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14. Abstract/Notes

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EXPERIMENTAL INVESTIGATION OF DOUBLE LAYERS FORMED BY ION-ACOUSTIC TURBULENCE

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Abstract

A small amplitude steady-state double layer is observed to form in a plasma traversed by cold drifting electrons, $v_d < v_e$. The double layer is shown to be associated with the anomalous resistivity caused by the ion-acoustic instability driven by the electron beam. The double layer is formed when the beam density is sufficiently large to enhance the instability by a bootstrap action, in agreement with particle simulation studies.

Numerical simulations, carried out by Sato and Okuda[1], 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. In this paper, the formation of steady-state small amplitude double layers ($e\phi/T_e < 1$) associated with this bootstrap mechanism is reported as observed in a multi-magnetic-dipole double-plasma device. As shown in Fig. 1, the usual grid separating the source and target plasmas has been replaced by a magnetic picket fence made of permanent magnets with a 0.15T magnetic flux density at the surface. The working pressure is 4.2 x 10^{-4}mbar (Argon) and typical plasma parameters are: electron density $n_e = 1.2 \times 10^{15}m^{-3}$, electron temperature T_e = 2.2eV, and ion temperature $T_i \lesssim$ 0.2eV. The plasma potential is measured by an emissive probe and 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.

When only the source plasma is turned on, a stream of cold electrons ($T_b \approx$ 0.3eV) diffuses through the magnetic fence, as a result of a selective collisional process, and is detected in the target chamber[2]. The diffusion process has classical and anomalous contributions affected by enhanced fluctuations which are always present in the magnetic sheath region ($-3cm \leq z \leq +3cm$). By turning on the target plasma, a density unbalance can be set up between the two plasmas, making possible to control the relative density of the cold beam streaming into the target plasma. If the net flow of cold electrons directed from the source chamber to the target chamber is small, a two electron temperature plasma is formed in the target chamber. In this case the cold 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 observed in the plasma in front of the magnetic sheath ($z \gtrsim 3cm$). Now, if the density of drifting cold electrons, relative to the density of plasma electrons, is increased to a sufficiently large value, there is a drastic change to a situation where strong turbulence can be detected in the region in front of 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, in this case, much larger than the ion-acoustic speed. Furthermore, it is observed that the beam electrons are rapidly heated, within the scale length of the double layer, up to the plasma electron temperature. Figure 2 shows the profiles of the potential of the double layer and of the associated peak density fluctuations outside the magnetic sheath. The extent of the sheath is determined, as also indicated in Fig. 2, by the profile of the induction due to the magnetic fence, measured along the z axis with a Hall probe. The total potential jump is of the order of 0.4V and the maximum value of the electric field, at the position $z \approx 5cm$, is estimated to be $E_z \approx -8.0V/m$. In these circumstances, the density ratio of beam electrons to plasma electrons is $n_b/n_e \cong 0.13$ and the drift velocity, which has a constant value along the double layer, is $v_d \cong 4.6 \times 10^4$m/s $\cong 20c_s$, where c_s is the ion-acoustic speed for a pure Argon plasma. The ion-acoustic turbulence driven by the electron beam produces an anomalous resistivity $\eta^* = m_e\nu^*/n_b e^2 \cong 7.0\Omega$m through the scattering of the electrons from the ion-acoustic fluctuations. The dc electric field E_z satisfies $eE_z = -\nu^* m_e v_d$, where the effective collision frequency of the beam electrons $\nu^* \cong 3.1 \times 10^7 s^{-1}$ far exceeds the electron-neutral collision frequency in the double-plasma discharge.

The spectrum of ion-acoustic turbulence is measured and compared with the prediction of the modified Kadomtsev spectrum from renormalized theory. Based on the theoretical formulation of Choi and Horton[3], the following expression is taken as a model for the spectral density:

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

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. Figure 3 shows the result of a best fit of the measured spectrum 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,

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

Considering that the theory[3] 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 ~45° 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%.

In order to check the role of the ion-acoustic turbulence in the formation of the double layer, a gradual quenching of the turbulence is effected by the introduction of small quantities of Helium in the Argon discharge to enhance Landau damping. The spectrum of the ion-acoustic turbulence is measured for relative concentrations of Helium ions, r, equal to 0, 0.03, 0.07 and 0.23. As shown in Fig. 4, for increasing concentrations of the light ion the level of fluctuations decreases and is almost nonexistent for r = 0.23. There is also a corresponding decrease in the value of v_d/c_s (≈20, 15, 12 and 4.2 for r = 0, 0.03, 0.07 and 0.23, respectively) and in the potential jump of the double layer, which does not form at the highest value of r, as shown in Fig. 5. In this case two electron temperatures are observed in the target plasma, as shown in Fig. 6 for r ≈ 0.24, 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. 6 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 ≈ 5cm). 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 total size of the double layer is about

$200\lambda_e$ (for r = 0), which is consistent with the minimum system length found in the simulations[1].

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.

In conclusion, the observation in the laboratory of small amplitude steady-state ion-acoustic double layers has been reported. The importance of turbulence in maintaining the double layer has been demonstrated. The measured spectrum of ion-acoustic turbulence has been compared with results from renormalized turbulence theory with reasonable agreement. Furthermore, the experiment has shown 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 particle simulation studies.

The authors wish to thank Prof. C.F. Kennel for suggesting the introduction of Helium in the experiment.

Figure Captions

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

Fig. 2. Peak electron density fluctuations and plasma potential profiles. The magnetic induction profile is shown inside the magnetic sheath region.

Fig. 3. Ion-acoustic turbulent density fluctuations spectrum. The histogram shows experimental values and the curve is a best fit according to renormalized turbulence theory.

Fig. 4. Electron density fluctuations spectrum as measured by a disk Langmuir probe at the position $z \cong 5$cm of peak turbulence. The data are taken for increasing concentration of Helium ions with respect to Argon ions ($r = n_{He^+}/n_{A^+}$), as indicated.

Fig. 5. Plasma potential profiles for increasing concentration r.

Fig. 6. Plasma and beam electron temperature profiles for increasing concentration r.

References

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[3]D. Choi and W. Horton, Phys. Fluids 17, 2048 (1974).

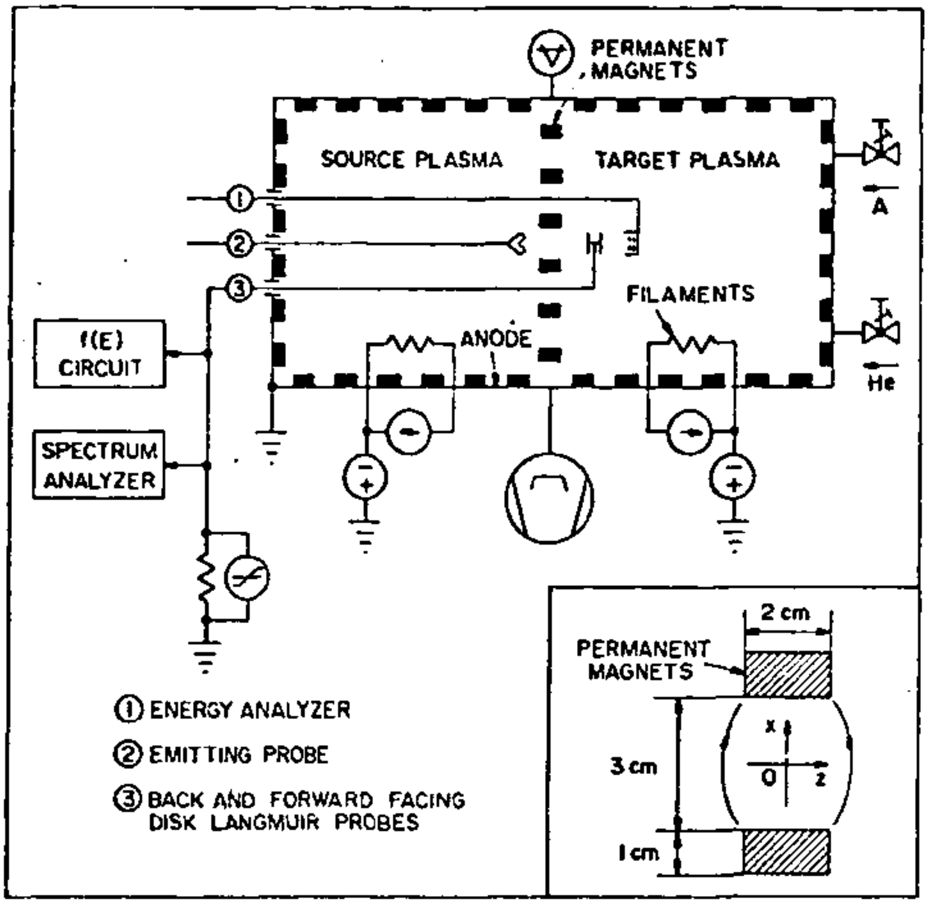
PERMANENT MAGNETS
SOURCE PLASMA
TARGET PLASMA
A
FILAMENTS
f(E) CIRCUIT
ANODE
He
SPECTRUM ANALYZER
2 cm
PERMANENT MAGNETS
3 cm
1 cm
x
0
z
① ENERGY ANALYZER
② EMITTING PROBE
③ BACK AND FORWARD FACING DISK LANGMUIR PROBES

Fig. 1

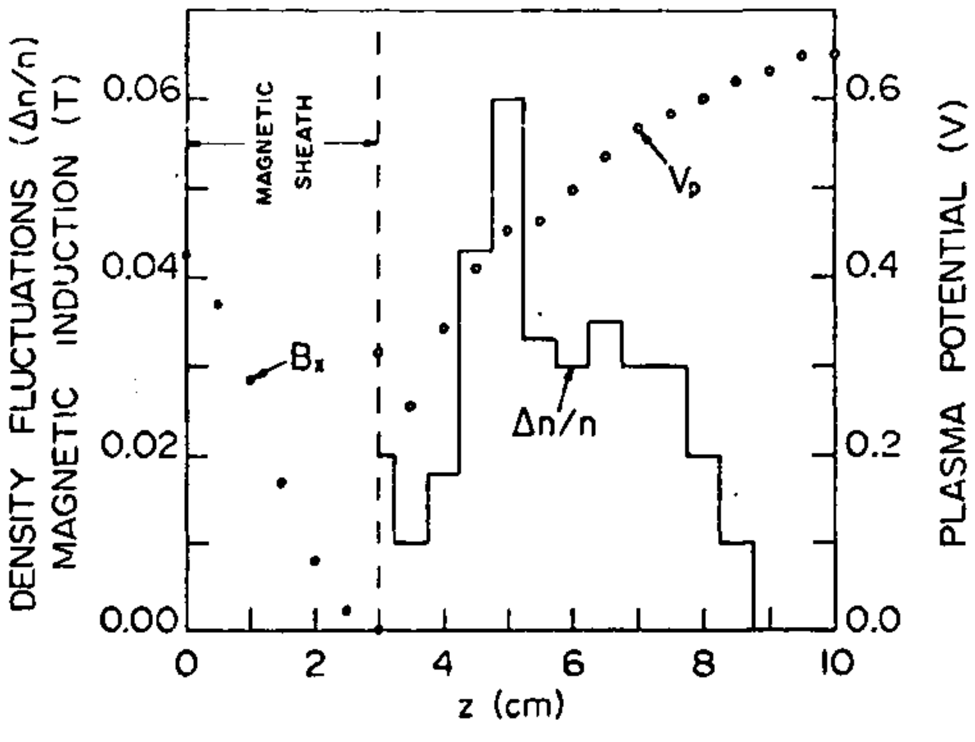
DENSITY FLUCTUATIONS (Δn/n)
MAGNETIC INDUCTION (T)
PLASMA POTENTIAL (V)
MAGNETIC SHEATH
Bx
Vp
Δn/n
0.00
0.02
0.04
0.06
0.0
0.2
0.4
0.6
0
2
4
6
8
10
z (cm)

Fig. 2

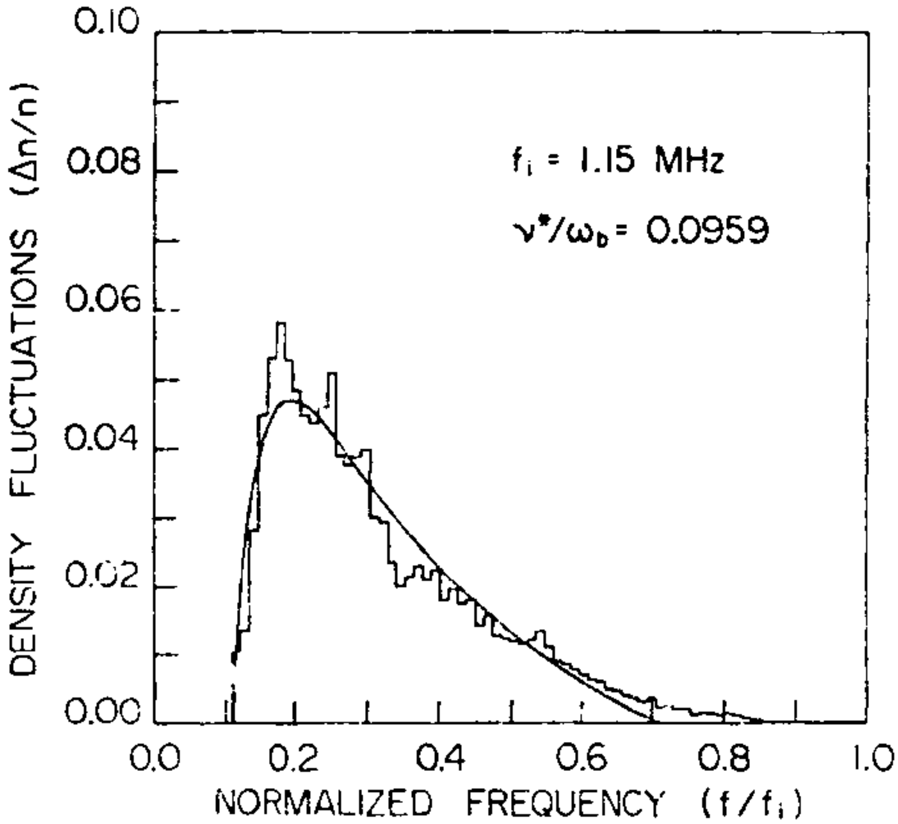
DENSITY FLUCTUATIONS (Δn/n)
0.10
0.08
0.06
0.04
0.02
0.00
f_i = 1.15 MHz
ν*/ω_b = 0.0959
0.0
0.2
0.4
0.6
0.8
1.0
NORMALIZED FREQUENCY (f/f_i)

Fig. 3

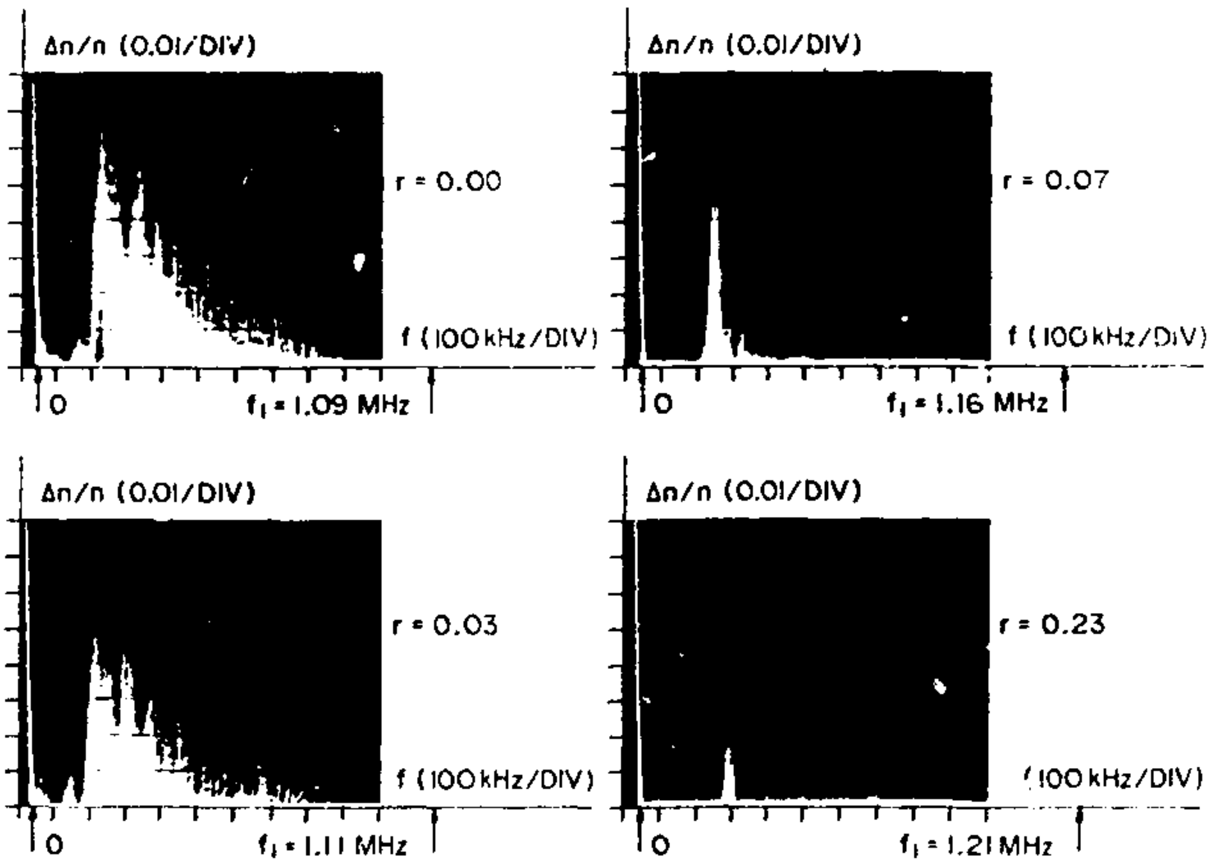
Δn/n (0.01/DIV)
r = 0.00
f (100 kHz/DIV)
0
f_i = 1.09 MHz
Δn/n (0.01/DIV)
r = 0.07
f (100 kHz/DIV)
0
f_i = 1.16 MHz
Δn/n (0.01/DIV)
r = 0.03
f (100 kHz/DIV)
0
f_i = 1.11 MHz
Δn/n (0.01/DIV)
r = 0.23
100 kHz/DIV)
0
f_i = 1.21 MHz

Fig. 4

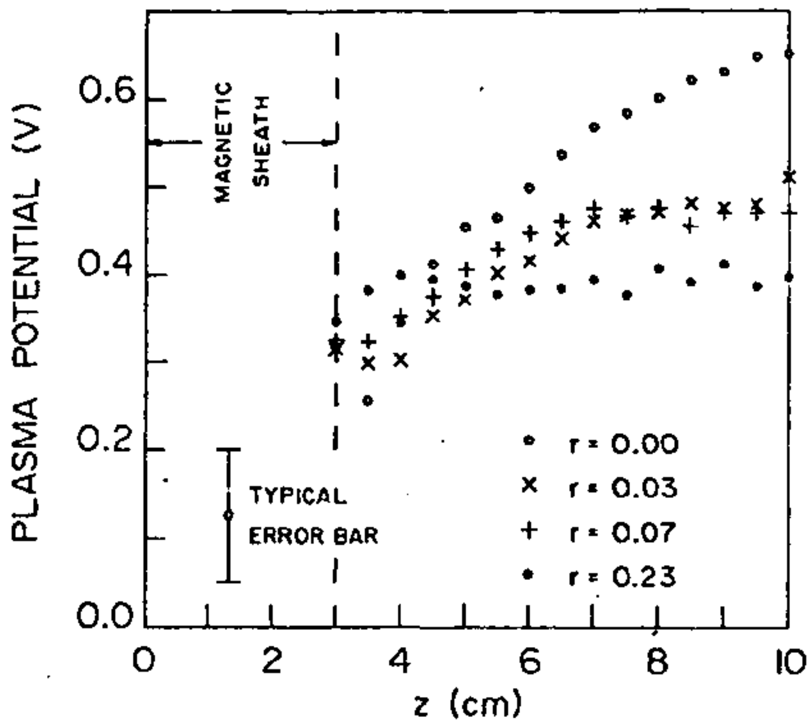
PLASMA POTENTIAL (V)
MAGNETIC SHEATH
TYPICAL ERROR BAR
r = 0.00
r = 0.03
r = 0.07
r = 0.23
z (cm)

Fig. 5

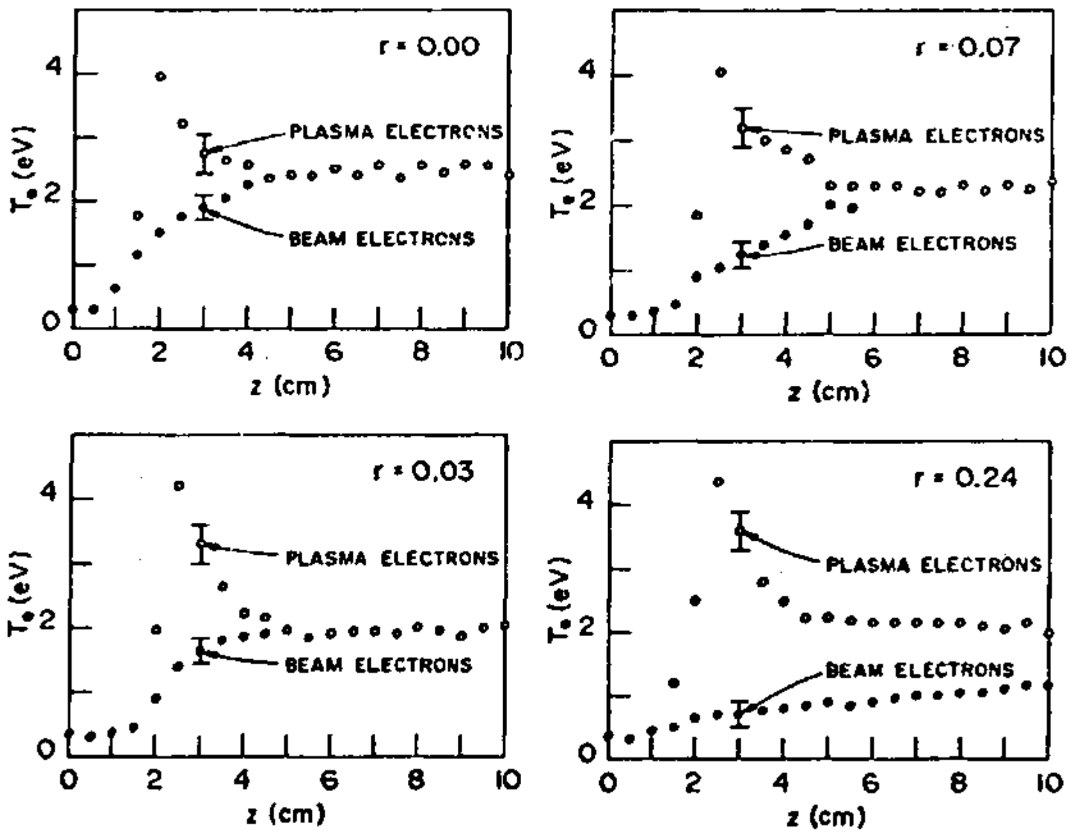
r = 0.00
r = 0.07
r = 0.03
r = 0.24
PLASMA ELECTRONS
BEAM ELECTRONS
T_e (eV)
z (cm)

Fig. 6