ELECTROSTATIC FIELD EFFECTS ON THE TRANSPORT OF MACROPARTICLES IN MAGNETIZED PLASMA DUCTS

M. Keidar, I. Beilis, R. L. Boxman, and S. Goldsmith

Tel Aviv University, Electrical Discharge and Plasma Laboratory, POB 39040, Tel Aviv 69978, ISRAEL

The motion of electrically charged macroparticles (MP's) in straight and quarter torus plasma guides used in vacuum arc deposition was analyzed. The mechanism of negatively charged MP transmission in the curved guide is repeated electrostatic reflection from the negatively charged wall. The transmission fraction decreases with increasing minor to major radius ratio, MP velocity, and plasma flux, and becomes negligible if the duct wall becomes positively charged with respect to the adjacent plasma. The calculated MP transmission fraction in a straight duct compares well with previous experimental measurements of 0.5 μm Ti MP's with a velocity of 20 m/s are assumed.

1.INTRODUCTION. The cathode spot of a vacuum arc produces a highly ionized, energetic plasma jet of vaporized cathode material which may be directed to a substrate to form a high quality coating or thin film, and a spray of molten droplets, referred to as macroparticles (MP's), which, if they reach the substrate, degrade the quality of the coating [1]. The plasma flux can be concentrated by magnetic collimation, while the MP spray can be filtered from the plasma jet by magnetically guiding the plasma around an obstacle using a magnetic field. Past theoretical analysis has focused on the transport of the plasma through the magnetized duct, and have tacitly assumed that MP's striking the duct wall either adhere, or mechanically bounce upon impact. The most studied filter is a duct in the form of quarter-torus with a magnetic field parallel to its walls [2]. It is known from several experimental works that the macroparticles have an exponentially decreasing size distribution and that the larger macroparticle are generally slower [3]. The MP traveling through the filter is charged through its interaction with the plasma. The characteristic charging time typically in the rarefied part of the plasma jet (e.g. about 10 cm from 100 A vacuum arc cathode) is about 10^{-5} s, and the charge accumulated on a 0.1 μm radius macroparticle is about 10^{-16} C[4].

None of previous works analyzed the MP motion in either straight and curved plasma guides. The objective of the present work is to present an analysis of MP motion in plasma guides, which takes into account the influence of momentum imparted by interactions with the plasma jet and from imposed electric fields, and the influence of surface charging of the duct walls. The model will be used to explain a previously observed reduction in the MP flux in a straight magnetized plasma duct.

2. MP FLOW MODEL. The plasma ions with large mass velocity impart some momentum to relatively slow MP's. Distortion of the plasma flow field by the MP's will be neglected. The equation of motion for an individual MP may written as:

$$M_p dV_p/dt = F_d + Q_p E \qquad (1)$$

where M_p, V_p, and Q_p, are the MP mass, velocity and charge, F_d is the drag force, and E is the electric field. Collisions between MP's are neglected. The collisions of the MP's with ions and electrons are taken into account in the drag force. For free molecular flow (Knudsen number $K_n >> 1$) the drag force can be expressed as:

$$F_d = \rho\sigma(V - V_p)^2 \qquad (2)$$

where V is the plasma velocity, ρ is the mass plasma density, and σ is the momentum transfer cross section. It was estimated that the value of σ depends on the ratio α between the energy acquired by an ion in the MP's electrostatic field, and ions initial kinetic energy and for $\alpha \geq 1$ the σ will be greater than the MP physical cross section. The system of equations (1) and (2) are supplemented with the MP trajectory equation:

$$dr/dt = V_p \qquad (3)$$

3. PLASMA MODEL. Consider a plasma flow in a guide with 'magnetized' electrons and 'unmagnetized' ions, i.e. $\rho_e << H << \rho_i$, where ρ_e and ρ_i are the Larmor radii for the electrons and ions respectively, and H is the characteristic duct size. We employ a hydrodynamic model assuming: (i) The flow may be considered isothermal. (ii) The plasma is considered quasi-neutral. (iii) The self magnetic field from the current carried in the plasma is small in comparison to the imposed magnetic field B_z. (iv) The system reaches a steady state. The following system of equations describes the plasma:

$$m_i(V_i \cdot \nabla)V_i = Z_i eE - Z_i \nabla P_i/N - m_e \nu_{ei}(V_i - V_e) \qquad (4)$$

$$0 = -eE - \nabla P_e/N + m_e \nu_{ei}(V_i - V_e) - e(V_e \times B) \qquad (5)$$

$$\nabla \cdot (V_\alpha N) = 0 \qquad \alpha = e, i \qquad (6)$$

where V_i and V_e are the ion and electron velocities, m_i and m_e are the ion and electron mass, P is the partial pressure, and ν_{ei} is the electron-ion collision frequency. Let us discuss the bulk of the plasma and the near-wall region separately with the assumption that the boundary sheath near the duct wall is thin. In the bulk of the plasma the pressure gradient force is considered to be small and may be neglected. The current in the ρ-direction normal to the duct boundary (Fig.1) $J_\rho=0$, and thus $V_{i\rho}=V_{e\rho}=V_\rho$. The solution of the Eq. (4)-(6) in the cylindrical coordinates with boundary condition $E_\rho(\varphi=0)=0$ and for constant ion velocity parallel to the duct wall V_φ is:

$$E_\rho=m_i V_\varphi^2/(Z_i eR)\cdot[\exp(-\gamma\rho\varphi)-1] \quad (7)$$

where $\gamma=B\beta_{ei}Z_i e/(m_i V_\varphi)$. For a Ti plasma jet with a velocity $V_\varphi\sim10^4$ m/s in a magnetic field B=0.01 T and Hall parameter $\beta_{ei}=10$ the radial attenuation coefficient $\gamma\sim10\ m^{-1}$. The maximum value of the electric field ($\gamma\rho\varphi>>1$) $E_{\rho max}\sim10^2$-10^3 V/m.

The wall may be have some electrical potential relative to the surrounding plasma. If the wall is isolated, and there is no magnetic field the wall has negative floating potential relative to the plasma. If a magnetic field is present this potential drop is changed. The influence of the magnetic field on the wall potential relative to the plasma in the MP filter was studied experimentally by Aksenov *et al.* [5], and Anders *et al.* [6] . It was found that for a well focused plasma the wall potential relative to the anode is negative up to 0.1 T magnetic field. In our model the influence of the magnetic field is taken into account as a parametric change of the wall potential with respect to the adjacent plasma.

4. MACROPARTICLE TRANSPORT THROUGH CURVED PLASMA DUCTS. In this section boundary conditions for the duct will be developed, and then the equations of motion for the MP's (Eqs. 1-3) will be solved in cylindrical coordinates subject to these conditions, first analytically in limiting cases, and then numerically.

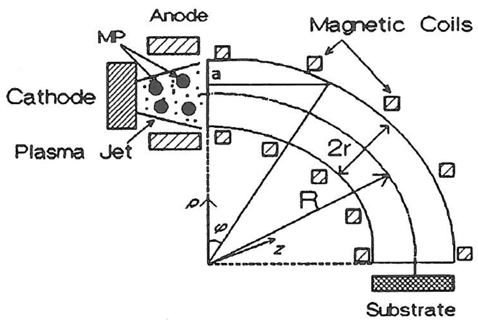

Figure 1. Schematic representation of the typical Filtered Vacuum Arc Deposition system

4.1. Duct Wall Conditions. If the plasma drag and electric field forces are sufficiently small, Eq.1 indicates that the macroparticle velocity may be considered constant in the plasma bulk. An interaction may occur at the duct wall, however. Two types of interactions are possible: **adherence** $\xi=\geq1$ and **reflection** $\xi<1$, where $\xi=M_p V_n^2/(2Z_p eU_W)$, $V_n=V_p\sin\varphi$ is the component of the MP velocity normal to the wall, φ is the azimutal angle, and U_W is the wall potential.

4.2. Analytic Estimation. Let us determine the maximum torus angle φ_{max} where an MP with a directed velocity initially parallel to the duct wall is reflected, which occurs when $\xi=1$:

$$\varphi_{max}=\sin^{-1}\sqrt{\frac{2Z_p eU_w}{M_p V_p^2}} \qquad (8)$$

The fraction f of the MP's transmitted through the torus by slipping (i.e. successive reflections from the wall sheath) $f = f(\varphi_{max})$ is estimated as $f=a/(2r)$ (see Fig. 1), where $a=(R+r)(1-\cos\varphi_{max})$ and r and R are the minor and major torus radii respectively. Using Eq. (8) this function may finally be expressed as:

$$f=\frac{R+r}{2r}\cdot\left(1-\cos\left\{\sin^{-1}\sqrt{\frac{2Z_p eU_w}{M_p V_p^2}}\right\}\right) \qquad (9)$$

The fraction of the MP transmitted through a toroidal plasma guide was

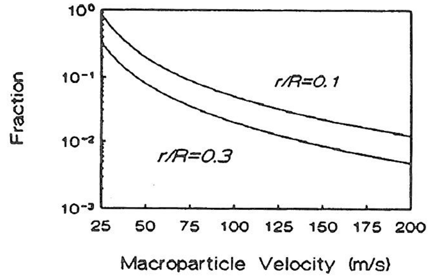

Figure 2. Calculated Ti MP transmission fraction in a toroidal duct for various r/R, as function of the initial MP velocity, for U_W=-10 V and R_p=0.1 μm.

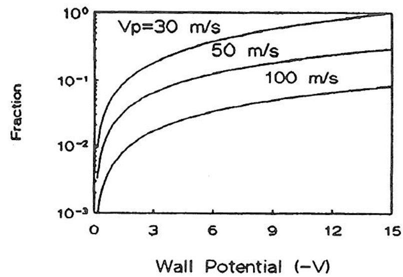

Figure 3. Calculated Ti MP transmission fraction for various MP initial velocities as function of the duct wall potential. r/R=0.1, R_p=0.1 μm.

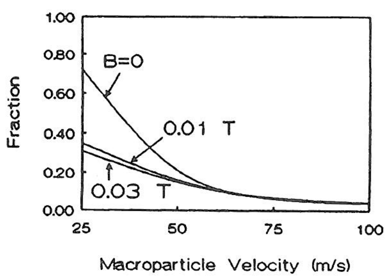

Figure 4. Calculated Ti MP transmission fraction for various magnetic fields in a toroidal plasma duct as function of the MP velocity. U_W=-10 V.

calculated as a function of the wall potential and MP velocity distribution for different ratios r/R (Fig. 2). In the case of the r/R=0.1 with the duct at floating potential, the fraction of the MP's transmitted through torus approaches 100% for R_p=0.1 μm Ti MP's having an initial velocity parallel to the duct wall. The dependence of the fraction of the MP's transmitted through quarter torus on the wall potential is presented on the Fig. 3. It may be seen that the MP transmission through curved ducts is determined by repeated electrostatic reflection of the charged MP from the negative charged wall. This effect is more significant for ducts with small r/R.

4.3. Numerical Examples and Discussion. The equations of MP motion (1)-(3) were written in component form and solved numerically in the cylindrical coordinate system (Fig. 1) with the duct wall conditions discussed above. The results of the integration of the equations in the Ti cathode case with an average MP radius R_p=0.1μm, and wall potential U_w=-10 V as function of the initial MP velocity V_p are presented in the Fig. 4. Here we see the influence of the polarization electric field E_p depend on the magnetic field in the plasma in the curved duct (Eq. 7) on the MP transmission. The radial electric field accelerates the MP's towards the wall, so that they approach the sheath with a larger normal velocity, and at an earlier azimuthal position. The magnetic field as we can see from the Eq. 7 influences only the size of the initial region, where electric field changes from zero to its maximum value. The influence of the plasma flux on the MP transmission in a curved duct is illustrated in Fig. 5. The plasma flux is expressed in terms of its convected ion current flux J_i. The mechanism for the reduction f with J_i is the increased drag force on the MP's which accelerates them in the axial direction, which in turn increases the centrifugal force in the direction of the duct wall.

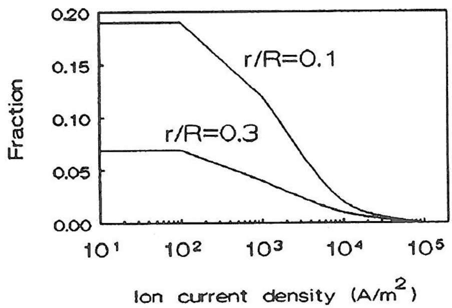

Figure 5. Ti MP transmission fraction as a function of the ion current density. V_p=50 m/s, U_w=-10 V.

5. MACROPARTICLE REDUCTION IN THE STRAIGHT MAGNETIZED DUCT. A significant reduction (up to a factor of 5) in the MP content in deposited films, as well as an increase in arc voltage, was observed experimentally by increasing of the axial magnetic field in a titanium cathode vacuum arc plasma generator [7] having an annular anode and a straight plasma duct. In this section a mechanism will be proposed to explain this result. The potential distribution in the interelectrode gap as a function of the magnetic field was not reported. Let us assume that the arc voltage increases with magnetic field by increasing the radial voltage drop, and let us use a parabolic approximation of the potential distribution.

The MP flow for different initial velocities V_p was calculated using Eqs. (1)-(3) in cylindrical coordinates. By calculation of the MP trajectories it is possible to estimate MP transmission through a straight duct. The MP collection time (i.e. arc duration) is much longer than the MP time of flight, i.e. $t \gg L_s/Vp$, where L_s is the distance between the cathode and the substrate. The results of this calculation with dependence on the magnetic field with the MP initial velocity as a parameter, and taking into account the experimental dependence of the potential drop on the magnetic field [7], are plotted in the Fig. 6. Also plotted are the experimental results. The calculated MP transmission was close to the measured for 0.1 μm radius MP's with 80 m/s and for 0.5 μm radius MP's with 20 m/s directed velocities.

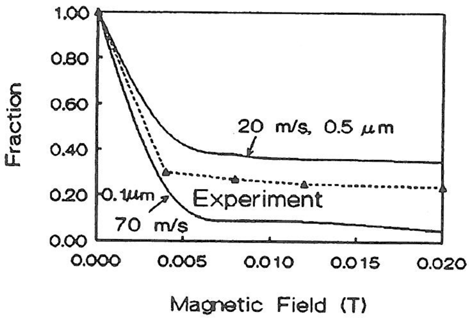

Figure 6. Calculated MP transmission through a magnetized straight duct for different initial MP velocities as function of the magnetic field.

6. CONCLUSIONS. The fraction of the MP's transmitted through quarter torus may be significant. The mechanism of the MP transmission is repeated electrostatic reflection of the charged MP's from the wall negative charged relative to the plasma. The transmission fraction should be negligible if the wall potential is positive, as will occur with the imposition of a strong magnetic field. The experimentally observed decrease in the MP transmission through straight duct with increasing magnetic field may be explained by the positive in the duct potential with respect to the adjacent plasma.

REFERENCES

[1] T. Utsumi and J. H. English. J. Appl. Phys. 46(1), 1975, 126-131.

[2] I. I. Aksenov, V. A. Belous, V. G. Padalka, V. M. Khoroshikh. Sov. J Plasma Phys. 4(4), 1978, 425-428.

[3] R.L.Boxman, S.Goldsmith. Surf. Coat.Technol, 52(1992) 39-50.

[4] M. Keidar, I. I. Beilis, R. L. Boxman, and S. Goldsmith. *Proc.* XVI-ISDEIV, SPIE, 1994, 140 (to be published in IEEE Trans. Plasma Sci., 1995).

[5] I. I. Aksenov, V. A. Belous, V. G. Padalka, V. M. Khoroshich. Fizika Plasma, 4, 1978, 758 (in Russian).

[6] A. Anders, S. Anders, I. G. Brown. To be published in Plasma Source Sci. and Technol., 1995.

[7] K. Akari, H. Tamagaki, T. Kimakiri, K. Tsuji, E. S. Koh, C. N. Tai. Surf. Coat. Technol., 43/44, 1990, 312.