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ANOMALOUS RESISTIVITY CAUSED BY CURRENT-DRIVEN ION ACOUSTIC INSTABILITIES

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Ion acoustic wave turbulence has been produced in a current-carrying discharge-tube plasma and electric conductivities of plasmas have been measured as a function of dc electric fields over the range 0.01 to 3 V/cm. Below 0.05 V/cm, the electric conductivity can be interpreted in terms of the collision time between electrons and neutral atoms. Above 0.05V/cm, the conductivity decreases as (electric field)$^{-1}$.

1. Introduction

It has been reported [1] that in the presence of turbulent fluctuations in plasmas, electric conductivities (or resistivities) of the plasma become much smaller (larger) than those calculated by using usual classical collision time [2]. This anomalous électric conductivity begins to be observed when dc electric fields produced in the plasma exceed a certain critical value, which is equal to the Dreicer field in the case of turbulent-heating experiments [1].

As is well-known, for $T_i \ll T_e$ ion acoustic waves are excited [3] when drift velocities of electrons v_d exceed the ion acoustic velocity $C_s=\sqrt{T_e/M}$, where T_i and T_e are the temperature of ions and electrons, respectively, and M is the mass of the ion. As v_d increases above C_s, the excitation of oblique waves becomes possible as well as of those propagation parallel of the drift velocity, and for $v_d \gg C_s$ the cone of permissible directions of the unstable waves opens up, so that the practically all waves having a positive propagation of the phase velocity in the direction of v_d are unstable.

To explane the turbulent spectrum produced by the ion acoustic instability, various models have been proposed theoretically [4][5]. Assuming that the turbulent spectrum of the ion acoustic wave caused by the current-driven ion acoustic instability is determined from the nonlinear Landau damping [4] by the ion, the anomalous conductivity is proportional to $E_0^{-1/2}$ [6], where E_0 is the dc electric field in the plasma. This $E_0^{-1/2}$-variation has been found by many experimentalists [1][7]. In most of the experiments, however, the relation between the anomalous electric conductivity and the fundamental nature of the wave such as the dispersion relation and the spectrum

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has not been measured in detail.

In this paper we report that the anomalous electric conductivity of the plasma caused by the ion acoustic wave turbulence is observed in a current-carrying discharge-tube plasma and decreases in proportion to E_0^{-1}. In Secs. 2 and 3 the experimental arrangement and the experimental results are described, and we summarize them in Sec. 4.

2. Experimental Arrangement

The experiment was performed using a glass discharge tube of 10 cm in diameter as shown in Fig. 1. The central part was constricted in order to increase the ratio of the electron drift velocity to electron thermal velocities in this region. The constriction part was 4.4 cm in diameter. The discharge was operated using Argon gas under pressures of $(0.8\text{-}1.5)\times10^{-3}$ Torr. The maximum discharge current was 1 A. In our experimental conditions, the discharge voltage was nearly constant. The density and the temperature of the plasma electron were measured by using the cylindrical Langmuir probes made of 0.7-mm diam tungsten wire and were found to be homogeneous along the positive column except for the hot cathode side of the constriction. Plasma density was varied in the range from 9×10^{9} to 3×10^{10} cm^{-3} by changing the discharge current, and the electron temperature was in the range of (3-6) eV.

Unstable waves in the plasma were picked up as potential fluctuations by the Langmuir probes and were analyzed by means of both the oscilloscope and the frequency spectrum analyzer. Density fluctuations of the waves were obtained from electron current fluctuations to the probe, biased at potential larger than the space potential. Phase velocities of the wave were measured from the phase difference of oscilloscope signals among the cylindrical Langmuir probes.

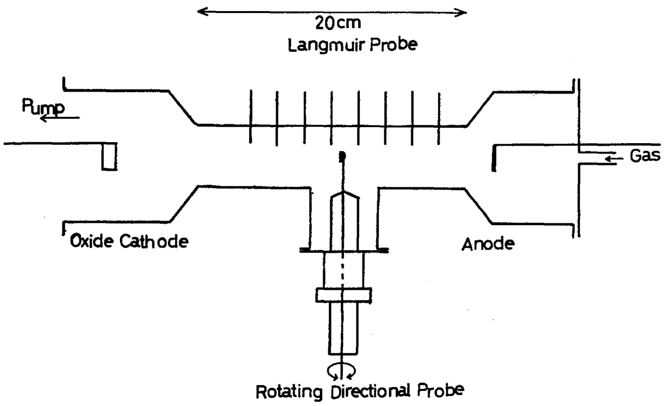

Fig. 1. Schematic diagram of the experimental apparatus.

The dc electric field along the constricted plasma was observed by measuring the space potential of the plasma on each of several Langmuir probes spaced 2 cm apart. A directional rotating probe [18] of 4 mm in diameter at the center of the constricted region was used to obtain the ratio of the electron drift velocity to the thermal velocity. The electric conductivity of the plasma was calculated by dividing the electric current density by the electric field. To take into account the electric current density acculately, the Langmuir probe movable radially was prepared, and the radial distribution of the plasma density was measured. That distribution was found to be a parabola.

3. Experimental Results

The electron drift velocity was measured as a function of the discharge current, I_d, by the rotating Langmuir probe. The ratio v_d/v_e increased with increasing the discharge current, while the thermal velocity of the electron was nearly constant, as shown in Fig. 2. The value v_d/C_s is found to be larger than 20 from Fig. 2, meaning that the unstable condition [3] for the ion acoustic instability is satisfied.

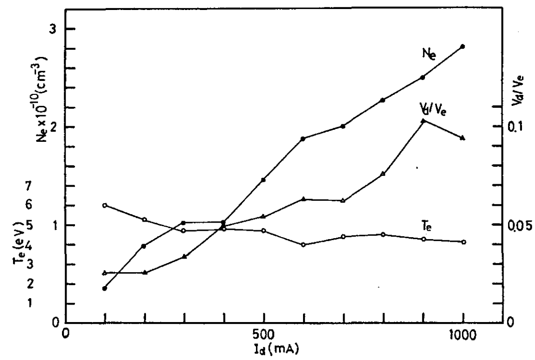

Fig. 2. The electron drift velocity, the ratio v_d/v_e and T_e as a function of the discharge current.

A typical frequency spectrum of the waves observed in the plasma is shown in Fig. 3, which indicates there are a number of higher harmonics of the waves and their intensities decrease monotonically in frequency. We measured the phase velocities of these waves as a function of the discharge current as shown in Fig. 4. When the discharge current was small, the observed phase velocity of the waves was in good agreement with the ion acoustic velocity, C_s. Thus, the wave observed in the present experiment is regarded as the ion acoustic wave excited by the current-driven ion acoustic instability. However, for the discharge current larger than 100 mA at the pressure of 10^{-3} Torr, the peak frequency of the waves became lower with

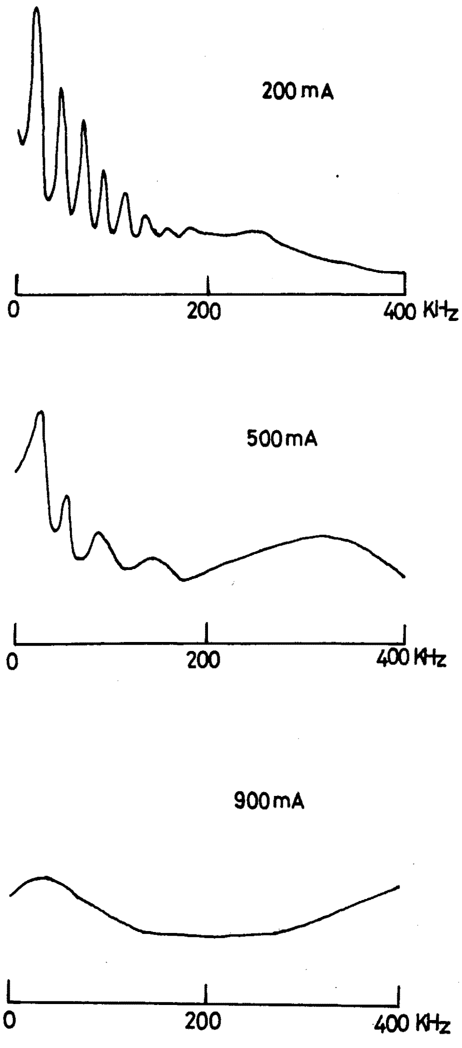

Fig. 3. A typical frequency spectrum as a function of the discharge current, where the ordinate is the wave amplitude in logarithmic units.

I_d, and the phase velocity was small by a factor of 1.3 compared with the ion acoustic velocity calculated from the electron temperature.

The ion acoustic wave becomes turbulent with increasing the discharge current. If we assume the frequency spectrum of the turbulent ion acoustic wave to be $f^{-\alpha}$, where f is the frequency and α the constant value, α was estimated to be from 2.1 to 2.44 in the present expreiment. It was also observed that above a certain discharge current, which corresponded to 600

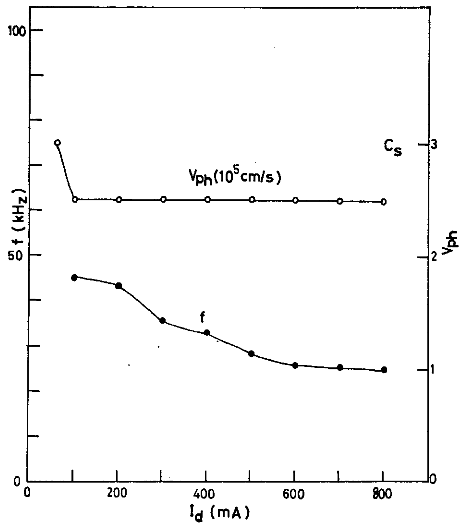

Fig. 4. Dependence of the peak frequency and the phase velocity on the discharge current.

mA for the pressure of 10^{-3} Torr, the sudden transition from the discrete spectrum to the continuous one occured.

The peak amplitude and its frequency were plotted as a function of the pressure at $I_d=400$ mA in Fig. 5, where a dotted line shows the collision frequency, ν_i, between the ion and neutral atom for $T_i=2\times10^3$ °K, which was not measured, but assumed. Figure 5 shows that the peak frequency is nearly equal to the collision frequency between the ion and the neutral atom, which sugests that the collision between the ion and the neutral atom is considered as the turbulent sink in the long wavelength region. It should also be noted from Fig. 5 that the peak amplitude of the wave decreases with increasing the pressure. In this case, the electron temperature remained almost constant, while the plasma density increased slightly with the pressure.

An example of our electric conductivity measurements as a function of the dc electric field is shown in Fig. 6, where the plasma density $n_e=2.77\times10^{10}$ cm^{-3}. Figure 6 shows that the electric conductivity decreases as E_0^{-1} in the range $E_0>0.1$V/cm, in which the fluctuation level of the wave was about 14 %. Since the collision frequency between the electron and the neutral atom is about 3 MHz in the present experiment, the classical electric conductivity is expected to be 1.5 mho/cm, whose value agrees nearly with that observed in the range $E_0\lesssim0.05$ V/cm. The relationship $\sigma\propto E_0^{-1}$ did not depend on the pressure although the pressure was not varied widely in our experiment.

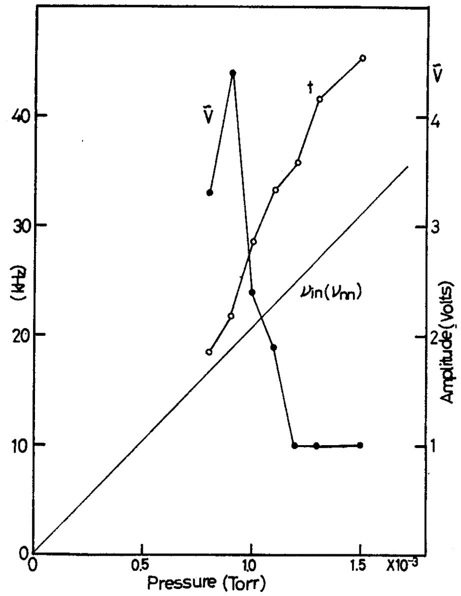

Fig. 5. The dependence of the peak frequency and the amplitude on the pressure.

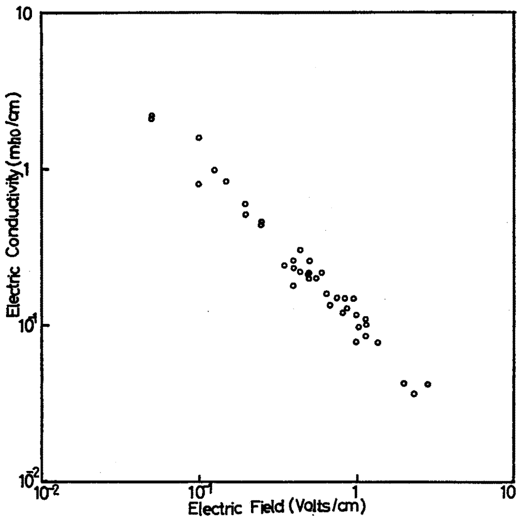

Fig. 6. Electric conductivity versus the dc electric field. The plasma density was 2.77×10^{10} cm^{-3}.

4. Discussion and Conclusion

The frequency at onset of the ion acoustic instability is given by the linear theory in the following [3)9)]:

$$f=(3/4\pi)(2/\pi)^{1/2}(v_e/v_d)\nu_i \qquad (1)$$

It is expected theoretically that the lower-limit frequency of the ion acoustic wave decreases with increasing v_d and increases with the pressure. Our experimental results agree qualitatively with above predictions, as shown in Fig. 4 and Fig. 5. We can estimate the collision frequency, ν_i, by substituting the experimental values into eq. (1). If the peak frequency in the present experiment corresponds to the onset frequency, for $I_d=400$ mA $\nu_i=$ 7 KHz, which is small by a factor of 3 compared with that assumed in Fig. 5. Complete interpretations for the experimental results may need theories including nonlinear effects.

As the discharge current increased, so that the electron drift velocity increased, the phase velocity of the observed wave became smaller than the ion acoustic velocity calculated from the electron temperature. The peak frequency of the wave shifted up to the low frequency comparable to the collision frequency between the ion and the neutral atom with the discharge current. Furthermore, it should be noted that the peak frequency does not correspond to the frequency that gives the maximum growth rate of the ion acoustic instability. That frequency is much larger than the peak frequency. Therefore, to explane these experimental results, the nonlinear effects should be considered. S. Watanabe et al [10)]. also have observed the slow phase velocity of the ion acoustic wave and explaned it by the mode-mode coupling theory [4)].

K. Nishikawa et al [5)]. have proposed that the magnitude of the saturation level is determined by competition between trapping of the electron in the potential troughs of the ion waves and collisional processes, which the ion wave tends to scatter them out of the trapped region of velocity space, so that saturation of the ion waves would set in when the bounce frequency of the electron is of the order of the effective collision frequency for untrapping. If the saturation comes from the electron trapping by the ion wave, the amplitude of the ion wave at the saturation level should increase with increasing the electron-neutral collision frequency. As seen from Fig. 5, our case is opposite.

The relationship $\sigma\propto E_0^{-1}$ has been observed in a current-carrying discharge-tube plasma by A. Hirose et al [7)]. They have attributed to the onset of the ion acoustic instability. In the present experiment, however, the fluctuation spectrum was rather continuous, which mans the fluctuation to be in the turbulent state, not the onset.

The critical field above which the electric conductivity begins to decrease was found experimentally to be about 0.05 V/cm, which is smaller than that observed by A. Hirose et al [7)].

In summary, the ion acoustic wave was excited by the current-driven ion acoustic instability in a current-carrying discharge-tube plasma. As the electron drift velocity was increased, the ion acoustic wave became turbulent and the resulting frequency spectrum was observed to be $f^{-(2.1\sim2.44)}$. On the other hand, the anomalous electric conductivity was found and the relationship $\sigma\propto E_0^{-1}$ was observed above 0.05 V/cm. Below 0.05 V/cm, the measured electric conductivity agreed with that calculated from the collision frequency between the electron and the neutral atom.

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