CAPTURE AND TRANSPORT OF MACROPARTICLES IN CURVED PLASMA DUCT AT LOW MAGNETIC FIELD IN THE PRESENCE OF AN ELECTRON BEAM

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The possibility of the macroparticles transport through a magnetic separator due to their capture by the electric field generated inside the duct becomes possible. The conditions are obtained under which transport of the macroparticles by the negative space charge is investigated. It is shown that if there is a space charge in the plasma duct then the interaction of positively charged macroparticles and the negative space charge takes place and as a result, capturing of the macroparticle through the magnetic separator takes place.

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INTRODUCTION

Nowadays, cathode arc deposition or Arc-PVD is one of the most promising plasma methods of treating the surfaces. The main disadvantage of this method is the presence of an erosion component in a plasma stream [1]. Erosion products are solid fragments and the melted droplets (we shall call them macroparticles, or the MPs) of cathode material with sizes of 0.1…30 microns, and their speed reaches 1…30 m/s [1-4]. The presence of MPs in plasma flow leads to a reduction of the quality of the processed surfaces. Filters are used to remove the MPs from plasma flow. These filters operation is based on the spread of the plasma flow caused by the magnetic field which excludes direct visibility for the MPs between the cathode and the processed surface. As a result MPs are deposited on the walls of the filter. However, experimental data shows that a small part of the MPs nevertheless passes through a filter [1]. One of the mechanisms of the MPs transport through the filter is changing their trajectories due to elastic collisions with the walls of the filter [1]. In this paper, we study the possibility for the MPs to pass through the magnetic filter due to their capture by an electric field produced by the space charge in a curved duct.

1. MOTION OF A MP IN A CURVED DUCT

The trajectory motion of a single MP in a curved plasma duct and the main determinant forces are studied. Both electromagnetic (Coulomb interaction, and the Lorentz force) and non-electromagnetic forces (gravity, centrifugal force) are known to impact on the charged MP. The MP placed in the beam-plasma system is also known to be exposed to charging by the plasma and the beam particles. The charge of the MP can be either negative or positive depending on the beam-plasma densities ratio and the energy of the electron beam [5,6]. Calculation of an ion and electron currents from plasma on the particle surface in a magnetic field is a difficult problem, but in some cases various approximate models are successfully used. An important problem is to obtain the magnitude of the MP charge because it is the charge that determines the physics of MP interaction with the environment.

1.1. CHARGE OF A MP IN A PLASMA OF A MAGNETIC FILTER OF A VACUUM ARC SYSTEM

If the magnetic field is not strong enough, such that

$$r_g >> \lambda_d >> a\,, \qquad (1)$$

then the OML (orbit motion limited) theory is used in a collisionless plasma. This theory was developed by Langmuir for describing the ion and electron current on a spherical probe. In (1), r_g is an electron Larmor radius, λ_d is a Debye length, a is a radius of the MP. In present work, we consider metallic plasma produced by the low pressure arc discharge with density $n_0=10^{10}…10^{12}$ cm^{-3}, electron temperature T_e is *1 eV*. Ionic component has direct velocity with the ion energy distribution close to the shifted Maxwellian one with average ion energy of 25…50 eV that depends on the cathode temperature [1]. The magnetic field B in the *filter is* 100 G. For this parameters, condition (1) is true and application of the OML theory is valid.

Thus, electron and ion currents from the plasma on the surface of the MP have the following form:

$$I_e = \sqrt{8\pi} a^2 n_0 v_{Te} \exp\left(e\varphi_a / T_e\right), \qquad (2)$$

$$I_i = \sqrt{\pi} n_0 < Z > v_{Ti} \pi a^2 \left(1 - < Z > e\varphi_a / T_i\right), \qquad (3)$$

where n_0 is a plasma density, $T_{e(i)}$ is plasma electron (ion) temperature, $v_{Te(i)} = \sqrt{T_{e(i)} / m_{e(i)}}$ is their thermal velocity, $< Z > = 1 \cdot \alpha_1 + 2 \cdot \alpha_2 + 3 \cdot \alpha_3$ is an average charge number of the ions, $\alpha1$, $\alpha2$, $\alpha3$ are relative concentration of ions with the charge Z= 1, 2, 3 respectively.

The interaction between the ionic component of the plasma flow and the substrate causes the generation of the secondary electrons flow which density is determined by the ion-electron secondary yield. Taking into account that there are ions with various charges in the plasma flow, it is advisable to use the averaged secondary yield

$$\delta_s^{i-e} = \alpha_1 \cdot \delta_{s1}^{i-e} + \alpha_2 \cdot \delta_{s2}^{i-e} + \alpha_3 \cdot \delta_{s3}^{i-e}\,, \qquad (4)$$

where δ_{sZ}^{i-e} is an ion-electron secondary yield for ions with a charge Z. Energy of the secondary electrons ε_e^{fl} is determined by a potential on the substrate and has negligible scatter corresponding to the energy spectrum of the secondary electrons. Secondary electrons flow density j_e^{fl} is expressed through the ion current density j_j to the substrate by the following relation: $j_e^{fl} = \delta_s^{i-e} j_i$. Current of the electrons generated on the substrate to the MP surface is determined from the OML theory:

$$I_e^{fl} = j_e^{fl} \pi a^2 \left(1 + e\varphi_a / T_i\right). \qquad (5)$$

The emission of electrons from the surface is an important process that affects on the magnitude of the MP charge. One can distinguish the following basic mechanisms of the electron emission: the ion-electron emission and electron-electron emission. Let discuss the influence of each of these mechanisms.

As it was already mentioned above, there are ions with different charges in the plasma flow. Therefore it is necessary to use the averaged value of secondary electron- ion yield (4). Thus, the value of the ion current, that causes the secondary electron emission from the surface of the MP, is determined by the following expression:

$$I_s^{i-e} = \delta_s^{i-e} I_i. \qquad (6)$$

Taking into account (3) and (6), we assume for convenience that an effective ion current:

$$I_i^{eff} = I_i + I_s^{i-e}, \qquad (7)$$

flows on the surface of the MP. Expression for the current of secondary electron-electron emission has a similar form: $I_s^{e-e} = I_e^{fl} \delta_s^{e-e}$, where δ_s^{i-e} is an electron-electron secondary yield. Similarly to the ion current, we introduce an effective electron current:

$$I_e^{eff} = I_e^{pl} + I_e^{fl} - I_s^{e-e}. \qquad (8)$$

Floating potential of the MP is determined from the condition of equality of currents (7) and (8) on its surface:

$$I_e^{eff}(\varphi_a) + I_i^{eff}(\varphi_a) = 0. \qquad (9)$$

Fig. 1 shows the numerical solution of eq. (9).

As it follows from the solution of the eq. (9), there is a range of energies of the electron flow, $\varepsilon_1 > \varepsilon_e^{fl} > \varepsilon_2$, within which a MP has a positive charge. This range corresponds to the energy of the electron flow in which the secondary electron-electron yield δ_s^{e-e} is greater than a unit. The maximum magnitude of the potential of the MP in the energy range $\varepsilon_1 > \varepsilon_e^{fl} > \varepsilon_2$ is determined by the energy spectrum of the secondary electrons.

1.2. CAPTURING AND TRANSPORTATION OF THE MP IN THE CURVED PLASMA DUCT

Let analyze the processes which determine the trajectory of the MP in a plasma duct.

Let consider the Coulomb force acting on the MP that is not located on the axis of duct. Keeping in mind that there is a negative space charge in this system [7] and MP can be positively charged one can find that the force is directed radially towards the center of the plasma duct, and its absolute value is determined by the expression:

$$F = Q_{mp} E,$$

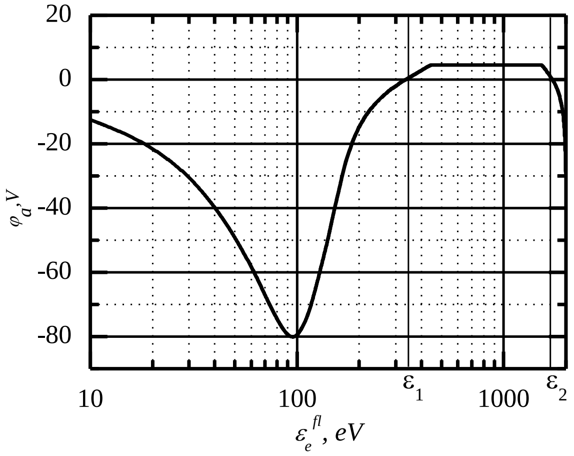

Fig. 1. The dependence of the floating potential of the tungsten MP versus energy of the electron flow ($n_o=10^{12}$ cm^{-3}; T_e=1 eV; T_i=25 eV)

where E is the electric field in the plasma duct, it can reach the values about 5 V/cm [6], Q_{mp} is a charge of the MP.

Centrifugal force F_c acts on the MP during its motion along the curved trajectory as well. It is directed toward the outer wall of the duct:

$$F_c = M_{mp} v^2 / R_0,$$

where M_{mp} is a mass of the MP, v is a velocity of the MP, R_0 is a radius of curvature of the duct.

The MP is subjected to a force of gravity as well:

$$F_g = M_{mp} g,$$

where g is acceleration of gravity. Estimations show that the main processes which determine the trajectory of the MP in a curved plasma duct are centrifugal repulsion and retention of the MP by the Coulomb force generated between the positively charged MP and negative space charge. To determine the conditions under which the MP can be transported in the plasma duct, let consider the relationship between the potential $U(r)$ and kinetic energies E_0 of the MP. Motion of the MP occurs in a spatial region where

$$E_0 > U(r). \qquad (10)$$

Those MPs, for which the condition (10) is not true, are in a potential well, which they cannot leave. The depth of the potential well is defined by the following expression:

$$U_0 = \left(\varphi(R) - \varphi(r_1)\right) Q_{mp},$$

where R is a radius of the plasma duct, r_1 is a distance from the axis of the plasma duct to the place of the MP formation. Let write down the condition that defines the parameters of that MP which is in the potential well and, therefore, can pass through the magnetic filter:

$$U_0 = M_{mp} v_0^2 / 2 < \left(\varphi(R) - \varphi(r_1)\right) Q_{mp}. \qquad (11)$$

Results of the numerical solution of inequality (11) is presented in Fig. 2.

The curves shown see in Fig. 2 are determined by a set of parameters (velocities of the MPs and their sizes). These curves separate MPs into two groups: those which pass through the separator and those which are deposited on its walls. For the first group of the MPs which pass through the filter, the condition (9) is true and the set of parameters of the MPs (velocities and sizes) are below the curves. Accordingly, those MPs, velocities and sizes of which take values in the region above the curves, are deposited on the walls of the filter.

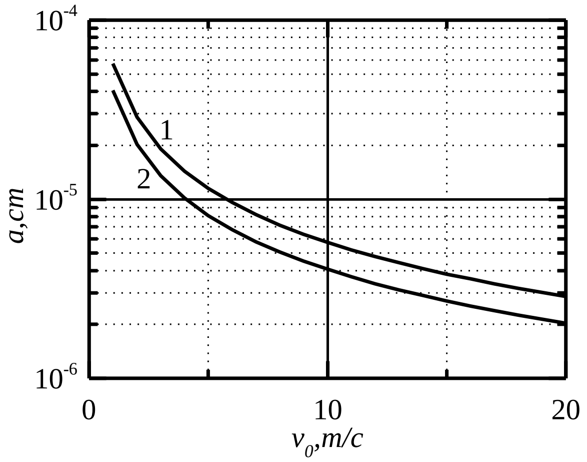

Fig. 2. Dependence of the critical size of the MPs versus initial velocity (1 – r_1=0; 2 – r_2=0.5R)

Thus, comparing the results of calculations carried out in the work and the results of experimental observations [1] we conclude that there are MPs in the plasma flow generated by vacuum arc which can pass through a magnetic separator.

CONCLUSIONS

In this paper, we theoretically studied the possibility of transporting the MPs produced in a vacuum-arc discharge through a magnetic separator and the following results were obtained.

1. The MP produced by the vacuum-arc plasma sources can be positively charged due to the process of secondary electron-electron emission as a result of its interaction with the electron flow generated in the substrate.
2. The main processes which determine the trajectory of the positively charged MP in a curved plasma duct are centrifugal repulsion and the MP interaction with the negative space charge.
3. The possibility of capture of the positively charged MP by the electric field generated by the negative space charge is demonstrated. The conditions and parameters of the MPs which can pass through a magnetic separator are defined.

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ЗАХВАТ И ТРАНСПОРТИРОВКА МАКРОЧАСТИЦ В КРИВОЛИНЕЙНОМ ПЛАЗМОВОДЕ В СЛАБОМ МАГНИТНОМ ПОЛЕ В ПРИСУТСТВИИ ЭЛЕКТРОННОГО ПУЧКА

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Изучена возможность транспортировки макрочастиц (МЧ) через магнитный сепаратор в результате их захвата электрическим полем, созданным отрицательным пространственным зарядом. Показано, что при условии существования пространственного заряда в плазмоводе происходит взаимодействие положительно заряженной МЧ и отрицательного пространственного заряда, в результате чего возможно удержание МЧ внутри плазмовода. Определены условия, при которых происходит траспортировка МЧ через сепаратор.

ЗАХОПЛЕННЯ І ТРАНСПОРТУВАННЯ МАКРОЧАСТИНОК У КРИВОЛІНІЙНОМУ ПЛАЗМОВОДІ В СЛАБКОМУ МАГНІТНОМУ ПОЛІ ЗА НАЯВНОСТІ ЕЛЕКТРОННОГО ПУЧКА

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Досліджено можливість транспортування макрочастинок (МЧ) крізь магнітний сепаратор у результаті їх захоплення електричним полем, що створюється від'ємним просторовим зарядом. Показано, що за умови існування просторового заряду в плазмоводі відбувається взаємодія позитивно зарядженої МЧ та негативного просторового заряду, внаслідок чого стає можливим утримання МЧ всередині плазмовода. Здобуто умови, за яких відбувається транспортування МЧ крізь магнітний сепаратор.