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MICROTURBULENCE IN THE PLT TOKAMAK

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Abstract

By heterodyne detection of scattered microwaves, density fluctuations have been observed in the PLT tokamak in the range of wavelengths 0.2-2 cm and with frequencies up to 200-300 kHz. The flux of runaway electrons onto the limiter was modulated in the same range of frequencies.

The level of turbulence was enhanced by the injection of energetic neutrals, and for ion temperatures in excess of 4 keV, a new type of oscillation was observed.

1. Introduction

The transport of electrons in tokamaks is at least two orders of magnitude larger than the value predicted by the neoclassical theory. Although some of these losses are certainly caused by impurity line radiation or by large scale MHD instabilities, to explain the behavior of electrons in tokamaks we must admit the existence of an anomalous transport, very likely produced by some kind of microturbulence. Unfortunately, in spite of a considerable theoretical effort, there is no generally accepted theory which explains this phenomenon. Not only the nature and the level of turbulence are uncertain, but also the mechanism which causes the anomalous transport is not clear.

In recent years several experiments[1-4] have shown the existence of a small-scale turbulence in tokamaks. Many features of the observed fluctuations agree with the theory of drift waves and the measured electron transport is consistent with the predictions of the quasilinear theory.[5] Nevertheless, this theory fails to explain the observed temperature dependence of the electron energy transport in tokamaks.[6]

In this paper we present additional experimental results on the features of microturbulence in the PLT discharge.

2. Scattering Apparatus

Density fluctuations were studied in PLT with scattering of 2 mm microwaves. The cross section for incoherent scattering of electromagnetic waves which propagate in the ordinary mode across a magnetic field is given by: $\sigma = \sigma_o S(\vec{k}, \omega)$, where σ_o is the Thomson cross section and $S(\vec{k}, \omega)$ is the spectral density of electron fluctuations. The frequency, ω, and the wave vector, $\vec{k}$, must satisfy the energy and momentum conservation, i.e., $\omega = \omega_s - \omega_i$ and $\vec{k} = \vec{k}_s - \vec{k}_i$, where the subscripts s and i refer to the scattered and incident wave, respectively. The total mean square density fluctuation is obtained by integration of $S(\vec{k},\omega)$ over the entire $(\vec{k},\omega)$ space: $(\tilde{n}_e)^2 = (2\ )^{-4}\int S(\vec{k},\omega)d\vec{k}d\omega$.

In order to determine the sign of ω, a heterodyne detection system was used in which the scattered wave was mixed with a larger reference wave having a different frequency from that of the incident wave. We used the same set of antennae of Ref. 5 which were all located on the same poloidal plane with scattering angles ranging from 2^0 to 60^0. Three scattering geometries used for the observation of fluctuations with $k \simeq 10\ cm^{-1}$ are shown in Fig. 1, where the respective detection efficiencies are displayed. Two of the scattering regions shown in Fig. 1 are on opposite and symmetrical sides of the vertical center line.

In the following, these two regions will be called the inside and the outside regions. The third region shown in Fig. 1 lies along the center-line. Several scattering regions of this type were used in the experiment with values of k ranging from 2 to 30 cm^{-1} and directions mainly along the poloidal magnetic field. Scattering geometries with values of k larger than 10 cm^{-1} had a better spatial resolution than that shown in Fig. 1, while the opposite was true for values of k smaller than 10 cm^{-1}. The k-resolution was $\Delta k \simeq \pm 2\ cm^{-1}$.

3. Density Fluctuations

The typical PLT discharge that was used in this study had (with standard notations): $a = 40$ cm, $B_T = 25$ kG, $I = 400$ kA, $\bar{n}_e = 2 - 4 \times 10^{13}\ cm^{-3}$, $\bar{T}_e = 750-1000$ eV, $T_i(0) \sim 800-900$ eV, $Z_{eff} = 1 - 2$. In this range of plasma parameters, electrons were in the banana regime. The parameter ν_*^e, the ratio of the effective collision frequency of trapped electrons to their bounce frequency, is displayed in Fig. 2 vs. the minor radius for the case of $\bar{n}_e = 2 \times 10^{13}\ cm^{-3}$. Its value was smaller than unity over most of the plasma cross section.

In low density discharges ($\bar{n}_e = 2 \times 10^{13}\ cm^{-3}$), density fluctuations were observed with frequency spectra nearly symmetric with respect to the zero frequency or, in other words, waves with phase velocities along both the electron and the ion diamagnetic directions were observed. This is in contrast to previous observations in ATC[2] and TFR[3] where a clear shift of the frequency spectra toward the electron diamagnetic side was observed. At larger plasma densities this shift was also observed in PLT, as it is illustrated in Fig. 3 which shows the frequency spectra of fluctuations with $k \simeq 10\ cm^{-1}$ in discharges with $\bar{n}_e = 2 \times 10^{13}\ cm^{-3}$ and $\bar{n}_e = 4 \times 10^{13}\ cm^{-3}$, respectively. In this range of densities we found that the values of $\tilde{n}_e/\bar{n}_e$ remained nearly constant. The level of turbulence observed on the outside region was larger than that observed on the inside regions. This is shown in Fig. 4 which contains the time evolution of the signals from the two regions produced by fluctuations with $k \simeq 10\ cm^{-1}$ and $f = 50$ kHz. The plasma density of this discharge was purposely increased by gas puffing. These data clearly show the ballooning structure of the observed turbulence both before and after the density rise. During the density rise we observed an enhancement of the level of turbulence which grew with the rate of density increase and with no apparent poloidal structure. Some values of the spectral density $S(k) = (2\pi)^{-1}\int_{-\infty}^{+\infty} S(k,\omega)d\omega$, measured in the central scattering regions, are plotted in Fig. 5 as a function of the wave number for $\bar{n}_e = 2 \times 10^{13}\ cm^{-3}$. The value of S(k) decreased monotonically in the range of $k \simeq 2\text{-}30\ cm^{-1}$. Nevertheless, when we consider the data of Fig. 5, we must remember that the lower part of the k-axis corresponds to small scattering angles with large scattering regions and poor k-resolution. A maximum of S(k) in the region $k\rho_i \simeq 0.5$, as it was found in ATC[1,2] and the theory of drift waves indicates,[5] could not have been resolved with the present apparatus.

Assuming that the observed turbulence is isotropic in the k-plane perpendicular to $\vec{B}$, and that $|\vec{k}_\perp| \simeq k$, from the data of Fig. 5 we get $(\tilde{n}_e/\bar{n}_e) = 0.5 \times 10^{-2}$. This is the same level of turbulence which was found previously in PLT[4].

4. Runaway Electron Fluctuations[9]

When energetic runaway electrons leave a tokamak discharge and encounter the limiter, they produce thick target bremsstrahlung. These hard xrays have been detected in PLT with sufficiently good frequency response to observe oscillations up into the MHz range. These measurements were made in discharges with a moderate content of runaway electrons so that the plasma parameters were unchanged by the existence or absence of this dilute electron population. We found that the average fluctuating amplitude of the x-ray flux was about 0.1-0.3 of the total flux and that its frequency spectrum, rather than resembling the white noise spectrum which would be expected from shot noise or short random bursts, was very similar to the spectrum of density fluctuations. A possible explanation of these results is that the observed oscillations are caused by a modulation, $\tilde{v}$, of the radial velocity of runaway electrons which is superimposed to their average outward velocity $\bar{v} \simeq a/\tau_R$. Since the runaway electron confinement time, τ_R, is in the range 5-50 ms on PLT,[7] we get $\tilde{v} \simeq (0.1-0.3)\, a/\tau_R \simeq (0.1-3) \times 10^3$ cm/sec. This velocity is consistent with $\vec{E} \times \vec{B}$ drifts caused by an electrostatic turbulence with the same features of the turbulence observed with scattering of microwaves.

5. Neutral Beam Injection

As mentioned earlier, the value $\tilde{n}_e/\bar{n}_e$ was nearly constant in ohmically heated discharges with average densities in the range of 2-4 x 10^{13} cm^{-3}. On the contrary, the injection of energetic neutrals[8] caused an enhancement of $\tilde{n}_e/\bar{n}_e$. This phenomenon is illustrated in Fig. 6 which shows the quantity $S(k)/(\bar{n}_e)^2$ in the range of ion temperature $T_i(0)$ = 1-4 keV. The points with values of $T_i(0)$ greater than 1 keV were obtained with neutral beam powers ranging from 1-2.5 MW. At every value of k the enhancement of the level of turbulence appeared as a broadening of the frequency spectrum.

The only major change of the electron parameters produced by the injection of neutrals was an increase of density, typically from $1\text{-}1.5 \times 10^{13}\ cm^{-3}$ to $2\text{-}3 \times 10^{13}\ cm^{-3}$. Little ($\simeq 20\%$) or no change of the average electron temperature was observed although the amount of injected power deposited into the electrons was in some cases larger than the ohmic power.

At values of ion temperatures in excess of 4 keV, a new type of fluctuation was observed. These oscillations were strongly localized on the outside region (with respect to the major radius) of the plasma column. While the signal from the outside scattering region was often ten times larger than the background level, we failed to detect the presence of these oscillations in the inside scattering area. At present, we know only the frequency spectrum for $k \simeq 10\ cm^{-1}$ which is displayed in Fig. 7. It peaks at about 50 kHz on both the ion and electron diamagnetic side. The only other information we possess is that, whenever the scattering system detected the presence of these fluctuations, a microwave interferometer, used for the measured of $\bar{n}_e$, lost track of the fringe count.

On the basis of these measurements we cannot exclude the possibility that these fluctuations might have been produced by a macroscopic instability. In fact, it is possible that the detected signal was caused by a large scale density fluctuation which modulatd the phase of the straight radiation.

6. Conclusions

Density fluctuations have been observed in the PLT tokamak in the range of wavelengths 0.2-2 cm, frequencies up to 200-300 kHz, and total amplitude $\tilde{n}_e \sim 5 \times 10^{-3}\ \bar{n}_e$. At low densities ($\bar{n}_e = 2 \times 10^{13}\ cm^{-3}$) the frequency spectra were centered around the zero frequency while in discharges with $\bar{n}_e = 4 \times 10^{13}\ cm^{-3}$ a shift toward the electron diamagnetic side was observed. The flux of runaway electrons onto the limiter was modulated in the same range of frequencies.

The level of turbulence was enhanced by the injection of energetic neutrals and a new type of oscillation was observed whenever the ion temperature was in excess of 4 keV.

Acknowledgments

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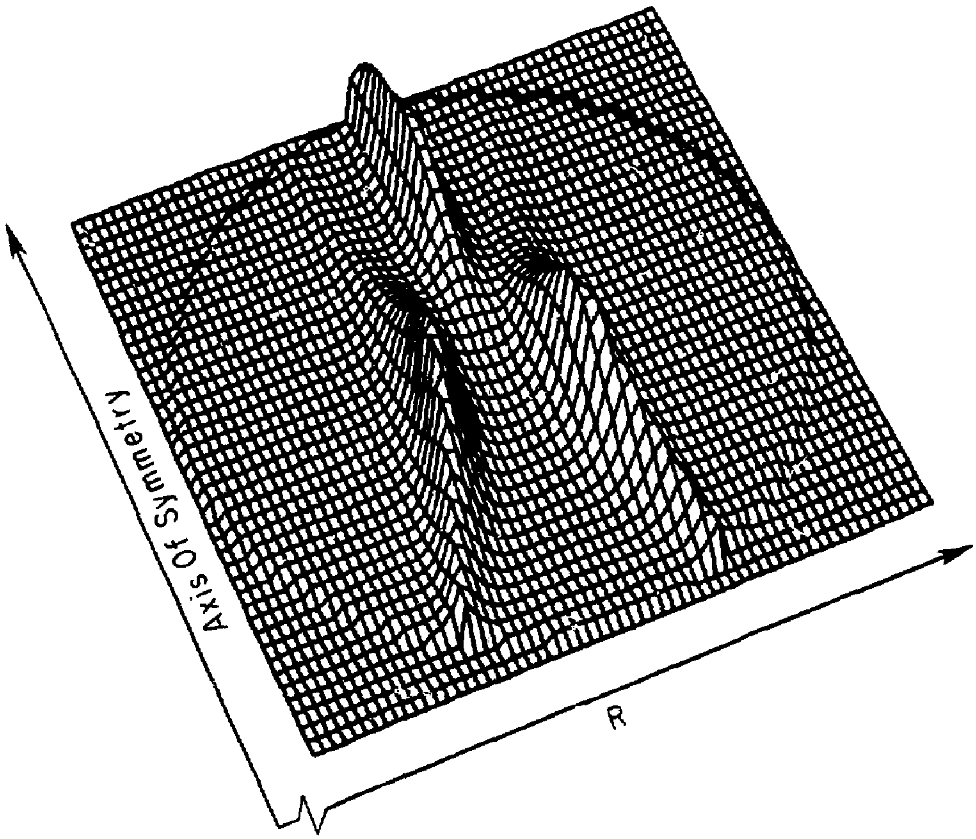

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Fig. 1. Scattering regions for the detection of fluctuations with $k = 10\ cm^{-1}$.

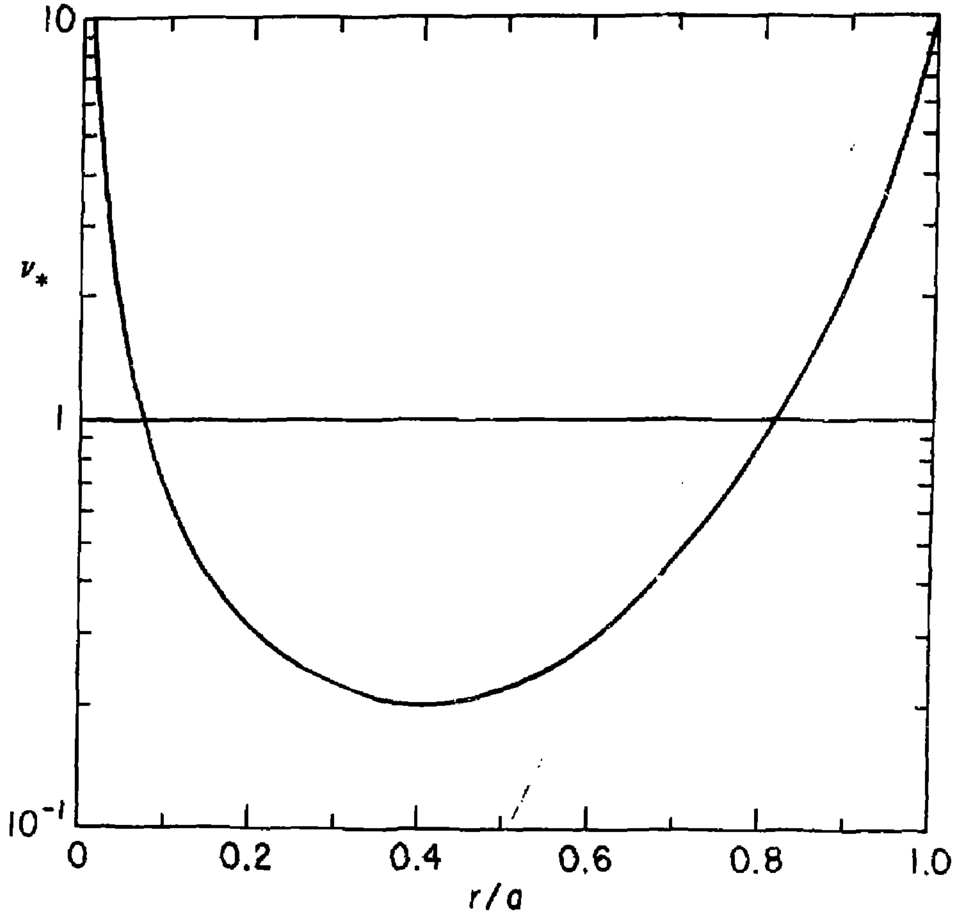

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Fig. 2. The collisional parameter ν_*^e of trapped electrons.

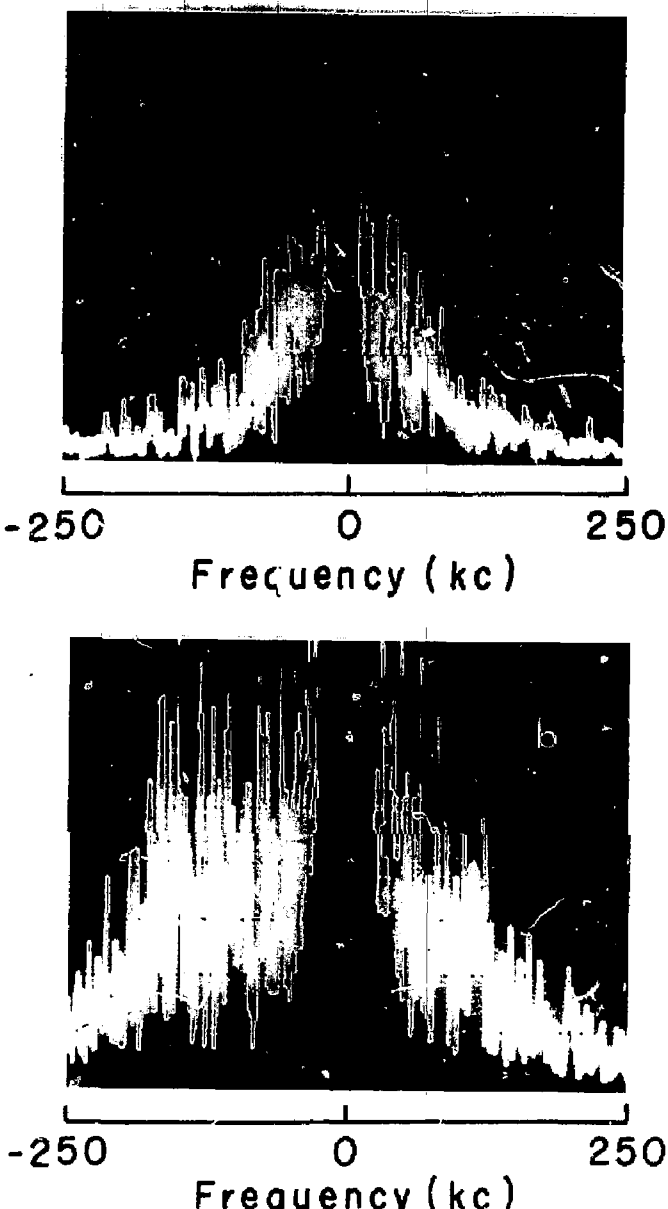

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Fig. 3. Frequency spectra of fluctuations with $k \simeq 10\ cm^{-1}$ and a) $\bar{n}_e = 2 \times 10^{13}\ cm^{-3}$, b) $\bar{n}_e = 4 \times 10^{13}\ cm^{-3}$. Negative frequencies correspond to phase velocities along the electron diamagnetic direction.

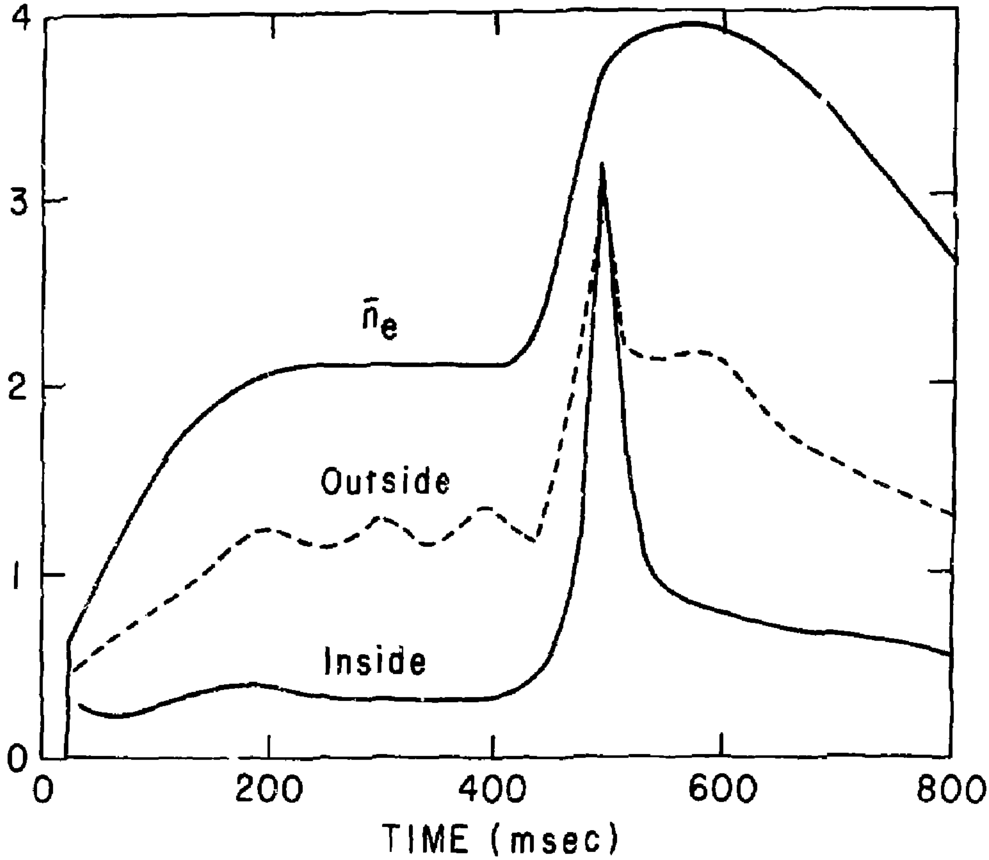

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Fig. 4. Time evolution of $\bar{n}_e$(10^{13} cm^{-3}) and that of $\bar{n}_e$(arb. units) in the inside and outside regions.

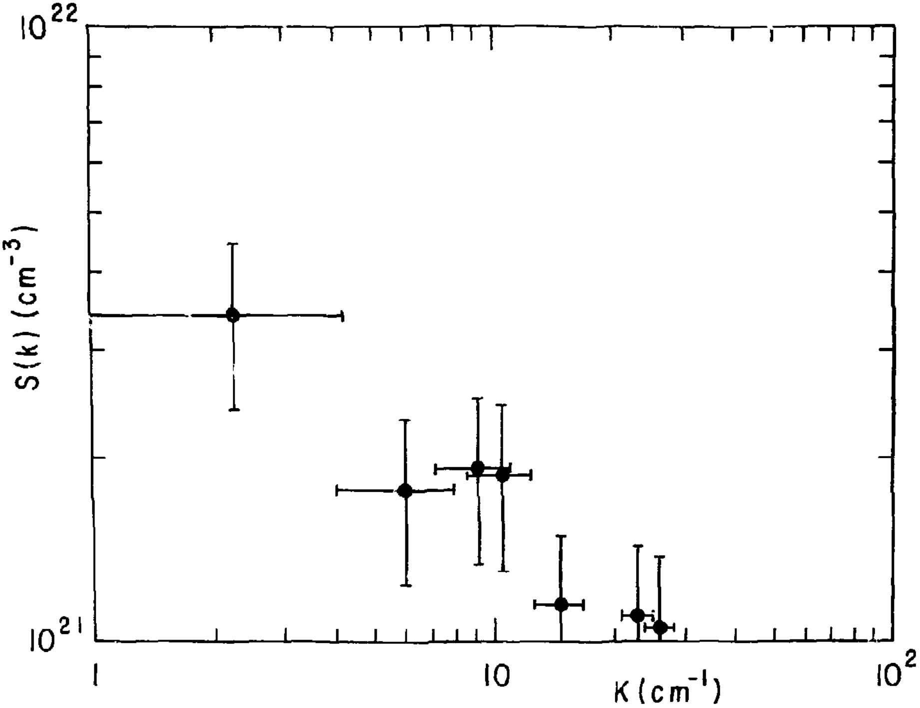

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Fig. 5. The spectral density S(k).

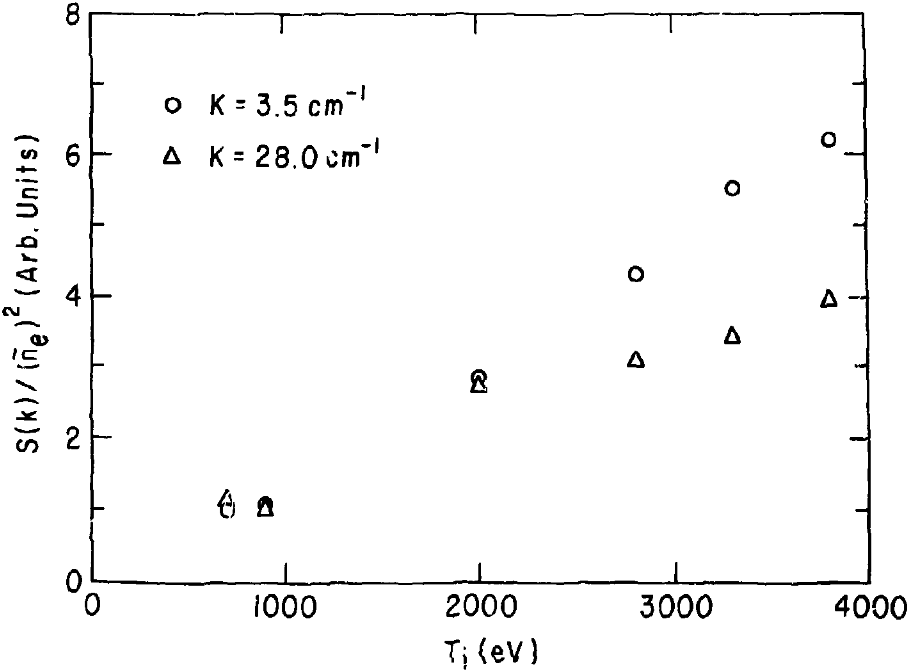

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Fig. 6. $S(k)/(\tilde{n}_e)^2$ vs $T_i(0)$.

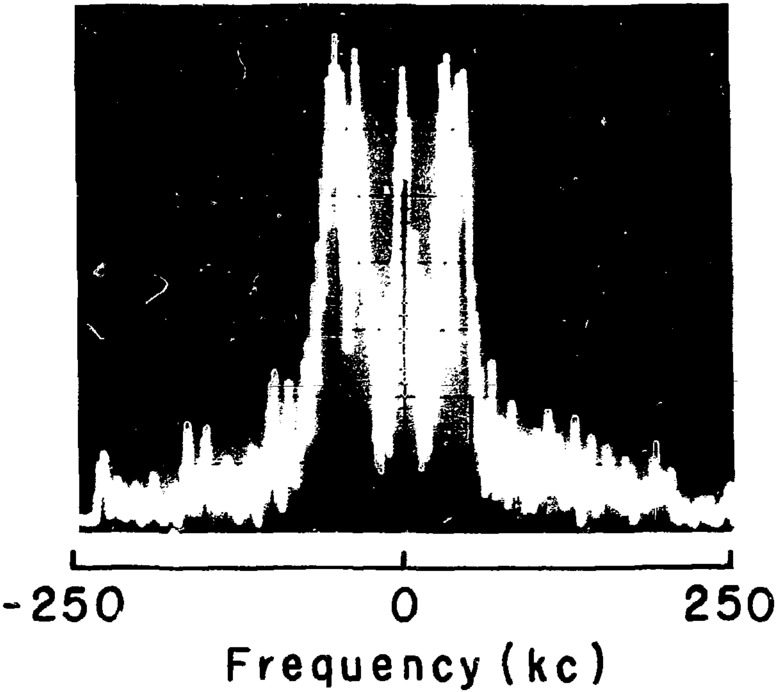

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Fig. 7. Frequency spectrum of fluctuations ($k = 10\ cm^{-1}$) in plasmas with $T_i(0) = 4.8$ keV.