

NUMERICAL AND EXPERIMENTAL STUDY OF A MICROSECOND PLASMA OPENING SWITCH DYNAMICS

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Abstract

Dynamics of a Plasma Opening Switch (POS), operating like a plasma piston and of a microsecond POS are numerically studied. Dependence of the conduction phase time versus both a number of particles in a plasma bridge cross-section and an electron magnetization value (Hall parameter) near a cathode is found. Results of modeling indicate that the phenomena of rarefied gap production could be described in the frame of magneto hydrodynamic (MHD) with account of the Hall effect, without using the erosion theory [1].

As known, a POS is the integral part of an Inductive Energy Storage (IES) system. Development of IES systems demands creation of the POS with predictable output characteristics. The present work as the previous [2, 3] is devoted to derivation of the POS conduction scaling. For this reason the 2-D two-fluid MHD code is run in the coaxial symmetry. The initial POS conditions are chosen to reproduce two types of POS operation: I) MHD regime, plasma accelerates as a whole by the $J \times B$ force (Fig.1). II) the Hall regime, characterised by high influence of the Hall effect (Fig.2).

The 2-D two-fluid MHD system with account of the Hall effect contains the following equations:

a) equation of the plasma density n :

$$\frac{\partial n}{\partial t} = -\text{div}(n\mathbf{V}), \quad (1)$$

b,c) equations of the plasma velocity $\mathbf{V} = (V_r, V_z)$ components

$$\frac{\partial(nm_i V_r)}{\partial t} = -\frac{H_\varphi}{4\pi} \frac{\partial(rH_\varphi)}{r\partial r} - \frac{\partial(rm_i n V_r^2)}{r\partial r} - \frac{\partial(m_i n V_r V_z)}{\partial z} - 2\frac{\partial(nT)}{\partial r}, \quad (2)$$

$$\frac{\partial(nm_i V_z)}{\partial t} = -\frac{1}{8\pi} \frac{\partial(H_\varphi^2)}{\partial z} - \frac{\partial(m_i n V_z^2)}{\partial z} - \frac{\partial(rm_i n V_r V_z)}{r\partial r} - 2\frac{\partial(nT)}{\partial z}, \quad (3)$$

Here m_i is the average ion mass in the plasma.

d) equation of the plasma temperature T :

$$3\frac{\partial(nT)}{\partial t} = -3\text{div}(nT\mathbf{V}) - 2nT\text{div}(\mathbf{V}), \quad (4)$$

e) equation of the magnetic field H_φ :

$$\frac{\partial \mathbf{H}_\varphi}{\partial t} = \nabla \times (\mathbf{V} \times \mathbf{H}_\varphi) - \nabla \times \left(\frac{\mathbf{H}_\varphi}{4\pi en} \times (\nabla \times \mathbf{H}_\varphi) \right) - \nabla \times \left(\frac{c^2}{4\pi\sigma} (\nabla \times \mathbf{H}_\varphi) \right), \quad (5)$$

where σ is the Spitzer coefficient of the plasma conductivity.

g) Maxwell equation for the current density:

$$\mathbf{j} = \frac{c}{4\pi} (\nabla \times \mathbf{H}_\varphi). \quad (6)$$

It is supposed: (1) the gap formation takes place near the cathode. The simulations are carrying out in the region near the cathode [$R_c = 2.5 \text{ cm}$, $R_{out} = 18 \text{ cm}$] and [$Z_0 = 0 \text{ cm}$, $Z_{load} = 30 \text{ cm}$]. The

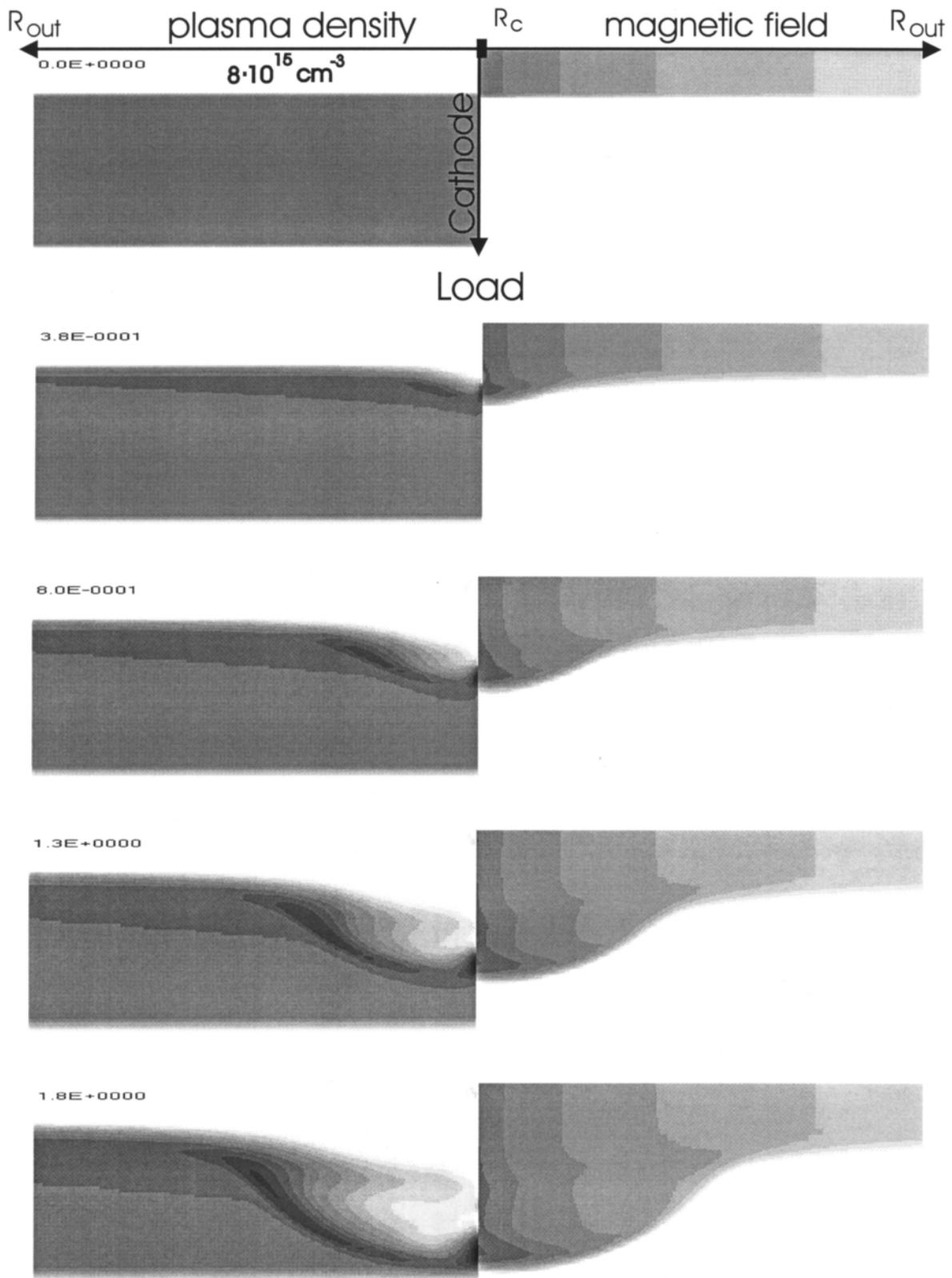


Fig. 1

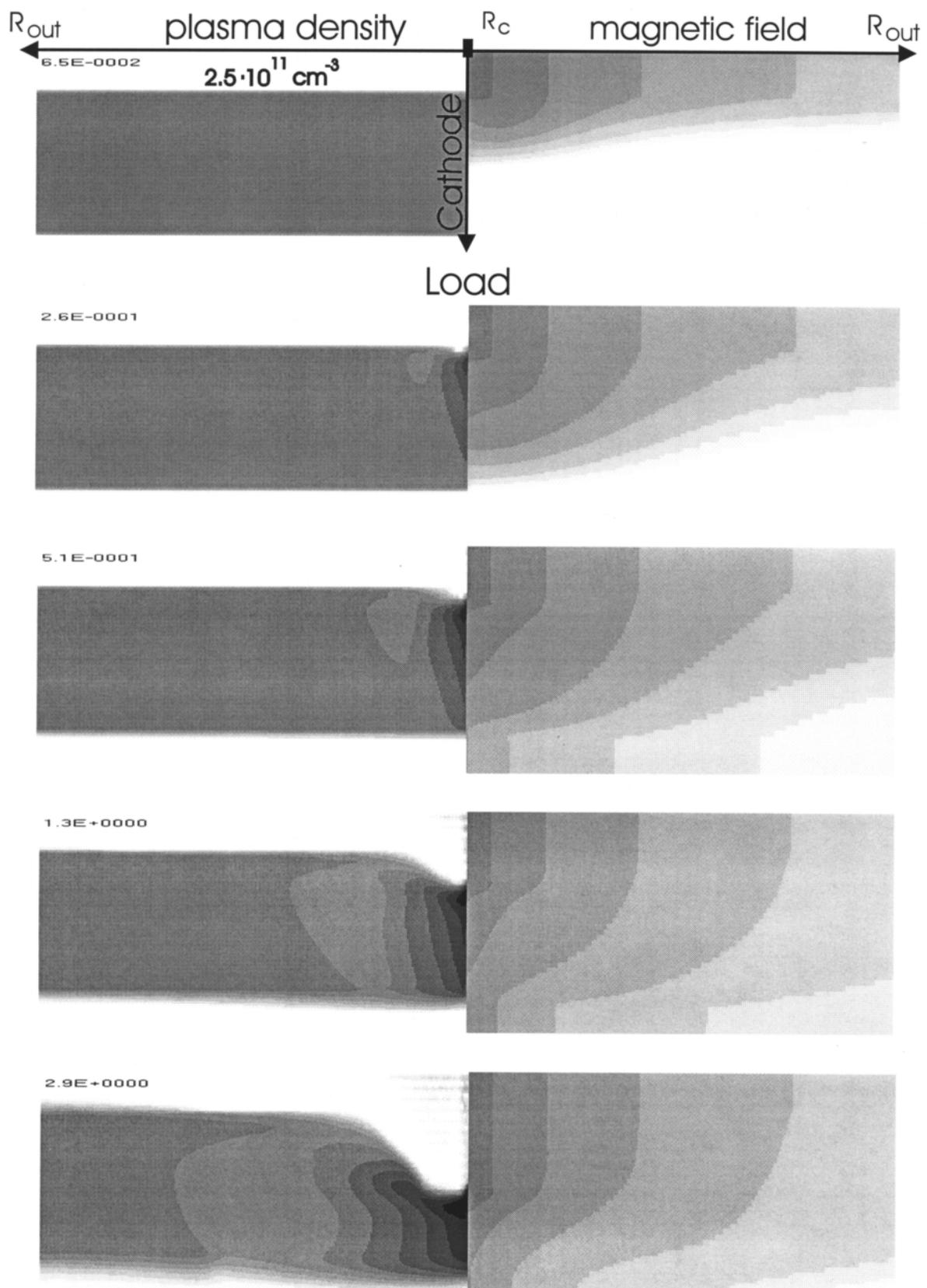


Fig.2

plasma width $l = 18 \text{ cm}$. (2) the influence of the near-anode dynamics is negligible. (3) the value of generator current, I_g , is constant. At initial moment the magnetic field already exists and is blocked by the uniform plasma bridge of some density (Fig.1a). The system (1-6) is solved in the dimensionless form. The dimensionless parameters of two-fluid MHD equations are the following: the time scale of the task, $T_A = 5lR_c\sqrt{4\pi n m_i}/I_g$; the number of electrons in a plasma cross-section, $\Pi_i = 4\pi n_e e^2 l^2/(m_i c^2)$; the Hall parameter, $(\omega\tau)_{ie} = 1.23 \cdot 10^{11} I_g T^{3/2}/(R_c n_e)$. Simulations are carried out for $(\omega\tau)_{ie} = 10$, $I_g = 200 \text{ kA}$ and hydrogen plasma, $n_i = n_e$. The plasma density is the unique modifying parameter.

The results of POS modeling, operating like MHD piston is shown on the Fig.1. In this case $\Pi_i = 100$ or $n_e = 8.5 \cdot 10^{15} \text{ cm}^{-3}$. In the fig.1 the central line is the cathode. Distribution of the magnetic field is shown at the right part and of the plasma density is at the left part. Darker color corresponds to higher value. The numerical value on the fig.1 is the ratio t/T_A . Magnetic field propagates along the cathode and pushes the plasma by the force $J \times B$ to the discharge volume.

The results of POS modeling, operating in opening regime are shown in the Fig.2. In this case $\Pi_i = 2.5 \cdot 10^{-3}$ or $n_e = 2.5 \cdot 10^{11} \text{ cm}^{-3}$. One can see, that due to the Hall effect the magnetic field penetrates into the plasma and pushes it in directions to the cathode and to the anode. This leads to production of the rarefied plasma gap in the discharge volume. It is important, that the gap formation is obtained for initially uniform plasma density, while in the work [3] the gap formation was demonstrated for a plasma density with some gradient near the cathode. The present results of modeling correlate better with the work [4] and show another mechanism of the gap production, than the erosion one [1].

The experimental results of the experiment [5] are given in the Fig.3. The characteristic discharge time in the fig.3 is $2 \mu\text{sec}$. In the Fig.3a the solid line corresponds to the generator current, while dashed line corresponds to the short-circuit current. The time dependance of the ion flux density to the cathode, measured under a plasma guns is shown in the fig.3б. The same dependance is in the Fig.3в, but the ion flux is measured between the plasma guns and a load. The Fig.3г presents the development of the radial gap formation, measured from the load side of coaxial POS. This picture was obtained by electron image streak camera in H_α lines of plasma luminescence. The simulated plasma behaviour in the fig.2 are in agreement with the experimental data in fig.3г.

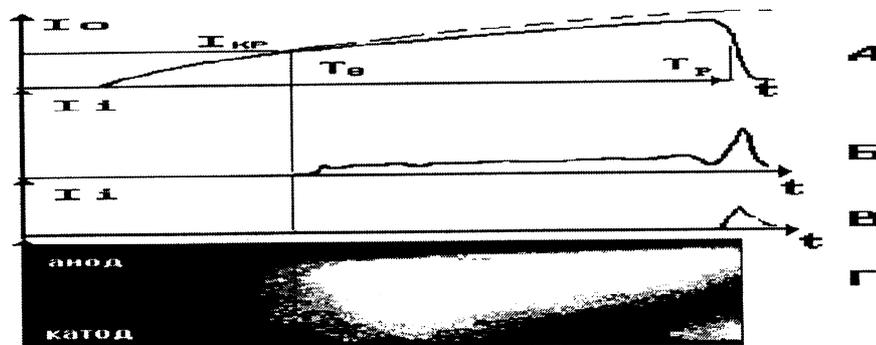


Fig.3: (a)The generator and the short-circuit current,
(б,в) the ion flux to the cathode,
(г) the streak camera photo of gap formation.

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