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# Study of directed plasma jets formed by high-current vacuum arc discharge

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**Abstract.** The work is devoted to the study of narrowly directed plasma jets in a vacuum, formed using a high-current vacuum arc discharge. The plasma jet was formed during the combustion of a vacuum arc discharge with initiation along the surface of a caprolon dielectric. The experiments were carried out on a pulse power generator IMRI-5 with an arc discharge current amplitude of 250 kA and a rising edge of 600 ns. The experimental setup is shown in Fig. 1. During the experiments, the image of the plasma jet was recorded at various times with an exposure of 10 ns, the current distribution along the plasma column, the radiation spectrum in the visible range, and the image of plasma propagation along the axis. 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. A steel rod with a diameter of 3 mm was used as a cathode. A plasma torch is formed in a plasma gun due to the pressure on the plasma from its own magnetic field of the arc discharge current distributed along the length of the plasma channel. Electrophysical measurements show that the front of the hydrogen jet moves at the beginning of the formation with a velocity of 30 cm/μs and slows down as it propagates along its axis. At the moment when the front of the plasma jet reaches the upper grid, its velocity is 5 cm/μs. Electrophysical measurements with B-dots show that the upper grid, located at a distance of 6 cm from the plasma gun, reaches 30% of the total arc discharge current.

**Key words:** plasma jet, vacuum arc discharge.

## 1. Introduction

The work is devoted to the study of narrowly directed plasma jets formed in a vacuum using a high-current vacuum arc discharge. Interest in this issue is due to the fact that in astrophysics there are a number of space objects in which the formation of very extended plasma jets consisting of ionized hydrogen is observed [1]. The study of cosmic jets and the elucidation of complex phenomena associated with them has long been based on a combination of analytical, observational and numerical studies. Given the presence of a sufficiently large volume of objects such as plasma jets observed in space, understanding of the process of their formation and interaction with other objects is still based only on theoretical models [2] and assumptions. Obviously, finding a real, experimentally controlled mechanism for the formation of such structures is extremely useful for studying such systems. In addition, there is great interest in modeling the interaction of hydrogen plasma jets with objects such as gas clouds or other plasmas that occur along the path of such a jet. Under certain conditions, results from laboratory experiments can be directly compared to astrophysical systems using scaling arguments. In this regard, it was desirable to find a method for forming hydrogen plasma jets [3].

Earlier [4], when conducting experiments on the formation of the plasma shell of liners, it was noticed that when using a high-current plasma gun, in which the end of the central rod cathode was located in the same plane as the anode, the formation of a plasma jet with weak divergence was observed. However, since the electrodes of such a plasma gun were made of aluminum, magnesium or bismuth, which easily evaporate at the current densities we used ($2\cdot10^6$ A/cm$^2$), the plasma jet mainly consisted of ions of the metal electrodes and hydrogen evaporating from the surface of the insulators. In order to minimize the amount of metal ions and increase the amount of hydrogen ions, we made all the electrodes from steel (which has a low erosion coefficient), and used caprolon as an insulator, from the surface of which the process of hydrogen evaporation is very active.

## 2. Experimental setup

The experiments were carried out on an experimental complex, which includes a pulse power generator IMRI-5 [5] and a set of both electrophysical and optical diagnostics. A plasma gun was used as a generator load unit (see Fig. 1), the electrodes of which were in the same plane and separated by a caprolon insulator.

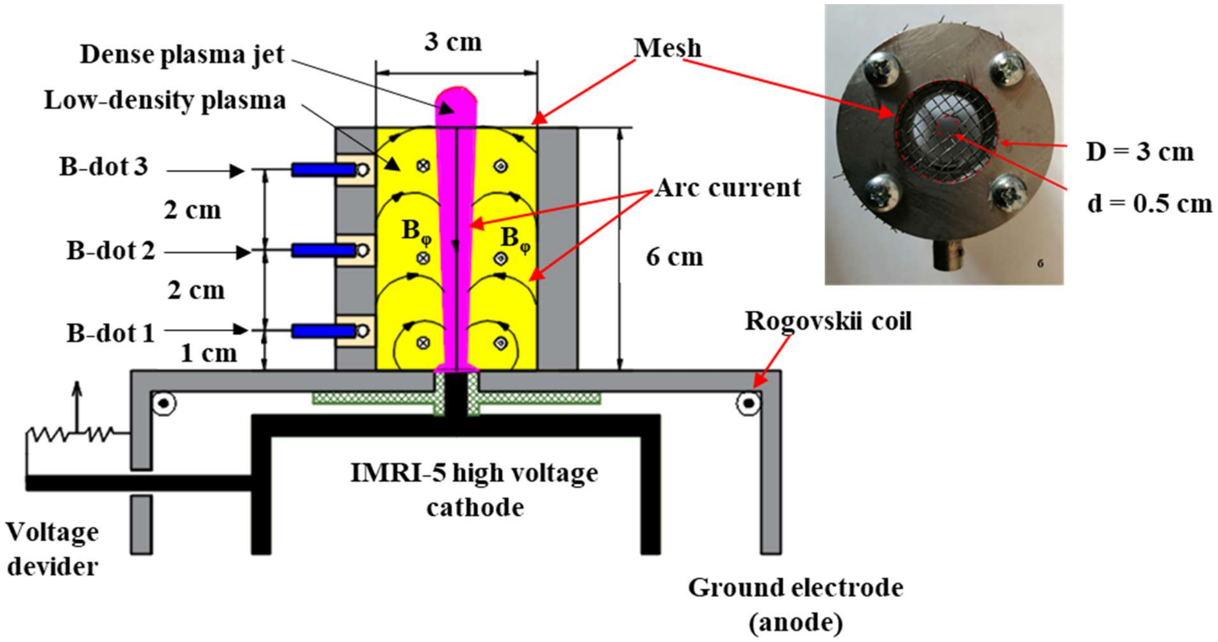

Fig. 1. Design of a plasma gun for jet formation and measurement scheme of current distribution along the height of the plasma jet.

A vacuum arc discharge was initiated by a breakdown along the surface of the end of a caprolon insulator. The diameter of the cathode located in the center of the gun was 3 mm. The diameter of the insulator was 10 mm. All gun electrodes were made of steel. The IMRI-5 pulse power generator has the following parameters: at a charging voltage of 72 kV in short-circuit mode, the current amplitude is 450 kA, the rise time is 450 ns, and when the IMRI-5 generator is used as a plasma gun, the current in the load is about 250 kA, the rise time current is 600 ns. Around the plasma jet there was a steel cylinder 6 cm high, at the end of which there was a steel mesh with a transparency of 75%.

## 3. Experimental results

Fig. 2 shows images of the plasma jet's own glow at various times relative to the beginning of the arc discharge current. To record the plasma jet image in the visible range, a 4-frame HSFC-Pro camera was used with an exposure time of 10 ns and a delay time between frames of 120 ns. It should be noted that the height of the observed plasma jet is limited by the dimensions of the vacuum chamber window. As can be seen from Fig. 2, the plasma jet begins to form from the very beginning of the high-current vacuum arc discharge. The initial diameter of the plasma jet is significantly smaller than the diameter of the arc discharge cathode and does not exceed 1 mm. As the height of the plasma column increases, its diameter also increases, without exceeding the diameter of the cathode. It is also clear that the hydrogen jet is subject to the development of hydrodynamic instabilities, which, as they develop, break the jet into separate clumps, which is very similar to what is observed in cosmic jets.

Since in experiments we observe the existence of an extended plasma structure with low divergence, it is logical to assume that such a structure can exist only if a current flows through the observed plasma sufficient to keep the plasma from radially expanding or, in other words, the system is in a Bennett equilibrium.

In order to understand how the current flowing through the plasma is distributed, measurements of the flowing current were carried out at different heights of the plasma column. A scheme of the measurement is shown in Fig. 1. To determine the total arc current, a Rogowski coil was used; to determine the arc current flowing at different distances from the plasma gun, B-dots were used, located at a distance of 1, 3 and 5 cm from the end of the plasma gun, the signals *dI/dt* of which were integrated over time. To calibrate the B-dots, additional measurements were carried out in which the section of the circuit on which the jet is formed was replaced with a metal rod connected to a grounded electrode; in short-circuit mode, the B-dots should measure the same *dI/dt*. The result obtained during these measurements is shown in Fig. 3.

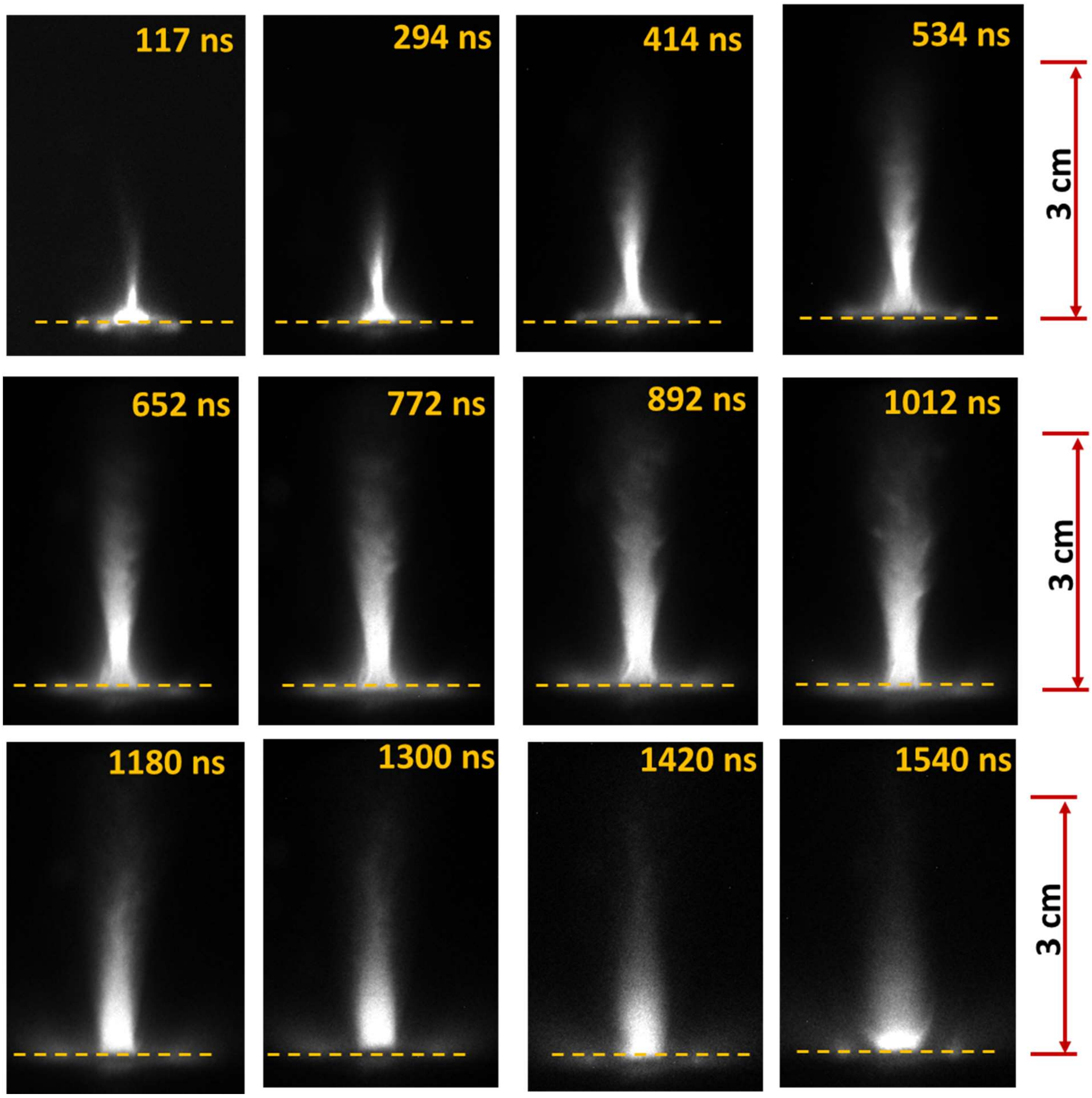

Fig.2. Hydrogen jet.

From Fig. 3 it can be seen that the current is distributed throughout the entire volume and part of the current is constantly lost as the height of the plasma column increases. It can be seen that at a height of 1 cm from the gun approximately half of the arc current flows, and at a height of 3 and 5 cm approximately 10% of the total current flows, which is about 30 kA, which is apparently quite enough to keep the plasma from radial expansion. It is also clear that the current at different altitudes begins to flow at different times, which gives us information about the velocity of movement of the plasma jet front.

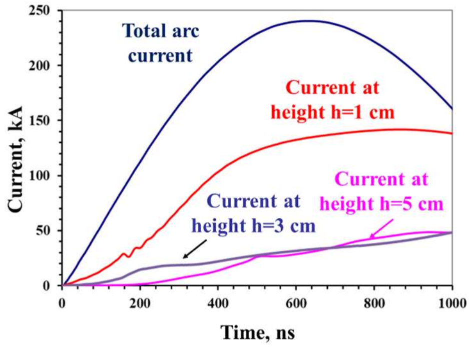

Fig.3. Current distribution in a plasma jet.

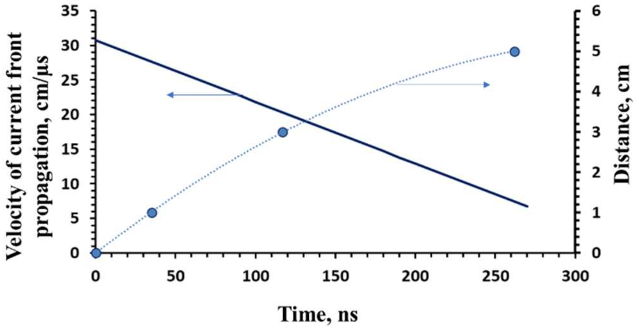

Fig.4. Plasma jet front. The circles are the time the current appears at various distances from the plasma gun; the dotted line is a second order polynomial; The solid line is the propagation velocity of the current-carrying jet plasma front.

Figure 4 shows the experimentally measured time of current appearance at different heights. It can be seen that the plasma propagation front initially has a velocity of about 30 cm/µs and slows down as it propagates and already at a height of 6 cm has a velocity of about 5 cm/µs.

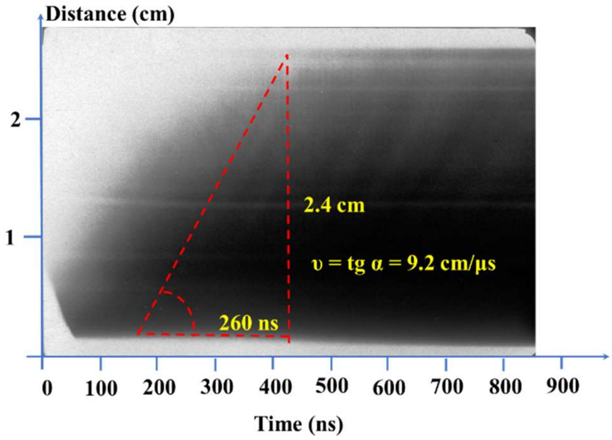

Fig. 5. The velocity of propagation of the dense part of the plasma jet.

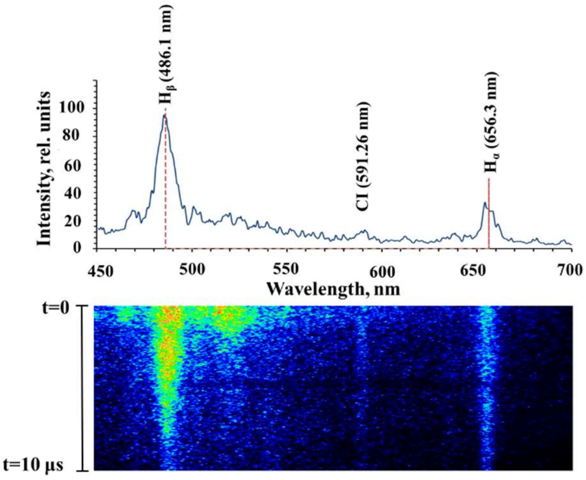

Fig. 6. Time scanning of the visible spectrum of a plasma jet.

When making estimates of the velocity of propagation of the current-carrying plasma front, we must understand that only the hottest, low-density part of the plasma moves at such velocity. The main part of the plasma jet moves much more slowly. To determine the velocity of propagation of the main mass of the jet plasma along its axis in the direction from the plasma gun, an optical chronograph with a slit FER-7 was used, with the chronograph slit located along the axis of propagation of the plasma jet. The chronograph sweep was 250 ns/cm. In this case, the tangent of the angle of inclination of the image of the propagating plasma relative to the time axis corresponds to its velocity, which is about 9 cm/µs.

In order to verify that the main substance of the plasma jet is hydrogen, in some experiments the visible spectrum of the plasma's own glow was recorded with time resolution. To record the visible spectrum of the plasma jet, a Hamamatsu Streak camera C10910 spectrometer with a slit scan was used. The spectrometer slit was located across the plasma jet at a distance of 1 cm from the end of the plasma gun. The resulting time-resolved spectrum is shown in Fig. 6. The same figure shows the intensity of spectral lines depending on the wavelength. As can be seen from the obtained spectrum, the main lines are the hydrogen lines $H_\alpha$ (656 nm) and $H_\beta$ (486.1 nm).

## 4. Conclusion

As a result of the research, a new method for forming a hydrogen plasma jet was developed. Using electrical probe measurements, the of propagation of the plasma jet front was estimated at various times and at a distance from 1 to 5 cm from the plasma gun. Near the plasma gun, the velocity of propagation of the plasma jet was about 300 km/sec, and by the time it arrived at the upper grid, the velocity slowed down to 50 km/sec. An optical chronograph showed that the velocity of movement of the main mass of the plasma jet is about 90 km/sec. Using spectral diagnostics, it was proven that plasma jet indeed consists mainly of hydrogen. The obtained spectral data in combination with optical and electrical measurements will make it possible to further simulate the process of formation of such plasma structures.

## Acknowledgement

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## 5. References

[1] Bo Reipurth, S. Heathcote, J. Morse, P. Hartigan, J. Bally, Hubble Space Telescope Images of the HH 34 Jet and Bow Shock: Structure and Proper Motions, *The Astronomical Journal*, vol. **123**(1), 362, 2002, doi: 10.1086/324738

[2] E.M. Urvachev, T.V. Loseva, A.N. Lyakhov, Yu.I.. Zetser, Numerical simulation if high-speed plasma jets outflow into vacuum (in Russian), *Phizika plazmy*, **49**(11), 1118–1126, 2023, doi: 10.31857/S0367292123601145

[3] S.V. Lebedev, et al., Exploring astrophysics-relevant magnetohydrodynamics with pulsed-power laboratory facilities, *Reviews of Modern Physics*, vol. **91**, 2019, doi: 10.1103/RevModPhys.91.025002

[4] A.G. Rousskikh, A.P. Artyomov, A.S. Zhigalin, et all., Radiographic Investigation of Metal-Puff Plasma Jets Generated by Vacuum Arcs, *IEEE TPS*, vol. **46**(10), 3487–3492, 2018, doi: 10.1109/TPS.2018.2849205

[5] A.G. Rousskikh, V.I. Oreshkin, A.Yu. Labetsky, S.A. Chaikovsky, and A.V. Shishlov, Electrical Explosion of Conductors in the High-Pressure Zone of a Convergent Shock Wave, *Technical Physics*, vol. **52**(5), 571–576, 2007, doi: 10.1134/S1063784207050064