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RESONANCE PHENOMENA IN AN ALKALI PLASMA SITUATED IN AN ALTERNATING ELECTRIC FIELD

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We investigated the behavior of a highly ionized thermal cesium plasma in which a longitudinal high-frequency current flowed. It was observed that in the frequency interval $\Omega_0 \sim \omega_{pe} k_z/k$ the high-frequency power is effectively absorbed in the plasma. The observed plasma heating is interpreted as a manifestation of parametric resonance in a magnetized plasma.

In earlier experiments[1,2] it was observed that in sufficiently strong high-frequency (HF) electric fields the electron temperature increases appreciably as a result of collisionless dissipation of the field energy. In order to clarify the heating mechanism, experiments were performed aimed at investigating the dependence of the heating efficiency on the frequency of the alternating current.

The experiments were performed with a setup constituting a unilateral Q machine (Fig. 1). We investigated a cesium plasma with the following parameters: pinch radius a = 1 cm, pinch length L = 25 cm, plasma density $n \sim 10^8$–10^9 cm^{-3}, initial plasma temperature $T_e \sim T_i \sim 0.2$ eV, degree of ionization $\eta \sim 20$–30%, longitudinal homogeneous magnetic field H_0 of intensity $(2-5) \times 10^3$ Oe. The plasma was produced in a niobium ionizer heated to 2000°K and, propagating along a magnetic field without collisions ($\lambda_{ei} > L$), recombined on a cold plate placed at a distance L from the ionizer.

We investigated the behavior of such a plasma through which a longitudinal high-frequency current flows. The frequencies of the alternating electric field could vary in the ranges 10^5 Hz $< f_0 < 3 \times 10^7$ Hz, 1.5×10^8 Hz $< f_0 < 10^9$ Hz, and $f_0 \approx 3 \times 10^9$ Hz. The high-frequency voltage was applied directly to the electrodes that bounded the plasma pinch at its ends. In the region of microwave frequencies $f_0 \approx 3 \times 10^9$ Hz, the wave applied to the plasma was the TM_{010} mode excited in a microwave resonator. All the measurements were performed in the continuous regime.

The measured dependence of the electron temperature on the frequency of the external field at a constant high-frequency amplitude of the voltage (V = 5 V) is shown in Fig. 2. The experimental data were obtained by the method of the double Langmuir probe and were averaged over many measurements. They show that the

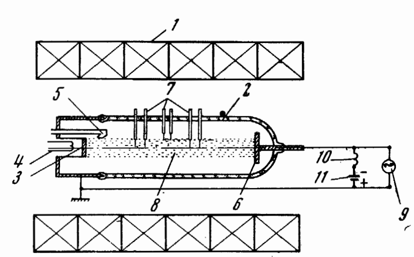

FIG. 1. Experimental setup: 1—solenoid; 2—glass chamber; 3—ionizer; 4—heater; 5—sputterer; 6—collector; 7—Langmuir probes; 8—plasma pinch; 9—HF generator; 10—inductance; 11—bias battery.

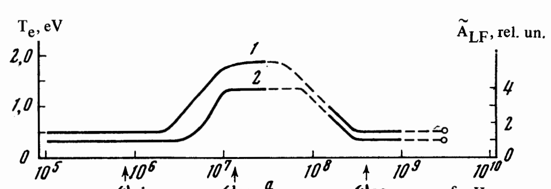

FIG. 2. Dependence of the electron temperature (curve 1) and of the amplitude of the LF oscillations (curve 2) of the plasma on the frequency of the applied electric field. Solid curves—average experimental data; dashed—extrapolation to the uninvestigated frequency region; points—experimental data at the frequency 3×10^9 Hz.

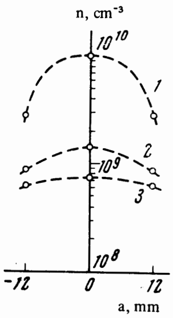

FIG. 3. Plasma density profile: curve 1—V = 0; 2—V = 5 V, f_0 = 2 MHz; 3—V = 5 V, f_0 = 9.7 MHz.

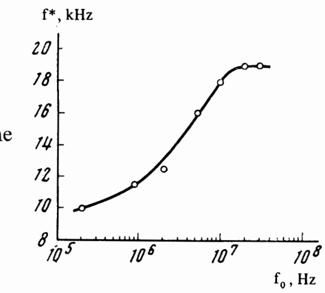

FIG. 5. Dependence of the frequency of the drift oscillations on the frequency of the electric voltage applied to the plasma (V = 5 V).

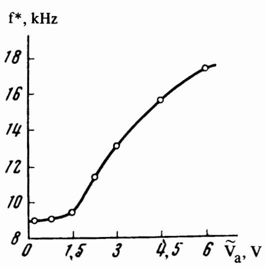

FIG. 4. Dependence of the drift-wave frequency on the amplitude of the applied HF voltage (f_0 = 6 MHz).

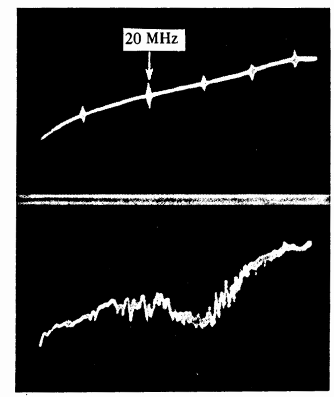

FIG. 6. Oscillograms illustrating the resonant "boost" of the HF voltage on the working circuit. The upper oscillogram was obtained in the absence of a plasma and the lower when the measuring volume was filled with a plasma having a density 2 × 10^9 cm^{-3}. Plasma radius a = 0.5 cm, length L = 25 cm. Frequency variation range 18-23 MHz.

strongest reaction of the plasma to the external field is observed in the frequency range $f_0 \sim$ 5—30 MHz. The electron temperature of the Q-machine plasma increases in this case to 2 eV. With changing temperature, the plasma density in the pinch decreases and the radial profile of the density broadens (Fig. 3).

The plasma heating is accompanied by excitation of intense high-frequency density oscillations. The fundamental harmonic of these oscillations is in the 1—5 kHz band. The amplitude of the low-frequency oscillations is shown on curve 2 of Fig. 2.

Measurements performed in the microwave band ($f_0 \approx 3 \times 10^9$ Hz) have shown that at field intensities E ~ 200 V/cm the parameters changed insignificantly, namely, the electron temperature did not exceed 0.5 eV, and the plasma density decreased by not more than 20—30% (Fig. 2, experimental points). It was also observed that in the frequency band 5—30 MHz there are strong changes in the amplitude and in the frequency of the drift potential oscillations of the plasma. These oscillations also exist in the plasma in the absence of a high-frequency current, and are localized on the periphery of the pinch; the frequency of the first harmonic of the oscillations lies in the 8—12 kHz band and varies in inverse proportion to the intensity of the magnetic field. When a high-frequency field is applied to the plasma, the amplitudes of the drift oscillations decrease and their frequencies increase.

The dependence of the frequency of the drift waves on an applied voltage having a frequency f_0 = 6 MHz is shown in Fig. 4. Since the frequency of the drift waves is proportional to the electron temperature:

$$\omega^* = k_y \frac{cT_e}{eH} \frac{\nabla n}{n}, \tag{1}$$

it follows that the observed increase of the frequency of the drift oscillations in the plasma during the flow of a high-frequency current can be related to the increase of the electron temperatures. It should be noted that the dependences of the drift-oscillation frequency (Fig. 5) and of the electron temperature (Fig. 2) on the frequency of the external high-frequency field were qualitatively the same.

Finally, a direct indication of the absorption of the high-frequency power in the resonance region is the selective change of the high-frequency voltage on the electrodes, a change connected with a decrease of the Q of the circuit. In these experiments, the high-frequency voltage was applied to the plasma from a standard meter of the frequency characteristic, the output voltage of which was maintained close to constant (V ≈ 4 V) while the frequency was varied in the range 1—25 MHz. When the measuring volume was filled with a plasma having a density $n \sim 2 \times 10^9$ cm^{-3}, an appreciable "boost" of the voltage was observed at frequencies 5—25 MHz, with a maximum in the region 20—22 MHz (Fig. 6). The frequency at which the maximum "boost" of the voltage takes place depends on the plasma density and varies approximately in proportion to $n^{1/2}$.

The foregoing experimental data, namely the increase of the plasma temperature, the broadening of the density profile, the excitation of low-frequency oscillations in high-frequency fields with frequency 5—30 MHz, all indicate that the plasma is unstable under these conditions. A satisfactory explanation of the obtained experimental data can be presented on the basis of the theory of parametric resonance in a plasma, as proposed and developed in[3,4]. According to the conclusions of these papers, when the overtone of the external frequency approaches one of the natural frequencies of the plasma, oscillations build up in the plasma with relatively large increments. The natural frequencies of the plasma oscillations in the presence of a magnetic field are given by the expression

$$(\omega_{re}^{\pm})^2 = \tfrac{1}{2}\{\Omega_{ce}^2 + \omega_{pe}^2 \pm [(\Omega_{ce}^2 + \omega_{pe}^2)^2 - 4\Omega_{ce}^2\omega_{pe}^2\cos^2\theta]^{1/2}\}, \quad (2)$$

where the notation is standard and θ is the angle between the magnetic field and the wave vector **k**. Under the conditions of the described experiment $\Omega_{ce} \gg \omega_{pe}$, and the expression for the natural frequencies can be transformed into

$$\omega_{re}^{+} \approx \Omega_{ce}, \quad (3)$$

$$\omega_{re}^{-} \approx \omega_{pe}\cos\theta \approx \omega_{pe}k_z/k. \quad (4)$$

If it is assumed that the fundamental mode of the natural oscillations is determined by the geometry of the system:

$$k_z \sim 2\pi/2L, \quad k_\perp \sim 1/a, \quad k_\perp \gg k_z, \quad (5)$$

then the frequency range 5–30 MHz, in which the unstable state of the plasma is most clearly pronounced, agrees well with the region of the natural frequencies $\omega_{re}^{-} \approx \omega_{pe}k_z/k \approx \omega_{pe}\pi a/L$ (Fig. 2). The appreciable width of the resonance region can be connected with excitation of oscillations in the system with different ratios of the wave numbers k_z and k. The fact that on approaching the frequency ω_{pe} and above it the state of the plasma remains stable is in good agreement with the theory[4], which predicts the largest growth increments of the oscillations when $\omega_{pe}k_z/k \leq \Omega_0 < \omega_{pe}$.

The observed collisionless plasma heating is apparently due to the development of high-frequency plasma waves under conditions of parametric resonance. Therefore near the resonance $\Omega_0 \sim \omega_{pe}k_z/k$ it is necessary to expect an increase of the stationary level of the plasma oscillations, determined by the conditions for their generation by an external high-frequency field and damping by thermal electrons. Experimental investigations of the spectrum of the high-frequency plasma oscillations have shown that under resonance conditions, plasma oscillations are indeed excited with frequencies close to the frequency of the external generator and its overtones. The oscillations were received with the aid of a long single antenna probe located on the axis of the plasma pinch, and were registered with a standard spectrum analyzer (S4-8). Typical plots of the amplitude of the signal received by the probe against the frequency of the external field are shown in Fig. 7. We see that filling of the measuring volume with plasma having a specified density leads to an amplification of the high-frequency signal received by the probe by an amount ~ 10–30 dB.

The frequencies at which the maximum amplification of the signal is observed are determined by the plasma density and lie near the lower electronic plasma frequency (4). This is illustrated in Fig. 8, which shows, in a logarithmic scale, the dependence of the plasma frequency (4) on the plasma density (dashed straight line), while the experimental points correspond to those values of the high-frequency field frequencies and plasma densities at which the amplification coefficient is maximal. The obtained dependences of the oscillation amplitude on the frequency of the high-frequency current and plasma density apparently indicate that they are of plasma origin.

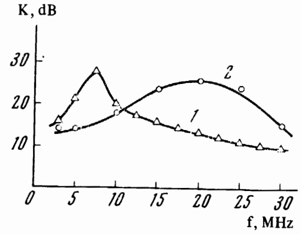

FIG. 7

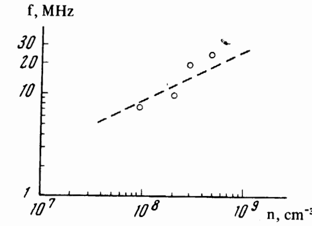

FIG. 8

FIG. 7. Amplitude of HF signal received from plasma against the external-field frequency: curve 1–n = 1 × 10^8 cm^{-3}; 2–n = 3 × 10^8 cm^{-3}.

FIG. 8. Dependence of the lower electron plasma frequency on the plasma density (dashed). Points–frequencies at which the maximum amplitude of the plasma oscillations is observed. Plasma radius a = 0.8 cm, length L = 25 cm.

Thus, the aggregate of the presented data and their analysis allow us to interpret the unstable state of the plasma resulting when a longitudinal current with frequency $\Omega_0 \sim \omega_{pe}k_z/k$ flows through the plasma as parametric resonance in the magnetized plasma. The observed collisionless plasma heating is apparently connected with the dissipation of the registered high-frequency plasma oscillations excited parametrically by the high frequency current.

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