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Study of influence of plasma gunner geometry on the density distribution of the plasma jet matter

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Abstract. The work is devoted to the study of the influence of the geometry of the plasma gun electrodes on the formation of the density profile of the plasma flow in a vacuum. The plasma was formed during a high-current vacuum arc discharge initiated along the surface of the dielectric. The experiments were carried out on a high-current generator IMRI-5 with a current amplitude in the load of 350 kA and a rise time of 600 ns. In the experiments, the image of the plasma jet was recorded at various times with an exposure of 3 ns, the voltage drop across the liner, the IMRI-5 current and its derivative. The plasma source is both the surfaces of the electrodes of the vacuum arc discharge and the dielectric along the surface of which the current of the IMRI-5 generator is initiated and flows. Aluminum was used as the cathode and anode material. The diameter of the rod cathode was 4 mm. During the research, two plasma gun geometries were used. In the first geometry, the end of the cathode lay in the same plane as the anode, and the thickness of the ring insulator was 2.5 mm. In this geometry, the initiation of the arc discharge and its combustion occur above the end plane of the insulator. In the second geometry, the end of the cathode was deepened into the anode on 5 mm relative to the plane from the anode. In this geometry, arc initiation and combustion is happening inside a hole in the insulator.

Key words: plasma jet, vacuum arc discharge.

1. Introduction

Previously, in [1–4], when conducting experiments on the formation and compression of the plasma shell of single and double-cascade metal-puff liners, the key role of the radial distribution of matter in the process of stabilization of RT-instabilities was shown. In [5] it was shown that the optimal case is when the radial distribution of the density of the substance corresponds to the power function $\rho(r) = \rho_0 \cdot (r/R_0)^{-s}$, where ρ_0 is the density of the substance at radius r, ρ_0 is the density of the substance at radius $r = R_0$, with $r \geq R_0$ and $s \leq -2$. All these conditions are observed when the liner shell is formed using a plasma gun, in which the liner substance is evaporated and delivered into the interelectrode gap of a pulse-power generator during a vacuum arc discharge. When using various modifications of the plasma gun, different compression parameters of such liners are recorded, so it was decided to study the factors influencing the initial conditions for the formation of the plasma shell of the liner and the final results of compression of such liners.

2. Experimental setup

Currently, in experiments with metal-puff liners, we use a plasma gun in two different modifications to form the plasma shell of the liner. These modifications (see Fig. 1a and Fig. 1b) differ only in the geometry of the cathode location relative to the annular anode.

In the first modification of the plasma gun (Fig. 1a), the end of the cathode and the anode are located in the same plane, while in the second modification the cathode is deepened inside the anode. The cathode and anode were made of aluminum. The capacitance of the plasma gun's capacitor bank is 20 µF. The charging voltage of the capacitor bank is 25 kV, arc current amplitude I_{pl} = 125 kA, current half-cycle $T_{1/2}$ = 11 µs. The inductance of the arc discharge circuit is L_{pl} = 570 nH with a resistance of the entire circuit at 40 mOhm. A vacuum arc discharge was initiated by a breakdown along the surface of the end of a polyethylene insulator. The diameter of the cathode located in the center of the gun was 4 mm. The diameter of the insulator was 9 mm.

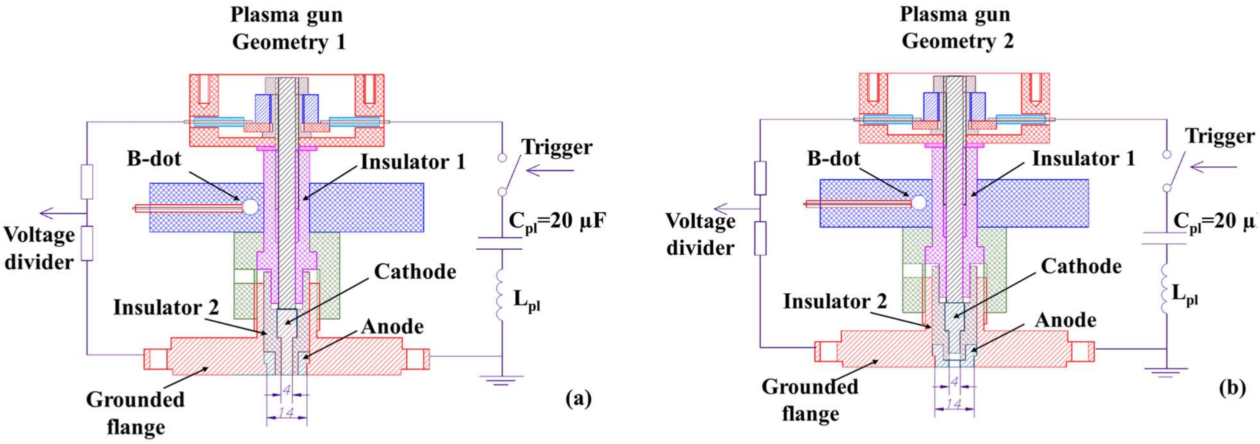

Fig. 1. Design and electrical circuit of a plasma gun for forming a plasma shell of a metal-puff liner.

After the plasma liner was formed, the main pulse-power generator IMRI-5 was switched on and a current begins to flow through the plasma shell, whose own magnetic field compresses the liner. The experiments were carried out on an experimental complex, which includes a pulse-power generator IMRI-5 [1] and a set of both electrophysical and optical diagnostics. The pulse-power generator IMRI-5 has the following parameters: at a charging voltage of 72 kV in short-circuit mode, the current amplitude is 450 kA, the rise time of the front is 450 ns.

3. Experimental results

From the moment the arc current begins to flow in the plasma gun, a plasma shell of the liner begins to form, the mass and initial radius of which depends on the delay time t_{del} of operation of the main pulse-power generator IMRI-5. By changing the delay time t_{del}, the liner compression time t_{impl} will also change. Fig. 2 shows a diagram of electrical measurements and the main parameters of the elements of the plasma gun circuit and of the IMRI-5 pulse-power generator circuit. As can be seen from Fig. 2, the delay time t_{del} of operation of the main high-current generator IMRI-5 relative to the arc discharge current is determined by the delay of operation of trigger 2 relative to trigger 1. After switching on the pulse-power generator IMRI-5, current $I_g(t)$ begins to flow through the liner, creating azimuthal magnetic field, which accelerates the substance of the plasma shell towards the axis of the system.

The calculation of the radial distribution of matter in the shell of the metal-puff liner was carried out based on the analysis of oscillograms of the current $I_g(t)$ flowing through the liner, its derivative $I_g(t)/dt$ and the voltage drop $U(t)$ in the section of the circuit where the liner is compressed. The calculation method is based on determining the inductance of the liner $L_l(t)$ at each moment of its compression based on the experimentally measured values of the current $I_g(t)$ flowing through the liner and the voltage drop $U(t)$ directly on the liner. Knowing the geometry of the load and the time dependence of the liner inductance $L_l(t)$, it is possible to calculate the dependence of the radius of the conductive shell of the liner $R_l(t)$ as a function of time. In order to verify the correctness of the calculation of the time dependence of the liner radius, optical recording of the plasma shell's own glow was carried out using a 4-frame HFSC-Pro optical camera with an exposure time of 3 ns. Having determined the dependence of the liner radius on time and knowing the current flowing through the liner, we can estimate the increment of the accelerated mass $dM_l(t)/dt$ at each moment of compression, and therefore estimate the mass of the liner at each moment of its compression. Accordingly, by calculating the mass of the liner, its velocity $\upsilon(t)$ and radius $R(t)$, we can also find the density of the substance $\rho(t)$ depending on the radius of the shell. The method for calculating the density profile of the liner shell material is described in detail in [6].

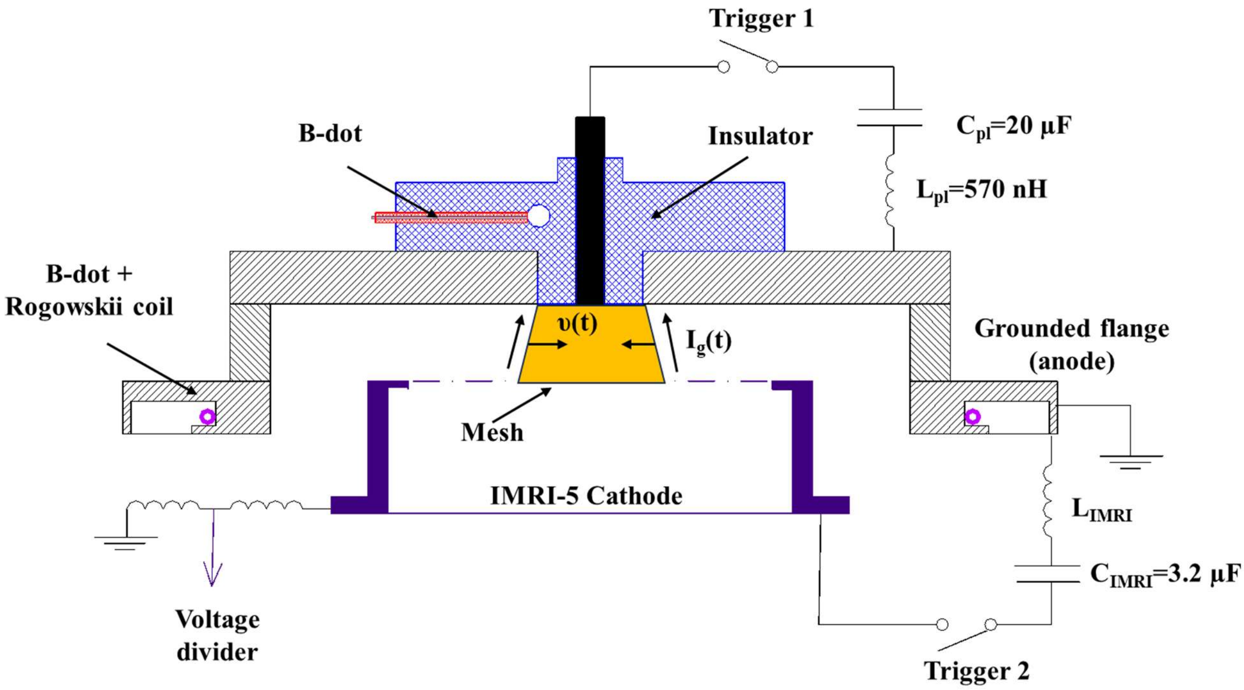

Fig. 2. Scheme of electrical measurements.

When analyzing the experimentally obtained data, we selected 4 shots that contain all the data on both optical imaging of the object under study and electrical measurements. Two of the selected shots were made with the first modification plasma gun (Shot#012 and Shot#017) and two with the second modification plasma gun (Shot#030 and Shot#033). In addition, to simplify the analysis of the obtained data, we tried to select shots made with initially close initial parameters. Table 1 shows such parameters of the selected shots as the delay time of operation of the IMRI-5 pulse-power generator relative to the beginning of the arc discharge current t_{del}, the compression time of the liner t_{impl}, which was determined from the time of maximum of the radiation pulse, and the amplitude of the signal from the vacuum X-ray diode (XRD). The radiation was recorded using a XRD with an aluminum photocathode located behind a filter made of aluminum foil 8 μm thick.

As can be seen from Table 1, Shot#017 and Shot#030 were made with a delay in the switching on of the pulse-power generator IMRI-5 relative to the start of current flow in the plasma gun t_{del} = 2.36 ± 0.04 μs, and Shot#012 and Shot#033 with a delay t_{del} = 3.36 ± 0.01 μs.

Table 1. Shot parameters.

Shot number	Plasma gun modification	Delay time t_{del} (μs)	Compression time t_{impl} (ns)	XRD (V)
Shot#012	1	3.37	769	1.6
Shot#017	1	2.31	569	17.6
Shot#030	2	2.36	525	27
Shot#033	2	3.35	644	9

Fig. 3 shows optical images of a imploding liner obtained in Shot#017 and Shot#030 with a delay in the switching on of the pulse-power generator IMRI-5 relative to the start of current flow in the plasma gun t_{del} = 2.36 ± 0.04 μs. In Fig. 3, on the left are images of the liner implosion obtained using a plasma gun of the first modification, and on the right, using a plasma gun of the second modification. This figure also shows typical oscillograms of current, voltage and signal from the XRD obtained in the Shot#030.

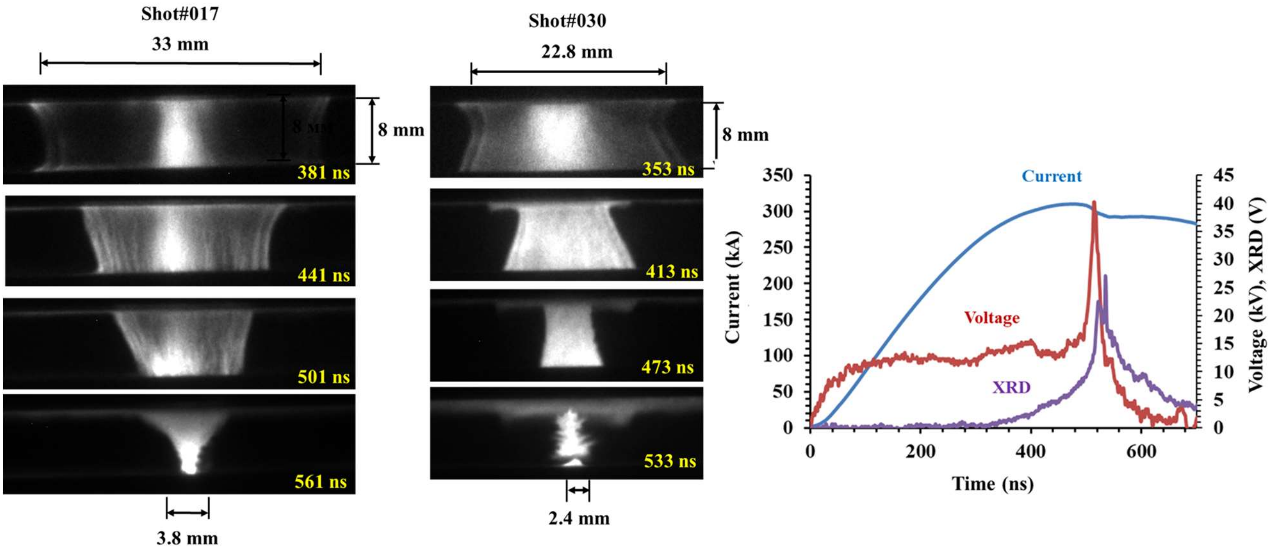

Fig. 3. Images of an imploding liner obtained in Shot#017 and Shot#030 at a delay t_{del} = 2.36±0.04 μs and an oscillogram of current, voltage and signal from the XRD, obtained in Shot#030.

Fig. 4 shows the calculated curves of the radius of the compressed liner for all 4 shots. In the same figure, circles and triangles show the values of the liner radii determined from optical images. It can be seen that the calculations agree quite well with what we observe using optical diagnostics.

Fig. 5 shows calculations of the plasma shell density profiles obtained using the method described in detail in [6].

4. Discussion of the obtained results

From the obtained optical images of implosion of metal-puff liners (see Fig. 4), we can conclude that the use of a plasma gun (both in the first and second modifications) to form a liner plasma shell makes it possible to form a shell in which, during implosion, the development of Rayleigh-Taylor instabilities are not observed. Based on the data illustrated in Figs. 4 and 5, both modifications of the plasma gun form plasma shells with a similar radial distribution of matter density, however, it can be argued that at the same time delays, the plasma gun of the first modification forms plasma shells of larger diameter.

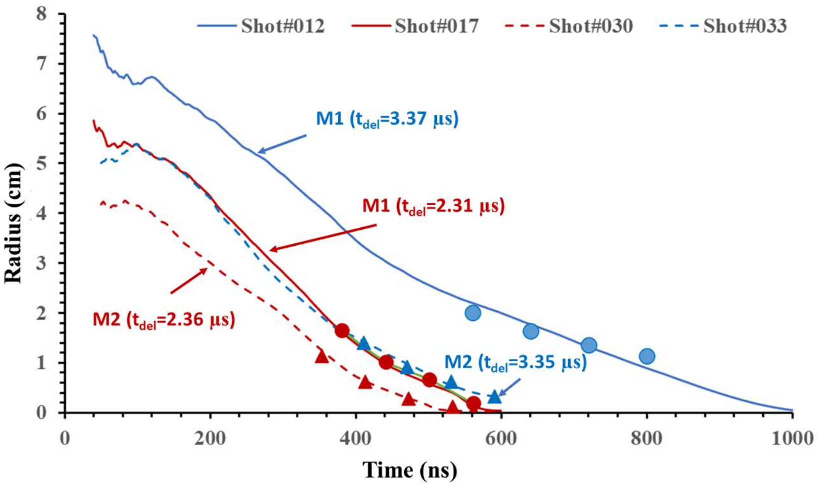

Fig. 4. Calculated liner implosion radius for all 4 shots. Circles and triangles show the values of liner radii determined from optical images.

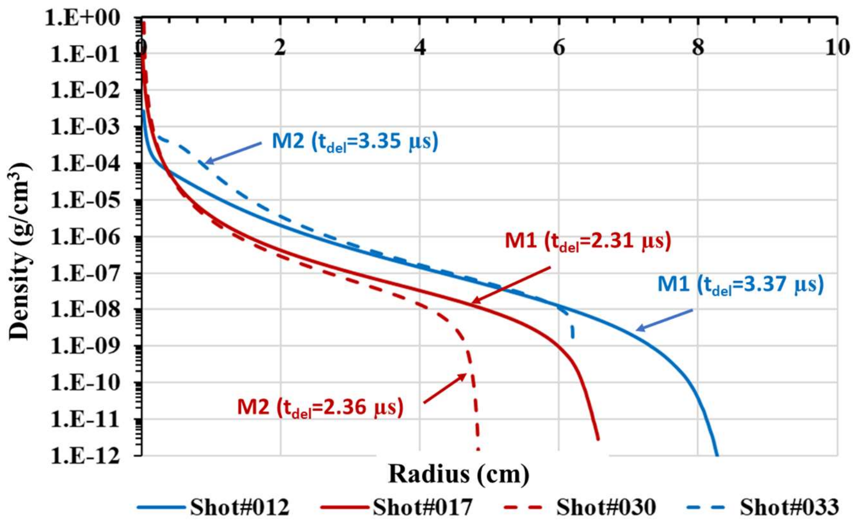

Fig. 5. Calculations of plasma shell density profiles.

Since the radial distribution of the substance in both modifications of the plasma gun is almost the same, and the radiation power for the first modification of the plasma gun is almost two times less compared to the second modification of the gun, it can be assumed that the effective compression of the liner, in this case, is hampered by the magnetic field of the "frozen" arc discharge into the plasma jet. Since the profile of the radial distribution of the density of matter is close to a power function with degree $s = -4.5$, the condition for suppression of PT-instabilities given in [5] is satisfied.

It should be noted that the types of plasma guns under consideration are characterized by a significantly different distribution of the shell material along its axis, since for these two modifications of the plasma gun the taper of the liner shell when compressed is directed in different directions (see Fig. 3). For the first modification, compression of the substance on the axis first occurs from above the liner and spreads from top to bottom, and for the second modification everything is exactly the opposite. It can be assumed that there is an intermediate design solution in which there will be no compression taper.

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