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## Abstract

## Full Text

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**PHYSICS**

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# EXPERIMENTAL INVESTIGATION OF LOW-FREQUENCY OSCILLATIONS IN A BOUNDED LOW-PRESSURE PLASMA PLACED IN A MAGNETIC FIELD

*(Presented by Academician M. A. Leontovich on 23 IX 1969)*

In a number of works ($^{1}$-$^{3}$) a substantial influence of boundaries perpendicular to the magnetic field on the excitation of low-frequency oscillations in a low-pressure plasma has been established experimentally. This is manifested above all in the fact that oscillations usually arise under conditions in which the plasma is charged positively with respect to the end electrodes. A number of theoretical works ($^{4}$-$^{6}$), differing substantially from one another, may be invoked to explain this fact. In Chen' s works ($^{4}$) it was shown that, in the presence of an electron layer at the end, drift oscillations "short-circuit" and the instability cannot develop, whereas an ion layer, with its low electrical conductivity, practically insulates the plasma from the conducting ends, as a result of which the development of oscillations with wavelengths substantially exceeding the longitudinal dimension of the system becomes possible. On the other hand, in ($^{5}$) it is shown that braking of electrons in the near-electrode layer, playing the role of dissipation, may lead to the buildup of a number of drift-type instabilities even in the absence of dissipation in the volume.

As in ($^{4}$), so also in ($^{5}$), the motion of ions was not taken into account. However, acceleration of ions as they are carried to the end (which requires the same sign of potential), as follows from ($^{6}$), may also lead to excitation of low-frequency oscillations, called by the author longitudinal ambipolar sound. In this case, in contrast to ($^{4}$, $^{5}$), not only the excitation conditions, but also the oscillation frequency itself proves to depend substantially on the potential difference between the plasma and the end electrode.

Figure 2

Figure 2: Figure 2

**Fig. 1.** Schematic drawing of the experimental apparatus. **K** –plane rectangular cathode, **D** –diaphragm, **A** –copper cylinder, **T** –end electrode.

On the basis of an analysis of the available experimental data it is difficult to give preference to any one of the theories. In this connection it seemed advisable to us to carry out an investigation of the excitation of low-frequency oscillations in a bounded plasma under controlled variation of the conditions at the ends.

A schematic drawing of the experimental apparatus is shown in Fig. 1. The discharge was produced by a heated cathode **K** and a copper cylinder **A** (44 cm long and with an internal diameter of 4.5 cm). The diameter of the stream of primary electrons was limited by a diaphragm connected with the cathode and having an internal diameter of 2.7 cm. To obtain a maximally homogeneous stream

electrons, a straight-channel cathode made of a tungsten strip 3 cm wide was used.

The metal end face $T$ of the discharge chamber, opposite the cathode, was insulated from cylinder $A$, which made it possible to vary its potential independently of the discharge conditions. In our experiments this potential did not exceed $\pm 35$ V relative to the grounded cylinder $A$, i.e., for primary electrons, whose energy is $\sim 300$ eV, the end electrode remained the anode in all regimes.

The discharge chamber was placed in a uniform magnetic field of strength up to 2000 Oe, directed along its axis. The pressure of the working gas (helium) was usually $(1 \div 5) \cdot 10^{-3}$ mm Hg; the electron temperature was $T_e \sim 3$ eV. The plasma density was varied within $5 \cdot 10^{9}$–$5 \cdot 10^{10}$ cm$^{-3}$ by changing the discharge current.

**Fig. 2.** Change in the plasma potential and the amplitude of the excited oscillations as a function of the end-electrode potential at $P = 6 \cdot 10^{-3}$ mm Hg, $H = 600$ Oe, helium gas.
1 –plasma potential $U_{\text{pl}}$, measured by a probe with $z_3 = 5$ cm, $r_3 = 0.7$ cm;
2 –$\Delta U = (U_{\text{pl}} - U_t)$ –potential difference between the plasma and the end electrode;
3 –oscillation amplitude in relative units.

To measure the plasma parameters and record oscillations, a system of single Langmuir probes (diameter 0.007 cm and length 0.7 cm) was introduced into the discharge chamber; the probes were oriented perpendicular to the magnetic field and located at various distances from the axis ($r_3$) and from the end electrode ($z_3$). The particle flux to the wall was monitored with a flat wall probe of diameter 0.4 cm, located in the central part of cylinder $A$, flush with the wall. By feeding signals from two probes, separated along the length or in azimuth,

Figure 3

Figure 3: Figure 3

to a two-beam oscilloscope, it was possible to study the spatial distribution of the oscillations. For spectral analysis of the oscillations that arose, instruments V6-2, S4-12, and S5-2 were used.

Under the conditions of our experiment it turned out that the principal factor affecting the stability of the plasma is the end-face potential. As can be seen from Fig. 2, when this potential $U_t$ is lowered, beginning at $U_t \simeq -10$ V, oscillations arise in the plasma, whose intensity increases rapidly as $U_t$ is decreased. The frequency of these oscillations is $\sim$ 10–20 kHz. The oscillations are perturbations of the density of the plasma particles, with the depth of density modulation reaching 20–30% at a sufficiently negative end-face potential (according to measurements with a probe at $r_3 = 1.2$ cm and $z_3 = 15$ cm). As the oscillation intensity increases, an increase in the flux of charges to the wall probe is observed.

**Fig. 3.** Oscillations of the electron current to probes shifted by 180° in azimuth ($z_3 = 10$ cm, $r_3 = 1.2$ cm).

A study of the spatial correlation of the signals to probes shifted in azimuth shows the presence of rotation of the density wave in the direction of the cyclotron rotation of the electrons, with azimuthal mode $m = 1$ (Fig. 3 shows an oscillogram of the oscillations at probes shifted by 180°). Probes separated along the length of the apparatus along a generatrix of the cylinder do not show a phase shift, which indicates that in

in the longitudinal direction no more than a half-wavelength fits. In contrast to ($^7$), no shorter-wavelength modes are observed when the magnetic field is varied. When the pressure is increased above $\sim 10^{-2}$ mm, oscillations of this type are not detected. It is characteristic that the frequency of the oscillations that arise is practically independent of the magnetic-field strength, the gas pressure, and the plasma density, but depends very substantially on $U_\tau$. A change in the potential $U_\tau$, as probe measurements show, affects practically only the plasma potential; the electron temperature and density remain practically unchanged. Figure 2 shows the dependence of the space potential for a probe with $z_3 = 5$ cm and $r_3 = 0.7$ cm, obtained from processing the electron branches of the probe characteristics (curve 1). Curve 2 gives the potential difference between the plasma and the end electrode, calculated from the same measurements,

$$\Delta U = U_{\text{pl}} - U_\tau .$$

It is interesting that over the entire range of variation $\Delta U > 0$, even for positive $U_\tau$, there is no regime in which, according to ($^4$), the instability cannot be excited. Nevertheless, oscillations arise only at negative values of $U_\tau$, for which

Fig. 4

Figure 4: Fig. 4

the plasma potential approaches the potential of the side walls and becomes negative with respect to them.

**Fig. 4.** Dependence of the oscillation frequency on the potential difference between the plasma and the end electrode (the continuous straight line is calculated, the points are experimental). Helium, $P = 6 \cdot 10^{-3}$ mm Hg, $H = 600$ Oe.

For $U_{\text{pl}} < 0$, excitation of the instability considered in ($^8$) is possible. However, the totality of other experimental facts cannot be explained within the framework of this theory. Indeed, as is seen from Fig. 2, at $U_\tau \lesssim 12$ V the plasma potential (and consequently the radial field as well) already practically does not change with $U_\tau$, and according to ($^8$) there should be no dependence of the oscillation frequency on $U_\tau$, which contradicts our experimental data. On the other hand, changing the magnetic field does not lead to a noticeable change in frequency.

In our opinion, the most satisfactory explanation of the experimental results obtained can be given on the basis of the theory ($^6$), which relates excitation of oscillations to the removal of ions in a longitudinal electric field. The fact that the oscillations arise at plasma potentials $U_{\text{pl}} \lesssim 0$ can be associated with a slowing of the radial loss of ions and an increase in the role of their longitudinal motion.

The most convincing proof of the applicability of ($^6$) to the interpretation of our results is the dependence of the oscillation frequency $f$ on the potential of the end electrode. Taking into account that in our case the role of the ambipolar potential $\varphi_0$ that accelerates the ions is played by the quantity $\Delta U$, the expression for the frequency according to ($^6$) can be written in the form:

$$f = \frac{p}{\pi L}\sqrt{\frac{2e\Delta U}{M}}, \tag{1}$$

where $p$ is the longitudinal mode of the oscillations, $e$ is the electron charge, $L$ is the length of the apparatus, and $M$ is the ion mass.

Figure 4 presents the calculated dependence of $f$ on $\sqrt{\Delta U}$ for oscillations with $p = 1/2$ in helium for our apparatus. The experimentally measured frequency values are indicated by points. As can be seen, both the character of the dependence and the absolute values of the frequencies for calculation and experiment turn out to be close. Similar measurements performed for neon give, at the same discharge currents and pressures, an oscillation frequency approximately half as large as for helium, with a similar dependence on $\Delta U$, which is in complete agreement with (1).

Let us note that the experimentally measured distribution of the potential along the length of the apparatus differs substantially from the parabolic distribution adopted in (6). Under our conditions, the main part of the voltage $\Delta U$ falls at the end electrode, while the change of potential along the plasma column does not exceed $1 \div 2$ V. Nevertheless, the good numerical agreement of the measured values of the oscillation frequency with the calculation by formula (1) indicates that the determining factor here is apparently the finite energy acquired by the ions.

The criterion for excitation of the instability, obtained in (6), can for our case be rewritten in the form:

$$\sqrt{\frac{2e\Delta U}{M}} > \frac{T_e}{2.6M}\,\frac{m}{p}\,\frac{L}{r_0}\,\frac{|\chi|}{\omega_{iH}}, \tag{2}$$

where $T_e$ is the electron temperature; $m$ is the number of the azimuthal mode; $r_0$ is the plasma radius; $\chi = \partial \ln n/\partial r$ is a quantity characterizing the radial density drop; $\omega_{iH}$ is the ion-cyclotron frequency.

An exact identification of the excitation threshold with the value given by (2) is difficult in our case because of the uncertainty in the value of $\chi$ (the radial density drop differs substantially from an exponential one). However, if one chooses $\chi = 1/r_0$, then for $m = 1$, $p = 1/2$, values of $\Delta U$ close to those observed in the experiment are obtained.

Thus, the results obtained can be satisfactorily explained on the basis of the theory (6). This fact, in our opinion, indicates the necessity of taking into account the longitudinal motion of ions when considering the stability of low-pressure plasma in systems bounded in length.

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