ANODE ELECTRICAL LAYER IN DISCHARGE WITH CLOSED HALL CURRENT

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The so-called plasma accelerators with closed Hall currents are now being developed actively [1-3]. In these devices the ions are accelerated by the electric field created as a result of the space charge of electrons drifting in crossed electric and magnetic fields along a quasi-closed path. In many cases it is found that practically the entire imposed potential difference is concentrated in a very thin electric layer near the anode. The formation of such a layer has been observed experimentally in the low-pressure discharge in a Penning cell and in the inverted magnetron [4-6]. Some questions of plasma discharge and acceleration relating to this sort of phenomenon were examined in [7, 8] in the diffusion approximation. The case of "vacuum discharge", in which the ion volume charge density can be neglected, was studied in [7]. Another case, in which the ion number density is determined by the external ion beam from the emitter-anode, and the volume charge of the secondary ions which are formed in the discharge is negligibly small, was investigated in [8]. In both cases it was assumed that the neutral atom number density is constant.

However it is not difficult to see that over a quite wide range of conditions the probability of ionization of neutral atoms in the layer may be close to one. Moreover, it should be emphasized that the layer is an "open system," since both the ions and the un-ionized neutral atoms after passing through the layer leave it freely. Therefore, for a correct determination of the layer characteristics it is necessary to take into account the entry and nonuniformity of the distribution of the working substance in the discharge. Of particular interest is the case of the self-maintained discharge with intense "burnup" of the neutrals, when all the ions are formed in the discharge gap and their volume charge must be taken into account.

In the following we shall examine the problem of the anode electrical layer in a discharge in a strong transverse magnetic field with account for influx and burnup of the neutral gas. We study this case of the self-maintained discharge with strong burnup of the neutrals and specifically the question of ionization of the neutral gas in the layer. An extension of the solutions for the regimes studied in [7, 8] is also obtained.

1. We direct the x coordinate across the layer, the z axis along the external uniform magnetic field, and we examine the plane case in which all is uniform in the y and z directions. It is convenient to locate the coordinate origin at the point at which the electric field is zero (Fig. 1). For accumulation of electrons near the anode it is necessary that the electron drift flux be closed. In the problem in question the Hall current is directed along the y axis and is closed at infinity. The external magnetic field is assumed to be sufficiently large so that the induced field can be neglected. Assuming the electrons at distances on the order of the layer thickness strongly magnetized and the ions nonmagnetized, in the diffusion approximation we can write the governing system of equations

$$\frac{dq}{dx} = \nu_i n_e, \quad \frac{dj_e}{dx} = \nu_i n_e \quad (\nu_i = \langle \sigma_i v_e \rangle n_n)$$
$$\frac{d^2\varphi}{dx^2} = 4\pi e (n_e - n_i), \quad j_e = b_{e\perp} n_e \frac{d\varphi}{dx} \quad \left(b_{e\perp} = \frac{e}{m} \frac{\langle \sigma_0 v_e \rangle}{\omega_e^2} n_n\right) \tag{1.1}$$
$$n_i = \frac{j_{i0}}{\sqrt{2eM^{-1}(\varphi_0 - \varphi) + v_{i0}^2}} + \int_x^{x_0} \frac{\nu_i n_e \, dx'}{\sqrt{2eM^{-1}[\varphi(x') - \varphi(x)] + v_0^2}}$$

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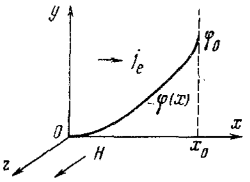

Fig. 1

Here q and j_e are the neutral and electron flux densities respectively, j_{i0} is the ion flux density from the anode, n_e, n_i, n_n are the particle concentrations; ν_i is the electron ionization collision frequency, φ is the potential, φ_0 is the imposed potential difference, e is the electron charge, m and M are the electron and ion masses, ω_e is the electron cyclotron frequency, $b_{e\perp}$ is the transverse electron mobility, σ_0 is the total collison section of electrons with loss of the directed momentum, v_e is the electron thermal velocity, v_{i0} is the initial ion velocity in the beam, v_0 is the mean directed velocity of the neutrals, x_0 is the anode coordinate. The boundary conditions for the layer-type solution have the form

$$\varphi(0) = \varphi'(0) = 0, \quad j_e(0) = 0, \quad q(0) = q_0 \ \text{ or } \ q(x_0) = q_0 \tag{1.2}$$

and the layer thickness x_0 is found from the condition

$$\varphi(x_0) = \varphi_0 \tag{1.3}$$

For $x > 0$ (1.1) describes the case in which the working substance is fed through the anode. It is not difficult to see that the same system of equations (with the replacement $j_e \to -j_e$) for $x < 0$ describes the other case, in which the neutral flux travels in the direction of the anode, if particles are not reflected from the wall.

In formulating (1.1), for simplicity we neglected the electron pressure gradient in comparison with the term containing the electric field. (Account for the dropped term has relatively little effect on the nature of the solution [7] and is the subject of a separate study.) However we shall assume that the electrons have energies considerably greater than the ionization potential. This makes it possible to consider the quantity $\langle \sigma_i v_e \rangle$ independent of the electron temperature, and the quantity $\langle \sigma_0 v_e \rangle$ will also be assumed approximately constant. Moreover, in the one-dimensional model being studied no account is taken for removal of electrons along the magnetic field, which occurs in actual finite schemes. This experimentally observed phenomenon [6] is most significant at the beginning of the layer and apparently leads to some deformation of the low-voltage part of the layer. The system of equations (1.1) is also not applicable for examining the "separation" region near the anode, in which the electrons pass freely to the anode from a distance approximately equal to the Larmor radius. Finally, it should be noted that we neglect the ionization of the neutrals by fast ions and ion charge exchange.

It should be particularly noted that (1.1) does not describe correctly the phenomenon in the region of small electric fields: first, because of the loss of electrons and ions from this region along the magnetic lines of force and, second, because the electron temperature at the beginning of the layer is low, so that the quantity $\langle \sigma_i v_e \rangle$ is also small, and it is possible that ionization by fast ions will play the dominant role in the region in question. Therefore, strictly speaking, the solution of (1.1) must be merged in the region of low electric fields with the quantities determined from the solution of the corresponding supplementary problem. In other words, the solution of the last problem would make it possible to determine for the model in question the boundary conditions in the region of small electric fields with account for the real physical conditions in this region. However this procedure is quite complicated and will not be examined here. For our purpose it is sufficient to consider only the approximate description of the anode layer of finite thickness within the framework of (1.1) with the natural "layer type" boundary conditions (1.2).

We introduce the following dimensionless quantities (primes will be dropped hereafter):

$$s = x / l^*, \ \eta = \varphi/\varphi^*, \quad n_e' = n_e / n^*, \quad n_i' = n_i / n^*, \ j_e' = j_e / q_0, \quad q' = q / q_0 \tag{1.4}$$

where

$$l^* = \left(\frac{e\varphi^*}{m\omega_e^2}\frac{\langle\sigma_0 v_e\rangle}{\langle\sigma_i v_e\rangle}\right)^{1/2}, \qquad n^* = \frac{v_0}{\langle\sigma_i v_e\rangle l^*}, \quad q_0 = n_0 v_0 \tag{1.5}$$

Here n_0 is the initial neutral concentration, φ^* is the characteristic potential value.

Then we can write (1.1) in the form

$$\frac{dq}{ds} = qn_e, \quad \frac{dj_e}{ds} = qn_e, \quad j_e = qn_e\frac{d\eta}{ds}, \quad \varkappa\frac{d^2\eta}{ds^2} = n_e - n_i, \quad n_i = \frac{\alpha}{\sqrt{\delta - \eta}} + \beta\int_s^{s_0}\frac{q' n_e'\, ds'}{\sqrt{\eta' - \eta + \varepsilon}} \tag{1.6}$$

Here

$$\alpha = \frac{j_{i0}}{v_0\omega_e}\left(\frac{M}{2m}\langle\sigma_i v_e\rangle\langle\sigma_0 v_e\rangle\right)^{1/2}, \quad \beta = \frac{n_0}{\omega_e}\left(\frac{M}{2m}\langle\sigma_i v_e\rangle\langle\sigma_0 v_e\rangle\right)^{1/2}$$

$$\varkappa = \frac{m\omega_e}{4\pi e^2}\left(\frac{e\varphi^*}{mv_0^2}\right)^{1/2}\frac{\langle\sigma_i v_e\rangle^{3/2}}{\langle\sigma_0 v_e\rangle^{1/2}}, \quad \delta = \frac{\varphi_0 + Mv_{i0}^2/2e}{\varphi^*}, \quad \varepsilon = \frac{Mv_0^2}{2e\varphi^*} \tag{1.7}$$

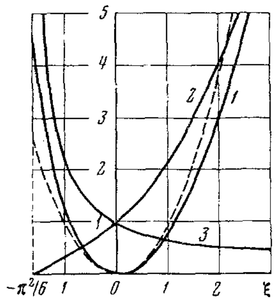

Fig. 2

The boundary conditions (1.2) take the form

$$\eta(0) = \eta'(0) = 0, \; j_e(0) = 0, \; q(0) = 1 \text{ or } q(s_0) = 1 \tag{1.8}$$

The layer thickness s_0 is found from the conditions

$$\eta(s_0) = \varphi_0 / \varphi^* \tag{1.9}$$

We see from (1.6) that the parameters δ and ε, due to the existence of the initial ion beam velocity and the nonzero thermal velocity of the neutral atoms, are of secondary importance, since the order of magnitude of the terms in which these parameters appear is determined by the magnitude of the parameters α and β. Thus, the nature of the solution is determined basically by the three dimensionless criteria $\alpha, \beta, \varkappa$. Specifically, physically different discharge states can be realized, depending on the relationship between their magnitudes. It is easy to see that $\alpha \sim j_{i0}/H$, $\beta \sim n_0/H$ and $\varkappa \sim H\sqrt{\varphi}$, i.e., only the parameter β depends on the neutral gas flowrate (or pressure), the criterion $\varkappa$ depends only on the accelerating voltage, and the parameter α is associated with the size of the external ion beam.

2. Let us first examine the "vacuum" discharge regime. In this case there is no external ion beam ($\alpha = 0$), and the concentration of the ions which form in the discharge gap can be neglected in comparison with the electron concentration ($\beta \ll 1$). The vacuum discharge regime is realized for sufficiently low pressure ($p \lesssim 10^{-3}$ Torr for the experimental conditions of [4-6]).

It is convenient to take $\varphi^* = \varphi_0$ as the potential measurement scale, and $q(0) = 1$ as the boundary condition. Then the solution of (1.6) with the conditions (1.8) is easily found in parameteric form

$$s = \varkappa^{-1}\Phi(z), \quad \eta = \varkappa^{-2}\Psi(z), \quad n_e = \varkappa\frac{e^z - 1}{ze^z}, \quad q = e^z \quad (j_e = q - 1) \tag{2.1}$$

Here

$$\Phi(z) = \int_0^z \frac{te^t\,dt}{e^t - 1}, \quad \Psi(z) = \int_0^z \frac{t^2 e^t\,dt}{e^t - 1} \tag{2.2}$$

The parameter z in (2.1) can take both positive (in the case of neutral flux from the anode) and negative (for neutral flux to the anode) values. The corresponding regions of variation of z are bounded by the conditions $0 \le z \le z_1$ and $z_2 \le z \le 0$, where z_1 and z_2 are the roots of the equation $\Psi(z_{1,2}) = \varkappa^2$. The layer thickness is found from the relation $s_0 = \varkappa^{-1}|\Phi(z_{1,2})|$. For comparison we note that the solution obtained under the assumption of uniform neutral density distribution in the layer [7] has the form

$$\eta = {}^1/_2 s^2, \; n_e = \varkappa, \; j_e = \varkappa s \; (s_0 = \sqrt{2}) \tag{2.3}$$

The solution (2.1) is shown in Fig. 2 in the form of the dependence of $2\varkappa^2\eta$, q and $n_e/\varkappa$ on $\xi = \varkappa s$ (curves 1, 2, 3 respectively). Also shown dashed is the parabola ξ^2 which is the solution (2.3). In contrast with (2.3), the electron concentration is not uniform across the layer. In this connection there is also a change of the layer thickness, the layer becoming thicker in the case of neutral flux from the anode and thinner in the case of flux in the opposite direction. For $\varkappa \ll 1$ the difference between (2.1) and (2.3) is naturally small. The probability of neutral ionization in the layer, and therefore nonuniformity of the neutral gas distribution, and the difference between the solutions become significant for ($\varkappa \sim 1$. This corresponds to very large values of the imposed voltages and magnetic fields. For example, for $\langle\sigma_i v_e\rangle \approx 10^{-7}$ cm^3/sec, $\langle\sigma_0 v_e\rangle / \langle\sigma_i v_e\rangle \approx 3$, $v_0 \approx 3 \cdot 10^4$ cm/sec, we find $H^2\varphi_0 \approx 10^{12}$ Oe$^2 \cdot$V.

3. Now let us examine the discharge regime with an external ion beam. We assume that the concentration of the ions which form in the discharge can be neglected in comparison with the ion concentration in the beam ($\beta \ll \alpha$). Then it follows from (1.6) that for ($\varkappa \ll \alpha$) there may be the quasineutral solution $n_e \approx n_i$. With the aid of (1.7) the condition for quasineutrality of the layer can be written in the form

$$\frac{\varkappa}{\alpha} \equiv \frac{j^*}{j_{i0}} \ll 1 \quad \left(j^* = \frac{m\omega_e^2}{4\pi e^2}\left(\frac{2e\varphi^*}{M}\right)^{1/2}\frac{\langle\sigma_i v_e\rangle}{\langle\sigma_0 v_e\rangle}\right) \tag{3.1}$$

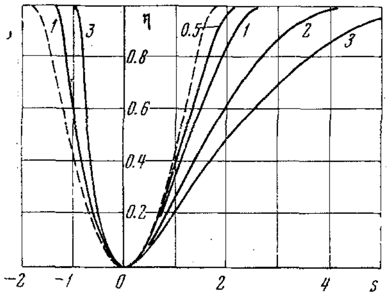

Fig. 3

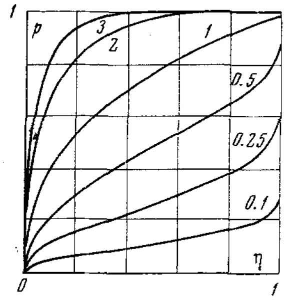

Fig. 4

The characteristic current ej^* depends only on the properties of the working medium and the magnitudes of the magnetic field and voltage. For $\varphi^* \approx 10^3$ V, $H \approx 10^3$ Oe, $(M/m)^{1/2} \approx 600$, $\langle \sigma_i v_e \rangle / \langle \sigma_0 v_e \rangle \approx 0.3$ we obtain $ej^* \approx 15$ mA/cm^2. Thus, for ion beams of sufficient density (3.1) may be satisfied. To solve the problem it is convenient to take $\varphi^* = \varphi_0 + Mv_{i0}^2/2e$ and the boundary condition $q(0) = 1$. Then $\delta = 1$ and the layer thickness is found from the relation

$$\eta(s_0) = \frac{1}{1+\mu} \qquad \left(\mu = \frac{Mv_{i0}^2}{2e\varphi_0} < 1\right) \tag{3.2}$$

We have for the charged particle density

$$n_e \approx n_i = \alpha / \sqrt{1-\eta} \tag{3.3}$$

Excluding n_e, q, and j_e from (1.6), we obtain

$$\frac{d^2}{ds^2}\sqrt{1-\eta} + \frac{\alpha}{\sqrt{1-\eta}}\frac{d}{ds}\sqrt{1-\eta} + \frac{1}{2\sqrt{1-\eta}} = 0 \tag{3.4}$$

The solution of the posed problem may be written in parametric form

$$\sqrt{1-\eta} = [(1-t)e^t]^{1/2\alpha^2}, \qquad s = \frac{1}{\alpha}\int_0^t \frac{[(1-u)e^u]^{1/2\alpha^2}du}{1-u}, \qquad q = \frac{1}{1-t} \tag{3.5}$$

In the general case the parameter t in (3.5) varies in the range $-\infty < t \le 1$. (The region $t > 0$ corresponds to the case of neutral flow from the anode, for $t < 0$ the neutral flow has the opposite direction.)

If neutral entry into and burnup in the layer is not considered, the problem reduces to the equation [8] which is obtained from (3.4) if we set $\alpha = 0$. In other words, the influence of nonuniformity of the neutral atom distribution in the layer can be found by comparing (3.5) with this formal solution. We find, as in the preceding case, that with increase of α the layer thickness increases significantly if the neutrals flow from the anode and decreases if the neutrals flow to the anode. Figures 3 and 4 show for different values of α (numerals on the curves) the potential $\eta(s)$ and neutral ionization probability distributions on the segment from 0 to s for the case of neutral flow from the anode: $p(\eta) = 1 - 1/q(\eta)$. (If the neutral flow has the opposite direction, the formula for the ionization probability changes: $p = 1 - q$.) For $\mu = 0$ the neutral ionization probability equals one. However μ clearly is always an appreciable quantity, primarily because of the existence of a stripping region near the anode. Therefore the regions of steep growth of $p(\eta)$ near $\eta = 1$ are excluded from consideration by the condition (3.2). The probability of neutral ionization in the layer will thus be close to one for $\alpha \gtrsim 1$. With the aid of (3.5) we can evaluate the order of magnitude of the dropped term in the Poisson equation and see that the quasineutrality condition (3.1) is not violated anywhere for the solution in question.

4. Finally, let us examine the case of self-maintained discharge in the absence of an external ion beam ($\alpha = 0$), when all the ions are formed in the layer and their space charge must be considered. In this case it is of interest to trace the evolution of the solutions with increase of the neutral gas pressure (or flowrate). We shall consider only the case when the neutrals arrive through the anode. Therefore we shall use the condition $q(s_0) = 1$ and take $\varphi^* = \varphi_0$.

It is not possible to find the exact analytic solution of (1.6) under the assumptions made. Having the solution (2.1) for $\beta = 0$, it is not difficult to write the approximate solution (1.6) in the form of an expansion in β. However it is lengthy, and for a reasonable number of terms it provides adequate accuracy only for $\beta \ll 1$. Therefore the problem was solved numerically by successive approximations, taking steps in β. The parameter ε, which accounts for the initial ion velocity, equal to the thermal velocity of the neutrals, is generally speaking very small. However it is obviously advisable to take a somewhat larger value in the calculations. The fact that in reality the ions formed in the region with small electric field ($d\eta/ds \to 0$) exit freely from the layer is to some degree accounted for by the increased value of ε. The computation results presented below were obtained with $\varepsilon = 10^{-2}$.

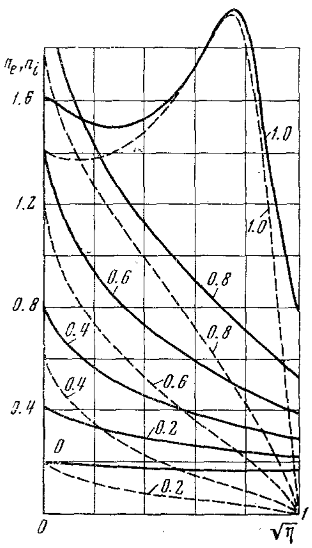

Fig. 5

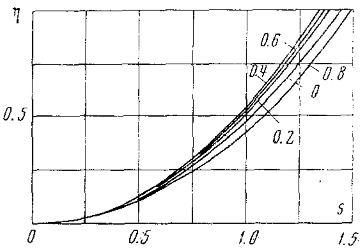

Fig. 6

The computational results are shown in Figs. 5-7. The relations $n_e(\sqrt{\eta})$ (solid curves) and $n_i(\sqrt{\eta})$ (dashed curves) are shown in Fig. 5 for $\varkappa = 0.2$ and different β (numerals on curves). The electron and ion concentrations increase with increase of β and become highly nonuniform, decreasing in the direction toward the anode. (In the model problem examined the ion and electron densities at the beginning of the layer do not coincide because of the simplifications made.) Figure 6 shows the potential distribution $\eta(s)$ for $\varkappa = 0.2$ (the numerals on the curves show the values of β). We see from the curves that with increase of β from zero the layer first becomes thinner and then, beginning at some $\beta = \beta_*(\varkappa)$, the layer expands. The fact that the layer thickness decreases for small β is related to the nature of the spatial distribution of the ions. Since $n_i \to 0$ as $s \to s_0$ and the electron current to the anode for small β increases faster than a linear function of β, the electric field potential near the anode increases and the layer thickness decreases. However the influence of nonuniformity of the neutral concentration owing to their burnup with further increase of β opposes this effect. The electron mobility increases in the direction toward the anode, leading to reduction of the electric field intensity near the anode and increase of the layer thickness. Figure 7 shows two families of curves $q(\sqrt{\eta})$ for $\varkappa = 0.05$ (dashed) and $\varkappa = 0.2$ (solid). For fixed $\varkappa$ the neutral burnup and consequently the nonuniformity of their distribution increase with increase of β (and also with increase of $\varkappa$). For example, for $\varkappa = 0.2$ and $\varkappa = 0.8$, the neutral ionization probability reaches 0.8. For smaller values of $\varkappa$ ($\varkappa < 0.1$) a solution could be obtained only up to $\beta = 0.4$–0.5, when the ionization probability in the layer is still relatively low. However it is clear from physical considerations that ionization begins to increase rapidly with further increase of β up to values on order of one.

It is of interest to compare, to the degree possible, the exact results obtained with the simple approximate formula of Zharinov for the ionization probability of the neutral atom in the layer. The ionization probability in the layer can be written in the form

$$P = 1 - \exp\left\{-\frac{\langle \sigma_i v_e \rangle}{v_0} \int_0^{x_0} n_e\, dx\right\} \tag{4.1}$$

The integral in the exponent is expressed approximately in terms of the average drift velocity $v_\rightarrow$ and the total drift flux J_H of the electrons arriving per unit length along the z axis

$$\int_0^{x_0} n_e\, dx = \frac{1}{v_\rightarrow} \int_0^{x_0} n_e c \frac{E}{H}\, dx = \frac{J_H}{v_\rightarrow} \tag{4.2}$$

Using the relation [8]

$$J_H \approx j_i \rho_i + \frac{cE_0^2}{8\pi eH} \qquad \left(j_i = Pq_0,\ \rho_i = \lambda \sqrt{\frac{2e\varphi_0}{M}} \Big/ \frac{eH}{mc}\right) \tag{4.3}$$

and the approximation

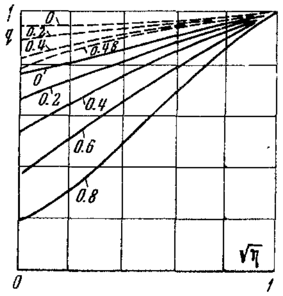

Fig. 7

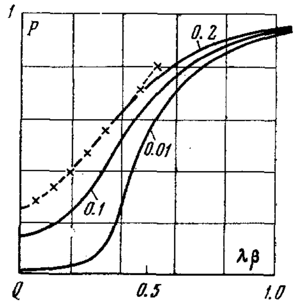

Fig. 8

$$v_{\to} \approx \frac{c\varphi_0}{Hx_0}, \qquad x_0 \approx \sqrt{2}l^*, \qquad E_0 \approx 2\frac{\varphi_0}{x_0}$$

it is not difficult to obtain the sought formula in the form

$$P \approx 1 - \exp\left[-\sqrt{2}\,(2\lambda\beta P + \varkappa)\right] \tag{4.4}$$

Here we have used the notations: j_i is the flux density of the ions formed in the layer, ρ_i is their average Larmor radius, E_0 is the intensity of the electric field on the anode, λ is the ratio of the average ion velocity to the maximal velocity. On the basis of (4.4) we can state that the neutral ionization probability in the layer for $\beta \gtrsim 1$ will be significant for all values of $\varkappa$. Figure 8 shows the relation $P(\lambda\beta)$ obtained from (4.4) for various values of $\varkappa$ (numerals on the curves), and for $\varkappa = 0.2$ a comparison is made with the value of P calculated exactly (crosses and dashed curve). We see that for $\lambda \approx 0.66$ there is good agreement up to $\beta \approx 0.6$. The discrepancy beginning with $\beta \gtrsim 0.7$ can be explained by the fact that the value of λ increases with increase of P, approaching one as $P \to 1$. Thus, if on some basis we can determine the value of λ appropriate for some range of values of the parameter β, then (4.4) permits rapid determination of the ionization probability.

In conclusion we note the following situation. We mentioned previously the increase of the layer thickness with increase of $\varkappa$ and β if the neutral flow comes from the anode. On the basis of simple physical considerations it is not difficult to explain this phenomenon and obtain the limiting value of the layer thickness for $\beta \gg 1$ ($\alpha \gg 1$). We write the total electron drift flux J_H in the form

$$J_H = \int_0^{x_0} j_e(\omega\tau)_e\,dx = \int_0^{x_0} q(x)\,p(x)\,(\omega\tau)_e\,dx \qquad \left(\tau_e = \frac{1}{\langle\sigma_0 v_e\rangle n_n}\right) \tag{4.5}$$

Then, using (4.3), omitting therein the drift current held back by the anode surface charge and considering that for $\beta \gg 1$

$$p \to 1, \quad \lambda \to 1, \quad \int_0^{x_0} p(x)\,dx \to x_0$$

we obtain

$$s_0 \to 2\beta \tag{4.6}$$

In the more general case, when there is also an external ion beam, we have in place of (4.6)

$$s_0 \to 2(\alpha + \beta) \tag{4.7}$$

The layer thickness without account for neutral arrival and burnup is equal in order of magnitude to the electron Larmor radius [7, 8], which makes questionable the applicability of the diffusion approximation used in those studies. The disclosed effect of increase of the layer thickness with increase of the neutral flux from the anode justifies the use of the diffusion approximation for sufficiently large flow rate and justifies the results obtained in this approximation.

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