QUASITRANSPARENCY AND INFORMATION TRANSPARENCY OF WAVE BARRIERS IN MAGNETOACTIVE INHOMOGENEOUS PLASMA IN THE CASE OF EXCITATION OF BERNSTEIN WAVES IN IT

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In the process of experimental investigations of the quasitransparency of a wave barrier in the inhomogeneous weakly magnetized plasma for waves that belong to the upper hybrid dispersion branch of oscillations, we have discovered the anomalous penetration of oscillations into the barrier and in the plasma beyond it in a certain frequency range. The investigation of this effect has demonstrated that it is conditioned by the excitation of Bernstein waves and their propagation in the plasma system. The peculiarities of their realization in the plasma system are determined. The possibilities of the existence of mechanisms of quasitransparency and information transparency of plasma wave barriers with participation of Bernstein waves are analyzed.

1. Introduction

The quasitransparency of plasma wave barriers predicted theoretically [1–5] and discovered experimentally [6–9] represents a fundamental property of inhomogeneous plasma with a hump-shaped spatial density distribution. The mechanisms of this phenomenon are based on the processes of transformation of waves in a prebarrier plasma and their regeneration in plasma beyond the barrier. In each individual case, the existence or absence of the quasitransparency of a plasma wave barrier is determined by the dispersion characteristics of a plasma formation, i.e., by the presence of the waves (including space-charge ones), for which the "barrier" is transparent, i.e. it is absent. It is essential that the waves, for which the barrier is present, can be transformed in the mentioned waves with the the subsequent inverse process in plasma beyond the barrier.

It was shown that, for the investigated mechanisms of the quasitransparency of plasma wave barriers, such "waves-transporters" of the initial wave through the barrier could be presented by Trivelpiece–Gould waves [4], van Kampen waves [1–3], and space-charge waves in an electron beam passing through a barrier [5].

In certain cases, the special attention is paid to the information transparency of plasma wave barriers. It consists in the transparency of a barrier only for the information contained in the amplitude modulation of the wave it exists for. In addition to all the mechanisms of quasitransparency of plasma wave barriers, this phenomenon is also realized through the mechanisms that, with initial waves being present before the barrier, provide the existence of waves in or beyond it which are of another kind and are characterized by the same frequency as the initial wave or are the same kind but with another frequency; or these mechanisms provide merely the plasma fluctuations with amplitude modulation proportional to that of the initial wave. In particular, such mechanisms include those predicted theoretically in [10–13], where the "wave-transporters" of amplitude modulation are van Kampen waves [10, 13], higher harmonics of the initial wave [11], and the waves representing a result of the plasma echo effect [12].

This paper is devoted to the experimental investigation of the effect discovered in studying the quasitransparency of a plasma barrier for waves belonging to the upper hybrid dispersion branch of the oscillations of weakly magnetized plasma (hereinafter — upper hybrid waves, oscillations) [9] by the mechanism

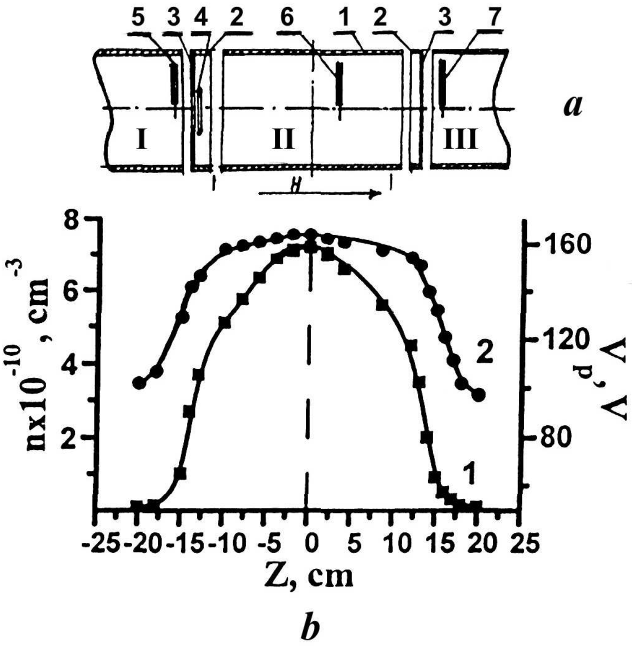

Fig. 1. *a* – Scheme of the gas-discharge system *I, III* – vacuum chambers; *II* -– discharge chamber; *1* – anode; *2* – cathode blocks; *3* – diaphragms; *4* – cathode; *5* – radio-frequency probe-vibrator; *6, 7* – radio-frequency probes; *b* – axial distributions of plasma density (*1*) and potential (*2*) in it: I_a = 0.83 A; V_a = 150 V; H = 93 Oe; $p = 2 \times 10^{-4}$ Torr

predicted theoretically in work [3]. These results indicate the possibility of the existence of mechanisms of quasitransparency and information transparency of plasma wave barriers, where "wave-transporters" can be presented by Bernstein waves [14].

2. Experimental Conditions

The investigations were performed on the same setup described in detail in [9], on which the effect had been discovered. Its principal part — a gas-discharge chamber — is schematically presented in Fig. 1,*a*. In order to obtain the inhomogeneous magnetoactive plasma with a nonmonotonic density profile along the magnetic field direction (hereinafter, the Z axis) in it, we impelled the plasma created in gas-discharge chamber *II* with a nonself-sustained Penning discharge to symmetricly flow out along the indicated axis into coaxial "vacuum" chambers *I* and *III* with a lower pressure of the working gas. These chambers are hollow copper cylinders 700 mm in length and 100 mm in inner diameter. A similar cylinder 180 mm in length served anode *1* of gas-discharge chamber *II*. It was separated from the vacuum chambers with isolated copper cathode blocks *2* and connected with them with the help of central orifices 30 mm in diameter in molybdenic reflectors-diaphragms *3* built in the cathode blocks. One of them (located from the side of chamber *I*) contained a built-in directly heated cathode *4* that had form of a ring 40 mm diameter made of a tungsten wire 0.5 mm in diameter. The plane of the ring was oriented normally to the magnetic field.

The working gas – argon – was supplied into the discharge chamber in the middle plane of the anode (Z=0) and continuously pumped out through the orifices in the reflectors and the "vacuum" chambers.

The stationary magnetic field uniform to within 4%, to which the gas-discharge chamber was subjected, was formed with a system of coils *5* coaxially located in the line of the chamber and supplied with direct current.

The investigations were performed in the following range of the discharge parameters: the anode current I_a= 0.8÷2.8 A, the discharge voltage V_a= 50÷200 V, the magnetic field strength H = 133 Oe, the argon pressure in chamber *II* $p = (2 \div 4) \times 10^{-4}$ Torr, while it was lower by a factor of 5–10 in chambers *I* and *III*.

Investigating the dependences of the effect from some parameter of the discharge, we held all the other parameters constant by means of the corresponding change in the cathode heating current that is the flow of electrons emitted by it.

In order to excite oscillations in the plasma system and investigate their characteristics and evolution, we used high-frequency coaxial probe-antennas with the working part (pins) length equal to 10 mm and a diameter of 0.5 mm located in chambers *I*, *II*, and *III* (*5*, *6*, and *7* in Fig. 1,*a*, respectively). These probes were also used as single cylindrical probes for the determination of the stationary parameters of plasma (density n, potential V_p, and electron temperature T_e)) by standard techniques. All the probes could be shifted in the line of the radius (r) of the chambers and along their Z axis.

The typical forms of the axial distributions of plasma density and potential in the gas-discharge system are illustrated in Fig. 1,*b*. In the earlier investigations [9], it was shown that a plasma system with such parameters and plasma density distribution contains a barrier of absorption kind for upper hybrid waves with frequencies 490≤ f ≤1000 MHz. The effect considered in the present paper was observed in the same frequency range. Like [9], in order to excite oscillations in the indicated frequency interval in the prebarrier plasma, a high-frequency monochromatic signal with frequency f_m lying in this range was supplied from a GSS-12 generator to probe-vibrator *5* in chamber *I*.

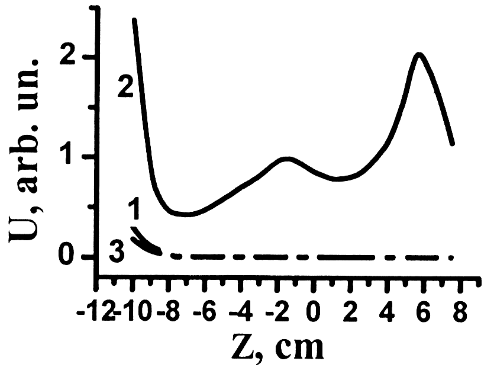

Fig. 2. Axial distributions of radio-frequency signal in the discharge chamber for waves with frequencies f_m= 500 (*1*), 560 (*2*), and 600 MHz (*3*): I_a = 1.3 A; V_a = 85 V; H = 133 Oe; $p = 2 \times 10^{-4}$ Torr

The intensity of the oscillations excited in plasma and its spatial distribution in chambers *II* and *III* were determined with the help of probes (*6* and *7*, respectively), whose signal entered a selective microvoltmeter P5-20 and was registered then by a two-coordinate recording potentiometer N-370 connected with electrical sensors of coordinates of the probes.

3. Experimental Results

The essence of the observed effect is demonstrated by the axial distributions of the intensity of plasma oscillations in gas-discharge chamber *II* presented in Fig. 2. According to theoretical prognoses, this region of plasma represents a barrier for upper hybrid waves, and their intensity must rapidly decrease practically up to zero as they get deeper into the barrier. For a barrier of sufficient width, these waves will be actually absent almost on the whole path through it. It is just the phenomenon observed in [9], and, as one can see, such a behavior of the axial dependence of the intensity of oscillations is realized for waves with frequencies f_m= 500 MHz and f_m= 600 MHz. The intensity of oscillations with an intermediate frequency f_m=560 MHz evolves in the barrier in quite another way. With the amplitude of the high-frequency signal at a probe-vibrator being the same, the intensity of oscillations at the beginning of the barrier is higher almost by an order of magnitude, and they don't completely damp in the barrier. Moreover, after the initial decrease of their intensity, they start to rise when approaching the exit from the barrier. The axial distribution of the intensity of these oscillations is no longer monotonous: there appears one or two maxima on it. With radial displacement from the geometrical axis

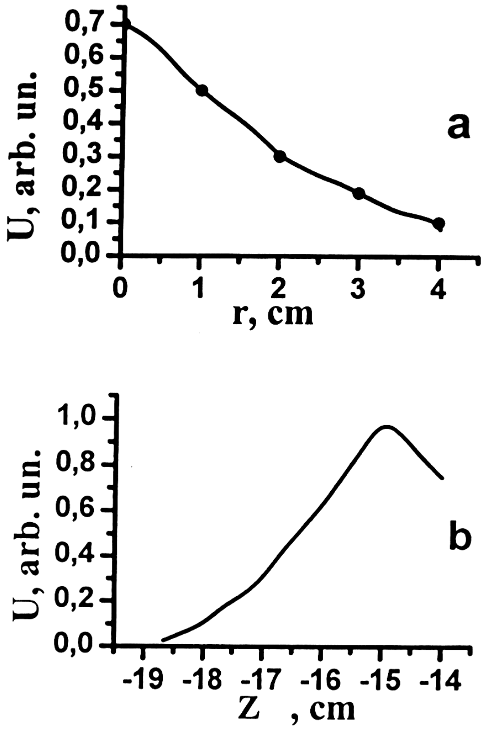

Fig. 3. Radial dependence of the intensity of a signal in the maximum of its axial distribution at the exit of the discharge chamber (*a*) and dependence of this signal on the axial coordinate of the probe-vibrator Z_m (*b*). I_a = 1.3 A; V_a = 85 B; H = 133 E; $p = 2 \times 10^{-4}$ Torr; f_m= 560 MHz

of the system, the intensity of oscillations decreases (see Fig. 3,*a*), but the behavior of their distribution along the magnetic field in parallel to the axis of the system remains the same as on it.

It turns out that the intensity of oscillations in the barrier essentially depends on the localization of a probe-vibrator in the prebarrier plasma. The data given in Fig. 3,*b* testifies that the effect essentially decreases as a probe-vibrator is shifted by a larger distance from the barrier to plasma with lower density.

The experiment has demonstrated that the investigated effect is realized in a rather narrow frequency range that amounts to 2–4% of the frequency of the maximum of their intensity, Fig. 4.

In order to clarify the impact of the plasma system parameters on the realization of the effect, we investigated its dependence on the parameters of the gas discharge used for the formation of plasma. It turned out that the intensity of the signal in the barrier decreased with reduction of the voltage across the discharge up to

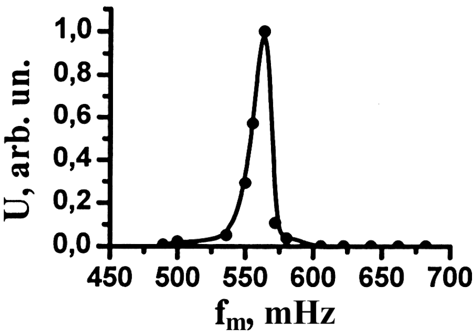

Fig. 4. Frequency dependence of the intensity of a signal at the maximum of its axial distribution at the exit of the discharge chamber (I_a = 2 A; V_a = 85 V; H = 133 Oe; $p = 2{\times}10^{-4}$ Torr)

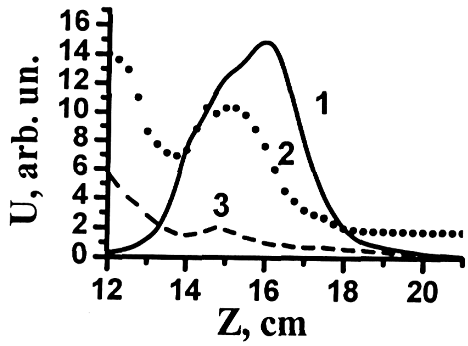

Fig. 6. Axial dependences of the signal intensity in chamber *III* for waves with frequencies f_m= 500 (*1*), 560 (*2*), and 580 MHz (*3*) (I_a = 1.3 A; V_a = 85 V; H = 133 Oe; $p = 2{\times}10^{-4}$ Torr)

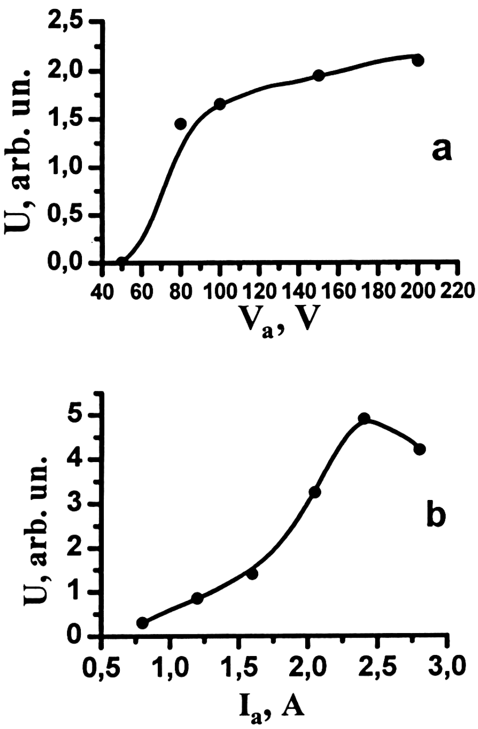

Fig. 5. Dependences of the intensity of a signal in the maximum of its axial distribution at the exit of the discharge chamber on the discharge voltage I_a = 1.3 A (*a*) and discharge current V_a = 85 V (*b*). H = 133 Oe; $p = 2{\times}10^{-4}$ Torr; f_m= 560 MHz

the complete disappearance at V_a $\leq$50 V, Fig. 5,*a*. The discharge voltage also influences the form of the axial distribution of the intensity of oscillations: at low voltages, one observes two maxima, while at higher ones -– only one of them localized close to the exit from the barrier.

With increase in the discharge current, the signal in the barrier first experiences a rather strong amplification and then passes through a maximum, Fig. 5,*b*. In this case, the character of the axial distribution of the intensity of oscillations in the barrier doesn't change.

In order to examine the peculiarities of the penetration of a signal beyond the barrier in the presence of the investigated effect, we studied the axial distributions of the signal intensity in chamber *III*, i.e. beyond the barrier, at various frequencies of the modulating signal. The result of this study is presented in Fig. 6.

At frequencies lower than those for which the effect takes place, the axial distribution of the intensity of oscillations in plasma beyond the barrier (curve *1*) is typical under the quasitransparency of a plasma wave barrier [9] conditioned by the mechanism predicted theoretically in [3]. Indeed, the oscillations are practically absent at the barrier exit and are regenerated in plasma beyond it with the intensity maximum lying in its certain region.

In the case where the oscillations in the prebarrier plasma are excited at a frequency, for which the effect takes place and the signal in the middle of the barrier is the most intensive (curve *2*), the oscillations at the barrier exit are characterized by a rather high intensity. At a distance from the barrier, it decreases and, against the background of this damping, one observes a maximum localized almost in the same region of plasma beyond the barrier as in the previous case. As a matter of fact, one observes here a superposition of two different processes at the same frequency.

A further increase of the signal frequency results in a decrease of the intensity of the both indicated processes up to the complete disappearance of oscillations.

4. Analysis of the Experimental Results and Conclusions

In order to clarify the nature of the observed effect, one should consider the frequency relations satisfied in the case of its realization in a plasma system.

We have

$$f_{ce} \leq f_{pe} < f_m < \sqrt{f_{pe}^2 + f_{ce}^2} < 2f_{ce}$$

in the plasma close to a probe-vibrator in chamber *I* and in the symmetric region of plasma in chamber *III* and

$$f_{ce} < f_m < 2f_{ce} < f_{pe} < \sqrt{f_{pe}^2 + f_{ce}^2}$$

in plasma at the center (Z=0) of discharge chamber *II*. Hence, as was already noted, the upper hybrid waves excited in chamber *I* cannot surmount the plasma barrier in chamber *II* and expand to chamber *III*. The same is true for the electromagnetic waves with a frequency f_m. In addition, at this frequency, they can't be excited at all in the experimental system, as follows from [15]. Under these conditions, the only waves with a frequency f_m that can simultaneously exist in plasma in chambers I, II, and III are Bernstein ones. In the earlier investigations of these waves (see, e.g., [14, 16–21]), a number of regularities of their realization in various plasma systems was established. Let's compare (at least qualitatively) some of them with the dependences for the investigated oscillations described in the previous chapter.

The axial dependences presented in Figs. 2 and 6 for the intensity of oscillations in the system locally excited in chamber *I* testify to the propagation of waves along the magnetic field. But, as was shown in works [14,16], in plasma with the Maxwellian distribution of electron velocity components in parallel and normally to the magnetic field direction, Bernstein waves can't propagate along the magnetic field as they undergo a very strong damping if the component of the wave vector $k_\parallel \neq 0$. Instead, they propagate almost without damping at the right angle to the magnetic field $k = k_\perp$.

Another situation arises in plasma, where the distribution of electron velocity components differs from the Maxwellian one due to the presence of a group of non-Maxwellian fast electrons [16,20,21], which is typical of beam-plasma systems [20,21]. In this case, there can exist "oblique" Bernstein waves that propagate without very strong damping at an angle θ to the magnetic field if the condition $\cos^2\theta < 0.1$ is satisfied and the velocity component of the non-Maxwellian part of the electron distribution in parallel to the magnetic field essentially exceeds the corresponding component of the thermal velocity of its Maxwellian part.

Thus, the propagation of Bernstein waves along the magnetic field observed in the experiment testifies, first, to their oblique propagation with respect to the magnetic field and, second, to the non-Maxwellian electron velocity distribution in the system. As follows from works [22—24], the latter fact does take place. In the plasma of the nonself-sustained Penning discharge with a flat heated cathode [22], the distribution of the electron velocity component parallel to the magnetic field includes both low-energy Maxwellian and high-energy non-Maxwellian components, the latter being formed mainly by primary electrons that had experienced the energy relaxation due to the collective processes of beam-plasma interaction [23]. In the experimental system, we used a cathode of toroidal form. As was shown in [24], a non-Maxwellian component of the distribution of the both components of the electron velocity in the interval between 0 and $\sqrt{\frac{2eV_k}{m}}$ is formed in this case due to the escape of primary electrons from the cathode layer to plasma at various angles to the magnetic field (in the range between 0 and 2π) even without energy loss during pair or collective collisions, where $V_k \leq V_a$ stands for the cathode drop of the potential. The presence of diaphragms in the experimental system (see Fig. 1,*a*) imposes certain critical conditions for the escape of primary electrons from chamber *II* to chamber *I*. Possibly, it is just the fact responsible for both the absence of the effect at a discharge voltage lower than 50 V and its increase with a rise of the discharge voltage (Fig. 5,*a*).

The essential peculiarity of the experimental plasma system consists in that the distribution function of the electron velocity components varies along the system axis due to a nonmonotonic (with a hump) distribution of the plasma potential along this axis (see Fig. 1,*b*) and its radial nonuniformity. Due to the existence of a potential well, the region of the motion of electrons that belong to the Maxwellian component of the longitudinal velocity distribution is practically limited by chamber *II*, while chambers *I* and *III* are available only for faster electrons of the non-Maxwellian component of the distribution. Due to the motion of electrons in a retarding electric field and their reflection from the walls of the potential well, the electron density decreases with increase in the distance to chamber *II*. The flow of these electrons both toward chamber *II* and in the opposite direction decreases. Moving through the plasma in the neighborhood of a probe-vibrator, these electrons interact with the high-frequency electric field formed by it. Accelerating as they move to chamber *II*, they actually form a modulated flow of fast electrons, and their velocity in the indicated chamber essentially exceeds the thermal velocity of Maxwellian electrons.

As follows from what was said above, there exist the conditions in the experimental system similar to those providing the excitation of "oblique" Bernstein waves in beam-plasma systems that also propagate along the magnetic field.

It is known [19] that the reduction of the beam current in beam-plasma systems results in a decrease of the intensity of Bernstein waves. This phenomenon correlates with an attenuation of the intensity of oscillations with decrease in the discharge current (Fig. 5,*b*) and with increase in the distance of a probe-vibrator from chamber *II* (Fig. 3,*b*). In the both cases, there takes place the reduction of the density of electrons in the neighborhood of a probe-vibrator that interact with a high-frequency field formed by it.

As was established (see, e.g., [17]), in a cylindrical column of radially (across the magnetic field) nonuniform plasma, Bernstein waves with a frequency in the range $f_{ce} \leq f_m \leq 2f_{ce}$ can exist only inside a coaxial cylinder of radius R with the condition $f_{pe}^2(R) = f_m^2 - f_{ce}^2$ being satisfied on its surface. When approaching this surface, the intensity of Bernstein waves decreases [21]. This phenomenon can be used for the explanation of the dependence presented in Fig. 3,*a*. Under the experimental conditions for $f_m=$ 560 MHz and $f_{ce}=$ 372 MHz, the concentration of plasma on the surface that bounds the region of existence of Bernstein waves amounts to $n = 2{\cdot}10^9$ cm^{-3}, and this surface is located near the anode surface.

The attenuation of Bernstein waves along the magnetic field is very strong close to cyclotron harmonics ($f_m = Nf_{ce}$), and oblique Bernstein waves are not observed in this case [21]. They can be observed only if f_m/f_m represents a half-integer number, and the attenuation is relatively weak [21]. The amplitude-frequency oscillation spectrum obtained in the experiment (Fig. 4) agrees well with this statement: the maximal intensity of oscillations is reached at a frequency equal to $\frac{3}{2}f_{ce}$ to within 1%.

The above consideration indicates that, in all respects, the observed effect represents a result of the excitation of Bernstein waves together with upper hybrid waves at the same frequency in a plasma system with a wave barrier for upper hybrid and electromagnetic waves. It is Bernstein waves that penetrate into the barrier and go through it to plasma beyond the barrier.

The performed investigations testify that Bernstein waves can play the role of waves-transporters in the mechanisms of quasitransparency and information transparency of wave barriers in inhomogeneous magnetoactive plasma. As is known, the first stage of these mechanisms lies in the transformation of waves in prebarrier plasma into waves-transporters, for which the barrier doesn't exists. The transformation of electromagnetic waves into Bernstein ones wasn't yet investigated, but, as was noted in work [20], some experimental results testify to its existence: Bernstein waves were excited in plasma with the help of external electromagnetic radiators.

The third stage of the mechanism characteristic of the quasitransparency of barriers is the inverse first stage. Bernstein waves excited in plasma were again registered in the experiments with the help of external receivers of electromagnetic waves, which is possible only in the case of the transformation of Bernstein waves to the electromagnetic ones.

As for the second stage — the propagation of waves-transporters in the barrier and through it — the earlier and these investigations evidence for that Bernstein waves can behave in this way with a barrier being oriented both normally to the magnetic field and in parallel to it.

The essential advantage of Bernstein waves over other waves-transporters lies in the absence of any limitation on the barrier height f_p/f_m in the frequency range $f_{ce} < f_m < 2f_{ce}$.

If we consider, like [8], that the excitation of Bernstein waves with a probe-vibrator in the experimental system simulates their excitation by an electromagnetic wave, the given investigations actually discover the information transparency of a barrier for the electromagnetic waves with participation of Bernstein waves. As for the quasitransparency of a barrier for an electromagnetic wave, the appearance of this effect in the system, where the electromagnetic wave can exist, raises no doubts.

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КВАЗІПРОЗОРІСТЬ ТА ІНФОРМАЦІЙНА ПРОЗОРІСТЬ ХВИЛЬОВИХ БАР'ЄРІВ У МАГНІТОАКТИВНІЙ НЕОДНОРІДНІЙ ПЛАЗМІ ПРИ ЗБУДЖЕННІ У НІЙ ХВИЛЬ БЕРНШТЕЙНА

Л.І. Романюк

Р е з ю м е

У процесі експериментальних досліджень квазіпрозорості хвильового бар'єра у неоднорідній слабкозамагніченій плазмі для хвиль, що належать до верхньогібридної дисперсійної вітки коливань, було виявлено в певному частотному діапазоні аномальне проникнення коливань у бар'єр та вихід їх у плазму за ним. Дослідження цього ефекту показало, що він зумовлений збудженням і поширенням у плазмовій системі хвиль Бернштейна. Визначено особливості їх реалізації у плазмовій системі. Аналізуються можливості існування механізмів квазіпрозорості та інформаційної прозорості плазмових хвильових бар'єрів за участі хвиль Бернштейна.