Spontaneous Fluctuations of a Temperature Filament in a Magnetized Plasma

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(Received 20 May 1999)

This experiment illustrates the spatiotemporal pattern of the fluctuations that spontaneously develop in a magnetized temperature filament whose transverse scale is comparable to the electron skin depth. A high-frequency mode exhibits a striking spiral structure and is identified as a drift-Alfvén eigenmode. A low-frequency mode is found to be localized near the center of the filament. It is documented that the fluctuations significantly increase the transport of heat beyond the prediction of classical theory based on Coulomb collisions.

PACS numbers: 52.25.Gj, 52.25.Fi, 52.35.Kt, 52.35.Qz

In neutral gases it is well known that localized increases in temperature give rise to spectacular three-dimensional structures (e.g., hurricanes, tornadoes) that radically alter the transport of heat and mass. In a strongly magnetized plasma the confining pressure provided by the magnetic field can arrest the growth of such structures and thus quiescent regions of elevated temperature can be maintained, which is the central idea behind magnetic fusion research. However, for a given magnetic field strength there is a limit on the magnitude of the temperature gradient beyond which narrow temperature filaments spontaneously develop fluctuations that induce a transition away from classical transport [1,2] (i.e., transport due to Coulomb collisions). The goal of this experimental study is to identify the spatiotemporal properties of the fluctuations exhibited by a controlled temperature filament which exceeds such a limit and thus results in transport rates above those predicted by classical theory. This topic is of broad interest because temperature filaments can arise in a wide class of plasma environments, e.g., solar corona [3], auroral ionosphere [4], auxiliary-heated confinement devices [5], and reconnection [6], which are the focus of intensive research at this time.

The experimental arrangement is identical to that used previously [7] to observe the heat transport exhibited by an expanding temperature plume. Under quiescent conditions heat was observed to be conducted at the classical rates, along as well as across the confining magnetic field. The experiment consists of injecting a low voltage (15–20 eV) electron beam of small transverse extent (3 mm diameter) into a large, magnetized helium plasma (10 m long, 40 cm diam, magnetic field strength $\sim 1-2$ kG) generated in the Large Plasma Device (LAPD) at the University of California, Los Angeles. For the purposes of the present study the ambient plasma is essentially of infinite extent. The fast electrons emitted from the beam cathode are slowed down and thermalized in a fairly short distance due to collisions with the slow bulk plasma electrons and ions (the frictional drag term in the Fokker-Planck equation). Under the conditions of the experiments reported here, the 20 V beam electrons are slowed down in a distance of 70 cm. Thus the role of the beam is simply to produce a heat source a few millimeters in diameter and about a meter in length. Typical beam currents of 200 mA are used, resulting in a heat source strength of approximately 0.2 $\mathrm{W/cm^3}$. When these power densities are applied to afterglow plasmas in which the ambient electron temperature decays to a low level of $T_e \lesssim 1$ eV at densities $n \sim 2 \times 10^{12}\ \mathrm{cm^{-3}}$, it is possible to locally increase T_e by 5–10 times the ambient value, thus generating steep temperature gradients which spontaneously develop large fluctuations in density, temperature, and magnetic field.

Figure 1 exhibits the temporal evolution of the ion saturation current measured by a small Langmuir probe at various radial positions across a temperature filament at an axial distance 285 cm away from the beam injector. The average value of the I_{sat} signal can be interpreted as a measure of T_e in the following way. Ion saturation current averaged over fluctuations, $\langle I_{\mathrm{sat}} \rangle$, is converted to electron temperature by assuming $\langle I_{\mathrm{sat}} \rangle \propto n_e T_e^{1/2}$. Since the low voltage beam does not produce ionization, the plasma density in the filament is the same as the plasma column

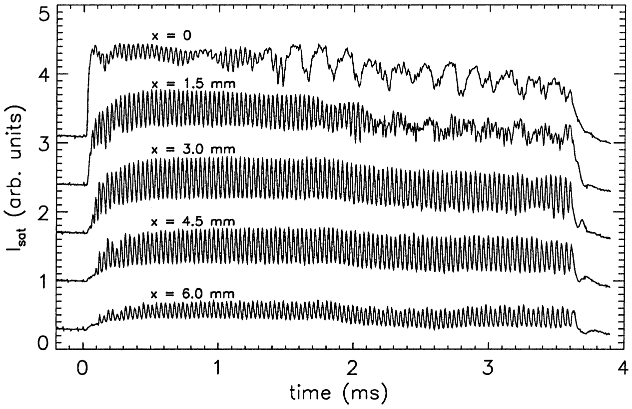

FIG. 1. Temporal evolution of ion saturation current at different radial positions across a temperature filament created by injecting a small, low-voltage beam into a large, strongly magnetized plasma. The transverse scale of the filament is comparable to the electron skin-depth. The average value of the curves represents temperature increases and the high-frequency fluctuations correspond to density fluctuations.

0031-9007/00/84(7)/1451(4)$15.00

density which is obtained from the phase shift recorded by a 56 GHz interferometer located 130 cm from the beam injection point. The magnitude of the electron temperature is calibrated using values obtained from Langmuir probe I-V traces. The electron temperature obtained using this technique agrees well with temperature measurements obtained with Langmuir probe voltage sweeps. For this pulsed-beam case one observes at the center of the filament ($x = 0$) a rapid temperature increase after beam turn-on at $t = 0$, followed by the development of high-frequency (~38 kHz) and low-frequency (~8 kHz) fluctuations of considerable amplitude. A detailed analysis of rapidly swept (5 μs) current–voltage (I-V traces) characteristics of the Langmuir probe indicates that the high-frequency fluctuations are representative of density variations ($\tilde{n}/n \sim 20\%$) while the low frequency fluctuations are predominately due to temperature changes ($\tilde{T}_e/T_e \sim 20\%$). By comparing the various traces in Fig. 1 it can be seen that the amplitude of the high-frequency oscillations peaks at an intermediate radial position ($x = 3.0$ mm, corresponding to the location of largest T_e gradient) while the low-frequency signal is localized near the center. At $x = 6.0$ mm one observes a modest increase in T_e with low-level fluctuations. The early increase in T_e can be explained quantitatively [7] in terms of classical transport.

The top panel of Fig. 2 displays the two-dimensional structure across the confining magnetic field of the high-frequency fluctuations in density at three selected times over an interval of 5.0 ion gyroperiods or about one half-cycle of the fluctuation period. The red color represents an increase, while the blue color is a decrease relative to the average value. This figure is obtained by taking an average over twenty, highly reproducible plasma pulses (at a repetition rate of 1 Hz) at every spatial location (with a grid resolution of 1.5 mm interpolated to 0.75 mm), thus indicating that the spontaneously generated structure undergoes phase locking that remains coherent over a significant time interval (greater than 100 ion gyroperiods). It is evident from Fig. 2 that the $\tilde{n}$ signal has an azimuthal mode number $l = 1$ and displays a spiral structure that can give rise to radial transport. Simultaneously with the fluctuations in density there appear fluctuations in the magnetic field $\tilde{B}$ in the direction transverse to the confining field (i.e., shear polarization). The $\tilde{B}$ fluctuations ($\tilde{B}/B \sim 10^{-4}$) are measured with small (2 mm) dB/dt loops that permit the determination of the local magnetic field vector in two dimensions across the filament, as shown in the bottom panel of Fig. 2. It is found that the magnetic structure is like a rotating dipole with a peak field at the center of the filament; physically, it is generated by two microscopic axial currents, embedded within the temperature filament (whose transverse scale is on the order of the electron skin depth, as indicated in Fig. 2), which rotate around the center of the filament. The sense of rotation of $\tilde{n}$ and $\tilde{B}$ corresponds to the direction of the electron diamagnetic drift associated with the transverse gradient in T_e. In order to obtain simultaneous ion saturation current and B-field data a probe larger than a single Langmuir probe was used. Some of the detailed variations in the spiral structure shown in Fig. 2 (such as the difference in the shape of the two spiral arms) are due to probe shadowing when this larger probe and probe

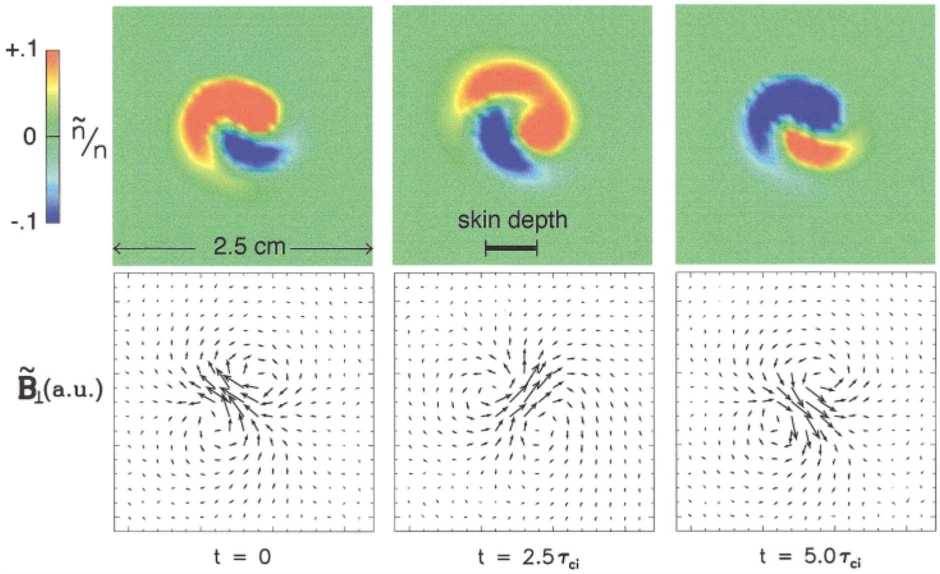

FIG. 2. Top (color): Snapshot at three different times of two-dimensional structure across the confining magnetic field of high-frequency density fluctuations that spontaneously develop in a narrow temperature filament. The red color is a density increase and blue is a decrease. Bottom: Self-consistent magnetic fluctuations having shear-mode polarization. Rotation is in the direction of electron diamagnetic drift. $t = 0$ is an arbitrary reference time and τ_{ci} is the ion gyroperiod.

shaft intersects the temperature filament. These effects are not present when a single small Langmuir probe is used. For completeness, it should be mentioned that a phase-locked spiral ($l = 2$) has been previously observed [8] in an argon plasma column generated by electron cyclotron waves, and a persistent spiral-arm structure has been formed [9] in a rotating plasma embedded in a stationary gas.

To quantitatively identify the nature of the high-frequency fluctuations, we compare the measured radial structure of the density and magnetic fluctuations with a theoretical calculation of unstable drift-Alfvén eigenmodes. The theory describes the electron behavior kinetically and includes the important effect of velocity-dependent pitch-angle scattering [10,11] (Lorentz model). The ion response is taken to be that of a cold, magnetized fluid (in the experiment $T_i \sim 0.5 - 1$ eV). The open symbols in Fig. 3 are the experimental measurements while the solid lines correspond to the theoretical predictions. The dashed line is an analytical fit to the measured temperature profile which facilitates the eigenmode calculation. It is found that the predicted radial structure of the most unstable drift-Alfvén mode is in excellent agreement with the observations. However, the predicted frequency is 26 kHz while the experimentally observed value is 38 kHz. This discrepancy suggests the possibility that a Doppler shift due to a static electric field in the radial direction may be contributing to the observed value in the stationary probe frame. Of course, there may be additional effects not included in the theory which may not alter the radial structure but give a small change in the real part of the eigenvalue.

To better elucidate the nature of the low-frequency fluctuations that appear to be highly localized in Fig. 1 the data is acquired with a grid spacing of 0.75 mm so that the spatial resolution of the Langmuir probe is not a limiting factor. Figure 4 displays the radial dependence of the electron temperature (solid line) along a radial cut across the filament, and the amplitude of the low-frequency fluctuations (dotted line). In contrast to the high-frequency mode in Fig. 3, the low-frequency structure peaks at the center of the filament and is identified as a $l = 0$ mode. It is consistently observed that the high-frequency modes develop earlier in time than the low-frequency fluctuations, as seen in Fig. 1, although the two processes can become blurred at high heating rates. While it is reasonable to expect that the low-frequency mode is ion acoustic, we have axial-correlation measurements which indicate that temperature maxima are transported along field lines much faster than the ion acoustic speed. Furthermore, the width and shape of the distribution of the fluctuations in I_{sat} corresponding to Fig. 4 are very similar to the distribution in the fluctuations of $T_e^{1/2}$ determined from voltage sweeps of the Langmuir probe. So it is consistent with the data to interpret the low-frequency fluctuations in I_{sat} as predominately temperature fluctuations, although at this stage we do not have a quantitative theoretical understanding of the driving mechanism for the low-frequency mode. However, the transport code used to analyze classical heat conduction predicts axial conduction of temperature fluctuations at rates faster than the ion acoustic speed and similar to those observed in the experiment.

Figure 5a displays the electron temperature profile in the direction transverse to the confining magnetic field at late times (7 ms) in the evolution of a temperature filament when the spontaneous fluctuations become broadband, at an axial distance of 410 cm from the beam injector. In Figure 5a the open circles correspond to measured values of T_e deduced from a consistent analysis [7] of Langmuir probe data. The dashed curve corresponds to the prediction of a two-dimensional transport code [7] that uses classical electron heat-conduction coefficients. Figure 5b shows the spectrum of the fluctuations at

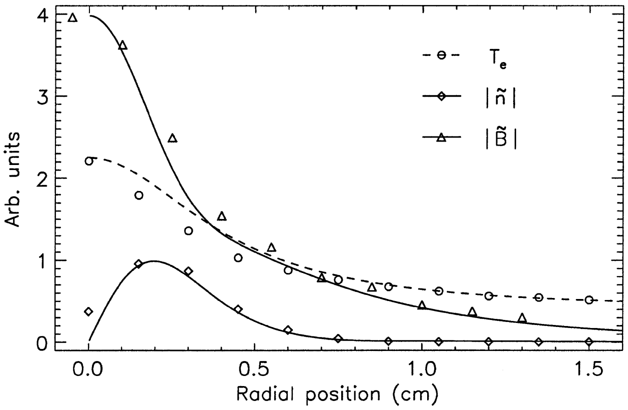

FIG. 3. Comparison between experimental measurements (discrete points) and theoretical predictions (solid curves) for the radial structure of the density and magnetic fluctuations associated with the most unstable drift-Alfvén eigenmode. The dashed curve is an analytical fit to the temperature profile used in the analysis.

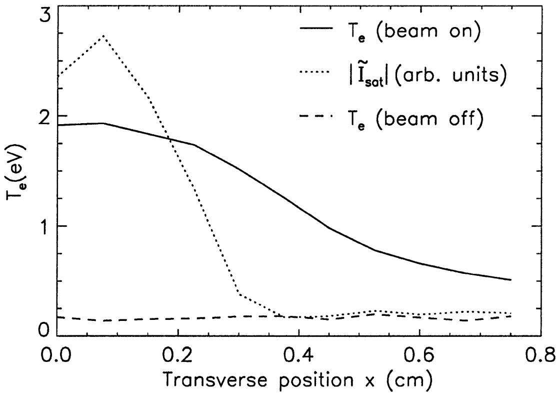

FIG. 4. Transverse structure of low-frequency mode (dotted curve) that characteristically develops after the onset of the spiral, high-frequency fluctuations of Fig. 2. The solid curve is the measured electron temperature profile of the filament and the dashed curve is the unperturbed profile.

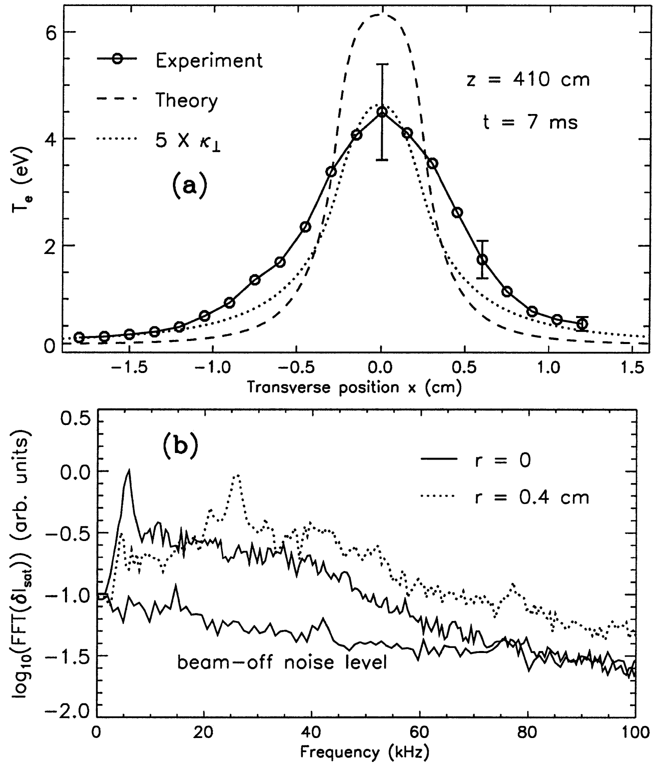

FIG. 5. (a) Electron temperature profiles across the confining magnetic field after the spontaneous fluctuations shown in Figs. 2 and 4 become broadband. The open circles are measured values of T_e, and the dashed curve is the prediction of classical transport theory. The dotted curve shows the predicted result if the classical perpendicular conductivity is multiplied by an anomaly factor of 5. (b) Frequency spectrum of I_{sat} fluctuations at two radial positions.

two radial positions. The spectrum in the center of the temperature filament ($r = 0$) has a clear peak at low frequency together with enhanced power (over the beam-off level) at higher frequencies. In the temperature gradient region of the filament ($r = 0.4$ cm) two peaks (at low and high frequencies) are evident together with a broadband component. It is evident from Fig. 5a that significant departures from classical transport theory are measured. The central temperature increases are considerably lower than predicted and significant increases are observed at radial positions well outside the original heat source. It should be emphasized that under quiescent conditions the observed T_e profiles agree [7] within experimental error with classical theory. To convey the sense of departure from classical behavior, the dotted curve in Fig. 5a shows the predicted result if the classical perpendicular conductivity is multiplied by an anomaly factor of 5.

In summary, it has been observed that a magnetized temperature filament spontaneously develops two types of fluctuations. A high-frequency mode with a striking spiral structure has been identified as a drift-Alfvén eigenmode. A lower frequency mode narrowly confined to the center and associated with temperature changes has not yet been theoretically explained. It has been documented that the fluctuations cause the heat transport to deviate significantly from the predictions of classical transport theory [1,2].

Research performed by A T. Burke and G. J. Morales was sponsored by DOE and ONR, and that of J. E. Maggs by ONR and NSF. The eigenmode calculations are a collaboration with Dr. J. R. Peñano.

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