Wave-barrier transmission for electron plasma waves in inhomogeneous plasma

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An analysis is given of the spatial characteristics of waves incident on a density barrier in inhomogeneous collisionless plasma, and the waves transmitted by it. It is shown that, in the plasma ahead of the barrier, the reflection of the excited wave from the barrier results in the appearance of a standing wave, and that a highly damped progressive wave is produced in the plasma past the barrier. Data are obtained on the dependence of the longitudinal component of the wave vector on the frequency and plasma density. The type of excited wave is established. The experimental results are in agreement with the idea of wave-barrier transmission by transport of perturbations across the barrier by particles captured by the wave in the pre-barrier plasma.

The first qualitative experimental confirmation of the wave-barrier transmission predicted by Lisitchenko and Oraevskiĭ[1] was reported in[2]. The present paper is devoted to a more detailed investigation of this phenomenon, especially the spatial characteristics of waves incident on the barrier and those transmitted by it.

The experiments were performed with the apparatus illustrated schematically in Fig. 1. The density barrier along the axis of the system was produced by plasma flowing into vacuum chambers I and III from the hot-cathode Penning discharge in chamber III. Chamber II consisted of a hollow cylindrical anode A with internal diameter of 100 mm, and 180 mm long, two straight-channel single-turn tungsten ring cathodes C, 40 mm in diameter, and two molybdenum reflectors R_1 and R_2 with central apertures, 20 mm in diameter. The distance between the reflectors (length of discharge) was 230 mm. A thin dielectric shield S (quartz disk, 25 mm in diameter and 0.2 mm thick) was introduced at right-angles to the axis of the system in the central plane of the discharge chamber. This was used to prevent direct entry of electrons from region I into region III.[2] Vacuum chambers I and III, which were penetrated by plasma through the apertures in the reflectors, were in the form of copper tubes with an internal diameter of 100 mm and length of 450 mm.

The working gas (argon) was supplied to chamber II, and the system was pumped through chambers I and III. Under working conditions, the pressure in the last two chambers was lower by almost an order of magnitude than in the discharge chamber. The entire system was placed in a magnetic field which was uniform to within 2%. The measurements were carried out when the discharge became time-independent. The results reported below were obtained (unless otherwise indicated) with the following discharge parameters: discharge current I_a = 0.4 A, voltage across the discharge V_a = 80 V, magnetic field H = 70 Oe, and argon pressure in the discharge chamber $p = 1.7 \times 10^{-4}$ Torr.

The excitation of waves in the plasma filling chamber I was achieved by applying the output of an hf generator to the vibrator probe V. This probe was displaced to a distance r = 10 mm from the axis of the system and could be moved along the entire chamber I. The amplitude of the hf signal applied to the vibrator probe was 0.5–4 V and the frequency was varied between 19 and 35 MHz.

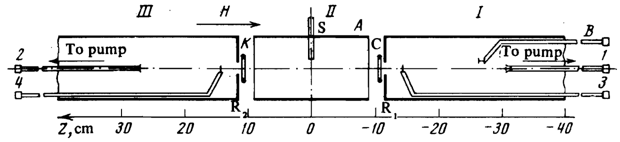

FIG. 1. Schematic diagram of the apparatus.

The main parameters of the barrier produced in the system, i.e., the axial distribution of plasma density and potential, were determined by two movable planar probes 1 and 2 equipped with guard rings. The axial distributions of the saturation ion current recorded by the probe and the potential of the floating probe were measured directly. Taking into account the relatively slow variation of the electron temperature along the axis of the system,[3] the axial profile of the floating-probe potential can be looked upon, to within a constant component, as equivalent to the true plasma potential. The plasma-density distribution along the axis of the system was determined from axial profiles of the saturation ion current to the probe, taking into account the acceleration of the ions in the penetrating plasma.[4]

The high-frequency oscillations in the plasma were investigated using six insulated high-frequency probes 3 and 4. The amplitude of the oscillations in the probe circuit was measured with a selective microvoltmeter, and the spectrum of the oscillations excited in the plasma was monitored with a panoramic frequency analyzer. The spatial variation in the phase of the recorded oscillations was determined from the change in the shift between the working and reference signals on the screen of a two-beam stroboscopic oscilloscope during the displacement of the probe. The reference signal was the signal applied to the vibrator probe.

The axial profiles of the saturation ion current to the probe, the floating-probe potentials, and the amplitude of the high-frequency oscillations were recorded with xy penrecorders. Figure 2 shows typical axial profiles of the plasma density and floating probe potential in the system. As can be seen, the density barrier is symmetric and characterized by a relatively sharp front and back. The plasma density in regions I and III is lower by roughly three orders of magnitude than the plasma density in the discharge region II. The axial profile of the potential is generally similar to the density profile, and the potential drop at the edges of

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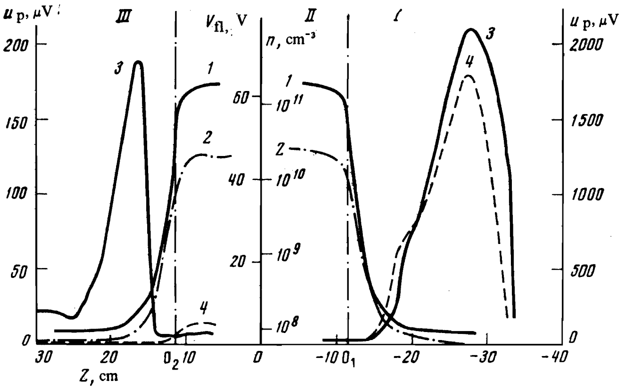

FIG. 2. Axial distribution of the plasma density (1), floating-probe potential (2), and amplitude of hf oscillations (3, 4); f = 19 MHz.

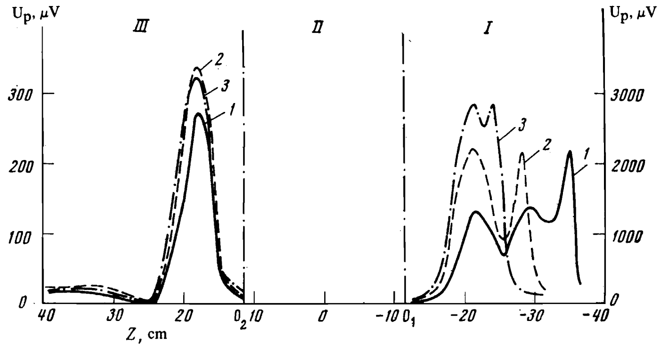

FIG. 3. Axial distributions of the amplitude of hf oscillations; 1 – Z_e = –35 cm; 2–Z_e = –28 cm; 3–Z_e = –24 cm; f = 28 MHz.

the barrier is much greater than kT_e/e in the discharge plasma and in the penetrating plasma ($kT_e/e \approx 4$ V). The appearance of this voltage drop unambiguously indicates that a beam of fast primary electrons penetrates the plasma.[4,5]

The spectrum of oscillations excited in regions I and III consists of a single peak at the excitation frequency. The oscillations are practically monochromatic. The half-width of the peak does not exceed 20 kHz, i.e., 0.1% of the frequency at the maximum. Typical axial distributions of the amplitude of the hf signal received by the probe in regions I and III are also shown in Fig. 2 (curve 3). As can be seen, the oscillation amplitude maximum in the first region is localized within an interval in which the density and plasma potential undergo a slow variation. The oscillation amplitude decreases relatively rapidly as the foot of the concentration barrier is approached, and is very small inside the barrier (region II), where the signal is of the order of the intrinsic plasma noise. In the plasma after the barrier, there is always a very sharp increase in the oscillation amplitude directly at the foot of the barrier and this is followed by a more gradual fall in the region where the plasma density undergoes a slow variation. The intensity of oscillations in regions I and III decreases relatively rapidly with radial distance from the axis of the system. The half-width of the radial amplitude profile is 2–4 cm.

The introduction of the dielectric disk into region II, which prevents the direct entry of electrons into regions I and II, has little effect on the axial profile of the oscillations in the pre-barrier plasma and leads to practically complete disappearance of oscillations throughout the plasma behind the barrier (curve 4 in Fig. 2). This is in complete agreement with measurements in given cross sections of the plasma column[2] and provides a more reliable confirmation of the mechanism put forward in[1] for the transmission through the wave barrier, namely, transport by particles captured by the wave.

Experiment has shown that the intensity of oscillations in regions I and III increases linearly when the amplitude of the high-frequency signal applied to the exciting probe increases from 0.5 to 4 V. The form of the axial profile of the oscillation intensity is unaffected by this. Most of the experiments in the present research were performed with u_b = 0.5 V.

The axial profiles of the oscillation amplitude shown in Fig. 3 for three longitudinal coordinates Z_e of the exciting probe demonstrate the effect of increasing distance from the barrier on the spatial distribution of the oscillation intensity in the system. Depending on the position of the exciting probe, the axial profile of the oscillation intensity in the plasma in region I has two or three peaks. It is important to note that the maximum recorded for $Z = Z_e$ is unrelated to the phenomenon which we are discussing: it is due to the capacitive coupling between the measuring probe and the exciting probe, and is present even in the absence of plasma in the system.

The displacement of the exciting probe does not affect the position of the maxima in the oscillation intensity excited in the plasma. However, as the exciting probe approaches the density barrier, there is a gradual removal of part of the axial distribution, since the oscillations behind the exciting probe ($|Z| > |Z_e|$) practically disappear. At the same time, the oscillation intensity at the peak nearest to the barrier is found to fall. There is also the striking fact that the axial intensity profile in the plasma behind the barrier (region III) and the position and size of the maximum are practically independent of the position of the exciting probe. All this is valid so long as Z_e is not equal to the coordinate of the intensity peak nearest to the barrier. Further displacement of the exciting probe in the direction of the barrier is associated with a reduction in the oscillation intensity excited in regions I and III. When the exciting probe penetrates the density barrier, the oscillations are found to disappear throughout the system.

The appearance of a number of peaks in the axial profile of the oscillation amplitude in the pre-barrier plasma may be an indication of the presence of a standing wave in this region. The formation of this wave is possible because of the reflection of the excited wave by the density barrier. The presence of the standing wave in region I is confirmed by direct phase measurements. It was found that, within the limits of the intensity maximum in region I, the phase of the oscillations remains practically constant, but outside these limits it falls rapidly. When there are two maxima on the intensity curve, the phase change between the maxima is roughly 180°. Outside the maxima and between them the phase of the oscillations varies rapidly, but not discontinuously, and this suggests a superposition of a standing and a traveling wave in this region. In the plasma behind the barrier, we always observe only one intensity maximum and a linear variation of phase throughout the region in which the oscillations exist. This enables us

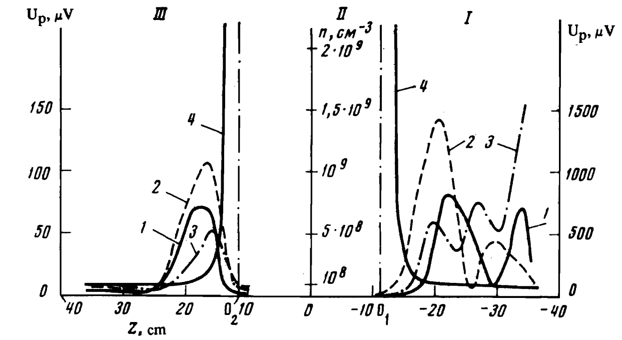

FIG. 4. Axial distributions of the amplitude of hf oscillations (1–3) and plasma density (4). $Z_e = -34$ cm; 1– f = 19 MHz; 2–f = 24 MHz; 3– f = 32 MHz.

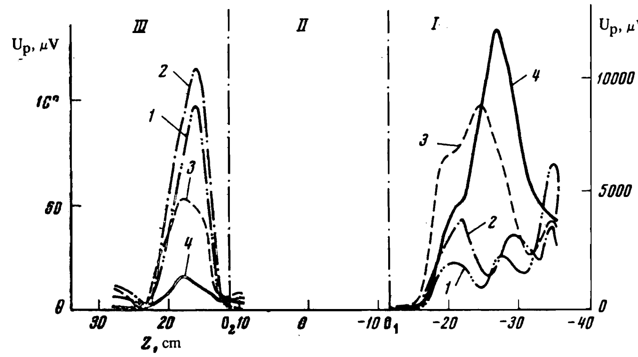

FIG. 6. Axial distributions of the amplitude of hf oscillations: 1–I_a = 0.3, n = 9.7 × 10^7 cm^{-3}; 2–I_a = 0.4 A, n = 1.3 × 10^8 cm^{-3}; 3–I_a = 0.8 A, n = 2.1 × 10^8 cm^{-3}; 4–I_a = 1 A, n = 2.9 × 10^8 cm^{-3}; $Z_e = -34$ cm; f = 28 MHz.

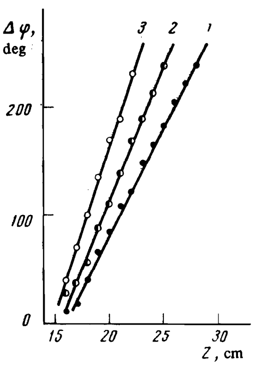

FIG. 5. Axial variation in the phase change in region III: 1–f = 19 MHz; 2–f = 24 MHz; 3–f = 32 MHz.

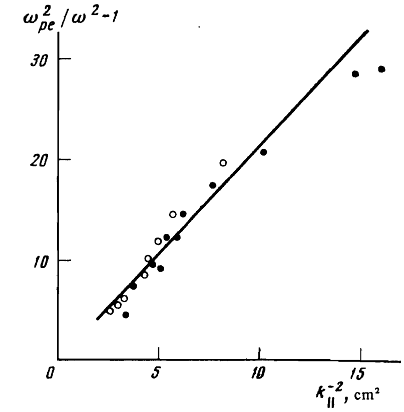

FIG. 7. The function $\omega_{pe}^2/\omega^2 - 1 = F(k_\parallel^{-2})$: •–region I; ○–region III.

to conclude that a rapidly attenuating wave, which travels in the Z direction, is produced in region III.

The axial dependence of the oscillation intensity in region I and the phases of the oscillations in region III were used to determine the longitudinal wavelength $\lambda_\parallel$ and the component $k_\parallel$ of the wave vector during excitation of waves with different frequencies. An example of this is shown in Figs. 4 and 5. These figures show that, as the frequency $k_\parallel$ increases, the intensity of oscillations in the regions I and III pass through a maximum. Moreover, the intensity maximum in region III undergoes a slight shift toward denser plasma with increasing frequency.

Analysis of the axial plasma density profiles obtained for different discharge currents shows that both inside and outside the barrier the plasma density increases roughly linearly with the discharge current. This is accompanied by a change in both the longitudinal wavelength and the oscillation intensity in the system. The data shown in Fig. 6 may serve as an illustration of this (plasma density is given for Z = 25 cm). They show unambiguously that there is an increase in the longitudinal wavelength in region I as the plasma density increases. An analogous conclusion follows from phase measurements in region III. We note that the character of the variation in the oscillation intensity before and after the barrier is different. Whilst the oscillation amplitude in region I always increases with the discharge current, in region III it passes through a maximum and then falls rapidly.

It is suggested in[2] that the waves excited in regions I and III grow at the frequencies of the electron plasma oscillations. Since, in these regions we have $\omega_{pe}^2 \ll \omega_{Be}^2$ (ω_{pe}, ω_{Be} is the electron Langmuir and cyclotron frequency), the absorbed oscillations may be associated with the branch (see[6])

$$\omega=\omega_{pe}\cos\theta, \qquad (1)$$

where

$$\cos\theta=k_\parallel/k, \quad k^2=k_\parallel^2+k_\perp^2.$$

Measurements of n and $k_\parallel$ in plasma before and after the barrier for different I_a and f_b enable us to construct the function

$$\omega_{pe}^2/\omega^2-1=F(k_\parallel^{-2}),$$

shown in Fig. 7. The experimental points lie with adequate accuracy on the straight line calculated from (1) on the assumption that $k_\perp$ is a constant equal to 1.5 cm^{-1}.

We have thus established both the spatial characteristics and the types of waves incident on the density barrier and those transmitted by it. We have shown that the resulting functions are in agreement with existing ideas on the mechanism responsible for the penetration of the wave barrier. Data have been obtained indicating that the transmission of the barrier (ratio of amplitudes in regions III and I) depends both on the barrier parameters and on the frequency of the excited waves. This is probably connected with the properties of the velocity spectrum of electrons in the penetrating plasma and the conditions of capture of particles by the wave. These topics will be the subject of further experiments.

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[1]V. V. Lisitchenko and V. N. Oraevskiĭ, Dokl. Akad. Nauk SSSR **201**, 1319 (1971) [Sov. Phys.-Dokl. 16, 1074 (1972)].
[2]V. N. Oraevskiĭ, L. I. Romanyuk, N. E. Svavil'nyĭ, and V. V. Ustalov, ZhETF Pis'ma Red. 17, 288 (1973) [JETP Lett. **17**, 207 (1973)].
[3]M. D. Gabovich, L. L. Pasechnik, and L. I. Romanyuk, Zh. Tekh. Fiz. 31, 87 (1961) [Sov. Phys.-Tekh. Phys. **6**, 61 (1961)].
[4]M. D. Gabovich, L. I. Romanyuk, and E. A. Lozovaya, Zh. Tekh. Fiz. **34**, 488 (1964) [Sov. Phys.-Tekh. Phys. 9, 380 (1964)].
[5]M. D. Gabovich, L. I. Romanyuk, and E. A. Lozovaya, Zh. Tekh. Fiz. 35, 94 (1965) [Sov. Phys.-Tekh. Phys. 10, 70 (1965)].
[6]A. B. Mikhaĭlovskiĭ, Teoriya plazmennykh neustoĭchivosteĭ (Theory of Plasma Instabilities), Vol. I. Chap. 8, Atomizdat, 1970.

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