Anomalous transport of electrons in an electric discharge with transverse magnetic field

K P Kirdyashev

Russian Academy of Sciences, Institute of Radio Engineering and Electronics, Vvedensky sq., 1, Fryazino, Moscow Region, 14190, Russia
E-mail: kpk@ms.ire.rssi.ru

Abstract. The experimental data showing the relationship of excitation of microwave oscillations with abnormally transport of electrons across the magnetic field in turbulent plasma are presented. The mechanism of the formation of the discharge current due to scattering of drift electrons in the near-electrode layers of the electric discharges on microwave oscillations has been substantiated. The conditions for the manifestation of the turbulent mechanism of anomalous electron transport through the magnetic barrier at the boundary of the toroidal electric discharge have been studied most fully. The mobility of electrons across a magnetic field is one of the main parameters of electric discharges that use crossed electric and magnetic fields for technological purposes.

1. Introduction

The investigations of the excitation of oscillations in an electric discharge with the transverse magnetic field are associated with determining the efficiency of magnetic plasma confinement and solving the problem of anomalous electron transport across the magnetic field. In the investigated discharge, the system of magnetic coils immersed in the plasma creates a closed toroidal region, in the center of which the magnetic field is close to zero. In the considered configuration of the magnetic field, electrons are confined by a magnetic barrier at the discharge boundary, as a result of which a potential well is created inside the plasma volume, which holds the ions. The studies carried out indicated the low values of the electron temperature and the depth of the potential well, since the essential feature of such discharges is the formation of discharge current due to the transfer of electrons across the magnetic field. This determines the small energy time of plasma confinement by the magnetic field in the electro-discharge mode of plasma formation.

The known mechanisms of electron transport across the magnetic field, based on collisions of electrons with heavy particles, do not allow substantiating the observed values of discharge currents. The experimentally established relationship between the formation of the discharge current and the excitation of microwave oscillations indicates the need to study possible mechanisms of plasma instability in the region of the discharge and the effect of excited oscillations on anomalous electron transport across the magnetic field. At present, there is no theory of microwave oscillations in the discharge, which is necessary for the interpretation of the results of the experimental studies, which takes into account the totality of factors essential for the development of instability. These factors include the inhomogeneity of the electric and magnetic fields, the distribution of plasma parameters in the zones of generation of microwave oscillations, the influence of nonlinear effects on the saturation of the amplitudes of the excited oscillations, and the distribution of currents in the electric discharge.

Similar phenomena are observed in various types of plasma devices designed to accelerate plasma, create plasma engines and solve technological problems in space. The study of microwave oscillations in an electric discharge with a plasma-confining magnetic barrier makes it possible to develop the method...
for diagnosing processes leading to the transport of electrons across the magnetic field. The study of microwave oscillations in the discharges with transverse magnetic fields is of particular interest to substantiate the mechanism of current formation across the magnetic field in the accelerating channel of the stationary plasma thruster [1]. The results of the research carried out in this work expand the possibilities of the analyzing the radio astronomical observations of cosmic sources of microwave radiation due to the development of plasma instability in transverse magnetic fields.

In this investigation the effect of microwave oscillations on the transport of electrons across the magnetic field and the formation of the discharge current is carried out. The modes of anomalous transverse plasma conductivity and anomalous resistance of the transverse current in the magnetic barrier region are identified.

2. Experimental setup and research procedures

The design features of the experimental setup with barrier magnetic field (Fig. 1) and the methods used for the experimental study of microwave oscillations in different regions of the discharge are presented in [2–3]. In the plasma setup under consideration, the discharge voltage is applied between an incandescent cathode installed near the zero of the magnetic field and the conducting metal walls of the magnetic coils. The formation of a magnetic barrier at the discharge boundary is provided by four coils with a current; to reduce the forces of attraction between the magnetic coils and improve the field configuration, four coils with oppositely directed currents are additionally introduced into the design of the magnetic system.

Figure 1. The design of the magnetic system of the experimental plasma setup: 1 – base of the structure, 2 – compensation coils, 3 – current-carrying conductors, 4 – cathode, 5 – supply of working gas (argon).

As follows from the distribution of magnetic force lines in the cross section of the discharge, the magnetic field is concentrated near the coils covering the outer region of the discharge (Fig. 2). With this configuration of the magnetic field, the electric discharge is formed with the current due to the transfer of electrons across the magnetic field. The investigated discharge is limited by the closed magnetic field line determined by the criterion of plasma confinement stability [4].

The experiments on the study of the relationship between the discharge current and the excitation of microwave oscillations were carried out when the gas (argon) was supplied to the region of the heated cathode mounted on the axis of the large torus. The modes of formation of the discharge are studied at the working gas flow rate of 1.5–5.4 mg/s, corresponding to various manifestations of microwave oscillations in the region of the magnetic barrier. With this design of the experimental plasma setup, the metal walls of the magnetic coils, which are at positive potential relative to the inner region of the discharge, should be considered as the anode.

According to the results of the probe measurements, the concentration of electrons in the barrier region of the discharge is $(3–7) \times 10^{10}$ cm$^{-3}$ at electron temperature in the range of 15–25 eV. The thickness of the discharge boundary in the region of the magnetic barrier is 0.5–0.7 cm. The plasma parameters decrease by more than an order of magnitude beyond the discharge boundary. The distribution of the plasma potential over the small radius of the torus indicates the presence of the potential well that traps ions.
inside the magnetic barrier. The potential drop in the region of the magnetic barrier is 50–70 V at discharge voltage in the range of 150–200 V.

The study of microwave oscillations in the barrier region of the discharge was carried out by recording the electromagnetic radiation of the discharge using broadband antennas installed inside the vacuum chamber outside the discharge [5–6]. The determination of the intensity and spectra of microwave radiation was carried out using frequency-tunable measuring receivers in the range 1.05–7.15 GHz, including the frequencies of electron plasma oscillations at the experimentally measured electron concentration in the barrier region of the discharge. The probe studies of the intensity and spectra of plasma oscillations in the region of the magnetic barrier in the frequency range 200–500 kHz were carried out.

**Figure 2.** The structure of the magnetic system of the experimental plasma setup and the distribution of the magnetic field in the cross-section of the discharge: barrier magnetic field coils (1–4), compensation coils (5–8), plasma confinement boundary (9), direction of radial displacement of probes when measuring plasma parameters and the intensity of microwave oscillations (10); magnetic lines of force (dashes), lines of constant magnetic field (solid lines).

In accordance with the applied measurement technique [7], when determining the intensity of the microwave radiation of the discharge, it was envisaged to register the radiation of the reference source, which was the gas-discharge lamp with configuration similar to the outer region of the toroidal discharge under study. The use of a reference source made it possible to determine the absolute values of the spectral density of microwave radiation of the discharge $W$ regardless of the measurement conditions and the equipment used. To characterize the degree of non-equilibrium of microwave oscillations in the region of the magnetic barrier, we considered the values $W/W_0$ normalized to the radiation energy density caused by thermal fluctuations in the barrier region of the discharge $W_0$.

The zones of generation of microwave oscillations in the discharge volume were identified based on the results of local measurements of oscillations using two-wire electrical probes. The one of microwave probes which was installed near the discharge boundary, the other probe moved in the cross section of the discharge. The scale of electric field disturbances perceived by microwave probes is determined by the distance between the conductors $\Delta l = 1.5–2$ mm. The applied microwave probes make it possible to register the fields of plasma waves in the discharge with the significant weakening of the contribution to the recorded signal from the components of the fields of electromagnetic radiation. The results of local measurements of the microwave energy were compared with the thermal level.

In earlier experiments [5–6], the study of the microwave emission spectra of the discharge was carried out by the method of sequential spectral analysis. Sequential spectral analysis is usually used in the study of processes, the nature of which changes rather slowly compared to the scanning period of the frequency of the measuring device. For the selected frequency tuning rate, the duration of the spectral analysis,
which ensures undistorted transmission of the spectral components of microwave oscillations in the investigated frequency range, was about 10 s, which significantly exceeds the characteristic period of the establishment of stationary parameters of the oscillations investigated in the discharge. The experimental spectra obtained as the result of successive analysis do not allow one to reveal the development in time of the discharge instability and the connection between the excitation of microwave oscillations at different frequencies. The method of modified parallel spectral analysis was applied, in which the envelopes of microwave oscillations were simultaneously recorded at two selected carrier frequencies within quasi-stationary time intervals corresponding to the duration of $10^2$–$10^3$ periods of microwave oscillations excited in the discharge.

3. The experimental results

The zones of generation of microwave oscillations are determined on the basis of the results of local measurements of the intensity of plasma waves and fields of electromagnetic radiation outside the magnetic barrier. The most intense oscillations are 3–4 orders of magnitude higher than the equilibrium level. The effects of competition between the anomalous transverse plasma conductivity and the anomalous resistance of the transverse current in the discharge are revealed based on the results of the performed experiments. The results obtained agree with the concept of an analogy between collisions of electrons with neutral particles and their scattering by chaotic oscillations of the electric field caused by high-frequency plasma instability.

![Figure 3](image)

**Figure 3.** The oscillations of the discharge current $I_D$(a) and the relative intensity of microwave radiation $W/W_0$ (b); diagram of the dependence of the discharge current on the intensity of microwave radiation (c). Discharge mode: gas consumption 5.35 mg/s, voltage 200 V, magnetic field $5\times10^{-3}$ T; the linear trend line, accuracy of approximation 0.36.

The non-equilibrium of plasma oscillations and electromagnetic radiation of the discharge manifests itself to the greatest extent at frequencies of 1.5–2.5 GHz, corresponding to the frequency range of electron plasma oscillations in the region of the magnetic barrier. It was found that with an increase in the flow rate of the working gas, a decrease in the intensity of microwave radiation, the broadening of the frequency spectrum and the shift of the radiation maximum to higher frequencies are observed. In the microwave radiation spectra obtained by the method of sequential spectral analysis, components with randomly varying intensity and frequency separation of 150–200 MHz are distinguished, corresponding to the electron cyclotron frequency in the magnetic barrier at the fields of 0.0050 and / - 0.0075 T.
The generation zone of intense microwave oscillations is located on the outer side of the discharge at a distance of 5.5–6.5 cm from the axis of the small torus, in which the electron concentration is $3 \times 10^{10} - 10^{11}$ cm$^{-3}$. The measurement results indicate the localization of the source of intense microwave oscillations near the boundary of plasma confinement by the barrier magnetic field. In the same region of the discharge, perturbations of the electric field potential are observed in the frequency range 350–500 kHz, associated with fluctuations in the concentration of electrons in the discharge. Based on the assumption that the excited oscillations are potential, the width of emission spectrum is determined by fluctuations in the plasma density caused by the plasma instability in the low-frequency region of the spectrum.

As follows from temporal intensity of the microwave radiation and oscillations at the individual frequencies, the instability developing in the discharge manifests itself in limited time intervals with subsequent breakdown of the oscillatory processes. The results of statistical processing of signals at the output of the measuring receivers indicate the presence of components in the autocorrelation functions, one of which appears at time intervals $\leq 50$ $\mu$s, the other corresponds to disturbance duration of 1–5 ms. It is characteristic that during these time intervals there are ejections of electrons and ions from the magnetic confinement region of the plasma, which are recorded by the oscillations of the electron and ion currents to the probes installed outside the magnetic barrier [3].

![Figure 4](image)

**Figure 4.** The oscillations of the discharge current $I_D$ (a) and the relative intensity of microwave radiation $W/W_0$ (b); the diagram of the dependence of the discharge current on the intensity of microwave radiation (c). Discharge mode: gas consumption 1.6 mg/s, voltage 200 V, magnetic field $5 \times 10^{-3}$ T; the exponential trend line, accuracy of approximation 0.81.

It should be noted that there is the significant scatter in the values of the correlation coefficients between the intensity of microwave radiation and plasma waves at different frequencies, which is the basis for concluding that the spectra of microwave oscillations in the barrier region of the discharge are...
strength of the electric and magnetic fields near the magnetic coils holding the plasma varies within the range (3.9‒4.2) ×10^8 cm/s. Another group of electrons is formed as the result of demagnetization of magnetic fields in this region of the discharge is determined from the results of measurements of the order of 250 cm², the concentration of the electron flows across the magnetic barrier holding the plasma is (1.4‒1.8) ×10^10 cm³. The electron drift velocity in the crossed electric and magnetic fields near the magnetic coils holding the plasma varies within the range (3.9‒4.2) ×10^6 cm/s. Another group of electrons is formed as the result of demagnetization of drifting electrons by collisions and their scattering on oscillations. The transfer of demagnetized electrons across the magnetic barrier, which ensures the creation of the discharge current, occurs in a layer with a size equal in order of magnitude to the electron cyclotron radius ρe. The concentration of these electrons in the region of the magnetic barrier can be estimated from the experimental values of the discharge current, the surface area of the metal shells of the magnetic coils, and the potential drop in the barrier region. The estimates show that with the effective surface area of the shells of the magnetic coils of the order of 250 cm² the concentration of the electron flows across the magnetic barrier holding the plasma is (1.4–1.8) ×10^9 cm⁻³.

Usually the plasma instabilities originate from reacting of interpenetrating electron beams and absence of effect magnetic field on the formation of different groups of electrons [7]. The experimentally observed excitation of microwave oscillations makes it possible to consider the velocity distribution of electrons in this region, which significantly differs from the equilibrium distribution. The frequency range of the microwave instability developing in the discharge corresponds to the high-frequency branch of electron oscillations calculated from the electron density and the magnetic field. The mechanism of the excitation of microwave fields in the plasmas with transverse magnetic field due to the interaction of spatially separate streams of electrons and forming discharge current.

When analysing the mechanism of excitation of microwave oscillations, we will proceed from the existence of two groups of electrons near the magnetic barrier. The constituent of electrons is held back by the magnetic field and creates the drift current in crossed electric and magnetic fields. As follows from the results of probe measurements, the estimate of the concentration of electrons forming drift current near the magnetic barrier is (2.4–8.5) ×10¹⁸ cm⁻³. The electron drift velocity in the crossed electric and magnetic fields in this region of the discharge is determined from the results of measurements of the strength of the electric and magnetic fields near the magnetic coils holding the plasma varies within the range (3.9–4.2) ×10⁶ cm/s. Another group of electrons is formed as the result of demagnetization of drifting electrons by collisions and their scattering on oscillations. The transfer of demagnetized electrons across the magnetic barrier, which ensures the creation of the discharge current, occurs in a layer with a size equal in order of magnitude to the electron cyclotron radius ρe. The concentration of these electrons in the region of the magnetic barrier can be estimated from the experimental values of the discharge current, the effective surface area of the magnetic coils, and the potential drop in the barrier region. The estimates show that with the effective surface area of the magnetic coils of the order of 250 cm² the concentration of the electron flows across the magnetic barrier holding the plasma is (1.4–1.8) ×10^9 cm⁻³.

The instability theory of the discharge
The experimentally observed excitation of microwave oscillations in the discharge indicates the development of instability in the range of electron plasma frequencies of the barrier region of the discharge, which makes it possible to consider the velocity distribution of electrons in this region, which significantly differs from the equilibrium distribution. The frequency range of the microwave instability developing in the discharge corresponds to the high-frequency branch of electron oscillations calculated from the electron density and the magnetic field. The mechanism of the excitation of microwave fields in the plasmas with transverse magnetic field due to the interaction of spatially separate streams of electrons and forming discharge current.

When analysing the mechanism of excitation of microwave oscillations, we will proceed from the existence of two groups of electrons near the magnetic barrier. The constituent of electrons is held back by the magnetic field and creates the drift current in crossed electric and magnetic fields. As follows from the results of probe measurements, the estimate of the concentration of electrons forming drift current near the magnetic barrier is (2.4–8.5) ×10¹⁸ cm⁻³. The electron drift velocity in the crossed electric and magnetic fields in this region of the discharge is determined from the results of measurements of the strength of the electric and magnetic fields near the magnetic coils holding the plasma varies within the range (3.9–4.2) ×10⁶ cm/s. Another group of electrons is formed as the result of demagnetization of drifting electrons by collisions and their scattering on oscillations. The transfer of demagnetized electrons across the magnetic barrier, which ensures the creation of the discharge current, occurs in a layer with a size equal in order of magnitude to the electron cyclotron radius ρe. The concentration of these electrons in the region of the magnetic barrier can be estimated from the experimental values of the discharge current, the surface area of the metal shells of the magnetic coils, and the potential drop in the barrier region. The estimates show that with the effective surface area of the shells of the magnetic coils of the order of 250 cm² the concentration of the electron flows across the magnetic barrier holding the plasma is (1.4–1.8) ×10^9 cm⁻³.

The considered model of the current sheet in the region of the magnetic barrier corresponds to the experimental distributions of the electric field potential in the cross section of the discharge [7]. The potential drop in the discharge region is 50–60 V and concentrated near the boundary of plasma confinement in the layer with dimensions of 0.7–1.2 cm. The size of the current layer, in which the interacting flows of electrons are generated, is of the order of the calculated values of the electron cyclotron radius in the barrier region. At electric field strength of ≥ 100–120 V/cm in the magnetic barrier, the directed velocity of the drift flow of electrons significantly exceeds their thermal velocity.
From the experiments carried out, it follows that the non-stationary nature of the excitation of microwave oscillations is manifested in sporadic discharge of the charge through the magnetic barrier. The excess charge is discharged when the plasma accumulating inside the magnetic barrier crosses the boundary of stable confinement. The electric discharge is accompanied by the formation of electron beams outside the magnetic barrier with a characteristic repetition period of discharge current surges close to the plasma confinement time under conditions of continuous ionization of the working gas. The modes of excitation of microwave oscillations and the formation of a discharge current make it possible to consider an electric discharge inside the magnetic barrier as the self-oscillating system with internal feedback formed by azimuthal electron beams. The formation of the fast electrons is evidenced by the maxima of the intensity of microwave oscillations near the magnetic barrier and in the axial region of the discharge.

The qualitative model of the discharge as the stochastic self-oscillating system is based on fluctuations in the delay of microwave signals in the internal feedback loop formed by the drift electron flow. In this case, the duration of envelopes of microwave emissions can be estimated from the average value of the phase delay of the microwave signal in the feedback loop. Indeed, for discharge modes with the potential drop in the magnetic barrier region within 50–60 V, the delay of the plasma wave carried by a drift electron beam is 10–50 \( \mu s \), which is consistent with the results of statistical processing of microwave radiation intensity oscillations.

The characteristic repetition period of the microwave emission can be estimated from the time of accumulation of electrons inside the magnetic barrier, which is associated with the effective frequency of ionization collisions of electrons with atoms of the working gas. With a cross section of argon ionization of the order of 10\(^{-18}\) cm\(^2\) by the electron beam with energy \( \geq 50 \) eV and characteristic values of the gas pressure in the discharge region, it follows that the stage of accumulation of electrons inside the magnetic barrier manifests itself at time intervals of 1–5 ms, corresponding to the frequency of microwave emission from the barrier discharge area.

5. Electron transport across the magnetic field

The main conclusion from the performed experiments is related to the estimation of the efficiency of electron transfer across the magnetic field of the barrier and the effect of microwave oscillations on the formation of the discharge current. The experimentally established relationship between the discharge current and the excitation of microwave oscillations makes it possible to consider the contribution of nonlinear effects to the development of microwave instability of the discharge, which leads to demagnetization of electron drift on oscillations and the change in the electron velocity distribution function. The formation of two streams of electrons as a result of their scattering on oscillations favours the development of instability in the region of plasma confinement by a magnetic field.

The comparison of the values of the discharge current with the intensity of the oscillations allows us to consider the excitation of microwave oscillations as the main factor leading to the scattering of drift flows of electrons by oscillations and their transfer across the magnetic field, which is the main mechanism of the discharge current formation. This conclusion follows from the analogy between pair collisions of particles in the plasma and the scattering of electrons by microwave oscillations excited in the discharge. Under the conditions of discharge formation, the current density due to the transfer of electrons across the magnetic field can be represented in the form [9]:

\[
J_D = e n_0 \left( e/m_e \right) E_{bar} \nu_{df} / (\omega_B + \nu_{df}^2).
\]  

We take into account the effective frequency of electron scattering in microwave oscillations \( \nu_{ef} \), cyclotron frequency of electrons \( \omega_B \) in the barrier discharge, the concentration drift electrons \( n_0 \). With the relation \( \nu_{df} \ll \omega_B \), in the experiment, the discharge current increases with increase in the frequency of electron scattering by oscillations:

\[
J_D = e n_0 \left( e/m_e \right) E_{bar} \nu_{df} / \omega_B^2.
\]  

The results of the performed experiments make it possible to consider the scattering of electrons by microwave oscillations as the determining factor in the anomalous transfer of electrons through the magnetic barrier and the formation of the discharge current. The regime of anomalous transverse plasma conductivity in the barrier region of the discharge corresponds to the experimental data. In accordance with [10], the effective frequency of electron scattering presented as a function of the energy of microwave oscillations in the discharge \( W_{sc} \),

\[
\nu_{df} = \left( 2W_{sc} / n_0^2 e \Delta U_{bar} \right)^{1/2} \omega_{Pr}.
\]
In this case, the experimental values of the concentration of the drift flux of electrons \( n_{\text{ef}} \), leading to the excitation of oscillations, and the potential difference in the barrier region of the discharge \( \Delta U_{\text{bar}} \) are taken into account. From the results of the measurements it follows that the maximum energy of microwave oscillations in modes with anomalous transverse plasma conductivity is 10^{-3}–10^{-2} / m^2. Based on these data, we estimate the effective frequency of electron scattering by microwave oscillations as 10^{8}–10^{9} s^{-1}, at which the regime of anomalous electron transfer through the magnetic barrier is realized. As follows from (3), the scattering of electrons by provides the mode of formation of the discharge current within 3–5 A/cm² at the concentration of electrons in the barrier region of the discharge \( n_{\text{ef}} \approx 10^{10}–10^{11} \) cm² and the electric field strength in the magnetic barrier 50–100 V/cm.

The maximum energy density of microwave oscillations at the quasi-linear stage of the development of plasma-beam instability in the investigated discharge region is determined based on the condition \( v_e \leq \omega_{Be} \) corresponding to the formation of drift electron flows:

\[
W_e = \frac{1}{2} \left( \frac{\omega_{Be}}{\omega_{pe}} \right)^2 n_{\text{ef}} e \Delta U_{\text{bar}}. \tag{6}
\]

When this value is exceeded, the demagnetization of electrons on oscillations predominates and the discharge transitions to the beam instability mode with the anomalous resistance of the barrier region of the discharge characteristic of this instability. Thus, in the barrier region of the discharge, the nonlinear mechanism of beam-plasma instability is realized, which is caused by the action of excited oscillations on the transfer of electrons across the magnetic field and the formation of the discharge current. The maximum transfer rate of electrons through the magnetic barrier, which form the discharge current, can be estimated from the displacement of electrons at the distance corresponding to their cyclotron radius during the scattering time by oscillations [11]:

\[
V_{\text{max}} = V_T e (\omega_{ef}/\omega_{Be}) \leq V_T. \tag{7}
\]

The rate of the removal of electrons from the discharge reaches maximum values corresponding to the thermal speed of electrons at the energy density of microwave oscillations (6).

**Conclusion**

The effects of competition between the anomalous transverse plasma conductivity and the anomalous resistance of the transverse current in the discharge are revealed based on the results of the performed experiments. The results obtained agree with the concept of the analogy between collisions of electrons with neutral particles and their scattering by chaotic oscillations of the electric field caused by high-frequency plasma instability. The dependence of the discharge current on the intensity of microwave oscillations indicates the nonlinear processes in the discharge, leading to the accumulation of electrons in the discharge. The registration of intensity and spectrum of microwaves oscillations is the effective diagnostics the modes discharge formation and electron transfer processes in various types of plasma devices with transverse magnetic field.

**Acknowledgements**

The work was performed according to the state task of the Kotelnikov Institute of Radio engineering and Electronics of Russian Academy of Sciences. I am grateful to the staff of the Science and Engineering Center of High Plasmodynamic Technologies at the Moscow Technological University (MIREA) for their help in performing these experiments and helpful discussions of the results obtained in this work.

**References**

[1] Morozov A I 2006 Introduction to Plasma Dynamics (Fizmatlit, Moscow) [in Russian].
[2] Morozov A I 1992 Plasma Phys. Rep. 18, 235.
[3] Morozov A I, Bugrova A I, Bishaev A M and Nevrovsy V A 1999 Tech. Phys. Lett. 25 700.
[4] Ohkava T and Yoshikawa M 1966 Phys. Rev. Lett. 17 685.
[5] Morozov A I, Kirdyashev K P, Bugrova A I and Bishaev A M 2001 Plasma Phys. Rep. 27 275.
[6] Kirdyashev K P, Morozov A I, Bugrova A I and Bishaev A M 2002 Tech. Phys. Lett. 28 700.
[7] Mikhailovskii A B 1971 Theory of Plasma Instabilities (Atomizdat, Moscow).
[8] Kirdyashev K P 1982 High-Frequency Wave Processes in Plasmodynamic Systems (Energoatomizdat, Moscow) [in Russian].
[9] Erofiev V S and Leskov L A 1974 Physics and Application of Plasma Thrusters [in Russian].
[10] Aref'ev V I and Kirdyashev K P 1975 Sov. Phys. Tech. Phys. 20 330.
[11] Kirdyashev K P 2016 Plasma Phys. Rep. 42 841.