INVESTIGATION OF ANOMALOUS ELECTRON TRANSPORTIN THE DISCHARGE OF THE CIRCULAR ELECTRON DRIFT ACCELERATOR

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In the stationary discharge with azimuthal electron drift in the crossed axial electric and radial magnetic fields an azimuthal plasma heterogeneity has been specially created. It is shown experimentally that the heterogeneity increase by only ≈6% can cause accelerator discharge current increasing by ≈100 % due to its electron component increase. Formula for the electron transport velocity calculation is determined. Hall parameters are calculated using this formula and the experimental data of other researches. Both Hall parameters are in good conformity with each other.

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1. ANALYSIS OF CURRENT PROBLEMS AND DEFINITION OF TASKS FOR RESEARCH

Stationary closed electron drift accelerators are widely used in various space and ground technologies. In many countries scientific researchers and engineers are going at upgrading these accelerators. In this field one of the fundamental scientific problems is uncertainty of regularities of anomalous plasma conductivity in crossed electric and magnetic fields.

Now when modeling and analyzing the plasma processes a so-called Bohm conductivity [1] in the form of coefficient $\mu=1/(16\,B)$ is used to describe the anomalous plasma conductivity and achieve precise results. So, the electron transport velocity is $V_{tr},=E\cdot\mu$, but basic physical processes of anomalous plasma conductivity are not clear yet.

Hypothesis about a strong effect of plasma (ion) heterogeneity (in the electron drift direction i.e. azimuthal direction) on the plasma conductivity was formulated earlier by the author Oghienko S.A. The reason of the plasma heterogeneity is an azimuthal heterogeneity of plasma-forming gas in the discharge interval (DI). To test and to develop the hypothesis about regularities of the anomalous plasma conductivity the following research problems were defined: 1) to investigate experimentally the influence of azimuthal heterogeneity of gas concentration distribution in DI on the discharge current by varying the magnetic field and discharge voltage; 2) to determine analytically the electron transport velocity as a function of the magnetic and electric fields, electron energy and azimuthal plasma heterogeneity in DI.

2. INVESTIGATION OF THE AZIMUTHAL PLASMA HETEROGENEITY INFLUENCE ON THE ELECTRON TRANSPORT

The thruster of M-70 type (made by one of the world leaders - firm “Fakel”, Russia) operating in the modes similar to the nominal one (Figs. 1, 3) was used in experiments as a closed electron drift accelerator.

The azimuthal heterogeneity of ion concentration in the DI plasma has been provided by the artificial azimuthal heterogeneity of gas concentration in the discharge chamber (DC) close to the anode gas-distributor surface (below – anode, Fig. 1). For this purpose a total fixed mass flow rate of gas was redistributed between the anode and two additional gas suppliers. As more than 95% of gas is ionized in the DC ionization zone, the relative heterogeneity of ion (plasma) concentration downstream meets the relative gas heterogeneity in this zone. It has been supposed, that when the total gas flow in DC is going through the anode gas-distributor, the azimuthal gas heterogeneity in DC is not created. Actually the gas heterogeneity near the anode includes a permanent value ≈ 3…3.5% because of the inaccuracies of gas-distributor fabrication.

During experiment in the accelerator DC close to the anode the gas heterogeneity $\varepsilon_{na}=\Delta n_a/n_a\cdot 100\%$ of discrete values: 0, 2.4, 4.5 and 8.5% was generated specially under the following operating conditions. The vacuum chamber was pumped out by oil-vapour pump up to residual pressure of $3\cdot10^{-5}$ Torr. Then the discharge was ignited and the accelerator started to operate in the mode close to the nominal one (mass flow rate of Xe in DC m_{DC}=2.16 mg/s, voltage U_d=300 V, a current I_d=2…2.4 A, magnetic induction B=15 mT).

Then the accelerator was heated to the discharge current stabilization under vacuum chamber pressure of $\approx2.2\cdot10^{-4}$ Torr. The discharge current was measured at the fixed Xe mass flow rate m_{DC}=2.16 mg/s with various discrete values of the discharge voltage and magnetic field.

Basing on the analysis results (Fig. 2) it has been concluded the following. The increase of the azimuthal gas heterogeneity ε_{na} in the vicinity of anode results in the increase of gas and ion heterogeneity $\Delta n_i/n_i\sim\varepsilon_{na}/10$ in ionization zone, being compensated by electrons. Consequently the discharge current I_d increases due to the electron component I_e increasing. The value I_e cannot be explained on the basis of the collisional classical theory of conductivity. The explanation of this will be given below.

Power, gas supply and measurement systems of stand SV-10K, developed by author Bilokin’ V.I. for plasma accelerator testing, were used in the experiment.

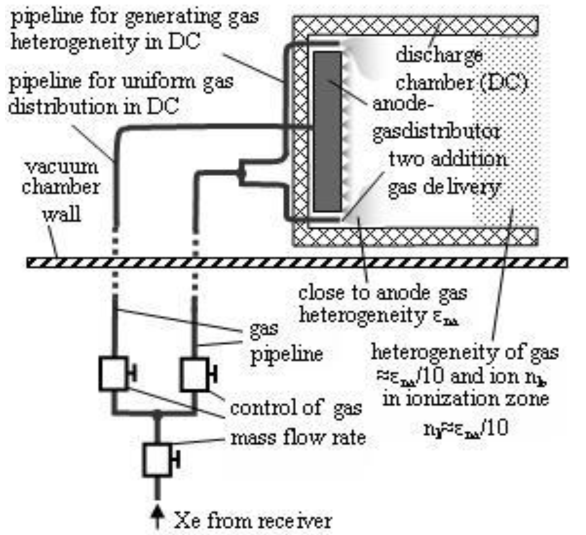

Fig. 1. Gas supply and distribution to the accelerator discharge chamber system

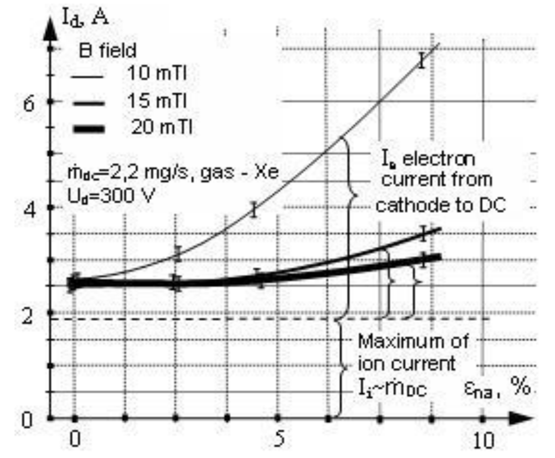

Fig. 2. Discharge current I_d as a function of the azimuthal gas heterogeneity ε_{na} close to the anode

3. ELECTRON TRANSPORT VELOCITY DETERMINING

3.1. COMPENSATION OF AZIMUTHAL ION CONCENTRATION HETEROGENEITY

It has been supposed that the compensation of azimuthal ion heterogeneity – ion overcharge $e\cdot\Delta n_i$ by the electron charge $e\cdot\Delta n_e$ is going in the next way. In the local self-consistent electric field E_{loc} of extent l_h (see Fig. 3) the electron drift velocity V_{dr} in the electron stream $n_e\cdot V_{dr}$=const of azimuthal direction decreases and, in turn, the electron concentration increases as $n_e \sim 1/V_{dr}$. The compensation effect $n_к$ of the charge $e\cdot\Delta n_i$ is determined as $n_к=\Delta n_e/n_e=\Delta n_i/n_i$.

The change in the electron concentration $\Delta n_e=-\text{const}\cdot\Delta V_{dr}/V_{dr}^2$ is determined after the law of azimuthal electron flow continuity. It has been supposed that the drift velocity V_{dr} decreases as a result of electron scattering in the field $E_{loc}\approx-\Delta\varphi/l_h$. In this case the electron (its guiding center) displaces oppositely to the drift direction for a distance $\Delta x_п\approx\Delta x$ during the period τ of electron cyclic motion. Approach of a single particle [2] was used as a simplification. Bidirectional electron motion lengthwise cycloid – a helical path projection onto the plane perpendicular to the magnetic induction, was analyzed. It has been assumed that the period of motion is $\tau=\text{const}_1$ and the distance $(L_c-\Delta x_п)$, which the electron passes along the azimuth, undergoes changes because of electron dispersion. Therefore, the azimuthal electron velocity $V_{dr}=L_c/\tau$ changes as $\Delta V_{dr}\approx(L_c-\Delta x_п)/\tau-L_c/\tau=-\Delta x_п/\tau$, and the value of ion charge compensation effect by electrons is $n_к=\Delta n_e/n_e\approx\Delta x_п/L_c$.

A more accurate equation for $\Delta n_e/n_e$ was found in view of electron motion features (in Fig. 3 – from point 0 to 1, through 2 to 3 and further). The cycloid length estimate was $L_c=2\cdot\pi\cdot E\cdot m/(e\cdot B^2)$.

Thus the guiding center displacement distance is $\Delta x_п\approx(\Delta x-\Delta R_l\cdot\cos(\gamma))$, but not $\Delta x_п\approx\Delta x$, as it has been roughly estimated above. The gyroradius change $\Delta R_l=R_{lк}-R_{lн}$ (see Fig. 1) is determined in view of: 1) electron velocity in the cycloid plane (without local field E_{loc} influence) $V_0=(4/3\cdot T_e/m)^{1/2}$; 2) gyroradius initial value $R_{lн}=m/(B\cdot e)\cdot(4/3\cdot T_e/m)^{1/2}$; 3) final value – $R_{lк}=m/(B\cdot e)\cdot(4/3\cdot T_e/m+\varepsilon_n\cdot 2/m)^{1/2}$ – after influence of the local field E_{loc}. The gyroradius change is $\Delta R_l=m/(B\cdot e)\cdot((4/3\cdot T_e/m+\varepsilon_n\cdot 2/m)^{1/2}-(4/3\cdot T_e/m)^{1/2})$.

The value of Δx (see Fig. 3) is determined as $\Delta x=\Delta\cdot\sin(\gamma)=R_l\cdot\sin(\alpha_0)\cdot\sin(\gamma)$.

The ratio between $\Delta\varphi\cdot e$ and ε_n, and the relation of γ and α_0 angles with the velocity components in points 0, 1 and 2 are determined by the energy conservation law, using the diagrams and models in Fig. 3. The ratio between ε_n and $\Delta\varphi$ is estimated as $\varepsilon_n/\Delta\varphi/e\approx 1/2$ and approximately $\sin(\gamma)\approx(l_h/2/R_l)^{1/2}$. Neglecting minor terms, $\sin(\alpha_0)\cdot\cos(\gamma)\approx(l_h/R_l)^{1/2}\cdot\Delta\varphi\cdot e/(4/3\cdot T_e\cdot l_h/R_l)$ was found.

Then charge compensation effect was calculated as $n_к=\Delta n_e/n_e=(\Delta x-\Delta R_l\cdot\cos(\gamma))/(2\cdot\pi\cdot E\cdot m/(e\cdot B^2))$. In view of the determined equations and neglecting minor terms of the order of $l_h^4/16/R_l^4$, $\Delta\varphi$ is expressed through l_h/R_l and discharge parameters as follow $\Delta\varphi\cdot e\approx 4/3\cdot T_e\cdot(n_к\cdot 2^{1/2}/R_l\cdot(2\cdot\pi\cdot E\cdot m/(e\cdot B^2))+l_h^3/(8\cdot R_l^3))/(1+l_h/(2\cdot R_l)-l_h^3/(8\cdot R_l^3))$.

An optimal l_h/R_l, by which $\Delta\varphi$ tends to the minimum, is determined from the condition $d(\Delta\varphi)/d(l_h/R_l)=0$. Neglecting minor terms, a required equation $l_h/R_l\approx 1.9\cdot(n_к\cdot 2^{1/2}/R_l\cdot(2\cdot\pi\cdot E\cdot m/(e\cdot B^2)))^{1/2}$ was found. Taking this ratio l_h/R_l, the minimal $\Delta\varphi$ (at which the electron concentration increases up to $n_к=\Delta n_e/n_e$ and, thus, the ion charge $e\cdot\Delta n_i$ is compensating) was determined as $\Delta\varphi\cdot e\approx n_к\cdot T_e\cdot\pi\cdot E\cdot m\cdot 8\cdot 2^{1/2}\cdot(R_l\cdot B^2\cdot e\cdot 3)$.

3.2. ELECTRON TRANSPORT VELOCITY DETERMINING

It was planned to find out the following values: 1) the electron displacement across the magnetic field by dispersion in the field of plasma heterogeneity, 2) the duration of the electron displacement, 3) the electron transport velocity and the Hall parameter, and 4) it was intended to compare the Hall parameter to the similar one from the experiments of other authors.

Because of dispersion in the local field E_{loc} (see Fig. 3) the electron displaces against the electric field E across the magnetic field B with velocity $V_{tr}\approx\Delta z/\tau$. In such a way, the anomalous plasma conductivity is realized.

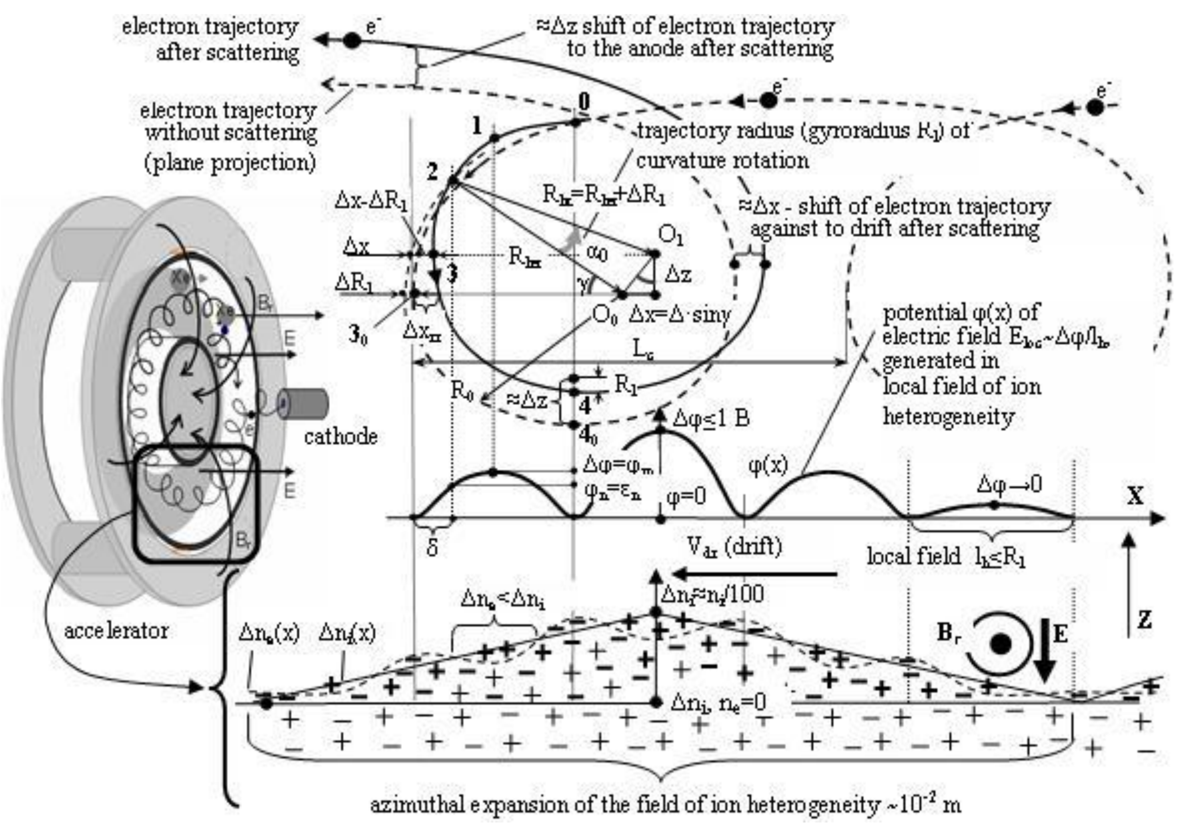

Fig. 3. Diagram of the electron scattering in the field of azimuthal plasma flow heterogeneity

The period of the electron azimuthal motion lengthwise cycloid is determined as $\tau=L_c/V_{dr}=2\cdot\pi\cdot m/(e\cdot B)$, and Δz – similar to Δx (see above). Then by the use of the set of equations obtained before, the electron transportation velocity across the magnetic field $V_{tr}\approx(R_l/l_h)^{1/2}\cdot\Delta\varphi\cdot e^2\cdot B\cdot 3\cdot R_l/(8\cdot\pi\cdot m\cdot T_e)$ is determined. Using the ratio l_h/R_l (by which $\Delta\varphi$ is minimum) found earlier, the equation for velocity is: $V_{tr}=R_l\cdot(n_\kappa/R_l\cdot(2\cdot\pi\cdot E\cdot m/(e\cdot B^2)))^{3/4}/(2\cdot\pi\cdot m/(e\cdot B))$.

After substituting the known values R_l and minimum $\Delta\varphi$, and making the conversions, the velocity $V_{tr}\approx(n_\kappa\cdot E/B)^{3/4}\cdot(T_e/(9\cdot\pi^2\cdot m))^{1/8}$ can be found. Here the ratio E/B is the azimuthal electron drift velocity in the electric field $V_{dr}=V_{drE}=E/B$. Then, in spite of the reasons of azimuthal drift, the transport velocity is determined as $V_{tr}\approx(n_\kappa\cdot V_{dr})^{3/4}\cdot(T_e/(9\cdot\pi^2\cdot m))^{1/8}$.

Let us specify the electron transport velocity V_{tr} in view of the displacement of a trajectory across the azimuthal drift, determined on the extreme point (point **4** in Fig. 3). V_{tr} is determined by the difference $V_{tr}\sim(\Delta z-\Delta R_l)$, while $R_0=V_0\cdot m/e\cdot B=(4/3\cdot T_e/m)^{1/2}\cdot m/e\cdot B$ and $R_1=(4/3\cdot T_e/m+(\Delta z-\Delta R_l)\cdot E\cdot 2/m)^{1/2}\cdot m/e\cdot B$. As a result $\Delta z-\Delta R_l=\Delta z/(1+E/B\cdot(3\cdot m/4/T_e)^{1/2})$ and the electron transport velocity can be calculated by the equation $V_{tr}\approx(n_\kappa\cdot V_{dr})^{3/4}\cdot(T_e/(9\cdot\pi^2\cdot m))^{1/8}/(1+E/B\cdot(3\cdot m/4/T_e)^{1/2})$.

In the gas ionization zone where the electric field is weak, the azimuthal electron drift velocity is $V_{dr}=V_{drB}$ in the magnetic field with a gradient grad(B). The gyroradius R_l is determined on values of electron velocity $V_\perp$ in the drift planes, value $V_\perp$ – on terms of electron temperature T_e (in units of J) as $m\cdot V_\perp^2/2\approx 2/3\cdot T_e$. The electron gradient drift velocity was determined using the induction B as $V_{drB}\approx T_e\cdot grad(B)/B^2/e\cdot 2/3$. The gradient drift velocity $V_{drB}\approx 2\cdot 10^5$ m/s is estimated at characteristic temperature $T_e\approx 20$ eV and induction $B\approx 0.6\cdot 15=9$ mT in the region of a minimum electric field, $grad(B)\approx 0{,}02/0.015$ T/m, whereas the drift velocity in the electric field is $V_{drE}=E/B\approx 2\cdot 10^6$ m/s.

The above formulas do determine the maximum values of a charge compensation effect n_κ and transport velocity V_{tr}. The average value of a transport velocity is estimated as $V_{trav}\approx V_{tr}(n_\kappa)/2$.

The Hall parameter $\omega\cdot\tau=V_{dr}/V_{tr}$ was calculated on the basis of electron transport model being offered and compare to Hall parameter calculated after the classical theory (frequency $\omega=e\cdot B/m$ and time between collisions $\tau\approx 1/(\sigma_{elast}\cdot n_a\cdot V_e)$) and also after known results [1].

Parameters of accelerator operation mode, values of fields, temperatures, azimuthal heterogeneity of ions, electron azimuthal drift velocity, velocity of transportation used in calculations are presented in Table. The value $n_k\approx\varepsilon_{na}\approx 0.035$ is taken as a characteristic one for the area close to the anode where the formation of a plasma flow in a low-voltage operation mode begins. The results of calculations for the parameter $\omega\cdot\tau$ are shown in Fig. 4.

The Poisson law was used to calculate a so-called anomalous electron transport velocity V_{tr} in the wide range of charge concentrations n_e (atypical for the Hall accelerator). Finally the equation V_{tr} is written down as

$$V_{tr}\approx\left(V_{dr}\right)^{3/4}\cdot\frac{n_k}{\sqrt{B}}\cdot\left(\frac{T_e\cdot n_e{}^2\cdot m}{\pi^2\cdot\varepsilon_0{}^2}\right)^{1/8}\cdot\frac{0.64}{1+E/B\cdot(3\cdot m/(4\cdot T_e))^{1/2}}.$$

Electron drift Hall parameters at the discharge voltage U_d=100 V

Parameters of accelerator operation mode		
Out of discharge chamber	At the cut of discharge chamber	In zone of gas ionization
$T_e \approx 3$ eV $E \approx 1.5 \cdot 10^3$ V/m B≈10 mTl $n_k = \Delta n_i/n_i \approx \varepsilon_{na} \approx 0.035$ $n_a \approx 5 \cdot 10^{18}$ m^{-3}, $n_e \approx 3 \cdot 10^{17}$ m^{-3}	$T_e \approx 15$ eV $E \approx 6 \cdot 10^3$ V/m B≈15 mTl $n_k = \Delta n_i/n_i \approx \varepsilon_{na} \approx 0.035$ $n_a \approx 10^{19}$ m^{-3}, $n_e \approx 3 \cdot 10^{17}$ m^{-3}	$T_e \approx 6$ eV $E \approx 10^3$ V/m B≈10 mTl $n_k = \Delta n_i/n_i \approx \varepsilon_{na} \approx 0.035$ $n_a \approx 5 \cdot 10^{19}$ m^{-3}, $n_e \approx 10^{17}$ m^{-3}
Electron transportation velocity and Hall parameter ω·τ calculated after proposal model		
$V_{tr} \approx 1.3 \cdot 10^4$ m/s $V_{dr} = 1.5 \cdot 10^5$ m/s, $\omega \cdot \tau = V_{dr}/V_{tr} \approx 12$	$V_{tr} \approx 3 \cdot 10^4$ m/s $V_{dr} = 4 \cdot 10^5$ m/s, $\omega \cdot \tau = V_{dr}/V_{tr} \approx 13$	$V_{tr} \approx 10^4$ m/s $V_{dr} = 10^5$ m/s, $\omega \cdot \tau = V_{dr}/V_{tr} \approx 10$
Hall parameter ω·τ was calculated in each zone after classical theory of particles collision (see Fig. 4) $\omega = e \cdot B/m$, $\tau \approx 1/(\sigma_{elast} \cdot n_a \cdot V_e)$		

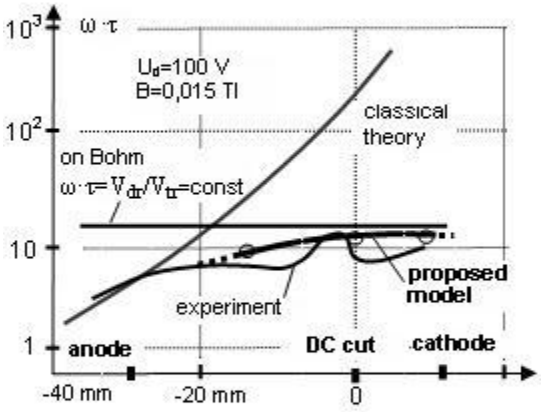

Fig. 4. Electron drift Hall parameter

CONCLUSIONS

The hypothesis about the influence of azimuthal ion charge heterogeneity in the plasma on the velocity of electron transport across the magnetic field and on the discharge current is confirmed experimentally in this research. The equation for the anomalous velocity of electron transport in the discharge across the magnetic field on the electron drift velocity, magnetic and electric fields, and – for the first time – on the azimuthal charge heterogeneity in the plasma has been determined analytically. The Hall parameter, calculated using the derived equation, and the similar Hall parameter, calculated on the base of experimental results by other authors [1], is in good conformity with each other (see Fig. 4) that confirms the equation obtained.

The equations under consideration can be used for further mathematical modeling of processes in the plasma in crossed electric and magnetic fields.

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ИССЛЕДОВАНИЕ АНОМАЛЬНОЙ ТРАНСПОРТИРОВКИ ЭЛЕКТРОНОВ В РАЗРЯДЕ УСКОРИТЕЛЯ С ЗАМКНУТЫМ ДРЕЙФОМ ЭЛЕКТРОНОВ

С.А. Огиенко, В.И. Белоконь

В стационарном разряде с азимутальным дрейфом электронов в скрещенных осевом электрическом и радиальном магнитном полях специально создавалась азимутальная неоднородность плазмы. Было показано, что увеличение этой неоднородности на ≈ 6% может привести к росту тока разряда до ≈ 100% из-за роста его электронной компоненты. Определена формула для расчёта скорости транспортировки электронов к аноду и рассчитан параметр Холла как с использованием этой формулы, так и – результатов экспериментов других авторов. Оба параметра Холла находятся в хорошем соответствии друг с другом.

ДОСЛІДЖЕННЯ АНОМАЛЬНОГО ТРАНСПОРТУВАННЯ ЕЛЕКТРОНІВ У РОЗРЯДІ ПРИСКОРЮВАЧА ІЗ ЗАМКНЕНИМ ДРЕЙФОМ ЕЛЕКТРОНІВ

С.А. Огієнко, В.І. Білоконь

У стаціонарному розряді із азимутальним дрейфом електронів у схрещених вісьовому електричному та радіальному магнітному полях спеціально створено азимутальну неоднорідність плазми. Було показано, що її збільшення на ≈ 6% може призвести до зростання розрядного струму до ≈ 100% внаслідок росту його електронної складової. Визначено формулу для розрахунку швидкості транспортування електронів до аноду та розраховано параметр Холла як з використанням цієї формули так і – результатів експериментів інших авторів. Обидва значення параметра Холла є у добрій відповідності один до одного.