doi: 10.56761/EFRE2022.S6-P-021102

Numerical model of high current plasma source

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Abstract. In this paper, we numerically analyze a “capillary” type plasma source used to create plasma liners in gas puff z-pinch experiments. It is shown that erosion from a plasma source of this type, observed in the experiment, is provided by evaporation of the electrodes. Moreover, the main contribution comes from evaporation from the anode. The calculation results are in qualitative agreement with the experimental data.

Keywords: high current vacuum arc, plasma source, cathode erosion, gas puff z-pinch.

1. Introduction

Recently, the Institute of High-Current Electronics has been using plasma sources in the configuration schematically shown in Fig.1 [1, 2] to pump plasma liners for subsequent z-pinch implosion. Formally, the discharge burning in a plasma source of this type is a vacuum arc. However, in this case, the discharge has an abnormally high average current density at the cathode. The average cathode current density here is the total current divided by the surface area of the cathode. In various experiments, a current from tens of kiloamperes to several megaamperes was passed through similar plasma sources [2–4]. Considering that the diameter of the cathode rod in the plasma gun was several millimeters, the average cathode current density reached 10^5–10^6 A/cm^2. Recall for comparison that the average cathode current density in modern high-current vacuum-arc interrupters is about 10^3 A/cm^2. Under such conditions, the specific cathodic erosion in interrupters remains close to the canonical cathodic specific erosion measured in low-current arcs (of the order of 15–170 μg/C for various metals [5]). By measuring the masses of plasma liners by various methods, it was concluded in [1–4] that the specific erosion of plasma sources (Fig.1.) should be ten times higher than the canonical specific cathodic erosion of low-current vacuum arcs.

Previously, we demonstrated that the average cathode current density at the level of 10^5 A/cm^2 can be the cause of anomalously high specific erosion [6]. It has been shown that, due to heating by cathode spots and plasma flows, the cathode surface can be heated to a temperature exceeding the boiling point. In this case, evaporation from the cathode surface between the cathode spots of metal vapors, followed by ionization in the combined plasma column of a vacuum arc, can become a significant addition to the erosion of cathode spots. However, in [6], an “open” electrode configuration was analyzed, in which the annular anode was in the same plane as the cathode. In this configuration, the current density at the anode remains significantly less than the cathode current density. The anode remains relatively cold, so evaporation from the anode can be neglected. In the “capillary” configuration (Fig.1) this is obviously not the case. In this paper, we evaluate the contribution to erosion of a capillary-type plasma source due to evaporation from the cathode and anode.

2. Experimental results

The experiment was carried out on the IMRI-5 generator (450 kA, 450 ns in short-circuit operation). The load of the IMRI-5 generator was a plasma gun. Experimental setup is sketched in Fig.1. The rod cathode and ring-shaped anode of the plasma gun was made of aluminum. The diameter of the Al cathode was 3 mm.

The discharge current with a load in the form of a plasma gun is shown in Fig.2 (blue curve). The current amplitude reached 325 kA. The pulse duration was 1.2 μs. The mass of the plasma jet emitted from the plasma gun was determined by x-ray radiography (Fig.2, black points). The approximation curve of mass versus time dependence (Fig.2, dashed curve) is numerically equal to the current pulse in kiloamperes multiplied by 0.45 and shifted from the beginning of the pulse by 0.4 μs.

Using an experiment in which the cathode and anode of a capillary plasma gun were made of different metals, it was shown that anode erosion makes a significant contribution to the total erosion of a given plasma source.

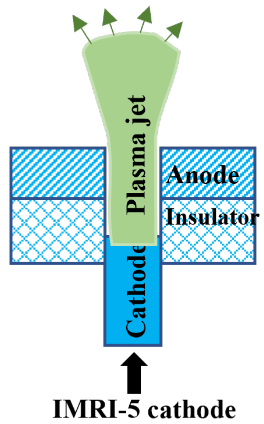

Fig.1. Sketch of plasma source.

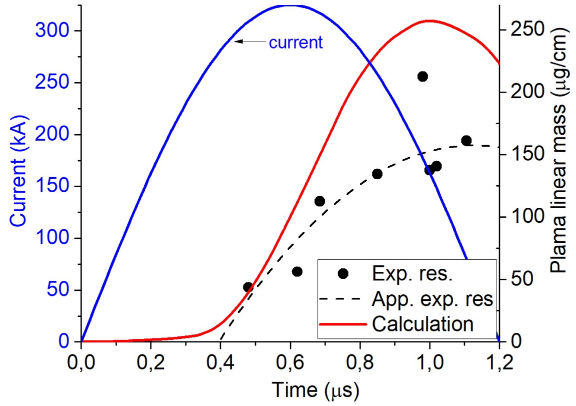

Fig.2. Plasma linear mass and arc current versus time. Points – experimental results; dashed curve – approximation of experimental results; red curve – calculation results; blue curve – current pulse.

3. Brief model description and some calculation results

The configuration and dimensions of the computational domain are shown in Fig.3, Fig.4. The plasma dynamics in the regions V1 and V2 was modeled using the two-temperature MHD approximation. The transfer of radiation by the P1 method and the processes of ionization and recombination were taken into account. Previously, a similar approach was used in [7] to simulate a high-current vacuum arc in a transverse magnetic field.

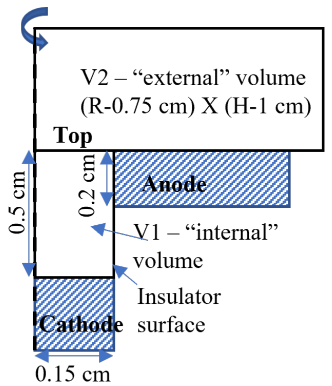

Fig.3. Arrangement and dimension of calculation domain.

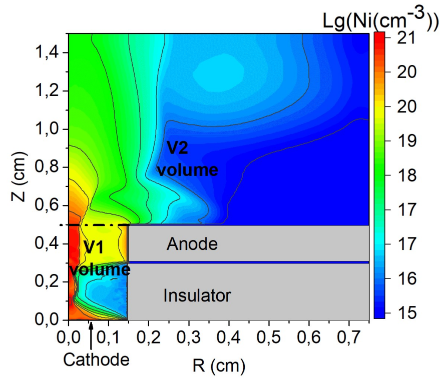

Fig.4. Ion density distribution for 400 ns time instant.

The model calculated the heating of the cathode and anode, followed by evaporation and ionization by metal vapor. To simplify the calculations, the so-called “maximum erosion" model was applied. Evaporation was calculated according to the Langmuir formula. Vapor condensation was not taken into account. When calculating the heating of the anode, contributions from the electron energy flow, radiation from the plasma and cooling by evaporation were taken into account. When calculating cathode heating, contributions from cathode spots, plasma radiation and evaporation cooling were taken into account. Erosion from the insulator surface is considered very approximately. It is postulated to be equal to half of the normal specific erosion of the cathode (aluminum, 15 μg/C).

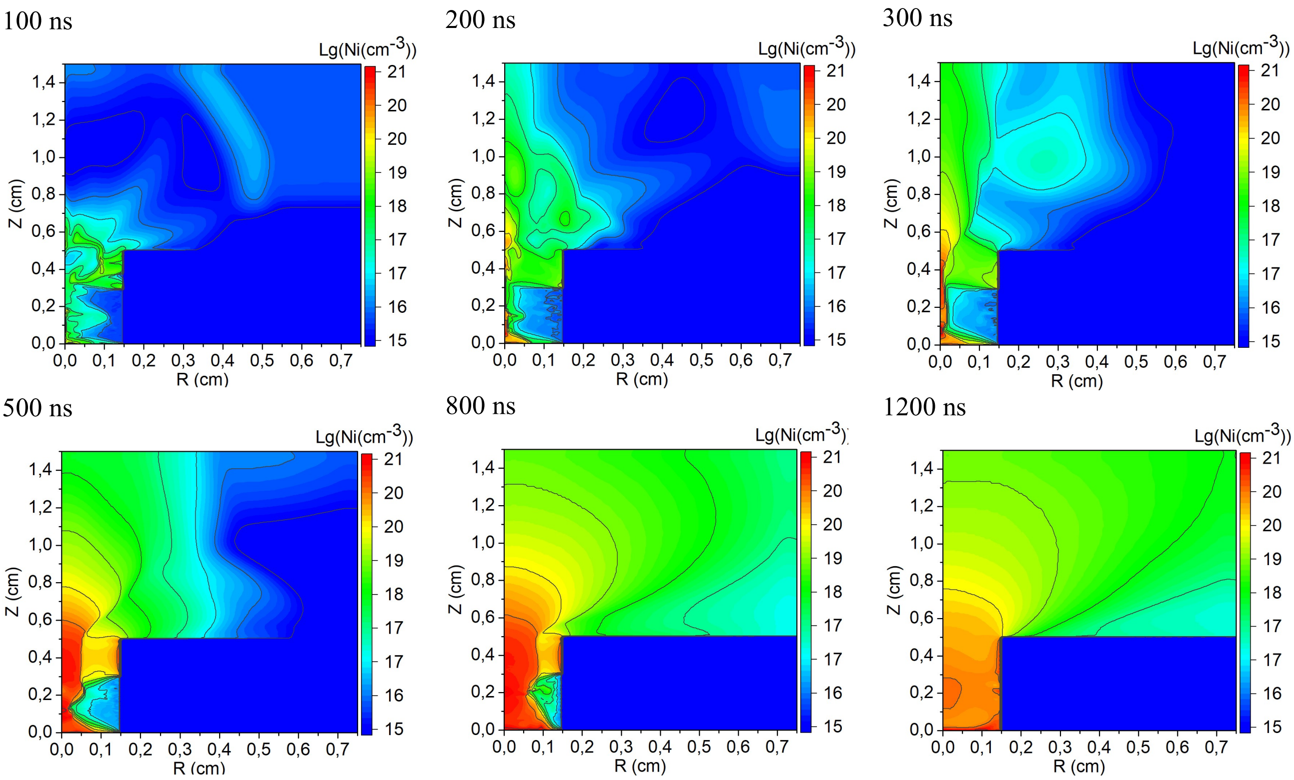

Fig.5. Ion density distribution at different instants.

The evolution of plasma in the gap over time is shown in Fig.4, Fig.5. Up to 300 ns, plasma is delivered to the gap mainly due to standard erosion from cathode spots and from the surface of the insulator. During this period, the plasma flow in the V1 region is pinched from time to time and is highly variable. After 300 ns, the main supplier of plasma to the interelectrode gap becomes the anode and remains so throughout the entire current pulse (Fig.6). The specific erosion of the cathode also increases but remains less than the anode one. The plasma flow after 400 ns is stable. It is this period that makes the main contribution to the erosion of the plasma gun. The erosion from the plasma gun in our configuration is the flow from V1 into V2 via the Top surface (Fig3, Fig.4). The main plasma flow from the gun (Fig.6, glue curve) starts after 400 ns, which agrees well with the experimental result (Fig.2, compare red curve with dashed curve).

The specific erosion of the plasma gun is shown in Fig.7. It can be seen that the specific erosion of the gun already after 200 ns significantly exceeds the standard specific cathodic erosion. After 600 ns, the specific erosion of the gun exceeds 2000 μg/C, which is more than 100 times higher than the standard erosion. The main contribution to this erosion comes from anode evaporation.

Comparing the calculated and experimental data, one can see that the model, despite the roughness of the evaporation model, predicts well the moment of the beginning of the main erosion of the plasma gun. However, at the maximum, the calculated linear mass of the plasma is almost two times greater than the mass obtained in the experiment. The reason for this is most likely a crude evaporation model.

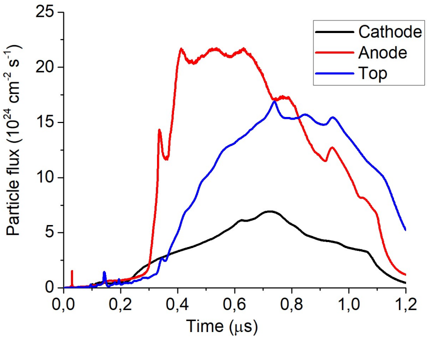

Fig.6. Ion fluxes from different surfaces.

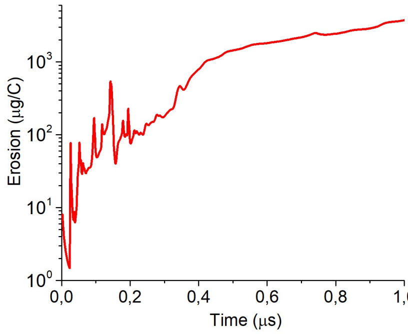

Fig.7. Specific ion erosion over Top surface.

4. Conclusion

A computational MHD model of a "capillary" plasma gun is constructed. It is shown that the erosion observed in the experiment from a plasma source of this type is provided by evaporation of the electrodes. Moreover, the main contribution comes from the evaporation of the anode. The calculation results are in qualitative agreement with the experimental data.

Acknowledgements

The work was supported by the Russian Science Foundation (Grants No 22-19-00686).

5. References

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