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14. Abstract/Notes

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DOUBLE LAYERS FORMED BY BEAM DRIVEN ION-ACOUSTIC TURBULENCE

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ABSTRACT

Small amplitude steady-state ion-acoustic double layers are observed to form in a plasma traversed by a beam of cold electrons. The importance of turbulence in maintaining the double layer is demonstrated. The measured wave spectrum is in approximate agreement with models derived from renormalized turbulence theory. The general features of the double layer are compared with results from particle simulation studies.

1. THE EXPERIMENTAL SET UP AND RESULTS

The formation of small amplitude, $e\phi/T_e < 1$, steady-state ion-acoustic double layers has been investigated in a multi-magnetic-dipole double-plasma device at INPE. In this device the usual grid that separates the source and target plasmas has been replaced by a magnetic picket fence[1], as shown schematically in Fig. 1. The magnetic picket fence is made up of permanent magnets with a 0.15T magnetic flux density at the surface. The magnets are spaced 3cm apart in such a way that the north pole of one row faces the south pole of the adjacent row. Figure 2(a) shows the profile of the x component of the magnetic induction measured along the z axis with a Hall probe. This profile defines the extent of the magnetic sheath region which separates the two plasmas. Discharges are made independently in the two chambers at an operating pressure $p \simeq 4.2 \times 10^{-4}$ mbar (Argon). Typical plasma parameters are: electron density $n_e = 1.2 \times 10^{15} m^{-3}$, electron temperature $T_e = 2.2eV$ and ion temperature $T_i \leq 0.2eV$. A plane Langmuir probe is used to measure the electron density and temperature. The ion temperature is estimated using a grid energy analyzer. The plasma potential profile is measured by an emissive probe

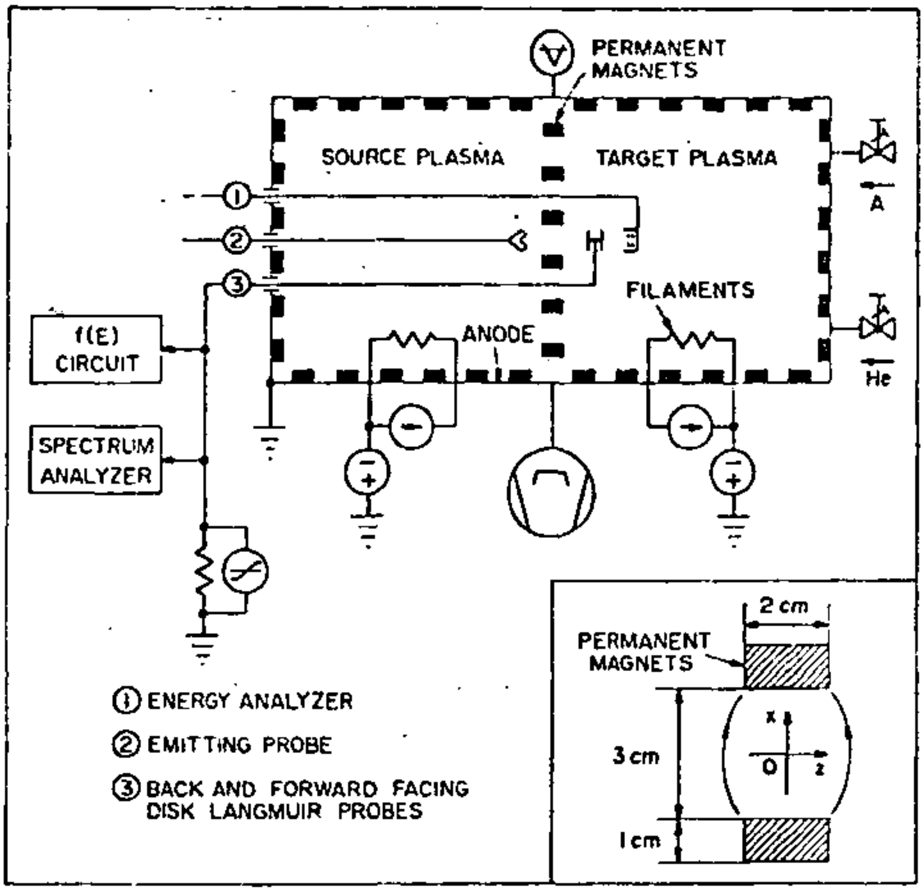

Fig. 1 - Schematic of the multi-magnetic-dipole double-plasma device. The inset shows a detail of the magnetic picket fence.

and the results are verified with data from Langmuir probes. The electron drift velocity is calculated from the beam current, given by the difference of the currents collected by back and forward facing disk Langmuir probes. This drift velocity can also be estimated from the shift of the electron energy distribution function detected by the double faced probe (a second harmonic detector circuit is used to obtain the energy distribution function from the probe characteristic curve).

When a discharge is maintained in the source chamber only, the plasma diffuses through the confining surface field of the magnetic picket fence into the target chamber. The electrons that diffuse across the magnetic field are predominantly of low energy (∿0.3eV) as a result of a selective collisional process (electron-ion collisions give rise to a diffusion process which is faster for low energy electrons). This

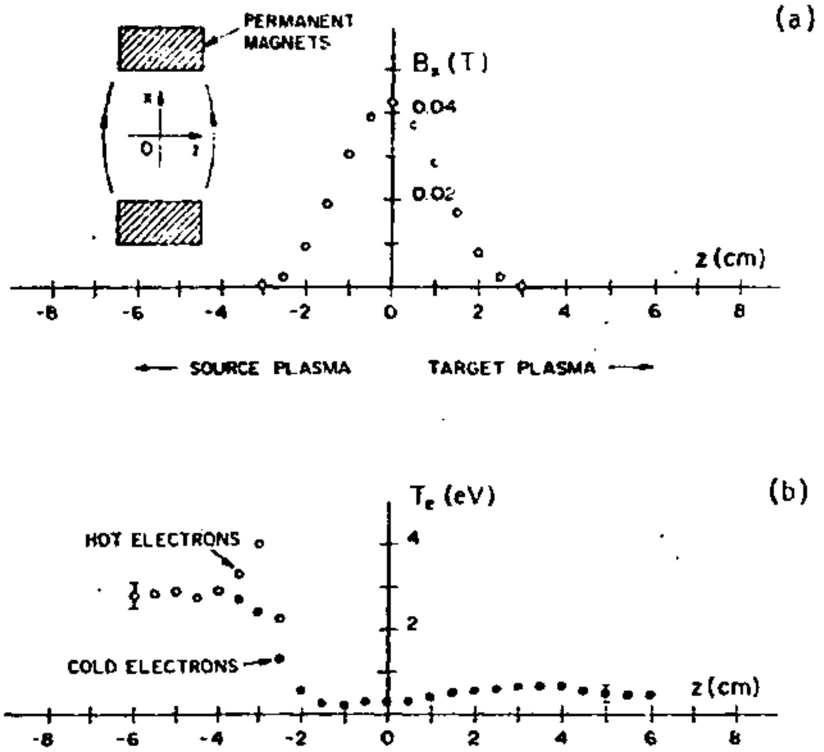

Fig. 2 - Profiles of the magnetic induction (a) and of the temperature of electrons diffusing across the picket fence (b).

diffusion process has classical and anomalous contributions affected by enhanced fluctuations which are always present in the magnetic sheath region ($-3\text{cm} \le z \le +3\text{cm}$). The positive part of the z axis in Fig. 2(b) shows the electron temperature profile of the stream of diffusing electrons (the negative part of the z axis corresponds to the source plasma). Now, by turning on the discharge in the target chamber as well, a density unbalance can be set up between the two plasmas and the net flow of cold electrons into the target plasma can be adjusted. If the relative density of the cold beam is small, a two electron temperature plasma is formed in the target chamber, as indicated by the temperature profiles shown in Fig. 3(b). Figure 3(a) shows the profile of the drift velocity of the cold electrons, normalized to the local ion-acoustic speed. It can be verified that the diffusing electrons are initially accelerated by the rise in plasma potential associated with the ion rich magnetic sheath and afterwards decelerated as the potential in the target chamber returns to approximately the same level as in the source chamber. The

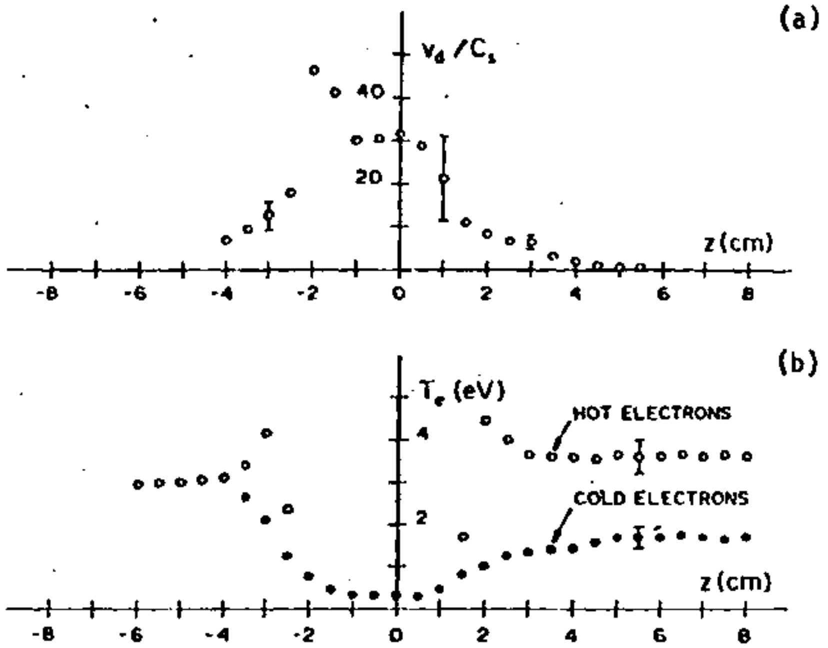

Fig. 3 - Profiles of the normalized drift velocity of the diffusing electrons (a) and of the electron temperature (b). In this case the plasma density in the target chamber is 67% of the density in the source chamber.

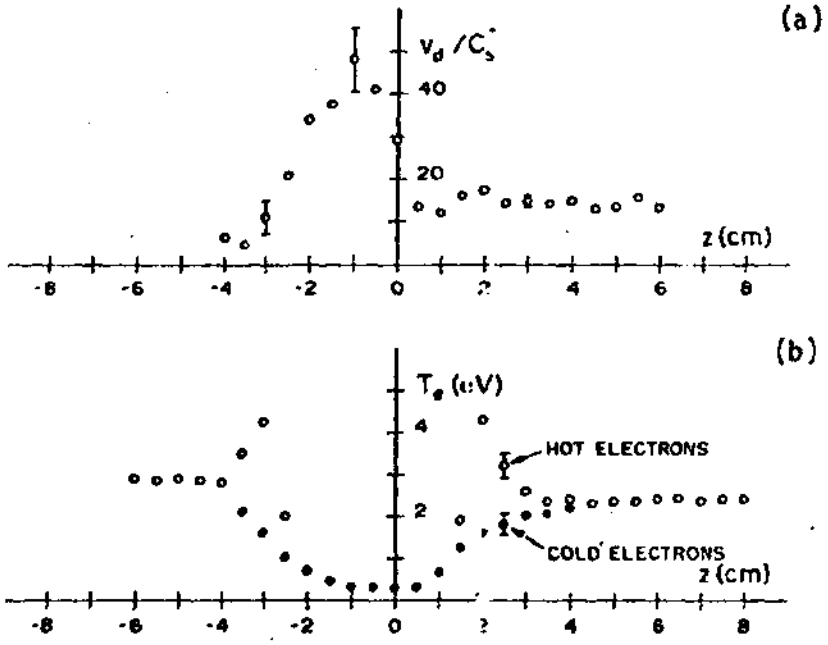

Fig. 4 - Profiles of the normalized drift velocity of the diffusing electrons (a) and of the electron temperature (b). In this case the plasma density in the target chamber is 30% of the density in the source chamber.

drift velocity of the cold electrons inside the magnetic sheath is much larger than the ion-acoustic speed, driving the ion-acoustic instability. From the temperature profiles in Fig. 3(b) one verifies that the beam electrons are heated up to about 1.7eV by the turbulent fields produced by the ion-acoustic turbulence inside the magnetic sheath. The temperature of the plasma electrons is, in this case, $T_e \simeq 3.6$eV. Outside the magnetic sheath, $z \gtrsim 3$cm, the beam electrons drift with a velocity which is typically a few times larger than the ion-acoustic speed, but lies bellow the threshold of the ion-acoustic instability. Accordingly, no enhanced fluctuations are detected in the plasma in front of the magnetic sheath.

There is a drastic change in the situation if the density of the beam electrons is increased to a sufficiently large value, in which case strong turbulence can be detected well beyond the magnetic sheath. A double layer is formed at the location where the turbulent density fluctuations exist and the beam electrons drift with a constant velocity which is much larger than the ion-acoustic speed ($\sim 15C_s$ in the case depicted in Fig. 4(a)). The electron temperature profile in Fig. 4(b) shows that the beam electrons are rapidly heated up to the plasma electrons temperature $T_e \approx 2.4$eV. The potential profile of the double layer in the region outside the magnetic sheath is shown in Fig. 5. In this case the density ratio of beam electrons to plasma electrons is $n_b/n_e \simeq 0.13$ and the drift velocity is $v_d \simeq 4.6 \times 10^4$m/s $\simeq 20C_s$. Figure 5 also shows the profile of peak density fluctuations, indicating the association with the potential structure, and the profile of the magnetic induction inside the magnetic sheath. The total potential jump is of the order of 0.4V and the maximum value of the electric field, at the position $z \approx 5$cm, is estimated to be $E_z \approx -8.0$V/m. Using Ohm's law, the effective collision frequency of the beam electrons is given by $\nu^* = -eE_z/(m_e v_d) \approx 3.1 \times 10^7 s^{-1}$, which is much larger than the electron-neutral collision frequency in the double-plasma discharge. The dc electric field is associated with an anomalous resistivity $\eta^* = m_e \nu^*/(n_b e^2) \approx 7.0\Omega m$ produced by the scattering of the beam electrons from the turbulent ion-acoustic fluctuations.

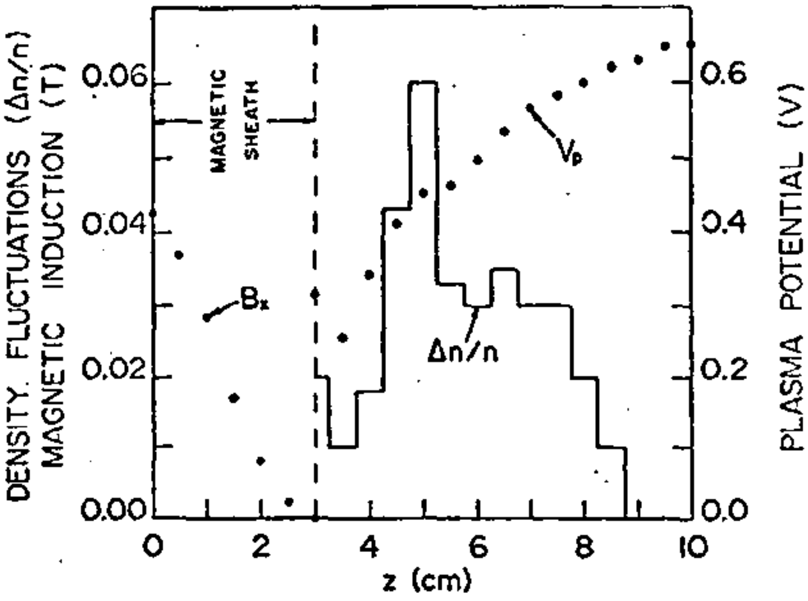

Fig. 5 - Peak electron density fluctuations and plasma potential profiles. The magnetic induction profile is shown inside the magnetic sheath region.

2. IMPORTANCE OF THE ION-ACOUSTIC TURBULENCE IN MAINTAINING THE DOUBLE LAYER

The role of the ion-acoustic turbulence in the formation of the double layer can be checked by gradually quenching the turbulence. This is accomplished by the introduction of Helium in the Argon discharge to enhance Landau damping. The measured spectra of turbulent density fluctuations are shown in Fig. 6 for relative concentrations of Helium ions ($r = n_{He+}/n_{A+}$) equal to 0, 0.03, 0.07 and 0.23. For increasing concentrations of the light ion the level of fluctuations decreases, being almost nonexistent for $r = 0.23$. The corresponding decrease in the potential jump of the double layer, which does not form at the highest value of r, is shown in Fig. 7. There is also a corresponding decrease in the value of v_d/C_s (≈20, 15, 12, 7.8 and 4.2 for r = 0, 0.03, 0.07, 0.14 and 0.23, respectively). The density ratio of beam to plasma electrons varies with the introduction of Helium, but is typically $n_b/n_e \approx 0.13$. For large concentrations of Helium ions, that is, when the double layer is not formed, two electron temperatures are observed in

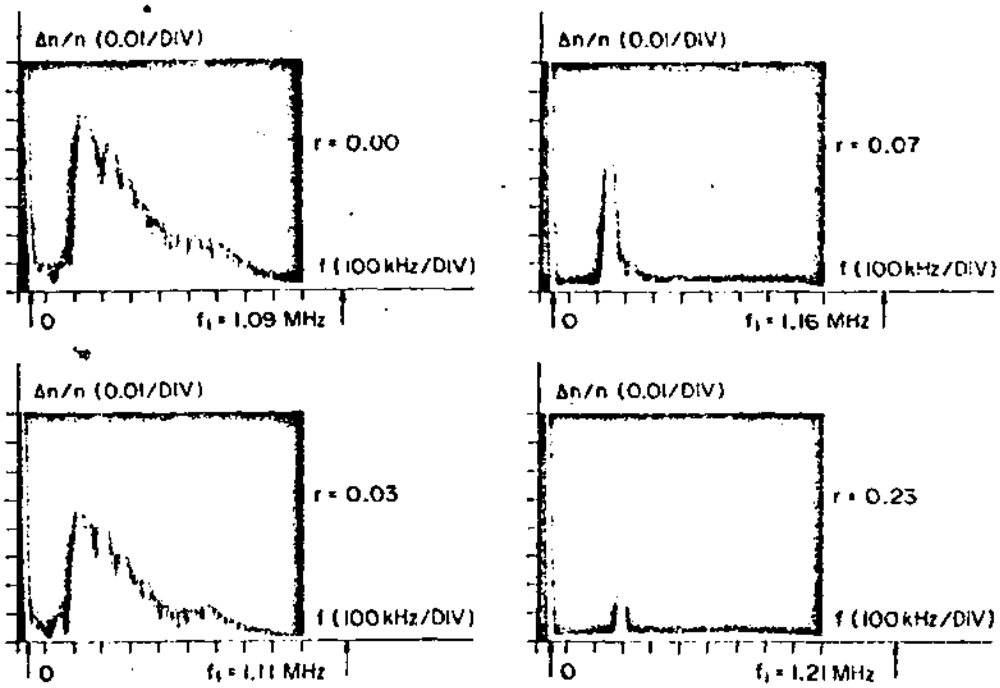

Fig. 6 - Electron density fluctuations spectrum as measured by a disk Langmuir probe at the position z ≅ 5cm of peak turbulence. The data are taken for increasing concentration, r, of Helium ions with respect to Argon ions, as indicated.

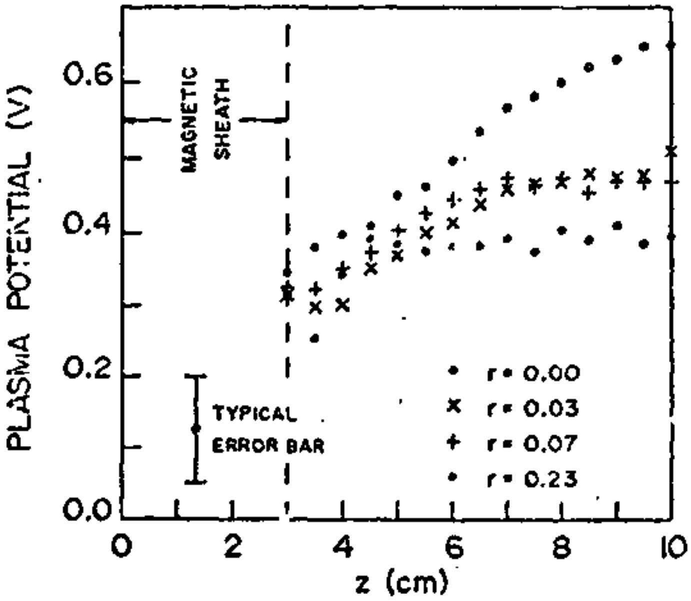

Fig. 7 - Plasma potential profiles for increasing concentration r.

the target plasma, where the situation is similar to the case of a low density beam in a pure Argon plasma. From the measured temperature profiles shown in Fig. 8 it can be verified that the cold beam electrons are rapidly heated by the turbulent fields, reaching the value of the plasma electrons temperature approximately at the position of peak density fluctuations ($z \approx 5$cm). This turbulent heating process occurs in a scale length which apparently determines the size of the double layer through a quenching of the instability by increased Landau damping.

The value of the drift velocity, measured in the presence of the double layer in the case of a pure Argon plasma, is consistently above the threshold value for the excitation of ion-acoustic instability predicted by linear theory. However, in the Argon-Helium mixture the double layer persists for drift velocities smaller than the threshold values computed from linear theory, suggesting that the threshold values are lowered in the presence of strong turbulence. Indeed, preliminary results show that it is required a beam of much higher density to form a double layer in a preexistent plasma mixture (in the absence of turbulence) than to sustain a double layer formed in a pure Argon plasma in which Helium was added subsequently.

3. COMPARISON WITH THEORY AND SIMULATIONS

The measured spectrum of ion-acoustic turbulence can be compared with the prediction of the modified Kadomtsev spectrum from renormalized theory. Based on the theoretical formulation of Choi and Horton[2], the following expression is taken as a model for the spectral density

$$I_\omega = \frac{C}{k\lambda_c}\left[\ln\left(\frac{1}{k\lambda_e}\right) - 2\left(\frac{\pi\nu^*}{\omega_b}\right)^{1/2}\left(\frac{1}{(k\lambda_e)^{1/2}} - 1\right)\right],$$

where C is a constant and

$$k\lambda_e = \frac{\omega/\omega_i}{(1 - \omega^2/\omega_i^2)^{1/2}}$$

for ion-acoustic waves. The plasma frequencies of the ions and of the beam electrons are denoted by ω_i and ω_b, respectively. Figure 9 shows

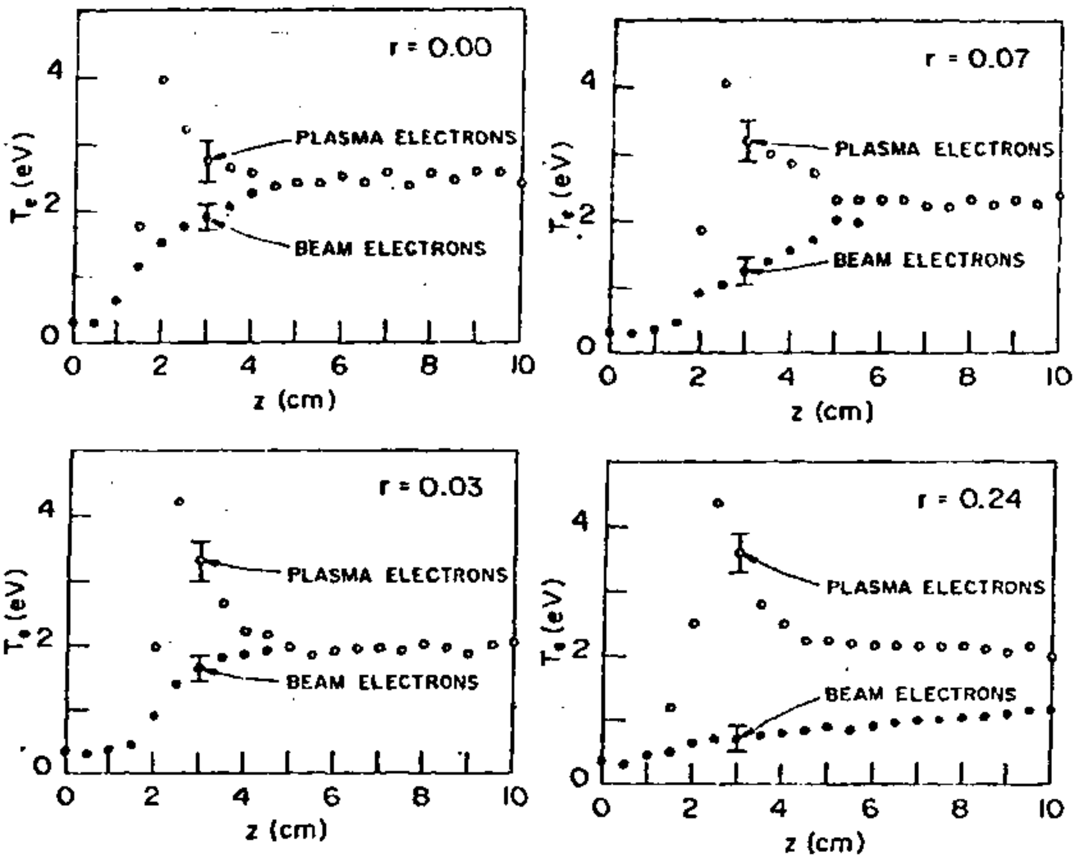

Fig. 8 - Plasma and beam electron temperature profiles for increasing concentration r.

the result of a best fit of the measured spectrum in a pure Argon discharge normalized to the experimental value of the ion plasma frequency. The fit coefficient $(\nu^*/\omega_b)_{fit} = 0.0959$ is greater than the experimental value,

$$(\nu^*/\omega_b)_{fit} \approx 2.2(\nu^*/\omega_b)_{exp} .$$

Considering that the theory assumes the wave spectrum to fill the half-space in the direction $\vec{v}_d$, the above result is remarkably good. An effective cone with an aperture of $\sim 45^o$ for the spectrum of unstable waves would account for the discrepancy. Besides, the experimental value of the drift velocity has errors as large as 50%. The effect of changing the value of the plasma frequency of the ions is shown in Fig. 10. It seems that the tail of the spectrum is not well represented by the

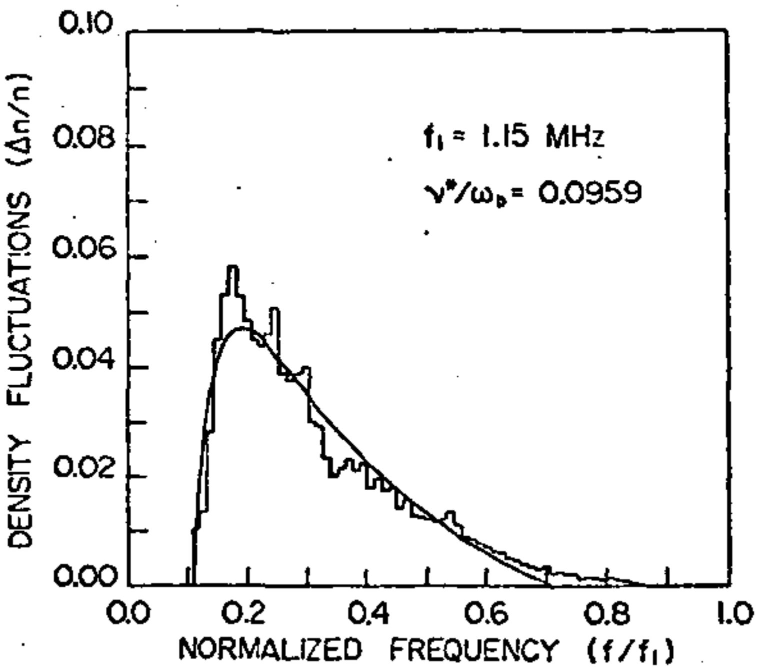

Fig. 9 - Ion-acoustic turbulent density fluctuations spectrum. The histogram shows experimental values and the curve is a best fit according to renormalized turbulence theory.

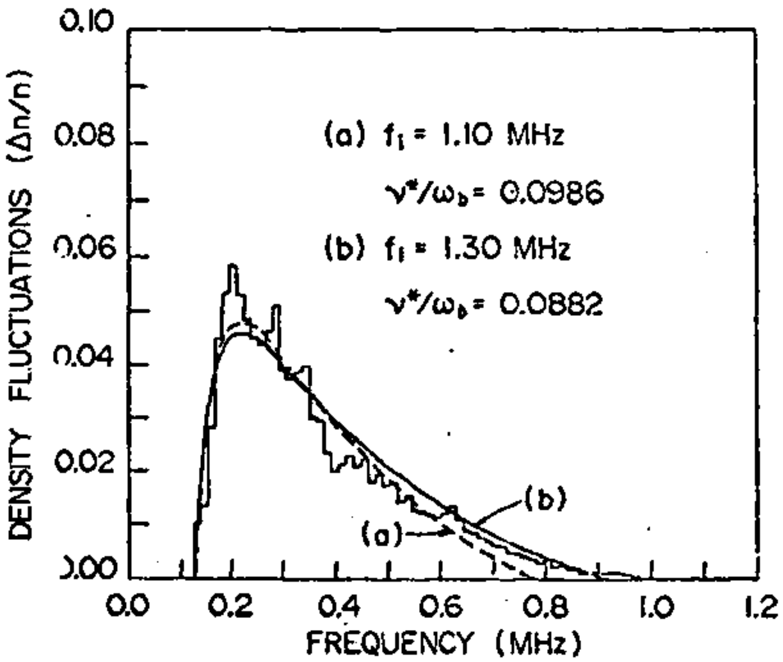

Fig. 10 - Effect, in the best fit curve, of changing the value of the plasma frequency of the ions.

theoretical model and that the mode structure is more complicated. One must keep in mind that the model is considerably simplified and that the situation considered in the theoretical work (current driven ion-acoustic turbulence) does not correspond completely to the experiment.

Finally, it is interesting to compare the experimental results with results from particle simulation studies. Numerical simulations, carried out by Sato and Okuda[3], have shown that double layers can be formed by the ion-acoustic instability excited by electrons drifting with a velocity smaller than the electron thermal speed ($v_d < v_e$). The simulations indicate that the anomalous resistivity associated with the instability gives rise to a dc potential buildup which accelerates the initially drifting electrons. For sufficiently large current densities and long systems the energy gained by the electrons from the dc potential, before the instability saturates, is large enough to bootstrap the instability to a new regime of enhanced instability, leading to the formation of a transitory double layer. The experiment reported in this paper shows the formation of steady-state small amplitude double layers ($e\phi/T_e < 1$) associated with the ion-acoustic turbulence. The experimental results show, also, that the double layer is formed when the beam density reaches a sufficiently high value. In this case, the dc potential across the region of localized resistivity is large enough to drastically change the configuration. The beam electrons are accelerated to much higher drift velocities and are rapidly heated by the turbulence associated with the double layer formation. These features can be explained in terms of the bootstrap action observed in the particle simulation studies. Furthermore, the total size of the double layer is about $200\lambda_e$ (for a pure Argon discharge), which is consistent with the minimum system length found in the simulations.

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