

Two-stage light-gas magnetoplasma accelerator for hypervelocity impact simulation

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Abstract. The development of macroparticles acceleration methods for high-speed impact simulation in a laboratory is an actual problem due to increasing of space flights duration and necessity of providing adequate spacecraft protection against micrometeoroid and space debris impacts. This paper presents results of experimental study of a two-stage light-gas magnetoplasma launcher for acceleration of a macroparticle, in which a coaxial plasma accelerator creates a shock wave in a high-pressure channel filled with light gas. Graphite and steel spheres with diameter of 2.5–4 mm were used as a projectile and were accelerated to the speed of 0.8–4.8 km/s. A launching of particle occurred in vacuum. For projectile velocity control the speed measuring method was developed. The error of this method does not exceed 5%. The process of projectile flight from the barrel and the process of a particle collision with a target were registered by use of high-speed camera. The results of projectile collision with elements of meteoroid shielding are presented. In order to increase the projectile velocity, the high-pressure channel should be filled with hydrogen. However, we used helium in our experiments for safety reasons. Therefore, we can expect that the range of mass and velocity of the accelerated particles can be extended by use of hydrogen as an accelerating gas.

1. Introduction

The extended duration of space-flight missions and increase of a probability of spacecraft collisions with micrometeoroids and space debris make it necessary to provide reliable shielding for spacecraft. Collision velocities are relatively large: up to 15 km/s for space debris and up to 70 km/s for meteoroids [1, 2]. The size of such particles varies from tens of micrometers to a few meters. As particle size decreases, their number is growing rapidly and collisions with a particle of size less than 1 cm are the most probable [2]. At present, much attention is given to the study of high-speed impact fastness of spacecraft elements, which are critical to the meteoroid/debris impact.

Characteristics of these materials are investigated experimentally by use of various types of launchers, which accelerate projectiles up to speeds of 10–12 km/s [3, 4]. At present, two-stage light-gas guns are one of the most reliable and tried-and-true methods of macroparticle launching in the high-speed range of 2.5–10 km/s [5]. Light-gas guns provide repeatability and stability of the experimental results. They can be easily equipped with stationary measurement systems and allow acceleration of bodies of a predetermined shape and a relatively large weight to sufficiently high velocities. The main direction for further research to improve the characteristics of light-gas



Table 1. Regime parameters.

Capacitance of the bank	1200 μF
Initial voltage	4 kV
The maximum value of the discharge current	280 kA
The working chamber volume of the magnetoplasma comprescor	3.8 cm^3
The volume of the working substance ($\text{C}_2\text{H}_5\text{OH}$)	0.4–1.5 ml
Typical rise time of the discharge current to a maximum value	24 μs
The length of the barrel	70 mm
The helium pressure in the high pressure channel	15 MPa

launchers is the use of combined facilities that merge the principles of traditional light-gas guns and other types of accelerating units, providing additional acceleration of the projectile [6]. In order to increase the mass and velocity of a projectile, combined systems consisting of a light-gas gun and a plasma accelerator are used increasingly. Thus, an electrodynamic compressor was used in [7] to increase the density of the plasma accelerated by a coaxial accelerator. This gun accelerates glass beads with a diameter of 125 microns to the speed up to 15 km/s. A two-stage launcher consisting of a gas gun with a light accelerating gas and coaxial plasma accelerator with a compression coil allowed to throw glass beads with a diameter of 0.6 mm to speed about 20 km/s [8].

Currently, the development of new combined launchers, which allow improving launching speed, projectile weight, energy conversion efficiency and service life of acceleration system, is an actual problem.

This paper concerns the two-stage light-gas magnetoplasma launcher, in which the coaxial plasma accelerator generates a shock wave in the high-pressure channel filled with light gas.

2. Operation principles and design of the two-stage light-gas magnetoplasma launcher

The ballistic facility (figure 1) consists of the launcher, vacuum chamber with windows, vacuum pump, capacitor bank, high-voltage power supply, pulse generator, start unit and the velocity meter for projectile speed measurements. The launcher is placed inside the vacuum chamber. An investigated target is installed on the projectile flight path at some distance from the barrel.

The launcher has two-stage construction consisting of a magnetoplasma compressor and a high-pressure channel (figure 2). The high-pressure channel is separated on both sides by diaphragms and filled with light gas (He). A projectile is placed in the barrel.

Magnetoplasma compressor consists of two coaxial electrodes. A working substance ($\text{C}_2\text{H}_5\text{OH}$) is placed between the electrodes. When capacitor bank is discharged, electrical breakdown of the interelectrode space is occurring and plasma is being generated and accelerated, accompanied by its contraction due to the interaction of the longitudinal component of the current with its own azimuthal magnetic field. Physical principles of operation and operating parameters of such erosion plasma accelerator were studied in details in [9–11].

As a result, a compression flow of high density and a temperature is formed behind the inner electrode edge. This flow bursts the diaphragm and generates a shock wave in the high-pressure channel filled with light gas. A projectile is accelerated in the barrel due to the energy of gas heated and compressed by a shock wave. Experimental facility settings that were used during the ballistic tests are given in table 1.

The process of projectile flight from the barrel was registered by use of high-speed camera. Photoregistration was carried out at a frame rate of 200 000 fps and 1 μs image exposure. A

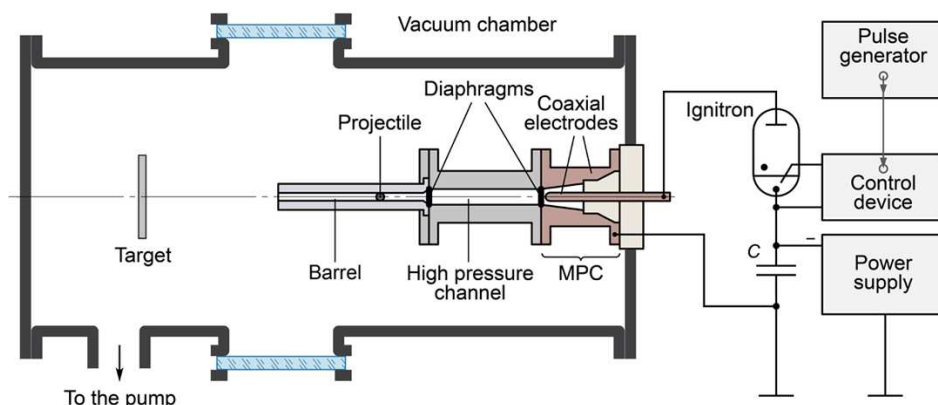


Figure 1. The scheme of the ballistic facility.



Figure 2. The photo of the two-stage launcher.

tubular halogen lamp with a power of 1 kW and irradiant body length of 189 mm was used as an illumination. Illumination was carried out at 45° to an optical axis of the camera in the direction of the test object. As we can see from the figure 3, obturation gas exits first from the barrel, the projectile and push light gas are the next. After some time, we see the output of the contact surface and the plasma.

3. Method of projectile velocity measuring

The projectile speed measuring method by barrel nozzle and opto-coupler was developed. It was used for velocity measurements of small bodies (2.5–4 mm) accelerated by light-gas magnetoplasma launcher in deep vacuum. A scheme of developed speed detector is shown in figure 4.

A thin wire and a thin strip of copper foil are fixed by use of a special barrel nozzle (figure 5) at a distance from each other behind the edge of the barrel and are connected to electrical



Figure 3. The high-speed photoregistration of the process of projectile output from the barrel.

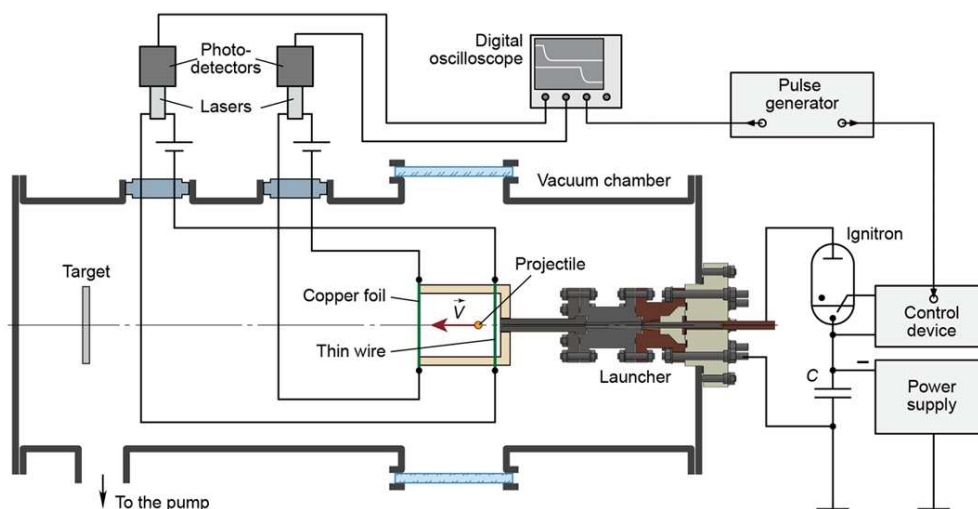


Figure 4. The scheme of projectile speed measurement.



Figure 5. The photo of the barrel nozzle with a thin wire and a strip of copper foil.

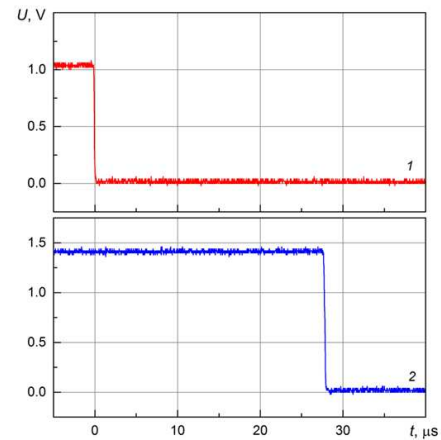


Figure 6. Typical oscillograms of photodetector signals.

circuits. Opto-couplers consisting of a semiconductor laser and a photodetector are used to protect against electrical noise.

A projectile breaks the wire and the foil after a shot. It causes the sequentially interruption of the signals from the optical sensors. The projectile speed can be calculated from the time interval between the interrupt signals and known distance between the wire and the foil. Typical oscillograms of photodetectors signals are shown in figure 6.

Projectile velocity measurements were made in a range of 0.8—4.8 km/s by the designed detector. Relative error of projectile speed measurement by use of this method was estimated by the formulas:

$$\delta_V = \frac{\Delta V}{V}, \quad (1)$$

$$\Delta V = \frac{\Delta L}{t} + \frac{L}{t^2} \Delta t, \quad (2)$$

where ΔV —absolute speed measurement error; V —projectile velocity; t —time interval between the interrupt signals; Δt —time measurement error; L —distance between the wire and the foil; ΔL —distance measurement error.

The error of projectile speed measurement by use of the presented method in the case of an ideal experiment is about 0.7%. In a real experiment, the push light gas can break through the walls of the barrel and the accelerated particle and cause fluctuations in a thin film. In this case, the measurement error increases to 5%. Thus, the presented method of speed measurement is pretty exact in a case of high degree of obturation.

4. Ballistic tests results

When conducting of experiments, investigated target was located at the projectile path behind the speed sensor. The angle of impact was 90°.

The result of a projectile impact on the aluminum plate of 10 mm thickness is shown in figure 7. Launched particle was a steel ball with a diameter of 2.5 mm, which was accelerated to a speed of 3.7 km/s. As a result of the impact, the crater with a diameter of 2.4 mm and a depth of 7.5 mm was formed. The molten material was pressed out from the crater and the

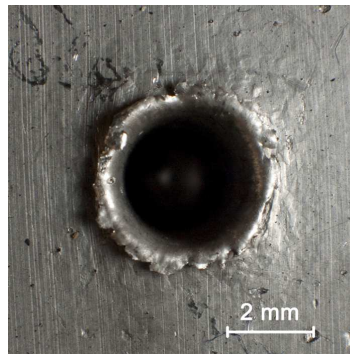


Figure 7. The photo of the aluminum plate after a high-speed impact.

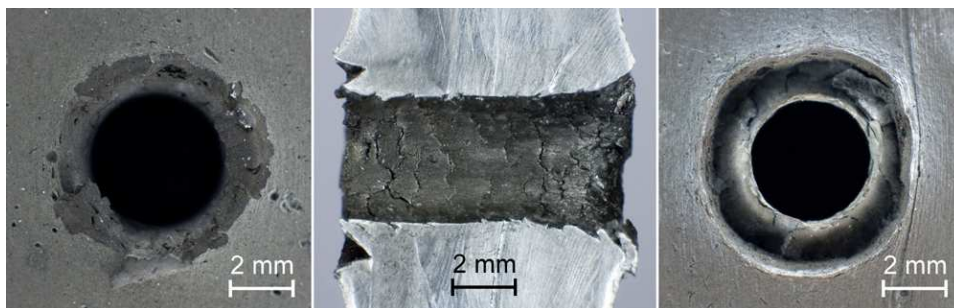


Figure 8. The photos of the duralumin plate of 8 mm thickness after a high-speed impact.



Figure 9. The photos of steel projectile 4 mm in diameter after the ballistic test.

roller was formed around it during solidification. The projectile stuck in the target, leaving the convexity on the target back side.

The results of projectile impact on the duralumin plate of 8 mm thickness are shown in figure 8. A steel ball with a diameter of 4 mm was accelerated to a speed of 4.25 km/s.

As we can see from figure 8, the steel projectile of 4 mm in diameter pierced duralumin plate of 8 mm thickness and formed shock wave, which causes the destruction of duralumin upon reflection from the free surface of the target and forms the centrally symmetric circular crater with a diameter twice the diameter of the projectile. Besides, the reverse shock wave, which was formed in the material of projectile caused the destruction of the projectile of high-duty bearing steel (figure 9).

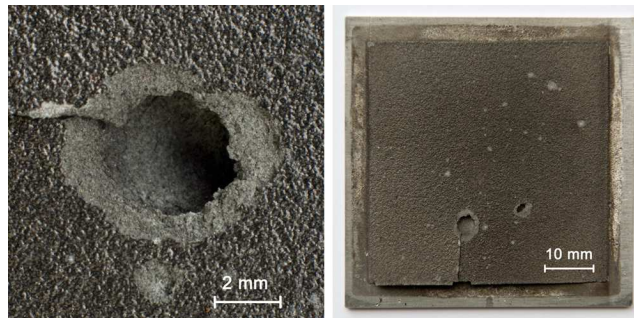


Figure 10. The photos of meteoroid shielding surface after high-velocity impact.



Figure 11. The high-speed registration of process of projectile collision with a target.

The result of a projectile impact on the meteoroid shielding element of increased resistance is shown in figure 10.

Launched particle was a graphite ball with a diameter of 2.5 mm, which was accelerated to a speed of 4.8 km/s. The meteoroid shielding element consisted of an aluminum substrate of 2 mm thickness and two-layer composite coating (viscous sublayer of NiAl and a top layer of high strength of Al_2O_3) modified by plasma flow impact. The element of meteoroid shielding was not broken after the impact of the accelerated particle. The crater with a diameter of 4 mm was formed on the surface of the target. The part of the composite coating was peeled off.

The process of projectile collision with a target was registered by use of high-speed camera. Photoregistration was carried out at a frame rate of 200 000 fps and 1 μs image exposure (figure 11). The target was duralumin plate of 2 mm thickness, which was located at a distance of 10 mm from the sample of a witness, composed of fluoroplastic of 8 mm thickness and lead of 3 mm thickness (figure 12). The speed of a projectile (steel ball with 2.5 mm diameter) was 1.5 km/s.



Figure 12. The photos of the target consisting of duralumin plate of 2 mm thickness, fluoroplastic plate of 8 mm thickness and lead plate of 3 mm.

5. Conclusions

The results of experimental study of a two-stage light-gas magnetoplasma launcher for acceleration of a macro particle, in which the coaxial plasma accelerator creates a shock wave in the high-pressure channel filled with light gas, has been presented. Graphite and steel spherical projectiles with diameter of 2.5–4 mm have been accelerated to the speed of 0.8–4.8 km/s. In order to increase the projectile velocity, the high-pressure channel should be filled with hydrogen. However, we used helium in our experiments for safety reasons. Therefore, we can expect that the range of mass and velocity of the accelerated particles can be extended by use of hydrogen as an accelerating gas. It is found that the resource of the barrel, in which projectiles are accelerated, is limited by 5–10 shots. The speed of a projectile decreases while the number of shots increases. It is due to the deformation of the barrel inner walls. The resource of the barrel can be improved by the use of projectile, which is made from a material of hardness lower than steel SH (aluminum, pyrolytic graphite).

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