ELECTRON CONDUCTIVITY IN ACD

V. I. Baranov, Yu. S. Nazarenko, V. A. Petrosov, A. I. Vasin
Keldysh Research Center
Onezhskaya 8, Moscow, 125438, Russia

Abstract

Electron conductivity in accelerators with closed drift of electrons (ACD) is the key to understanding of processes going in ACD plasma. In consequence, a great deal of scientific papers is devoted to this subject [1-4]. This paper is aimed at showing the extent to which elaboration of this problem has been realized to date. This work is also intended to make things clear regarding some fine aspects of this problem. Here are meant the questions of the near-wall conductivity and the conductivity caused by oscillations, which are building up due to nonuniformity of plasma parameters (concentration and magnetic field). The novelty of this paper is as follows: an estimated conductivity by oscillations in terms of parameters of anomalous erosion, the model of nonelastic collisions in the near-wall conductivity, the electron transfer mechanism in the near-cathode region of the beam where the magnetic field is still great, but the electric field is already small.

Classical conductivity by collisions

Reasonably the consideration should be conducted in cylindrical coordinates r, φ, z because of axially symmetric geometry of the channel in ACD. Ion acceleration in ACD is implemented by the axial electric field, E_z, applied between the anode and cathode (a voltage, $U \sim 300$ V). The radial magnetic field B_r (150 – 200 G maximally) magnetizes electrons whereby the propellant ionization and smallness of an electron longitudinal current as compared to an ion current are provided. B_r causes electrons in the acceleration channel to move, for the most part, on Larmour circles with a radius r_L.

$$r_L = v_e / \Omega,$$

where v_e – the mean electron velocity;
Ω – Larmour rotational frequency:

$$\Omega = eB / mc\,.$$

Typical quantities of the Larmour rotational frequency and the radius for the acceleration layer:

$$\Omega \sim 2 \cdot 10^9\ \text{c}^{-1},\ r_L \sim 1\ \text{mm}.$$

The action of the axial electric field, E_z, results in the occurrence of azimuthal velocity of electron drift:

$$V_\varphi = cE_z / B_r \approx (1 \div 2)10^8\ \text{, cm/s.} \qquad (1)$$

The electron frictional force ($\nu m V_\varphi$), caused by this drift velocity results in its turn an electrons drift from the cathode to the anode

$$V_z = (\nu / \Omega) V_\varphi, \qquad (2)$$

where ν - the frequency of electron collisions. Just this drift velocity defines the electron conductivity in the ACD plasma.

Let us estimate that velocity under the assumption that ν is defined by only classical collisions with atoms and ions, i.e.

$$\nu^{-1} = \nu_{ei}^{-1} + \nu_{ea}^{-1}\,.$$

A typical concentration of charged particles at the exit of ACD acceleration channel comprises $n = 10^{12}$ cm^{-3}, and that of neutral atoms, $n_a = 10^{13}$ cm^{-3}. Then the quantity of the frequency of collisions between electrons and xenon atoms, ν_{ea} equals:

$$\nu_{ea} = n_a \sigma_{ea} v_e \approx (2-4) \cdot 10^6, s^{-1},$$

here σ_{ea} – the cross-section of electron scattering by a xenon atom..

The electron-ion collision frequency ν_{ei}, is calculated through the Coulomb scattering cross-section, σ_q

$$\sigma_q = 4\pi\Lambda(e^2 / m v_e^2)^2,$$

here Λ - «Coulomb» logarithm ($\Lambda \sim 10$),

$$\nu_{ei} = n \sigma_q v_e \approx 1.3 \cdot 10^8 / (\varepsilon, eV)^2,\ \text{s}^{-1}.$$

Kinetic energy of electrons, ε, in the acceleration layer is high and may reach a few tens of electron-volt, i.e. collisions with atoms play a leading part.

Then for the longitudinal electron velocity we obtain an estimated $V_z \sim 10^5$ cm/s. This quantity is much less (almost by an order) than a real velocity of electrons in the acceleration layer, V_e. The latter may be estimated by knowing a mass flow rate G and a total current I though the accelerator

$$G = n V_I S M_{Xe},$$

$$I = n(V_I + V_e) Se.$$

Here S – the channel section, V_I – the ions velocity, $V_I = (2eU/M_{Xe})^{1/2}$, whence we obtain

$$V_e = V_I \left(\frac{M_{Xe}}{G}\frac{I}{e} - 1\right) \approx 6 \cdot 10^5\ \text{, cm/s.}$$

The estimation carried out shows that in the ACD acceleration layer other possible mechanisms of electron transfer are to be significant, namely: electron scattering on plasma instabilities and electron collisions with channel walls.

However, before proceeding to these questions the following should be noted. In the region between the acceleration layer and anode where xenon ionization takes place the atom concentration is higher, an electron temperature (energy) is lower, therefore, similar estimates for this region reveal the classical conductivity by collisions with atoms and ions would be quite sufficient to provide the electron delivery to the anode.

Electron conductivity by plasma oscillations

Frequency of collisions with oscillations

By growth of plasma instability by some type of oscillations electric fields, periodic in time and space, originate in plasma. An electron can change its part by interaction with these fields just as it does in the field of a ion and an atom by collisions. Therefore, to characterize electron interaction with plasma oscillations the effective frequency of collisions or the frequency of scattering by oscillations, ν_{osc}, may be introduced.

If the frequency of plasma oscillations, ω, is much less than the Larmour frequency of electrons, Ω, then the perturbed electric fields, E', may be considered as stationary ones. It is evident that the azimuthal component of the perturbed field E'_φ can contribute to the electron drift in the axial direction

$$V_z = \frac{<nV_z>}{n} = \frac{c}{B_r}\frac{<n' \cdot E'_\varphi>}{n}.$$

Here brackets < > mean azimuth averaging, and prime ′ – the perturbed quantity. In terms of (1,2) we obtain from here:

$$\frac{\nu_{osc}}{\Omega}V_\varphi = \frac{c}{B_r}\frac{<n' \cdot E'_\varphi>}{n},$$

or

$$\frac{\nu_{osc}}{\Omega} = \frac{<n'E'_\varphi>}{n \cdot E_z}.$$

I.e. the effective frequency of electron scattering may be evaluated with an upper bound through a quantity of fluctuations of electron concentration and electric field.

$$\frac{\nu_{osc}}{\Omega} \le \frac{|n'|}{n}\frac{|E'_\varphi|}{E_z}. \qquad (3)$$

Let us now consider possible oscillations in ACD plasma. Low-frequency (tens of kilohertz) oscillations of discharge current and voltage have revealed themselves easiest by stand testing. These are the so-called ionization oscillations [5], they have a direct relationship to the ion or full conductivity, but not to electron one. In support of this interpretation one can point to the following fact. Oscillations regimes were observed where a discharge voltage diverged insignificantly from the nominal value, but by no more than 10%, and a discharge current decayed to zero, then it increased up to the double nominal value.

Only the two types of plasma oscillations can influence, for the most part, directly on electron conductivity in ACD. First, this are the oscillations caused by the relative motion of electrons and ions in the acceleration zone. Just due to these oscillations the so-called «anomalous» erosion of acceleration channel walls originates [6]. Second, these are oscillations associated with nonuniformity of plasma parameters: concentration and magnetic field [7].

Scattering by oscillations caused by relative motion of electrons and ions

For the acceleration layer the plasma dynamics equations are written in the following form (in this section we denote the azimuth coordinate as y, and φ - the perturbed potential)

$$\begin{aligned} &\frac{\partial n_i}{\partial t} + div(n_i V_i) = 0; \quad \frac{\partial V_i}{\partial t} + (V_i \nabla)V_i = \frac{e}{M_{Xe}}E; \\ &\frac{\partial n_e}{\partial t} + div(n_e V_e) = 0; \\ &\frac{\partial V_e}{\partial t} + (V_e \nabla)V_e = -\frac{e}{m}(E + \frac{1}{c}[V_e \times B]); \\ &divE = 4\pi e(n_i - n_e). \end{aligned} \qquad (4)$$

Considering an undisturbed ion velocity is directed chiefly along the axis V_i = {0,0,V_z}, the azimuth electron velocity is V_e = {0,U_y,0}, we obtain from this system the following dispersion equation [6]:

$$\frac{\omega_i^2}{(\omega - k_z V_z)^2} + \frac{\omega_e^2}{(\omega - k_y U_y)^2 - \Omega^2} = 1, \qquad (5)$$

where ω_i, ω_e – plasma frequencies of ions and electrons (ω^2=4πe^2n/m). At moderate frequencies ω <<$k_y U_y$, the conditions for build-up of oscillations may be written as follows [8]:

$$\frac{\Omega}{\omega_e}\omega_i < \omega - k_z V_z < \omega_i; \qquad (6)$$

$$\frac{\Omega}{U_y} < k_y < \frac{\omega_e}{U_y}. \qquad (7)$$

In [8] it is shown that not only the azimuthal spatial period of grooves of anomalous erosion, but also their inclination follows from these oscillations. In this work we use a quantity of a depth of these grooves to evaluate the effect of oscillations in hand on electron conductivity in the acceleration layer. Let us suppose as in [8], that the ion concentration near the channel walls defines an erosion rate. Then the ratio of a depth of erosion grooves h, to a full depth of erosion H, will be proportional to the ratio of perturbation of the concentration in oscillations to the mean ion concentration, i.e.

$$\frac{n'}{n} = \frac{h}{H}. \qquad (8)$$

To use (3) it is necessary to evaluate further the quantity of E'_{φ}/E'_z. For small perturbations from system (4) we have the following relationships:

$$\frac{E'_y}{E_z} = \frac{\varphi}{U}k_y l = \frac{n'}{n}\frac{(\omega - k_z V_z)^2}{k_y^2}\frac{M_{Xe}}{eU}k_y l, \quad (9)$$

where l – the length of the acceleration layer, U – the outside potential applied to the discharge ($E_z \sim U/l$).

From (5), in terms of that for ACD $\Omega^2 << (k_y U_y)^2 << \omega_e^2$, we obtain an estimate for a quantity of the phase velocity of oscillations:

$$\frac{(\omega - k_z V_z)^2}{k_y^2} \approx U_y^2 \frac{m}{M_{Xe}}. \quad (10)$$

From (3) in view of (9) and (10) we obtain:

$$\frac{\nu_{osc}}{\Omega} \leq \frac{(n')^2}{n^2}\frac{mU_y^2}{eU}k_y l. \quad (11)$$

From experimental measurements the typical quantity of h/H equals about 0.1. Then (11) gives (ν_{osc}/Ω)$\leq 10^{-1}$, i.e., $\nu_{osc} < 2\cdot 10^8$ s^{-1} which corresponds to the longitudinal electron velocity (2), $V_z \leq 2\cdot 10^7$ cm/s.

Thus, the estimated value of the electron longitudinal velocity in the acceleration layer, stemming from plasma oscillations, would give a sufficiently great quantity as compared with the real electron velocity ($V_z = 6\cdot 10^5$ cm/s). This means the considered type of plasma oscillations may play a leading part in transfer of electron current in the acceleration layer.

A more exact quantity of conductivity by this type of oscillations may be obtained by numerical calculations. In [4] is made the attempt to numerically simulate the electron conductivity by oscillations. Some results were there obtained, but it is difficult to interpret them, since, first, the plasma model, which in its parameters is very far from the up-to-date ACDs was calculated; second, the equation of electron motion was omitted by derivation of the dispersion equation of oscillations. It resulted in the fact that the amplitudes of perturbed parameters have appeared in the expression for the oscillation frequency, allowing no possibility to classify somehow these oscillations. The problem of numerical simulation of oscillations in the ACD channel requires further elaboration.

Scattering by oscillations caused by nonuniformity of plasma parameters

A second possible type of plasma oscillations that are of considerable importance in ACD is the type by which oscillations are caused by nonuniformity of plasma concentration and a quantity of radial magnetic field. Oscillations of this type were systematically analyzed in [7]. Here we define more exactly the derivation of the dispersion equation of these oscillations, as well we will show a new field of their application for ACD.

$$\begin{cases} \frac{dn_i}{dt} + div(n_i\vec{V}) = 0; \\ \frac{dn_e}{dt} + div(n_e\vec{V}) = 0; \\ \frac{d\vec{V}_i}{dt} + (\vec{V}\vec{\nabla})\vec{V} = \frac{e}{M}\vec{E}; \\ \frac{d\vec{U}}{dt} + (\vec{U}\vec{\nabla})\vec{U} = -\frac{e}{M}(\vec{E} + 1/c[\vec{U}x\vec{B}]) - \\ \qquad -\frac{T\vec{\nabla}n_e}{mn_e} - \nu\vec{U}; \\ div\vec{E} = 4\pi e(n_i - n_e). \end{cases} \quad (12)$$

As differentiated from the previous case we assume that concentrations, velocities and magnetic field are nonuniform on the axis. Then, for a perturbed electron velocity we obtain the following expressions:

$$\begin{cases} u_x = i(\frac{e\varphi}{m} - \frac{T}{m}\frac{n_e}{N})\frac{k_y\Omega - ik_x(\omega + k_yU - i\nu)}{\Omega(\frac{dU}{dx} - \Omega) + (\omega + k_yU - i\nu)^2}; \\ u_y = i(\frac{e\varphi}{m} - \frac{T}{m}\frac{n_e}{N})\frac{k_x(\frac{dU}{dx} - \Omega) - ik_y(\omega + k_yU - i\nu)}{\Omega(\frac{dU}{dx} - \Omega) + (\omega + k_yU - i\nu)^2}, \end{cases} \quad (13)$$

where φ and n_e – perturbed potential and density of electrons, ν - full frequency of electron collisions. Should the conditions

$$|\Omega| >> |\omega + k_yU - i\nu|, \quad |\Omega| >> |\partial U/\partial x|, \ |k_x| \cong |k_y| \quad (14)$$

be fulfilled, then (13) may be brought to the form:

$$u_x = -\frac{c}{B_z}\frac{\partial\varphi^*}{\partial y}, \quad u_y = \frac{c}{B_z}\frac{\partial\varphi^*}{\partial x}, \quad (15)$$

where

$$\varphi^* = \varphi - \frac{T}{e}\frac{n_e}{N}, \ ik_y \to \frac{\partial}{\partial y}, \ ik_x \to \frac{\partial}{\partial x}.$$

Approximation (15) was used, for example, in [9], but therein it was supposed that only the conditions $\omega << \Omega$ and $\nu << \Omega$ are fulfilled instead of (14). However, for the acceleration layer in up-to-date ACDs the fulfillment of the constraint $\Omega >> k_yU$ is far more severe, as $\Omega \sim 2\cdot 10^9$ s^{-1}, and $U \sim 2\cdot 10^8$ cm/s, therefore, $k_y << 10$ cm, i.e. a wave length $\lambda_y = 2\pi/k_y \geq 5$ cm. In other words, only large-scale perturbations may be researched with help of approximation (15) in the acceleration layer of ACD, thereat, not only on the azimuth coordinate but on the axis also, since the condition $k_x \sim k_y$ is to be fulfilled.

Use of equations (15) instead of more general (13) allows simplifying the dispersion equation and bringing it to the form:

$$\frac{k_x^2-(ik_x/N)\partial N/\partial x}{(\omega+k_yV-i\cdot\partial V/\partial x)^2}+$$
$$+\frac{k_y^2}{(\omega+k_xV)(\omega+k_xV-i\,\partial V/\partial x)}+ \qquad (16)$$
$$+\frac{k_y/L}{\Omega_i(\omega+k_yU)}=\frac{k^2}{\omega_i^2}$$

where Ω_i – the Larmour ion frequency, and the notation is introduced.

$$\left[\frac{1}{B}\frac{\partial B}{\partial x}-\frac{1}{N}\frac{\partial N}{\partial x}\right]\equiv L^{-1}. \qquad (17)$$

However, equation (16) is still too complicated for analysis. Therefore, we make a next simplification being restricted to consideration of small-scale perturbations, i.e. of those ones whose wave length is far less than longitudinal nonuniformities of plasma

$$|k_x|>>\left|\frac{1}{N}\frac{\partial N}{\partial x}\right|,\left|\frac{1}{V}\frac{\partial V}{\partial x}\right|. \qquad (18)$$

Then equation (16) may be brought to the form

$$\frac{1}{(\omega+k_xV)^2}+\frac{k_y/L}{k^2\Omega_i(\omega+k_yU)}=\frac{1}{\omega_i^2} \qquad (19)$$

or, if $\omega_i>>\omega$,

$$(k_y/L)(\omega+k_xV)^2+k^2\Omega_i(\omega+k_yU)=0\,. \qquad (20)$$

These equations (with an accuracy of notations and signs before k_x and k_y) were used for analysis of oscillations in the ACD channel in [7,9]. From (20) we obtain that imaginary ω (which corresponds to build-up of oscillations) originate under the condition:

$$a(a-4b)<0, \quad \text{where}$$
$$a=L\Omega_ik^2/k_y\,,\ b=k_yU-k_xV \qquad (21)$$

In the acceleration layer an electron drift velocity, U, is large (note that $U<0$), i.e.

$$|k_yU|>>|k_xV|,\ |\Omega_iL|. \qquad (22)$$

In this case the condition of the oscillation build up is fulfilled at $L<0$. For the first time these oscillations were apparently observed in [1], where the acceleration channel had a length of 13 cm, the magnetic field was uniform, B = 500 G, propellant - argon, an applied voltage - 200 V. At such parameters we obtain from (20) that the azimuthal velocity of wave propagation is approximately 4-5 times less than the drift velocity U, an oscillation frequency - $5\cdot10^4$ s^{-1}, which was observed in experimental measurements.

In up-to-date ACDs the magnetic field configuration is selected so that in the acceleration zone reverse inequality, $L>0$, is fulfilled, in this connection, the type of oscillations in hand is not excited.

It should be noted that for the acceleration zone in up-to-date ACDs where the drift velocity is great, the use of (19), (20) is not quite correct, as we have seen that on the one hand, for applicability of this approximation the oscillations must be large-scale, on the other-small-scale (18). With a further more care one should view the analysis results for various special cases of oscillations, $k_x << k_y$ or $k_x >> k_y$ carried out in [7], since in (14) we used the condition $k_x \sim k_y$.

Plasma instabilities at small electron drift velocities

Let us point to one more region in ACD plasma, where, in our opinion, equations (19), (20) may be fully applied for the analysis of oscillations excitation. Downstream of the acceleration zone in the region of cathode location the longitudinal electric field is sharply decreased (down to units of volt per cm) whereas the magnetic field remains still high (~100 G). In this region electrons would remain as being magnetized, and a single mechanism, acceptable from the viewpoint of magnitude, which provides the transfer of electrons across the magnetic field, is the scattering by oscillations. The electron drift velocity U decreases here by about two orders, i.e. instead of condition (22) we have the following one:

$$|k_yU|\le|k_xV|.$$

But in this case it would be sufficient to select for k_x a sign, opposite to that of the quantity «a» in (21), and such oscillations will be excited at any L. Furthermore, it is easy to verify that these oscillations do not also depend on a sign of U, i.e. on the direction of fields E_x and B_z. They are an universal mechanism of electron transfer across the enough strong magnetic field B_z due to the weak field E_x.

Near-wall conductivity of electrons

Elastic collisions with the wall

Electron collisions with acceleration channel walls result in initiation of additional electron conductivity. It may be estimated by the same formulas we used for electron collisions with heavy particles. But for this purpose a certain effective mean frequency of electron collisions with walls, ν_w, is to be known. In [2] the model of coarse wall is proposed:

$$\nu_w=\frac{V_e}{b}\Theta\,. \qquad (23)$$

Here V_e – the thermal velocity of electrons, b – the distance between walls, Θ - the roughness coefficient of walls ($0\le\Theta\le1$). In its sense the roughness coefficient is a mean relative quantity of variations of the electron drift velocity ($\Delta U/U$) by collisions with wall. Owing to availability of the near-wall potential barrier a large share of electrons is reflected there from. And a typical scale of wall roughness is less than the quantity of the Debye distance of electron, then, obviously, we should assume, $\Theta=0$, as the reflecting surface becomes parallel with the direction of the drift velocity.

In [10] it is proposed to additionally take into account a decrease in the electron flow near the wall as compared with that not far from the boundary of the near-wall layer

$$\Theta = \frac{(nV_e)_w}{nV_e}\frac{\Delta U}{U}. \qquad (24)$$

In the same work it is noted quite true with an increase of the relative quantity of the near-wall barrier $[\Delta\Phi/(kT_e)]$ the near-wall conductivity decreases and vanishes at $[\Delta\Phi/(kT_e)] > 5$ practically. Therefore, the assertion in [11] the near-wall conductivity would be the chief mechanism of electron transfer from the ionization zone to the anode is erroneous. Really, in the ionization zone electrons spend their energy chiefly in ionization processes, their temperature decreases and becomes much less than the first threshold of electron multiplication for a channel walls material, ε^*. Then processes of secondary electron emission can be neglected, and the near-wall barrier becomes very high ($\Delta\Phi/(kT_e)\sim6$ for xenon), and the near-wall conductivity is low respectively.

Non-elastic collisions with the wall

Up to the present it was supposed electron collisions with the wall or with the near-wall barrier are elastic, as a result of these collisions the electrons gain energy, travelling along the acceleration field. However, if the electron energy becomes compared with ε^*, a large share of electrons reach directly the wall, experiencing non-elastic collisions with a full loss of the drift velocity ($\Delta U/U\sim1$). This means such processes also result in emergence of conductivity, thereat, their role may be well significant in the acceleration layer of ACD.

Our calculations [12] show in terms of secondary electron emission the dependence of the relative quantity of the near-wall barrier $[\Delta\Phi/(kT_e)]$ on electron temperature T_e has a threshold character. In other words, at electron temperatures less than ε it weakly depends on T_e, and then sharply decays to zero. In this case it is evident the energy ε^* is an upper boundary for T_e in the acceleration zone. The quantity of the maximum electron energy in the channel depends on wall material characteristics and usually makes up several tens of electron-volt. A frequency of non-elastic collisions with the wall may be estimated as follows [13].

$$\nu_w = \frac{V_{eII}}{b}\exp(-\Delta\Phi / kT_{eII}), \qquad (25)$$

where V_{eII}, T_{eII} – thermal velocity and temperature in the magnetic field direction. Here it is taken into account that in the acceleration layer the electron energy is substantially anisotropic [14] as electrons in the electric field gain energy in the direction transverse to B, but in the direction longitudinal with reference to B their energy grows slowly, mainly, at the expense of relatively rare collisions with particles. Formula (25) can be brought to the form [13]:

$$\nu_w = \frac{V_i}{b}\frac{1}{1 - T/\varepsilon^*}. \qquad (26)$$

Formula (26) was used in calculations of the plasma flow in the channel [13, 15]. From (25), (26) it follows in particular that ν_w can change most essentially: from $V_{eII}/b\sim10^8\ s^{-1}$ to $V_{iII}/b\sim10^5\ s^{-1}$.

Note the interesting feature of the near-wall conductivity by non-elastic collisions. By a small variation (an increase) in the electron temperature due to the threshold dependence of $\Delta\Phi$ on T_e, we can obtain: $\nu_w \sim V_{eII}/b \sim 10^8\ s^{-1}$, providing the possibility for passing the electron current 10 times more than the real one over the acceleration layer. The question is why does this not take place? The answer resides in the following. The maximum quantity of the current that is allowed to pass between the cathode and the anode is defined by the resistance of the whole plasma gap. And if the near-wall conductivity can provide a large current flow over the acceleration layer, over the rest of plasma regions a large current cannot pass (s. also [15]). Also note the mechanism here described may be realized as independent process of electron transfer across B only in the maximum-current regime. In this case, the electric intensity E is to be very high so that an electron after its egress from the wall may gain the lost energy simply by the motion on the Larmour radius, i.e. $m/[2(cE/B)^2] \sim \varepsilon^*$. If this condition is not fulfilled, this process can not go without any other mechanisms of electrons warning up. To compensate for the energy lost by the wall the electrons must experience elastic scattering, which moves them along E and increases their energy. But elastic scattering is not a single mechanism of compensating for energy of electrons, for example, their warming up is possible by electron heat conduction.

Conclusion

The work deals with the analysis of chief mechanisms of electron conductivity in the up-to-date ACDs: the classical conductivity by collisions with particles, conductivity by plasma instabilities, near-wall conductivity. The quantity of conductivity has been estimated, the discharge regions where one or other type of conductivity plays a decisive role – have been determined. In the region from the anode to the acceleration layer, classical collisions with atoms and ions are principal. In the acceleration layer the basic part belongs to the near-wall conductivity and electron scattering by oscillations caused by the relative motion of ions and electrons (the same oscillations result in the initiation of anomalous erosion of walls of insulators). In the region from the acceleration layer to the cathode and downstream of the beam the electron transfer across the magnetic field is provided by azimuth oscillations caused by nonuniformity of plasma concentration and radial magnetic field.

References

[1] Janes G., Dotson J. "Experimental research in oscillations and anomalous electron diffusion attendant thereon in Hall direct-current accelerators operating under low pressures» in «Applied magnetic hydrodynamic», M., «Mir», 1965 (in Russian).

[2] Morozov A. I. «The effect of near-wall conductivity in the well-magnetized plasma«, Jhurn. Prikl. Math. i Tekhn. Fiz., 1968, Issue 3, pp. 19-22 (in Russian).

[3] Baranov V.I., Vasin A.I., Nazarenko Yu.S., Petrosov V.A, Yashnov Yu.M., «Energy Model and Mechanisms of Acceleration Layer Formation for Hall Thrusters», AIAA 97-3047.

[4] Hirakava M. «Electron Transport Mechanism in a Hall Thruster», IEPC 97-021.

[5] Baranov V.I., Vasin A.I., Nazarenko Yu.S., Petrosov V.A, Yashnov Yu.M., «Mechanism of Ionization Oscillations in Accelerators with Closed Drift of Electrons», IEPC 95-59.

[6] Baranov V.I., Nazarenko Yu.S., Petrosov V.A., Puzanov S.V., Vasin A.I., Yashnov Yu.M. "Mechanism of Abnormal Erosion of Dielectric under Influence of Plasma Flow" - Letters to JTP, vol. 20, issue 5, 1994, p.p. 72-75 (in Russian).

[7] Yesipchuk Yu. V., Tilinin G. N. «Drift instability of plasma in ACD«, ZhTF, 1976, v. 46 Issue 4, pp.718-729 (in Russian).

[8] Baranov V.I., Vasin A.I., Nazarenko Yu.S., Petrosov V.A, Yashnov Yu.M., «Anomalous Erosion in Accelerators with Closed Drift of Electrons», IEPC 95-43.

[9] Morozov A. I., Yesipchuk Yu. V., Kapulkin A. M., Nevrovsky V. A., Smirnov V. A. "The effect of magnetic field configuration on the regime of ACD operation", ZhTF, v. 42, Issue 3, pp. 612-619, 1972 (in Russia).

[10] Yegorov V. V., Kim V., Semenov A. A., Shkarban I. I. "Near-wall processes and their influence on operation of accelerators with closed drift of electrons", In book: «Ion Injectors and Plasma Accelerators», Moscow, Publishing House Energoatomizdat, 1990, p.p. (in Russian).

[11] Bugrova A.I., Morozov A.I. "Peculiarities of Physical Processes in Accelerators with Closed Drift of Electrons and Extent Zone of Acceleration"-In book: «Ion Injectors and Plasma Accelerators», Moscow, Publishing House Energoatomizdat, 1990 (in Russian).

[12] Baranov V.I., Vasin A.I., Nazarenko Yu.S., Petrosov V.A, Puzanov S.V. Yashnov Yu.M., "On efficiency of the near-wall conductivity in the plasma accelerator with closed drift of electrons", - Letters to JTP, Issue 15, v. 21, 1995 (in Russian).

[13] Baranov V.I., Vasin A.I., Nazarenko Yu.S., Petrosov V.A, Yashnov Yu.M., «Energy model and Near Wall Processes in ACD», IEPC 97-60.

[14] Baranov V.I., Vasin A.I., Nazarenko Yu.S., Petrosov V.A, Yashnov Yu.M., "Function of Electron Distribution in Accelerators with Closed Drift of Electrons", IEPC-95-61.

[15] Baranov V.I., Vasin A.I., Nazarenko Yu.S., Petrosov V.A, «The Principle of Current Maximality for Discharge Simulation in ACD», IEPC 99-103.