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Electron transport across magnetic field in gas-discharge nonneutral electron plasma

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Abstract

For investigation of the influence of vortex structures and asymmetry of electric and magnetic fields on the processes of electron transport across the magnetic field, the model of electron sheath considered in [1,2] has been used. The investigations were carried out by comparison and analysis of experimental and theoretical dependencies of discharge current on the magnetic field and on the value of disturbance of field symmetry. The obtained results give evidence that the disturbance of field symmetry causes the neoclassical transport of electrons, and the influence of vortex structure on the discharge electron sheath leads to the transverse mobility of electrons strongly different from that of classical.

1. Introduction

Nonneutral plasmas consist of the charged particles of only (or mainly) one sign. As a result, they are characterized by large intrinsic electric fields which have a strong influence on the behavior and on the stability of the plasmas. Nonneutral plasmas are of great interest for investigation of nonlinear collective phenomena, neoclassical and turbulent transport across the magnetic field, simulation of large-scale geophysical phenomena and for technical applications. One of the simplest and the most efficient way of obtaining and studying of nonneutral electron plasma is the use of discharge in crossed electric and magnetic fields. In the simplest case, for the discharge device the geometries of magnetron, inverted magnetron and Penning cell are used. The discharge parameters are such that ions are not magnetized and leave the discharge gap without collisions. At the same time, the electrons are strongly magnetized and are trapped by the magnetic field. Under such conditions, the sheath of nonneutral electron plasma is formed near the anode surface and the whole discharge voltage falls on it [3-5].

In [1,2] the theoretical model of electron sheath of gas-discharge nonneutral electron plasma was considered, the limitation of sheath electron density in this plasma is determined not by the balance between the ionization and diffusion, but by the "critical" density of electrons, at which the diocotron instability is arisen. The threshold of appearance of diocotron instability is very sensitive to the size of gap between the sheath and the anode surface. At calculation of the gap, the value of disturbance of anode alignment (nonuniformity of magnetic field, tilting of magnetic field about the anode axis, mechanical inhomogeneity on the anode surface) and the value of electron Larmour radius near the anode surface were considered. Let us give the main equations of this model [1]:

$$r_c^2\left(r_a^2+r_0^2-2r_0r_1\right)=r_0^2\left(r_a^2-r_1^2\right) \qquad (1)$$

$$V_0 = \pi e\left(r_1^2 - r_1^2 \ln\frac{r_1^2}{r_a^2} - r_0^2 + r_0^2 \ln\frac{r_0^2}{r_a^2} \right) n_e \tag{2}$$

$$B^2\left(\left(r_a \pm d \right)^2 - r_1^2 \right)^2 = 8\pi mc^2 \left(r_a \pm d \right)^2 \left(r_0^2 - r_1^2 \right)\left(\ln r_1^2 - \ln\left(r_a \pm d \right)^2 \right) n_e \tag{3}$$

Here, B is the uniform magnetic field, V_0 is the discharge voltage, n_e is the electron density, considered to be uniform, r_a is the anode radius, r_1 is the radius of sheath boundary from the anode side, r_0 is the radius of sheath boundary from the cathode side, r_c is the cathode radius, d is the value of anode misalignment, which, in the case of annular protuberance on the anode surface is equal to the height of this protuberance h, and when the magnetic field is not parallel to the anode axis, it equals αL, where L is the anode length, and α is the angle between the anode axis and the magnetic field

$$d = \begin{cases} h \\ \alpha L \end{cases} \tag{4}$$

The set of equations (1) - (3) allows to determine n_e, r_0 and r_1 for any geometrical (r_a, r_c, L) and electrical (B, V_0) discharge parameters, as well as for the given value of the anode misalignment d. The model is very simple. It does not contain any empirical coefficient, uncertain parameters and, therefore, it can be easily used for comparison of experimental and theoretical characteristics of electron sheath. Such comparison was made in [1] and it showed not only the qualitative but also the quantitative agreement with the experimental results. This model allowed, for the first time, to describe quantitatively the influence of anode misalignment on the characteristics of electron sheath.

Since the model does not depend on the mechanism of electron transport across the magnetic field, it can be used for studying the influence of vortex structures and asymmetry of fields on the electron transport across the magnetic field being the aim of the given work.

However, before starting the investigations, let us consider some problems connected with the dynamics and the symmetry of the electron sheath. The model of electron sheath describes the "critical" electron density (n_{cr}) and the geometrical dimensions of the sheath at the moment preceding directly the origination of diocotron instability. The development of diocotron instability, the formation of quasi-stable vortex structure and the ejection of electrons from the sheath to the cathode along the magnetic field is a rapid, collisionless process. Besides, the sheath losses a part of electrons, as a result of which, the density of electron sheath decreases. Then, the electron density is restored as a result of ionization of the neutral gas atoms by the electrons. Hence, the electron density in the sheath is changed periodically. This is evidenced by the oscillogram of the ion current in the inverted magnetron presented in Fig.1 [6]. Therefore, for the correct comparison of experimental and theoretical results, it is necessary to use the average value of electron density n_e for a period, and not its maximum value n_{cr}. The estimations show that as a rather good approximation, the average value of electron density in the inverted magnetron, can be taken to be $n_e = n_{cr}$. As for the magnetron geometry, the vortex (or vortices) exists in it permanently [7] and, hence, the electron density is always less (possibly, significantly less) than the critical value. Therefore, for the magnetron we will make only the qualitative comparison between the theory and the experiment taking $n_e = n_{cr}$.

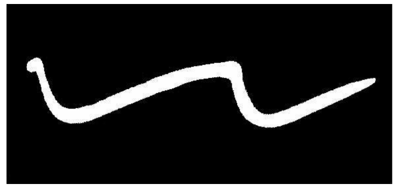

Fig.1. Oscillations of ion current in inverted magnetron [6]
$r_a = 0.9cm$; $r_c = 4cm$; $L = 5cm$; $V_0 = 5kV$; $B = 1kG$; $p = 8\times10^{-5}Torr$.

The next problem is connected with the alignment, as, at the comparison of the theory with the experiment one of the main criteria of agreement is the dependence of characteristics of discharge electron sheath on the value of anode misalignment. In the experiments three methods of anode misalignment have been used.

The first method consisted in that on the end of preliminarily aligned anode the thin rings of different thicknesses are put [8]. This method is connected with the switching of the discharge off, and with other inconveniencies, but it does not lead to the disturbance of azimuthal symmetry of the sheath and, therefore, is the closest experimental analogue of the considered model. The results of measurements with just such misalignment are in very good qualitative and quantitative agreement with the theoretical model of electron sheath [1].

The second method consisted in the change of the angle between the anode axis and the uniform magnetic field [5, 9]. It allowed to change smoothly the tilt angle of magnetic field by turning the solenoid without switching the discharge off. This method creates the controlled disturbance of azimuthal and axial symmetries of electric and magnetic fields in the discharge electron sheath and, therefore, is especially useful for studying the effects connected with the fields asymmetry, e.g. by formation of resonance sheath [5, 10]. Nevertheless, the results of measurements with such misalignment are in satisfactorily qualitative and, even, quantitative agreement with the theoretical model of the electron sheath not considering the field asymmetry, giving the evidence of the correctness of the used assumptions in it.

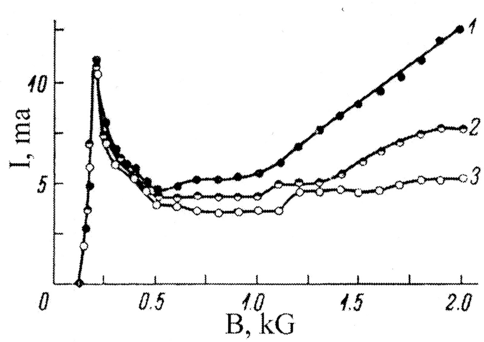

Fig.2. Effect of nonuniformity of the magnetic field in the magnetron geometry [9]
$r_a = 3.2cm$; $r_c = 0.9cm$; $L = 7cm$; $V_0 = 4kV$; $p = 8\cdot10^{-5}Torr$; $1-(\Delta B/B) = 0.002$, $2-0.008$, $3-0.016$

The third method consisted in the change of the uniformity of magnetic field [9]. For the estimation of the uniformity the value $\Delta B/B$ was used. Here B is the value of magnetic field in the central part of the solenoid just where the anode centre was located, and ΔB is the change of magnetic field along the anode (the difference in the value of magnetic field between the central part of the anode and its ends). In this case, the azimuthal symmetry of the sheath was kept as well. In the first publications with the inverted magnetron, when the effect of anode alignment was discovered [8,5], the uniformity of the magnetic field was $\Delta B/B = 0.016$. Later, by means of correcting coils, the uniformity of the magnetic field was improved up to $\Delta B / B = 0.002$ [9], allowing to observe the effect of anode alignment in the magnetron geometry as well. Fig.2 shows the dependence of discharge current on the magnetic field in magnetron geometry for different values of $\Delta B / B$ [9]. Therefore, for obtaining the increasing dependence of the discharge current on the magnetic field, the uniformity of magnetic field in the magnetron geometry should be much better than in the geometry of inverted magnetron.

2. Asymmetry-induced transport

Now, let us use the model of electron sheath considered above for studying the influence of asymmetries of electric and magnetic fields on the transport of electrons across the magnetic field. For this purpose let us make the comparison of experimental and theoretical dependencies of the discharge current (electron current on the anode) on the value of anode misalignment. Let us determine the discharge current as an electron current through the cylindrical surface limited by the anode length L and by the sheath radius r_1

$$I = 4\pi^2 e^2 L b_{tr} n_e^2 (r_0^2 - r_1^2) \tag{5}$$

Here b_{tr} is the mobility of electrons across the magnetic field. For comparison of the theory with the experiment we use the relative value of the discharge current I / I_0, where I_0 is the value of the discharge current at $d = 0$. As the discharge parameters are kept unchanged at the anode misalignment, the discrepancy between the experimental and the theoretical curves will be connected with the dependence of the transverse mobility of electrons on the value of anode misalignment. First, let us make the comparison for the anode misalignment without the disturbance of the azimuthal symmetry of the sheath. In fig.3, the solid line shows the theoretical dependence of the relative value of discharge current on the height of annular protuberance on the anode surface ($d = h$) in the inverted magnetron. The dots show the experimental values of the discharge current, taken from [8].

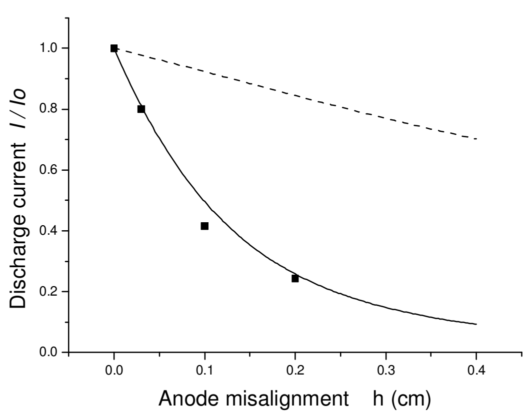

Fig.3. Dependence of discharge current on the thickness of rings in the inverted magnetron.
$B = 1kG$; $V_0 = 4kV$; $p = 3\times10^{-4} Torr$; $r_a = 0.9cm$; $r_c = 5cm$; $L = 7cm$

As it is seen from the figure, the agreement is quite good. This gives the evidence that the anode misalignment at the absence of the disturbance of azimuthal symmetry of the sheath does not have the influence on the value of the transverse electron mobility. For the comparison, in the same figure the dashed line shows the theoretical dependence of the relative value of discharge current on the height of annular protuberance on the anode surface without taking into account the diocotron instability.

Let us now compare the theory with the experiment when the magnetic field is tilted relative to the anode axis by angle α, i.e. the anode misalignment is accompanied with the appearance of the asymmetry of electric and magnetic fields. In Fig.4, the solid line shows the theoretical dependence of the relative value of discharge current on the angle between the anode axis and the magnetic field ($d = \alpha L$) in the inverted magnetron. The dots show the experimental values of the discharge current, taken from [5].

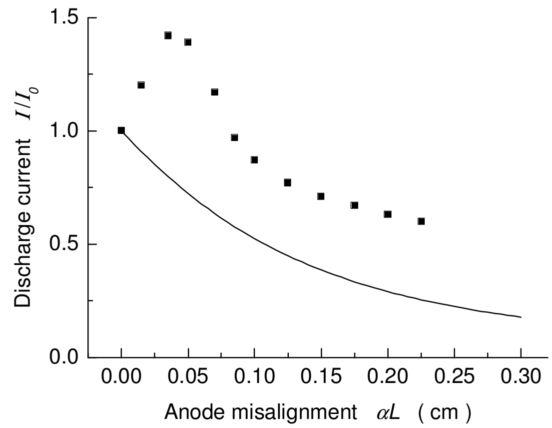

Fig.4. Dependence of discharge current on angle α in the inverted magnetron
$B = 1kG$; $V_0 = 4kV$; $p = 2.7\times10^{-4}Torr$; $r_a = 0.9cm$; $r_c = 3cm$; $L = 5cm$

As it is seen from the figure, the asymmetries of electric and magnetic fields lead to the increase of the transverse electron mobility. This is manifested especially strongly in the region of very small angles $\alpha < \alpha_0$, when the extent of misalignment is less than the dimensions of electron Larmor radius. In this case, the size of gap between the sheath and the anode depends weakly on α and is approximately equal to the electron Larmor diameter. But, the asymmetry becomes pronounced, especially, in the inverted magnetron. A thin asymmetric structure appears both, in the distribution of electron density [10] and in the distribution of electron ejection current on the discharge radius [11]. The formation of a thin asymmetric structure at small angles α can be connected with the existence of bounce-rotation resonances, with the dynamics of vortex structures or with the formation of zones with anomalous transport.

In Fig.5, the solid line shows the dependence of the relative value of discharge current on the angle between the anode axis and the magnetic field ($d = \alpha L$) in the magnetron geometry of discharge device. The dots show the experimental values of the discharge current, taken from [9]. At first sight, there is a good agreement between the theory and the experiment that should give evidence of the independence of transverse mobility on the asymmetry of fields in the magnetron geometry. However, we should take into account that the theoretical dependence is calculated for electron density $n_e = n_{cr}$. Actually, in the magnetron geometry the electron density is much less and then the theoretical dependence will be lowered, meaning that the result is the same as in the geometry of inverted magnetron, i.e. that the asymmetry leads to the increase of the transverse mobility of electrons.

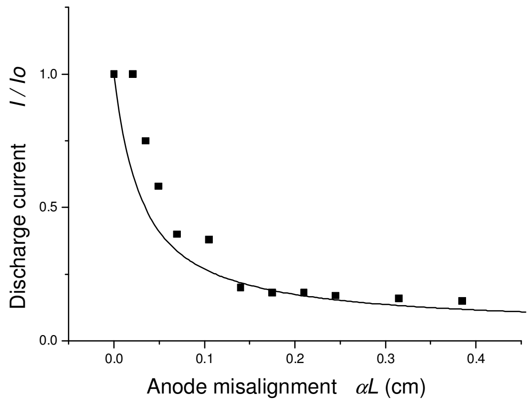

Fig.5 Dependence of discharge current on angle α in magnetron geometry
$B = 1.8kG$; $V_0 = 4kV$; $p = 1.5\times10^{-4}Torr$; $r_a = 3.2cm$; $r_c = 0.9cm$; $L = 7cm$

Thus, at a small anode misalignment, the sheath, practically, keeps the cylindrical shape being significant for determination of the conditions of appearance of the diocotron instability. However, the asymmetry of electric and magnetic fields appeared simultaneously with the anode misalignment has a strong influence on the trajectory of electron motion. The resonance regions are formed, there appears the asymmetry in distribution of electron density and the radial displacement of electrons is increased, leading to the increase of electron mobility across the magnetic field [10]. So, one can consider that in the electron sheath there appears the asymmetry-induced neoclassical transport at the disturbance of fields symmetry. The neoclassical transport was first investigated theoretically in toroidal confinement systems, and then in tandem mirror machines. In gas-discharge nonneutral electron plasma the first theoretical investigation of neoclassical transport was made in [10]. Then the systematic theoretical and experimental investigations of neoclassical transport have been carried out in pure electron plasma [12-26]. Such investigations are being carried out as well at the present, however, the mechanism responsible for the asymmetry-induced transport is still undetermined. Penning-Malmberg cells and the magnetron gas-discharge devices with nonneutral electron plasma have lots in common with tandem mirror machines. However, they have their own peculiarities: (i) the uniform magnetic field in the whole volume, (ii) the thin electrostatic mirrors at the ends, (iii) the large radial electric fields unambiguously connected with the space charge. Such definition allows to create easily the controlled asymmetry of the given type and thus, to study purposefully the asymmetry-induced transport and the ways of its suppression. For example, one can give the angle between the anode axis and the magnetic field [6,9,10,16,19,23,26], create the disturbance of electric field in the given place and of the given value [15,18,21,23,26], create the additional azimuthal magnetic field [22], simulate the trapped drift modes of toroidal confinement systems [27], etc.

3. Vortex-induced transport

The formation, interaction and dynamics of vortex structures having their own electric fields, strongly affect the processes taking place in the sheath of nonneutral electron plasma. Even one stable vortex structure strongly changes the properties of electron sheath. In the sheath there is a shear of velocities and the sheath electrons going past the vortex structure repeatedly for the time between the electron-neutral collisions. As the vortex structure has its own electric field, the sheath electrons passing it deviate to the anode or to the cathode. The electrons deviated to the cathode appear in the region of much lower retarding potential and a part of them go to the cathode along the magnetic field. Thus, alongside with the electron current from the vortex structure there is also a current of electrons from the adjacent region of electron sheath. The both currents are continuous and rotate together with the vortex structure about the axis of the discharge device [28]. The electrons deviated to the anode increase their radial displacement and thus increase the velocity of electron radial current. The formation, interaction and radial displacement of vortex structures have even stronger influence on the electron sheath leading to the large radial displacements of electrons and to the powerful pulse ejection of electrons along the magnetic field. All these, more or less regular processes, form the intense electron current along the magnetic field and the enhanced transport of electrons across the magnetic field.

One of the main criteria at the investigation of the character of transverse electron mobility is its dependence on the value of magnetic field. For understanding the role of vortex structures in this process, it is necessary to exclude the influence of the asymmetry of fields. Hence, the comparison of theory with experiment should be made for the aligned anode. However, we have a very good possibility to compare the theory with the experiment also for the anode misalignment, when there is no disturbance of the azimuthal symmetry of the sheath. This is the experiment with rings put on the aligned anode. Fig.6 shows the experimental dependences of the discharge current on magnetic field for different thickness of rings in the inverted magnetron [8].

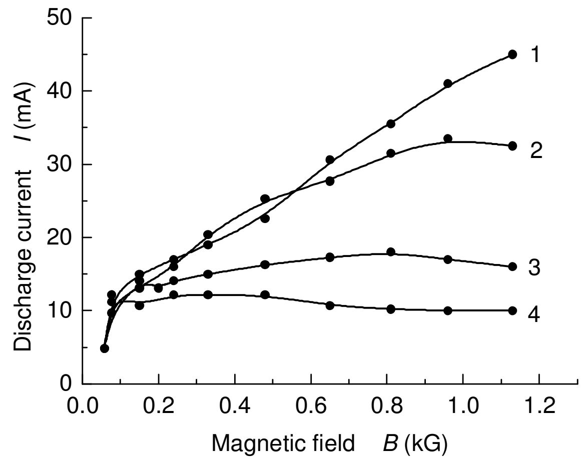

Fig.6 Dependence of the discharge current on magnetic field in the inverted magnetron [8]

$B=1kG$; $V_0=4kV$; $p=3\times10^{-4}Torr$; $r_a=0.9cm$; $r_c=5cm$; $L=7cm$

$1-h=0,\quad 2-0.03,\quad 3-0.1,\quad 4-0.2cm$

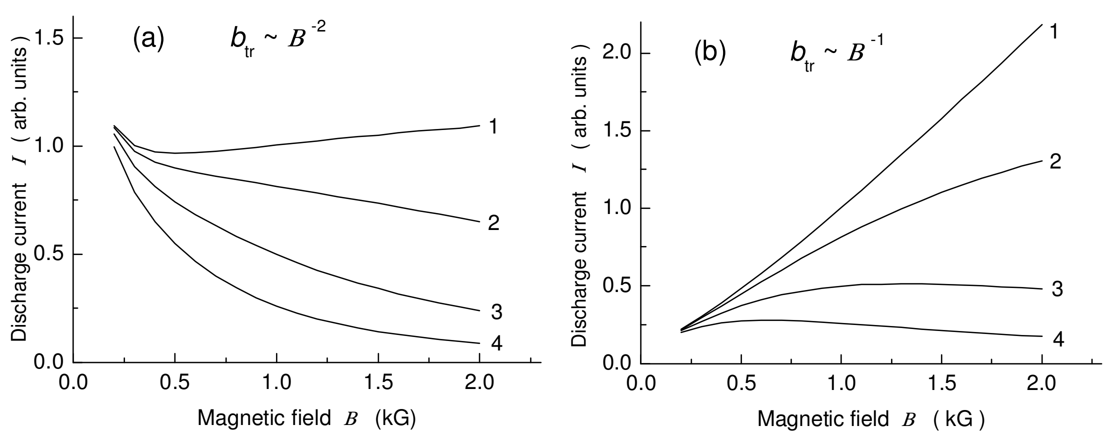

Fig.7 Theoretical dependence of the discharge current on magnetic field

$B=1kG$; $V_0=4kV$; $p=3\times10^{-4}Torr$; $r_a=0.9cm$; $r_c=5cm$; $L=7cm$

Fig.7 presents the theoretical dependences of the discharge current on magnetic field in the inverted magnetron, calculated for the same discharge parameters and ring thicknesses. On the left figure, the transverse mobility as the inverse square of the magnetic field $b_{tr} \sim B^{-2}$ is used, and on the right figure - the transverse mobility, inversely proportional to the magnetic field $b_{tr} \sim B^{-1}$. The theoretical values of the discharge currents are given in arbitrary units, as the numerical coefficient of mobility is not known for us. As it is seen from the figure, the qualitative agreement of the theory with the experiment is given by the transverse electron mobility being inversely proportional to the magnetic field.

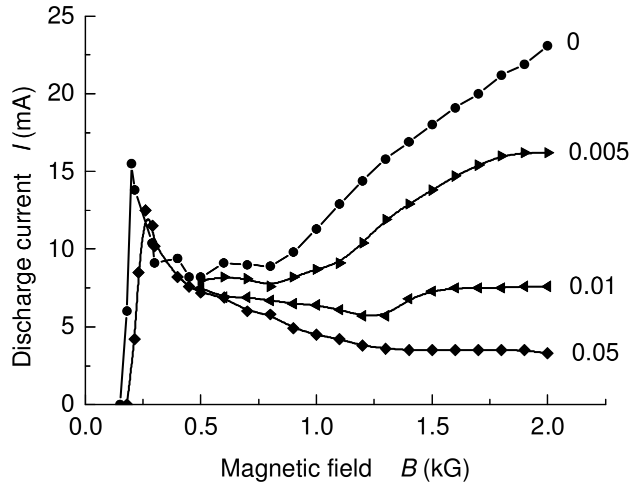

Fig.8. Dependence of the discharge current on magnetic field in the magnetron geometry [9]
$V_0 = 4kV$; $p = 1.5\times10^{-4} Torr$; $r_a = 3.2cm$; $r_c = 0.9cm$; $L = 7cm$

In the case of the anode misalignment by the tilt of magnetic field relative to the anode axis, the effect caused by the field asymmetry will be imposed on the effect connected with the vortex structures. Fig.8 gives the experimental dependences of the discharge current on magnetic field for different angles α between the anode axis and the magnetic field in the magnetron geometry of discharge device, taken from [9]. The value of angle α in radians is indicated on the curves themselves.

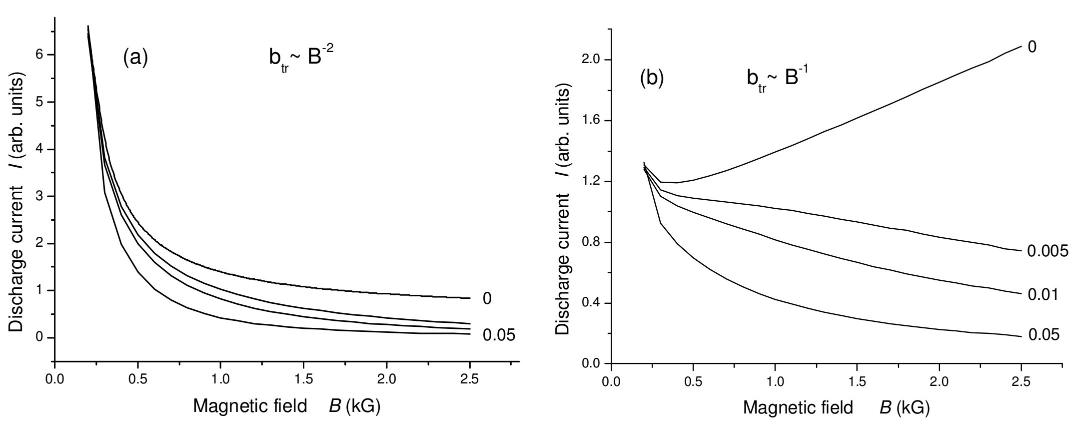

Fig.9. Theoretical dependence of the discharge current on magnetic field
$V_0 = 4kV$; $p = 1.5\times10^{-4} Torr$; $r_a = 3.2cm$; $r_c = 0.9cm$; $L = 7cm$

Fig.9 gives the theoretical dependences of the discharge current on magnetic field in the magnetron geometry of discharge device calculated for the same discharge parameters and angles α.

Here, as in Fig.7, on the left, the mobility $b_{tr} \sim B^{-2}$ is used and on the right - $b_{tr} \sim B^{-1}$. As it is seen from the figure, the satisfactory agreement with the experiment is only in the case $\alpha = 0$ for $b_{tr} \sim B^{-1}$.

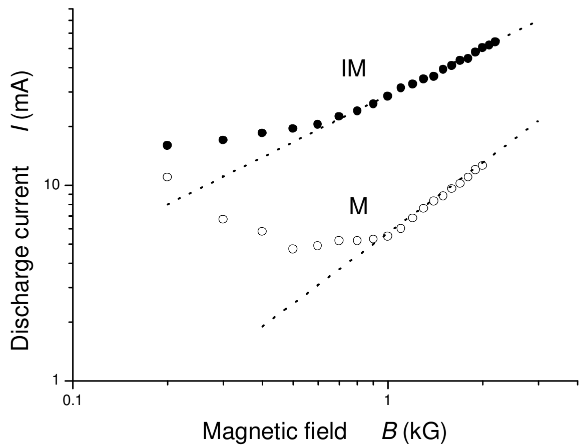

Fig.10. Experimental dependence of discharge current on magnetic field for the aligned anode
Inverted magnetron: $V_0 = 4kV$; $r_a = 0.9cm$; $r_c = 3.2cm$; $L = 7cm$
Magnetron: $V_0 = 4kV$; $r_a = 3.2cm$; $r_c = 0.9cm$; $L = 7cm$

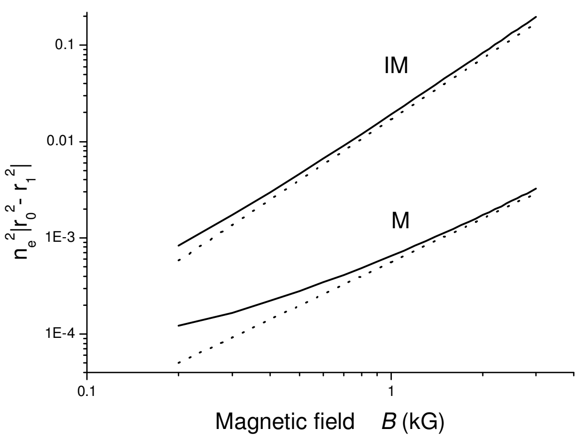

Fig.11. Theoretical dependence of $n_e^2 \left| r_0^2 - r_1^2 \right| = f(B)$ on magnetic field
for the discharge parameters in Fig.10

Generally speaking, from equation (5) one can determine a type of dependence of the transverse electron mobility on magnetic field, if we compare the experimental dependence of the discharge current $I = f(B)$ with the theoretical dependence $n_e^2 \left| r_0^2 - r_1^2 \right| = f(B)$. Then, according to (5)

$$b_{tr} = \left(\frac{1}{4\pi^2 e^2 L} \right) \frac{I}{n_e^2 \left| r_0^2 - r_1^2 \right|} \tag{6}$$

Fig.10 presents the experimental dependences $I = f(B)$ in the magnetron (M) and in the inverted magnetron (IM) for $\alpha = 0$. In fig.11 the solid curves show the theoretical dependences $n_e^2 \left| r_0^2 - r_1^2 \right| = f(B)$ in the magnetron (M) and in the inverted magnetron (IM) for the aligned anode for the same discharge parameters as in Fig.10. The dependence of transverse electron mobility on magnetic field determined from Figs. 10 and 11 is the following: for the geometry of inverted magnetron at magnetic fields larger than 0.5kG, $b_{tr} \propto B^{-1.3}$; for the magnetron geometry at magnetic fields larger than 1.0kG, $b_{tr} \propto B^{-0.3}$. These measurements were not of systematic character. However, one can affirm that the dependence of the transverse electron mobility on magnetic field is significantly weaker than in the case of classical mobility, giving the evidence of the strong influence of the vortex structure on the processes of transport in the discharge electron sheath.

4. Conclusion

In conclusion it should be noted that quasi-stationary sheath of gas-discharge nonneutral electron plasma is a strongly non-linear medium, in which the wide spectrum of different physical phenomena take place. Simultaneously, this medium is subjected to a strong influence of different external actions, e.g., the disturbance of field symmetry. The influence of the field asymmetry on the processes in electron sheath has been studied quite intensively, especially in pure electron plasma. The less attention is given to the vortex structures, practically, always existing in the gas-discharge electron plasma. However, the vortex structure, being even single and quasi-stable has not less but, probably, even larger influence on the processes in the electron sheath, including, the electron transport across the magnetic field.

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ელექტრონების გადატანა მაგნიტური ველის განივ აირგანმუხტვად არანეიტრალურ ელექტრონულ პლაზმაში

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რეზიუმე

მაგნიტური ველის განივ ელექტრონების გადატანის პროცესებზე გრიგალური სტრუქტურებისა და ელექტრული და მაგნიტური ველების ასიმეტრიის გავლენის გამოსაკვლელად გამოიყენება [1,2]-ში განხილული ელექტრონული შრის მოდელი. კვლევები ჩატარდა განმუხტვის დენის მაგნიტური ველისგან და ველების სიმეტრიის დარღვევის სიდიდისგან ექსპერიმენტური და თეორიული დამოკიდულებების შედარებისა და ანალიზის გზით. მიღებული შედეგები მოწმობენ იმაზე, რომ ველების სიმეტრიის დარღვევა იწვევს ელექტრონების ნეოკლასიკურ გადატანას, ხოლო გრიგალური სტრუქტურის გავლენა განმუხტვის ელექტრონულ შრეზე – ელექტრონების განივ ძვრადობას, რომელიც კლასიკურისგან ძლიერ განსხვავდება.

Перенос электронов поперек магнитного поля в газоразрядной ненейтральной электронной плазме

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Резюме

Для исследования влияния вихревых структур, и асимметрии электрического и магнитного полей на процессы переноса электронов поперек магнитного поля используется модель электронного слоя рассмотренная в [1,2]. Исследования проводились путем сравнения и анализа экспериментальных и теоретических зависимостей тока разряда от магнитного поля и величины нарушения симметрии полей. Полученные результаты свидетельствуют о том, что нарушение симметрии полей вызывает неоклассический перенос электронов, а влияние вихревой структуры на электронный слой разряда приводит к поперечной подвижности электронов, сильно отличающейся от классической.