 and VSK-5. The inductive probes were spaced 150–250 mm apart, as was dictated by the railgun construction. Probe readings were registered by the multichannel devices ADAM-TMS-2008 and then processed on PC AT/ 286.

Experimental investigations have been carried out using a railgun of type T2M whose cross section is shown in Fig. 2. The accelerator body is made of high-strength steel, thermally treated to a Rockwell

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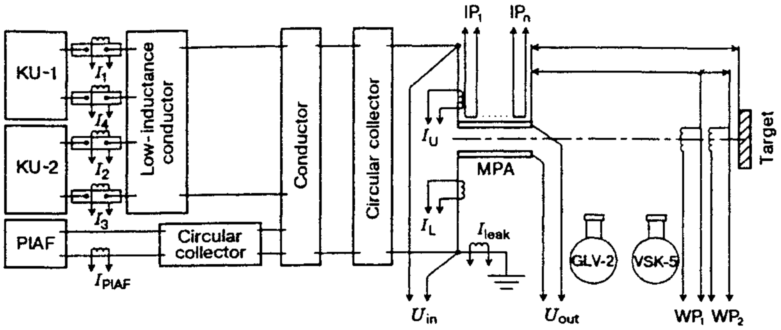

Fig. 1

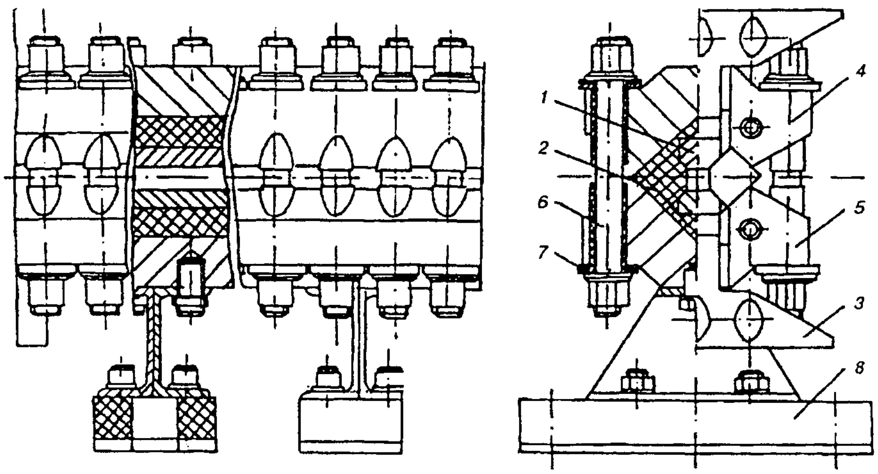

Fig. 2

hardness of 380–420 MPa. It consists of the top 4 and the bottom 5, attached together by the studs 6. The studs are made of steel, thermally treated to a hardness of 1400–1600 MPa, with a relative elongation greater than 8%. The length of the bore is 2 m; the bore caliber and its shape and configuration can be changed according to experiment requirements by replacing the internal module. The latter consists of the rails 1 and the inter-rail unsulators 2. Post-assembly finishing of the bore is carried out using the special reamer set. In that case deviations of the bore size do not exceed 20 μm. Usually, the rails are made of thermally treated special bronze while the insulators are made of fiberglass. Electric current is supplied to the rails via the copper bus-bars 3.

The stress analysis of the facility has shown that it will remain operating at currents up to 2 MA.

Experiments have been carried out at time rate of change of current $\approx 10^9$ A/sec, a typical value for an EMMU-10 installation.

Macroparticle with an Initiator of the Simplest Construction (shown in Fig. 3, where 1 is the screw, 2 is the copper foil, 3 is the polycarbonate). The foil mass was changed from 0.1 to 0.25 g. The main results of that series of experiments are given in Table 2.

Figure 4 explains the introduced concepts of the time of foil explosion t_1 and the time of plasma armature formation t_2.

Analysis of the experiments shows that the simplest initiator provides a stable formation of the plasma armature at initial velocities of up to 700 m/sec. Attempts to use this initiator at initial velocities of 900–1000 m/sec failed: the initiation was unstable; it could either end at the mid-bore or not happen at all.

Duet Projectile (Fig. 5). As it is evident from its name, the duet projectile consists of two parts: the

TABLE 1

Battery modules	Capacitance, F	Charging voltage, kV	Main commutator
KU-1	0.037	up to 8.5	Air discharger
KU-2	0.048	up to 8.5	Air discharger
PIAF-2.5	0.05	up to 10.0	Ignitrons

TABLE 2

Initial velocity, m/sec	Time of foil explosion t_1	Time of plasma armature formation t_2
	μsec	
0	40–50	150–160
700	25	100–120
900–1100	Unstable initiation	

macroparticle 1 with the initiator 4 and the auxiliary armature, which is 2 to 5 times more massive than the macroparticle; the felt wad 3 is placed between the two. The idea of the duet projectile was first proposed by A. D. Lebedev [3]. The duet construction of the projectile allows one to restrict the volume where the plasma armature is formed at the initial stage of its development.

Using the duet projectile, stable initiation and formation of the plasma armature were achieved at initial velocities of up to 1100 m/sec. In that case the time of foil explosion t_1 = 50–70 μsec, while the time of plasma armature formation t_2 lies in the range between 200 and 300 μsec.

Typical dependences of the velocity V, the projectile displacement X, the accelerator circuit current I, the output voltage U_{out}, and the armature length l_p on time are given in Fig. 6a,b.

It was found in the process of experiments that: 1) at initial velocities higher than 1100 m/sec the initiation processes and formation of the plasma armature becomes unstable again, 2) the duet design of the projectile does not protect the armature from exfoliation during the change of current gradient in the accelerator circuit.

Armature of Transient Type. Two constructions of the macroparticle with the transient armature are shown in Fig. 7. Using the screw 1 in the tail of the macroparticle, an aluminum alloy ring or a "staple" is mounted, whose mass can be varied from 2 to 10 g depending on that of the macroparticle (2 is the polycarbonate).

During the projection of the macroparticle with the initiator of this construction the regime of current flowing through the contact rail/armature passes the following three stages in turn: the metal regime, the quasimetal (microarc) regime, and the arc regime. This can be judged from the appearance of the output voltage plot. Typical dependences of the velocity, the projectile displacement, the accelerator circuit current, the output voltage, and the armature length on time are given in Fig. 8a,b.

Using the macroparticle with the transient armature, reliable initiation and formation of the plasma armature were achieved at initial velocities up to 1200 m/sec. There are some indirect indications concerning the acceleration of macroparticles weighing as much as 50–300 g [3] which allow one to claim that this construction will operate, at least, at initial velocities from 1800 to 2000 m/sec.

The transient armature design allows also one to get rid of the voltage peak in the accelerator circuit, caused by explosion of the initiator. This improves the railgun power supply performance.

Experiments have shown that once the plasma armature has been formed, it remains stable at a positive current gradient in the accelerator circuit. Such conditions of the electric current flow have the following characteristic features: the length of the plasma armature ranges from 3 to 5 calibers of bore, and calculations using the electrotechnical approximation method with the use of armature effective dimensions

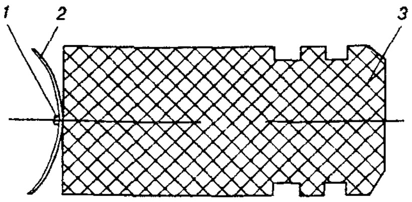

Fig. 3

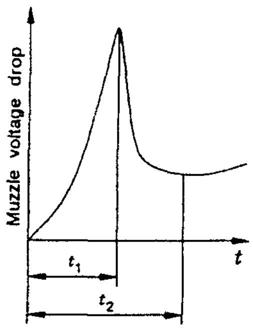

Fig. 4

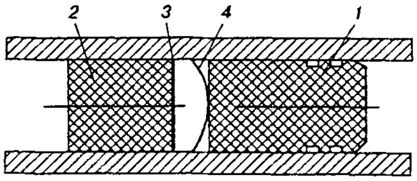

Fig. 5

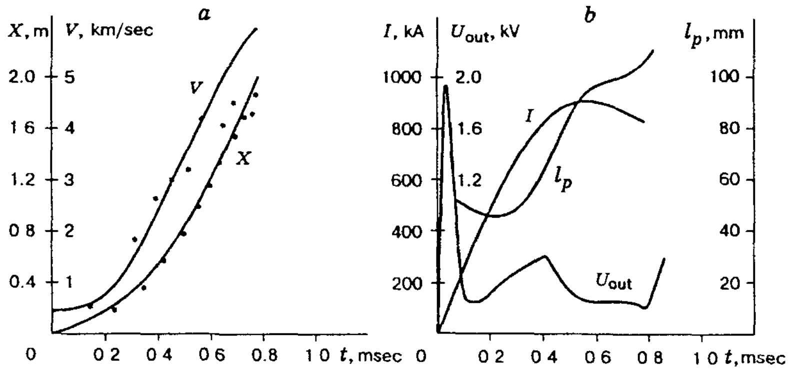

Fig. 6

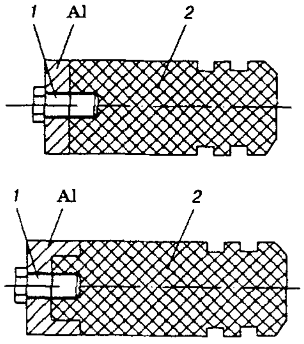

Fig. 7

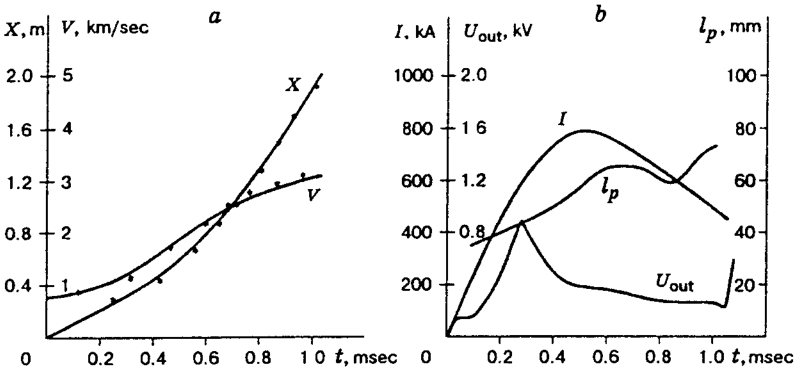

Fig. 8

taken from the same experiment are in agreement with the experimental data.

If the current in the accelerator circuit has sections with sharp changes in gradient, then the plasma armature exfoliates and its length drastically increases (up to 10 calibers and even higher).

Note that the armature exfoliation only happens if its formation was completed prior to the moment of change of the current gradient. If at the moment of change of the gradient regime the current flowing through the contact surface rail/armature is of metal or microarc character, then in the future the plasma armature is normally formed and remains compact even at negative current gradient in the accelerator circuit.

Therein lies the advantage of the transient armature. All the above can be illustrated by the dependences of the plasma armature length on time for the duet projectile and for the macroparticle with the transient armature, which are given in Figs. 6 and 8, respectively. Use of the transient armature ensures a stable acceleration of the macroparticle while reducing the current down to 0.6 of its maximum value, which is especially important when using a power supply based on energy accumulators of the inductive type.

In this manner, a comparative analysis was performed of various initiator constructions, which provide for stable formation of the plasma armature in a railgun at initial velocities of up to 1200 m/sec. Also, a solution was proposed which enables the plasma armature to remain compact during the change of the current gradient in the accelerator circuit. The results of these investigations can be used in the acceleration of macroparticles to hypervelocities in railguns.

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