Small-Scale Density Fluctuations in the Adiabatic Toroidal Compressor*

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A new class of density fluctuations has been observed in the adiabatic toroidal compressor (ATC) tokamak by spectral analysis of scattered microwaves. The observed frequency spectrum is consistent with that of drift waves with amplitudes that are maximum in the wavelength range 0.5–1.0 cm where the transverse inertia of ions is important for plasma stability. The total density fluctuation is $\tilde{n}_e \gtrsim 5\times10^{-3}\bar{n}_e$. We estimate that these fluctuations could account for a large fraction of the electron energy losses of the ATC discharge.

One of the most intriguing and worrying phenomena in tokamaks is the large transport of the electron heat. It is universally acknowledged that this anomalous loss is caused by microinstabilities[1,2] but any direct evidence of the existence of these phenomena in tokamaks was missing up to now. In this Letter I report the first experimental observation of small-scale density fluctuations in a tokamak.

To detect the presence of small-scale density fluctuations in the adiabatic toroidal compressor (ATC) discharge I used the scattering of microwaves. The output of a 70-GHz oscillator, with a power of 20 W, was launched into the plasma as a wave in the ordinary mode. An array of antennas was installed inside the vacuum vessel so that it was possible to make measurements at six scattering angles between 11° and 64°. The geometry was such that the vector $\vec{k}=\vec{k}_i-\vec{k}_s$ ($\vec{k}_i$ and $\vec{k}_s$ being the wave vectors of the incident and the scattered waves, respectively) was along the poloidal direction of the tokamak configuration. The scattering region was midway between the center and the edge of the plasma minor cross section.

A homodyne detection system was used in which the received wave was mixed with a larger reference wave directly from the microwave oscillator. The signal from a crystal detector was sampled (2000 times with a maximum sampling frequency of 5 MHz), stored in an electronic waveform recorder, and analyzed with a spectrum analyzer. The frequency spectral resolution was primarily limited by the length of the sampling window (typically 0.4–1.0 msec).

The scattering cross section, which is defined as the fraction of the incident flux which is scattered at the frequency $\omega_0+\omega$ (ω_0 = frequency of the incident wave) per unit volume, solid angle, and frequency, is

$$\sigma = r_0^2 S(\vec{k},\omega), \tag{1}$$

where r_0 is the classical electron radius and $S(\vec{k},\omega)$ is the power spectrum of electron density fluctuations, given by[3]

$$S(\vec{k},\omega)=\lim_{\substack{V\to\infty\\T\to\infty}}\frac{2}{VT}|n_e(\vec{k},\omega)|^2, \tag{2}$$

with

$$n_e(\vec{k},\omega)=\int_T dt\int_V d^3r\, e^{-i(\omega t+\vec{k}\cdot\vec{r})}n_e(\vec{r},t) \tag{3}$$

and $\vec{k}=\vec{k}_i-\vec{k}_s$.

The use of Eq. (1) implies that the linear dimensions of the scattering volume are much larger than the wavelength of density fluctuations. For tokamaks we expect that $k_\parallel \equiv |\vec{k}\cdot\vec{B}|/|\vec{B}|\simeq 1/qR$, where $\vec{B}$ is the magnetic field, q is the safety factor, and R is the major radius. For such long wavelengths the second condition is not satisfied but we may consider $n_e(\vec{r},t)$ to be constant along the magnetic field lines and replace Eq. (1) by

$$\sigma = r_0^2 L_\parallel S(\vec{k}_\perp,\omega), \tag{4}$$

where $L_\parallel$ is the average dimension of the scattering volume along the magnetic field and $S(k_\perp,\omega)$ is the spectral density obtained by replacing $\vec{k}$ by $\vec{k}_\perp=\vec{k}-(\vec{k}\cdot\vec{B})\vec{B}/|\vec{B}|^2$ and $\vec{r}$ by $\vec{r}_\perp=\vec{r}-(\vec{r}\cdot\vec{B})\vec{B}/|\vec{B}|^2$ in Eqs. (2) and (3).

The scattering volume, which was determined by the radiation patterns of the launching and the receiving antennas, was a decreasing function of the scattering angle θ_s. Its average dimension along the minor radius varied from ~ 10 cm for $\theta_s = 11°$ to ~ 5 cm for $\theta_s = 64°$. Therefore the values of $S(\vec{k}_\perp,\omega)$ obtained from Eq. (4) were averaged over large portions of the plasma minor cross section.

The frequency spectra of the homodyne signals measured at four scattering angles are shown in Fig. 1. They were produced by density fluctuations with wavelengths $\lambda_\perp = 2\pi/|\vec{k}_\perp| = \pi/|\vec{k}_i|\sin(\theta_s/2)$ in the range 0.4–2.3 cm. These results were

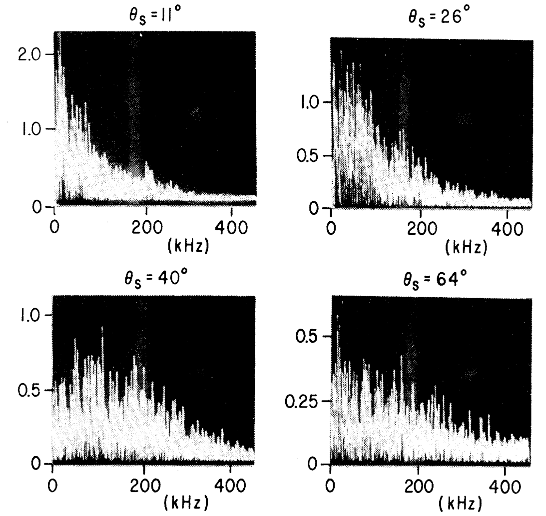

FIG. 1. Spectra of microwaves scattered by density fluctuations with wavelengths of $\lambda(11°) = 2.3$ cm, $\lambda(26°) = 1.0$ cm, $\lambda(40°) = 0.6$ cm, $\lambda(64°) = 0.4$ cm. θ_s is the scattering angle; the ordinate is in arbitrary units and is proportional to the electric field of scattered microwaves.

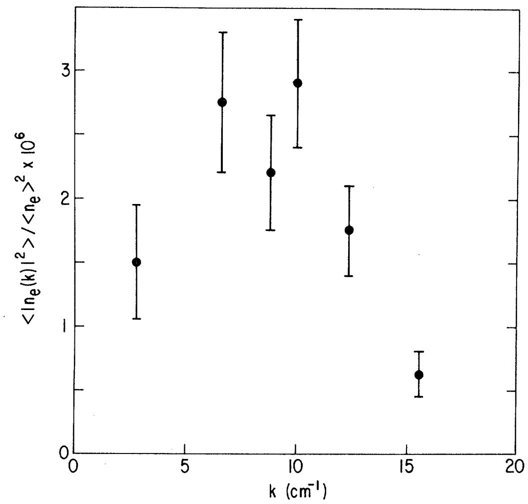

FIG. 2. Amplitude of density fluctuations as a function of $k = 2|\vec{k}_i|\sin(\theta_s/2)$; $\langle n_e\rangle$ is the average electron density.

obtained in a typical uncompressed ATC discharge[4] where (with standard notation) $a = 16$ cm, $R = 80$ cm, $B_t = 20$ kG, $\bar{n}_e = 2\times 10^{13}$ cm^{-3}, $\bar{T}_e = 400$ eV, $\bar{T}_i = 150$ eV, $I_p = 70$ kA, $q = 4.5$, $Z_{\rm eff} = 5$. The gross electron energy confinement time was 5 msec.

The range of observed frequencies is that of drift waves. For the central region of the scattering volume we calculate a drift frequency of ~ 150 kHz for $\lambda_\perp \simeq 1$ cm. Both the finite angular aperture of the antennas and the average over large scattering volumes contributed to the spectral broadening we observed. A considerable increase of the spectrum width occurs as the scattering angle is increased from 11° to 40°. At larger angles no remarkable change of the spectrum width was detected. This was due to the effects of the finite ion transverse inertia on the frequency of drift waves.

The total mean-square density fluctuation is given by

$$\langle|\tilde{n}_e|^2\rangle = (2\pi)^{-3}\int S(\vec{k}_\perp,\omega)d\vec{k}_\perp d\omega, \quad (5)$$

where the region of integration is the entire $(\vec{k}_\perp, \omega)$ space. The function $\langle|n_e(\vec{k}_\perp)|^2\rangle = (1/4\pi^3)\int S(\vec{k}_\perp, \omega)d\omega$, which was obtained by integrating the spectral density over the measured frequency range, is shown in Fig. 2 for six values of $\vec{k}_\perp = \vec{k}_i - \vec{k}_s$. It reaches a maximum for values of $k_\perp = |\vec{k}_\perp|$ such that $(k_\perp\rho)^2 \simeq 1$, where $\rho = c(m_i T_e)^{1/2}/eB$, indicating that the transverse inertia of ions plays a role in the observed fluctuations.

I measured only the scattering produced by waves with their wave vector along the poloidal magnetic field. For drift waves in tokamaks one expects a strong localization of perturbations around rational magnetic surfaces due to the shear of magnetic lines. The width of localizations is $\Delta \simeq \rho(L_S/L_n)^{1/2}$ where $L_n = (d\ln n_e/dr)^{-1}$ is the density scale length and $L_S = (qR/r)/(d\ln q/dr)$ is the shear length. Since in the ATC discharge $L_n/L_S \simeq 5\times 10^{-2}$, we expect that the spectrum of the observed turbulence extends to the region where $|\vec{k}\cdot\nabla p|/|\nabla p| \gg 1$ cm^{-1} (∇p = pressure gradient). Therefore, by integrating the function $\langle|\tilde{n}_e(k_\perp)|^2\rangle$, shown in Fig. 2, over the variable $k_\perp = 2|\vec{k}_i|\sin(\theta_s/2)$ we obtain a lower limit to the mean-square density fluctuation induced by the observed microinstabilities. From the data of Fig. 2 we get $(\langle|\tilde{n}_e|^2\rangle)^{1/2} \gtrsim 5\times 10^{-3}\bar{n}_e$.

For values of $L_n/L_S \simeq 5\times 10^{-2}$ the ATC discharge is unstable with respect to collisionless drift waves like the universal mode[5] or the current-driven mode.[6] Moreover, in some region of the discharge the effective collision frequency of trapped electrons reaches values very close to that of the bounce frequency so that we anticipate the appearance of the dissipative trapped-electron mode.[7] Nevertheless, one the basis of present experimental results we cannot rule out the existence of other types of drift instabilities.

To evaluate the effects of the observed turbulence on the electron transport we shall rely on the usual estimate of the anomalous diffusion associated with the presence of electrostatic fluctuations. The diffusion coefficient is[8]

$$D \simeq \sum_k \frac{\gamma_k}{\omega_k^2}\left(\frac{k_\theta \varphi_k c}{B}\right)^2,$$

where φ_k is the amplitude of the electrostatic potential of the $\vec{k}$ mode, ω_k and γ_k are the real and the imaginary part of the frequency, k_θ is the poloidal component of the wave vector, and the sum is over all the existing modes. For a low-frequency electrostatic wave we can take $\tilde{n}_k/\bar{n}_e \simeq e\varphi_k/T_e$. If $\gamma_k/\omega_k \simeq 10^{-1}$ the level of the observed fluctuations accounts for the total electron losses of the ATC discharge.[4]

In conclusion I have observed a new class of small-scale density fluctuations in the ATC tokamak. Their frequency spectrum is consistent with that of drift waves and their amplitudes are maximum in the range of wavelengths where the transverse inertia of ions plays a role in the plasma stability. The amplitude of these fluctuations are sufficient to explain a large fraction of the electron energy losses of ATC.

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Shock Waves Generated by an Oscillating Electric Field in an Expanding Plasma

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A strong radio-frequency field applied to an expanding plasma is found to produce a shock at the surface where the local plasma frequency matches the applied frequency. The shock propagates towards the upstream overdense region with the ion-acoustic speed relative to the plasma flow. The density jump at the shock front is found to be proportional to the field amplitude.

Recent experiments[1,2] and numerical simulations[3] have indicated that when an intense oscillating electric field is applied to a plasma, it modifies the plasma density profile and makes plasma cavities near the plasma wave cutoff where the applied pump field frequency ω_0 equals the local electron plasma frequency ω_{pe}. In contrast to the above experiments which have been carried out in a stationary plasma, a laser-produced plasma interacts with the laser light while the plasma is expanding. In the present experiment, we intend to study the evolution of the plasma density in an

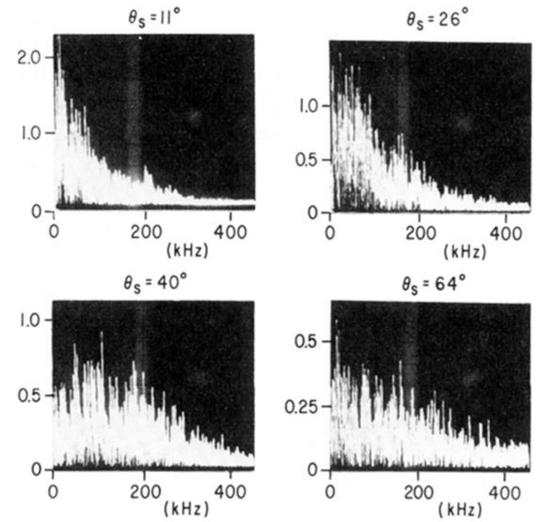

FIG. 1. Spectra of microwaves scattered by density fluctuations with wavelengths of $\lambda(11°) = 2.3$ cm, $\lambda(26°) = 1.0$ cm, $\lambda(40°) = 0.6$ cm, $\lambda(64°) = 0.4$ cm. θ_s is the scattering angle; the ordinate is in arbitrary units and is proportional to the electric field of scattered microwaves.