CHARACTERISTICS OF UNSTABLE WAVES IN A WEAKLY IONIZED HIGH-FREQUENCY MAGNETOPLASMA*

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Results of an experimental study of fluctuations of an unstable weakly ionized magnetoplasma with no axial drift is reported. Correlation measurements indicate that the observed waves propagate primarily in the azimuthal direction and that the parametric dependence of the phase velocity on pressure and magnetic field seem to be similar to that expected for a drift wave. The waves appear to be nonlocal in nature, the characteristic azimuthal and radial-mode numbers being unity.

It is well recognized that high-frequency discharges may be used to generate weakly ionized plasmas which are presumably not subject to a dc axial drift of electrons and ions. A number of authors[1-4] have reported the onset of fluctuations and anomalous transport in high-frequency discharges immersed in a magnetic field once the magnetic field exceeds a certain critical value, the critical value depending primarily on the neutral-gas pressure and discharge-tube radius. These experiments have been summarized in a recent review paper[5] where it is shown that the onset criteria obey the same scaling laws though the experiments may differ in geometry, power coupling mechanism, and degree of ionization. On the other hand, the identification of the instability responsible for this phenomenon has not been made to date. Instabilities may be identified by comparing theoretical and experimental onset data and by comparing the theoretical and experimental phase velocities of the density and potential perturbations. Although a great deal of experimental onset data is available[5] for such a comparison, no phase-velocity data exist. With the aid of auto- and cross-correlation techniques we have measured the phase velocity of the plasma-density perturbations traveling in both the axial and azimuthal directions. It is the purpose of this Letter to present the results of such measurements made in an unstable hydrogen discharge. In addition, the radial variation of the fluctuating plasma density is presented. The observed variation appears to be consistent with that of an $n=1$ radial mode.

The experiments described in this paper were carried out in an E-type (capacitively coupled) high-frequency discharge which has been described elsewhere.[1] The resulting fractional ionization is less than 10^{-5}. The ion temperature is approximately 0.04 eV, while the electron temperature lies between 2 and 3 eV. The correlator used in these experiments was a special wideband (near dc to 1 MHz), solid-state analog device designed for this purpose.[6]

The azimuthal phase velocity was determined by measuring the cross-correlation function between fluctuations in ion-saturation current to a reference double probe and a second double probe spaced 30° apart in azimuth. The axial phase velocity was determined by measuring the cross-correlation function between the same reference probe and a third double probe displaced 16.5 cm along the axis of the tube but at the same azimuthal angle as the reference probe.

Figure 1 displays the results of such a measurement which was made in a hydrogen discharge. The double probes were biased into the ion saturation-current region, with the exposed tips being positioned at a distance of $R_p = 2.2$ cm from the tube axis. In this particular case the probe signal was nearly sinusoidal with its frequency spectrum peaking at approximately 115 kHz. The solid circles represent the autocorrelation function $R_{\text{auto}}(\tau)$ of the fluctuations measured at the

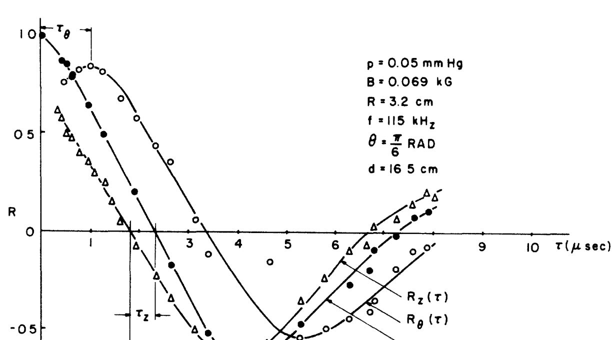

FIG. 1. Experimentally determined auto- and cross-correlation functions.

reference probe. The open circles designate the cross-correlation function $R_\theta(\tau)$ measured between the reference probe and a probe separated by 30° in azimuth. Note that the peak is shifted by $\tau_\theta = 1$ μsec. The triangles represent the cross-correlation function $R_z(\tau)$ measured between the reference probe and a probe spaced a distance $d = 16.5$ cm down the axis of the tube. Its positive maximum would actually occur at some negative time delay or positive time advance. We may estimate this time advance τ_z by comparing the difference in zero crossings of $R_{\text{auto}}(\tau)$ and $R_z(\tau)$. In this case τ_z is approximately 0.5 μsec.

The azimuthal phase velocity of the wave is given by $v_{p\theta} = R_p\theta/\tau_\theta = 1.1$ cm/μsec. The wave travels in the direction of the electron diamagnetic drift. The axial phase velocity is given by $v_{pz} = d/\tau_z = 33$ cm/μsec. In this case the z component of the phase velocity is antiparallel to the magnetic field. Knowing the phase velocities $v_{p\theta}$ and v_{pz} and the radian frequency ω one can estimate the parallel and perpendicular wave numbers $k_\parallel$ and $k_\perp$. For $\omega = 7.2\times10^5$ rad/sec one finds $k_\parallel = -0.022$ cm^{-1} and $k_\perp = 0.62$ cm^{-1}, indicating that the wave is traveling primarily in the azimuthal direction.

The results of a parametric study of the dependence of the measured phase velocity on pressure and magnetic field are given in Fig. 2. In the upper graph of Fig. 2 a plot of the experimentally measured phase velocity $v_{p\theta}$ (onset) versus pressure is shown. The term $v_{p\theta}$ (onset) denotes the value of the azimuthal phase velocity measured as closely as possible to the onset of fluctuations at the critical value of magnetic field for that particular pressure. For reference purposes, Fig. 2 also shows the expected parametric dependence on pressure and magnetic field of two characteristic and possibly relevant velocities, namely, the ion acoustic speed $c_s = (kT_e/M_i)^{1/2}$ and the electron diamagnetic drift speed $v_D = (kT_e/eB) \times |n_0^{-1}(dn_0/dr)|$. Values of the electron temperature and their dependence on magnetic field, pressure, and tube radius were calculated for a diffusion-dominated discharge. The computed values of T_e were found to be consistent with experimental measurements. For the purposes of estimating v_D, the term $|n_0^{-1}(dn_0/dr)|$ was replaced by the reciprocal of the discharge-tube radius, $R^{-1} = 0.285$ cm^{-1}. For low pressures we note that the computed values of v_D and c_s are very close to the measured azimuthal phase velocity. At high pressures v_D and c_s are considerably different in magnitude.

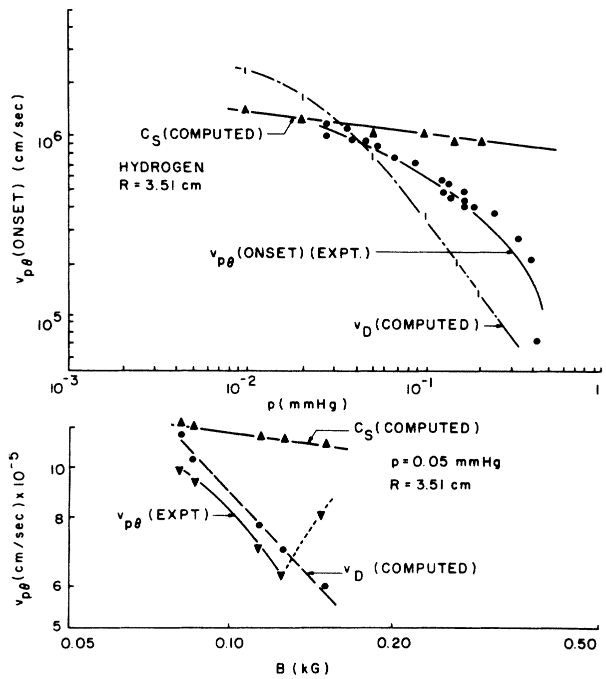

FIG. 2. Parametric dependence of $v_{p\theta}$, v_D, and c_s on the magnetic field B and neutral-gas pressure p.

The lower graph of Fig. 2 indicates the dependence of $v_{p\theta}$ on B for a pressure of 0.05 mm Hg. At this pressure we note, from the upper graph, that $v_{p\theta}$(onset) is very close to both v_D and c_s. However, as the magnetic field is increased beyond the critical field of approximately 0.08 kG, we note that the measured phase velocity exhibits a nearly $1/B$ dependence for magnetic fields less than 0.125 kG. Above this value, the measured phase velocity increases abruptly and was observed to coincide with a sudden increase in the rate of enhanced plasma transport. Since this is a constant current discharge, the loss of plasma must be balanced by an increase in the ionization rate which is brought about through an increase of electron temperature. The abrupt increase of $v_{p\theta}$ for $B > 0.125$ kG may thus be due to this increase in T_e.

The parametric dependence of $v_{p\theta}$ on p and B shown in Fig. 2 appears to resemble that of v_D more closely than that of c_s. This does not necessarily indicate that the observed wave is a "drift" wave or due to a drift instability. Such an identification should not be attempted merely on the basis of the data presented here. Any conclusive identification would necessarily require consideration of the conditions under which the fluctuations onset as well as their phase velocities.

Such a detailed study is beyond the scope of this Letter but will be treated elsewhere in a future paper.

In order to examine the radial characteristics of the wave, we measured both the steady-state and fluctuating components of the ion density as a function of radial position using a movable double probe biased in the ion saturation-current region. The results of such a measurement made in a large-radius (6.25 cm) tube are shown in Fig. 3. The steady-state density on the axis of the discharge was approximately 10^8 cm^{-3}. The amplitude of the fluctuating density is maximum at approximately 3.25 cm from the tube axis. The numbers adjoining the closed circles in Fig. 3 denote the frequency of the fluctuations in kHz as measured by a spectrum analyzer. The amplitude of the fluctuations were weakest near the center of the tube and near the tube wall. The fluctuating portion of the density $\tilde{n}_{max}$ was measured and found to be roughly 30% of the steady-state density $n_0(r=3.25$ cm). Thus the instability appears to be rather highly developed though the magnetic field (37.3 G) is only a few gauss greater than that value at which the onset of fluctuations occurs ($B_c=31$ G). The radial dependence of the fluctuation amplitude clearly shows that the unstable waves are not localized.

From the data of Fig. 1 it is estimated that $k_\perp=0.62$ cm^{-1}. This corresponds to azimuthal wavelength of ≈10 cm. For probe tips located at 2.2 cm, $2\pi R_p \approx 13.8$ cm; thus, the excited mode is very likely an $m=1$ azimuthal mode. The radial dependence of the fluctuation amplitude shown in Fig. 3 demonstrates that the fluctuations are not localized in radius; in fact, Fig. 3 strongly suggests an $n=1$ radial mode.

A detailed comparison of this data with existing theories is outside the scope of this Letter; however, a few brief comments are in order on this point. The conditions necessary for the onset of the ion-acoustic instability described by Timofeev,[7] are satisfied by this experiment. However, it should be emphasized that this theory is valid for planar geometry and localized modes where $k_x \gg |n_0^{-1}\partial n_0/\partial x|$. When applied to cylindrical geometry, this theory predicts instability of higher order modes, i.e., $m^2 \gg n^2 \gg 1$. Since the data presented here strongly suggest a low-order $m=1$, $n=1$, nonlocalized mode, there does not seem to be a firm basis for comparing the data with the localized higher order modes of Timofeev. Instead a nonlocal type of analysis such as that used by Crawford, Ewald, and Self[8] is necessary. For nonlocalized modes such as $m=1$, $n=1$, the nonlocal analysis does not seem to yield a simple relation between the phase velocity and v_D or c_s. It is possible that the experimentally observed parametric dependence of the phase velocity on pressure and magnetic field would come out of such an analysis for the $m=1$, and $n=1$, though this is not entirely evident at this time.

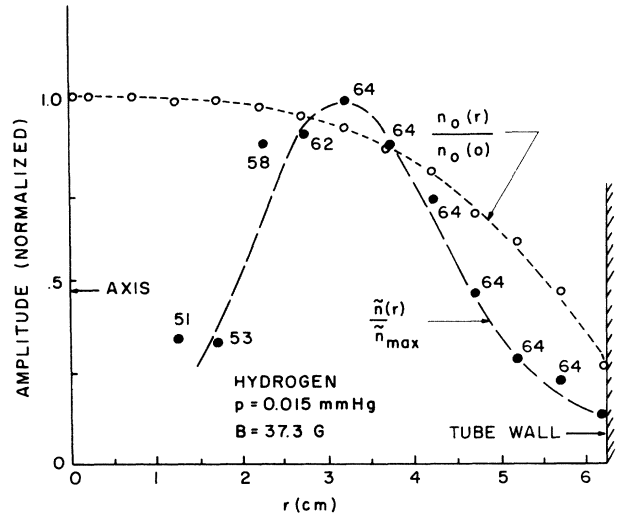

FIG. 3. Measured radial dependence of the fluctuating and steady-state components of the ion density $\tilde{n}$ and n_0, respectively (normalized to their maximum values).

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