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Turbulent Temperature Fluctuations in the Princeton Large Tokamak Plasma

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We present the first experimental evidence for the existence of turbulent temperature fluctuations in plasmas. These measurements were accomplished by a spectral analysis of blackbody electron cyclotron emission. The fractional fluctuation in the mean electron energy is up to 10% for typical Princeton Large Tokamak discharges. The spectrum of temperature turbulence extends well beyond the electron diamagnetic-drift frequency f_* and shows no resemblance to the simultaneously existing turbulent density fluctuations.

There have been extensive experimental studies of turbulent density fluctuations (such as those associated with drift waves, ion acoustic waves, electron plasma waves, etc.) in linear and toroidal plasma devices.[1] The purpose of these studies has been to identify the cause of turbulent density fluctuations and to examine the possible dependence of the observed apparent anomalous particle- and energy-confinement properties as well as the observed anomalous skin effect and the electrical resistivity of plasmas on the level of turbulence. These anomalous transport and resistive properties of plasmas can be caused not only by turbulent density fluctuations but also by turbulent temperature fluctuations. It is needless to say that a clear understanding of turbulence in toroidal plasmas is of vital importance to and is of considerable current interest in tokamak fusion research. To our knowledge no prior experimental study of turbulent temperature fluctuations in plasmas has been reported in the literature.

The apparent reason for the total lack of experimental information on temperature fluctuations in plasma is due to the fact that the conventional plasma diagnostic techniques (such as the scattering of electromagnetic waves from plasmas, Langmuir probes in low-density, low-temperature laboratory plasmas, etc.) are capable of measuring only the density fluctuations and are not at all sensitive to temperature fluctuations. In this Letter we wish to present the first experimental evidence for the existence of turbulent temperature fluctuations in plasmas. These measurements of temperature turbulence in the Princeton Large Tokamak (PLT) plasma were accomplished by a spectral analysis of blackbody emission near the second harmonic of the electron cyclotron frequency[2] (i.e., $f \approx 2f_{ce}$).

Figure 1 is a schematic block diagram of the

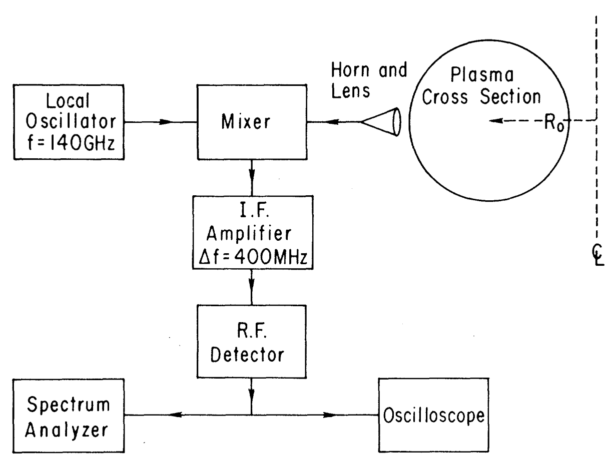

FIG. 1. Block diagram of the experimental arrangement.

experimental arrangement. Blackbody microwave emission near the second harmonic of the electron cyclotron frequency, $f \approx 2f_{ce}$, from the PLT plasma is collected by the receiver horn and is mixed with a fixed amount of reference signal from a local oscillator ($f \approx 140$ GHz). The resultant radio-frequency (rf) output is amplified (by an amplifier of bandwidth $\Delta f \approx 400$ MHz) and is then detected with an rf detector. The signal from the output of the detector is displayed on a scope to provide measurements of the absolute value of the electron temperature T_e, and is also Fourier analyzed in the spectrum analyzer so as to make measurements on the turbulent temperature fluctuations $\delta T_e(f)$.

The receiving antenna (a horn-lens combination) is located in the equitorial plane along the major radius R and is oriented to receive extraordinary waves propagating mainly perpendicularly relative to the toroidal magnetic field B_φ. Here $R = R_0 + r$, where $R_0 = 132$ cm is the nominal major radius at the center of the plasma. Since in tokamaks $B_\varphi \propto R^{-1}$, the emitting blackbody second-harmonic layer $f \approx 2f_{ce}(R)$ can be placed at the desired R or r by choosing the appropriate magnetic-field level $B_\varphi(R_0)$ for the fixed receiver frequency $f \approx 140$ GHz. Thus we can measure the radial distribution of the level of temperature turbulence $\delta T_e(f, r)$ in the plasma. The spatial resolution is set by the receiver bandwidth $\Delta f \approx 400$ MHz, which gives a layer thickness $\Delta R \approx 0.4$ cm, and by the lobe width $\Delta\theta \approx \pm 2°$ of the horn-lens combination located at $r \approx 50$ cm, which gives a spot diameter $d \approx 3$ cm. Consequently, our method is sensitive to fluctuations with correlation lengths $L > d$.

From hot-plasma theory,[3] one can show that for electromagnetic waves of $f \approx 2f_{ce}$ propagating perpendicularly relative to B_φ (i.e., $\theta \approx \pi/2$) the imaginary part of the wave number $k_I \approx (4\pi^2 f_{pe}^2 \kappa T_e / 2mc^3)[(6-b)/(6-2b)]^2 \delta(f - 2f_{ce})$,where $b = 4\pi n mc^2/B^2 = (f_{pe}/f_{ce})^2 > 1$, and f_{pe} is the electron plasma frequency. The total optical depth for absorption of the radiation in a geometrical path length l is given by $\tau = \int_0^l dl\, 2k_I$. For our receiver system, the output signals on the scope are proportional to the emitted power P. That is,

$$P = \kappa T_e(R) \Delta f [1 - \exp(-\tau)], \qquad (1)$$

since the receiving antenna is approximately one dimensional. The output signal on the spectrum analyzer is then proportional to δP, which in turn is proportional to δT_e if $\tau \gg 1$ (i.e., when the emitting second-harmonic layer is optically thick). In a tokamak $f_{ce} \propto R^{-1}$, and for $f \approx 2f_{ce}$ one gets $\tau \approx (R/2f_{ce})(4\pi^2 f_{pe}^2 \kappa T_e / mc^3)[(6-b)/(6-2b)]^2$. For $b < 1$, $\tau \propto nT_e$ and thus $\delta P/P \approx \delta T_e/T_e + \tau(\exp\tau - 1)^{-1}[\delta T_e/T_e + \delta n/n]$. Hence, $\delta P/P \approx 2\delta T_e/T_e + \delta n/n$ for $\tau \ll 1$, and $\delta P/P \approx \delta T_e/T_e$ for $\tau \gg 1$. That is, for a tenuous plasma, the fractional fluctuation in the emitted power is a consequence of the fractional fluctuations in both the temperature and density. But for an optically thick[2] (i.e., black) plasma, $\delta P/P$ is determined only by $\delta T_e/T_e$. For our plasma conditions, τ varied from the value 7.3 at $r = 0$ (i.e., the plasma center) to the value 1 at $r = 30$ cm. Our measurements of the absolute value of $P(R)$ in conjunction with the laser Thomson-scattering measurements of $T_e(R)$ show that the $2f_{ce}$ layer is optically thick for $r \lesssim 25$ cm. ($\tau \gtrsim 2$ for blackbody emission.) Furthermore, as we shall see later, our measurements of $\delta P/P$ in conjunction with the 2-mm-microwave scattering measurements of $\delta n/n$ clearly show that $\delta P/P \gg \delta n/n$ and the frequency power spectra of δP and δn are quite different. Hence, we believe that our measurements of $\delta P/P$ reported in this Letter are clearly a consequence of $\delta T_e/T_e$ resulting from the existence of turbulent temperature fluctuations in the PLT plasmas.

In Fig. 2(a), we present the temporal evolution of $P(R \approx 142$ cm) for a typical PLT discharge.[4] The $T_e(R, t)$ obtained from this data by using Eq. (1) with $\tau \gg 1$ is in very good agreement with the corresponding laser Thomson-scattering measurements of $T_e(R, t)$. In Fig. 2(b), we show the power spectrum of the turbulent temperature fluctuations at $t \approx 200$ msec. From the data of Figs. 2(a) and 2(b) we find that $\delta P/P \approx \delta T_e/T_e \approx 0.1$. In Fig. 2(c) we show the corresponding instrumental-noise level[5] (i.e., the spectrum in the absence of plasma). The signal-to-noise ratio is remarkably good. The 2-mm-microwave scattering measurements in PLT show the presence of turbulent drift-wave density fluctuations similar to those which were detected in the adiabatic toroidal compressor (ATC) tokamak.[1] In Fig. 2(d), we show the frequency spectrum of the density fluctuations in PLT with a wavelength $\lambda \approx 1.4$ cm. It should be noted from Figs. 2(b) and 2(d) that the spectrum of the temperature fluctuations is quite different from that of the density fluctuations. In particular, the spectrum of δT_e is much broader and extends to much higher frequencies[6] than that of δn. Moreover, our measurements indiate that $\delta n/n \ll \delta T_e/T_e$.

By changing the toroidal magnetic field $B_\varphi(R_0)$

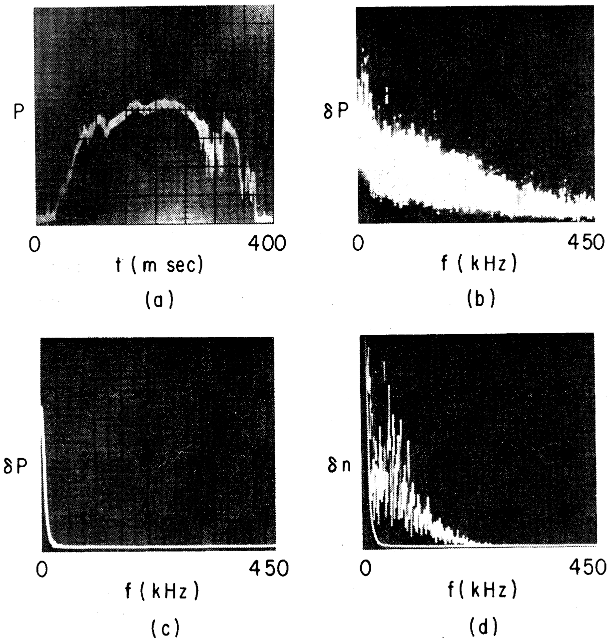

FIG. 2. (a) The temporal evolusion of P; (b) the frequency spectrum of δP fluctuations at $t \approx 200$ msec; (c) the instrumental-noise level; (d) the frequency spectrum of the density fluctuations. Conditions are as follows: $B_\varphi(R_0) \approx 27$ kG; $T_e(0) \approx 1.0$ keV; $n \approx 3\times 10^{13} \times (1 - r^2/40^2)$ cm^{-3}; $f_* \approx 50$ kHz for $\lambda \approx 1.5$ cm.

from 25 to 29 kG, it was possible to measure the radial distribution of the level of temperature turbulence in PLT from $r \approx 0$ cm to $r \approx 20$ cm. Our measurements indicate that $\delta T_e/T_e$ is fairly constant in this radial interval. For values of r ranging from 30 cm to the PLT plasma (i.e., 40 cm), δP fluctuations have contributions both from δT_e and δn fluctuations, since T_e and n are decreasing towards the plasma edge and in this range $\tau < 1$.

It is now physically instructive to pose the following questions: Are these (1) really turbulent temperature fluctuations, (2) thermodynamic equilibrium fluctuations of the photon–occupation-number density[7] in the $2f_{ce}$ blackbody layer, or δT_e fluctuations (3) due to stochastic wandering of the magnetic-field lines (i.e., magnetic braiding)[8] due to some background density wave turbulence or (4) due to local fluctuations in the current density $j(r)$ [since $j(r) \propto T_e^{3/2}(r)$] resulting from a stochastic breakup of the magnetic islands[8] by the background drift-wave, drift-tearing-mode, Alfvén-wave turbulence, etc.? (5) Is it a direct consequence of the simultaneously existing density fluctuations due to drift-wave turbulence[9]? (6) And finally is it a new normal mode of an inhomogeneous toroidal plasma corresponding to a temperature wave which has gone unstable, etc.? Our principal aim in posing these theoretical questions is to stimulate the interest of plasma theoreticians towards the problems of plasma temperature turbulence, since to our knowledge no analysis of this problem exists in the literature.

In order to answer the questions (1), (2), and (5), let us suppose that photons are produced with random phases Φ from a large number N of uncorrelated gyrating electrons in the second-harmonic blackbody layer. Let τ_0 be the lifetime of the photon (i.e., the time between the processes of emission and reabsorption). The photon number is proportional to the field energy

$$W = E_0^2 \exp(-t/\tau_0)\left(\sum \exp i\varphi_j\right)^*\left(\sum \exp i\varphi_j\right),$$

where E_0 is the electric-field intensity from a single gyrating electron. Then one can show[7] that the fractional fluctuations in the field energy

$$(\langle \delta W^2\rangle/\langle W\rangle^2)^{1/2} = [(\langle W^2\rangle - \langle W\rangle^2)/\langle W\rangle^2]^{1/2} \approx 1,$$

and $\langle \delta W^2\rangle \propto \exp(-2t/\tau_0)$. Thus the fractional fluctuations in the field energy is of order unity, and the half-width of the power spectrum of $\langle \delta W^2\rangle^{1/2}$ is $\Delta f_0 \approx (2\pi\tau_0)^{-1}$. If we assume that the $2f_{ce}$ layer still remains a blackbody, then $\delta W/W \approx \delta P/P \approx \delta T_e/T_e \approx 1$. However, at equilibrium one can show[7] that the fractional fluctuations of the mean electron energy in the grand-canonical ensemble is

$$F = [\langle \delta\epsilon^2\rangle/\langle\epsilon\rangle^2]^{1/2} = [\langle \delta T_e^2\rangle/T_e^2]^{1/2}$$
$$= [(\kappa T_e^2/U^2)(\partial U/\partial T_e)_N + (\langle \delta N^2\rangle/U^2)(\partial U/\partial N)_{T_e}^2]^{1/2},$$

where U is the internal energy[10] and at equilibrium $U = N\kappa T_e$. Hence, at equilibrium $F \approx \delta T_e/T_e \approx 2^{1/2}\delta N/N \approx 2^{1/2}N^{-1/2} \lesssim 10^{-7}$ for our experimental conditions. Since experimentally we find that the $2f_{ce}$ layer is a blackbody,[2] from the equipartition theorem it follows that $\delta W/W$ must remain equal to F and that the free fluctuations $\delta W \sim W$ are not allowed. Hence, we believe that our measurements are really measurements of turbulent temperature fluctuations and not of thermodynamics equilibrium fluctuations. Finally, we wish to state that the causes of this turbulence mentioned in questions (3)–(6) are likely candidates for our measurements.[11]

In conclusion, we have presented the first experimental evidence for the existence of turbulent temperature fluctuations in plasmas. The fractional fluctuation $F = \delta T_e/T_e$ is up to 10% for typical PLT discharges. Such large levels of temperature turbulence may be partly responsible for the observed anomalous transport and resistive properties of tokamak plasmas.

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[5]An additional check on the instrumental-noise level was also made by feeding into the receiver arm an amount of microwave power from a separate klystron which gives the same deflection on the scope as that shown at $t = 200$ msec of Fig. 2(a). The result was found to be identical to that of Fig. 2(c). Further, the low-frequency response of our receiver system was found to be flat from 0 to 1 MHz.

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Solitonlike Motion of a Dislocation in a Lattice

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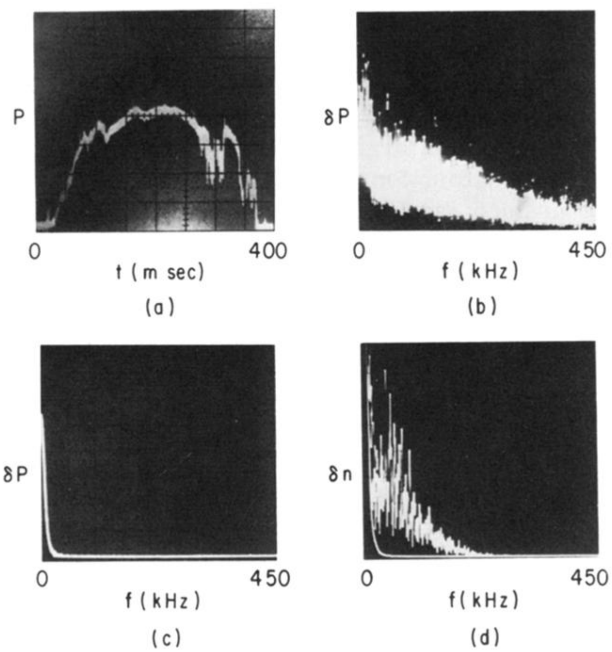
It is shown that an almost loss-free mode of motion for a straight screw dislocation exists in a three-dimensional lattice. Thus dislocations can move at velocities of the order of half the speed of sound at stress levels corresponding to a strain $s < 10^{-3}$, even in the presence of a much higher static Peierls stress. A strain of this magnitude can be provided by lattice vibrations, so that the dislocation-phonon complex moves in a solitonlike mode, requiring no external stress.

The radiation losses of a moving dislocation in an otherwise-perfect crystal at zero temperature are due to the emission of phonons resulting from the rearrangement of atoms in the core of the dislocation. Linear continuum elasticity predicts no radiation loss for a velocity $v < 1$ (in units of the speed of sound), but this is simply because all effects due to the discreteness of the medium (including the Peierls stress) are absent in this theory. The one-dimensional Frenkel-Kontorova model gives rise to the sine-Gordon equation, if displacement differences are replaced by derivatives; this equation has "soliton" solutions[1] that represent a dislocation in uniform, loss-free motion at zero stress for any $v < 1$. Keeping finite differences, Earmme and Weiner[2] discovered



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