On plasma sheath motion in coaxial electrode system

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Abstract. Current-plasma sheath dynamics in coaxial pulsed plasma system was simulated in this work by means of one-fluid MHD code and two-dimensional “snow plough” model.

1. Introduction

The phenomenon of self-acceleration of current-plasma sheath with its own magnetic field during its motion between coaxial electrodes is used in various devices: plasma accelerators [1, 2], non-cylindrical z-pinches [3–5], plasma thrusters [6, 7] etc. Plasma sheath mass losses on the electrodes are often neglected in models that describe plasma motion in coaxial systems. It is correct for equilibrium flow. However, the phenomenon of electrode influence on plasma motion in pulsed plasma systems is much more complex compared with equilibrium flow theories, because the accumulation of matter takes place near the electrodes surface.

Such matter accumulation process is poorly studied experimentally [5, 8]. To carry out such researches one needs to develop special electrodes with diagnostic windows along them, get rid of spurious irradiation from plasma. Such electrode modification will lead to device operation changes. However such studies are essential for development and creation of workable equipment. Not all presently existing numerical models of plasma dynamics in coaxial electrode systems allow to simulate the interaction of current-plasma sheath with electrodes [9–11]. Consequently there is a challenge to create a code for numerical simulation of plasma motion and interaction in coaxial electrode system and to develop by its means optimal electrode system configurations for each specified task.

The problem of pulsed plasma dynamics in coaxial electrode system was considered. Plasma motion was simulated by one-fluid MHD code used earlier for modelling of Z-pinches [12] and two-dimensional model “Snow plough” which is often used for plasma focus sheath simulation [13].

2. Simulation results

2.1. MHD model

For the sake of simplicity and clarity the dynamics of current-plasma sheath was simulated in electrode system with coaxial cylindrical electrodes.

Simulation of plasma motion between two coaxial electrodes by means of one-fluid MHD code shows that only a small fraction of working substance is carried away by current-plasma sheath, but substantial fraction is left behind.
After consideration of working substance distribution changing in time (figure 2) one can notice that on the initial stage of movement plasma sheath completely pushes off the gas (figure 2a). During farther movement growth of plasma sheath’s mass stops. Mass of gas that is carried away by the sheath in unit time becomes equal to the mass of leaking along the electrodes substance.

Simulation results show that the value of axial component of left behind plasma’s velocity (~$10^5$–$10^6$ cm/s) is by 1–2 orders of magnitude less than plasma sheath’s velocity (~$2 \cdot 10^7$ cm/s). The main mass of working substance is lost during plasma sheath interaction with outer electrode. Left behind plasma is distributed along the electrode in the shape of “wavy” structure, which period depends on the width of interelectrode gap (figure 3).
Figure 2. Working substance mass distribution along electrode system axis 0.65 μs, 0.9 μs, and 1.15 μs after discharge beginning.

Figure 3. Working substance distribution dependence on the interelectrode gap width \( d \).

2.2. “Snow Plough” model
In addition to MHD modelling plasma sheath motion was simulated by means of two-dimensional “snow plough” model. Electrode system geometry and all initial parameters (pressure and working gas type, energy content, outer circuit parameters) were the same as in MHD model. Simulation of consecutive motion of current-plasma sheath is presented on figure 4. Contrary to MHD model where current-plasma sheath has finite thickness in “snow plough” model the sheath is infinitely thin.
Figure 4. Consecutive motion of current-plasma sheath in coaxial cylindrical electrode system.

With the same initial parameters the value of current-plasma sheath velocity along the electrodes obtained by means of “snow plough” model differs from the one obtained by MHD code by less than 10%. Working substance distribution along the axis in “snow plough” simulation is also similar to MHD model (figure 5). The distribution has a sawtooth shape due to bigger step size in “snow plough” model.

Figure 5. Working substance mass distribution along electrode system axis 1.25 μs after discharge beginning.

The main difference between current sheath dynamics in “snow plough” model and in MHD model involves lacking of “wavy” structure of substance flown from the sheath. Current-plasma sheath in “snow plough” model has curved inward sections only on the initial stages of its development. These sections will be considered below.

3. Results analysis

The results of MHD simulation show that particles from plasma sheath have a radial component of velocity besides of axial one (figure 6). In accordance with this data, one can suppose that carried away particles drift along plasma sheath towards outer electrode, collide with it, lose part of their kinetic energy and then travel in a “wavy path”.

On the assumption of this theory, one can suppose that if the interelectrode gap is made widened then the particle losses on the electrode surface will be mitigated. For the sake of simplicity let us assume that radial and axial components of the velocities of particles in current-plasma sheath $V_r = \text{const}$, $V_z = \text{const}$ (which is not technically correct) along all sheath. In this case if the electrode surface is at an angle $(\alpha) \geq \frac{V_r}{V_z}$, then the particles from plasma sheath will not reach it and the “wavy” structure will not develop. As a check on this assumption electrode system with widened outer electrode ($tg(\alpha) = \frac{V_r}{V_z}$) was simulated (figure 7). The results of simulation show that the “wavy” structure does not appear.
Figure 6. Particle motion pattern in relation to current-plasma shell.

Figure 7. Working substance distribution in electrode system with widened interelectrode gap.

Besides plasma that is flowing out of the current-plasma sheath along its path there is another slowly moving along the outer electrode plasma formation. This phenomenon is presented in MHD simulation as well as on early steps of plasma sheath development in “snow plough” simulation (figures 7 and 4 respectively).

Current-plasma sheath development was closely examined on the stage of its separation from the insulator in MHD model. It was noticed that current-plasma sheath consists of two components: slowly moving one and fast moving one drawn along the inner electrode (figure 8). The fast component outruns the slower one. The substance from their intersection area is pushed from the inner electrode towards the outer electrode and plasma is left behind fast moving sheath.

4. Possible negative effects due to left behind plasma

Presence of left behind plasma can lead to appearance of parasitic bypassing currents in the interelectrode gap (figure 9). Such bypassing currents can lead to changes in electrical parameters of devices, their malfunction and failure in achievement of required parameters of operation.

For working substance losses mitigation it is recommended that the electrode system should have widening interelectrode gap. The law of gap widening for each device will depend on radial and axial plasma sheath particles velocities relation $V_r/V_z$. Velocity of particles depends on initial electrical parameters of the device, electrode system dimensions and used working substance.
Figure 9. Distribution of working substance density (shades of blue) and current density (shades of gray) in discharge camera obtained by means of MHD simulation.

It is obvious that the widening interelectrode gap will result in increase of the discharge camera’s basic dimensions and in increase of its inductance. But it is not necessary that the electrode system should have cylindrical shape. Selection of the optimal configuration of the discharge camera for each practical task will demand additional experimental and theoretical research.

5. Conclusions

In this work current-plasma sheath dynamics in coaxial electrode system was simulated by means of one-fluid MHD code and two dimensional “snow plough” model.

Unlike most of other, simulations used in current work allowed to obtain and analyze data about the influence of electrodes on effectiveness of working substance sweeping by current-plasma sheath. It is determined that only small fraction of gas is carried away by moving plasma sheath, but substantial fraction of substance is left behind the sheath.

Explanation of the observed phenomenon is given. It is supposed that the losses of working substance by the plasma sheath during its interaction with electrode occur due to special aspects of plasma motion inside the sheath and its dynamics during the stage of separation from the insulator.

In order to mitigate working substance losses it is recommended that the electrode system should have widening interelectrode gap.

Acknowledgements

This work has been partly supported by National Research Nuclear University MEPhI in the framework of the Russian Academic Excellence Project (contract No. 02.a03.21.0005, 27.08.2013).

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