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Dynamics of solitary vortex structure in collisional pure and gas-discharge nonneutral electron plasmas

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Abstract

The analysis of the results of experimental investigations of equilibrium, interaction and dynamics of vortex structures in pure electron and gas-discharge electron nonneutral plasmas during the time much more than the electron-neutral collision time has been carried out. The problem of long confinement of the column of pure electron plasma in Penning-Malmberg trap is considered. The mechanism of self-sustaining long-lived stable vortex structure in gas-discharge nonneutral electron plasma is proposed. The collapse of electron sheath in gas-discharge plasma of Penning cell is described. The analysis of the interaction between the stable vortex structure and the symmetric electron sheath, as well as of the action of vortex structures on the transport of electrons along and across the magnetic field is made.

1. Introduction

In [1] the general mechanisms and the differences in the process of formation, interaction and dynamics of vortex structures in pure electron and gas-discharge electron nonneutral plasmas during a short collisionless time interval following the origination of diocotron instability were studied. The analysis of experimental results showed that the process of formation of stable vortex structure proceeds in both plasmas practically in the same way, and the observed differences connected with the different initial parameters of electron plasma. Independent of the initial number of vortex structures, at the end of the process of collisionless evolution in both plasmas only one stable vortex structure is left. However, in pure electron plasma, the vortex structure is shifted to the axis of trap, and in gas-discharge electron plasma, it remains in the electron sheath near the anode surface. The further evolution and dynamics of vortex structure takes place with the participation of electron-neutral collisions. The gas-discharge electron plasma differs from the pure electron plasma in that it exists unlimitedly long at the expense of ionization. Besides, the ionization takes place not only in plasma sheath, but also inside the vortex structure. The other characteristic feature of gas-discharge plasma is the ejection of electrons from the plasma and vortex structures to the end cathodes along the magnetic field in the form of continuous flux and periodically following pulses.

The present work deals with the comparable analysis of the behavior of vortex structures in pure electron and gas-discharge electron nonneutral plasmas in the presence of electron-neutral collisions. In section 2, the process of expansion of the column of pure electron plasma in Penning-Malmberg trap, and the problems connected with its confinement at low pressures of neutral gas are considered. In section 3, the behavior of stable vortex structure in gas-discharge electron plasma is studied at different geometries and at different pressures of neutral gas. In section 4, the mechanism of self-sustention of long-lived stable vortex structure in gas-discharge electron plasma is considered. In section 5 the collapse of electron sheath in gas-discharge plasma in Penning cell at the pressures when the density of neutral plasma becomes comparable to the density of electron sheath is described. In final section 6, the interaction between the stable vortex structure and the symmetric electron sheath, as well as the action of vortex structure on the transport of electrons along and across the magnetic field is discussed.

2. Long confinement of pure electron plasma column

A pure electron plasma is formed by injection of electrons into Penning-Malmberg trap and, therefore, its initial state can have the arbitrary given density and shape (the central column, the hollow column, several columns shifted from the axis, etc). However, independent of the initial conditions and of the consequent collisionless processes, the initial state for the time interval $\Delta t \gg \nu_0^{-1}$ (ν_0 is the frequency of electron-neutral collisions) will be the axisymmetric picture with one vortex structure located on the axis of confinement device and the background of low density surrounding it. Under the action of electron-neutral collisions, the vortex structure (the electron plasma column) will be expanded. The velocity of expansion is proportional to the pressure of neutral gas. Consequently, one could expect a strong increase of the time of plasma confinement at the transition to very low pressures. However, the experiment did not prove such suggestion. In [2], the time of confinement (the time during which the electron density at the column center was halved) of the central column of pure electron plasma in the wide range of neutral gas pressure (He, $10^{-10} < p < 10^{-3} Torr$) was measured. It turned out that for the pressure of neutral gas $p > 10^{-7} Torr$, the time of confinement is determined by the classical mobility of electrons across the magnetic field, and at lower pressures, the time of confinement does not depend any more on the pressure [2, 3].

In this range of pressures the frequency of electron-neutral collisions becomes less than the frequency of electron-electron collisions. However, electron-electron collisions cannot be the reason of the observed expansion of electron column. Consequently, there is another process of radial transport of electrons that becomes dominant at low pressures. In [2] it was assumed that this process can be the asymmetry-induced transport. The asymmetry-induces transport in nonneutral plasma located in cylindrical symmetric trap is the transport of charged particles across the magnetic field occurred as a result of distortion of cylindrical symmetry caused by the imperfect construction of experimental device and by a small asymmetry of electric and magnetic fields. Thought his process has been studied for a long period of time, the mechanisms of such process, as well as the agreement between the considered theories and experiment have not been fully understand yet [4].

Thus, the attempt to increase the time of confinement of electron (ion) plasma in Penning-Malmberg trap at the expense of decreasing the neutral-gas pressure was not crowned with success. Nevertheless, the method was found allowing to counteract not only the radial expansion of electron plasma column, but to compress the electron column increasing multiply its density. This is the so-called “rotating wall” technique [5,6].

The description of stable state of nonneutral plasma in strong magnetic field, in cylindrically symmetric trap at low pressure of neutral gas is based on conservation of angular momentum. Small static asymmetries of trap construction, of electric and magnetic fields create the resistance to rotation of nonneutral plasma, and the condition of conservation of angular momentum leads to its expansion. To counteract this expansion the technique of rotating wall was developed, in which the rotating electric field is used for increasing the angular velocity of nonneutral plasma. This leads to the stabilization or to the decrease of the average radius of plasma column, i.e. to the increase of confinement or to the radial compression of plasma. In general case, the torque from the rotating electric field will compress the plasma if the rotating electric field frequency is larger than the plasma rotation frequency. Here, two regimes are possible. In [5], the frequency of applied electric field was in resonance with Trivelpiece-Gould modes and was much higher than the frequency of plasma rotation. This is the “slip” regime. In [6], the other regime was used, when the frequency of applied electric field is close to the frequency of plasma rotation. In this regime, the plasma was compressed and its density was increased until the frequency of plasma rotation approaches the fixed applied frequency. This is the “low-slip” regime. In Fig.1 taken from [6], the upper part shows the process of compression of electron column under the action of rotating wall field. The lower part of the figure shows the process of expansion of the profile of column density after the field of rotating wall is detached. As it is seen from the figure, the rate of plasma expansion is much slower than the rate of compression. At continuously attached rotating wall, the compressed plasma of high density was confined in the stable state for an indefinite time (24 hours in this experiment).

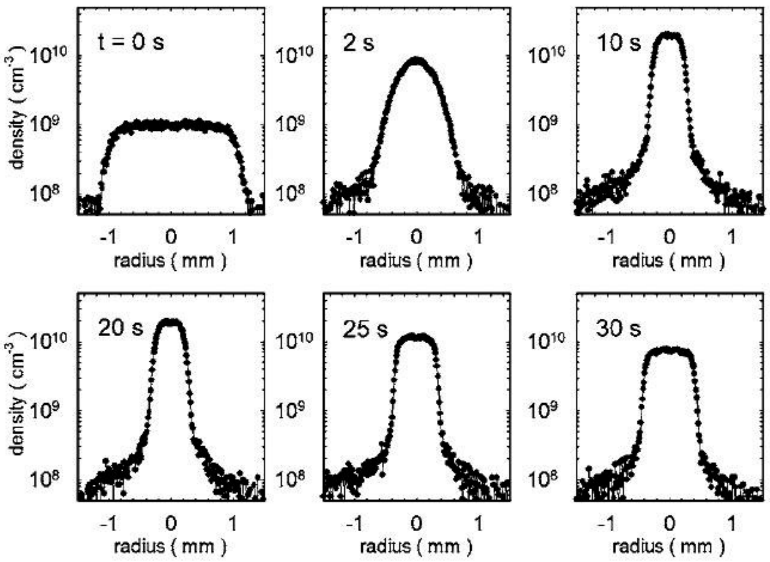


Fig.1. Evolution of the profile of electron column density
at compression (upper part) and at expansion (lower part) [6]

3. Stability of vortex structure in gas-discharge electron plasma

The behavior of vortex structures in gas-discharge electron plasma during the time much more than the electron-neutral collision time depends on the geometry of discharge device and on the pressure of neutral gas. As a result of the appearance of diocotron instability, in the geometry of inverted magnetron a stable vortex structure is formed rapidly ($\Delta t \ll \nu_0^{-1}$) and then it “decays” slowly ($\Delta t \gg \nu_0^{-1}$) [7, 8]. Hence, during the most period of time we observe one quasi-stable vortex structure, the charge of which is decreased slowly. At last, the vortex structure disappears and during some time (before appearing the next diocotron instability) the only symmetric electron sheath is left without vortices and oscillations. In Fig. 2, the oscillograms of this process are given. The upper oscillogram is the oscillations of electric field on the anode wall probe. The lower oscillogram is the full current of electrons on the end cathodes.

The process of development of diocotron instability and of formation of quasi-stable vortex structure is accompanied by the pulse of electron current along the magnetic field to the end cathodes.

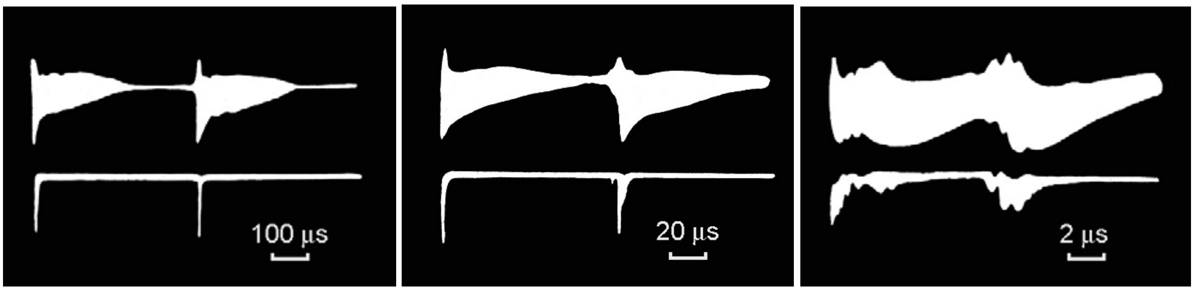


Fig.2. Diocotron instability and vortex structures in inverted magnetron [8]
$r_a = 1.0cm$; $r_c = 3.2cm$; $L = 7cm$; $B = 1.8kG$; $V = 0.9kV$; $p = 2\times10^{-6}$, 1×10^{-5}, $1\times10^{-4} Torr$.

In magnetron geometry and in Penning cell, there exists one stable vortex structure at low pressures of neutral gas. At the pressures lower than $1\times10^{-5} Torr$ (here and below the pressures of argon are given for the parameters of discharge and geometric dimensions of the device at which the experiments were made), the vortex structure approaches slowly the anode increasing gradually its own charge [9, 10]. At the definite moment of time, there arise the strong radial oscillations of the structure being accompanied by ejection of electrons to the end cathodes along the magnetic field. The period of radial oscillations of vortex structure is much more than the period of its rotation about the axis of discharge device. Therefore, during the radial oscillations the vortex structure performs a spiral motion. The ejection of electrons takes place at the moments the vortex structure moves away from the anode surface. Let us call such radial oscillations of vortex structure the orbital instability. The orbital instability continues during the time much less than the electron-neutral collision time (5-8 radial oscillations in magnetron, and about 10 – in Penning cell). As a result of orbital instability, the vortex structure losses about a third of its charge and returns to the initial (smaller) orbit. This process is repeated periodically after the interval of time much more than the electron-neutral collision time.

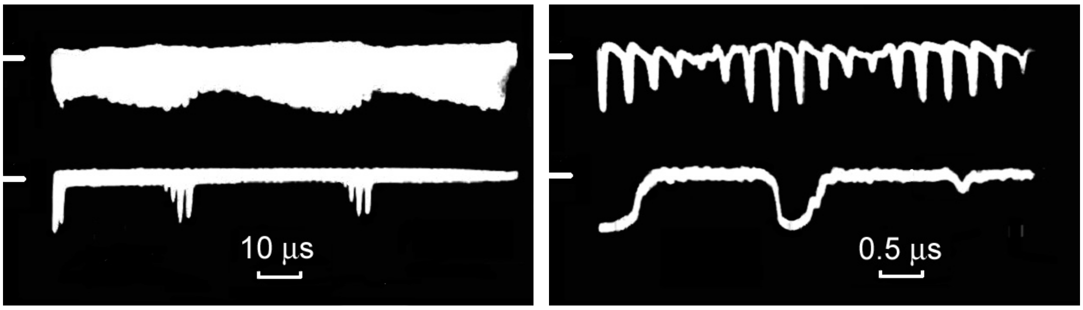


Fig.3. Periodically repeated orbital instability in magnetron
$r_a = 3.2cm$; $r_c = 1.0cm$; $L = 7cm$; $B = 1.2kG$; $V = 1.5kV$; $p = 6\times10^{-6} Torr$.

Fig. 3 shows the oscillograms of this process in magnetron. The upper oscillogram is the oscillations of electric field on the anode wall probe, and the lower one - the full current of electrons on the end cathodes. Here and below, the little lines on the oscillograms (to the left) indicate the initial position of the sweep trace.

Both, the average frequency of repetition of orbital instability in magnetron and the frequency of repetition of diocotron instability in inverted magnetron are proportional to the pressure of neutral gas. Both, in magnetron and in inverted magnetron, during the most period of time of periodically repeated processes the vortex structure is quasistable. The difference is in that in the inverted magnetron the charge of vortex structure decreases slowly, and in the magnetron – increases slowly. However, in the narrow range of neutral gas pressure, $(1-2)\times10^{-5} Torr$, the vortex structure in the magnetron geometry remains always stable [9]. Fig. 4 shows the oscillograms of oscillations of electric field on the anode wall probe (upper) and on the cathode wall probe (lower) in magnetron in this range of neutral gas pressure. As it is seen from the figure, the vortex structure does not have "tails", and its charge and orbit remain unchanged.

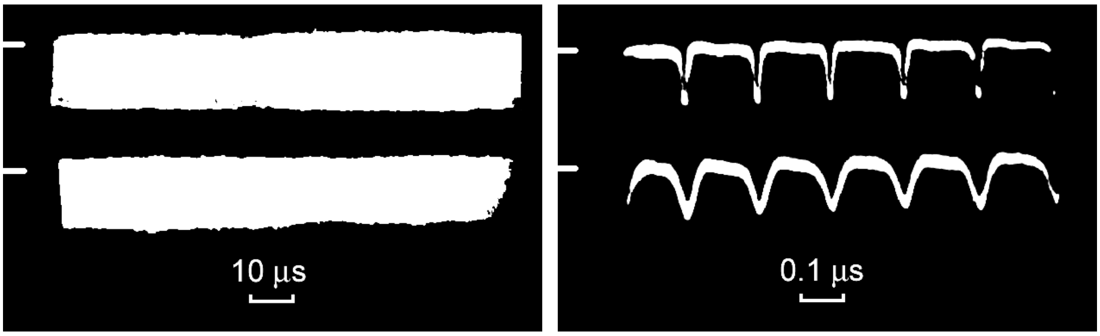


Fig.4. Stable vortex structure in magnetron
$r_a = 3.2cm$; $r_c = 1.0cm$; $L = 7cm$; $B = 1.5kG$; $V = 1.0kV$; $p = 1\times10^{-5} Torr$.

So, in gas-discharge electron plasma, in the time interval $\Delta t \gg \nu_0^{-1}$, the vortex structure in magnetron geometry exists indefinitely long and keeps its charge and dimensions despite the electron-neutral collisions. Even in the geometry of inverted magnetron where the vortex structure "decays" slowly, its expansion in time is not observed. Fig.5 shows the fragments of oscillations of electric field on the anode wall probe (upper oscillogram) in inverted magnetron taken at the moment when the stable vortex structure is fully formed (left), and at the moment close to its full decay (right). The lower oscillogram is the electron current on the end cathodes.

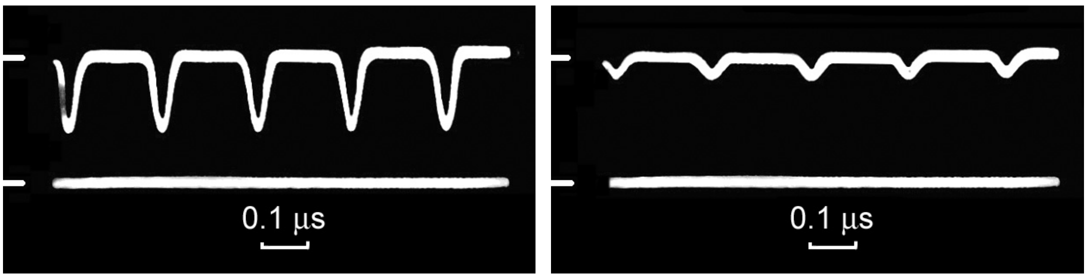


Fig.5. Decay of vortex structure in inverted magnetron
$r_a = 2.0cm$; $r_c = 3.2cm$; $L = 7cm$; $B = 1.5kG$; $V = 1.0kV$; $p = 2\times10^{-5} Torr$

4. The model of self-sustaining stable vortex structure

The stability of vortex structure at the presence of electron-neutral collisions can be connected with the simultaneous existence of two processes in the vortex structure: ionization and ejection of electrons to the end cathodes along the magnetic field. The pulses of electron current on the end cathodes appear at the formation of vortex structures, at their approach and at radial shift of vortex structure from the anode surface [7-10], i.e. the moments when the local decrease of potential barrier takes place or when the vortex structure itself shifts to the region with less potential barrier. At the same time, a part of electrons with the energy sufficient to overcome the decreased potential barrier goes to the end cathodes along the magnetic field. However, beside the pulses of electron current, there is the continuous flux of electrons from the vortex structure to the end cathodes along the magnetic field [11]. Fig. 6 taken from [11] shows the continuous flux of electrons from the vortex structure in the case of one stable vortex structure (left) and in the case of two approaching vortex structures (right).

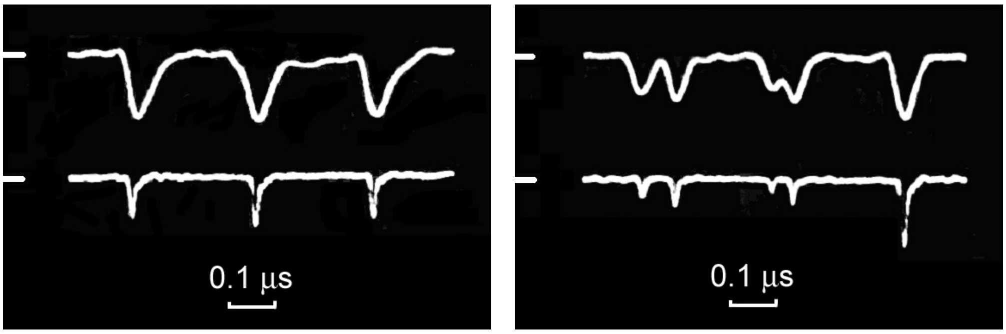


Fig.6. Continuous electron ejection from vortex structure in Penning cell [12]
$r_a = 3.2cm$; $L = 7cm$; $B = 1.9kG$; $V = 1.0kV$; $p = 1\times10^{-5}Torr$

Upper oscillograms are the signals from the anode wall probe, and lower oscillograms– the current of electrons through the narrow radial slit in the end cathode. The slit was located on the same azimuth as the wall probe and the width of slit was much less than the diameter of vortex structure. As is seen from the figure, the continues current of electrons flows from the vortex structure along the magnetic field and rotates together with the vortex structure around the axis of discharge device.

The average value of total electron current on the end cathodes is rather high and make about 50% of the value of discharge current [12,13]. Therefore, this mechanism of losing the electrons is necessary to be taken into account together with the ionization and transverse diffusion at the consideration of processes taking place both, in vortex structure and in electron sheath of discharge.

In [14] the model of stable vortex structure was proposed, in which from the periphery of vortex structure on the side nearest to the cylindrical cathode, a continuous ejection of electrons takes place to the end cathodes along the magnetic field. The ejection of electrons compensates the ionization in the vortex structure and the expansion of the vortex structure due to electron-neutral collisions. Let us consider this process in more detail. The vortex structure rotates about its own axis. Therefore, the electrons of vortex structure approach periodically the anode and the cathode. In this case, the "longitudinal energy" acquired by vortex electrons at the expense of electron-neutral collisions near the anode, can be enough for overcoming the potential barrier near the cathode after they approach the cathode. The farther are the electrons from the vortex center, the more is the value of the "longitudinal energy" acquired by electrons near the anode and the less is the potential barrier near the cathode, and consequently, the more probable is the escape of electrons along the magnetic field. The electrons originating in the vortex structure at the expense of ionization are moved to the periphery of the structure at the expense of electron-neutral collisions and go to the end cathodes along the magnetic filed by the considered mechanism. Therefore, the transverse dimension of the structure and its charge remain unchanged. If the balance between these processes is disturbed, the charge of vortex structure will increase slowly, or on the contrary, will decrease slowly. Thus, the above-considered mechanism of the balance of processes of ionization and of escape of the electrons along the magnetic field can explain the stability of vortex structure in magnetron in the range of pressure $(1-2)\times10^{-5}Torr$, the increase of the charge of vortex structure in magnetron at lower pressure and the decrease of the charge of vortex structure in inverted magnetron.

In the proposed model the electron exchange between the vortex structure and the electron sheath is absent. Consequently, the vortex structure is considered as an isolated object. Therefore, the mechanism of stabilization of vortex structure should not depend on the geometry (magnetron, inverted magnetron, Penning cell) and on the background. However, the background, geometry and the place of location of vortex structure in the discharge gap will have an influence on the dimension and the shape of vortex structure. This is connected with the value of gradient of the containment potential along the radius of discharge device on the diameter of vortex structure. In particular, if, as a result of radial shifting the vortex structure appears in the center of Penning cell, the action of above-considered mechanism of stabilization of vortex structure will be stopped. The vortex structure will start to expand and the charge will increase. This will lead to the formation of a circular sheath, then to the diocotron instability and further to the formation of stable off-axis vortex structure. Thus, in the gas-discharge electron plasma there works not only the mechanism of self-sustention, but the mechanism of self-recovery of stable vortex structure as well.

For describing the model of stable vortex structure, let us consider two cylindrical coordinate systems: the fixed (r,θ,t) with the center on the axis of discharge device, and the moving (ρ,ϑ,t) with the center on vortex axis. For simplification of the problem let us use the planar geometry and assume that the background equals zero, i.e. the electric field between the anode and the cathode $E_o = const$. Then, for the electrons of vortex structure in the moving coordinate system (moving with the velocity of vortex structure drift $u_d = cE_o/B$), the continuity equation will have the following form:

$$\frac{\partial n_v}{\partial t}+\frac{1}{\rho}\frac{\partial}{\partial\rho}\left(\rho n_v u\right)=\nu_i n_v-\Gamma \tag{1}$$

Here n_v is the density of electrons, ν_o is the frequency of electron-neutral collisions, ν_i is the frequency of ionization, Γ is the loss of electrons along the magnetic field. Taking into account the Poisson equation and the classical transverse mobility of electrons, in the stationary case ($\partial/\partial t = 0$) equation (1) will have the following form:

$$n_v^2+\frac{1}{\rho}\frac{\partial n_v}{\partial\rho}\int_0^{\rho} n_v\rho d\rho=\frac{B^2}{4\pi mc^2}\frac{1}{\nu_o}\left(\nu_i n_v-\Gamma\right) \tag{2}$$

Let us solve this problem in the following way. On the basis of experimental data, let us give the value of electron density and determine Γ. Then, using the obtained value Γ, let us find the dependence of the density of electron current to the end cathodes on the discharge radius in magnetron geometry and compare the obtained result with the experiment.

At $\rho = 0$, the electrons are not displaced on the radius, and thus, $\Gamma(\rho = 0) = 0$. Then, from (2) it follows that:

$$n_v(\rho=0)=n_o=\frac{B^2}{4\pi mc^2}\frac{\nu_i}{\nu_o} \tag{3}$$

This value of density is close to the experimentally measured density of vortex structures [8, 9, 15]. In our model, the shape of distribution of electron density in vortex structure is not of fundamental importance and we will use the Gaussian profile of density. Then:

$$n_v=n_o\exp\left(-\frac{\rho^2}{\rho_v^{\,2}}\right) \tag{4}$$

where, ρ_v is the radius of vortex structure. Substituting (4) into (2), we will find:

$$\Gamma(\rho) = 2\nu_i n_o \left(1 - \exp\left(-\frac{\rho^2}{\rho_v^{\,2}}\right)\right) \exp\left(-\frac{\rho^2}{\rho_v^{\,2}}\right) \tag{5}$$

Now, let us use the obtained value of Γ for magnetron geometry with stable vortex structure and electron sheath (background), the density of which, according to the experimental data is about by an order of magnitude less than the density of electrons of the vortex structure. In (5), the electron losses are distributed uniformly in vortex structure circle. However, as $\omega_v >> \omega_o >> \nu_o$ (ω_o is the angular velocity of rotation of vortex structure about the axis of discharge device, and ω_v is angular velocity of rotation of vortex structure about its own axis), for distribution of electron density in vortex structure, it is not very important whether the electrons escape from the whole vortex structure circle or from any of its point. At this point there should be a minimum potential barrier along the magnetic field. Therefore, passing to the fixed coordinate system, let us assume that in the magnetron the electrons escape from vortex structure on the straight line segment connecting the vortex structure center with the center of discharge device, i.e. at the points of maximum approach of electrons near the cathode. In fixed coordinate system, the electron flux from the vortex structure will be uniformly distributed on the discharge device circle due to the rotation of vortex structure around the axis of discharge device. Hence, for Γ we can write the following relation:

$$2\pi r\Gamma(r) = 2\pi\rho\Gamma(\rho) \qquad \text{where} \quad \rho = r_v - r \tag{6}$$

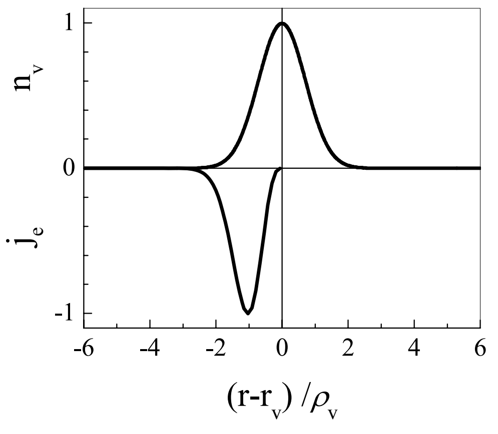
r_v is the radius of the orbit of vortex structure in magnetron geometry. The density of electron current from the vortex structure on the end cathode will be equal to

$$j_e = e\Gamma(r)L/2$$

Here, L is the anode length. Finally, we will obtain:

$$j_e = \begin{cases} \left(L\nu_i n_o\right)\dfrac{r_v - r}{r}\left(1 - \exp\left(-\left(\dfrac{r_v - r}{\rho_v}\right)^2\right)\right)\exp\left(-\left(\dfrac{r_v - r}{\rho_v}\right)^2\right) & \mathit{for} \quad r \le r_v \\ 0 & \mathit{for} \quad r > r_v \end{cases} \tag{7}$$

Fig. 7 (left) shows the dependence of n_v and j_e on the radius of fixed coordinate system. Though the vortex structure is the isolated system, its influence on the electron sheath is rather great. In the sheath there is the velocity shear and each electron of the sheath passes the vortex structure many times for the collision interval. As the vortex structure has its own electric field, the sheath electrons deviate to the anode or to the cathode while passing the vortex structure. The electrons deviated to the cathode, appear in the region of low containment potential and a part of them escape to the end cathodes along the magnetic field. Thus, alongside with the electron current from the vortex structure, there is also the current of electrons from the sheath to the end cathodes. This current is located closer to the cylindrical cathode than the current from the vortex structure. The both currents are continuous and rotate together with the vortex structure around the axis of discharge device. Fig. 7 (right) shows the experimental dependence of the density of electron current along the magnetic field on the radius of end cathode in the magnetron geometry for different magnetic field in the region of neutral gas pressures, when one stable vortex structure is observed. As it is seen from the figure, the considered model of vortex structure is in qualitative agreement with the experimental results.



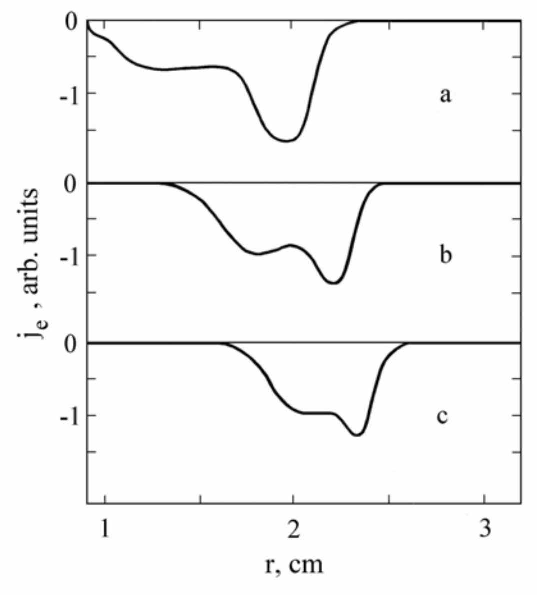


Fig.7. Continuous electron ejection from vortex structure in magnetron
(right: $V = 4kV$; $p = 2\times10^{-5}Torr$; a - $B = 1.2$, b - 1.5 , c - $1.8kG$)

5. Collapse of gas-discharge electron sheath

At higher pressure of neutral gas, both, in magnetron and in inverted magnetron, there exist simultaneously several vortex structures, and higher is the pressure, the more is their number. This, probably, is caused by the fact that the decay rate of vortex structure increases with the pressure slower than the growth rate of electron density in the sheath. Consequently, the new vortex structure formed as a result of the next diocotron instability appears earlier than the preceding structure has time to decay.

Under these conditions, the interaction of vortex structures becomes the dominant process in electron plasma. It should be noted that these simultaneously existed vortex structures are not coherent. They appear at different time, move on different circular orbits with different angular velocities [9]. The vortex structures periodically approach each other, sometimes they merge, and sometimes the new structures are formed and all these processes are accompanied by ejection of electrons along the magnetic field to the endplate cathodes [7-10]. Fig.8 gives the oscillograms showing the process of approaching the vortex structures at different pressures of neutral gas. The upper oscillograms show the oscillations of electric field on the anode wall probe, and the lower – the full current of electrons on the end cathodes.

By its structure, the Penning cell is the closes analog of the Penning-Malmberg cell, as there is not a central cathode in it. However, at the pressures above $5\times10^{-5}Torr$ the average density of ions in Penning cell begins to approach the density of electrons, and in gas-discharge electron plasma in Penning cell there appear the new effects [18]. In pure electron plasma the ions are absent and such kind of problem does not arise.

In contrast to a magnetron and an inverted magnetron, in a Penning cell the ions oscillate along the radius inside the hollow cylindrical anode and, at the same time, they move slowly along the axis of a cylinder towards the end cathodes. Outside the anode sheath in the central region of a Penning cell, ions are neutralized by electrons. With the increase of neutral gas pressure the density of ions increases and, as a result, becomes comparable to the density of electrons. This is the so-called transition mode of discharge, in which the electron sheath is “enclosed” between the anode and the neutral plasma of about the same density as the sheath. In the transition mode the discharge current shows a strong nonlinear dependence on the pressure: first, it increases rapidly, passes the maximum, then decreases, passes the minimum and then again increases sharply. The electron sheath disappears and the discharge changes abruptly to the low-voltage glow discharge in the transverse magnetic field.

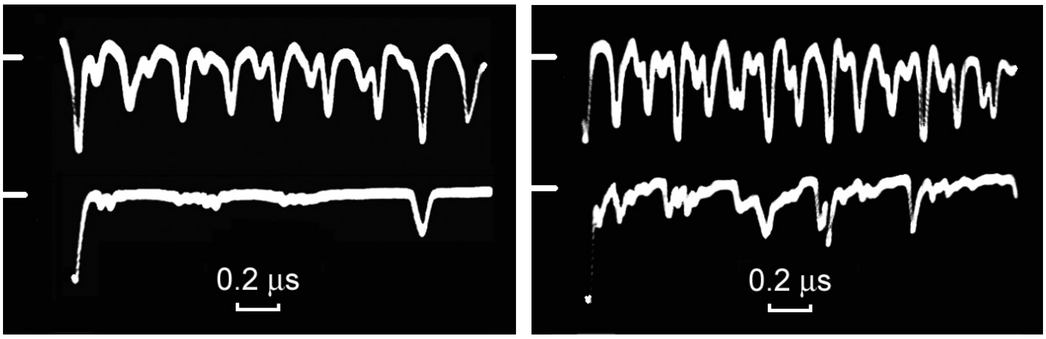


Fig.8. Approach of vortex structures in magnetron
$r_a = 3.2cm$; $r_c = 1.0cm$; $L = 7cm$; $B = 1.5kG$; $V = 1.5kV$; $p = 1\times10^{-4}, 4\times10^{-4} Torr$

The behavior of vortex structures in transition mode was studied in [18]. The experiments was carried out in modified Penning cell, in which a flat cathode was located on the one end of cylindrical anode, as in Penning cell, and on the other end a cylindrical cathode was located, as in Penning-Malmberg cell. At such modification, the characteristics of discharge and the behavior of vortex structures remain the same as in Penning cell with flat cathodes. Behind the cylindrical cathode a flat collector was placed serving for measuring the current of electrons or ions ejected along the magnetic field from the electron sheath and the neutral plasma. For observation of vortex structures a diamagnetic probe was used instead of wall anode probe. This method is described in detail in [19] and consists in that only one narrow slit is cut along the whole length of the cylindrical anode, and an insulated diamagnetic probe, consisting of several turns of rf cable, is placed around the anode. When the inhomogeneity (vortex structure) passes by the slit, the image charge induced by it overcomes the slit in the anode by the current flowing around the anode circle backwards, and generating the pulse of magnetic field registered by the diamagnetic probe. The signal from the diamagnetic probe is similar to the signal from the wall probe and therefore, it is convenient to use a diamagnetic probe for the external cylindrical electrode being under a high potential. Besides, a diamagnetic probe is capable to register abrupt changes of diamagnetic properties of electron sheath caused, e.g. by a partial or a full loss of electrons of the sheath.

The results of investigations showed that at the beginning of transition mode, the signals from collector and diamagnetic probe have the same form as in magnetron. However, starting from the pressures that correspond about to a half of a discharge current maximum, the observed pattern changes significantly. There appear the strong relaxation oscillations. Fig.9 shows the oscillograms of oscillations on the diamagnetic probe (lower), on the collector (upper left), and on the wall probe of cylindrical cathode (upper right). The similar oscillations are observed on both sides of discharge current maximum.

First of all, let us pay attention to the large positive pulses on the oscillogram of diamagnetic probe. Each pulse is caused by an abrupt increase of magnetic field due to a sharp decrease of diamagnetic properties of electron sheath as a result of a partial or a full ejection of sheath electrons to the anode. This is indicated by the physical processes taking place before and after the appearance of a pulse.

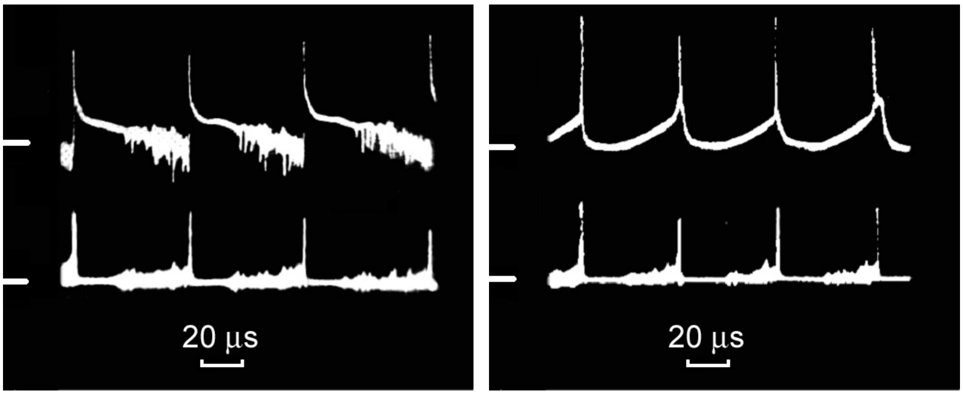


Fig.9. Collapse of electron sheath in Penning cell
$r_a = 3.2cm$; $L = 7cm$; $B = 1.0kG$; $V = 1.2kV$; $p = 1.0\times10^{-4}Torr$

On the oscillogram of diamagnetic probe each pulse is preceded by the oscillations connected with the motion of vortex structures. The vortex structures are formed at the moment of appearing the diocotron instability in the discharge electron sheath as in the case of low pressures of neutral gas. In the transition mode the annular electron sheath is located between the anode and the neutral plasma density of which is about equal to sheath density. The sheath density, as well as the plasma density increases in time until the diocotron instability appears and the formation of vortex structures starts. The formation and the interaction of vortex structures are accompanied by the ejection of electrons along the magnetic field to the end cathodes (upper left oscillogram in Fig.9). However, in contrast to low pressures, when the formation of vortex structures limits the increase of electron sheath density, in the transition mode the plasma density and the electron sheath density continue to increase, as is evidenced by a continuous increase of ion current on the cylindrical cathode (upper right oscillogram in Fig.9). The increase of electron sheath density at the fixed discharge voltage should be accompanied by its compression. This process will be continued until the sheath transforms into one-Larmor sheath, and its density reaches the Brillouin limit. Such sheath is unstable and the ejection of the electrons to the anode takes place causing thus the jump of magnetic field. As it is seen from the oscillograms, at the same time, on the collector and on the cylindrical cathode the large narrow pulses are observed that are caused by an abrupt increase of electric field on the cathodes. On the screened collector such pulse does not present. This confirms as well the distortion of electron sheath. The appearance of longitudinal electric field causes an increase of ion current from the plasma to the collector and a decrease of ion current to the cylindrical cathode (upper right oscillogram in Fig.9). Then, the electron sheath begins to recover. Its density increases as is evidenced by the decrease of ion current on the collector and by the increase of ion current on the cylindrical cathode. Further, the whole process is repeated. Thus, we have a periodically repeated process: the compression of electron sheath and its subsequent rapid distortion, i.e. the collapse of electron sheath. The compression of electron sheath with the increase of neutral gas pressure was discovered long ago [20]. However, in the transition mode there is not a continuous (gradual or abrupt) transition from the anode potential drop to the cathode one. In fact, the electron sheath in the transition mode "runs" periodically the complete cycle of its development from the formation of anode sheath to its maximum compression and subsequent distortion.

It should be noted that in the transition mode the vortex structures continue to be formed and to generate the electron flux along the magnetic field to the end cathodes. The formation of vortex structures is observed up to the transition to the glow discharge, while, the ejection of electrons to the end cathodes exists only up to the maximum of discharge current.

6. Discussion and conclusion

Thus, there is a certain difference in the behavior of vortex structure in pure electron and gas-discharge electron nonneutral plasmas in time interval $\Delta t \gg \nu_0^{-1}$, when the electron-neutral collisions play a significant role. In pure electron plasma the vortex structure is located on the axis of experimental device (on-axis state) and is expanded continuously until it disappears fully. For its long confinement and compression, it is necessary to use the rotating electric field - “rotating wall” technique. In gas-discharge electron plasma the vortex structure is located near the anode surface (off-axis state). This is a stable, self-organizing, self-sustaining and self-recovering structure retaining its charge and profile. In a certain sense, the vortex structure in gas-discharge electron plasma can be considered as a soliton-like structure, inside of which the formation of particles and on the periphery their removal take place.

In general, the gas-discharge electron plasma is a long existed “symbiosis” of stable off-axis vortex structure and of symmetrical electron sheath. This combination is characterized by a strong mutual effect of both components on each other and has the new surprising properties. One of them is the ejection of electrons from vortex structures and neighboring regions of electron sheath to the end cathodes. The electron ejection current is rather great, exists always and is a new mechanism of the loss of electrons from the vortex structure and electron sheath. In the vortex structure this current compensates the ionization in vortex structure and its expansion at the expense of electron-neutral collisions. In the electron sheath the electron ejection current limits the electron density. In [16,17], the model of electron sheath was considered, in which the equilibrium density of electrons is determined not by a balance between the ionization and the mobility of electrons across the magnetic field, as it was assumed earlier, but by a “critical” electron density, at which there appears the diocotron instability generating the vortex structures. The model describes well the current characteristics of discharge in the crossed electric and magnetic fields both, in magnetron geometry and in the geometry of inverted magnetron [17].

The vortex structures located in discharge electron sheath have an influence on the transport of electrons across the magnetic field. Even in the case of one stable vortex structure, the sheath electrons pass the vortex structure multiply during the mean free time. As the vortex structure has its own electric field, the sheath electrons passing by the vortex structure deviate to the anode or to the cathode increasing thus their radial shifts. When the radial shifts exceed significantly the Larmor radius of the electron, there appears the neoclassical transport of electrons across the magnetic field. At relatively high pressures of neutral gas ($p > 10^{-4} Torr$), in the discharge electron sheath there exists simultaneously several vortex structures, and the higher is the pressure, the more is their number. At a great number of vortex structures, their movement and interaction become chaotic that can lead to the turbulent transport of electrons across the magnetic field.

The electron sheath (background), in its turn, has the influence on the behavior of vortex structures, for example, on the radial drift of vortex structures and on the formation of vortex crystals.

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Динамика уединенной вихревой структуры в столкновительных чистой и газоразрядной ненейтральных электронных плазмах

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Резюме

Приводится анализ результатов экспериментальных исследований равновесия, взаимодействия и динамики вихревых структур в чисто электронной и газоразрядной электронной ненейтральных плазмах, в течение времени, много большего времени электрон-нейтральных столкновений. Рассмотрена проблема длительного удержания столба чисто электронной плазмы в ловушке Пеннинга-Малмберга. Предложен механизм самоподдержания долгоживущей стабильной вихревой структуры в газоразрядной ненейтральной электронной плазме. Описан коллапс электронного слоя в газоразрядной плазме ячейки Пеннинга. Анализируется взаимодействие между стабильной вихревой структурой и симметричным электронным слоем, а также, влияние вихревых структур на перенос электронов вдоль и поперек магнитного поля.

განმხოლოებული გრიგალური სტრუქტურის დინამიკა დაჯახებად სუფთა და აირგანმუხტვად არანეიტრალურ ელექტრონულ პლაზმებში

ნიკოლოზ ა. კერვალიშვილი

რეზიუმე

წარმოდგენილია სუფთა ელექტრონულ და აირგანმუხტვად ელექტრონულ არანეიტრალურ პლაზმებში გრიგალური სტრუქტურების წონასწორობის, ურთიერთ ქმედების და დინამიკის ექსპერიმენტული კვლევების შედეგების ანალიზი მიმდინარე დროში, რომელიც ბევრად მეტია ელექტრონ-ნეიტრალთან შეჯახების დროზე. განხილულია სუფთა ელექტრონული პლაზმის სვეტის ხანგრძლივი შეკავების პრობლემა პენინგ-მალმბერგის მახეში. შემოთავაზებულია ხანგრძლივარსებული სტაბილური გრიგალური სტრუქტურის თვითდამჭერი მექანიზმი აირგანმუხტვად არანეიტრალურ ელექტრონულ პლაზმაში. აღწერილია ელექტრონული შრის კოლაპსი პენინგის უჯრედის აირგანმუხტვად პლაზმაში. გაანალიზებულია სტაბილურ გრიგალურ სტრუქტურასა და სიმეტრიულ ელექტრონულ შრეს შორის ურთიერთქმედება, ასევე გრიგალური სტრუქტურების გავლენა მაგნიტური ველის განივ და გასწვრივ ელექტრონების გადატანაზე.