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THE INTERACTION OF PLASMA WITH A SOLID SURFACE*

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A theory describing the interaction of plasma with a solid surface is formulated. An infinite plasma interacting with an infinite planar wall was chosen as a model for theoretical considerations. A flux of charged particles to the wall in ambipolar approximation was calculated as a first step. Equations describing an electrostatic sheath are presented taking into account heating, variation of the ioh mobility and the electron-ion recombination. Boundary conditions are studied in more detail when particles can be emitted or reflected at the wall surface.

ВЗАИМОДЕЙСТВИЕ ПЛАЗМЫ С ТВЁРДОЙ ПОВЕРХНОСТЬЮ

В рабо те сформулирована теория, описывающая взаимодействие плазмы с твёрдой поверхностью. В качестве модели для теоретического рассмотрения была выбрана бесконечная плазма, взаимодействующая с бесконечной плоской стенкой. В амбиполярном приближении рассчитан поток заряжённых частиц, падающих на стенку. Приведены уравнения, описывающие электростатическую оболочку с учётом нагрева, изменения подвижности ионов и электрон-ионной рекомбинации. Более подробно изучены граничные условя для случая, когда частицы могут испускаться поверхностью стенки или же от неё отражаться.

I. INTRODUCTION

The plasma treatment of solid material is based on the interaction of particles present in the plasma with a target surface. Near the wall the properties of plasma change entirely, since an electrostatic sheath adjacent to the solid surface is formed. In this region the condition of quasineutrality must fail since to balance ion and electron fluxes to the wall the ion concentration must exceed the electron concentration by a factor equal to the ratio of their normal velocities at the wall. It is clear that the interaction of the plasma with the solid surface is strongly influenced by the properties of the region close to the wall.

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In the present paper we aim at finding information about the sheath, namely, the flux density and velocity of charged particles when striking the surface, and the boundary conditions with respect to properties of the solid surface.

II. A PLASMA MODEL

In many applications the plasma dimensions are so large that the electron-ion recombination must be taken into consideration. Then as a good approximation an infinite plasma interacting with an infinite planar wall can be used as a model for the theoretical consideration which enables us to formulate the problem on a onedimensional basis.

When α is the ionization rate and β the recombination coefficient, the production rate of the charged particles can be written as

$$\frac{\delta n_+}{\delta t}=\frac{\delta n_-}{\delta t}=\alpha n_- - \beta n_- n_+ , \tag{1}$$

where n_+ and n_- are the number densities of ions and electrons, respectively. In the plasma far from the wall quasineutrality is present and number densities of electrons and ions are the same, and reach the equilibrium number density

$$n_+ = n_- = n_0 = \alpha/\beta . \tag{2}$$

III. FLUX OF CHARGED PARTICLES TO THE WALL IN AMBIPOLAR APPROXIMATION

In this approximation no net current is supposed to flow to the wall (the solid surface is made of insulator or it is held at the floating potential). Then the charged particles move to the wall by ambipolar diffusion which can be described by the equation $(n = n_+ = n_-)$

$$-D_a \frac{d^2 n}{dz^2}=\frac{\delta n}{\delta t} . \tag{3}$$

Here D_a is the ambipolar diffusion coefficient and z is the coordinate normal to the planar wall. Insertion of (1) into the last equation yields

$$\frac{D_a}{n_0 \alpha}\frac{d^2 n}{dz^2}=-\frac{n}{n_0}+\left(\frac{n}{n_0}\right)^2 . \tag{4}$$

Integration of this equation yields the result

$$\frac{D_a}{n_0^2 \alpha}\left(\frac{dn}{dz}\right)^2=\frac{1}{3}+\frac{2}{3}\left(\frac{n}{n_0}\right)^3-\left(\frac{n}{n_0}\right)^2 , \tag{5}$$

where we have assumed that $dn/dz=0$ for $n=n_0$. This result can be written as $(\Lambda^2 = D_a/\alpha)$

$$dz=-\frac{\Lambda}{n_0}\sqrt{3}\left[\left(1-\frac{n}{n_0}\right)\left(2\frac{n}{n_0}+1\right)^{1/2}\right]^{-1} dn \tag{6}$$

and integrated again for the boundary condition $n=0$ at the wall $(z=0)$

$$\frac{z}{\Lambda}=-\ln\left[\frac{\sqrt{3}-1}{\sqrt{3}+1}\,\frac{\sqrt{3}+\left(2\frac{n}{n_0}+1\right)^{1/2}}{\sqrt{3}-\left(2\frac{n}{n_0}+1\right)^{1/2}}\right] . \tag{7}$$

The result is plotted in Fig. 1 together with the flux density of the charged particles

$$j=-D_a\frac{dn}{dz}=n_0\left(\frac{\alpha D_a}{3}\right)^{1/2}\left(1-\frac{n}{n_0}\right)\left(2\frac{n}{n_0}+1\right)^{1/2} . \tag{8}$$

The flux density at the wall is given by

$$j_w = n_0\left(\frac{\alpha D_a}{3}\right)^{1/2}=n_0^{3/2}\left(\frac{D_a \beta}{3}\right)^{1/2} . \tag{9}$$

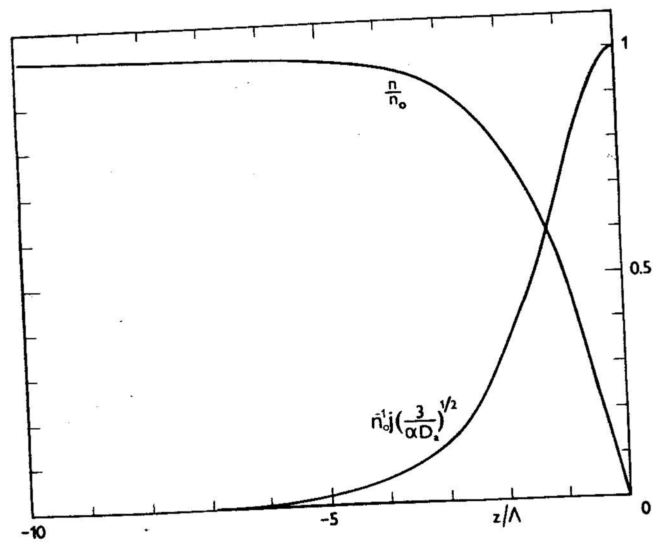

Fig. 1. Normalized number density n/n_0 and normalized flux density $j(3/\alpha D_a)^{1/2}$ as functions of normalized distance z/Λ in the ambipoar approximation.

IV. SHEATH

The ambilopar approximation cannot give any information about the sheath. The problem of a plasma sheath near the wall has long been studied (see for example [1—5]). Unfortunately, the progress that has been made so far as regards the theory is still subject to several restrictions. In the present paper we have used the conception of Forrest and Franklin [6] as a starting point. In our study the heating of positive ions, variation of the ion mobility in the electric field and electron-ion recombination will be also taken into consideration.

Poisson's equation describes the electrostatic field produced by a charge imbalance

$$\frac{d^2\Phi}{dz^2} = -\frac{e}{\varepsilon_0}(n_+ - n_-)\,, \tag{10}$$

where e is the elementary charge, ε_0 the permitivity of free space and Φ the electrostatic potential. The generation of charged particles is given by the continuity equations

$$\frac{d}{dz}(n_+V_+) = \frac{\delta n_+}{\delta t}; \quad \frac{d}{dz}(n_-V_-) = \frac{\delta n_-}{\delta t}\,. \tag{11}$$

By using (1) and integrating we have

$$n_+V_+ - n_-V_- = i_w/e\,, \tag{12}$$

where i_w is the net electric current density at the wall.

The momentum equation for the positive ions can be written as [7]

$$V_+\frac{dV_+}{dz} = -\frac{e}{m_+}\frac{d\Phi}{dz} - \frac{1}{n_+}\frac{d}{dz}(n_+ < c_z^2 >) - \nu_+V_+ - V_+\frac{1}{n_+}\frac{\delta n_+}{\delta t}\,. \tag{13}$$

Here V_+ and V_- are drift velocities of charged particles, m_+ the mass of the ion, c_z the z component of the random velocity and ν_+ the collision frequency for the momentum transfer.

The collision frequency is either a constant (constant mean free time) or it varies with the drift velocity of the ion. For a special case of the constant mean free path the collision frequency can be written as follows [8]

$$\nu_+ = \nu_{+0}(1 + am_+V_+^2/kT_g)^{1/2}, \tag{14}$$

where ν_{+0} is the „zero-field" collision frequency, T_g the gas temperature and a numerical factor determined by the natura of the ion-atom interaction. The heating of positive ions in the electric field is described by the z component of the random energy [8]

$$m_+\langle c_z^2\rangle = kT_g + \gamma m_+V_+^2\,, \tag{15}$$

where γ is a numerical factor.

Similarly, we can also write the momentum equation for the electrons. But, considering the fact that the electron drift velocity is much smaller than the random velocity of electrons, the electron density very nearly satisfies the Boltzmann relation [8, 9]

$$n/n_0 = \exp(e\Phi/kT_-)\,. \tag{16}$$

The numerical solution of this problem is presented in [10].

V. BOUNDARY CONDITIONS

Now we try to study the processes at the solid surface in more detail. In order to strike the wall the z component of the particle velocity of the drift V_w and the random velocity c must be a positive one. The flux density of the striking particles can be written as

$$j_s = 2\pi\int_0^{V_w}\int_0^{\pi}(V_w + c\cos\delta)\,c^2 f(c,\vartheta)\sin\vartheta\,d\vartheta\,dc + 2\pi\int_{V_w}^{\infty}\int_0^{\vartheta_m}(V_w + c\cos\vartheta)\,c^2 f(c,\vartheta)\sin\vartheta\,d\vartheta\,dc\,, \tag{17}$$

where ϑ_m must obey the following relation

$$V_w + c\cos\vartheta_m = 0\,. \tag{18}$$

As the velocity distribution is axially symmetric, the distribution function f does not depend on the variable φ.

The flux density at the wall due to the drift is $j_w = j_s + j_r$, where j_r represents the flux density of the particles with a negative velocity at the wall. For nonemitting and nonreflecting walls $j_r = 0$. Generally, the wall can reflect failling particles and their emission is also possible. Then we have

$$j_r = -\varkappa j_s - j_e \text{ and } j_w = (1-\varkappa)\,j_s - j_e\,, \tag{19}$$

where $\varkappa$ is the reflection coefficient and J_E the flux density of the emitted particles. The formulae (17), (18) and (19) represent the boundary conditions in the most general form.

In order to understand these conditions we make a rough approximation when the distribution function f is supposed to be independent of ϑ. The formula (17) can be integrated over ϑ to give

$$j_s = \frac{1}{2}n_wV_w + 2\pi V_w\int_0^{V_w} c^2 f(c)\,dc + \pi V_w^2\int_{V_w}^{\infty} cf(c)\,dc + \pi\int_{V_w}^{\infty} c^3 f(c)\,dc\,. \tag{20}$$

In the limit where the random velocity of particles is very much greater than the drift velocity we may put $V_w \to 0$. Then

$$j_s = \frac{1}{2} n_w V_w + \frac{1}{4} n_w \langle c \rangle , \qquad (21)$$

where $\langle c \rangle$ is the mean speed. The drift velocity at the wall is given by

$$V_w = \frac{1}{2} \frac{1-\varkappa}{1+\varkappa} \langle c \rangle - \frac{j_e}{2(1+\varkappa)} . \qquad (22)$$

In a special case when the drift of particles is controlled only by diffusion, equation (21) yields the familiar results [11]

$$j_s = \frac{1}{4} n_w \langle c \rangle - \frac{1}{2} D \frac{dn}{dz} . \qquad (23)$$

In case of the reverse limit, when the drift velocity is large in comparison with the random velocity, we may put $V_w \to \infty$. Then

$$j_s = n_w V_w = j_w \qquad (24)$$

and the boundary condition has the form

$$\varkappa j_w + j_e = 0 . \qquad (25)$$

As $\varkappa$, j_w and j_e must be positive numbers or zero, we get $j_e = 0$ and $\varkappa j_w = 0$. Therefore, the last case can occur only for nonemitting and nonreflecting walls.

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