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Spectrum of Small-Scale Density Fluctuations in Tokamaks

E. Mazzucato
Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08544

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The power spectrum of plasma density fluctuations in the range of frequencies of drift waves has been investigated in the Princeton Large Torus tokamak. The results suggest that the observed fluctuations evolve to a strong nonlinear state, and therefore they emphasize the need for a complete nonlinear theory of drift waves in tokamaks to assess their effects on plasma transport.

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The tokamak is the most successful of all the magnetic confinement schemes. Nevertheless, this type of configuration is still plagued by anomalous heat losses which remain one of its most critical issues.

It has been known for a long time that the turbulence produced by drift-wave instabilities can adversely affect the transport of plasma. More recently Horton and Estes[1] have shown that the confinement of electrons in several Ohmically heated tokamaks is consistent with the predictions of the quasilinear theory of drift waves. Nevertheless the role played by these instabilities in the transport of plasma is not yet completely understood.

In this Letter, new data on the spectrum of density fluctuations in the range of frequencies of drift waves are presented. Their implications are that a complete nonlinear interaction of drift waves is essential for assessing their effects on the confinement of plasma in tokamaks.

Drift waves are excited by the free energy stored in the plasma by macroscopic inhomogeneities. According to the linear theory of drift waves in tokamaks,[2] the range of frequencies is $\omega/\omega_*{}^e \lesssim 1$, where $\omega_*{}^e = k_\theta c T_e/eBL_n$ (with k_θ the poloidal wave number and $L_n = |d\ln n/dr|^{-1}$ the density scale length). The upper limit, $\omega \approx \omega_*{}^e$, is reached by electron drift waves with long wavelengths (i.e., $k_\theta \rho_i \ll 1$, with ρ_i the ion Larmor radius) that propagate along the electron diamagnetic direction. The ion inertia and the finite ion Larmor radius come into play when $k_\theta\rho_i \gtrsim 1$ with the result of decreasing the value of $|\omega|$. As the ion temperature profile becomes steeper than the density profile (i.e., $\eta_i = d\ln T_i/d\ln n > \eta_0 \simeq 1\text{–}2$) the sign of ω is reversed, and we have drift waves which propagate along the ion diamagnetic direction. Various experimental observations[3-5] have indicated that a small-scale turbulence exists in tokamaks in a range of frequencies around $\omega_*{}^e$, with wavelengths $\lambda \gtrsim \rho_i$ and amplitude $\langle(\tilde{n})^2\rangle^{1/2} \simeq \langle n\rangle/(kL_n)$. One intriguing result has been the broad frequency spectra of the observed fluctuations whose spectral width $\delta\omega = (2\text{–}4)\omega_*{}^e$. If this is a real feature of the microturbulence of tokamaks it means that the plasma fluctuations induced by drift instabilities evolve very rapidly to a nonlinear state. Unfortunately the poor spatial resolution of those measurements could not rule out the possibility that the observed broadenings were simply produced by radial variations of plasma parameters. To clarify this crucial point, the power spectrum of density fluctuations in the range of frequencies of drift waves has been investigated in the Princeton Large Torus tokamak with scattering of microwaves.

An array of antennas, all located in the same poloidal plane, was used for launching an electromagnetic wave and for collecting the waves scattered by plasma density fluctuations. The incident wave had a frequency of 140 GHz, and its electric field was parallel to the toroidal magnetic field.

The process of incoherent scattering by electron density fluctuations can be characterized by the differential cross section[6]

$$\sigma=\sigma_0 S(\vec{k},\omega),$$

where $\sigma_0=(e^2/mc^2)^2$ 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 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. Once the spectral density is known, the mean square density fluctuation is obtained with an integration over the entire $(\vec{k},\omega)$ space,

$$\langle(\tilde{n})^2\rangle=(2\pi)^{-4}\int S(\vec{k},\omega)d^3k\,d\omega.$$

A good spatial resolution was obtained by using high-gain antennas (≃ 38 dB). In general the radial extent of the scattering region (≃ 10 cm for $k\simeq 6$ cm^{-1}) was a decreasing function of k. On the contrary, the k resolution (≃ ± 1 cm^{-1}) was almost independent of the value of k. For most of the scattering geometries the average wave vector $\vec{k}$ was mainly along the poloidal direction.

For detecting the scattered waves, a heterodyne scheme with a frequency resolution of 10 kHz was employed. To avoid the deterioration of the spatial resolution produced by refractive effects, we limited our investigation to discharges with a central density of 2×10^{13} cm^{-3}. The rest of the plasma parameters were (with standard notations) $a=40$ cm, $R=134$ cm, $B_t=32$ kG, $I_p=420$ kA, $T_{e0}=1.5$ keV, $T_{i0}=0.8$ keV, $A=1$, and $Z_{\rm eff}\simeq1$. The electron energy confinement time was ≃ 10 msec. In this range of parameters the value of ν_*^e, the ratio of the effective collision frequency of trapped electrons to their bounce frequency, was less than 1 over most of the plasma column and reached a minimum of ≃ 0.1 at $r=12$ cm.

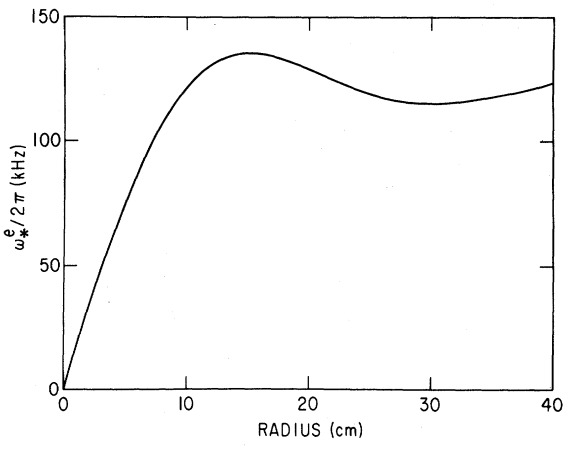

FIG. 1. Plot of ω_*^e vs the minor radius for $k_\theta=10$ cm^{-1}.

Shown in Fig. 1 is the radial dependence of ω_*^e, for $k_\theta=10$ cm^{-1}, calculated by using the electron temperature and density profiles as determined by Thomson scattering measurements. Notice that ω_*^e is almost constant in the region $r>10$ cm.

The power spectrum $S(k,\omega)$ of density fluctuations observed at three radial locations is shown in Fig. 2. These data clearly illustrate three important features of the microturbulence of tokamaks: (1) The spectra are shifted toward one side of the frequency axis; (2) the spectral width at half intensity has several times (2–4) the value of ω_*^e; (3) the spectral width of fluctuations at the boundary of the plasma column (where the

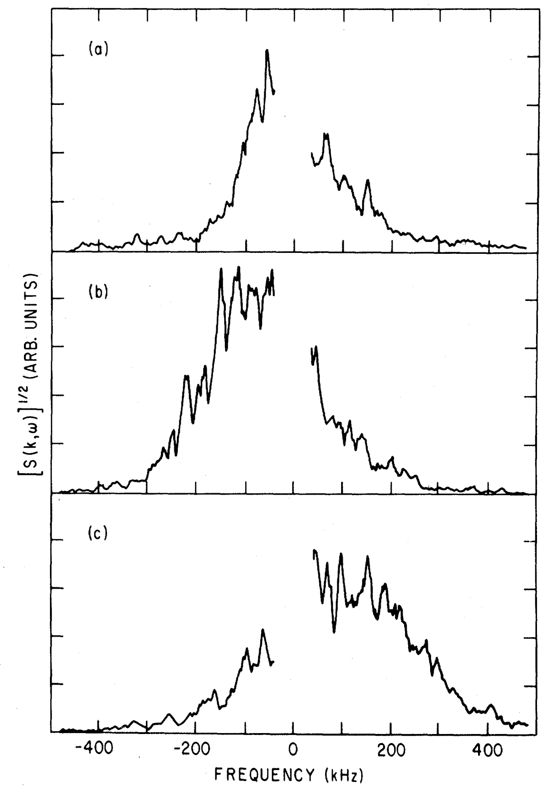

FIG. 2. Frequency spectra of density fluctuations: (a) $r=5$ cm, $k=5$ cm^{-1}; (b) $r=16$ cm, $k=7$ cm^{-1}; (c) $r=30$ cm, $k=6$ cm^{-1}.

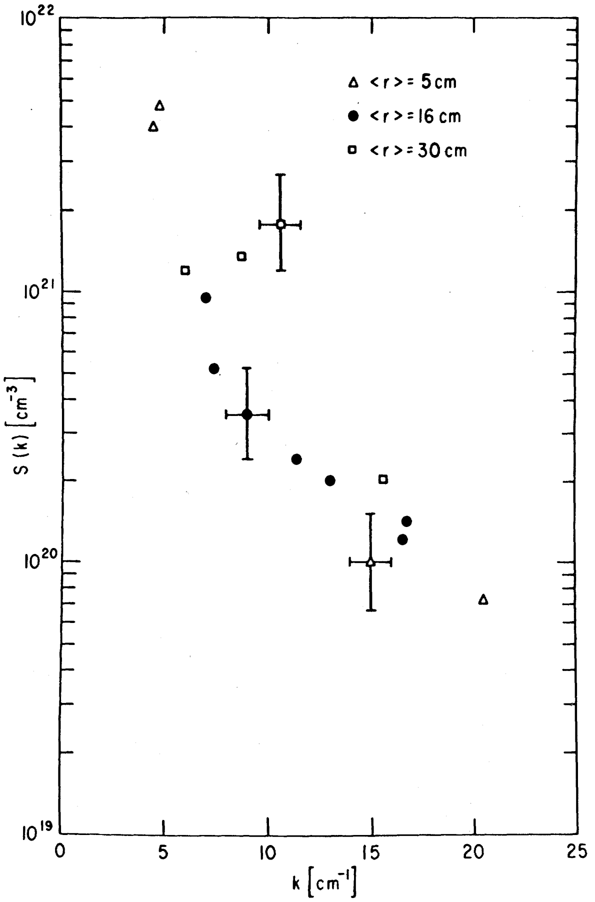

FIG. 3. Values of $S(k) = (2\pi)^{-1}\int_{-\infty}^{+\infty} S(k,\omega)\,d\omega$.

plasma collisionality increases) is larger than that of fluctuations in the central region.

The observed spectral shifts change sign when the direction of $\vec{k}$ or that of the toroidal magnetic field is reversed. They indicate that either the observed fluctuations tend to propagate along the electron diamagnetic direction or that the plasma column rotates because of a radial electric field produced by a negative plasma potential.

Shown in Fig. 3 are the values of $S(k) = (2\pi)^{-1} \times \int_{-\infty}^{+\infty} S(k,\omega)d\omega$. In the range of k of Fig. 3, $S(k)$ decreases monotonically in the central region of the plasma column, while it has a maximum at $k \simeq 10$ cm^{-1} in the outer region. The position of this maximum corresponds to the condition $k\rho_i \simeq 0.5$, which is in agreement with previous observations in adiabatic toroidal compressor[3] and TFR[5] and more recently in the WT tokamak.[7] Because of the large central temperatures, the spatial resolution was not sufficient to determine if $S(k)$ also exhibited the same behavior in the central region of the plasma column.

As mentioned earlier, the total density fluctuation is obtained by integrating $S(\vec{k},\omega)$ over the entire $(\vec{k},\omega)$ space. Because of the limited region of $\vec{k}$ space which was investigated, only a rough estimate of $\langle(\tilde{n})^2\rangle$ can be given here. By assuming that the observed turbulence is isotropic in the plane perpendicular to $\vec{B}$ and that its range of parallel wave numbers $|k_\parallel| = |\vec{k}\cdot\vec{B}|/|\vec{B}|$ is smaller than the instrumental k resolution, we estimate that the value of $\langle(\tilde{n})^2\rangle^{1/2}/\langle n\rangle$ is 4×10^{-3} at $r\simeq 5$ cm, 6×10^{-3} at $r = 15$ cm, and 2×10^{-2} at $r = 30$ cm.

In conclusion, the results presented in this Letter indicate that the previously observed frequency spectra[3-5] are not the result of instrumental effects, but they are a real feature of the microturbulence caused by drift instabilities in tokamaks. The broad spectra suggest that the observed fluctuations evolve to a strong nonlinear state, and therefore they emphasize the need for evaluating their effects on plasma transport in tokamaks.

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