Compact railguns for acceleration of mm-size bodies and their applicability in plasma technologies

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The problem of acceleration of small-size pellets (1-3 mm) to high speeds (more than 5 km/s) attracts considerable attention of researchers. This subject is important for investigations in the area of high-temperature plasma where pellets are used to bring fuel to the zone of thermonuclear reactions, to carry out diagnostics of plasma, and also to control the reactor operating regimes [1-4]. Injection of pellets made of a material with a high atomic number is regarded as a tool for emergency shut-down of thermonuclear reactors. The speed of pellets on modern ITER-like setups must be higher than 5 km/s to bring a material to the central zone of the reactor. There are also other areas where high-speed pellets of the mm-size can be used.

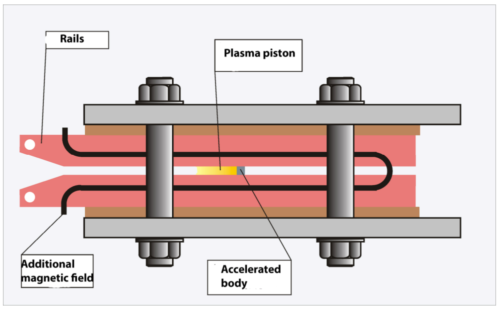
Acceleration of mm-size bodies to hypervelocities is a complicated problem because losses appreciably increase and the acceleration efficiency considerably decreases with decreasing accelerator calibre. These effects are most pronounced at the final stage of acceleration. In the classical setups, i.e., two-stage light-gas guns, speeds at the gun output for bodies 2−3mm in size are not higher than 3 km/s. The main competitor of light-gas guns in these application areas is an electromagnetic rail accelerator (railgun) with a plasma piston where electric energy of the capacitor bank is converted into the kinetic energy of the body to be accelerated.

The first experiments on pellet acceleration were performed in the framework of a "fast railgun" approach that has been developed previously [5]. According to this, the body speed is increased at a maximum possible acceleration limited from above by one of two factors: armature strength and electric explosion of the electrode surface. For copper rail electrodes this explosion takes place at a linear current density above 43kA/mm. In a rail channel of 10 × 10mm cross section, this approach allowed an ~1g polycarbonate cube to be accelerated up to about 7.1 km/s over a path length of 0.6 m [6]. However, this approach failed in the first experiments with a 1×1mm channel, where a polycarbonate cube with a 1mm edge size and a mass of ~1 mg was accelerated to the velocity 1 km/s, in the railgun with rail length of 120 mm and the amplitude of a trapezoidal current pulse of ~40 kA. If we try to estimate acceleration dynamics the results will show that the cubic armature must acquire a velocity of ~6–7 km/s at a channel length of 100 mm due to the accelerating (Ampere's) force in a railgun that depends on the current in the rails and plasma piston as $F = L'I^2/2$, where I is the discharge current and L' is the linear inductance ($L' \approx 0.3$ μH/m in our case).

So a detailed analysis of the experimental data was done and it was found that for small (~1 mm) interelectrode distances, the limitation of maximum velocity at 1–1.2 km/s is caused by catastrophic erosion of electrodes. In the initial stage of acceleration there was evidence of significant electrode melting such that liquid metal drops (reaching a size of ~1 mm) almost shorted the rails. The length of this zone was about ~20 mm, and it was symmetric relative to the initial position of the armature. In other regions (about 80 mm long) up to escape from the channel; no erosion of the rails was observed. This implies that the armature obtains a velocity of ~1 km/s due to expansion of the heated vapor of copper rather than due to electrodynamic acceleration.

A technical solution to the task of eliminating the catastrophic erosion of electrodes at the initial stage of acceleration in mm-sized channels is ensured by applying an additional external pulsed magnetic field in direction and comparable in magnitude (~10 T) with the magnetic field of rails. This solution allowed us to create a compact railgun of original design capable of accelerating 1 and 2mm-sized dielectric solid armatures up to velocities on the order of 6 km/s. Figure 1 shows a schematic diagram of the railgun and photo of railgun channel. The accelerating channel is equipped with two serially connected coils that create an additional external pulsed magnetic field with a direction parallel to that generated by the current passing in rail electrodes. The coils are situated symmetrically on both sides of the channel over its entire length and powered from an independent source. Capacitor banks for powering both the channel and coils were based on long LC lines and connected to loads via ignitron discharge gaps. These storages generated trapezoidal pulses with a steep front pulse and extended plateau. The load current was varied by changing the charging voltage of capacitors. The maximum stored energy in a capacitor bank powering the discharge was 12 kJ, and that powering the coils was 25kJ. Channel electrodes were made of copper in the form of flat rectangular plates of 1 : 4 or 1 : 5 aspect ratios. The electrode geometry and arrangement of magnetic coils ensured the concentration of magnetic field in the interelectrode gap, which led to a two to threefold increase in the magnetic field induction in the gap. Side insulator walls were made of an organic glass that allowed monitoring of a plasma piston moving along the channel. The accelerated body was placed in the channel at a

(a) (b)



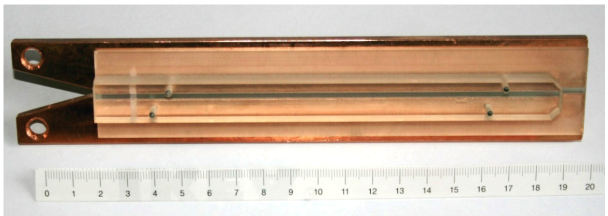


Figure 1. Scheme of railgun (a) and photo of railgun channel (b)

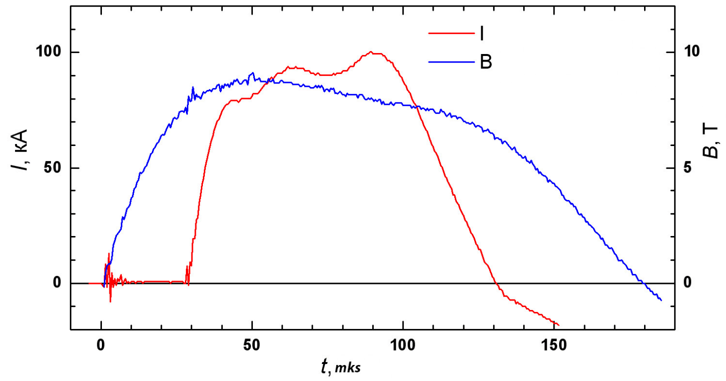


Figure 2. Discharge current (I) and magnetic field induction (B) in the channel of railgun

distance of several calibers from the back edge. The discharge was initiated via thin graphite stripes applied onto the side walls of the channel, which connected the electrodes. The current pulse to magnetization coils has been applied 20–30 µs before the accelerating pulse, so that the magnetic field in the channel would be close to maximum at the moment of pulse application to electrodes. As a result, the formation of a plasma piston in the channel and the armature acceleration begin before the moment when current and electrode erosion in the channel reach maximum levels. Figure 2 shows the typical forms of a discharge current and magnetic field induction in a railgun with 2mm channel.

All railgun shots and free flights of the accelerated body (pellet) were studied in air at atmospheric pressure. The pellet velocity was measured using a system of thinfilm sensors. The first sensor was situated at a distance of 150–200mm from the railgun front, and the distance between sensors was 100–110 mm. In addition, pellets were also monitored by a laser schlieren technique. In the experiments a maximum velocities was obtained - for 1mm cube 4.5 km/s and for 2 mm cube 5.7 km/s. Figure 3 presents schlieren picture of 2mm pellets flight in air at atmospheric pressure. The image reveal flying cube, as well as their orientation, and shock waves structure. Although the average acceleration of a pellet during its motion in the channel exceeded 10^7 m/s2, the images show that pellets remain intact.

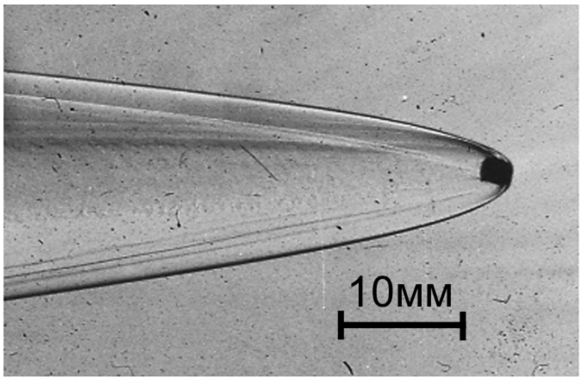


Figure 3. Schlieren photo of 2x2x2 mm3 pellet in fight in air at atmospheric pressure

Conclusions

The application of an additional pulsed magnetic field allow us to suppress catastrophic erosion of electrodes in compact railguns with mm-sized channels. Also this field increases the effective acceleration of a plasma piston.

Now it is possible to accelerate 1 and 2mm-sized solid bodies up to velocities on at level of ~6 km/s.

Short acceleration time and stable temporal characteristics of proposed compact railguns make possible their high-precision synchronization with other pulsed devices.

It is believed that, in thermonuclear research, the proposed devices can be used for a deep introduction of fuel into the reaction zone by accelerating LiD pel lets. Small acceleration times and high pellet velocities are important characteristics for the potential use of railgun accelerators.

Acknowledgments

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