Measurement of the expansion velocity of the plasma high-current vacuum arc discharge

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Abstract. In this work, we present experimental results on measuring the velocity of vacuum arc discharge plasma expansion. In the experiments, two designs of plasma guns were used. In the first version, the end of the arc discharge cathode was located below the plane of the anode, and the surface of the insulator separating them was parallel to the axis of symmetry of the plasma gun. In this design, the arc discharge plasma escapes the anode through a hole, the diameter of which coincides with the diameter of the cathode. In the second variant, the plane of the end face of the arc discharge cathode coincided with the plane of the anode, and the surface of the insulator separating them was located perpendicular to the axis of symmetry of the plasma gun. To obtain an image of plasma in the optical range, an FER-7 optical streak camera was used. Based on the results obtained, it can be concluded that the expansion velocity of the plasma of a high-current vacuum arc discharge does not depend on the design of the guns considered in this experiment.

1. Introduction

Currently, fast Z-pinch devices are widely used to obtain dense high-temperature plasma [1-3]. The compression of fast Z-pinches occurs under the action of a powerful current pulse, which creates a magnetic field pressure on the outer surface directed radially to the axis of the plasma shell. Traditionally, multiwire, gas and foam liner shells are used as compressible material. In recent years, the Institute of High Current Electronics has been intensively investigating an alternative method of forming the plasma shell of the liner, namely the metal-puff Z-pinch [4, 5]. The Metal-puff Z-pinch is a fully ionized metal plasma jet. To generate plasma, a pulsed vacuum arc discharge with a current amplitude of 100-200 kA is used. When using a metal-puff Z-pinch, it is assumed that most of the plasma jet material remains on the system axis, in which the pinch is compressed. In this regard, it becomes important to determine the velocity of the plasma outflow from the plasma gun into vacuum. In the presented work, the velocity of the plasma jet was measured for two designs of a vacuum-arc plasma source (plasma gun). To determine the plasma velocity, the velocity of the displacement of the plasma glow boundary along the axis direction of the plasma flow in the visible spectral range was recorded.

2. Experimental setup and results

Experiments on measuring the velocity of the outflow of a plasma jet from a plasma gun into a vacuum gap were carried out using plasma guns based on a vacuum-arc plasma source. The plasma...
The arc current was sinusoidal with an amplitude of up to 350 kA and a quarter-period duration of about 600 ns. The plasma jet was a jet of ionized metal evaporated from the surface of the arc electrodes. In the experiments, two designs of plasma guns were used. In the first version, the end face of the arc discharge cathode was located inside the insulator separating the cathode and the anode (figure 1), and the insulator surface separating them was parallel to the axis of symmetry of the plasma gun. In this design, the plasma jet flows into vacuum through the anode via a hole whose diameter coincides with the diameter of the cathode and the hole in the insulator. The cathode diameter $d$ varied from 3 to 6 mm. The distance from the cathode to the anode along the surface of the insulator, $h_1$, varied from 2 to 6 mm. The length of the anode channel ($h_2$) was unchanged and amounted to 3 mm.

In the second version, the arc discharge cathode end face surface coincided with the surface of the anode (figure 2), and the surface of the insulator separating them was located perpendicular to the axis of symmetry of the plasma gun.

The main difference between the plasma guns used is that in a plasma gun with a collimator (scheme 1), the entire arc discharge current flows between the electrodes only inside the hole connecting the cathode and anode (inside the collimator) and does not go beyond the anode. When using scheme 1, the evaporated and ionized substance of the arc electrodes enters the vacuum in the form of a wide jet expanding at a certain angle to its axis.

When using an open-type plasma gun (scheme 2), a significant part of the arc current is carried away by the plasma and carried out into the vacuum gap outside the gun. The intrinsic magnetic field of the arc discharge current keeps the plasma from expanding. The evaporated and ionized substance of the arc electrodes enters the vacuum gap in the form of a plasma column, the diameter of which is close to the diameter of the arc discharge cathode [7].

The following types of diagnostics were used: the voltage drop along the arc was measured using an active voltage divider; the Rogowski coil was used to measure the total current $I(t)$ flowing through the arc; a slit streak camera FER-7 was used to register the velocity of the plasma glow boundary along the axis of the plasma jet in the visible range of the spectrum [8].
Figure 3. Experiment scheme ($f$ is the focal length of the lens).

Figure 3 shows the scheme of the experiment. The distance from the plasma jet axis to the lens was equal to two focal lengths $f$ of the given lens, and the same distance was from the lens to the streak camera slit. As the plasma jet spread away from the plasma gun, its glow fell on the streak camera slit. The streak camera slit was located parallel to the axis of the plasma gun, that is, parallel to the $Z$ coordinate. The plasma glow on the streak camera was recorded with a time base of 750 ns/cm. The slit height was 9 mm, width 200 $\mu$m. The plasma velocity along the $Z$ axis was calculated from the angle of plasma image inclination to the time axis for a given time base and a known image scale (see figure 4), $v \propto a/b$.

Figure 4 shows a chronogram of the aluminum jet movement obtained in a shot with the open-type plasma gun.

Table 1 shows the calculation data for the plasma expansion velocity, calculated from the images obtained with the slit streak camera FER-7, depending on the cathode diameter and the distance $h_1$ between the cathode and anode over the insulator surface.

Figure 4. Chronogram of the plasma jet motion.
Table 1. The calculation data for the plasma expansion velocity.

| Cathode diameter \( d \) (mm) | Channel depth along the insulator \( h_1 \) (mm) | Velocity \( v \) (cm/µs) |
|-------------------------------|--------------------------|-------------------|
| Setup 1                       |                          |                   |
| 3                             | 2                        | 2.7               |
| 3                             | 3                        | 2.9               |
| 3                             | 4                        | 2.9               |
| 3                             | 6                        | 3                 |
| 4                             | 3                        | 2.7               |
| 4                             | 6                        | 2.6               |
| 6                             | 2                        | 2.6               |
| 6                             | 4                        | 3                 |
| 6                             | 6                        | 2.9               |
| Setup 2                       |                          |                   |
| 3                             | 0                        | 2.7               |
| 4                             | 0                        | 3                 |
| 6                             | 0                        | 2.9               |

3. Conclusion

It follows from the data obtained that the averaged velocity of the plasma jet for Setup 1 is \( v = 2.84^{+0.16}_{-0.24} \) cm/µs, for Setup 2 \( v = 2.87^{+0.11}_{-0.07} \) cm/µs. Based on the results obtained, it can be concluded that the expansion velocity of the plasma of a high-current vacuum arc discharge does not depend on the design of the guns considered in this experiment.

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